New Quarkonium Results from *BABAR*

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On behalf of the  **Collaboration**

Moriond QCD 2008, La Thuile, March 08-15

- Update on $B \rightarrow X(3872)\ K$ with $X(3872) \rightarrow J/\psi\ \pi^+\pi^-$
- Measurement of $m(B^0) - m(B^+)$ using $B \rightarrow J/\psi\ K^{(*)}$ decays
- New and improved results on hadronic transitions between Upsilon states: $\Upsilon(mS) \rightarrow \Upsilon(nS)\ \{\eta, \pi^+\pi^-\}$, $1 \leq n < m \leq 4$

BaBar Status in a Nutshell

- Runs 1-6 (1999-2007): ~ 480 fb^{-1} integrated @ Y(4S) [10% 'offpeak']
- Run 7 expectation: run 10 months @ Y(4S) ⇒ ~50% dataset increment

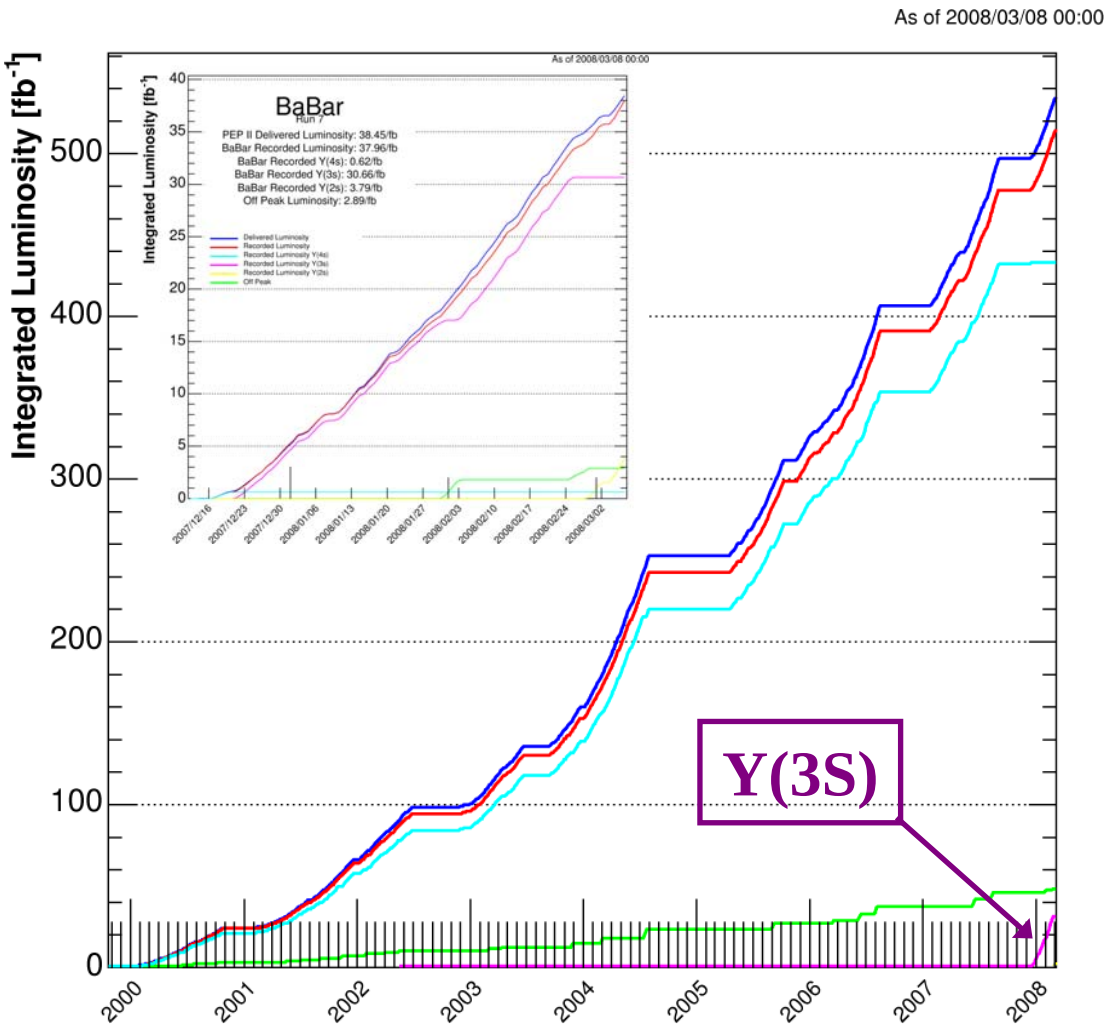
☹ Bad FY08 U.S. budget
→ plans changed quickly to avoid immediate shutdown

- Decision to run @ Y(3S)
→ Energy change done in 1 day during the Xmas break

☺ Goal (~30 fb^{-1}) achieved end of February

- Run 7 to end of April 6th
→ Take data @ Y(2S)
→ Possibly other short specific runs in the coming month

- Then BaBar data taking is over
→ symposium end of October at SLAC



Update on $B \to X(3872)\ K$ with $X(3872) \to J/\psi\ \pi^+\pi^-$

$B \to X(3872)\, K$ with $X(3872) \to J/\psi\, \pi^+\pi^-$

- X(3872) puzzling since it was discovered by Belle in $B \to J/\psi\, \pi^+\pi^-\, K$ decays (2003)
  $\to$ Doesn't seem to match any predicted charmonium state
- $m_X = 3871.4 \pm 0.6$ MeV/c^2, $\Gamma_X < 2.3$ MeV @ 90% C.L. [PDG'07]
- Quantum numbers not established; CDF angular analysis favours $J^{PC} = 1^{++}$ and 2^{-+}
- $X \to DD^{(*)}$ decays observed
  $\Rightarrow$ measured mass a few MeV higher ($\sim 4\sigma$ diff.)

Belle, PRL 97, 162002 (2006)
BaBar, PRD-RC 77, 011102 (2008)

$\Rightarrow$ 2 different states: X(3872) and X(3875)?
A threshold effect? [$M(D^0)+M(D^{*0})=3871.1\pm0.06$ MeV/c^2]

Dunwoodie, Ziegler
PRL 100, 062006 (2008)

$\Rightarrow$ Several open interpretations, among which:

✓ DD* molecule $\Rightarrow$ X above threshold;
need small R_X ratio

$$R_X = \frac{B\left(B^0 \to XK^0\right)}{B\left(B^+ \to XK^+\right)}$$

✓ Tetraquark $\Rightarrow$ small width; charged partners missing

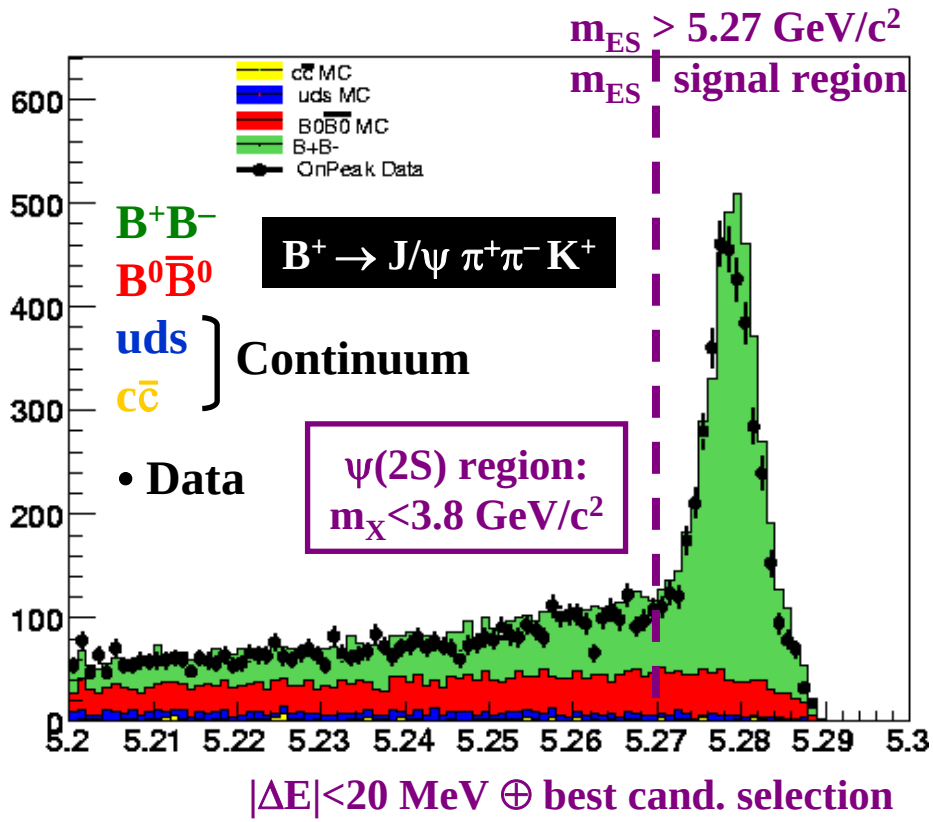
$\Rightarrow$ **Improved measurements needed to disentangle all these possibilities**

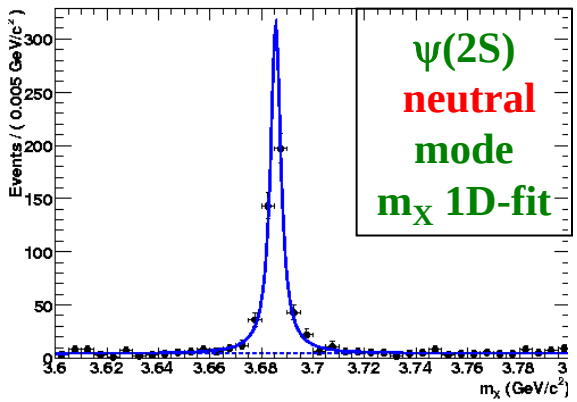
$B \to X(3872)\, K$ with $X(3872) \to J/\psi\, \pi^+\pi^-$

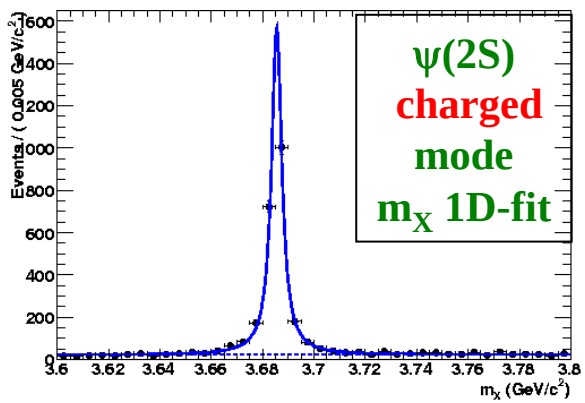
- Update of the previous BaBar analysis
  → Final result, full Runs 1–6 statistics
  → Neutral and charged K final states
- Blind analysis
- Kinematic variables:

$$\begin{cases} m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_{B}} \\ \Delta E = E^{*}_{B} - \sqrt{s}/2 \end{cases}$$

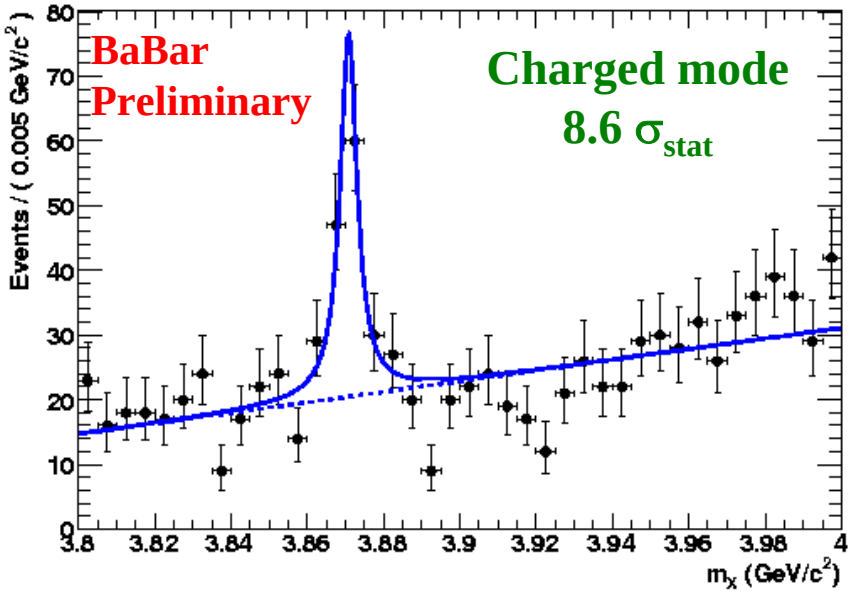
- Perform 1D unbinned max. likelihood (UML) m_X fits in m_{ES} signal region
  → signal PDF: Breit-Wigner
  → background PDF: polynom
- $\psi(2S)$ decays: control sample
  ↳ $J/\psi\, \pi^+\pi^-$
  ⇒ Same final state, close masses, very narrow
  ⇒ Fit results agree with PDG stat. errors smaller for B.F.



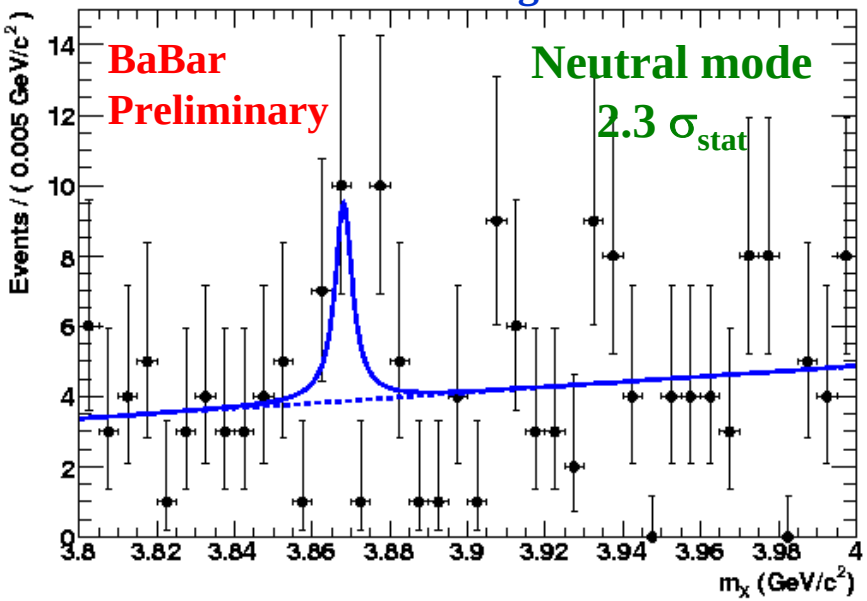




m_X Fit Results



Width fixed to the charged mode value



$B^+ \equiv B(B^+ \to X\,K^+, X \to J/\psi\,\pi^+\pi^-) = (8.40 \pm 1.55 \pm 0.74) \times 10^{-6}$

$B^0 \equiv B(B^0 \to X\,K^0, X \to J/\psi\,\pi^+\pi^-) < 6.03 \times 10^{-6}$ @ 90% C.L. (stat. $\oplus$ syst.)

$= (3.46 \pm 1.93 \pm 0.40) \times 10^{-6}$

- 1D fits $\Rightarrow$ more parameters floated $\Rightarrow$ systematics significantly reduced

- $R_X \equiv B^0/B^+ = 0.41 \pm 0.24 \pm 0.05$
  < 0.73 @ 90% C.L.

Consistant with previous analysis; errors largely improved

Belle
(600 fb^{-1}, prelim.)
$R_X = 0.94 \pm 0.24 \pm 0.10$

$\psi(2S)$: $R_\psi = 0.81 \pm 0.05 \pm 0.01$ ← better than PDG

Mass and Width Estimations

- Use the $\psi(2S)$ results to correct the X(3872) measured masses:

$$m_X = m_{X,fit} - M_{\psi(2S),fit} + \boxed{m_{\psi(2S)}}$$

PDG 2007: 3686.09 ± 0.04 MeV/c^2
$m_{fit} - m_{PDG} \approx -0.6$ MeV/c^2

$m_X = 3871.4 \pm 0.6 \pm 0.1$ MeV/c^2 for $B^+ \to X K^+$
$= 3868.7 \pm 1.5 \pm 0.4$ MeV/c^2 for $B^0 \to X K^0$

In excellent agreement with previous measurements

$\Rightarrow \Delta m = m_{X,\text{ charged mode}} - m_{X,\text{ neutral mode}} = 2.7 \pm 1.6 \pm 0.4$ MeV/c^2

- Natural width Γ_N determined from the charged mode

$\to m_X$ shape $\Leftrightarrow$ convolution of two BW: signal & resolution

Determined from signal MC (X generated with no width)

$$\Rightarrow \Gamma_N = \boxed{\Gamma_{fit}} - \Gamma_{MC}$$

FWHM

$\to$ Procedure tested and validated using the $\psi(2S)$ control samples

$\to$ Result: $\Gamma_N < 3.26$ MeV @ 90% C.L. (stat. $\oplus$ syst.)
$= 1.05 \pm 1.52 \pm 0.24$ MeV

Syst. error estimated by varying PDF shapes

Measurement of $m(B^0) - m(B^+)$ using $B \to J/\psi\, K^{(*)}$ decays

$m(B^0) - m(B^+)$ Measurement using $B \to J/\psi\, K^{(*)}$

- $\Delta m \equiv m(B^0) - m(B^+) = 0.37 \pm 0.24$ MeV/c^2 (PDG 2007)
  → π, K and D mass differences known more accurately
  → Contributes to the ratio $R_{+/0}$ of charged/neutral decay rates

$$R_{+/0} = \frac{\Gamma\left(Y(4S) \to B^+ B^-\right)}{\Gamma\left(Y(4S) \to B^0 \overline{B}^0\right)}$$

- Large BaBar $B\overline{B}$ sample: Runs 1-4 dataset, ~ 232M events ⇒ better precision

- Use decays with very little background: $B^+ \to J/\psi\, K^+$ and $B^0 \to J/\psi\, K^{*0}$ with
  $J/\psi \to \mu^+\mu^-/e^+e^-$ $\quad$ $K^{*0} \to K^+\pi^-$

- $B\overline{B}$ threshold close to Y(4S) mass ⇒ B mesons produced almost at rest:
  $p^*_B \approx 0.320$ GeV/c << $\sqrt{s}$ (≈10.58 GeV)

$m(B^0) - m(B^+)$

consequently: $\boxed{\Delta m} = -\boxed{\Delta p^*}$

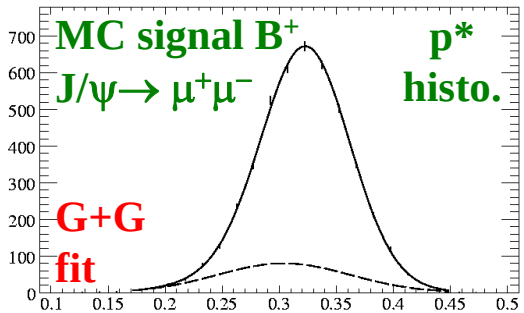
$p^*(B^0) - p^*(B^+)$

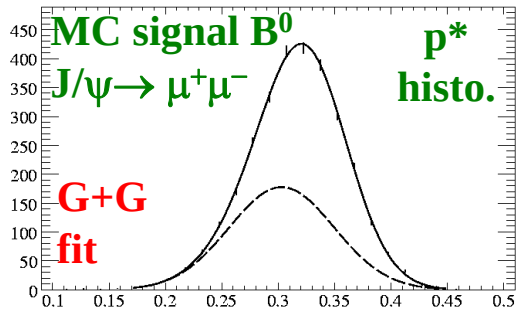
$$\frac{p^*(B^0) + p^*(B^+)}{m(B^0) + m(B^+)}$$

Known well-enough; weak influence on final result

$\sigma \sim 41_{ecm} \oplus 12_{res}$ MeV/c, no bias from reco.

- E_{cm} energy spread (~5 MeV)
  ⇒ broad p* distributions
- No dependance on Y(4S) lineshape
  ⇒ mean of p* histograms gives Δm



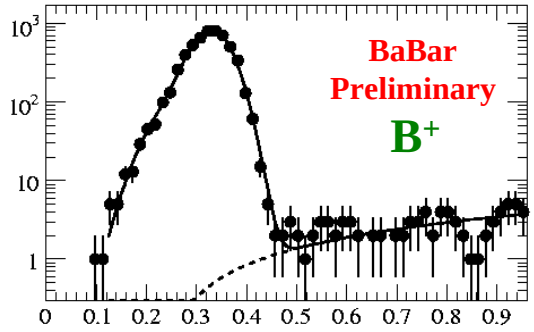


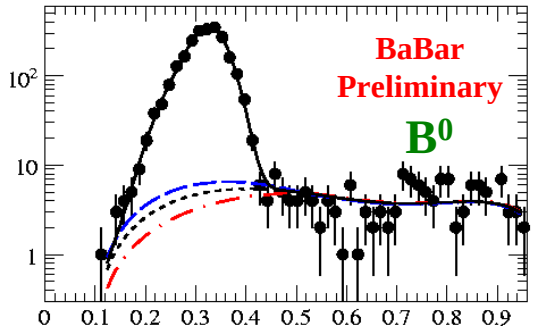
$m(B^0) - m(B^+)$ Measurement using $B \to J/\psi\, K^{(*)}$

- Bkg ⇒ distorted spectra ⇒ mean values extracted from ML fits
  - ✓ Deal with $J/\psi \to \mu^+\mu^-$ and e^+e^- separately; no charge dependence
  - ✓ Signal PDF shape: double Gaussian, parameters free in the fit (data/MC diff.)
  - ✓ Polynomial PDF shape for bkg: coefficients from MC; normalization free
  - ✓ Simultaneous fit of the B^0 and B^+ samples
    → means difference, sigmas ratio and fraction **forced to be equal**

res. effects << E spread

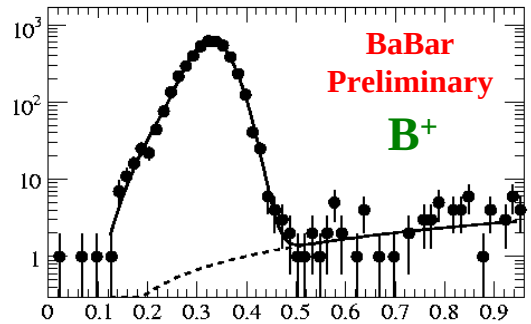
- Dominant systematics: detector simulation, signal & bkg PDF shapes, momentum magnitude bias, histo binnings

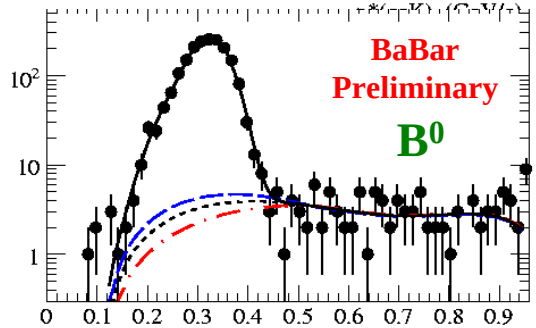




Fit results

$J/\psi \to \mu^+\mu^-$	$J/\psi \to e^+e^-$
p* mean = $321.6 \pm 0.6_{stat}$ MeV/c	p* mean = $321.1 \pm 0.7_{stat}$ MeV/c
p* mean = $316.8 \pm 0.9_{stat}$ MeV/c	p* mean = $314.7 \pm 1.1_{stat}$ MeV/c





$m(B^0) - m(B^+)$ Results

- p^* difference: $\Delta p^*(J/\psi \to \mu^+\mu^-) = -4.8 \pm 1.1 \pm 0.4$ MeV/c
  $\Delta p^*(J/\psi \to e^+e^-) = -6.4 \pm 1.3 \pm 0.5$ MeV/c

  Diff = 1.6 ± 1.7 MeV/c

  Weighted mean $\Delta p^*(\text{combined}) = -5.5 \pm 0.8 \pm \underbrace{0.5}$ MeV/c

  Highly correlated syst.
  ⇒ largest (e^+e^-) choosen

- B mass difference: $m(B^0) - m(B^+) = 0.33 \pm 0.05 \pm 0.03$ MeV/c^2

  → Compatible with current world average; error 4× smaller
  → Significance of $\Delta m > 0$ greater than 5σ

- The result can be used to estimate the kinematics contribution to R
  → $R^{kin}_{+/0} = 1.051 \pm 0.009$

$$R^{kin}_{+/0} = \left[\frac{p^*(B^+)}{p^*(B^0)}\right]^3 \approx 1 + \frac{3 m_B \Delta m_B}{(p^*_B)^2}$$

- Experimentally: $R_{+/0} = 1.037 \pm 0.028$
  → Compatible within errors
  → Unknown effects (Coulomb + wave function) not seen yet

Dubynskiy et al.
PRD75 113001 (2007)

New and improved results on hadronic transitions between Upsilon states:

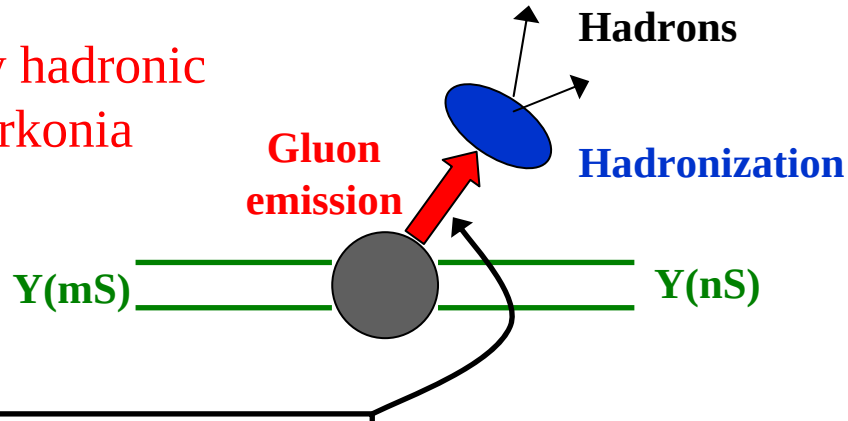
$\Upsilon(mS) \to \Upsilon(nS)\{\eta, \pi^+\pi^-\}$

Hadronic Transitions between Υ States

- $b\bar{b}$ system offers unique opportunities to study hadronic transitions between bound states of heavy quarkonia

  $\Rightarrow$ 5 $\Upsilon(mS) \rightarrow \Upsilon(nS)\ \pi^+\pi^-$ transitions

  $\Rightarrow$ 4 kinematics-allowed $\Upsilon(mS) \rightarrow \Upsilon(nS)\ \eta$ transitions



- Experimental results allow tests of **QCD Multipole Expansion**

  $\rightarrow$ width ratios: some theoretical uncertainties cancel
  exp. systematics are smaller as well

- Reconstruct Υ(nS) decays in lepton pairs and $\eta \rightarrow \pi^+\pi^-\pi^0$ **(ll ≡ e^+e^-, $\mu^+\mu^-$)**

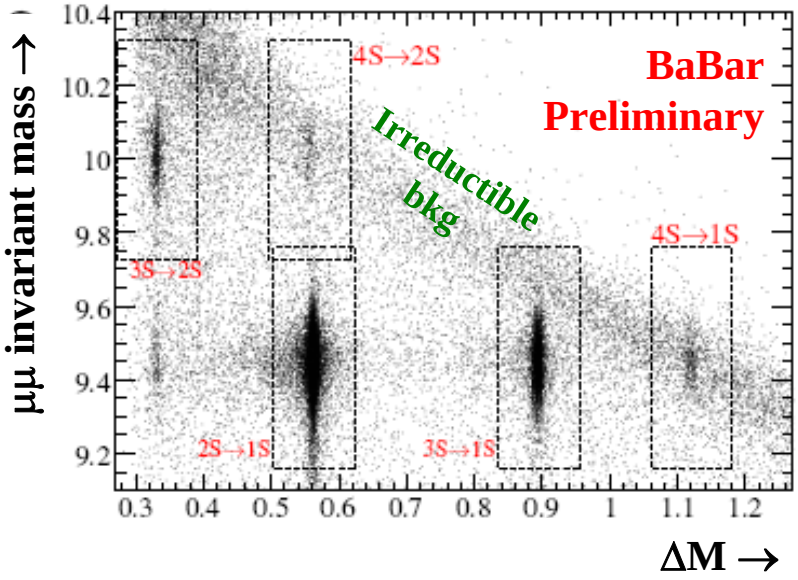
  $\Rightarrow$ higher efficiency w.r.t. $\eta \rightarrow \gamma\gamma$

  $\Rightarrow$ same charged tracks in all final states

- Invariant mass diff. (ΔM) $\rightarrow$ transitions

$$\Delta M = M_{\pi\pi ll} - M_{ll}$$

- Runs 1-5 BaBar dataset
  Υ(3S,2S) transitions studied in ISR events



Computing the event yields

- $\Upsilon(mS) \to \Upsilon(nS)\ \pi^+\pi^-$

$$\Delta M = M_{\pi\pi ll} - M_{ll}$$

1D-UML fit to ΔM in bins of $\{\cos(\theta_{hel,\pi^+}); m_{\pi\pi}\}$

$\Rightarrow$ no assumption on angular distribution

Signal PDF: Voigtian (res. param. fixed to MC)

Background PDF: linear (coeff. free in the fit)

$$N_{sig} = \Sigma_{bins}\ N_{sig}^{bin\ i} / \mathbf{eff}^{bin\ i}$$

- $\Upsilon(mS) \to \Upsilon(nS)\ \eta$

Define { signal box in plane $\{\Delta M_\eta; m(\pi^+\pi^-\pi^0)\}$; sidebands

$\Rightarrow$ if enough events with $|m_{3\pi}-m_\eta|<35$ MeV/c^2:

1D-UML fit to ΔM_η:

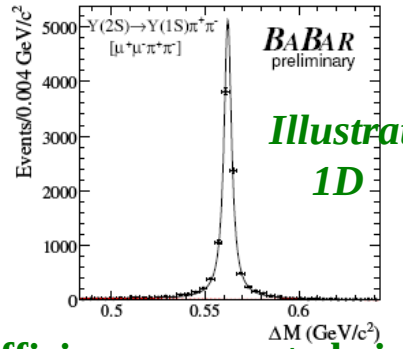
Voigtian (BW⊗Gaussian) PDF for signal; constant for bkg

$\Rightarrow$ if not, compute upper limits

$$\Delta M_\eta = M_{3\pi ll} - M_{ll} - M_{3\pi}$$

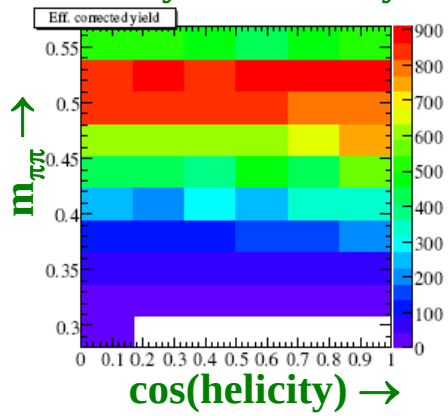
$\Upsilon(2S) \to \Upsilon(1S)\ \pi^+\pi^-$

$\Upsilon(1S) \to \mu^+\mu^-$

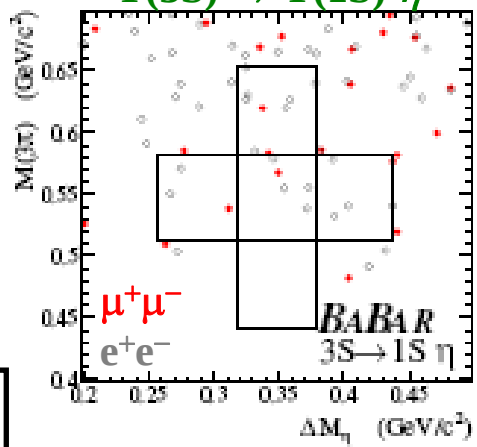


Illustrative 1D fit

Efficiency-corrected yield



$\Upsilon(3S) \to \Upsilon(1S)\ \eta$

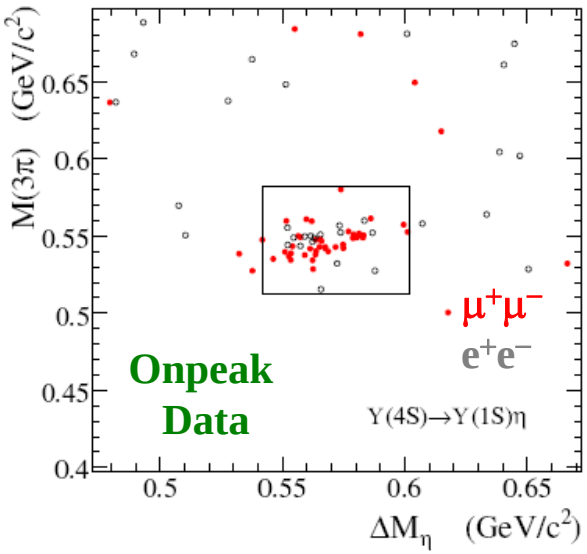


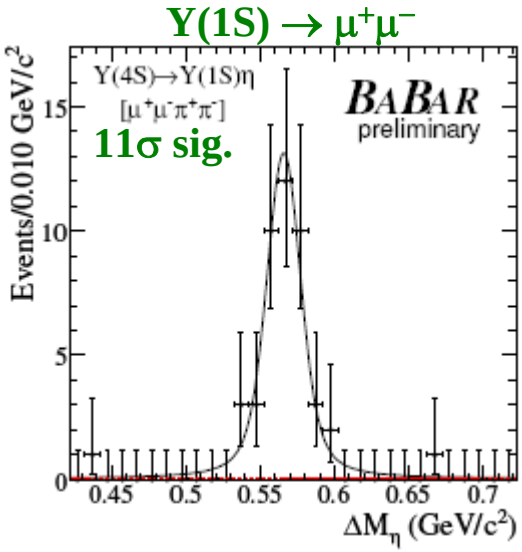
Main Results (1/2)

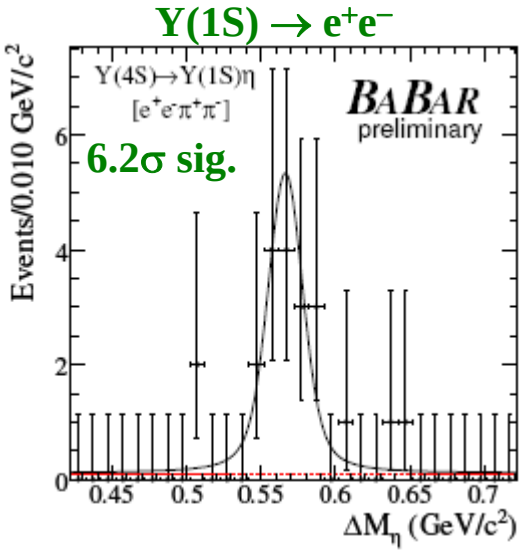
- Several systematics accounted for:
  - ✓ Y(4S) yield/ISR luminosity; tracking; PID; event selection
  - ✓ π^0; fitting procedure; efficiency/acceptance corrections

cancel in ratios

- **First observation of Y(4S) → Y(1S) η: BF = (1.96±0.06±0.09) × 10^{-4}**







- 55 ± 7 events ‘onpeak’
  No event in signal box for ‘offpeak’
  (40MeV below Y(4S) peak)

Prob.(continuum) = 0.4%

Main Results (2/2)

$\Rightarrow$ Large ratio of transition widths

$$\frac{\Gamma\left(Y(4S)\to Y(1S)\eta\right)}{\Gamma\left(Y(4S)\to Y(1S)\pi^+\pi^-\right)} = 2.41\pm0.40\pm0.12$$

Not expected!

- Improved measurements

$$\frac{\Gamma\left(Y(4S)\to Y(2S)\pi^+\pi^-\right)}{\Gamma\left(Y(4S)\to Y(1S)\pi^+\pi^-\right)} = 1.16\pm0.16\pm0.14$$

$$\frac{\Gamma\left(Y(3S)\to Y(2S)\pi^+\pi^-\right)}{\Gamma\left(Y(3S)\to Y(1S)\pi^+\pi^-\right)} = 0.577\pm0.026\pm0.060$$

- Improved 90% C.L. upper limits

$$\frac{\Gamma\left(Y(2S)\to Y(1S)\eta\right)}{\Gamma\left(Y(2S)\to Y(1S)\pi^+\pi^-\right)} < 5.2\times10^{-3}$$

$$\frac{\Gamma\left(Y(3S)\to Y(1S)\eta\right)}{\Gamma\left(Y(3S)\to Y(1S)\pi^+\pi^-\right)} < 1.9\times10^{-2}$$

Consistant with CLEO preliminary:
$B(Y(2S)\to Y(1S)\eta) = (2.51\pm0.71\pm0.50)\times10^{-4}$

With $B(Y(2S)\to Y(1S)\pi^+\pi^-) = (18.8\pm0.6)\times10^{-2}$ (PDG) one gets $\sim(1.3\pm0.5)\times10^{-3}$ for the ratio

$\rightarrow$ A lot more results in the BaBar preprint to be submitted soon

Conclusions

- New results from BaBar in the quarkonium area:

  ✓ $B \to X(3872)\ K$ with $X(3872) \to J/\psi\ \pi^+\pi^-$
  $\Rightarrow$ improved branching fractions, mass and width measurements

  ✓ Better measurement of $m(B^0) - m(B^+)$ using $B \to J/\psi\ K$ decays
  $\Rightarrow$ mass difference inconsistent with 0 @ 5σ significance

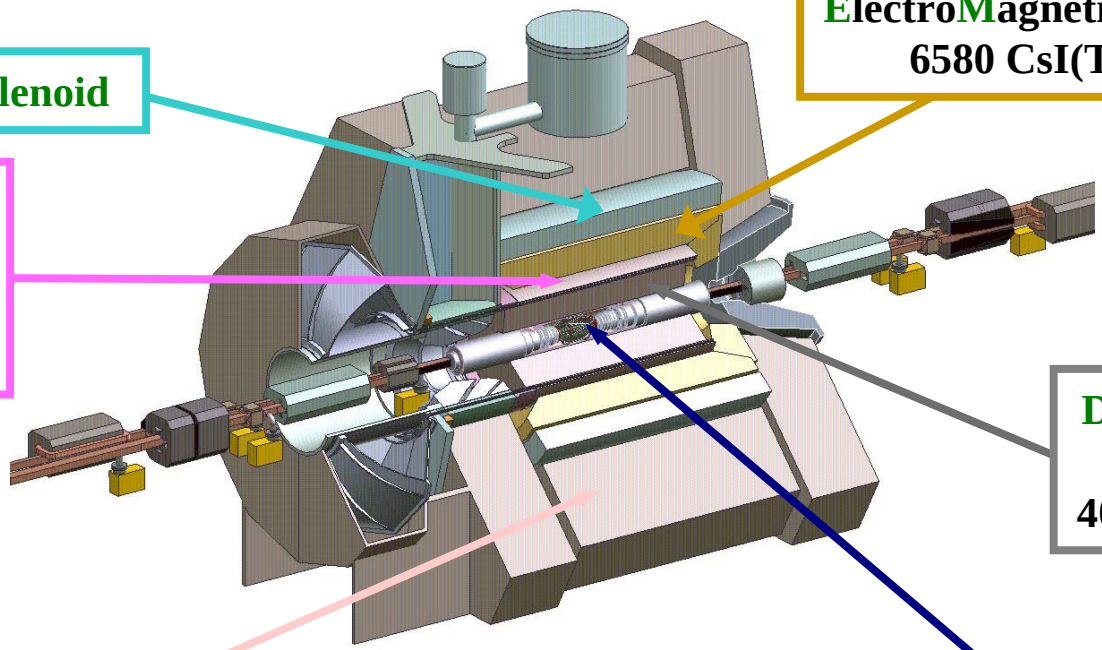
  ✓ Hadronic transition of Upsilons
  $\Rightarrow$ Observation of a large $\Upsilon(4S) \to \Upsilon(1S)\ \eta$ signal
  unlikely to come from continum events
  $\Rightarrow$ Width ratio measurements and upper limits improved

- Preliminary results
  Preprints to be made public/submitted to journal in the coming days

… To be continued!

BACKUP

The BABAR Detector



1.5 T Solenoid

ElectroMagnetic Calorimeter: 6580 CsI(Tl) crystals

DIRC: Cerenkov detector for PID. 144 quartz bars, ~11000 PMTs

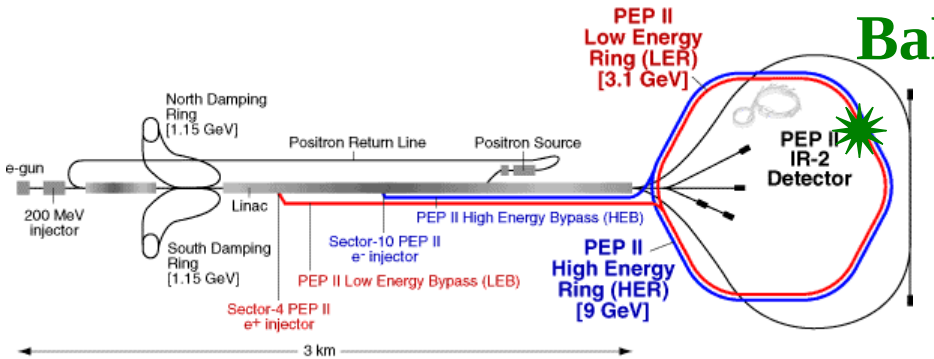
e^+ **(3.1GeV)**

Drift Chamber for tracking. 40 stereo layers

e^- **(9 GeV)**

Instrumented Flux Return for muon / neutral hadrons. Iron, RPCs & LSTs

Silicon Vertex Tracker 5 layers, double-sided strips



BaBar

BABAR, NIM A479, 1 (2002)

Systematics for the $m(B^0) - m(B^+)$ measurement

TABLE II: Summary of the systematic uncertainties for the measurement of Δp^*. All units are MeV/c.

	$\mu\mu$	ee
Signal Fit-Function	0.12	0.17
B^+ Background Fit-Function	0.01	0.03
B^0 Background Fit-Function	0.25	0.16
Histogram Binning	0.08	0.08
Momentum Bias	0.18	0.18
Detector Simulation	0.27	0.44
Quadratic Sum	0.43	0.54