Risultati recenti sullo studio di stati di charmonio a *BABAR*

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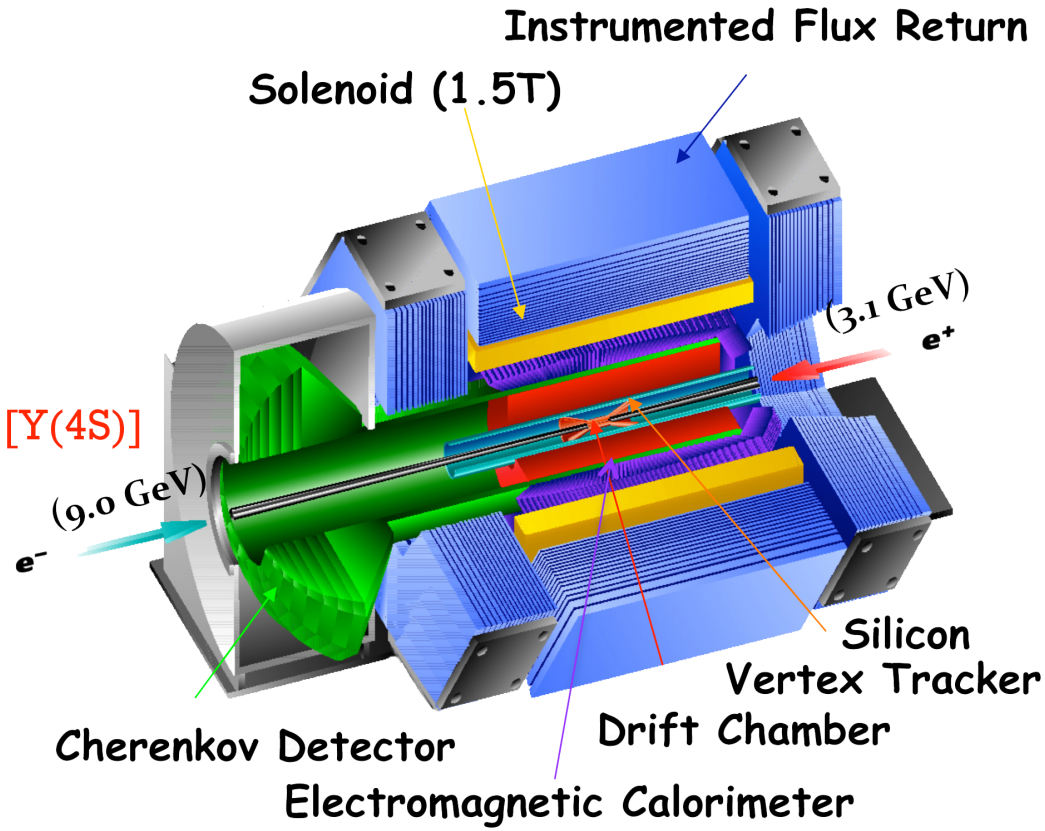
Incontri di fisica delle alte energie
9-11th April 2014

Outline

- Introduction
- Study of $B^{0,\pm} \to J/\psi K^+ K^- K_S^{0,\pm}$ and search for $B^0 \to J/\psi\phi$
  Preliminary results
- Dalitz plot analysis of $\eta_c \to K^+ K^- \eta$ and $\eta_c \to K^+ K^- \pi^0$ in two photon interactions
  Preliminary results
- Summary

The *BABAR* experiment and data sample

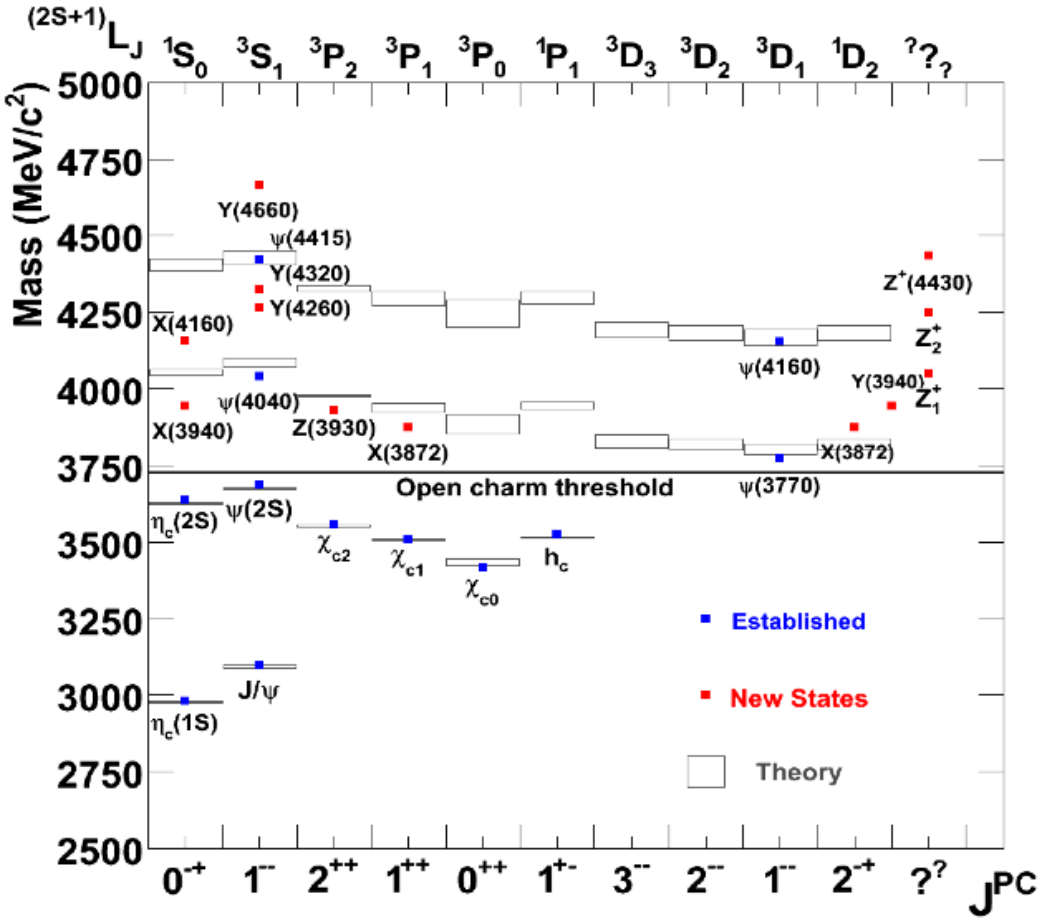


Features

- Data taking: 1999-2008
- Asymmetric beam energies; at the $\Upsilon(4S)$ ($\sqrt{s}$=10.58 GeV): E_{e^-}=9 GeV, E_{e^+}=3.1 GeV;
- Recorded 535 fb^{-1} in total:
  - $\Upsilon(4S)$: 433 fb^{-1}
  - $\Upsilon(3S)$: 30 fb^{-1}
  - $\Upsilon(2S)$: 14 fb^{-1}
  - Off-Peak: 54 fb^{-1}
  - Scan: 3.9 fb^{-1}

BABAR is a B factory: 467 million $B\bar{B}$ pairs in the total data sample.
BABAR is also a *c* factory: 1.3 million charm events per fb^{-1}.

Charmonium spectrum

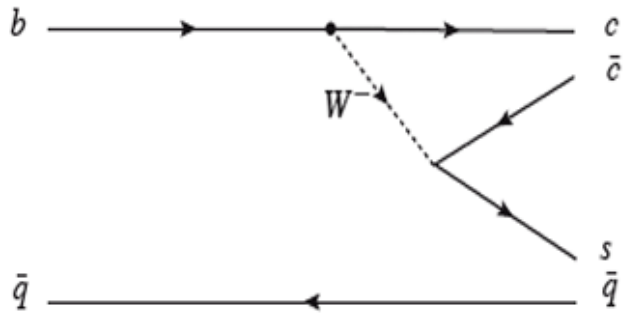


- Below the $D\bar{D}$ threshold, all expected states have been observed, with properties in good agreement with theory; there are no additional states.
- Many unexpected states have been reported above the $D\bar{D}$ threshold, seemingly too many with $J^{PC} = 1^{--}$. Several exotic hypotheses as to their nature: tetraquarks, hadronic molecules, hybrids, glueballs, hadro-quarkonia.
- These result mainly from Belle and *BABAR* , with significant contributions also from CDF, D0, CLEO, LHCb and BES.

Eur. Phys. J.C71, 1534 (2011)

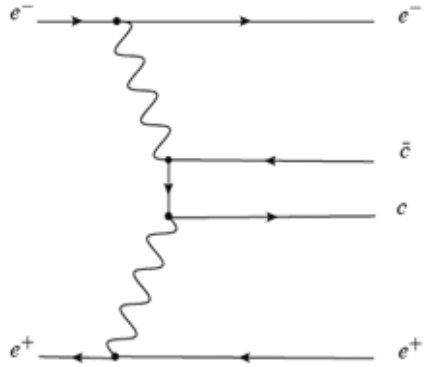
Experimental methods for charmonium production at the B-factories

B meson decays



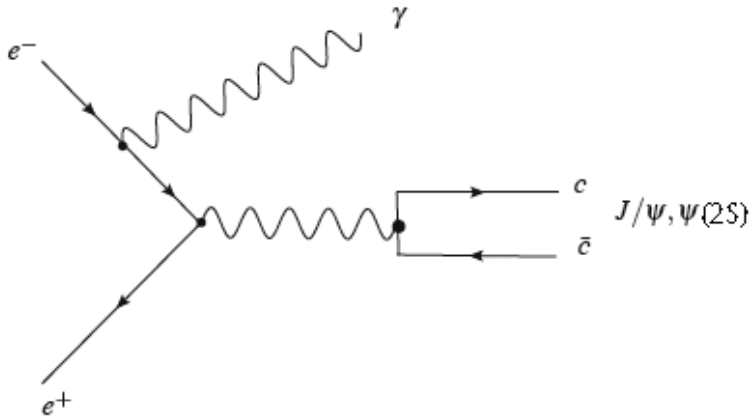
States of any quantum numbers can be produced

Two-photon production



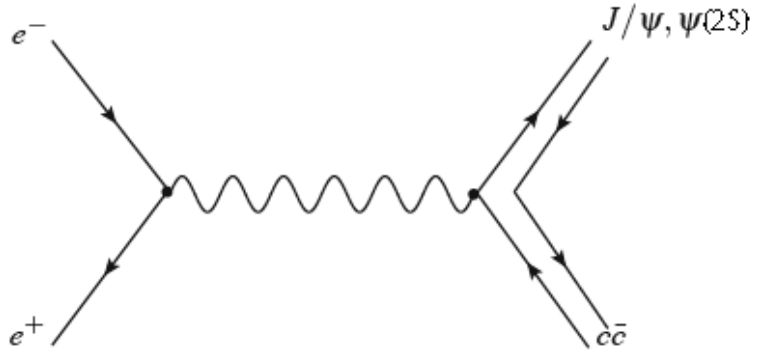
Only states with J^{PC} = $0^{\pm+}$, $2^{\pm+}$, $4^{\pm+}$,....., 3^{++}, 5^{++},..... can be produced

Initial State Radiation (ISR)

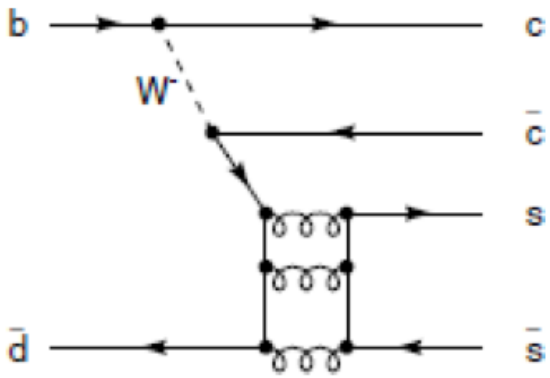


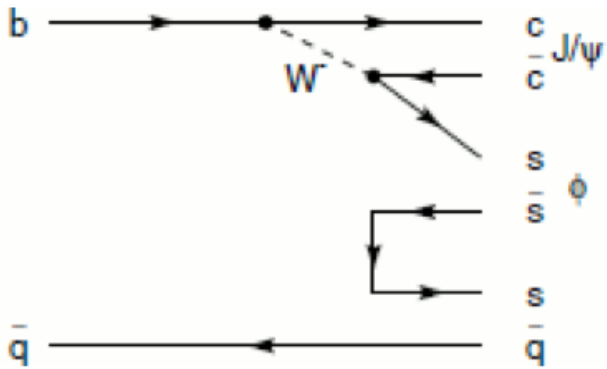
Only states with $J^{PC} = 1^{--}$ can be produced

Double charmonium production



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





Study of $B^{0,\pm} \to J/\psi K^+ K^- K_S^{0,\pm}$ and search for $B^0 \to J/\psi\phi$

Preliminary results

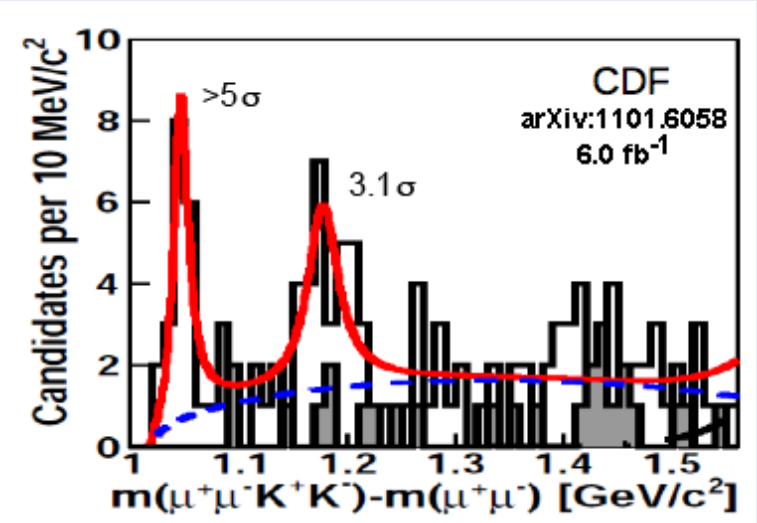
Motivation

2009 + 2011

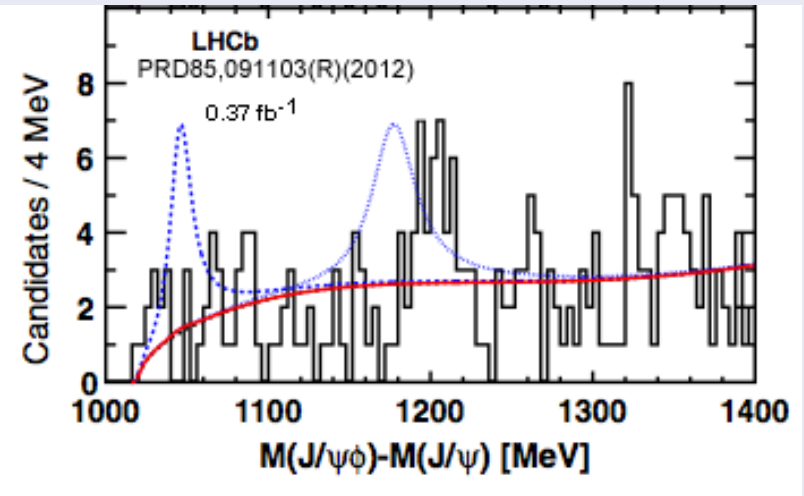
CDF studied the decay mode:
$B^+ \to J/\psi\phi K^+$; $\phi \to K^+K^-$; $J/\psi \to \mu^+\mu^-$
The observed two narrow peaks, looking at the $J/\psi\phi$ invariant mass, named X(4140) and X(4270).

PRL102,242002(2009)

arXiv:1101.6058(2011)



2012



LHCb did not confirm these peaks
2.4σ disagreement with CDF

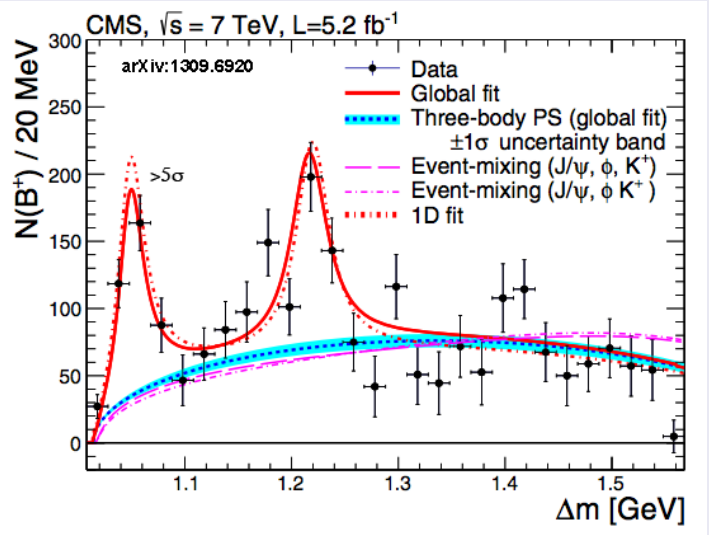
PRD85,091103(2012)

Motivation

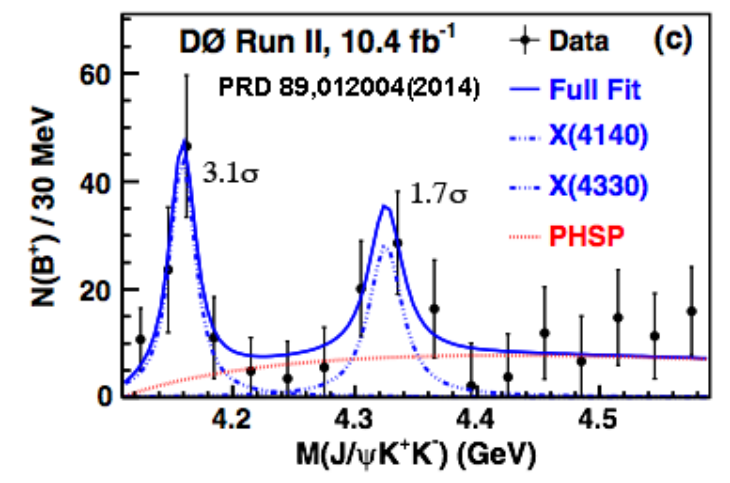
2013

CMS confirmed the presence of the two resonances

arXiv:1309.6920(2013)



2014



D0 saw evidence for the two resonances

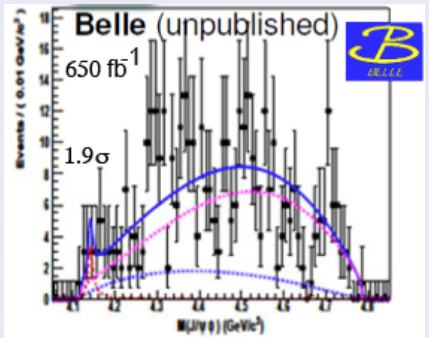
PRD89,012004(2014)

Motivation

2009

Belle did the study (unpublished)
Unable to conclude due to low efficiency at threshold

Lepton-Photon Conference 2009



Summary of the previous results

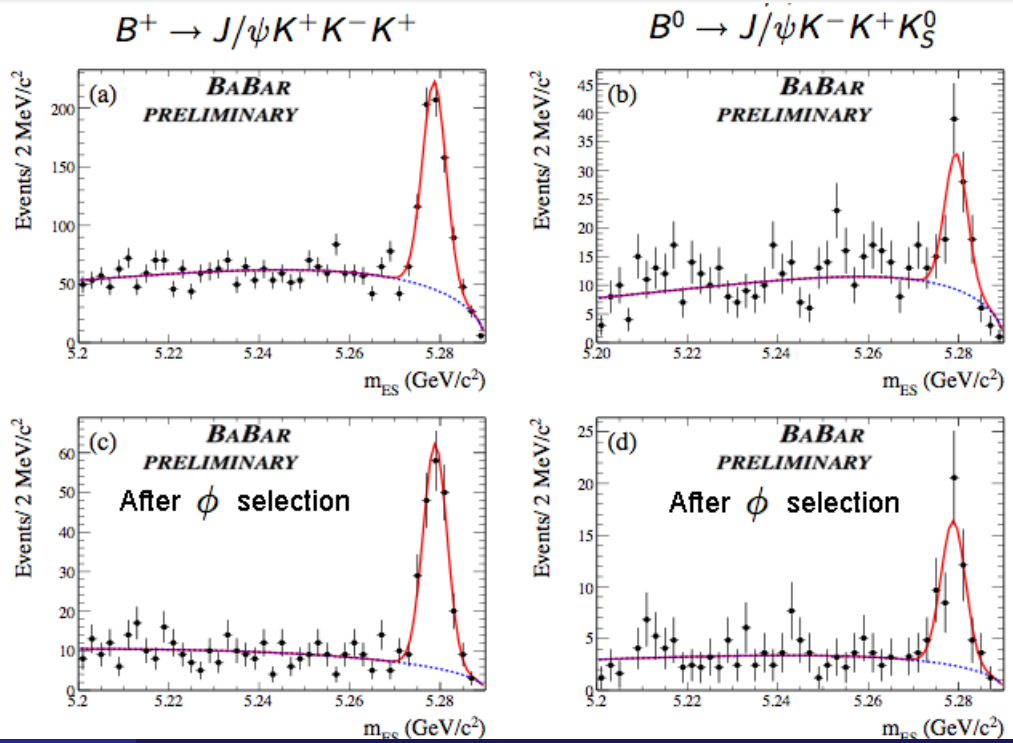
	X(4140)			X(4270)		
Reference	Mass (MeV/c^2)	Width (MeV)	Significance	Mass (MeV/c^2)	Width (MeV)	Significance
CDF PRL102,242002(2009)	$4143 \pm 2.9 \pm 1.2$	$11.7\ ^{+8.3}_{-5.0} \pm 3.7$	3.8σ	Possible signal		
CDF arXiv:1101.6058	$4143.4\ ^{+2.9}_{-3.0} \pm 0.6$	$15.3\ ^{+10.4}_{-6.1} \pm 2.5$	$>5\sigma$	$4274.4\ ^{+8.4}_{-6.7} \pm 1.9$	$32.3\ ^{+21.9}_{-15.3} \pm 7.6$	3.1σ
LHCb PRD85,091103(R) (2012)	No signal			No signal; excess at ~ 4.3 GeV/c^2		
D0 PRD89,012004(2014)	$4159 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6\ ^{+3.0}_{-8.0}$	3.1σ	~ 4360	30.0 (fixed)	1.7σ
CMS arXiv:1309.6920	$4148.0 \pm 2.4 \pm 6.3$	$28\ ^{+15}_{-11} \pm 19$	$>5\sigma$	$4313.8 \pm 5.3 \pm 7.3$	$38\ ^{+30}_{-15} \pm 16$	-

BABAR analysis

- Study of the processes $B^0 \to J/\psi K^+ K^- K^0_S$, $B^\pm \to J/\psi K^+ K^- K^\pm$ and $B^0 \to J/\psi\phi$
  - $J/\psi \to e^+e^-$; $\mu^+\mu^-$ and $\phi \to K^+K^-$
  - The full $\Upsilon(4S)$ *BABAR* dataset has been used, 424 fb^{-1}
  - Perform the branching fraction and branching ratio measurements
  - Search for the resonances X(4140) and X(4270) in the $J/\psi\phi$ invariant mass distribution
  - Search for the suppressed decay $B^0 \to J/\psi\phi$

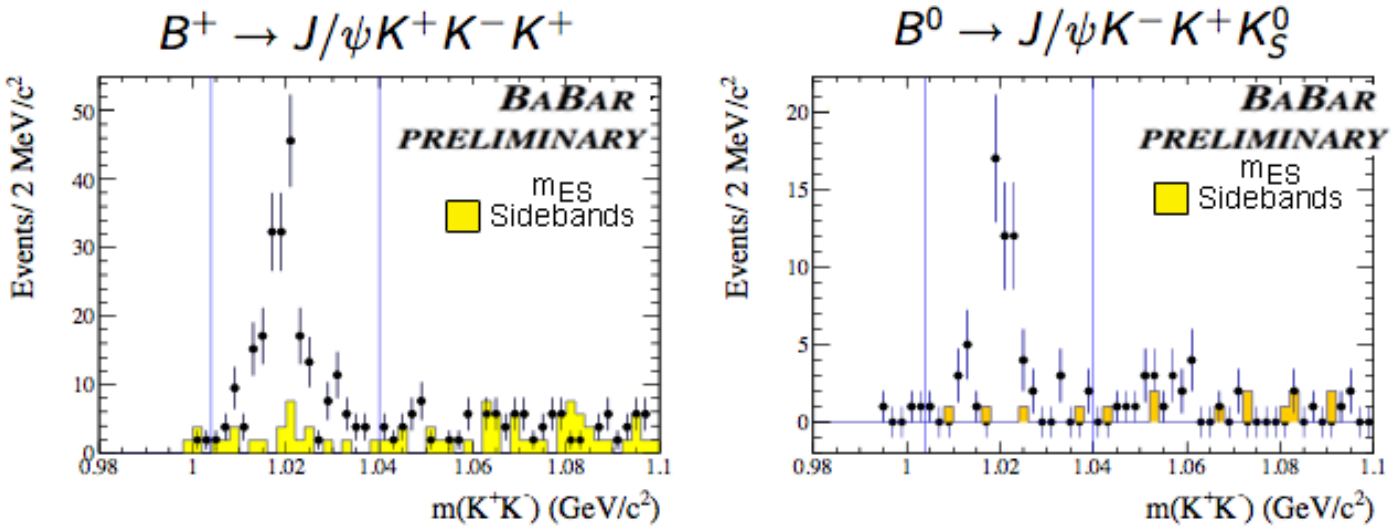
Unbinned maximum likelihood fits to the m_{ES} distributions are performed to determine the yields and obtain BF and BR measurements.

$$m_{ES} = \sqrt{((s/2 + \vec{p_i} \cdot \vec{p_B}/E_i)^2 - \vec{p_B}^2}$$



Branching fraction

Observation of a clear $\phi \to K^+K^-$ signal:



Branching Fraction Measurements

B channel	Event yield	$\mathcal{B}$ $(\times 10^{-5})$
$B^+ \to J/\psi K^+K^-K^+$	595^{+32}_{-31}	6.05 ± 0.33 (stat) ± 0.24 (sys)
$B^+ \to J/\psi \phi K^+$	200 ± 14	4.57 ± 0.32 (stat) ± 0.13 (sys)
$B^0 \to J/\psi K^-K^+K^0_S$	74 ± 12	3.55 ± 0.57 (stat) ± 0.15 (sys)
$B^0 \to J/\psi \phi K^0_S$	50 ± 7	2.53 ± 0.35 (stat) ± 0.09 (sys)

CDF, LHCb, D0, and CMS, do not obtain BF measurements.

Branching ratio measurements

$$R_+ = \frac{\mathcal{B}(B^+ \to J/\psi K^+ K^- K^+)}{\mathcal{B}(B^+ \to J/\psi \phi K^+)} = 1.32 \pm 0.12 \pm 0.07$$
$$R_0 = \frac{\mathcal{B}(B^0 \to J/\psi K^+ K^- K^0_S)}{\mathcal{B}(B^0 \to J/\psi \phi K^0_S)} = 1.40 \pm 0.30 \pm 0.08$$

R_+ and R_0 are the same within error, indicating that the fraction of ϕ production is the same for the $B^\pm$ and B^0 decay modes.

$$R_\phi = \frac{\mathcal{B}(B^0 \to J/\psi \phi K^0_S)}{\mathcal{B}(B^+ \to J/\psi \phi K^+)} = 0.55 \pm 0.10 \pm 0.02$$
$$R_{2K} = \frac{\mathcal{B}(B^0 \to J/\psi K^+ K^- K^0_S)}{\mathcal{B}(B^+ \to J/\psi K^+ K^- K^+)} = 0.59 \pm 0.13 \pm 0.03$$

The ratio of the BFs for the $B^\pm$ and B^0 decay modes involving the ϕ is the same within error as that for the $J/\psi KKK$ final states.

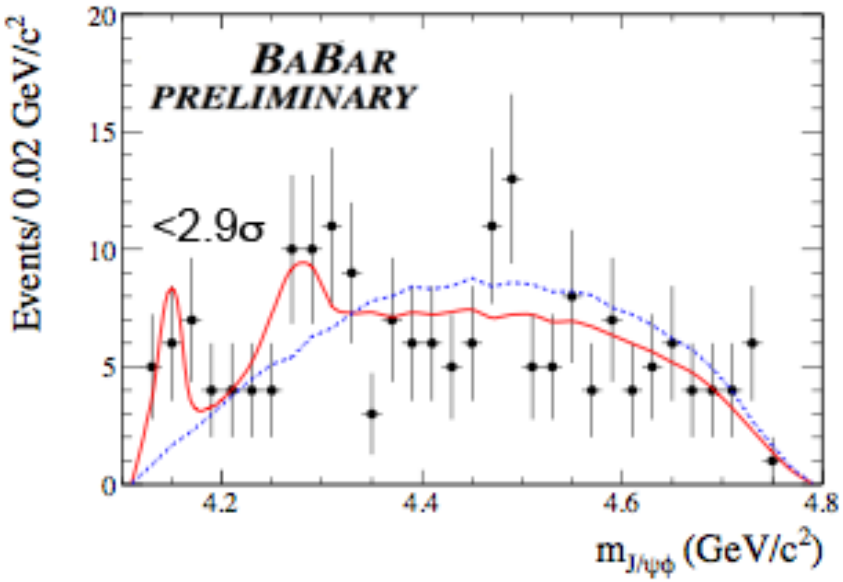
CDF, LHCb, D0, and CMS, do not obtain any such BR measurements.

Search for resonances in the $J/\psi\phi$ mass spectrum

We search for the resonant states claimed by CDF in the $J/\psi\phi$ mass spectrum.

- Ingredients:
  - Background: a uniform distribution (i.e. phase space)
  - Signal: two incoherent S-wave relativistic Breit-Wigner distributions with fixed mass and width values (because of limited statistics):
    X(4140): m=4143.4 MeV/c^2, $\Gamma = 15.3$ MeV
    X(4270): m=4274.4 MeV/c^2, $\Gamma = 32.3$ MeV
    from CDF arXiv:1101.6058
  - 2D efficiency map taken into account in the fit

- Results of the fit:
  - Fit with two CDF resonances:
    $\chi^2/NDF = 17.2/13$ (red curve)
  - Fit with no resonances:
    $\chi^2/NDF = 24.0/15$ (blue curve)



Search for resonances in the $J/\psi\phi$ mass spectrum

The *BABAR* Preliminary fit fractions, for the fit assumption of two resonances, are as follows:

$$f(4140) = (7.3 \pm 2.5 \pm 3.8)\%;\ \mathrm{UL}(90\%\ \mathrm{CL}) = 12.1\%$$
$$f(4270) = (7.7 \pm 3.7 \pm 5.2)\%;\ \mathrm{UL}(90\%\ \mathrm{CL}) = 16.4\%$$

From the other experiments:

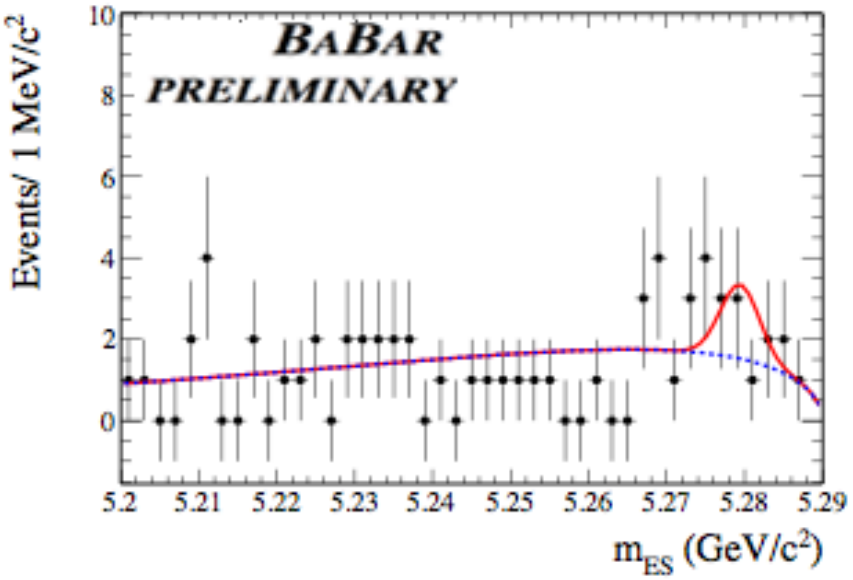
Experiments	$f(4140)$ [%]	$f(4270)$ [%]
CDF	$14.9 \pm 2.9 \pm 2.4$	-
LHCb	<7	< 8
D0	$19 \pm 7 \pm 4$	-
CMS	13.4 ± 3.0 (*)	18.0 ± 7.3 (*)

(*) Estimated from number of signal events quoted

We find that the hypothesis that the events are distributed uniformly on the Dalitz plot gives a worse description of the data, although, in order to access the presence of resonant behavior, higher statistics and a full Dalitz plot analysis are needed.

Search for the decay $B^0 \to J/\psi\phi$

We search for the decay $B^0 \to J/\psi\phi$ which is suppressed.



B channel	Event yield	$\mathcal{B}(X10^{-5})$
$B^0 \to J/\psi\phi$	6 ± 4	<0.101 (*)

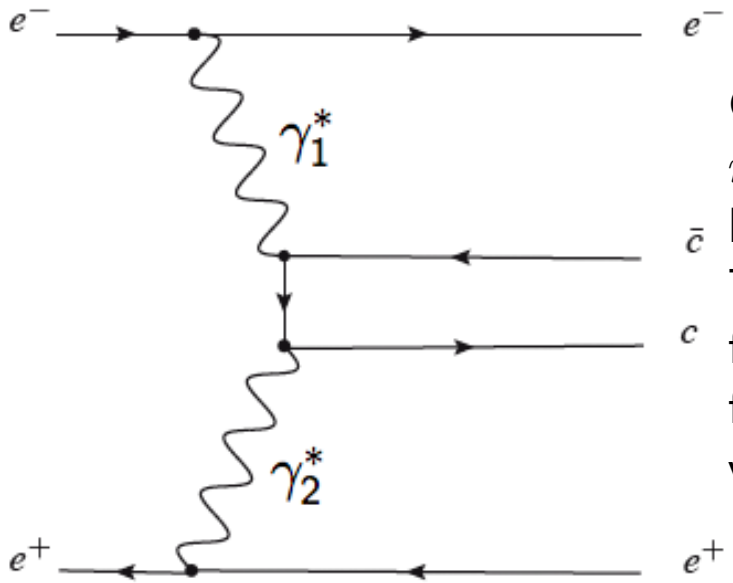
(*) UL(90% CL)

No evidence for this decay.

Dalitz plot analysis of $\eta_c \to K^+K^-\eta$ and $\eta_c \to K^+K^-\pi^0$

We study the reactions $\gamma_1^*\gamma_2^* \to K^+K^-\eta$ and $\gamma_1^*\gamma_2^* \to K^+K^-\pi^0$

Final state e^+ and e^- produced at low angle $\Rightarrow$ the γ_i^* are quasi-real



C-parity positive $\Rightarrow$ $\eta_c(1S), \chi_{cj}(1P), \eta_c(2S)\ldots$ but χ_{c1} forbidden (Yang Theorem) and χ_{c0} forbidden for 3-pseudoscalar-meson final states (parity conservation).

and perform Dalitz plot analyses for the decays $\eta_c \to K^+K^-\eta$ and $\eta_c \to K^+K^-\pi^0$.

Preliminary results

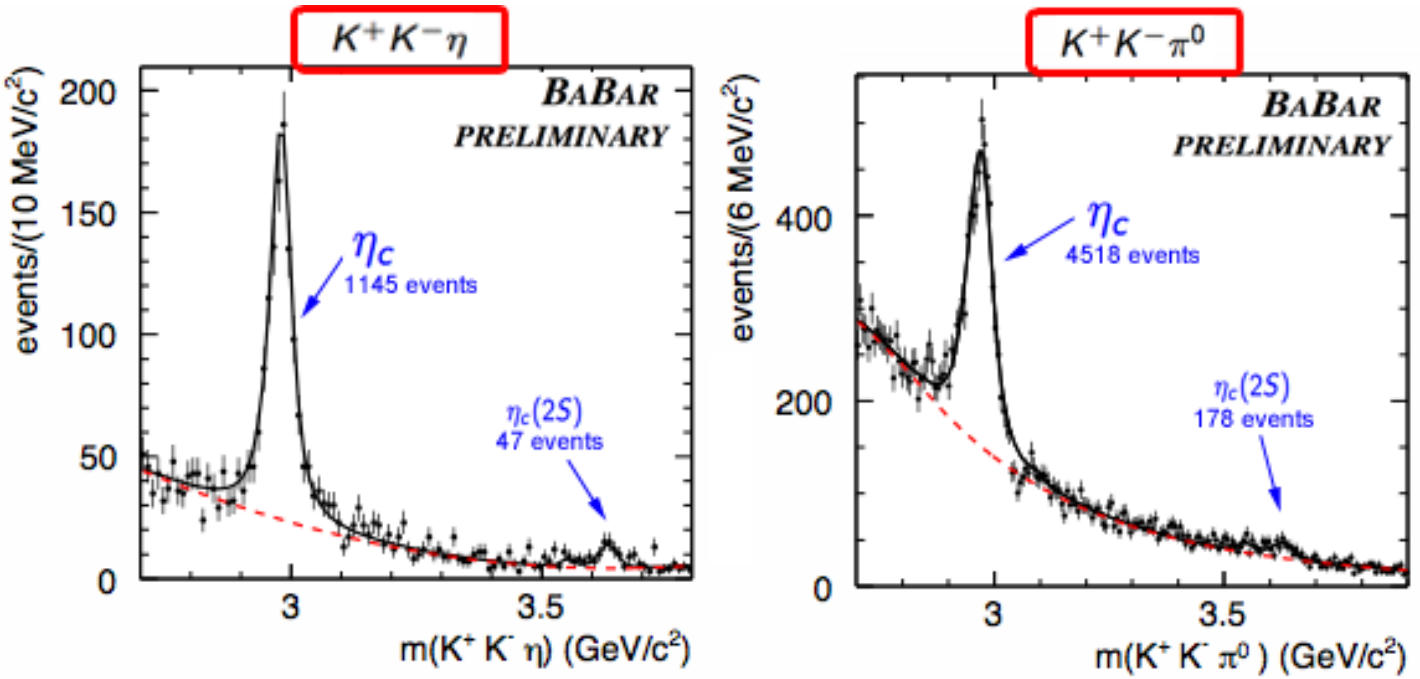
Motivation

- Many $\eta_c(1S)$ and $\eta_c(2S)$ decays are still missing or have been studied only with low statistics.
- The sum of the measured BF's for the $\eta_c(1S)$ is only $\sim$20%, while that for the $\eta_c(2S)$ is $<$5% PRD 86, 010001 (2012).
- BESIII (PRD 86,092009(2012)) has reported measurements of η_c branching fractions via the decay sequence $\psi(2S) \to \pi^0 h_c \to \gamma\eta_c$ but they obtained only $N(\eta_c \to K^+K^-\eta) = 6.7 \pm 3.2$ events and $N(\eta_c \to K^+K^-\pi^0) = 54.9 \pm 9.2$ events.
- No Dalitz plot analysis has been published for η_c decay to three pseudoscalar mesons.
- It turns out that η_c decays provide new information on scalar-meson states and on gluonic state candidates.
- We use an integrated luminosity of 519 fb^{-1} to study the reactions:

$$\gamma\gamma \to K^+K^-\eta$$
$$\text{with: } \eta \to \gamma\gamma \text{ or } \eta \to \pi^+\pi^-\pi^0$$
$$\gamma\gamma \to K^+K^-\pi^0$$

and report preliminary results

Mass spectra



Resonance parameters from fits:

Resonance	Mass (MeV/c^2)	Γ (MeV)
$\eta_c \to K^+K^-\eta$	$2984.1 \pm 1.1 \pm 2.1$	$34.8 \pm 3.1 \pm 4.0$
$\eta_c \to K^+K^-\pi^0$	$2979.8 \pm 0.8 \pm 3.5$	$25.2 \pm 2.6 \pm 2.4$
$\eta_c(2S) \to K^+K^-\eta$	$3635.1 \pm 5.8 \pm 2.1$	11.3 (fixed)
$\eta_c(2S) \to K^+K^-\pi^0$	$3637.0 \pm 5.7 \pm 3.4$	11.3 (fixed)

First observation of $\eta_c \to K^+K^-\eta$

First evidence of $\eta_c(2S) \to K^+K^-\eta$

Branching ratios

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

Weighted mean of the BR values for the two η decay modes:

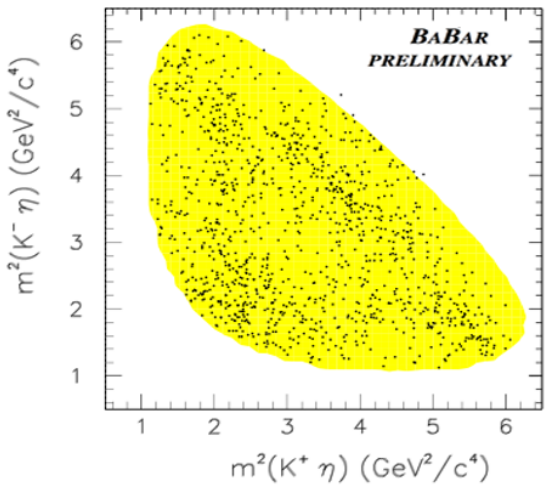
$$\mathcal{R}(\eta_c) = \frac{\mathcal{B}(\eta_c \to K^+K^-\eta)}{\mathcal{B}(\eta_c \to K^+K^-\pi^0)} = 0.571 \pm 0.025 \pm 0.051$$

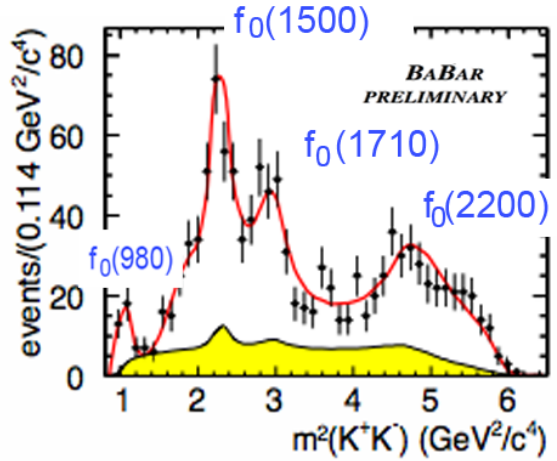
BESIII: $\mathcal{R}(\eta_c)$=0.46±0.23 (PRD 86,092009(2012)).
For the $\eta_c(2S)$ ($\eta \to \gamma\gamma$ only):

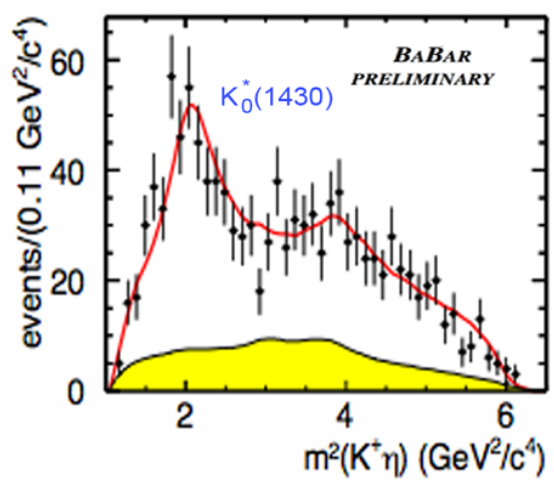
$$\mathcal{R}(\eta_c(2S)) = \frac{\mathcal{B}(\eta_c(2S) \to K^+K^-\eta)}{\mathcal{B}(\eta_c(2S) \to K^+K^-\pi^0)} = 0.82 \pm 0.21 \pm 0.27$$

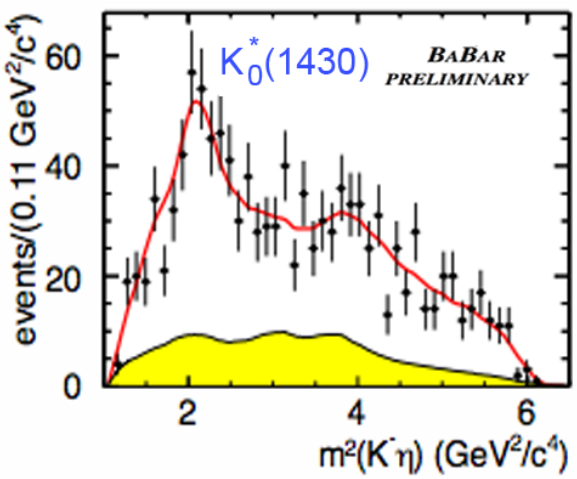
Dalitz plot analyses of $\eta_c \to K^+K^-\eta$

We perform Dalitz plot analyses of the $K^+K^-\eta$ system in the η_c mass region using unbinned maximum likelihood fits, which take into account background from the η_c sideband regions (yellow histograms).









- The K^+K^- amplitudes must have I=0
- First evidence for the decay mode $K_0^*(1430)^\pm \to K^\pm\eta$
- Observation of the $K_0^*(1430)$ as a Breit-Wigner peak [see also Fig. 12 in *BABAR* Collaboration, PRD 81, 052010 (2010)]

Dalitz plot analyses of $\eta_c \longrightarrow K^+K^-\eta$

Fit results:

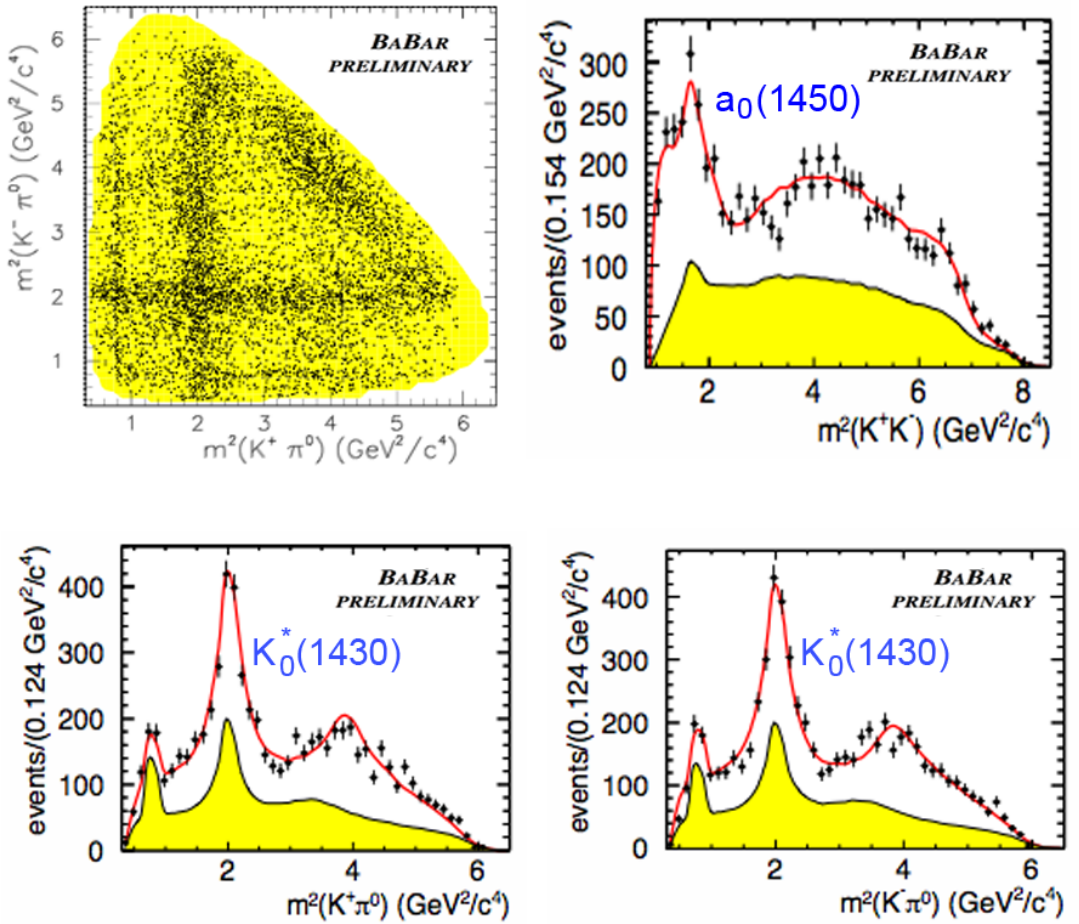
Final state	Fraction %
$f_0(1500)\eta$	$23.7 \pm 7.0 \pm 1.8$
$f_0(1710)\eta$	$8.9 \pm 3.2 \pm 0.4$
$K_0^*(1430)^+K^-$	$16.4 \pm 4.2 \pm 1.0$
$f_0(2200)\eta$	$11.2 \pm 2.8 \pm 0.5$
$K_0^*(1950)^+K^-$	$2.1 \pm 1.3 \pm 0.2$
$f_2'(1525)\eta$	$7.3 \pm 3.8 \pm 0.4$
$f_0(1350)\eta$	$5.0 \pm 3.7 \pm 0.5$
$f_0(980)\eta$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

Significant contributions from $f_0(1500)\eta$ and $f_0(1700)\eta$ (both gluonium candidates)

Note: $K^{*+}K^-$ notation represents the amplitude which has been symmetrized in order that the decay conserve C-parity.

Dalitz plot analyses of $\eta_c \to K^+K^-\pi^0$

We perform Dalitz plot analyses of the $K^+K^-\pi^0$ system in the η_c mass region using unbinned maximum likelihood fits, which take into account background from the η_c sideband regions (yellow histograms).



- The K^+K^- amplitudes must have I=1
- The $K^\pm\pi^0$ mass spectrum is dominated by the $K_0^*(1430)$ resonance.

Dalitz plot analyses of $\eta_c \longrightarrow K^+K^-\pi^0$

Fit results:

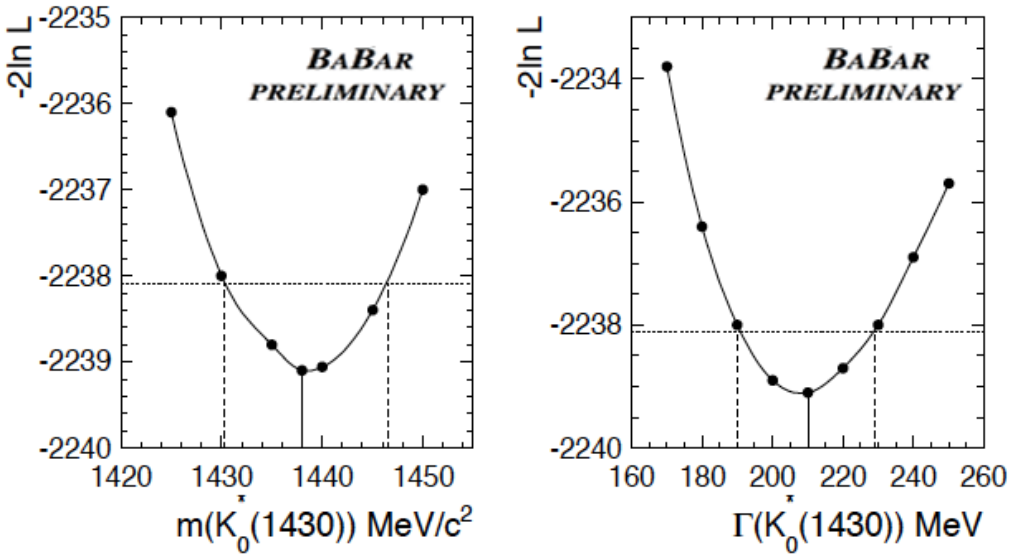
Final state	Fraction %		
$K_0^*(1430)^+K^-$	$33.8 \pm$	$1.9 \pm$	0.4
$K_0^*(1950)^+K^-$	$6.7 \pm$	$1.0 \pm$	0.3
$a_0(980)\pi^0$	$1.9 \pm$	$0.1 \pm$	0.2
$a_0(1450)\pi^0$	$10.0 \pm$	$2.4 \pm$	0.8
$a_2(1320)\pi^0$	$2.1 \pm$	$0.1 \pm$	0.2
$K_2^*(1430)^+K^-$	$6.8 \pm$	$1.4 \pm$	0.3
NR	$24.4 \pm$	$2.5 \pm$	0.6
Sum	$85.8 \pm$	$3.6 \pm$	1.2
χ^2/ν		$212/130$	

Significant contributions from $K_0^*(1430)$

Note: $K^{*+}K^-$ notation represents the amplitude which has been symmetrized in order that the decay conserve C-parity.

$K_0^*(1430)$ parameters

From the Dalitz plot analysis of both $\eta_c \to K^+K^-\eta$ and $\eta_c \to K^+K^-\pi^0$ we perform a likelihood scan to obtain the best-fit parameters for the $K_0^*(1430)$.



$$m(K_0^*(1430)) = 1438 \pm 8 \pm 4 \text{ MeV/c}^2$$

Good agreement with LASS experiment (Nucl.Phys.B 296, 493(1988))

$$\Gamma(K_0^*(1430)) = 210 \pm 20 \pm 12 \text{ MeV}$$

3σ smaller than then LASS result (Nucl.Phys.B 296, 493(1988))

We obtain also the $K_0^*(1430)$ branching ratio:

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

Summary

- New results on the $B \to J/\psi\phi(K)$ channel:
  - Branching fraction and branching ratio measured
  - X(4140) and X(4270): no definite conclusion on their existence
  - No significant signal found in $B \to J/\psi\phi$
- New results on $\eta_c \to K^+K^-\pi^0$ and $\eta_c \to K^+K^-\eta$.
  - Large signal seen in both channels
  - First observation of $\eta_c \to K^+K^-\eta$ and first evidence for $\eta_c(2S) \to K^+K^-\eta$
  - First Dalitz plot analysis of these decays
  - First observation of the decay $K_0^*(1430) \to K^\pm\eta$ and first time seen as a peak

Conclusion

- Quarkonium spectroscopy is a very interesting field, many new exotic states have been discovered in recent years;
- Still many missing pieces need to be found to have the full picture;
- The *BABAR* experiment switched off in 2008, but still produces many interesting results!
  - 529 papers in total
  - 26 papers in 2013

THANKS FOR YOUR ATTENTION!