CP Violation and CKM Matrix

CP Violation in Standard Model:

★ 1973: Kobayashi & Maskawa: CP violation in K decays explained in SM with 3 generations

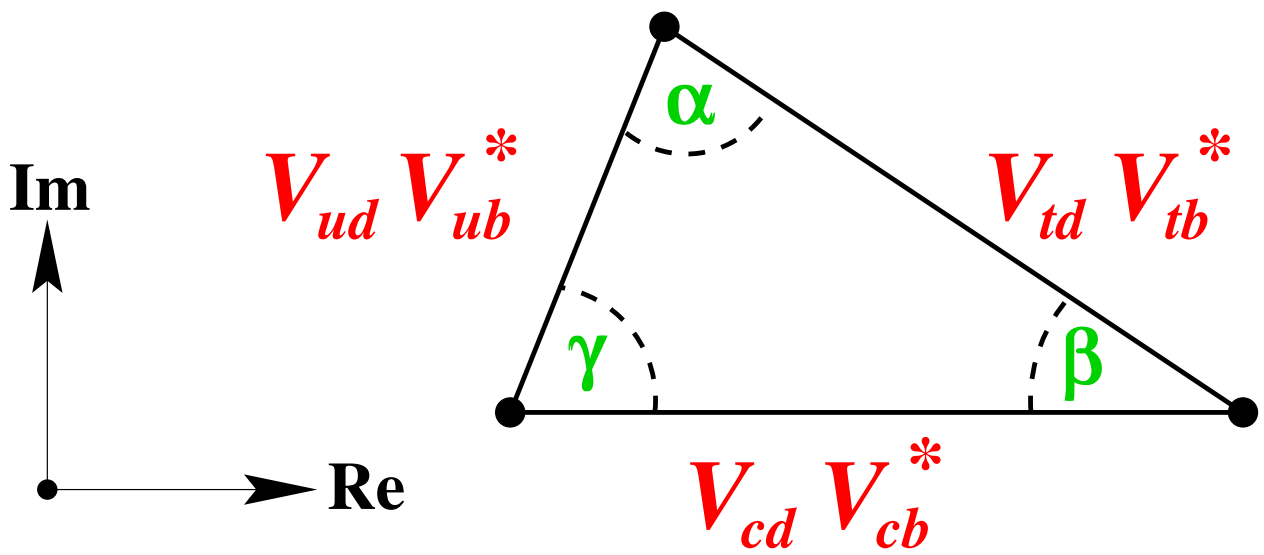
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Three angles plus one complex phase $\rightarrow$
$\rightarrow$ responsible for CP violation

★ Unitarity of $V_{\rm CKM}$ ($V^\dagger V = 1$):

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

★ Triangle relation in complex plane



★ CP violation in B system if $\alpha, \beta, \gamma \neq 0, \pi$

CP Violation and CKM Matrix

★ **Current knowledge of CKM matrix:**

Use Wolfenstein parametrization: emphasizes hierarchy of CKM matrix

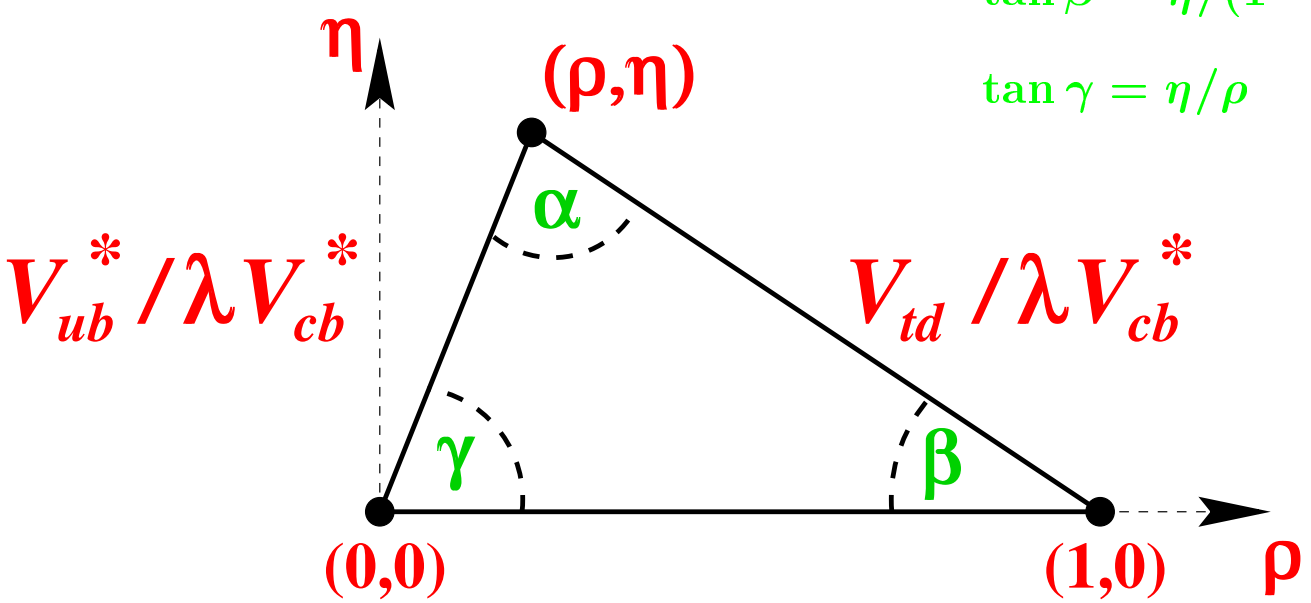
$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- $|V_{us}| = \lambda = \sin\theta_{\rm c}$ $\quad$ $\theta_{\rm c}$: Cabibbo angle
- $\lambda = 0.2196 \pm 0.0023$ from $K \to \pi\ell\nu$
- $A = 0.82 \pm 0.04$ from $|V_{cb}| = A\lambda^2 = 0.0395 \pm 0.0017$
- ρ and η related to CP violation

$$\tan\alpha = \frac{\eta}{\eta^2 - \rho(1-\rho)}$$

$$\tan\beta = \eta/(1-\rho)$$

$$\tan\gamma = \eta/\rho$$



→ CP violation through measuring angles

CP Violation and CKM Matrix

- CP violation in mixing (indirect CP violation)

  B^0 decays: $\Gamma(B^0 \to \ell^- \bar{\nu} X) \neq \Gamma(\bar{B}^0 \to \ell^+ \nu X)$ $\quad [Re(\epsilon_B)]$

  Kaons: $\frac{\Gamma(K_L \to \pi^- \ell^+ \nu) - \Gamma(K_L \to \pi^+ \ell^- \bar{\nu})}{\Gamma(K_L \to \pi^- \ell^+ \nu) + \Gamma(K_L \to \pi^+ \ell^- \bar{\nu})} = (3.27 \pm 0.12) \cdot 10^{-3}$

  $[Re(\epsilon_K)]$

- CP violation in decay (direct CP violation)

  Charged B decays: $\Gamma(B^+ \to f) \neq \Gamma(B^- \to \bar{f})$

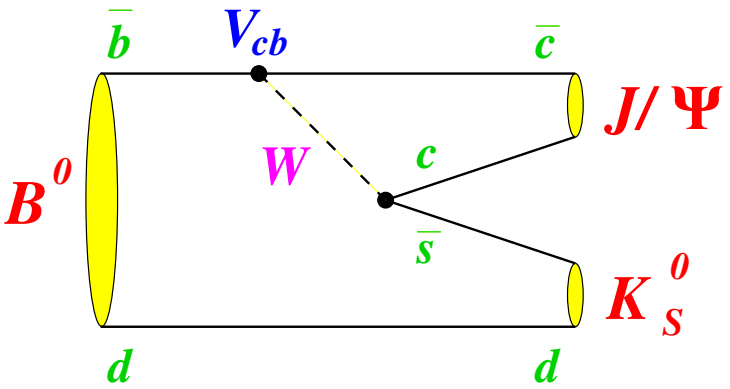
  K system: $Re(\epsilon'/\epsilon) = (21.3 \pm 2.8) \cdot 10^{-4}$ (KTeV & NA48)

- "Mixing induced" CP violation

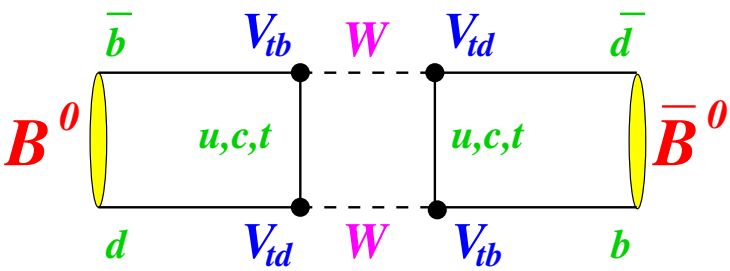
  Interference of direct decay $B^0 \to f_{CP}$ into CP eigenstate f_{CP} with mixed decay $B^0 \to \bar{B}^0 \to f_{CP}$

  B^0 decays: $\Gamma(B^0 \to J/\psi K_S^0) \neq \Gamma(\bar{B}^0 \to J/\psi K_S^0)$

The golden decay mode: $B^0/\bar{B}^0 \to J/\psi K_S^0$



direct decay

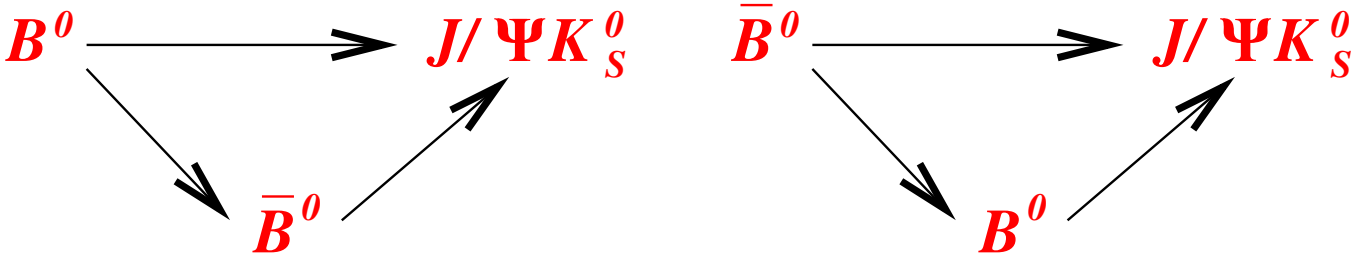


mixed decay

$\longrightarrow J/\Psi K_S^0$

CP Violation and CKM Matrix

Interference between direct decay with mixed decay:



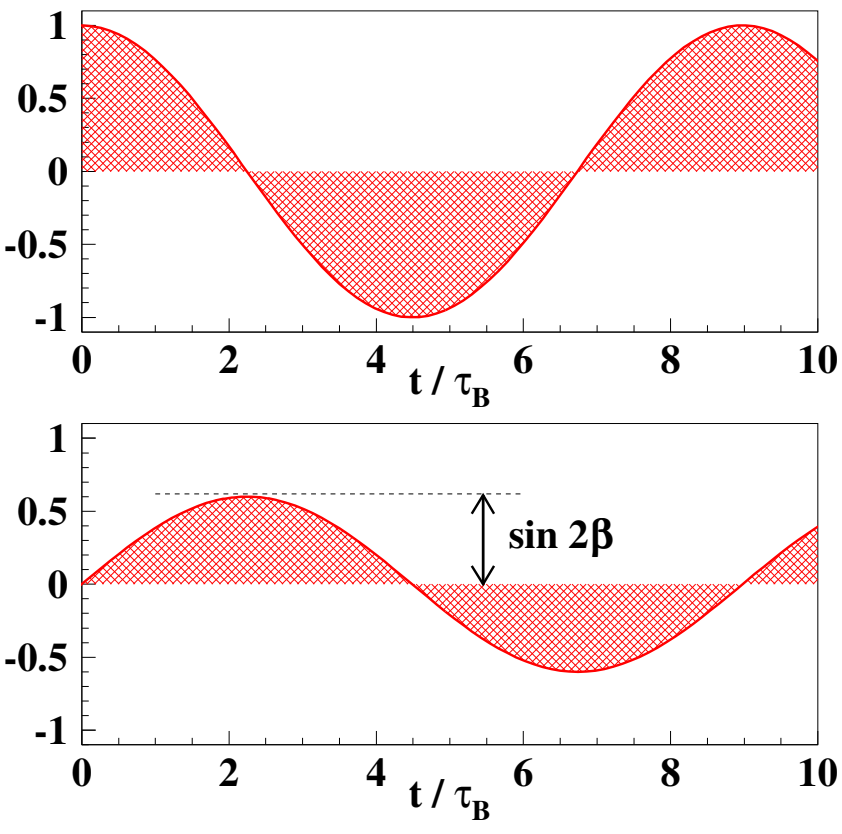
- Time dependence:

$$\frac{dN}{dt}(B^0 \to J/\psi K^0_S) \propto e^{-\Gamma t}\,(1 - \sin 2\beta\, \sin \Delta m_d t)$$

$$\frac{dN}{dt}(\bar{B}^0 \to J/\psi K^0_S) \propto e^{-\Gamma t}\,(1 + \sin 2\beta\, \sin \Delta m_d t)$$

$$\mathcal{A}_{CP}(t) = \frac{\Gamma(\bar{B}^0 \to J/\psi K^0_S) - \Gamma(B^0 \to J/\psi K^0_S)}{\Gamma(\bar{B}^0 \to J/\psi K^0_S) + \Gamma(B^0 \to J/\psi K^0_S)} = \underline{\sin 2\beta\, \sin \Delta m_d t}$$

- Connection between $B^0 \bar{B}^0$ mixing and CP violation



Search for CP Violation

$$\mathcal{A}_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to J/\psi K^0_S) - \Gamma(B^0(t) \to J/\psi K^0_S)}{\Gamma(\bar{B}^0(t) \to J/\psi K^0_S) + \Gamma(B^0(t) \to J/\psi K^0_S)}$$

Time dependent : $\mathcal{A}_{CP}(t) = \sin 2\beta \, \sin \Delta m_d \, t$

Ingredients for CP violation measurement:

- Need to reconstruct $B^0 \to J/\psi K^0_S$
- Need time dependence (SVX)
- Need to know B flavour at production

Figure of merit to compare tags:

* Effective tagging efficiency: $\varepsilon \mathcal{D}^2$

For CP violation measurement:

$$\mathcal{A}^{\rm obs}_{CP} = \mathcal{D} \cdot \mathcal{A}_{CP}$$

$$\Delta \sin 2\beta \simeq \frac{1 + (\Delta m_d \tau_B)^2}{\Delta m_d \tau_B} \cdot \frac{1}{\sqrt{\varepsilon \mathcal{D}^2 N}} \cdot \sqrt{\frac{S+B}{S}}$$

Search for CP Violation

- Measure asymmetry

$$\mathcal{A}(t) = \frac{N(\bar{B}^0(t)) - N(B^0(t))}{N(\bar{B}^0(t)) + N(B^0(t))} = \mathcal{D} \sin 2\beta \sin \Delta m_d t$$

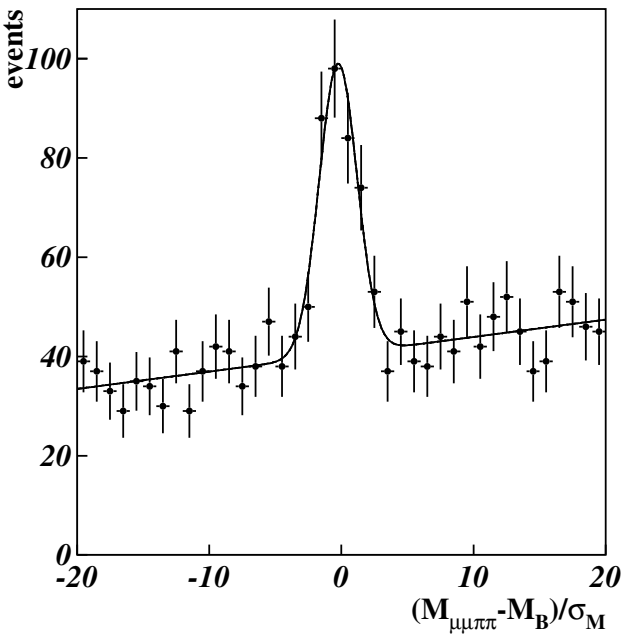
★ CDF's published result: (summer 1998)

- Use SST to tag B flavour at $t = 0$
- Reconstruct $B^0 \to J/\psi K^0_S$ in SVX $\Rightarrow \mathcal{A}(t)$

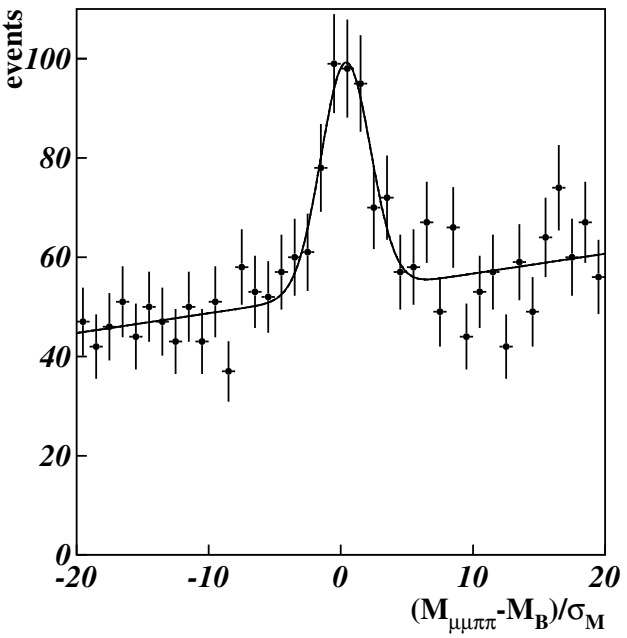
★ Update of CDF's $\sin 2\beta$ result: (published)

- Include lepton tag and jet charge tag
- Include $J/\psi K^0_S$ events with $\mu^+\mu^-$ not in SVX

$B^0 \to J/\psi K^0_S$ yield: 395 ± 31 events



SVX: 202±18



non-SVX: 193±26

Search for CP Violation

★ Calibration of flavour tags:

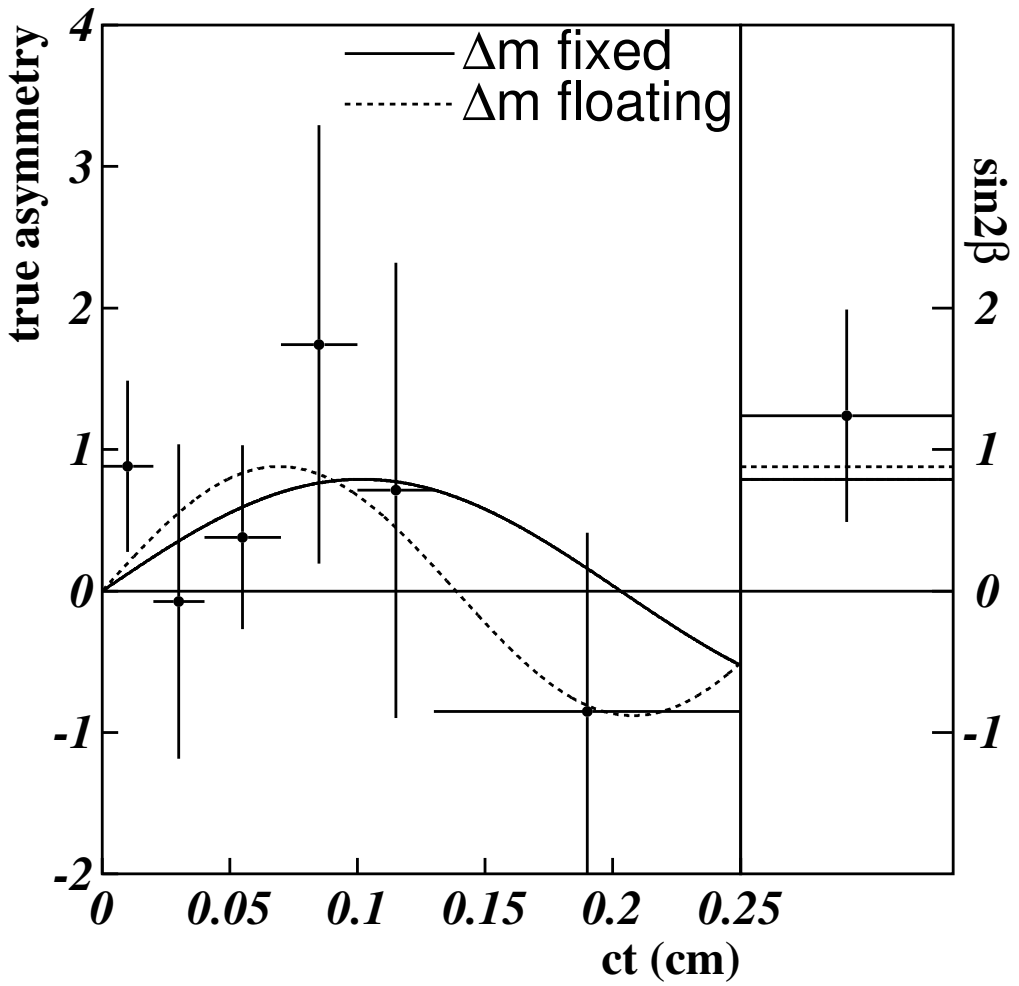
- Use (998 ± 51) $J/\psi K^+$ events to calibrate tags
  - lepton tag: $\mathcal{D} = (62.5 \pm 14.6)\%$, $\varepsilon\mathcal{D}^2 = (2.2 \pm 1.2)\%$
  - jet charge: $\mathcal{D} = (23.5 \pm 6.9)\%$, $\varepsilon\mathcal{D}^2 = (2.2 \pm 1.3)\%$
- Use same side tag from published analysis
  - SST (SVX): $\mathcal{D} = (16.6 \pm 2.2)\%$, $\varepsilon\mathcal{D}^2 = (1.0 \pm 0.3)\%$
  - non-SVX: $\mathcal{D} = (17.4 \pm 3.6)\%$, $\varepsilon\mathcal{D}^2 = (1.2 \pm 0.5)\%$

★ Combining flavour tags:

- Example: Same side tag ($\mathcal{D} = 16.6\%$) and jet charge tag ($\mathcal{D} = 23.5\%$)
- If both tags agree:
  $\mathcal{D}_{\text{eff}} = (\mathcal{D}_1 + \mathcal{D}_2)/(1 + \mathcal{D}_1\mathcal{D}_2) = 38.6\%$
- If tags disagree:
  $\mathcal{D}_{\text{eff}} = (\mathcal{D}_1 - \mathcal{D}_2)/(1 - \mathcal{D}_1\mathcal{D}_2) = 7.2\%$

- Each event is weighted by its dilution in the likelihood fit
- Allow for charge asymmetry in tagging algorithms

Search for CP Violation



Amplitude of $J/\psi K^0_S$ asymmetry:

- Solid line: unbinned max. likelihood fit

$$\sin 2\beta = 0.79 \pm 0.39 \pm 0.16$$

- Dashed line: Allow Δm_d to float in fit

$$\sin 2\beta = 0.88^{+0.44}_{-0.41}, \qquad \Delta m_d = (0.68 \pm 0.17)\ \mathrm{ps}^{-1}$$

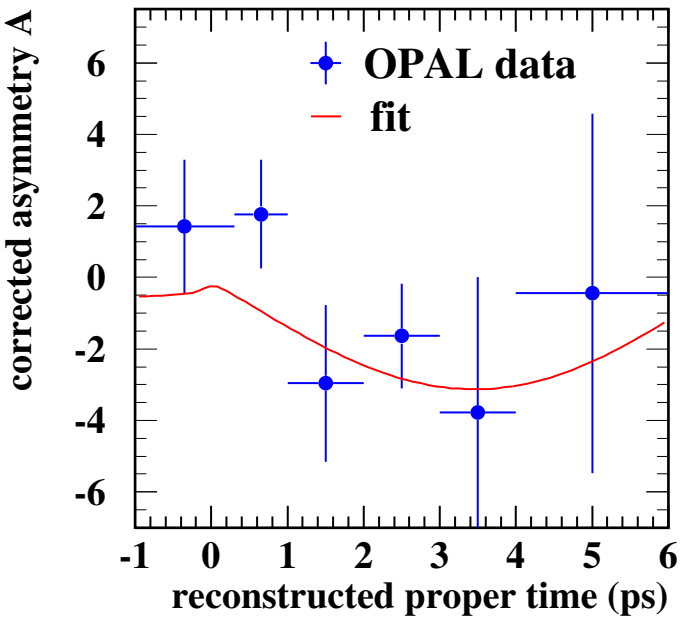
- Limit: $0 < \sin 2\beta < 1$ at 93% C.L.
- Demonstration that CP violation measurement is feasible at hadron collider in Run II!

Search for CP Violation

- OPAL:

- 24 $J/\psi K^0_S$ candidates
  purity $\sim 60\%$

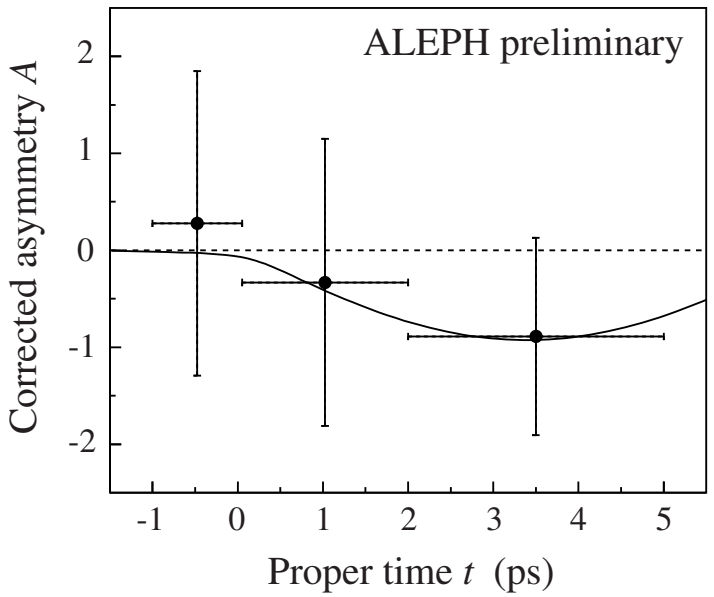
- $\sin 2\beta = 3.2^{+1.8}_{-2.0} \pm 0.5$



- ALEPH:

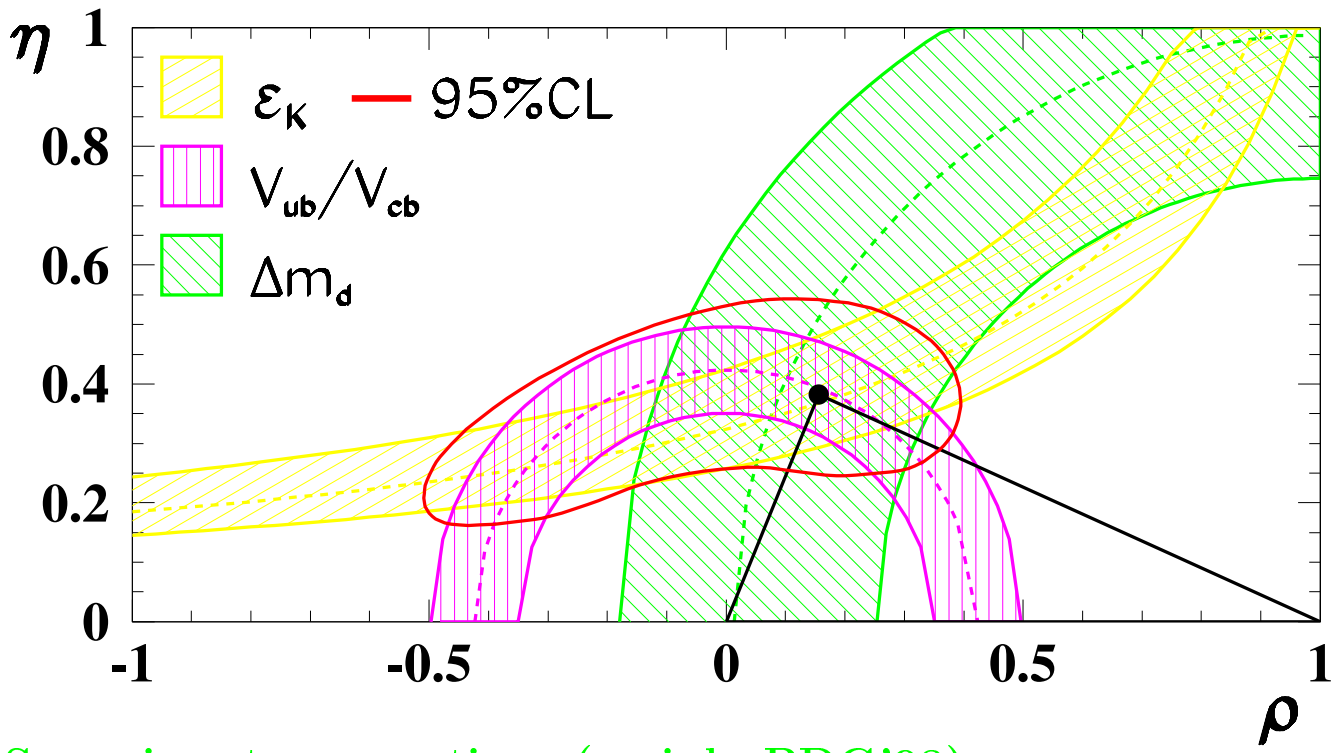
- 23 $J/\psi K^0_S$ candidates
  purity $\sim 71\%$

- $\sin 2\beta = 0.93\ ^{+0.64}_{-0.88}\ ^{+0.36}_{-0.24}$



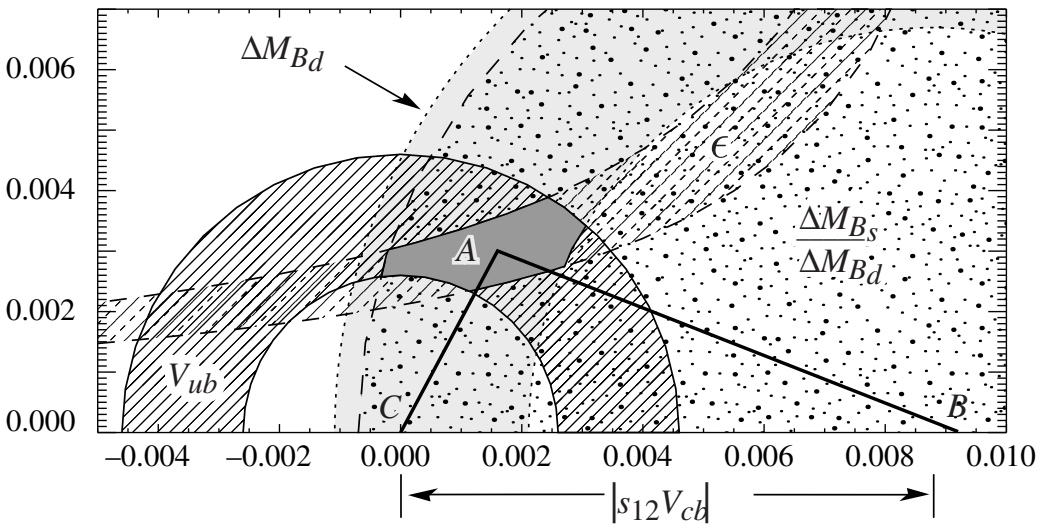
CKM Constraints

Constraints on CKM matrix:



Some input assumptions (mainly PDG'98):

- $\Delta m_d = (0.464 \pm 0.018)$ ps^{-1}, $f_B\sqrt{B_B} = (201 \pm 42)$ MeV
- $|V_{ub}|/|V_{cb}| = 0.093 \pm 0.016$, $|V_{cb}| = 0.0395 \pm 0.0017$
- $|\epsilon_K| = (2.28 \pm 0.019) \cdot 10^{-3}$
- Current constraint from PDG 2000:



Future of CP Violation

Experiment	$\Delta \sin 2\beta$	Start	Comments
BaBar	0.059	1999	(1)
Belle	0.06	1999	(2)
HERA-B	0.13	2000	(3)
CLEO III	dir. CP violation		(4)
DØ	0.07	2001	(5)
CDF	0.07	2001	(6)

(1): 30 $f\mathrm{b}^{-1}$; for $\sin 2\beta$: combine $J/\psi K_{S,L}^{0(*)}$, $D^{(*)}D^{(*)}$;
for $\sin 2\alpha$: combine $\pi\pi$, $\rho\pi$, $a_1\pi$.

(2): 100 $f\mathrm{b}^{-1}$; for $\sin 2\beta$: combine $J/\psi K_{S,L}^{0(*)}$;
for $\sin 2\alpha$: combine $\pi\pi$, $\rho\pi$.

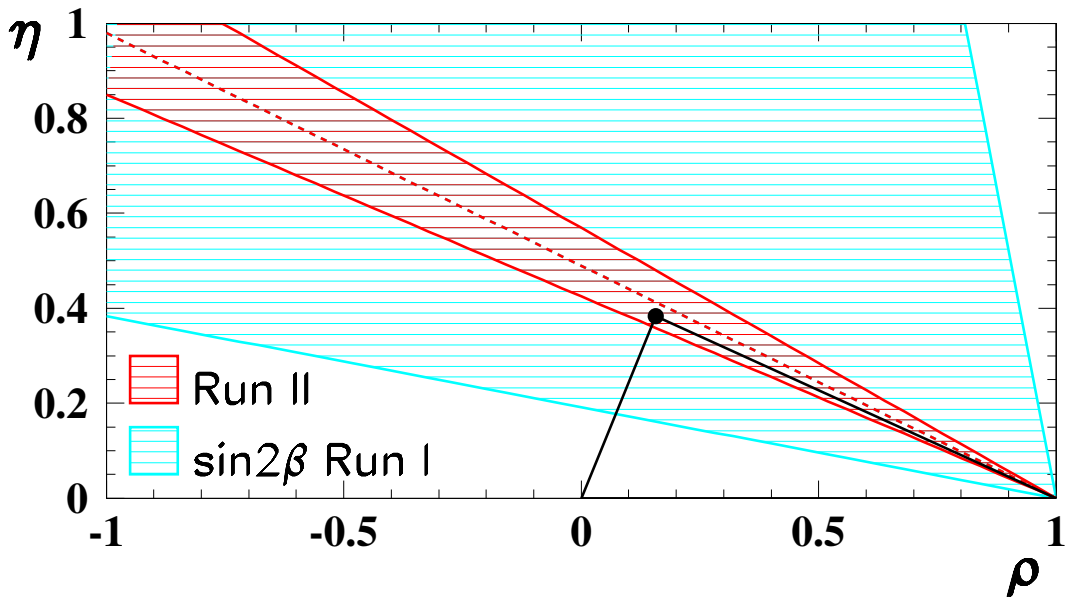
(3): 1 year; assume cross section of 12 nb.

(4): 20 fb^{-1}; use $B \to DK$, 4σ measurement of $\sin^2\gamma$.

(5): 2 fb^{-1}; central tracking, full η for tagging.

(6): 2 fb^{-1}.

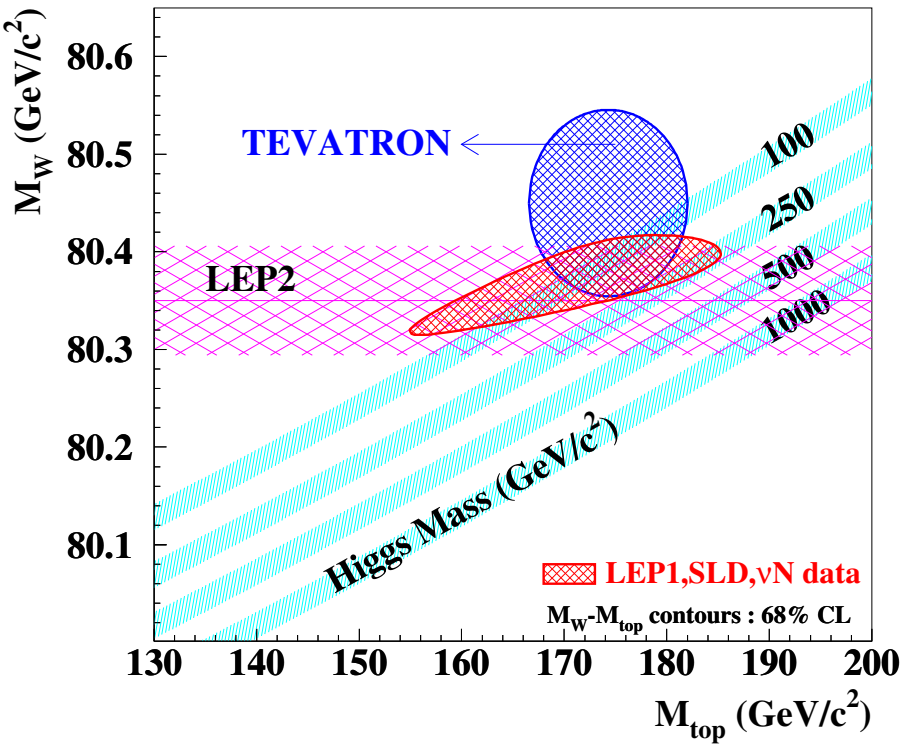
CDF now and in Run II ($\Delta \sin 2\beta \sim 0.07$ in 2 fb^{-1})



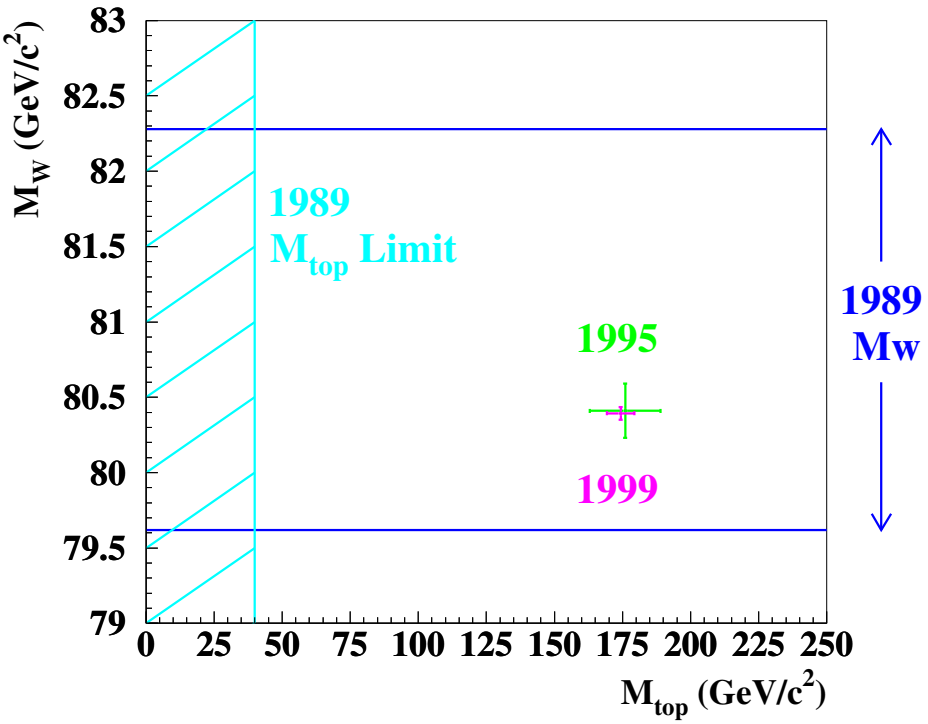
Golden Age of CKM Physics ?

From decade of precision EW measurements to decade of precision CKM measurements?

1999:



1989:



Prospects for B_S^0 Oscillations

* Prospects for $B_S^0 \bar{B}_S^0$ flavour oscillations:

  Measure $|V_{td}|/|V_{ts}|$

  Additional inner layer of Si improves σ_t:

  – $\sigma_t = 0.060$ ps $\rightarrow 0.045$ ps

  $\Rightarrow \sigma_t$ important if Δm_S unexpectedly large

  ToF enhances effectiveness of flavour tagging

  – $\varepsilon \mathcal{D}^2 = 11.3\%$ (same side tag on kaons)

  Signal: 15,000 - 23,000 $B_S^0 \rightarrow D_S^- \pi^+$, $D_S^- 3\pi$ events from two-track hadronic trigger (2 fb^{-1})

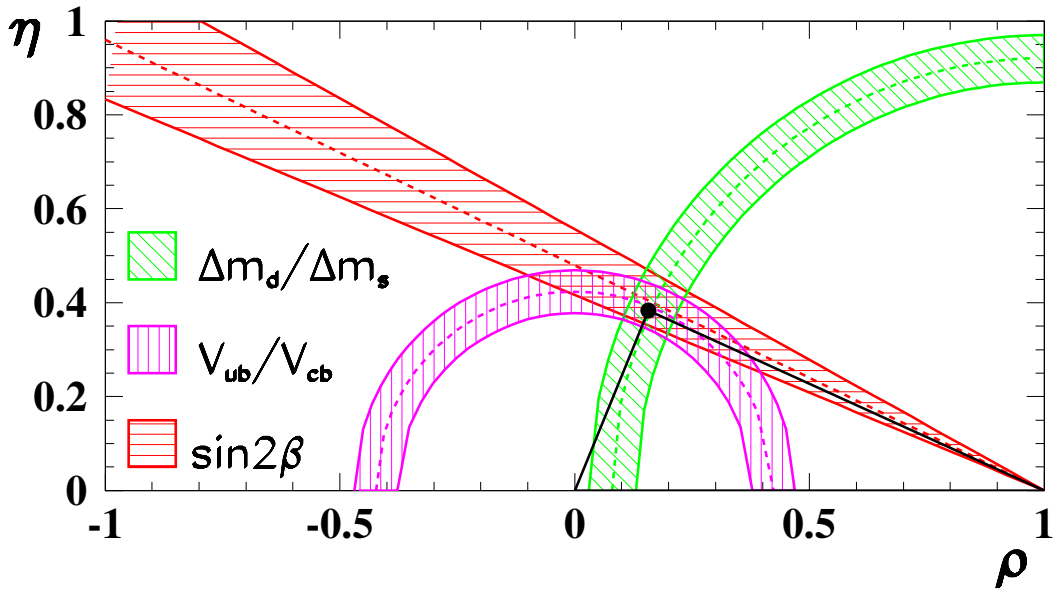
* For 20k events: 5σ measurement for

  $\Delta m_S < 40$ ps^{-1}

  current limit: $\Delta m_S < 14.6$ ps^{-1} (95% C.L.)

* Physics with B_S^0 mesons unique to Tevatron

  CDF will overconstrain CKM triangle

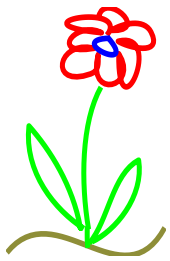


Conclusions

Heavy Flavour Decays: CKM & CP

- The Fundamentals: CP & CKM
- Experimental environment
- B Lifetimes
- B Oscillations
- CP Violation

Golden age of CKM physics ahead of us



"You see things as they are
and ask 'Why?'
I see things as they never were
and ask 'Why not'?"

(George Bernard Shaw)