Preliminary Results on $h_c(1S)$ and $h_c(2S)$ from BaBar

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for

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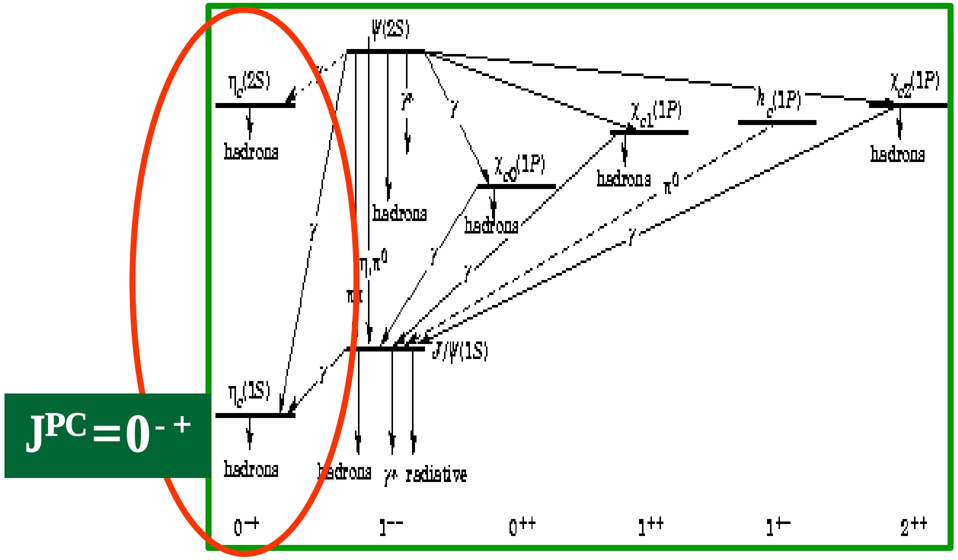
Overview



h$_c$ (2^1S_0), or *h$_c$*', radial excitation of firmly established *h$_c$* (1^1S_0)

First observed by CrystalBall

in M1 radiative decay of ψ(2S)

Observed only recently

by B-factories (Belle/BaBar/Cleo)

BaBar measurements in e^+e^- collisions at *U(4S)* :

- B Decays: *B* ® *h$_c$* *X*
  - *B* ® *h$_c$* *K* , "golden mode" for CP-violation studies
    - ➢sin2β measurement
    - ➢Branching fractions products
    - ➢Search for new *h$_c$* decay modes
- *gg* production:
  - e^+e^- ® $e^+e^-g^*g^*$ ® $e^+e^-h_c^{(')}$
    - ➢*h$_c$* mass and width
    - ➢*h$_c$*' observation, mass and width

$h_c^{(')}$ Spetroscopy in $\gamma\gamma$ Fusion

Resonance Parameters of $h_c(1^1S_0)$

- Still large spread of experimental results on mass and <u>width</u>
- Total width dominated by two-gluon component
- PQCD predicts quite accurately:

$$\frac{\Gamma_{tot}}{\Gamma_{gg}} \approx \frac{9a_s^2}{8a^2} \times \frac{1+4.8a_s/p}{1-3.4a_s/p}$$

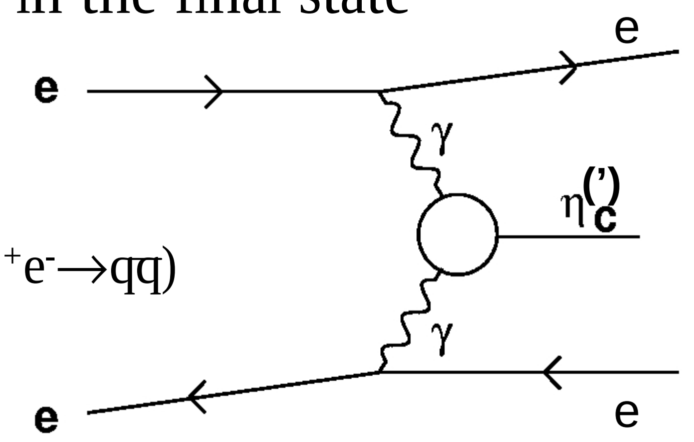
Kwong et al.
Phys Rev D37,3210(1988)

Precise measurements of Γ_{tot} and $\Gamma_{\gamma\gamma}$ allow test of these calculations

PDG(2003) : G_{tot} **= 16.1$^{+3.1}_{-2.8}$** MeV , average over range 7–27MeV
Recent results from Belle, E835 non included in this average

$\gamma\gamma$ Fusion Production and Selection

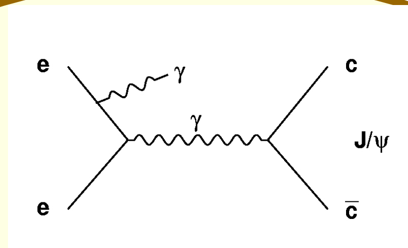
- **Production:** Virtual photon flux falls as $1/q^2$, $q^2 \sim -4EE' \sin^2(\theta/2)$
  Cross-section falls very rapidly with increasing scattering angle
  $\Rightarrow$ e^+ and e^- are not detected $\Rightarrow$ γ's aligned with beams
  $\Rightarrow$ Balanced momenta of particles in the final state
- **Selection**
  - 2 photon events:
    $\Sigma p^T < 0.5$ GeV/c
    E^{tot} (LAB) < 9 GeV (to suppress $e^+e^- \rightarrow qq$)
  - Fully reconstruct h_c ® $K_s^0 K^+ p^-$:
    - $Ks \rightarrow \pi^+\pi^-$
      $0.491 < M(\pi^+\pi^-) < 0.503$ GeV/c^2
      $\cos\theta(K_s) > 0.99$
    - Apply Particle ID criteria on charged K candidate
    - Fit the $K_S K^+ \pi^-$ vertex (prob(χ^2)>1%)



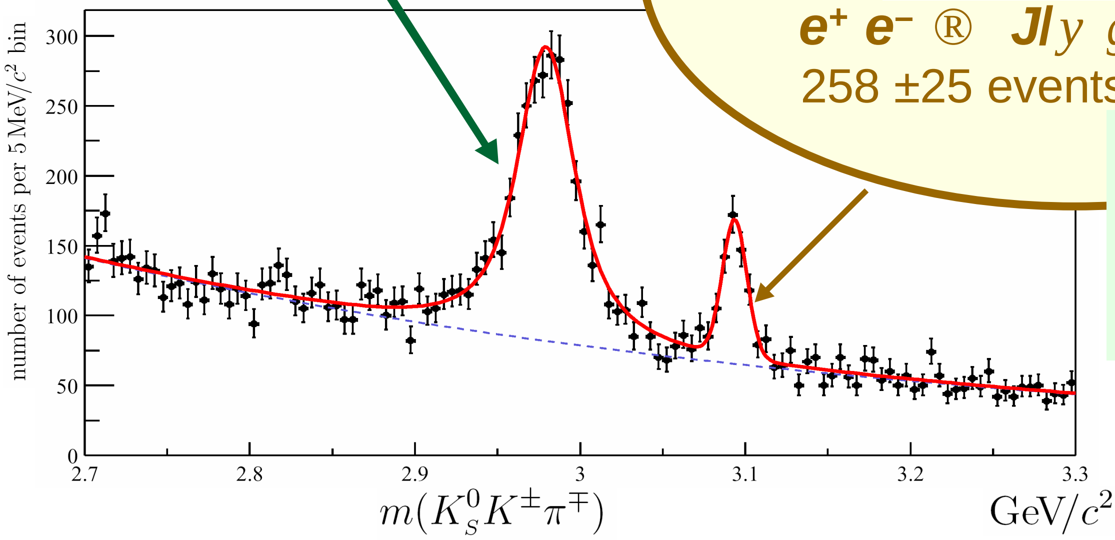
Invariant Mass Spectrum

L = 88 fb^{-1}

$e^+ e^- \to e^+ e^- h_c$
1715 ±70



e$^+$ e$^-$* ® *J/y g
258 ±25 events



J/y ISR production allows control of resolution and calibration

N(J/y)/N(h$_c$) = 15.0± 1.6 % within expectations

- Fit model:

  J/ψ: Gaussian, η_c: Gaussian ⊗ Breit-Wigner, Bkg: Exponential

- Fit parameters: $M_{J/\psi}$, $M_{\eta c}$, $\sigma_{J/\psi}$, $\Gamma_{\eta c}$, $N_{J/\psi}$, $N_{\eta c}$ and backg coeffs.
- η_c Mass resolution constrained by J/ψ

Preliminary Results

$m\ (h_c)^* \ = \ 2983.3 \pm 1.2\ (\text{stat}) \pm 1.8 (\text{syst})\ \text{MeV}/c^2$

$\Gamma_{tot}(h_c) \ = \ 33.3 \pm 2.5\ (\text{stat}) \pm 0.8\ (\text{syst})\ \text{MeV}/c^2$

Other results from the same fit allow to control systematics:

$m(J/y)^*$	$= 3095.1 \pm 0.8$ MeV	(i.e., ~−1.8 MeV from PDG)
$\sigma\ (J/y)$	$= 7.5 \pm 0.8$ MeV	(MC: $\sigma(J/y) = 8.1 \pm 0.2$ MeV
		$s(h_c) = 7.3 \pm 0.1$MeV)

*Mass central values include -1.1 MeV correction due to shift observed in MC for both J/ψ and η_c mass peaks

Systematic uncertainty on *m*:

- mass scale (from J/ψ mass peak shift) 1.8 MeV

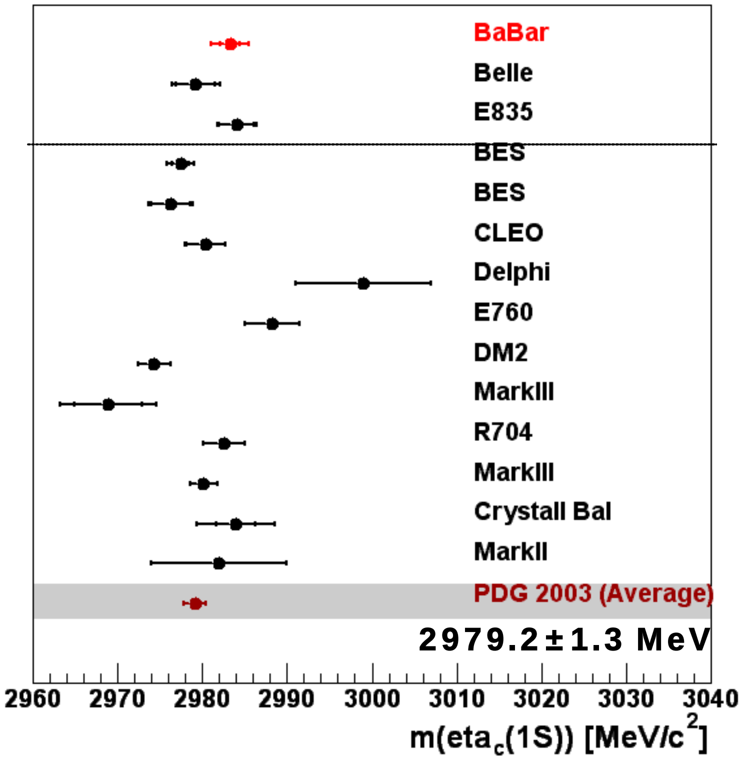
Systematic uncertainty on Γ :

- background subtraction (fit on different mass ranges) 0.7 MeV
- mass resolution(fit using MC width) 0.4 MeV

h_c Mass and Width

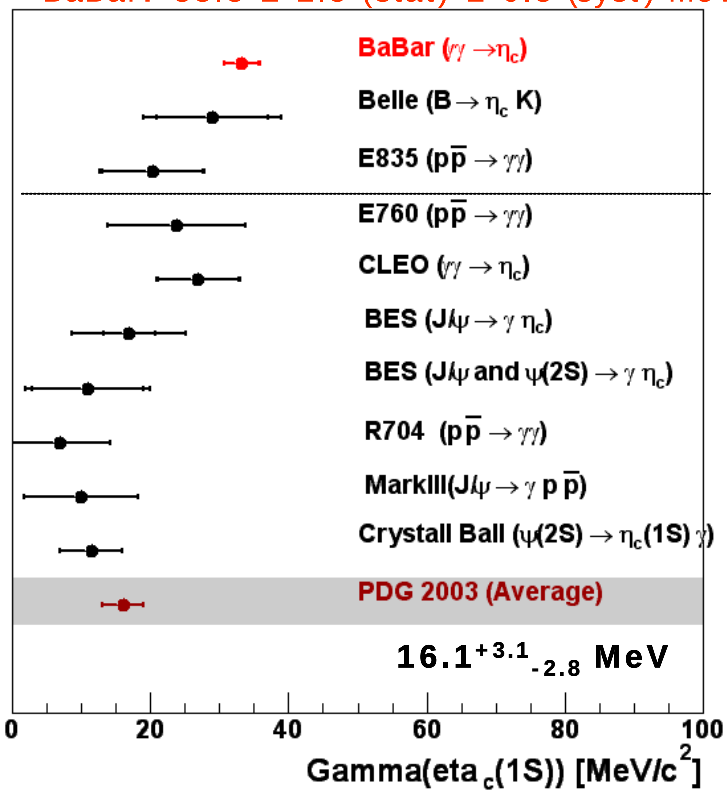
$m(h_c)$

BaBar: 2983.3 ± 1.2 (stat) ± 1.8(syst) MeV



$\Gamma(h_c)$

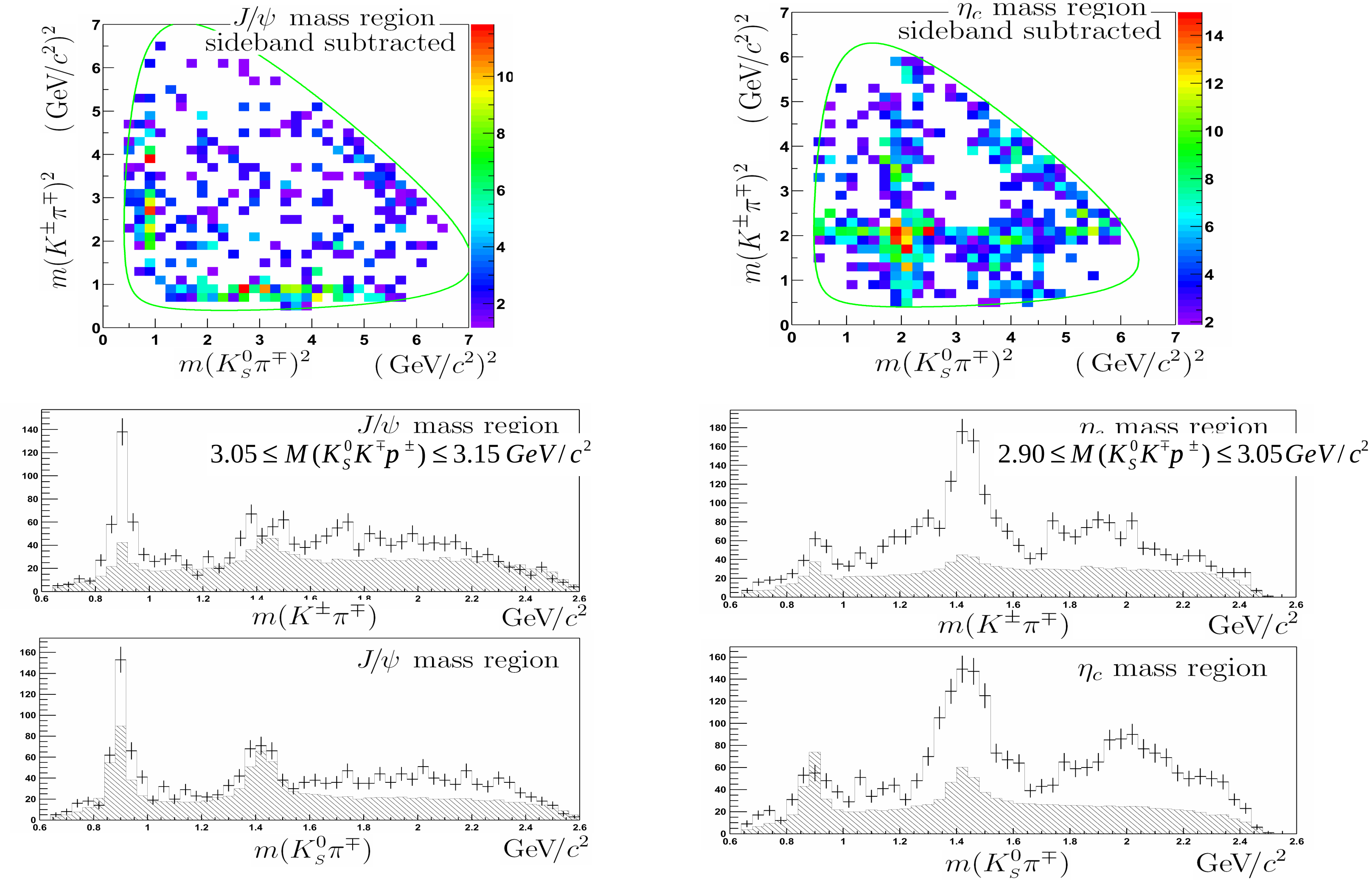
BaBar: 33.3 ± 2.5 (stat) ± 0.8 (syst) MeV



PDG Average without BaBar,Belle,E835

Dalitz Plots

- J/ψ and η_c decays to $K_sK\pi$ show pattern of $K\pi$ resonances



The $h_c(2S)$ State

- Hyperfine splitting predicted by heavy quark potential models: $m(y(2S)) - m(h_c(2S)) \in (42, 103)\ \mathrm{MeV}/c^2$

- First claim: Crystal Ball (PRL 48:70, 1982) $m(h_c(2S)) = (3595 \pm 5)\ \mathrm{MeV}/c^2$, $\Gamma(h_c(2S)) < 8\ \mathrm{MeV}/c2$

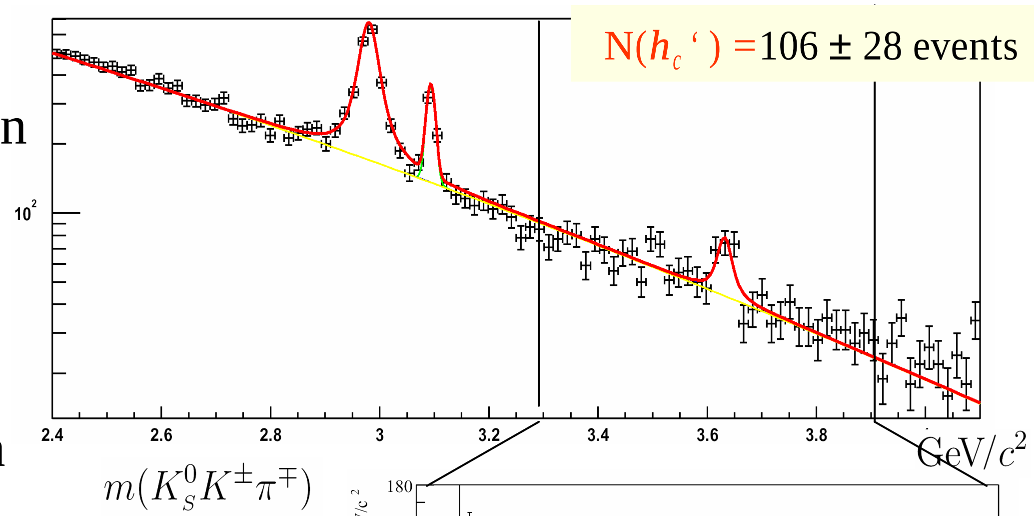
- Recent evidences (at higher masses):
  - $B \to h_c(2S)\, K$ decays (Belle,PRL89:102001,2002)
  - $e^+e^- \to J/y\ \ h_c(2S)$ (Belle, PRL 89:142001, 2002)
  - $e^+\ e^- \to e^+\ e^-\ h_c(2S)$ (CLEO, hep-ex/0306060)

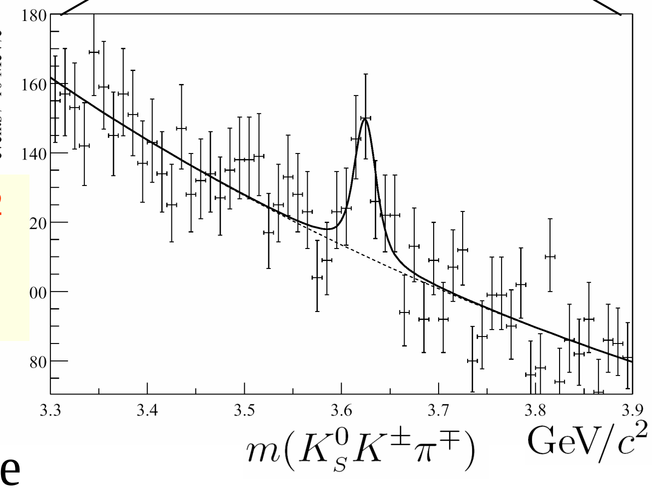
Invariant Mass Spectrum in the η_c' Region

- Gaussian resolution function width determined from MC: $\sigma(\eta_c') = 8.5 \pm 0.6$ MeV

- MC mass peak shift (–0.4 MeV) used to correct data

- Results:





Preliminary

m (h_c ') = 3632.5 ± 5.0 (stat) ± 1.8(syst) MeV / c^2

Γ_{tot} (h_c') = 20 ± 10 (stat) ± 4 (syst) MeV / c^2

Systematic on *m* determined by J/ψ peak shift
Systematic on *G* from resolution and fit mass range

Is it $h_c(2^1S_0)$?

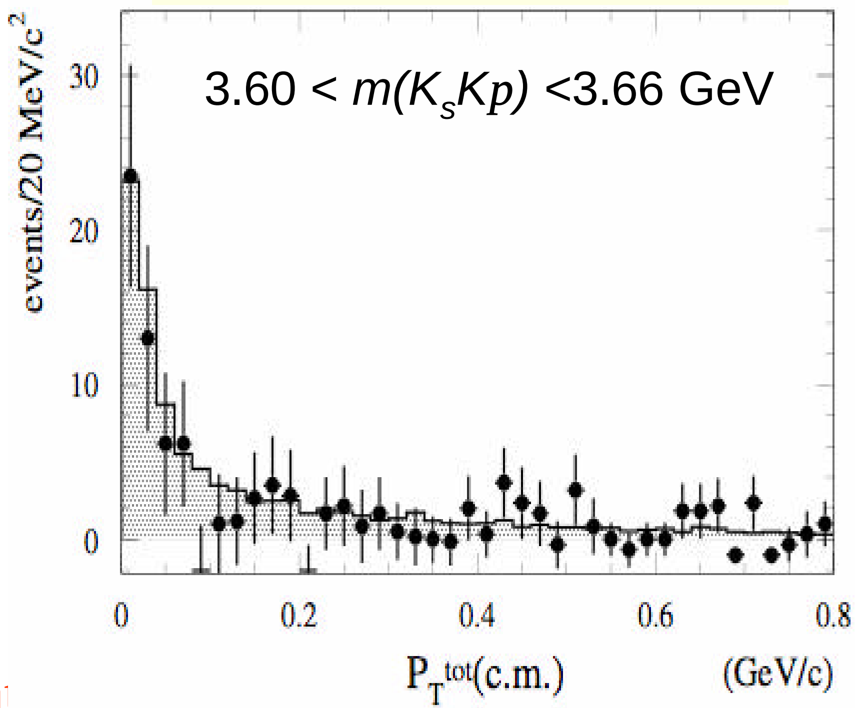
Quantum numbers not measured rigorously but:

- $J^P = 0^+$ excluded by final state
- ISR excluded: decay products concentrated in forward hemisphere like η_c and in contrast to J/ψ (e^+e^- asymmetric collider $\Rightarrow$ larger acceptance for J/ψ decay products in backward hemisphere)
- P_T^{tot} peaked at zero, characteristics of quasi-real photons fusion $\Rightarrow$ rules out J=1 state
- J>2 disfavored for low mass

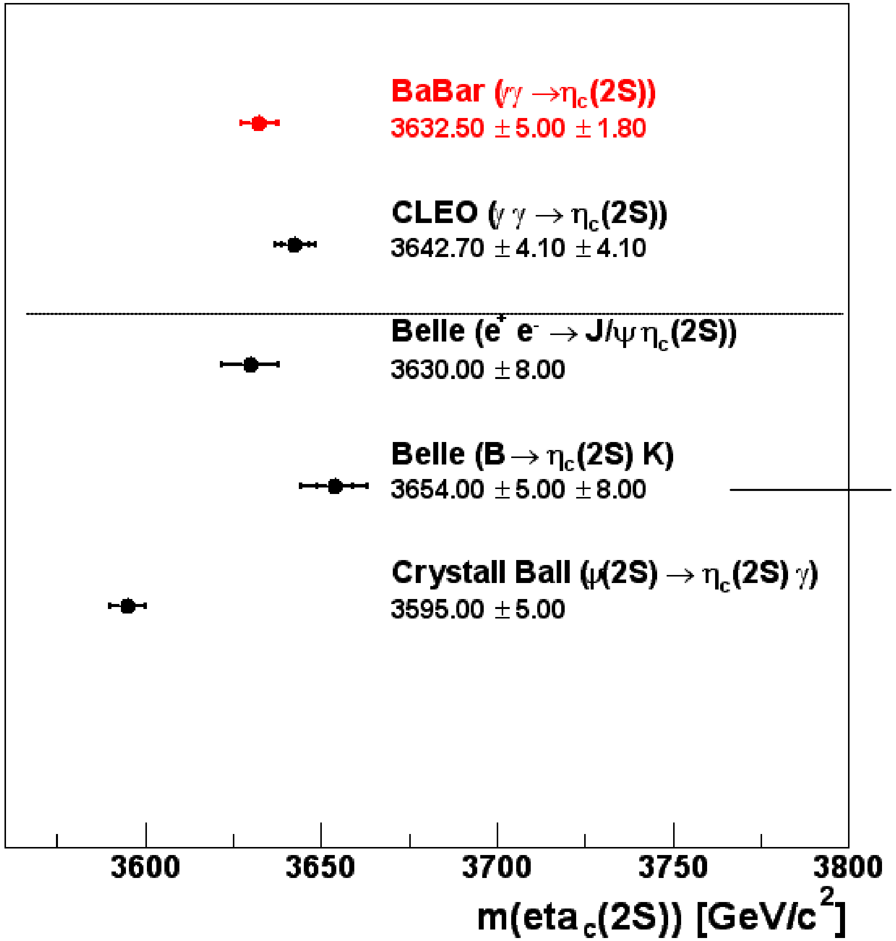
charmonium states

$\Rightarrow$ Supporting evidence for $J^{PC} = 0^{-+}$ sta

Background Subtracted Plot from *m* sidebands



$h_c(2S)$ Mass: Summary of Results



PDG(2003) uses this only for average 3654 ±10 MeV

Production in B ® $h_c K$:
CP Violation and
h_c Branching Fractions

η_c Decay Channels

- Few known η_c decay modes (~25% fraction of total width)
- Modes with high B.F. and low combinatorial background analyzed for BaBar measurement of $B(B \text{®} h_c K)$

$\eta_c \rightarrow K_s K^+ \pi^- + c.c.$

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

$\eta_c \rightarrow 2(K^+ K^-)$

- Current effort in BaBar to reconstruct more decay channels and to search for new ones, like:

$\eta_c \rightarrow p \bar{p} \pi\pi$

CP violation studies would also benefit of additional statistics.

B Reconstruction and Event Selection

Common to all *B* ® h_c *K* analyses:

- Full reconstruction of the B candidate through its decay products
- ***B*** signal identification based on 2 quasi-independent kinematical variables:

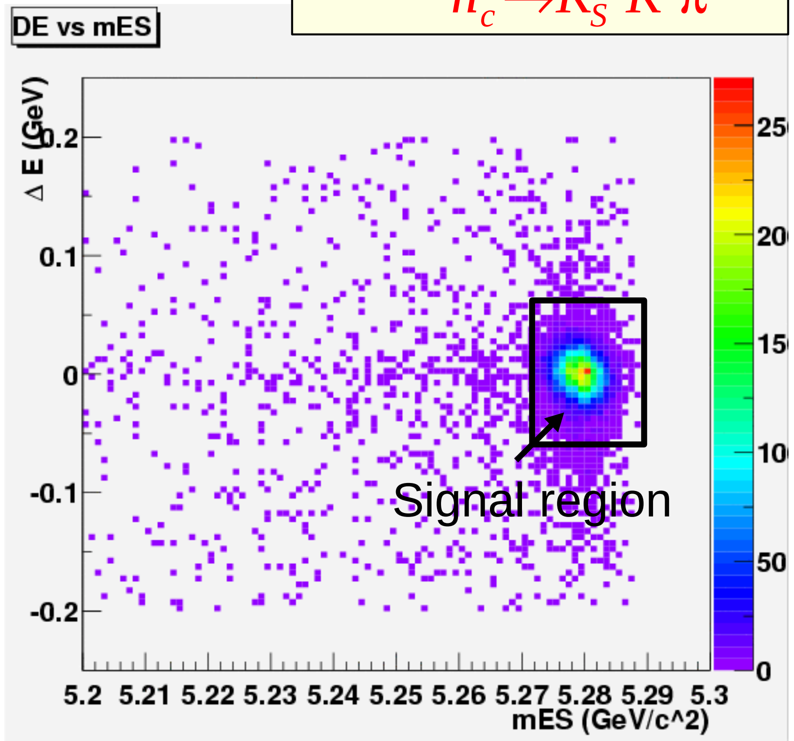
$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$

$$\Delta E = E_B^* - E_{beam}^*$$

- Continuum background suppression based on shape variables and energy flow into cones *a la CLEO* combined in a Fisher
- Peaking background in (m_{ES},ΔE) signal region discriminated through invariant mass of the charmonium system (m_X)

$B^+ \to h_c K^+$

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

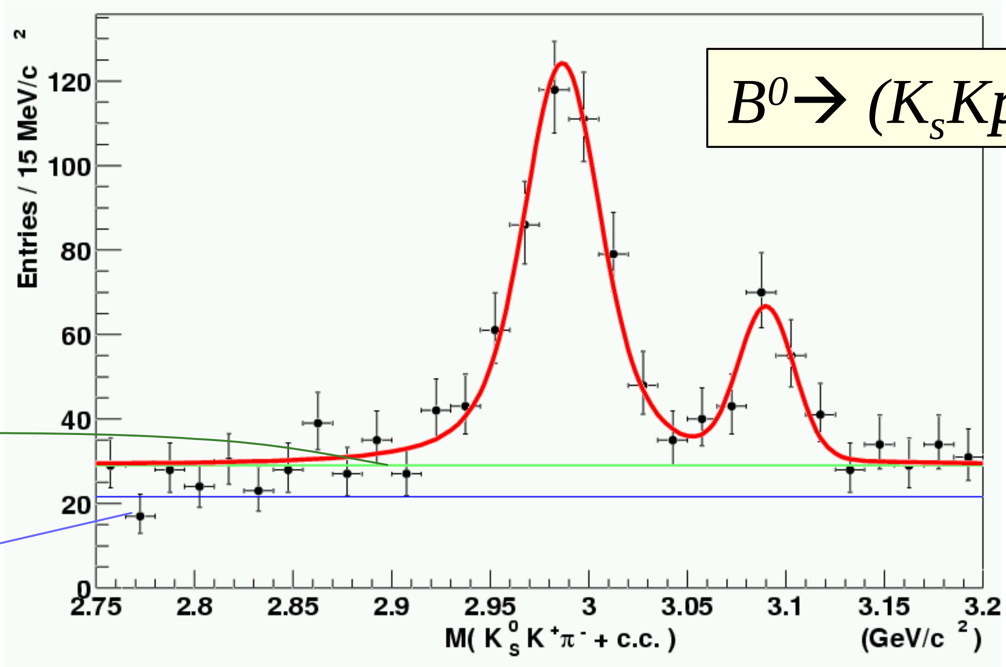


m_X: Invariant Mass of Charmonium System

2D unbinned maximum likelihood fit in $\{m_X, m_{ES}\}$ plane to extract signal.

Four components:

- $B \rightarrow h_c K$
- $B \rightarrow J/\psi\ K$
- Peaking Bkg
- Combinatorial



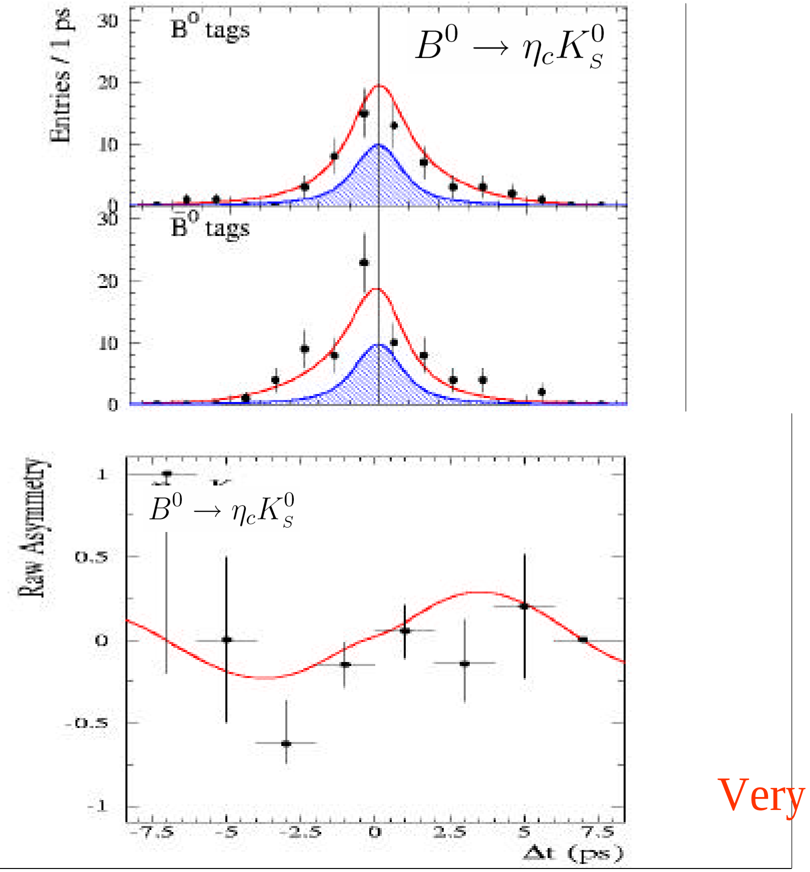
$B^0 \rightarrow (K_s K p) K_s^0$

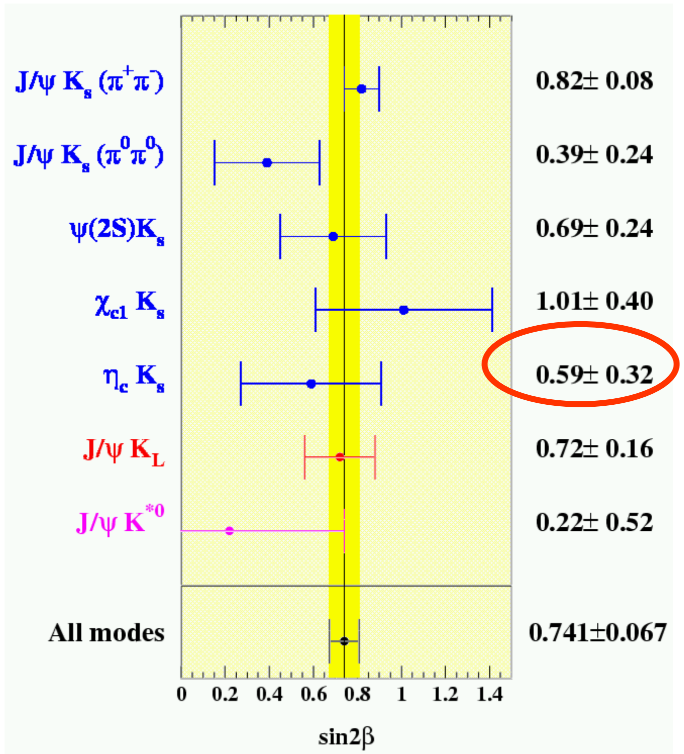
m_X for m_{ES}>5.270 MeV

Time-Dependent Analysis (L=80.8 fb^{-1})

Using neutral B decays where signal is significant

$B^0 \rightarrow h_c K_s^0$ with h_c ® $K_s^0 K^+ p^-$ and h_c ® $K^+ K^- p^0$



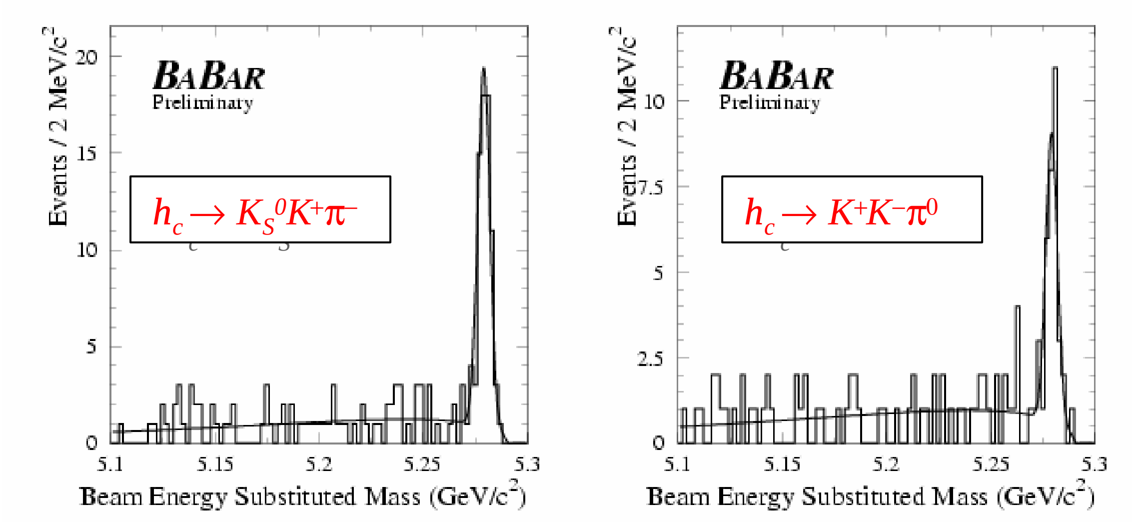


Very good consistency with other golden modes

PRL 89: 201802,2002

Branching Fraction of $B \rightarrow h_c\ K$

Preliminary measurements on L=20.7 fb^{-1} (hep-ex/0203040)



Using only well-established modes: h_c ® $K^0K^+p^-$ and h_c ® $K^+K^-p^0$

Amplitudes related by isospin.

$B(\ B^+ \rightarrow h_c\ K^+) = (\ 1.50 \pm 0.19 \pm 0.15 \pm 0.46\ ^{(*)}\ ) \times 10^{-3}$

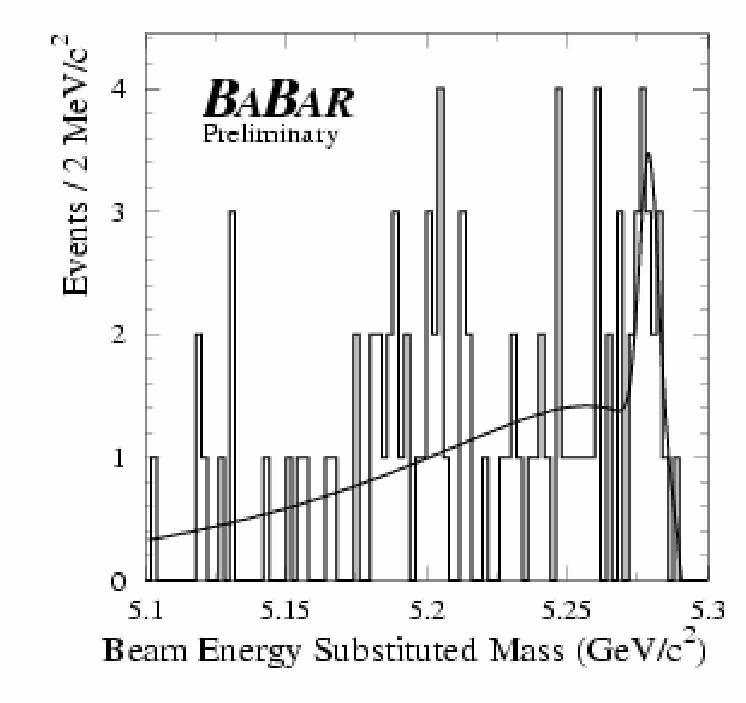
$B(\ B^0 \rightarrow h_c\ K^0) = (\ 1.06 \pm 0.28 \pm 0.11 \pm 0.33\ ^{(*)}\ ) \times 10^{-3}$

(*) error due to $B(h_c$ ® $K\overline{K}p) = 5.5 \pm 1.7\ \%$ (PDG2002)

Systematic error mostly from Kaon ID, tracking, K_S reconstruction

$B \to \eta_c K$ with $\eta_c \to K^+K^-K^+K^-$

(hep-ex/0203040)



Kaons identified with tight criteria to suppress huge combinatorial

Includes $\eta_c \to \phi\phi$

(~5 events expected)

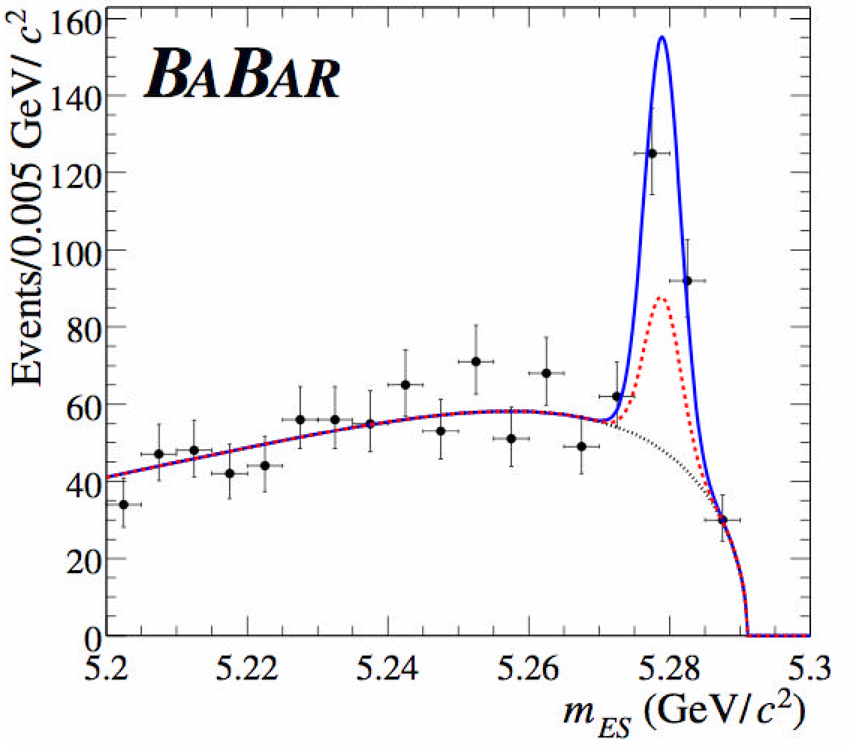
Yield (m_{ES} >5.27 GeV)	17
Combinatorial	7.4 ± 1.8
Peaking Background	1.7 ± 2.7

Note: About 80 events expected using PDG B(2.2% ± 1.2%) for $\eta_c \to 2(K^+K^-)$ our efficiency (12%) and our preliminary measurement of $B(B^+ \to \eta_c K^+)$

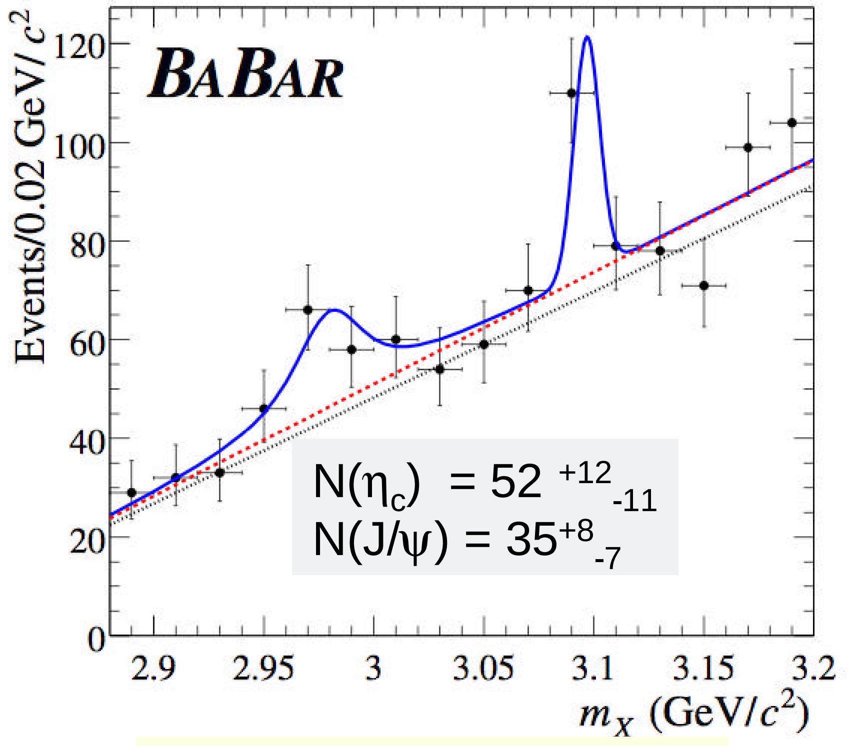
$B \to h_c K$ with $h_c \to p\,\bar{p}\,\pi^+\pi^-$ (L=81.9 fb^{-1})

Only upper limits on *B* reported so far (<1.2 % @ 90 %CL, Mark-II)

$h_c \to \lambda\bar{\lambda}$ vetoed



Signal significance 7σ

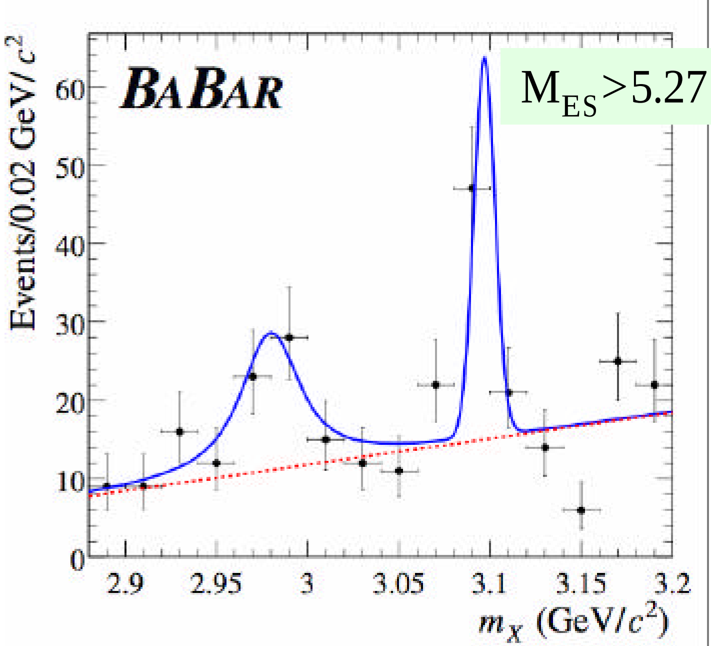


Expected $N(J/\psi) = 42 \pm 5$

Branching Fractions Results

Preliminary

Yield extraction cross-checked with alternative fitting method



M_{ES}>5.271GeV

$B(B^{\pm} \rightarrow \eta_c K^{\pm}) \times B(\eta_c \rightarrow p\bar{p}\pi\pi) =$
$= (7.6^{+1.7}_{-1.6} \pm 0.9)\ 10^{-6}$

Using our preliminary value for $B(B^{+} \rightarrow h_c K^{+})$, we obtain:

$B(\eta_c \rightarrow p\bar{p}\pi\pi) = (5.1^{+1.3}_{-1.2} \pm 0.8 \pm 1.6^{*})\ 10^{-3}$

*error due to $B(h_c$ ® $K\bar{K}p) = 5.5 \pm 1.7\ \%$

Summary

- $\gamma\gamma$ fusion at BaBar provides high statistics for charmonium spectroscopy

  Preliminary precise measurements of η_c mass and width

$$m\,(h_c) \;=\; 2983.3 \pm 1.2\,(\text{stat}) \pm 1.8(\text{syst})\ \text{MeV}/c^2$$

$$\Gamma_{tot}\,(h_c) = \quad 33.3 \pm 2.5\,(\text{stat}) \pm 0.8\,(\text{syst})\ \text{MeV}/c^2$$

  Observation of η_c'. Preliminary results:

$$m\,(h_c') \;=\; 3632.5 \pm 5.0\,(\text{stat}) \pm 1.8(\text{syst})\ \text{MeV}/c^2$$

$$\Gamma_{tot}\,(h_c') = \quad 20 \pm 10\,(\text{stat}) \pm 4\,(\text{syst})\ \text{MeV}/c^2$$

- η_c production in B decays successfully used for CP violation studies and decay rates measurements
- Observation of $\eta_c \rightarrow p\bar{p}\pi\pi$. Preliminary Branching Fraction:

$$B(\eta_c \rightarrow p\bar{p}\pi\pi) = (5.1^{+1.3}_{-1.2} \pm 0.8 \pm 1.6)\ 10^{-3}$$

Additional slides

BaBar Detector

Detector of Internally Reflected Cherenkov light

Identifies particles by their Cherenkov radiation

K-π separation $>3.4\sigma$ for $P<3.5$ GeV/c

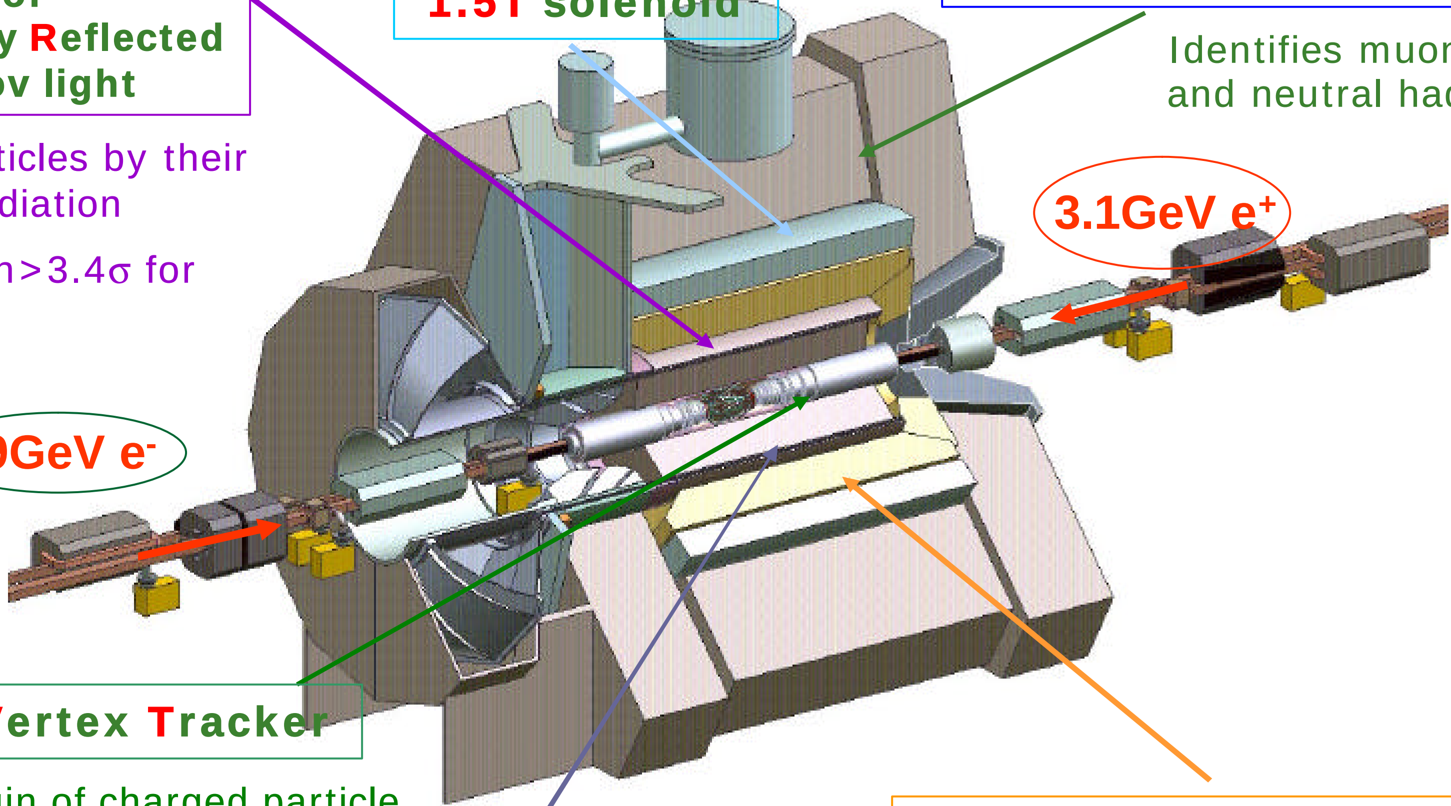
1.5T solenoid

Instrumented Flux Return

Identifies muons and neutral hadrons

3.1GeV e^+

9GeV e^-



Silicon Vertex Tracker

Measures origin of charged particle trajectories + dE/dx
97% efficiency

Drift CHamber

Measures momentum of charged particles + dE/dx
$\sigma(p_T)/P_T=0.13\%P_T\oplus0.45\%$

ElectroMagnetic Calorimeter

Measures energy of electrons and photons
$\sigma(E)/E=1.33\%E^{-1/4}\oplus2.1\%$