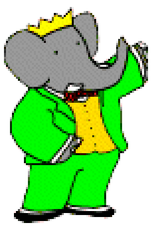
Branching Fraction and CP asymmetry in $B^0 \to \pi^0 \pi^0$ Decays



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IOP Dublin, March, 2005

Overview

- Introduction & motivation $B^0 \to \pi^0 \pi^0$
- Analysis procedure
- Results
- Summary

The CKM matrix & CP violation

CKM matrix describes mixing between flavor and weak eigenstates in the Standard Model.

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

3x3 unitary matrix:
3 real parameters,
1 phase: only source of CPV in SM

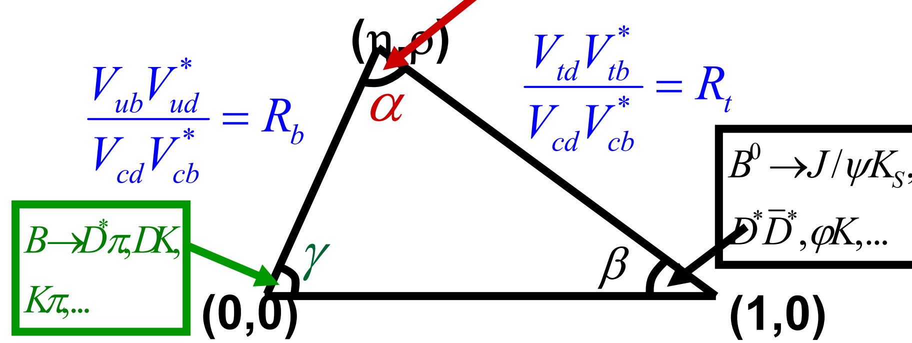
Unitarity implies $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

Wolfenstein parameterization

$$V_{CKM} \approx \begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

CP violating phases

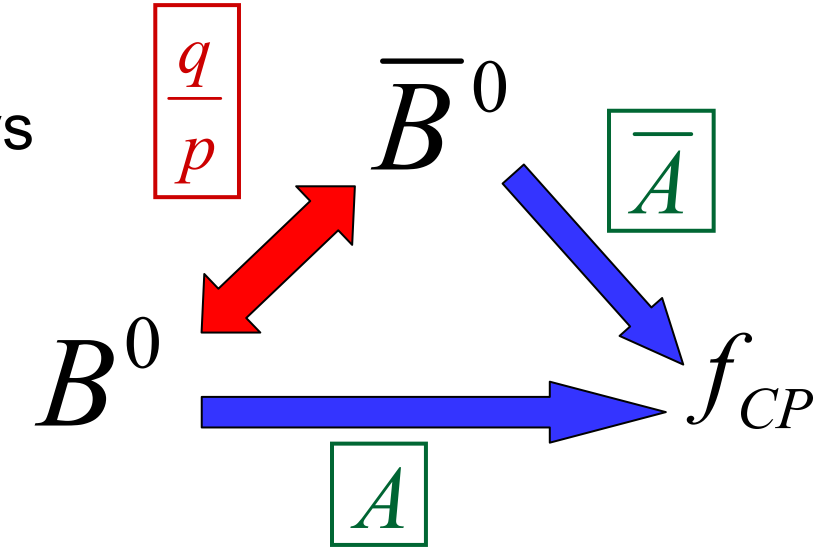
$B \to \pi\pi, \rho\pi, \rho\rho$ This talk



Area of triangle is equivalent to the amount of CP violation in SM

Observing CP Violation at *BABAR*

Three observable effects in **B** decays to a final state **f**:



CP violation in mixing ($|q/p| \neq 1$)

$$B^0 \to \overline{B}^0 \neq \overline{B}^0 \to B^0$$

(direct) CP violation in decay ($|\overline{A}/A| \neq 1$)

$$B^0 \to f \neq \overline{B}^0 \to \bar{f}$$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}}{A}$$

(indirect) CP violation in the interference between mixing and decay ($\mathrm{Im}\lambda_{f_{CP}} \neq 0$)

Time dependent effect is sensitive to measure unitarity triangle angles

How to measure α from $B^0 \to \pi^+\pi^-$ decays

Decays sensitive to α

$$\boxed{B^0 \rightarrow \pi^+\pi^-}$$

Time dependent cp asymmetry:

$$a_{\pi\pi}(t) = \frac{\Gamma_{B^0\to\pi\pi} - \Gamma_{\overline{B}^0\to\pi\pi}}{\Gamma_{B^0\to\pi\pi} + \Gamma_{\overline{B}^0\to\pi\pi}}$$

Can be written as:

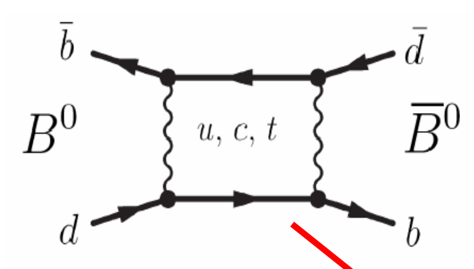
$$= S_{\pi\pi}\sin(\Delta m_B \Delta t) - C_{\pi\pi}\cos(\Delta m_B \Delta t)$$

$$S \propto 2\,\mathrm{Im}\,\lambda \qquad \mathrm{C} \propto 1 - |\lambda|^2$$

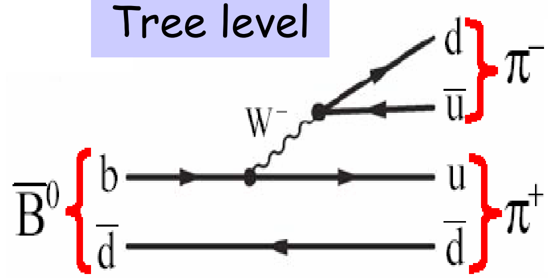
Indirect CP relevant to α

Direct CP

B^0-$\overline{B}^0$ mixing



Tree level



$$\lambda = \frac{q}{p}\frac{\overline{A}}{A} = e^{i2\alpha}$$

$$S_{\pi\pi} = \sin 2\alpha$$
$$C_{\pi\pi} = 0$$

$$a_{\pi\pi}(t) = \sin(2\alpha)\,\sin(\Delta m_B \Delta t)$$

Measuring α in presence of penguins

Coefficients of time-dependent CP Asymmetry in $B^0 \to \pi^+\pi^-$ decays

Tree level

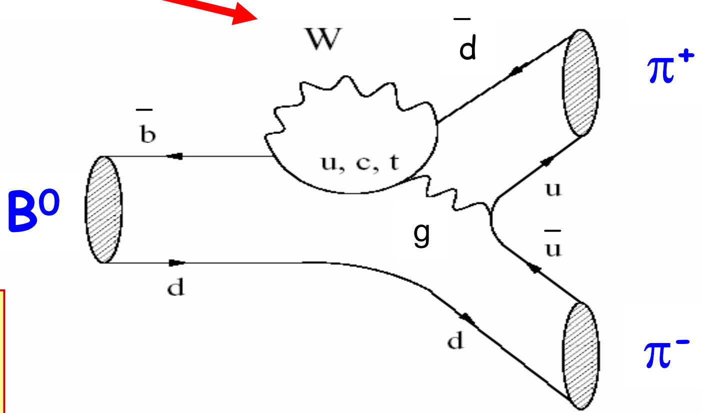
$$S_{\pi\pi} = \sin 2\alpha$$
$$C_{\pi\pi} = 0$$

But penguin diagrams are not negligible!!!

Penguin

- Carry a different phase compared to tree level
- Measure α_{eff}

$$S_{\pi\pi} = \sqrt{1 - C_{\pi\pi}^2}\,\sin 2\alpha_{eff}$$
$$C_{\pi\pi} \propto \sin\delta$$



Measure $\alpha_{eff} = \alpha + \delta\alpha_{peng}$ need to bound $|\alpha - \alpha_{eff}|$

Need Isospin analysis

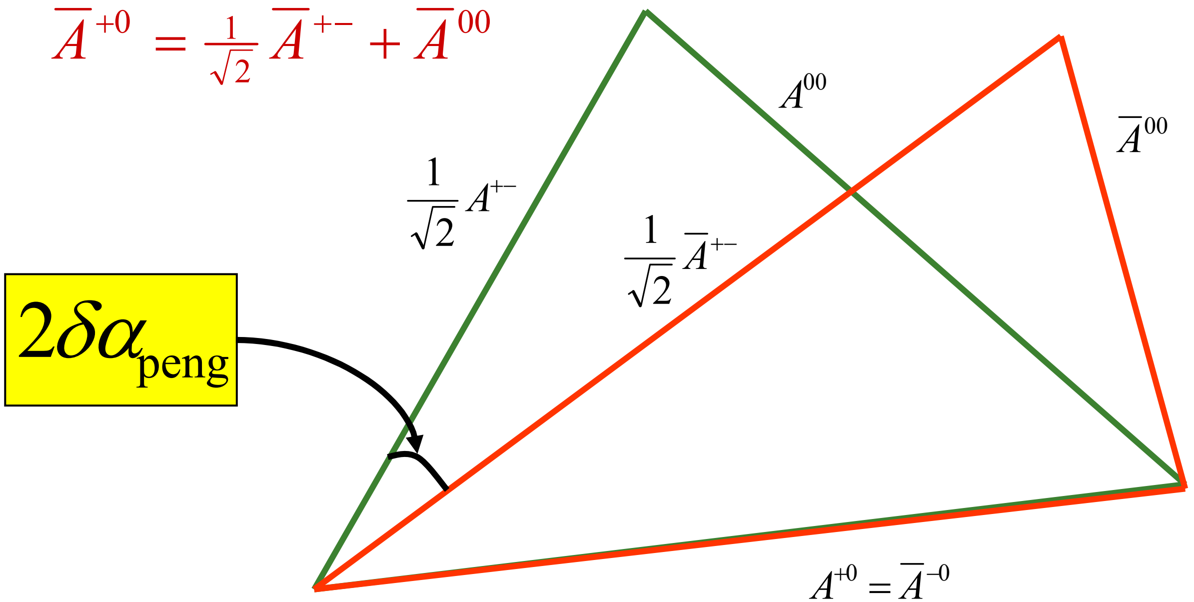
Measuring α from B → π π Isospin

Isospin relates different amplitudes

Gronau-London: PRL **65**, 3381 (1990)

$$A^{+0} = \frac{1}{\sqrt{2}} A^{+-} + A^{00}$$

$$\bar{A}^{+0} = \frac{1}{\sqrt{2}} \bar{A}^{+-} + \bar{A}^{00}$$



Need to measure:

$$A^{+-} = A(B^0 \to \pi^+\pi^-)$$
$$\bar{A}^{+-} = A(\bar{B}^0 \to \pi^+\pi^-)$$
$$A^{00} = A(B^0 \to \pi^0\pi^0)$$
$$\bar{A}^{00} = A(\bar{B}^0 \to \pi^0\pi^0)$$
$$A^{+0} = A(B^+ \to \pi^+\pi^0)$$
$$\bar{A}^{-0} = A(B^- \to \pi^-\pi^0)$$

BaBar has measured all BFs to carried out the isospin analysis

small A^{00} & $\bar{A}^{00}$ ➡ small $\delta\alpha_{peng}$

$$\sin^2(\alpha_{eff} - \alpha) < \frac{\langle \mathrm{BF}(B^0 \to \pi^0\pi^0)\rangle}{\mathrm{BF}(B^+ \to \pi^+\pi^0)}$$

Grossman-Quinn bound
PRD 58, 017504 (1998)

$B^0 \to \pi^0 \pi^0$ CP asymmetry

Time dependent CP asymmetry

$$a_{\pi^0\pi^0}(t) = -C_{\pi^0\pi^0}\mathrm{Cos}(\Delta m_b t) + S_{\pi^0\pi^0}\mathrm{Sin}(\Delta m_b t)$$

Neutral B mixing probability

PDG 2004

Integrating over time

$$A_{\pi^0\pi^0} = -(1-2\chi)(1-2\omega)C_{\pi^0\pi^0}$$

Need tagging to identify the B flavor

Mistag probability

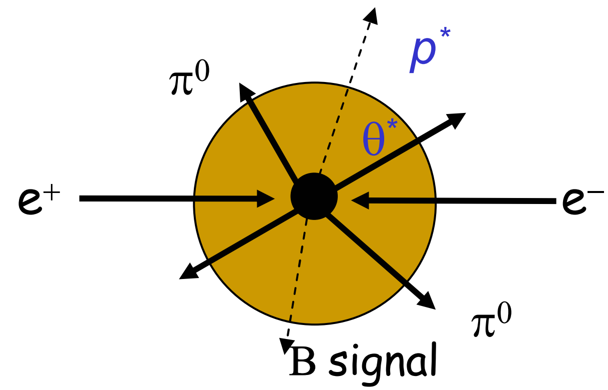
Time integrated CP asymmetry

$$\boxed{A_{\pi^0\pi^0} = \frac{\overline{N}_{\pi^0\pi^0} - N_{\pi^0\pi^0}}{\overline{N}_{\pi^0\pi^0} + N_{\pi^0\pi^0}}}$$

Analysis procedure

Data sample:

- •227 million B pairs collected at the Υ(4S) energy
- •16 fb-1 of data recorded 40 MeV below the Y(4S)

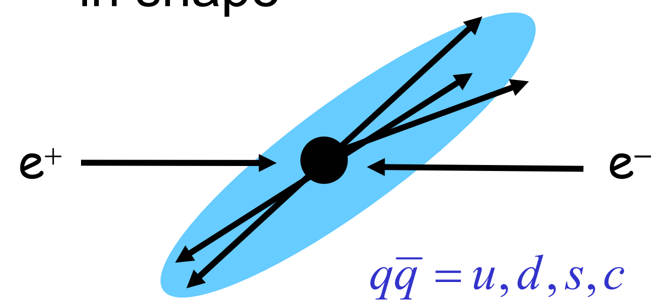


Event Selection:

- $B^0\left(\overline{B}^0\right)$ Decays from combination of 4 photons to make 2 π^0 s
- •Photons not matched to any charged track in the detector
- π^0 mass required

$$110 < m_{\gamma\gamma} < 160\ (\mathrm{MeV}/\mathrm{c}^2)$$

B events are spherical in shape



- **Event shape variables for background suppresion (~80%)**

Background events from light quark production have jet-like topology

Backgrounds

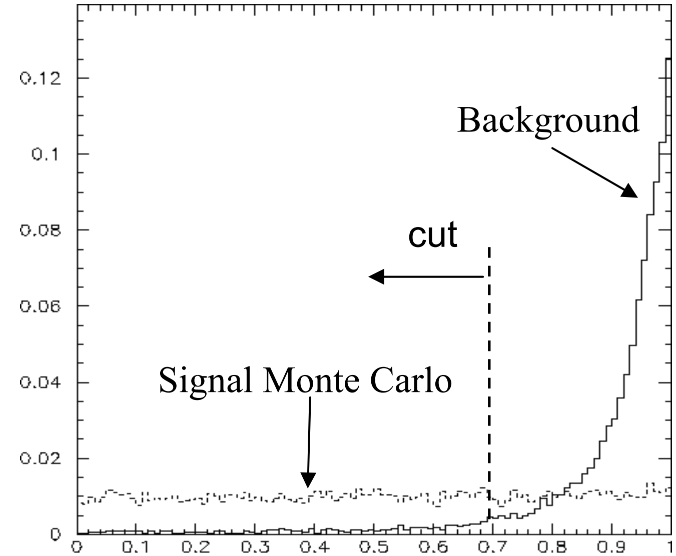
Main Backgrounds

Continuum (u,d,s,c quarks)

B background

$$B^{\pm} \rightarrow \rho^{\pm} \pi^{0}$$
$$\rho^{\pm} \rightarrow \pi^{\pm} \pi^{0}$$

When charged π is missed



Cosine of the angle between the sphericity axes of the B and of the rest of the event
$|\cos(\theta_s)| < 0.7$

Final efficiency 1.3% and use world average BF to fix number of events in fit

Babar PRL 93, 051802 (2004), Belle hep-hex/0406006

Analysis procedure

With a preselected sample of 8153 events

- Method

Extended ML fit simultaneously determines:

$$N_{\pi^0\pi^0}\;,\;N_{q\bar{q}}\;,\;A_{\pi^0\pi^0}\;,\;A_{q\bar{q}}$$

Yields & Asymmetries

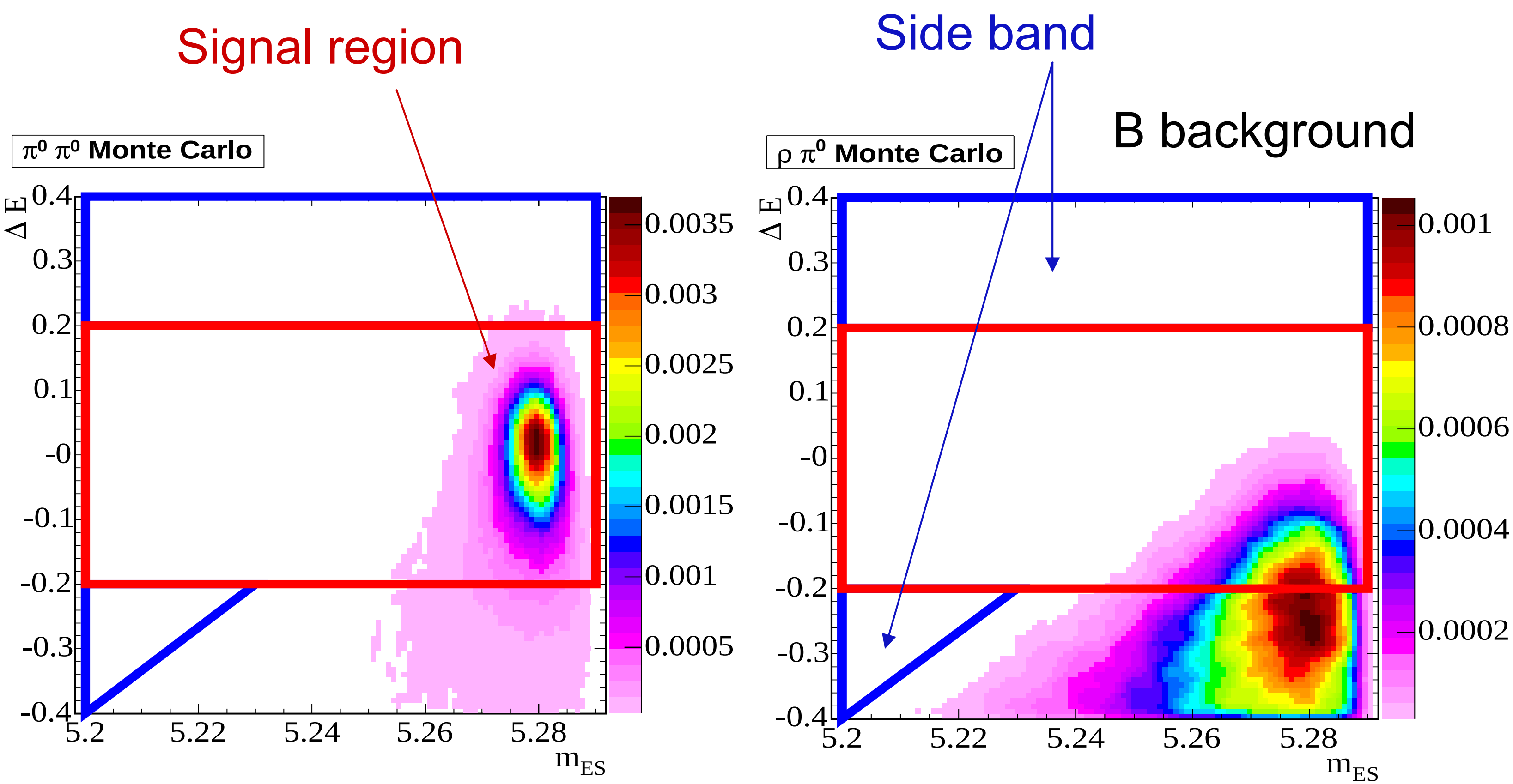
and uses:

- **Kinematic variables for signal selection**
- **Event shape for signal-background sepatation**
- **Use of tagging information**

$$m_{ES}, \Delta E, Fisher$$

PDF Parameterization

$$\Delta E = E_B^* - E_{beam}^*$$

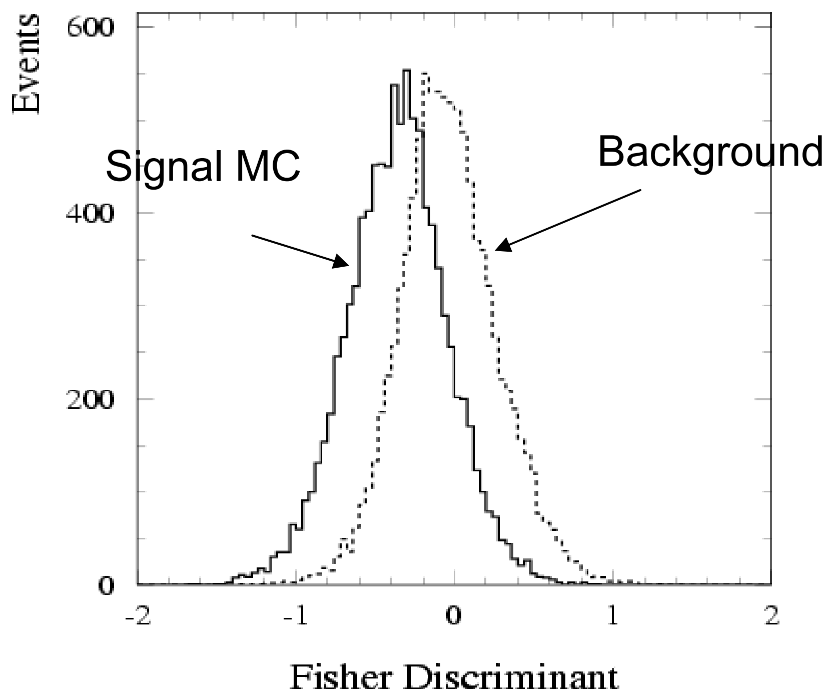


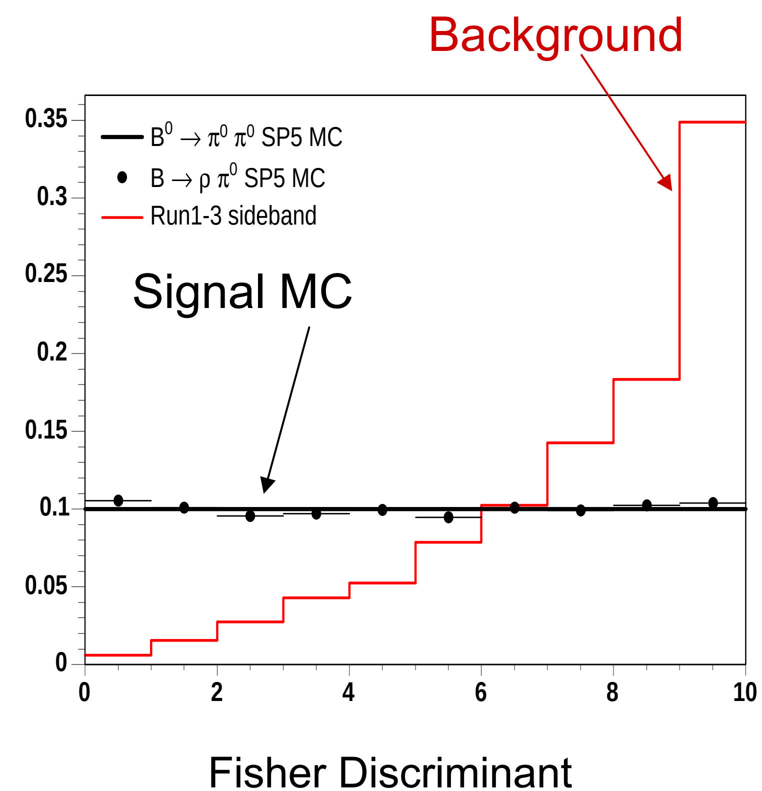
$$5.2 < \quad m_{ES} = \sqrt{E_{beam}^{*2} - P_B^{*2}}$$

(GeV/c^2)

Background suppression

•Continuum rejection using event shape variables





$$F = 0.53 - 0.60 \times \sum_i p_i^* + 1.27 \times \sum_i p_i^* \left|\cos(\theta_i^*)\right|^2$$

Parametric Step Function, 10 bins (9 free params.)

Parameterized for each tagging category

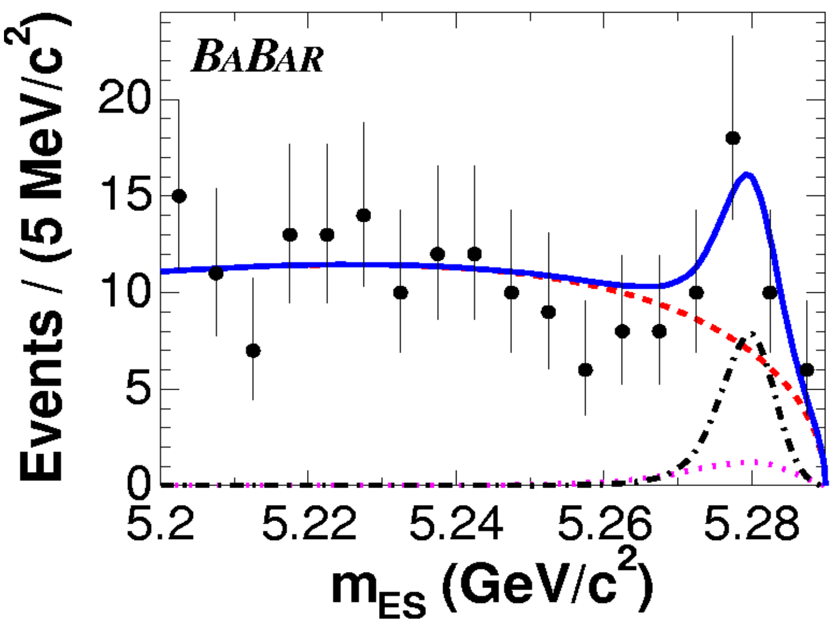
Results

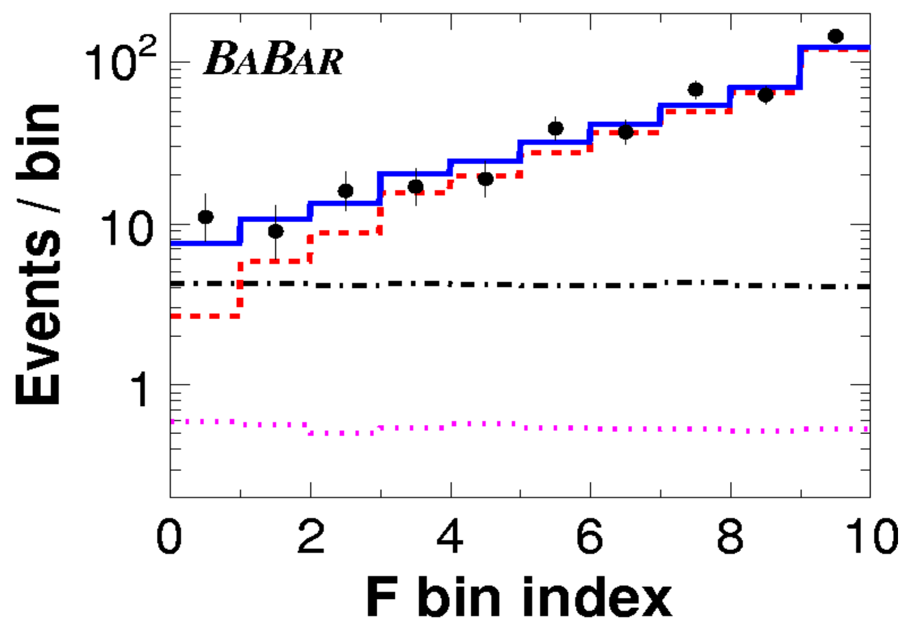
significance $5.2\ \sigma$

Events $N_{\pi^0\pi^0} = 61 \pm 17$

Reconstruction efficiency $\varepsilon(23.5\%)$

$$BF_{\pi^0\pi^0} = (1.17 \pm 0.32 \pm 0.10) \times 10^{-6}$$
$$C_{\pi^0\pi^0} = -0.12 \pm 0.56 \pm 0.06$$





$$\text{Fit} = q\bar{q}\ \text{bkgd} + B^{\pm} \rightarrow \rho^{\pm}\pi^{0} + \text{signal}$$

Systematic errors and checks

Main sources of systematic errors

Source	ΔN_{00}	ΔC_{00}
Uncertainty in $\rho\pi$ BF	+-2.12	+-0.012
Uncertainty in $\rho\pi$ Asymmetry	+-.4	+-0.051
π reconstruction	+-4.45	+-0.014
ΔE-Mes Monte Carlo corrections	+-1.12	+-0.015
Tagging efficiencies	+-0.01	+-0.032

Cross checks

Fit compatible with 2003 result

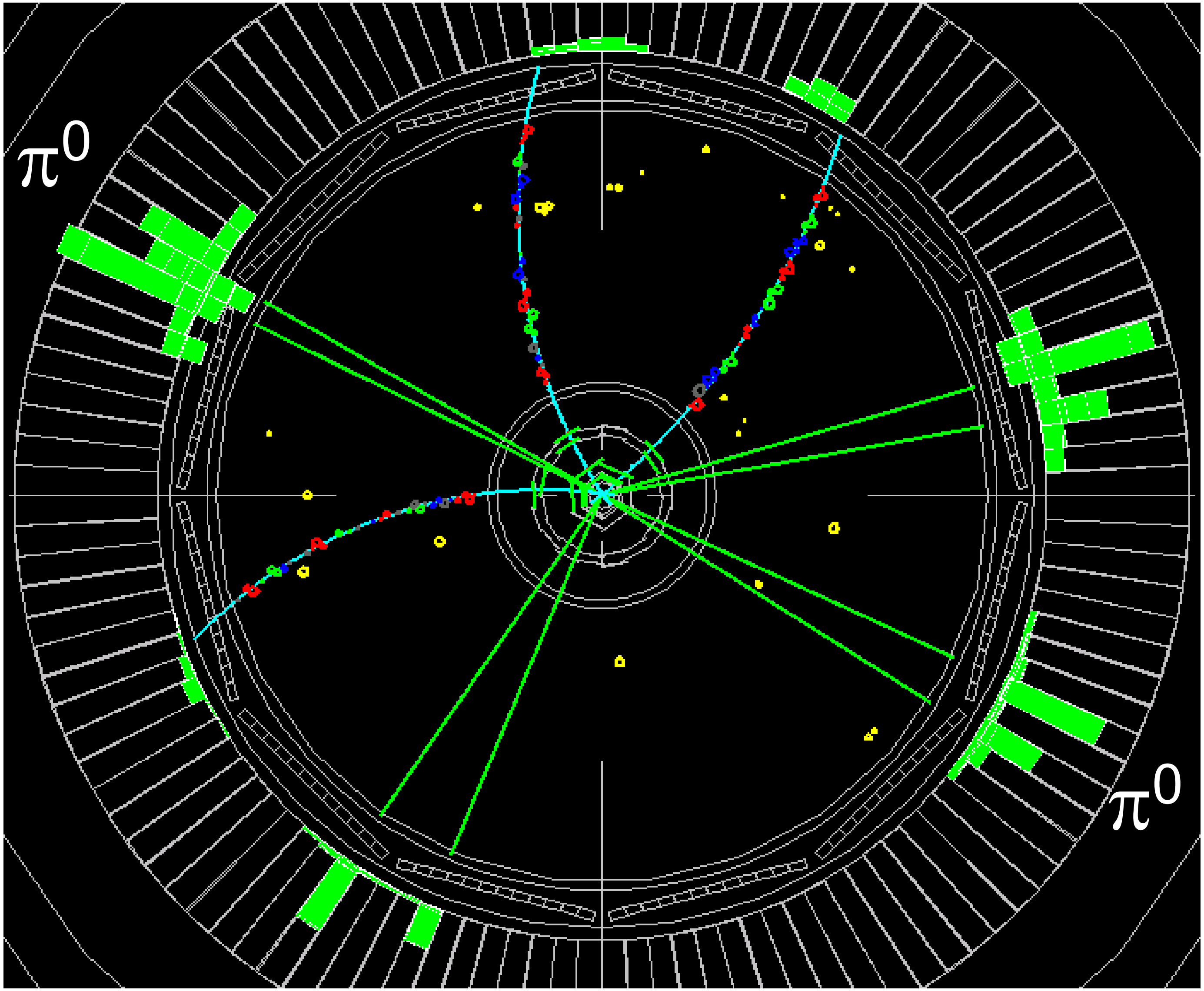
Fit performed on different data samples are consistent

Toy MC studies to look for potential fit bias

Cut & Count analysis compatible with Likelihood fit result

Using MC, check for crosstalk Between different species, minimal

Signal Event



Summary $B^0 \rightarrow \pi^0 \pi^0$

$$BF_{\pi^o \pi^o} = (1.17 \pm 0.32 \pm 0.10) \times 10^{-6}$$

$$C_{\pi^o \pi^o} = -0.12 \pm 0.56 \pm 0.06 \quad [-0.88, 0.64] \quad 90\% \, \text{C.L.}$$

significance $5.0\ \sigma$ Including systematics

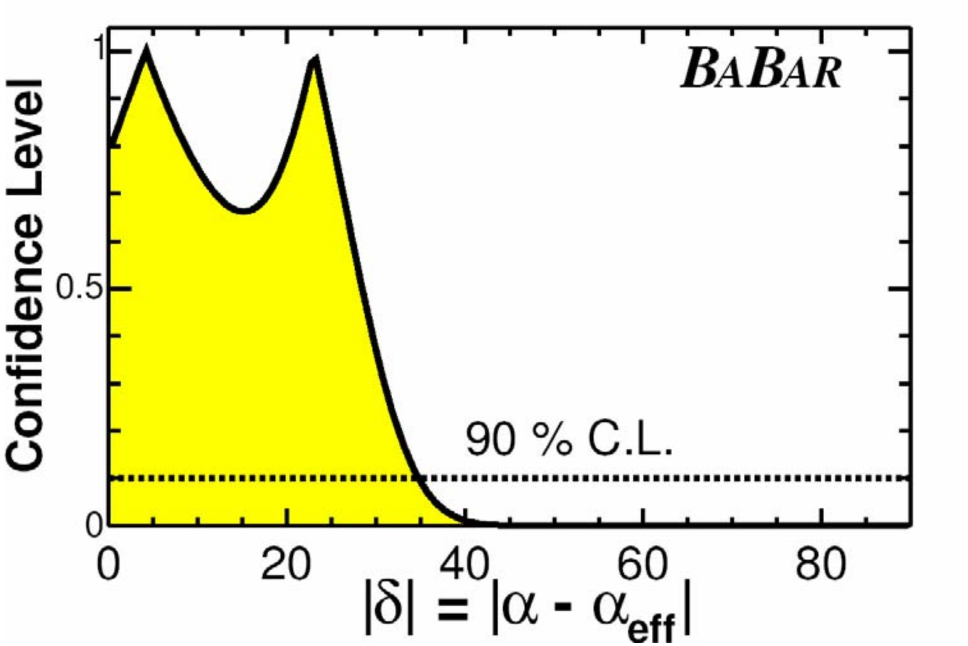
Hep-ex/0408081, submitted to PRL

Isospin analysis

$$|\alpha - \alpha_{eff}| < 35^{O}$$

90% C.L.

Need Super B-factory to get useful bound

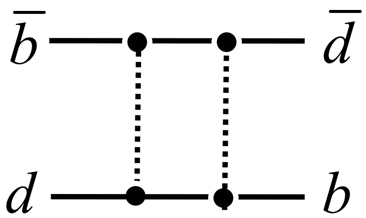


Backup slides

Interference of suppressed
$b \rightarrow u$ "tree" decay with mixing

but: "penguin"
is sizeable!

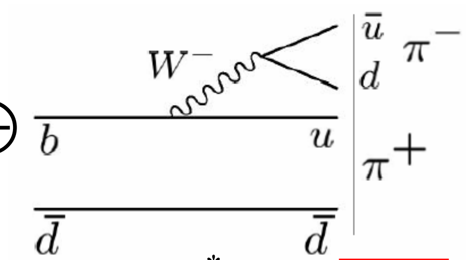
B^0 mixing



$q/p \propto V_{tb}^* V_{td} / V_{tb} V_{td}^*$

$\oplus$

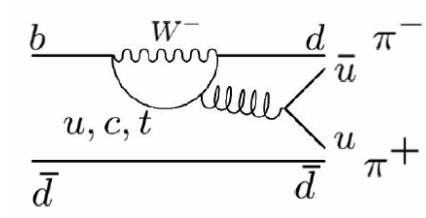
B^0 decay: tree



$A \propto V_{ub}^* V_{ud}$ $\propto \lambda^3$

$\oplus$

B^0 decay: penguin



$A \propto V_{td}^* V_{tb}$ $\propto \lambda^3$

$$\lambda_{\pi\pi} = \frac{q}{p} \frac{\overline{A}_{\pi\pi}}{A_{\pi\pi}} = e^{-i2\beta} e^{-i2\gamma} = e^{i2\alpha}$$

$$\lambda_{\pi\pi} = e^{i2\alpha} \frac{T + Pe^{+i\gamma} e^{i\delta}}{T + Pe^{-i\gamma} e^{i\delta}}$$

Coefficients of time-dependent CP Asymmetry

With no penguins

$$S_{\pi\pi} = \sin 2\alpha$$
$$C_{\pi\pi} = 0$$

With large penguins
and |P/T| ~ 0.3

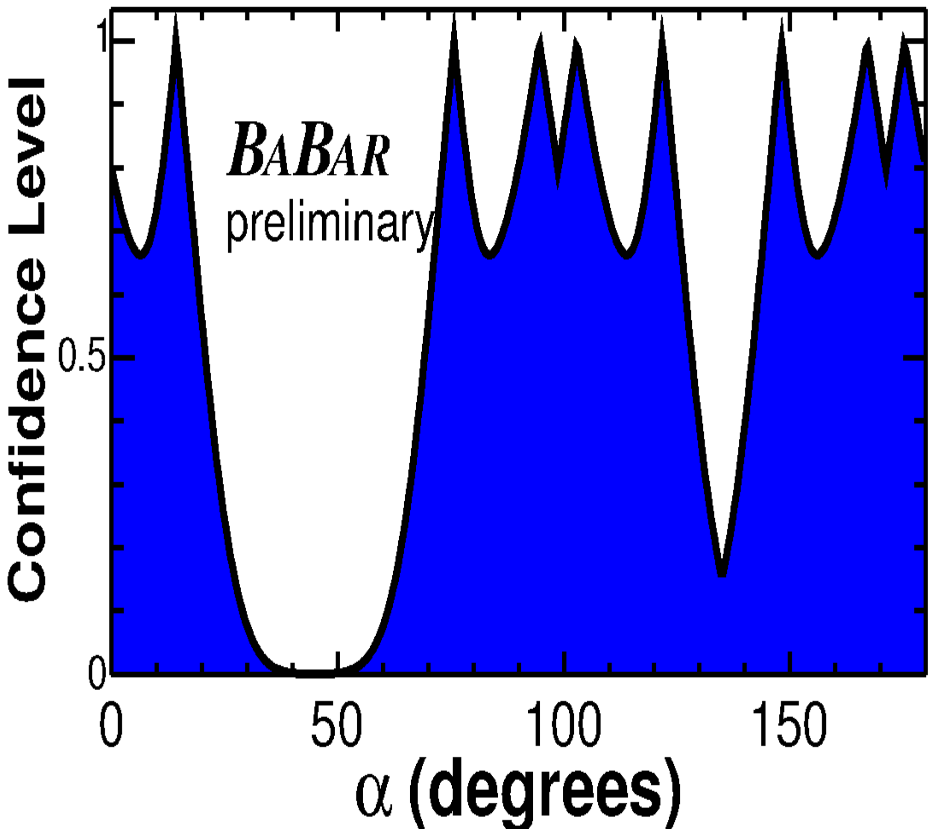
$$S_{\pi\pi} = \sqrt{1 - C_{\pi\pi}^2} \sin 2\alpha_{eff}$$
$$C_{\pi\pi} \propto \sin \delta$$

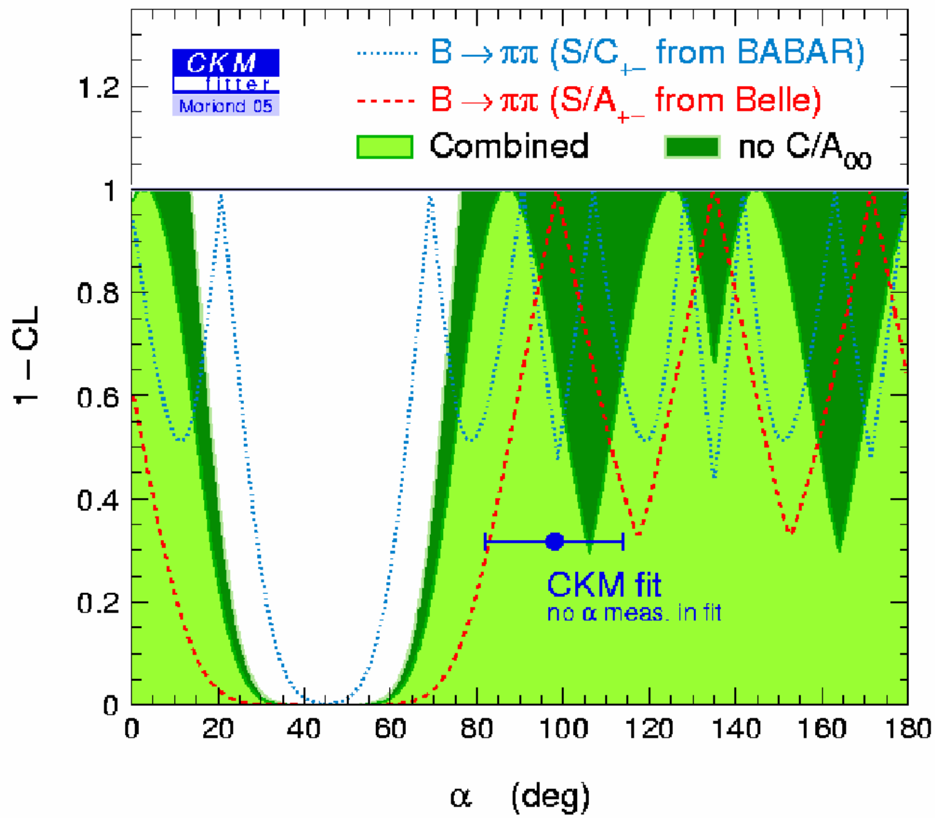
Scan on α

Babar 2004

$S = -0.30 \pm 0.17 \pm 0.02$

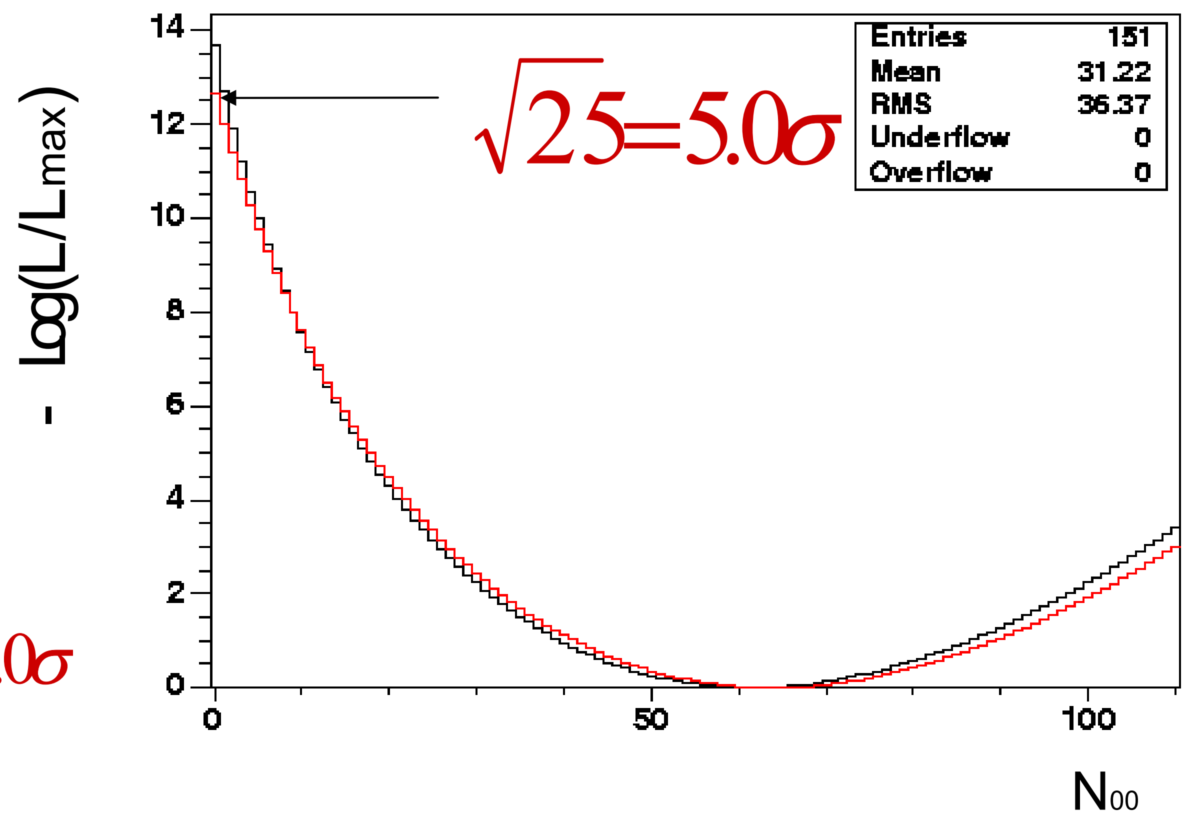
$C = -0.09 \pm 0.15 \pm 0.03$





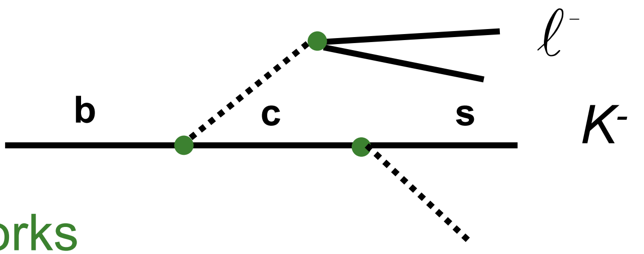
Significance calculation

The significance is defined as root square of the change In the log likelihood when the asymmetry is fixed to zero.



$$\sqrt{\Delta(-2\log L)_0} = 5.0\sigma$$

B Flavour Tagging



- Tagging algorithm with physics-based neural networks
  - Inputs include leptons, kaons, slow-π (from D*), and high-momentum tracks
  - Outputs combined and categorized by mistag probability (*w*)

- 5 mutually exclusive hierarchical categories:

  - Lepton – isolated high-momentum leptons
  - Kaon I – high quality kaons or correlated K^+ and slow-π^-
  - Kaon II – lower quality kaons, or slow-π
  - Inclusive – unidentified leptons, poor-quality kaons, high-momentum tracks
  - Untagged – no flavour information is used

efficiency

mistag probability

Category	ϵ_c (%)	ω_c (%)	$\Delta\omega_c$ (%)	Q_c (%)
Lepton	9.1 ± 0.2	3.3 ± 0.7	-1.6 ± 1.3	8.0 ± 0.3
Kaon I	16.6 ± 0.2	9.5 ± 0.7	-2.8 ± 1.3	10.7 ± 0.4
Kaon II	19.8 ± 0.3	20.6 ± 0.8	-5.3 ± 1.3	6.7 ± 0.4
Inclusive	20.1 ± 0.3	31.7 ± 0.9	-2.6 ± 1.4	2.7 ± 0.3
Untagged	34.4 ± 0.5			
Total Q				28.4 ± 0.7

67% of events have some flavour information

$$Q = \varepsilon(1-2w)^2 = (28.4 \pm 0.7)\%$$

PDF Parameterization

Variable	Signal PDF	Background PDF
m_{ES}	2-D smoothed hist.	Argus
ΔE	2-D smoothed hist.	Poly2
Fisher	Steep function (10 bins)	Steep function (10 bins)