Measurements of CP Asymmetries and Branching Fractions in $B^0 \to p^+p^-, K^\pm p^\mp, K^+K^-$

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BaBar Collaboration

Measuring CP Violation with Neutral B's

- CP violation arises from a **single phase in CKM matrix:**

Wolfenstein Parameterization

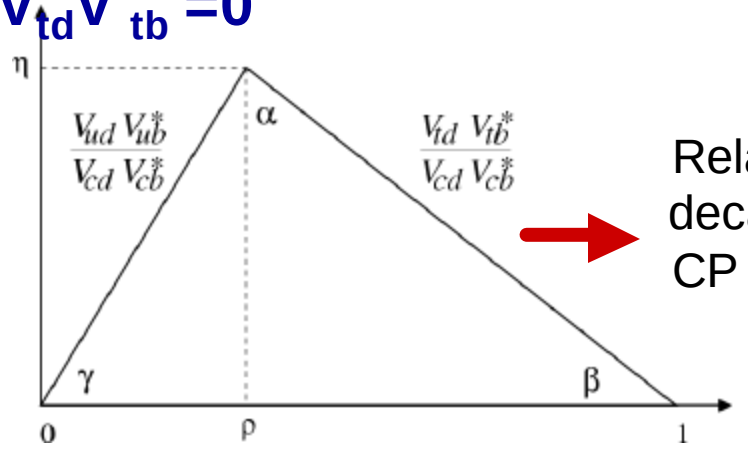
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Complex Phase

Unitarity

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

Represented as triangle



Relate angles to decays of B's to CP Eigenstates

Measuring Angles with B^0's

$$A_{f_{CP}} = \frac{\Gamma(\overline{B}^0_{phys}(t) \to f_{CP}) - \Gamma(B^0_{phys}(t) \to f_{CP})}{\Gamma(\overline{B}^0_{phys}(t) \to f_{CP}) + \Gamma(B^0_{phys}(t) \to f_{CP})}$$

Look for time-dependent decay asymmetry

Oscillate w/ mixing freq

CP Eigenstate

$$= S_{f_{CP}} \sin \Delta m_d t - C_{f_{CP}} \cos \Delta m_d t$$

Amplitudes:

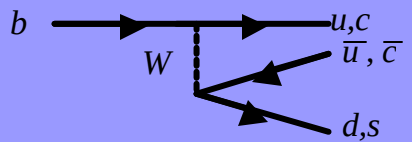
Carry CPV Info

mixing

Decay amplitude ratio

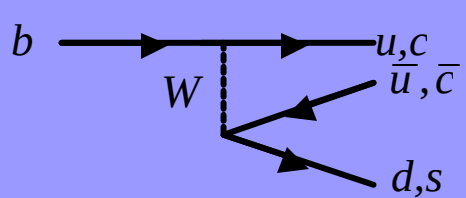
$$C_{f_{CP}} = \frac{1 - |?_{f_{CP}}|^2}{1 + |?_{f_{CP}}|^2} \qquad S_{f_{CP}} = \frac{2\,\mathrm{Im}\, l_{f_{CP}}}{1 + |l_{f_{CP}}|^2}$$

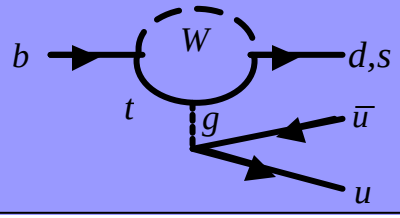
$$?_{f_{CP}} = \frac{q}{p} \cdot \frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

Mode	$?_{f_{CP}}$ Tree 	$\mathrm{Im}(?_{f_{CP}})$
$B^0 \to J/y\ K_s$	$-\frac{V_{td}V_{tb}^*}{V_{tb}V_{td}^*}\frac{V_{cb}V_{cs}^*}{V_{cs}V_{cb}^*}\frac{V_{cs}V_{cd}^*}{V_{cd}V_{cs}^*}$	$\sin 2b$
$B^0 \to p^+p^-$	$\frac{V_{td}V_{tb}^*}{V_{tb}V_{td}^*}\frac{V_{ud}V_{ub}^*}{V_{ud}V_{ub}^*}$	$\sin 2a$

Next Leading Diagram

Mode	Tree Amplitude (T)	Hadronic Penguin Amplitude (P)
$B^0 \to J/y\ K_s$	$\sim V_{cb}V_{cs}^* \approx ?^2$	$\sim ?^2 + O(?^4)e^{-i?}$
$B^0 \to p^+p^-$	$\sim V_{ub}V_{ud}^* \approx ?^3 e^{-i?}$	$\sim V_{tb}V_{td}^* \approx ?^3 e^{i\beta}$
$B^0 \to K^+p^-$	$\sim V_{ub}V_{us}^* \approx ?^4 e^{-i?}$	$\sim V_{tb}V_{ts}^* \approx ?^2$





- In the case of $B^0 \to J/\psi\ K_s$ Tree/Penguin carry **same** phase ➔ Measure sin 2β
- *Br*($B^0 \to K^+\pi^-$) >> *Br*($B^0 \to \pi^+\pi^-$) ➔ Penguin contributions may be **large**
- But for $B^0 \to \pi^+\pi^-$ Tree/Penguin may contribute w/ **different** phases

$$\Rightarrow ?_{pp} = e^{2ia}\,\frac{1-\frac{P}{T}e^{i(d-a)}}{1-\frac{P}{T}e^{i(d+a)}} \equiv |?_{pp}|\,e^{2ia_{Eff}}$$ ← "α Effective"

- Charmless 2-body B decays:
  - $B^0 \rightarrow \pi^+\pi^-$ sensitive to sin 2α
  - $B^0 \rightarrow K^+\pi^-$ may exhibit direct CP violation:

$$A_{Kp} = \frac{\Gamma(\bar{B}^0 \rightarrow K^- p^+) - \Gamma(B^0 \rightarrow K^+ p^-)}{\Gamma(\bar{B}^0 \rightarrow K^- p^+) + \Gamma(B^0 \rightarrow K^+ p^-)}$$

  - The Branching Fractions may help $\alpha_{Eff} \rightarrow \alpha$ and $Br \rightarrow \gamma$

- In ~60 Million B Decays (~55/fb) recorded w/ BaBar
  - Extracted the Branching Fractions
  - Measured asymmetry $A_{K\pi}$
  - Measured the time dependent asymmetries $S_{\pi\pi}$ and $C_{\pi\pi}$
- All results are preliminary

Analysis Issues

Looking for $B \rightarrow \pi\pi, K\pi, KK$ is very different than looking for $B \rightarrow J/\psi\, K_s$:

- Rare Decays: *Br*'s ~ 10^{-5} – 10^{-6}
  - → Maximize efficiency: loose selection + global likelihood fit.
- Large background from

$$e^+e^- \rightarrow q\bar{q},\ (q = u, d, s, c)$$

  - → Use multivariate techniques to discriminate against background.
- Must separate $B \rightarrow \pi^+\pi^-, K^+\pi^-, K^-\pi^+, K^+K^-$
  - → BaBar's Ring Imaging Cherenkov detector (DIRC)

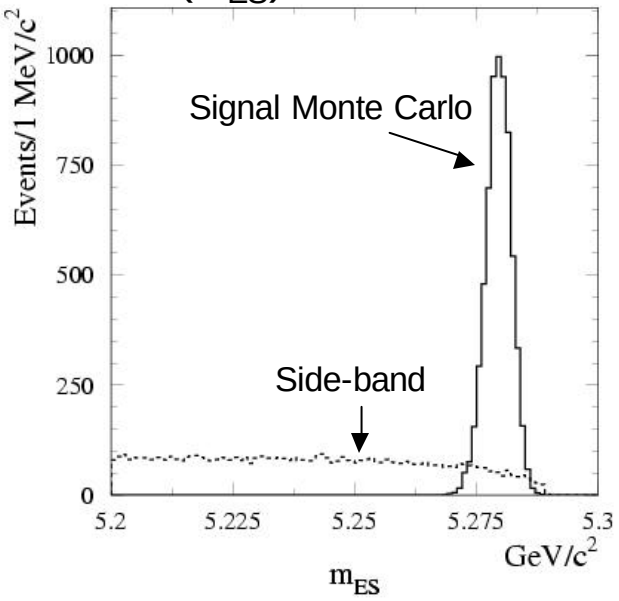
Kinematics

$$m_{\mathrm{ES}} = \sqrt{E^{*2}_{\mathrm{beam}} - p^{*2}_{B}}$$

≈ 325 MeV

- Resolution dominated by the small uncertainty in beam energy

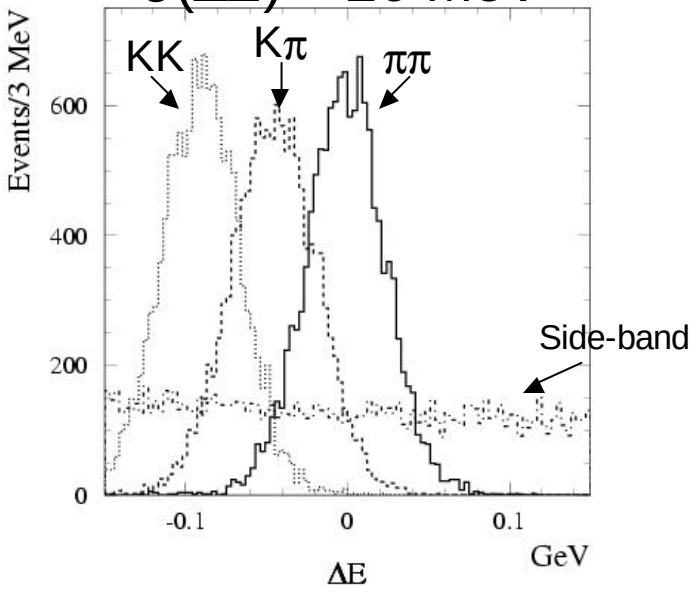
$\sigma(m_{\mathrm{ES}}) \approx 2.6$ MeV/c^2



$$\Delta E = E^{*}_{B} - E^{*}_{\mathrm{beam}}$$

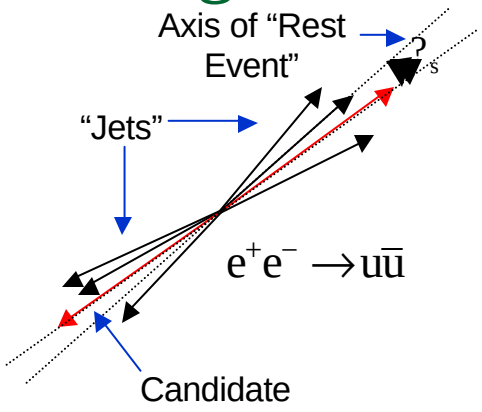
- Dominated by tracking resolution
- Assume $\pi\pi$ mass
- Momentum dependent shift for $K\pi$ and KK

$\sigma(\Delta E) \approx 26$ MeV

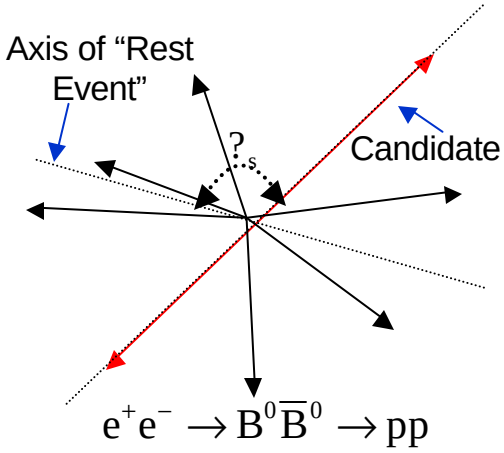


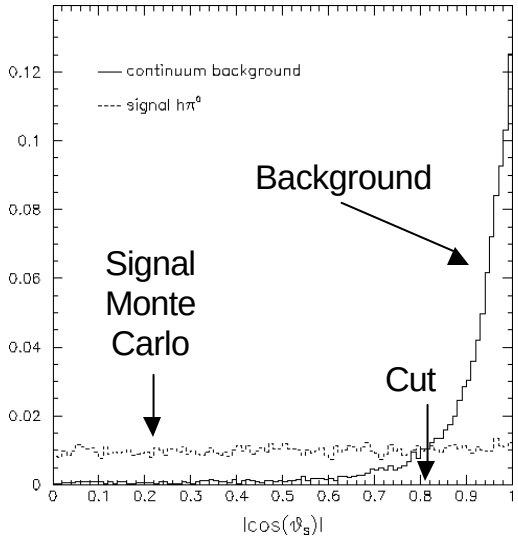
(All distributions are normalized to the same area)

Background Suppression



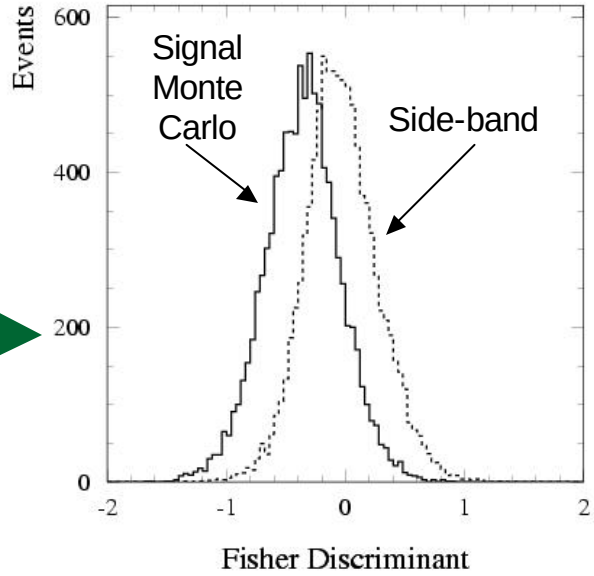
- All background from $e^+e^- \to q\bar{q},\ (q = u, d, s, c)$ where picked 1 track from each fragmenting quark





Angle btw candidate and "*Rest of Event*" axes. ($\cos\theta_s$)

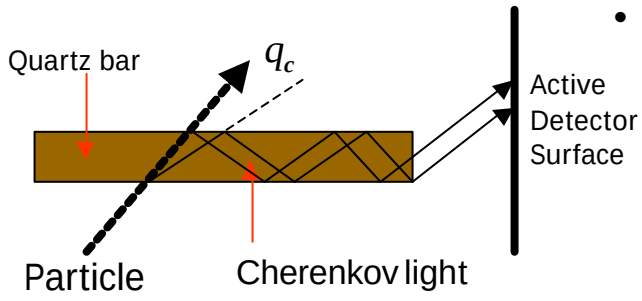
Optimized linear combination of energy flow into cones about candidate. (Fisher Discriminant)



(All distributions are normalized to the same area)

Particle Identification (DIRC)

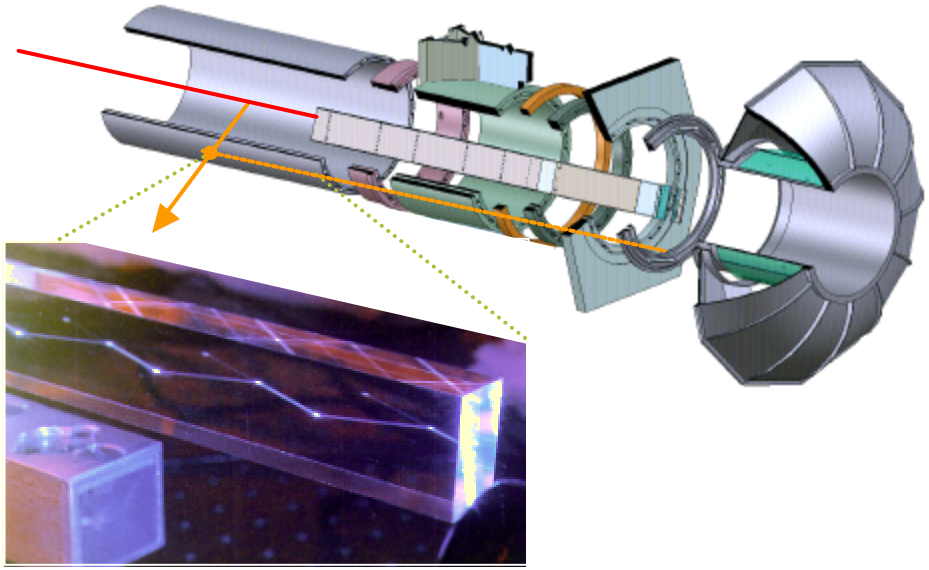
(Detector of Internally Reflected Cherenkov Light)

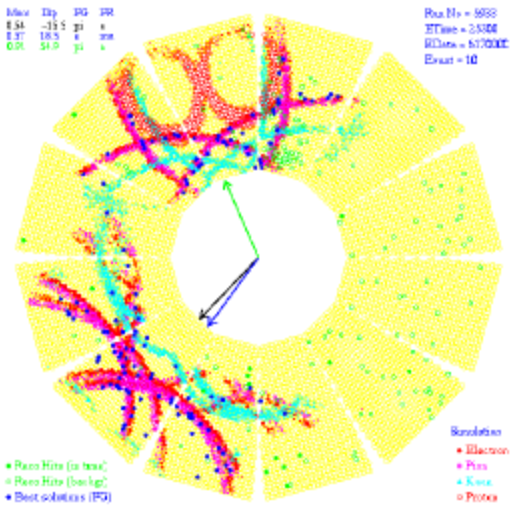


- Measure Angle of Cherenkov Cone in quartz

$$\cos ?_c = \frac{1}{n\beta}, p = m\beta g$$

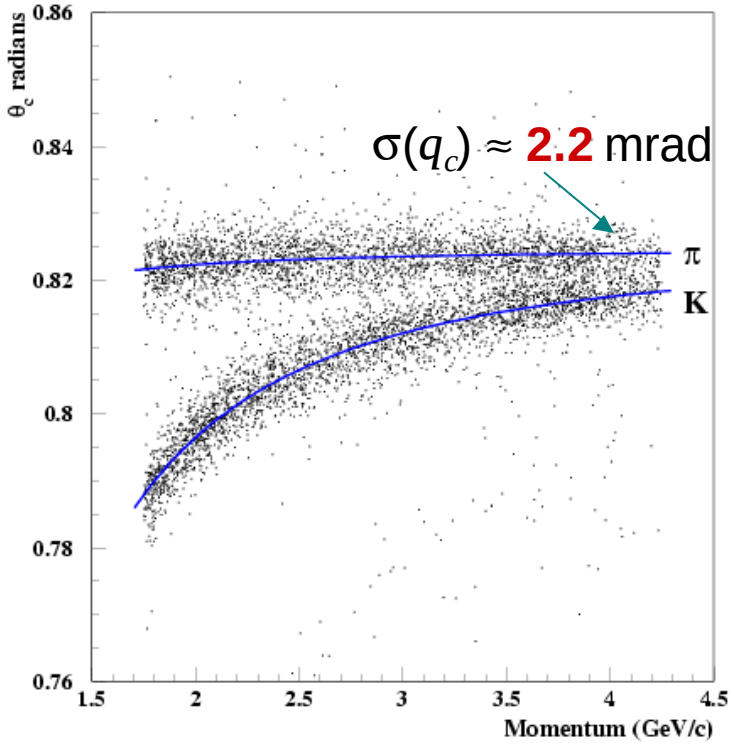
  - Transmitted by internal reflection
  - Detected by PMTs

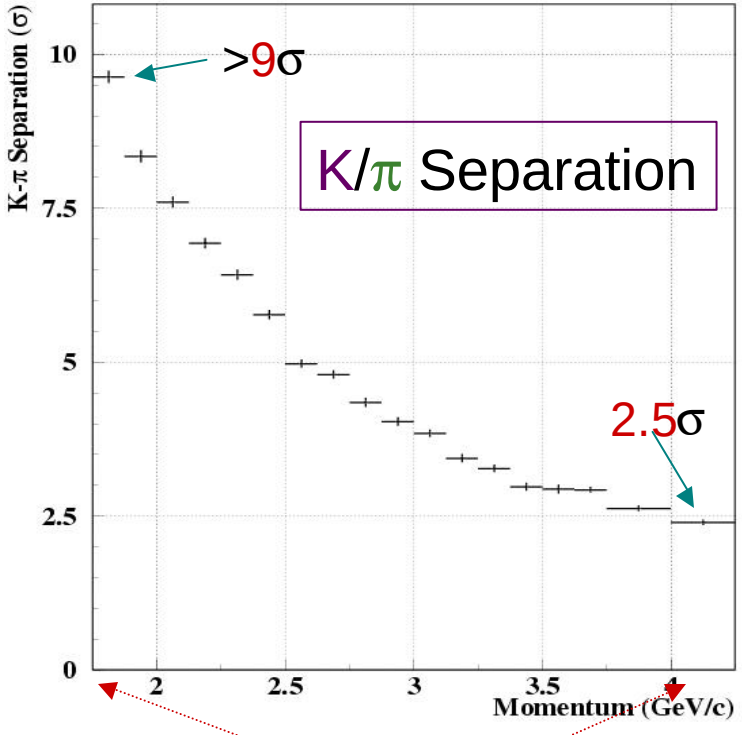




Particle Identification (DIRC) cont'.

- DIRC θ_c resolution and K-π separation measured in data $\Rightarrow D^{*+} \rightarrow D^0\pi^+ \rightarrow (K^-\pi^+)\pi^+$ decays



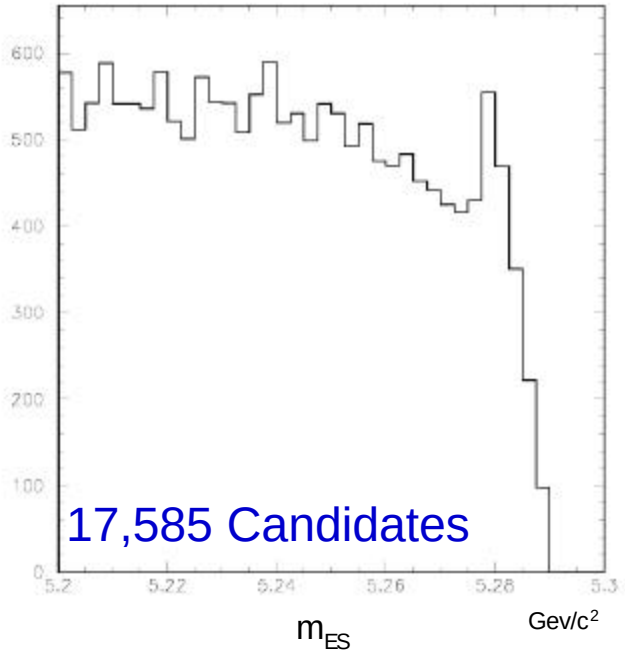


Momentum range of 2-body B Decays at BaBar

Extracting the Branching Fractions

Selected Sample

Signal ε ~38%



Maximum Likelihood Fit

- Isolate Signal
- Separate:

$B^0 \rightarrow \pi^+\pi^-, K^+\pi^-, K^-\pi^+, K^+K^-$

Measure: $N_{pp}, N_{Kp} N_{KK}, A_{Kp}$

Branching Fraction Results

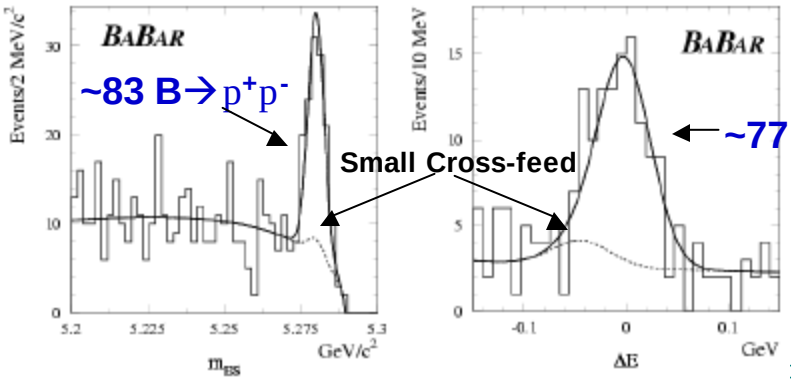
Mode	Yield	Branching Fraction (10^{-6})	Kπ Asymmetry ($A_{K\pi}$)
$B^0 \to p^+p^-$	124^{+16}_{-15}	$5.4 \pm 0.7 \pm 0.4$	
$B^0 \to K^+p^-$	402.7 ± 24	$17.8 \pm 1.1 \pm 0.8$	$-0.05 \pm 0.06 \pm 0.01$
$B^0 \to K^+K^-$	0.6^{+8}_{-7}	<1.1 (90% CL)	

Consistent with CLEO, Belle, and BaBar PRL

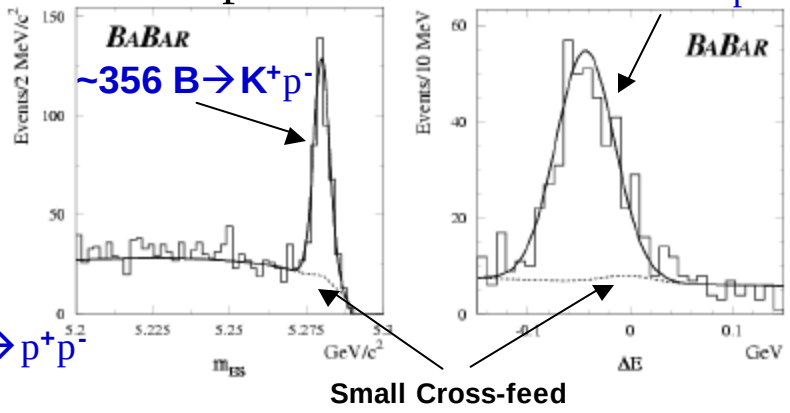
Likelihood projections:

- Remove 1 variable from fit
- Cut on probabilities used in fit

$B^0 \to p^+p^-$



$B^0 \to K^+p^-$

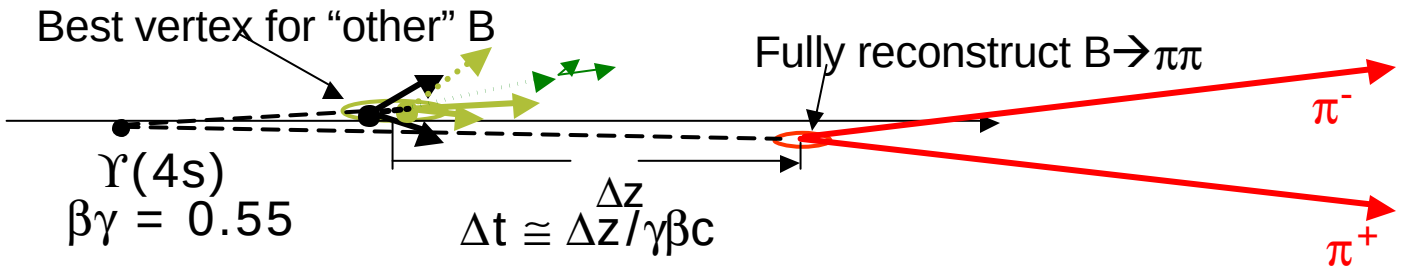


Measuring Time-dependent CP Violation

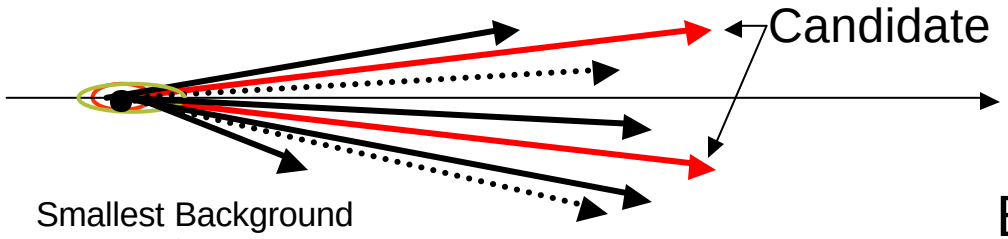
- Extend the Branching Fraction analysis to extract CP information
- Time-dependent analysis needs information on:
  - Time structure of the decays: Vertexing
  - Flavor content of the decays: Flavor tagging
  - → Use same techniques as BaBar's sin 2β analysis

Vertexing (Δt)

- Signal- We make flying B pairs

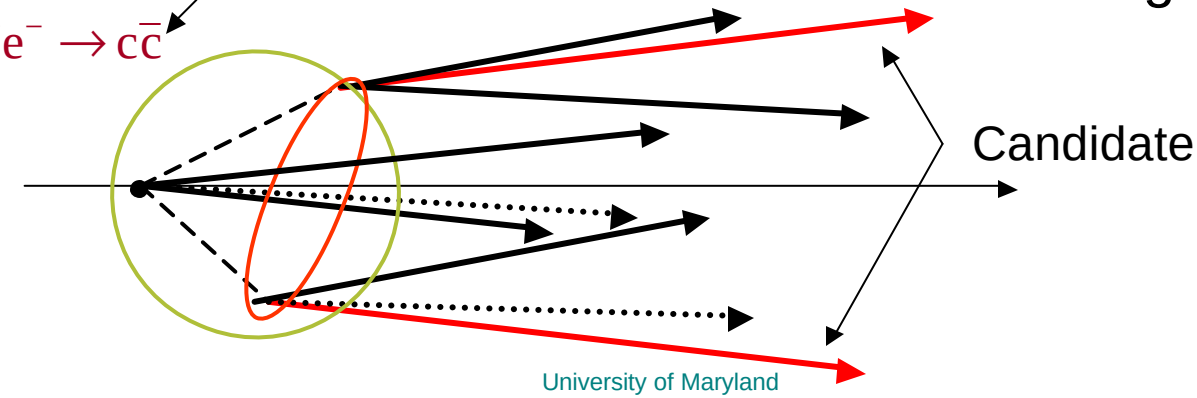


- $e^+e^- \to q\bar{q},\ (q = u,d,s)$



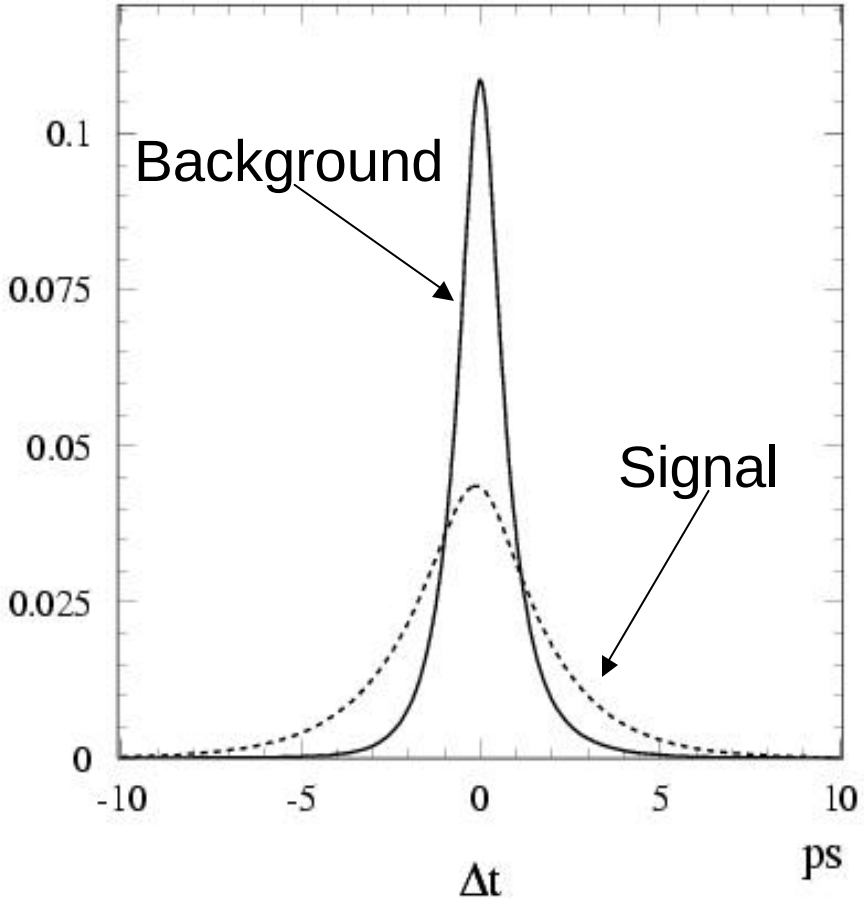
Background $\Delta t \sim 0$

- $e^+e^- \to c\bar{c}$



Vertexing (Δt) cont'.

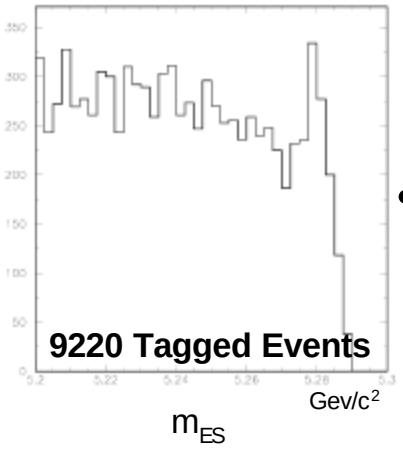
- Since Δt resolution is **dominated** by the "*other*" B, signal resolution determined from **large** sample of fully reconstructed B's using same model as sin 2β analysis.
- Background shape determined from sidebands.



Flavor Tagging

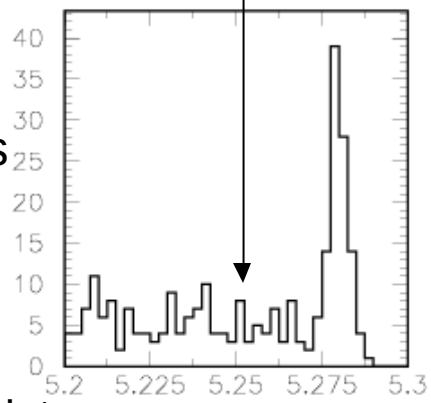
• Use same flavor tagging as sin 2β measurement

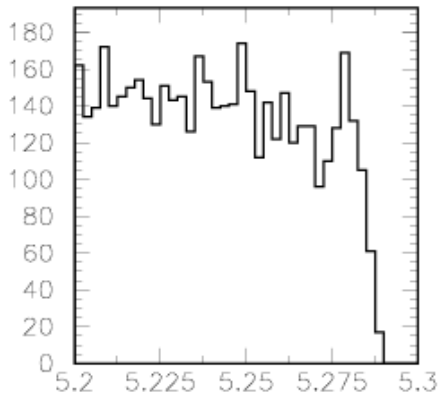
• Look for tracks whose charge carry flavor information in various categories.

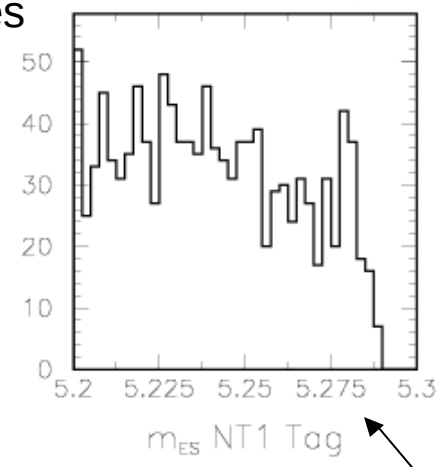


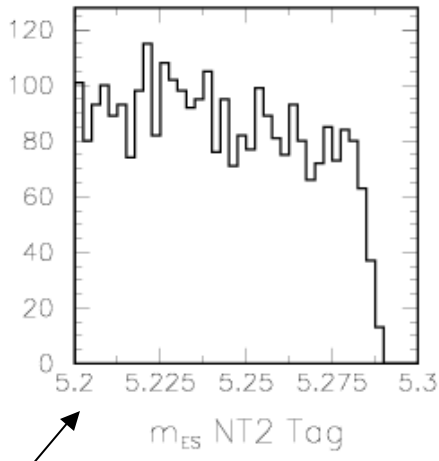
Separate into categories

Few Leptons in background









Multivariate Tag Categories

• Exploit mixing to measure signal performance (Dilutions) and efficiencies in **large** sample of fully reconstructed B's.

Mixing / Lifetime Validation

- Measure B lifetime using $B^0 \to p^+p^-/K^\pm p^\mp$

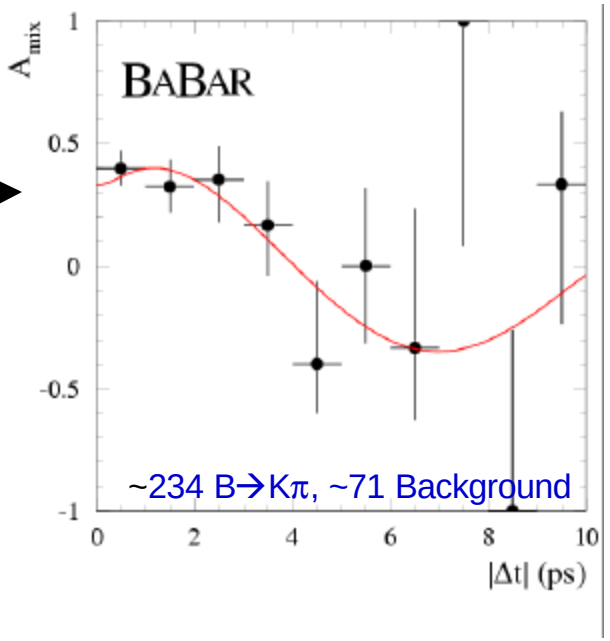
$$\Rightarrow t = 1.66 \pm 0.09\ \text{ps}$$

- Measure Δm_d using $B^0 \to K^+p^-$

Cross-check

$$\Rightarrow \Delta m_d = 0.517 \pm 0.062\ \text{ps}^{-1}$$

Select B→Kπ sample and plot the asymmetry between mixed/unmixed events.

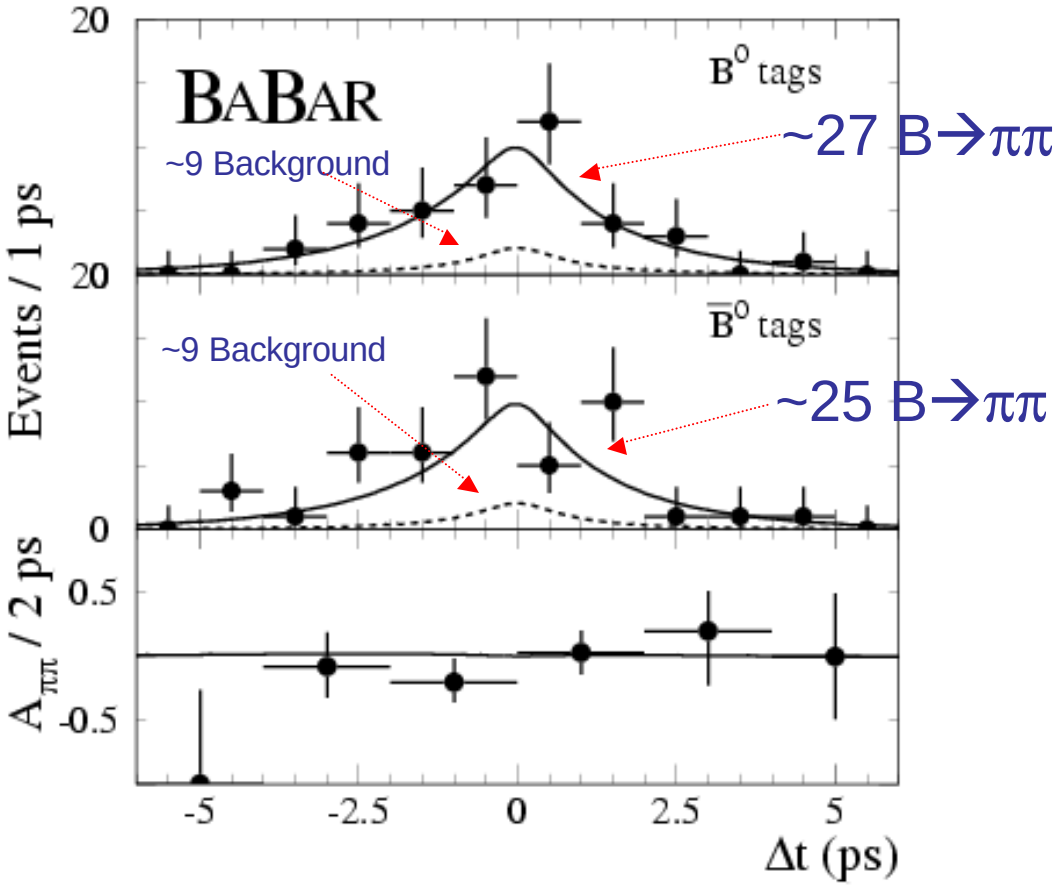


Time-dependent CP Measurement

$$S_{pp} = -0.01 \pm 0.37 \pm 0.07 \ [-0.66, +0.62]$$

$$C_{pp} = -0.02 \pm 0.29 \pm 0.07 \ [-0.54, +0.48]$$

90% CL



Select B→ππ sample and plot the asymmetry between mixed/unmixed events.

Time-dependent CP Measurement

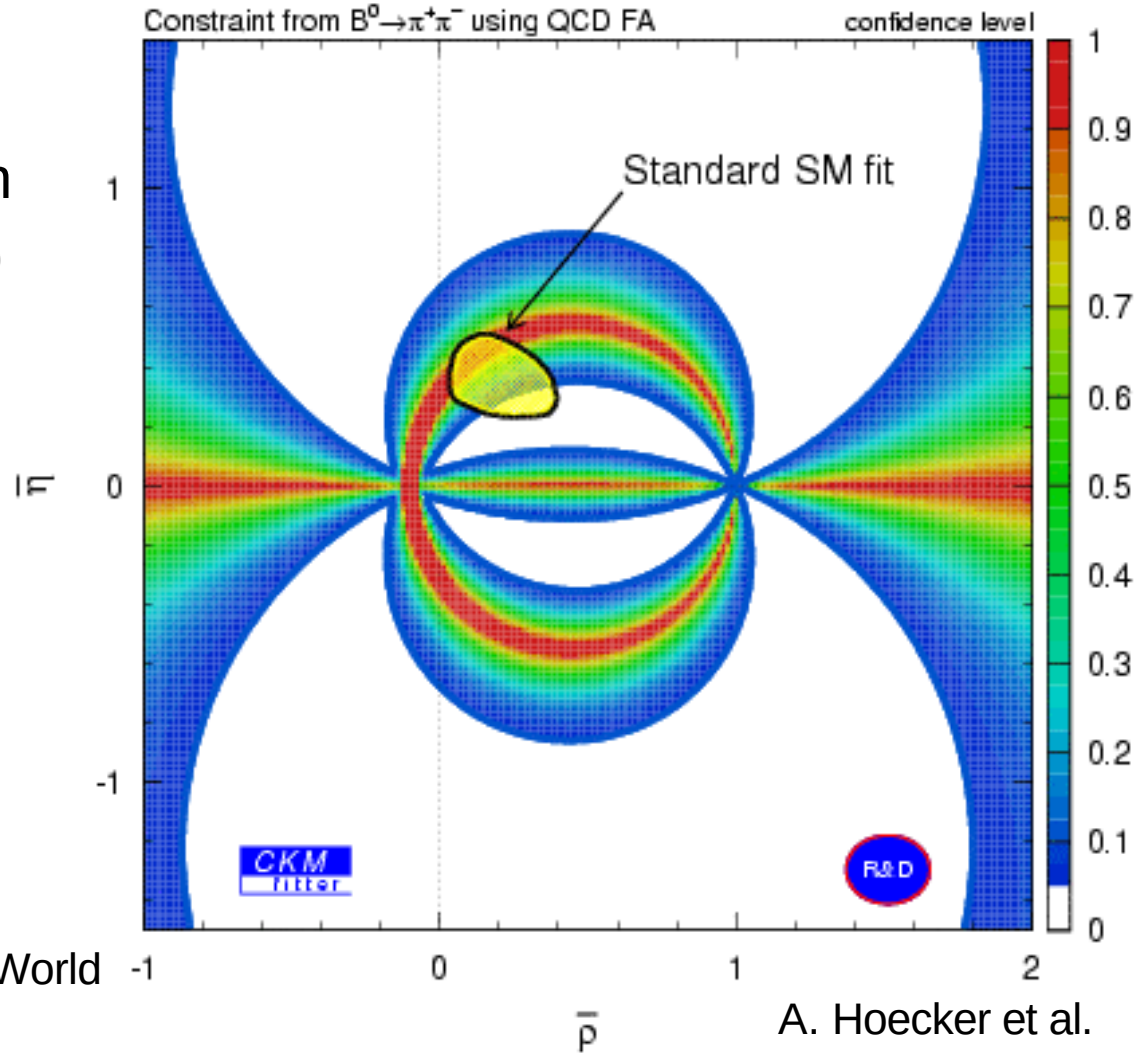
Using $S_{\pi\pi}$ and QCD Factorization

(BBNS)

"Standard SM fit":

- ε
- V_{ub}/V_{cb}
- Δm_d
- Δm_s
- sin 2β

Summer World Average



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Summary of Results

Belle: Not sure about signs

$S_{\pi\pi} = -1.21\ ^{+0.38}_{-0.27}\ ^{+0.16}_{0.13}$

$-C_{\pi\pi} = 0.94^{+0.25}_{-0.31} +/- 0.09$

$S_{pp} = -0.01 \pm 0.37 \pm 0.07\ [-0.66, +0.62]$

$C_{pp} = -0.02 \pm 0.29 \pm 0.07\ [-0.54, +0.48]$

90% CL

$A_{Kp} = -0.05 \pm 0.06 \pm 0.01\ [-0.15, +0.05]$

Mode	BaBar (10^{-6}) (60M B's)	CLEO (10^{-6}) (9.66M B's)	Belle (10^{-6}) (11.1M B's)
$B^0 \to p^+ p^-$	$5.4 \pm 0.7 \pm 0.4$	$4.3^{+1.6}_{-1.5} \pm 0.5$	$5.9^{+2.4}_{-2.1} \pm 0.5$
$B^0 \to K^+ p^-$	$17.8 \pm 1.1 \pm 0.8$	$17.2^{+2.5}_{-2.4} \pm 1.2$	$18.7^{+3.3}_{-3.0} \pm 1.6$
$B^0 \to K^+ K^-$	< 1.1 (90% CL)	< 1.9	< 2.7