Recent results from *BABAR*

The XXth International Workshop
Quantum Field Theory and High Energy Physics

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On behalf of the BABAR Collaboration

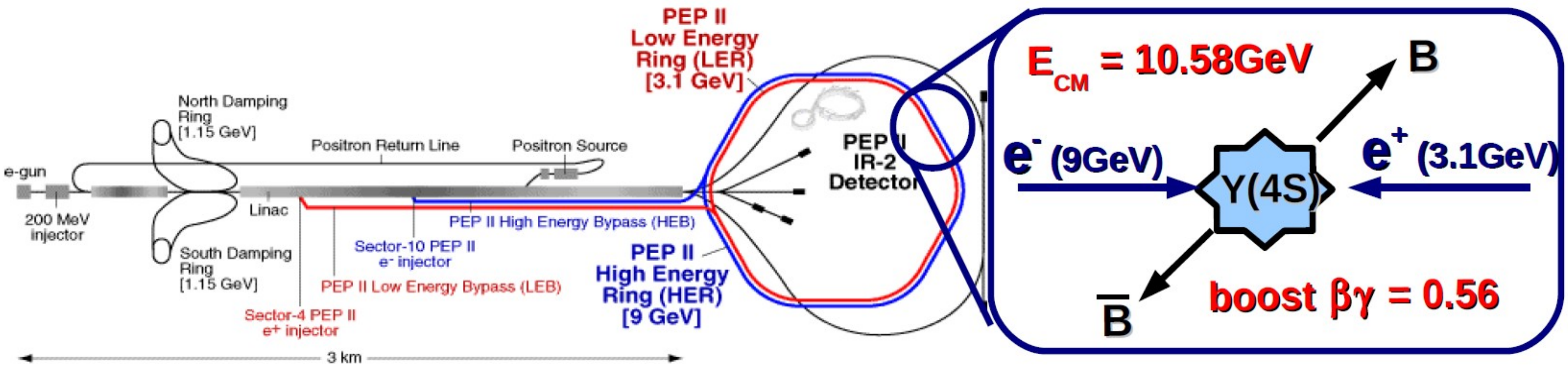
Outline

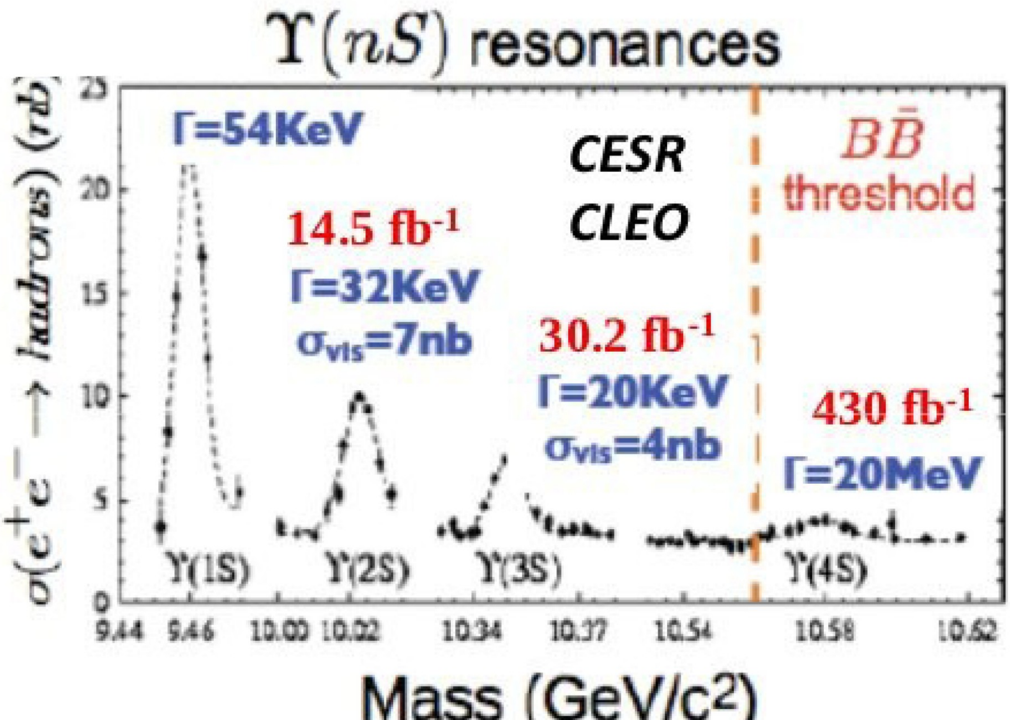
- Introduction
  - The experimental environment, BABAR dataset and detector
  - Experimental Issues

- Recent highlights
  - **Branching Fraction (BF) of Hadronic B-decays**
    - Color-suppressed decays $\overline{B}^0 \rightarrow D^{(*)0} h^0$ ($h^0 = \pi^0, \eta, \omega, \eta'$)
    - $\overline{B}^0 \rightarrow \Lambda^+_c \overline{\Lambda} K^-$
  - **CP Violation (CPV)**
    - CPV in $\tau^- \rightarrow \pi^- K^0_S (n\pi^0) \nu_\tau$, n = 0,1,2
    - T-odd correlations in $D^+/D^+_s \rightarrow K^+ K^0_S \pi^+ \pi^-$ decays
    - $B^+ \rightarrow K^+ \pi^0 \pi^0$
  - **Bottomonium Spectroscopy**
    - Bottomonium radiative transitions with converted photons ($\gamma \rightarrow e^+ e^-$)

- Conclusions

PEP-II: a B factory at SLAC





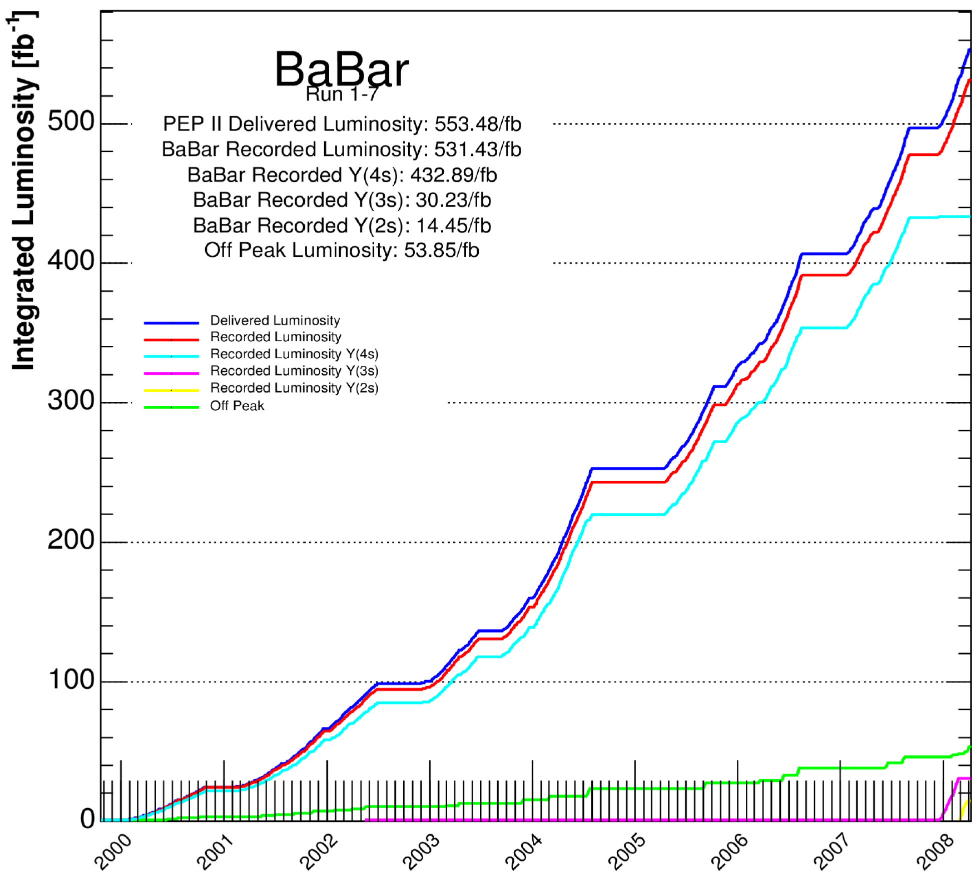
$e^+e^- \rightarrow$	Cross-Section (nb)
$b\bar{b}$	1.10
$c\bar{c}$	1.30
$s\bar{s}$	0.35
$u\bar{u}$	1.39
$d\bar{d}$	0.35
$\tau^+\tau^-$	0.94
$\mu^+\mu^-$	1.16
e^+e^-	~ 40

Important background for many analyses $e^+e^- \rightarrow q\bar{q}$ (q = u,d,s,c)

BABAR Physics

7 Runs over the course of 9 years

- 1^{st} collision May 26, 1999
- Final data taken 12:43 p.m., Apr 2008



469 submitted/published papers:

- CPV, CKM angles: α, β, γ
- Semi-Leptonic B decays: $|V_{ub}|$, $|V_{cb}|$
- B – B mixing: $|V_{td}|$
- D – D mixing
- Precision measurements, rare decays of B, charm hadrons, τ
- Spectroscopy, discovery of new states
- QCD
- Limits on new physics (NP)

31 publications in 2010

~470×10^6 $B\bar{B}$ (0.5 × Belle)

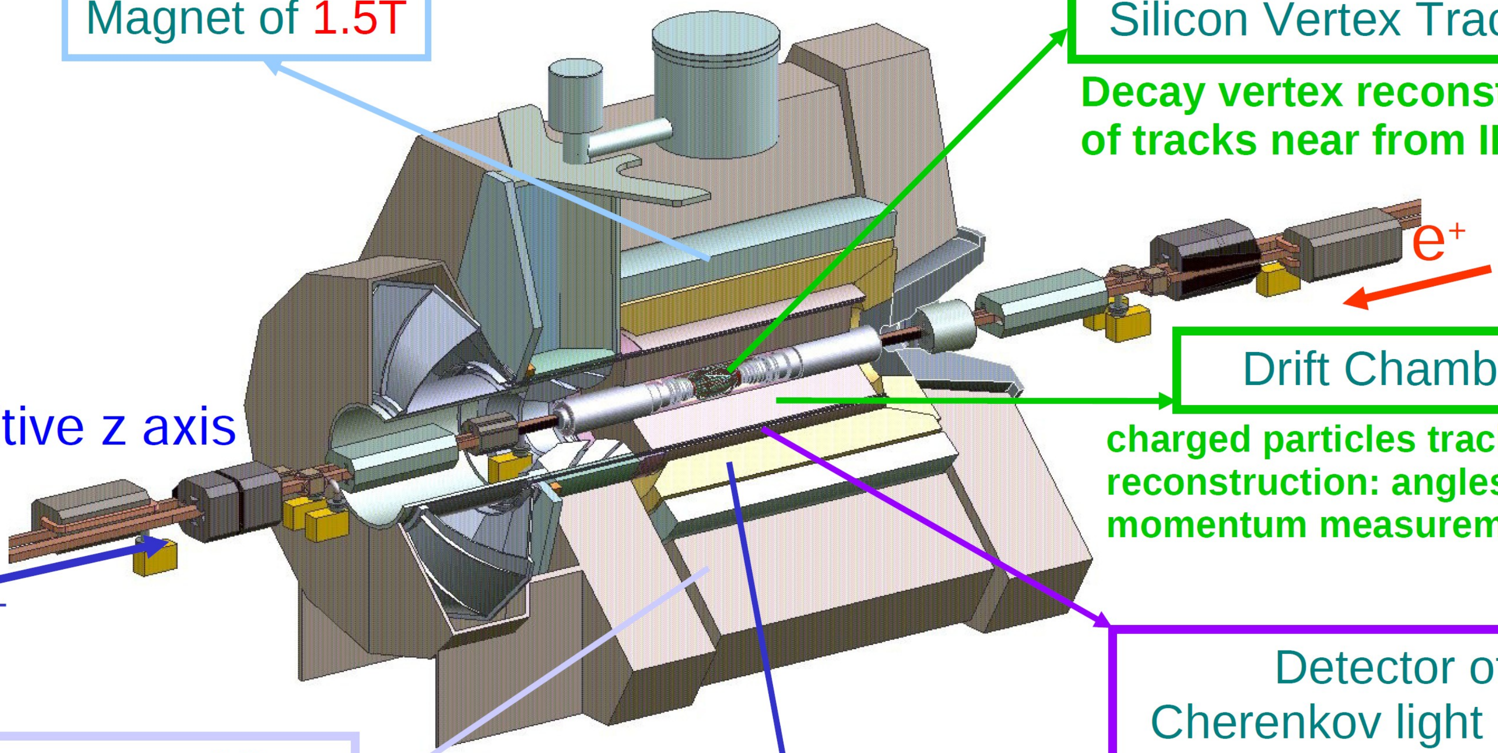
~690×10^6 $c\bar{c}$

~500×10^6 $\tau^+\tau^-$

~1.2×10^8 Υ(3S) (7 × Belle+CLEO)

~1.0×10^8 Υ(3S) (0.5 × Belle+CLEO)

BABAR Detector



Magnet of 1.5T

Silicon Vertex Tracker (SVT)

Decay vertex reconstruction of tracks near from IP

e^+

positive z axis

Drift Chamber (DCH)

charged particles tracks deviation reconstruction: angles and momentum measurements.

e^-

Detector of Cherenkov light (DIRC)

Charged particles ID

K/π separation >2.5σ until 4GeV/c²

Intrumented flux return (IFR)

$\mu^{+/-}$ Identification

Electromagnetic calorimeter (EMC)

Detection of γ, e^- identification

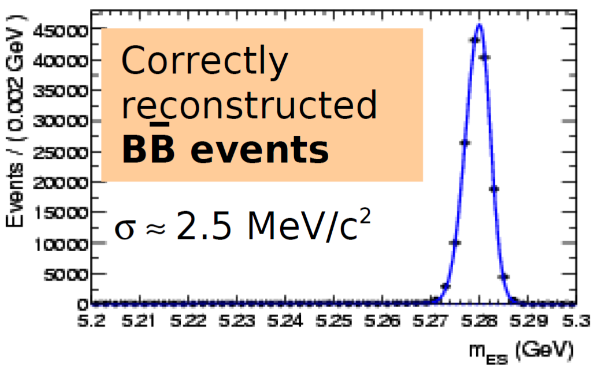
and $\pi^0 \to \gamma\gamma$ reconstruction, Measurements of Energy

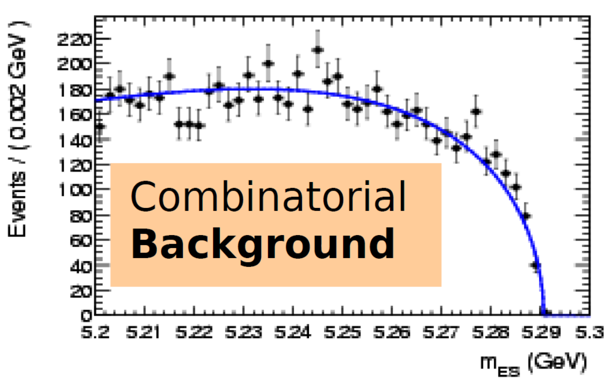
Experimental Issues

- Small S/B ratio, mostly continuum ($e^+e^- \to q\bar{q}$, $q \neq b$) background.
- Use kinematical and event-shape variables to discriminate:

Beam-energy substituted mass

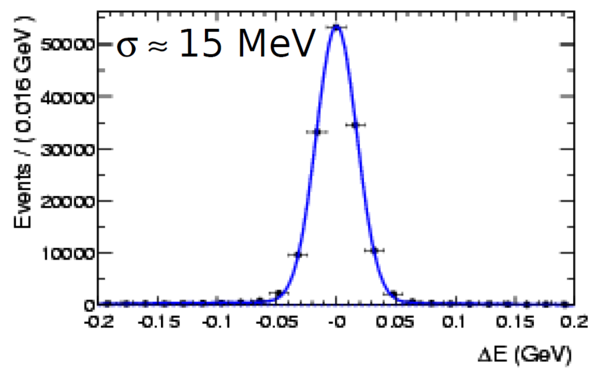
$$m_{ES} = \sqrt{E^{*\,2}_{beam} - p^{*\,2}_{B}}$$

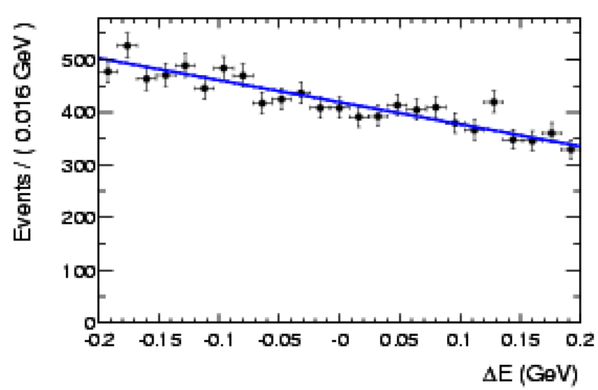




Energy difference

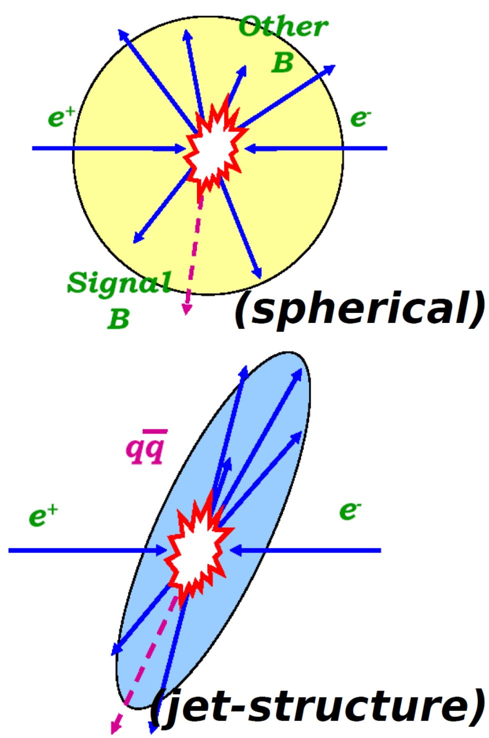
$$\Delta E = E^{*}_{B} - E^{*}_{beam}$$





Event topology

(multivariate methods)



Branching Fraction of Hadronic B Decays

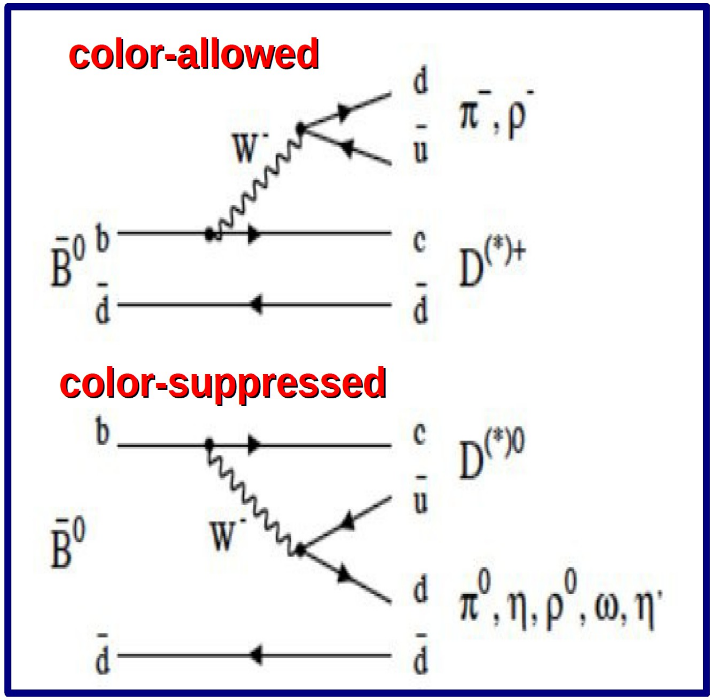
- $\overline{B}^0 \to D^{(*)0} h^0$, $h^0 = \pi, \eta, \omega, \eta'$
- $\overline{B}^0 \to \Lambda^+_c \overline{\Lambda} K^-$

$\bar{B}^0 \to D^{(*)0}h^0$: Motivation

- Neutral $\bar{B}^0 \to D(*)^0 h^0$ decays proceed through color-suppressed internal $W^\pm$ diagrams
- Strong interactions in the final state (FSI) can modify decay dynamics
  - Perturbative QCD (pQCD)

    e.g. PRD 69, 094018 (2004),
    PRD 68, 097502 (2003)
  - Soft Collinear Effective Theory (SCET)

    e.g. PRD 65, 054022 (2002),
    PRD 68, 114009 (2003),
    PRL 608, 77 (2005)



- Previous BF measurements seems to disagree with factorization approximation
- Non-factorizable contributions my be dominant for color-suppressed modes
- Stronger experimental constraints needed to distinguish among QCD models (pQCD, SCET, ...)

$\overline{B}^0 \to D^{(*)0} h^0$: Strategy

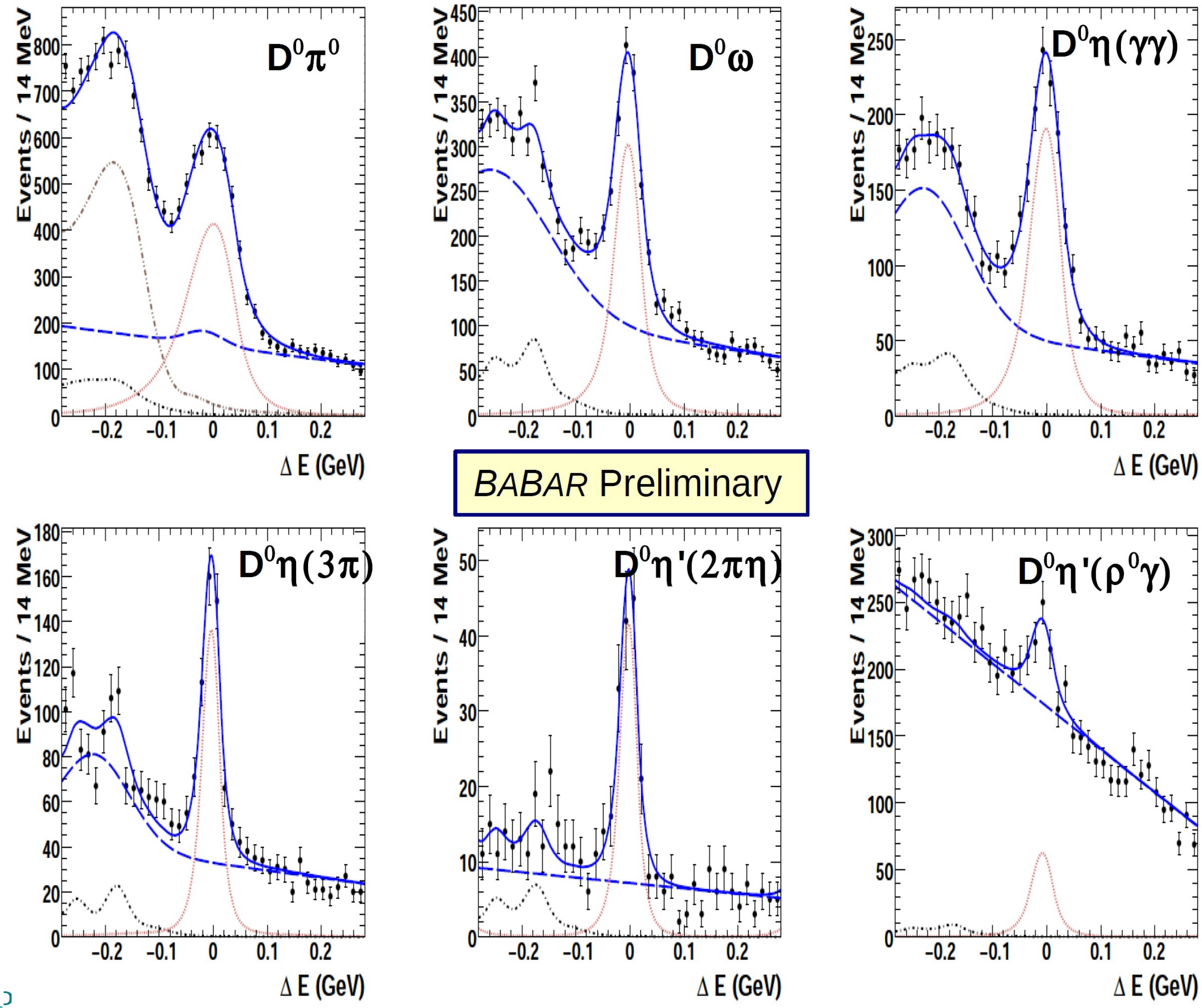
- **$D^{(*)0}$ candidates:**
  - D^0: reconstructed in several modes ($K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, $K^0_S\pi^+\pi^-$).
  - $|M_{REC}(D^0) - M_{PDG}(D^0)| < \sim 3\sigma$ (5.0,5.5,6.1,11.0 MeV/c^2)
  - D^{*0}: reconstructed in $D^{*0} \to D^0(\pi^0/\gamma)$. $|M(D^{*0}) - M(D^0)| < 1\sigma$ (1.3–7 MeV/c^2)
- **h^0 candidates** reconstructed in several modes: $\pi^0 \to \gamma\gamma$, $\eta \to (\gamma\gamma/\pi^+\pi^-\pi^0)$, $\omega \to \pi^+\pi^-\pi^0$, $\eta' \to (\rho^0\gamma/\pi^+\pi^-\eta(\to\gamma\gamma))$. Mass window depends on resolution
- **B^0 candidates:**
  - A total of 72 modes counting all $D^{(*)0}h^0$ combinations
  - Signal window $m_{ES} > 5.27$ GeV/c^2
- Use Fisher to further reduce continuum $q\overline{q}$ background
- $B^- \to D^{(*)0} h^-$ ($h^- = \pi^-, \rho^-$,) as control sample (Data vs MC comparison)
- Signal yields extracted with unbinned maximum likelihood fit to ΔE variable
- Cross-feed between $\overline{B}^0 \to D^{*0}h^0 \Leftrightarrow \overline{B}^0 \to D^0 h^0$ modes estimated with iterative procedure

$\overline{B}^0 \to D^{(*)0} h^0$: Results (I)

Data Sample:
454×10^6 $B\overline{B}$

$\overline{B}^0 \to D^0 h^0$ modes

- For every $h^0 = \pi^0$, η, ω, η' mode the plot show the measurement integrated on the D^0 modes ($K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, $K^0_S\pi^+\pi^-$)
- Signal yields are extracted with significances above 5σ

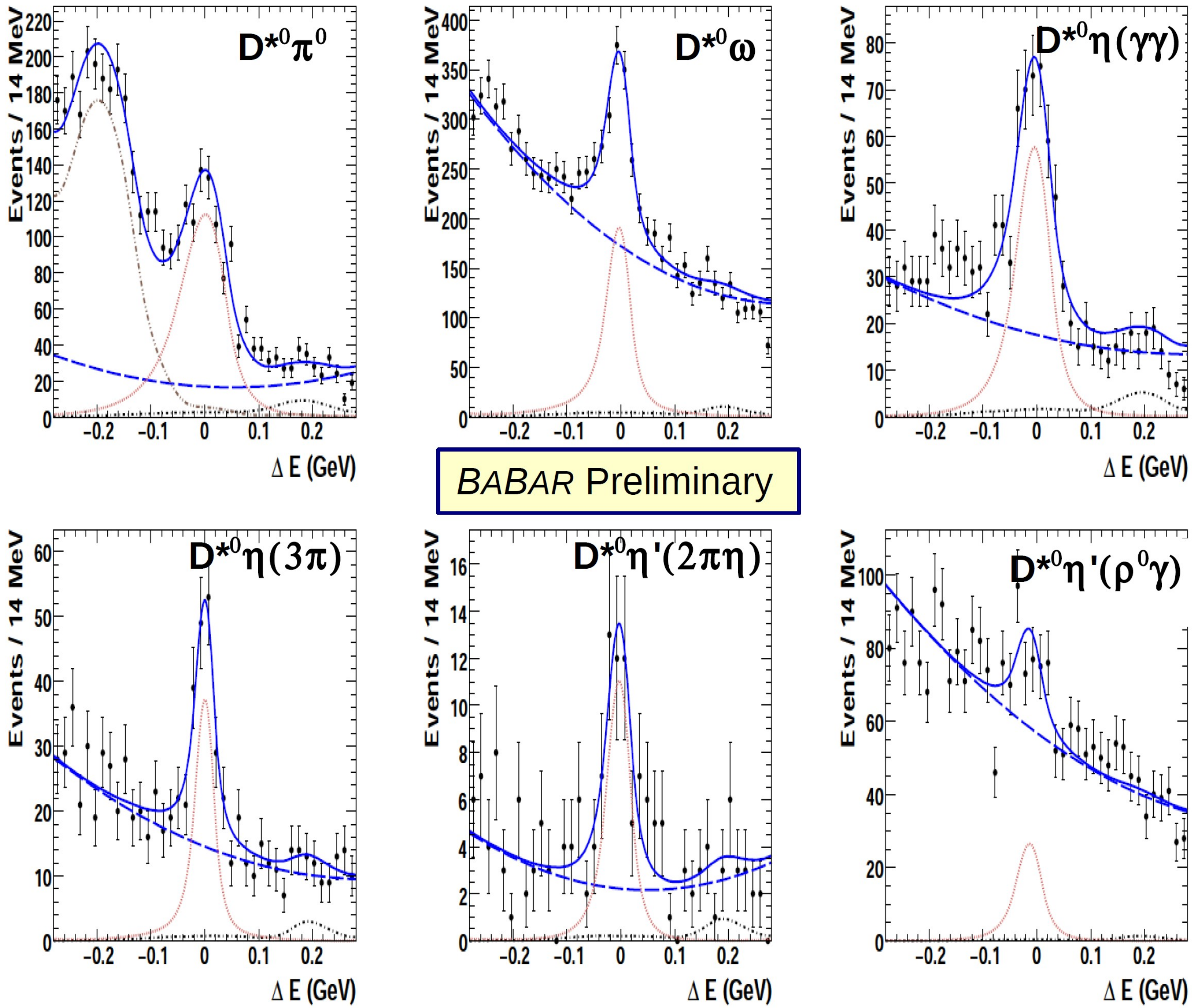


$\overline{B}^0 \to D^{(*)0} h^0$: Results (II)

Data Sample:
454×10^6 $B\overline{B}$

$\overline{B}^0 \to D^{*0} h^0$ modes

- Plots corresponds to $D^{*0} \to D^0\pi^0$
- For every $h^0 = \pi^0$, η, ω, η' mode the plot show the measurement integrated on the D^0 modes ($K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, $K^0_S\pi^+\pi^-$)
- Signal yields are extracted with significances above 5σ



$\overline{B}^0 \to D^{(*)0}h^0$: Results (III)

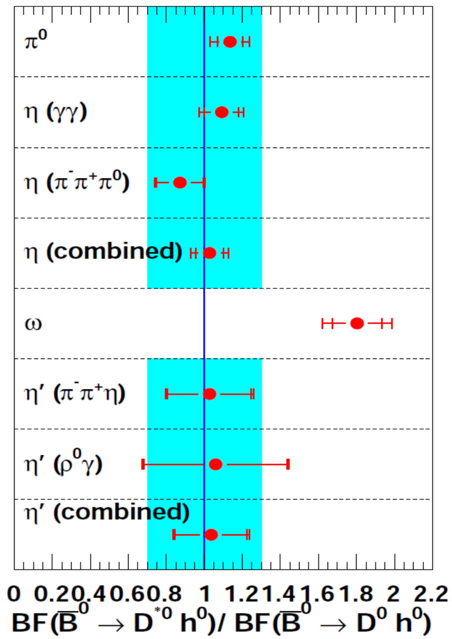
Data Sample:
454×10^6 $B\overline{B}$

- BFs consistent with previous measurements
- $BF(\overline{B}^0\to D^{*0}h^0)/BF(\overline{B}^0\to D^0h^0)$ consistent with 1.0 (within 30%) as expected by SCET but disagrees with pQCD

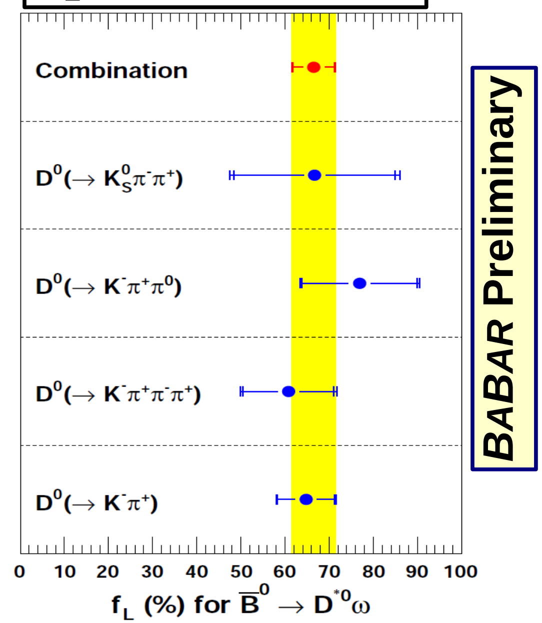
arXiv: 1107.5751
To be submitted to PRD

BABAR Preliminary

$\mathcal{B}(\overline{B}^0 \to)$ $(\times10^{-4})$	This measurement
$D^0\pi^0$	$2.69 \pm 0.09 \pm 0.13$
$D^{*0}\pi^0$	$3.05 \pm 0.14 \pm 0.28$
$D^0\eta$	$2.53 \pm 0.09 \pm 0.11$
$D^{*0}\eta$	$2.69 \pm 0.14 \pm 0.23$
$D^0\omega$	$2.57 \pm 0.11 \pm 0.14$
$D^{*0}\omega$	$4.55 \pm 0.24 \pm 0.39$
$D^0\eta'$	$1.48 \pm 0.13 \pm 0.07$
$D^{*0}\eta'$	$1.48 \pm 0.22 \pm 0.13$



f_L Measurement



- Measure f_L for $B^0\to D^{*0}\omega$ mode for the first time!

$f_L = (66.5 \pm 4.7_{stat} \pm 1.5_{syst})\%$

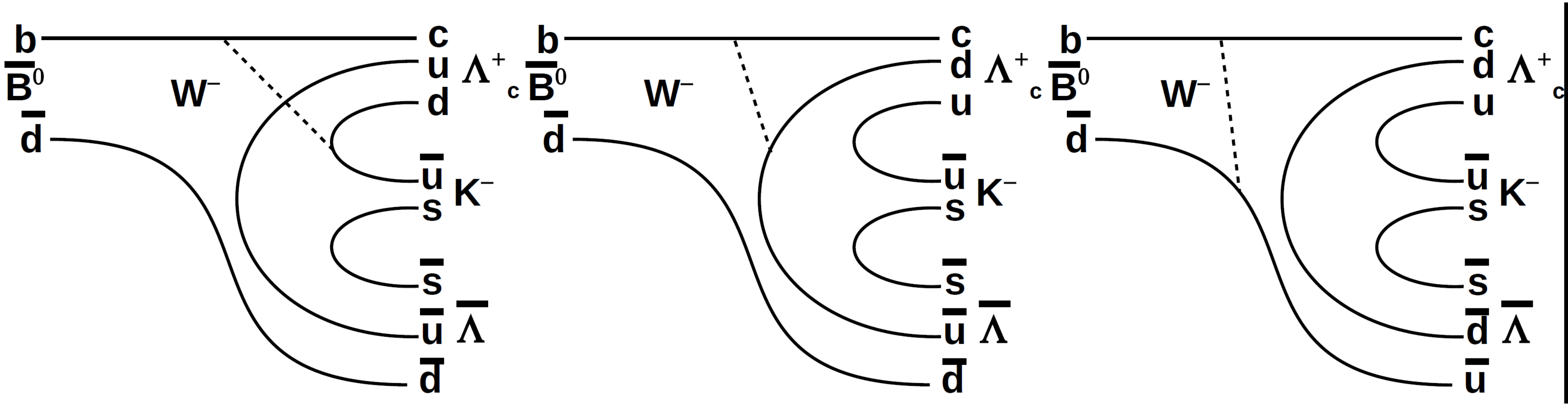
- Much lower value than HQET predictions

$f_L = (89.5 \pm 1.9)\%$ e.g. PRD 42, 3732 (1990), PRL 264, 455 (1991)

$\overline{B}^0 \to \Lambda^+_c \overline{\Lambda} K^-$: Motivation

- BF(B$\to$baryons) ~7%, but sum of known modes accounts only ~1%
- B$\to$baryons poorly understood theoretically $\Rightarrow$ study of as many exclusive modes as possible can help to understand the decay mechanism
- Threshold enhancement in bayon-antibaryon mass has been observed
- B$\to$baryons may provide evidence of new/poorly known resonances

$\overline{B}^0 \to \Lambda^+_c \overline{\Lambda} K^-$ Feynman diagrams

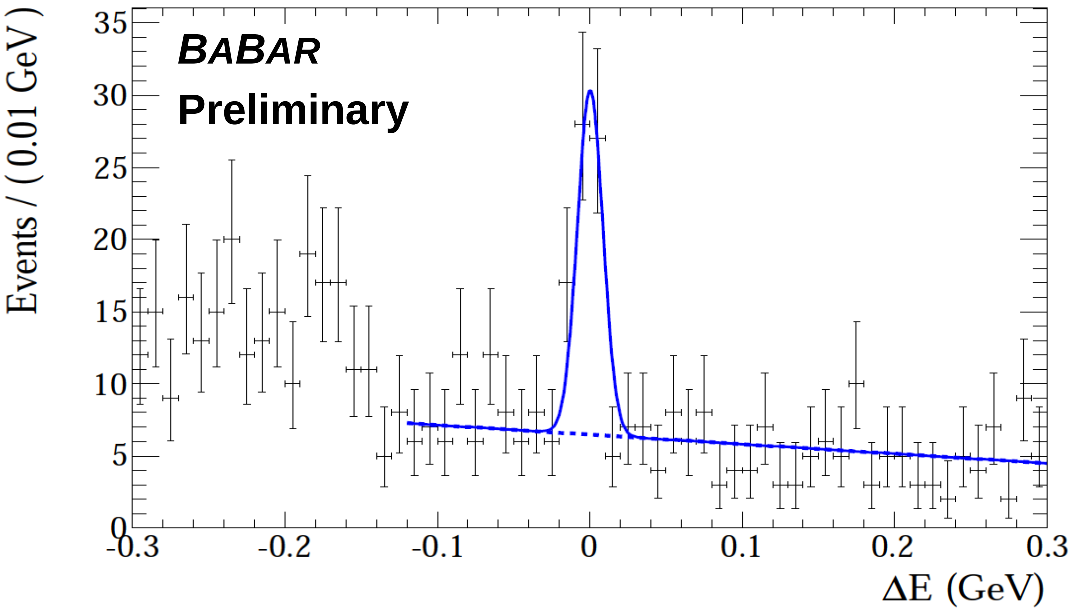


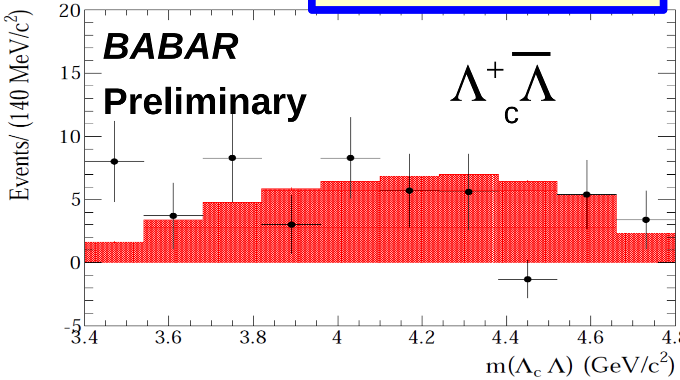
$\overline{B}^0 \to \Lambda^+_c \overline{\Lambda} K^-$: Strategy

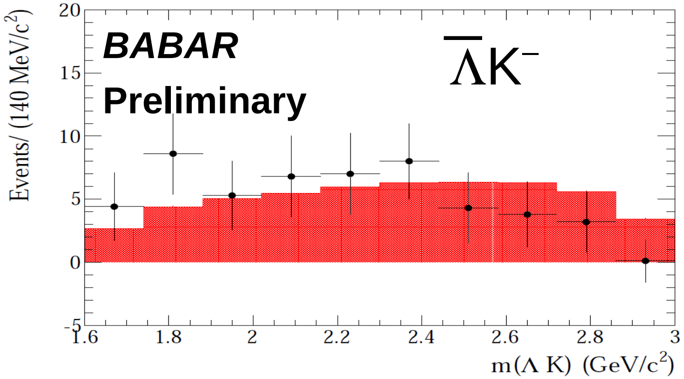
- **Λ^+_c candidates:** $\Lambda^+_c \to pK^-\pi^+$. Vertexing, $2.273 < M(\Lambda^+_c) < 2.299$ GeV/c^2
- **$\overline{\Lambda}$ candidates:** $\overline{\Lambda} \to \overline{p}\pi^+$. Vertexing, $1.113 < M(L) < 1.119$ GeV/c^2
- **B^0 candidates:**
  - Mass constraint (Λ^+_c mass fixed to PDG) of $\Lambda^+_c \Lambda K^-$ to same vertex
  - Signal window $5.272 < m_{ES} < 2.288$ GeV/c^2
- Distance between B and $\overline{\Lambda}$ vertexes in xy plane > 0.4cm
  - Rejection of 99.6% of $\overline{B}^0 \to \Lambda^+_c \overline{p} K^- \pi^+$ background
  - Rejection of 18.0% of combinatoric background
- Signal yield extracted with binned maximum likelihood fit to ΔE variable
- In the BF measurement, efficiency is corrected accounting for the phase-sapce distribution (two-body invariant masses) observed on data

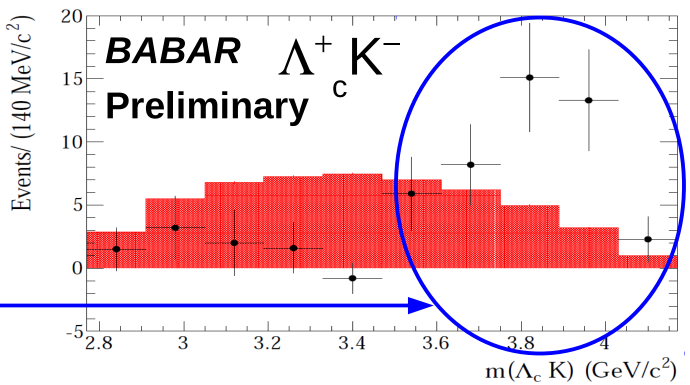
$\bar{B}^0 \to \Lambda_c^+ \bar{\Lambda} K^-$: Results

Data Sample:
471×10^6 $B\bar{B}$









- Signal Yield: 51 ± 9 events , ~8σ significance

$$BF(\bar{B}^0\to\Lambda_c^+\bar{\Lambda}K^-) = (3.8\pm0.8_{stat}\pm0.2_{syst}\pm1.0_{\Lambda c})\times10^{-5}$$

- Within signal region look at all combinations of 2-body invariant masses of the $\bar{B}^0\to\Lambda_c^+\bar{\Lambda}K^-$ final state. Enhancement at high $(\Lambda_c^+K^-)$ mass

arXiv: 1107.5751
Submitted to PRD

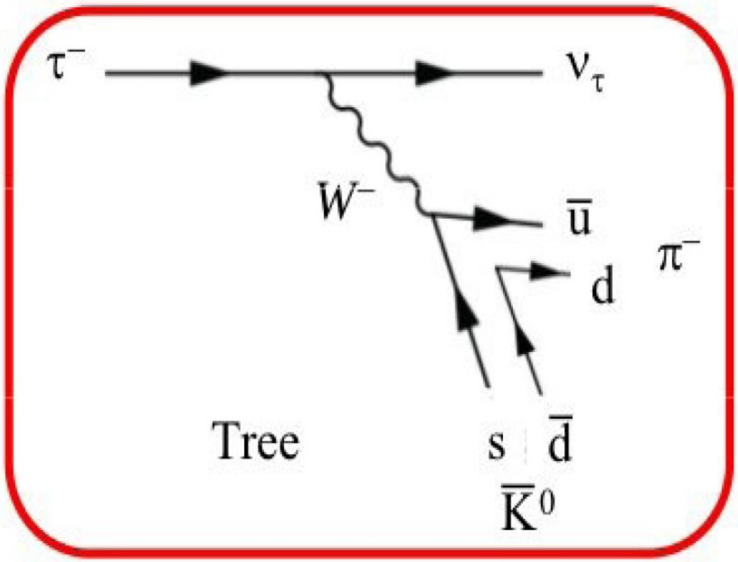
CP Violation

- CPV in $\tau^- \rightarrow \pi^- K^0{}_S (n\pi^0)\nu_\tau$, n = 0,1,2
- T-odd correlations in $D^+/D^+{}_s \rightarrow K^+ K^0{}_S \pi^+ \pi^-$
- $B^+ \rightarrow K^+ \pi^0 \pi^0$

CPV in $\tau^- \to \pi^- K^0_S (n\pi^0) \nu_\tau$: Motivation

- Standard Model (SM) predicts no CPV in $\tau^- \to \pi^- \overline{K}^0 \nu_\tau$ decays
- CPV in the Kaon sector induces a non-zero A_{CP} on the $\tau^- \to \pi^- K^0_S \nu_\tau$ final state

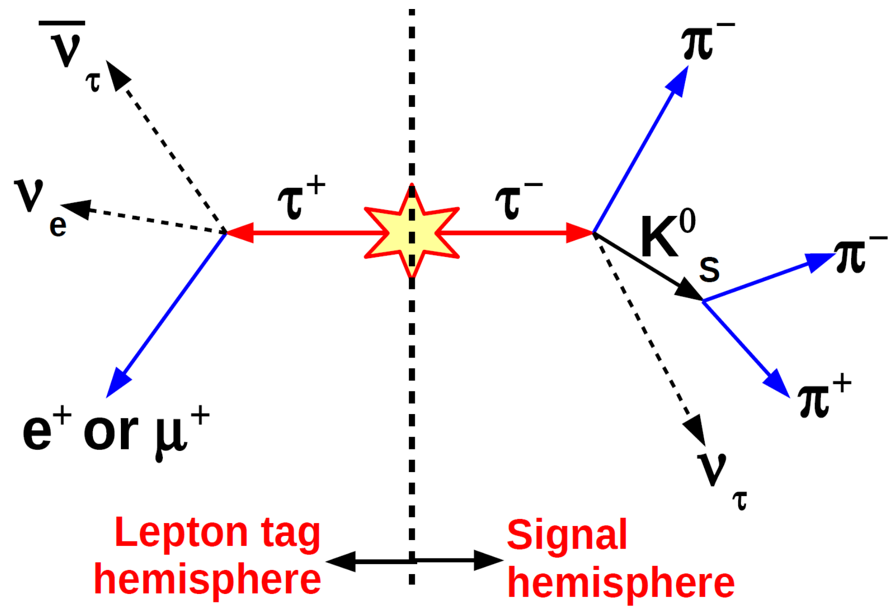
$$A_{CP} = \frac{\Gamma(\tau^+ \to \pi^+ K^0_S \overline{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K^0_S \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K^0_S \overline{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K^0_S \nu_\tau)}$$



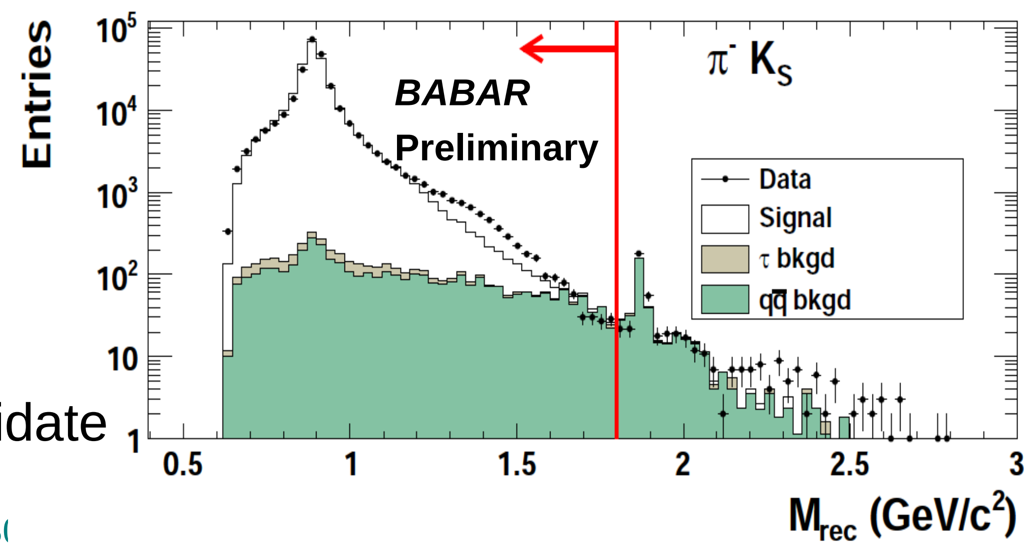
- SM prediction $A^{SM}_{CP} = (0.332 \pm 0.006)\%$ PLB 625, 47 (2005)
- A deviation of the measured A_{CP} from A^{SM}_{CP} would be a hint of NP
  - e.g. an additional CPV phase from Charged Higgs boson PLB 398, 407 (1997)
- Additional π^0s in the final state are not expected to change the A_{CP}
  - Can consider the modes $\tau^- \to \pi^- K^0_S (n\pi^0) \nu_\tau$, with n=0,1,2

CPV in $\tau^-\to\pi^-K^0_s(n\pi^0)\nu_\tau$: Strategy

- Leptonic tag technique very useful to reduce backgrounds



- Tag-side: only hard leptons (e,μ)
  - p^*_l > 4.0 GeV/c (rejects non-τ decays backgrounds)
- Signal-side:
  - $M(\pi^-K^0_s(n\pi^0)) < 1.8$ GeV/c^2 (rejects $q\bar{q}$ backgrounds)
  - Likelihood ration to reduce remaining backgrounds
  - $q\bar{q}$: visible energy, # neutral clusters, Thrust , total p_T
  - K^0_s: displaced vertex, $M(K^0_s)$, momentum and θ of K^0_s candidate



CPV in $\tau^- \to \pi^- K^0_S (n\pi^0)\nu_\tau$: Results

Data Sample:
437×10^6 $\tau^+\tau^-$

- Measure raw A_{CP} after subtracting continuum $q\bar{q}$ and non-K^0_S τ-decays. Raw A_{CP} corrected by
  - Different $K^0/\overline{K}^0$ interactions with material
  - (0.14±0.03)% for e-tag and (0.14±0.02)% for μ-tag
  - Dilution from backgrounds modes with A_{CP} different than signal

***BABAR* Preliminary**

Source	Fractions (%)	
	e-tag	μ-tag
$\tau^- \to \pi^- K^0_S (\geq 0\pi^0)\,\nu_\tau$	78.4 ± 4.0	77.4 ± 4.0
$\tau^- \to K^- K^0_S (\geq 0\pi^0)\,\nu_\tau$	4.2 ± 0.3	4.0 ± 0.3
$\tau^- \to \pi^- K^0 \overline{K}^0\,\nu_\tau$	15.6 ± 3.7	15.7 ± 3.7

$A^{SM}_{CP} = (-0.332\pm 0.006)\%$

$A^{SM}_{CP} = 0.0$

Result:

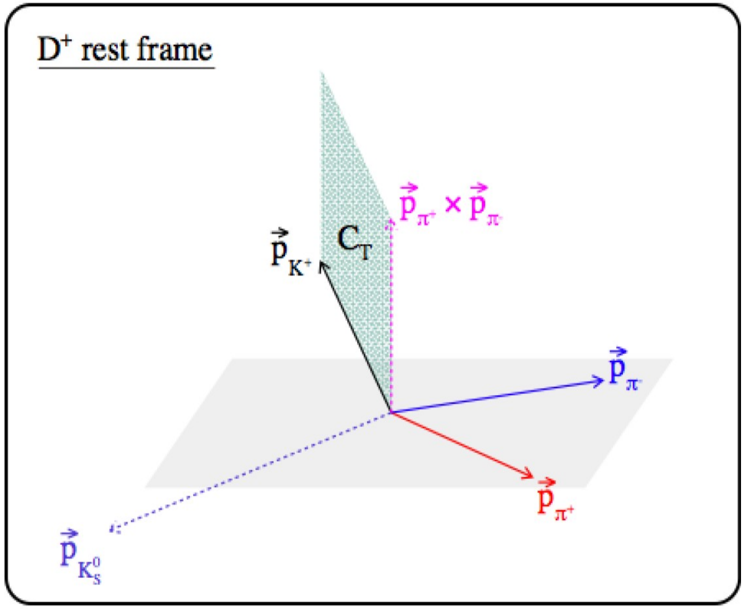
$A_{CP}(\tau^- \to \pi^- K^0_S (n\pi^0)\nu_\tau) = (-0.45 \pm 0.24_{stat} \pm 0.11_{syst})\%$

arXiv: 1109.1527
Submitted to PRD

CPV in $D^+/D^+_s \to K^+K^0_s\pi^+\pi^-$: Motivation

- Direct CPV in D decays:
  - CKM suppressed in SM $O(10^{-3})$. NP can increase/reduce effect
  - Current experimental precision $O(10^{-3})$
- New strategy based on Bigi hep-ph/0107102
- CPT invariance: T-violation $\Rightarrow$ CPV
- Define T-odd observable

$$C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$$



- Build the following asymmetries

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)} \qquad \bar{A}_T = \frac{\Gamma(\bar{C}_T > 0) - \Gamma(\bar{C}_T < 0)}{\Gamma(\bar{C}_T > 0) + \Gamma(\bar{C}_T < 0)}$$

Measured on $D^+_{(s)}$ — Measured on $D^-_{(s)}$

- Final state interaction (FSI) may induce T-odd asymetries $A_T \neq 0$
- Remove FSI effects by measuring

  A T-violation observable

$$\mathcal{A}_T \equiv \tfrac{1}{2}(A_T - \bar{A}_T)$$

CPV in $D^+/D^+_s \to K^+K^0_s\pi^+\pi^-$: Strategy

Data Sample:
520 fb^{-1}

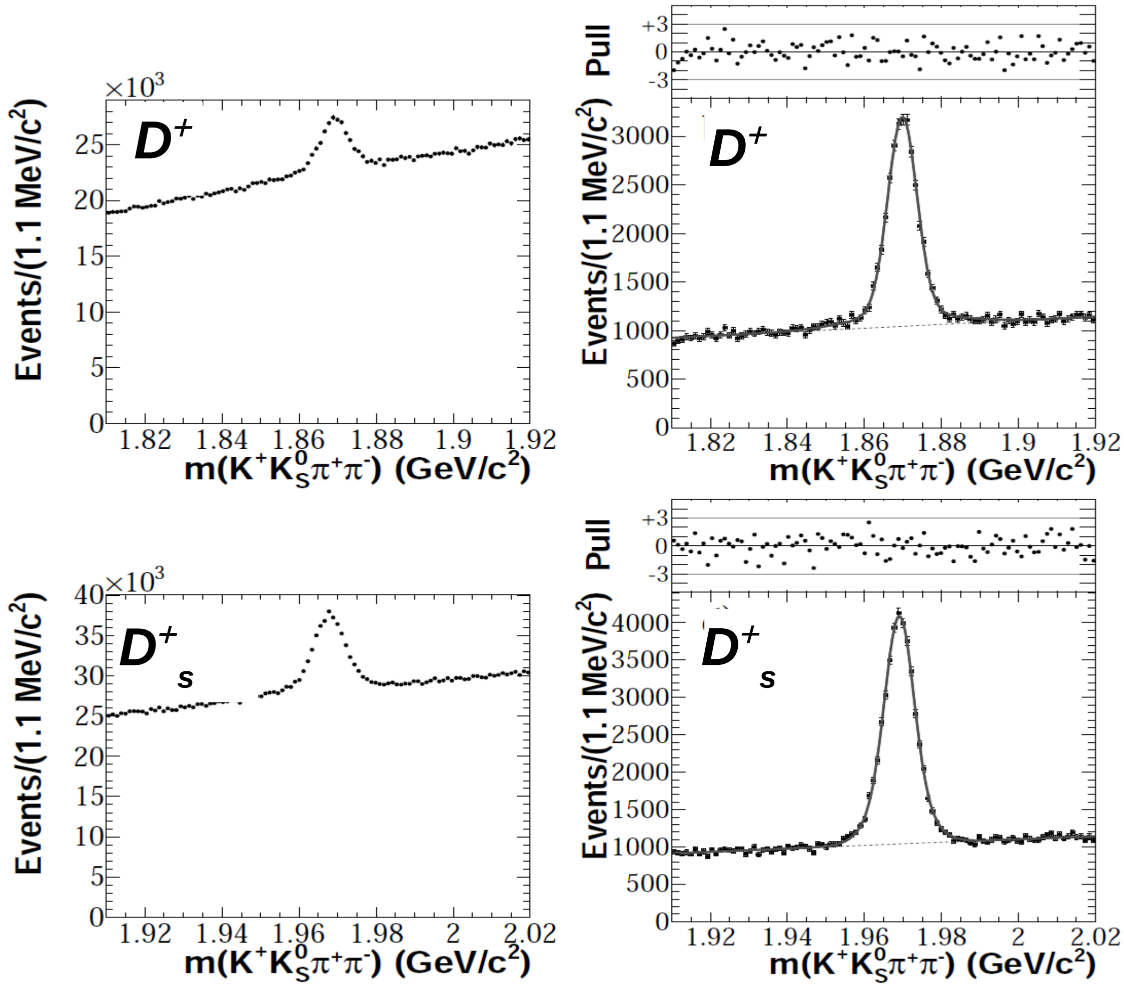
- Inclusive $D^+_{(s)}$ reconstruction

  $e^+e^- \to XD^+_{(s)}$; $D^+_{(s)} \to K^+K^0_s\pi^+\pi^-$; $K^0_s \to \pi^+\pi^-$
- $p^*(D^+_{(s)}) > 2.5$ GeV/c
- 21k D^+ Cabibbo-suppressed
- 30k D^+_s Cabibbo-favored
- Use Likelihood ratio (LR) technique
  - Decay distance in the transverse plane L_{xy}
  - CM $p^*(D^+_{(s)})$
  - Vertexing probability difference $P_1 - P_2$

    $P_1 \equiv$ 4 particle vertex

    $P_2 \equiv$ primary vertex

Before LR cut | After LR cut

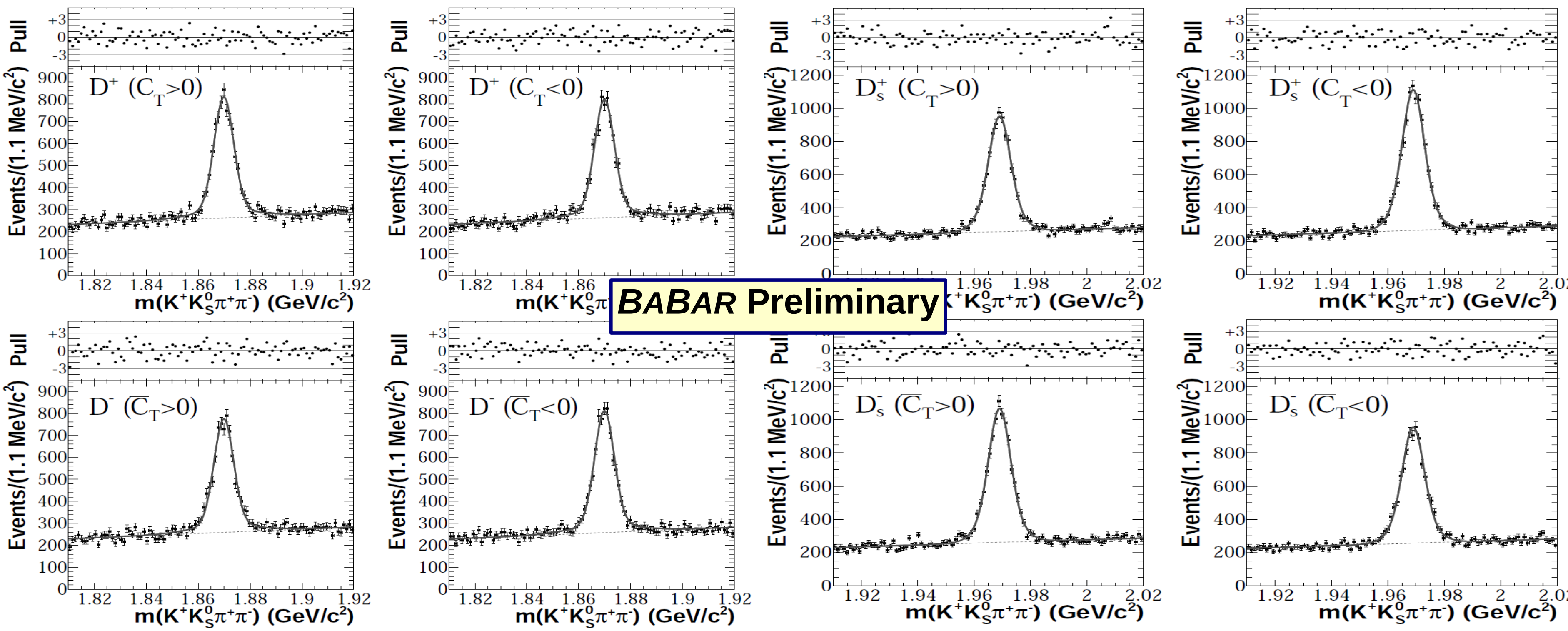


CPV in $D^+/D^+_s \to K^+K^0_s\pi^+\pi^-$: Results (I)

PRD 84, 031103 (2011)

Data Sample: 520 fb^{-1}

$D^+ \to K^+K^0_s\pi^+\pi^-$ | $D^+_s \to K^+K^0_s\pi^+\pi^-$



CPV in $D^+/D^+_s \to K^+K^0_s\pi^+\pi^-$: Results (II)

PRD 84, 031103 (2011)

Data Sample: 520 fb^{-1}

$D^+ \to K^+K^0_s\pi^+\pi^-$

$A_T(D^+) = (+11.2 \pm 14.1_{stat} \pm 5.7_{syst})\times10^{-3}$

$A_T(D^-) = (+35.1 \pm 14.3_{stat} \pm 7.2_{syst})\times10^{-3}$

$D^+_s \to K^+K^0_s\pi^+\pi^-$

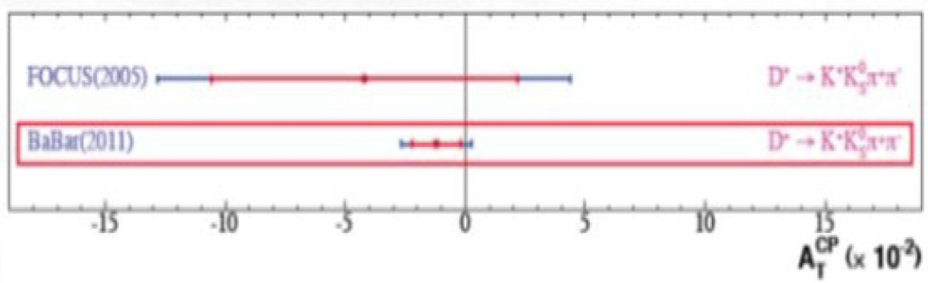
$A_T(D^+_s) = (-99.2 \pm 10.7_{stat} \pm 8.3_{syst})\times10^{-3}$

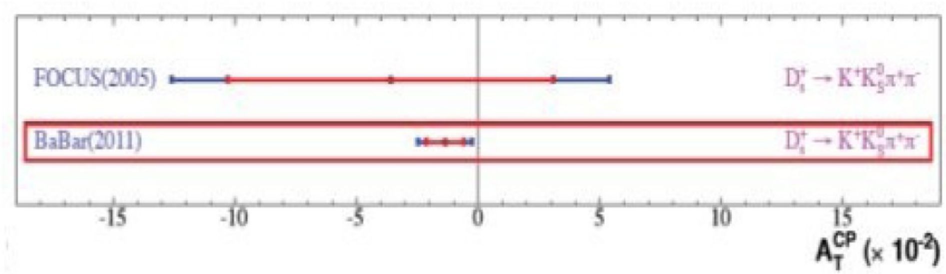
$A_T(D^-_s) = (-72.1 \pm 10.9_{stat} \pm 10.7_{syst})\times10^{-3}$

Large FSI in D^+_s than D^+ decays arXiv: 1107.1232 (2011)

$\mathcal{A}_T(D^+) = (-12.0 \pm 10.0_{stat} \pm 4.6_{syst})\times10^{-3}$

$\mathcal{A}_T(D^+_s) = (-13.6 \pm 7.7_{stat} \pm 3.4_{syst})\times10^{-3}$





- **T-violation asymmetry consistent with 0**
- **A factor of 10 improvement over previous results**

Similar BABAR analysis with

$D^0 \to K^+K^-\pi^+\pi^-$ (~47k D^0)

$\mathcal{A}_T(D^0) = (+1.0 \pm 5.1_{stat} \pm 4.4_{syst})\times10^{-3}$

PRD 81, 111103 (2010)

$B^+ \to K^+\pi^0\pi^0$: Motivation

- Expected $A_{CP}(K^+\pi^-) \approx A_{CP}(K^+\pi^0)$
- Experiment finds

$A_{CP}(K^+\pi^0) = +0.050 \pm 0.025$

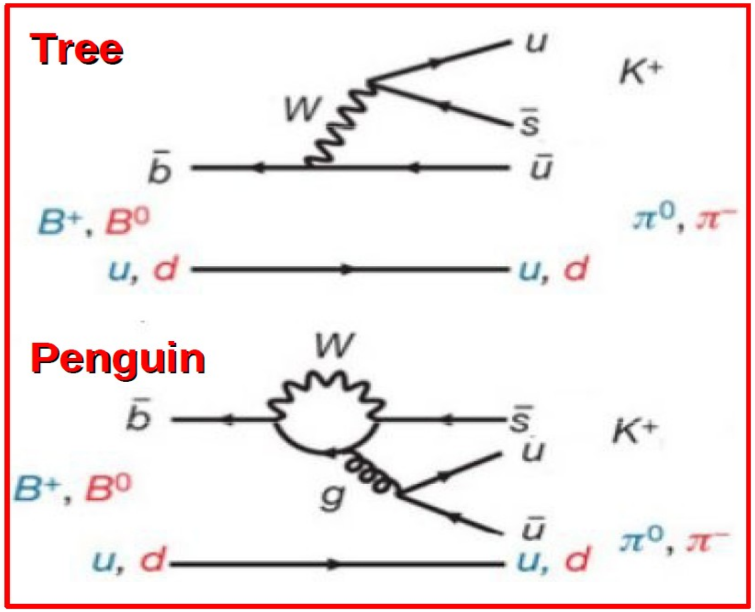
$A_{CP}(K^+\pi^-) = -0.098 \pm 0.012$

5σ difference

"Kπ puzzle"

SM o NP?

Mod. Phys. Let. A 24, 1983 (2009)

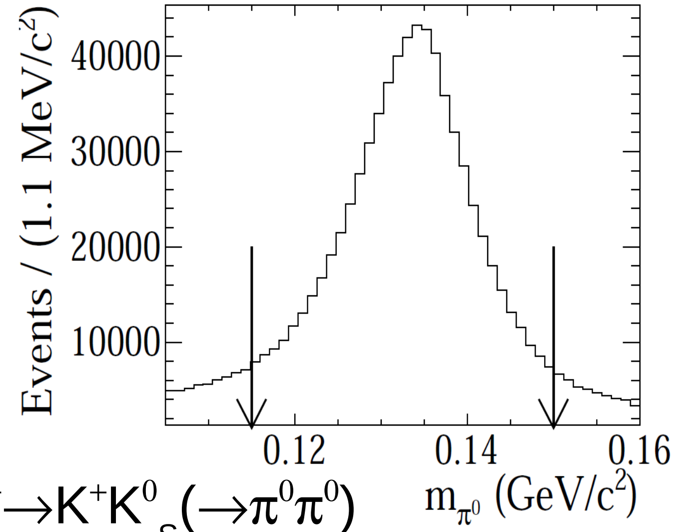


- Large hadronic uncertainties in SM ⇒ no clear interpretation in terms of NP
- Larger Tree/Penguin ratio expected for $B \to K^*\pi/K\rho$ modes ⇒ Larger CP asymmetries
- Is there a similar puzzle in the $B \to K^*\pi$ system? Need to compare

  $A_{CP}(K^{*+}\pi^-) \approx A_{CP}(K^{*+}\pi^0)$. $K^{*+}\pi^0$ contributes to $B^+ \to K^+\pi^0\pi^0$
- Dominant contributions to $B^+ \to K^+\pi^0\pi^0$ Dalitz plot may help clarify interpretation of inclusive time-dependent CP-asymmetry of $B^0 \to K^0_S\pi^0\pi^0$.

  SM expects $S_{CP}(B^0 \to K^0_S\pi^0\pi^0) = -\sin(2\beta)$

$B^+ \to K^+\pi^0\pi^0$: Strategy



- $\pi^0 \to \gamma\gamma$. $115 < M(\pi^0) < 150$ MeV/c^2
- B^+: mass constraint (π^0 mass fixed to PDG) fit of $K^+\pi^0\pi^0$ to same vertex
- ΔE correlated with Dalitz Plot (DP) $\Rightarrow$ not used in the fit. Signal window $-150 < \Delta E < 50$ MeV
- Veto: $0.40 < M(\pi^0\pi^0) < 0.55$ GeV/c^2 to exclude $B^+ \to K^+K^0_S(\to\pi^0\pi^0)$

  Background (rejects 96% and keeps ~100% of signal)
- Use Neural Net (NN_{out}) to further reduce continuum $q\bar{q}$ background. Apply loose cut $NN_{out} > 0.3 \Rightarrow$ rejects (keeps) 82% (90%) of continuum (signal)
- Signal yield and global A_{CP} extracted with unbinned maximum likelihood fit to m_{ES} and NN_{out} variables
- Fraction of self-cross-feed (SCF) events strongly dependent on DP. Iterative method to estimate SCF fraction using sPlots NIM A555, 356 (2005)

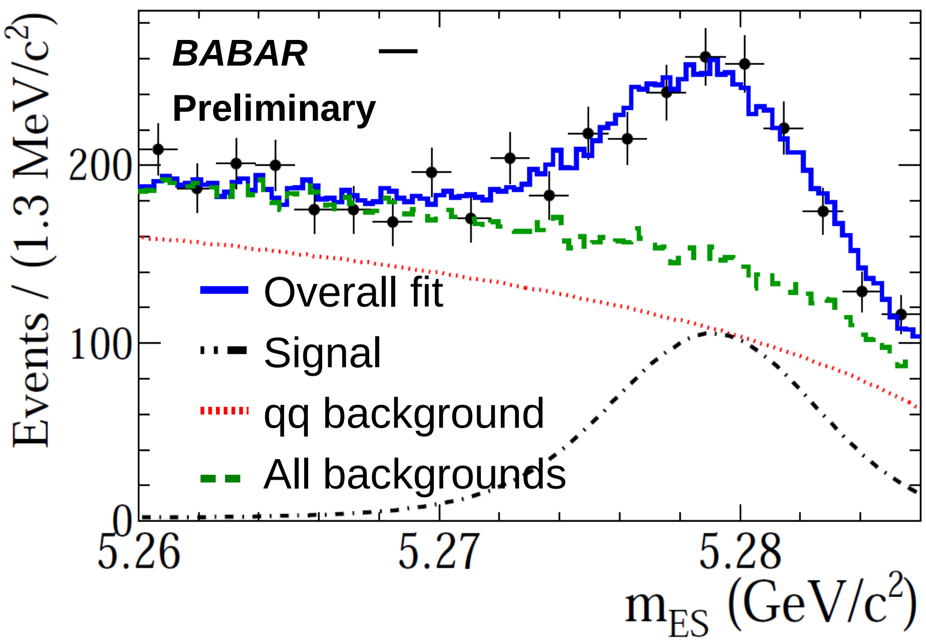
$B^+ \to K^+\pi^0\pi^0$: Results (I)

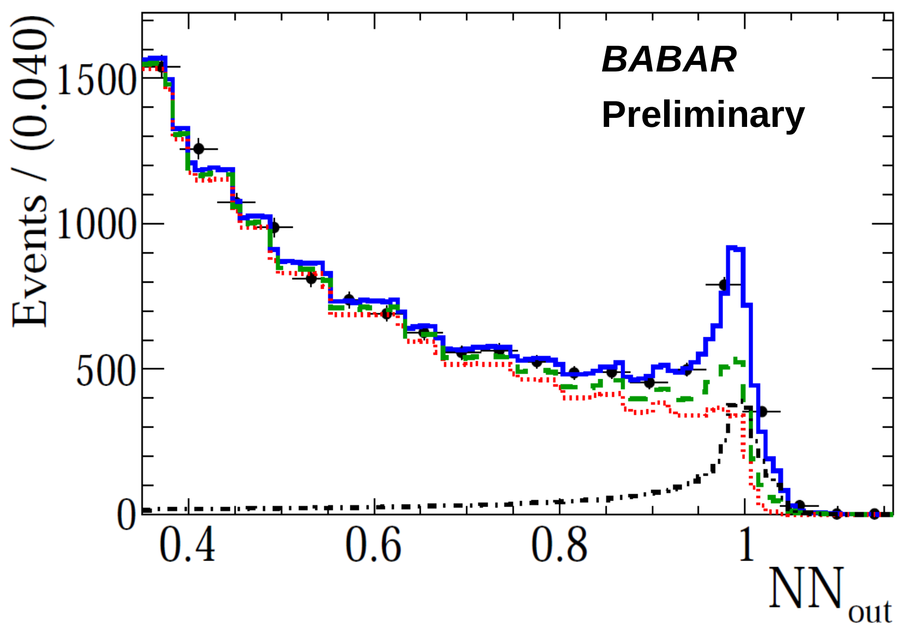
Data Sample:
471×10^6 $B\bar{B}$

To be submitted to PRD

Inclusive $B^+ \to K^+\pi^0\pi^0$ measurement:

- Convergence after 4 iterations $\Rightarrow$ Signal Yield = 1220 ± 85 and f_{SCF} = 9.7%
- 10σ significance including systematic effects!
- $BF(B^+ \to K^+\pi^0\pi^0) = (16.2 \pm 1.2_{stat} \pm 1.5_{syst})\times10^{-5}$
- $A_{CP}(B^+ \to K^+\pi^0\pi^0) = (-6.0 \pm 6.0_{stat} \pm 4.0_{syst})\%$





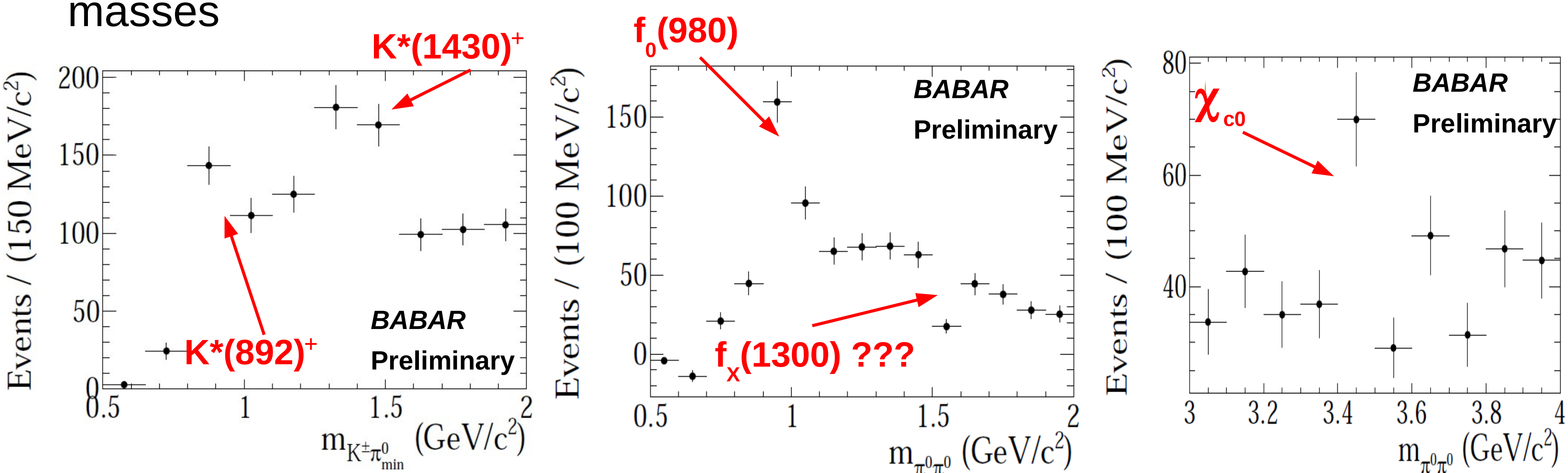
$B^+ \to K^+\pi^0\pi^0$: Results (II)

Data Sample:
471×10^6 $B\overline{B}$

To be submitted to PRD

Quasi-two-body contributions:

- Use sPlot technique to obtain DP distributions from m_{ES}-NN_{out} fit.
  Project DP onto the 2-body invariant masses
- Signal peaks from $K^*(892)^+\pi^0$, $f_0(980)K^+$, $\chi_{c0}K^+$ are clearly seen
- Broad peak at ~1400 MeV/c^2 in the $K^+\pi^0$ mass, possibly from $K^*_{0/2}(1430)^+\pi^0$
- No enhancement from $f_X(1300)$ in pipi mass. Deap at ~1500 MeVc^2
- BF and A_{CP} extracted from fit to 2-body invariant masses around resonant masses



$B^+ \to K^+\pi^0\pi^0$: Results (III)

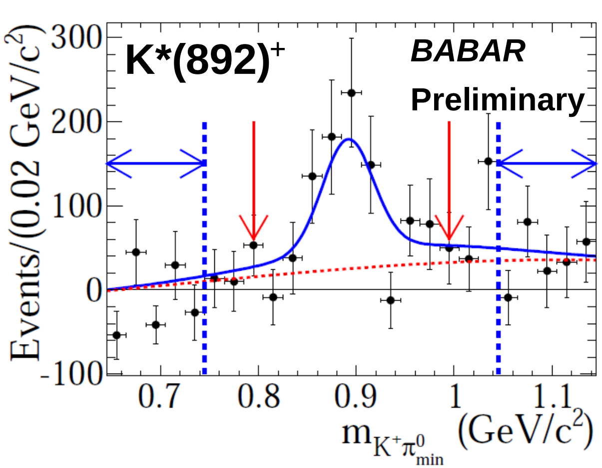
Data Sample:
471×10^6 $B\overline{B}$

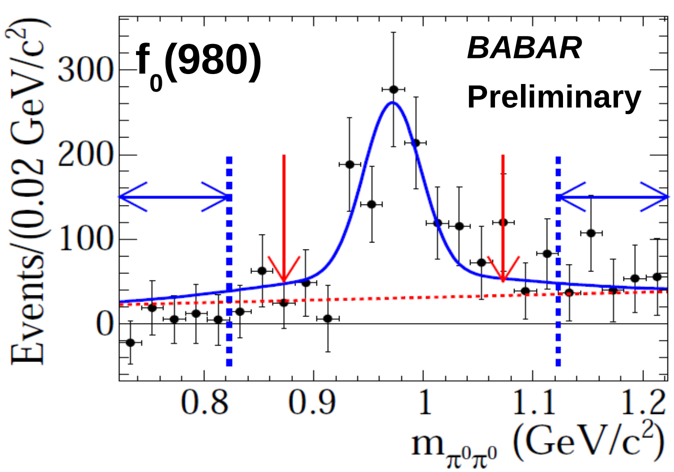
To be submitted to PRD

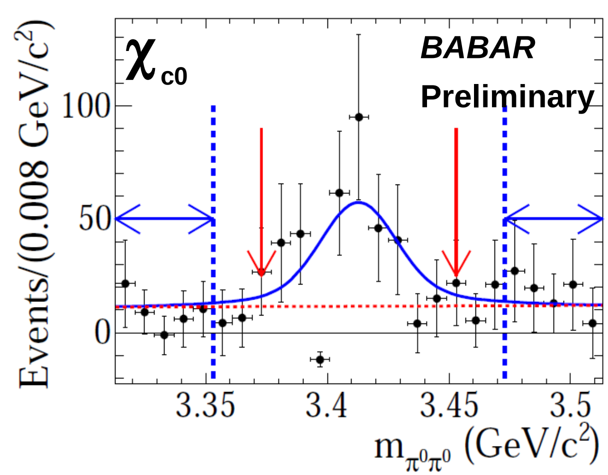
- First inclusive measurement of $B^+ \to K^+\pi^0\pi^0$!
- More statistics is needed to better test $A_{CP}(K^{*+}\pi^-) \approx A_{CP}(K^{*+}\pi^0)$

Mode	$\mathcal{B}(B^+ \to Rh \to K^+\pi^0\pi^0)$	$\mathcal{B}(B^+ \to Rh)$	A_{CP}
$B^+ \to K^+\pi^0\pi^0$	$(16.2 \pm 1.2 \pm 1.5) \times 10^{-6}$	$\cdots$	$-0.06 \pm 0.06 \pm 0.04$
$B^+ \to K^*(892)^+\pi^0$	$(2.7 \pm 0.5 \pm 0.4) \times 10^{-6}$	$(8.2 \pm 1.5 \pm 1.1) \times 10^{-6}$	$-0.06 \pm 0.24 \pm 0.04$
$B^+ \to f_0(980)K^+$	$(2.8 \pm 0.6 \pm 0.5) \times 10^{-6}$	$\cdots$	$0.18 \pm 0.18 \pm 0.04$
$B^+ \to \chi_{c0}K^+$	$(0.51 \pm 0.22 \pm 0.09) \times 10^{-6}$	$(18 \pm 8 \pm 3 \pm 1) \times 10^{-5}$	$-0.96 \pm 0.37 \pm 0.04$

To be compared with
$A_{CP}(K^+\pi^-) = -0.25 \pm 0.07 \pm 0.02$





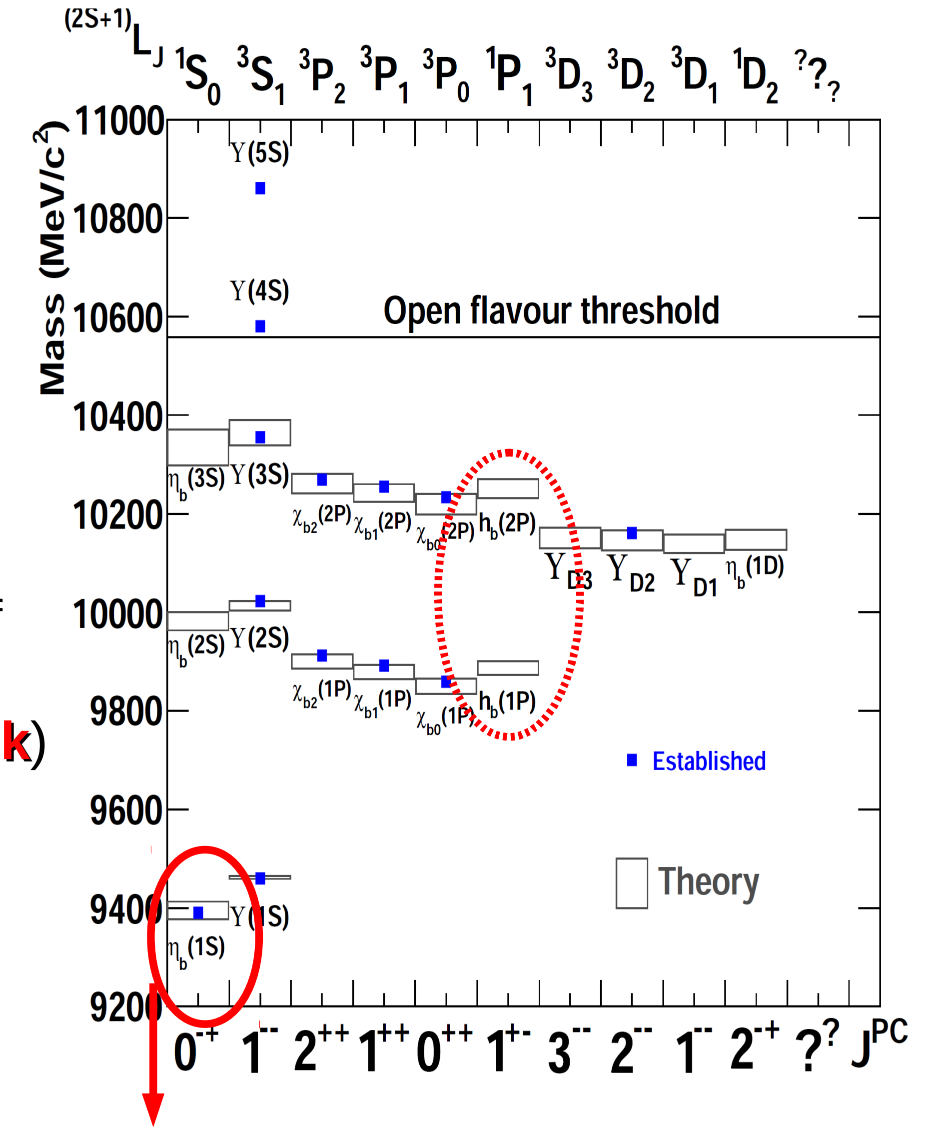


Bottomonium Spectroscopy

- **Bottomonium ($b\bar{b}$) radiative transitions with $\gamma \to e^+e^-$**

The $b\bar{b}$ Spectrum: Introduction

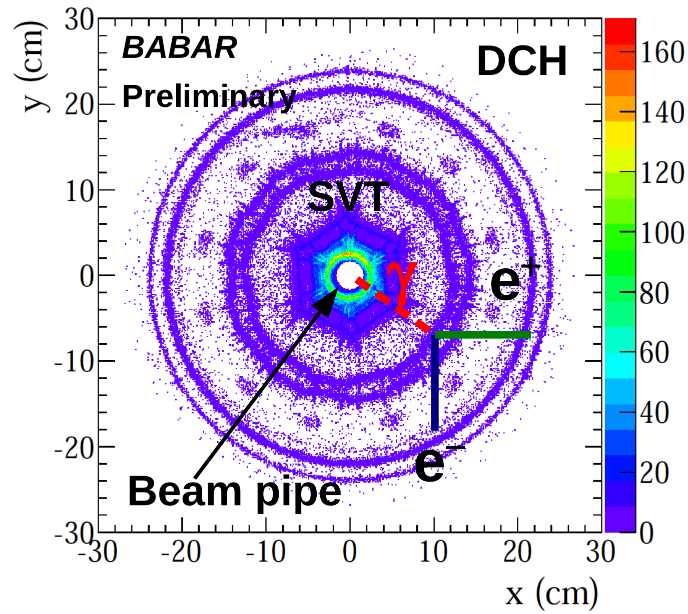
- Studies of $b\bar{b}$ (bottomonium) and $c\bar{c}$ (charmonium) bound states provide insight about inter-quark forces
- Searches of predicted states (**Not discussed here**)
  - Discovery and confirmation of the bottomonium ground state (L=0,S=0) η_b(1S) after 30 years of hunting
  - Searches of the h_b(1P) state to understand hyperfine mass-splitting of P-wave states
- Study of radiative transitions (**This talk**)
  - Measurement of electric (E1) and magnetic (M1) transition rates
  - Better understanding of model-dependencies of inter-quark potential
  - Useful spectroscopic studies of mass measurements



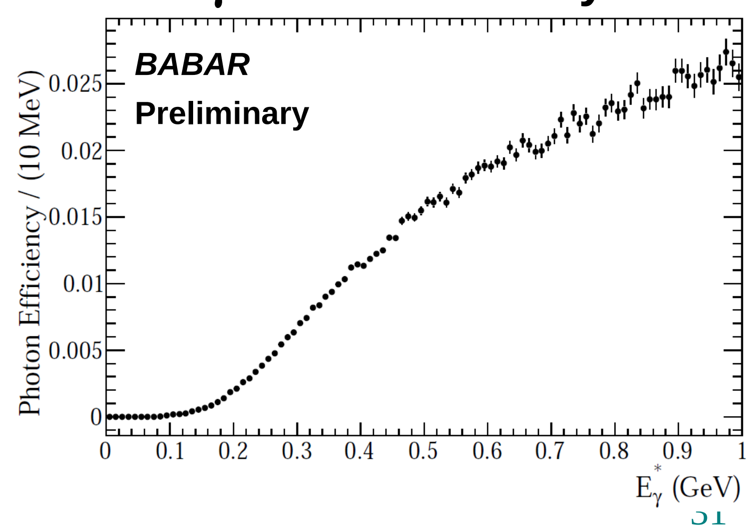
PRL 101, 071801 (2008)

$b\bar{b}$ transitions using $\gamma\to e^+e^-$: Motivation

- Bottomonia radiative transitions well described by effective potential models (non-relativistic)
- Higher-order relativistic and model-dependent effects may play substantial role in suppressed radiative transitions (e.g. E1 $\Upsilon(3S)\to\gamma\chi_{bJ}(1P)$ and "hindered" M1 $\Upsilon(nS)\to\gamma\eta_b(n'S)$)
- Doppler broadening and detector resolution (EMC) may lead to unresolved radiated photon energies from different transitions
- Want to separate the individual contributions for more precise mass-splitting measurements
- Use converted photons ($\gamma\to e^+e^-$) in detector material
- Pros: lower resolution (~5MeV) than EMC detected γ (~25MeV)
- Cons: decreased efficiency (0.1 – 2.5%)

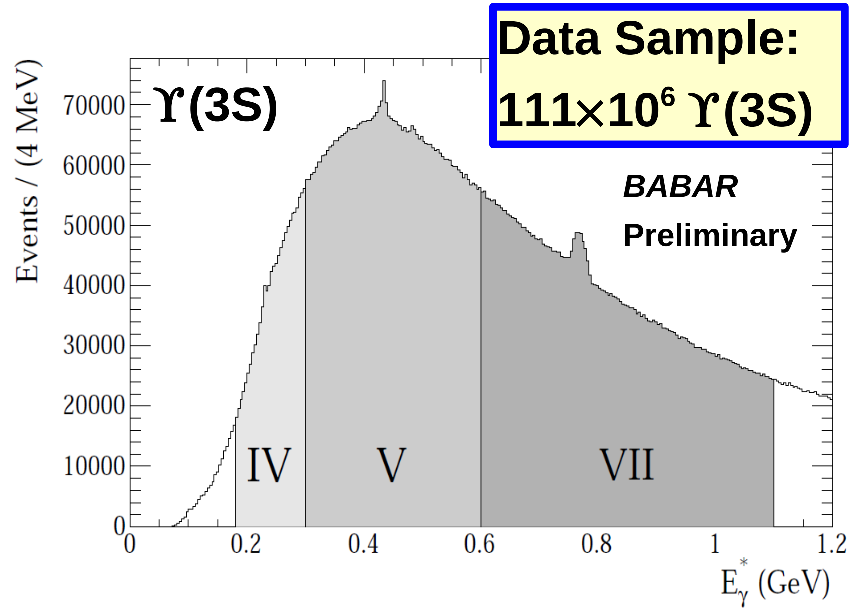


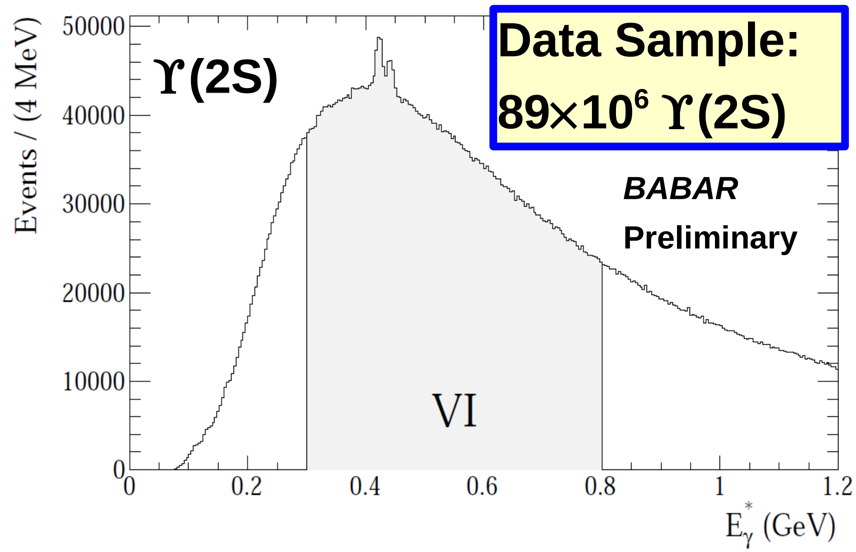
$\gamma\to e^+e^-$ efficiency



$b\bar{b}$ transitions using $\gamma\rightarrow e^+e^-$: Strategy

- Selection
  - N_{tracks} and distribution ($|\cos(\theta_{thrust})|$) consistent with a multi-hadron event
  - Good photon conversion candidate: χ^2 fit, $m(e^+e^-)$, ρ_γ and π^0 veto
- Fit to CM photon energy spectrum (E^*_γ) in four different regions
  - IV. $\Upsilon(3S)$: $180 < E^*_\gamma < 300$ MeV.
    - $\chi_{bJ}(2P)\rightarrow\gamma\Upsilon(2S)$
  - V. $\Upsilon(3S)$: $300 < E^*_\gamma < 600$ MeV.
    - $\Upsilon(3S)\rightarrow\gamma\chi_{bJ}(1P)$ and $\Upsilon(3S)\rightarrow\gamma\eta_b(2S)$
  - VII. $\Upsilon(3S)$: $600 < E^*_\gamma < 1100$ MeV.
    - $\chi_{bJ}(2P)\rightarrow\gamma\Upsilon(1S)$ and $\Upsilon(3S)\rightarrow\gamma\eta_b(1S)$
  - VI. $\Upsilon(2S)$: $300 < E^*_\gamma < 800$ MeV.
    - $\chi_{bJ}(1P)\rightarrow\gamma\Upsilon(1S)$ and $\Upsilon(2S)\rightarrow\gamma\eta_b(1S)$





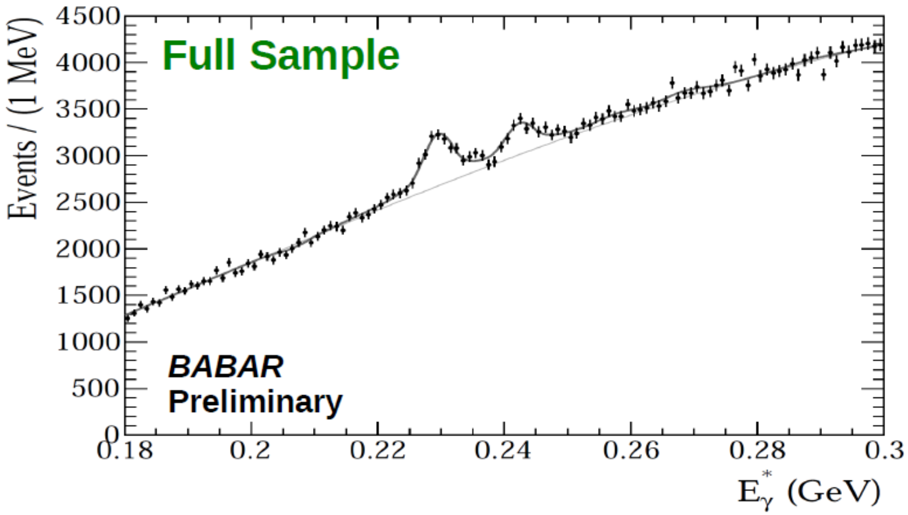
$b\bar{b}$ transitions using $\gamma \rightarrow e^+e^-$: Results (I)

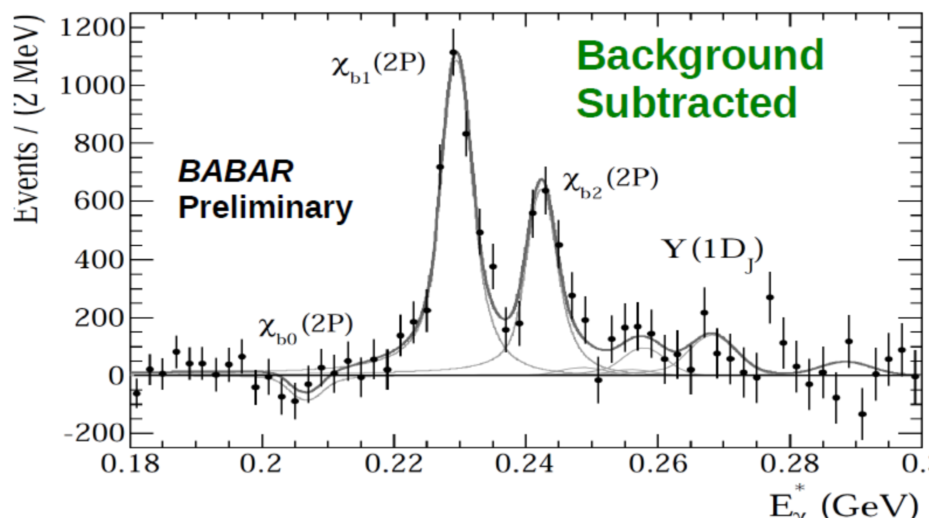
arXiv: 1104.5254
Accepted by PRD

Data sample:
$111\times10^6\ \Upsilon(3S)$

Region IV. $\Upsilon(3S)$: 180 < E^*_γ < 300 MeV

- Measurement of $\chi_{bJ}(2P)\rightarrow\gamma\Upsilon(2S)$ transitions (J = 1,2 **most precise!**)
- Potentially sensitive to D-wave $b\bar{b}$ states (6): $\Upsilon(1D_J)\rightarrow\gamma\chi_{bJ}(1P)$





Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%) *BABAR*	CUSB	CLEO
$\chi_{b0}(2P)\rightarrow\gamma\Upsilon(2S)$	205.0	-347 ± 209	0.105	$-4.7\pm2.8^{+0.7}_{-0.8}\pm0.5\ (<2.8)$	3.6 ± 1.6	<5.2
$\chi_{b1}(2P)\rightarrow\gamma\Upsilon(2S)$	229.7	4294 ± 251	0.152	$18.9\pm1.1\pm1.2\pm1.8$	13.6 ± 2.4	21.1 ± 4.5
$\chi_{b2}(2P)\rightarrow\gamma\Upsilon(2S)$	242.3	2462 ± 243	0.190	$8.3\pm0.8\pm0.6\pm1.0$	10.9 ± 2.2	9.9 ± 2.7

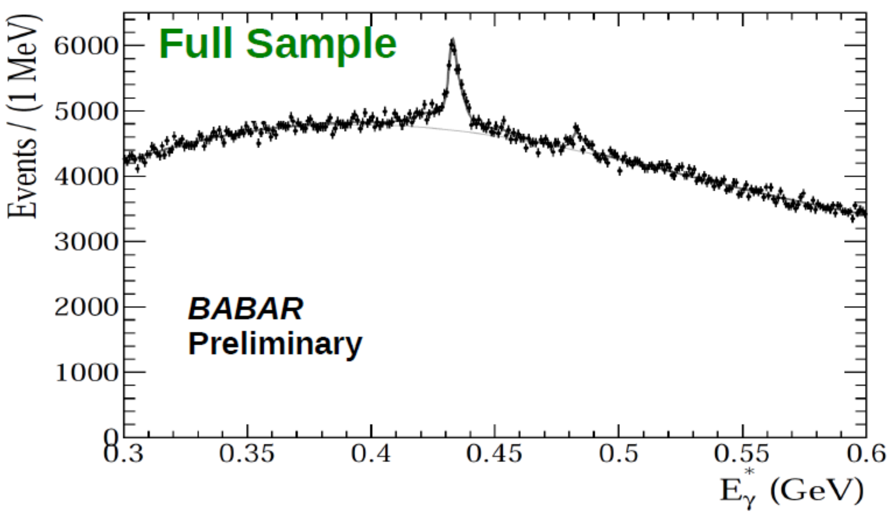
$b\bar{b}$ transitions using $\gamma\to e^+e^-$: Results (II)

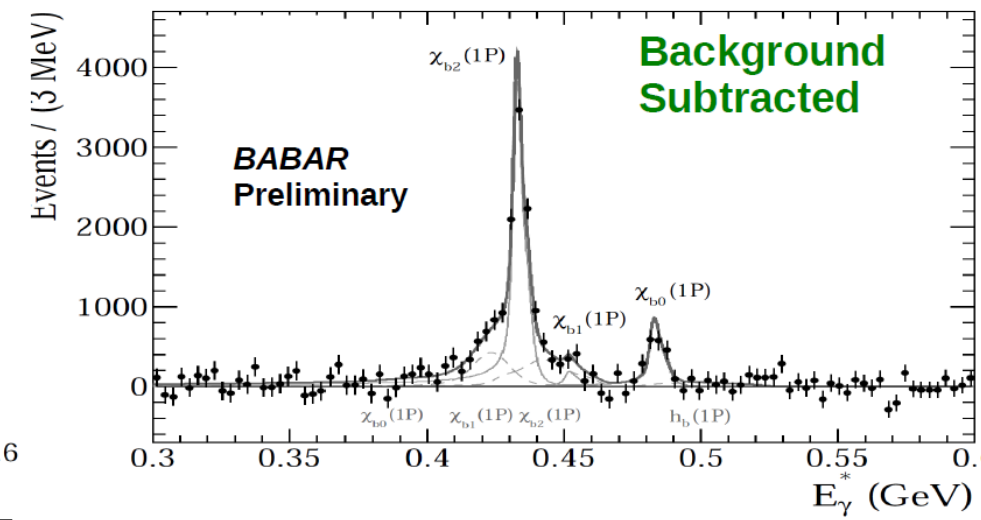
arXiv: 1104.5254
Accepted by PRD

Data sample:
$111\times10^6\,\Upsilon(3S)$

Region V. $\Upsilon(3S)$: $300 < E^*_\gamma < 600$ MeV

- Measurement of $\Upsilon(3S)\to\gamma\chi_{bJ}(1P)$ and $\Upsilon(3S)\to\gamma\eta_b(2S)$ transitions
- Complicated: Overlaps with $\chi_{bJ}(1P)\to\gamma\Upsilon(1S)$. Many ways to produce $\chi_{bJ}(1P)$
- $\Upsilon(3S)\to\gamma\eta_b(2S)$ in $335 < E^*_\gamma < 375$ MeV. BF $< 1.9\times10^{-3}$ at 90% CL





Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction ($\times10^{-3}$) *BABAR*	CLEO
$\Upsilon(3S)\to\gamma\chi_{b2}(1P)$	433.1	9699 ± 318	0.794	$10.5\pm0.3^{+0.7}_{-0.6}$	7.7 ± 1.3
$\Upsilon(3S)\to\gamma\chi_{b1}(1P)$	452.2	483 ± 315	0.818	$0.5\pm0.3^{+0.2}_{-0.1}$ (<1.0)	1.6 ± 0.5
$\Upsilon(3S)\to\gamma\chi_{b0}(1P)$	483.5	2273 ± 307	0.730	$2.7\pm0.4\pm0.2$	3.0 ± 1.1

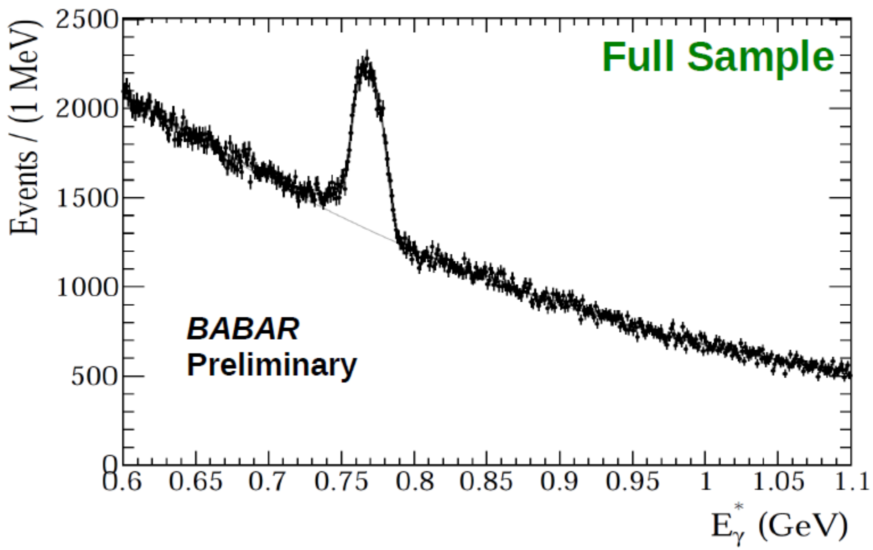
$b\bar{b}$ transitions using $\gamma\to e^+e^-$: Results (III)

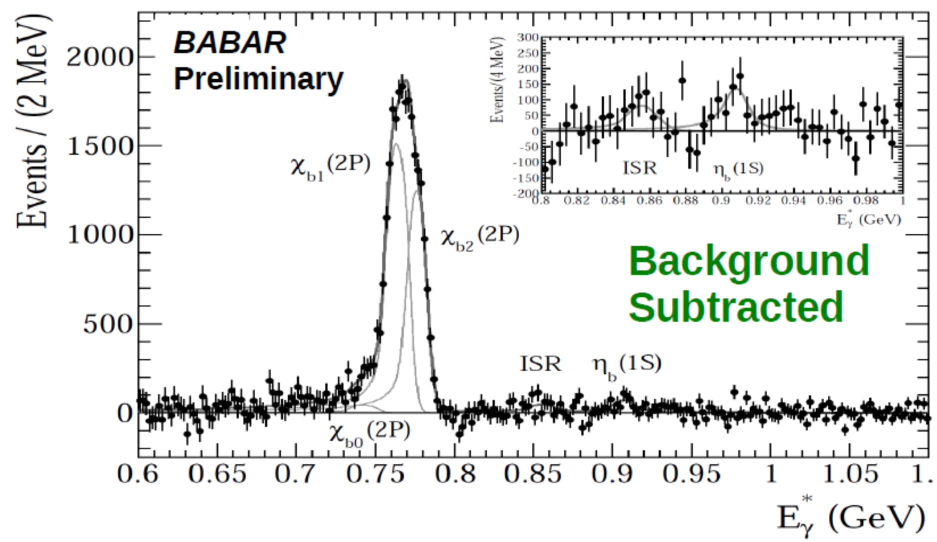
arXiv: 1104.5254
Accepted by PRD

Data sample:
$111\times10^6\,\Upsilon(3S)$

Region VII. $\Upsilon(3S)$: $600 < E^*_\gamma < 1100$ MeV

- Measurement of $\chi_{bJ}(2P)\to\gamma\Upsilon(1S)$ and $\Upsilon(3S)\to\gamma\eta_b(1S)$ transitions
- Most precise measurement of BF($\chi_{b1,2}(2P)\to\gamma\Upsilon(1S)$)
- BF($\Upsilon(3S)\to\gamma\eta_b(1S)$): ~2.7σ significance (including systematics)





Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%) *BABAR*	CUSB	CLEO
$\chi_{b0}(2P)\to\gamma\Upsilon(1S)$	742.7	469^{+260}_{-259}	1.025	$0.7\pm0.4^{+0.2}_{-0.1}\pm0.1$ (<1.2)	<1.9	<2.2
$\chi_{b1}(2P)\to\gamma\Upsilon(1S)$	764.1	14965^{+381}_{-383}	1.039	$9.9\pm0.3^{+0.5}_{-0.4}\pm0.9$	7.5 ± 1.3	10.4 ± 2.4
$\chi_{b2}(2P)\to\gamma\Upsilon(1S)$	776.4	11283^{+384}_{-385}	1.056	$7.0\pm0.2\pm0.3\pm0.9$	6.1 ± 1.2	7.7 ± 2.0
$\Upsilon(3S)\to\gamma\eta_b(1S)$	$907.9\pm2.8\pm0.9$	933^{+263}_{-262}	1.388	$0.058\pm0.016^{+0.014}_{-0.016}$ (<0.085)	-	-

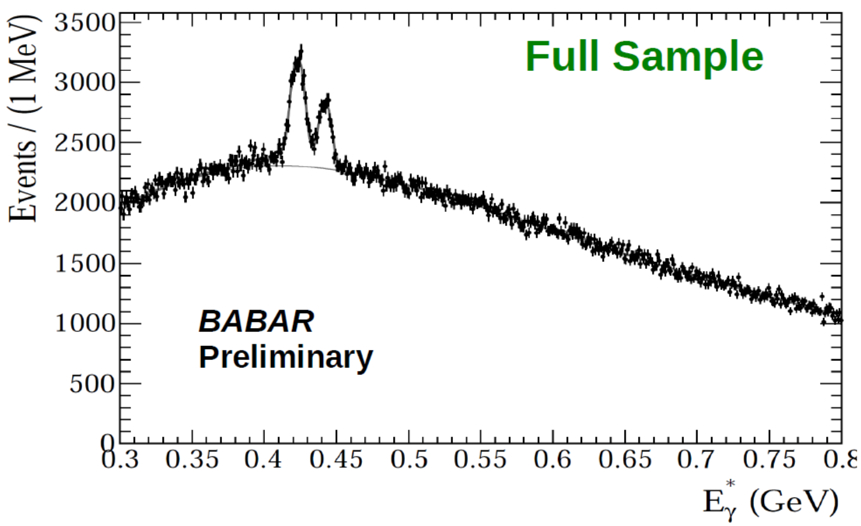
$b\bar{b}$ transitions using $\gamma \to e^+e^-$: Results (IV)

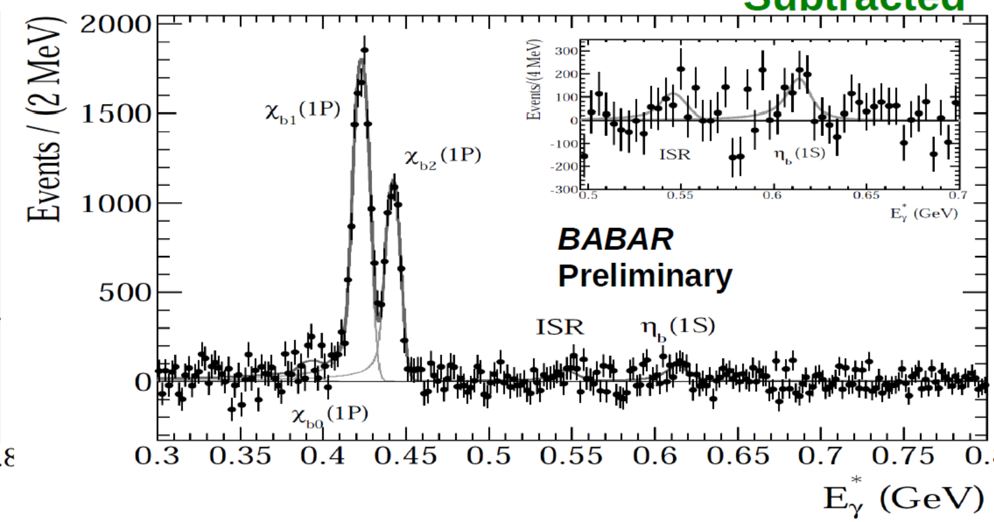
arXiv: 1104.5254
Accepted by PRD

Data sample:
$89\times10^6\ \Upsilon(2S)$

Region VI. $\Upsilon(2S)$: $300 < E^*_\gamma < 800$ MeV

- Measurement of $\chi_{bJ}(1P)\to\gamma\Upsilon(1S)$ and $\Upsilon(2S)\to\gamma\eta_b(1S)$ transitions
- Most precise measurement of BF($\chi_{b1,2}(1P)\to\gamma\Upsilon(1S)$)
- BF($\Upsilon(2S)\to\gamma\eta_b(1S)$): ~1.7σ significance (including systematics)





Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%) *BABAR*	CB	CUSB	CLEO
$\chi_{b0}(1P)\to\gamma\Upsilon(1S)$	391.5	391 ± 267	0.496	$2.2\pm1.5^{+1.0}_{-0.7}\pm0.2\ (<4.6)$	<5	<12	1.7 ± 0.4
$\chi_{b1}(1P)\to\gamma\Upsilon(1S)$	423.0	12604 ± 285	0.548	$34.9\pm0.8\pm2.2\pm2.0$	34 ± 7	40 ± 10	33.0 ± 2.6
$\chi_{b2}(1P)\to\gamma\Upsilon(1S)$	442.0	7665^{+270}_{-272}	0.576	$19.5\pm0.7^{+1.3}_{-1.5}\pm1.0$	25 ± 6	19 ± 8	18.5 ± 1.4
$\Upsilon(2S)\to\gamma\eta_b(1S)$	$613.7^{+3.0+0.7}_{-2.6-1.1}$	1109 ± 348	1.050	$0.11\pm0.04^{+0.07}_{-0.05}\ (<0.21)$	-	-	-

$b\bar{b}$ transitions using $\gamma \to e^+e^-$: Results (V)

Decay	BABAR (%)	Theory (%)
$\mathcal{B}(\chi_{b0}(2P) \to \gamma \Upsilon(2S))$	(< 2.9)	1.27
$\mathcal{B}(\chi_{b1}(2P) \to \gamma \Upsilon(2S))$	19.1 ± 2.3	20.2
$\mathcal{B}(\chi_{b2}(2P) \to \gamma \Upsilon(2S))$	8.2 ± 1.4	10.1
$\mathcal{B}(\chi_{b0}(2P) \to \gamma \Upsilon(1S))$	(< 1.2)	0.96
$\mathcal{B}(\chi_{b1}(2P) \to \gamma \Upsilon(1S))$	9.9 ± 1.1	11.8
$\mathcal{B}(\chi_{b2}(2P) \to \gamma \Upsilon(1S))$	$7.1^{+1.0}_{-0.9}$	5.3
$\mathcal{B}(\chi_{b0}(1P) \to \gamma \Upsilon(1S))$	(< 4.6)	3.2
$\mathcal{B}(\chi_{b1}(1P) \to \gamma \Upsilon(1S))$	36.2 ± 2.8	46.1
$\mathcal{B}(\chi_{b2}(1P) \to \gamma \Upsilon(1S))$	$20.2^{+1.6}_{-1.8}$	22.2

PRD 38, 279 (1988)

arXiv: 1104.5254
Accepted by PRD

- BF(χ_{bJ}(nP)$\to\gamma$Y(mS)) from E^*_γ spectrum. Some of the most precise measurements
- Theoretical predictions in reasonable agreements with our measurements

- Y(3S)$\to\gamma\chi_{bJ}$(1P): J = 1 suppressed w.r.t J = 0,2
- Expected small transition rate ⇒ relativistic corrections
- No good agreement with any particular model

Source	$J=0$	$J=1$	$J=2$
BABAR	55 ± 10	< 22	216 ± 25
Moxhay-Rosner	25	25	150
Grotch *et al.*	114	3.4	194
Daghighian-Silverman	16	100	650
Fulcher	10	20	30
Lähde	150	110	40
Ebert *et al.*	27	67	97

Conclusions

- *BABAR* last data collected in 2008, but collaboration still very active
- Many results (over 100 ongoing analyses) on a variety of topics
- *BABAR* continues to produce interesting and competitive results
- Stay tuned for more results

Backup