# Experimental Study of $\beta$ and $\alpha$

1. A brief reminder of the CKM triangle
2. Measurements of $\sin\ 2\beta$
3. Details of the CDF measurement
4. Plans and Prospects for
   - $\sin\ 2\beta$
   - $\sin\ 2\alpha$
5. Summary


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# The CKM Triangle

Unitary CKM matrix governs weak decay of quarks

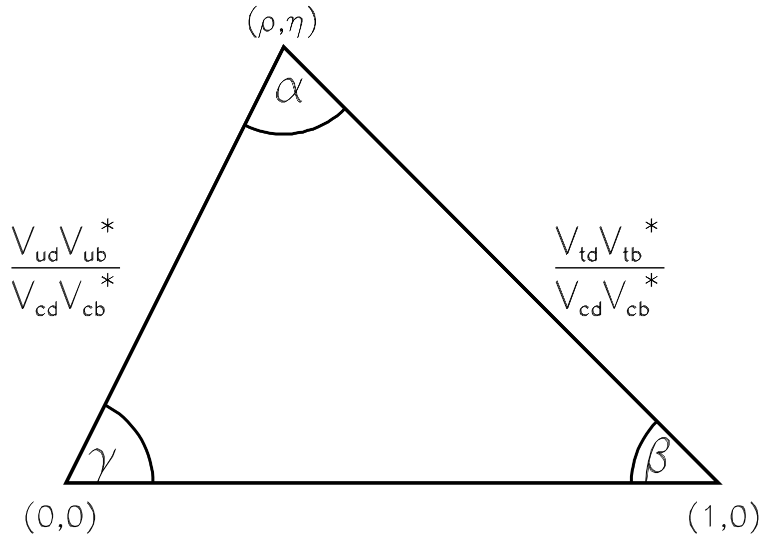
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfenstein parametrisation:

$$V_{\text{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

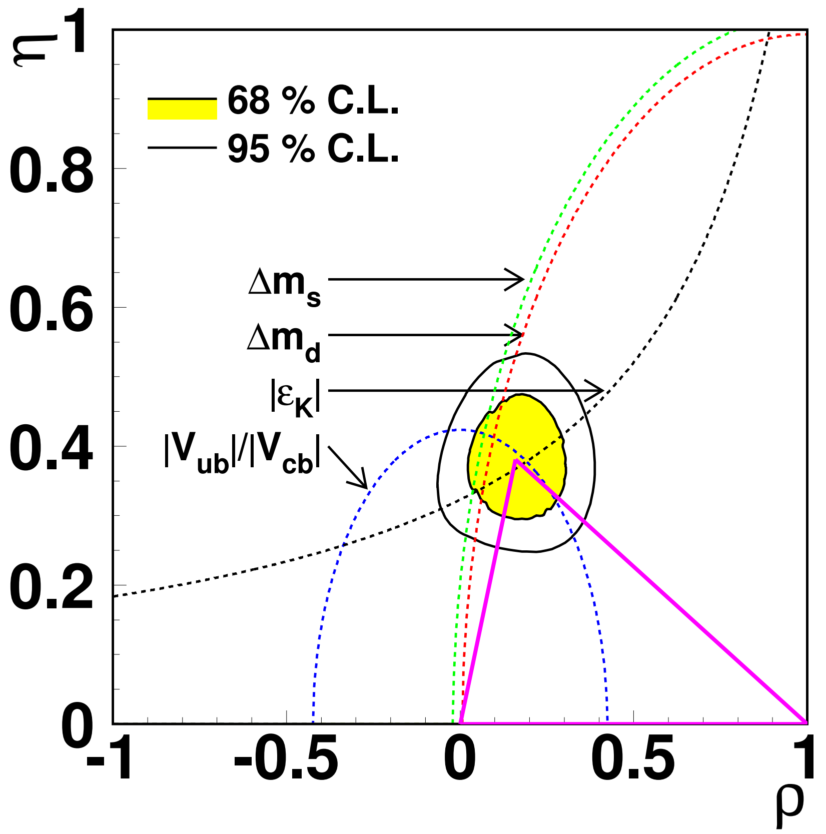
Unitarity $\rightarrow V^\dagger V = 1$ gives:

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



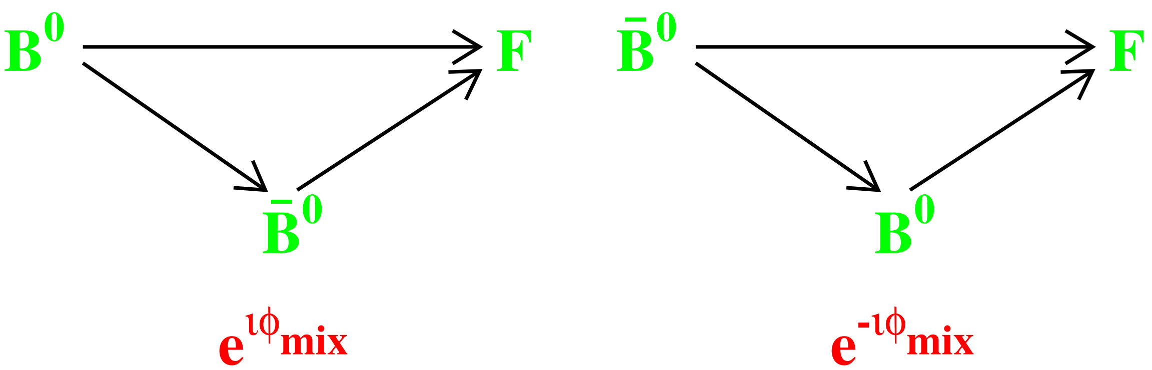

$$\alpha = \arg\left(\frac{-V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \qquad \beta = \arg\left(\frac{-V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \qquad \gamma = \arg\left(\frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

# Constraints on $\beta$ from CKM Matrix




| Experiment | sin $2\beta$ | Reference |
|---|---|---|
| | | |
| CKM model fit | $0.75 \pm 0.09$ | S. Mele, PRL**59**, 113011 (99) |

# The CP Asymmetry

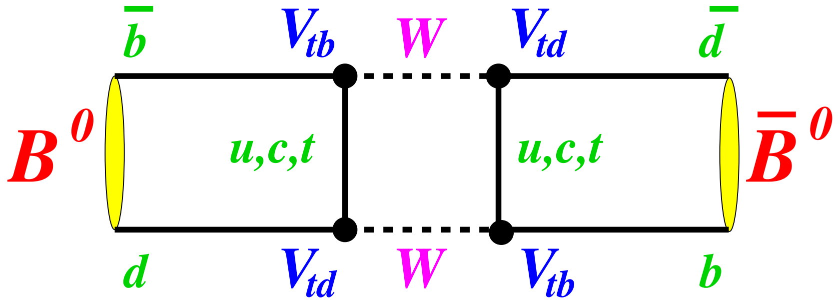



- Results in:

$$\frac{dN}{dt}(B^0 \to J/\psi K^0_S) \sim 1 - \sin\ 2\beta\ \sin\ \Delta m t$$

$$\frac{dN}{dt}(\bar{B}^0 \to J/\psi K^0_S) \sim 1 + \sin\ 2\beta\ \sin\ \Delta m t$$

- CP phase easily seen in CKM matrix element $V_{td}$




- $B^0$ and $\bar{B}^0$ produced at equal rates develop asymmetry:

$$\begin{aligned} A_{CP}(t) &= \frac{\frac{dN}{dt}(\bar{B}^0 \to J/\psi K^0_S) - \frac{dN}{dt}(B^0 \to J/\psi K^0_S)}{\frac{dN}{dt}(\bar{B}^0 \to J/\psi K^0_S) + \frac{dN}{dt}(B^0 \to J/\psi K^0_S)} \\ &= \sin\ 2\beta\ \sin\ \Delta m t \end{aligned}$$

# Experimental Considerations

- Production mechanism can be important
  - At hadron collider $b\bar{b}$ not produced in coherent state
    * time averaged asymmetry does not vanish
    * time dependent asymmetry msmt. improves precision
  - At $B$ factory $B^0\bar{B}^0$ produced in coherent P-wave state
    * CP asymmetry only builds after first $B$ meson decays
    * Must measure asymmetry to access CP information
- Both require tagging of original $B^0$ flavour to see asymmetry

$$A_{CP}^{obs} = \mathcal{D} A_{CP}$$

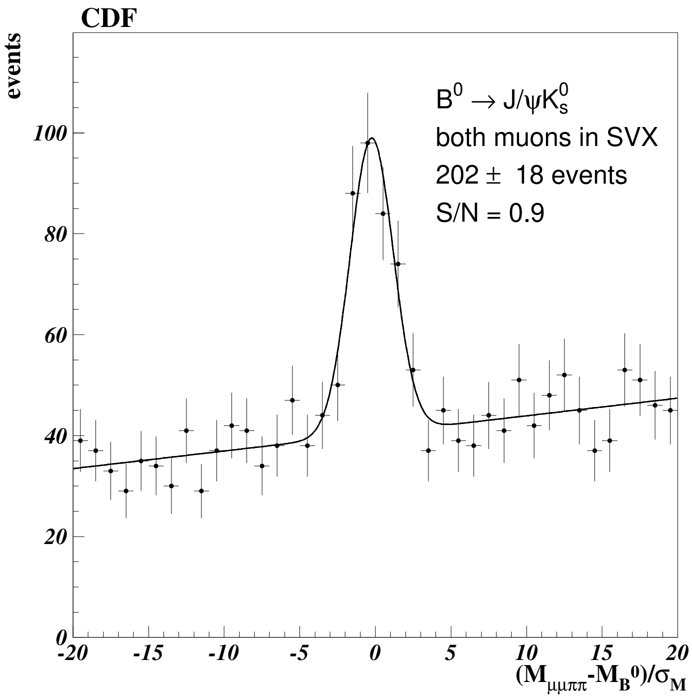
- $\mathcal{D}$ is the "tagging dilution"
  - $\mathcal{D} = (N_r - N_w)/(N_r + N_w)$
  - $N_r(N_w)$ are the number of right (wrong) tags
  - Constrain $\mathcal{D}$ from data
- Precision on sin $2\beta$ given by

$$\delta \sin\ 2\beta \approx 0.47 \frac{1}{\sqrt{\epsilon \mathcal{D}^2}} \sqrt{\frac{S+B}{S^2}}$$

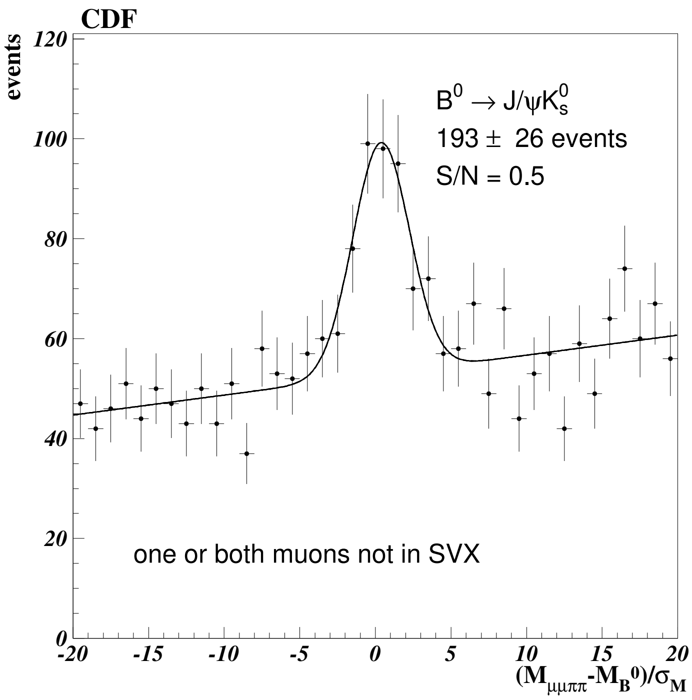
  - $\epsilon$ is fraction of events with a tag
  - $S$ is number of signal events
  - $B$ is number of background events

# CDF Data Sample

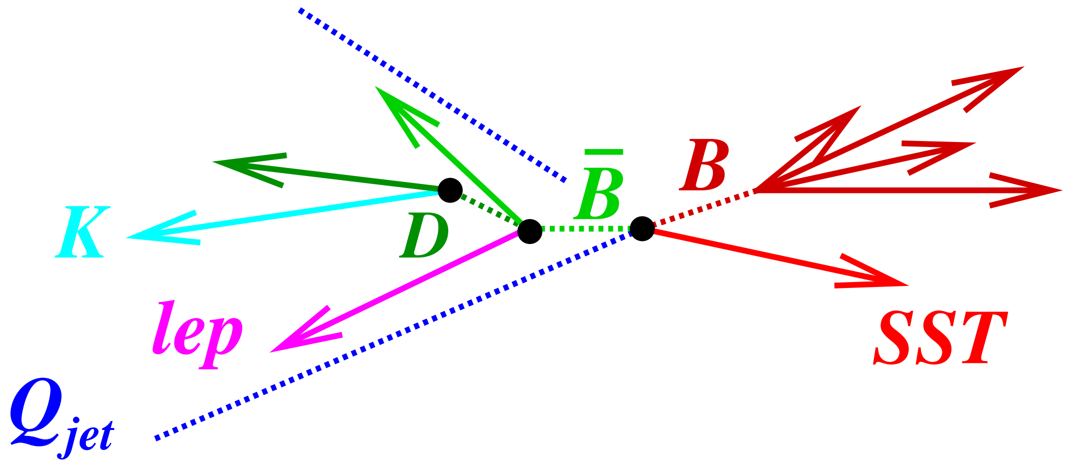
Both $J/\psi$ muons have SVX information ($\approx$ 200 events)




One or both $J/\psi$ muons lack SVX information ($\approx$ 200 events)



## Methods for Tagging Initial $B^0$ Flavour




Determine the flavour ($B^0$ vs $\bar{B}^0$) at time of production

Opposite-Side Tagging

- Charge of opposite-side jet (JETQ)
- Soft $e$ or $\mu$ tag from semi-leptonic decay of opposite $B$ (SLT)

Same-Side Tagging

- Same-side SVX and non-SVX pion tagging (SST)

# Jet Charge Tagging (JETQ)

- Opposite-side $b$ quark can fragment into any $B$ meson
- Identify flavour of $b$ quark through charge of opposite jet
- Use a variant of *JADE* track cluster algorithm
  - optimised for low $p_t$ jets
- Weight individual track charges by
  - transverse momentum
  - impact parameter ($T_i \approx 0$ for displaced tracks)

$$Q_{jet} = \frac{\Sigma\ q_i p_i (2 - T_i)}{\Sigma\ \ p_i (2 - T_i)}$$

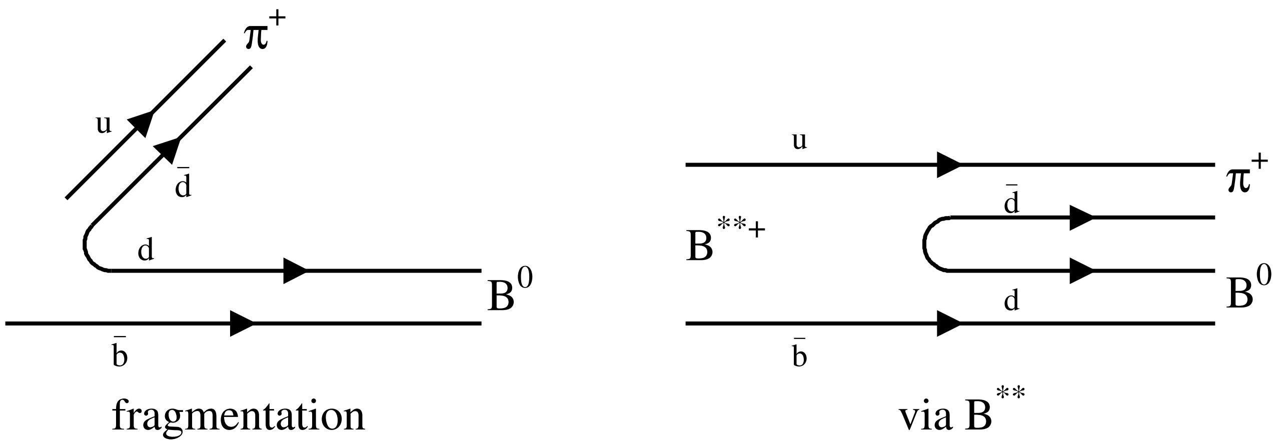
  - $Q_{jet} > 0.2 \rightarrow b$
  - $Q_{jet} < -0.2 \rightarrow \bar{b}$
  - $|Q_{jet}| < 0.2 \rightarrow$ **no tag**
- 40% of $J/\psi K^0_S$ have a jet charge tag
- $\mathcal{D} = 0.235 \pm 0.069$ calibrated on $J/\psi K^{\pm}$ sample

## Soft Lepton Tagging (SLT)

- Identify flavour of opposite $B$ hadron through $b \to l\nu X$ decay
- Semileptonic branching ratio leads to $\approx 6\%$ efficiency
- Electron selection
  - Central track ($p_t > 1$ GeV/c) matched to EM shower
- Muon selection
  - Central track ($p_t > 2$ GeV/c) matched to muon stub
- When present: $\mathcal{D} = 0.625 \pm 0.146$ on $J/\psi K^{\pm}$ sample

## Same Side Tagging (SST)

- Opposite tagging limited
  - other $b$ is central only 50% of the time
  - if other $b$ is $B^0$ or $B_s^0$ it mixes
- Exploit correlated fragmentation on same side




- Use semi-leptonic $B$ meson decays to calibrate SVX sample

$$\mathcal{D} = 0.166 \pm 0.022$$

- Use $B^{\pm} \to J/\psi K^{\pm}$ sample to calibrate non-SVX sample

$$\mathcal{D} = 0.174 \pm 0.036$$

## Summary of Flavour Tagging

| Tagger | Events | efficiency ($\epsilon$) | Dilution ($\mathcal{D}$) |
|---|---|---|---|
| SST | SVX | $35.5 \pm 3.7$ % | $16.6 \pm 2.2$ % |
| SST | non-SVX | $38.1 \pm 3.9$ % | $17.4 \pm 3.6$ % |
| SLT | all | $5.6 \pm 1.8$ % | $62.5 \pm 14.6$ % |
| JETQ | all | $40.2 \pm 3.9$ % | $23.5 \pm 6.9$ % |

Tagging algorithms all contribute similar statistical power:

| Tagger | $\epsilon\mathcal{D}^2$ |
|---|---|
| SST | $2.1 \pm 0.5$ % |
| SLT | $2.2 \pm 1.0$ % |
| JETQ | $2.2 \pm 1.3$ % |

Expect combination of algorithms (with correlations) to give:

$$\epsilon\mathcal{D}^2 = 6.3 \pm 1.7\%$$

$\sim 400$ $J/\psi K_s^0$ events equivalent to $\sim 25$ perfectly tagged events

## Combining Different Taggers

- Example: SST ($\mathcal{D} = 16.6\%$) and JETQ ($\mathcal{D} = 21.5\ \%$)

  - If the taggers agree:

$$\begin{aligned}\mathcal{D}_{eff} &= (\mathcal{D}_{\mathrm{SST}} + \mathcal{D}_{\mathrm{JETQ}})/(1 + \mathcal{D}_{\mathrm{SST}}\mathcal{D}_{\mathrm{JETQ}}) \\ \mathcal{D}_{eff} &= (0.235 + 0.166)/(1 + 0.235 * 0.166) = \ 39\ \%\end{aligned}$$

  - If the taggers disagree:

$$\begin{aligned}\mathcal{D}_{eff} &= (\mathcal{D}_{\mathrm{SST}} - \mathcal{D}_{\mathrm{JETQ}})/(1 + \mathcal{D}_{\mathrm{SST}}\mathcal{D}_{\mathrm{JETQ}}\ ) \\ \mathcal{D}_{eff} &= (0.235 - 0.166)/(1 - 0.235 * 0.166) = \ 7\ \%\end{aligned}$$

  - Sign of the tag governed by JETQ result

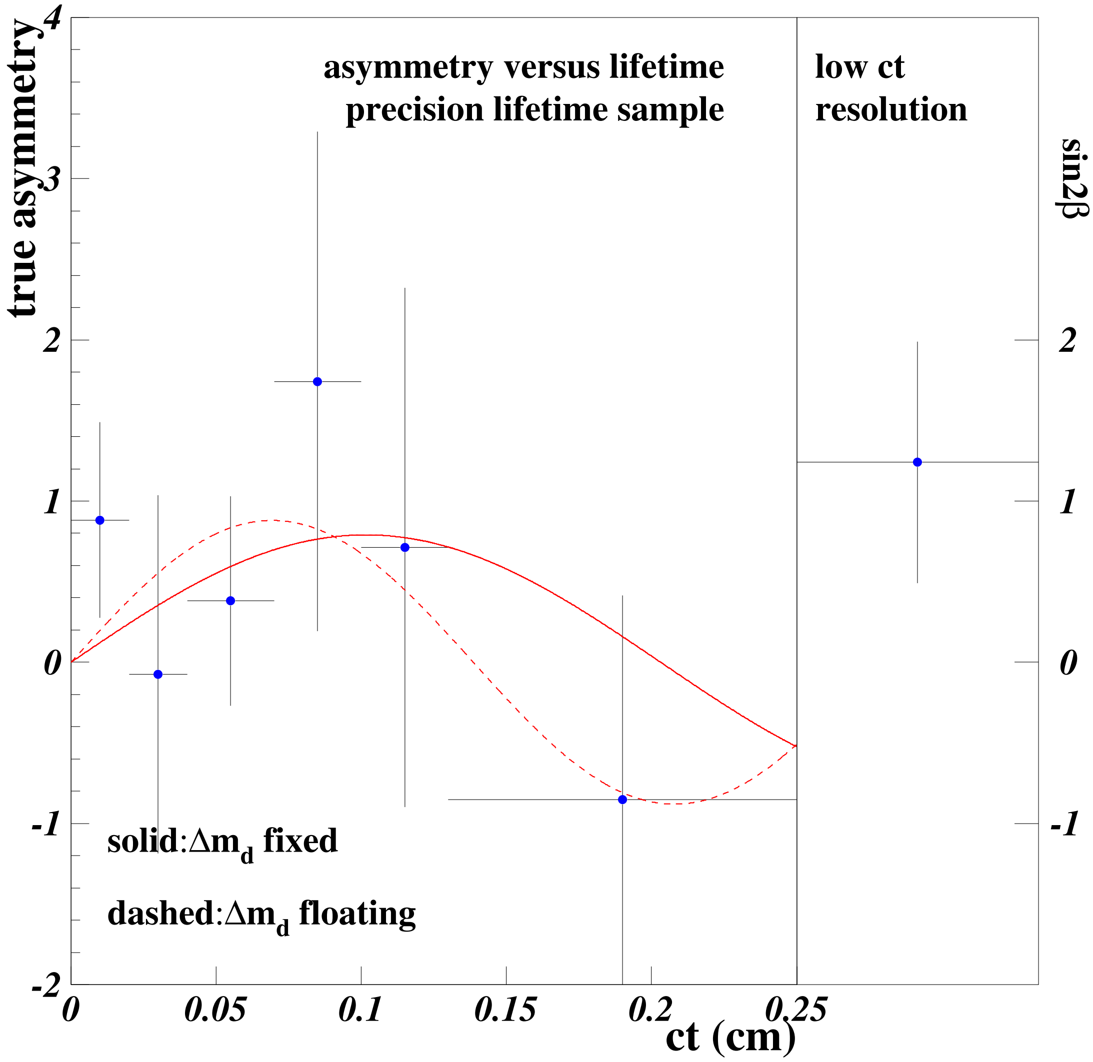
- Each event is weighted in the fit by its effective dilution

  (SLT has much higher dilution $\rightarrow$ over-rules JETQ if both present)

# Overview of CDF Fit for $\sin\ 2\beta$

- Combine all information in maximum likelihood fit
- Allow for charge asymmetries in efficiencies and dilution
  - possible charge biases in tracking at low $p_t$
  - $K^{\pm}$ interaction rate differences
  - Charge asymmetric backgrounds (beampipe spallation)
- No significant asymmetries observed
- Likelihood function includes event-by-event probabilities for
  - Observed decay length
  - Reconstructed candidate mass
  - Efficiency and tagging probability
- Include constraints from other data ($B^+ \to J/\psi K^+$)
  - tagging efficiencies
  - dilutions
- Take external inputs for $\tau_{B^0}$, $\Delta m_d$, $m_B$
  - Allow them to float within their errors

# Result of Combined Fit




## Measure

$$\sin\ 2\beta = 0.79^{+0.41}_{-0.44}(stat + syst)$$

## Systematic Uncertainties

Can split off systematic uncertainty

$$\sin 2\beta = 0.79 \pm 0.39(stat) \pm 0.16(syst)$$

| Effect | Evaluated | $\delta \sin 2\beta$ |
|---|---|---|
| $\mathcal{D}$ | in fit | 0.16 |
| $\Delta m_d$ | in fit | 0.01 |
| $\tau_{B^0}$ | in fit | 0.01 |
| $m_B$ | refit | 0.01 |
| charge bias | external | negligible |
| $K_L^0$ regen. | external | negligible |

- Systematic dominated by $\delta\mathcal{D}$ measured in data
  - Uncertainty will scale with more data

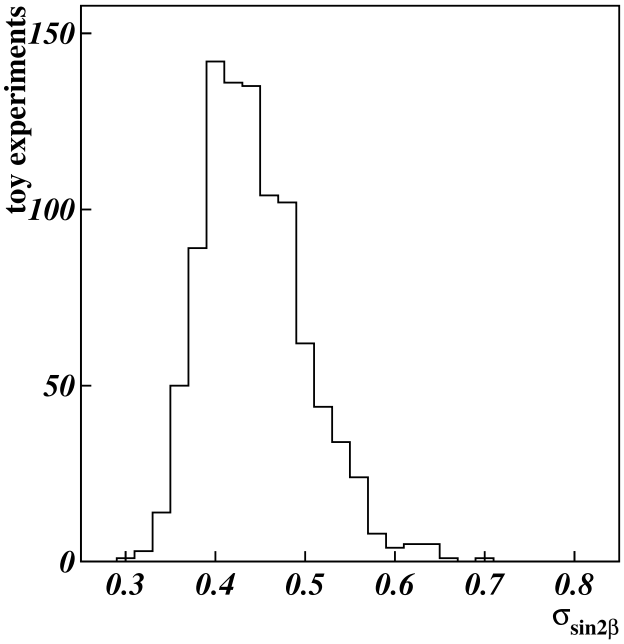
## Individual Results from Sub-samples/Sub-tags

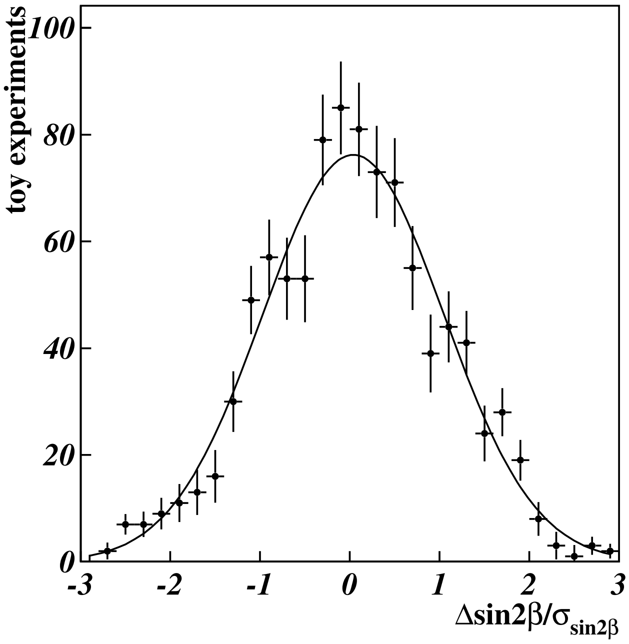
| Tagger | sin $2\beta$ | Uncertainty |
|---|---|---|
| full fit | 0.79 | $^{+0.41}_{-0.44}$ |
| SST | 2.03 | $^{+0.84}_{-0.77}$ |
| SLT | 0.52 | $^{+0.61}_{-0.75}$ |
| JETQ | -0.31 | $^{+0.81}_{-0.85}$ |

- Are the three sub-results consistent?
- $\chi^2$ of 4.6 for 2 degrees of freedom ($\mathcal{P}$ =10%)

# Toy Monte Carlo Test of Fit Results

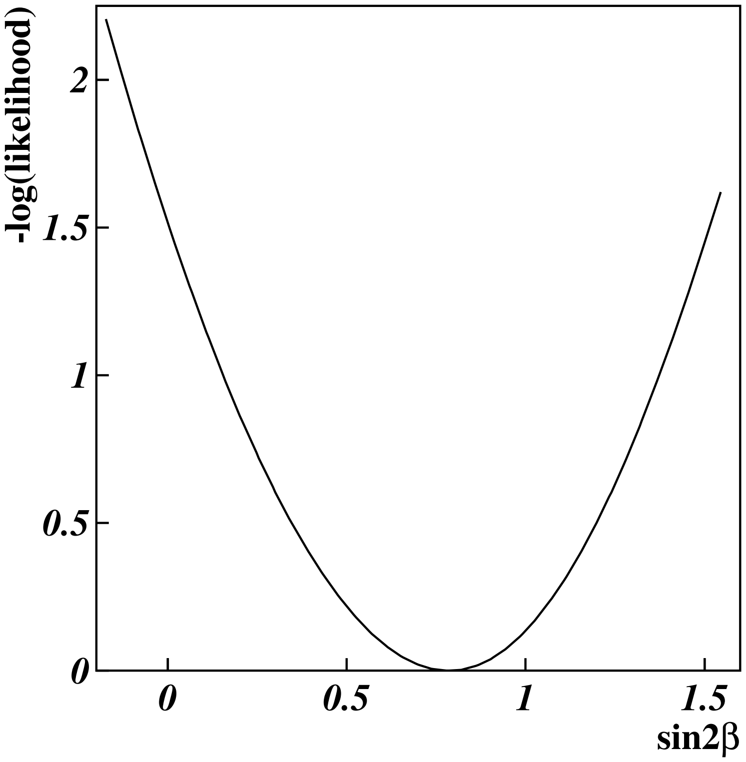
- Generate 1000 simulated "experiments" with
  - 400 $J/\psi K^0_S$ candidates 50-50 split with lifetime info
  - Backgrounds and tagging dilutions as observed
- Expected uncertainties support what we see in data (left)
- Fit returns errors consistent with fit value (right)



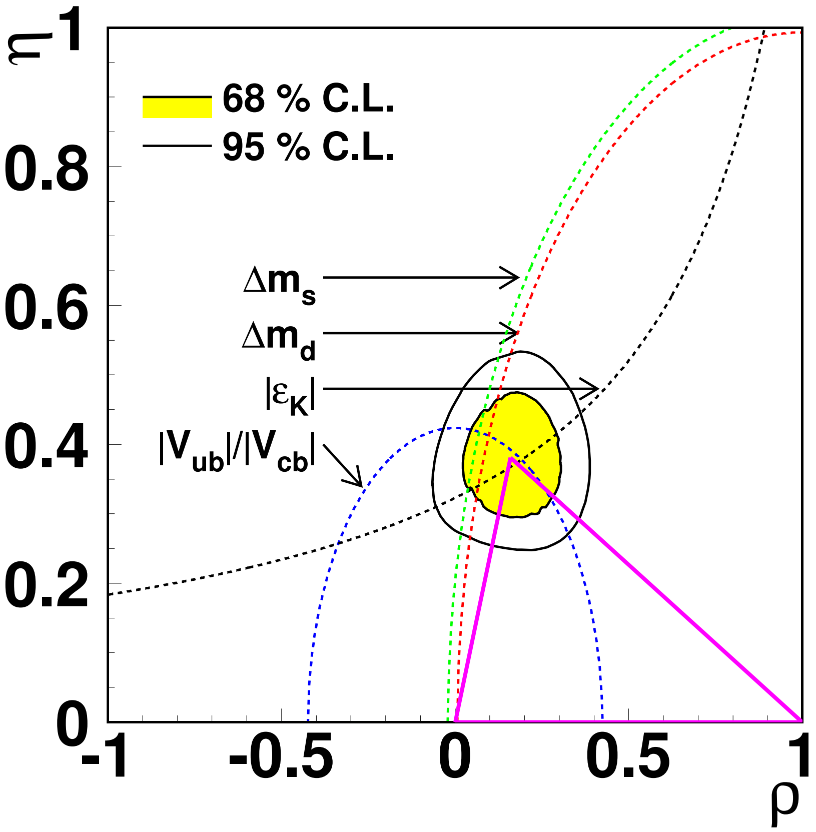
# Have We Seen CP-Violation in $B$ Decays?

Scan likelihood function:




- Feldman and Cousins frequentist limit:
  - $0 < \sin\ 2\beta < 1$ at 93% CL
- Bayesian limit (assuming flat prior in $\sin\ 2\beta$):
  - $0 < \sin\ 2\beta < 1$ at 95% CL
- Assume $\sin\ 2\beta = 0$ and our uncertainty
  - Integrate Gaussian from $0.79 \to \infty$:
  - $Prob(\sin\ 2\beta > 0.79) = 3.6\ \%$
- Best direct evidence for CP violation in $B$ sector

## Determinations of $\beta$




| Experiment | $\sin\ 2\beta$ | Reference |
|---|---|---|
| OPAL | $3.2^{+1.8}_{-2.0}(stat) \pm 0.5(sys)$ | Euro. Phys. **C5**, 379 (98) |
| CDF (initial) | $1.8 \pm 1.1(stat) \pm 0.3(sys)$ | PRL**81**, 5513 (98) |
| CDF (update) | $0.79 \pm 0.39(stat) \pm 0.16(sys)$ | hep-ex/9909003 |
| ALEPH (prelim) | $0.93^{+0.64}_{-0.88}(stat)^{+0.36}_{-0.24}(sys)$ | R. Forty, this conference |
| Average | $0.82 \pm 0.38$ | My average |
| CKM model fit | $0.75 \pm 0.09$ | S. Mele, PRL**59**, 113011 (99) |

## Prospects for $\sin\ 2\beta$ at Tevatron

- Run II at CDF will see:
  - $\times$20 increase in luminosity (initially)
  - $\times$1.5 increase in SVX acceptance
  - $\times$2 for improved $\mu$ coverage and lower $p_t$ for $J/\psi$
- Will yield 10,000 $J/\psi K_S^0$ decays for 2 fb$^{-1}$
- Calibration samples will grow by similar factor
- Even if no improvement in flavour tagging expect

$$\delta \sin\ 2\beta \approx 0.08$$

- Further improvements should come from
  - Addition of $J/\psi \to e^+e^-$ final states
  - Improvements to flavour tagging (TOF in CDF)
- D0 will have similar capabilities

## Prospects for $\sin\ 2\beta$ at $B$ Factories

- Wider range of final states being attacked

| State | Babar (30 fb$^{-1}$) | Belle (100 fb$^{-1}$) |
|---|---|---|
| $J/\psi K_S^0(\pi^+\pi^-)$ | 0.12 | 0.10 |
| $J/\psi K_S^0(\pi^0\pi^0)$ | 0.30 | 0.20 |
| $J/\psi K_L^0$ | 0.15 | 0.12 |
| $D^{*+}D^{*-}$ | 0.44 | |

- Expect sizeable fraction of “1 yr” datasets by next summer

- $D^{*+}D^{*-}$ will start to investigate penguin phases

## $\boxed{\textbf{Prospects for } \sin\ 2\alpha}$

- $B^0 \to \pi^+\pi^-$ is simplest CP eigenstate related to $\alpha$
- $\mathcal{B}(B^0 \to K^+\pi^-)$ suggests penguin amplitudes significant

- Focus first on $\pi^+\pi^-$ asymmetry ($A_{\pi^+\pi^-}$)
- Determine non-CKM contribution to relative phases later

## CDF All Hadronic Trigger

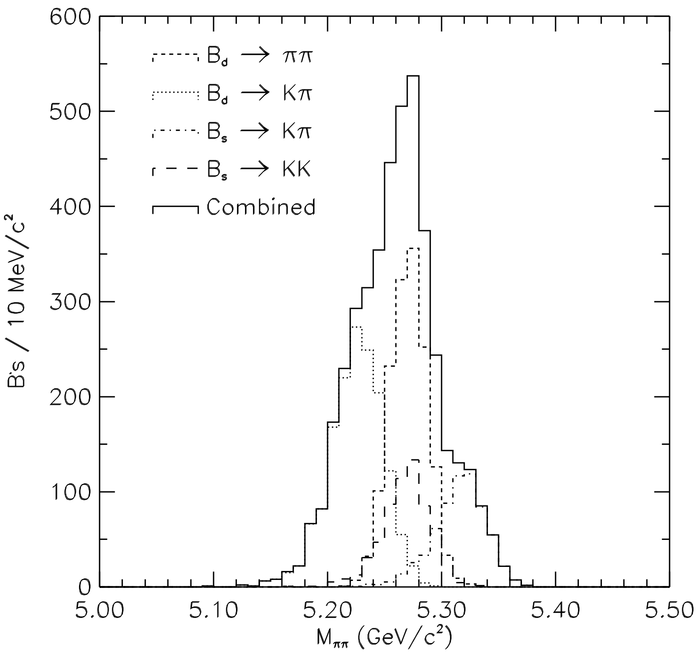
- Level 1: 2 tracks with $p_t > 2$ GeV/c
  - $\sigma_{p_t} \approx 0.02 p_t^2$
  - L1 can run up to 50 kHz deadtimeless
- Level 2: Both tracks with $d > 100$ $\mu$m
  - $\sigma_d \approx 20 \oplus 40/p_t$ $\mu$m
  - beamspot smaller than 25 $\mu$m
- Level 3: Use full reconstruction
  - factor of 2-5 further reduction

| Luminosity | $T_{\text{cross}}$ (ns) | $\overline{N_{p\bar{p}}}$ | L1 (kHz) | L2 (Hz) |
|---|---|---|---|---|
| $0.7 \times 10^{32}$ | 396 | 2 | 18 | 39 |
| $2.0 \times 10^{32}$ | 132 | 2 | 30 | 67 |
| $1.7 \times 10^{32}$ | 396 | 5 | 28 | 38 |

- Yield in 2 $\text{fb}^{-1}$:
  - 4000 - 7000 $B^0 \to \pi^+\pi^-$ ($\mathcal{B} = 0.5 \times 10^{-5}$)
  - 16000 - 28000 $B^0 \to K^+\pi^-$ ($\mathcal{B} = 1.9 \times 10^{-5}$)

## Backgrounds to $B \to \pi^+\pi^-$

- Physics backgrounds
  - Use invariant mass to distinguish $\pi\pi$ from $K\pi$ and $KK$




  - dE/dx in tracking chambers
  - Will have TOF but ...
    - One sigma $\pi - K$ separation up to 1.6 GeV/c
    - Mainly for flavour tagging (an additional $\epsilon\mathcal{D}^2 \sim 2.4\%$)
  - $K\pi$ has $\cos\Delta m_d$ time dependence
- QCD light quark fakes + heavy quark combinatorics
  - studied with run I data, estimate S:B $>$ 1:4
  - subject of study at ongoing FNAL $B$ Physics workshop
- Expect $\delta A_{\pi^+\pi^-} \sim 0.13$ (for 5000 events)

## $\boxed{\textbf{Prospects for } A_{\pi^+\pi^-} \textbf{ at } B \textbf{ Factories}}$

- Wider range of modes being studied at $B$ factories
- Asymmetry in $\pi^+\pi^-$ thoroughly studied
  - Babar $\delta A_{\pi^+\pi^-} = 0.26$ (30 fb$^{-1}$)
  - Belle $\delta A_{\pi^+\pi^-} = 0.15$ (100 fb$^{-1}$)
- Interpretation of asymmetry in terms of $\alpha$ complicated by
  - Weak phases from penguin contributions
  - Strong phases may be measured (see below)
  - Could introduce systematic of $\delta\alpha = 0.2$ (or larger)

# Constraining Penguin Contributions

- Study isospin symmetry in $B$ decays (Gronau, London)
  - $B^0 \to \pi^+\pi^-$, $B^0 \to \pi^0\pi^0$, $B^- \to \pi^-\pi^0$
  - $\mathcal{B}(B^0 \to \pi^0\pi^0) \sim 10^{-6} \to$ very low statistics
- Even more ambitious study $B \to \pi\pi\pi$ decays (Quinn, Snyder)
  - Dalitz analysis of modes $\rho^{\pm,0}\pi^{\mp,0}$
  - Extract 10 Amplitudes (5 tree, 5 penguin)
- Too many variables to predict outcome at this stage

## Summary

- CDF has made first meaningful measurement of sin $2\beta$
- $\sigma_{b\bar{b}}$ at hadron machines
  - allows us to compete with $B$ factories
  - despite higher backgrounds/lower dilutions
- Experimental measurements with $\delta \sin 2\beta \approx 0.1$ on horizon
- Tools in place to attack $\pi^+\pi^-$ asymmetry
  - ideas exist to pin down penguin contributions
  - will take time/luminosity to sort out

- Should make significant progress between now and BCP4