Rare B Meson Decays

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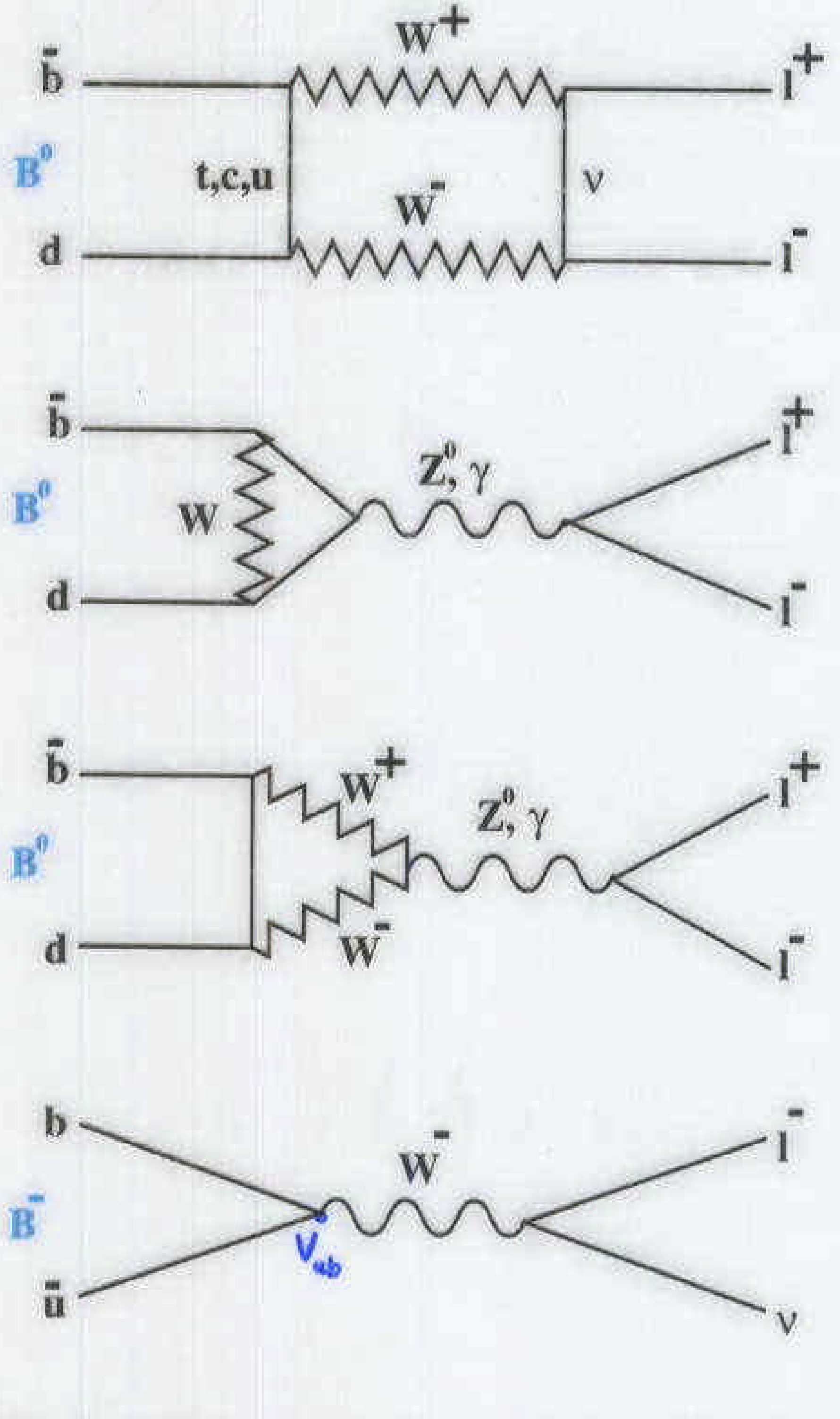
Abstracts: #541, 544, 545, 546

- 541: $B \to \tau\nu_\tau$
- 546: $B \to e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp$
- 544: $B \to$ charmless (PP, PV) states
  - $B \to \pi\pi, K\pi, KK, \eta' K$, CP asymmetries,
  - $B \to \eta' K$,
  - $B \to \rho\pi, \omega\pi, K^*\pi$
- 545: $B \to \phi K$

Use complete CLEO II data sample of 9.66×10^6 $B\bar{B}$ events.

Leptonic B Decays: $B \to l^+l^-, B \to \tau\nu$



Standard Model Expectations

- $BR(B^0 \to e^+e^-) \simeq 2.6 \times 10^{-15}$
- $BR(B^0 \to \mu^+\mu^-) \simeq 1.1 \times 10^{-10}$
- $BR(B^0 \to e^\pm\mu^\mp)$ forbidden
- $BR(B^+ \to \tau^+\nu_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$
  $\simeq$ 2-10 $\times 10^{-5}$
  $= (4.08 \pm 0.24) \times 10^{-4} \frac{|V_{ub}|}{|V_{td}|}$

Cross Section Enhanced Due to New Physics:

- Two Higgs doublet Models
- SUSY
- Pati-Salam Leptoquark Models

Present Status:

- $BR(B^0 \to e^+e^-) < 59 \times 10^{-7}$ (CLEO, 1994)
- $BR(B^0 \to \mu^+\mu^-) < 6.8 \times 10^{-7}$ (CDF, 1998)
- $BR(B^0 \to e^\pm\mu^\mp) < 35 \times 10^{-7}$ (CDF, 1998)
- $M_{LQ} > 21.7$ TeV/c^2 (CDF, 1998)
- $BR(B^+ \to \tau^+\nu_\tau) < 5.7 \times 10^{-4}$ (L3, 1997)

Analysis: $B \to l^+ l^-$

Signal Event Selection

- 2 Track with Lepton ID and Opposite Charge
- Beam Constrained Mass
  $M_B - \sqrt{E_{beam}^2 - (p_{l^+} + p_{l^-})^2} \leq 3\sigma$
- Energy Constraint
  $E_{l^+} + E_{l^-} - E_{beam} < 75 MeV(\mu\mu), < 100 MeV(e\mu, ee)$

Background Study (not much is expected)

- $B\bar{B}$ backgrounds (< 0.02 events)
  - Generic $B\bar{B}$ backgrounds
  - $b \to c(u) l\nu$
  - $B^0 \to K^+\pi^-, \pi^+\pi^-$ etc
- $\tau^+\tau^-$ backgrounds (< 0.5 events)
- $e^+e^- \to q\bar{q}$ where $q = u, d, s, c$ (< 0.2 events)

Analysis: $B \to \tau\nu_\tau$

New Technique:

Fully reconstruct one B and study decays of other B

Reconstruction of charged B (8200 events)

- $B^+ \to D^{(*)} + n\pi$, n=1,2..5
- D reconstructed in 8 modes $D \to K + n\pi$
- use $D^* - D$ mass constraint

Search for other B decay: $B \to \tau \to$ one prong (e, μ, π)

Found 6 candidates compatible with background

Likelihood fit to the kinematics of the reconstructed B (no additional information in the single track) gives an upper limit

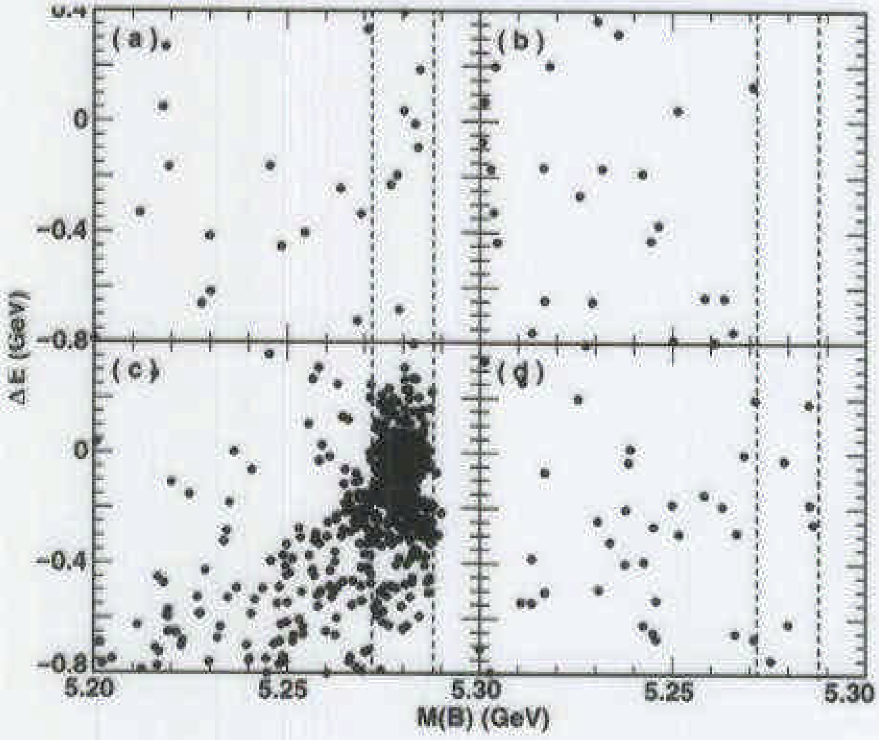
$$\mathrm{BR}(B \to \tau\nu_\tau) < 8.4 \times 10^{-4} \text{ (90\% CL)}$$

Byproduct

Require consistency with kaon kinematics/identification

$$\mathrm{BR}(B \to K\nu\nu) < 2.4 \times 10^{-4} \text{ (90\% CL)}$$

$B \to \tau\nu$ in Data and Monte Carlo



(a) $B\bar{B}$ Monte Carlo

(b) Continuum Monte Carlo

(c) Signal Monte Carlo

(d) Data

Results

Decay Mode	Efficiency (with errors)	Evts	UL @ 90% C.L.
$B^0 \to e^+e^-$	$31.3 \pm 0.4 \pm 2.4\%$	0	$< 8.3 \times 10^{-7}$
$B^0 \to \mu^+\mu^-$	$42.4 \pm 0.5 \pm 3.2\%$	0	$< 6.1 \times 10^{-7}$
$B^0 \to e^\pm\mu^\mp$	$43.6 \pm 0.5 \pm 7.1$ %)	2	$< 15 \times 10^{-7}$
$B^+ \to \tau\nu_\tau$	32.9 ± 0.1 %	0.96	$< 8.4 \times 10^{-4}$

New Limit on Leptoquarks

$$\Gamma(B^0 \to e^\pm\mu^\mp) = \pi\alpha_s^2(M_{LQ})\frac{1}{M_{LQ}^4}F_B^2 m_B^3 R^2$$

$$R = \frac{m_B}{m_b}\left(\frac{\alpha_s(M_{LQ})}{\alpha_s(m_t)}\right)^{-\frac{4}{7}}\left(\frac{\alpha_s(m_t)}{\alpha_s(m_b)}\right)^{-\frac{12}{23}}$$

$M_{LQ} > 26.9$ TeV at 90% CL

New Limit on $B \to \tau\nu_\tau$:

BR(B→ $\tau\nu_\tau$) $< 8.4 \times 10^{-4}$

New Limit on $B \to K\nu\nu$:

BR(B→ $K\nu\nu$) $< 2.4 \times 10^{-4}$

Charmless Hadronic Two-Body B Decays

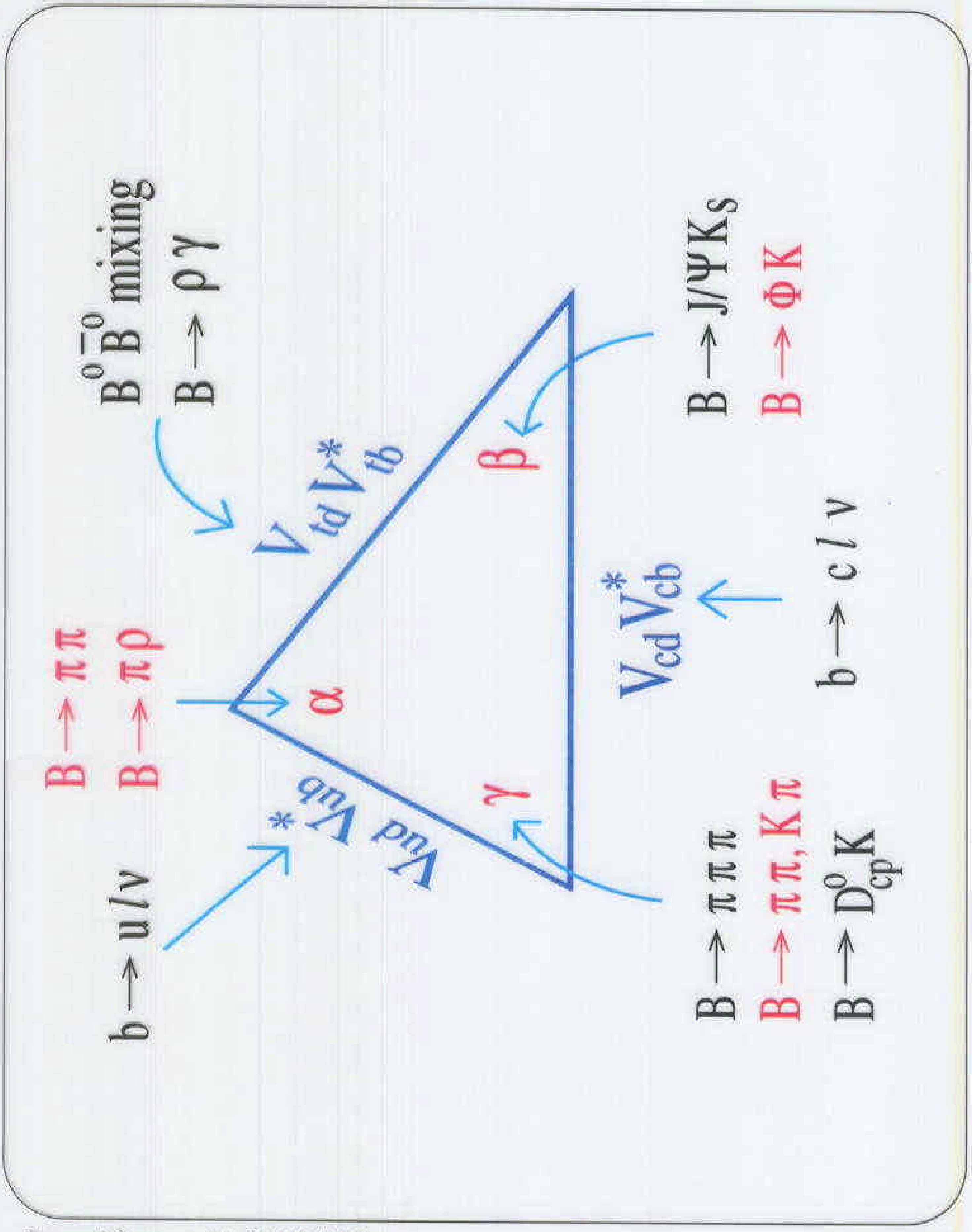
Goals:

- Construct a coherent description of the weak quark couplings and their phases.
- Establish CP violation outside kaon sector: direct or mixing induced.
- Test unitarity of CKM matrix.
- Search for non-SM physics.

Two main types of diagrams:

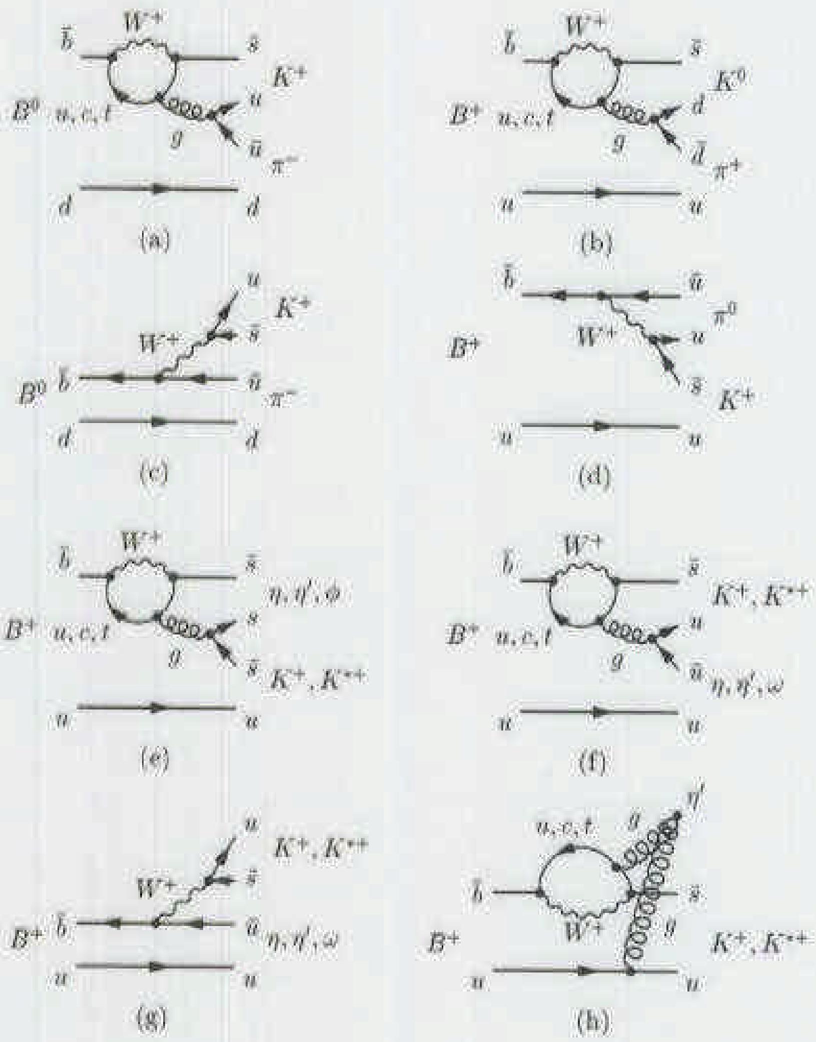
- $b \to u$ spectator (tree) diagrams (suppressed by V_{ub}),
- $b \to s$ penguin diagrams (suppressed by loops),
  - EM penguins: $b \to s\gamma$ (seen by CLEO in 1993),
  - gluonic penguins: $b \to sg$ (seen by CLEO in 1997).

Ratios of branching fractions allow to extract information on angles of unitarity triangle.


$B^0\bar{B}^0$ mixing
$B \rightarrow \rho\gamma$
$B \rightarrow \pi\pi$
$B \rightarrow \pi\rho$
$b \rightarrow u\, l\, \nu$
$V_{td}V_{tb}^*$
$V_{ud}V_{ub}^*$
$V_{cd}V_{cb}^*$
α
β
γ
$B \rightarrow J/\Psi K_S$
$B \rightarrow \Phi K$
$b \rightarrow c\, l\, \nu$
$B \rightarrow \pi\pi\pi$
$B \rightarrow \pi\pi, K\pi$
$B \rightarrow D^0_{cp}K$

Feynman Diagrams

Dominant diagrams for charmless hadronic B decays.



- Usually, there is more than one contribution → **interference**

► Must measure many related modes

Analysis Technique for Rare B Decays

Signal: $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ $(\sigma \sim 1$ nb$)$

Background: $e^+e^- \to q\bar{q}$, $q = u, d, s, c$ $(\sigma \sim 3$ nb$)$

Initial selection constraints:

- $m_B \equiv \sqrt{E^2_{\rm beam} - |\sum_i \mathbf{p}_i|^2}$ $(\sigma_{m_B} \approx 2.5$ MeV$)$
- $\Delta E \equiv \sum_i E_i - E_{\rm beam}$ $(\sigma_{\Delta E} \approx 20\text{-}30$ MeV$)$
- Continuum suppression via event shape (continuum "jetty", $B\overline{B}$ "spherical")

Yields determined from unbinned maximum likelihood fits.

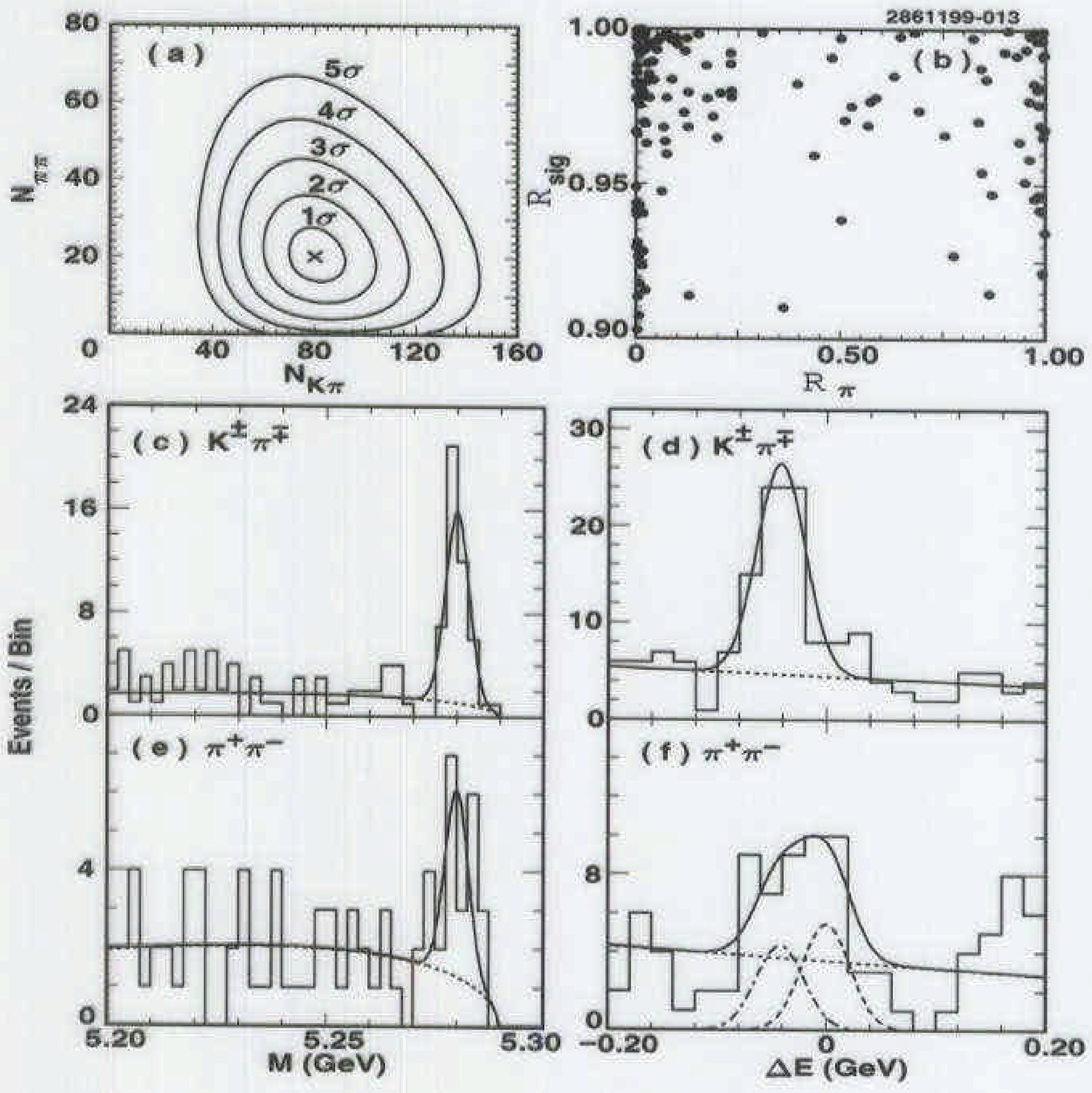
Variables used to distinguish signal from background:

- Mass and energy of B candidates: m_B and ΔE.
- Fisher discriminant - *linear combination of 11 shape variables.*
- B candidate flight direction.
- Resonance masses and helicity angle for VP decays.
- dE/dx and ΔE for particle ID.

  At high p, weak separation of $K^\pm$ and $\pi^\pm \Rightarrow$
  Simultaneously fit for both components
  (*e.g.* $B \to K^\pm\pi^\mp/\pi^\pm\pi^\mp$).

Dominant remaining background - cross-feed from other rare B decays.

Illustration of Fit Results for $B \to K^{\pm}\pi^{\mp}$, $\pi^{\pm}\pi^{\mp}$



$B \to K\pi,\ \pi\pi$

(For modes with K^0, yields are for K^0_S, all other numbers for K^0.)
(All upper limits at 90% C.L.)

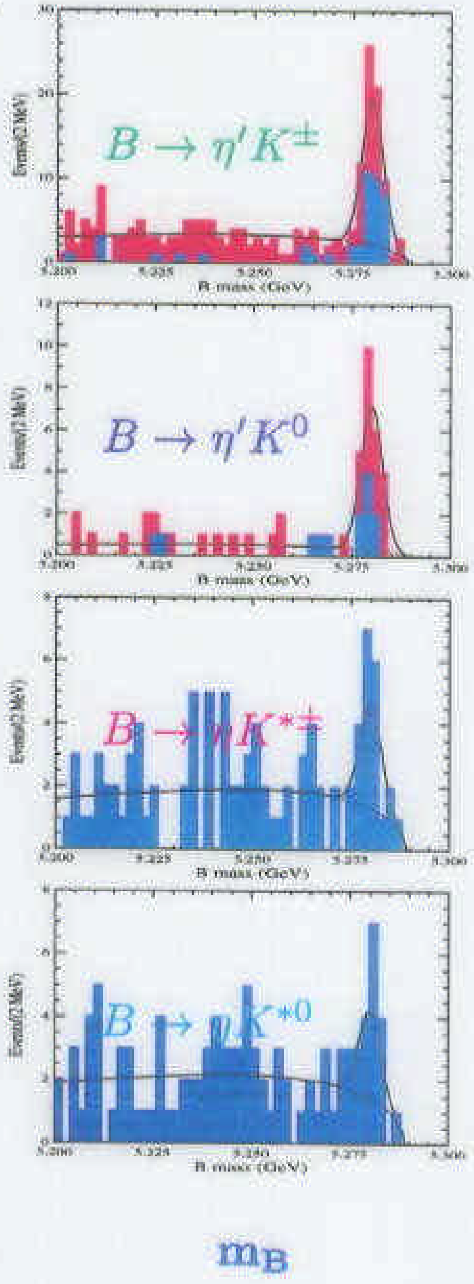
Mode	$\epsilon(\%)$	Yield	Signif.	$\mathcal{B}(10^{-6})$
$K^\pm\pi^\mp$	48	$80.2^{+11.8}_{-11.0}$	11.7σ	$17.2^{+2.5}_{-2.4}\pm1.2$
$K^0\pi^\pm$	14	$25.2^{+6.4}_{-5.6}$	7.6σ	$18.2^{+4.6}_{-4.0}\pm1.6$
$K^\pm\pi^0$	38	$42.1^{+10.9}_{-9.9}$	6.1σ	$11.6^{+3.0+1.4}_{-2.7-1.3}$
$K^0\pi^0$	11	$16.1^{+5.9}_{-5.0}$	4.9σ	$14.6^{+5.9+2.4}_{-5.1-3.3}$
$\pi^\pm\pi^\mp$	48	$20.0^{+7.6}_{-6.5}$	4.2σ	$4.3^{+1.6}_{-1.4}\pm0.5$
$\pi^\pm\pi^0$	39	$21.3^{+9.7}_{-8.5}$	3.2σ	< 12.7
$\pi^0\pi^0$	29	$6.2^{+4.8}_{-3.7}$	2.0σ	< 5.7
$K^\pm K^\mp$	48	$0.7^{+3.4}_{-0.7}$	0.0σ	< 1.9
$K^\pm K^0$	14	$1.4^{+2.4}_{-1.3}$	1.1σ	< 5.1
$K^0\bar{K}^0$	5	0	0.0σ	< 17

PRL 80, 3456 (1998), PRL 85, 515 (2000) + Abstract #544

- General agreement with theoretical expectations.
- All four $K\pi$ and $\pi^+\pi^-$ modes finally observed!
- $\pi^+\pi^-$ rate small and only UL for $\pi^0\pi^0 \to$ no strong phase enhancement
- Gluonic penguins are large.

Modes with η' and η

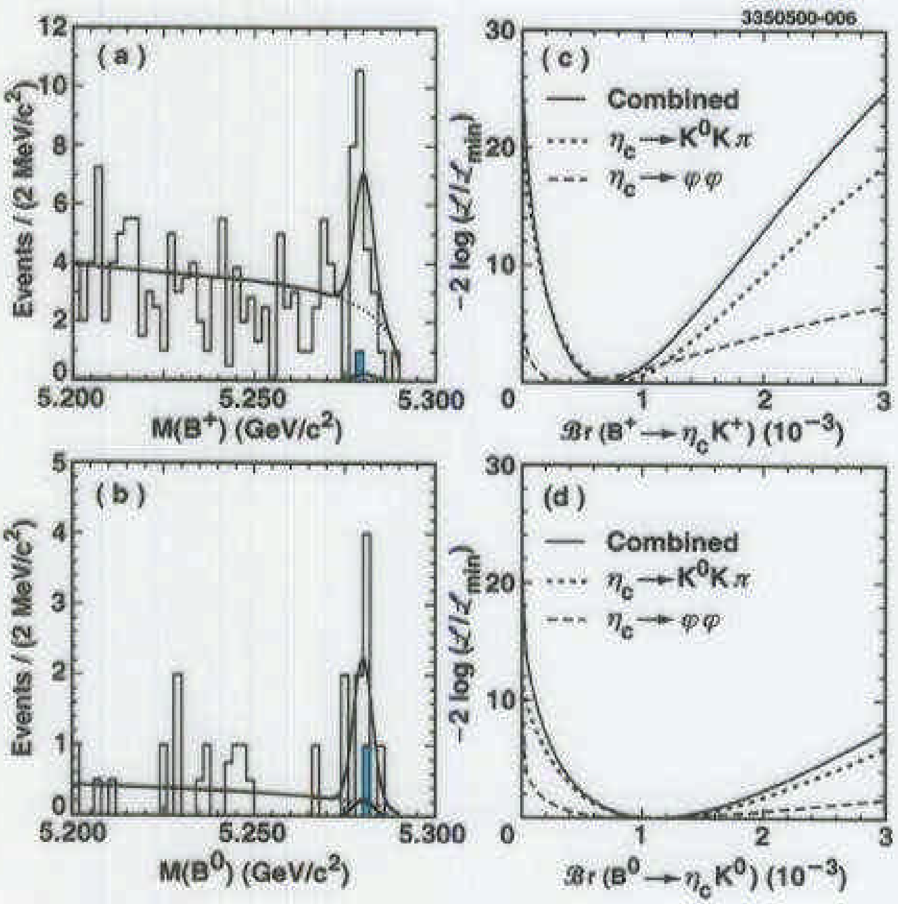
Mode	Signif.	$\mathcal{B}$ (10^{-6})
$B^+ \to \eta' K^+$	16.8σ	$80^{+10}_{-9} \pm 7$
$B^0 \to \eta' K^0$	11.7σ	$89^{+18}_{-16} \pm 9$
$B^+ \to \eta' \pi^+$	0.0σ	< 12
$B^0 \to \eta' \pi^0$	0.0σ	< 5.7
$B^+ \to \eta' K^{*+}$	1.8σ	< 35
$B^0 \to \eta' K^{*0}$	1.8σ	< 24
$B^+ \to \eta' \rho^+$	2.4σ	< 33
$B^0 \to \eta' \rho^0$	0.0σ	< 12
$B^+ \to \eta K^+$	0.8σ	< 6.9
$B^0 \to \eta K^0$	0.0σ	< 9.3
$B^+ \to \eta \pi^+$	0.6σ	< 5.7
$B^0 \to \eta \pi^0$	0.0σ	< 2.9
$B^+ \to \eta K^{*+}$	4.8σ	$26.4^{+9.6}_{-8.2} \pm 3.3$
$B^0 \to \eta K^{*0}$	5.1σ	$13.8^{+5.5}_{-4.6} \pm 1.6$
$B^+ \to \eta \rho^+$	1.3σ	< 15
$B^0 \to \eta \rho^0$	1.3σ	< 10



PRL 80, 3710 (1998) + PRL 85, 520 (2000)

Interpretation of results still unclear.

- Decay rate into η' larger than that into η.
- Interference of gluonic penguin diagrams: constructive for $\eta' K$ and ηK^* and destructive for ηK and $\eta' K^*$ (Lipkin 1991) is qualitatively OK but numerical problems remain.
- Intrinsic charm content of η' has been proposed but no corresponding enhancement of the $B \to \eta_c K$ channel has been seen. CLNS 00/1680,hep-ex/0007012



$$\mathrm{BR}(B^0 \to \eta_c K^0) = (1.09^{+0.55}_{-0.42} \pm 0.12 \pm 0.31) \times 10^{-3}$$

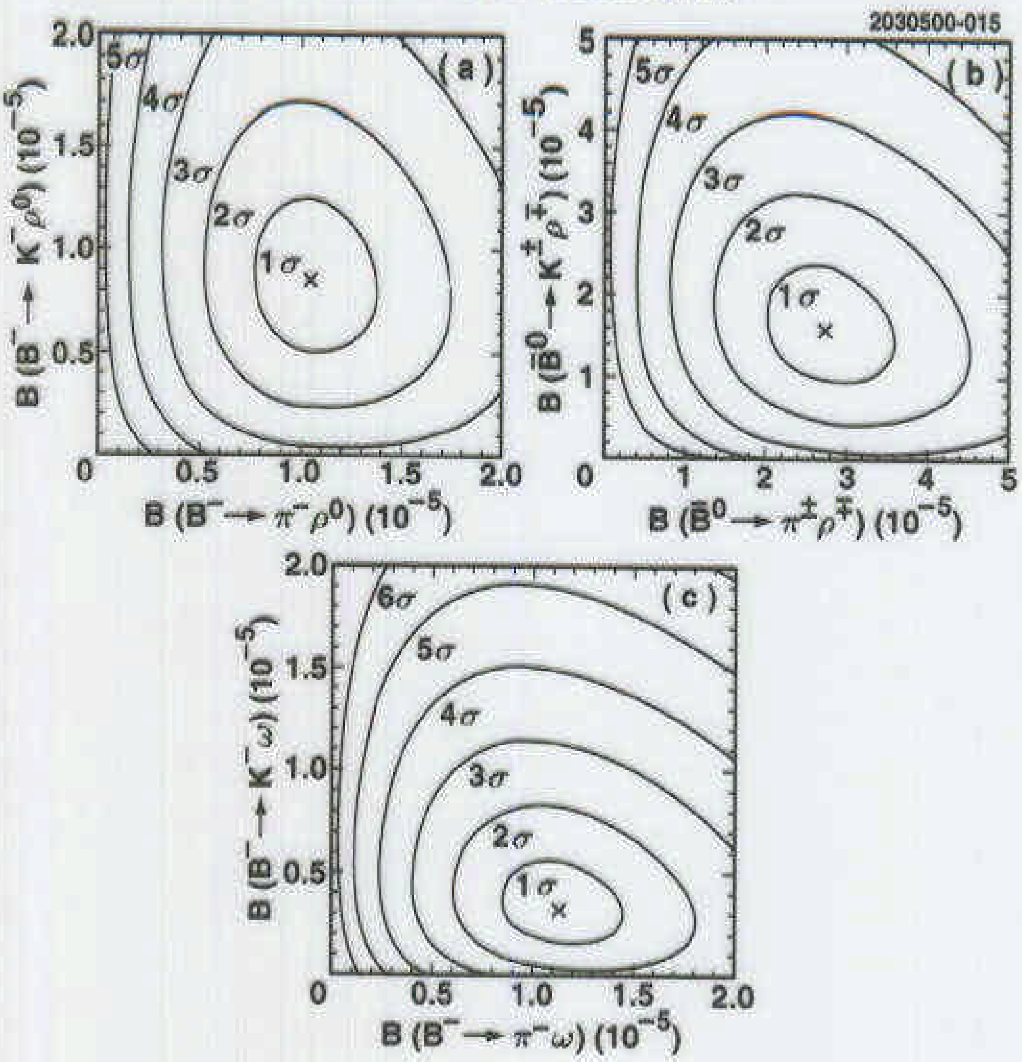
$$\mathrm{BR}(B^+ \to \eta_c K^+) = (0.69^{+0.26}_{-0.21} \pm 0.08 \pm 0.20) \times 10^{-3}$$

Exclusive $b \to u$ Transitions

- First observation of hadronic $b \to u$ transition.
- New study: 14 channels of B decays to (π or K)+(ρ, K^*, ω) CLNS 99/1652, hep-ex/0006008.

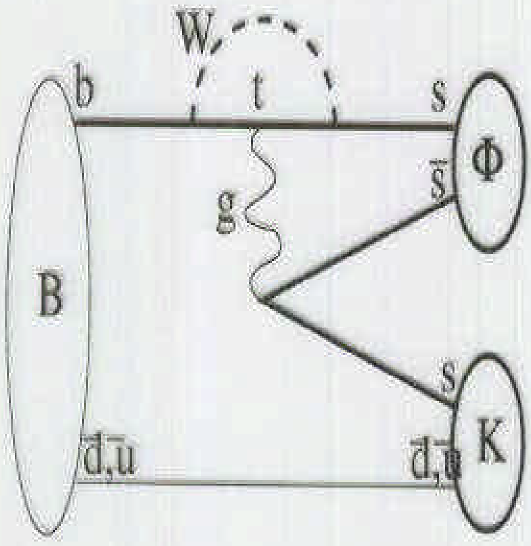
Mode	Yield	Signif.	$\mathcal{B}$ (10^{-6})	Theory
$B^- \to \pi^- \rho^0$	$29.8^{+9.3}_{-9.6}$	5.4σ	$10.4^{+3.3}_{-3.4}\pm 2.1$	0.4 - 13.0
$B^- \to K^- \rho^0$	$22.4^{+10.7}_{-9.1}$	3.7σ	< 17	0.0-6.1
$B^- \to \pi^0 \rho^-$	$23.7^{+8.4}_{-7.4}$	5.1σ	< 43	3.0 - 27.0
$B^- \to \pi^0 K*-$	$2.6^{+4.2}_{-2.6}$	1.0σ	< 31	0.5 - 24.0
$B^- \to \pi^- \omega$	$28.5^{+8.2}_{-7.3}$	6.2σ	$11.3^{+3.3}_{-2.9} \pm 1.4$	0.6 - 24
$B^- \to K^- \omega$	$7.9^{+6.0}_{-4.7}$	2.1σ	< 7.9	0.2 - 14.0
$B^- \to \pi^- K^{*0}$	$13.4^{+6.2}_{-5.2}$	3.6σ	< 16	3.4 - 13.0
$B^- \to K^- K^{*0}$	$0.0^{+2.2}_{-0.0}$	0.0σ	< 5.3	0.2 - 1.0
$B^0 \to \pi^\pm \rho^\mp$	$31.0^{+0.4}_{8.3}$	5.6σ	$27.6^{+8.4}_{-7.4} \pm 4.2$	12 - 93
$B^0 \to K^\pm \rho^\mp$	$16.4^{+7.8}_{-6.6}$	3.5σ	< 32.3	0. 0- 12.0
$B^0 \to \pi^0 \rho^0$	$5.4^{+6.5}_{-4.8}$	1.2σ	< 5.5	0.0 - 2.5
$B^0 \to \pi^0 \omega$	$1.5^{+3.5}_{-1.5}$	0.6σ	< 5.5	0.0 - 12.0
$B^0 \to K^0 \omega$	$7.0^{+3.8}_{-2.9}$	3.9σ	< 21	0.0 - 17.0
$B^0 \to \pi^0 K^{*0}$	$0.0^{+3.0}_{-0.0}$	0.0σ	< 3.6	0.7 - 6.1

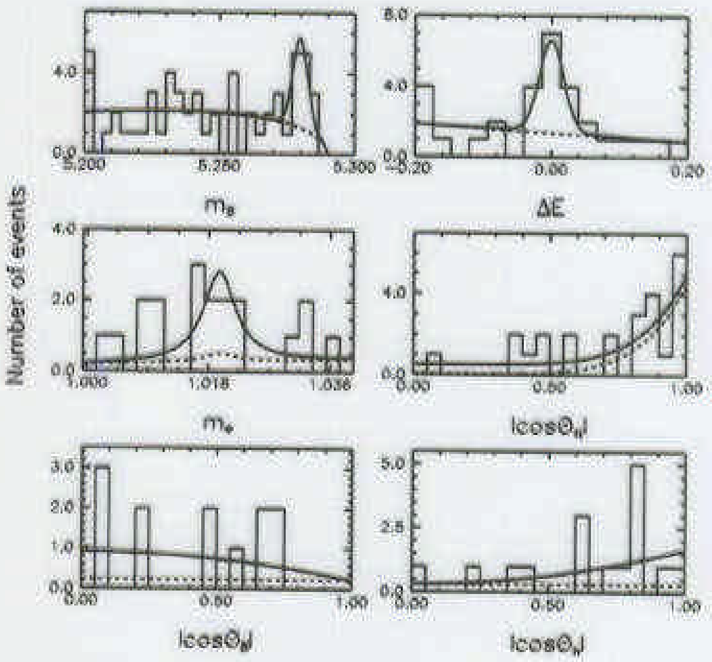
Likelihood contours



- $(\rho^{\mp}\pi^{\pm}/\rho^{\mp}K^{\pm})$ and $(\rho^{0}\pi^{\pm}/\rho^{0}K^{\pm})$ fitted simultaneously
- In general - good agreement with theoretical expectations
- $\mathcal{B}(B \to \rho^{\pm}\pi^{\mp})/\mathcal{B}(B \to \rho^{0}\pi^{\mp})$ smaller than expected (> 4)
- No significant yields in ΔS=1 transitions (as expected in factorization based models)
- Full Dalitz analyses of these modes can determine α and γ

$B \to \phi K$ - Preliminary





- Pure gluonic penguin, simple final state, sensitive to $\sin 2\beta$
- Theoretical uncertainties are large
  - Deshpande+He: inclusive $B \to \phi X_s \sim (0.6 - 2.0) \times 10^{-4}$
  - ϕK fraction of $\phi X_s \sim 10\%$

$BR(B^- \to \phi K^-) = (6.4^{+2.5+0.5}_{-2.1-2.0}) \times 10^{-6}$

$BR(B^0 \to \phi K^0) = (5.9^{+4.0+1.1}_{-2.9-0.9}) \times 10^{-6} \to < 1.2 \times 10^{-5}$ at 90% CL

Combined result: $BR(B \to \phi K) = (6.2^{+2.0+0.7}_{-1.8-1.7}) \times 10^{-6}$

CP Asymmetry Measurements

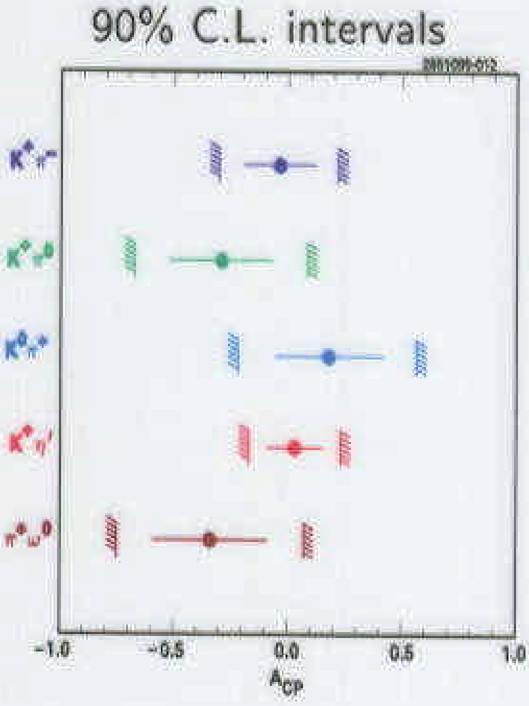
Direct CP asymmetry can result from interference of two amplitudes with different strong and weak phases.

- Factorization model predictions are small, but new physics and/or final state interactions can enhance the strong phase.
- Definition

$$\mathcal{A}_{CP} \equiv \frac{\mathcal{B}(\bar{B} \to f) - \mathcal{B}(B \to \bar{f})}{\mathcal{B}(\bar{B} \to f) + \mathcal{B}(B \to \bar{f})}$$

- Parent B flavor self-tagged by high-p charged particle.
- $\mathcal{A}_{C\mathcal{P}}$ included as free parameter in ML fits.

Mode	Yield	$\mathcal{A}_{C\mathcal{P}}$
$K^\pm\pi^\mp$	$80.2^{+11.8}_{-11.0}$	-0.04 ± 0.16
$K^\pm\pi^0$	$42.1^{+10.9}_{-9.9}$	-0.29 ± 0.23
$K^0\pi^\pm$	$25.2^{+6.4}_{-5.6}$	$+0.18 \pm 0.24$
$K^\pm\eta'$	100^{+13}_{-12}	$+0.03 \pm 0.12$
$\omega\pi^\pm$	$28.5^{+8.2}_{-7.3}$	-0.34 ± 0.25



- No $\mathcal{A}_{C\mathcal{P}}$ observed, but allowed range significantly reduced.
- All measurements are statistics-limited.

Summary

- New limits on fully leptonic B decays have been set.
- Over past few years CLEO measured or set upper limits on over 60 exclusive charmless hadronic B decays.
- New results this year: $B \to \pi\pi, \eta K^*, \eta' K, \pi\rho, \pi\omega, \phi K, \eta_c K$
- All branching fractions are small - typically few$\times 10^{-6}$.
- Most measurements are in reasonable agreements with theoretical models - probably due to lack of experimental precision.
- Future, higher statistics measurements will be able to extract the information on the sides and angles of the unitarity triangles.
- Data indicate existence of many contributing and interfering diagrams.

Status of the Theory