SEARCH FOR CP VIOLATION AT CLEO

- Observation of $B \rightarrow \pi^+\pi^-$ and $B \rightarrow K\pi$
- $B \rightarrow K\pi, K\eta', \omega\pi$
- $B \rightarrow K^*\gamma$ and $b \rightarrow s\gamma$
- $B^+ \rightarrow J/\psi\, K^+$
- Future prospects with CLEO-III

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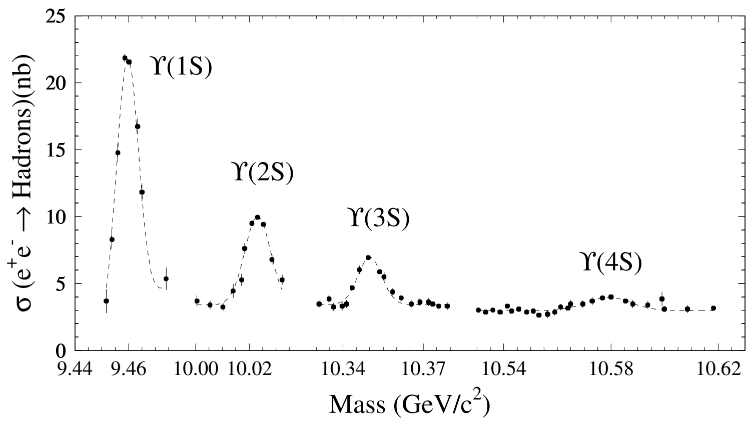
ASPEN WINTER CONFERENCE 2000

Introduction

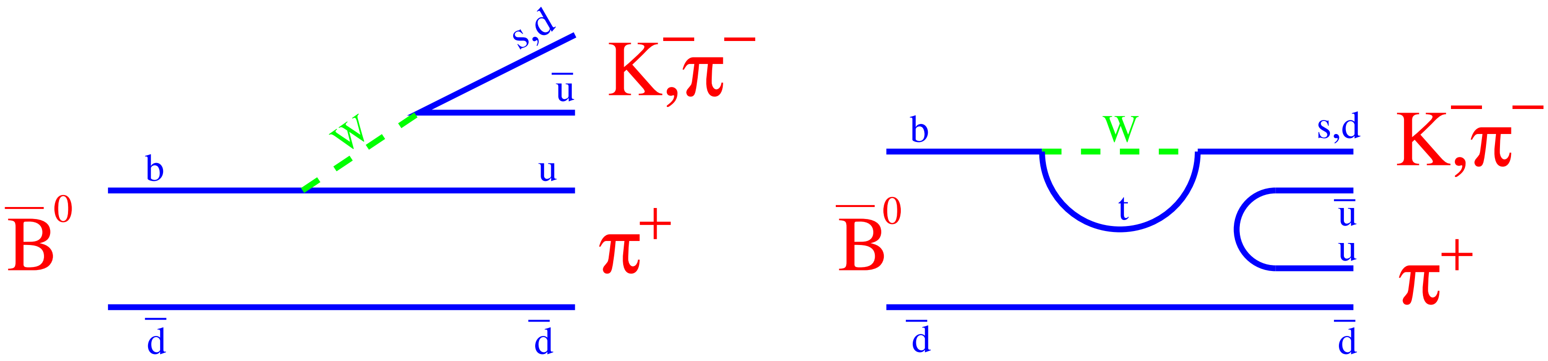
- 2/3 of data at $\Upsilon(4S)$
  $P_B \sim 300$ MeV
- 1/3 of Continuum data
  study $e^+e^- \to q\bar{q}$.



- Cleo II - 5 fb^{-1} with $3.3 \times\ 10^6 B\overline{B}$ pairs
- Cleo II + II.5 - 14 fb^{-1} with $9.7 \times\ 10^6 B\overline{B}$ pairs
  Analyses use full Cleo II + II.5 data sample unless noted.

- **Cleo III Upgrade**
  CESR phase III - Expect $\sim\ 10$ fb^{-1}/year
  New silicon detector and drift chamber
  RICH particle ID + $dE/dx \geq\ 4\sigma\ K/\pi$ separation for B daughters

Introduction to $B \rightarrow K^+\pi^-$ and $B \rightarrow \pi^+\pi^-$



- $B \rightarrow K\pi$ - penguin amplitude seems to dominate
- $B \rightarrow \pi\pi$ - unknown strength of penguin amplitude

- **Experiment:**

  Major Background $e^+e^- \rightarrow q\bar{q}$ continuum events

  two-jet events gives high momentum back to back tracks

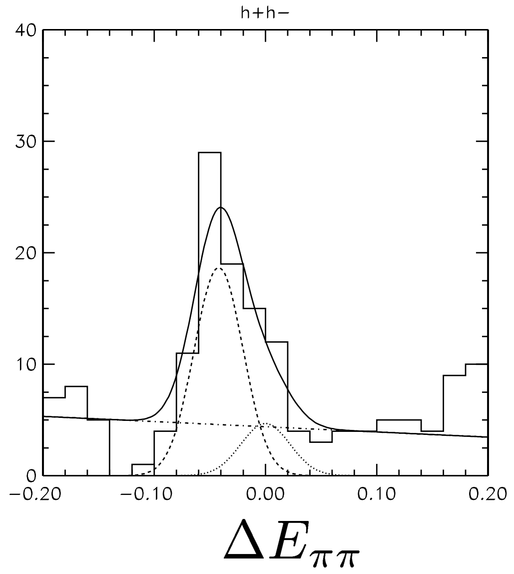
  Use event shape information to suppress continuum backgrounds

$K-\pi$ Separation for $B \rightarrow K^+\pi^-(\pi^+\pi^-)$

- ΔE Separation Reconstruct $B \rightarrow h^+h^-$

$$\Delta E_{\pi\pi} = E_\pi + E_\pi - E_{\text{beam}}$$

$B \rightarrow K^+\pi^-$, ΔE centered at -42 MeV



- $K-\pi$ separation (standard deviations)

	$\sigma_{\Delta E}$	ΔE	dE/dx
CLEO II	25	1.7σ	1.7σ
CLEO II.5	20	2.1σ	2.0σ

- CLEO III - $4\sigma K-\pi$ separation with RICH + dE/dx

Details of Analysis Technique

- **Event Shape**
  - $\cos\Theta_S$ - angle between B candidate sphericity axis and rest of event.
    Signal flat, $q\overline{q}$ peaked at ± 1
    $|\cos\Theta_S| < 0.8$ removes 83 of $q\overline{q}$ background
- **Fisher Discriminant - linear combination of variables**
  $\mathcal{F} = \sum_{i=1}^{N} \alpha_i y_i$ with α_i from MC
  - $\cos\Theta_B$ - angle between sphericity axis and beam
  - R2 - Fox-Wolfram H_2/H_0 ratio
  - Energy flow around sphericity axis - 9 variables
- **Unbinned maximum-likelihood fit**
  - Uses ΔE, MB, $\mathcal{F}$, $\cos\Theta_B$, dE/dx
  - Fit for $h^+h^-, h^+\pi^0, h^+K_S^0, \& \ K_S^0\pi^0$

$B \rightarrow K^+\pi^-$ and $B \rightarrow \pi^+\pi^-$ Fit Results

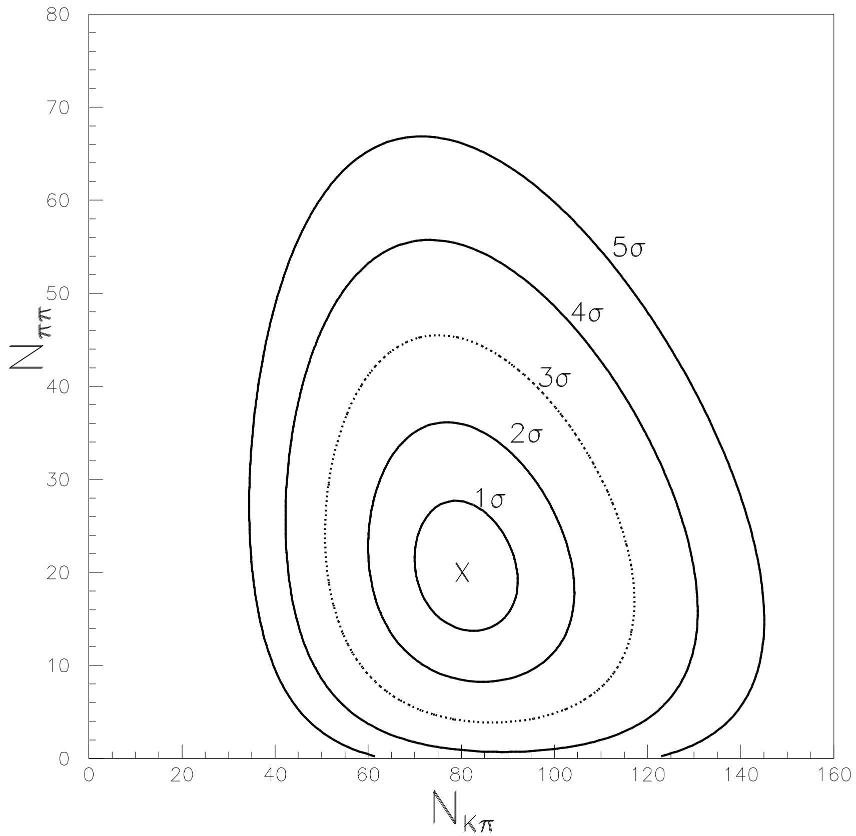
- **Unbinned maximum-likelihood fit**

  ΔE, MB, $\mathcal{F}$, $\cos\Theta_B$, dE/dx

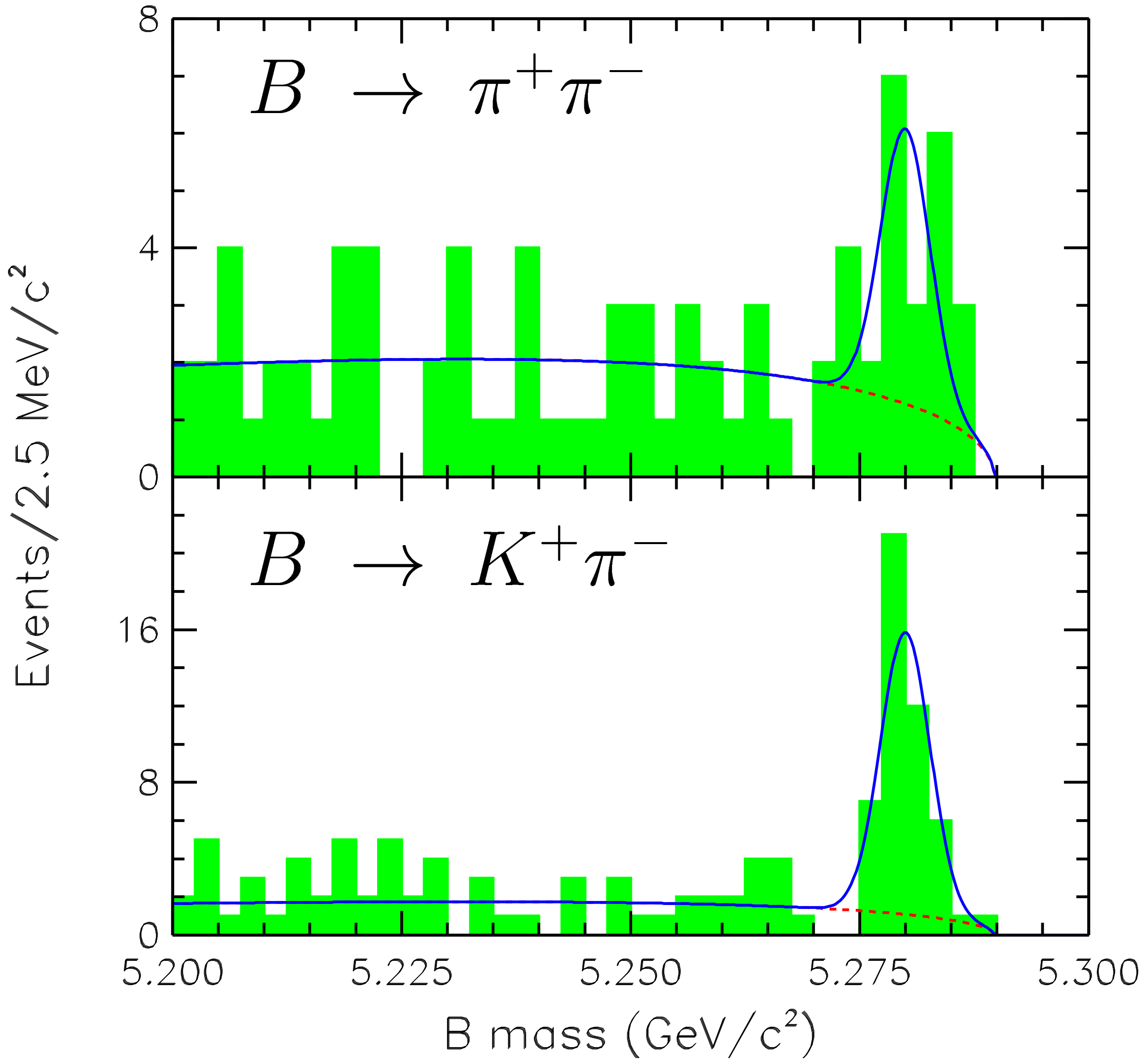
  $\mathcal{F}$ - Fisher Discriminant - linear combination of event shape variables

- Fit for h^+h^-, $h^+\pi^0$, $h^+K^0_S$, and $K^0_S\pi^0$

$B \rightarrow h^+h^-$ Fit Results



$B \to \pi^+\pi^-$ and $B \to K^+\pi^-$



$B \rightarrow K\pi$ and $B \rightarrow \pi\pi$, Summary

hep-ex/0001010

Mode	N	$\mathcal{B} \times 10^6$
$\pi^\pm\pi^\mp$	$20.0\,^{+7.6}_{-6.5}$	$4.3\,^{+1.6}_{-1.4} \pm 0.5$
$\pi^\pm\pi^0$	$21.3\,^{+9.7}_{-8.5}$	< 12.7
$K^\pm\pi^\mp$	$80.2\,^{+11.8}_{-11.0}$	$17.2\,^{+2.5}_{-2.4} \pm 1.2$
$K^\pm\pi^0$	$42.1\,^{+10.9}_{-9.9}$	$11.6\,^{+3.0}_{-2.7}\,^{+1.4}_{-1.3}$
$K^0\pi^\pm$	$25.2\,^{+6.4}_{-5.6}$	$18.2\,^{+4.6}_{-4.0} \pm 1.6$
$K^0\pi^0$	$16.1\,^{+5.9}_{-5.0}$	$14.6\,^{+5.9}_{-5.1}\,^{+2.4}_{-3.3}$

- All $B \rightarrow K\pi$ modes observed
- $B \rightarrow \pi^+\pi^-$ observed

  Unknown penguin contribution $\Rightarrow$ More difficult to measure

  CKM angle α at asymmetric B-factories

Measurement of CKM angle α via $B \rightarrow \pi^+\pi^-$

- B decays to CP eigenstates

  Theoretically clean measurement of CKM parameters if one decay amplitude,

  Interference between $B^0 - \overline{B}^0$ mixing and decay gives CP violation.

- $B \rightarrow \pi^+\pi^-$ - Theoretically clean without penguin amplitude - different weak phase than tree amplitude - can have direct CP violation

- Direct CP Violation

$$\mathcal{A}_{\text{CP}} \equiv \frac{\mathcal{B}(\overline{B}\rightarrow f)-\mathcal{B}(B\rightarrow \overline{f})}{\mathcal{B}(\overline{B}\rightarrow f)+\mathcal{B}(B\rightarrow \overline{f})}$$

- $B \rightarrow K^+\pi^-$ vs. $B \rightarrow \pi^+\pi^- \Rightarrow$ Unknown penguin amplitude

- Use $B \rightarrow \pi\pi$ isospin analysis but $B \rightarrow \pi^0\pi^0$ very difficult experimentally

Search for Direct $\mathcal{A}_{\mathrm{CP}}$ in $B \rightarrow K\pi, K\eta', \omega\pi$

- **Direct CP Violation:** 2 or more amplitudes - different weak and strong phases
- $\mathcal{A}_{\mathrm{CP}} \equiv \frac{\mathcal{B}(\overline{B}\to f)-\mathcal{B}(B\to\overline{f})}{\mathcal{B}(\overline{B}\to f)+\mathcal{B}(B\to\overline{f})}$
- 2 Amplitudes P & T with $P \gg T$,
  $\mathcal{A}_{\mathrm{CP}} \propto 2\frac{|T|}{|P|} \sin\Delta\phi_{\mathrm{weak}} \sin\Delta\phi_{\mathrm{strong}}$
- Cannot calculate absolute value and phases from first principles
- Large $\mathcal{A}_{\mathrm{CP}}$ - Final state interactions (FSI) could enhance
  $\mathcal{A}_{\mathrm{CP}}\sim$20-40%, New physics $\mathcal{A}_{\mathrm{CP}}\sim$40-60 %
  He *et al.*, Phys. Rev. Lett. 81, 5738 (1998), Charles, Phys. Rev. D 59, 054007 (1999),
  Neubert JHEP 9902, 014 (1999), Deshpande *et al.*, Phys. Rev. Lett 82, 2240 (1999)
- Small $\mathcal{A}_{\mathrm{CP}}$ - Using factorization, Ali, Kramer, & Lü find $\mathcal{A}_{\mathrm{CP}}\sim$ 5 %
  neglects soft FSI Phys. Rev. D **59**, 014005 (1999)

$\mathcal{A}_{\text{CP}}$ Systematics - Details

- **Charge asymmetries depend only on high momentum tracks**
  - Particle that tags B flavor has momentum of 2.3 - 2.8 GeV/c
  - Tracking - detector & reconstruction

    Use independent sample of tracks with P= 2.0 - 3.0 GeV/c

    $\mathcal{A}_{\text{CP}}$ uncertainty = $\pm\ 0.002$
- **Differential charge-correlated efficiency**
  - Using $D^0 \to K^- \pi^+$, $\mathcal{A}_{\text{CP}}$ uncertainty = $\pm\ 0.002$
  - Charged-correlated momentum mismeasurement $<$ 0.4 MeV
- dE/dx - Calibrated to remove charge asymmetry

  Checked with large sample of $D^0 \to K^- \pi^+ (\pi^0)$ decays, $\mathcal{A}_{\text{CP}}$ - $\pm\ 0.01$
- **Background $\mathcal{A}_{\text{CP}}$-** continuum sample $\mathcal{A}_{\text{CP}}$ = 0.0
  - Consistent within statistics - error varies from 0.01 ($\omega\pi^\pm$) to 0.04 ($K^0\pi^\pm$)

RESULTS - $\mathcal{A}_{\rm CP}$ in $B \to K\pi, K\eta', \omega\pi$

hep-ex/0001009

	Events	$\mathcal{A}_{\rm CP}^{\rm Theory}$ (Ali *et al.*)	$\mathcal{A}_{\rm CP}$	90% CL Region
$K^\pm\pi^\mp$	$80.2^{+11.8}_{-11.0}$	$[+0.037, +0.106]$	-0.04 ± 0.16	$[-0.30, 0.22]$
$K^\pm\pi^0$	$42.1^{+10.9}_{-9.9}$	$[+0.026, +0.092]$	-0.29 ± 0.23	$[-0.67, 0.09]$
$K^0_S\pi^\pm$	$25.2^{+6.4}_{-5.6}$	$+0.015$	$+0.18 \pm 0.24$	$[-0.22, 0.56]$
$K^\pm\eta'$	100.0^{+13}_{-12}	$[+0.020, +0.061]$	-0.03 ± 0.12	$[-0.17, 0.23]$
$\omega\pi^\pm$	$28.5^{+8.2}_{-7.3}$	$[-0.120, +0.024]$	-0.34 ± 0.25	$[-0.75, 0.07]$

- **SUMMARY** - No evidence for direct CP violation
  - Systematics: dE/dx (K^+ vs. K^-) - $\pm 0.01\%$, Tracking - $\pm 0.002\%$
  - This measurement rules out large part of parameter space
  - Measurements are statistics limited and will be for a long time

Statistics

$$\sigma^2_{A_{cp}} = \frac{1 - A_{cp}^2}{S}\left(1 + \frac{B}{S}\left(\frac{1 + A_{cp}^2}{1 - A_{cp}^2}\right) - 2\rho\sqrt{\frac{1 - A_{cp}^2}{4} + \frac{B^2}{S^2} + \frac{B}{S}}\right)$$

$S = S^+ + S^-$ = total signal

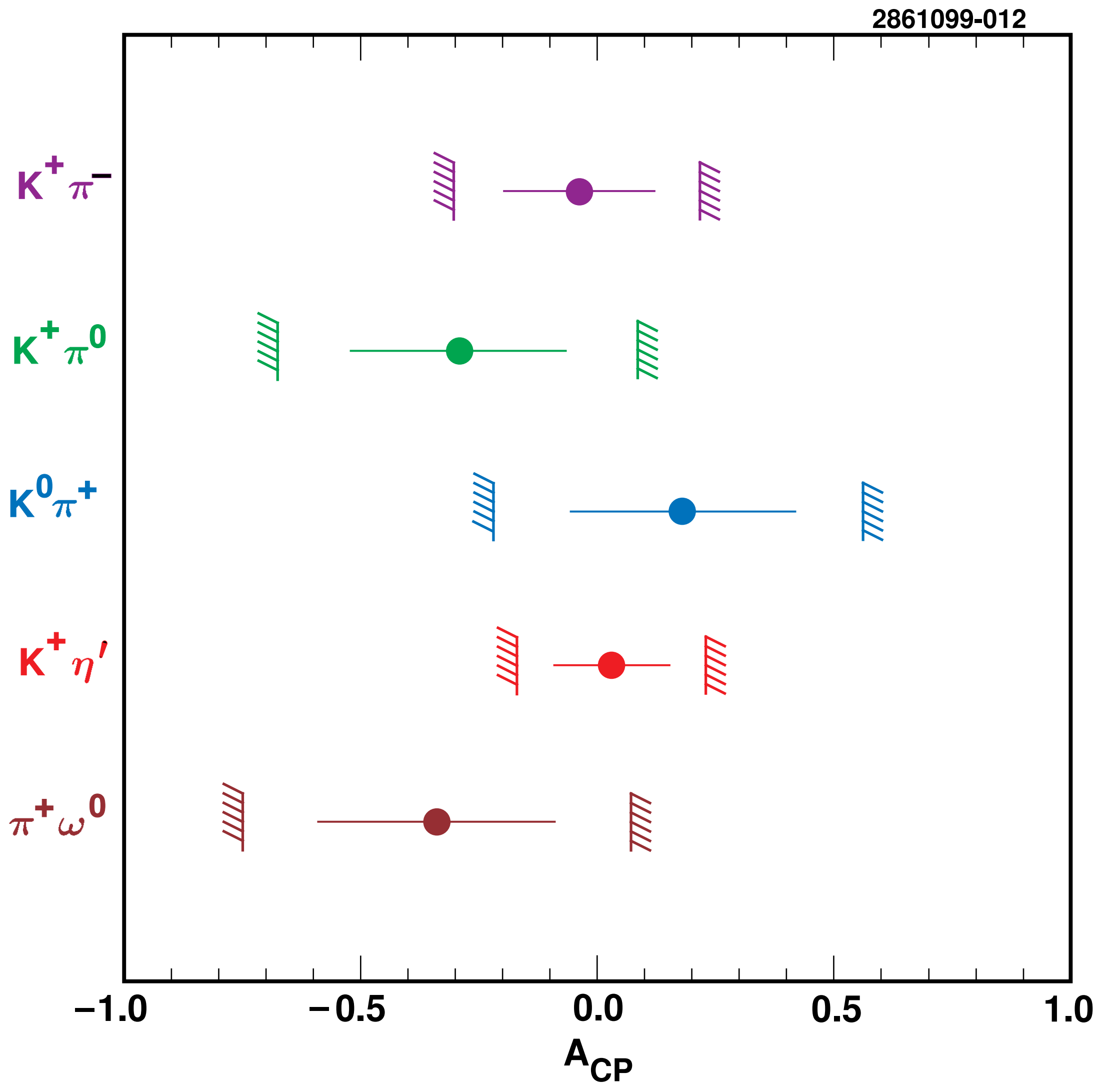
$B = B^+ + B^-$ = total background

$\rho = S^+, S^-$ fitting correlation

For typical parameters, $\sigma^2 \sim 2/S$, so for $S \sim 100$, expect precision around ± 0.15

Acp measurements are statistics-dominated now, and will be for a long time to come.

$\mathcal{A}_{\rm CP}$ 90% C.L. Region for $B \to K\pi, K\eta', \omega\pi$



Search for $\mathcal{A}_{CP}$ in $b \to s\gamma$ Decays

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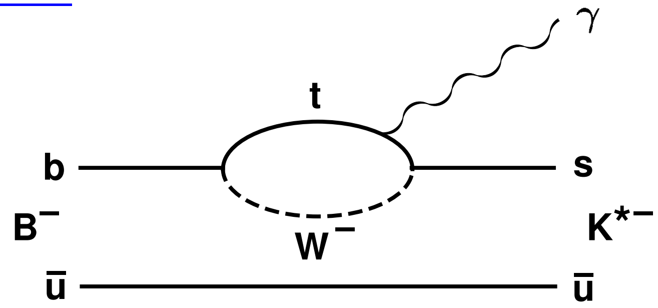


- **Radiative B Decays:**

  Study Standard Model (SM) processes, V_{ts} & V_{td} and search for new physics

- **Theory** - Standard Model $\mathcal{A}_{CP} \sim 1$ %

  Non-SM physics $\Rightarrow$ possibly large $\mathcal{A}_{\rm CP}, 10 - 50\,\%$

  Wolfenstein & Wu, PRL **73**, 2809; Asatrian & Ioannissian, PRD **54**, 5642; Kagan & Neubert, PRD **58**, 094012

- **Experiment** - Exclusive analysis - Uses flavor specific final states

  Inclusive analysis - larger efficiency and mistag dilution (~10%)

- **Backgrounds:** $e^+e^- \to q\bar{q} \quad (q = u, d, s, c)$ and Initial state radiation

  Reject photons from π^0 and η decay

$b \to s\gamma$ Inclusive Analysis

CLEO CONF 99-10, hep-ex/9908022

- Partial update using $3.3 \times 10^6 B\overline{B}$ pairs (CLEO II data only)
  $\mathcal{B}(b \to s\gamma)$ - systematics limited - CLEO II + II.5 update in progress
- Experiment: $\mathcal{B}(b \to s\gamma) = (3.15 \pm 0.35 \pm 0.32 \pm 0.26) \times 10^{-4}$
- Theory: SM NLO prediction - $\mathcal{B}(b \to s\gamma) = (3.28 \pm 0.33) \times 10^{-4}$

K. Chetyrkin *et al.*, Phys. Lett. B **425**, 414 (1998), A. Kagan and M. Neubert, Eur. Phys. J. **C7**, 5 (1999).

Search for $\mathcal{A}_{\text{CP}}$ in $b \to s\gamma$ decays

- $\mathcal{A}_{\text{CP}} = (+0.16 \pm 0.14 \pm 0.05) \times (1.0 \pm 0.04)$

  90% CL limits: $-0.09 < \mathcal{A}_{\text{CP}} < 0.42$

- Expected sensitivity with entire CLEO II/II.5 data sample
  $\mathcal{A}_{\text{CP}} \pm$ (7-9) %, $\mathcal{B}(b \to s\gamma) \pm$ (10-17) %

$B \to K^*\gamma$

hep-ex/9912057 - submitted to PRL

- **1993 - $B \to K^*\gamma$ observed - first evidence for $b \to s$ transitions**

R. Ammar *et al.*, Phys. Rev. Lett. **71**, 674 (1993)

- **CLEO II + CLEO II.5** - 9.7 $\times 10^6$ $B\overline{B}$'s

$\mathcal{B}(B^0 \to K^{*0}(892)\,\gamma) = (4.55\,^{+0.72}_{-0.68} \pm 0.34) \times 10^{-5}$

$\mathcal{B}(B^+ \to K^{*+}(892)\,\gamma) = (3.76\,^{+0.89}_{-0.83} \pm 0.28) \times 10^{-5}$

Search for $\mathcal{A}_{\mathrm{CP}}$ with self tagging modes

- $\mathcal{A}_{\mathrm{CP}} = \frac{1}{1-2\eta} \frac{\mathrm{N}(\overline{B}\to\overline{K}^*\gamma) - \mathrm{N}(B\to K^*\gamma)}{\mathrm{N}(\overline{B}\to\overline{K}^*\gamma) + \mathrm{N}(B\to K^*\gamma)}$ η- mistag fraction
- $K^* \to K^+\pi^-$ - only mode without mistag ~ 0

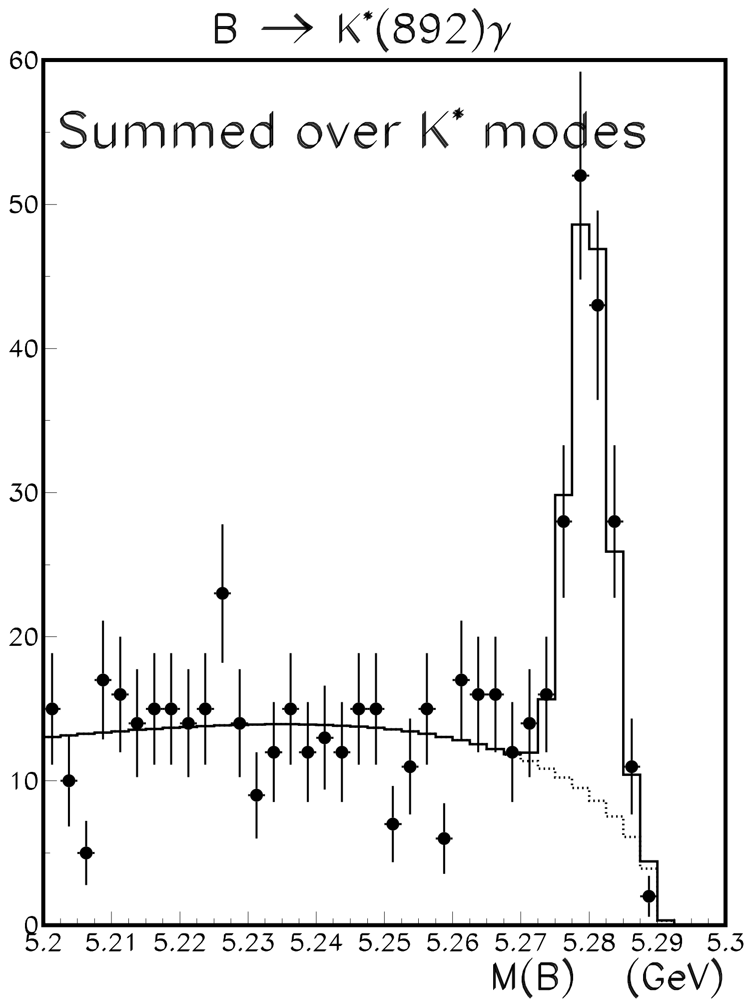
η- mistag fraction = (3.45 ± 0.02) %

Exclude K/π dE/dx cross-over region (cut 62 % efficient)

Cleo III - RICH will improve efficiency

Search for $\mathcal{A}_{\mathrm{CP}}$ in $B \to K^*\gamma$ decays

- 126 ± 15 $B \to K^*\gamma$ events
- Small Systematics: 2.5 % total
  - K^* cross feed < 1 %
  - $K^\pm$ and $\pi^\pm$ detector and reconstruction asymmetry < 1.5 %



- Combine B^0 and B^+ Signal:

$$\boxed{\mathcal{A}_{\mathrm{CP}} = +0.08 \pm 0.13 \pm 0.03}$$

- Background sample:

$$\mathcal{A}_{\mathrm{CP}} = +0.01 \pm 0.06$$

Search for $b \to d\gamma$ Decays

- Find no evidence for $b \to d\gamma$ decays

  $\mathcal{B}(B^0 \to \rho^0\gamma) < 1.7 \times 10^{-5}$ $\mathcal{B}(B^+ \to \rho^+\gamma) < 1.3 \times 10^{-5}$

  $\mathcal{B}(B^0 \to \omega\gamma) < 0.92 \times 10^{-5}$

- $\mathcal{B}(B \to \rho\gamma)/\mathcal{B}(B \to K^*(892)\gamma) < 0.32$ at 90% $C.L.$

  Assume top quark dominates EW penguin, No long distance contributions

  $\frac{\mathcal{B}(B\to(\rho,\omega)\gamma)}{\mathcal{B}(B\to K^*\gamma)} = \frac{|V_{td}|^2}{|V_{ts}|^2}\xi \Rightarrow |V_{td}/V_{ts}| < 0.75$ at 90 % CL $(\xi = 0.58)$

  ξ - ratio of $B \to \rho\gamma$ & $B \to K^*\gamma$ form factors A. Ali *et al.*,Z.Phys.C **63**, 437 (1994).

  other values of ξ are 0.77 and 0.81 ± 0.09 S.Narison (1994) and J.M.Soares (1994)

- PDG99: $|V_{td}/V_{ts}|$ < 0.24 via B_d^0 and B_s^0 mixing

  Different assumptions and systematics

- CLEO III: 60 fb^{-1} - give $\sim$10 $B \to \rho\gamma$ reconstructed events

  10% statistical measurement on $|V_{td}/V_{ts}|$

$b \to d\gamma$: ΔE $vs. M_{\pi\pi}$

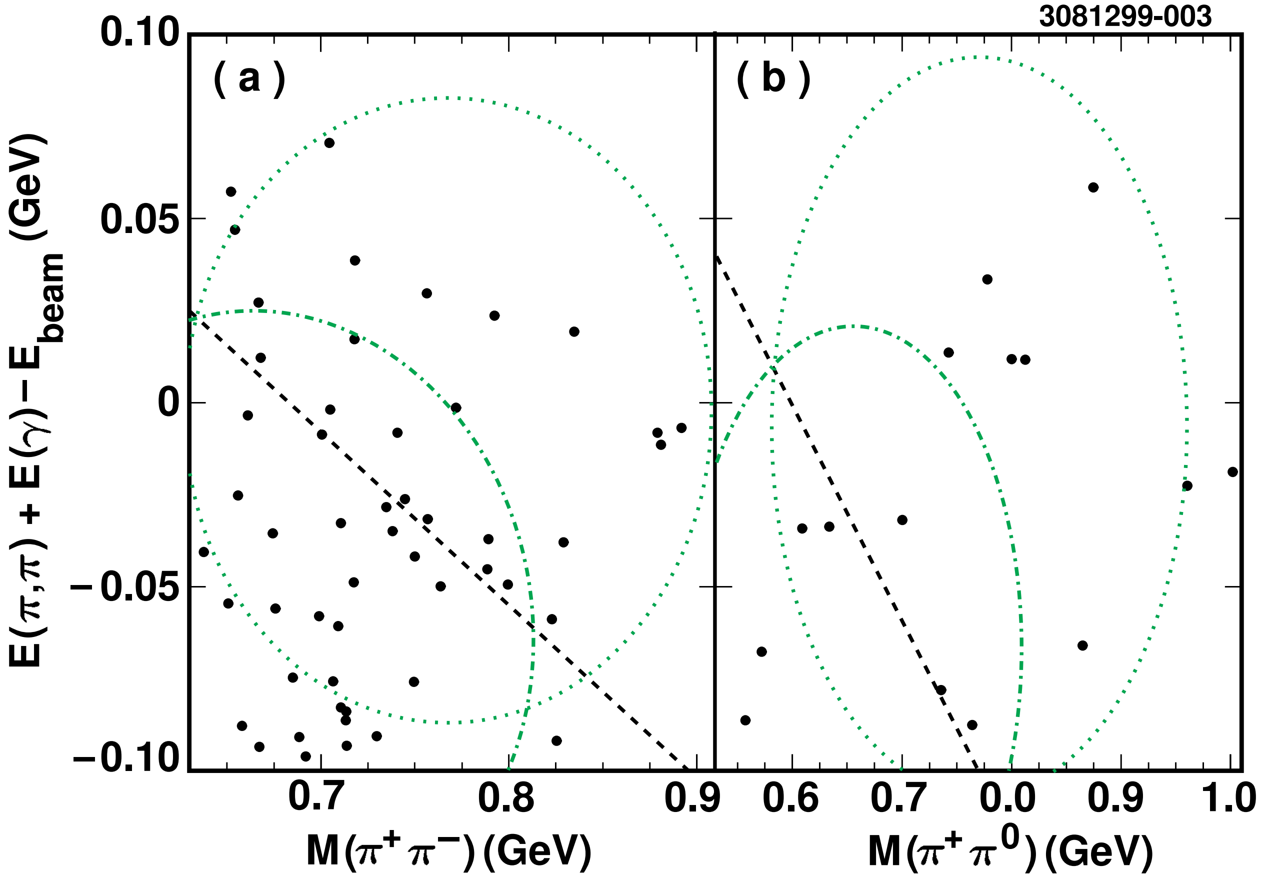
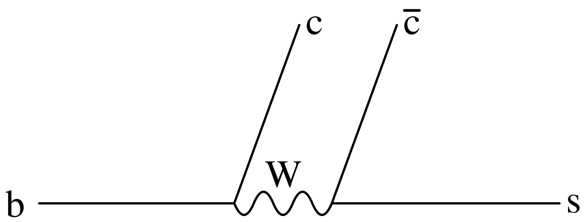
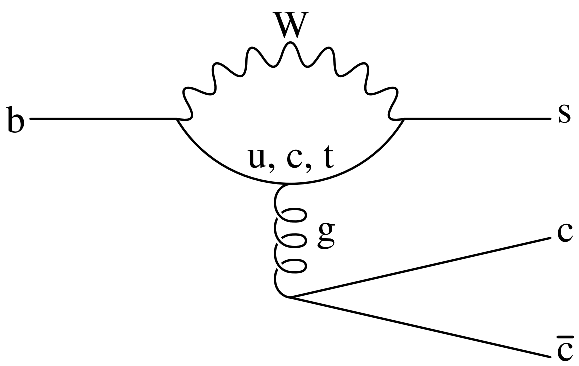


FIG. 2. The ΔE vs $M(\pi\pi)$ distributions for a) $B^0 \to \rho^0\gamma$ and b) $B^+ \to \rho^+\gamma$ candidates. Candidates above the diagonal dashed line survive the final selection criterion. The dotted [dot-dash] line approximates the limits that would contain 90% of the $B \to \rho\gamma$ [$B \to K^*\gamma$] candidates.

Search for $\mathcal{A}_{\rm CP}$ in $B^{\pm} \rightarrow J/\psi(')K^{\pm}$





- Standard Model - relative weak phase is small

  $\chi = \mathrm{Arg}(\frac{V_{cb}V^*_{cs}}{V_{tb}V^*_{ts}}) \sim \eta\lambda^2 \sim 0.02$

- For $\sin 2\beta$ via $B \rightarrow J/\psi K_S$ normally taken as zero

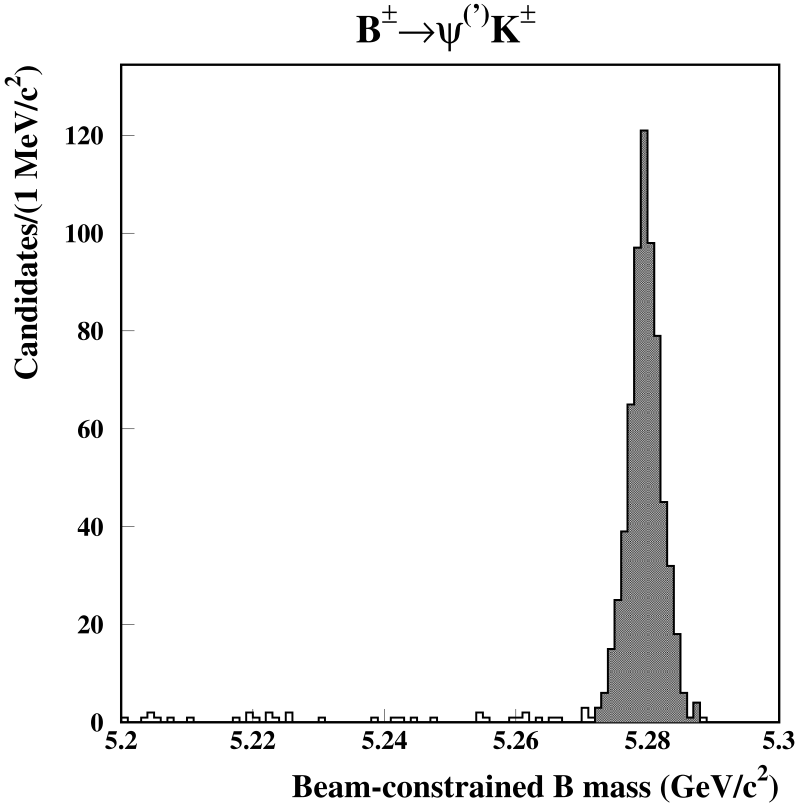
- Clean experiment: Large signal, almost background free

$B^{\pm} \rightarrow J/\psi^{(\prime)} K^{\pm}$ (Preliminary Results)

654 $B^{\pm} \rightarrow \psi^{(\prime)} K^{\pm}$ events

- 534 $B^{\pm} \rightarrow \psi K^{\pm}$ events
- 120 $B^{\pm} \rightarrow \psi^{\prime} K^{\pm}$ events

$6.0^{+1.0}_{-0.8}$ background events



- **Small $\mathcal{A}_{\mathrm{CP}}$ systematics**

  Backgrounds - 0.3%

  K^{+} vs. K^{-} detection - 0.3%

  Total systematics - 0.4%

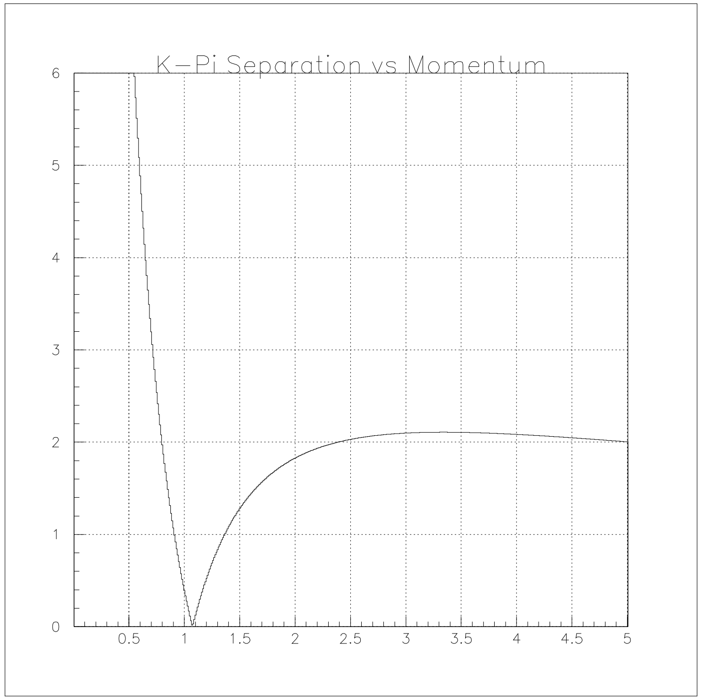
- $\mathcal{A}_{\mathrm{CP}} = \dfrac{\mathcal{B}(B^{+} \rightarrow \psi^{(\prime)} K^{+}) - \mathcal{B}(B^{-} \rightarrow \psi^{(\prime)} K^{-})}{\mathcal{B}(B^{+} \rightarrow \psi^{(\prime)} K^{+}) + \mathcal{B}(B^{-} \rightarrow \psi^{(\prime)} K^{-})}$

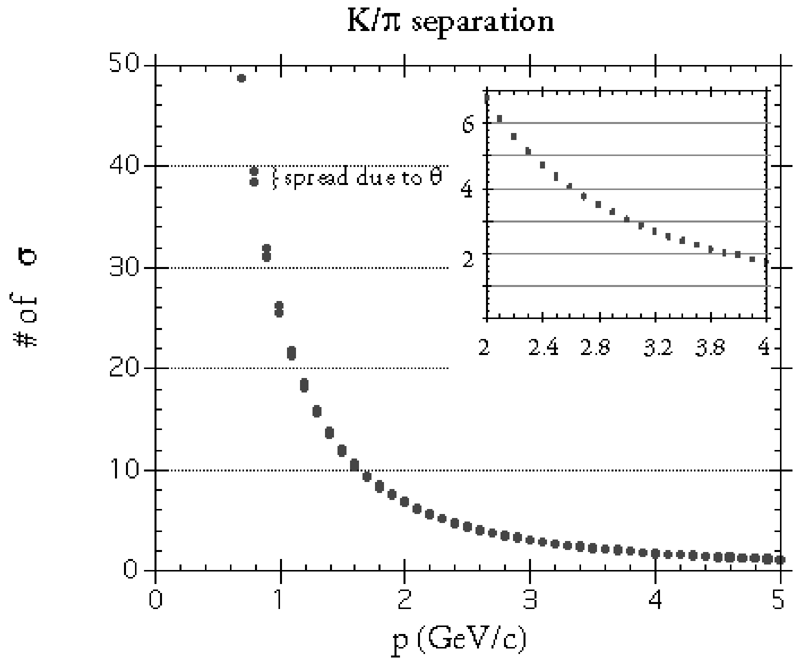
  $\mathcal{A}_{\mathrm{CP}} = (-1.8 \pm 3.9)\ \%$

  90 % C.L. Region - [-8.2 %, +4.6 %]

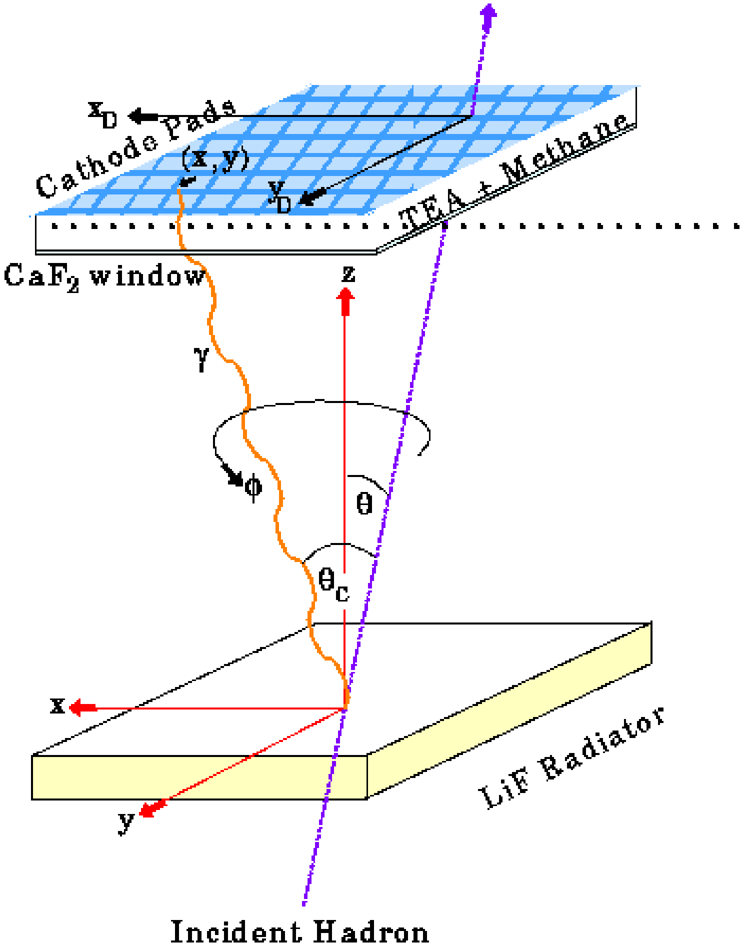
CLEO III Upgrade

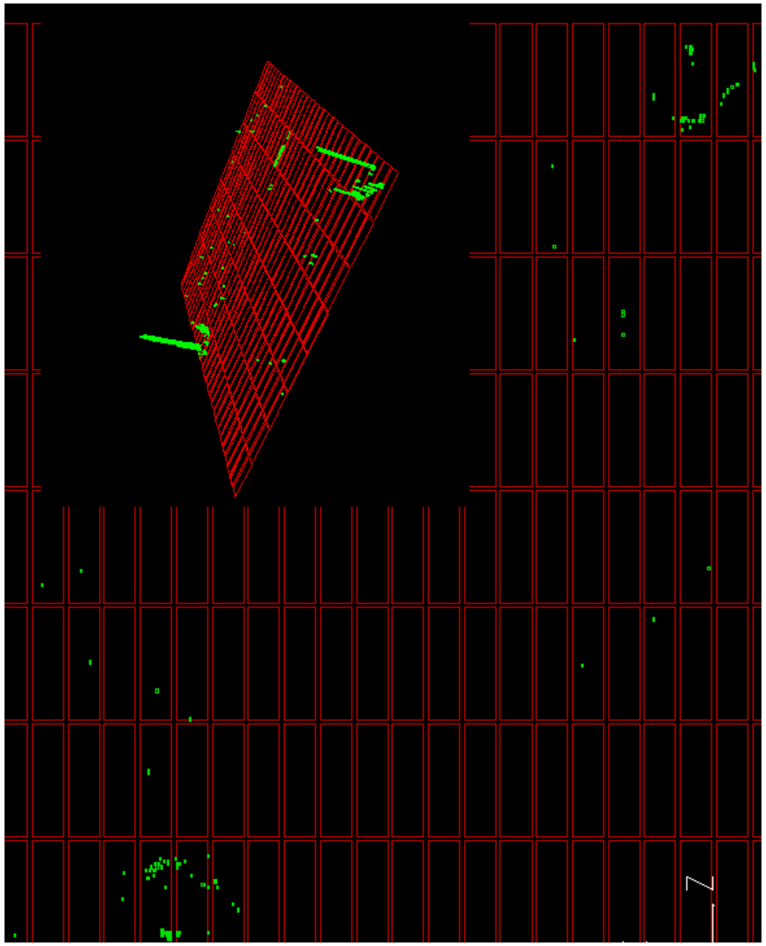
- **RICH - Čerenkov based detector for particle ID**
- **Will install 4 layer silicon vertex detector in February**
- dE/dx **and RICH** $K - \pi$ **Separation**





RICH $e^+e^- \to e^+e^-$ Event





Details on RICH Detector - See Tomasz Skwarnicki's talk at BCONF99

http://www.phys.ntu.edu.tw/english/bcp3/talk_doc/dec3/skwarnicki_dec3.pdf

Summary

- **Observation of $B\to\pi^+\pi^-$ and all $B\to K\pi$ modes** hep-ex/0001010
- $B\to K\pi$, **K**η', $\omega\pi$ $\mathcal{A}_{\text{CP}}$ **Sensitivity = (15-25)%** hep-ex/0001009
- **Radiative B Decays** - Updated inclusive & exclusive branching fractions
  - $b\to s\gamma$ $\mathcal{A}_{\text{CP}}$ Sensitivity = 20% hep-ex/9908022
  - $B\to K^*\gamma$ $\mathcal{A}_{\text{CP}}$ Sensitivity = 13% hep-ex/9912057
  - $\frac{\mathcal{B}(B\to(\rho,\omega)\gamma)}{\mathcal{B}(B\to K^*\gamma)} \Rightarrow |V_{td}/V_{ts}| < 0.75$ at 90 % C.L.
- $B\to\psi^{(')}K$ $\mathcal{A}_{\text{CP}}$ **Sensitivity = 4%**

Need More & Better Data - Coming Soon !

- $\mathcal{A}_{\text{CP}}$ **Sensitivity with 50** fb^{-1}, $50\times\ 10^6 B\overline{B}$ **pairs:**
  $B\to K\pi\sim$7%, $B\to$K$\eta'\sim$4%, $B\to K^*\gamma\sim$6%, $B\to\psi^{(')}K\sim$1%