$B_s^0 \bar{B}_s^0$ Mixing

- $\Delta m_s / \Delta m_d \Rightarrow |V_{ts}/V_{td}|$ with less theory uncertainty.
- If SM fits are correct, it should be just around the corner:

$$15.4 < \Delta m_s < 20.3 \text{ ps}^{-1}.$$

- Experimental challenge: seeing very rapid oscillations.

  Need $p(B_s^0)$ of each event to get proper time.

  Difficult if missing particles exist, e.g. $\bar{B}_s^0 \to \ell^- \bar{\nu} D_s^+ X$.

  Want full reconstruction $\bar{B}_s^0 \to D_s^+ \pi^-$, $D_s^+ \pi^+ \pi^- \pi^-$.
- Employ impact parameter track trigger (SVT) at level-2.

  Resolution ~ 40 μm for $p_T > 2$ GeV/c.
- Expect 5000 to 30000 $\bar{B}_s^0 \to D_s^+ (n\pi)^-$ decays in 2 fb^{-1}.

  S/B: 1/2 to 2.

  $\sigma_t = 45 \oplus (\sigma_p/p)\, t$ fs (~ 14 μm).

  Flavor tagging: $\epsilon D^2 = 11\%$.

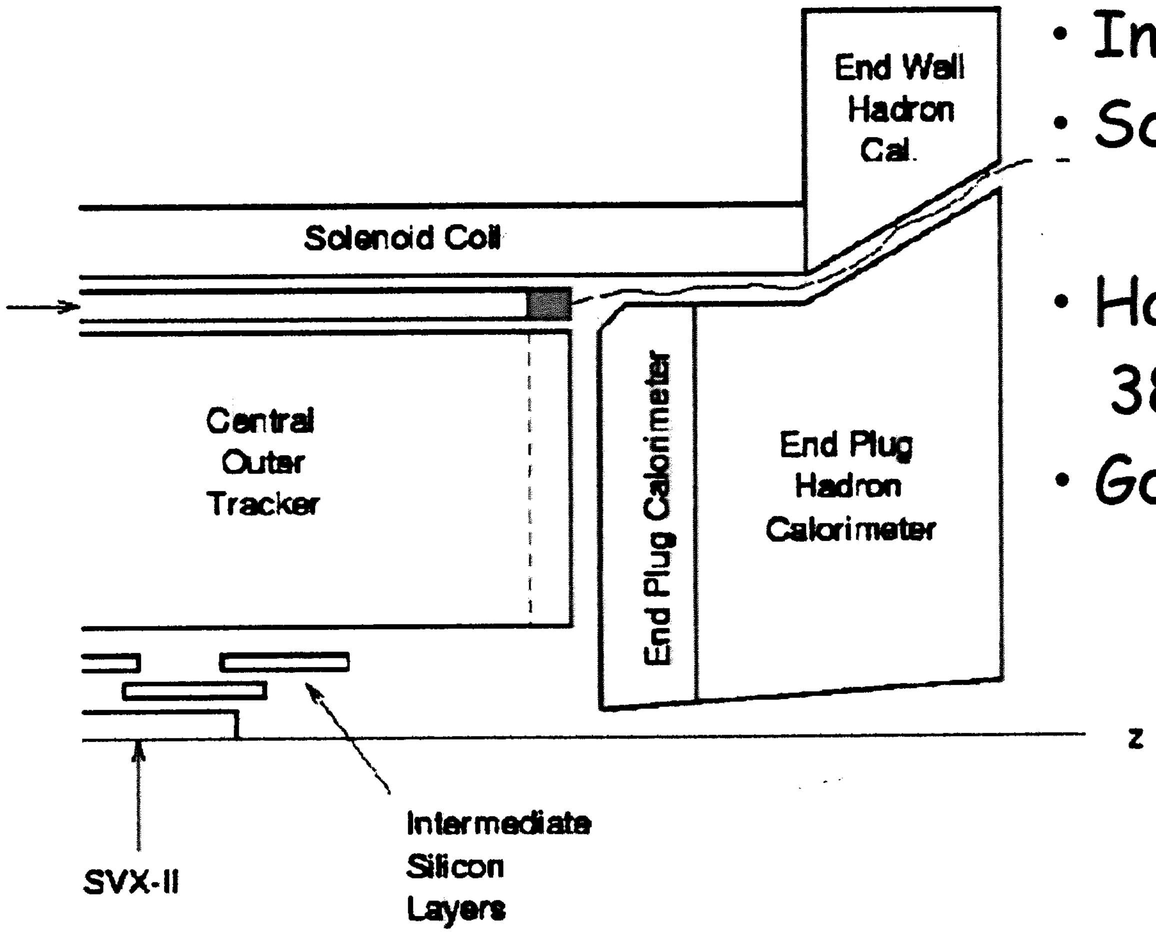
  Can observe Δm_s up to 40 ps^{-1} as a > 5-σ effect.

  Once seen, Δm_s will be measured to a few %.

$\Rightarrow$ $|V_{td}/V_{ts}|$ also determined to a few %.

New additions for *B* physics: Time-of-flight counter
Innermost Si layer

CDF-II TOF counter



Detector

- Located at r = 1.4 m
- Inside 1.4 Tesla solenoid
- Scintillator Bicron BC408
  4 x 4 x 270 cm^3 216本
- Hamamatsu R7761 PMTs
  38 mm, 19-stage fine mesh
- Goal: $\sigma_T \sim 100$ ps

Purpose

- 2σ K/π separation
  up to 1.6 GeV/c
- *B* flavor tagging

Impact of TOF and Layer 00 on B^0_s mixing

Signal

- $B^0_s \to D^-_s \pi^+, D^-_s \pi^+ \pi^+ \pi^-$
- ~20 k events / 2 fb^{-1}

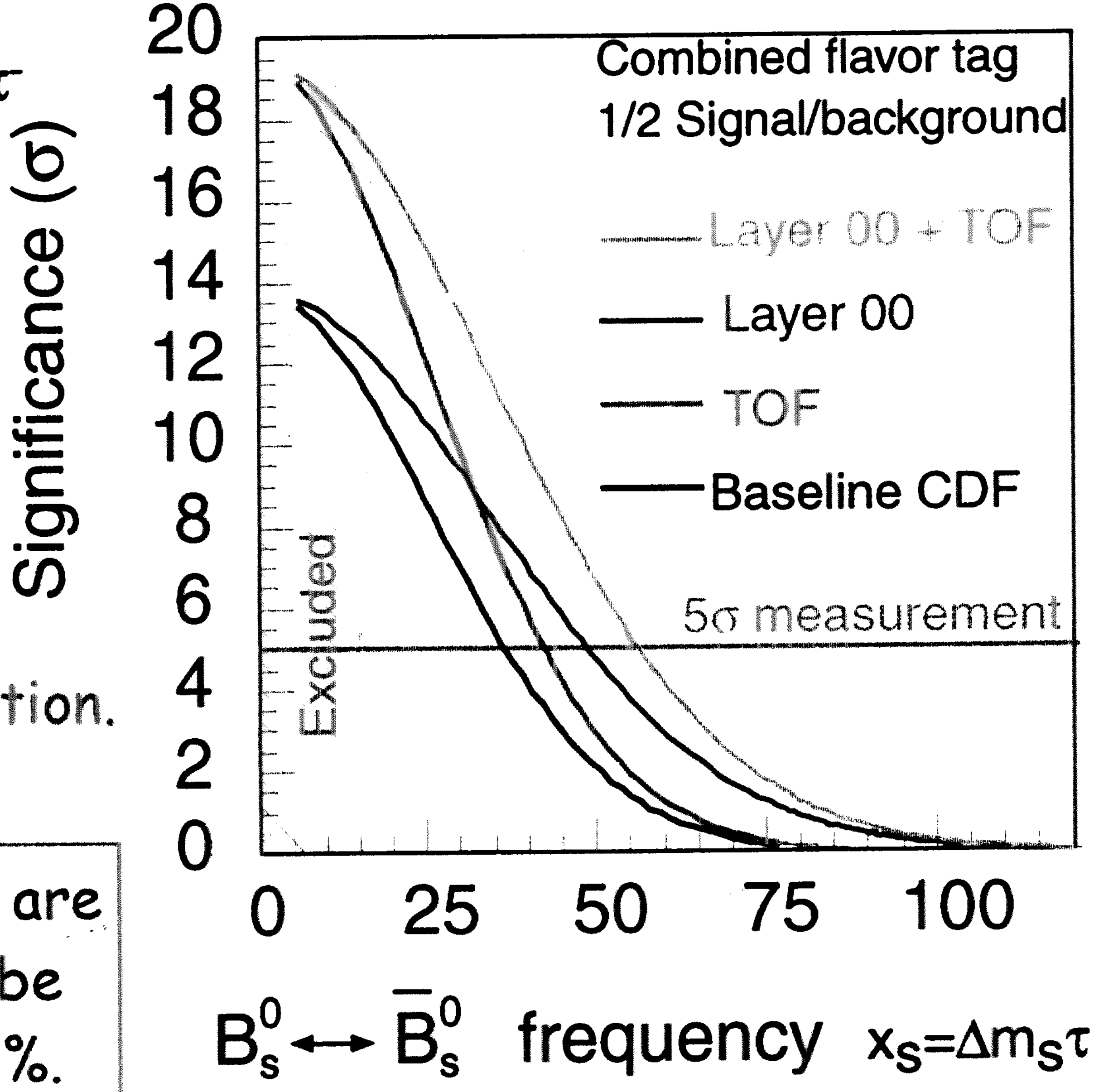
TOF

- Improves flavor tags.
- Helps at lower x_s.

Layer 00

- Improves vertex determination.
  → proper time resolution.
- Helps at higher x_s.

Once the oscillations are established, Δm_s will be determined to a few %.



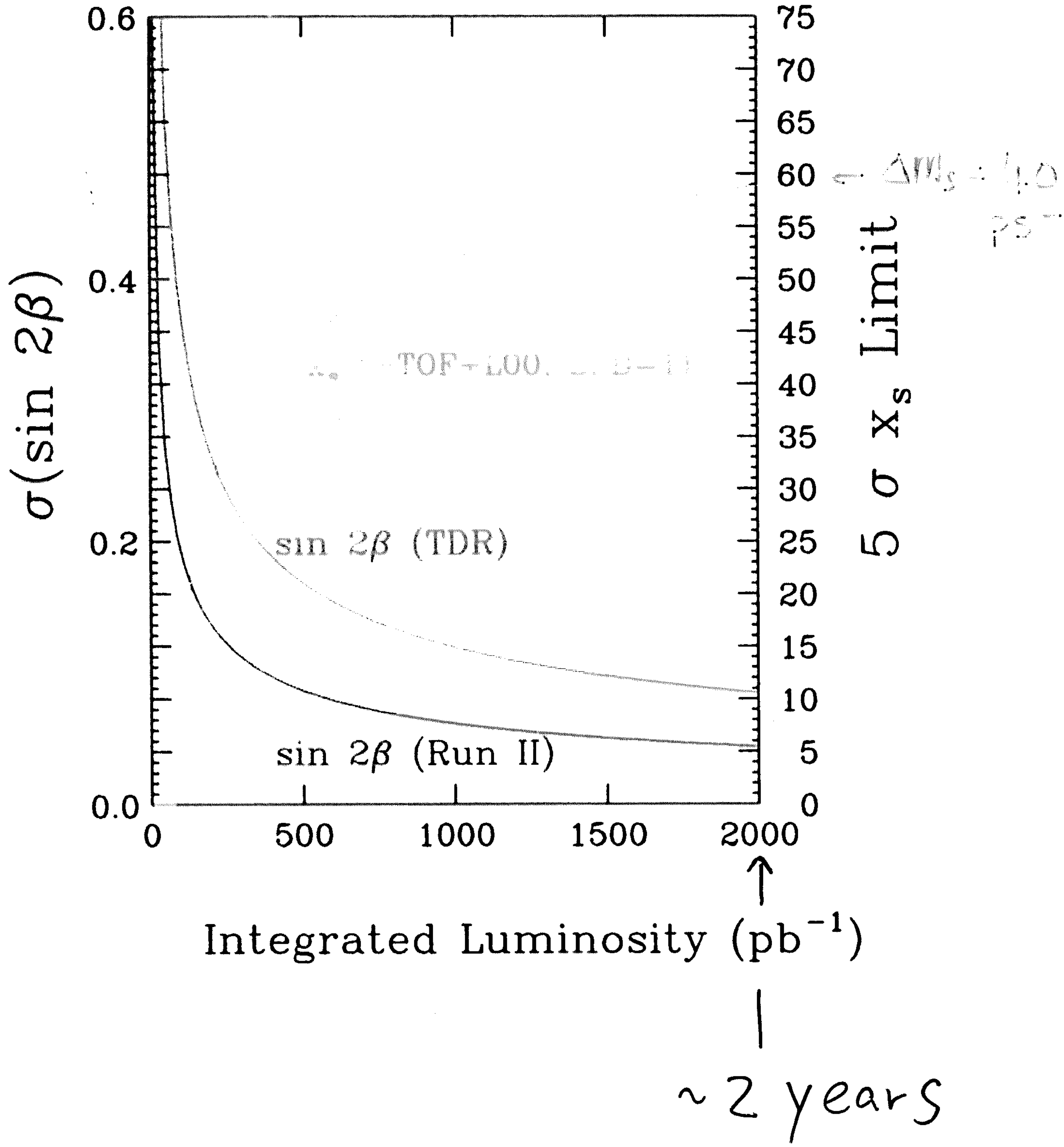
($\tau = 1.5$ ps)

Run II projections

sin 2β precision from $J/\psi\ K^0_S$ (2 fb^{-1})

TDR: 10 k signal, $\varepsilon D^2 = 6.7\% \rightarrow \pm 0.084$

New: 28 k signal, $\varepsilon D^2 = 9.1\% \rightarrow \pm 0.043$

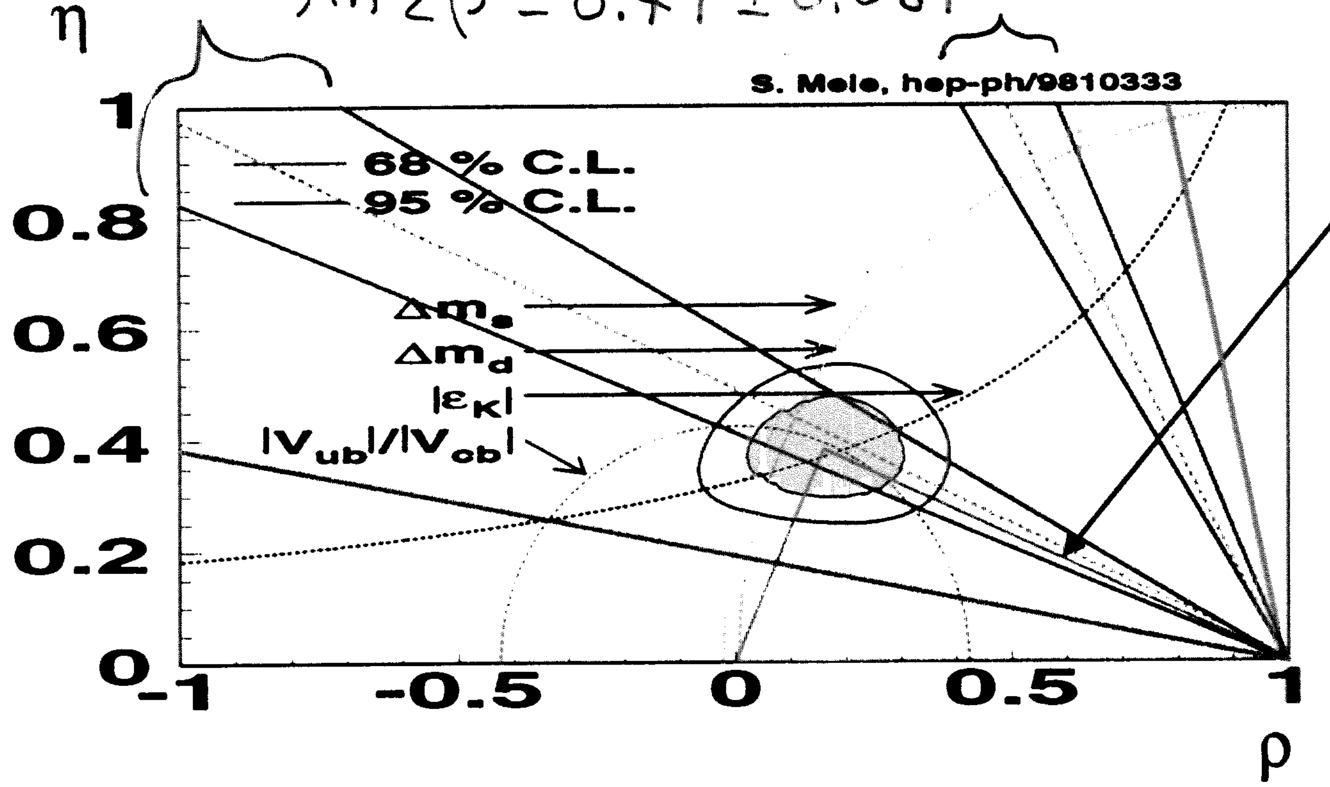


B Physics in CDF Run II   Two Major Goals:

I. Precision $\sin(2\beta)$ from $B^0/\bar{B}^0 \rightarrow J/\psi K^0_S$

II. $B^0_s - \bar{B}^0_s$ Oscillation $\rightarrow \Delta m_s / \Delta m_d$

$\sin 2\beta = 0.79 \pm 0.084$



$|V_{td}| / \lambda |V_{ts}|$

Can be the first meaningful test of the unitarity triangle.

Run II (cont'd) Probing angle γ (phase of V_{ub})

- $B^0 \to \pi^+ \pi^-$ once thought to be the mode for $\sin 2(\pi-\gamma-\beta)$.
  (assuming $b \to u$ tree dominance over penguin)
- CLEO finds much larger $K^- \pi^+$ and tiny $\pi^+ \pi^-$.
- Not just small rates, but also means penguin pollution.
  $\to$ Relation to $\sin(2\alpha)$ less clear.
- Strategies proposed, but are challenging experimentally...

New approach : R. Fleischer, Phys. Lett. B 459, 306 (1999).
Throw in $B^0_s \to K^+K^-$, measure asymmetries in both B^0 and B^0_s.

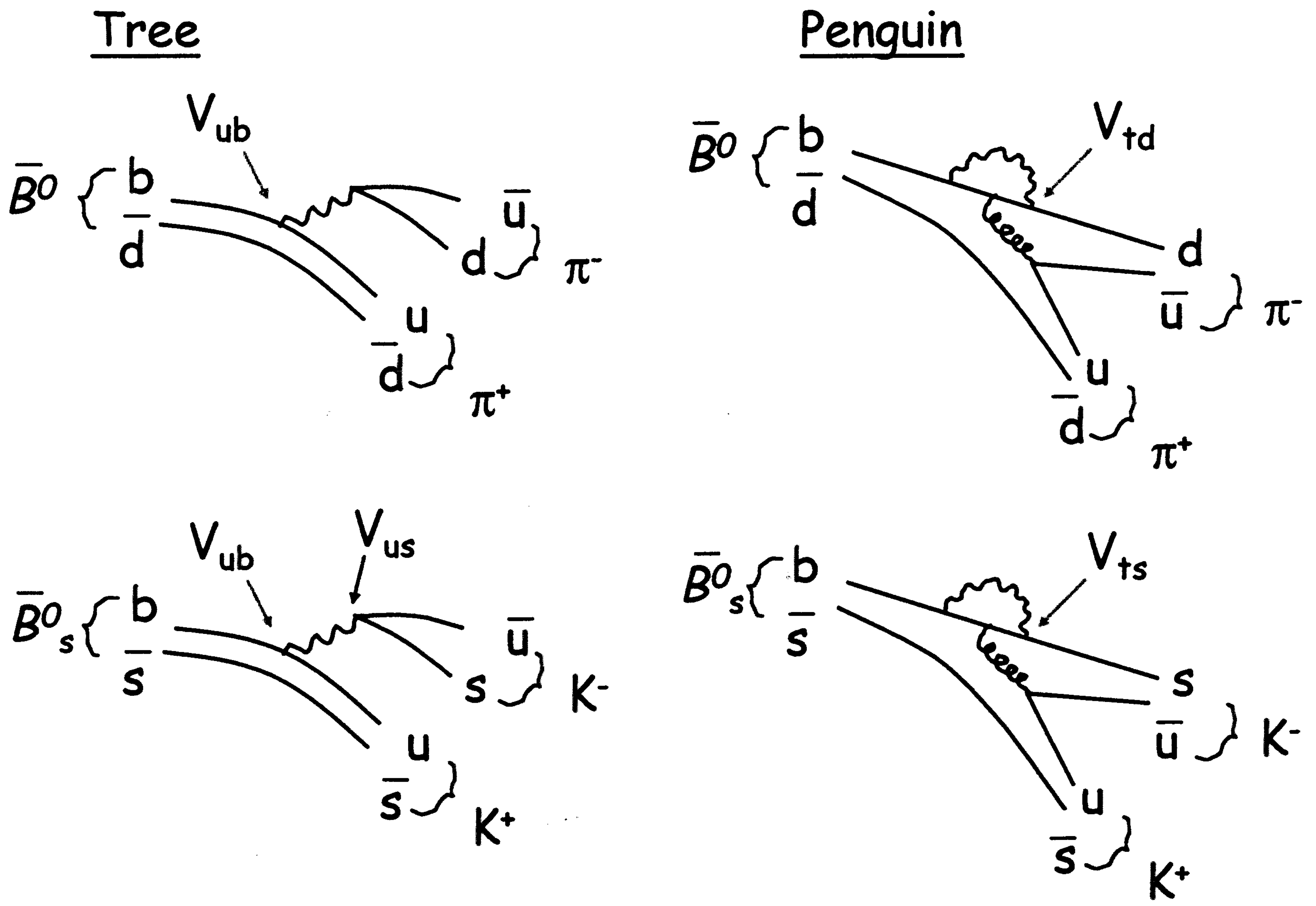
In general, for a decay $B^0 \to f$ (f = CP eigenstate) :

$$A_{CP}(t) = A^{dir} \cos(\Delta m t) + A^{mix} \sin(\Delta m t).$$

A^{dir} : "direct" CP violation, A^{mix} : CP violation thru mixing.

Experimentally, measure 4 A's from $B^0 \to \pi^+ \pi^-$ and $B^0_s \to K^+K^-$.

Then extract β, γ and penguin and tree decay amplitudes.



Tree
Penguin
$\bar{B}^0$
b
$\bar{d}$
V_{ub}
$\bar{u}$
d
π^-
u
$\bar{d}$
π^+
V_{td}
$\bar{B}^0_s$
$\bar{s}$
V_{us}
s
K^-
$\bar{s}$
K^+
V_{ts}

Angle γ (phase of V_{ub}) continued

Four CP asymmetries to measure. ($\lambda = \sin\theta_c$)

- $A^{dir}(B^0 \to \pi^+\pi^-) = -2d \sin\theta \sin\gamma \,/\, (1 - 2d\cos\theta\cos\gamma + d^2)$
- $A^{mix}(B^0 \to \pi^+\pi^-) = [\sin 2(\beta+\gamma) - 2d\cos\theta \sin(2\beta+\gamma) + d^2 \sin 2\beta]$
  $/ \, [1 - 2d\cos\theta\cos\gamma + d^2]$
- $A^{dir}(B^0_s \to K^+K^-) \sim 2(\lambda^2/d) \sin\theta \sin\gamma$
- $A^{mix}(B^0_s \to K^+K^-) \sim 2(\lambda^2/d) \cos\theta \sin\gamma$

If no penguin,
$A^{dir} = 0$ $\quad (B^0, B^0_s)$
$A^{mix} = \sin 2(\beta+\gamma)$ (B^0)
$A^{mix} = \sin(2\gamma)$ $\quad (B^0_s)$

Four unknowns to extract :

- β, γ = angles of the unitarity triangle.
- d = ratio of penguin (P) to tree (T) decay amplitudes,
  θ = phase of "P/T"
  $d\, e^{i\theta} \equiv \lambda |V_{cb}/V_{ub}| \,/\, (1-\lambda^2/2)\, [\, P \,/\, (T+P)\,]$

Expect ~5 k $B^0 \to \pi^+\pi^-$, ~10 k $B^0_s \to K^+K^-$
$\to$ angle γ to ~10°.

$B^0_{(s)} \to \pi\pi, \pi K, KK$ samples

- Problem: we measure $\mathcal{A}_{dir}, \mathcal{A}_{mix}$ for time dependence $x_d = 0.7$, $x_s = 26$
- Observed asymmetries are diluted by:

  $\mathcal{A}_{obs} = \mathcal{A}_{\pi^+\pi^-} \times f_{\pi\pi}$

  $\mathcal{A}_{obs} = \mathcal{A}_{K^+K^-} \times f_{KK}$,

  $f_{\pi\pi}, f_{KK}$= respective fractions in mass window
- First determine signal rates *before* flavor tagging

  Use dEdx with Mass $\Rightarrow$

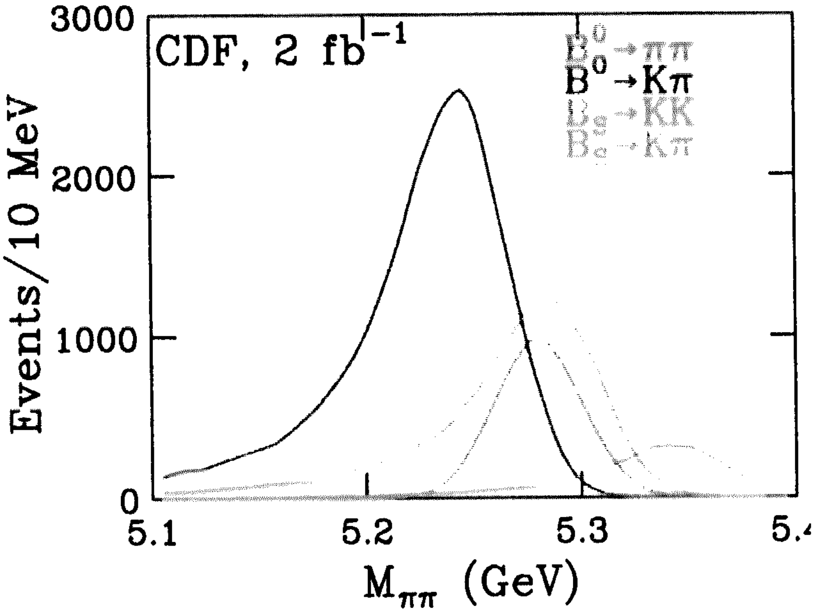
  $\Rightarrow$Fitted errors on $f_{\pi\pi}, f_{KK}, f_{K\pi} \sim 1 \div 4\%$ on each signal

  Higher math$\Rightarrow$ 1σ dEdx separation on $K\pi$ gives

  $\times 2.3$ larger error on f_π than perfect separation , still just a few %

  $f_{\pi\pi}, f_{KK}$ are same for tagged/untagged samples

  $\Rightarrow$ negligible errors on measured $\mathcal{A}_{CP}$



- Nominal BR's, $\sigma(B^0), \sigma(B^0_s)$

  20000 $B^0 \to K^+\pi^-$

  10000 $B^0_s \to K^+K^-$

  5000 $B^0 \to \pi^+\pi^-$

  2500 $B^0_s \to K^-\pi^+$
- Also QCD combinatorics (flat)

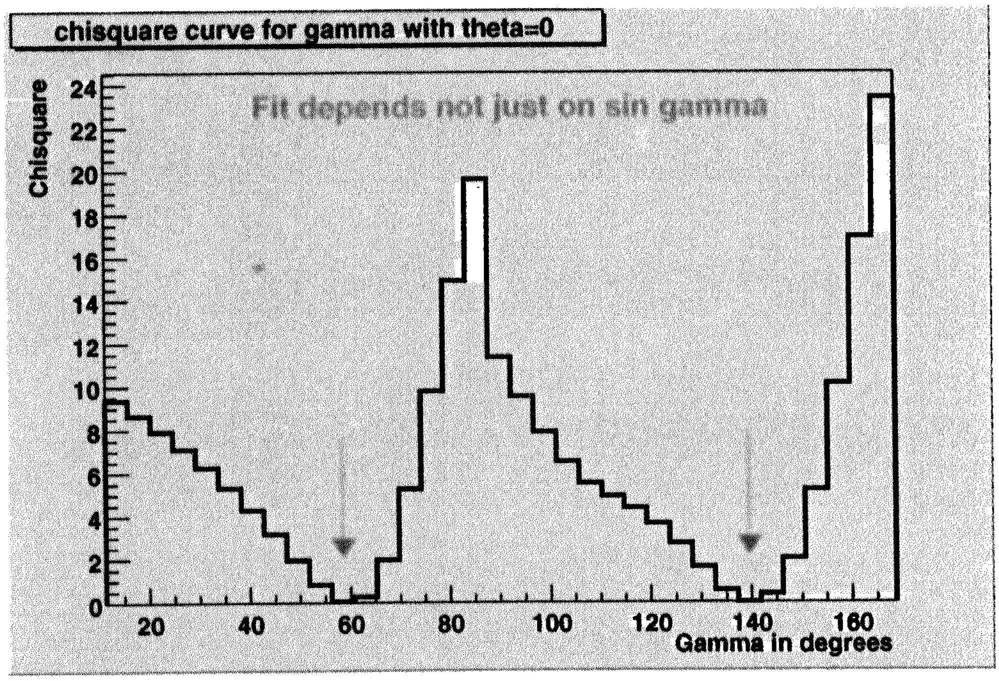
  $B^0 + B_s$:QCD $\sim$ 1:1

Measuring γ — the Result

Experimental Errors for "nominal assumptions":

$$\sigma_{Acp} \sim 0.08 \text{ for } B_s \to K^+ K^-$$
$$\sigma_{Acp} \sim 0.11 \text{ for } B_d \to \pi^+ \pi^-$$

χ^2 fit for γ:



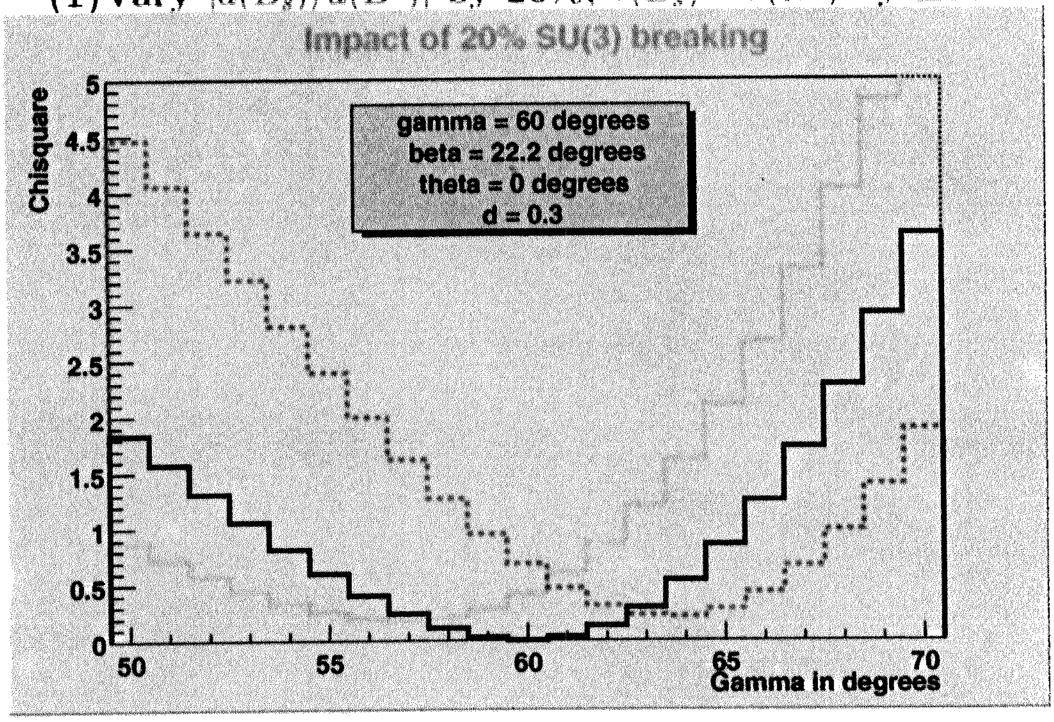
σ_γ [illegible] $^{[illegible]}_{-6.8} \pm 3$ degrees

Systematic Error due to SU(3) breaking of 20%:

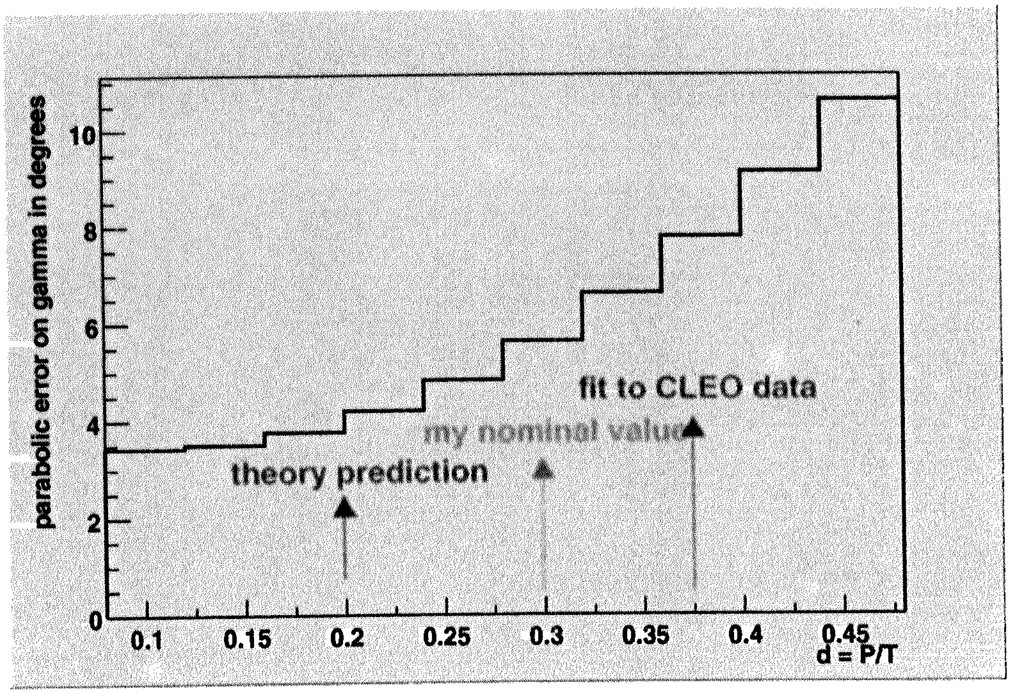
$\sim$ 1/2 the expected experimental error !!!

Stability of Errors on γ

(1) Vary $|d(B_s)/d(B^0)|$ by 20%, $\theta(B_s) - \theta(B^0)$ by $\pm 10°$



(2) Vary central value of $|d|$ used in fits



Other Topics

- Search for CP-violation in $B_s^0/\bar{B}_s^0 \to J/\psi\phi$
  A_{CP} to $\sim \pm 0.1$. Expect ~ 0 in SM, new physics if substantial.
- Width difference $\Delta\Gamma$ in $B_s^0\bar{B}_s^0$ system
  Potential for CP studies with untagged B_s^0 decays.
  $\sigma(\Delta\Gamma/\Gamma) \simeq 0.024$ from $J/\psi\phi$ vs. $D_s^+\pi^-$.
  Also, direct check with $D_s^{(*)+}D_s^{(*)-}$.
- Rare decays:
  $B \to \mu^+\mu^- K^{(*)}$, ~ 60 events in 2 fb^{-1}.
  Need more data for forward/backward asymmetry.
  Also $(B^0 \to K^{*0}\gamma)$ / $(B^0 \to \rho^0\gamma)$
  and $(B_s^0 \to \phi\gamma)$ / $(B_s^0 \to K^{*0}\gamma) \Rightarrow |V_{ts}/V_{td}|$.
- Angle γ from $B_s^0 \to D_s^{\mp}K^{\pm}$?
  Theoretically clean, but BG from $D_s^-\pi^+$ tough.
  Hope to see signal in 2 fb^{-1}.
- Precision lifetime ratios : B_s^0/B^0, B_c^+/B^0, Λ_b/B^0
- Full reconstruction of $B_c^+ \to J/\psi\pi^+$, $B_s^0\pi^+$ ...
- QCD b and c production, onium polarization.

Much of them pretty complementary to $\Upsilon(4S)$.

Lifetime Difference, $\frac{\Delta\Gamma}{\Gamma}$

- **Full Mass and Decay Matrix**

$$H_{eff} = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

- **Eigenstates have masses $M \pm \frac{\Delta M}{2}$, widths $\Gamma \pm \frac{\Delta\Gamma}{2}$**

  M_{12} due to virtual intermediate states (tt)

  Γ_{12} due to real intermediate states ($D\overline{D}$)

  $\Delta\Gamma = 2\cos\Delta\Phi|\Gamma_{12}|$ ($\Delta\Phi = arg[M_{12}^*\Gamma_{12}]$)

  CP impurity in eigenstates, $\Re(\epsilon) = \sin\Delta\Phi|\frac{\Gamma_{12}}{4M_{12}}|$

- **For K_L K_S system**

  $\Delta\Gamma \simeq 100\%$ due to common $K \to 2\pi$ intermediate state

  Also, phase difference is large, so $Re(\epsilon)$ is "large"

- **In B^0 and B_s^0 systems**

  $\Delta\Gamma$ small (random mix of intermediate states)

  $\Delta\Phi$ is small- $6.4°(B^0)$, $-0.2°(B_s)$ by CKM unitarity,
  so $\Re(\epsilon) \simeq 2\ 10^{-4}(B^0)$, $5\ 10^{-6}(B_s)$

- **For B^0, B_s^0 mesons, we have**

  B_s^0, $b+s \to ccs+s \sim 1$

  B_d^0, $b+d \to ccd+d \sim \sin^2\theta_c$

  $\frac{\Delta\Gamma}{\Gamma}(B_s^0) = 15 \pm 5\%$ (Hashimoto, '99)

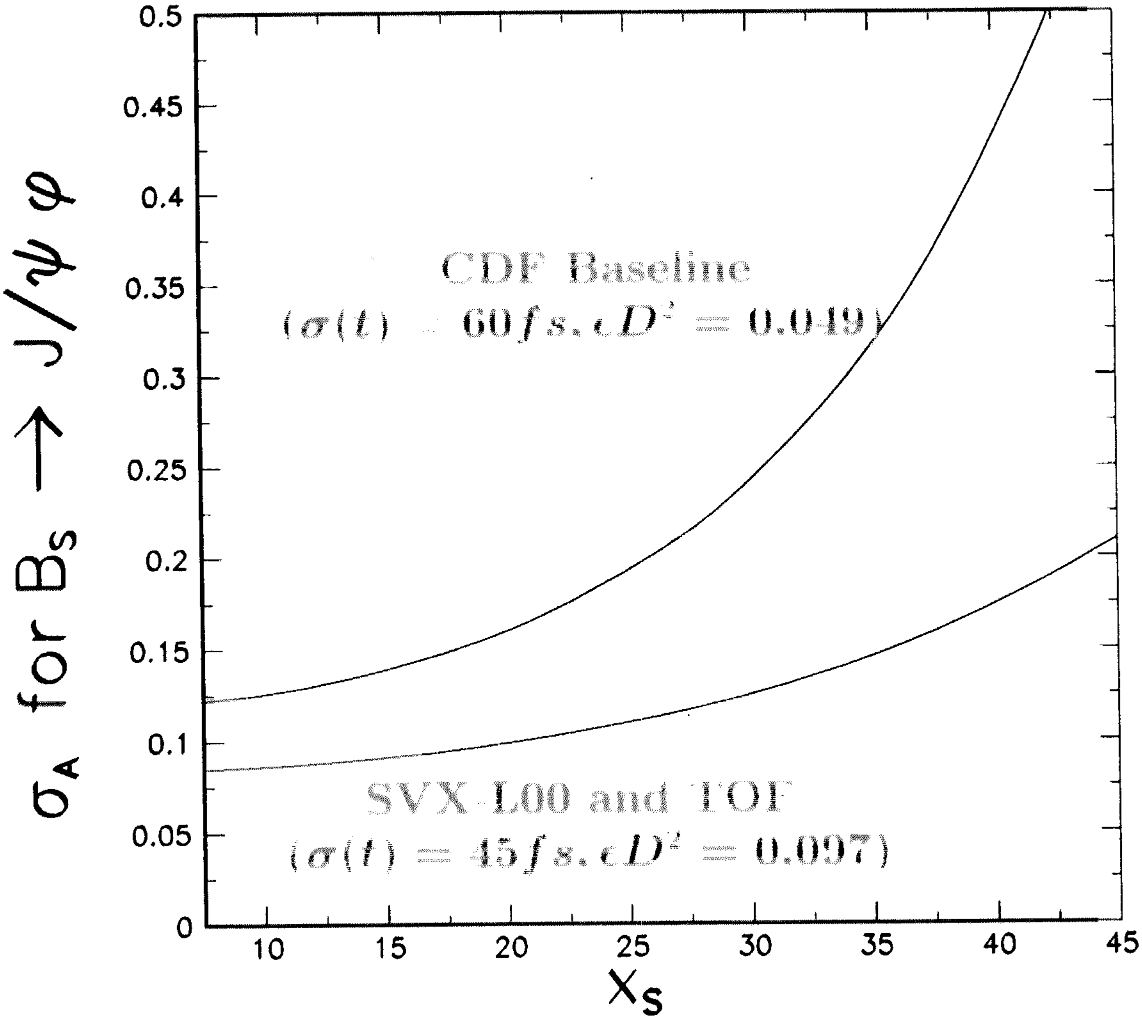
  $\frac{\Delta\Gamma}{\Gamma}(B_d^0) < 1\%$

  Numerically, $\frac{\Delta\Gamma}{\Delta M} \simeq (5.6 \pm 2.6)10^{-3}$

Conclusion: $\Delta\Gamma(B_s^0)$ should be detectable ($\sim 15\%$)
but $\Delta\Gamma(B_d^0)$, also $\Re(\epsilon)$, probably not

CP Violation in $B_s^0/\overline{B_s^0} \to J/\psi\phi$

- Expect ~6000 $B_s^0/\overline{B_s^0} \to J/\psi\phi$ events in 2 fb^{-1} (CDF)
- Expect small asymmetry: $Arg[M_{12}(B_s^0)] \sim -2^\circ$ in S.M.
- Assumes prior determination of ΔM_s
- CP asymmetry ($Arg[M_{12}(B_s^0)]$)
  $\Rightarrow$ input to determination of γ via $B^0 \to \pi^+\pi^-$, $B_s^0 \to K^+K^-$



Measurements of $\Delta\Gamma(B_s)$

Ignore CP violation in B_s mixing (negligible in S.M.)

$\Rightarrow B_{sH}, B_{sL}$ are (heavy, light) $CP = \pm 1$ eigenstates

[1]Decays $B_s \to D_s^- \ell^+ \nu$ are 50:50 mix of B_{sH}, B_{sL}

Fit to $(\exp^{-\Gamma_L t} + \exp^{-\Gamma_H t})$

Not very sensitive:

[2]Isolate $CP = +1$ B_{sL} decays with modes

$B^0_{sL} \to J/\psi\phi,\ B^0_{sL} \to D_s^{+(*)} D^{-(*)},\ J/\psi\eta ...$

$\Rightarrow \Delta\Gamma_s = 2[\overline{\Gamma} - \Gamma(B_{sL})],\quad \overline{\Gamma} = \Gamma(B^0_s)$ from $B_s \to D_s\pi$

[3]Directly evaluate the Γ_{12} term in the mixing matrix

$\Gamma_{12} \sim [\Sigma_f A(B^0_s \to f) A^*(\overline{B^0_s} \to f)]$

Final state $f = D_s^{-(*)} D_s^{+(*)}$ should dominate sum

Direct measurement of $|\Gamma_{12}|$ $\sqrt{}$ sample *pure* $CP = +1$

CERN-EP-2000-096 (lepbosc.web.cern.ch/LEPBOSC/)

R. Aleksan *et al.*, Phys. Lett. B316 (1993) 567

[4]New Physics Scenarios

New physics possible in M_{12}, not Γ_{12}

Large $\Delta\Phi \Rightarrow \Delta\Gamma$ "too small"

Any anomalous phase in M_{12} will show up in $B_s \to J/\psi\phi$ CP asymmetry

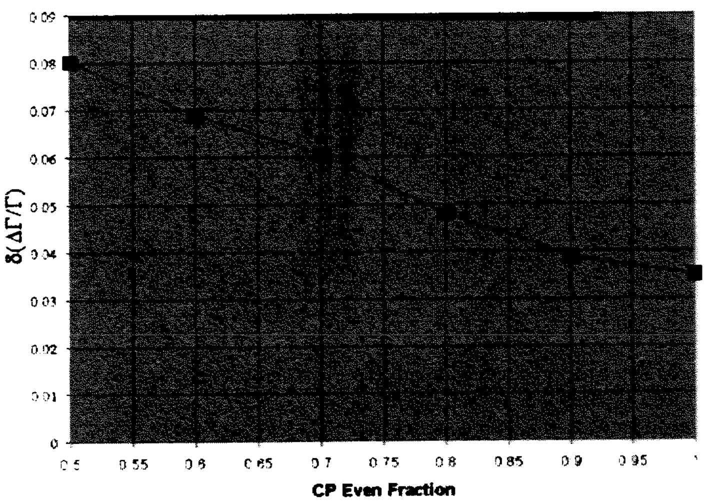
Measured $|\Gamma_{12}| >> \Delta\Gamma/2$

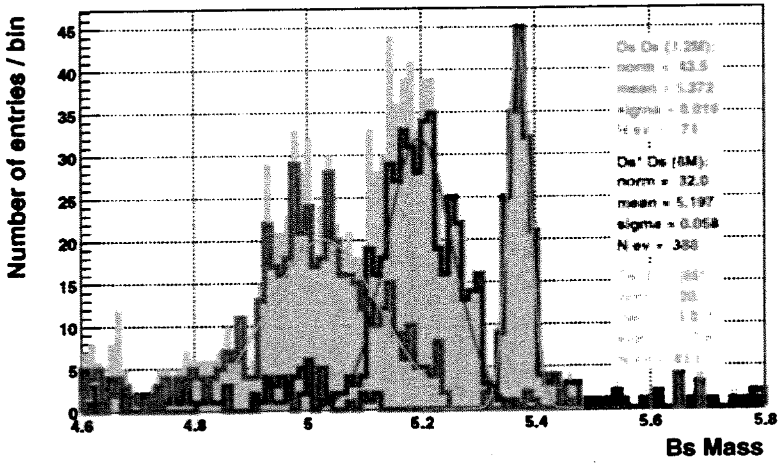
$\Delta M_s >>$ Standard model, $\Delta\Gamma$ "normal"

i.e. Phase of M_{12} OK, but not magnitude

CDF Run II $\Delta\Gamma(B_s)$ Projections

$\delta(\Delta\Gamma/\Gamma)$ as a function of CP Even fraction in $B_s \to J/\Psi\ \Phi$





Angular distribution $\Rightarrow$

$CP = +1\ J/\psi\phi$ fraction

Run I: 83±19% ($J/\psi\phi$)

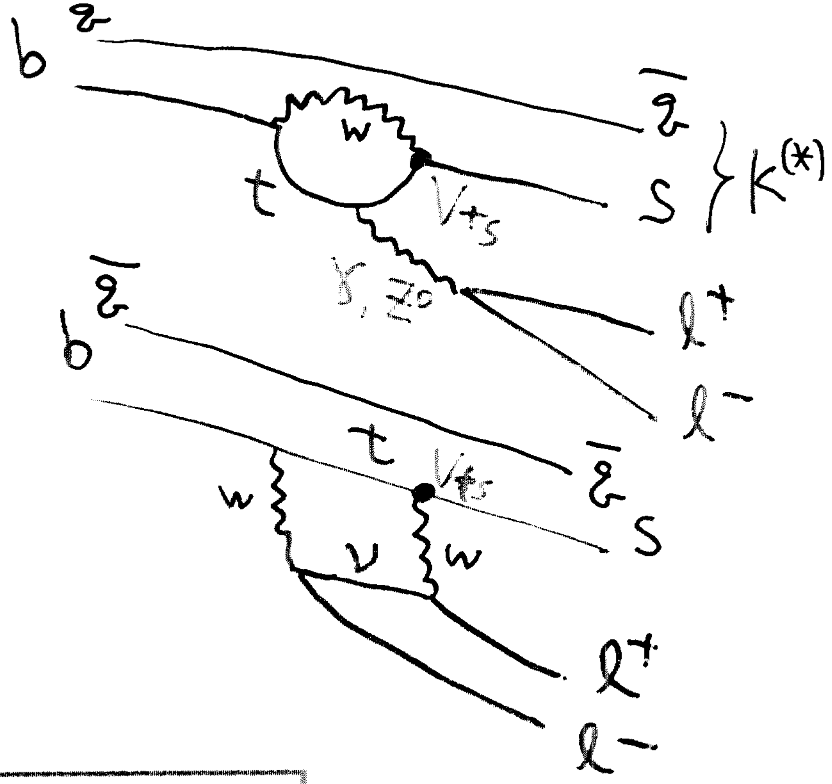
Run I: 87±13% ($J/\psi K^{*0}$)

$\Rightarrow$ Direct check of $|\Gamma_{12}(B_s)|$

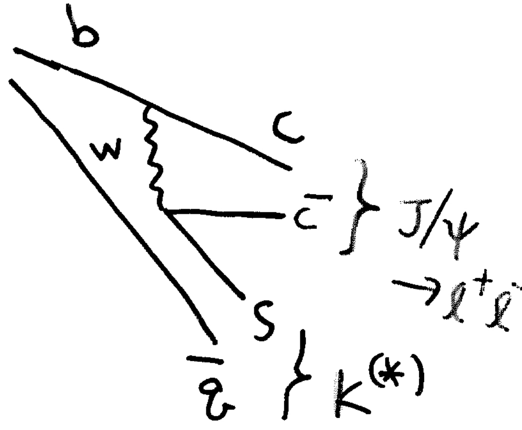
Rare Decays $B \to K^{(*)} l^+ l^-$

- $b \to s$ FCNC transition
- Z^0 penguin and box diagram in addition to EM penguin.
- $|V_{ts}|$
- SM predicts B.R. ~ 10^{-7} to 10^{-6}.
- New physics could enhance it.
- Has yet to be observed.

PRL 83, 3378 (1999)

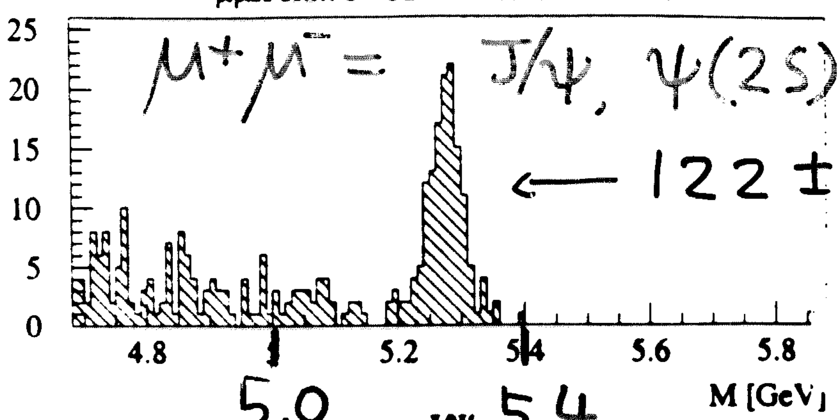


$l^+ l^-$ can be resonant, e.g. J/ψ, $\psi(2S)$.
→ Indistinguishable from $b \to c\bar{c}s$
Look at non-resonant mass region.



LOOK FOR EXCLUSIVE MODES

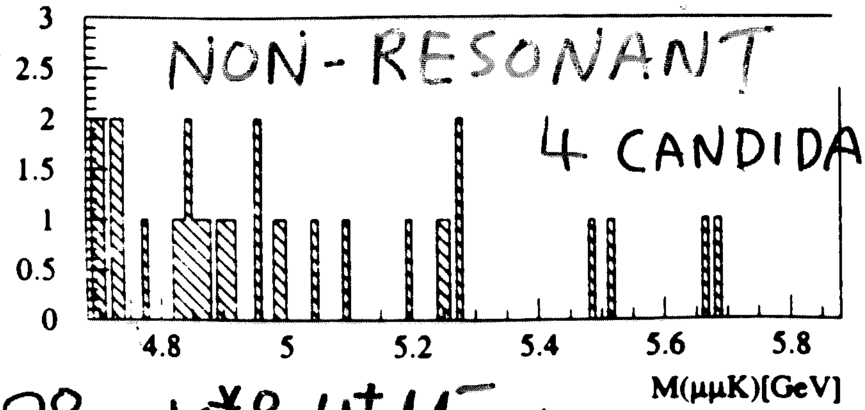
$B^+ \to K^+ \mu^+ \mu^-$ 110 pb^{-1}!



← 122 ± 11 SIGNAL FOR NORMALIZATION

1999

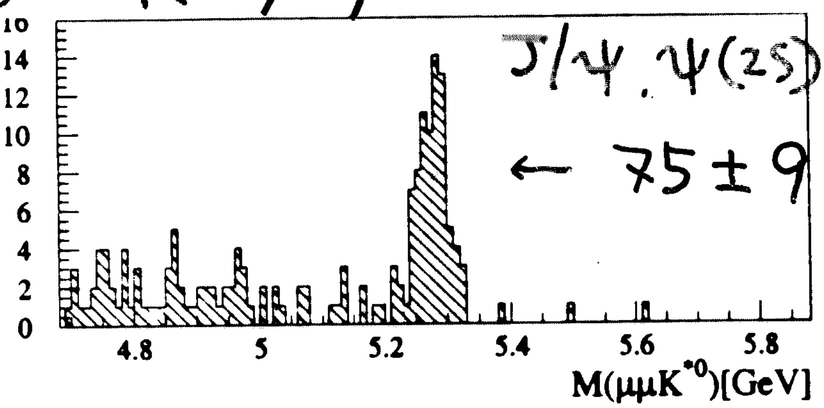
SM: $(5.9 \pm 2.1) \times 10^{-7}$



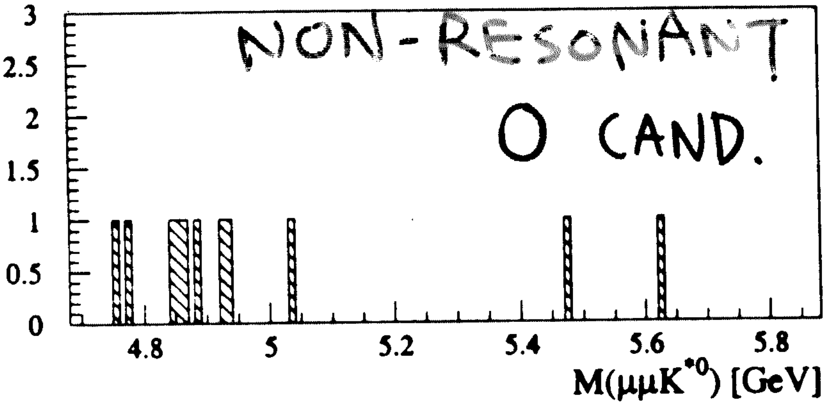
4 CANDIDATES

$BF < 5.2 \times 10^{-6}$ (90% CL)

$B^0 \to K^{*0} \mu^+ \mu^-$



← 75 ± 9 SIGNAL FOR NORMALIZATION

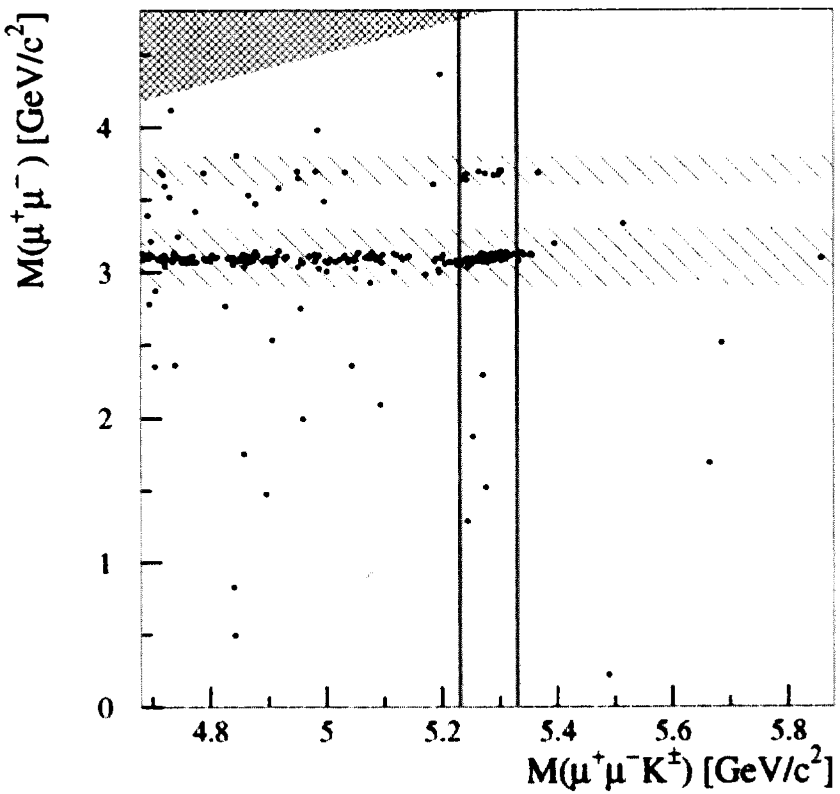


0 CAND.

$BF < 4.0 \times 10^{-6}$ (90% CL)

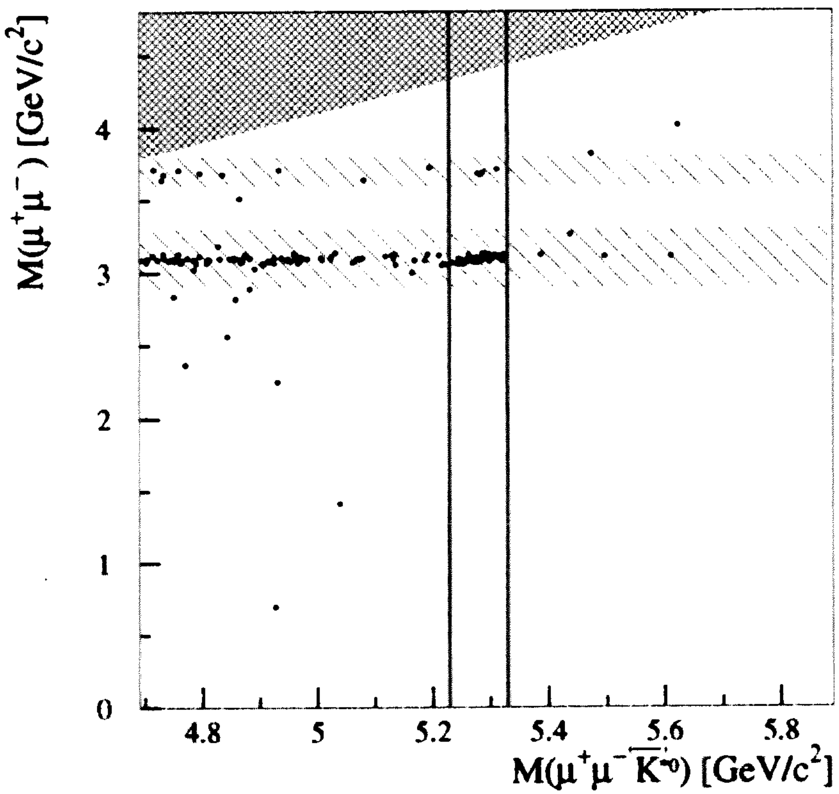
SM: $(2.0 \pm 0.7) \times 10^{-6}$

$B^+ \to K^+ \mu^+ \mu^-$



- 4 candidates
- BR < 5.2×10^{-6} @90% CL
- SM: $(5.9 \pm 2.1) \times 10^{-7}$

$B^0 \to K^{*0} \mu^+ \mu^-$

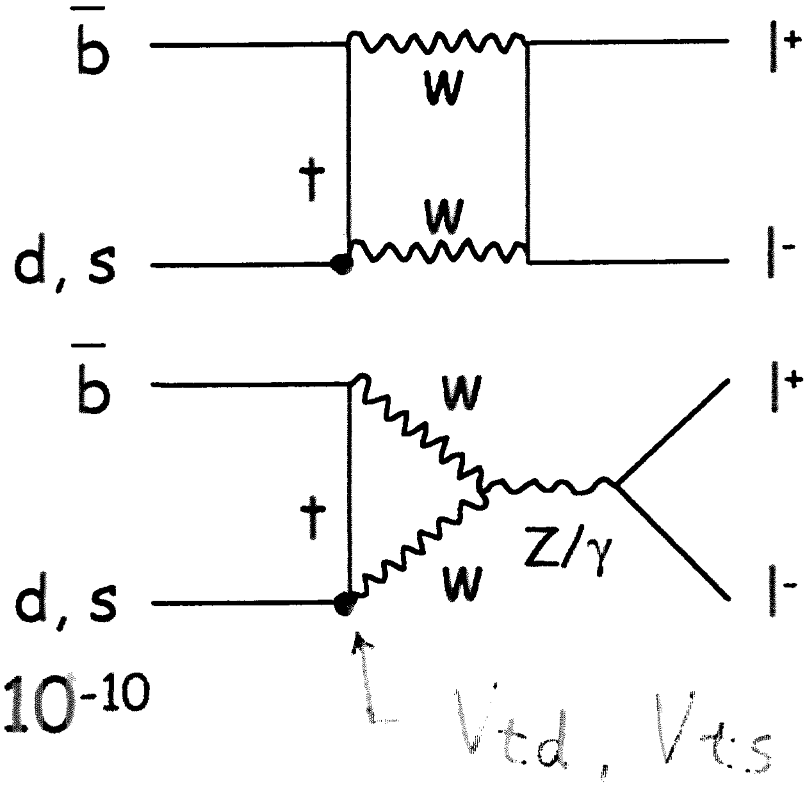


- 0 candidate
- BR < 4.0×10^{-6} @90% CL
- SM: $(2.0 \pm 0.7) \times 10^{-6}$

Expected signal ~ 0.5 event each.
Should see a handful of signal events in Run II.

Even Rarer Decays: $B^0, B^0_s \to l^+l^-$

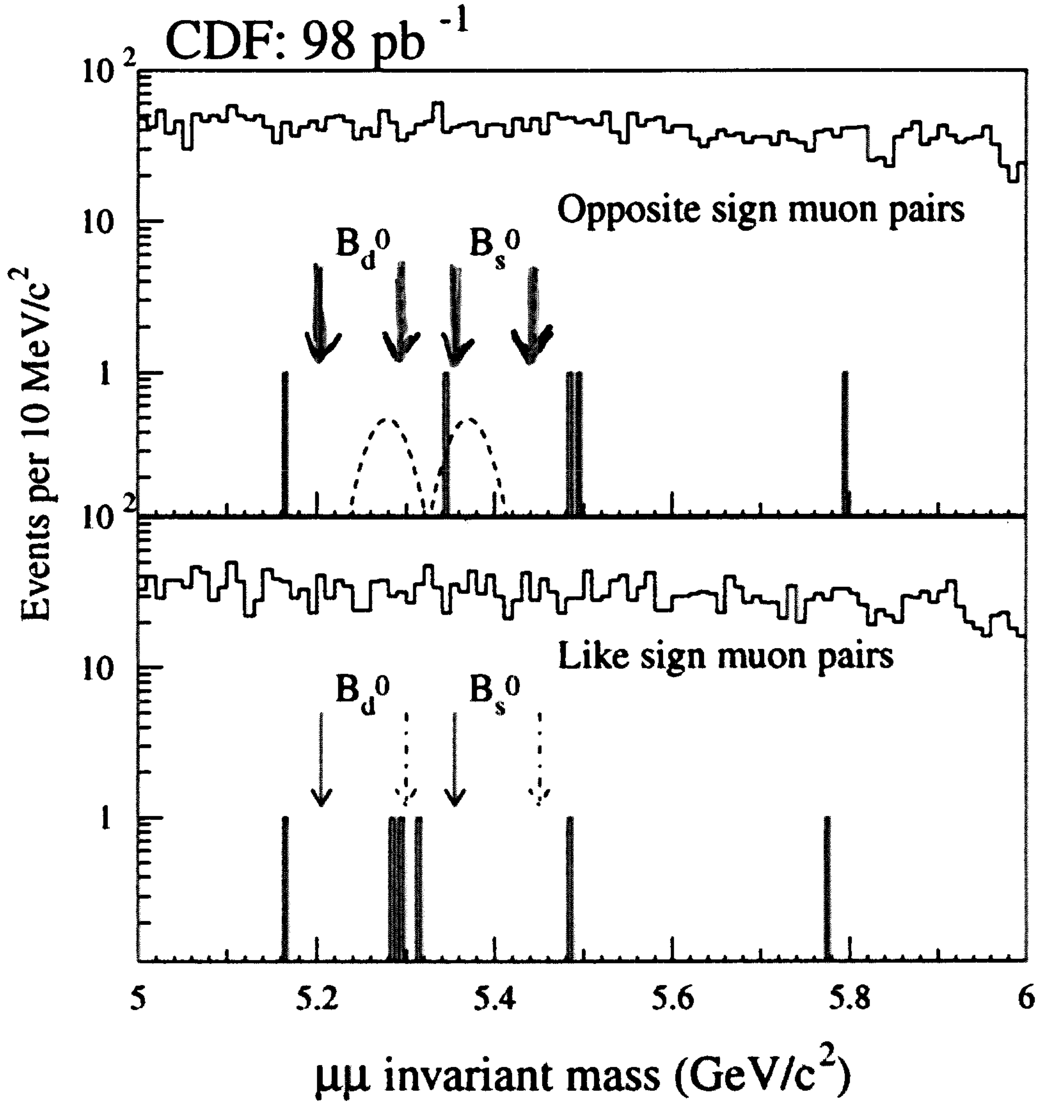
- V_{td} for B^0, V_{ts} for B^0_s
- Helicity suppressed.
- B.R. very small.



SM predictions:

- $B^0 \to \mu^+\mu^-$ $(1.5 \pm 1.4) \times 10^{-10}$
- $B^0_s \to \mu^+\mu^-$ $(3.5 \pm 1.0) \times 10^{-9}$
- $B^0 \to e^+e^-$ $(3.4 \pm 3.1) \times 10^{-15}$
- $B^0_s \to e^+e^-$ $(8.0 \pm 3.5) \times 10^{-14}$

Rare Decays $B^0, B^0_s \to \mu^+\mu^-$ PRD 57, 3811 (1998)



One candidate in the overlap region of B^0 and B^0_s mass windows.

B.R. < 8.6×10^{-7} for B^0

B.R. < 2.6×10^{-6} for B^0_s

@ 95% C.L.

Also looked for decays to $e^+\mu^-$, $e^-\mu^+$

B.R. < 4.5×10^{-6} for B^0

B.R. < 8.2×10^{-6} for B^0_s

PRL 81, 5742 (1998)

Still long way to go...

Summary

- Major upgrades complete for Run-II CDF.
  Has just started taking data.

  Vastly improved B physics potential :

  Integrated luminosity $\times 20$ by 2003– 2004.

  CDF : better vertexing, impact parameter track trigger.

- Two major measurements of the CKM triangle, perhaps well before 2 fb^{-1}.

  $\sin 2\beta$ to ± 0.043.

  Δm_s up to 40 ps^{-1} (expect $\sim$ 17 ps^{-1} in SM).

- Some optimism for third major measurement.
  Angle γ to $\sim 10°$ from $B^0 \rightarrow \pi^+\pi^-$ plus
  $B_s^0 \rightarrow K^+K^-$
  (modulo SU(3) breaking effects).

- B_s^0 measurements unique to CDF, and play important roles.

- Many other measurements expected.
  Some benefit from (or require) more than 2 fb^{-1}.
  Expect 15 fb^{-1} by the end of 2007.

- Then we quit. BTeV starts in 2008.