

Search for CP Violation in B mixing and decay at *BABAR*

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On behalf of the  **BABAR** collaboration

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Outline

- New **preliminary** results for **direct CP violation** searches
 - First observation of $B \rightarrow b_1 h$ decays
 - First observation of $B^+ \rightarrow K^+ K^- \pi^+$ decay
 - Update on $B^+ \rightarrow \{\eta, \eta', \omega\} h^+$
 - Update on $B^\pm \rightarrow h^\pm \pi^0$ and $B^0 \rightarrow \pi^0 \pi^0$
- All asymmetries **statistically dominated**
- All results use the **full Runs 1-5 BaBar dataset** (~ 383 million $B\bar{B}$ pairs)
- See **J. Burke** talk for additional details, including **branching fractions**
- See **M. Bomben** and **J. Thompson** talks for **β charm(less) measurements**
- Other topic-related BaBar results:
 - CP violation observed in $B^0 \rightarrow \eta' K^0$
 - Observation of CP violation in $B^0 \rightarrow \pi^+ \pi^-$ and $B^0 \rightarrow K^+ \pi^-$

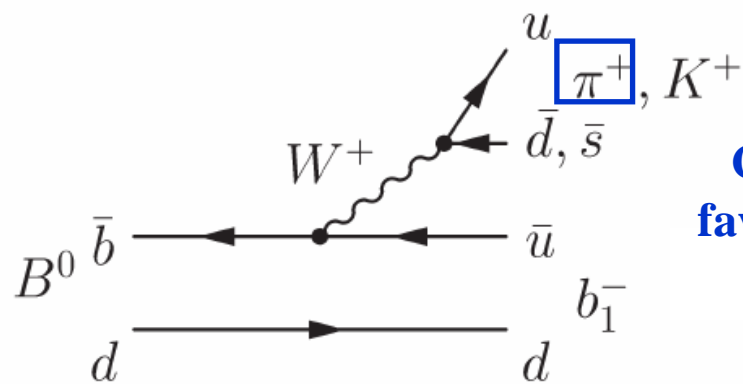
Charmless
B decays

Charmless B decays

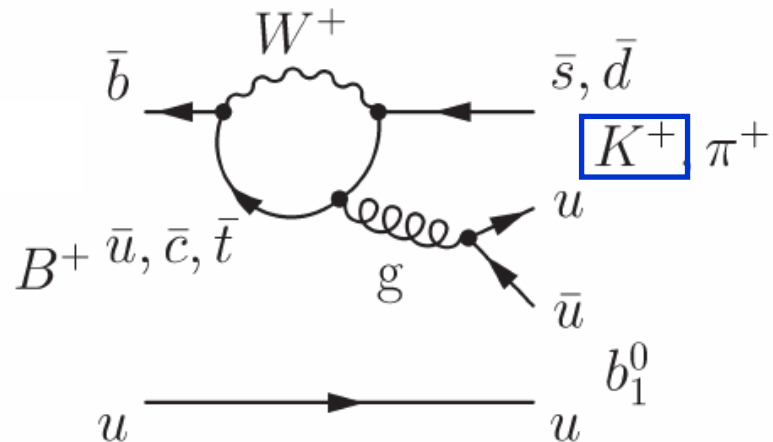
- Proceed through $b \rightarrow u$ tree diagrams
 $b \rightarrow \{s,d\}$ penguin diagrams
- Trees and penguins can have similar amplitudes
 - Interferences potentially lead to significant direct CP violation
 - Search for New Physics processes
- Measurements add constraints on the CKM parameters
- **Phenomenological interest:** comparing measurements allow one to test/improve theoretical calculations and validate models
- More details about the analysis procedures can be found in backup slides and in other EPS BaBar presentations

$B \rightarrow b_1 h$

- Several decay searched: $B^+ \rightarrow b_1^0 h^+$, $B^0 \rightarrow b_1^\mp \pi^\pm$, $B^0 \rightarrow b_1^- K^+$
 - First observation/evidence depending on the channel
 - $B^0 \rightarrow a_1^+ \pi^-$ observed in 2006; evidences for $B^+ \rightarrow (a_1 \pi)^+$



CKM
favoured



- b_1 reconstructed through $b_1 \rightarrow \omega (\rightarrow \pi^+ \pi^- \pi^0) \pi$, $\pi^0 \rightarrow \gamma \gamma$
Assumption: $BF(b_1 \rightarrow \omega \pi) = 100\%$
- Extended maximum likelihood fits (b_1 and ω masses included)
 - Signal (truth-matched and misreconstructed), $q\bar{q}$ and charm B-bkg, charmless B-bkg species

B → b₁h: direct CPV parameters

- Charge asymmetries

$$A_{ch} = \frac{\Gamma^- - \Gamma^+}{\Gamma^- + \Gamma^+}$$

Net charge of the final state f or charge of the flavor-associated particle (K, π)

with $\Gamma^\pm \equiv \Gamma(B \rightarrow f^\pm)$

- Two additional measured quantities for $B^0 \rightarrow b_1^\mp \pi^\pm$:

C and ΔC
Flavor-dependent direct CPV **Dilution** ← **Aiming at testing SM prediction**

$$A_{ch} = \frac{\Gamma(\bar{B}^0 \rightarrow b_1^+ \pi^-) + \Gamma(B^0 \rightarrow b_1^+ \pi^-) - [\Gamma(\bar{B}^0 \rightarrow b_1^- \pi^+) + \Gamma(B^0 \rightarrow b_1^- \pi^+)]}{\Gamma(\bar{B}^0 \rightarrow b_1^+ \pi^-) + \Gamma(B^0 \rightarrow b_1^+ \pi^-) + [\Gamma(\bar{B}^0 \rightarrow b_1^- \pi^+) + \Gamma(B^0 \rightarrow b_1^- \pi^+)]}$$

$$C + A_{ch} \Delta C = \frac{\Gamma(B^0 \rightarrow b_1^+ \pi^-) + \Gamma(B^0 \rightarrow b_1^- \pi^+) - [\Gamma(\bar{B}^0 \rightarrow b_1^+ \pi^-) + \Gamma(\bar{B}^0 \rightarrow b_1^- \pi^+)]}{\Gamma(B^0 \rightarrow b_1^+ \pi^-) + \Gamma(B^0 \rightarrow b_1^- \pi^+) + [\Gamma(\bar{B}^0 \rightarrow b_1^+ \pi^-) + \Gamma(\bar{B}^0 \rightarrow b_1^- \pi^+)]}$$

$$\Delta C + A_{ch} C = \frac{\Gamma(\bar{B}^0 \rightarrow b_1^- \pi^+) + \Gamma(B^0 \rightarrow b_1^+ \pi^-) - [\Gamma(B^0 \rightarrow b_1^- \pi^+) + \Gamma(\bar{B}^0 \rightarrow b_1^+ \pi^-)]}{\Gamma(\bar{B}^0 \rightarrow b_1^- \pi^+) + \Gamma(B^0 \rightarrow b_1^+ \pi^-) + [\Gamma(B^0 \rightarrow b_1^- \pi^+) + \Gamma(\bar{B}^0 \rightarrow b_1^+ \pi^-)]}$$

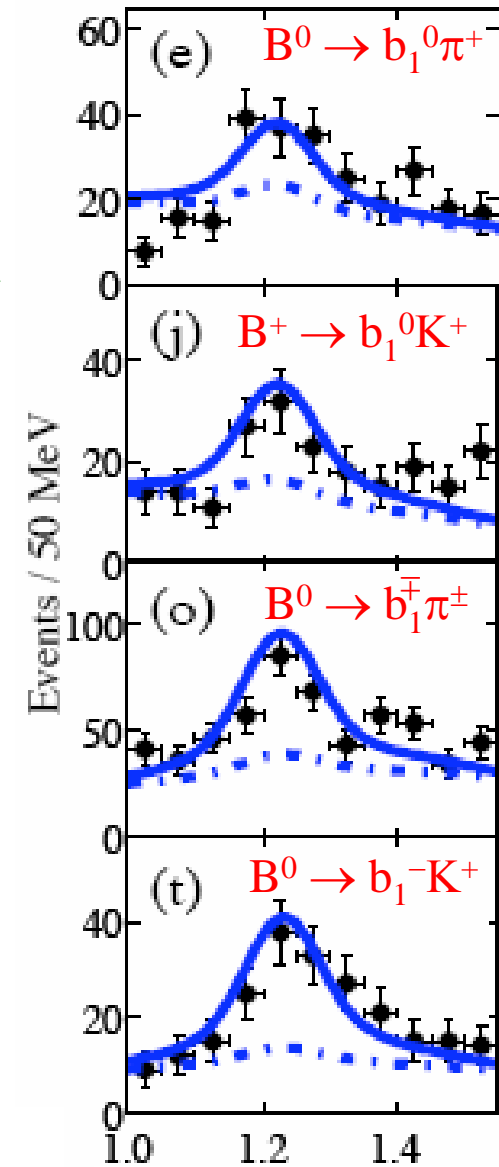
Systematics

- **Charge-dependent effects**
(interactions, reconstruction, PID)
→ bias -0.010 ± 0.005 for modes with K
 0.000 ± 0.005 for modes with π
- **B-bkg asymmetry**: ~ 0.01 for all modes
- **Systematics on C and ΔC completely dominated by uncertainties assigned from possible bias observed in toy studies**
- Systematics from tagging and PDF parameterizations much smaller

A_{ch}

C
 ΔC

Signal-enriched plots
(likelihood cut)
 b_1 mass plots



BaBar preliminary

Results

$$A_{\text{ch}}(\text{B}^+ \rightarrow \text{b}_1^0 \pi^+) = 0.05 \pm 0.16 \pm 0.02$$

$$A_{\text{ch}}(\text{B}^+ \rightarrow \text{b}_1^0 \text{K}^+) = -0.46 \pm 0.20 \pm 0.02$$

$$A_{\text{ch}}(\text{B}^0 \rightarrow \text{b}_1^- \text{K}^+) = -0.07 \pm 0.12 \pm 0.02$$

$$A_{\text{ch}}(\text{B}^0 \rightarrow \text{b}_1^\mp \pi^\pm) = -0.05 \pm 0.10 \pm 0.02$$

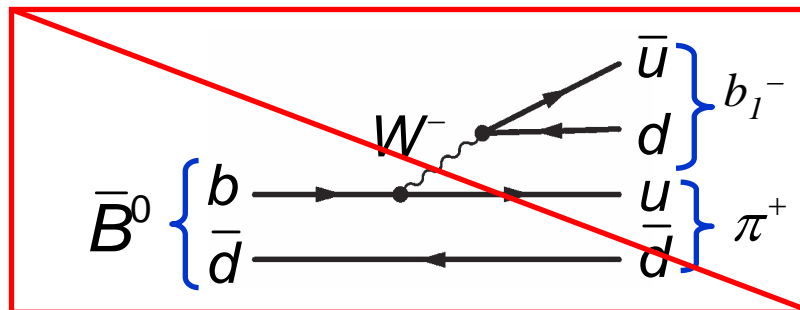
$$C(\text{B}^0 \rightarrow \text{b}_1^\mp \pi^\pm) = -0.21 \pm 0.23 \pm 0.05$$

No evidence for
direct CP-violating
asymmetries

$$\Delta C(\text{B}^0 \rightarrow \text{b}_1^\mp \pi^\pm) = -1.04 \pm 0.23 \pm 0.08$$

Consistent with the expected suppression of $\text{B}^0 \rightarrow \text{b}_1^+ \pi^-$:
weak axial vector current **odd** in G-Parity, b_1 **even**

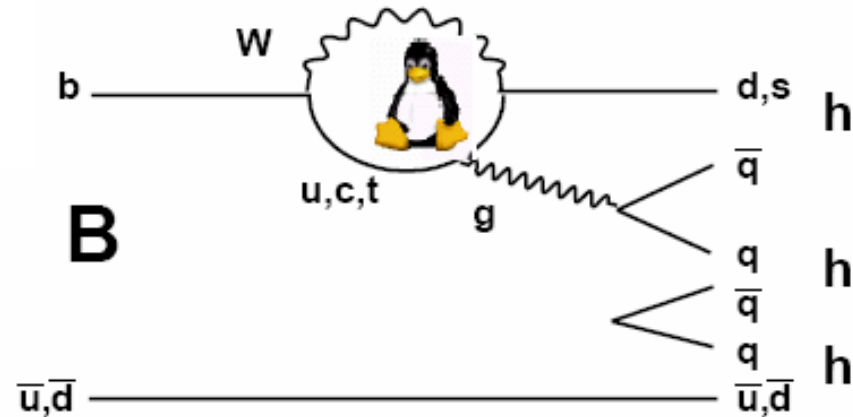
Experimental
BF: $(0 \pm 10)\%$



Forbidden!



- Main contribution from $b \rightarrow d$ penguin



- 3 body analysis

→ Extended maximum likelihood fit

Species: signal, continuum background,
 3 $B\bar{B}$ background classes → $\left\{ \begin{array}{l} K^+\pi^+\pi^-, K_S^0 K^+ \\ K^+K^-K^+, K^+K^- K_S^0, \bar{D}^0\pi^+ \\ \text{Other decays} \end{array} \right.$

→ Not a full Dalitz Plot (DP) analysis yet

→ DP dependence accounted for the inclusive branching fraction

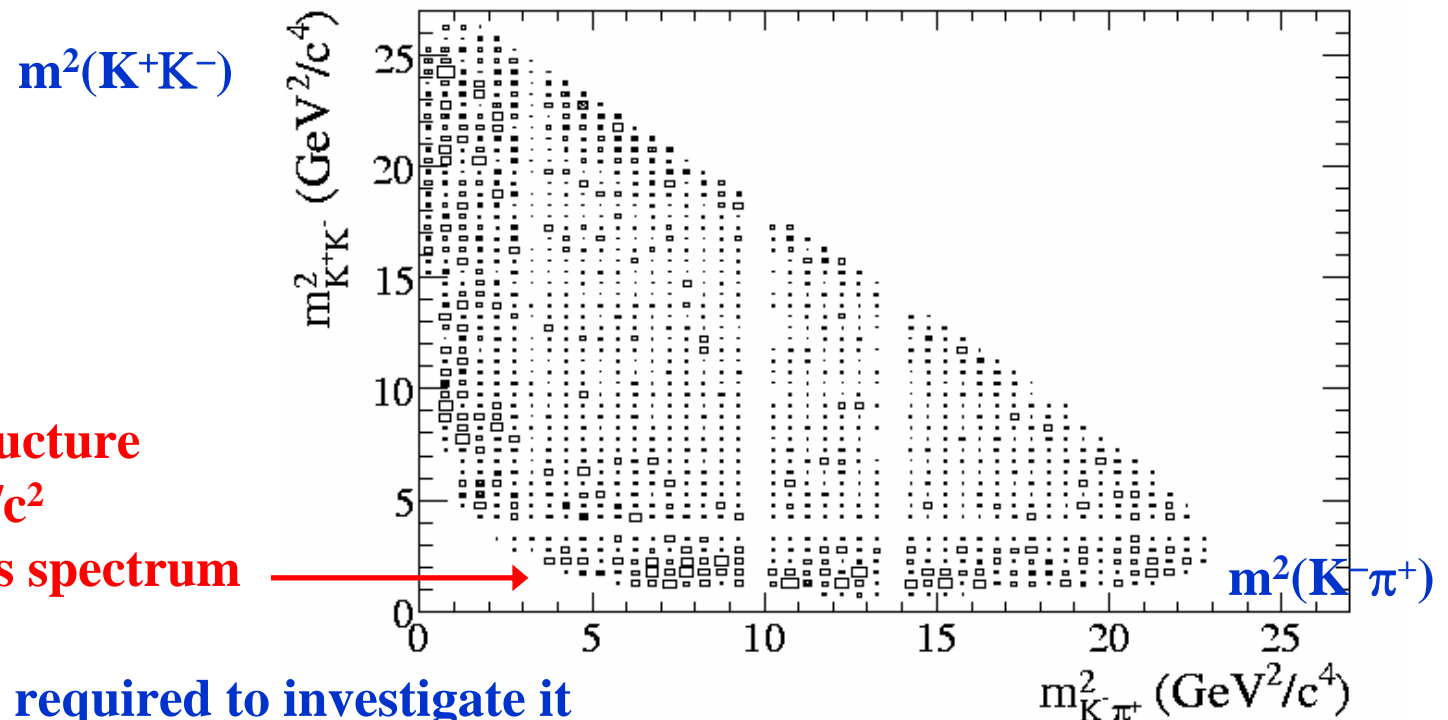
$B^+ \rightarrow K^+K^-\pi^+$ Charge Asymmetry

- Asymmetry computed by fitting separately B^- and B^+ samples
- Systematics dominated by **detector charge asymmetry (2%)** and **B-bkg contents uncertainty (1.5%)**

$$A_{ch} = \frac{\Gamma(B^- \rightarrow K^+K^-\pi^-) - \Gamma(B^+ \rightarrow K^+K^-\pi^+)}{\Gamma(B^- \rightarrow K^+K^-\pi^-) + \Gamma(B^+ \rightarrow K^+K^-\pi^+)} = \underline{-0.004 \pm 0.104 \pm 0.025}$$

No significant asymmetry

**Broad scalar structure
around $1.5 \text{ GeV}/c^2$
in the K^+K^- mass spectrum**



→ **Full DP** analysis required to investigate it

$B^+ \rightarrow \{\eta, \eta', \omega\} h^+$ Update

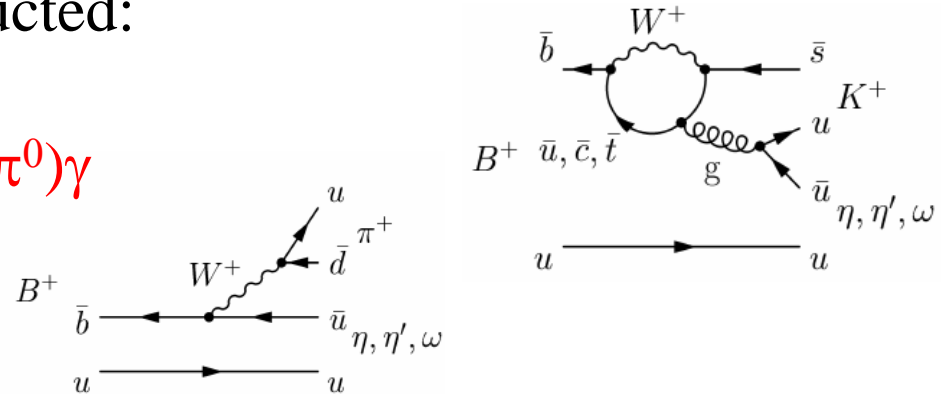
0706.3893 [hep-ex]
Submitted to PRD-RC

- Different decay chains reconstructed:

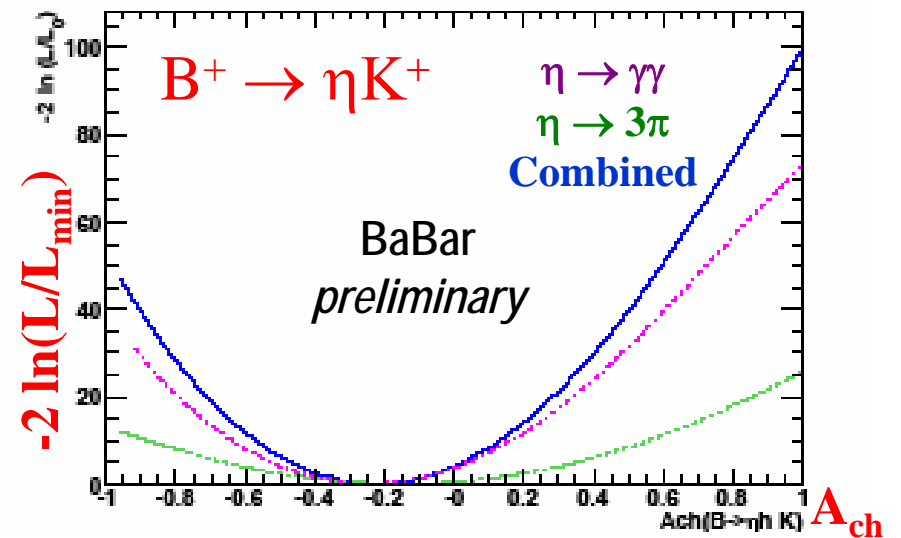
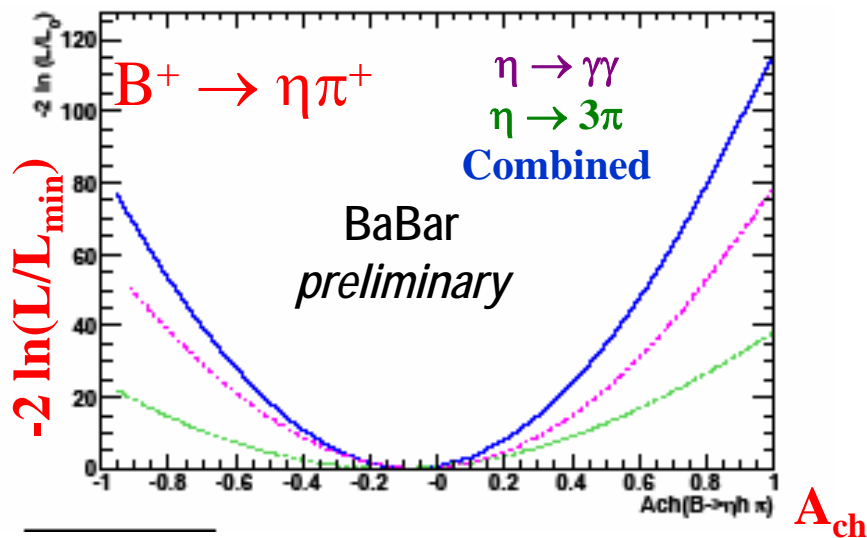
$$\eta \rightarrow \gamma\gamma \text{ and } \eta \rightarrow \pi^+\pi^-\pi^0$$

$$\eta' \rightarrow \pi^+\pi^-\pi^0 \text{ and } \eta' \rightarrow \rho^0(\rightarrow \pi^+\pi^0)\gamma$$

$$\omega \rightarrow \pi^+\pi^-\pi^0$$



- Extended maximum likelihood fit **separately** for each decay chain
- Likelihoods **combined** (+ systematics) \Rightarrow **charged asymmetries**
- All systematics lower than 1%



$B^+ \rightarrow \{\eta, \eta', \omega\}h^+$ Results

Charged asymmetry	Previous BaBar result	New BaBar result
$B^+ \rightarrow \eta\pi^+$	$-0.13 \pm 0.12 \pm 0.01$	$-0.08 \pm 0.10 \pm 0.01$
$B^+ \rightarrow \eta K^+$	$-0.20 \pm 0.15 \pm 0.01$	$-0.22 \pm 0.11 \pm 0.01$
$B^+ \rightarrow \eta'\pi^+$	$0.14 \pm 0.16 \pm 0.01$	$0.21 \pm 0.17 \pm 0.01$
$B^+ \rightarrow \eta'K^+$	$0.03 \pm 0.03 \pm 0.02$	$0.010 \pm 0.022 \pm 0.006$
$B^+ \rightarrow \omega\pi^+$	$-0.01 \pm 0.10 \pm 0.01$	$-0.02 \pm 0.08 \pm 0.01$
$B^+ \rightarrow \omega K^+$	$0.05 \pm 0.09 \pm 0.01$	$-0.01 \pm 0.07 \pm 0.01$

- No evidence for direct CP-violation charge asymmetry

(BaBar+Belle+Cleo)

- World average: A_{ch} for $B^+ \rightarrow \eta\pi^+$ (ηK^+) is negative and 2.3 (3.0) σ away from 0 whereas theoretical predictions are positive

$B^\pm \rightarrow h^\pm \pi^0$ and $B^0 \rightarrow \pi^0 \pi^0$ Updates

- Analysis similar to ICHEP2006
 - Merged π^0 s and γ conversions used to reconstruct events
- **Extended maximum likelihood fits**
 - Signal, continuum and B-background components
 - Simultaneous fit of the $B^\pm \rightarrow \pi^\pm \pi^0$ and $B^\pm \rightarrow K^\pm \pi^0$ species
- **Time-integrated CP asymmetry** in $B^0 \rightarrow \pi^0 \pi^0$ dominated by **B-bkg CP content** and **tagging**
- **Detector charge asymmetry better controlled** (control samples)
 - **dominant systematic error reduced** for the charged asymmetries
- Main other systematics: PDF parameterizations (ΔE and Fisher)

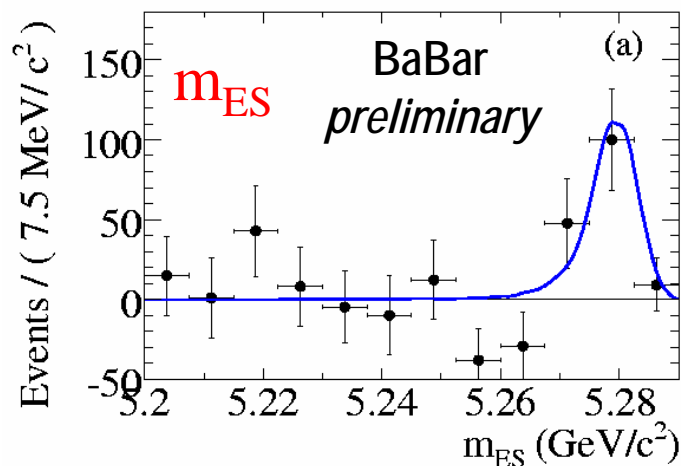
0707.2798 [hep-ex]
Submitted to PRD-RC

Results

$$C_{\pi^0\pi^0} = \frac{\Gamma(B^0 \rightarrow \pi^0\pi^0) - \Gamma(\bar{B}^0 \rightarrow \pi^0\pi^0)}{\Gamma(B^0 \rightarrow \pi^0\pi^0) + \Gamma(\bar{B}^0 \rightarrow \pi^0\pi^0)} \quad A_{h^+\pi^0} = \frac{\Gamma(B^- \rightarrow h^-\pi^0) - \Gamma(B^+ \rightarrow h^+\pi^0)}{\Gamma(B^- \rightarrow h^-\pi^0) + \Gamma(B^+ \rightarrow h^+\pi^0)}$$

Asymmetry	ICHEP 2006	EPS 2007
$C_{\pi^0\pi^0}$	$-0.33 \pm 0.36 \pm 0.05$	$-0.49 \pm 0.35 \pm 0.05$
$A_{\pi^+\pi^0}$	$-0.019 \pm 0.088 \pm 0.014$	$0.033 \pm 0.083 \pm 0.009$
$A_{K^+\pi^0}$	$0.016 \pm 0.041 \pm 0.012$	$0.030 \pm 0.039 \pm 0.010$

- Shifts in central values due to new data



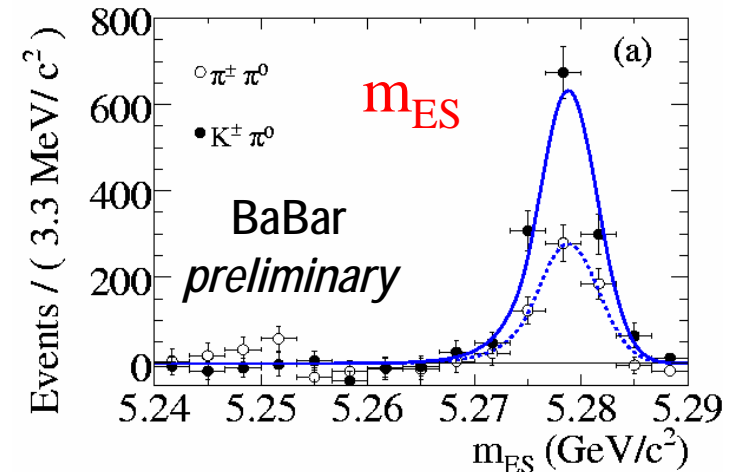
$B^0 \rightarrow \pi^0\pi^0$

sPlots: weighting technique

Simultaneously:

- **projection**
- **background suppression**

Nucl. Instrum. Meth. A
555, 356 (2005)



$B^0 \rightarrow h^+\pi^0$

Results

$$C_{\pi^0\pi^0} = \frac{\Gamma(B^0 \rightarrow \pi^0\pi^0) - \Gamma(\bar{B}^0 \rightarrow \pi^0\pi^0)}{\Gamma(B^0 \rightarrow \pi^0\pi^0) + \Gamma(\bar{B}^0 \rightarrow \pi^0\pi^0)} \quad A_{h^+\pi^0} = \frac{\Gamma(B^- \rightarrow h^-\pi^0) - \Gamma(B^+ \rightarrow h^+\pi^0)}{\Gamma(B^- \rightarrow h^-\pi^0) + \Gamma(B^+ \rightarrow h^+\pi^0)}$$

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Results used to improve constraints on α

Very different from the $K^+\pi^-$ asymmetry measured by BaBar

$$A_{K^+\pi^-} = -0.107 \pm 0.018^{+0.007}_{-0.004}$$

→ Color-suppressed tree and electroweak penguin amplitudes are important

M. Gronau and J. L. Rosner, Phys. Rev. D **71**, 074019 (2005); M. Gronau, Phys. Lett. B **627**, 82 (2005); M. Gronau and J. L. Rosner, Phys. Rev. D **59**, 113002 (1999); H. J. Lipkin, Phys. Lett. B **445**, 403 (1999).

Å. Buras *et al*, Phys. Rev. Lett. **92**, 101804 (2004); A. Buras *et al* Nucl. Phys. B **697**, 133 (2004).

Conclusions

- Several new/updated BaBar measurements of direct CP violation
 - First observations/evidence of the $B \rightarrow b_1 h$ modes
 - First observation of $B^+ \rightarrow K^+ K^- \pi^+$
 - Updates on $B^+ \rightarrow \{\eta, \eta', \omega\} h^+$ and $B^\pm \rightarrow h^\pm \pi^0$, $B^0 \rightarrow \pi^0 \pi^0$
- No new evidence for direct CP violation in charmless B-decays
- More results to be expected: new data & complex analysis techniques
- Experimental and theoretical improvements benefit from each other

- CP violation observed in $B^0 \rightarrow \eta' K^0$ PRL 98, 031801 (2007)

$$S = 0.58 \pm 0.10 \pm 0.03$$

$$C = -0.16 \pm 0.07 \pm 0.03$$

- Observation of CP violation in $B^0 \rightarrow \pi^+ \pi^-$ and $B^0 \rightarrow K^+ \pi^-$

$$S_{\pi\pi} = -0.60 \pm 0.11 \pm 0.03 \quad (5.2\sigma)$$

$$C_{\pi\pi} = -0.21 \pm 0.09 \pm 0.02 \quad (2.2\sigma)$$

$$A_{K\pi} = -0.107 \pm 0.018^{+0.007}_{-0.004} \quad (5.5\sigma)$$

hep-ex/0703016
Submitted to PRL

BACKUP

- Statistical tool allowing the distribution of a variable (x) for a given fitted species (n) to be computed from the other variable PDFs
- An sWeight is assigned to each event e :

$${}_s W_n(\vec{y}_{\text{event } e}) = \frac{\sum_{j=1}^{N_S \text{ species}} \text{Cov}_{nj} f_j(\vec{y}_{\text{event } e})}{\sum_{k=1}^{N_S \text{ species}} N_k f_k(\vec{y}_{\text{event } e})}$$

with N_S species, the f_j s being the PDFs from the fit w/o x and the \vec{y} vector containing the values of the other variables for the event

- sWeights verify $\sum_{\text{events } e} {}_s W_n(\vec{y}_{\text{event } e}) = N_n$ with N_n the number of events in species n
- The histogram of the variable x for species n weighted by the corresponding sWeights provides an estimation of the distribution for this variable.

Common Analysis Techniques

- Discrimination variables

- ✓ Energy-substituted mass $m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$

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

- ✓ Event shape * = e⁺e⁻ CM frame

- q \bar{q} (q={u, d, s, c}) dominant background

- cuts + Fisher/NN for further discrimination

- PID by combining info from SVT, DCH and DRC

- EMC used for neutral particles and electrons

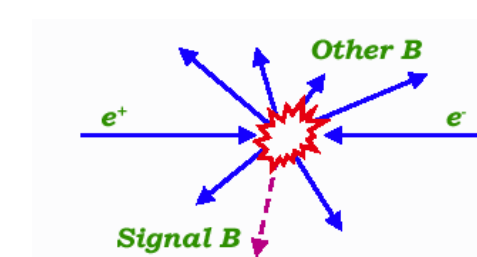
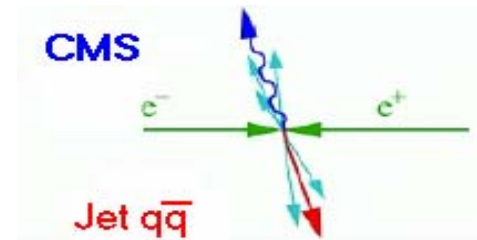
- Extended maximum likelihood fit:

$$L = \exp\left(-\sum_{\text{species } k} n_k\right) \prod_{\text{events } i} \left[\sum_{\text{species } k} n_k P_k(\vec{x}_i; \vec{\alpha}_k) \right]$$

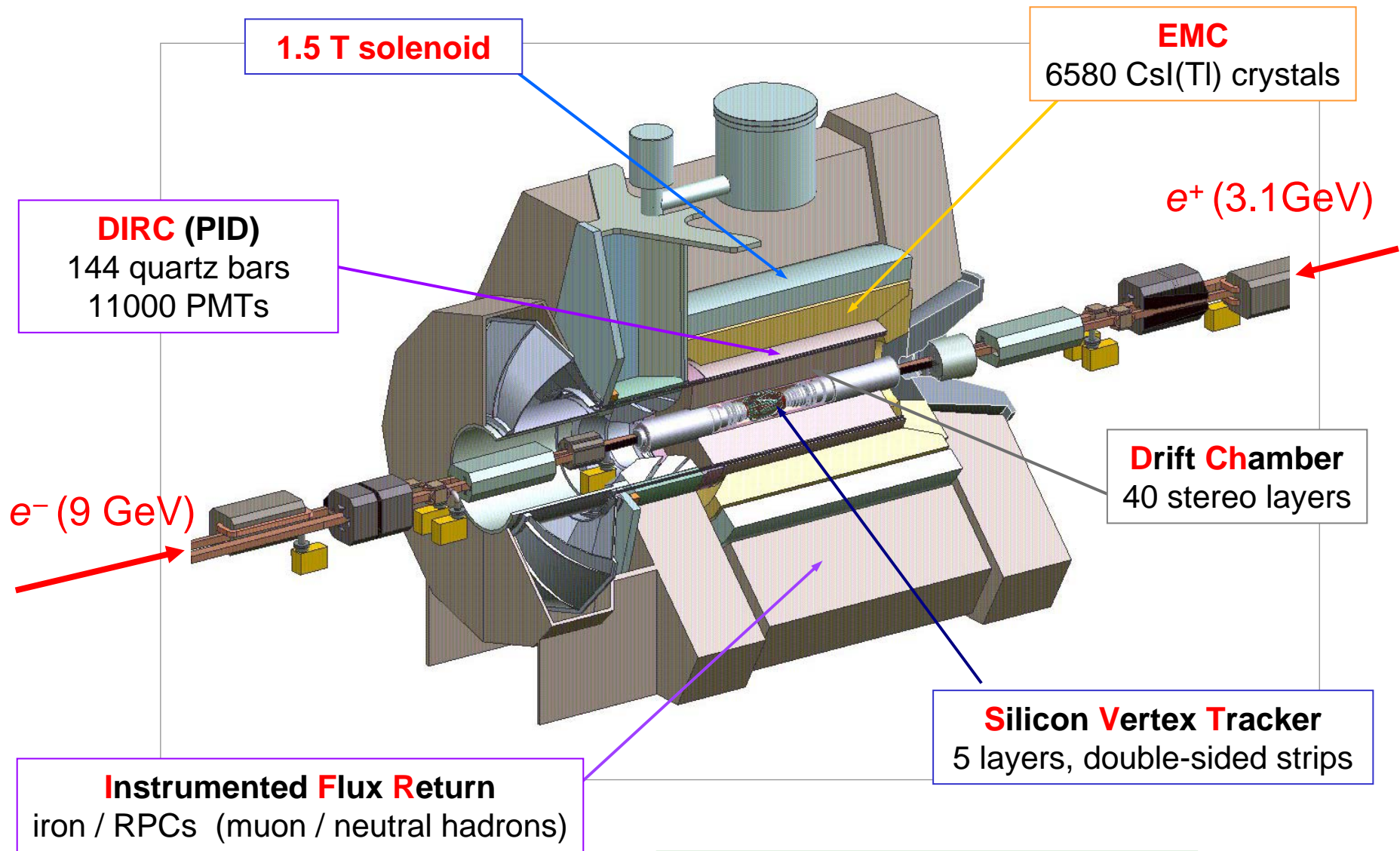
Number of events
Parameters

PDFs
Variables

7 mutually exclusive and complete tagging categories

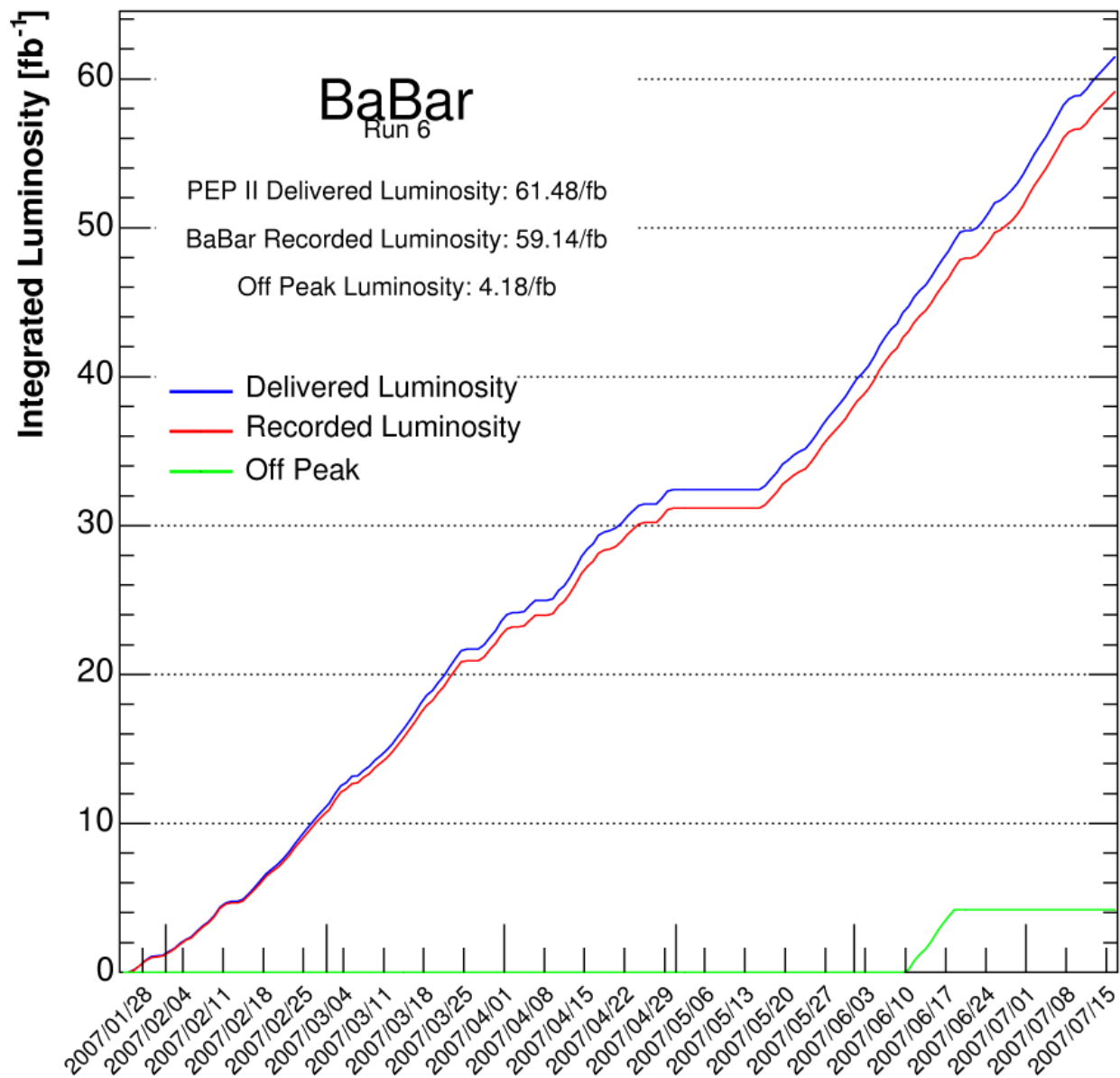


The *BABAR* detector



Performances

As of 2007/07/18 00:00



- Runs 1-5
(these analysis):
~ 383 millions B pairs

- Run 6:
more than 64 millions
additional B pairs

+ ~ 9.5% offpeak data
[40 MeV below Y(4S)]