Measuring Mixing and CP-Violation at CDF

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CDF Collaboration

Hyperons, Charm and Beauty Hadrons
Genova, Italia

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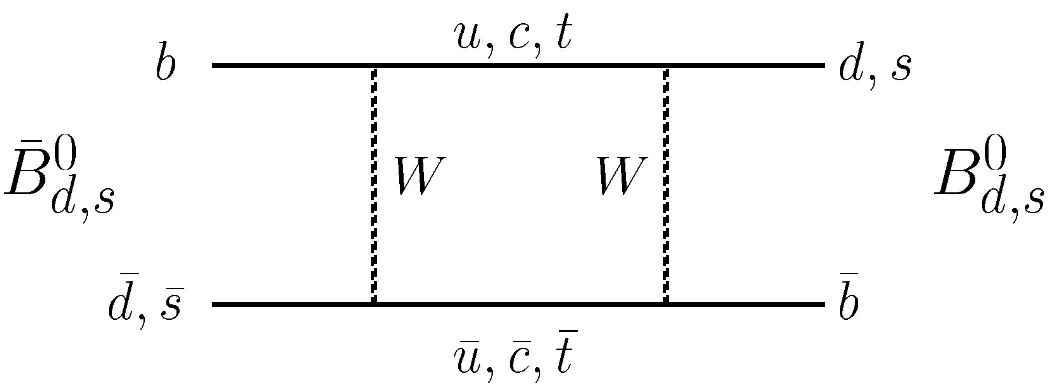
$B^0 - \bar{B}^0$ Mixing

- Like with K^0–$\overline{\mathrm{K}}^0$, higher-order weak interactions mix meson-antimeson states.



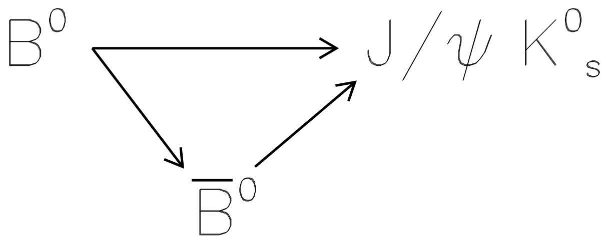
$$\frac{N_{\overline{\mathrm{B}}^0 \to \overline{\mathrm{B}}^0}(t) - N_{\overline{\mathrm{B}}^0 \to \mathrm{B}^0}(t)}{N_{\overline{\mathrm{B}}^0 \to \overline{\mathrm{B}}^0}(t) + N_{\overline{\mathrm{B}}^0 \to \mathrm{B}^0}(t)} = \cos \Delta m t$$

$$\begin{aligned} \Delta m_d &\sim m_{B_d^0}\, m_t^2\, F(m_t^2/m_W^2)\, |V_{tb}^* V_{td}|^2 \\ \Delta m_s &\sim m_{B_s^0}\, m_t^2\, F(m_t^2/m_W^2)\, |V_{tb}^* V_{ts}|^2 \end{aligned}$$

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s^0}\, |V_{tb}^* V_{ts}|^2}{m_{B_d^0}\, |V_{tb}^* V_{td}|^2}$$

CP-Violation: $\sin 2\beta$

- Two paths for $B_d^0 \to J/\psi \mathrm{K}_S^0$:



- Interference between these leads to a time-dependent asymmetry:

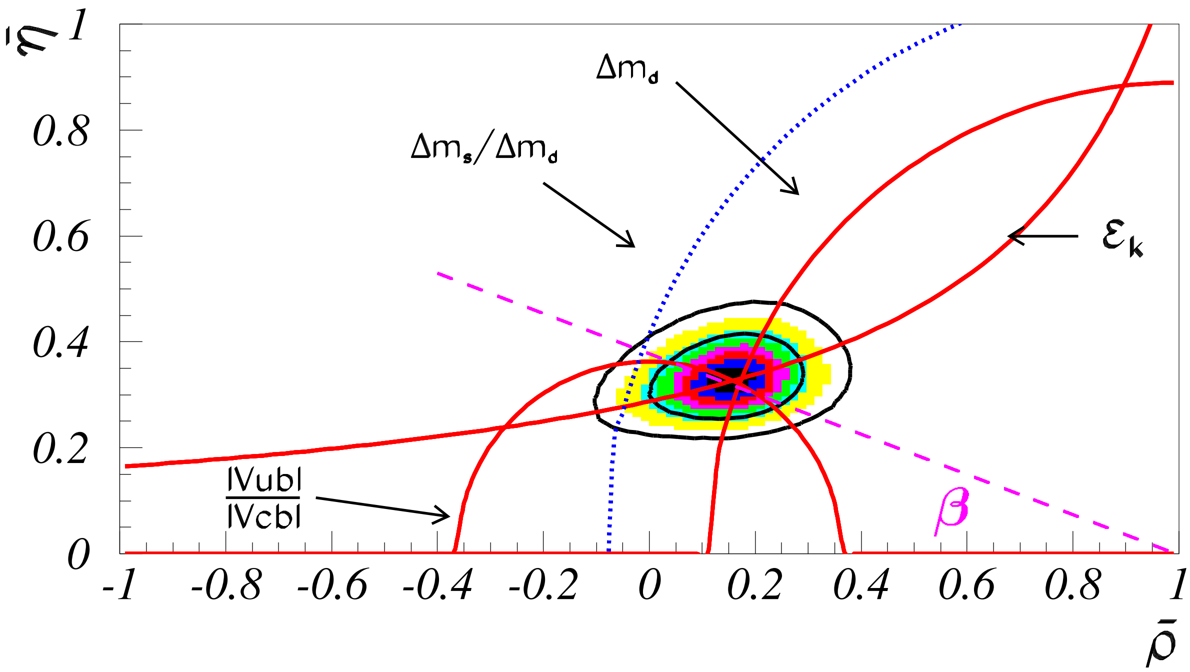
$$\frac{N_{\overline{\mathrm{B}}^0 \to J/\psi \mathrm{K}_S^0}(t) - N_{\mathrm{B}^0 \to J/\psi \mathrm{K}_S^0}(t)}{N_{\overline{\mathrm{B}}^0 \to J/\psi \mathrm{K}_S^0}(t) + N_{\mathrm{B}^0 \to J/\psi \mathrm{K}_S^0}(t)} = \sin 2\beta \sin \Delta m_d t$$

$\Rightarrow$ Phase delay comes because effect is due to *interference.*

$\Rightarrow$ Amplitude is $\sin 2\beta$.

Indirect CKM Constraints

See Parodi et al.



- Indirect evidence constrains (assuming Standard Model):

$$\sin 2\beta \simeq 0.6 \pm 0.1$$

- Experimental Measurements:

$$\begin{array}{rcll} \Delta m_d & = & 0.474 \pm 0.018\,\mathrm{ps}^{-1} & \text{(PDG)} \\ \Delta m_s & > & 9.1\,\mathrm{ps}^{-1}(\text{at } 95\% \text{ C.L.}) & \text{(PDG)} \\ \sin 2\beta & = & 3.2^{+1.8}_{-2.0} \pm 0.5 & \text{(OPAL)} \end{array}$$

Measuring Mixing and CP Violation at CDF

- Need 3 items on information for each event:
  - Flavor of meson originally produced.
    - Use *flavor tagging*.
  - Proper time of decay.
    - Reconstruct partial or complete B-decay vertex.
  - Flavor of meson at time of decay.
    - Comes from decay products.
    - Not available for CP-Violation studies.

Flavor-Tagging at CDF

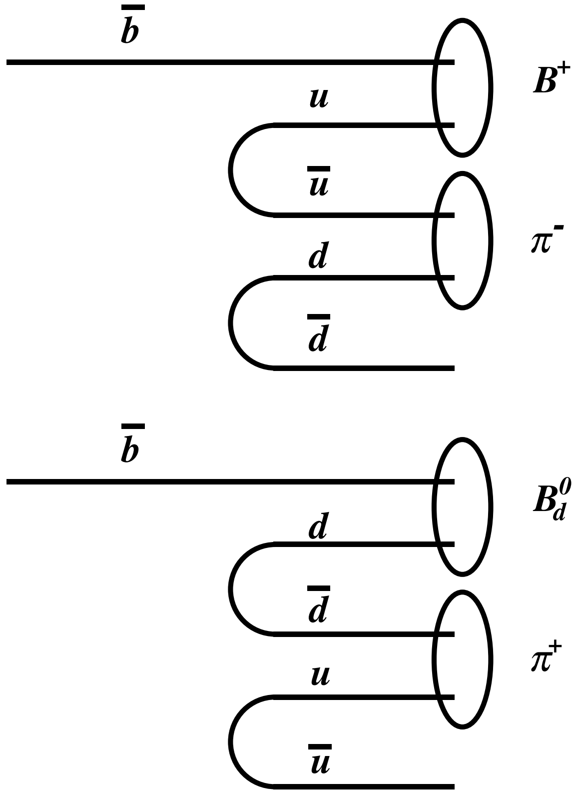
Three Techniques:

- Opposite-Side Lepton Tagging.
  - Attempts to identify semileptonic decay of away-side B-hadron.
- Opposite-Side Jet-Charge Tagging.
  - Searches for displaced vertex from away-side B-hadron.
  - Uses statistical methods for determining flavor.
- Same-side Tagging.
  - Uses correlations with particles produced along with the B-hadron being tagged.
  - Correlations come from B^{**} and fragmentation.

Principle Behind Same-side Tagging

Correlations are expected from: (Gronau et al., 1993)

- Fragmentation:



- B^{**} Decay:

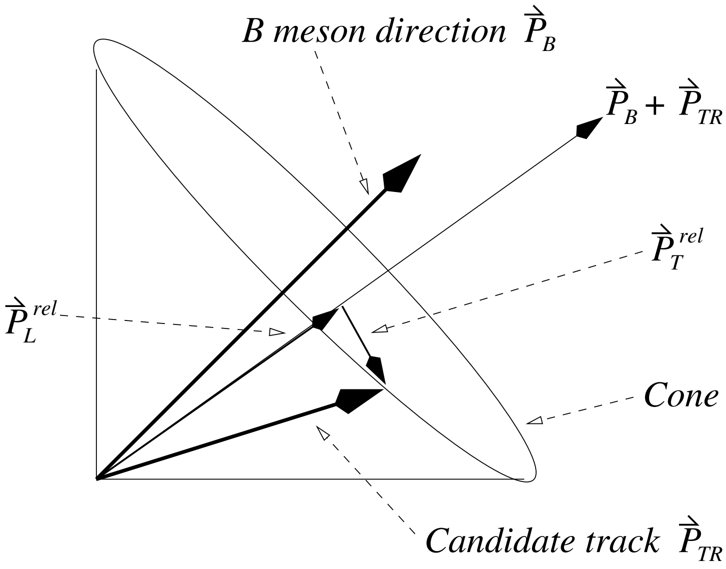
$$B^{0**} \to B^+\pi^-$$
$$B^{+**} \to B^0\pi^+$$

$\Rightarrow$ Correlation is same for fragmentation and for B^{**}.

Same-side Tagging at CDF

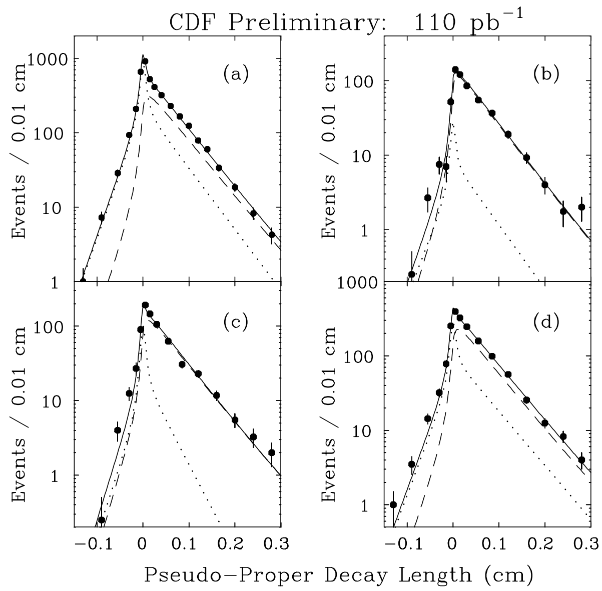
- Consider Tracks with:
  - $\Delta R < 0.7$ from B-meson.
  - $p_T > 400$ MeV/c.
    - Maximize efficiency, minimize detector bias.
  - ≥ 3 hits in silicon tracker.
  - Consistent with primary vertex in r–ϕ and z.

- If multiple candidates:
  - Select one with minimum p_T^{rel}

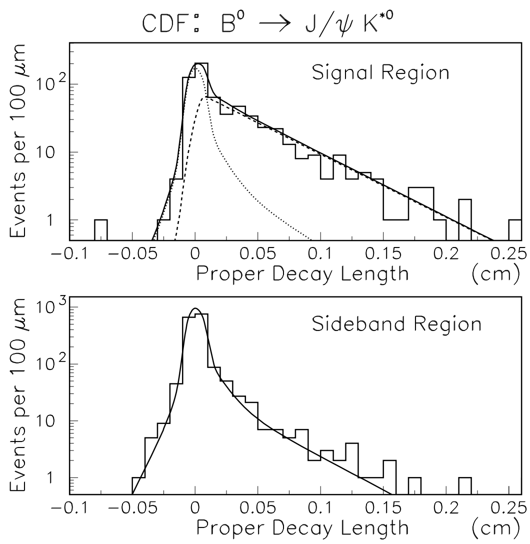


Decay-Time Measurement at CDF

$\underline{B \rightarrow \ell D X}$



$\underline{B \rightarrow J/\psi \mathrm{K}^{*0}}$

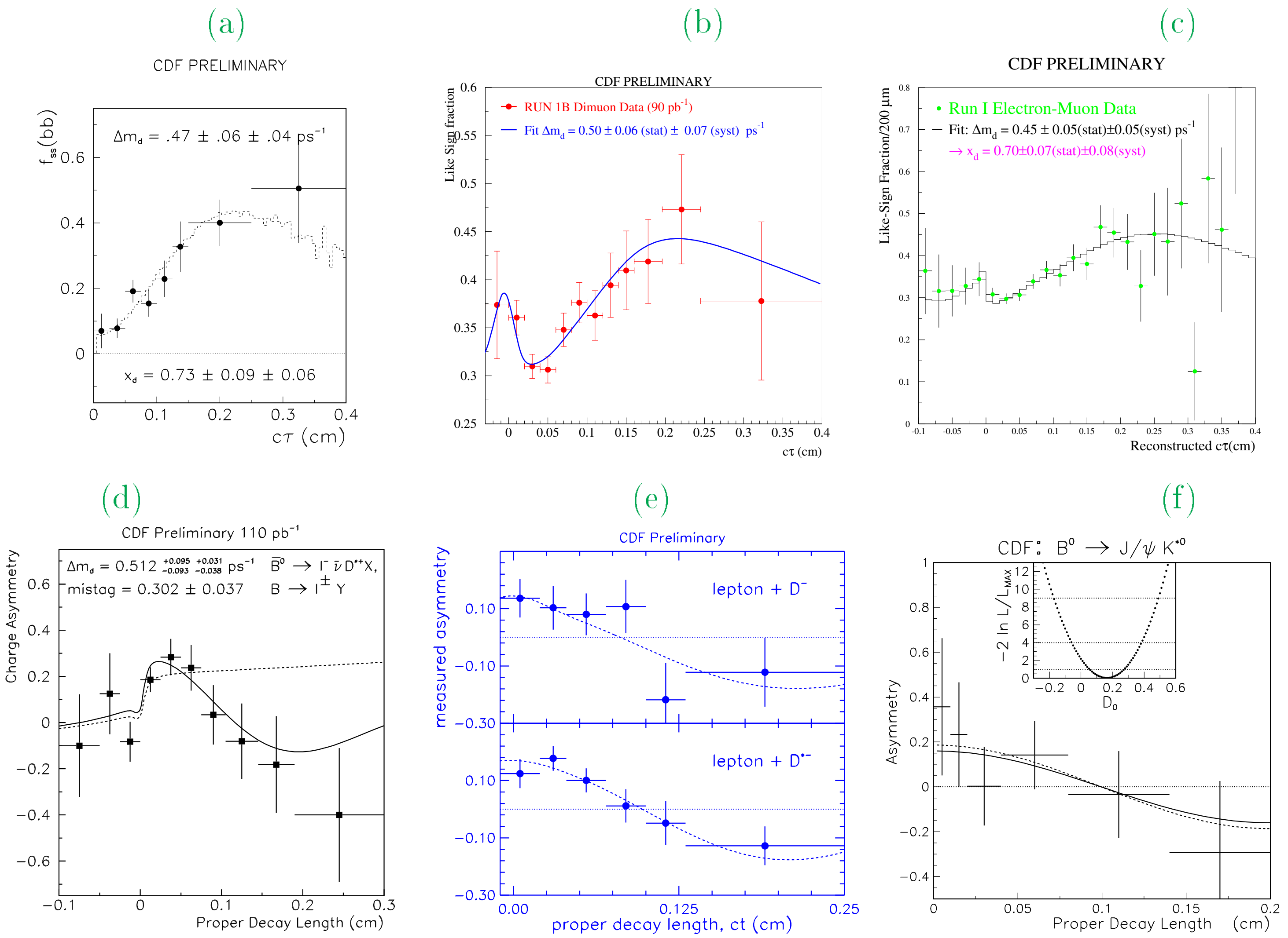


Proper Decay-Length Resolution:

$$\ell D X \Rightarrow \sigma_{ct} \approx 52\,\mu\mathrm{m} + 0.075 \times ct.$$
$$J/\psi \mathrm{K}^{*0} \Rightarrow \sigma_{ct} \approx 40\,\mu\mathrm{m}.$$

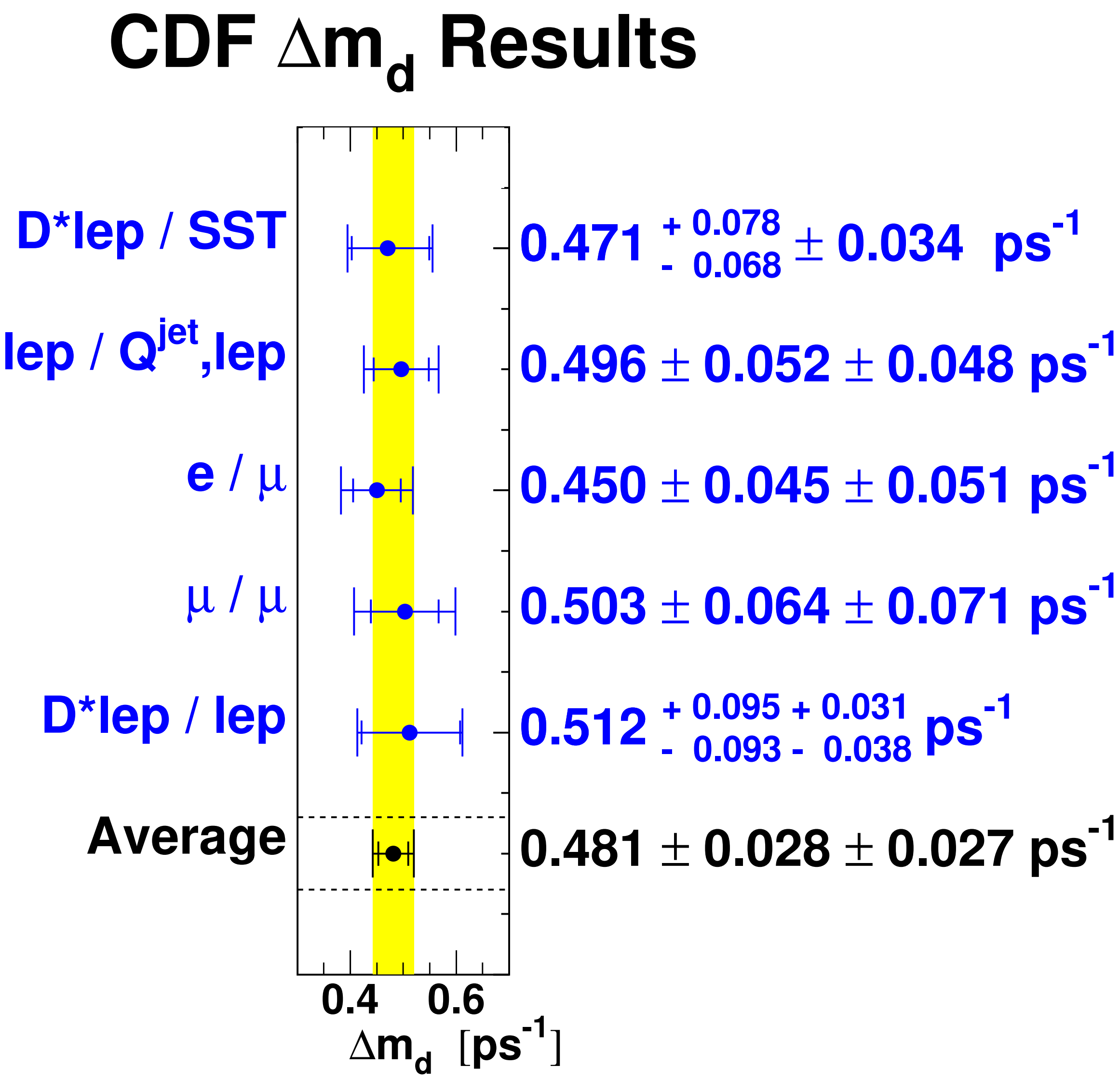
$$c/\Delta m_d \approx 600\,\mu\mathrm{m}.$$
$$c/\Delta m_s < 33\,\mu\mathrm{m}.$$

CDF B_d^0 Oscillation Measurements

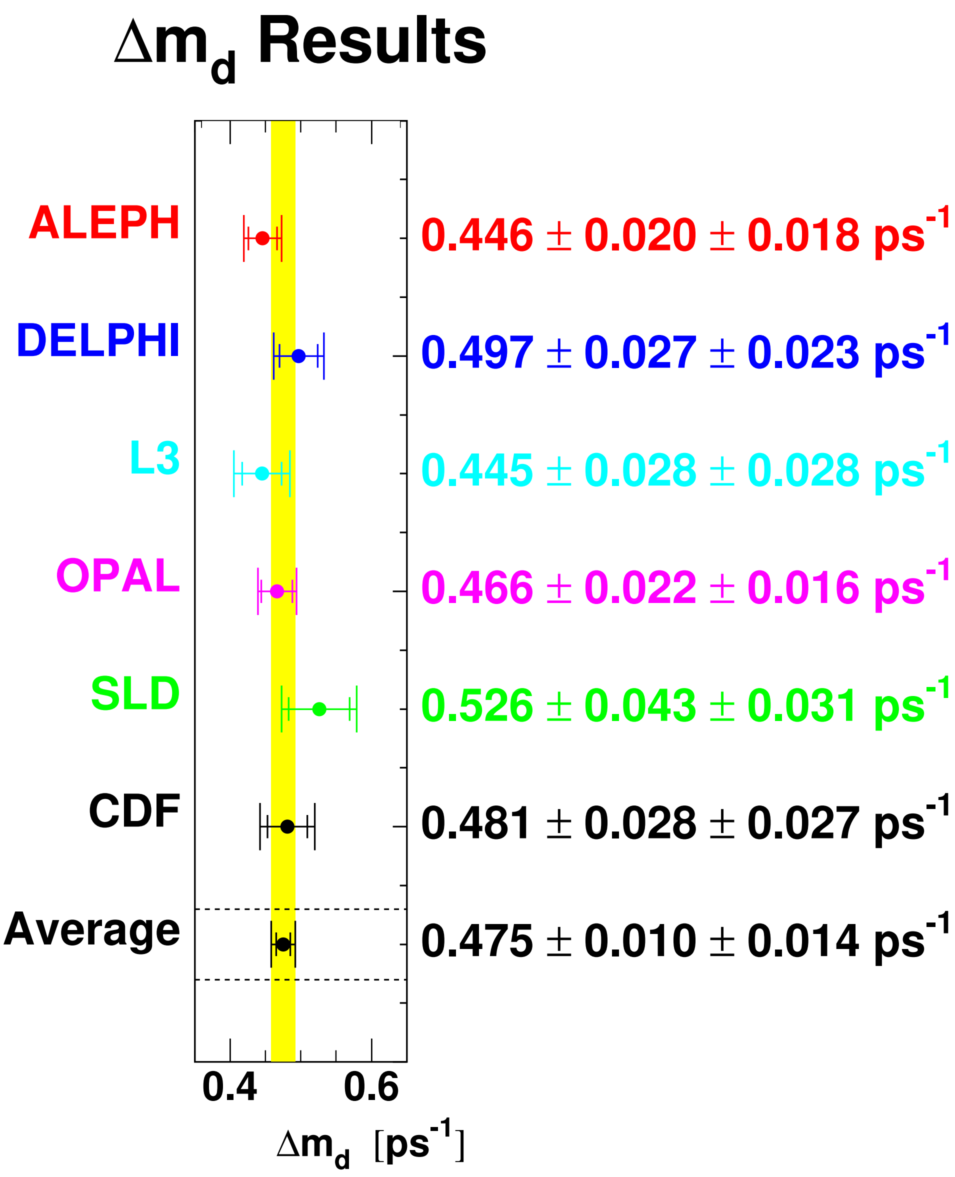


Plot	B Ident.	Flavor Tag	Plot	B Ident.	Flavor Tag
a	ℓ + Vertex	ℓ or Jet-charge	d	$\mu + D^{(*)}$	μ
b	μ + Vertex	μ	e	$\ell + D^{(*)}$	Same-side Tag
c	e, μ + Vertex	μ, e	f	$J/\psi K^{*0}$	Same-side Tag

CDF Oscillation Summary

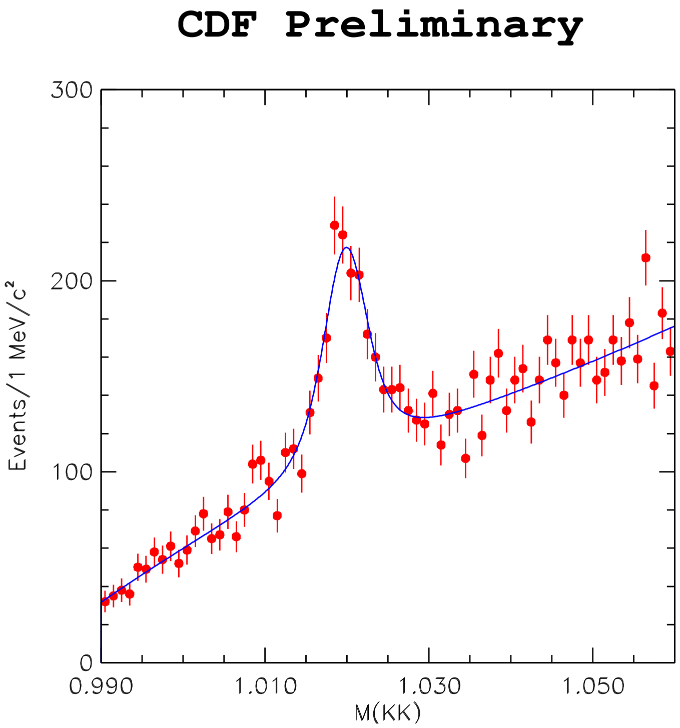


World Oscillation Summary



Measuring Δm_s at CDF

- Data Sample: $\mu\mu$ Trigger.
- Look for $B_s^0 \to \mu\phi X$.



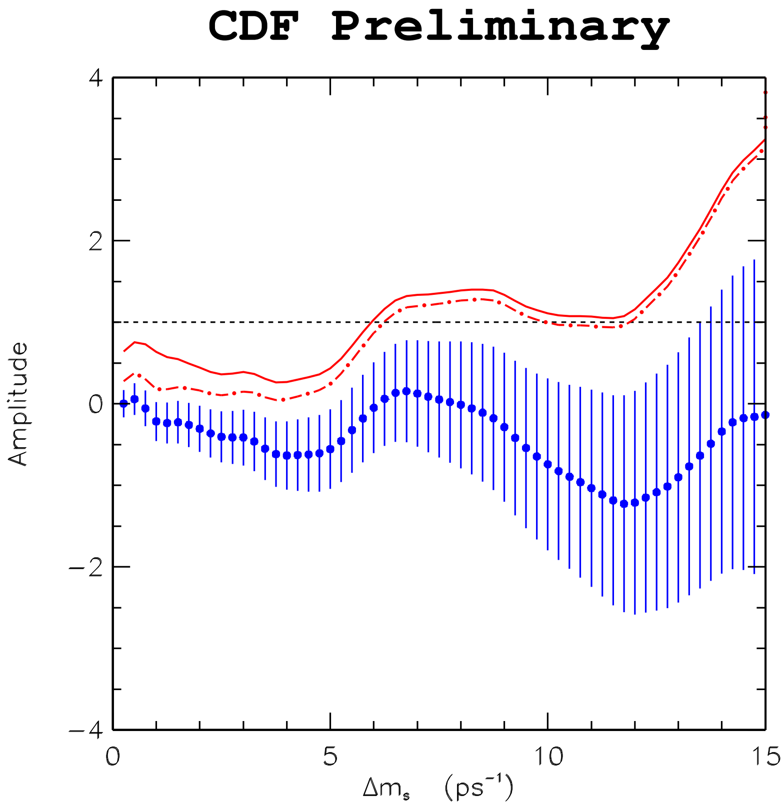
* 1068 candidates with B_s^0 purity of 61%.

- Use second μ for tag.

* $R_{mistag} = 0.24 \pm 0.08$.

Measuring Δm_s at CDF

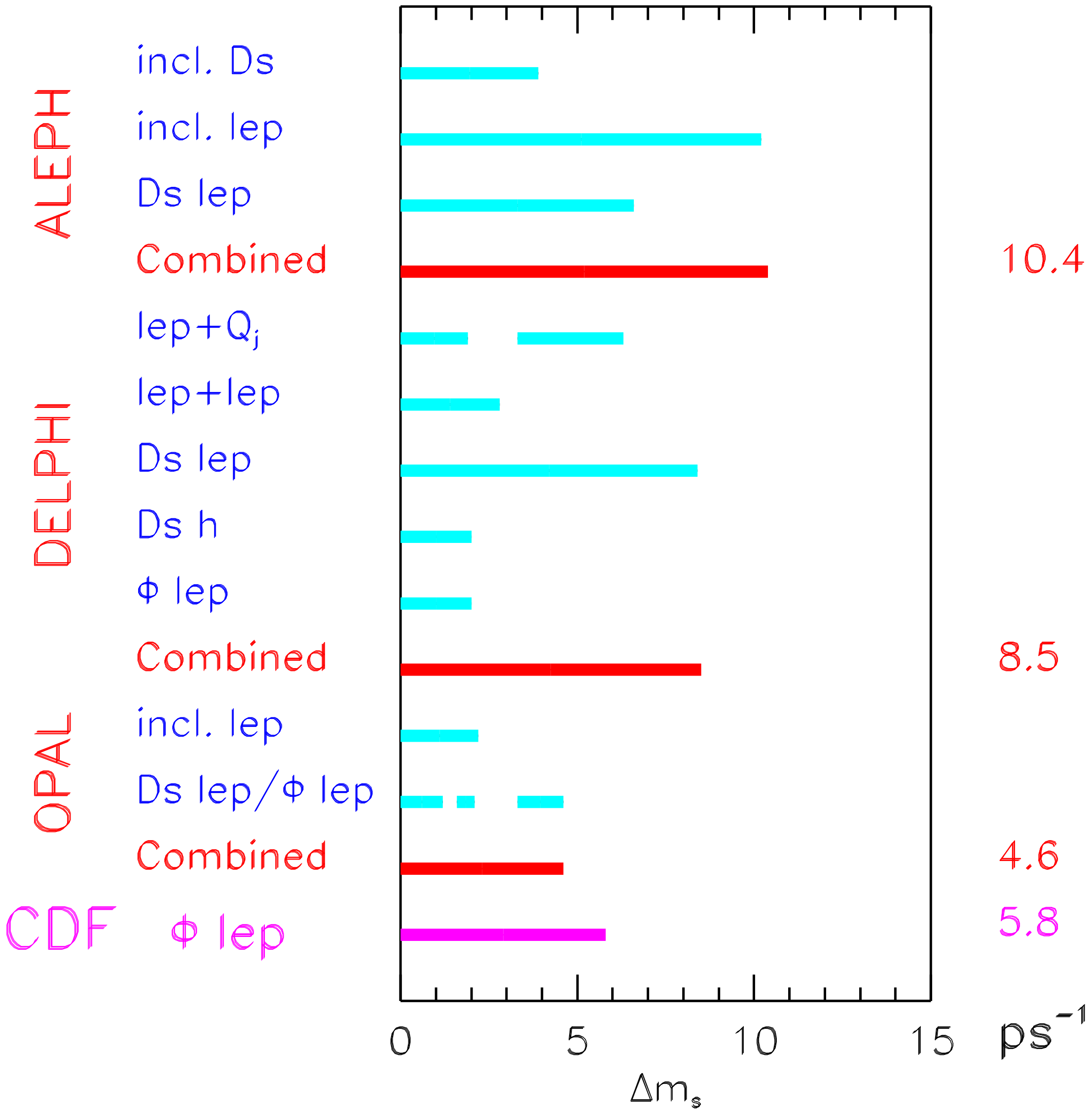
- Setting a limit on Δm_s (using "amplitude approach" as done by LEP):



  * Dashed: statistical uncertainties only.
  * Solid: statistical and systematic uncertainties combined.

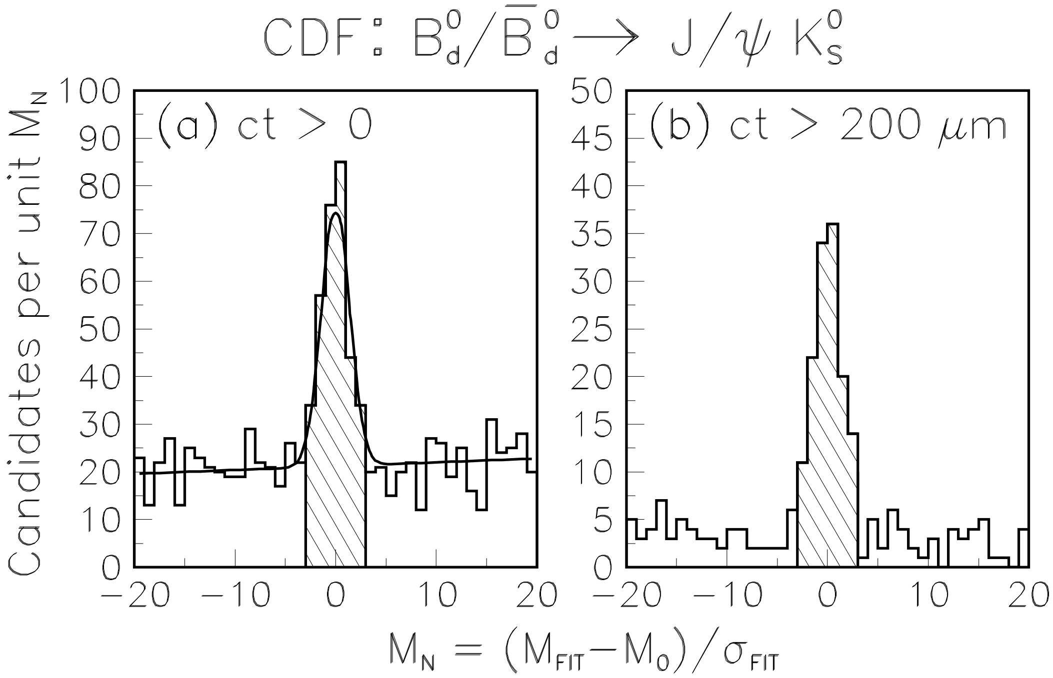
- We exclude $\Delta m_s < 5.8$ at 95% C.L.

World limits on Δm_s



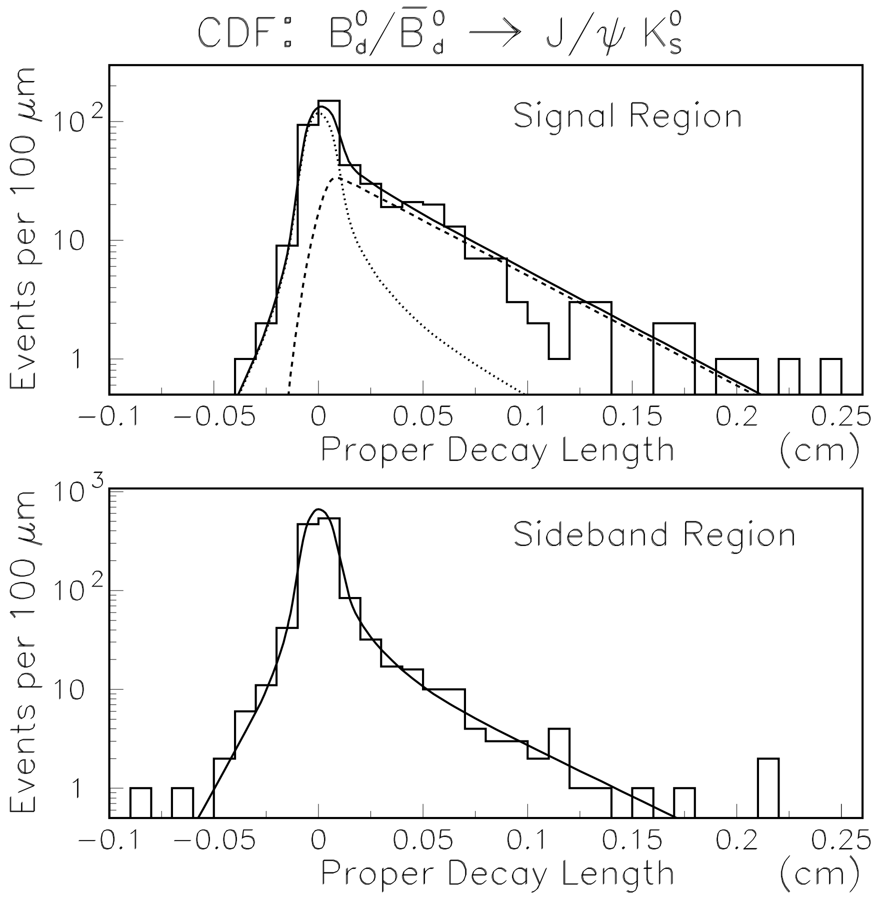
Measuring $\sin 2\beta$ at CDF: $J/\psi \mathrm{K}^0_S$

- Reconstruct $\mathrm{B}^0_\mathrm{d} \to \mathrm{J}/\psi \mathrm{K}^0_\mathrm{S}$
  * $J/\psi \to \mu^+\mu^-$, $\mathrm{K}^0_S \to \pi^+\pi^-$



- $\sim$ 200 Signal events.
  - For $ct > 0$, $S/N \sim 1.6$.
  - For $ct > 200\,\mu\mathrm{m}$, $S/N \sim 6.2$.

$J/\psi K^0_S$ Lifetime Distribution



- $\sigma_{ct} \sim 50\,\mu\text{m}$.

Tagging $J/\psi K^0_S$

- Use Same-side tagging.

$$\mathcal{A}_{CP}(t) = \frac{N_- - N_+}{N_- + N_+} = \mathcal{D} \sin 2\beta \sin \Delta m_d t$$

  – Asymmetry is reduced by dilution factor

$$\mathcal{D} = 1 - 2R_{mistag}$$

- Need to know the dilution.

$$\begin{aligned} \ell D X &: \mathcal{D} = 0.181 \pm 0.028^{+0.023}_{-0.015} \\ J/\psi K^{*0} &: \mathcal{D} = 0.165 \pm 0.112^{+0.018}_{-0.021} \end{aligned}$$

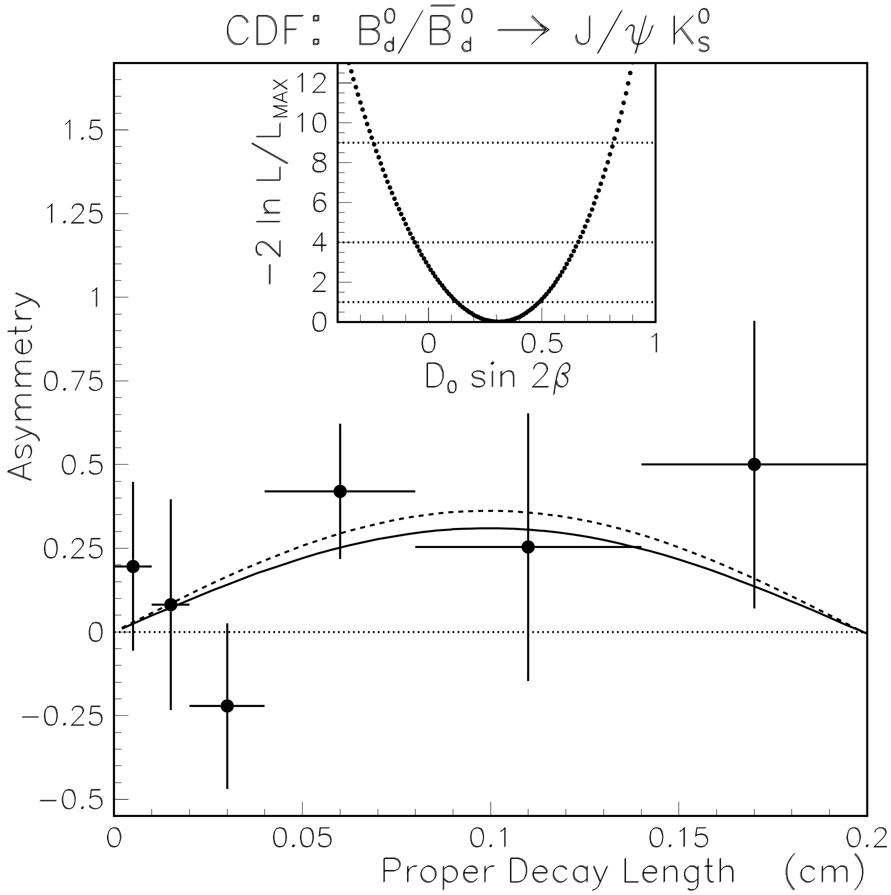
  – Combine these (with measurements from charged B mesons) using Monte Carlo.

$$\mathcal{D}(J/\psi K^0_S) = 0.166 \pm 0.018\,(\text{data}) \pm 0.013\,(\text{MC})$$

  ∗ Effect of Monte Carlo extrapolation is small.

Measuring the Asymmetry in $J/\psi K^0_S$

- Measure asymmetry *vs ct*:



- Dashed curve: simple χ^2 fit.
- Solid curve: unbinned maximum likelihood fit.

$$\mathcal{D} \sin 2\beta = 0.31 \pm 0.18$$

Systematic Uncertainties on $\mathcal{D}\sin 2\beta$

Systematic uncertainties on $\mathcal{D}\sin 2\beta$:

- $\Delta m_d = 0.474 \pm 0.031$
  - $\delta\mathcal{D}\sin 2\beta = {}^{+0.029}_{-0.025}$
- $c\tau(B_d^0) = 468 \pm 18\,\mu$m.
  - $\delta\mathcal{D}\sin 2\beta = \pm 0.001$
- Uncertainty on corrections for detector biases:
  - $\delta\mathcal{D}\sin 2\beta = {}^{+0.016}_{-0.019}$

$$\mathcal{D}\sin 2\beta = 0.31 \pm 0.18\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})$$

Exclusion of $\sin 2\beta \leq 0$

$$\mathcal{D} \sin 2\beta = 0.31 \pm 0.18\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})$$

- Uncertainty and central value for $\sin 2\beta$ *both* scale with $1/\mathcal{D}$.

  $\Rightarrow$ Exclusion of $\sin 2\beta \leq 0$ does not depend on $\mathcal{D}$, and can be calculated from the *raw* asymmetry.

- We exclude $\sin 2\beta \leq 0$ at 90% C.L.*

  – This result does *not* depend on the external dilution measurements nor on the Monte Carlo dilution extrapolation.

* We use the prescription of Feldman and Cousins, Phys. Rev. D **57**, 3873 (1998).

Extraction of $\sin 2\beta$

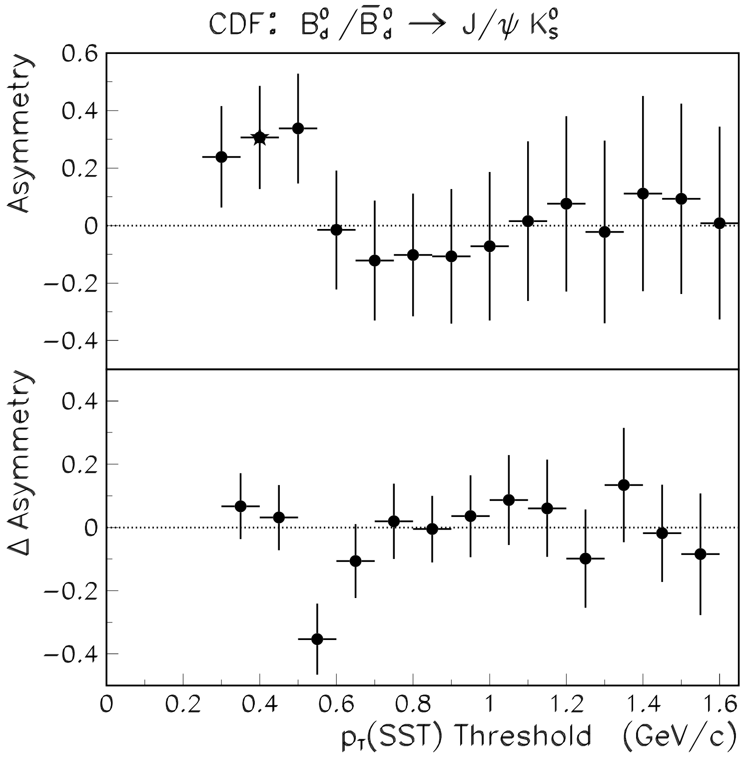
$$\mathcal{D}(J/\psi \mathrm{K}_S^0) = 0.166 \pm 0.018\,(\mathrm{data}) \pm 0.013\,(\mathrm{MC})$$

$$\mathcal{D}\sin 2\beta = 0.31 \pm 0.18\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})$$

$$\sin 2\beta = 1.8 \pm 1.1\,(\mathrm{stat}) \pm 0.3\,(\mathrm{syst})$$

Robustness Studies

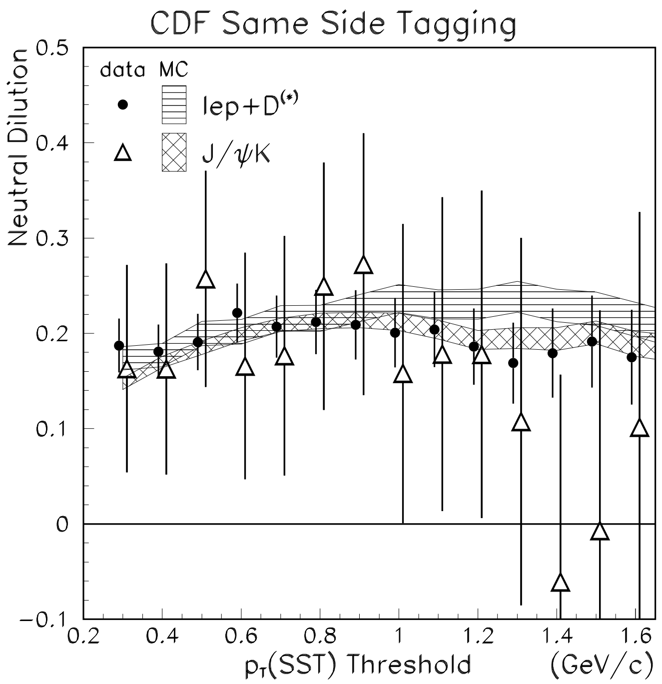
- Can we make the asymmetry go away?
  - Varied many cuts with little or no effect.
  - Varying p_T(SST) threshold shows striking effect:



    * Points on top plot are partially correlated.
    * Differences (bottom plot) are mostly uncorrelated.
  - Effect is not expected from any known systematic.
  - Effect is consistent with a statistical fluctuation.
    * Result is as robust as can be expected.

Robustness Studies

- Is this a systematic effect?
  - Study dependence of $\mathcal{D}$ on $p_T(SST)$.

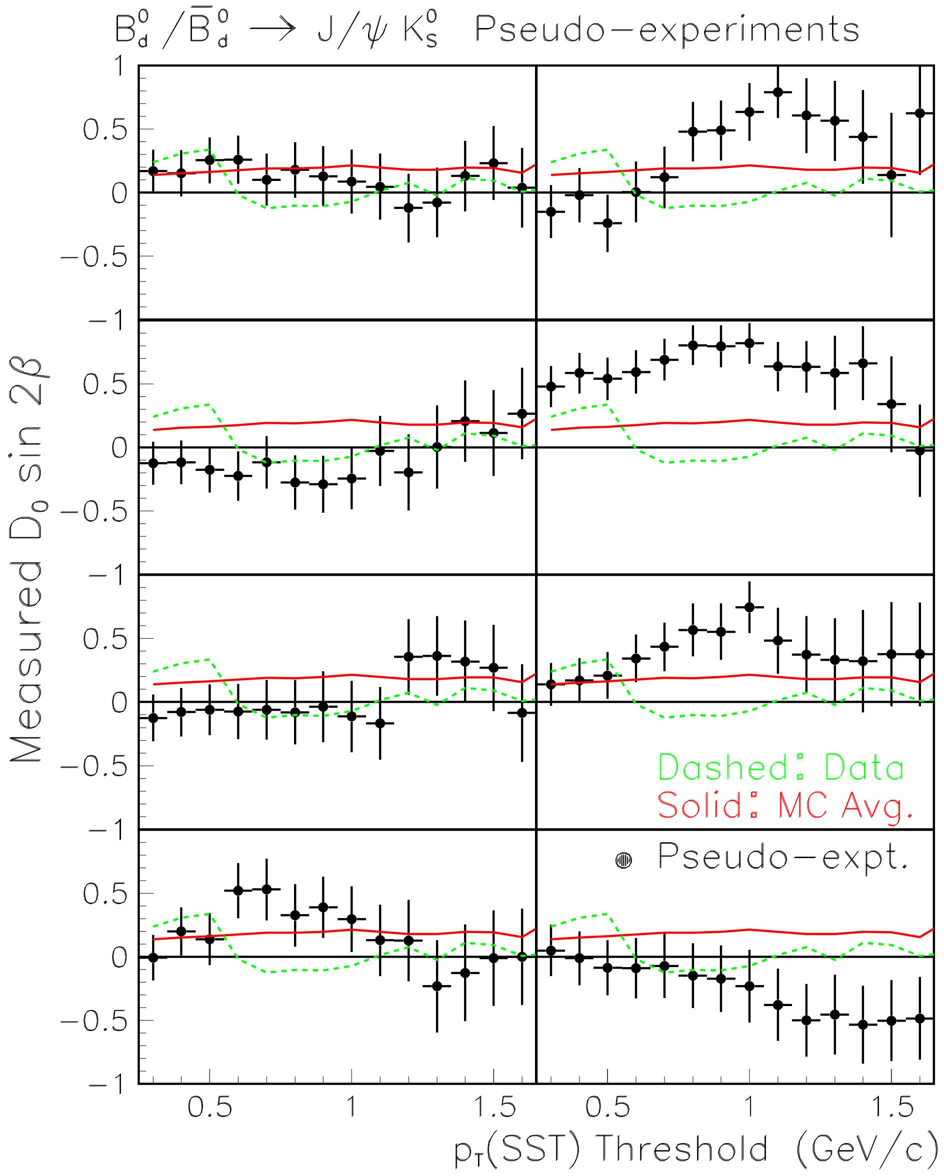


    - ∗ Dilution appears pretty flat.
  - Other systematic effects?
    - ∗ Detector-bias corrections also change slowly.
    - ∗ Other data samples do not show this effect.

$\Rightarrow$ Effect is not expected from any known systematic.

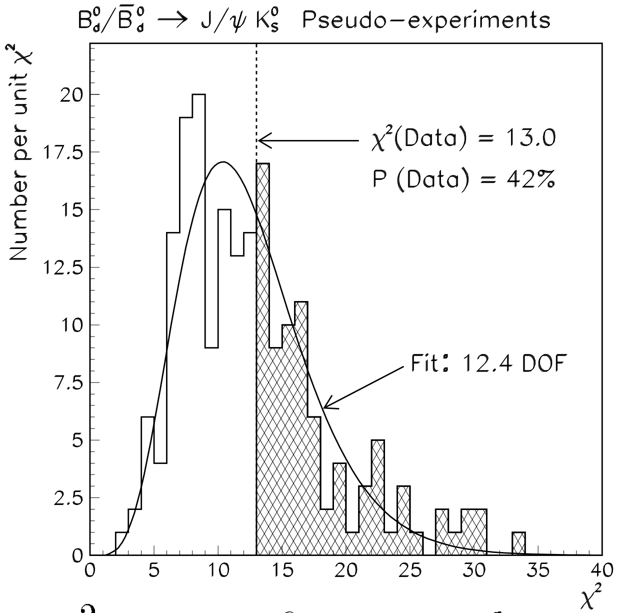
Robustness Studies

- Could it be a statistical effect?
  - Examine effect in Monte Carlo samples:



Robustness Studies

- To quantify the likelihood of the shape in the data:
  - Calculate a χ^2, based on the differences.
  - Compare with Monte Carlo.

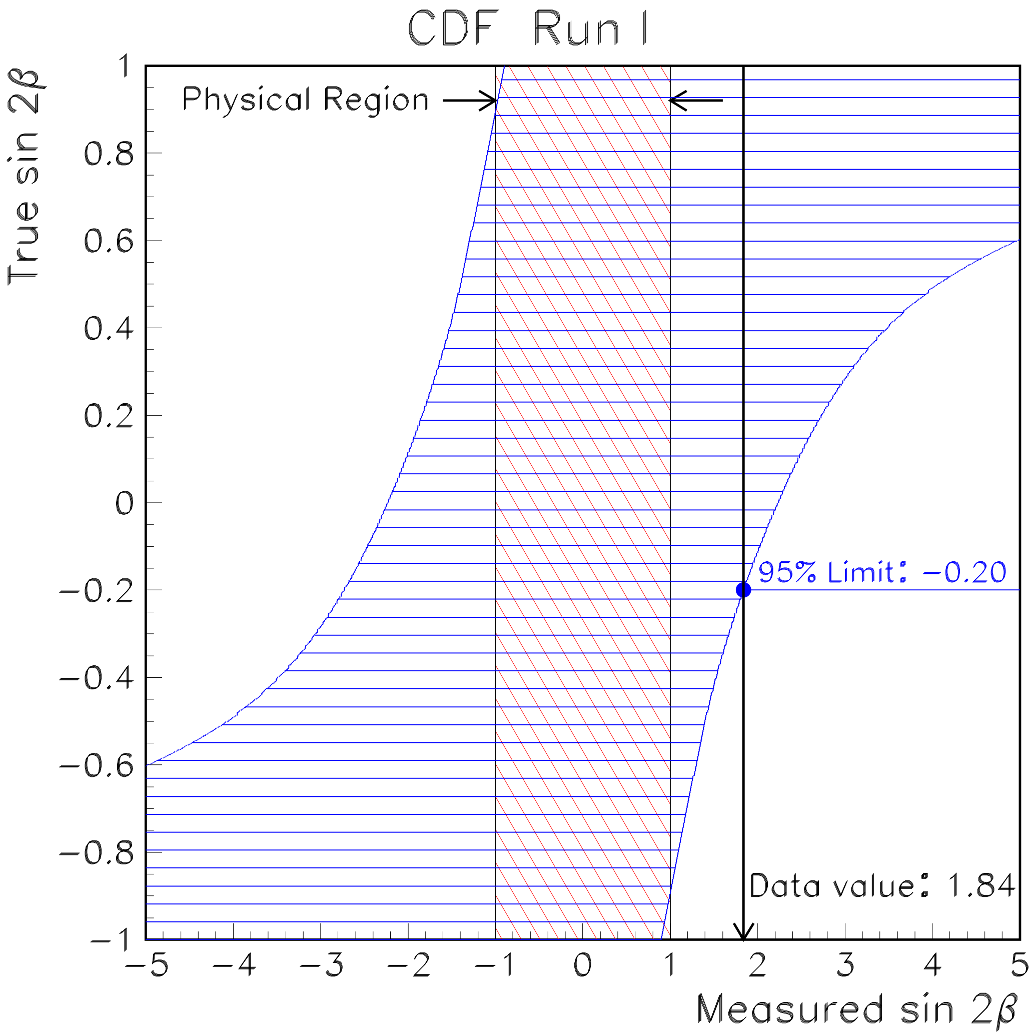


  - Data has $\chi^2 = 13.0$ for $\sim$ 13 degrees of freedom.
    - $*$ 42% of MC samples were higher.

- Conclude effect is statistical.
  - Result is as robust as can be expected.

Interpreting the Result as a Limit

- Use prescription of Feldman and Cousins to calculate a 95% C.L. limit: *



– Exclude $\sin 2\beta \leq -0.20$ at 95% C.L.

* G.J. Feldman and R.D. Cousins, Phys. Rev. D **57**, 3873 (1998).

Summary of CDF $\sin 2\beta$ Results

- Using ℓDX data, $J/\psi \mathrm{K}^{*0}$ data, and Monte Carlo, we derive:

$$\mathcal{D}(J/\psi \mathrm{K}^0_S) = 0.166 \pm 0.018\,(\mathrm{Data}) \pm 0.013(\mathrm{MC})$$

- For ~ 200 $J/\psi \mathrm{K}^0_S$ events, we have:

$$\mathcal{D} \sin 2\beta = 0.31 \pm\ 0.18\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})$$

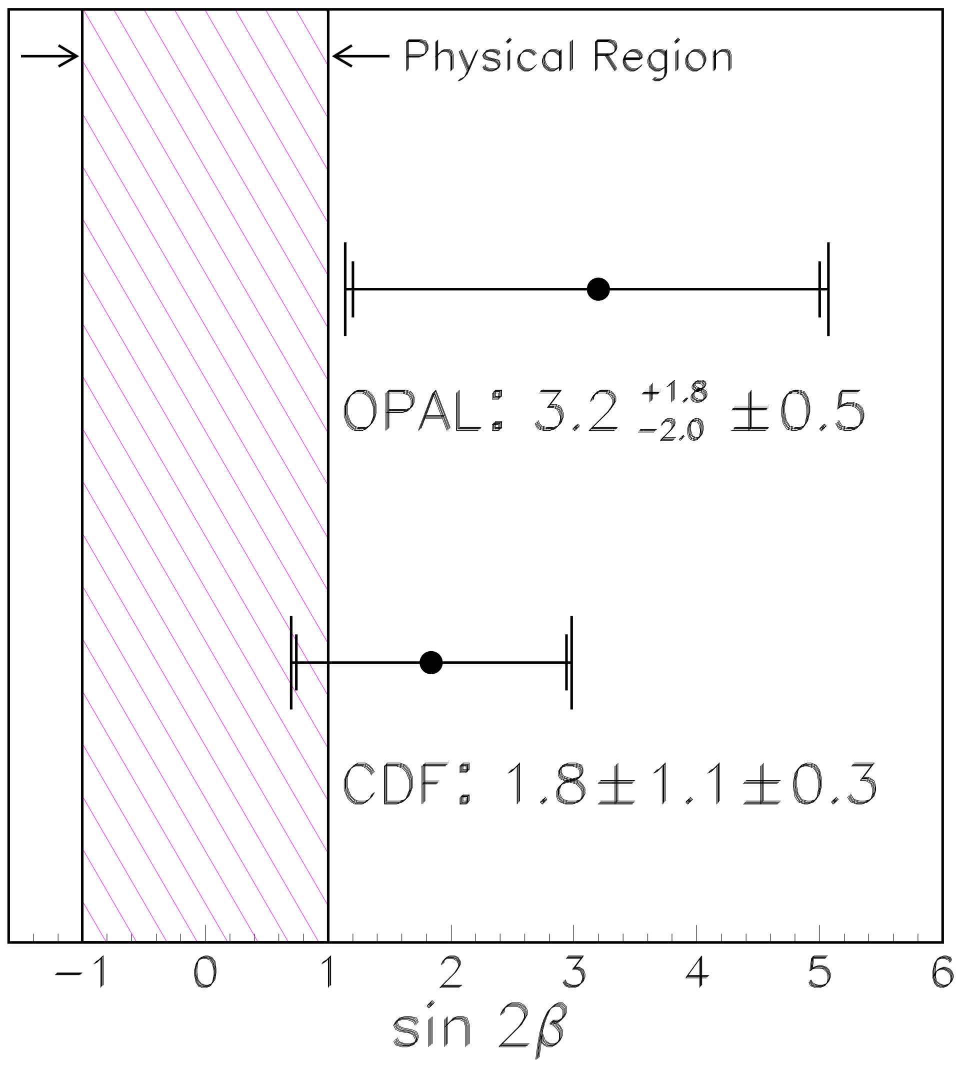
  – We exclude $\sin 2\beta \leq 0$ at 90% C.L., independent of the value of $\mathcal{D}$.

- Combining these, we measure:

$$\sin 2\beta = 1.8 \pm 1.1\,(\mathrm{stat}) \pm 0.3\,(\mathrm{syst})$$

  – We exclude $\sin 2\beta < -0.20$ at 95% C.L.

Summary of World $\sin 2\beta$ Results



Mixing and CP-Violation at CDF: Summary

- B_d^0 Mixing.
  - Multiple Tagging algorithms and datasets.
  - Combined: $\Delta m_d = 0.481 \pm 0.0289 \pm 0.026 ps^{-1}$.
- B_s^0 Mixing.
  - Using inclusive $B_s^0 \to \mu\phi X$, we exclude $\Delta m_s < 5.8$ at 95% C.L.
- $\sin 2\beta$.
  - $\sin 2\beta = 1.8 \pm 1.1\,(\mathrm{stat}) \pm 0.3(\mathrm{syst})$
  - We exclude $\sin 2\beta < 0$ at 90% C.L., independent of the dilution $\mathcal{D}$.
  - We exclude $\sin 2\beta < -0.20$ at 95% C.L.
  - Submitted for publication: FERMILAB-Pub-98/188-E and 189-E.
- Looking forward to $\times 10$ luminosity and an improved detector in Run II.
  - See talk by D. Lucchesi, tomorrow.