B Leptonic and Electroweak Penguin Decays

Steven Robertson
Canadian Institute of Particle Physics
for the
BaBar Collaboration

2007 Aspen Winter Conference on Particle Physics
Aspen, Colorado, January 8-13 2007

Outline

- **Rare B decays and New Physics**
- **Leptonic B decays:**

  $\mathbf{B^+ \rightarrow \tau^+ \nu}$

  $\mathbf{B^+ \rightarrow \mu^+ \nu}$ **and** $\mathbf{B^+ \rightarrow e^+ \nu}$

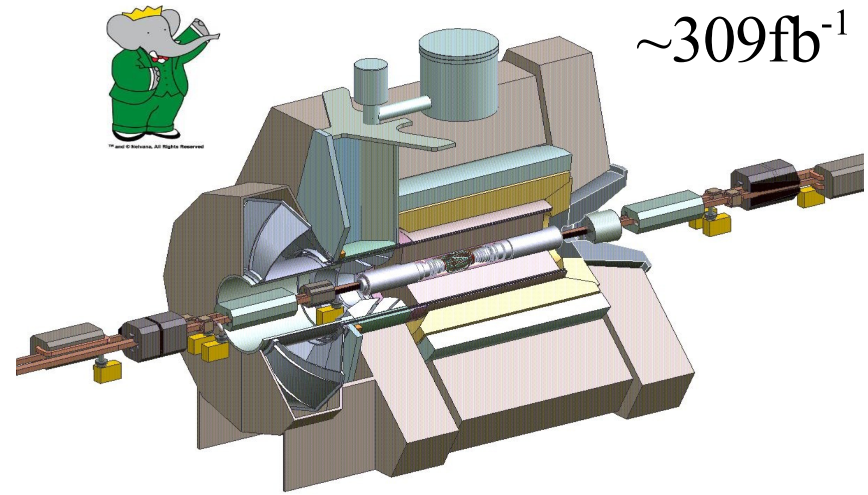
  Radiative modes: $\mathbf{B^+ \rightarrow \ell^+ \nu \gamma}$

- **Electroweak FCNC processes:**

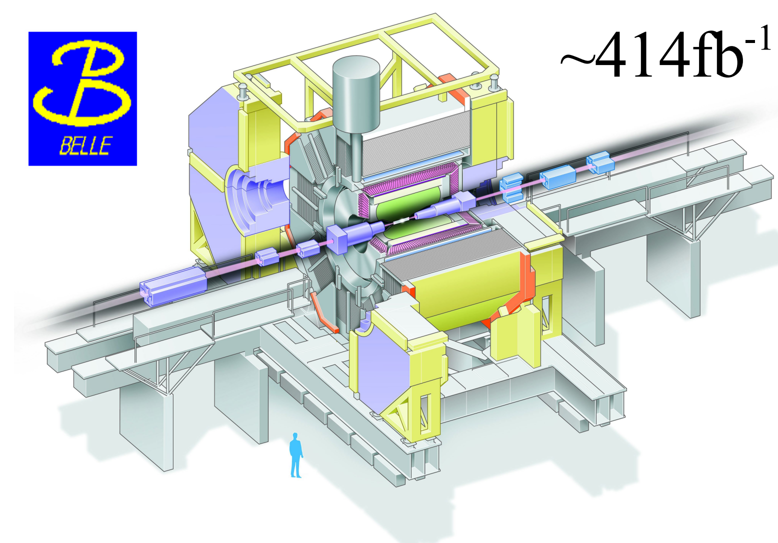
  $\mathbf{B \rightarrow X_{s/d}\, \gamma}$

  $\mathbf{B \rightarrow K^{(*)} \ell^+ \ell^-}$

- **Conclusions**



$\sim 309 fb^{-1}$

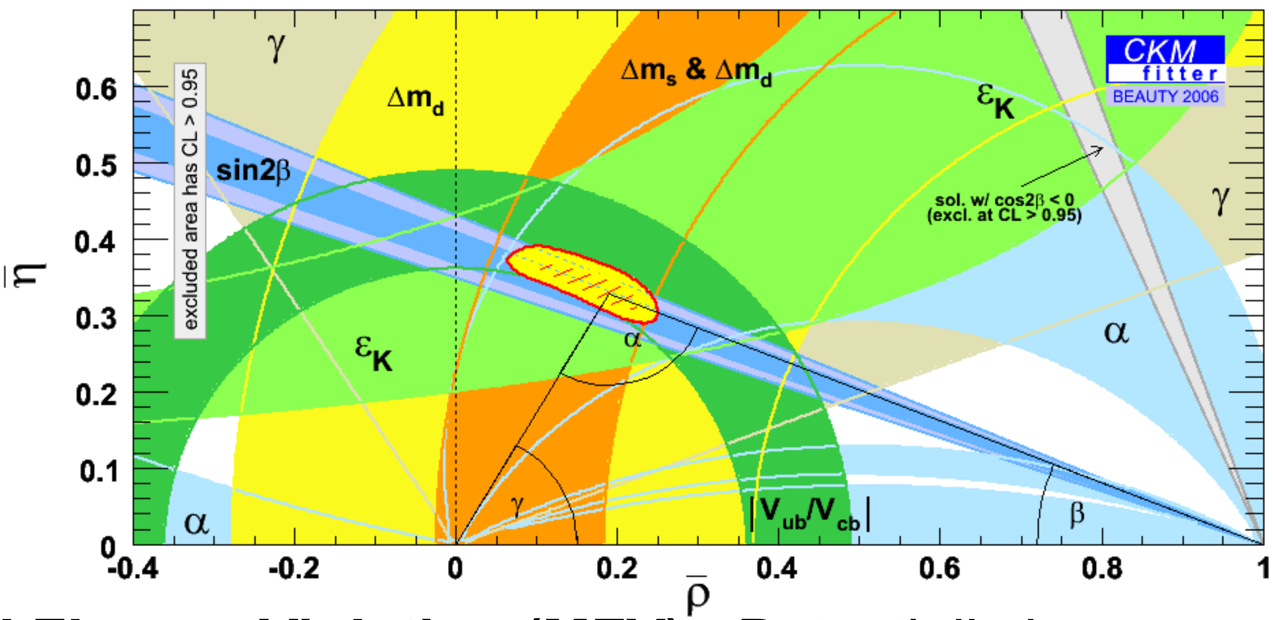


$\sim 414 fb^{-1}$

Why Rare Decays?

Overall Unitarity Triangle determination from tree and $\Delta F=2$ processes ($B_{d,s}$ and K mixing) is consistent with Standard Model expectations

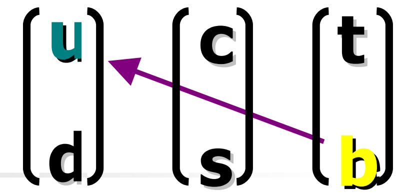
- presentation by P. Dauncey (Weds morning)
- implies that the scale associated with New Physics is >>1 TeV unless "phase" of New Physics is the same as the SM phase



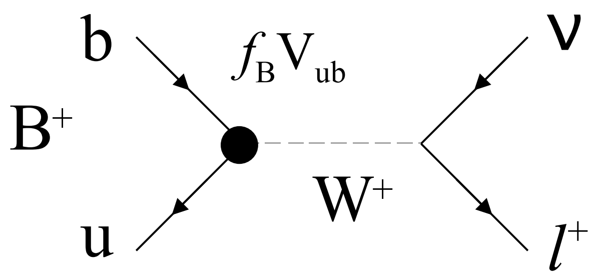
Minimal Flavour Violation (MFV) - Potentially large non-SM effects in rare meson decays even in absence of evidence of new physics in the (tree-level) UT determination

G. D'Ambrosio et al., Nucl.Phys.B645:155-187,2002

Leptonic B decays



Leptonic B decays are helicity-suppressed EW tree processes in the SM:



Standard Model Rates

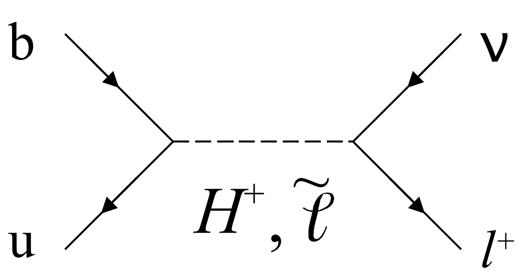
$B(B^+ \to \tau^+\nu) \sim 1\times10^{-4}$

$B(B^+ \to \mu^+\nu) \sim 4\times10^{-7}$

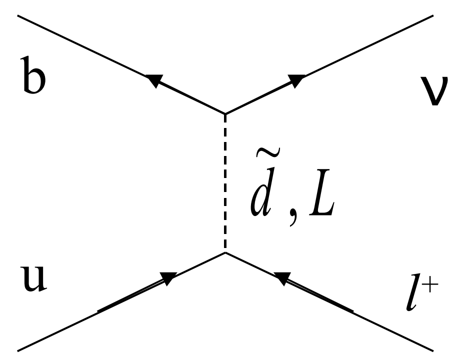
$B(B^+ \to e^+\nu) \sim 10^{-12}$

$$\mathcal{B}r(B^+ \to \ell^+\nu_\ell) = \frac{G_F^2}{8\pi}|V_{ub}|^2 f_B^2 m_B m_\ell^2 \tau_B \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2$$

New physics contributions can arise from diagrams with internal lines containing non-SM particles:

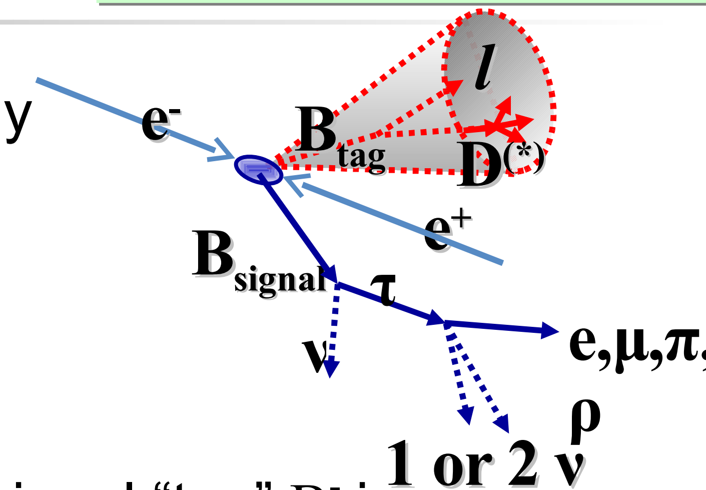


Charged Higgs, scalar sparticles in R-parity violating models, Pati-Salam leptoquarks



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

Standard Model Rate
$\mathcal{B}(B^+ \rightarrow \tau^+\nu) \sim 1\text{x}10^{-4}$



Large SM branching fraction, but experimentally challenging due to presence of several final states with multiple neutrinos

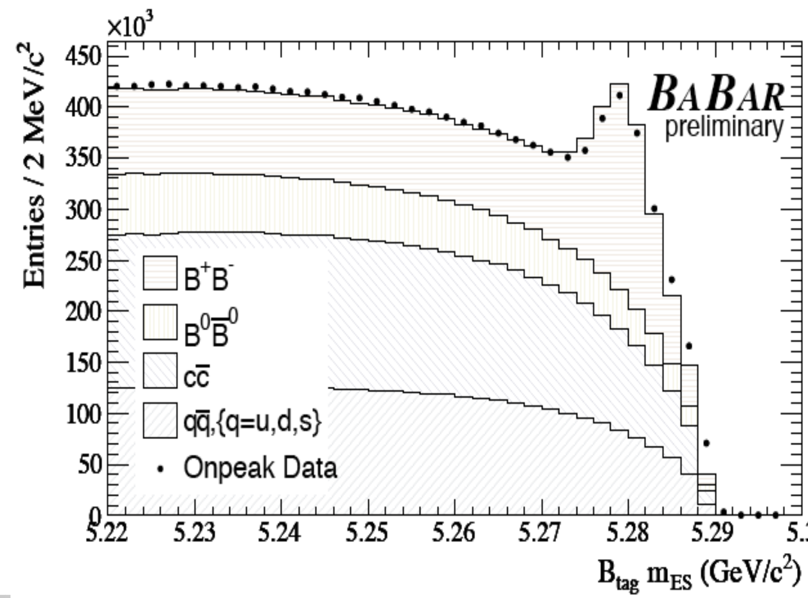
- few kinematic constraints which can be exploited for background suppression

Solution is to reconstruct the decay of the non-signal "tag" B^- in $\Upsilon(4S) \rightarrow B^+B^-$ in one of a large number of exclusive decay modes, then attribute all other particles to the decay of the "signal" B^+ candidate

- $B^- \rightarrow D^{(*)0} X^-$ Hadronic tags
  - yield ~2700/fb^{-1}

$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_B} \qquad \Delta E = E_B - E_{CM}/2$$

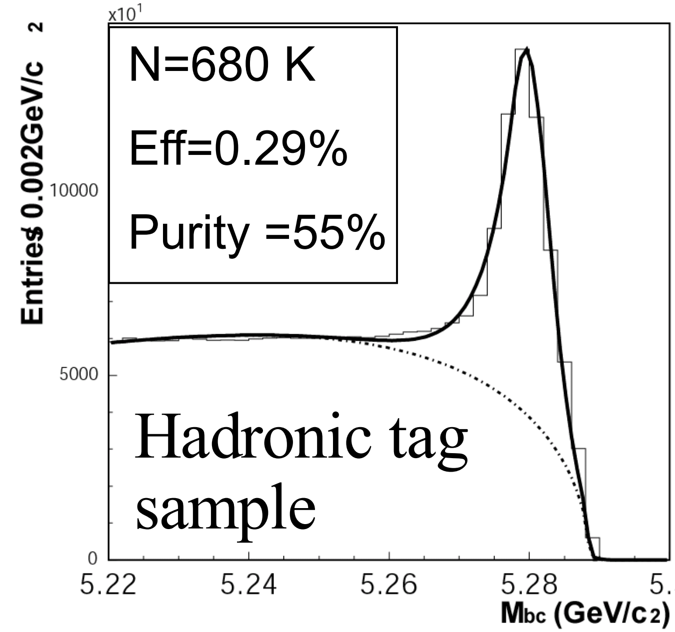
- $B^- \rightarrow D^0 l^- \nu X^0$ Semileptonic tags
  - yield ~6000/fb^{-1}
    - presence of additional neutrino does not significantly impact analysis

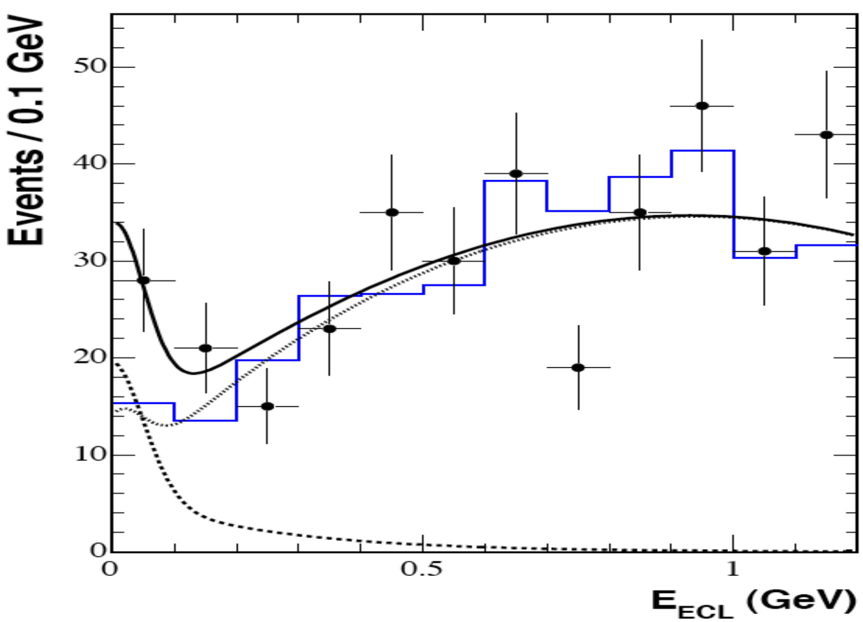


Belle $B^+ \to \tau^+ \nu$ results

Belle recently reported first evidence for $B^+ \to \tau^+ \nu$ based on 414fb^{-1} of data
Phys. Rev. Lett. 97, 251802 (2006)

- signal modes: $\tau^+ \to e^+ \nu\nu$, $\tau^+ \to \mu^+ \nu\nu$, $\tau^+ \to \pi^+ \nu$, $\tau^+ \to \rho^+(\pi^+\pi^0)\nu$, $\tau^+ \to a_1^+(\pi^+\pi^-\pi^+)\nu$
- signal extracted from a fit to the E_{ECL} distribution (sum of calorimeter energy not associated to either tag B or signal B candidates)





Observed an excess above background across all signal channels with E_{ECL} shape compatible with signal:

$$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = (1.79^{+0.56}_{-0.49}(\text{stat})^{+0.46}_{-0.51}(\text{syst})) \times 10^{-4}$$

(3.5σ significance)

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

hep-ex/0608019

BABAR Semileptonic tag analysis based on 324 x 10^6 BB pairs

- Raw tag reconstruction efficiency (6.77 ± 0.05 ± 0.10) x 10^{-3}
- signal modes: $\tau^+ \to e^+ \nu\nu$, $\tau^+ \to \mu^+ \nu\nu$, $\tau^+ \to \pi^+ \nu$, $\tau^+ \to \rho^+(\pi^+\pi^0)\nu$

Overall signal yield obtained by likelihood-based combination of observed yields in individual channels (with uncertainties included)

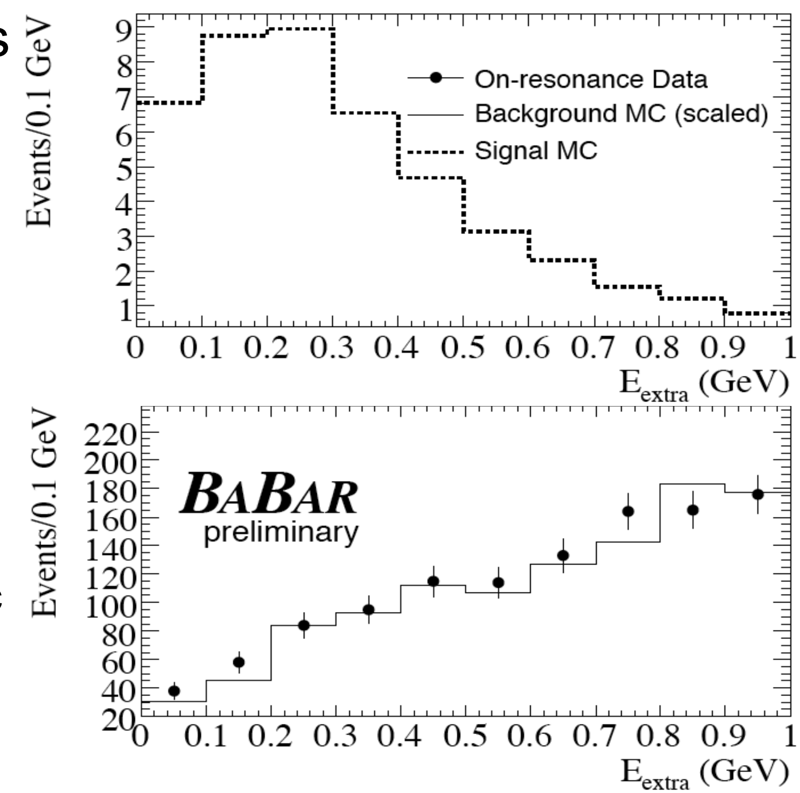
- Use "double-tagged" $B^- \to D^0 l^- \nu X^0$ events to validate E_{extra} and other systematics

Slight excess observed across all signal channels:

$B(B^+ \to \tau^+ \nu)$ = (0.88 ± 0.70 ± 0.11) x 10^{-4}
(1.3σ significance)

$B(B^+ \to \tau^+ \nu) < 1.8 \times 10^{-4}$ @ 90% CL

- A previous BABAR analysis using a combination of hadronic and semileptonic tags on a smaller dataset reported $B(B^+ \to \tau^+ \nu) < 2.6 \times 10^{-4}$ @ 90% CL (B. Aubert et al. PRD 73 057101 (2006))



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

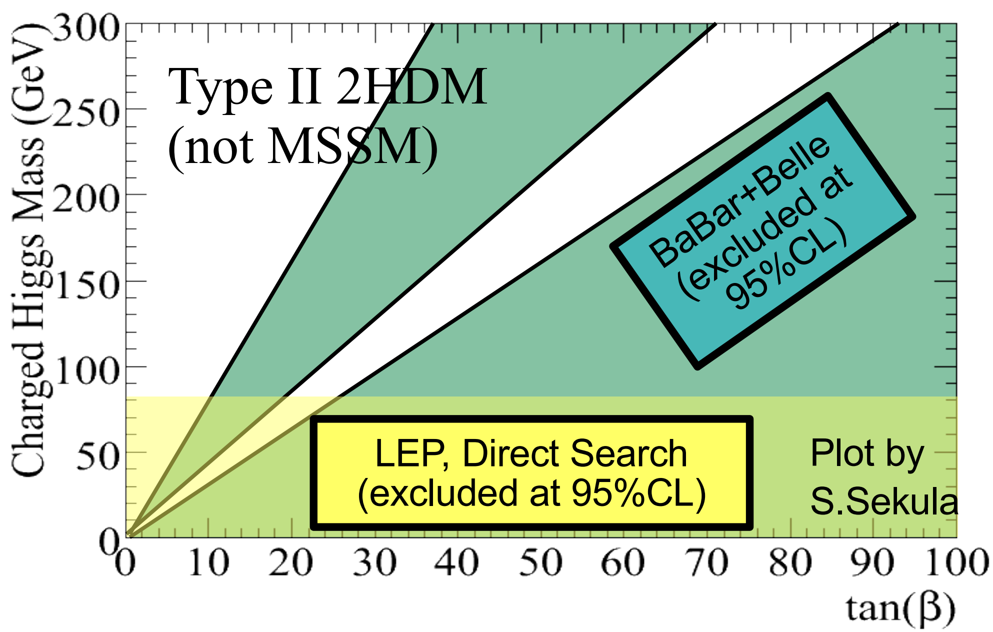
BABAR/Belle combination: **$\mathcal{B}(B^+ \to \tau^+\nu) = (1.31 \pm 0.48) \times 10^{-4}$** (~2.5σ)

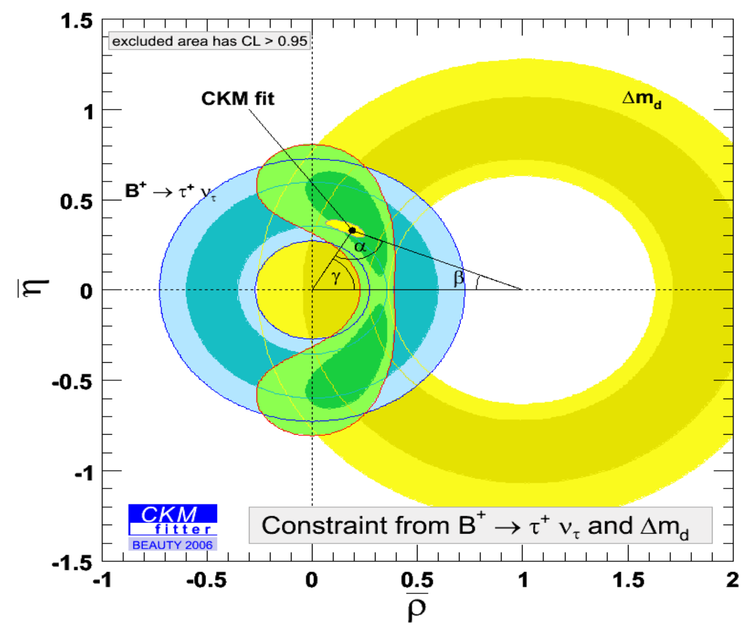
- Comparison with "SM" can be interpreted either as constraint on $|V_{ub}|$ (taking f_B from lattice), or as a direct constraint on New Physics (taking $|V_{ub}|f_B$ from Unitarity Triangle fit)

$$R_{B\tau\nu} = \frac{\mathcal{B}^{SUSY}(B_u \to \tau\nu)}{\mathcal{B}^{SM}(B_u \to \tau\nu)} = \left[1 - \left(\frac{m_B^2}{m_{H\pm}^2}\right) \frac{\tan^2\beta}{(1+\epsilon_0 \tan\beta)}\right]^2$$

No lepton flavour dependence!

- Using "SM" value from UTFit: $\mathcal{B}(B^+ \to \tau^+\nu) = (0.85 \pm 0.13) \times 10^{-4}$



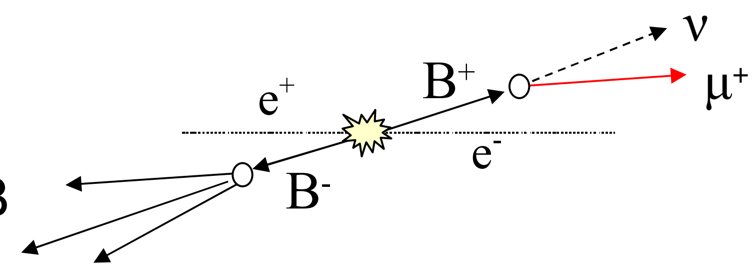


$B^+ \to l^+\nu$ (l = e, μ)

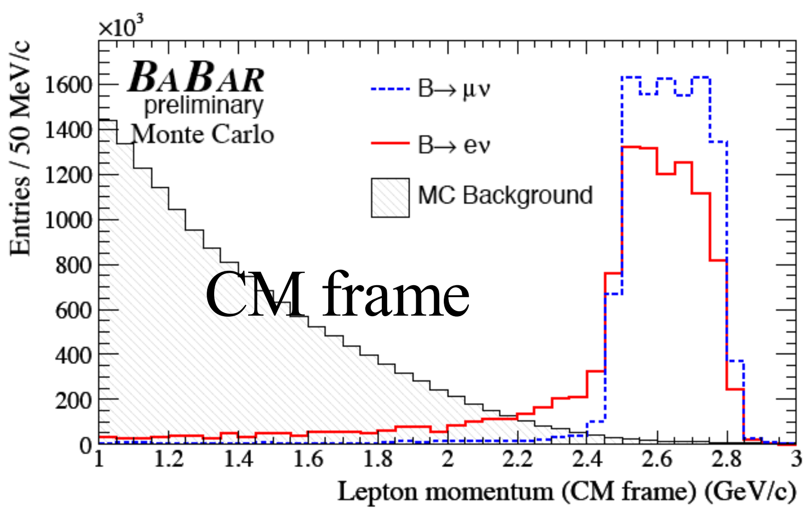
Standard Model Rates
$\mathcal{B}(B^+ \to \mu^+\nu) \sim 4\times10^{-7}$
$\mathcal{B}(B^+ \to e^+\nu) \sim 10^{-12}$

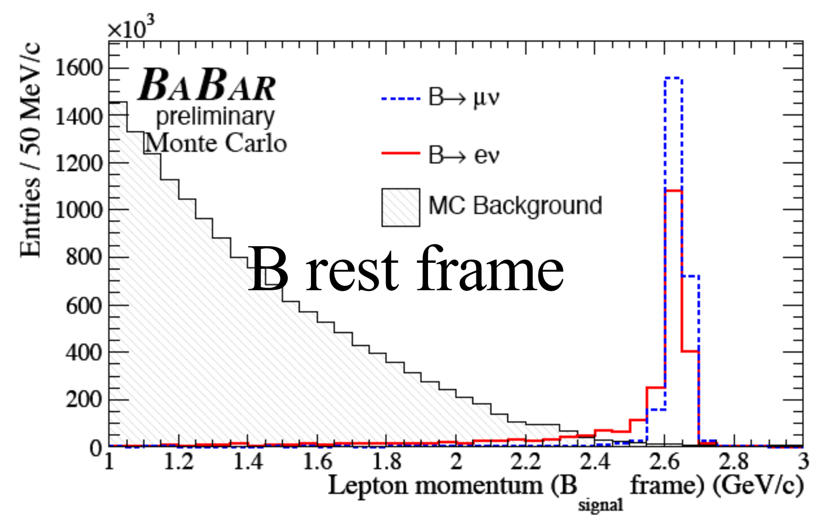
Potentially large LFV effects entering at one-loop in e.g. SUSY grand unification scenarios: different enhancements of e, μ and τ modes

Can use the same B reconstruction method to search for other leptonic modes (e, μ):



- only 1 neutrino, so reconstruction of tag B completely constrains event kinematics:
- Signal B rest frame estimated from tag B 4-vector, permitting 2-body signal kinematics to be exploited:





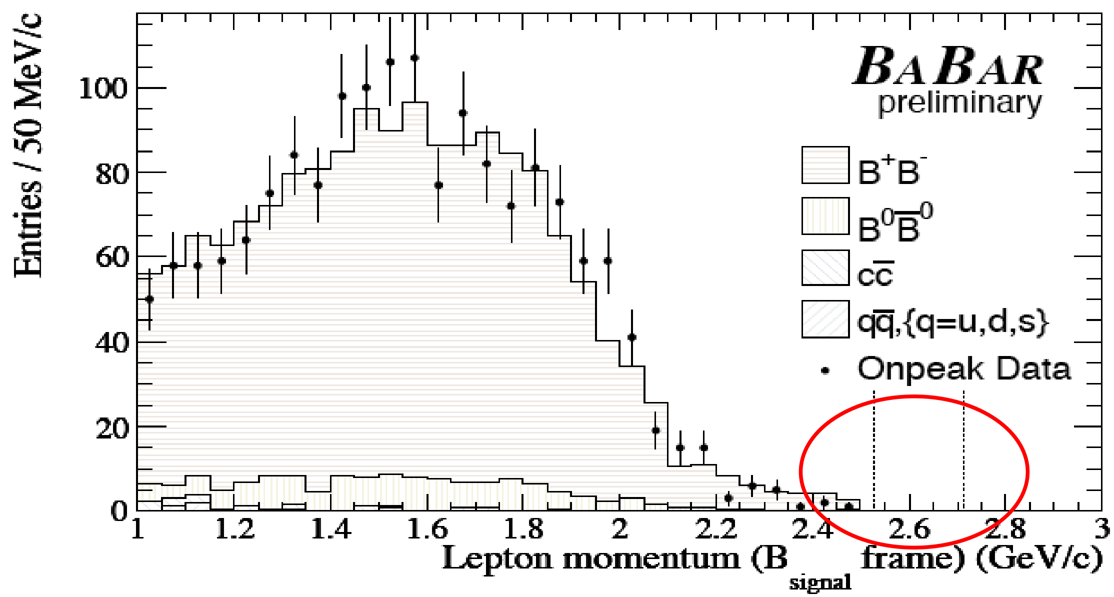
$B^+ \to l^+\nu$ (l = e, μ)

hep-ex/0607110

BABAR hadronic tagged analysis based on 229 x 10^6 BB pairs

- observed 0 events in each of e and μ channels with expected backgrounds of a 0.23 and 0.12 events respectively

$\mathcal{B}(B^+ \to e^+\nu) < 7.9 \times 10^{-6}$
$\mathcal{B}(B^+ \to \mu^+\nu) < 6.2 \times 10^{-6}$
at 90% CL



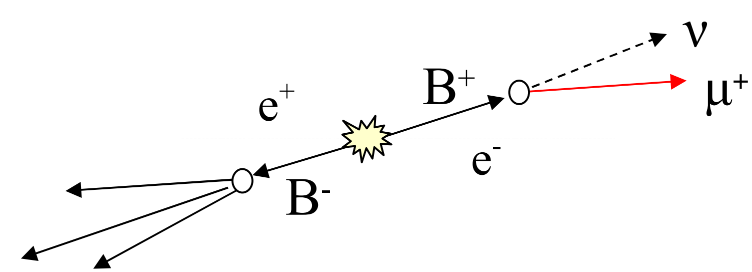
Method free from experimental issues relating to background modeling and estimation, but currently statistically limited

- complementary approach to, but not (yet) fully competitive with, "inclusive" analysis method which has been used previously by BABAR, Belle and Cleo...

Inclusive $B^+ \to l^+\nu$ (l = e, μ)

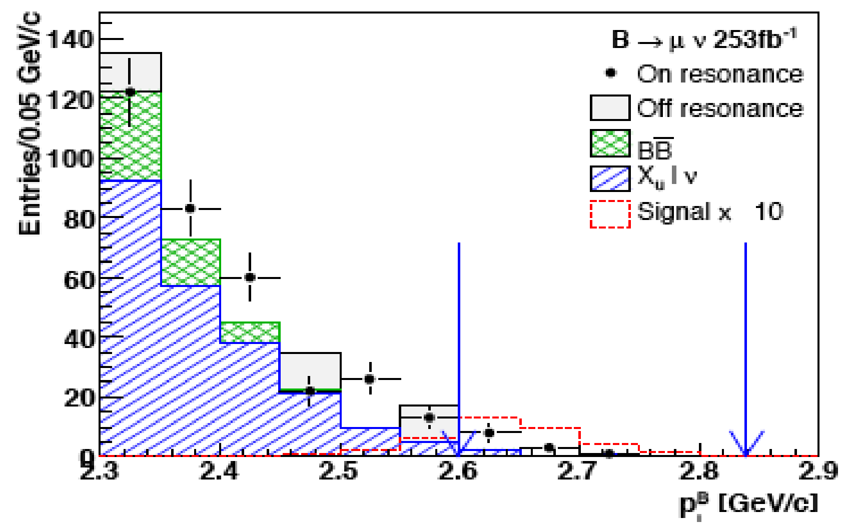
hep-ex/0611045

Reconstruct accompanying B by 4-vector sum of particles recoiling against a high momentum lepton



- Recent Belle analysis based on 253 fb^{-1}:
- Efficiencies much higher than exclusive method, but also higher backgrounds: ϵ_μ=(2.18 ± 0.06)% ϵ_e=(2.39 ± 0.06)%
- Extract signal from fit to M_{bc} distribution in region: 5.1< M_{bc} < 5.29; -0.8 (-1.0) < ΔE <0.4 GeV for μ(e)

$B(B^+ \to \mu^+\nu) < 1.7 \times 10^{-6}$
$B(B^+ \to e^+\nu) < 0.98 \times 10^{-6}$



Experimental sensitivity within a factor of ~2 of SM rate!

- Similar method has been used in previous publications by BABAR, Belle and Cleo

$B^+ \to l^+\nu\gamma$ (l = e, μ)

Presence of photon removes helicity suppression and hence universality of leptonic branching fractions is recovered

$$\Gamma(B^+ \to l^+\nu\gamma) = \alpha \frac{G_F^2 |V_{ub}|^2 m_B^5}{288\pi^2} f_B^2 \left(\frac{Q_u}{\lambda_B} - \frac{Q_b}{m_b}\right)^2$$

- λ_B related to B light cone distribution amplitude
- SM Br($B \to l\nu\gamma$) ~(1-5)x10^{-6}

(Korchemsky, Pirjol and Yan, Phys Rev D61, 114510, 2000)

Recent BABAR analysis based on 232M BB pairs:

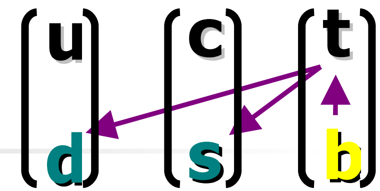
Br($B \to \mu\nu\gamma$) < 5.2 x 10^{-6}

Br($B \to e\nu\gamma$) < 5.9 x 10^{-6}

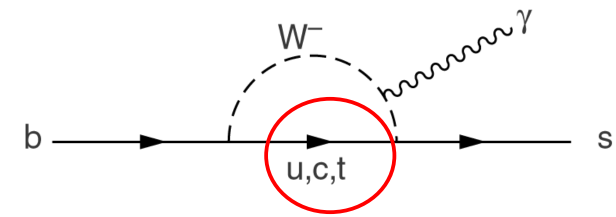
Br($B \to l\nu\gamma$) < 5.0 x 10^{-6} (combined)

- Experimental sensitivity approaching SM rate!

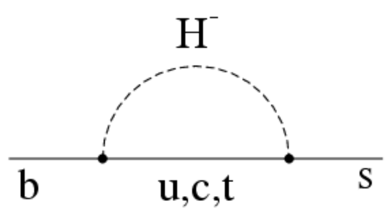
FCNC decays

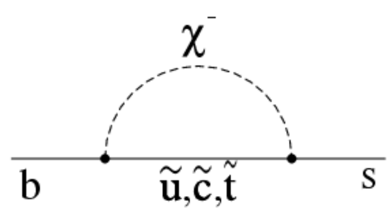


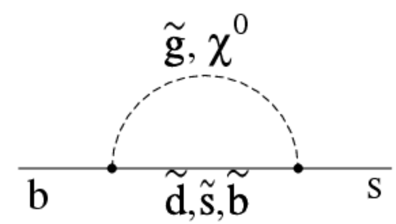
Flavour changing neutral current (FCNC) processes do not occur in SM at tree level



- Loop-mediated processes can have large contributions from non-SM diagrams of same order as leading SM contributions:







SM dominated by t-quark contribution

Low-energy effective Hamiltonian for b →s (or d) transitions:

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu)\, O_i(\mu)$$

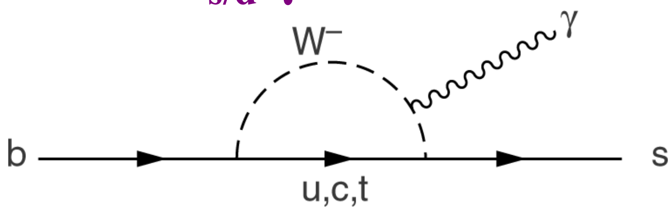
Products of field operators
(nonperturbative hadronic matrix elements;
HQE in inverse powers of m_b)

Wilson coefficients
(calculated perterbatively; encode short-distance physics)

- New Physics can enter via non-SM values of Wilson coefficients

Electroweak FCNCs

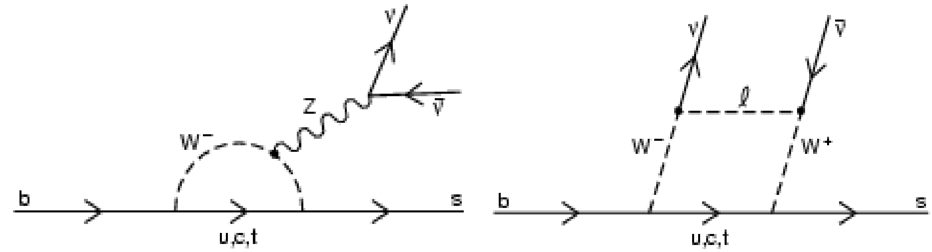
$B \to X_{s/d}\, \gamma$



C_7 (Photon penguin) only

Observables: branching fractions E_γ (or m_{had}) spectrum, A_{CP}

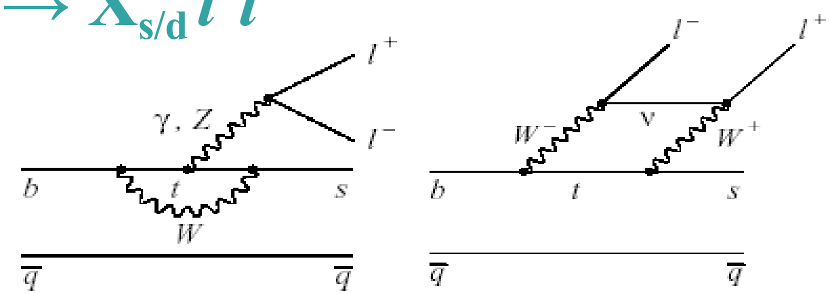
$B \to X_{s/d}\, \nu\nu$



C_{10}^{ν} only

Observables: branching fractions

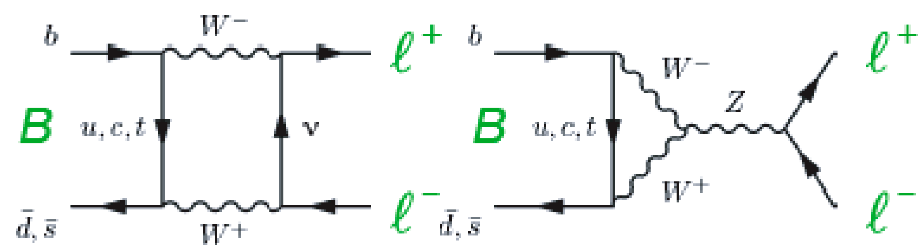
$B \to X_{s/d}\, l^+ l^-$



C_7 ,C_9 (Vector EW) and C_{10}

Observables: (partial) branching fractions, dilepton A_{FB}, A_{CP}

$B_{s/d} \to l^+ l^-$



C_{10} (Axial vector EW) only

Observables: branching fractions

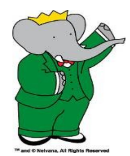
$B \to X_{s,d}\,\gamma$

Studies of radiative FCNC modes has become a major industry at the B factories

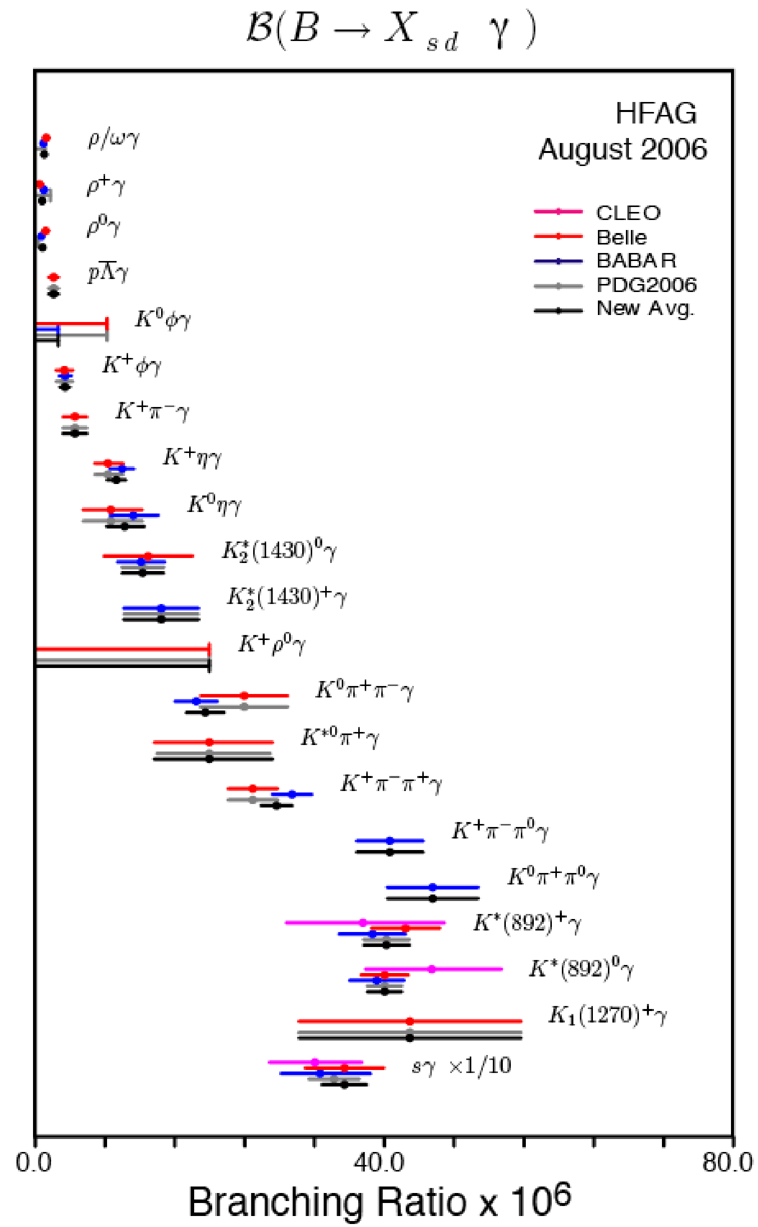
- precise determination of $b \to s\gamma$ in both inclusive and exclusive modes

  Phys.Rev.Lett.97:171803,2006.

  Phys.Rev.D72:052004,2005



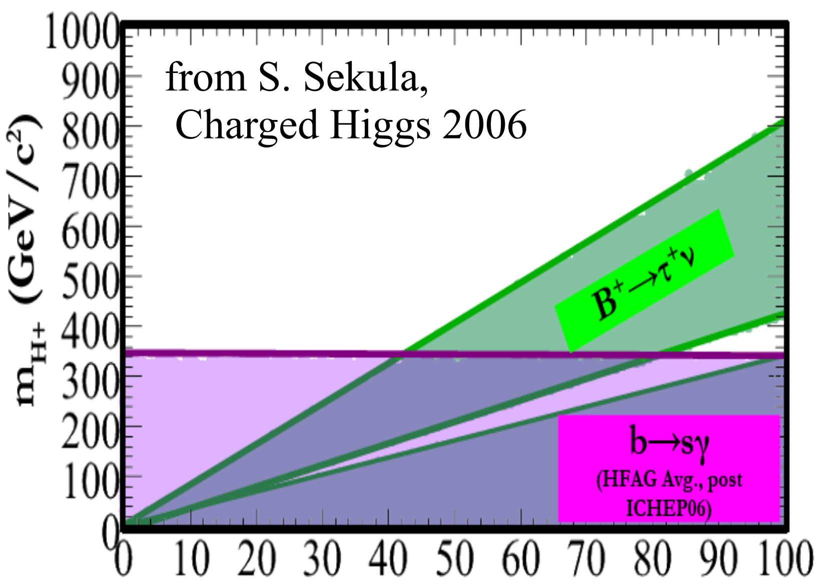
- extraction of HQET parameters from photon energy spectrum
  - beyond scope of this talk...
- recent observations of CKM suppressed $b \to d\gamma$ decays in exclusive modes

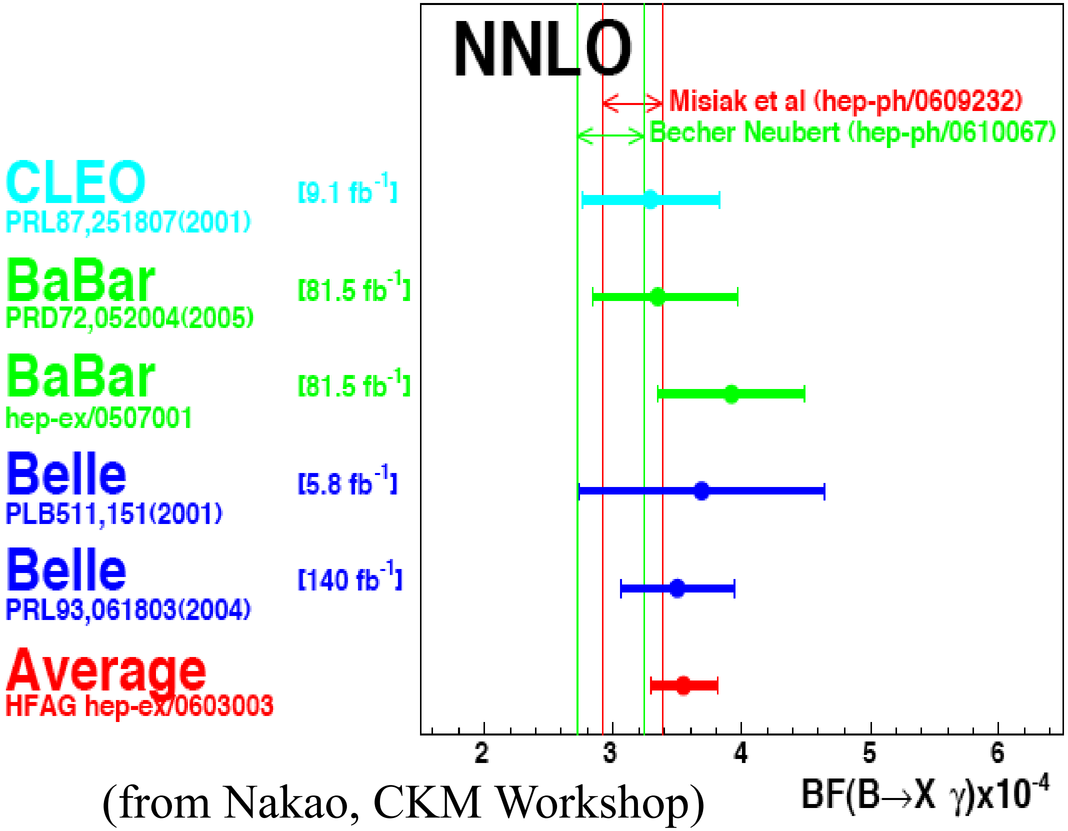


$B \to X_s \gamma$

Inclusive $B \to X_s \gamma$ measurement is one of the most sensitive indirect probes of New Physics

- Recent improvements to NNLO calculations resulted in a downward shift to the SM range for $B \to X_s \gamma$
- Experimental average now slightly high, effectively opening a window for New Physics!



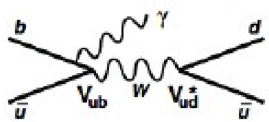


(from Nakao, CKM Workshop)

$B\to\rho(770)\gamma$ and $B\to\omega(782)\gamma$

CKM suppressed FCNC modes have simple relation to $b\to s\gamma$ modes

- Comparison of rates for (exclusive) $b\to d\gamma$ and $b\to s\gamma$ can be used to extract off-diagonal CKM elements relating to top quark



Weak annihilation correction

$\Delta R = 0.1 \pm 0.1$

Ali, Lunghi, Parkhomenko, PLB 595,323 (2004)

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

Flavour SU(3) breaking

$\zeta = 1.17 \pm 0.09$

(ratio of form factors from LC sum rules)

Ball and Zwicky, JHEP 0604, 046 (2006); Ball and Zwicky, hep-ph/0603232

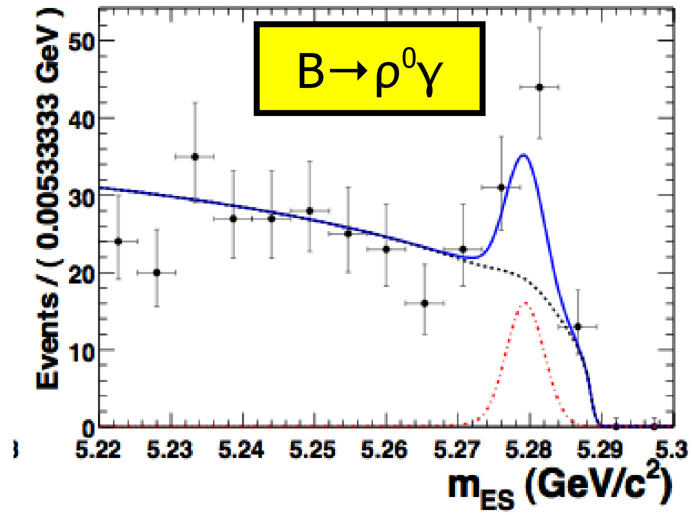
Experimentally challenging due to small signal branching fractions and high backgrounds

- substantial backgrounds due to photons arising from π^0, η and $b\to s\gamma$ decays

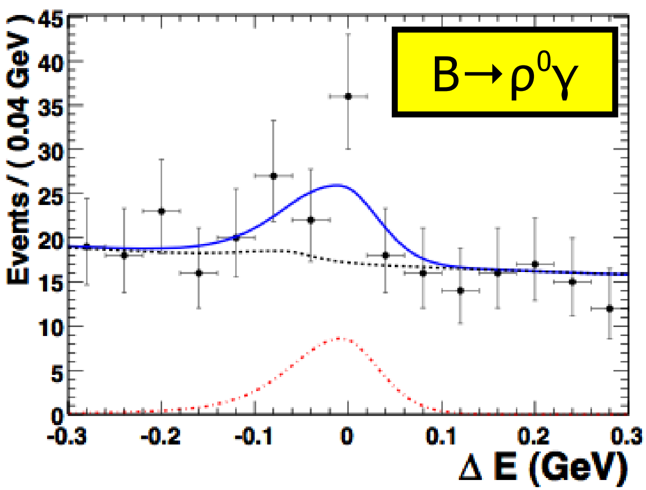
B→ρ(770)γ and B→ω(782)γ

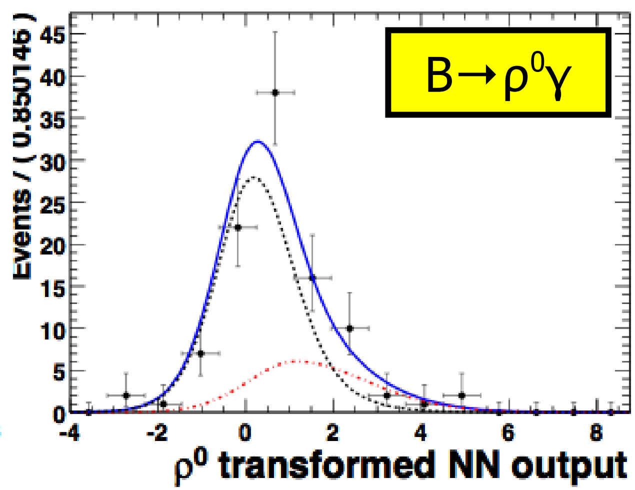
Signal extracted from a maximum likelihood fit to signal + background

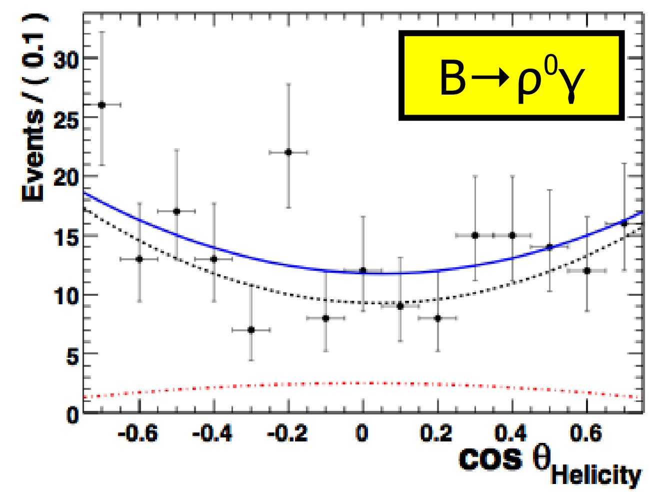
- B→ργ: m_{ES}, ΔE, NN, $\theta_{helicity}$ (4 parameters)
- B→ωγ: + Dalitz angle (5 parameters)



-- Signal -- Background — S+B

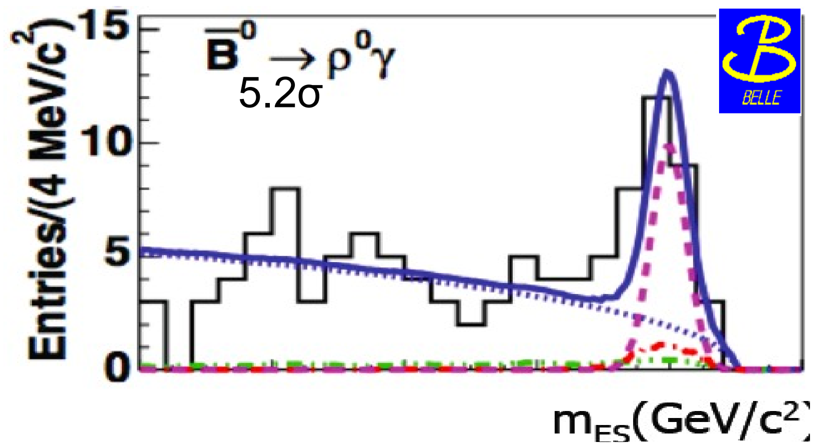


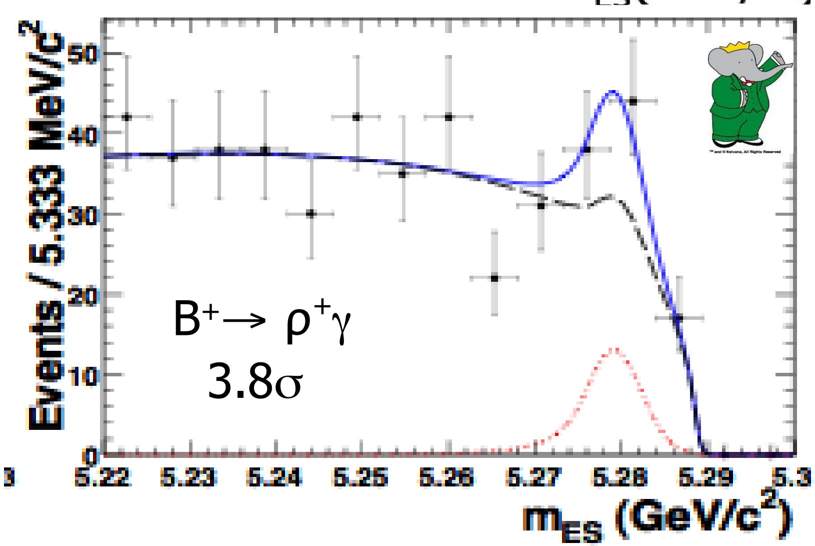




$B \to (\rho/\omega)\gamma$ results

Belle PRL 96, 221601 (2006)



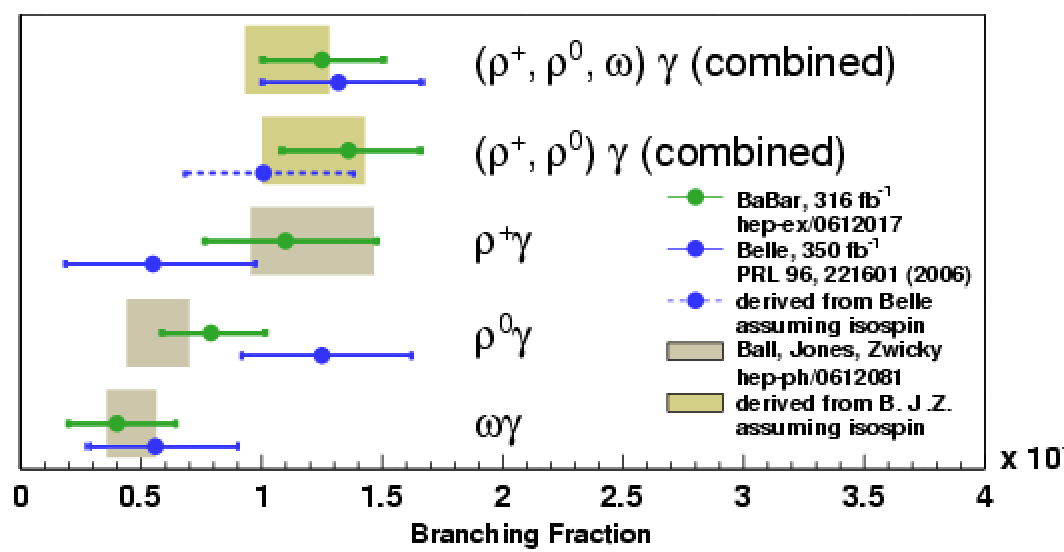


BABAR hep-ex/0612017
to appear in PRL (316fb^{-1})

BABAR $B \to (\rho/\omega)\gamma$

Mode	N_{signal}	*Significance*	$BF(10^{-6})$
$B^+ \to \rho^+\gamma$	$42.0^{+14.0}_{-12.7}$	3.8σ	$1.10^{+0.37}_{-0.33} \pm 0.09$
$B^0 \to \rho^0\gamma$	$38.7^{+10.6}_{-9.8}$	4.9σ	$0.79^{+0.22}_{-0.20} \pm 0.06$
$B^0 \to \omega\gamma$	$11.0^{+6.7}_{-5.6}$	2.2σ	$0.40^{+0.24}_{-0.20} \pm 0.05$
Combined BF		6.4σ	$1.25^{+0.25}_{-0.24} \pm 0.09$

Isospin test: $$\frac{\Gamma(B^+ \to \rho^+\gamma)}{2\Gamma(B^0 \to \rho^0\gamma)} - 1 = -0.35 \pm 0.27$$



Determination of $|V_{td}/V_{ts}|$

Combination of BABAR and Belle results premits extraction of ratio $|V_{td}/V_{ts}|$:

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

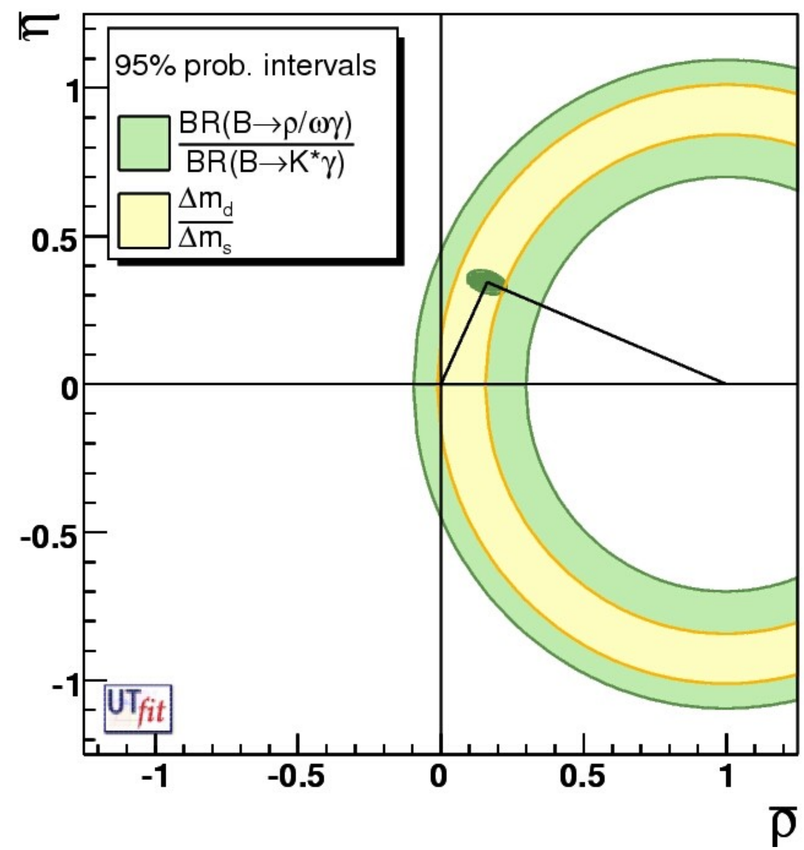
	$B(B \to (\rho/\omega)\gamma)$ (10^{-6})
BABAR	$1.25\,^{+0.25}_{-0.24} \pm 0.09$
Belle	$1.32\,^{+0.34+0.10}_{-0.31+0.09}$
Average	$1.28\,^{+0.20}_{+0.20} \pm 0.06$

$$|V_{td}/V_{ts}|_{\rho/\omega\gamma} = 0.202\,^{+0.017}_{+0.016}\,(\text{exp}) \pm 0.015\,(\text{th})$$

- Experimental uncertainties currently comparable to theory

Good agreement with results from B mixing (combination of B_d and B_s)

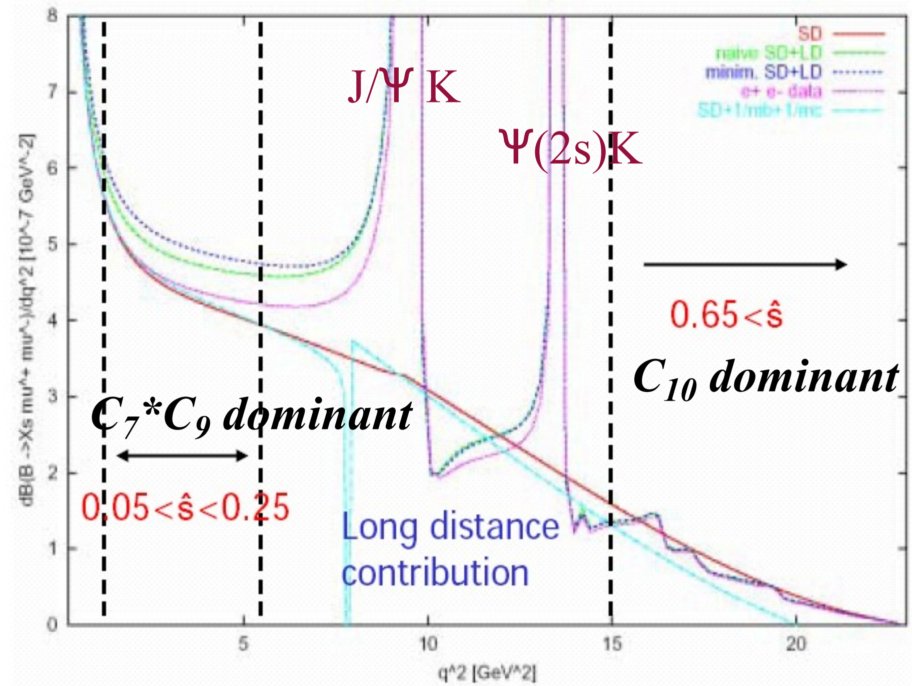
(See also Ball, Jones, Zwicky hep-ph/0612081)

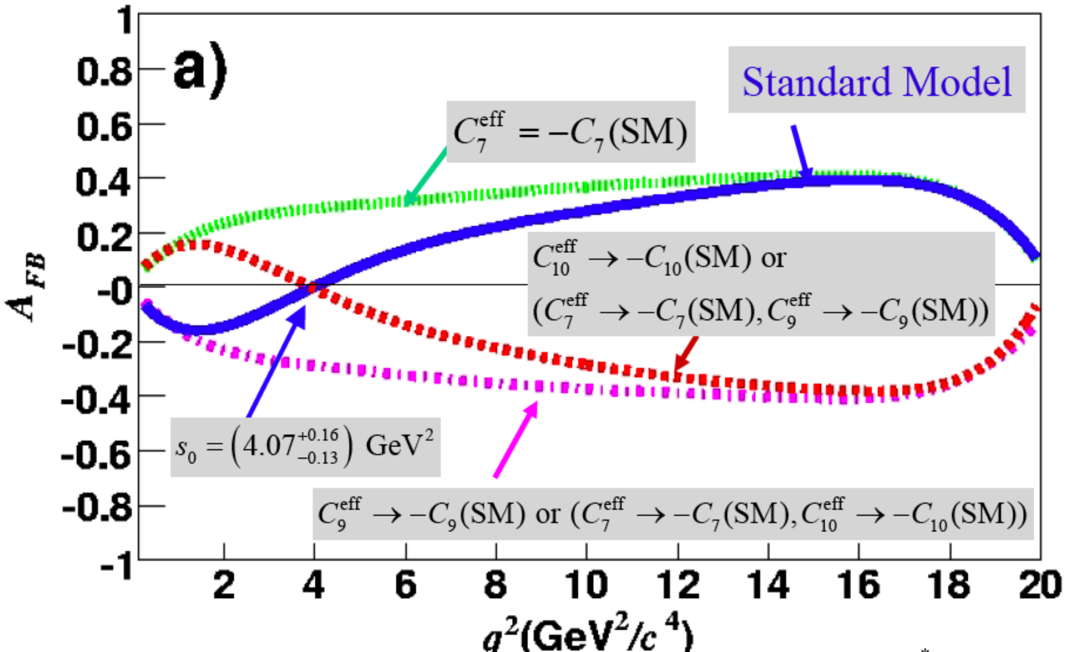


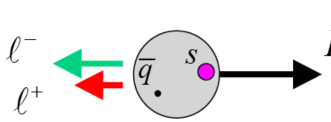
$B \to K^{(*)} l^+ l^-$

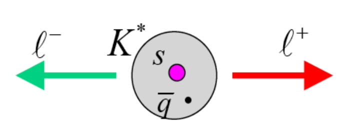
$B \to X_s l^+ l^-$ receives contributions from C_7 (photon penguin), C_9 (vector EW) and C_{10} (axial-vector EW)

- Also substantial long-distance contributions (J/Ψ K and Ψ(2s)K)







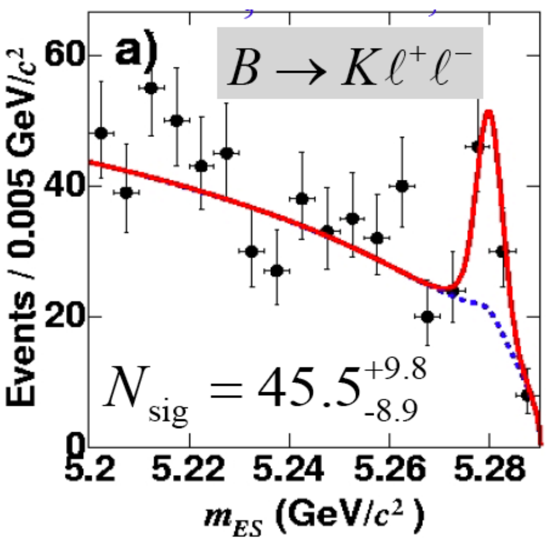


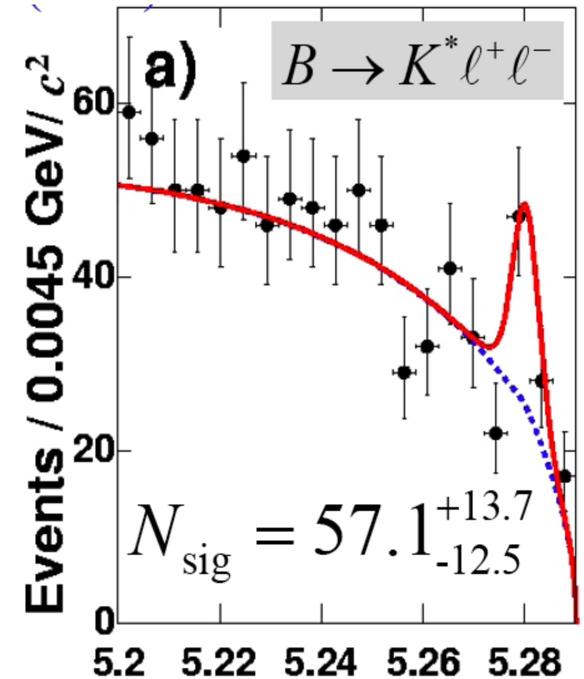
Interference between contributing amplitudes produces asymmetries in lepton angular distribution

- A_{FB} sensitive to non-SM values of Wilson coefficients

B→ $K^{(*)}l^+l^-$ Results

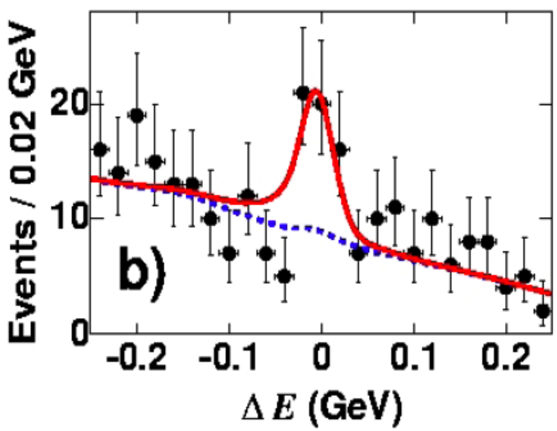
Signals clearly visible for both B→Kl^+l^- and B→$K^*l^+l^-$ in current BABAR (and Belle) data samples:

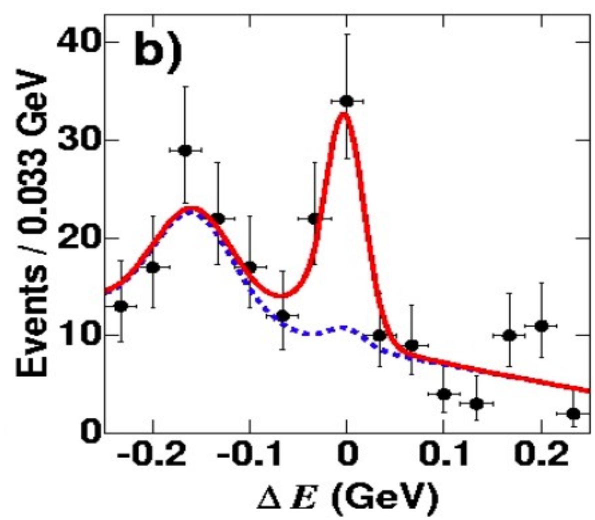


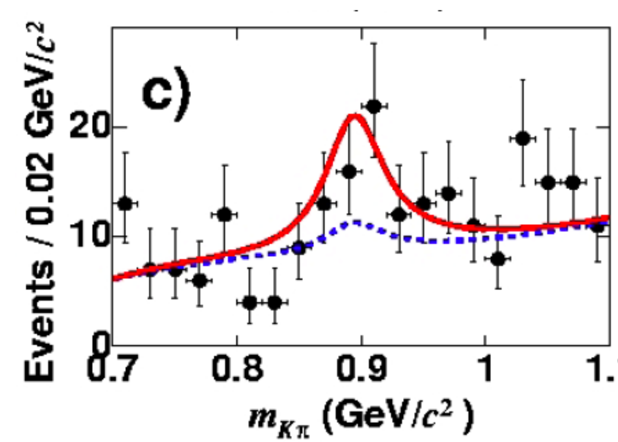


Signal extracted from fit to

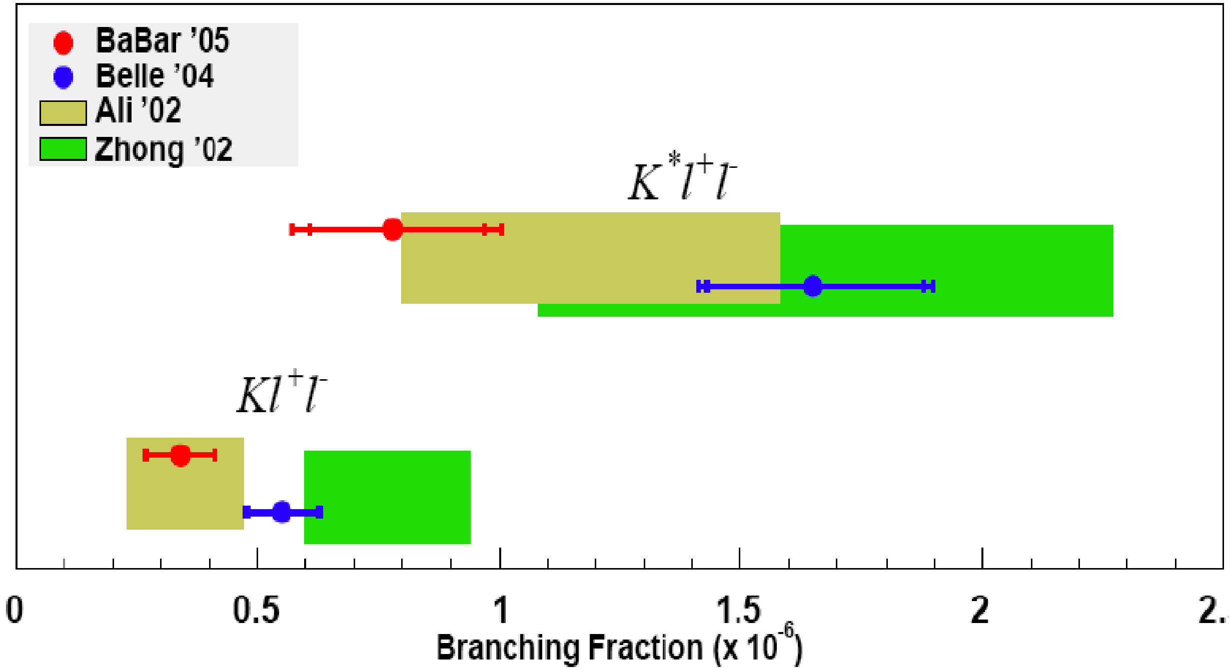
- m_{ES} and ΔE for Kl^+l^- (2D)
- + $m_{K\pi}$ for $K^*l^+l^-$ (3D)







$B \to K^{(*)} l^+ l^-$ Branching Fractions



BABAR (209 fb^{-1}) PRD 73, 092001 (2006)

$$B(B \to K l^+ l^-) = (0.34 \pm 0.07 \pm 0.02) \times 10^{-6} \quad (6.6\sigma)$$

$$B(B \to K^* l^+ l^-) = (0.78\,^{+0.19}_{-0.17} \pm 0.11) \times 10^{-6} \quad (5.7\sigma)$$

Belle preliminary (253 fb^{-1}) hep-ex/0410006

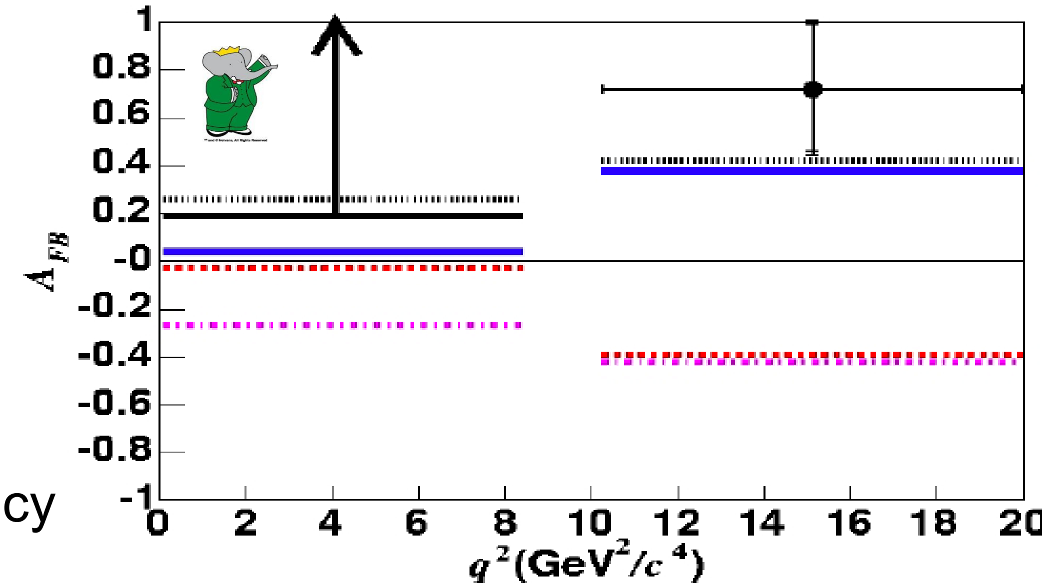
$$B(B \to K l^+ l^-) = (0.550\,^{+0.75}_{+0.70} \pm 0.027) \times 10^{-6}$$

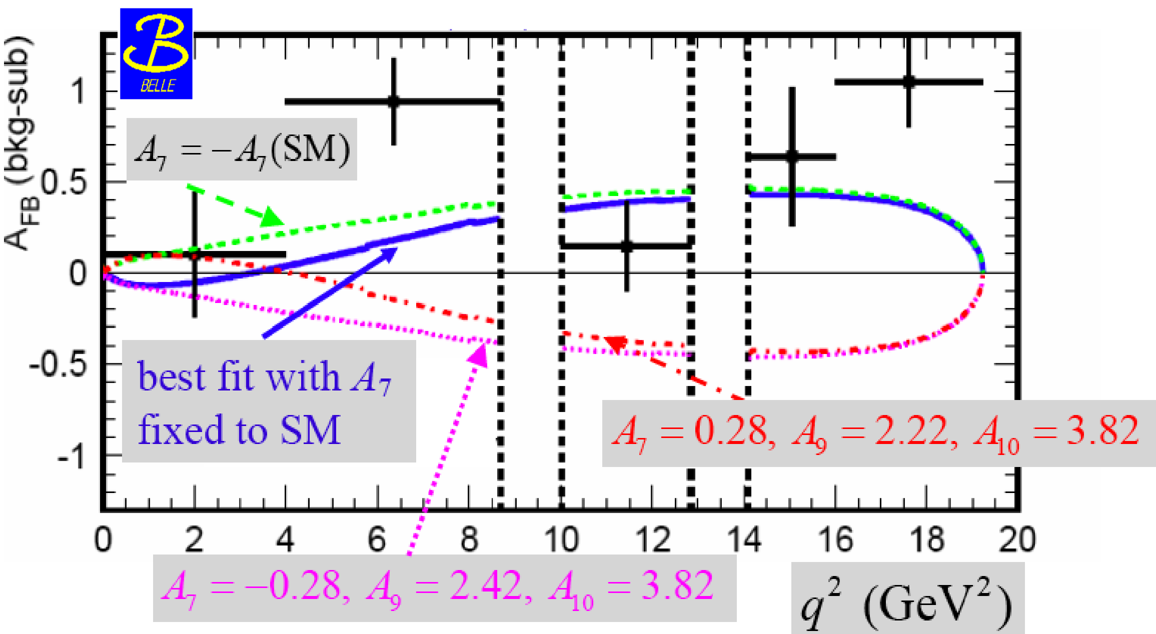
$$B(B \to K^* l^+ l^-) = (1.65\,^{+0.23}_{-0.22} \pm 0.11) \times 10^{-6}$$

Determination of A_{FB}

BABAR and Belle have both reported first results of A_{FB} determination in specific q^2 regions with sensitivity to Wilson coefficients

- Favours SM value for C_{10} (high q^2) but less consistency in low q^2 region





PRD 73, 092001 (2006)

PRL 96 251801 (2006)

Conclusion

Rare B decays are a very interesting place to look for New Physics!

- First indications of signal in $B^+ \to \tau^+ \nu$ and approaching sensitivity to SM rates in $B^+ \to \mu^+ \nu$ and $B^+ \to l^+ \nu\gamma$
- Observation of CKM-suppressed b→d FCNC modes ($B \to (\rho/\omega)\gamma$) and precise determination of CKM-favoured $b \to s\gamma$
- First determinations of kinematic observables (q^2 spectrum and A_{FB}) in $B \to K^{(*)} l^+ l^-$

Anticipate more than a factor of two data before the end of nominal PEP-II and KEKB programs around 2008