Dalitz Plot Analyses and Charmonium Production at BaBar

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Overview

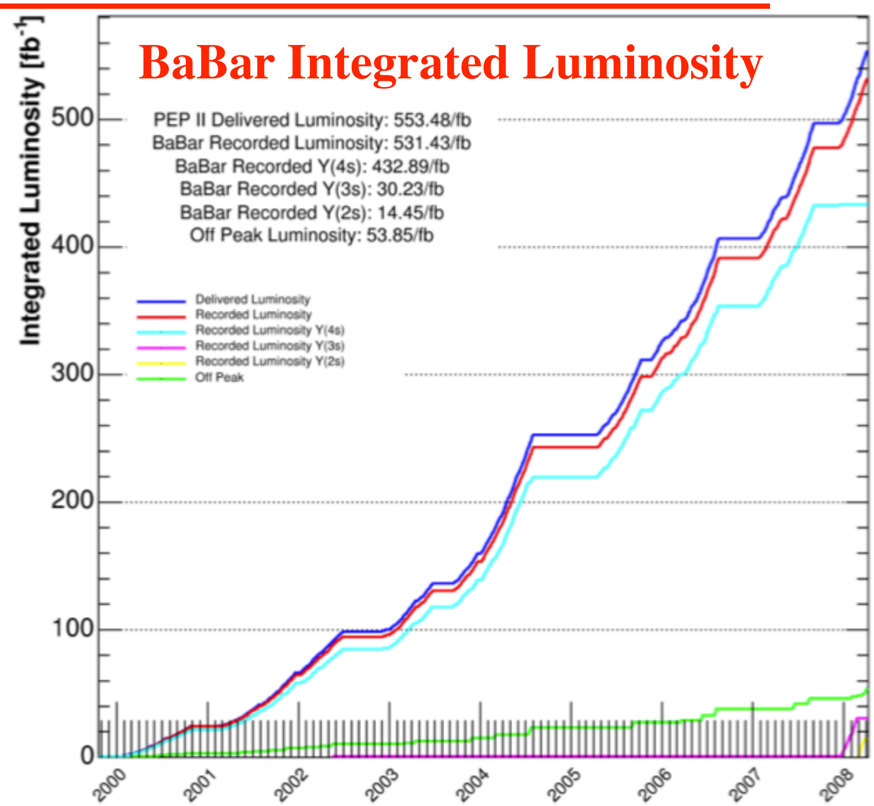
- "Measurement of the $I = 1/2$ $K\pi$ $\mathcal{S}$-wave amplitude from Dalitz plot analyses of $\eta_c \to K\overline{K}\pi$ in two-photon interactions"

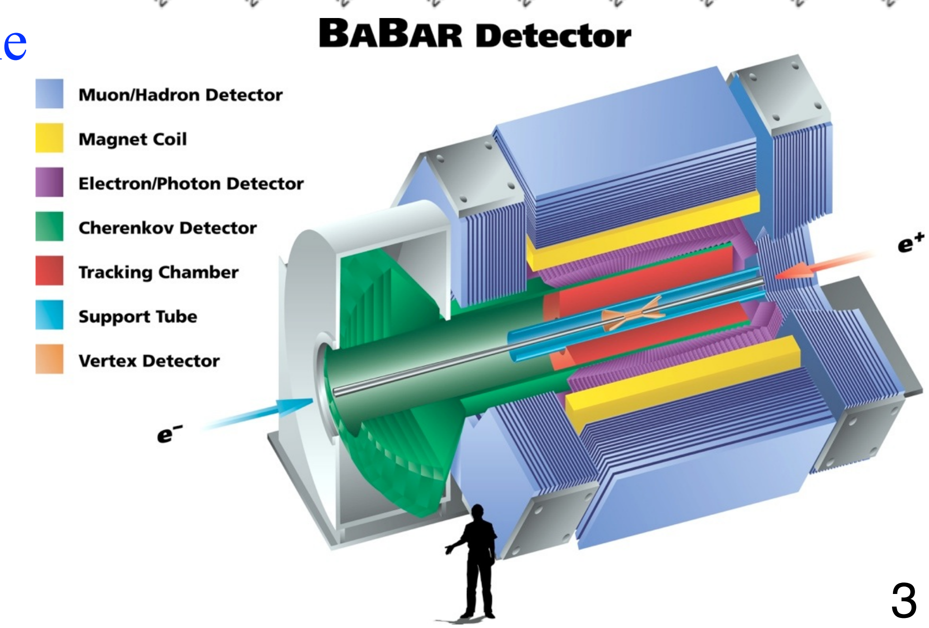
Phys. Rev. D 93, 012005 (2016)

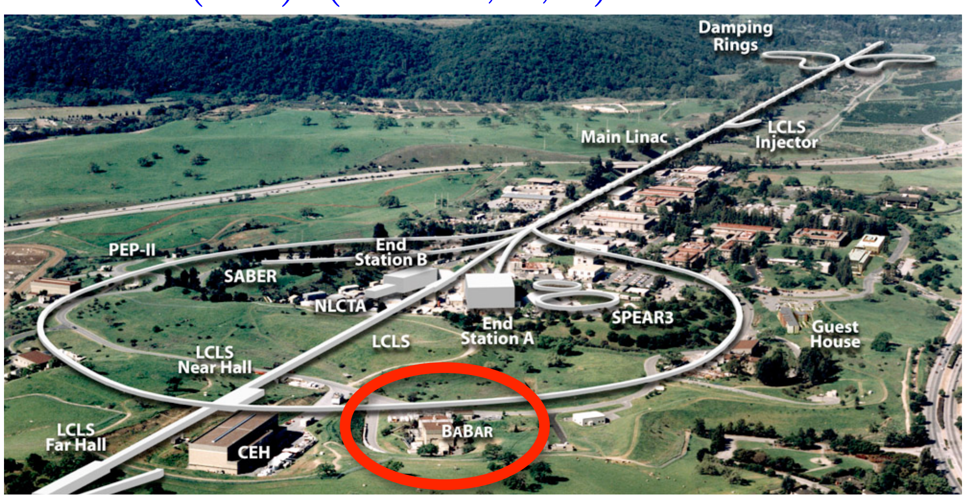
We study the processes $\gamma\gamma \to K^0_S K^\pm \pi^\mp$ and $\gamma\gamma \to K^+ K^- \pi^0$ using a data sample of 519 fb^{-1} recorded with the *BABAR* detector operating at the SLAC PEP-II asymmetric-energy e^+e^- collider at center-of-mass energies at and near the $\Upsilon(nS)$ ($n = 2, 3, 4$) resonances. We observe η_c decays to both final states and perform Dalitz plot analyses using a model-independent partial wave analysis technique. This allows a model-independent measurement of the mass-dependence of the $I = 1/2$ $K\pi$ $\mathcal{S}$-wave amplitude and phase. A comparison between the present measurement and those from previous experiments indicates similar behavior for the phase up to a mass of 1.5 GeV/c^2. In contrast, the amplitudes show very marked differences. The data require the presence of a new $a_0(1950)$ resonance with parameters $m = 1931 \pm 14 \pm 22$ MeV/c^2 and $\Gamma = 271 \pm 22 \pm 29$ MeV.

The BaBar Experiment

- Data collected by BaBar detector at Stanford Linear Accelerator Center
- Asymmetric-energy e^+ and e^- beams
- Designed to be a B factory, operating primarily at $\Upsilon(4S)$ resonance, producing 470×10^6 $B\overline{B}$ pairs
- Also a charm factory: 676×10^6 charm events
- This analysis uses $519\ \mathrm{fb}^{-1}$ collected at center-of-mass (CM) energies at and near the $\Upsilon(nS)$ $(n = 2, 3, 4)$ resonances





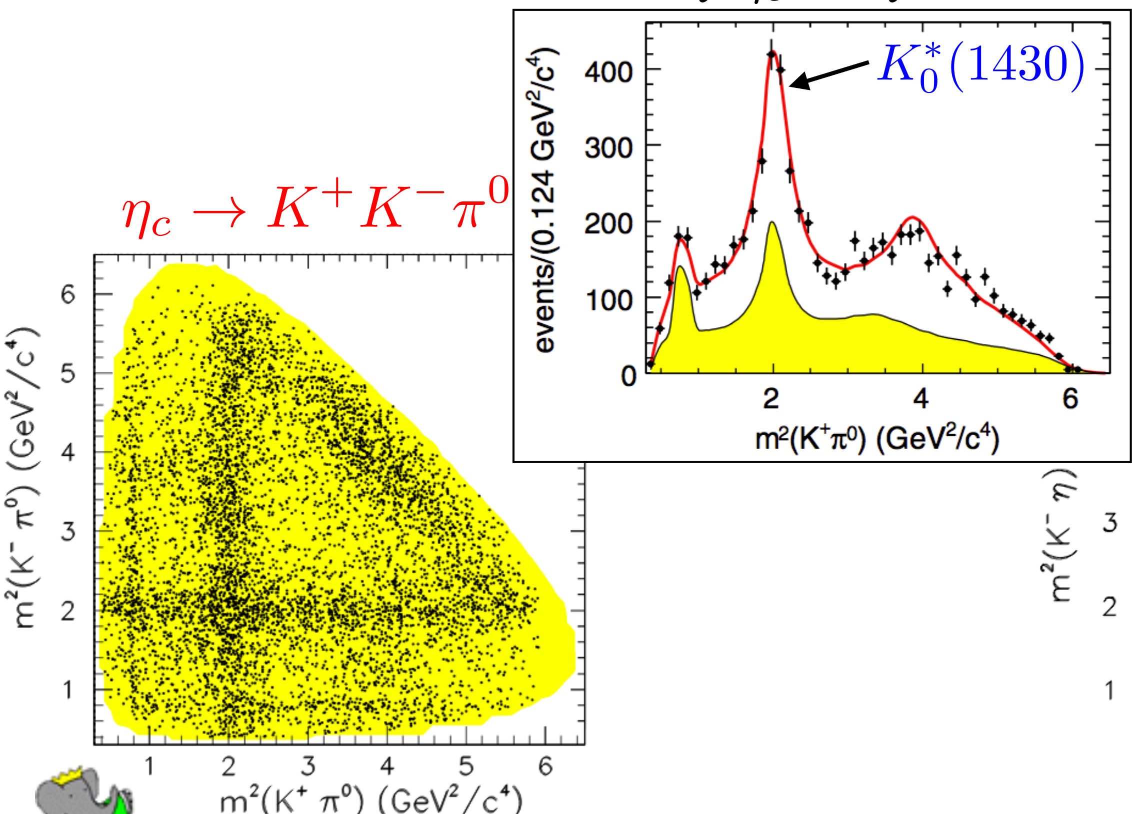


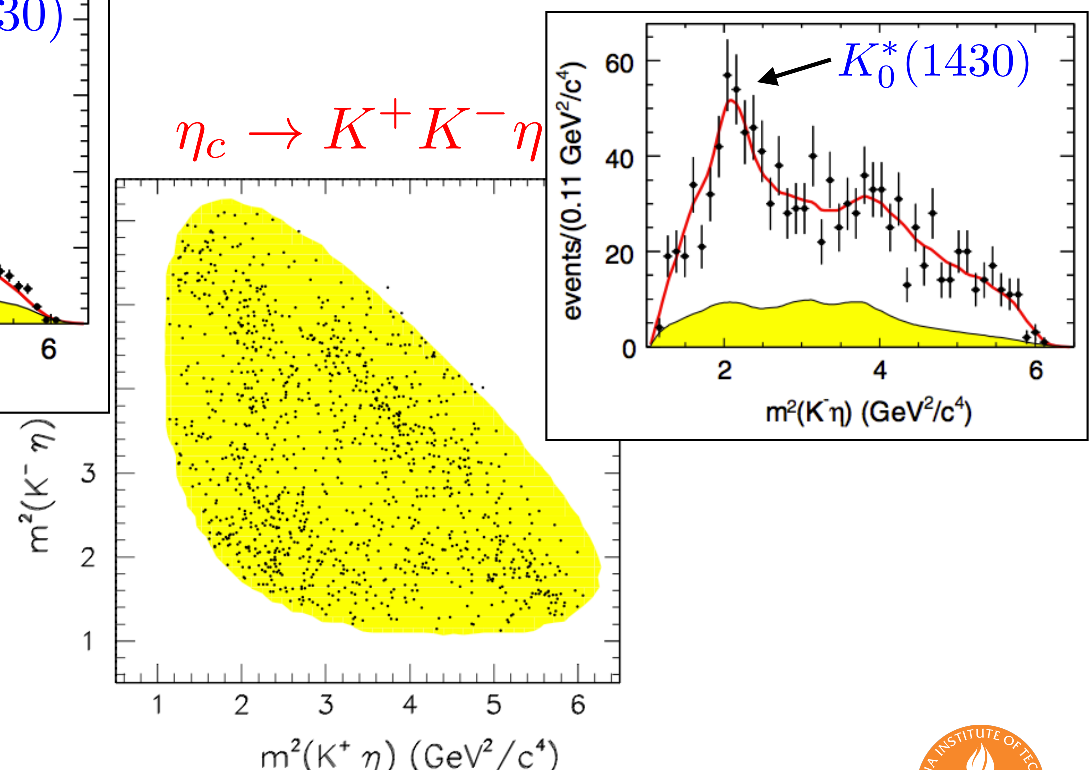
Previous BaBar Dalitz Analyses

- Previously, the BaBar experiment performed a Dalitz plot analysis of $\eta_c \to K^+K^-\pi^0$ and $\eta_c \to K^+K^-\eta$ using an isobar model

Phys. Rev. D 89, 112004 (2014)

  - Reported first observation of $K_0^*(1430) \to K\eta$
  - Intermediate scalar mesons dominate: $\eta_c \to$ pseudoscalar + scalar
    - Therefore, 3-body η_c decays are a valuable probe of scalar meson properties

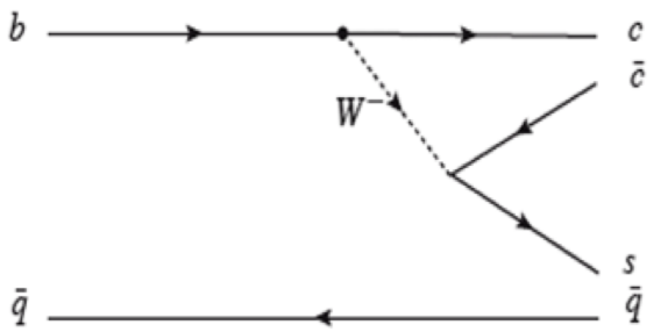




$$\frac{\mathcal{B}(K_0^*(1430) \to \eta K)}{\mathcal{B}(K_0^*(1430) \to \pi K)} = \mathcal{R}(\eta_c)\frac{f_{\eta K}}{f_{\pi K}} = 0.092 \pm 0.025 \pm 0.010$$

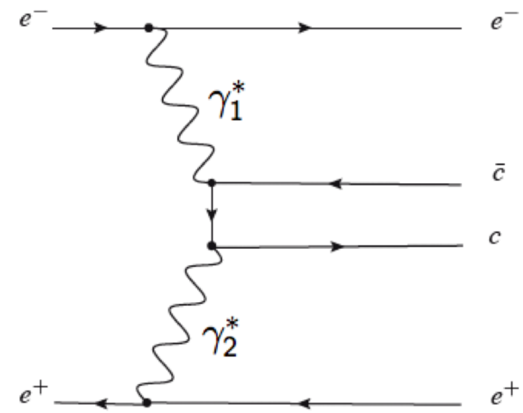
Charmonium Production at BaBar

B meson decays



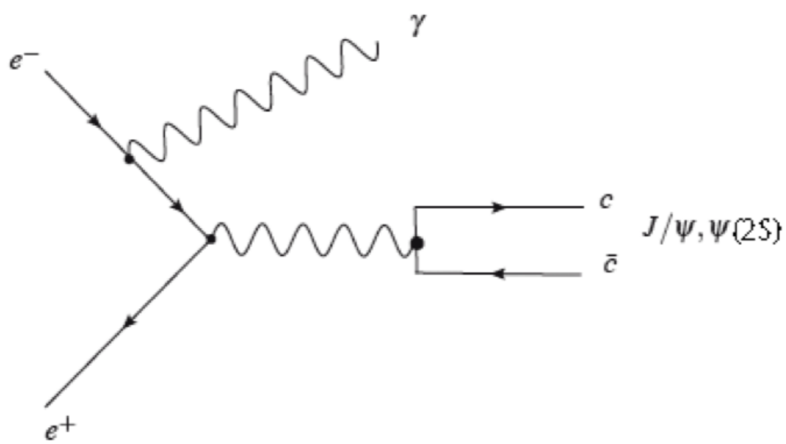
States of any quantum numbers can be produced

Two-photon production



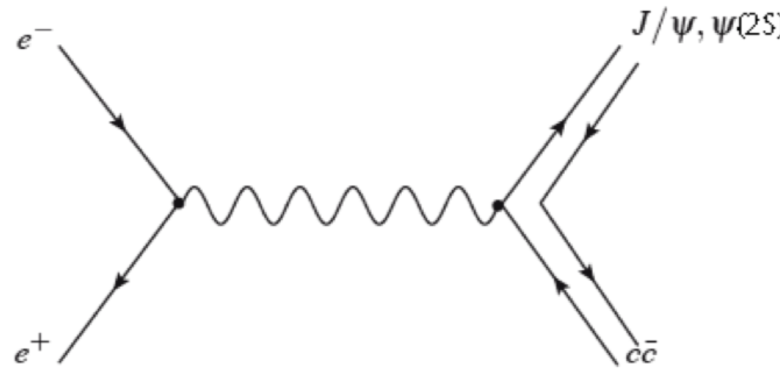
Only states with J^{PC} = $0^{\pm+}$, $2^{\pm+}$, $4^{\pm+}$,......, 3^{++}, 5^{++},....... can be produced

Initial State Radiation (ISR)



Only states with $J^{PC} = 1^{--}$ can be produced

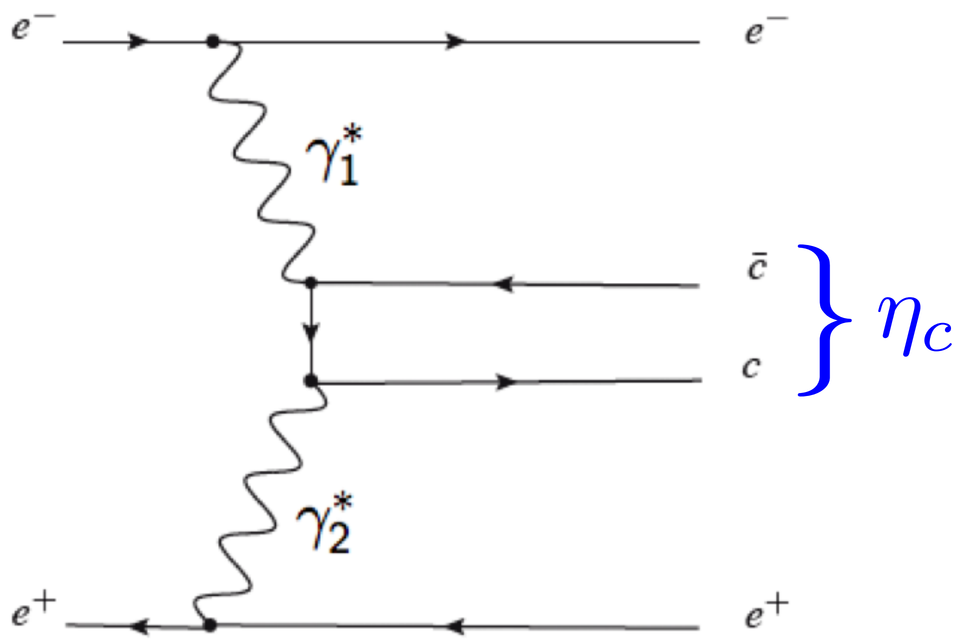
Double charmonium production



Only charmonium states with C=+1 are allowed to be produced in association with the J/ψ or the ψ(2S)

Two-Photon Charmonium Production

- Two-photon charmonium production:



- The e^+/e^- beam particles are scattered at small angles and undetected in the final state
- Interaction produces resonances with $J^{PC} = 0^{\pm+},\ 2^{\pm+},\ 4^{\pm+}...,\ 3^{++},\ 5^{++},\ ...$
  - (Note: $K\overline{K}\pi$ cannot be in a $J^P = 0^+$ state due to angular momentum and parity conservation)

Event Selection I

- We consider the two-photon processes:

$\gamma\gamma \to K_S^0 K^+ \pi^-, \ K_S^0 \to \pi^+ \pi^-$

- Require exactly 4 well-measured charged particle tracks with transverse momenta $> 0.1 \text{ GeV}/c$ (relative to beam axis)
- Loose PID requirement on tracks
- No more than 5 photon candidates with energy above 100 MeV
- Perform vertex fit to pair of oppositely charged tracks to select K_S^0 candidate
- Combine K_S^0 candidate with two oppositely charged tracks, fit to common vertex, and require it to be within the interaction region

$\gamma\gamma \to K^+ K^- \pi^0$

- Require exactly 2 well-measured charged particle tracks with transverse momenta $> 0.1 \text{ GeV}/c$ (relative to beam axis)
- Loose PID requirement on tracks
- Reconstruct π^0 from photon pairs where $E_\gamma > 50 \text{ MeV}$
- Kinematically fit photon pairs to π^0 hypothesis and require candidate to emanate from primary vertex

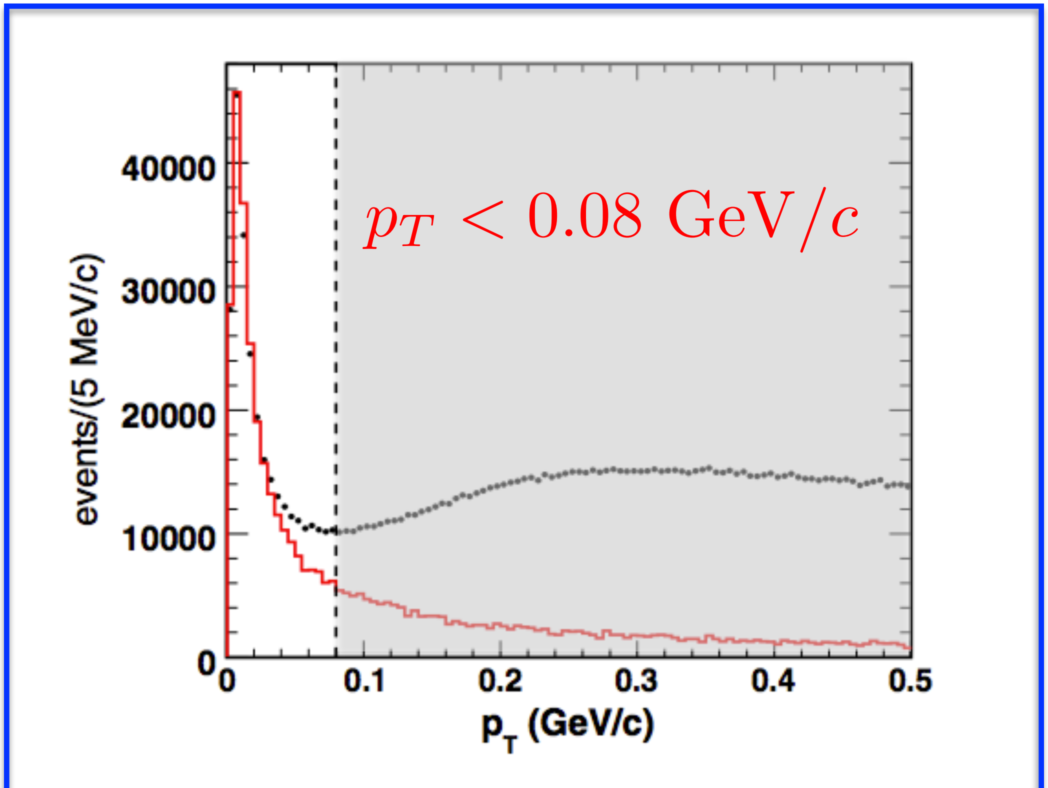
Event Selection II

- Additional cut to remove ISR background dominated by $J^{PC} = 1^{--}$ resonance production:

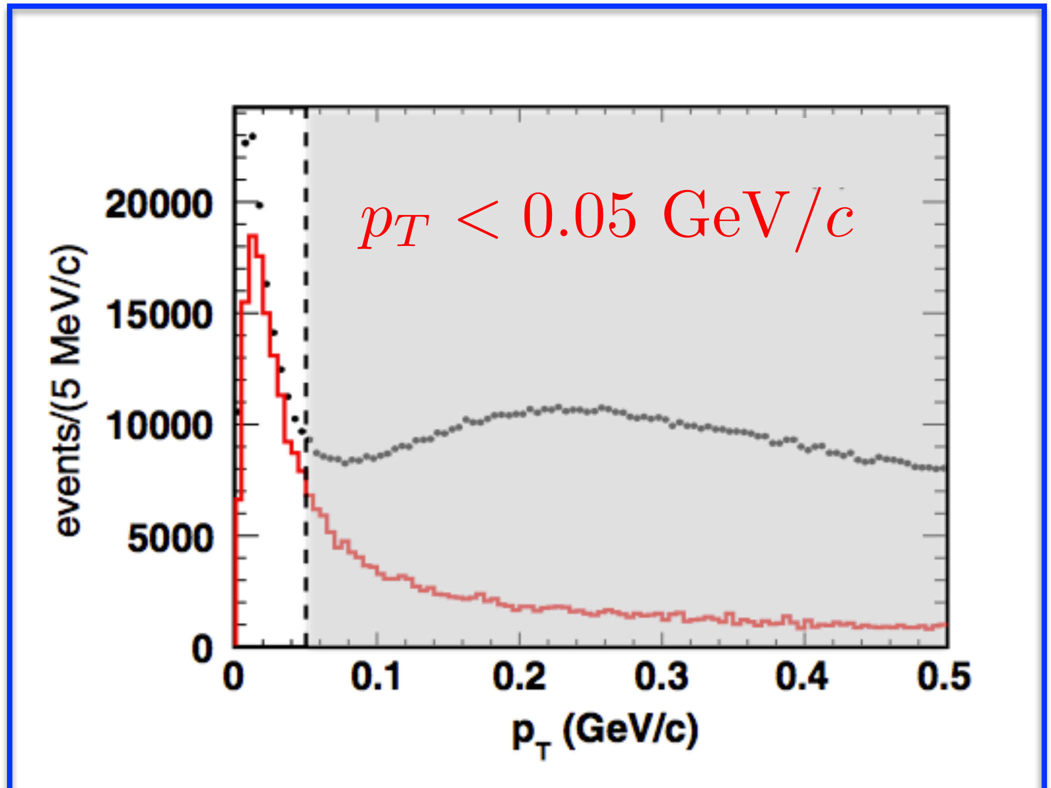
$$M_{\text{rec}}^2 \equiv (p_{e^+e^-} - p_{\text{rec}})^2 > 10\ \text{GeV}^2/c^4$$

- Final selection on transverse momentum (p_T):

$\gamma\gamma \to K_S^0 K^+ \pi^-,\ K_S^0 \to \pi^+\pi^-$



$\gamma\gamma \to K^+ K^- \pi^0$



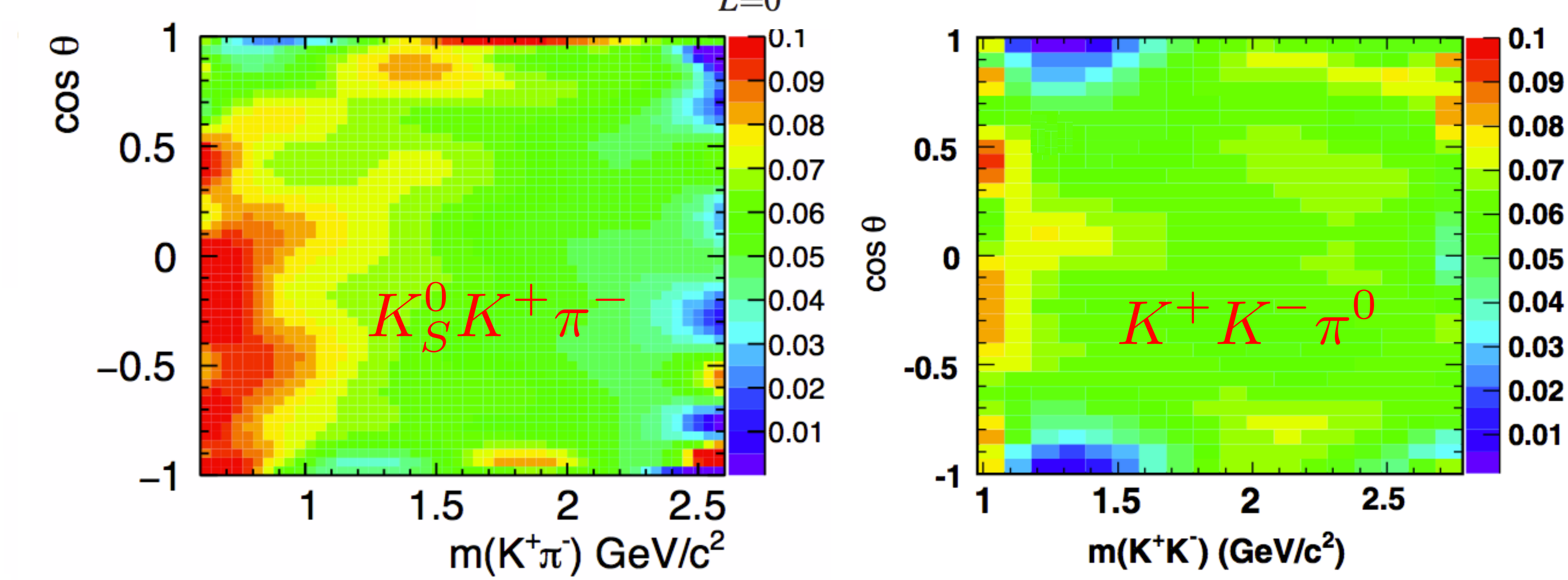
Efficiency

- Compute efficiency using fully simulated signal MC in which the η_c decays uniformly in phase space

- Express efficiency as function of $m(K^+\pi^-)$ $(m(K^+K^-))$ and $\cos\theta$, where θ is the angle, in the $K^+\pi^-$ (K^+K^-) rest frame between the direction of the K^+ and the boost from the $K^0_S K^+\pi^-$ $(K^+K^-\pi^0)$ rest frame

- Smooth the efficiency map by parameterizing with Legendre polynomials in intervals of m:

$$\epsilon(\cos\theta) = \sum_{L=0}^{12} a_L(m) Y^0_L(\cos\theta)$$



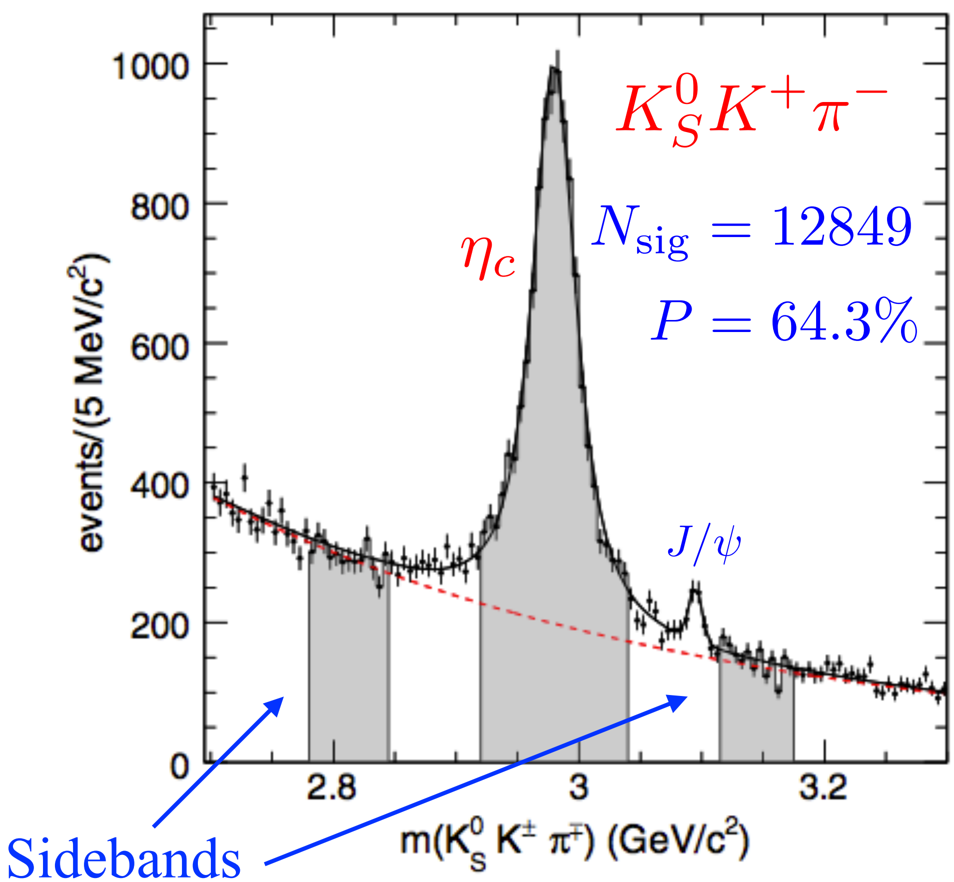
- Significant efficiency loss in $\cos\theta \approx \pm 1$ regions due to low momentum kaons ($p_{K^\pm} < 200$ MeV$/c$, $p_{K^0_S} < 100$ MeV$/c$) and pions ($p_{\pi^\pm} < 100$ MeV$/c$)

Mass Spectra

- Fit η_c signal peaks using Breit-Wigner convolved with mass resolution function
  - Model background with 2nd order polynomial
  - Purity: $P = N_{\rm sig}/(N_{\rm sig} + N_{\rm bkg})$

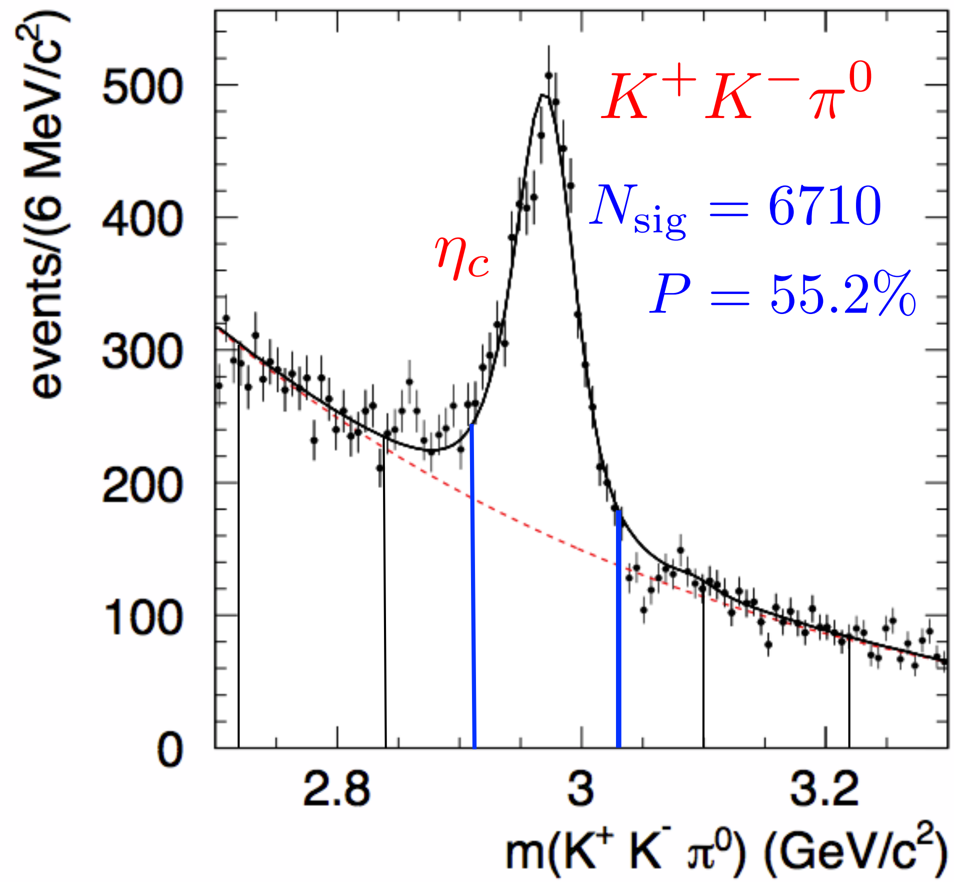
$m = 2980.8 \pm 0.4\ {\rm MeV}/c^2$

$\Gamma = 33 \pm 1\ {\rm MeV}$



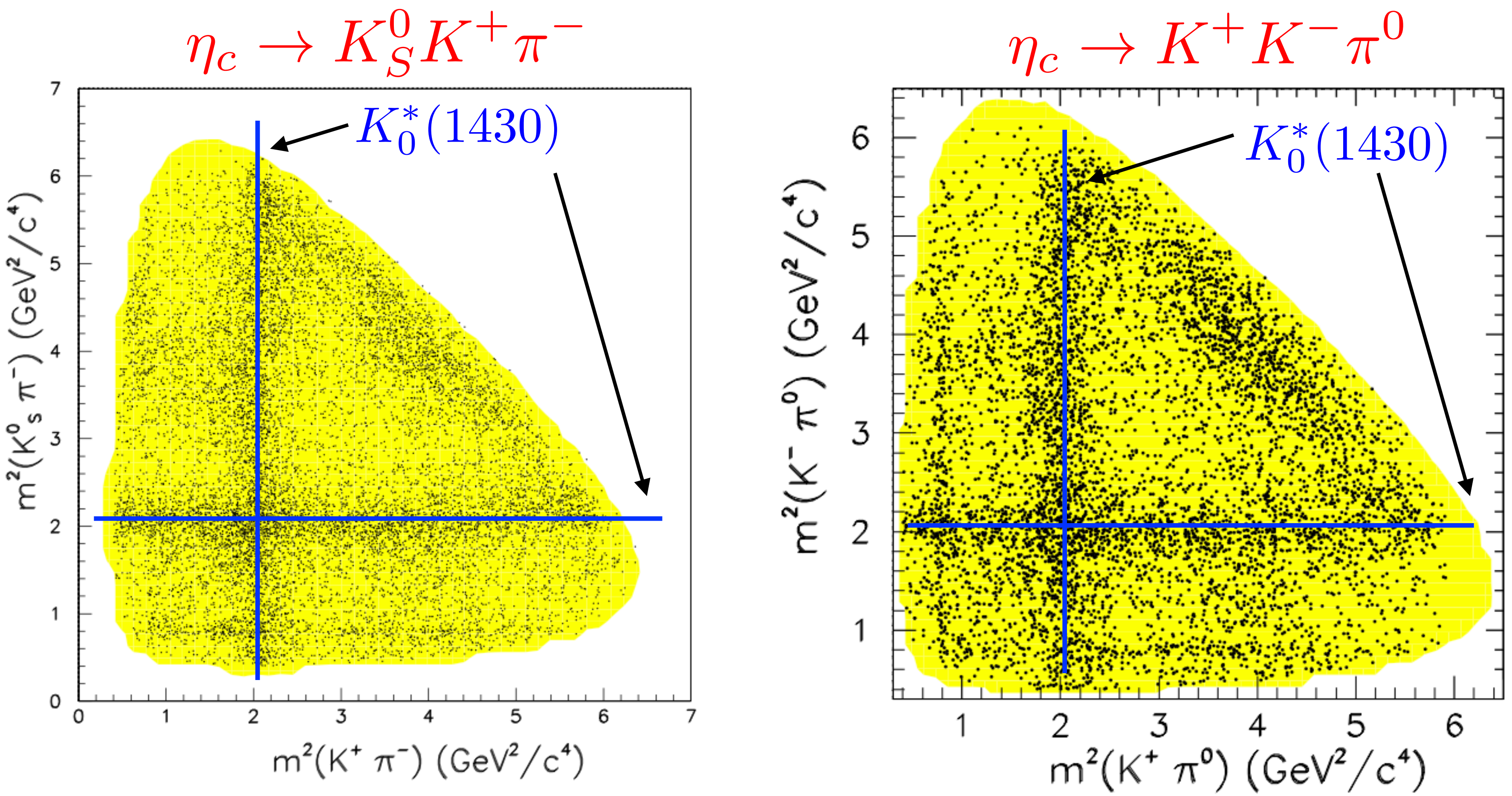
$m = 2979.8 \pm 0.8\ {\rm MeV}/c^2$

$\Gamma = 25.2 \pm 2.6\ {\rm MeV}$



Dalitz Plots

- Dalitz Plot Distributions In η_c Signal Region:



Motivation

- Scalar mesons ($J^P = 0^+$) remain a puzzle in light meson spectroscopy
  - Too many states to readily accommodate within the quark model
  - Large decay widths: overlap between $\mathcal{S}$-wave and other amplitudes
- Structure of the $I = 1/2\ K\pi\ \mathcal{S}$-wave is a long-standing problem
  - Source of large systematic uncertainties in analyses involving decays of heavy flavored hadrons
- Previous measurements of $I = 1/2\ K\pi\ \mathcal{S}$-wave:
  - LASS Experiment: **Nucl. Phys. B 296, 493 (1988)**
  - E791 Experiment: **Phys. Rev. D 73, 032004 (2006)**

Dalitz Plot Analysis Methods I

- Analyze Dalitz plots using unbinned maximum likelihood fits in the η_c mass region and two fit approaches:

Phys. Lett. B 592, 1 (2004)

  - Isobar Model: Resonances described by Breit-Wigner functions
  - Model-Independent Partial Wave Analysis (MIPWA): Phys. Rev. D 73, 032004 (2006)
    - Express amplitude as sum of partial waves:

$$A = A_1 + c_2/c_1 A_2 e^{i(\phi_2 - \phi_1)} + c_3 A_3 e^{i(\phi_3 - \phi_1)} + ...$$

      where A_1 is the $K\pi$ $\mathcal{S}$-wave amplitude

    - For the $K\pi$ $\mathcal{S}$-wave contribution, divide the $K\pi$ mass spectrum into 30 mass intervals with $60\ \mathrm{MeV}$ width and, for each bin, add to the fit two new free parameters corresponding to the amplitude and phase of the $K\pi$ $\mathcal{S}$-wave within the bin
    - Since the η_c is decaying through the strong interaction, we can apply isospin conservation, which means that the $K\pi$ $\mathcal{S}$-wave must have $I = 1/2$

Dalitz Plot Analysis Methods II

- Analyze Dalitz plots using unbinned maximum likelihood fits in the η_c mass region and two fit approaches:

  Phys. Lett. B 592, 1 (2004)

  - Isobar Model: Resonances described by Breit-Wigner functions
  - Model-Independent Partial Wave Analysis (MIPWA): **Phys. Rev. D 73, 032004 (2006)**
    - The interference between the two $K\pi$ modes is positive for η_c decays. Therefore, the $K\pi$ amplitude is symmetrized with respect to the two modes and we have:

$$A_{S-wave} = \frac{1}{\sqrt{2}}\left(a_j^{K^+\pi^-} e^{i\phi_j^{K^+\pi^-}} + a_j^{K_S^0\pi^-} e^{i\phi_j^{K_S^0\pi^-}}\right) \text{ for } \eta_c \to K_s^0 K^+\pi^-$$

$$A_{S-wave} = \frac{1}{\sqrt{2}}\left(a_j^{K^+\pi^0} e^{i\phi_j^{K^+\pi^0}} + a_j^{K^-\pi^0} e^{i\phi_j^{K^-\pi^0}}\right) \text{ for } \eta_c \to K^+K^-\pi^0$$

where $a^{K^+\pi^0}(m) = a^{K^-\pi^0}(m)$ and $\phi^{K^+\pi^0}(m) = \phi^{K^-\pi^0}(m)$

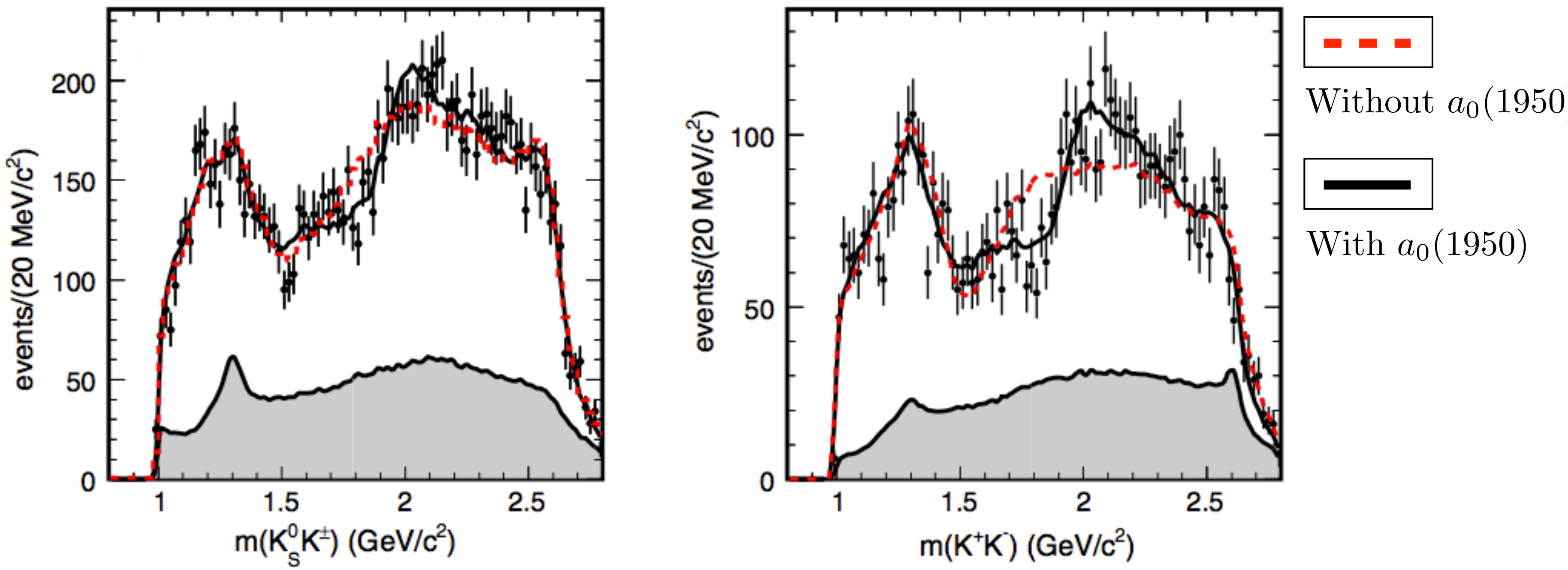
    - The $K_2^*(1420)$, $a_0(980)$, $a_0(1400)$, $a_2(1310)$, ... are represented by Breit-Wigner functions multiplied by corresponding angular functions

- Background is fit separately using the sidebands and interpolated into the η_c signal region

MIPWA Fit

- The fits to both Dalitz plots improve when a new $a_0(1950)$ resonance is added to the fit:

$\eta_c \to K^0_S K^+ \pi^-$ $\eta_c \to K^+ K^- \pi^0$



Significance : 2.5σ Significance : 4.2σ

- $a_0(1950)$ parameters from fits:

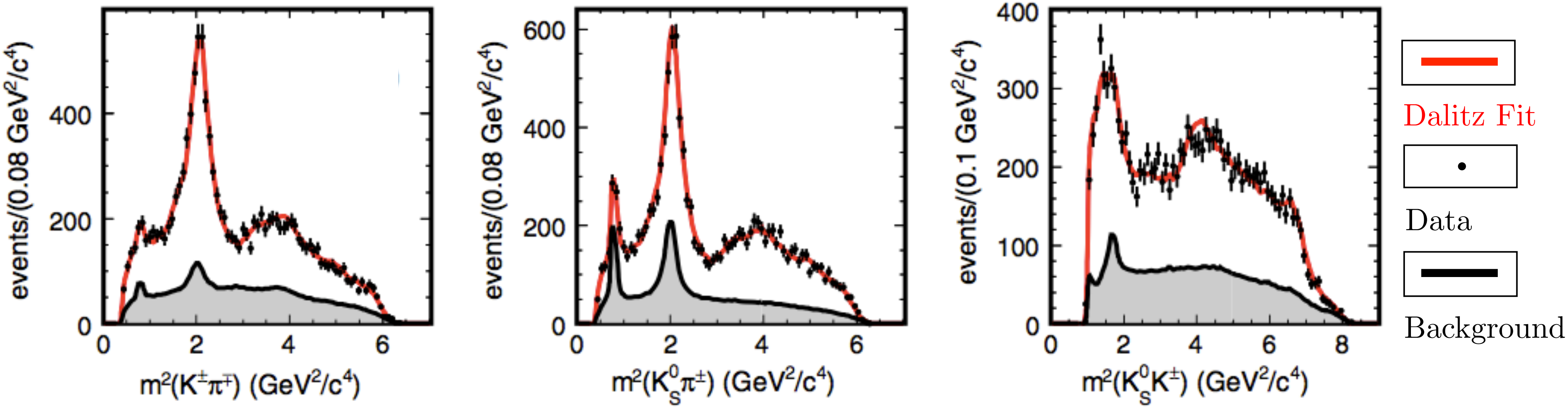
$\eta_c \to K^0_S K^+ \pi^-$: $m\,(a_0(1950)) = 1949 \pm 32$ MeV$/c^2$, $\Gamma\,(a_0(1950)) = 265 \pm 36$ MeV

$\eta_c \to K^+ K^- \pi^0$: $m\,(a_0(1950)) = 1927 \pm 15$ MeV$/c^2$, $\Gamma\,(a_0(1950)) = 274 \pm 28$ MeV

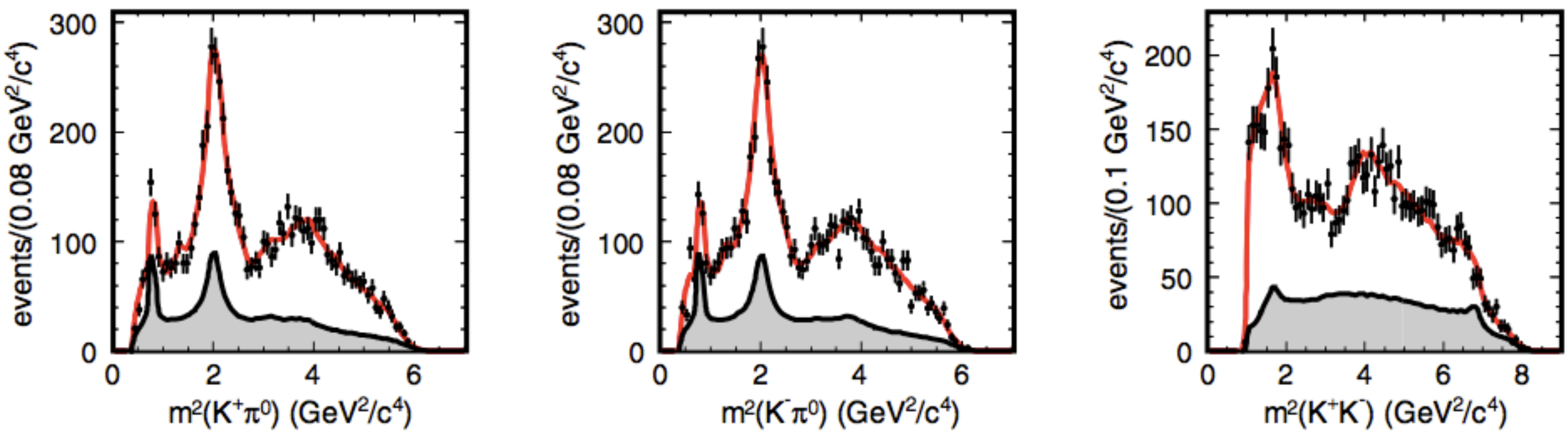
Weighted Mean: $m\,(a_0(1950)) = 1931 \pm 14$ MeV, $/c^2$ $\Gamma\,(a_0(1950)) = 271 \pm 22$ MeV

MIPWA Fit Projections

- $\eta_c \to K_S^0 K^+ \pi^-$ MIPWA Fit Projections:



- $\eta_c \to K^+ K^- \pi^0$ MIPWA Fit Projections:



MIPWA Fit Fractions

- MIPWA fit results:

Amplitude	$\eta_c \to K^0_S K^\pm \pi^\mp$ Fraction (%)	$\eta_c \to K^0_S K^\pm \pi^\mp$ Phase	$\eta_c \to K^+ K^- \pi^0$ Fraction (%)	$\eta_c \to K^+ K^- \pi^0$ Phase
$(K\pi\ \mathcal{S}\text{-wave})\ \overline{K}$	$107.3 \pm 2.6 \pm 17.9$	0.	$125.5 \pm 2.4 \pm 4.2$	0.
$a_0(980)\pi$	$0.83 \pm 0.46 \pm 0.80$	$1.08 \pm 0.18 \pm 0.18$	$0.00 \pm 0.03 \pm 1.7$	
$a_0(1450)\pi$	$0.7 \pm 0.2 \pm 1.4$	$2.63 \pm 0.13 \pm 0.17$	$1.2 \pm 0.4 \pm 0.7$	$2.90 \pm 0.12 \pm 0.25$
$a_0(1950)\pi$	$3.1 \pm 0.4 \pm 1.2$	$-1.04 \pm 0.08 \pm 0.77$	$4.4 \pm 0.8 \pm 0.7$	$-1.45 \pm 0.08 \pm 0.27$
$a_2(1320)\pi$	$0.15 \pm 0.06 \pm 0.08$	$1.85 \pm 0.20 \pm 0.23$	$0.61 \pm 0.23 \pm 0.3$	$1.75 \pm 0.23 \pm 0.42$
$K_2^*(1430)^0\overline{K}$	$4.7 \pm 0.9 \pm 1.4$	$4.92 \pm 0.05 \pm 0.1$	$3.0 \pm 0.8 \pm 4.4$	$5.07 \pm 0.09 \pm 0.3$
Total	116.8 ± 2.8		134.8 ± 2.7	
$-2\log\mathcal{L}$	-4314.2		-2339	
χ_2/N_{cells}	301/254=1.17		283.2/233=1.22	

- Good agreement between the two η_c decay modes
- $(K\pi\ \mathcal{S}\text{-wave})\overline{K}$ amplitude dominates with small contributions from the $K_2^*(1430)^0\overline{K}$ and the new $a_0(1950)\pi$
- Total fractions well over 100% indicate significant interference effects
- Good description of the data

Isobar Fit Fractions

- Isobar fit results:

  - $K\pi$ $\mathcal{S}$-wave is modeled as superposition of interfering $K_0^*(1430)$, $K_0^*(1950)$, and non-resonant contributions

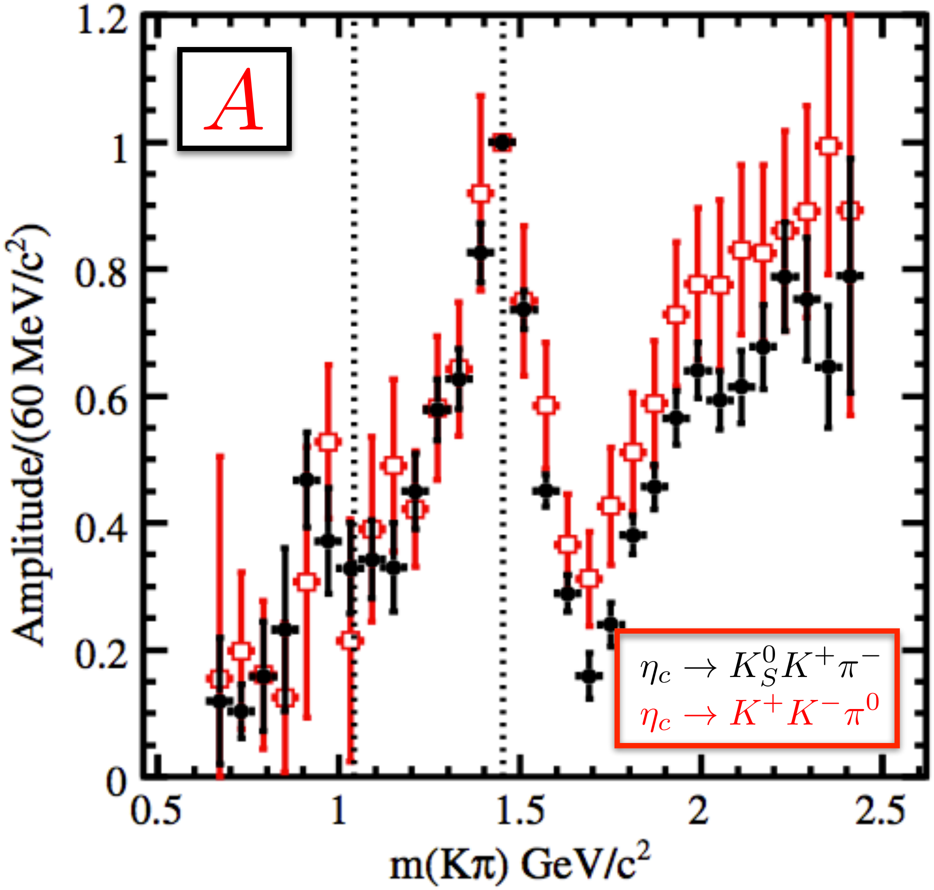
	$\eta_c \to K_S^0 K^\pm \pi^\mp$		$\eta_c \to K^+ K^- \pi^0$	
Amplitude	Fraction (%)	Phase	Fraction (%)	Phase
$K_0^*(1430)K$	40.8 ± 2.2	0.	28.1 ± 3.3	0.
$K_0^*(1950)K$	14.8 ± 1.7	-1.00 ± 0.07	6.0 ± 1.2	-0.89 ± 0.09
NR	18.0 ± 2.5	1.94 ± 0.09	29.5 ± 4.4	-4.5 ± 0.08
$a_0(980)\pi$	10.5 ± 1.2	0.94 ± 0.12	4.8 ± 1.3	0.08 ± 0.23
$a_0(1450)\pi$	1.7 ± 0.5	2.94 ± 0.13	1.2 ± 0.5	3.05 ± 0.29
$a_0(1950)\pi$	0.7 ± 0.2	-1.76 ± 0.24	1.0 ± 0.4	-0.54 ± 0.24
$a_2(1310)\pi$	0.2 ± 0.2	-0.53 ± 0.42	3.7 ± 1.0	-0.45 ± 0.41
$K_2^*(1430)^0 K$	2.3 ± 0.7	-1.55 ± 0.11	7.4 ± 1.5	-1.71 ± 0.12
Total	88.8 ± 4.3		81.8 ± 6.1	
$-2\log\mathcal{L}$	-4290.7		-2200.8	
χ^2/N_{cells}	467/256=1.82		383/233=1.63	

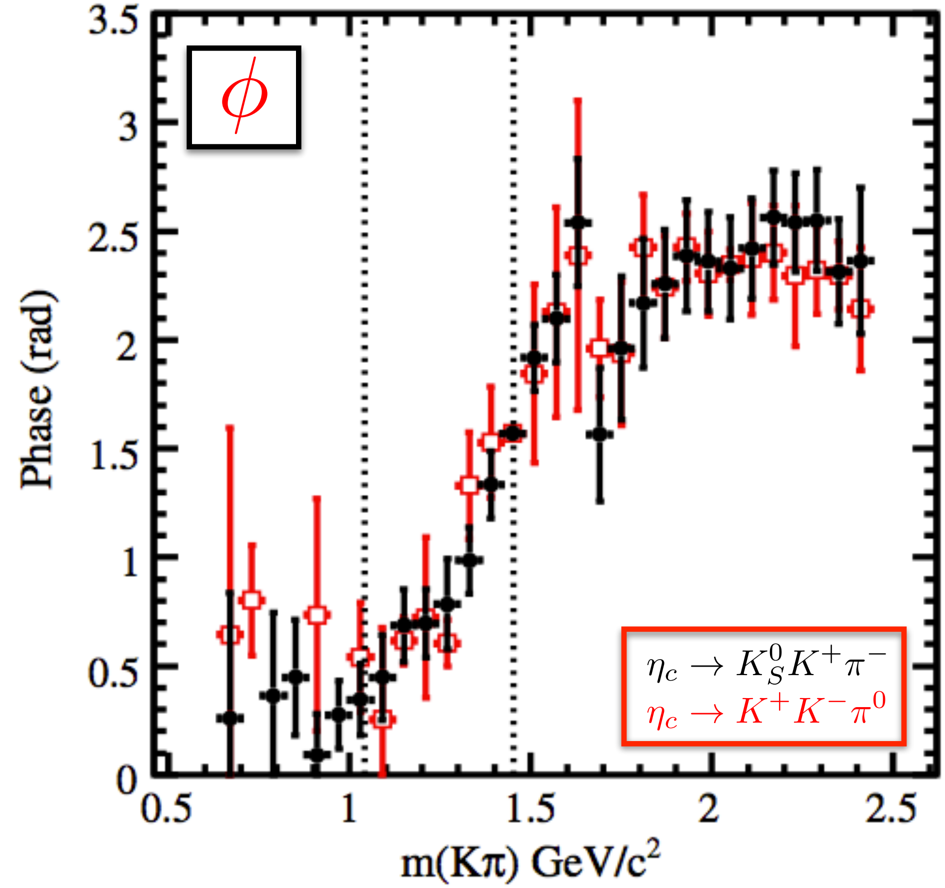
$K\pi$ $\mathcal{S}-$wave

- Poor agreement between the two η_c decay modes

MIPWA $K\pi$ $\mathcal{S}$-wave Amplitude And Phase

- I=1/2 $K\pi$ $\mathcal{S}$-wave amplitudes and phases from MIPWA fits:



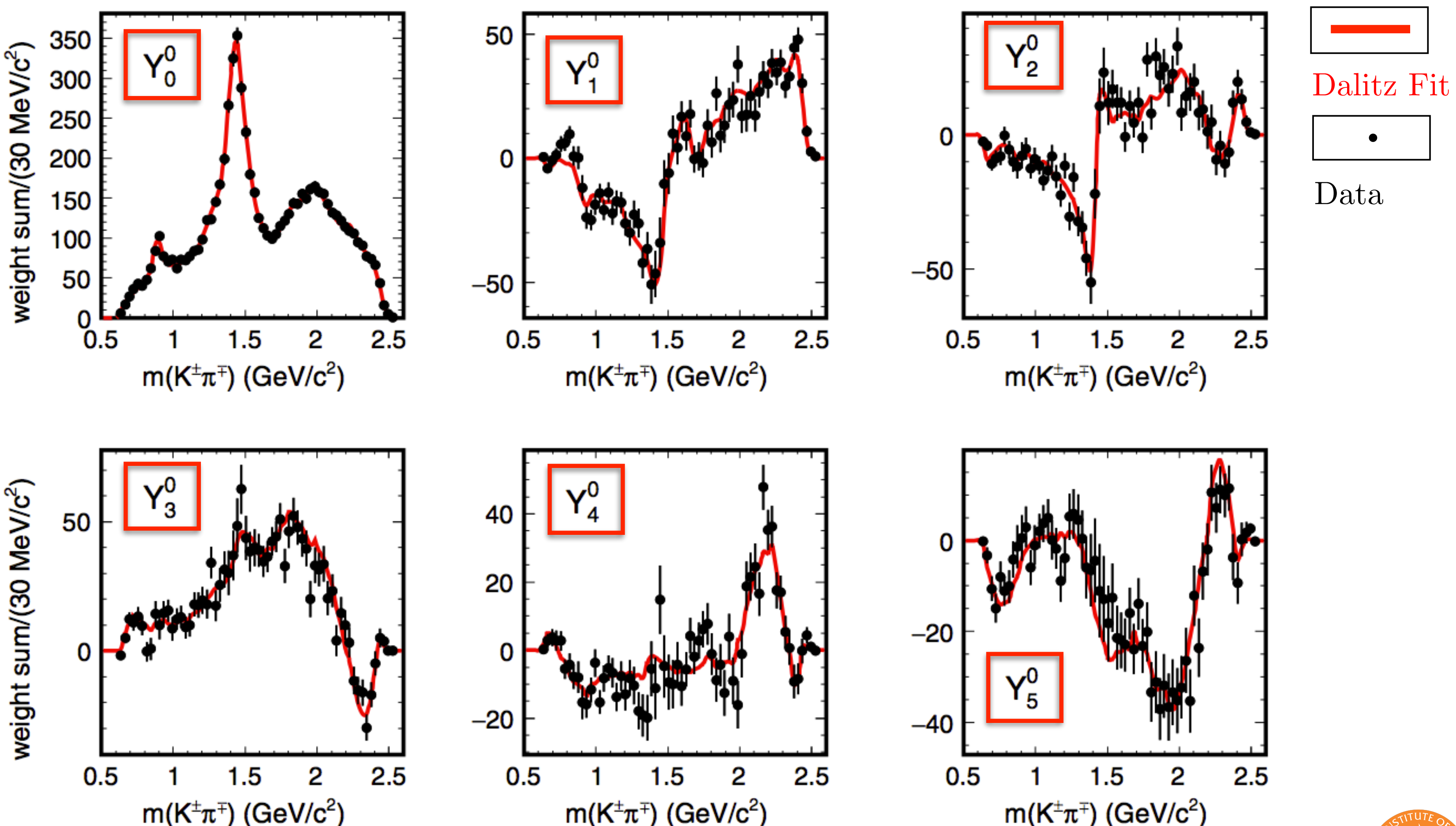


- Clear peak at $K_0^*(1430)$ resonance
- Broad dip around $1.7\ \mathrm{GeV}/c^2$ is likely related to $K_0^*(1950)$

- Phase varies by about π in $K_0^*(1430)$ resonance region
- Phase dip around $1.7\ \mathrm{GeV}/c^2$ is likely related to interference with $K_0^*(1950)$ resonance

Legendre Moments I

- Legendre moment distributions are generated by weighting each event by the relevant $Y_L^0(\cos\theta)$ function

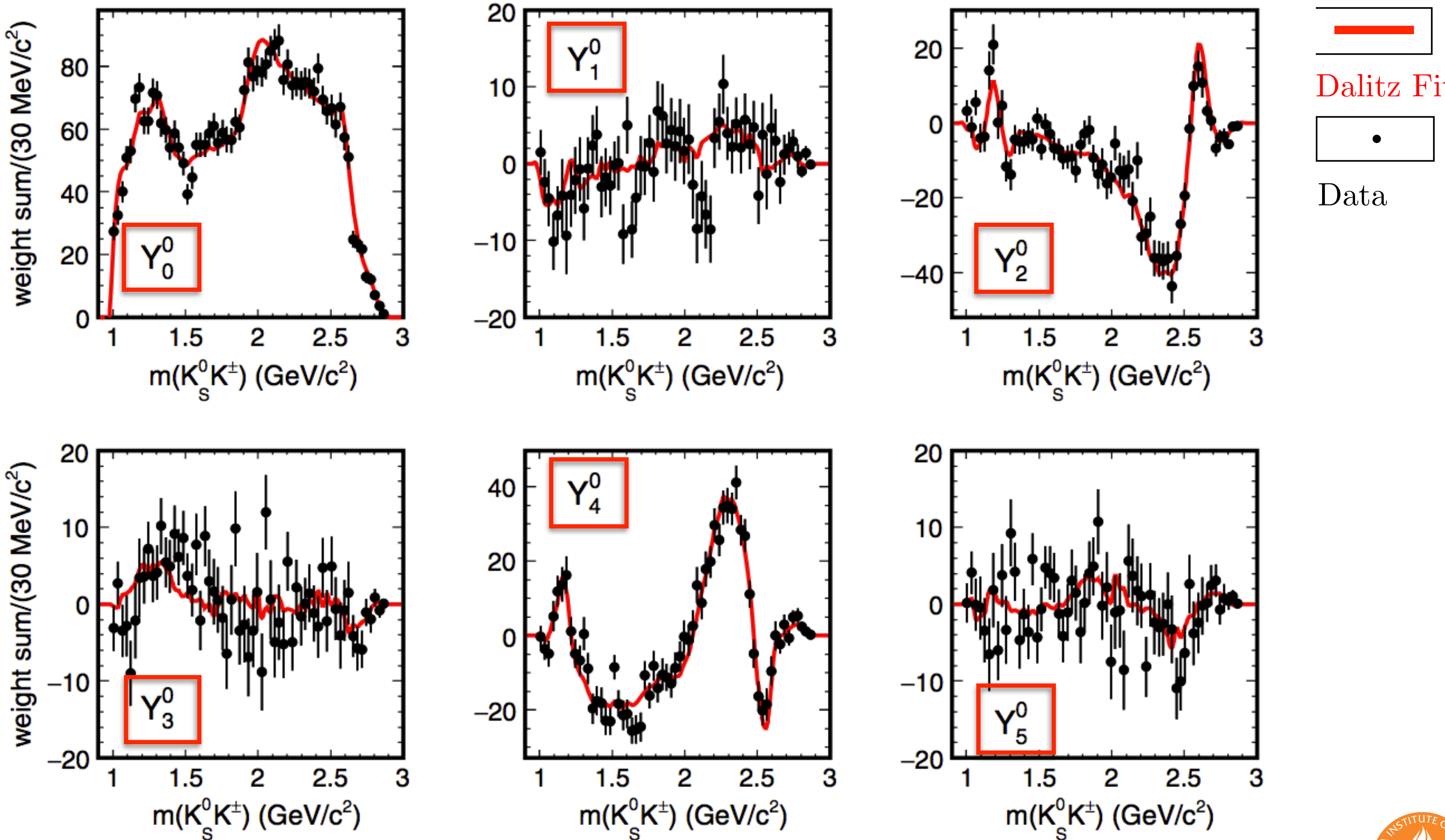


$\eta_c \to K^0_S K^+ \pi^-$

$m(K^\pm \pi^\mp)$

Legendre Moments II

- Legendre moment distributions are generated by weighting each event by the relevant $Y_L^0(\cos\theta)$ function

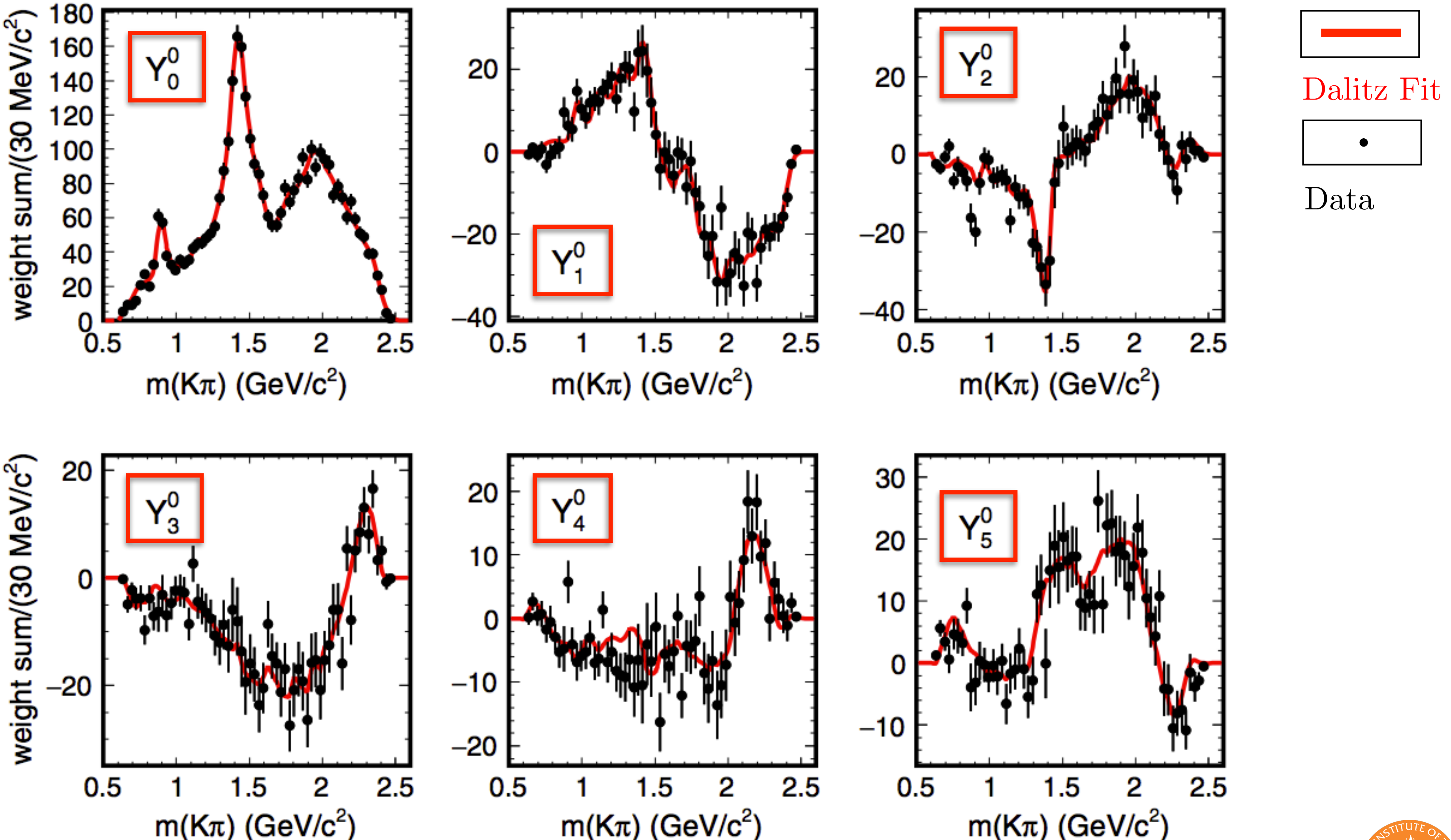


$\eta_c \to K_S^0 K^+ \pi^-$

$m(K_S^0 K^\pm)$

Legendre Moments III

- Legendre moment distributions are generated by weighting each event by the relevant $Y_L^0(\cos\theta)$ function

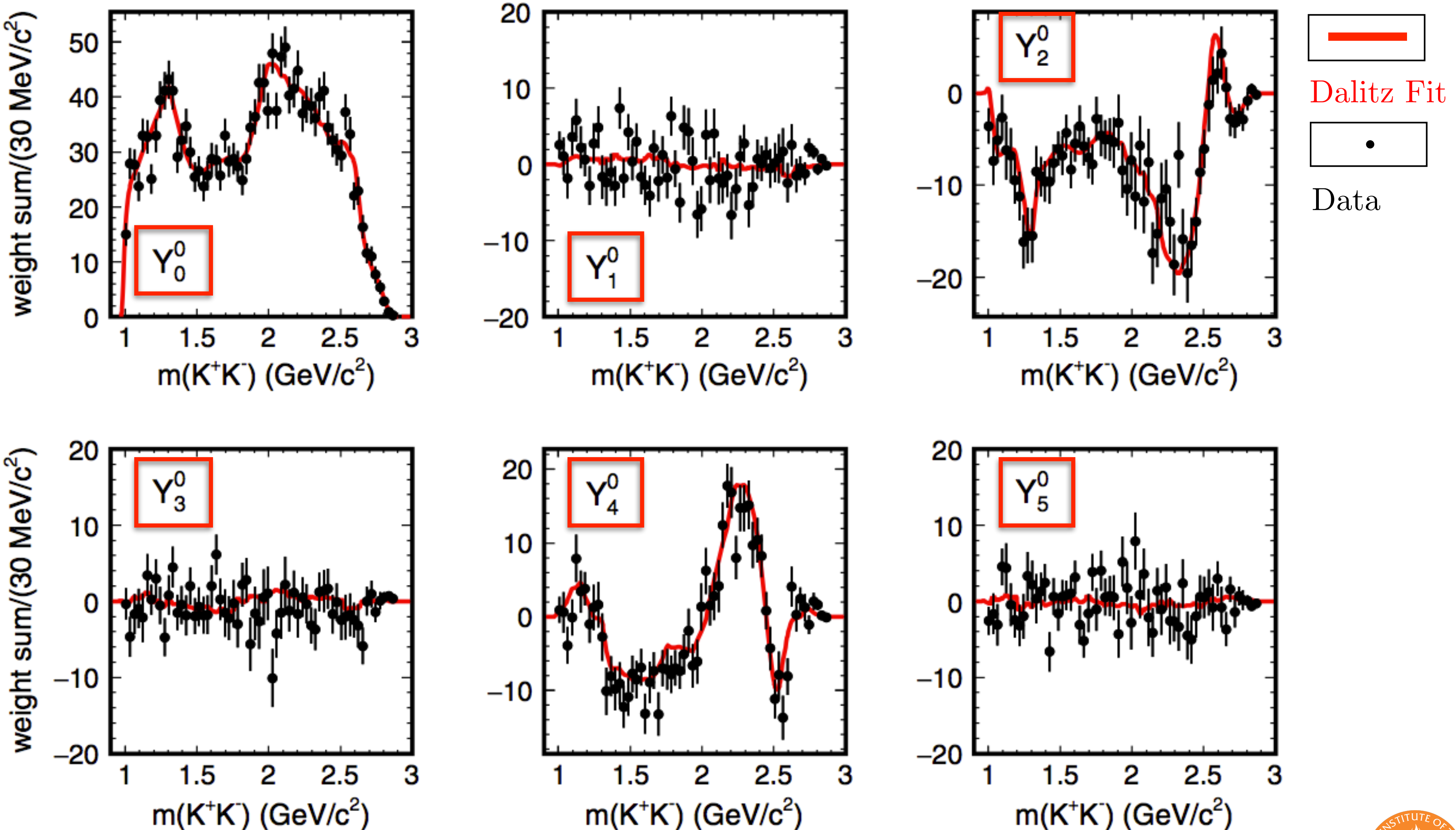


$\eta_c \to K^+K^-\pi^0$

$m(K^\pm\pi^0)$

Legendre Moments IV

- Legendre moment distributions are generated by weighting each event by the relevant $Y_L^0(\cos\theta)$ function



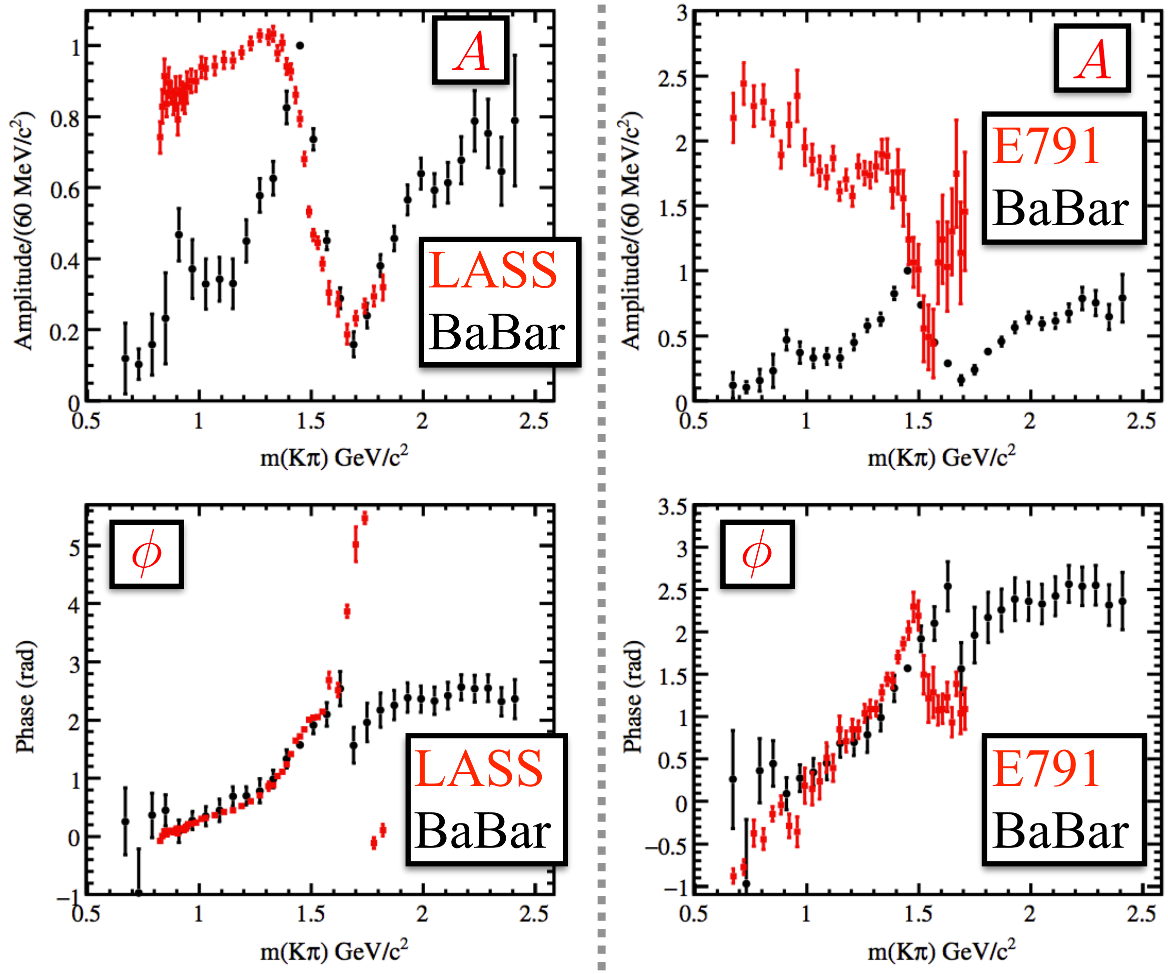
$\eta_c \to K^+K^-\pi^0$

$m(K^+K^-)$

Comparison With LASS and E791

- I=1/2 $K\pi$ $\mathcal{S}$-wave amplitude and phase comparisons with LASS and E791

- LASS phase shifted by -0.6 rad
- LASS suffers from 4-fold ambiguity above $1.82\ \mathrm{GeV}/c^2$
- Difficult to separate I=1/2 and I=3/2 contributions in E791 experiment
- E791 measurements only go up to $1.72\ \mathrm{GeV}/c^2$
- Similar phase behavior up to about $1.5\ \mathrm{GeV}/c^2$
- Disagreement in mass-dependence of amplitudes



LASS: $K^- p \to K^- \pi^+ n$

Nucl. Phys. B 296, 493 (1988)

E791: $D^+ \to K^- \pi^+ \pi^+$

Phys. Rev. D 73, 032004 (2006)

BaBar MIPWA (present analysis): $\eta_c \to K^0_S K^+ \pi^-$

Summary

- We have performed Dalitz plot analyses of the decays $\eta_c \to K^0_S K^+ \pi^-$ and $\eta_c \to K^+ K^- \pi^0$ using an isobar model and a MIPWA method
  - We find the MIPWA approach provides a better description of the data than the isobar model
  - The data require the presence of a new $a_0(1950)$ with parameters:

$$m = 1931 \pm 14 \pm 22 \text{ MeV}/c^2$$
$$\Gamma = 271 \pm 22 \pm 29 \text{ MeV}$$

  - and significances of 2.5σ and 4.2σ for the $K^0_S K^+ \pi^-$ and $K^+ K^- \pi^0$ modes, respectively
- We extract the $K\pi$ $I = 1/2$ $\mathcal{S}$-wave amplitude and phase and find good agreement between the two η_c decay modes
  - The $K\pi$ $\mathcal{S}$-wave is dominated by the $K^*_0(1430)$ resonance
- Comparing our present measurement with previous experiments indicates a similar trend for the phase up to a mass of 1.5 GeV$/c^2$, but the amplitudes exhibit significant disagreement

Backup Slides

Systematic Uncertainties

- Average fractional systematic uncertainties on the amplitude and phases for $\eta_c \to K^0_S K^+ \pi^-$ and $\eta_c \to K^+ K^- \pi^0$ MIPWA

	$\eta_c \to K^0_S K^\pm \pi^\mp$		$\eta_c \to K^+ K^- \pi^0$	
Effect	Amplitude (%)	Phase (%)	Amplitude (%)	Phase (%)
Bias	9	7	8	14
Spline	4	5	4	5
Resonances	7	13	7	4
Purity	1	1	1	6
Efficiency	13	6	10	4
Total	18	17	15	17

- To calculate each systematic uncertainty contribution, we perform a new fit and, for each mass bin, calculate absolute value of the fractional deviation of the $K\pi$ $\mathcal{S}$-wave amplitude and phase from the reference fit
  - The resulting distributions are fit using a Gaussian with zero mean
  - We take the σ from the fit as the systematic uncertainty

Systematic Uncertainties

- Average fractional systematic uncertainties on the amplitude and phases for $\eta_c \to K^0_S K^+ \pi^-$ and $\eta_c \to K^+ K^- \pi^0$ MIPWA

	$\eta_c \to K^0_S K^\pm \pi^\mp$		$\eta_c \to K^+ K^- \pi^0$	
Effect	Amplitude (%)	Phase (%)	Amplitude (%)	Phase (%)
Bias	9	7	8	14
Spline	[illegible]	5	4	5
Resonances	[illegible]	[illegible]	[illegible]	[illegible]
Purity	[illegible]	[illegible]	[illegible]	[illegible]
Efficiency	[illegible]	[illegible]	[illegible]	[illegible]
Total	18	17	15	17

Calculate uncertainty associated with fit bias by generating MC simulated data using nominal MIPWA fit parameters and refitting.

Systematic Uncertainties

- Average fractional systematic uncertainties on the amplitude and phases for $\eta_c \rightarrow K^0_S K^+ \pi^-$ and $\eta_c \rightarrow K^+ K^- \pi^0$ MIPWA

	$\eta_c \rightarrow K^0_S K^\pm \pi^\mp$		$\eta_c \rightarrow K^+ K^- \pi^0$	
Effect	Amplitude (%)	Phase (%)	Amplitude (%)	Phase (%)
Bias	9	7	8	14
Spline	4	5	4	5
Resonance	7	13	7	4
Purity				
Efficiency				
Total				

Rather than using a constant amplitude and phase within each mass bin, we use a cubic spline to interpolate the amplitude and phase within each bin

Systematic Uncertainties

- Average fractional systematic uncertainties on the amplitude and phases for $\eta_c \to K^0_S K^+ \pi^-$ and $\eta_c \to K^+ K^- \pi^0$ MIPWA

Effect	$\eta_c \to K^0_S K^\pm \pi^\mp$ Amplitude (%)	Phase (%)	$\eta_c \to K^+ K^- \pi^0$ Amplitude (%)	Phase (%)
Bias	9	7	8	14
Spline	4	5	4	5
Resonances	7	13	7	4
Purity	1	1	1	6
Efficiency	[illegible]	[illegible]	[illegible]	[illegible]
Total	[illegible]	[illegible]	[illegible]	[illegible]

Refit, removing low significance resonances such as the $a_0(980)$ and $a_2(1310)$

Systematic Uncertainties

- Average fractional systematic uncertainties on the amplitude and phases for $\eta_c \to K^0_S K^+ \pi^-$ and $\eta_c \to K^+ K^- \pi^0$ MIPWA

	$\eta_c \to K^0_S K^\pm \pi^\mp$		$\eta_c \to K^+ K^- \pi^0$	
Effect	Amplitude (%)	Phase (%)	Amplitude (%)	Phase (%)
Bias	9	7	8	14
Spline	4	5	4	5
Resonances	7	13	7	4
Purity	1	1	1	6
Efficiency	13	6	10	4
Total	18	17	15	17

Refit after increasing and decreasing the purity of the signal

Systematic Uncertainties

- Average fractional systematic uncertainties on the amplitude and phases for $\eta_c \to K^0_S K^+ \pi^-$ and $\eta_c \to K^+ K^- \pi^0$ MIPWA

	$\eta_c \to K^0_S K^\pm \pi^\mp$		$\eta_c \to K^+ K^- \pi^0$	
Effect	Amplitude (%)	Phase (%)	Amplitude (%)	Phase (%)
Bias	9	7	8	14
Spline	4	5	4	5
Resonances	7	13	7	4
Purity	1	1	1	6
Efficiency	13	6	10	4
Total	18	17	15	17

Evaluate the effect of the efficiency variation as a function of $K\overline{K}\pi$ mass by computing separate efficiencies in the regions above and below the η_c mass