Rare B Decays

Adrian Bevan*

KEK Topical Conference 6
(Feb 6th-8th 2007)

~~Note: L. Silvestrini is giving a theory talk on this subject on Thursday.~~

Queen Mary
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*From the BaBar Collaboration

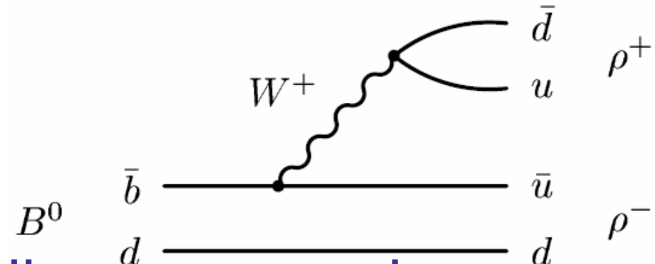
Overview

- General Motivation
- The KEK-B/PEP-II and the Belle/BaBar detectors
- Results
  - (Semi-)Leptonic and radiative rare B decays
    - $B \to l\upsilon$,
    - $B \to K^*ll$
    - $B \to d\gamma$ transitions
  - Hadronic charmless rare B decays
    - $K^*\rho$
    - $a_1\rho$
    - $\rho\pi$
    - Searches for direct CP violation
- Summary

General Motivation

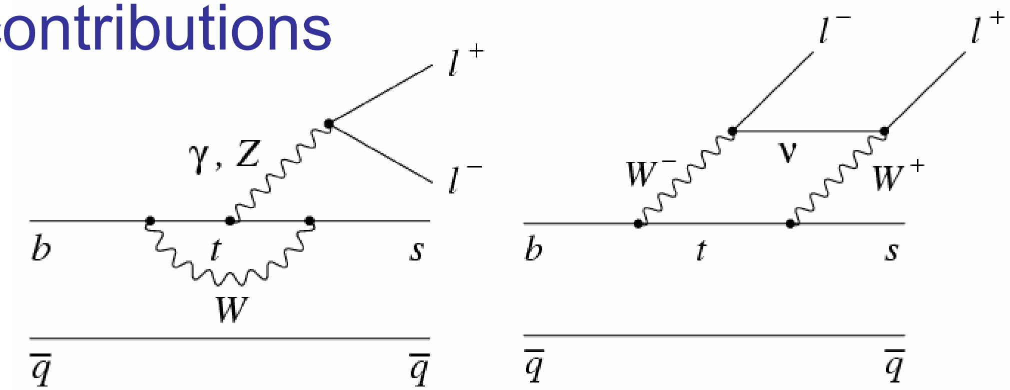
Large Branching Fractions

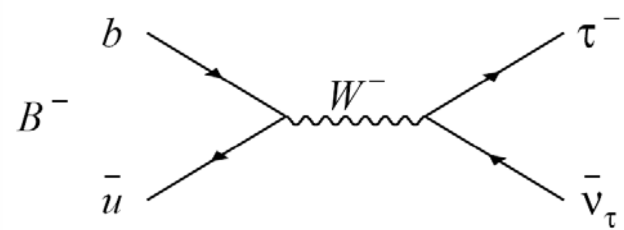
- Tree level contributions are understood well



- Higher order diagrams can be more difficult to calculate, and can be sensitive to new heavy particles (H^+, SUSY particles etc.). Many rare decays only have higher order contributions

Small Branching Fractions (Rare)





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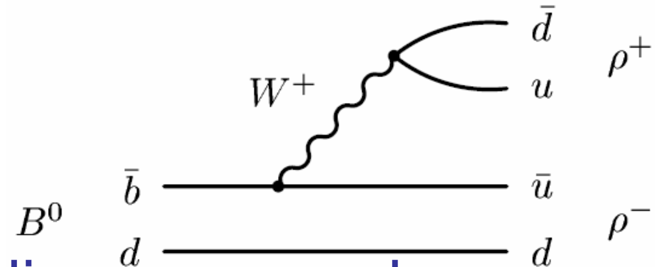

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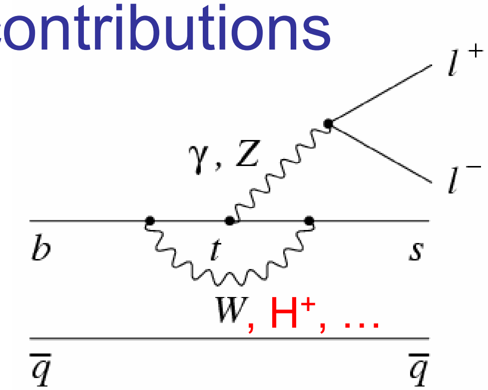
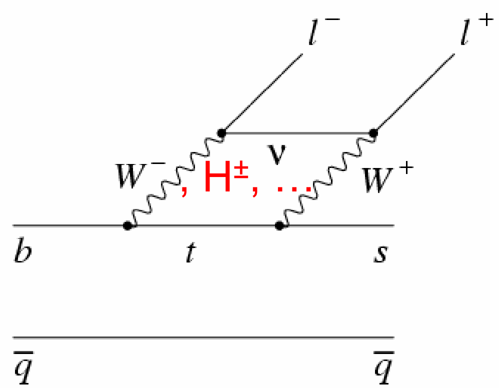
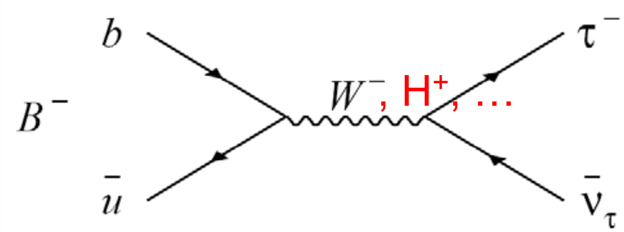
Small Branching Fractions (Rare)

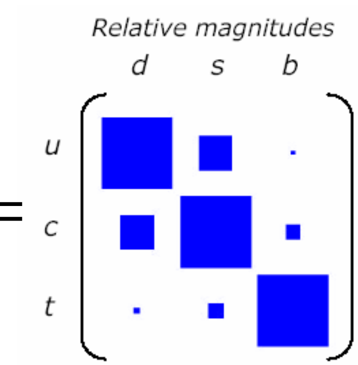






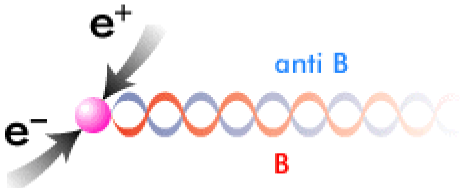
  - Provide useful tests of loop calculations.
  - Could help us look beyond the SM.
  - CKM matrix helps us estimate hierarchy of related decays.

$V_{CKM} =$

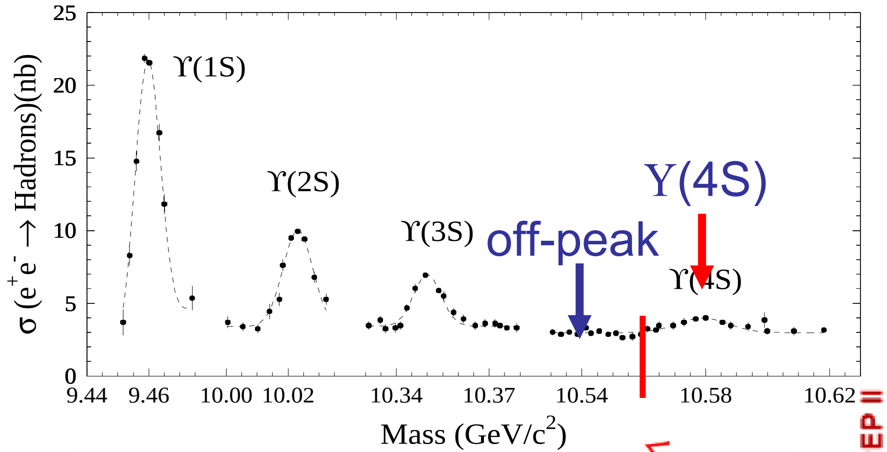


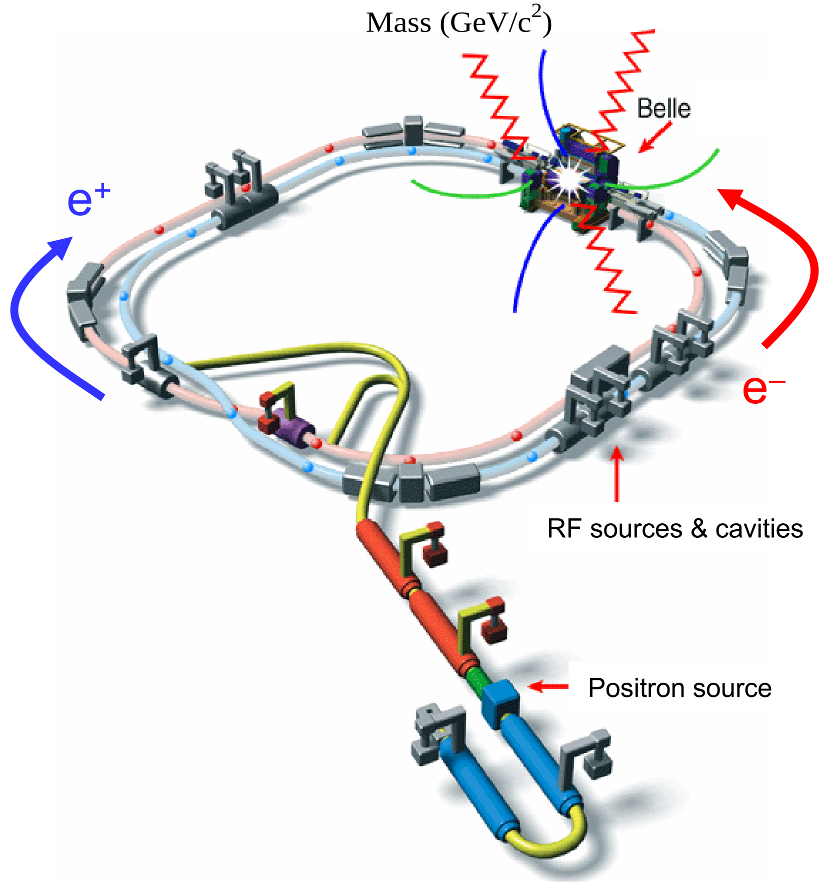
KEK-B/PEP-II

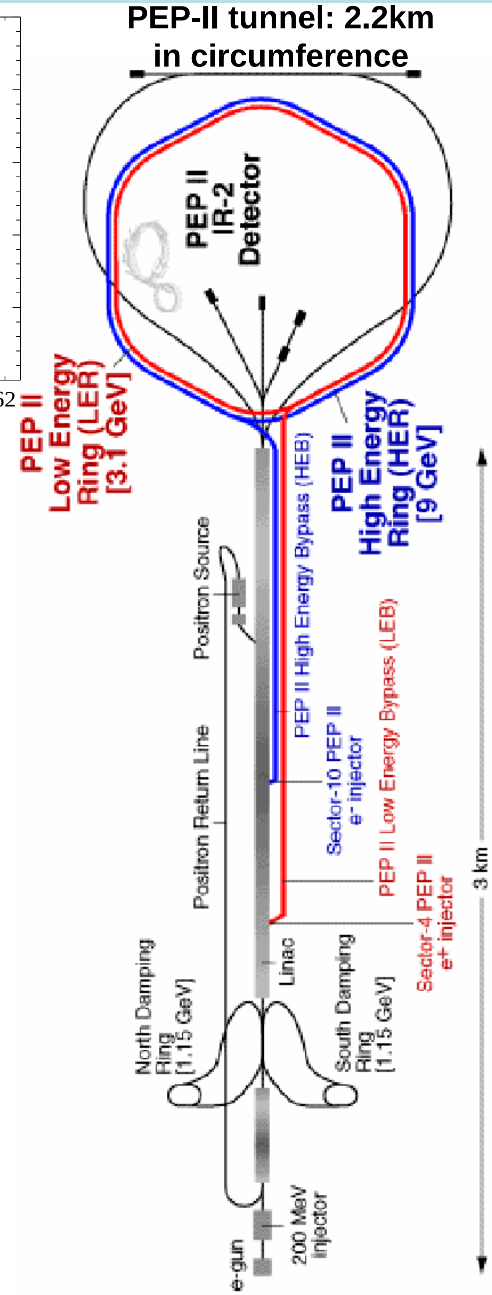
- Asymmetric energy e^+e^- collider
- Study decay of B meson pairs.



- Record data at the Υ(4S) ~90% of the time.
- Run below the $b\bar{b}$ production threshold for background studies.

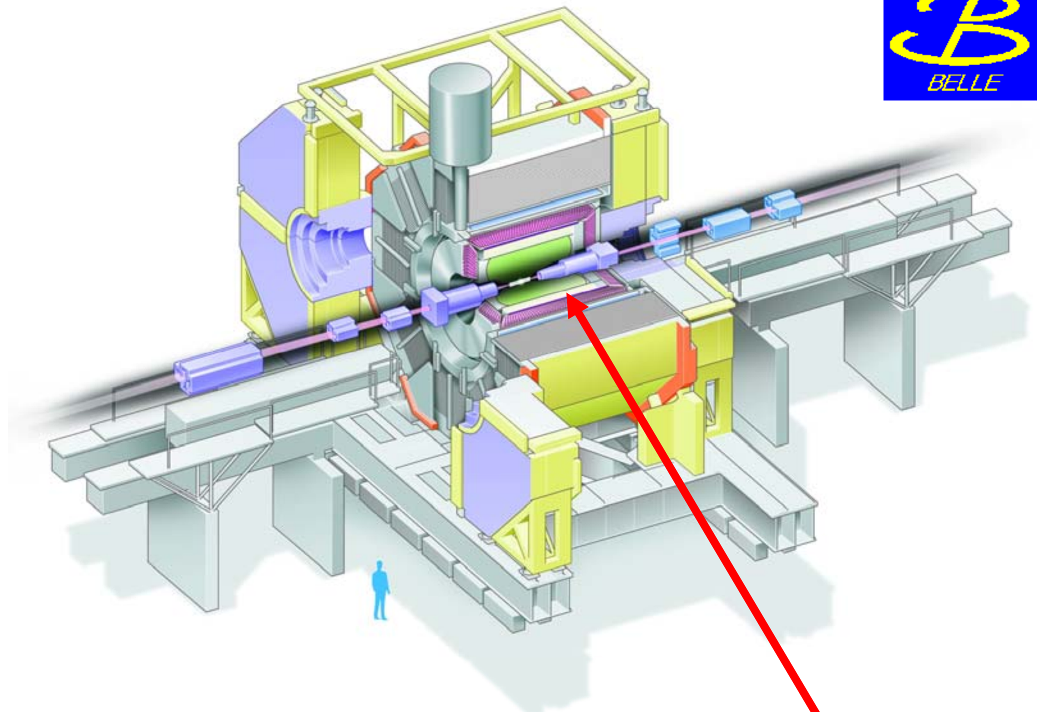


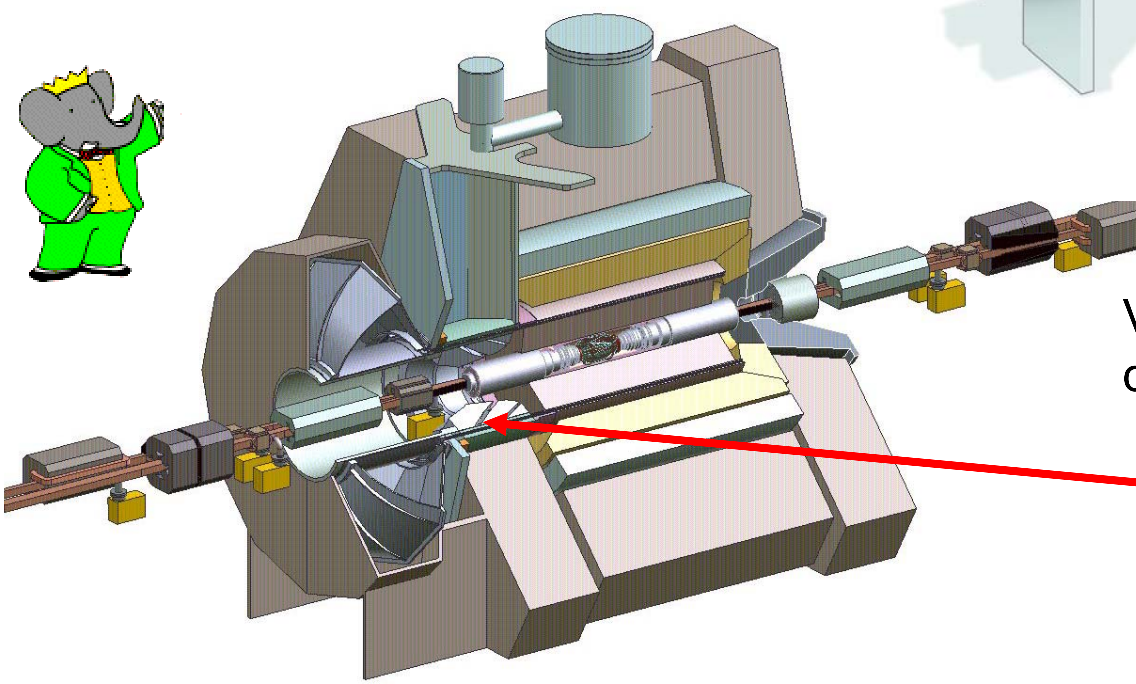




BaBar and Belle detectors

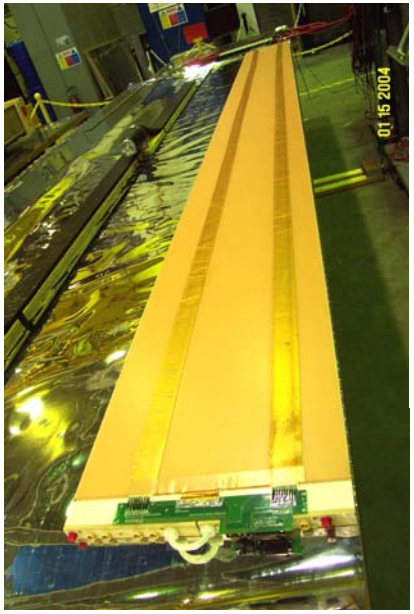
- BaBar recently upgraded its muon system and DCH electronics.

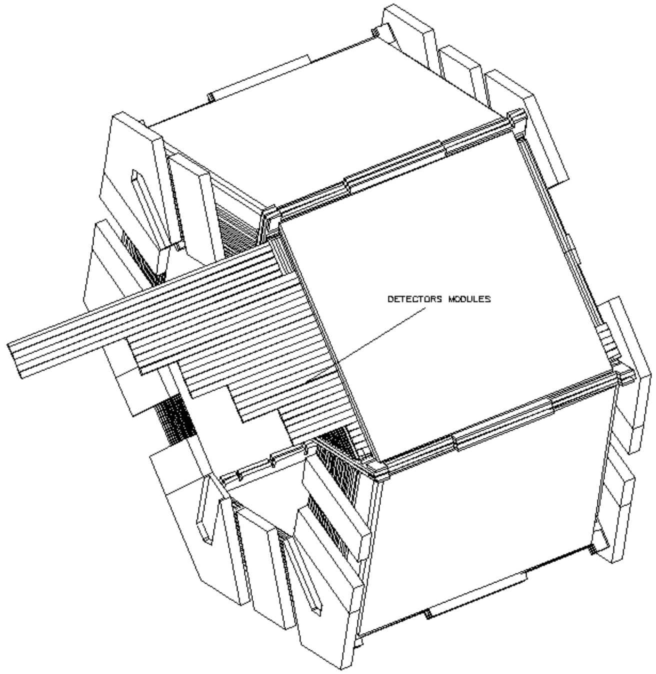


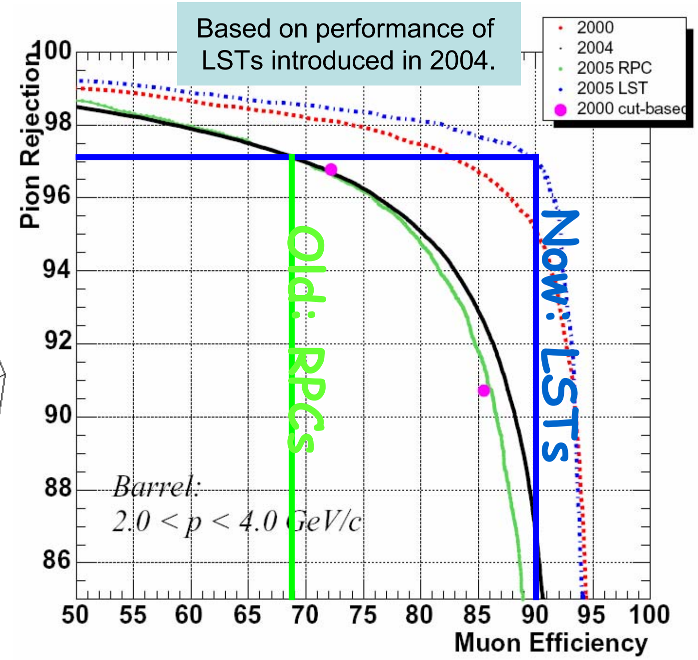


Very similar detectors. Main difference is PID:
Belle: Aerogel Cherenkov & ToF
BaBar: DIRC

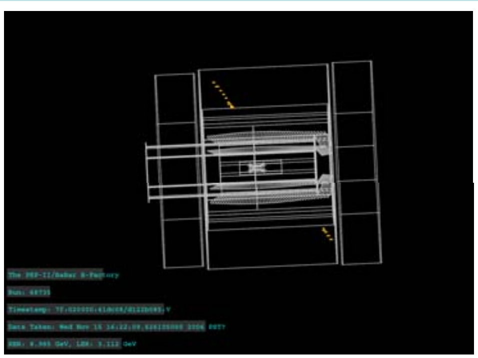
IFR upgrade to LSTs

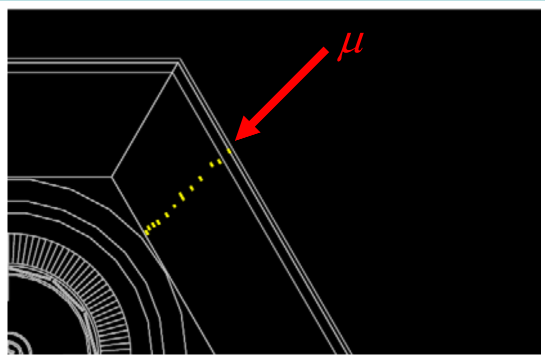


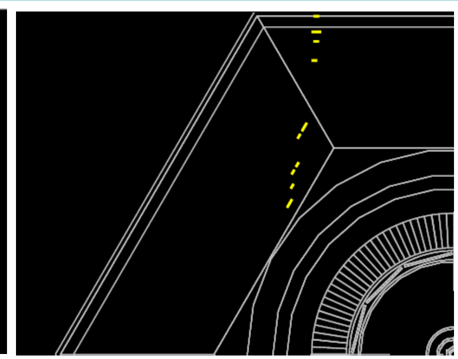




Bottom & top LST sextants installed summer 2004.
Remaining LST sextants installed autumn 2006.
The fully upgraded LST system recorded its first cosmic rays November 2006

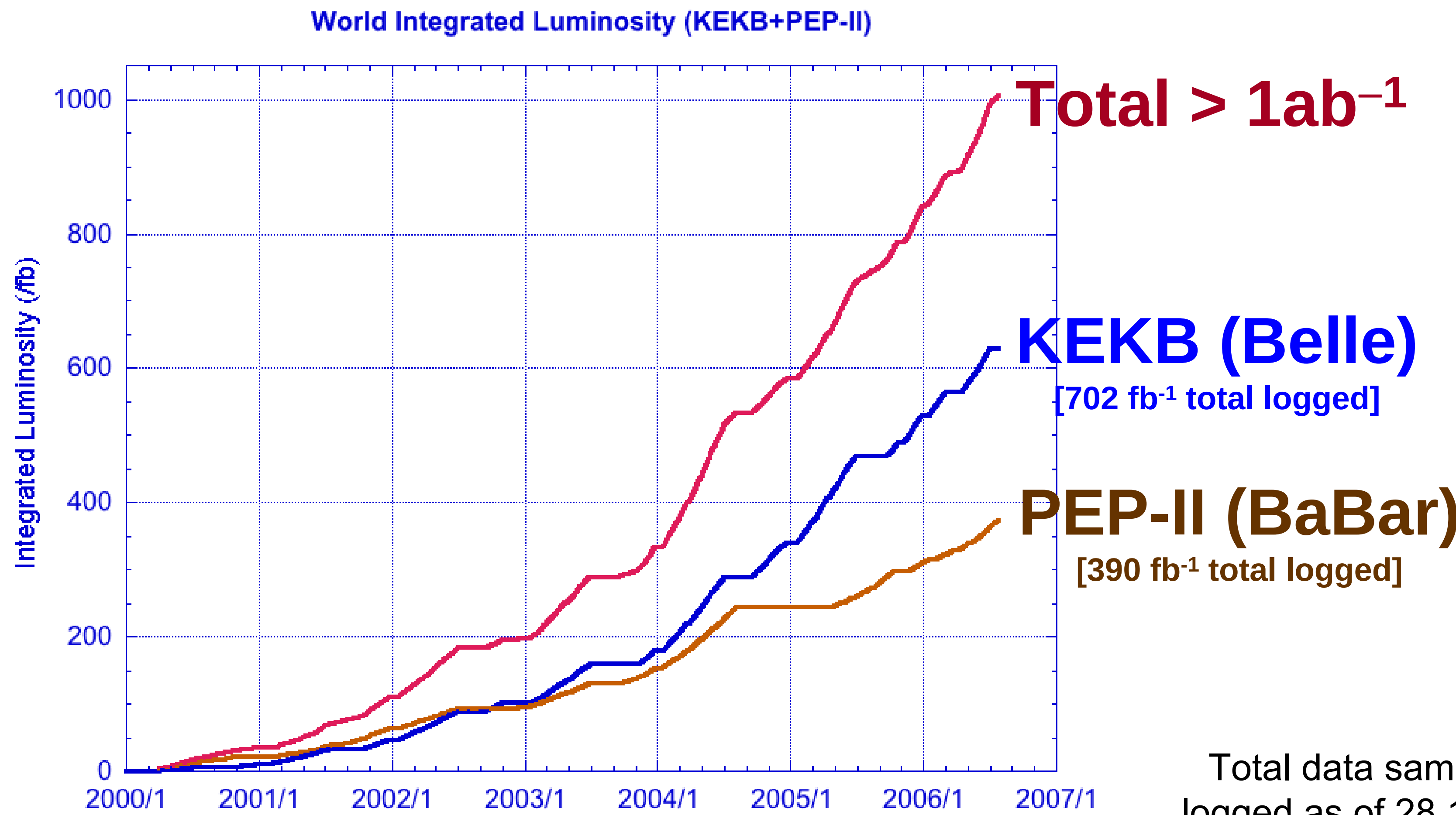






Integrated luminosity

- B-factories have recorded over 10^9 B-pairs
- Dataset will double by the end of the program.



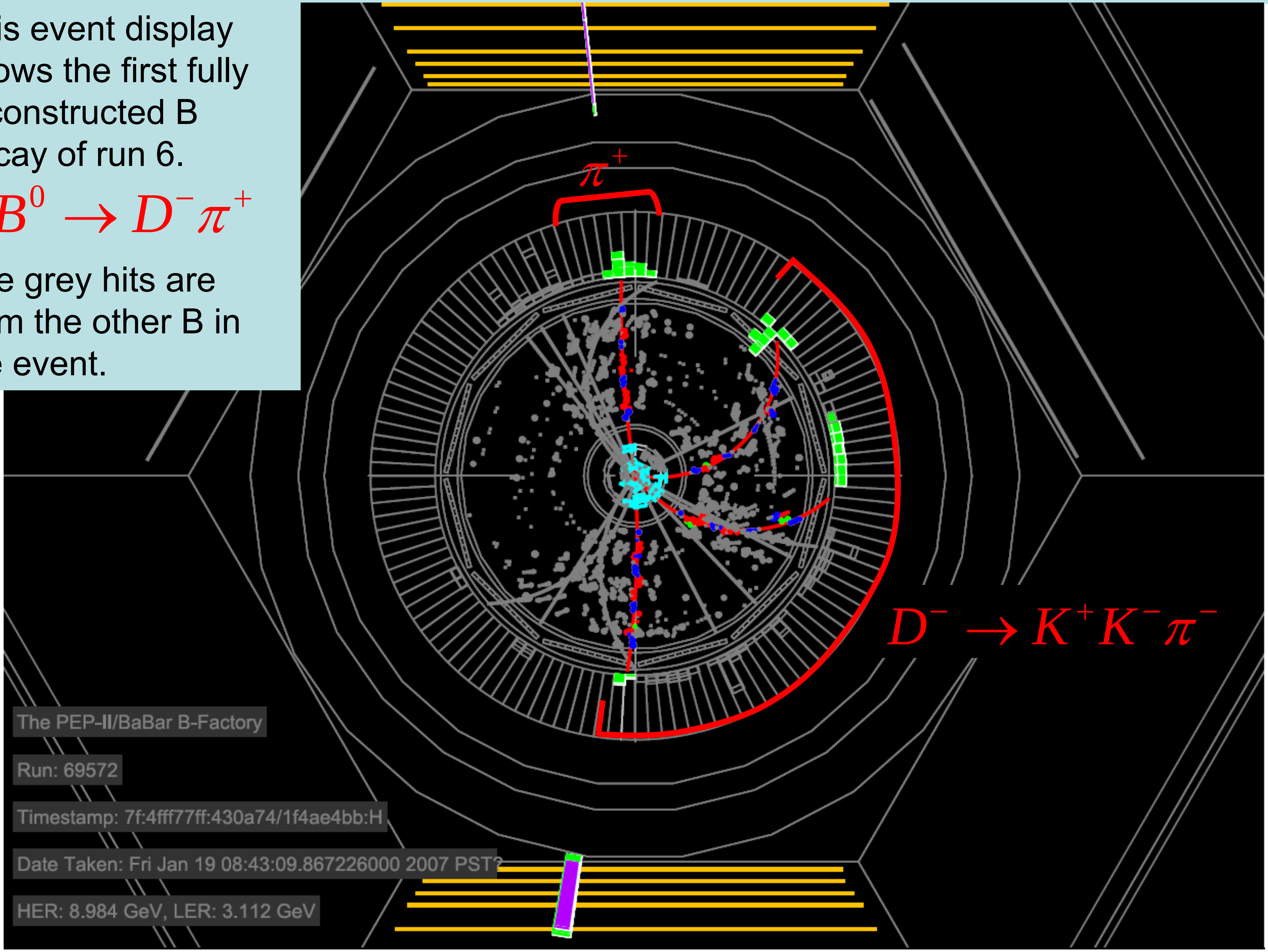
Total data samples logged as of 28.1.2007

BaBar is taking data again

This event display shows the first fully reconstructed B decay of run 6.

$$B^0 \rightarrow D^- \pi^+$$

The grey hits are from the other B in the event.

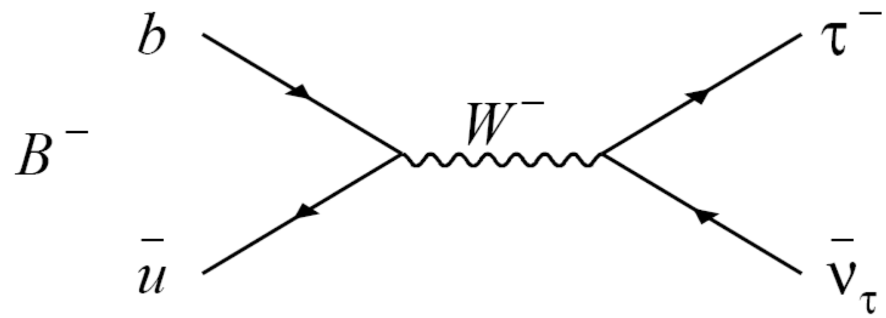


RESULTS

- **(Semi-)Leptonic and radiative rare B decays**
  - **$B \rightarrow l\upsilon$**
  - **$B \rightarrow K^{*}ll$**
  - **$B \rightarrow d\gamma$**

$B^+ \to \tau^+ \nu$

- Suppressed by V_{ub}

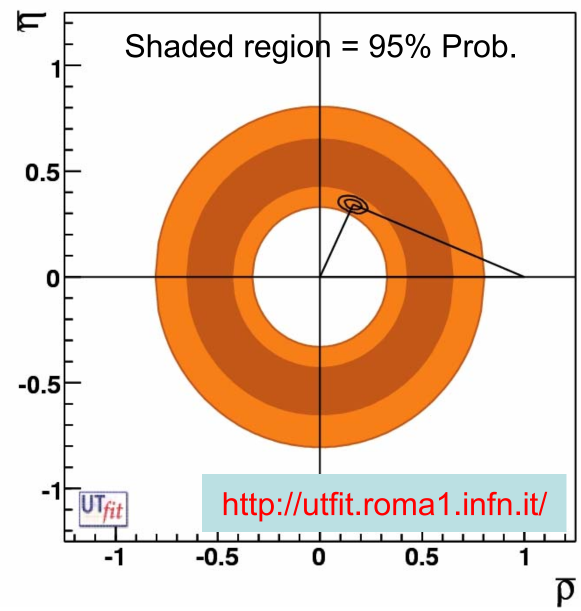


SM prediction
$(1.59 \pm 0.40) \times 10^{-4}$

$$\mathcal{B}_{SM}(B^+ \to l^+ \upsilon_l) = \frac{G_F^2 m_B m_l^2}{8\pi}\left(1 - \frac{m_l^2}{m_B^2}\right) f_B^2 |V_{ub}|^2 \tau_B$$

- Within the SM, this measurement can be used to constrain f_B.

- Can constrain the apex of the unitarity triangle using this measurement
  - Complements the angle measurements (Y.J. Kwon's talk this morning)



$B^+ \rightarrow \tau^+ \nu$

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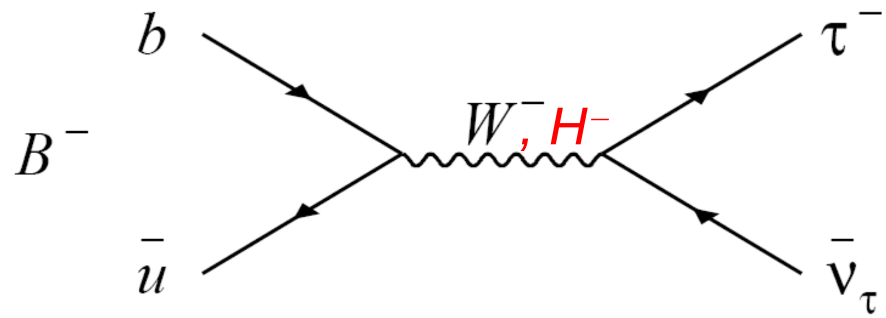

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  - Within the SM, this measurement can be used to constrain f_B.
- Can replace W^+ with H^+
  - $\mathcal{B}$ can be suppressed or enhanced by a factor of r_H

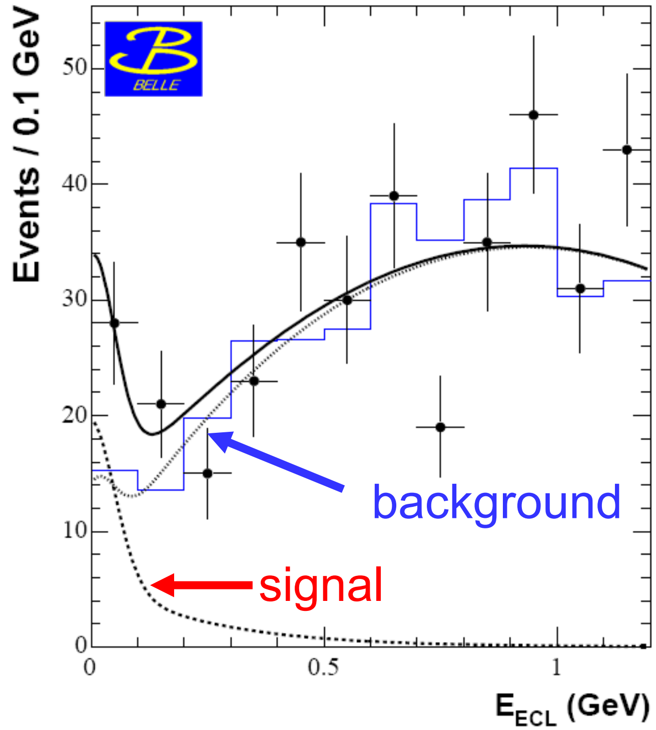
$$r_H = \left(1 - \frac{m_B^2}{m_H^2} \tan^2\beta\right)^2$$

2HDM: W.S. Hou, PRD **48**, 2342 (1993).

$B^+ \to \tau^+ \nu$

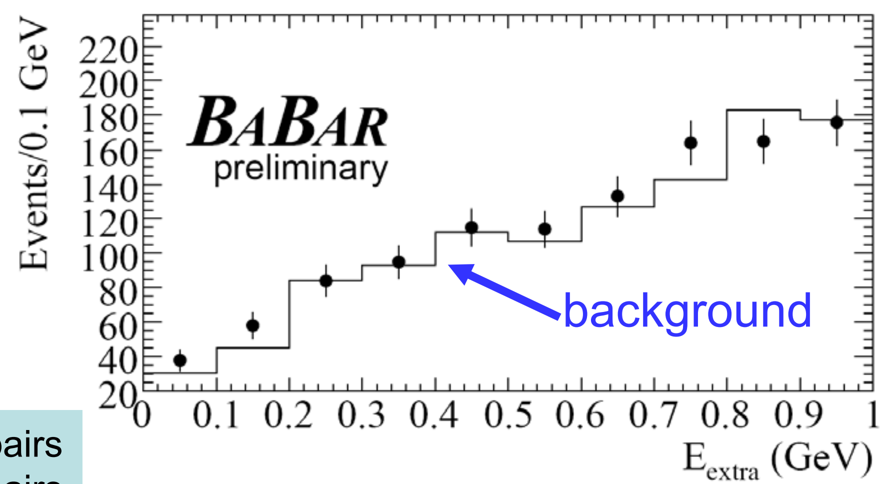
hep-ex/0608019
PRL**97** (2006) 251802

- Reconstruct signal decay.
- and other B in the event:
  - Belle: fully reconstruct B mesons in 180 channels.
  - BaBar: Tag with $B \to D^{(*)} l \upsilon$.
- Look at the remaining energy in the calorimeter: signal peaks at $E_{ECL/extra}=0$.



$$\mathcal{B} = (1.79^{+0.56+0.39}_{-0.49-0.46}) \times 10^{-4}$$

(revised). 3.5 σ significance



$$\mathcal{B} = (0.88^{+0.68}_{-0.67} \pm 0.11) \times 10^{-4}$$

$$BF < 1.80 \times 10^{-4} @ 90\%CL$$

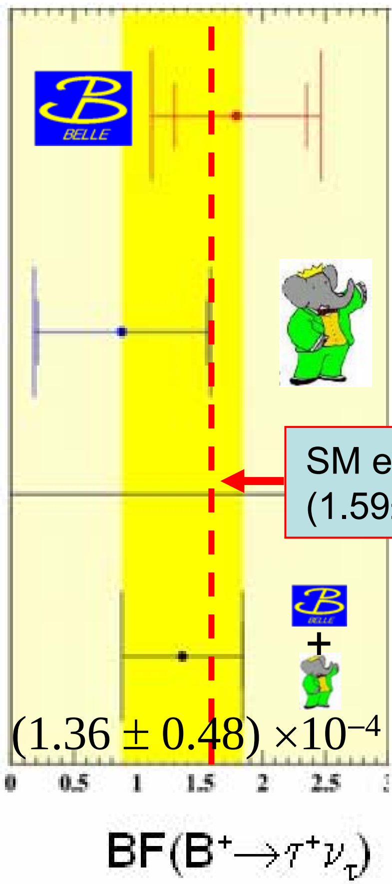
BaBar: 320×10^6 B pairs
Belle: 449×10^6 B pairs

Constraints from $B^+ \to \tau^+ \nu$

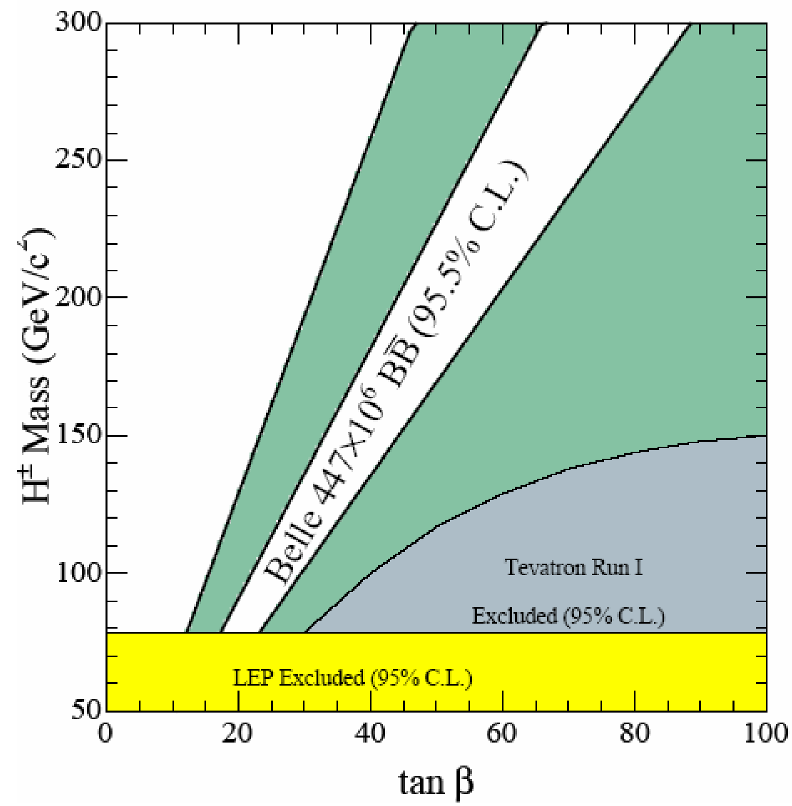
hep-ex/0608019
PRL **97** (2006) 251802

e.g. the 2HDM of W.S. Hou, PRD **48**, 2342 (1993).

- SM prediction can be enhanced/reduced by a factor r_H: $r_H = \left(1 - \frac{m_B^2}{m_H^2} \tan^2\beta\right)^2$



SM expectation
$(1.59 \pm 0.4) \times 10^{-4}$



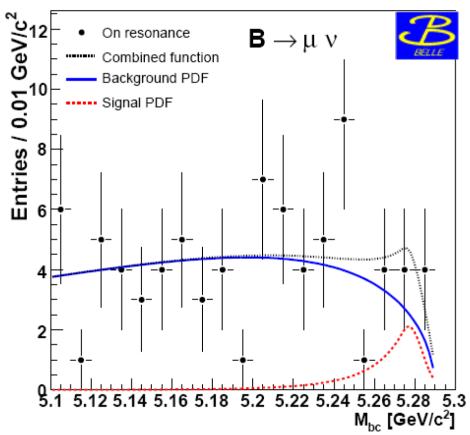
$B^+ \to e^+\nu$, $\mu^+\nu$

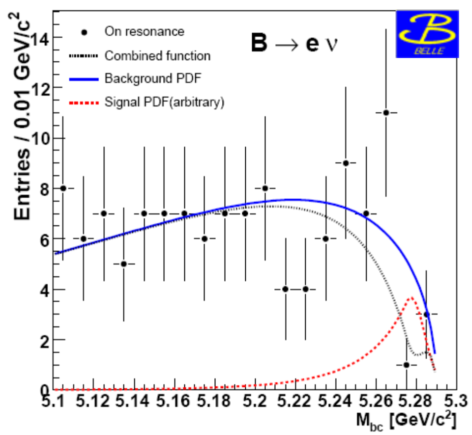
hep-ex/0607110
hep-ex/0611045

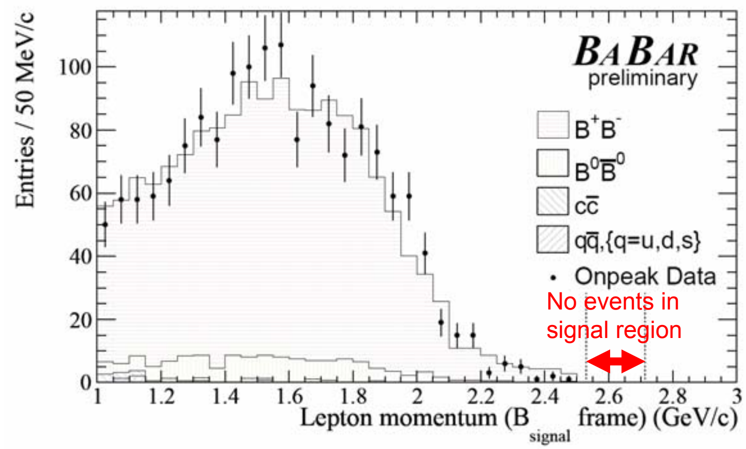
- Same physics motivation as $\tau^+\nu$.

$$\mathcal{B}_{SM}(B^+ \to l^+\upsilon_l) = \frac{G_F^2 m_B m_l^2}{8\pi}\left(1-\frac{m_l^2}{m_B^2}\right) f_B^2\,|V_{ub}|^2\,\tau_B$$

BaBar: 229×10^6 B pairs
Belle: 277×10^6 B pairs







- These searches give null results. Upper limits are shown for **BaBar** and **Belle.**
- Consistent with SM.
- Best limits within a factor of 2 of SM

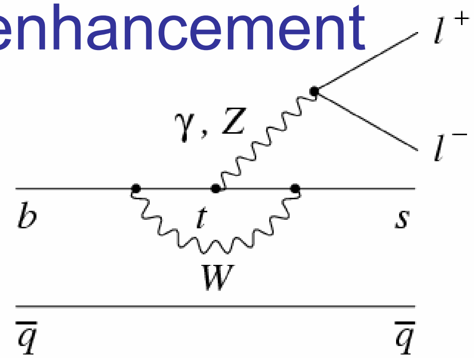
$$\mathcal{B}(B^+ \to e^+\upsilon_e) < 7.9\times10^{-6}\ \text{(90\% CL)}$$
$$\mathcal{B}(B^+ \to e^+\upsilon_e) < 9.8\times10^{-7}\ \text{(90\% CL)}$$
$$\mathcal{B}(B^+ \to \mu^+\upsilon_\mu) < 6.2\times10^{-6}\ \text{(90\% CL)}$$
$$\mathcal{B}(B^+ \to \mu^+\upsilon_\mu) < 1.7\times10^{-6}\ \text{(90\% CL)}$$

B→K$^{(*)}$ll

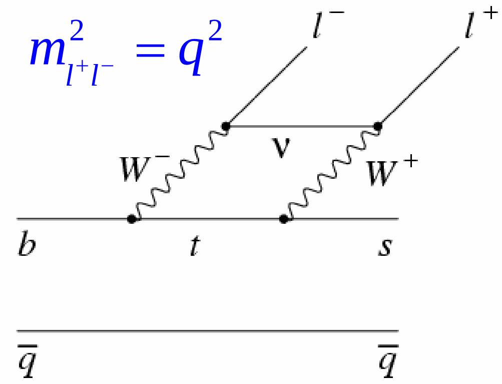
F. Kruger, et al. PRD**61** 114028 (2000), Erraturm D**63** 019901 (2001); F. Kruger, E. Lunghi PRD **63** 014013 (2001); G. Hiller & F. Kruger PRD**63** 014013 (2001); Q. Yan et al PRD62 094023 (2000). etc.

- Flavor Changing Neutral Current, sensitive to NP in loops.
- A_{CP}=0 in SM can get NP enhancement

$$\mathcal{A}_{CP} = \frac{\bar{N} - N}{\bar{N} + N}$$



$$m^2_{l^+l^-} = q^2$$



- $$R_K = \frac{\Gamma(B \to K\mu\mu)}{\Gamma(B \to Kee)} = 1.0000 \pm 0.0001 \text{ (SM)}$$

  $$R_{K^*} = \frac{\Gamma(B \to K^*\mu\mu)}{\Gamma(B \to K^*ee)} \approx 0.75 \text{ to } 1.0 \text{ depending on } q^2 \text{ region (SM)}$$

  - $R_{K^{(*)}}$ can be enhanced for Higgs doublet models with large tanβ.
- The forward backward asymmetry A_{FB} in the differential decay rate g, has a SM distribution as a function of q^2, deviations from this indicate NP.

$$A_{\rm FB}(q^2) = \frac{\int_{-1}^{1} {\rm sgn}(\cos\theta) g(q^2,\theta)\, d\cos\theta}{\int_{-1}^{1} g(q^2,\theta)\, d\cos\theta}.$$

  - θ is the angle between the lepton (+/–) momentum and B ($\bar{B}$/B) in the dilepton rest frame

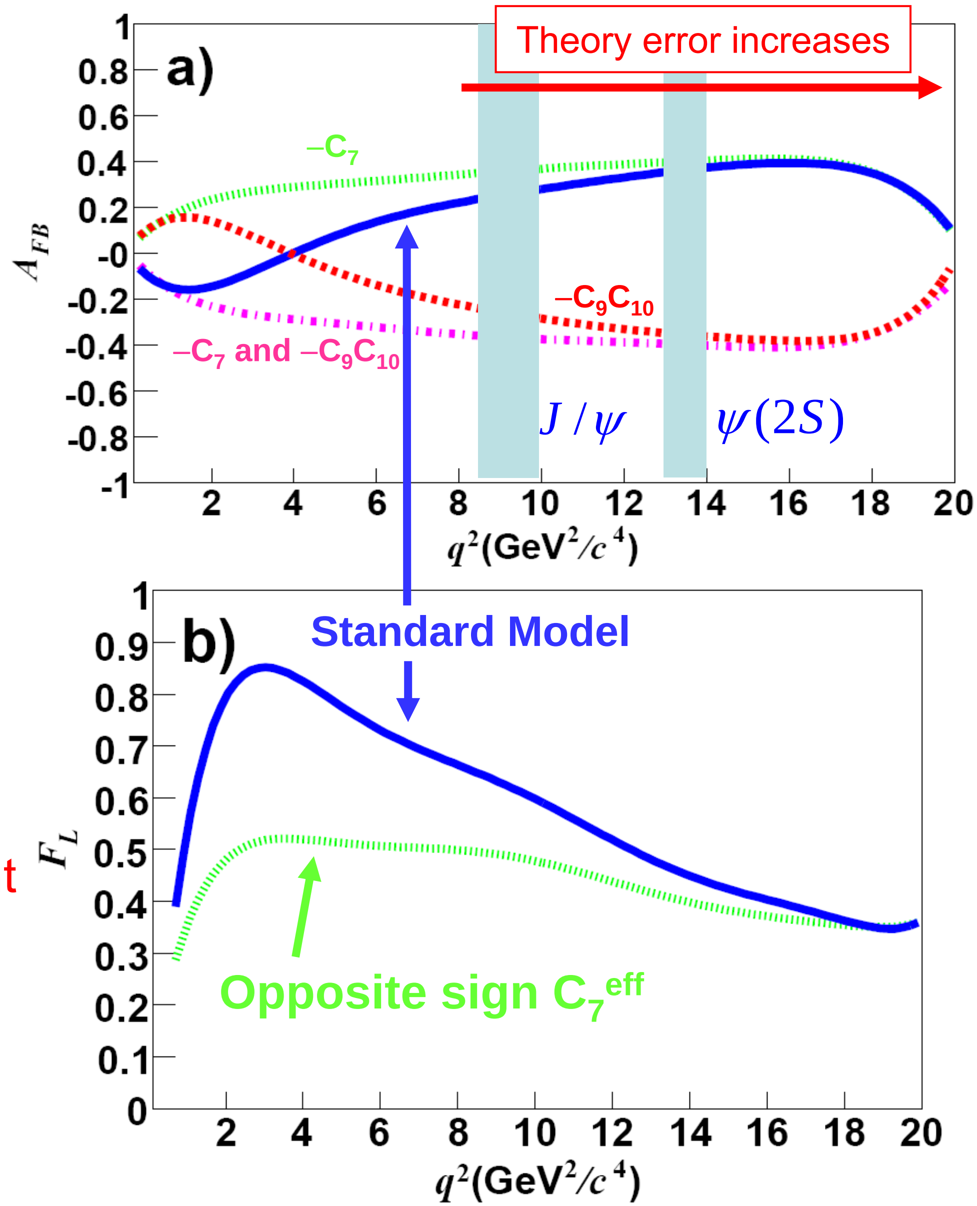
$B \to K^{(*)}ll$

Figures from PRD**73** (2006) 092001

- Shape of $A_{FB}(q^2)$ can be used to test SM
  - measure effective parameters related to Wilson coefficients C_i.

C_7	– γ electroweak penguin
C_9	– Z^0 electroweak penguin
C_{10}	– box diagram

- K^*ll has $F_L(q^2)$
  - F_L=fraction of longitudinally polarised events.
  - Deviations from SM expectations can signal right handed currents.

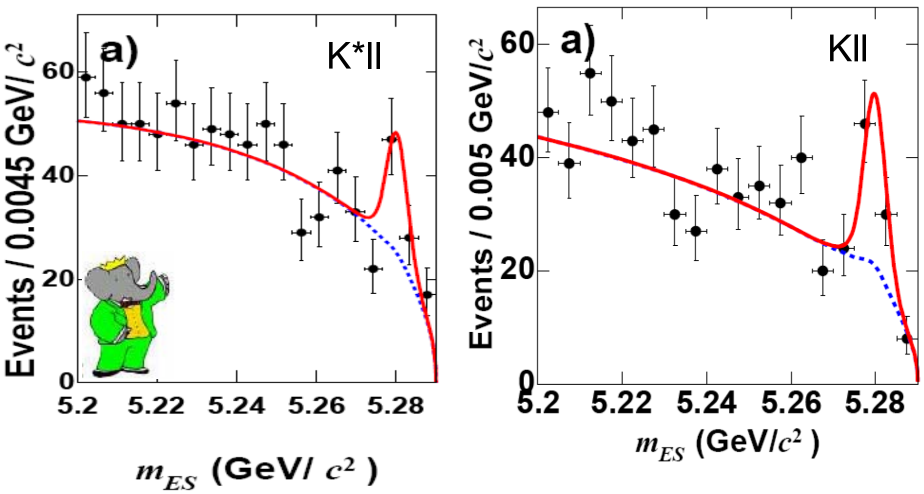


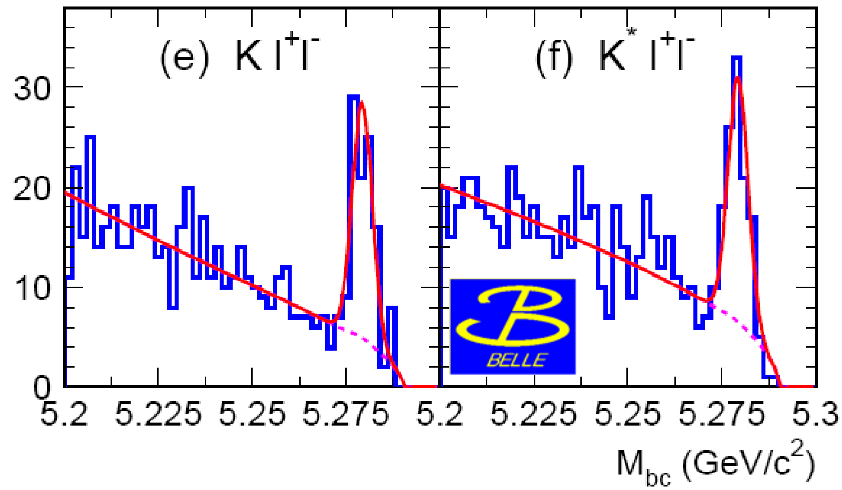
A. Ali et al. PRD**66** 034002 (2002); PRD**61** 074024 (200); F. Kruger & J. Matias PRD71 094009 (2005).

$B \rightarrow K^{(*)}ll$

hep-ex/0410006
PRD**73** (2006) 092001

- These modes have the smallest measured branching fraction of any observed B decay.





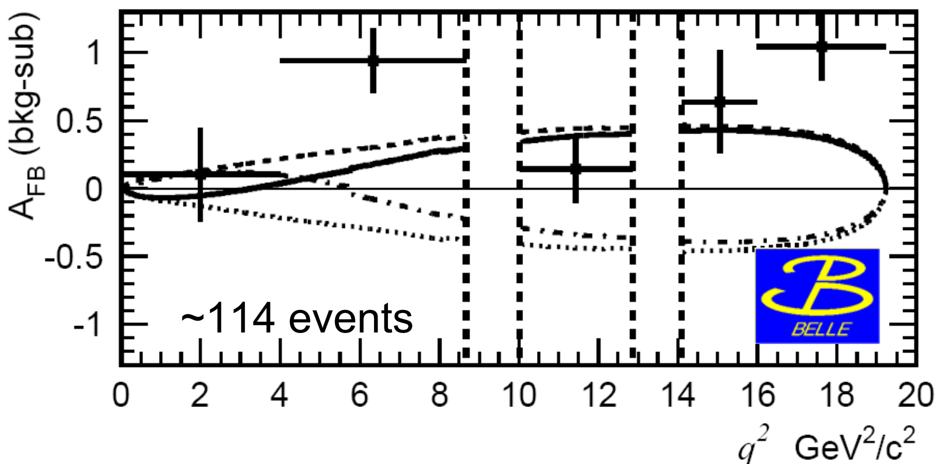
$$\mathcal{B}(B \rightarrow Kll) = (0.34 \pm 0.07 \pm 0.02) \times 10^{-6}$$
$$\mathcal{B}(B \rightarrow K^{*}ll) = (0.78^{+0.19}_{-0.17} \pm 0.11) \times 10^{-6}$$
$$R_K = 1.06 \pm 0.48 \pm 0.08$$
$$R_{K^*} = 0.91 \pm 0.45 \pm 0.06$$
$$\mathcal{A}_{CP}(B \rightarrow Kll) = -0.07 \pm 0.22 \pm 0.02$$
$$\mathcal{A}_{CP}(B \rightarrow K^{*}ll) = 0.03 \pm 0.23 \pm 0.03$$

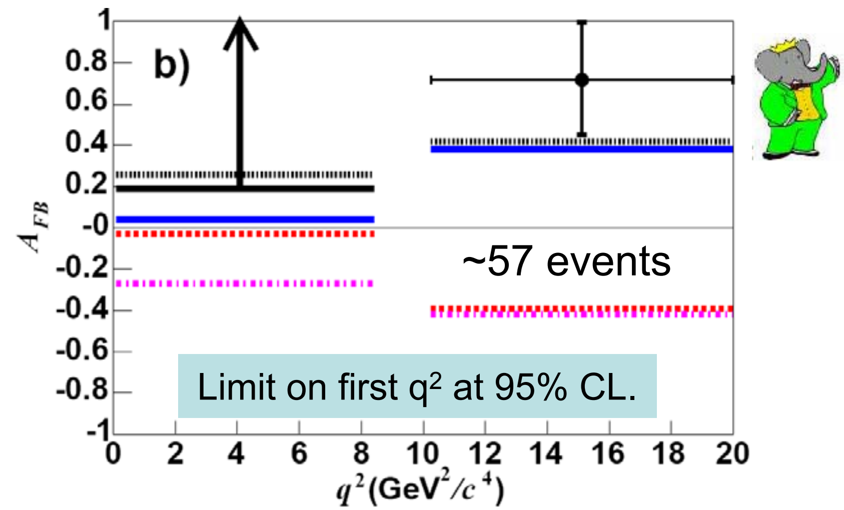
$$\mathcal{B}(B \rightarrow Kll) = (0.55 \pm 0.07 \pm 0.03) \times 10^{-6}$$
$$\mathcal{B}(B \rightarrow K^{*}ll) = (1.65^{+0.23}_{-0.22} \pm 0.10) \times 10^{-6}$$
$$R_K = 1.38 \pm 0.40 \pm 0.07$$
$$R_{K^*} = 0.98 \pm 0.30 \pm 0.08$$

B→K(*)ll

PRL**96** (2006) 251801
PRD**73** (2006) 092001

- First A_{FB} measurements from the B-factories are compatible with SM.

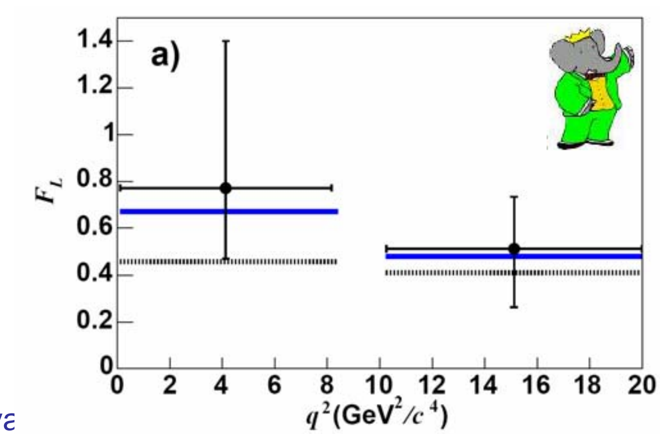




- C_i could be complex BSM: should test this in the future.

A. Hovhannisvan *et al.* hep-ph/0701046, A. Cornell *et al.* hep-ph/0505136

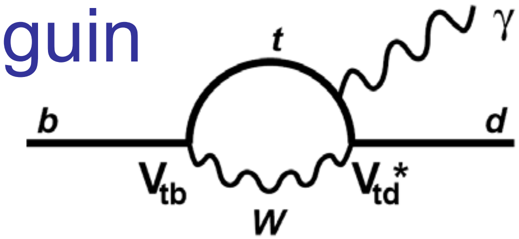
- Also measured F_L to be compatible with SM



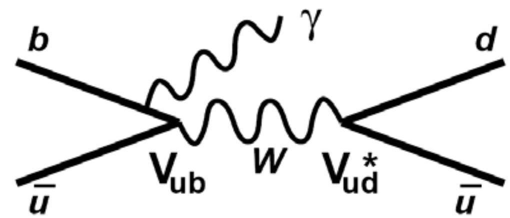
BaBar: 229×10⁶ B pairs
Belle: 386×10⁶ B pairs

B→dγ transitions: ωγ, ργ

- Radiative penguin decay



B^0 and B$^\pm$ decays



Only B$^\pm$ decays

- The ratio of dγ/K*γ measures $|V_{td}/V_{ts}|$.

$$\frac{\mathcal{B}[B \to (\rho/\omega)\gamma]}{\mathcal{B}(B \to K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1 - m_\rho^2/M_B^2}{1 - m_{K^*}^2/M_B^2}\right)^3 \zeta^2 [1 + \Delta R].$$

Difference in decay dynamics

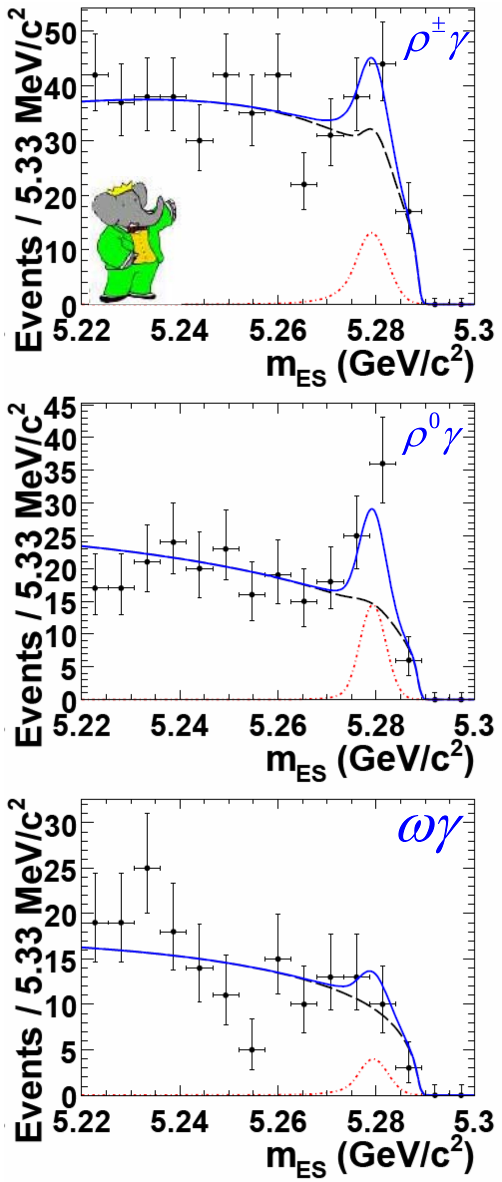
Ratio of form factors

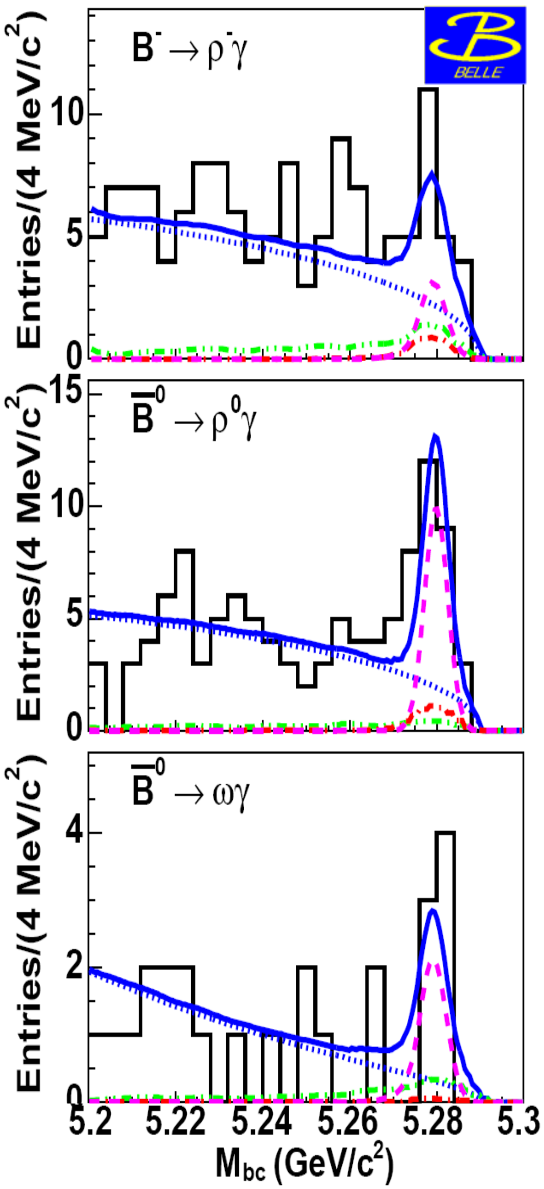
- Any inconsistency between this and the constraint from $\Delta m_d/\Delta m_s$ would indicate new physics.
  - CDF measure $|V_{td}/V_{ts}|$=0.2060±0.0007 (exp) ±0.007 (th)

CDF Collaboration hep-ex/0609040

$B \to d\gamma$ transitions: $\omega\gamma$, $\rho\gamma$

RPL**96** (2006) 221601
hep-ex/0612017





BaBar: 347×10^6 B pairs
Belle: 386×10^6 B pairs

- Both experiments observe $b \to d\gamma$ decays.
- With very consistent results.

$$\mathcal{B}(B \to \rho\gamma, \omega\gamma) = (1.25 \pm 0.25 \pm 0.09) \times 10^{-6}$$

$$\frac{\mathcal{B}(B \to \rho\gamma, \omega\gamma)}{\mathcal{B}(B \to K^*\gamma)} = 0.030 \pm 0.006$$

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.200 \pm 0.020 \pm 0.015$$

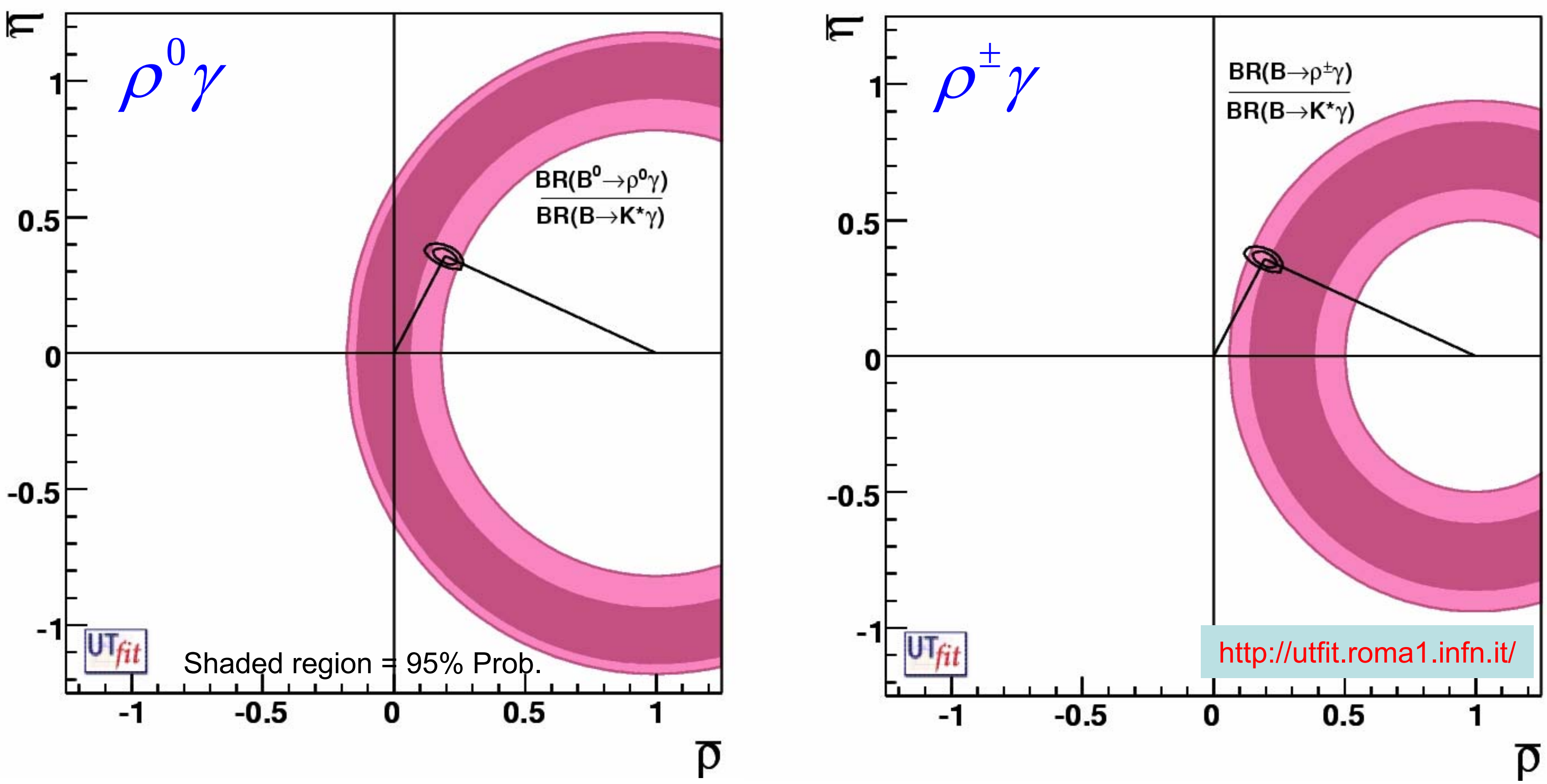
$$\mathcal{B}(B \to \rho\gamma, \omega\gamma) = (1.32^{+0.34}_{-0.31} \pm 0.10) \times 10^{-6}$$

$$\frac{\mathcal{B}(B \to \rho\gamma, \omega\gamma)}{\mathcal{B}(B \to K^*\gamma)} = 0.032 \pm 0.006 \pm 0.002$$

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.199 \pm 0.026^{+0.018}_{-0.015}$$

$B \to d\gamma$ transitions: $\omega\gamma$, $\rho\gamma$

- Can constrain the unitarity triangle using $B \to K^* \gamma$
  - Orthogonal to constraint from $B^+ \to \tau^+ \upsilon$
  - Compliments angle measurements (Y.J. Kwon's talk this morning)

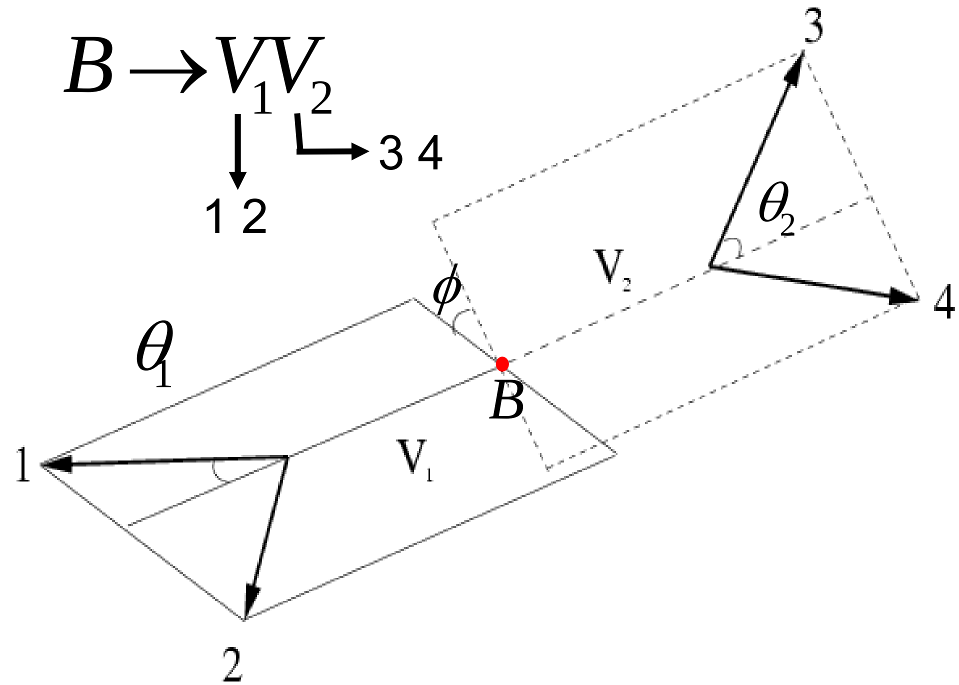


RESULTS

- Charmless hadronic rare B decays.
  - $B \rightarrow K^* \rho$
  - $B^0 \rightarrow a_1 \rho$
  - $B^+ \rightarrow \rho^+ \pi^0$
  - Direct CP Violation searches

B→VV decays

- 11 observables
  - 6 amplitudes, A_0, A_{+1}, A_{-1} + C.C.
  - 5 phases
- Simplify analysis to separating transverse and longitudinal events when have low statistics.
  - Measure polarisation: f_L
- Analogous to B→K*ll and H→ZZ→$l^+l^-l^+l^-$



$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\Phi} \propto \left| \sum_{m=-1,0,1} A_m Y_{1,m}(\theta_1,\Phi) Y_{1,-m}(\theta_2,\Phi) \right|^2$$

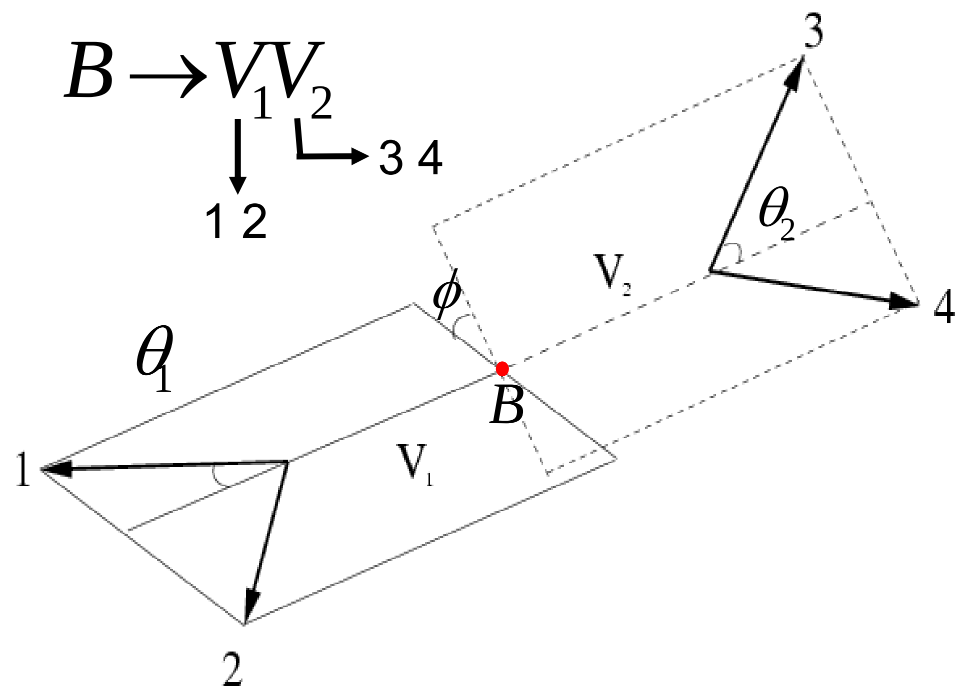
$$\propto \begin{cases} \frac{1}{4}\sin^2\theta_1 \sin^2\theta_2 (|A_{+1}|^2 + |A_{-1}|^2) + \cos^2\theta_1 \cos^2\theta_2 |A_0|^2 \\ +\frac{1}{2}\sin^2\theta_1 \sin^2\theta_2 [\cos 2\Phi \Re(A_{+1}A_{-1}^*) - \sin 2\Phi \Im(A_{+1}A_{-1}^*)] \\ +\frac{1}{4}\sin 2\theta_1 \sin 2\theta_2 [\cos\Phi \Re(A_{+1}A_0^* + A_{-1}A_0^*) - \sin\Phi \Im(A_{+1}A_0^* - A_{-1}A_0^*)] \end{cases}$$

$$f_L = \frac{|A_0|^2}{\sum_{m=-1,0,1} |A_m|^2}$$

Integrate over Φ …

B→VV decays

- 11 observables
  - 6 amplitudes, A_0, A_{+1}, A_{-1} + C.C.
  - 5 phases
- Simplify analysis to separating transverse and longitudinal events when have low statistics.
  - Measure polarisation: f_L
- Analogous to $B \to K^*ll$ and $H \to ZZ \to l^+l^-l^+l^-$



$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2} \propto \left\{ f_L \cos^2\theta_1 \cos^2\theta_2 + \tfrac{1}{4}(1 - f_L)\sin^2\theta_1 \sin^2\theta_2 \right\}$$

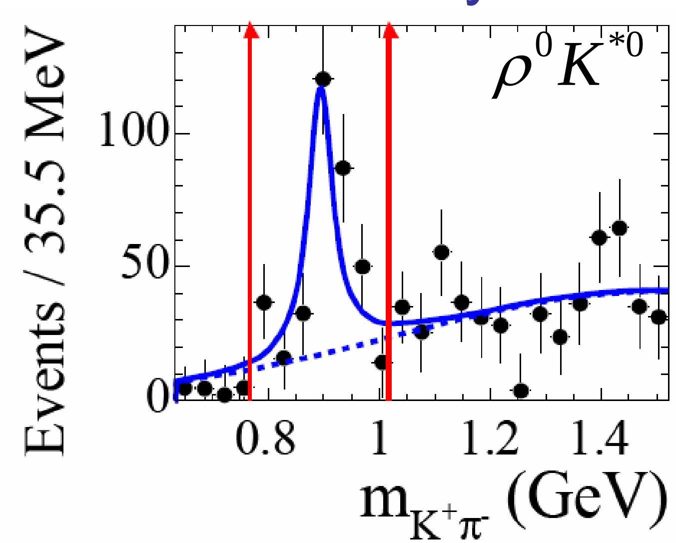
$$f_L = \frac{|A_0|^2}{\sum_{m=-1,0,1} |A_m|^2}$$

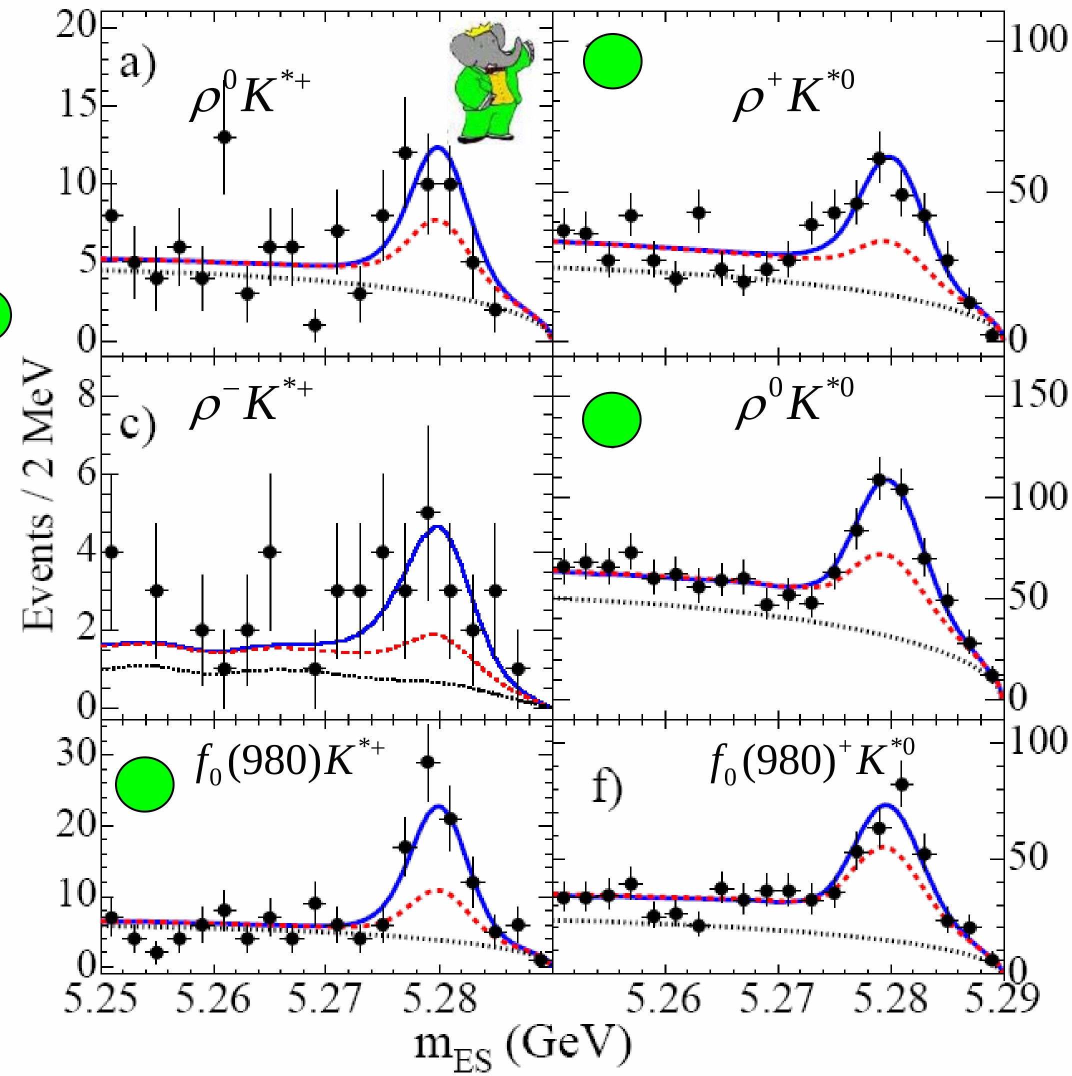
…. to simplify the angular correlation.

B→K*ρ

PRL**97** (2006) 201801

- 232×10^{6} B Pairs
- BF~few 10^{-6}.
- 2 VV modes and f_0K^{*+} have been observed.
- Understanding non-resonant Kπ background is critical for these analyses.





B→K*ρ

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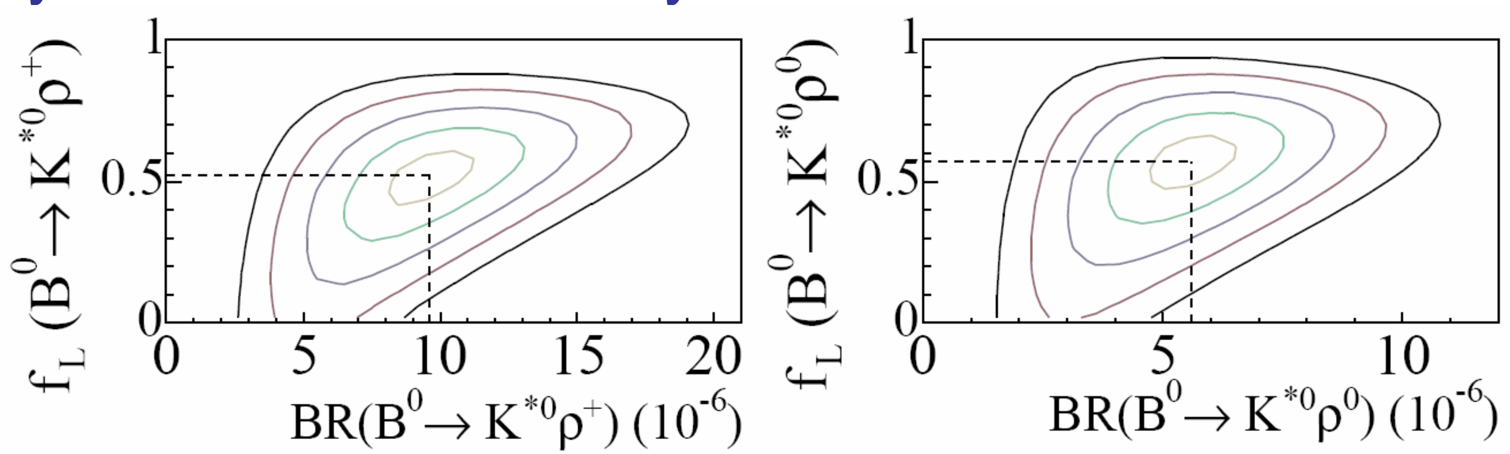
- For penguins we expect f_L~0.5,
  trees we expect f_L~1.0.
- The interest is in trying to understand the underlying dynamics of these decays.



Mode	n_{sig}	$S(\sigma)$	$\mathcal{B}(10^{-6})$	f_L	$\mathcal{A}_{CP}$
$\rho^0 K^{*+}$		2.5	$3.6^{+1.7}_{-1.6} \pm 0.8$ (6.1)	$[0.9 \pm 0.2]$	–
$\to \rho^0 K^{*+}_{K^+\pi^0}$	19^{+16}_{-15}	1.3	$3.2^{+2.7}_{-2.4} \pm 0.9$	$[0.8^{+0.3}_{-0.5}]$	–
$\to \rho^0 K^{*+}_{K^0_S\pi^+}$	32^{+19}_{-17}	2.1	$3.8^{+2.2}_{-2.1} \pm 0.9$	$[1.0 \pm 0.3]$	–
$\rho^+ K^{*0}$	194 ± 29	7.1	$9.6 \pm 1.7 \pm 1.5$	$0.52 \pm 0.10 \pm 0.04$	$-0.01 \pm 0.16 \pm 0.02$
$\rho^- K^{*+}_{K^+\pi^0}$	60^{+25}_{-22}	1.6	$5.4^{+3.8}_{-3.4} \pm 1.6$ (12.0)	$[-0.18^{+0.52}_{-1.74}]$	–
$\rho^0 K^{*0}$	185 ± 30	5.3	$5.6 \pm 0.9 \pm 1.3$	$0.57 \pm 0.09 \pm 0.08$	$0.09 \pm 0.19 \pm 0.02$
$f_0(980) K^{*+}$		5.0	$5.2 \pm 1.2 \pm 0.5$	–	$-0.34 \pm 0.21 \pm 0.03$
$\to f_0(980) K^{*+}_{K^+\pi^0}$	40^{+13}_{-12}	3.8	$6.2^{+2.1}_{-1.9} \pm 0.7$	–	$-0.50 \pm 0.29 \pm 0.03$
$\to f_0(980) K^{*+}_{K^0_S\pi^+}$	37^{+14}_{-12}	3.2	$4.2^{+1.5}_{-1.4} \pm 0.5$	–	$-0.13 \pm 0.30 \pm 0.01$
$f_0(980) K^{*0}$	83 ± 19	3.5	$2.6 \pm 0.6 \pm 0.9$ (4.3)	–	$-0.17 \pm 0.28 \pm 0.02$

$B^+ \to K^{*0}\rho^+/a_1\rho$ & α from $\rho\rho$

PRL**97** (2006) 201801
PRD**74** (2006) 031104

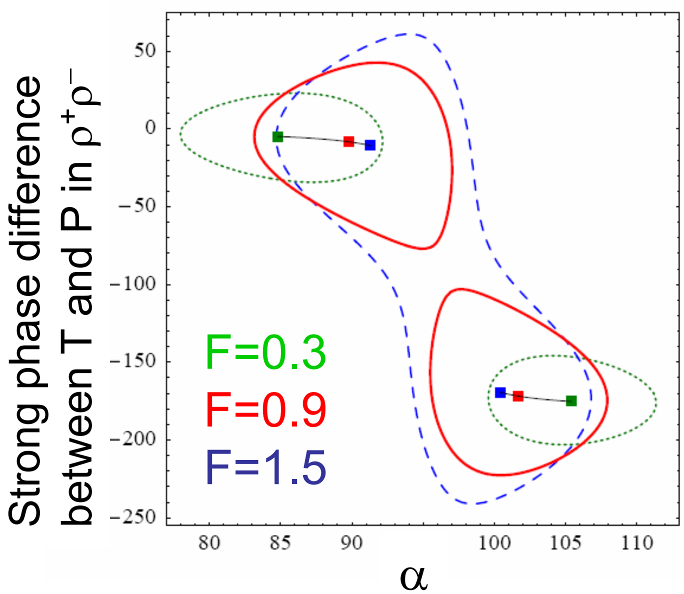
- $B^+ \to K^{*0}\rho^+$ is a pure penguin decay that can be related to the penguin amplitude in $B^0 \to \rho^+\rho^-$.

Beneke et al., Phys.Lett. B638 (2006) 68-73

$$\mathcal{B}(B^+ \to K^{*0}\rho^+) = (9.6 \pm 1.7 \pm 1.5) \times 10^{-6}$$

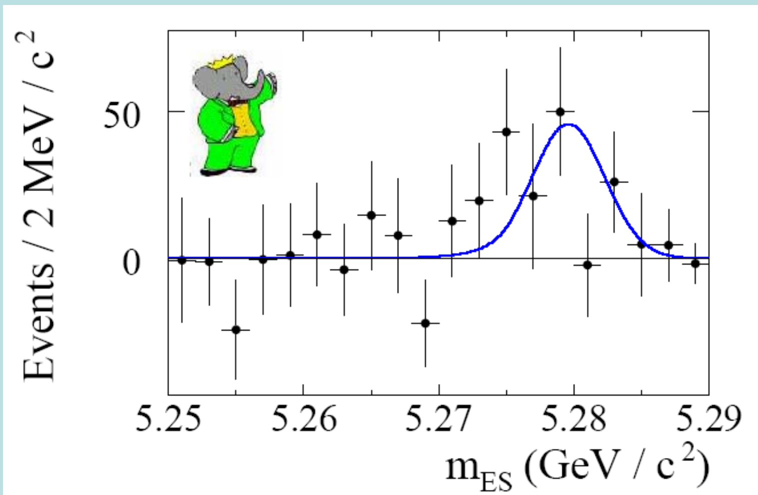
- This approach gives a more precise measurement of the unitarity triangle angle than traditional methods.

$\sigma(\alpha)$~7°(expt.)±1.5 °(th.)



- $a_1\rho$ is a significant background to other rare decays like $\rho\rho$.
- Recent search provides useful upper limit on this decay.

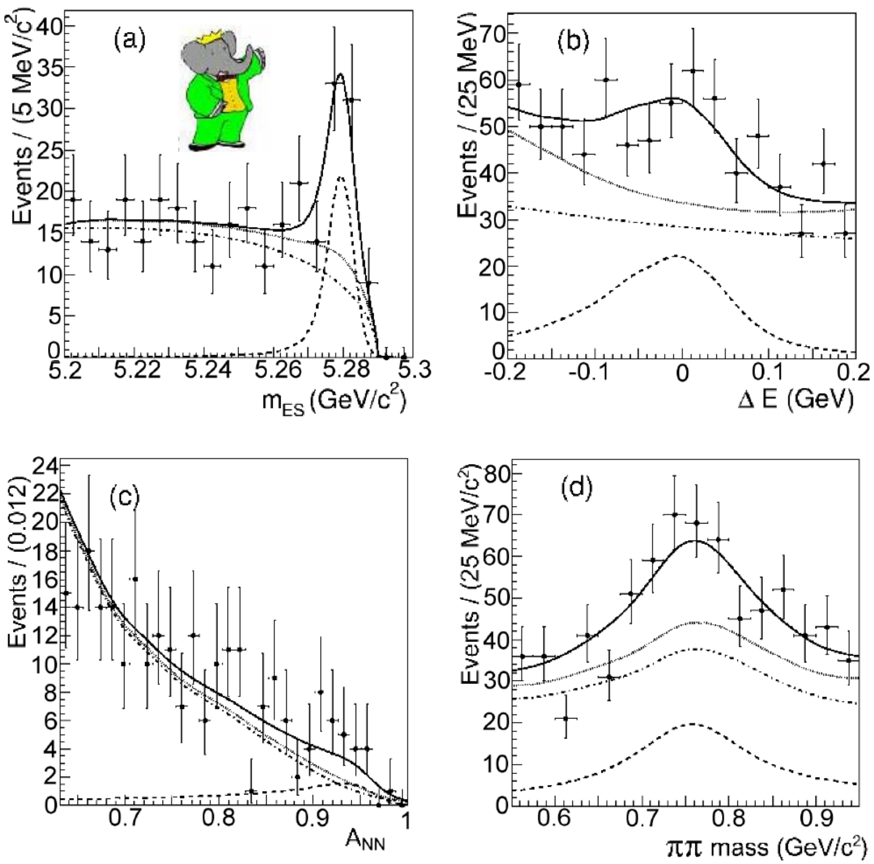
$$\mathcal{B}(B^0 \to a_1^\pm \rho^\mp) < 61 \times 10^{-6} \quad (90\% \text{ CL})$$



$B^+ \to \rho^+\pi^0$

hep-ex/0701035

- Recently updated by BaBar using 227×10^6 B pairs



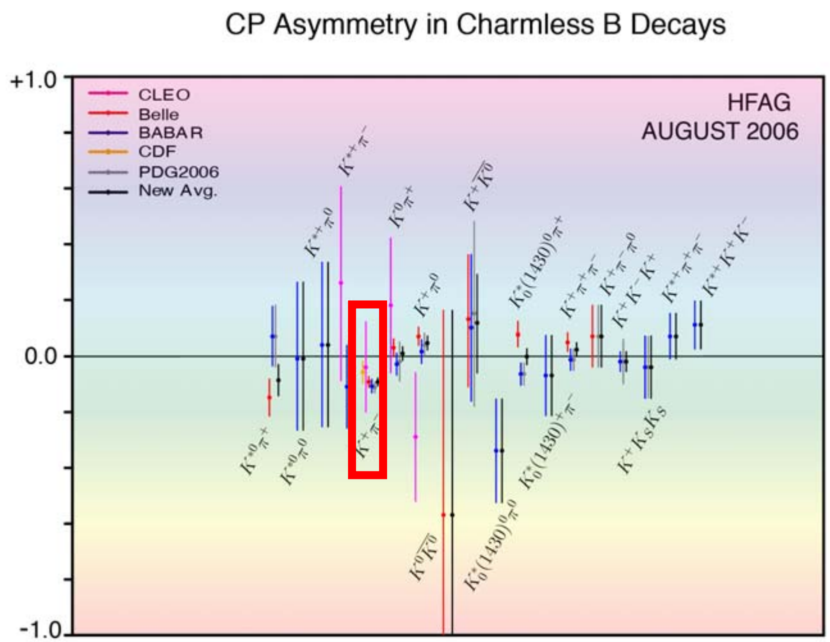
- Useful input for an isospin analysis of $B\to\rho\pi$ decays.
- Can also search for direct CP violation in this mode:

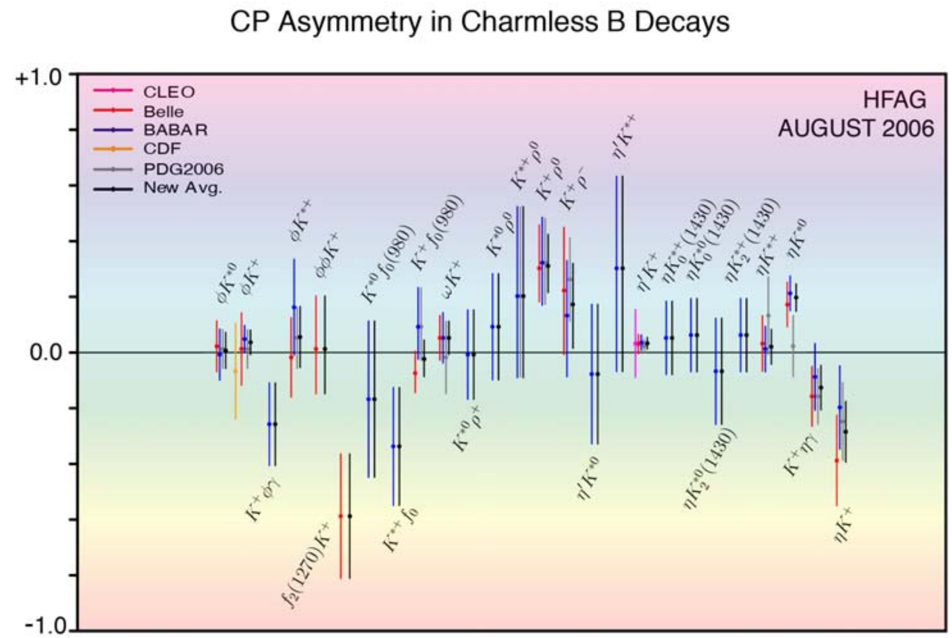
$$\mathcal{A}_{CP} = \frac{\bar{N} - N}{\bar{N} + N}$$

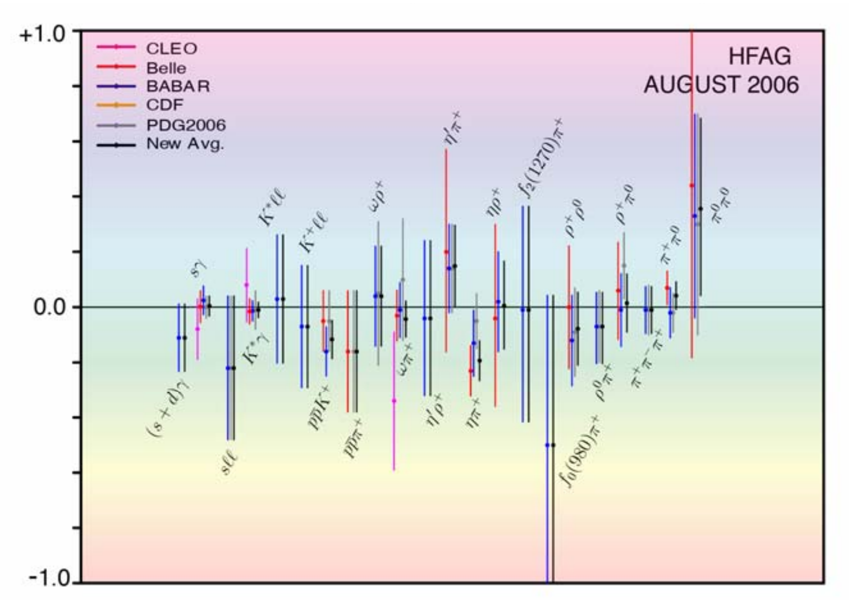
$$B(B^+ \to \rho^+\pi^0) = (10.2 \pm 1.4 \pm 0.9)\times 10^{-6}$$

$$\mathcal{A}_{CP} = -0.01 \pm 0.13 \pm 0.02$$

Searches for direct CP violation







- There is a huge effort from the B-factories in trying to observe direct CP violation.
- Two signals observed so far in $B^0 \to \pi^+\pi^-$ and $K^+\pi^-$

(Y.J. Kwon's talk this morning)

Summary

- Rare B decays provide a useful testing ground for theoretical calculations.
  - Loop dominated can also be used to constrain possible physics contributions beyond the standard model.
  - Provide constraints of the unitarity triangle that compliment the angle and mixing measurements.
  - $B^+ \to K^{*0}\rho^+$ can be used to constrain theoretical uncertainty in the determination of α.

- The B-factories have recorded $1ab^{-1}$ of data and will double this by the end of 2008.
  - More stringent bounds on the triangle and NP model parameter space to come.