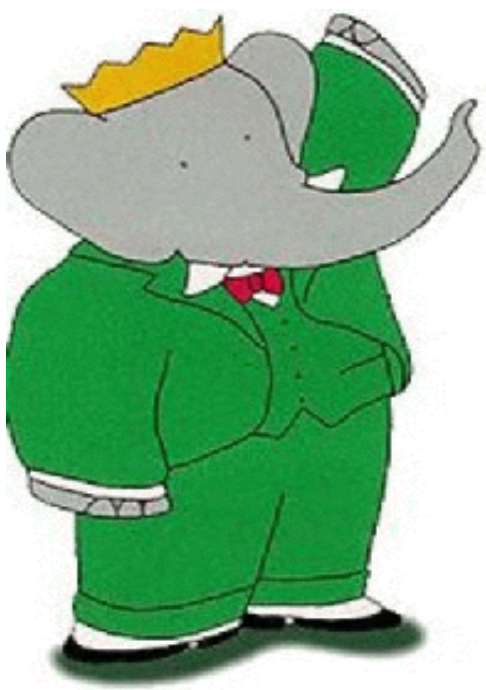
Dalitz plot analyses of $\eta_c \rightarrow K^+K^-\pi^0$ and $\eta_c \rightarrow K^+K^-\eta$ in two photon interactions

International Workshop on Heavy Quarkonium
Nov. 10-14th , 2014



Racha Cheaib
McGill University

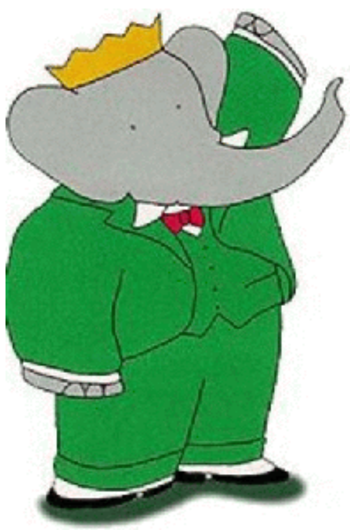
McGill

On behalf of the BaBar Collaboration

Outline

Phys. Rev. D 89, 112004 (2014)

- Physics Motivation
- $\gamma\gamma \rightarrow K^+K^-\eta$ and $\gamma\gamma \rightarrow K^+K^-\pi^0$
- η_c Dalitz plot analyses
- $K_0^*(1430)$ resonance

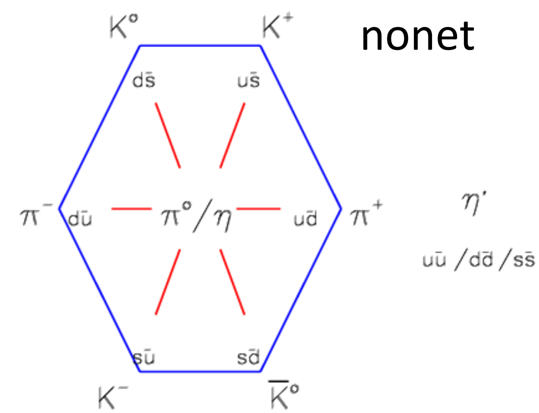


Phys. Rev. D 89, 112004 (2014)

Theoretical Motivation

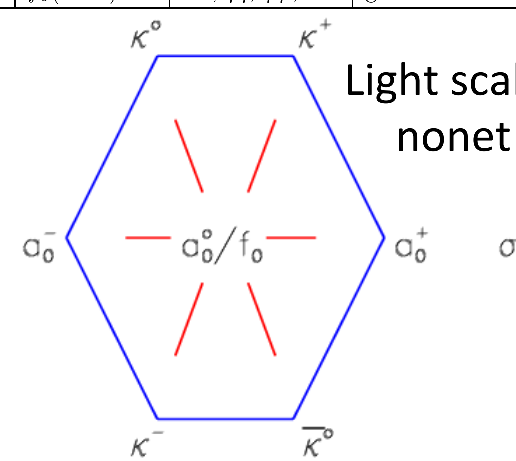
- Low mass charmonium states are an excellent probe for light meson spectroscopy.
- Scalar mesons (J^{PC}=0^{++}) are still a puzzle.
  - Too many states: inconsistent with quark model
  - Large decay widths: overlap between resonance and background.
- Search for scalar glueballs: $f_0(1500)$, $f_0(1710)$, etc…?
- No Dalitz plot analysis of η_c (J^{PC}=0^{-+}) 3-body decays has been done.
- Many η_c (~40%) or η_c (2S) (>80%) decays are missing or observed with low statistics.
  - BES III result on $\eta_c \rightarrow K^+K^-\eta$ is based on a yield of 6.7±3.2 events. (Phys. Rev. D **86** , 092009 (2012))

Pseudoscalar nonet



Isospin	State	Decays	Nature
1	$a_0(980)$	$\eta\pi, K\bar{K}$	$K\bar{K}$ molecule
0	$f_0(980)$	$\pi\pi, K\bar{K}$	$K\bar{K}$ molecule
1	$a_0(1450)$	$\eta\pi$	$Q\bar{Q}$ 0^{++} nonet
0	$f_0(1370)$	$\pi\pi, \eta\eta, \rho\rho$	$Q\bar{Q}$ 0^{++} nonet
	$[f_0'(\text{“1600”})]$	$[K\bar{K}, \eta\eta, \eta\eta']$	$Q\bar{Q}$ 0^{++} nonet
1/2	$K_0^*(1430)$	$K\pi$	$Q\bar{Q}$ 0^{++} nonet
0	$f_0(1500)$	$\pi\pi, \eta\eta, \eta\eta', 4\pi^0$	glueball

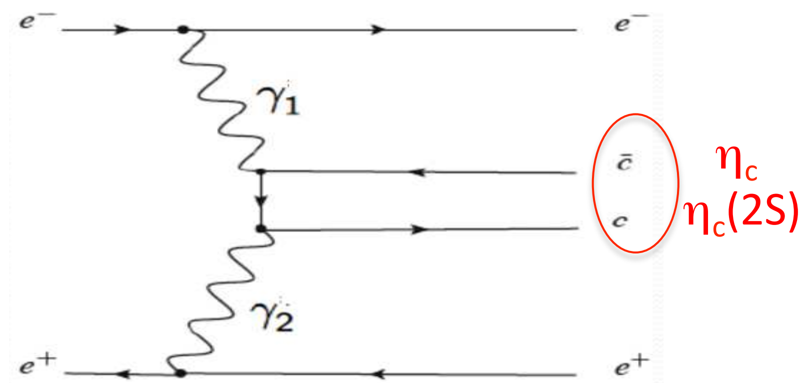
Light scalar nonet



Phys. Rev. D 89, 112004 (2014)

η_c and $\eta_c(2S)$ in two photon interactions:

- Two photon interactions are used to produce charmonium states.
- e+ e- beam particles are scattered at small angles and undetected in the final state.



- Produced resonances can only have $J^{PC}=0^{\pm+}, 2^{\pm+}, 3^{++}, 4^{\pm+}$, etc … with the exception that $K^+K^-\eta$ and $K^+K^-\pi^0$ cannot be in a $J^P=0^+$ state.

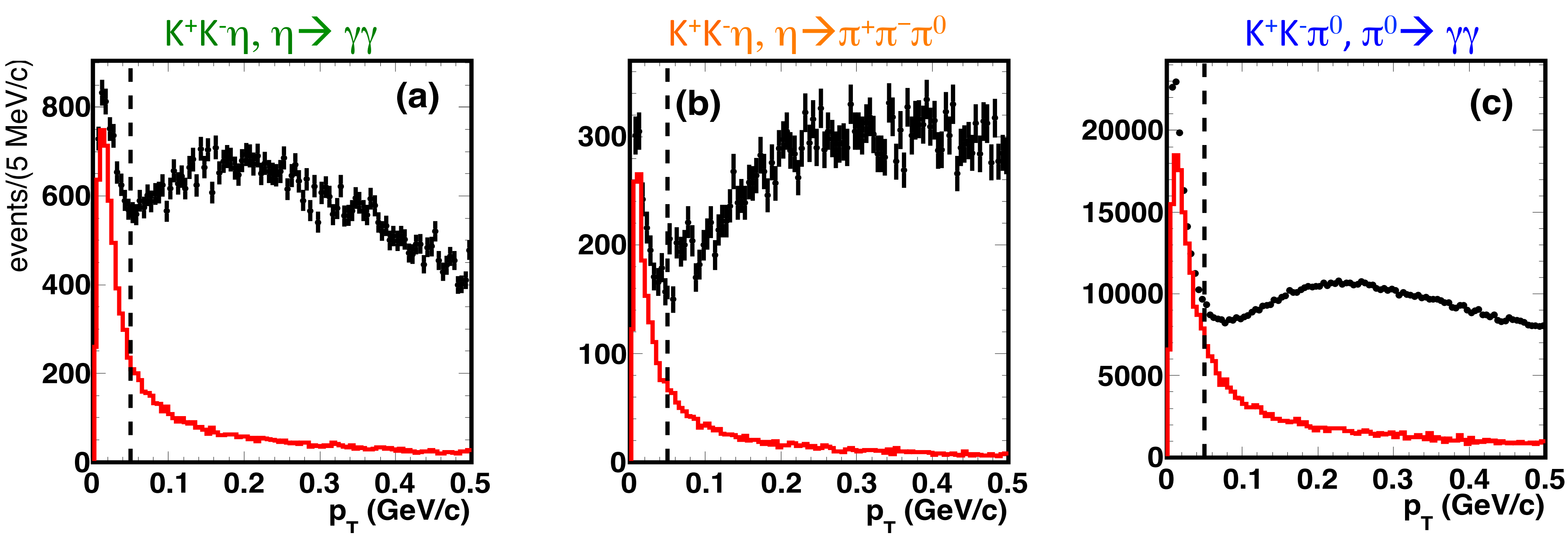
- The following three photon interactions are considered using an integrated luminosity of 519 fb^{-1}:
  - $\gamma\gamma \rightarrow K^+K^-\eta$, $\eta \rightarrow \gamma\gamma$
  - $\gamma\gamma \rightarrow K^+K^-\eta$, $\eta \rightarrow \pi^+\pi^-\pi^0$
  - $\gamma\gamma \rightarrow K^+K^-\pi^0$, $\pi^0 \rightarrow \gamma\gamma$

Phys. Rev. D 89, 112004 (2014)

Event Selection

- Selection criteria optimized to yield largest η_c signal in data.
- Exactly two tracks for $\gamma\gamma \rightarrow K^+K^-\eta$, $\eta \rightarrow \gamma\gamma$ and $\gamma\gamma \rightarrow K^+K^-\pi^0$, $\pi^0 \rightarrow \gamma\gamma$ with loose kaon PID and 4 tracks for $\gamma\gamma \rightarrow K^+K^-\eta$, $\eta \rightarrow \pi^+\pi^-\pi^0$ with loose kaon and pion PID.
- No additional γ veto due to the presence of soft photon background.
- p_T , transverse momentum, cut at p_T<0.05 GeV/c.

Distributions in η_c signal region



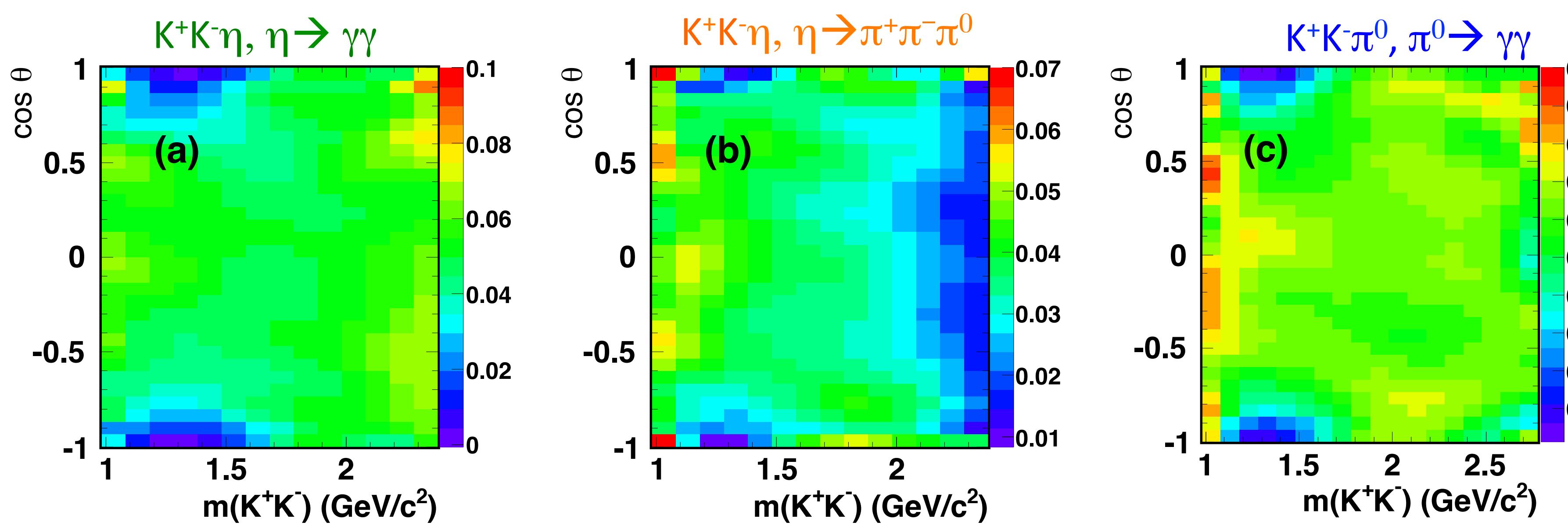
Phys. Rev. D 89, 112004 (2014)

Efficiency

- MC signal events in which the η_c and $\eta_c(2S)$ mesons decay uniformly in phase space.
- Restrict mass regions to η_c and $\eta_c(2S)$ signal.
- Efficiency: $N_{reconstructed}/N_{generated}$
- Express as a function of $m(K^+K^-)$ and $\cos\theta_{K^+}$:

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

Distributions in η_c signal region



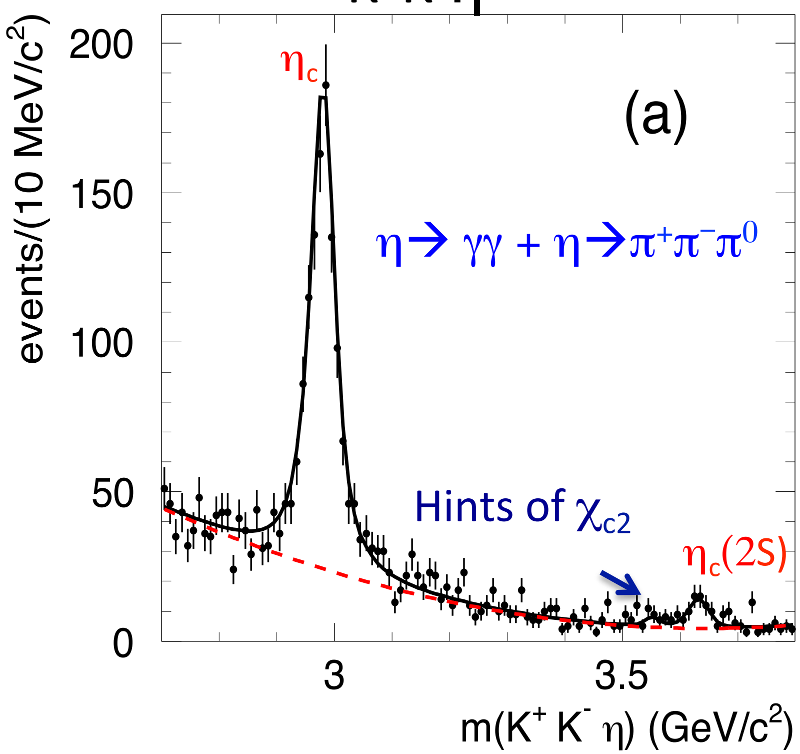
- Efficiency loss due to low momentum kaons and low momentum π^0 in $\eta \to \pi^+\pi^-\pi^0$.

Phys. Rev. D 89, 112004 (2014)

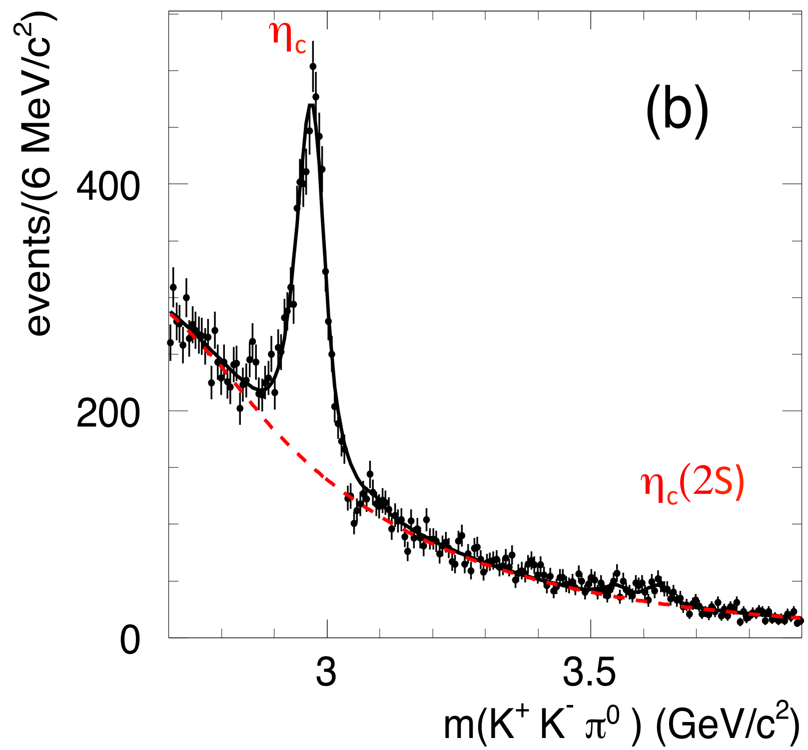
Mass Spectra

- Strong η_c signal and small enhancement at $\eta_c(2S)$.
- Each resonance is fit with a Breit-Wigner function convolved with the resolution function.

$K^+K^-\eta$



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



First observation of η_c , $\eta_c(2S) \rightarrow K^+K^-\eta$, $K^+K^-\pi^0$

Phys. Rev. D 89, 112004 (2014)

Branching fraction calculation

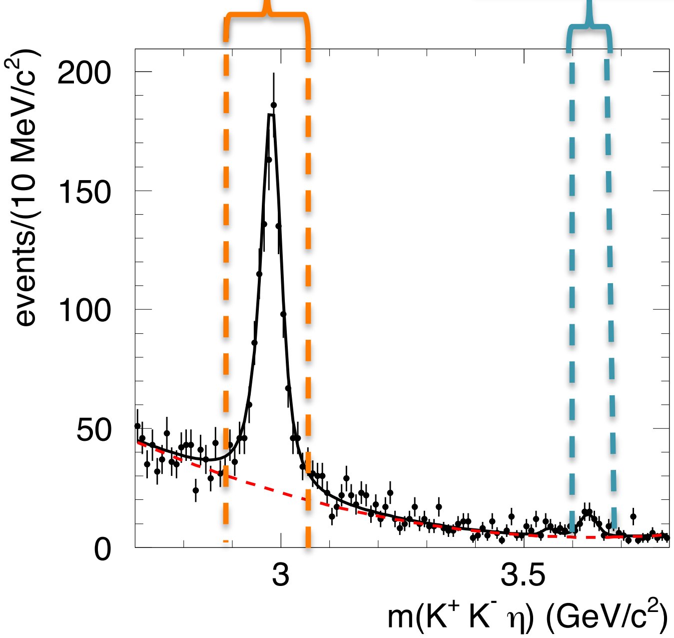
$$\mathcal{R} = \frac{\mathcal{B}(\eta_c/\eta_c(2S) \to K^+K^-\eta)}{\mathcal{B}(\eta_c/\eta_c(2S) \to K^+K^-\pi^0)} = \frac{N_{K^+K^-\eta}}{N_{K^+K^-\pi^0}} \frac{\epsilon_{K^+K^-\pi^0}}{\epsilon_{K^+K^-\eta}} \frac{1}{\mathcal{B}_\eta}$$

η_c signal region

$\eta_c(2S)$ signal region

Yield from fitted mass spectra

η PDG branching fraction



- Use of 2D efficiency $\varepsilon(m_{K+K-},\cos\theta_{K+})$ functions for η_c signals .
- Apply sideband subtraction of non-negligible backgrounds in the η_c signal regions:
  - Assign a weight $w=1/\varepsilon(m,\cos\theta)$ for signal-region events and a weight $w=-f/\varepsilon(m,\cos\theta)$ to events in the sideband region.
  - f is used to match the fitted η_c signal-to-background ratio in the sidebands.
- Use average efficiency value from simulation for $\eta_c(2S)$.

Phys. Rev. D 89, 112004 (2014)

Branching fraction measurement

$$\mathcal{R}(\eta_c) = \frac{\mathcal{B}(\eta_c \to K^+K^-\eta)}{\mathcal{B}(\eta_c \to K^+K^-\pi^0)} = 0.571 \pm 0.025 \pm 0.051$$

BES III measurement of 0.46±0.23 (Phys. Rev. D **86**, 092009 (2012)) consistent with this result.

$$\mathcal{R}(\eta_c(2S)) = \frac{\mathcal{B}(\eta_c(2S) \to K^+K^-\eta)}{\mathcal{B}(\eta_c(2S) \to K^+K^-\pi^0)} = 0.82 \pm 0.21 \pm 0.27$$

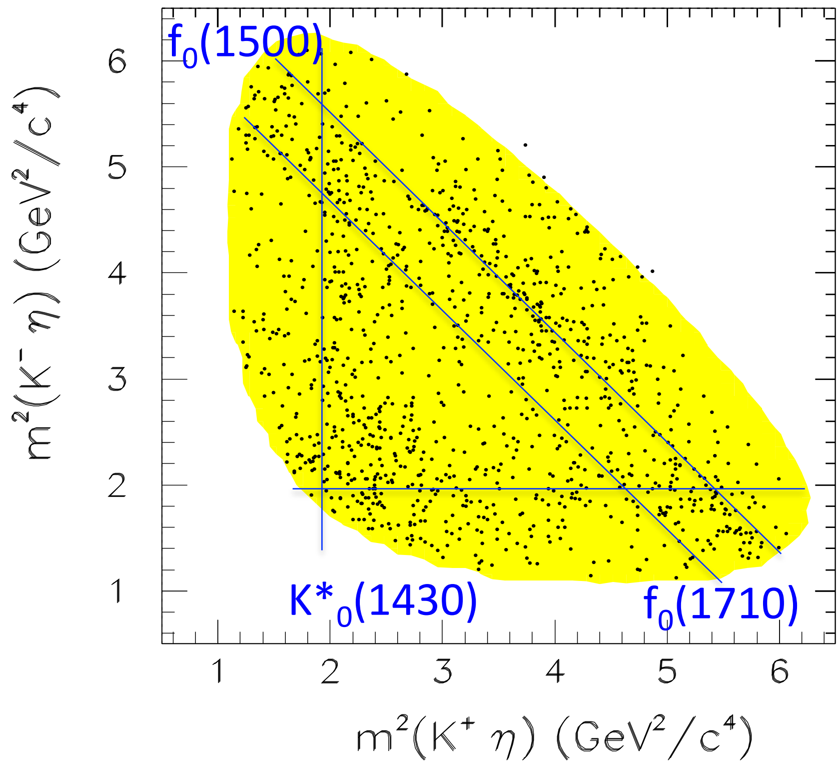
Channel	Event yield	Weights	$\mathcal{R}$	Significance
$\eta_c \to K^+K^-\pi^0$	$4518 \pm 131 \pm 50$	17.0 ± 0.7		$32\ \sigma$
$\eta_c \to K^+K^-\eta\ (\eta \to \gamma\gamma)$	$853 \pm 38 \pm 11$	21.3 ± 0.6		$21\ \sigma$
$\mathcal{B}(\eta_c \to K^+K^-\eta)/\mathcal{B}(\eta_c \to K^+K^-\pi^0)$			$0.602 \pm 0.032 \pm 0.065$	
$\eta_c \to K^+K^-\eta\ (\eta \to \pi^+\pi^-\pi^0)$	$292 \pm 20 \pm 7$	31.2 ± 2.1		$14\ \sigma$
$\mathcal{B}(\eta_c \to K^+K^-\eta)/\mathcal{B}(\eta_c \to K^+K^-\pi^0)$			$0.523 \pm 0.040 \pm 0.083$	
$\eta_c(2S) \to K^+K^-\pi^0$	$178 \pm 29 \pm 39$	14.3 ± 1.3		$3.7\ \sigma$
$\eta_c(2S) \to K^+K^-\eta$	$47 \pm 9 \pm 3$	17.4 ± 0.4		$4.9\ \sigma$
$\mathcal{B}(\eta_c(2S) \to K^+K^-\eta)/\mathcal{B}(\eta_c(2S) \to K^+K^-\pi^0)$			$0.82 \pm 0.21 \pm 0.27$	
$\chi_{c2} \to K^+K^-\pi^0$	$88 \pm 27 \pm 23$			$2.5\ \sigma$
$\chi_{c2} \to K^+K^-\eta$	$2 \pm 5 \pm 2$			$0.0\ \sigma$

Phys. Rev. D 89, 112004 (2014)

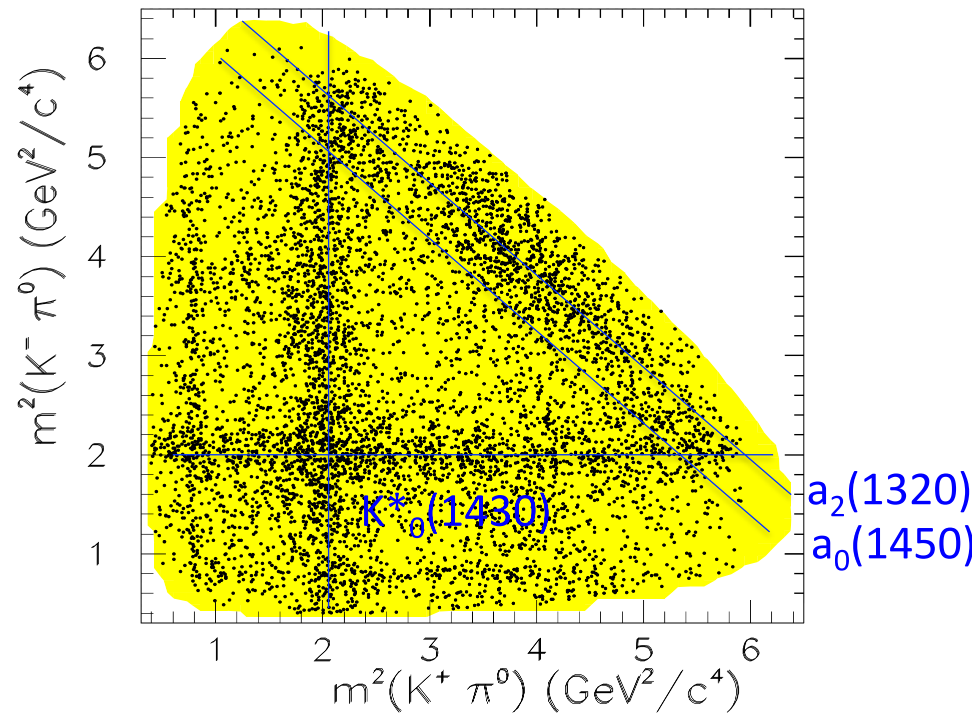
η_c Dalitz plot analyses

- Unbinned maximum likelihood fit.
- Amplitudes parameterized as in the standard pseudoscalar→three pseudoscalars.
- Full interference allowed among amplitudes.

$\eta_c \rightarrow K^+K^-\eta$



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



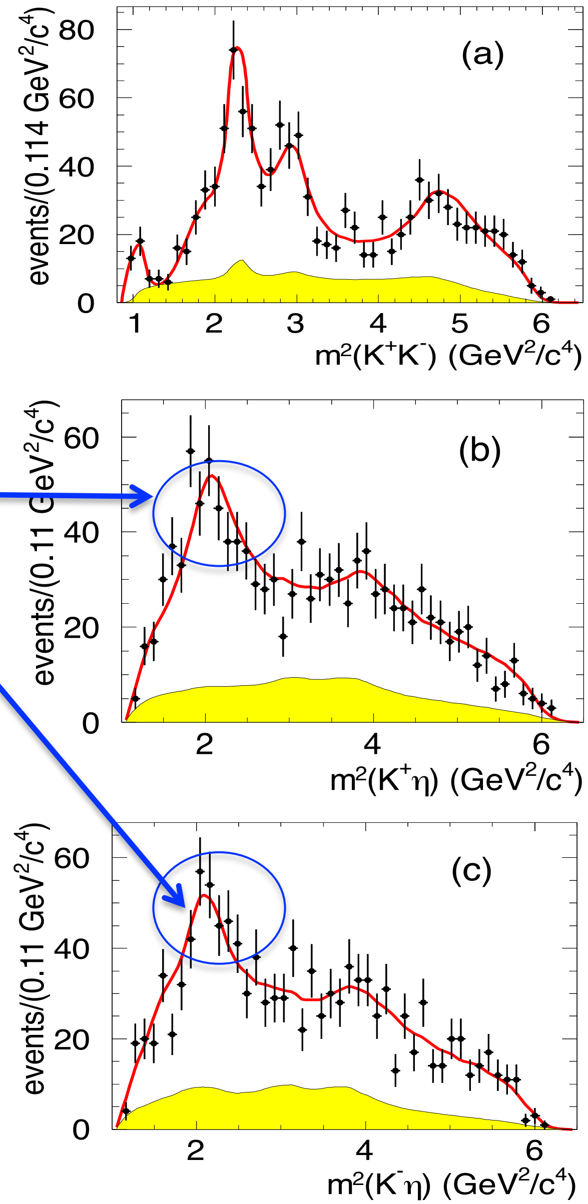
Phys. Rev. D 89, 112004 (2014)

Dalitz plot analysis: $\eta_c \rightarrow K^+K^-\eta$

- Dominance of scalar meson amplitudes.
- K*K amplitudes symmetrized to conserve C-parity.
- Observation of $f_0(980)$, $f_0(1500)$, $f_0(1720)$, $f_0(2200)$.
- First observation of $K^*(1430) \rightarrow K\eta$ as a Breit-Wigner Peak.

Final state	Fraction %	Phase (radians)
$f_0(1500)\eta$	23.7 ± 7.0 ± 1.8	0.
$f_0(1710)\eta$	8.9 ± 3.2 ± 0.4	2.2 ± 0.3 ± 0.1
$K_0^*(1430)^+K^-$	16.4 ± 4.2 ± 1.0	2.3 ± 0.2 ± 0.1
$f_0(2200)\eta$	11.2 ± 2.8 ± 0.5	2.1 ± 0.3 ± 0.1
$K_0^*(1950)^+K^-$	2.1 ± 1.3 ± 0.2	-0.2 ± 0.4 ± 0.1
$f_2'(1525)\eta$	7.3 ± 3.8 ± 0.4	1.0 ± 0.1 ± 0.1
$f_0(1350)\eta$	5.0 ± 3.7 ± 0.5	0.9 ± 0.2 ± 0.1
$f_0(980)\eta$	10.4 ± 3.0 ± 0.5	-0.3 ± 0.3 ± 0.1
NR	15.5 ± 6.9 ± 1.0	-1.2 ± 0.4 ± 0.1
Sum	$\boxed{100.0 \pm 11.2 \pm 2.5}$	
χ^2/ν	87/65	

- Adequate description of data. $\chi^2 = \sum_{i=1}^{N_{cells}} \left(N^i_{obs} - N^i_{\exp}\right)^2 / N^i_{\exp}$
- Background fitted using sum of incoherent resonances: $f'_2(1525)$, $f_0(2200)$, $K^*_3(1780)$, $K^*_0(1950)$ and interpolated from Dalitz analysis of the sideband regions .



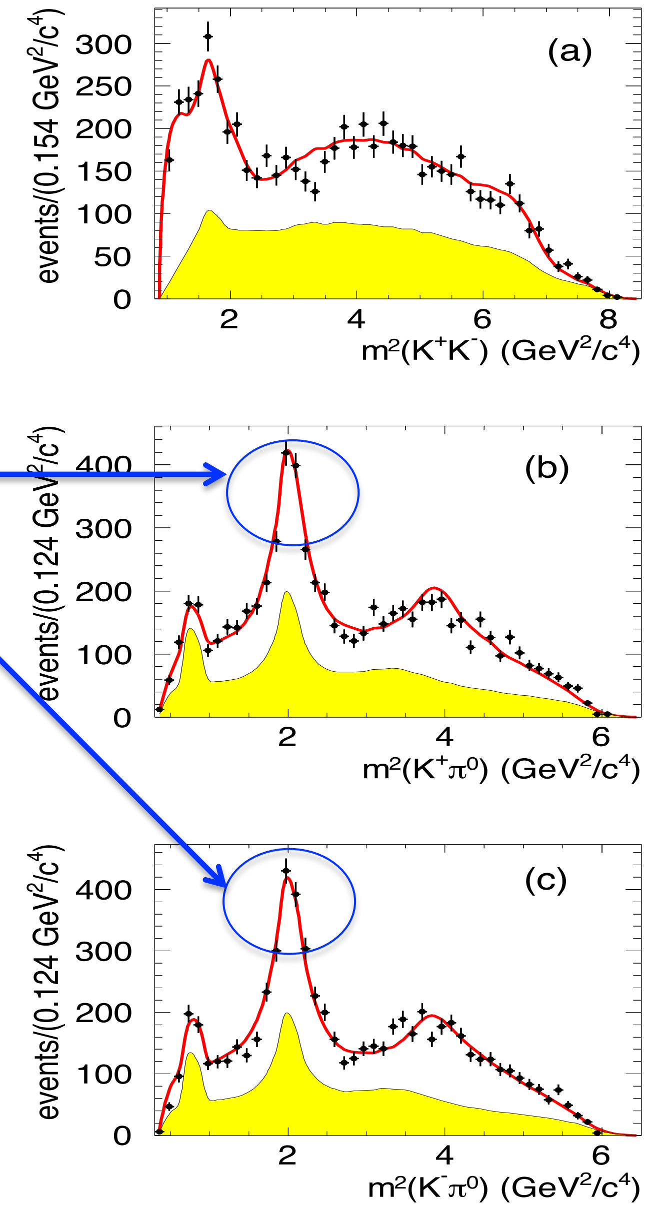
Phys. Rev. D 89, 112004 (2014)

Dalitz plot analysis: $\eta_c \rightarrow K^+K^-\pi^0$

- Dominance of scalar meson amplitudes and contributions from spin-2 resonances.
- Observation of $a_0(980)$, $a_2(1320)$, and $a_0(1450)$.
- Residual $\gamma\gamma \rightarrow K^+K^-$ background.
- First observation of $K^*(1430) \rightarrow K\pi^0$ as a Breit-Wigner peak.

Final state	Fraction %	Phase (radians)
$K_0^*(1430)^+K^-$	$33.8 \pm 1.9 \pm 0.4$	0.
$K_0^*(1950)^+K^-$	$6.7 \pm 1.0 \pm 0.3$	$-0.67 \pm 0.07 \pm 0.03$
$a_0(980)\pi^0$	$1.9 \pm 0.1 \pm 0.2$	$0.38 \pm 0.24 \pm 0.02$
$a_0(1450)\pi^0$	$10.0 \pm 2.4 \pm 0.8$	$-2.4 \pm 0.05 \pm 0.03$
$a_2(1320)\pi^0$	$2.1 \pm 0.1 \pm 0.2$	$0.77 \pm 0.20 \pm 0.04$
$K_2^*(1430)^+K^-$	$6.8 \pm 1.4 \pm 0.3$	$-1.67 \pm 0.07 \pm 0.03$
NR	$24.4 \pm 2.5 \pm 0.6$	$1.49 \pm 0.07 \pm 0.03$
Sum	$85.8 \pm 3.6 \pm 1.2$	
χ^2/ν	212/130	

Interference effects!



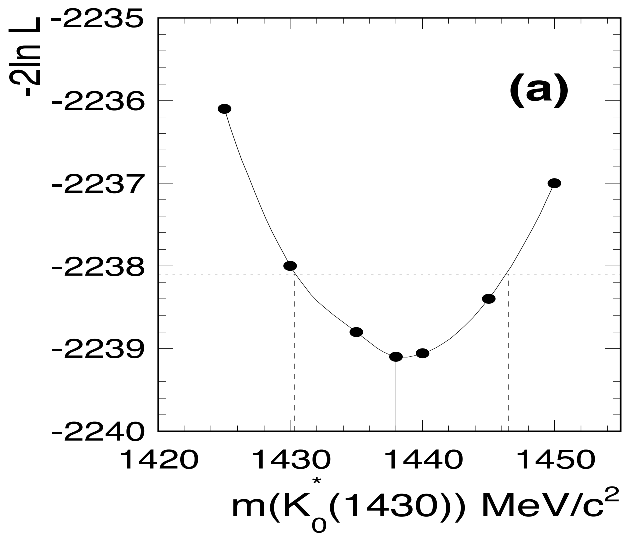
- The description does not fit the data well.
- Background in sidebands dominated by spin-1 resonances including: $a_2(1320)$, $K^*(892)$, $K^*_0(1950)$, $K^*_0(1430)$, $K^*_2(1430)$, $K^*(1680)$.

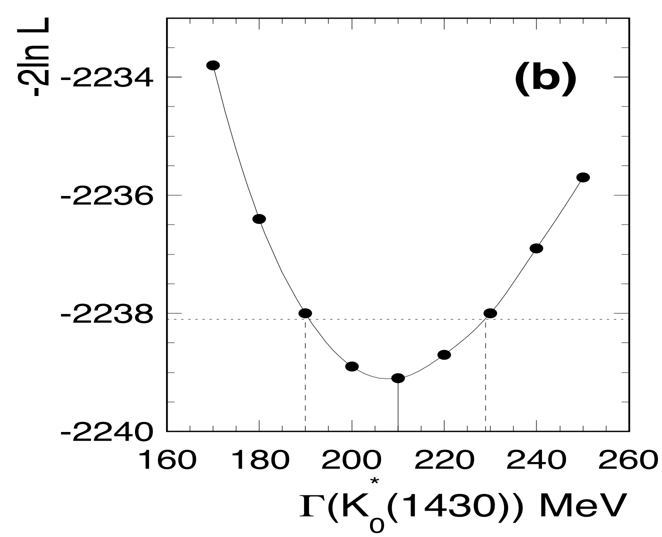
Phys. Rev. D 89, 112004 (2014)

$K^*_0(1430)$ Scalar Meson

- First observation of $K^*_0(1430) \rightarrow K\eta$ and first observation of $K^*_0(1430) \rightarrow K\pi$ as a Breit-Wigner peak .
- Likelihood scan to obtain best-fit parameters for the $K^*_0(1430)$.
- Best previous measurement by LASS experiment gives $m=1435\pm5\,MeV/c^2$ and $\Gamma=279\pm6$ MeV. (Nucl. Phys. B 296, 493 (1988))

Scan of $\eta_c \rightarrow K^+K^-\pi^0$ likelihood.





Fix width to 210 MeV and then scan likelihood as a function of the mass: $m=1438\pm8\pm4\,MeV/c^2$

Fix mass to 1435 MeV/c^2 and scan likelihood as a function of Γ: $\Gamma=210\pm20\pm12$ MeV

- Mass values agree with that from LASS experiment but width is ~3σ smaller.

Phys. Rev. D 89, 112004 (2014)

$K^*_0(1430)$ Branching Ratio

- First observation of $K^*_0(1430) \rightarrow K\eta$ permits a measurement of the branching ratio:

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

where $f_{\eta K}=0.164\pm0.042\pm0.010$ and $f_{\pi K}=0.338\pm0.019\pm0.004$.

- Non-resonant amplitude "*NR*" can represent a S-wave $K\pi$ or $K\eta$ system resulting in correlation between ϕ_{NR} (relative phase) and $f_{\pi K}$.

$\phi_{NR}=\pi/2$ gives $f_{\pi K}=(33.3\pm1.8)\%$ and $\phi_{NR}=3\pi/2$ gives $f_{\pi K}=(67.0\pm2.2)\%$

- Accounted for in systematic uncertainties by removing NR contribution and calculating the changes of the negative log likelihood for $\eta_c \rightarrow K^+K^-\pi^0$ and $\eta_c \rightarrow K^+K^-\eta$.

- LASS experiment studied $K^-p \rightarrow K^-\eta p$ at 11 GeV/c^2 (Phys. Lett. B 201,169 (1988)) and found no evidence of $K^*_0(1430)$, only $K^*_3(1780)$. However, from LASS study of $K^-p \rightarrow K^-\pi^+n$:

$$\Gamma(K_0^*(1430) \to K\pi)/\Gamma(K_0^*(1430)) = 0.93 \pm 0.04 \pm 0.09$$

which is **NOT** in conflict with our result. (Nucl. Phys. B 296, 493 (1988))

Conclusion

Phys. Rev. D 89, 112004 (2014)

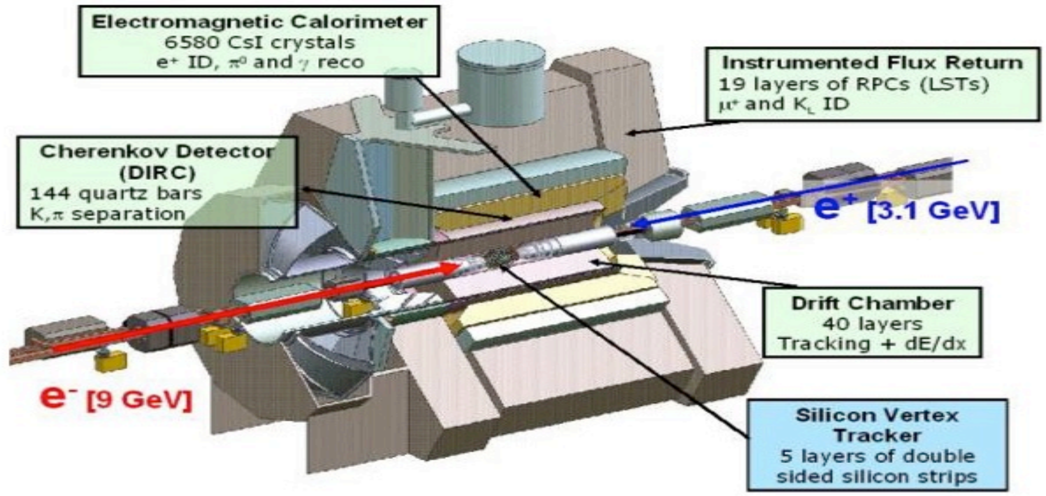
- First observation of η_c and $\eta_c(2S)$ in the $K^+K^-\eta$ and $K^+K^-\pi^0$ channel produced in two-photon interactions.
- First Dalitz plot analysis of $\eta_c \rightarrow K^+K^-\eta$ and $\eta_c \rightarrow K^+K^-\pi^0$.
  - Dominance of scalar meson resonances.
- First observation of $K^*_0(1430)$ as a Breit-Wigner peak in $K\eta$ and $K\pi$.
  - Determination of $K^*_0(1430)$ parameters and branching fraction ratio.

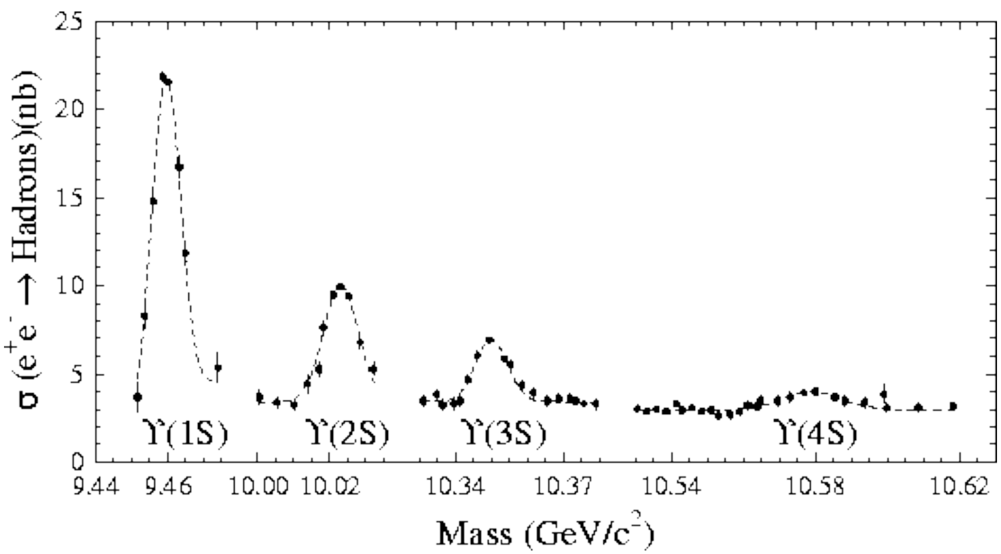
BACK UP SLIDES

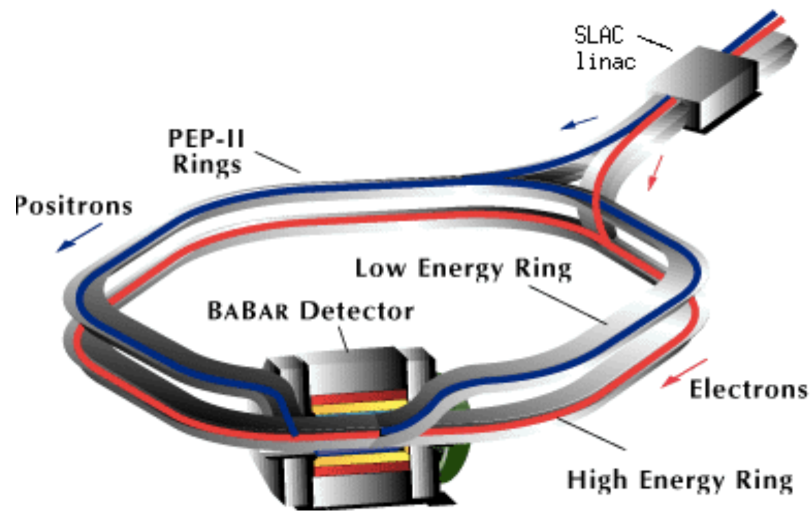
BaBar Experiment:

Phys. Rev. D 89, 112004 (2014)

- Located at SLAC National Accelerator Laboratory
- Asymmetric e+e- collisions at CM energy of 10.58 GeV .
- Data collection 1999 to 2008.





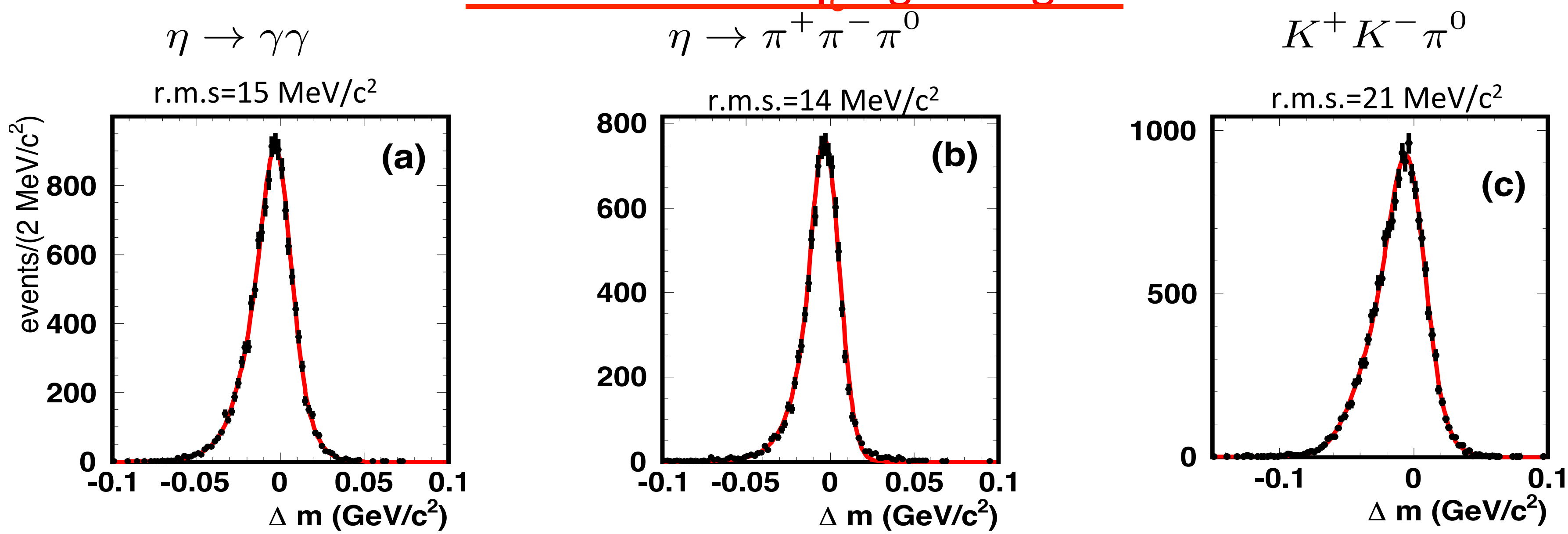


Phys. Rev. D 89, 112004 (2014)

Mass Resolution

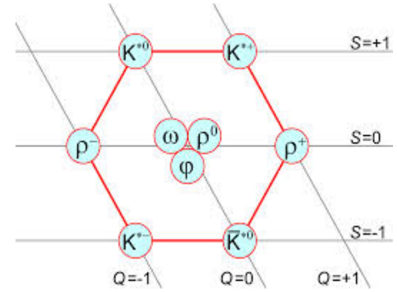
- Δm is the difference between the generated and reconstructed $K^+K^-\pi^0$ and $K^+K^-\eta$ invariant mass.
- Distribution fit with a Crystal Ball function for $K^+K^-\eta$, $\eta \rightarrow \pi^+\pi^-\pi^0$ and a sum of a Crystal Ball and Gaussian for $K^+K^-\eta$, $\eta \rightarrow \gamma\gamma$ and $K^+K^-\pi^0$, $\pi^0 \rightarrow \gamma\gamma$.

Distributions in η_c signal region



- Same fitting procedure for η_c (2S) with r.m.s.=18, 15, and 24 MeV/c^2 .

Pseudoscalar meson mixing angle



- For even angular momentum *l* ,

$$R_l = \frac{\mathcal{B}(K_l^* \to K\eta)}{\mathcal{B}(K_l^* \to K\pi)} = \frac{1}{9}(\cos\theta_p + 2\cdot\sqrt{2}\cdot\sin\theta_p)^2 \cdot (q_{K\eta}/q_{K\pi})^{2l+1}$$

where θ_p is the SU(3) octet-singlet mixing angle and $q_{K\eta}$ and $q_{K\pi}$ is the kaon momentum in the $K\eta$ or $K\pi$ rest frame.

- No evidence for $K^*_2(1430)$ in $K^-p \rightarrow K^-\eta p$ reaction *(Phys. Lett. B 201 169 (1988))*. Resulting upper limit is:

$$\mathcal{B}(K_2^*(1430) \to K\eta)/\mathcal{B}(K_2^*(1430) \to K\pi) < 0.92\%\ at\ 95\%\ C.L$$

- For l=2, the upper limit R_2=0.0092 corresponds to $\theta_p=-9.0^o$.
- Current analysis R_0=0.092 corresponding to $\theta_p=3.1^o$.

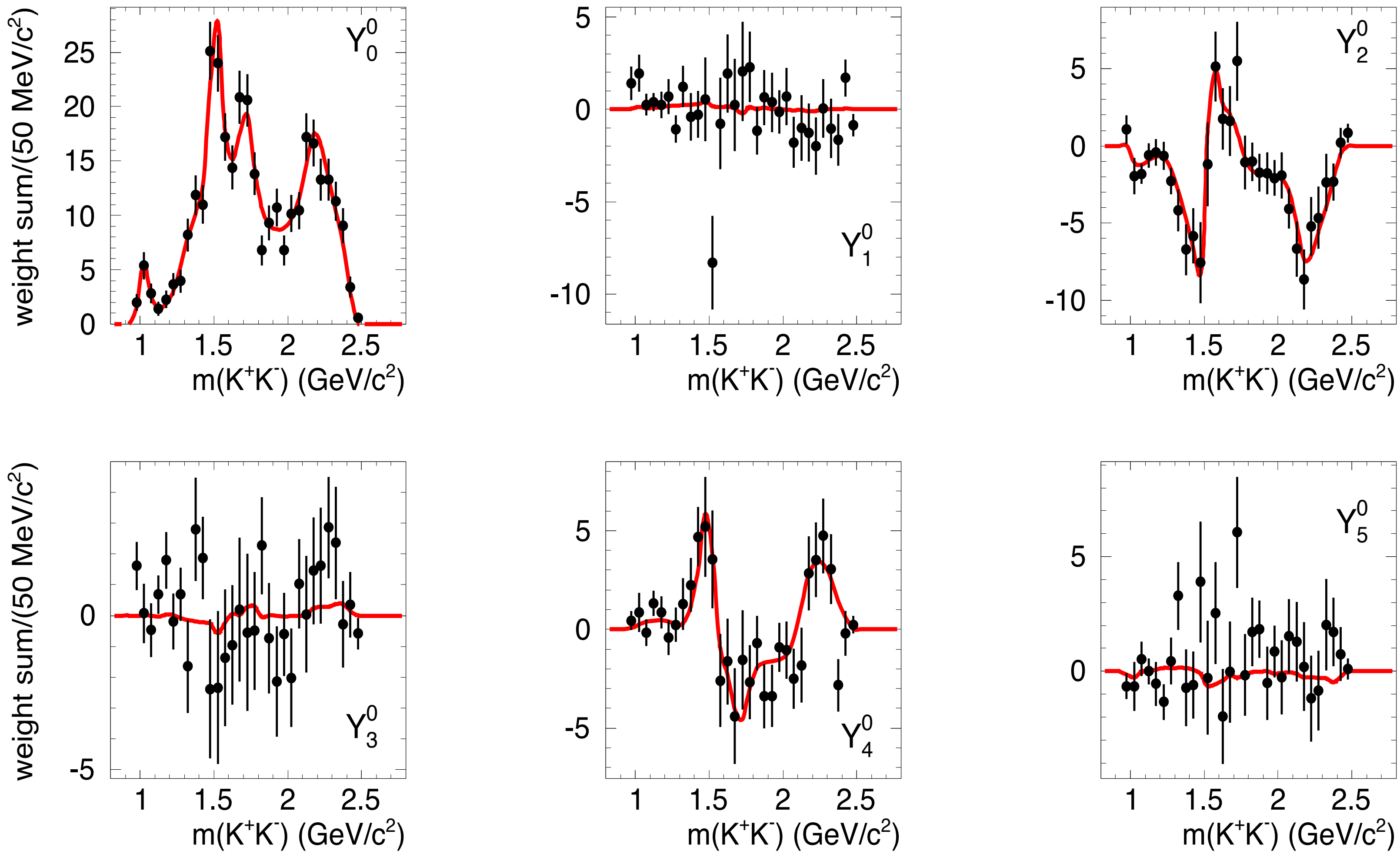
Lattice QCD calculation of $\theta_p=(-14.1\pm2.8)^o$.
Phys. Rev. Lett. **105**, 241601 (2010)

- In *Int. J. Mod. Phys. A 15, 159 (2000)*, it is argued that one must consider two separate angles for the octet and the singlet states.
  - Octet angle, θ_8, is about -20º.
  - Singlet angle, θ_1, ranges between 0 and 10º.

Legendre Polynomial Moments

$\eta_c \rightarrow K^+K^-\eta$

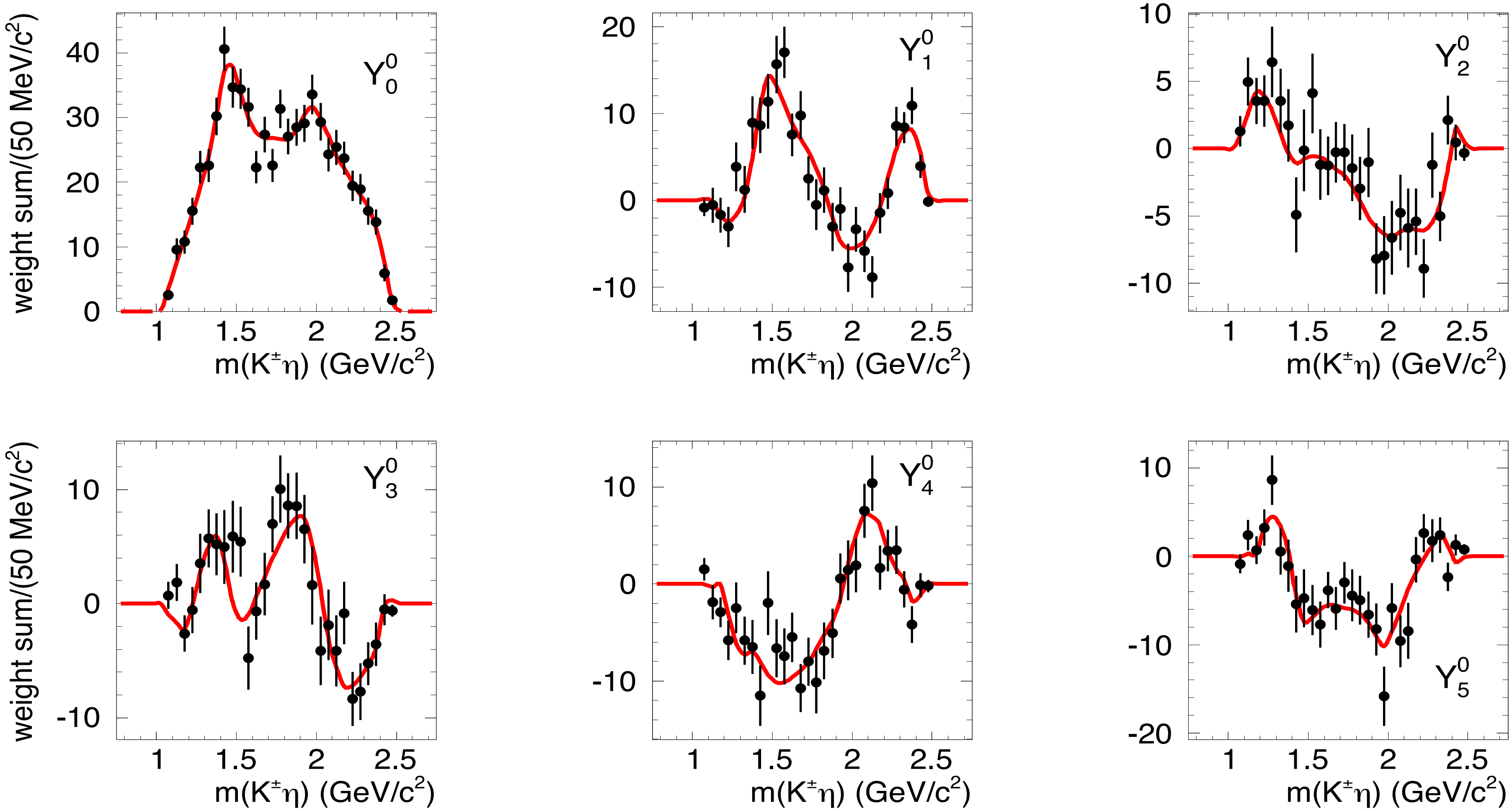
Superimposed curves result from the Dalitz plot analysis.



Legendre Polynomial Moments

$\eta_c \rightarrow K^+K^-\eta$

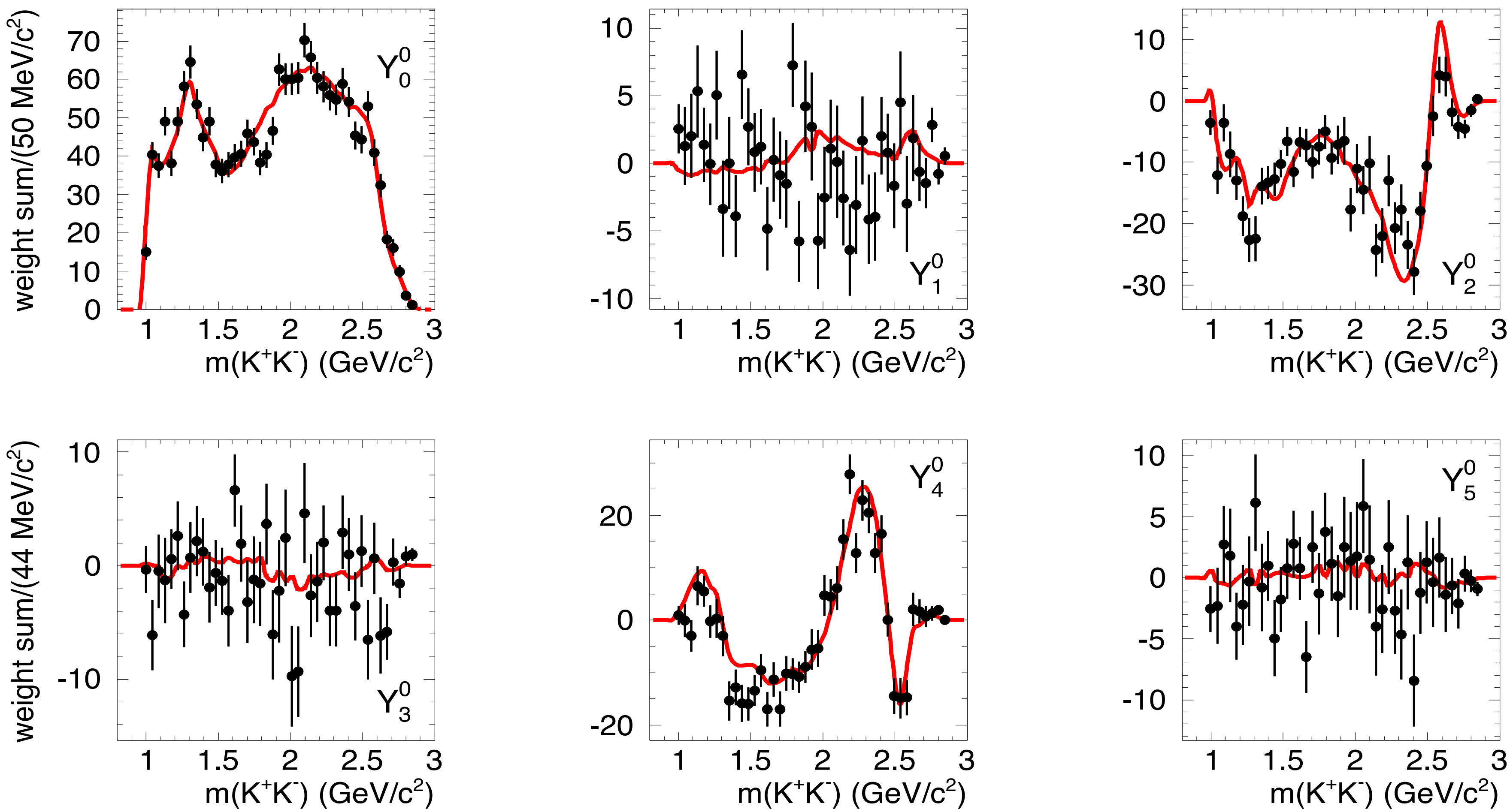
Superimposed curves result from the Dalitz plot analysis.



Legendre Polynomial Moments

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

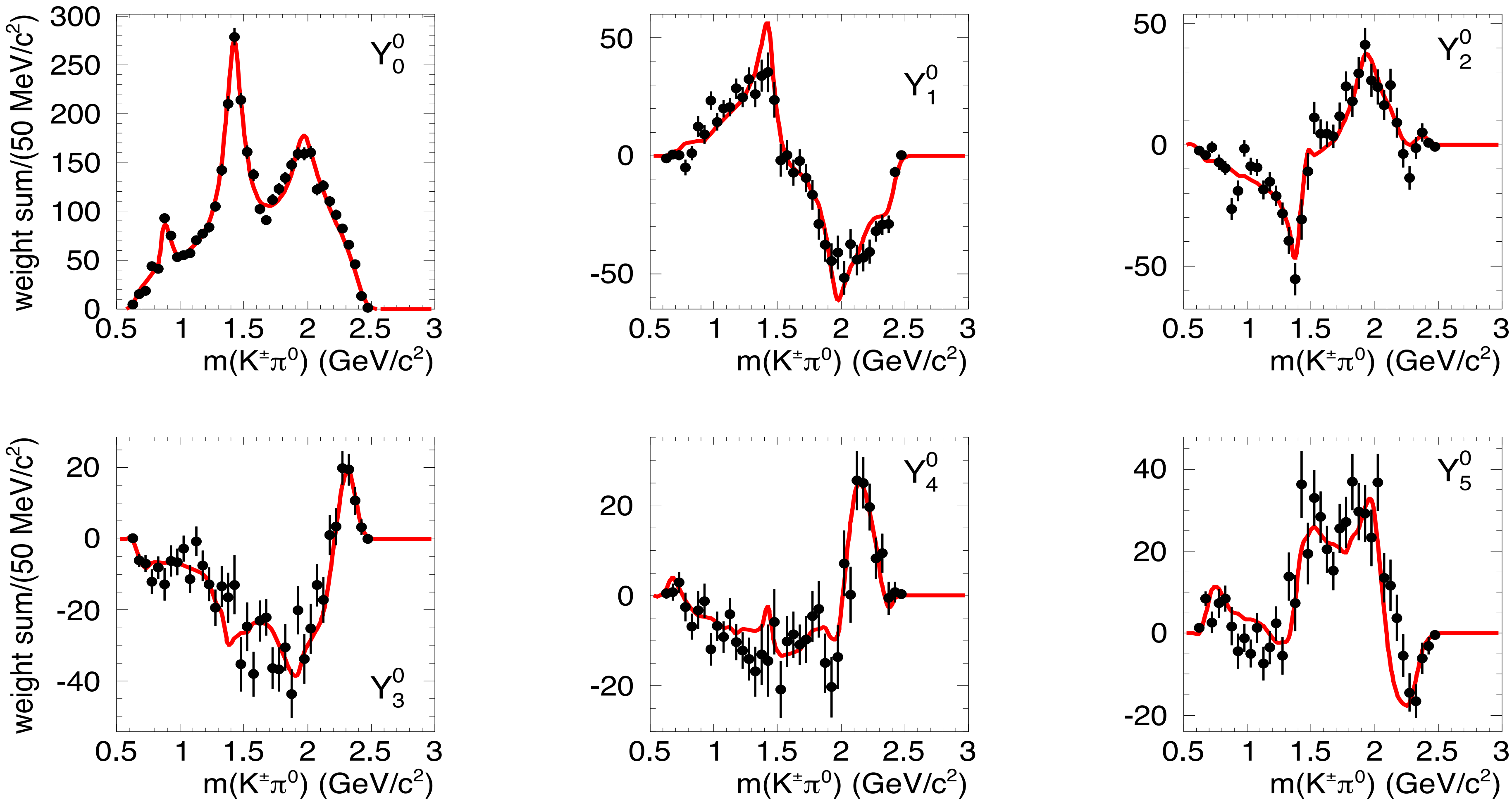
Superimposed curves result from the Dalitz plot analysis.



Legendre Polynomial Moments

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

Superimposed curves result from the Dalitz plot analysis.



Resonance Parameterization

- Each amplitude is parameterized as the product of a complex Breit-Wigner and a real angular term T:

$$A(x, y) = BW(m) \times T(\Omega).$$

- Relativistic BW is written as: D→rc, r→ab

$$BW(M_{AB}) = \frac{F_r F_D}{M_r^2 - M_{AB}^2 - i\Gamma_{AB} M_r} \qquad \Gamma_{AB} = \Gamma_r \left(\frac{p_{AB}}{p_r}\right)^{2J+1} \left(\frac{M_r}{M_{AB}}\right) F_r^2$$

  – F_r and F_D are form factors

- $f_0(980)$ amplitude parameterized as:

$$\rho_{KK} = 2p/m$$

$$A_{f_0(980)} = \frac{1}{m_0^2 - m^2 - i m_0 \Gamma_0 \rho_{KK}},$$

$$m_0 = (0.922 \pm 0.003_{\text{stat}})\ \text{GeV}/c^2,$$

$$\Gamma_0 = (0.24 \pm 0.08_{\text{stat}})\ \text{GeV}.$$

  – Coupled channed BW (Flatte) formalisim does not take into account coupling to tjhe ππ channel:

- $a_0(980)$ amplitude parameterized using Flatte formalism, because of its coupling to KK and πη:

$$F_0 = \beta_0' \frac{\begin{pmatrix} g_1 \\ g_2 \end{pmatrix}}{m_0^2 - m^2 - i(\rho_1 g_1^2 + \rho_2 g_2^2)}.$$

References

- D. Asner, Phys. Lett. B 592, 664 (2004)
- P. del Amo Sanchez et al. (BABAR Collaboration), Phys. Rev. D 83, 052001 (2011).
- A. Abele et al. (Crystal Barrel Collaboration), Phys. Rev. D 57, 3860 (1998)
- D. Aston et al. (LASS Collaboration), Phys. Lett. B 201, 169 (1988)
- T. Feldmann, Int. J. Mod. Phys. A 15, 159 (2000).

$K^*_0(1430)$

S-wave is complicated!

- The total S-wave can be written as:

$$a_{1/2}+(1/2)*a_{(3/2)}$$

- The $K^*_0(1430)$ resonance is added coherently to an effective-range description such that the amplitude actually decreases rapidly at the resonance mass.

Guess: The physics reason behind the BW peak in this analysis might be related to the ccbar annihilation mechanism in the η_c decay.