Study of Inclusive and Exclusive B Decays to Charmonium Final States with *BABAR*

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On behalf of the *BABAR* collaboration

- The Data Sample and B Counting
- Yield of $B \to J/\psi\, X$
- Branching Ratios for $B \to \psi(2S) X$ and $B \to \chi_{c1} X$
- Branching Ratios for Exclusive Decays of B to Charmonium
- Yield of $B \to J/\psi\, K^0_L$
- Determination of B^0 and $B^{\pm}$ masses
- Angular Analysis of $B^0 \to J/\psi\, K^*$
- Summary

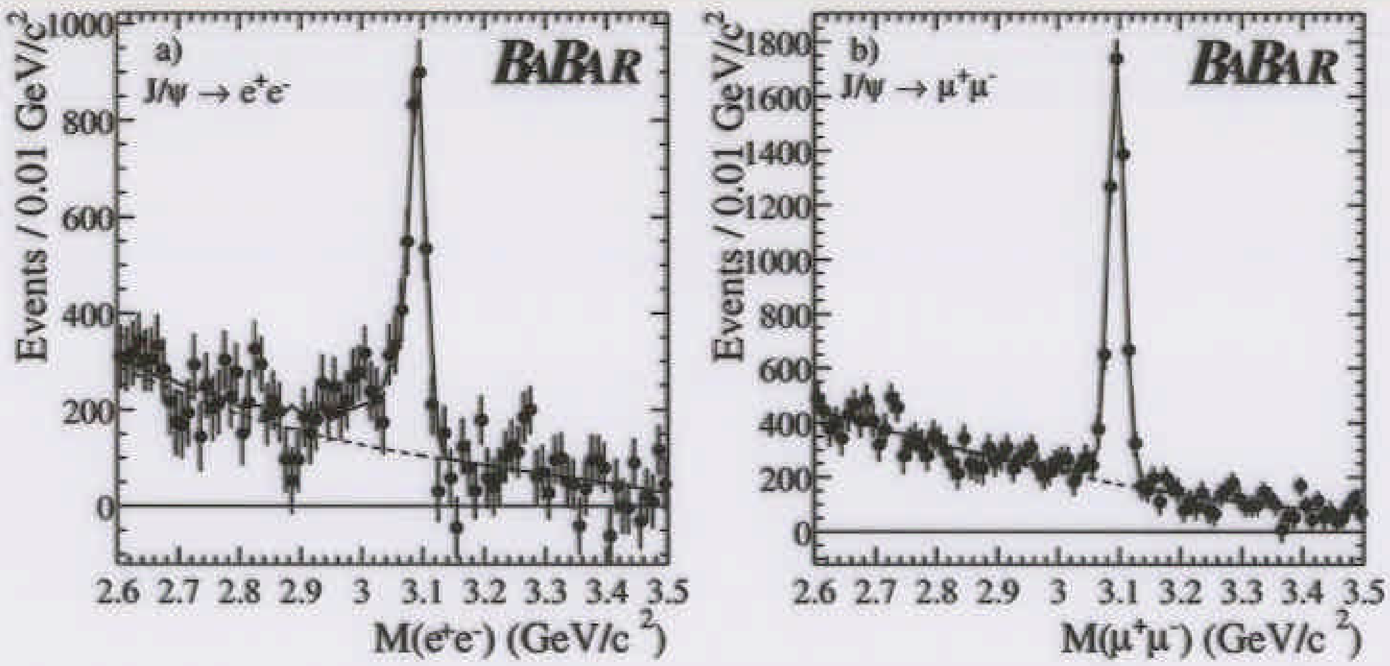
All results are *PRELIMINARY*

Data Sample and B counting

- $\approx$ 7.7 fb^{-1} at the $\Upsilon(4S)$ resonance
- $\approx$ 1.2 fb^{-1} taken below the $B\overline{B}$ threshold
- B Counting:
  - Count the # of (selected) hadronic events (both on and off-peak)
    - * use only charged tracks in well-defined fiducial region
    - * require 4 or more charged tracks
    - * require observed energy > 5 GeV.
    - * reject Bhabha, $\mu^+\mu^-$ and $\tau^+\tau^-$ events by rejecting "jet-like" events
    - * reject beam-wall events: primary vertex within 0.5 cm of beamspot in x-y
  - Subtract the continuum contribution as determined by off-peak running, normalized by the ratio of the number of observed $\mu^+\mu^-$ events
  - procedure yields $(8.46 \pm 0.14)\,10^6$ *selected* $B\overline{B}$ events
  - assume $B^0\overline{B}^0$: B^+B^- = 1:1

Inclusive Decays of B to J/ψ

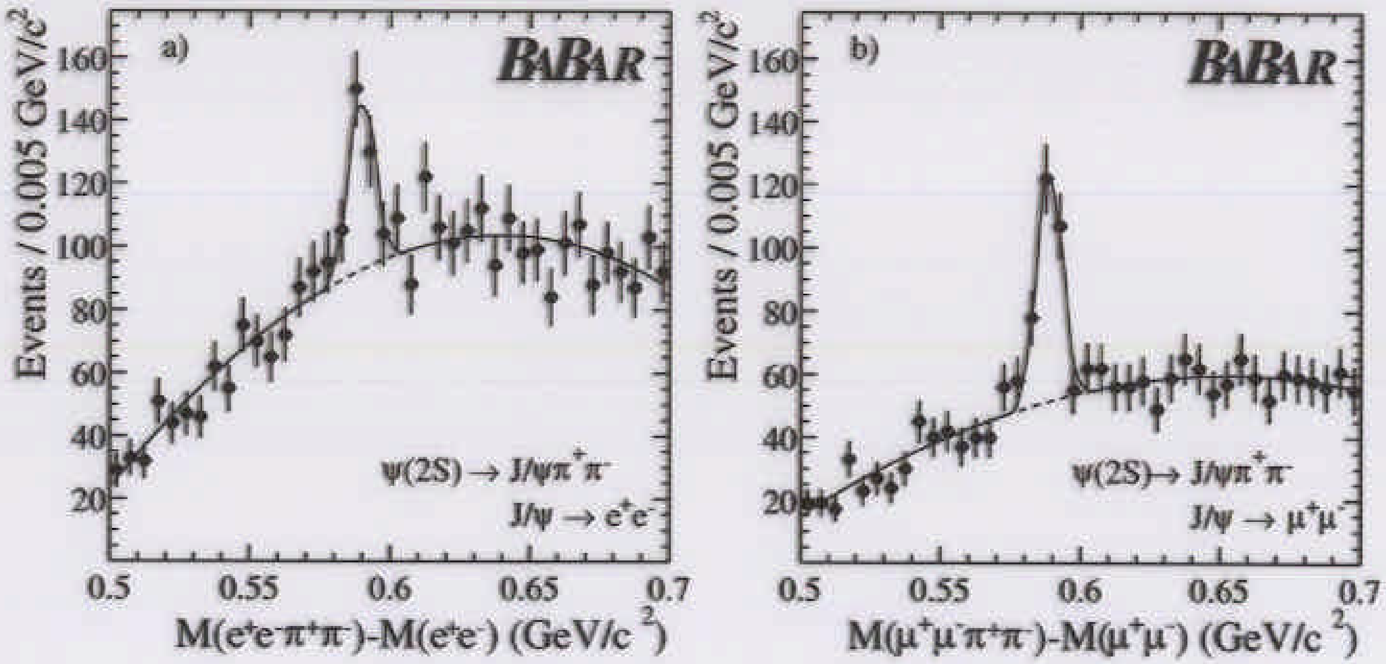
- J/ψ reconstruction
  - require electron or muon ID for *both* leptons
    - $E_{EMC}/p \approx 1$, cluster shape, $dE/dx \approx (dE/dx)_e$
    - $E_{EMC} \approx \mathrm{MIP}$, $\lambda_{int}^{IFR} \approx \lambda_{int,MIP}^{IFR}, \cdots$
  - do *not* use explicit Bremsstrahlung recovery
    - instead take the shape of the radiative tail from full detector simulation
    - leave normalization of radiative tail free in fit



mode	yield
$J/\psi \to e^+e^-$:	$4290 \pm 100 \pm 180$
$J/\psi \to \mu^+\mu^-$:	$5490 \pm 90 \pm 90$

Inclusive Decays of B to $\psi(2S)$

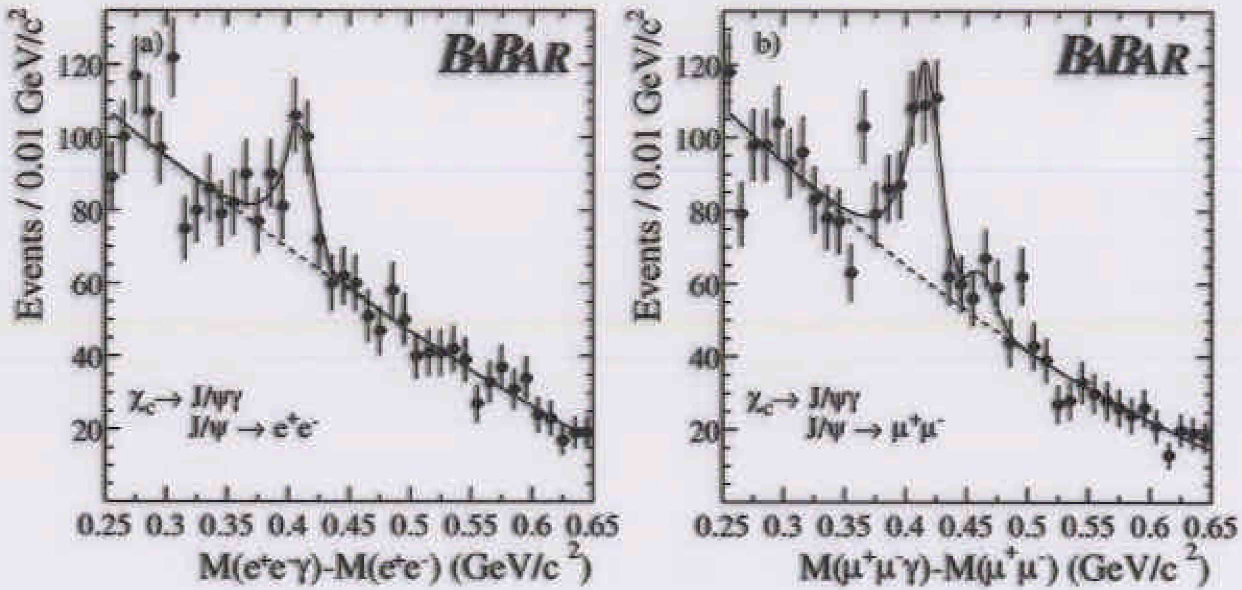
- $\psi(2S) \rightarrow \ell^+ \ell^-$ and $\psi(2S) \rightarrow J/\psi\, \pi^+ \pi^-$
- Measure rate relative to $B \rightarrow J/\psi$
- Use PDG branching ratio for $B \rightarrow J/\psi$ to normalize



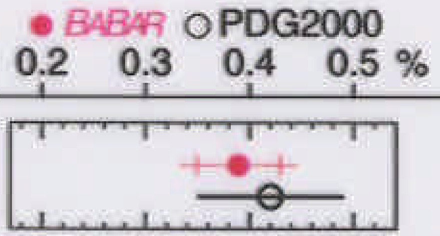
mode	yield	$Br(B \rightarrow \psi(2S) X)$ (%)
$\psi(2S) \rightarrow e^+ e^-$:	$131 \pm 29 \pm 2$	$0.26 \pm 0.03 \pm 0.04$
$\psi(2S) \rightarrow \mu^+ \mu^-$:	125 ± 19	
$\psi(2S) \rightarrow e^+ e^- \pi^+ \pi^-$:	126 ± 44	$0.24 \pm 0.03 \pm 0.03$
$\psi(2S) \rightarrow \mu^+ \mu^- \pi^+ \pi^-$:	162 ± 23	
combined:		$0.25 \pm 0.02 \pm 0.02$
PDG2000:		0.35 ± 0.05

Inclusive Decays of B to χ_c

- Combine J/ψ with an isolated "good" γ
- Fit with Crystal Ball function
  - shape of tail fixed to MC
- Fit includes χ_{c2} normalization
  - use same resolution as χ_{c1}
  - $\chi_{c2} - \chi_{c1}$ mass difference fixed to PDG value



mode	yield	Br($B \to \chi_{c1} X$) (%)
$J/\psi \to e^+e^-$	$129 \pm 26 \pm 13$	$0.39 \pm 0.04 \pm 0.04$
$J/\psi \to \mu^+\mu^-$	$204 \pm 47 \pm 12$	



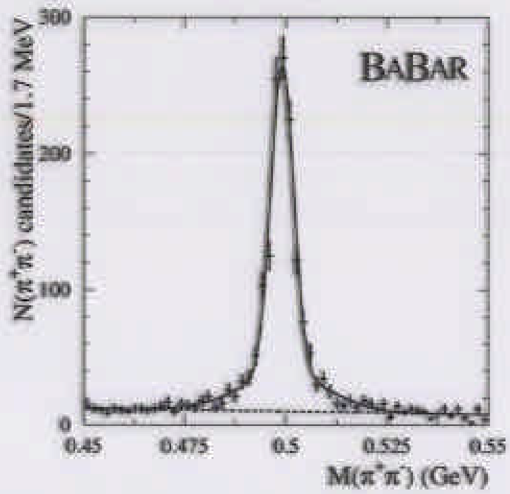
mode	yield	Br($B \to \chi_{c2} X$) (%)
$J/\psi \to e^+e^-$	3 ± 21	< 0.24 (90%CL)
$J/\psi \to \mu^+\mu^-$	47 ± 21	

Exclusive Modes

Start with reconstructed J/ψ, $\psi(2S)$ and χ_c, then search for K^0_S, $K^\pm$, K^{*0} or $K^{*\pm}$ to make a two-body B decay.

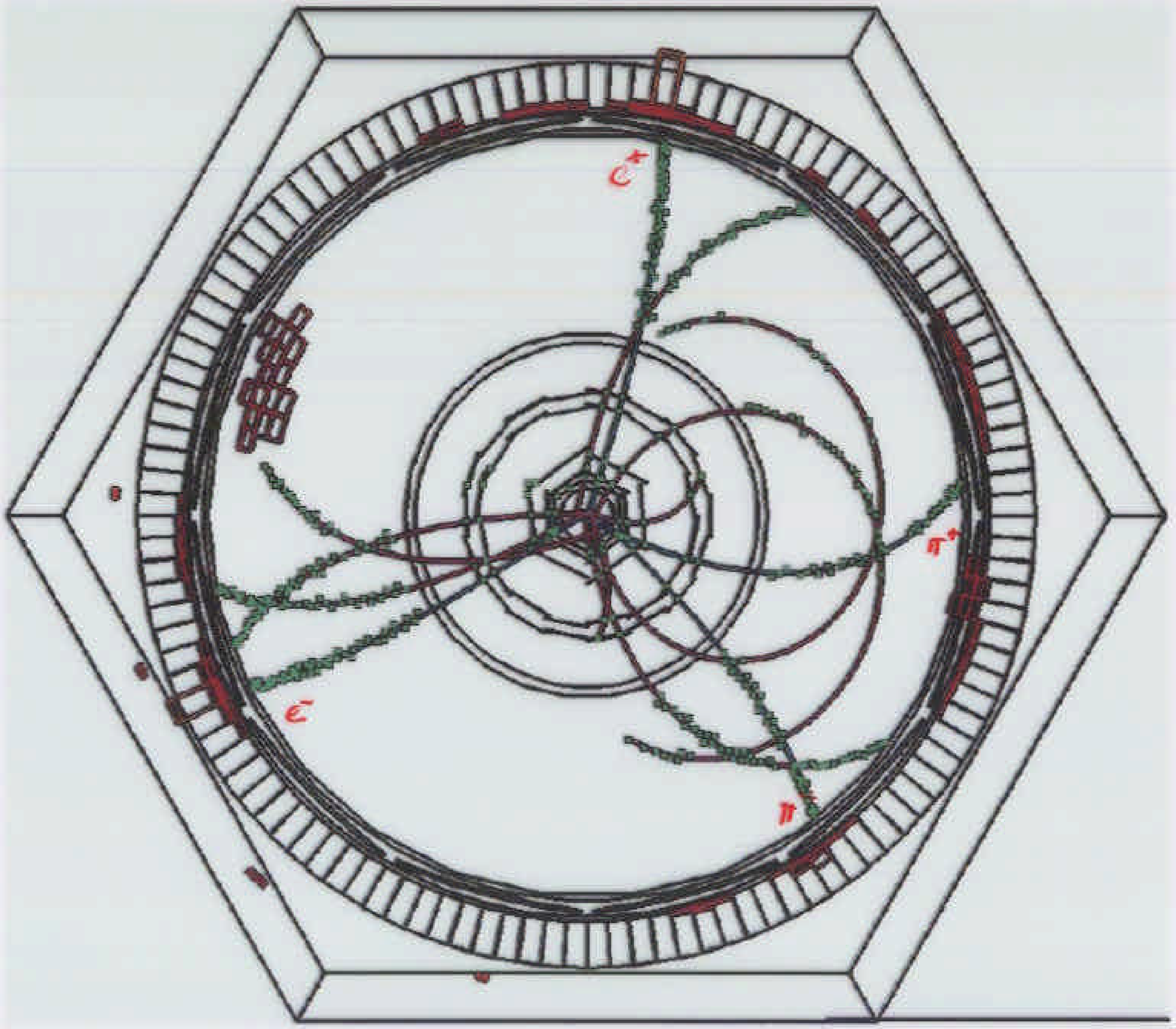
- J/ψ reconstruction
  - loosen PID compared to inclusive modes
    - * only one lepton must be identified
  - recover Bremsstrahlung γ in case of $J/\psi \to e^+e^-$
    - * do not re-use γ reconstructed as Bremsstrahlung
  - $-50 < M_{\mu^+\mu^-} - M_{J/\psi,\mathrm{PDG}} < 50\,\mathrm{MeV}/c^2$
  - $-250 < M_{e^+e^-} - M_{J/\psi,\mathrm{PDG}} < 50\,\mathrm{MeV}/c^2$
  - constrain J/ψ to PDG mass
- $\psi(2S)$ reconstruction
  - $-50 < M_{e^+e^-} - M_{\psi(2S),\mathrm{PDG}} < 50\,\mathrm{MeV}/c^2$
  - $-250 < M_{\mu^+\mu^-} - M_{\psi(2S),\mathrm{PDG}} < 50\,\mathrm{MeV}/c^2$
  - $-15 < (M_{J/\psi\pi^+\pi^-} - M_{J/\psi}) - \Delta M_{\mathrm{PDG}} < 15\,\mathrm{MeV}/c^2$
- χ_c reconstruction
  - $0.35 < M_{J/\psi\gamma} - M_{J/\psi} < 0.45\ \mathrm{GeV}/c^2$

- K^0_S reconstruction
  - $K^0_S \to \pi^+\pi^-$ and $K^0_S \to \pi^0\pi^0$

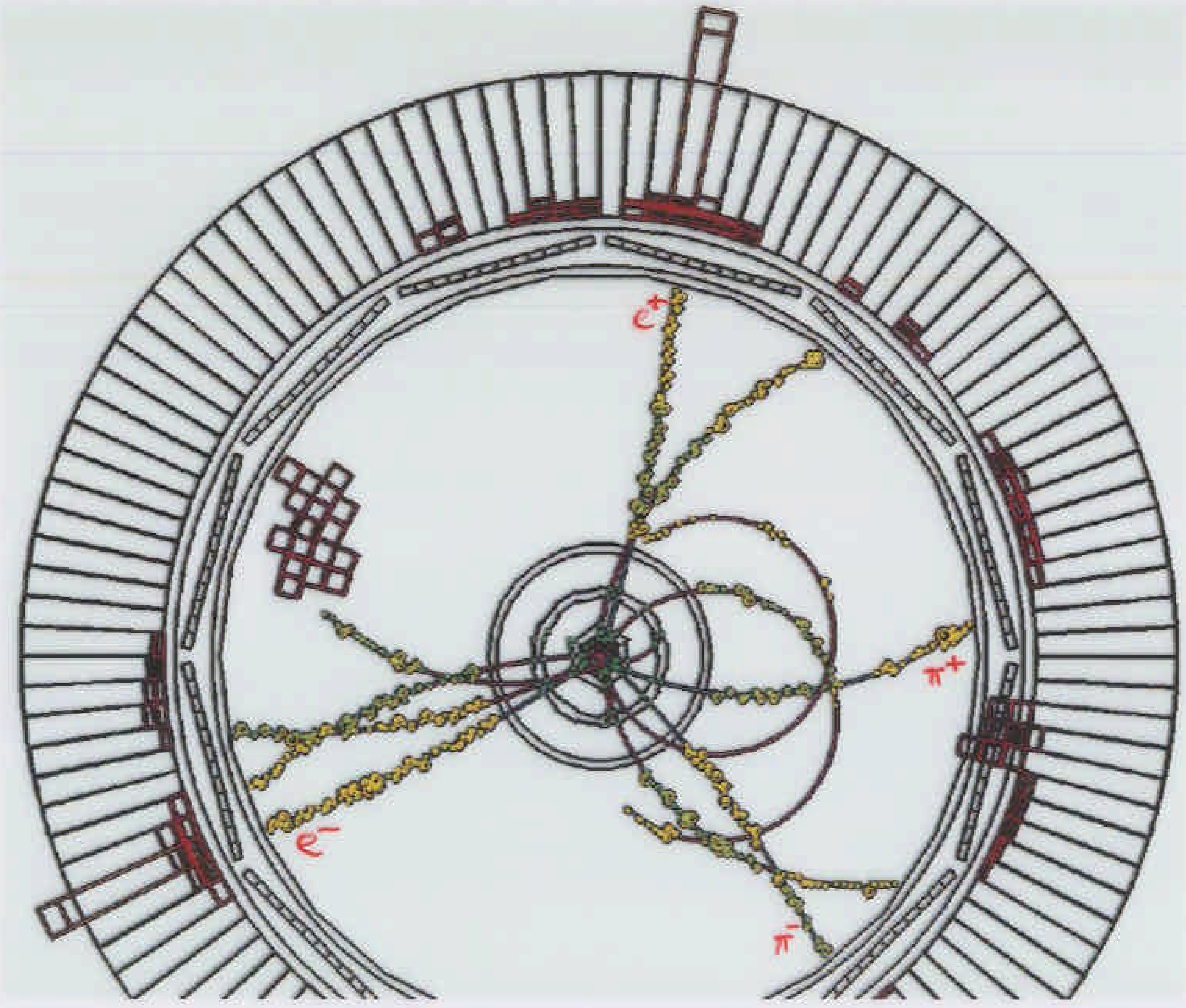


  - select K^0_S in window around PDG mass
  - constrain K^0_S to PDG mass
- $K^\pm$ reconstruction
  - apply loose $K^\pm$ ID (i.e. reject "good" $\pi^\pm$) in most modes
- K^* reconstruction
  - $K^{*0} \to K^+\pi^-$ and $K^{*0} \to K^0_S\pi^0$
  - $K^{*\pm} \to K^\pm\pi^0$ and $K^{*\pm} \to K^0_S\pi^\pm$
  - apply loose $K^\pm$ ID (i.e. reject "good" $\pi^\pm$)
  - select K^* in window around PDG mass

Fisheye View of $B^0 \rightarrow J/\psi\, K_s^0$ candidate



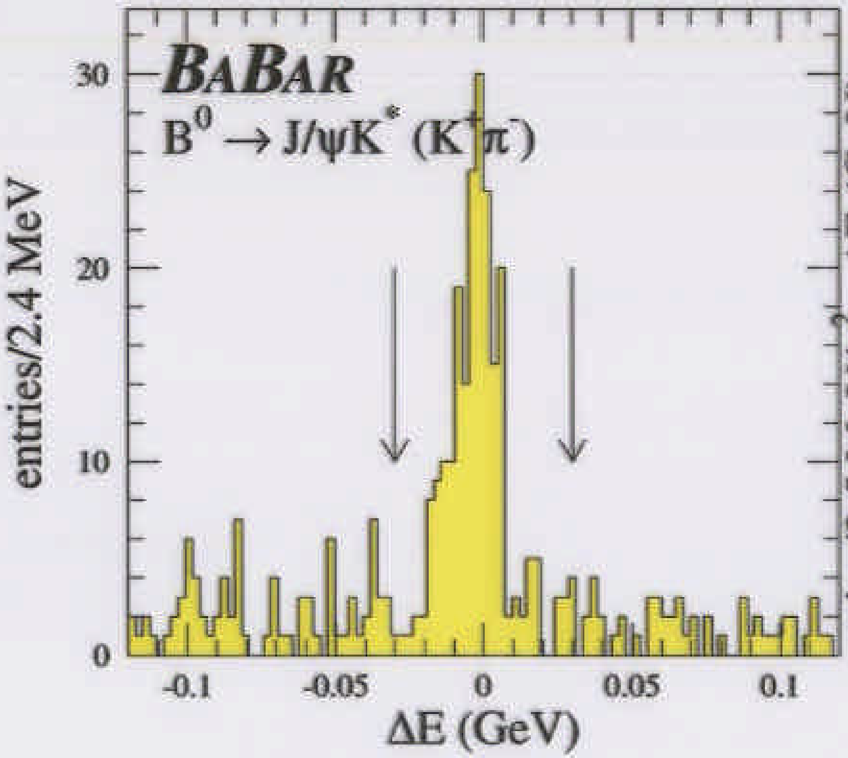
XY View of $B^0 \to J/\psi\, K_s^0$ candidate

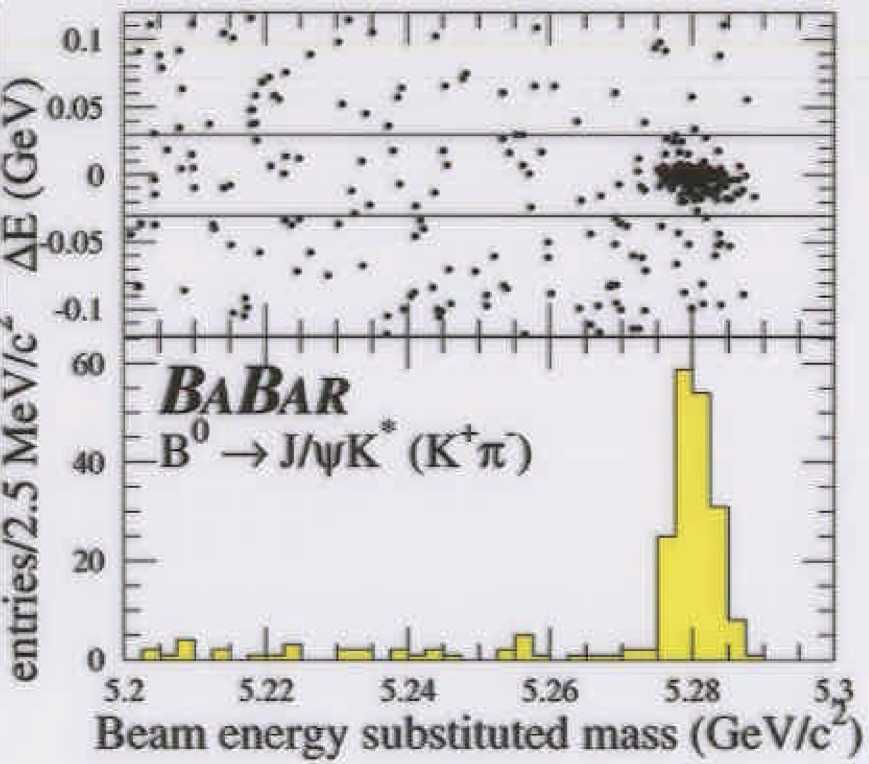


Exclusive B Reconstruction

The Two Main Distinguishing Variables (computed in the $\Upsilon(4S)$ frame):

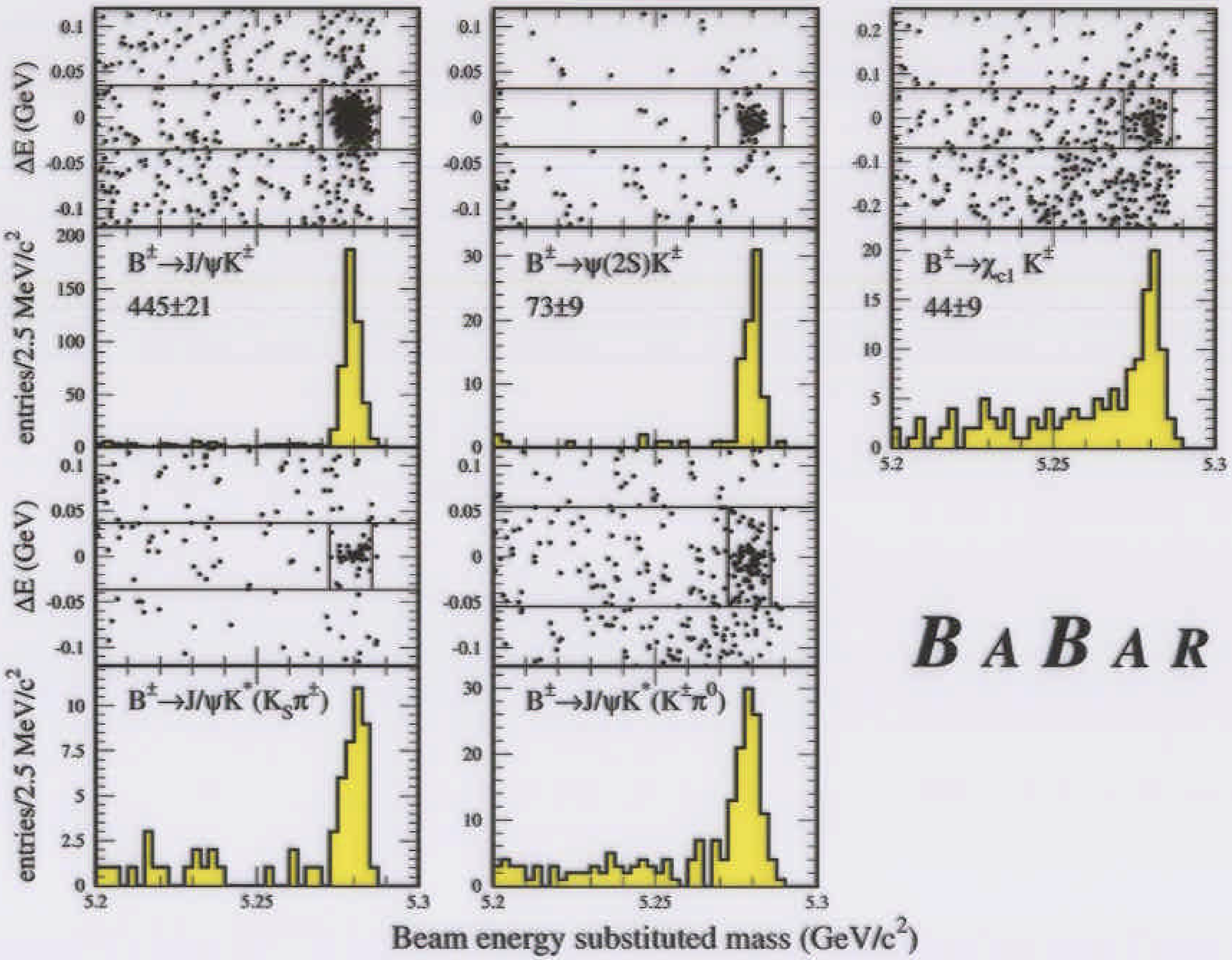
- $\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$
- $m_{ES} = \sqrt{\left(\frac{1}{2}\sqrt{s}\right)^2 - P_B^{*2}}$
  - use the fact that the beam energy is much better known than the particle energies are measured



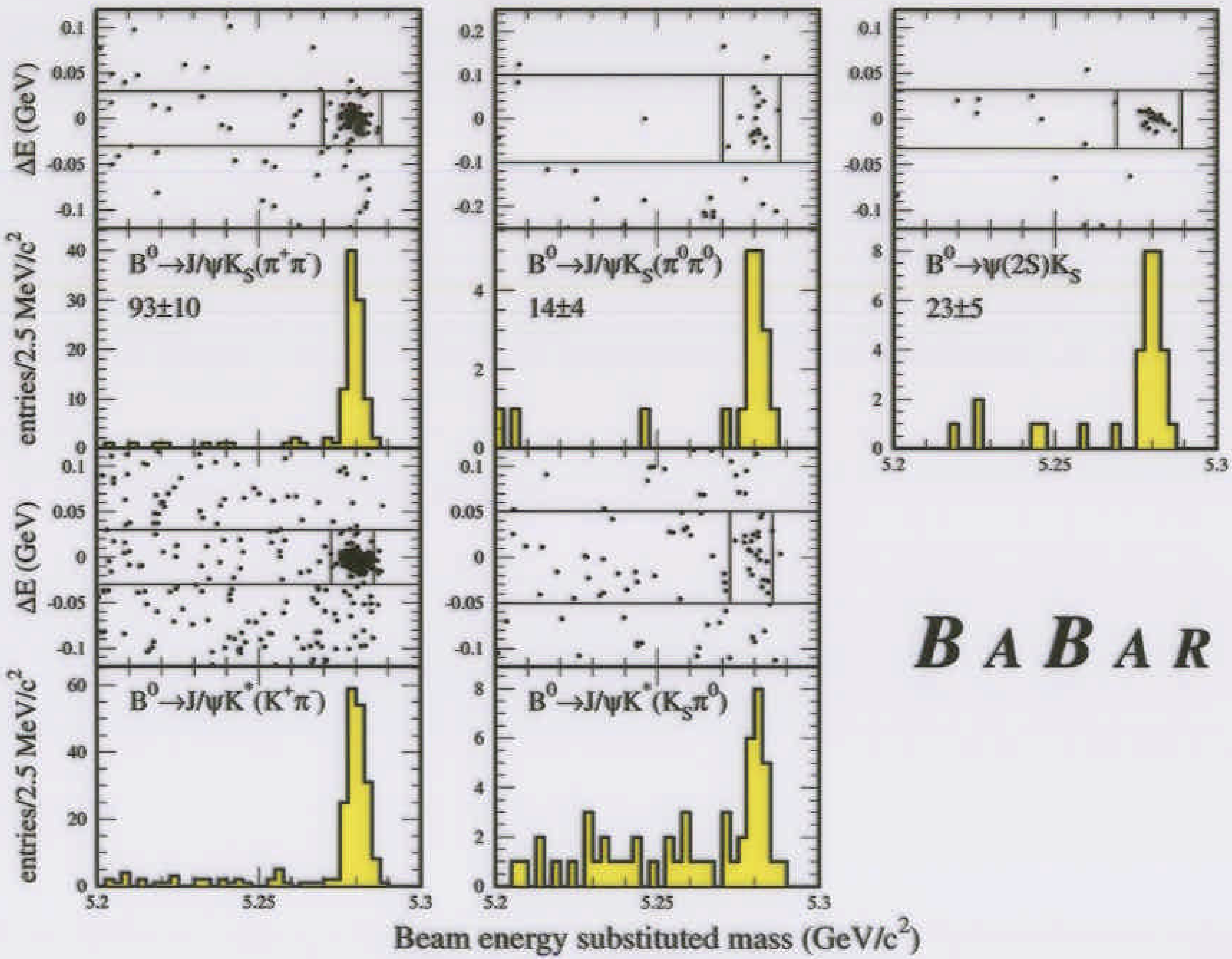


- In case of multiple candidates per event, in general pick the one with smallest $|\Delta E|$.
- In addition, cut on variables like J/ψ helicity angle, B production angle, thrust, ...

Exclusive $B^{\pm}$ Modes



Exclusive B^0 Modes



Exclusive Branching Ratios

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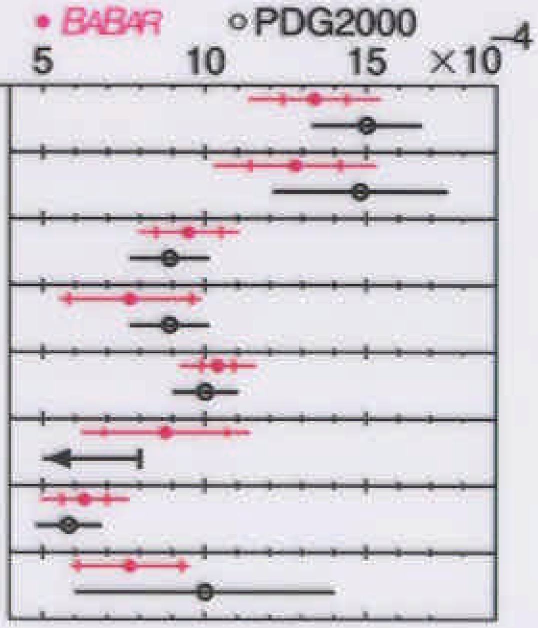
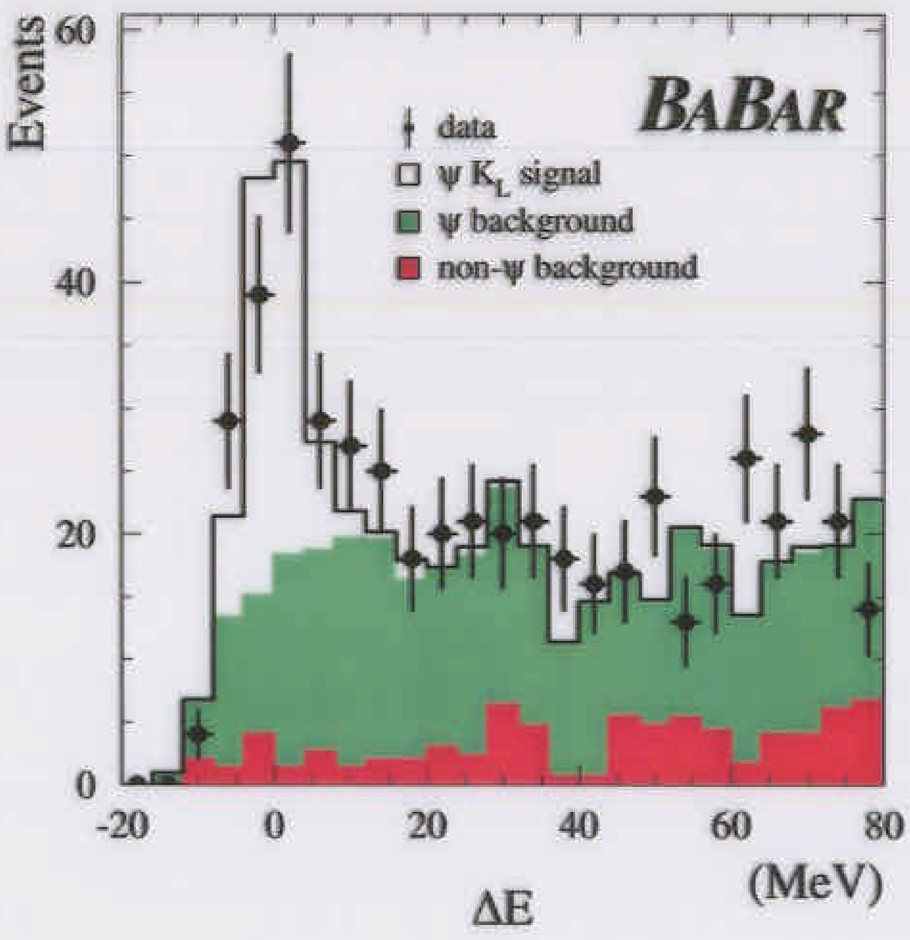
- The # of B's from B-counting
- The # of signal and background events in general by fitting m_{ES} with Argus background function and Gaussian signal
  - crosschecked with sidebands in ΔE.
- In case K^* channels, use likelihood fit to account for cross feed amongst K^* decay modes
- Efficiency from full MC simulation and Control Samples

- Systematic uncertainties:
  - B counting: 3.6%
  - Fit: 0.9–8.6%
  - Tracking Efficiency: 2.5% per track
  - Neutral Efficiency: 0.6–11%
  - PID Efficiency: 2.5–8.8%
  - Tracking Resolution: 0.6–2.6%
  - Branching Ratio of Secondary Decay: 2.2 – 13.1%
  - MC Statistics: 0.5–5.8%

Decay Channel	Yield	Br ($\times 10^{-4}$)
$J/\psi\, K^{*0}$	188 ± 14	$13.4 \pm 1.0 \pm 1.8$
$J/\psi\, K^{*\pm}$	126 ± 12	$12.8 \pm 1.4 \pm 2.1$
$J/\psi\, K^0(K^0_S \to \pi^+\pi^-)$	93 ± 10	$9.5 \pm 1.0 \pm 1.2$
$J/\psi\, K^0(K^0_S \to \pi^0\pi^0)$	14 ± 4	$7.7 \pm 1.9 \pm 1.1$
$J/\psi\, K^\pm$	445 ± 21	$10.4 \pm 0.5 \pm 1.0$
$\psi(2S) K^0(K^0_S \to \pi^+\pi^-)$	23 ± 5	$8.8 \pm 1.9 \pm 1.8$
$\psi(2S) K^\pm$	73 ± 8	$6.3 \pm 0.7 \pm 1.2$
$\chi_{c1} K^\pm$	44 ± 9	$7.7 \pm 1.6 \pm 0.9$



$B \to J/\psi\, K_L^0$ Yield

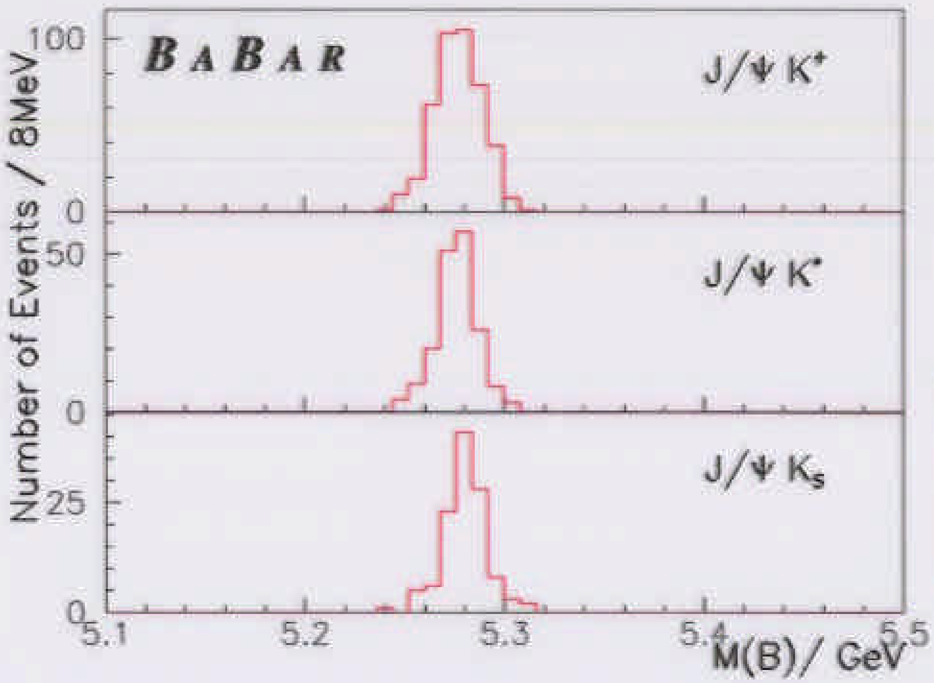


- Veto events reconstructed as signal in other exclusive modes
- Measure the K_L^0 *direction* from EM Calorimeter and/or Instrumented Flux Return
- Impose m_B constraint to determine K_L^0 energy
- Look in ΔE for signal
  - Count events with $\Delta E < 10\,\mathrm{MeV}$
  - Subtract Backgrounds
    - scale J/ψ backgrounds with J/ψ yield
    - subtract non-J/ψ backgrounds using J/ψ sidebands

- Yield: $82 \pm 14 \pm 9$ events
  - Expect 93 from MC simulations and PDG branching ratio for $B^0 \to J/\psi\, K^0$

Measurement of B^0 and B^+ masses

use $B^0 \to J/\psi(\mu^+\mu^-)K^0_S(\pi^+\pi^-)$, $B^0 \to J/\psi(\mu^+\mu^-)K^{*0}(K^+\pi^-)$, $B^\pm \to J/\psi(\mu^+\mu^-)K^+$ only



PDG2000:

$$M(B^0) = 5279.4 \pm 0.5\,\text{MeV}$$
$$M(B^\pm) = 5279.0 \pm 0.5\,\text{MeV}$$
$$M(B^0) - M(B^\pm) = 0.33 \pm 0.28\,\text{MeV}$$

- Fit to "raw" (i.e. reconstructed, *unconstrained*) B mass
  - Main systematic uncertainty is due to the momentum scale of the tracking system
  - Compare J/ψ and K^0_S masses to PDG2000 to correct scale and to estimate systematic uncertainties
  - Constrain J/ψ and K^0_S to PDG2000 values

$$M(B^0) = 5279.0 \pm 0.8(\text{stat} + \text{unc.sys}) \pm 0.8\,\text{MeV}$$
$$M(B^\pm) = 5278.8 \pm 0.6(\text{stat} + \text{unc.sys}) \pm 0.4\,\text{MeV}$$

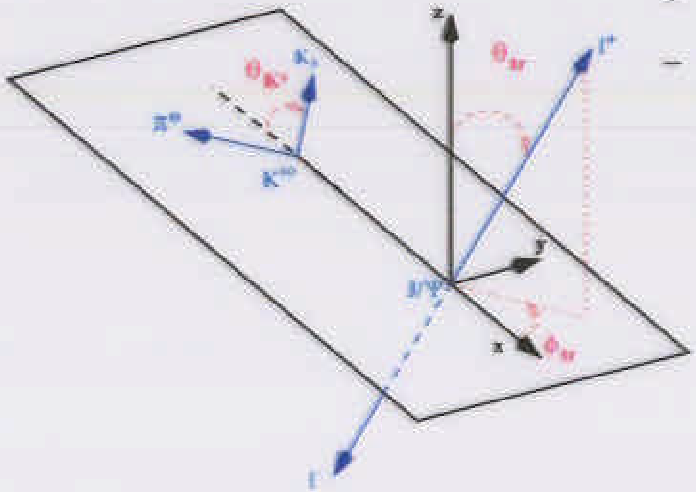
- B^0–$B^\pm$ Mass Difference: use beam energy substituted mass
  - much better resolution
  - systematic uncertainty due to beamenergy drops out of difference

$$M(B^0) - M(B^\pm) = 0.28 \pm 0.21 \pm 0.04\,\text{MeV}$$

Angular Analysis of $B \to J/\psi K^*$

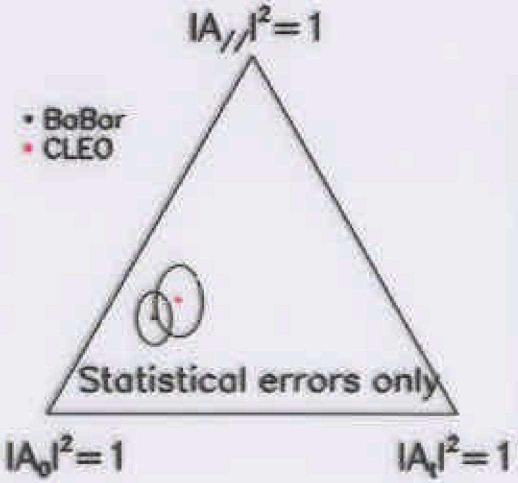
$B \to J/\psi K^*$ decay through 3 amplitudes: $A_0, A_\parallel$ (CP even) and $A_\perp$ (CP odd)
Must measure their relative contributions before $J/\psi K^*$ can be used in $\sin(2\beta)$!

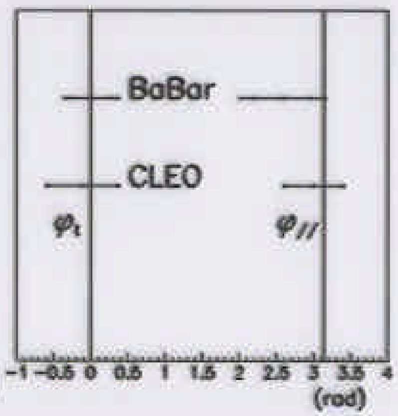
$$\frac{1}{\Gamma}\frac{d^3\Gamma}{d\cos\theta_{tr}\, d\cos\theta_{K^*}\, d\phi_{tr}} = \frac{9}{32\pi}\{ \; 2\cos^2\theta_{K^*}(1-\sin^2\theta_{tr}\cos^2\phi_{tr})|A_0|^2 + \sin^2\theta_{K^*}(1-\sin^2\theta_{tr}\sin^2\phi_{tr})|A_\parallel|^2$$
$$+ \sin^2\theta_{K^*}\sin^2\theta_{tr}|A_\perp|^2 + \sin^2\theta_{K^*}\sin 2\theta_{tr}\sin\phi_{tr}\Im(A_\parallel^* A_\perp)\times\xi$$
$$- \frac{1}{\sqrt{2}}\sin 2\theta_{K^*}\sin^2\theta_{tr}\sin 2\phi_{tr}\Re(A_0^* A_\parallel) + \frac{1}{\sqrt{2}}\sin 2\theta_{K^*}\sin 2\theta_{tr}\cos 2\phi_{tr}\Im(A_0^* A_\perp)\times\xi\}$$



- Use only *all-charged* final state modes to reduce systematic error from background subtraction
- Use unbinned extended likelihood fit enforcing $|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2 = 1$

$|A_0|^2 =$	$0.60 \pm 0.06 \pm 0.04$
$|A_\perp|^2 =$	$0.13 \pm 0.06 \pm 0.02$
$|A_\parallel|^2 =$	0.27
$\varphi_\parallel =$	$2.58 \pm 0.39 \pm 0.20$
$\varphi_\perp =$	$0.01 \pm 0.27 \pm 0.10$





Summary

- Measured Ratio of Branching Ratios for inclusive B decays to Charmonium
  - $B \to \psi(2S)$ / $B \to J/\psi$
  - $B \to \chi_{c1}$ / $B \to J/\psi$
- Measured branching ratios for exclusive B decays to Charmonium
  - $B^0 \to J/\psi K^0$ (both $K_S^0 \to \pi^0\pi^0$ and $K_S^0 \to \pi^+\pi^-$)
  - $B^0 \to J/\psi K^{*0}$
  - $B^0 \to \psi(2S) K^0$
  - $B^\pm \to J/\psi K^\pm$
  - $B^\pm \to J/\psi K^{*\pm}$
  - $B^\pm \to \psi(2S) K^\pm$
  - $B^\pm \to \chi_{c1} K^\pm$
- Observed the $B \to J/\psi K_L^0$ signal
- Measured the B^0 and $B^\pm$ masses, and their difference
- Measured the transversity amplitudes in $B \to J/\psi K^*$ decays
- You will see (some of) these events (and more) again on Monday
- Will continue to take data until end of October, then restart in February 2001
  - There is a *LOT* more data on the way!

All results are *PRELIMINARY*