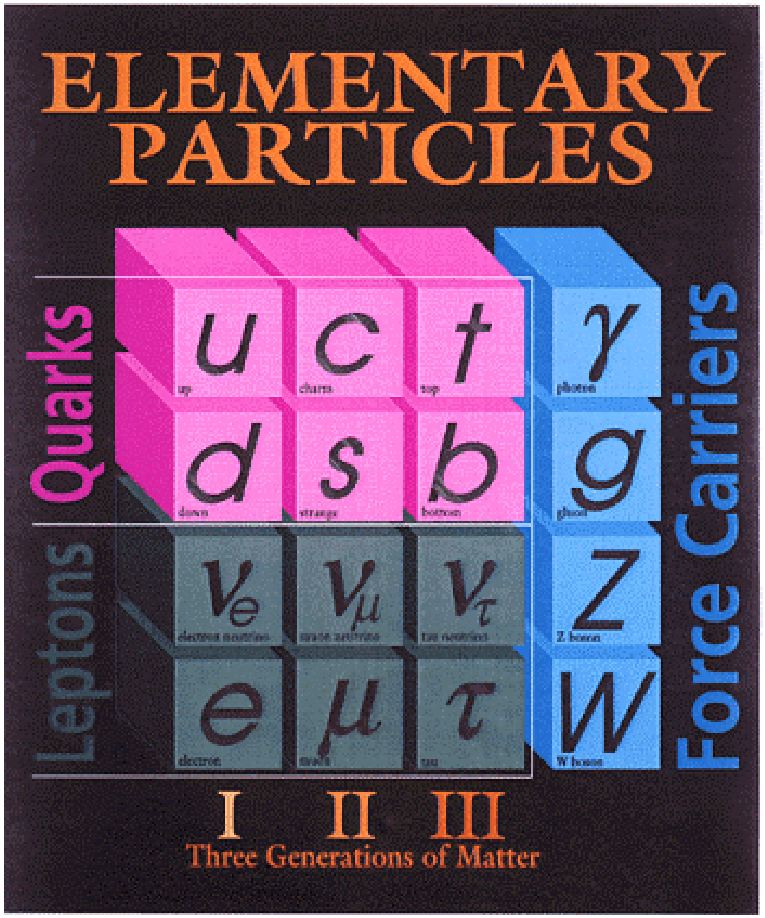
What is *B* physics ? Why?

Quarks and leptons come in three "generations".
Gauge bosons mediate their interactions.



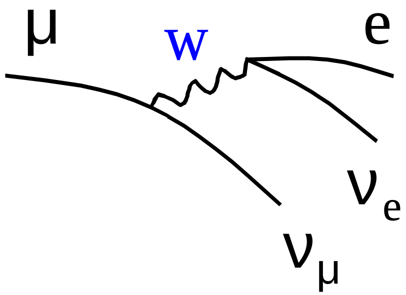
- *B* physics = studies of production and decay of the bottom (*b*) quark.
- Can learn about the weak interaction between the quarks, esp. the Cabibbo-**小林-益川** (CKM) matrix.
- Interesting phenomena expected, e.g. $\not{CP}$.

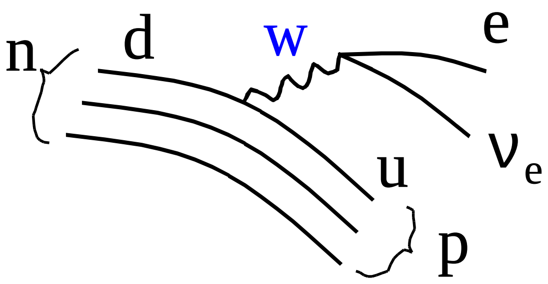
Weak Interaction

Coupling of quarks and $W^{\pm}$ and Z^0 bosons

Examples:

- muon decay
- neutron β decay





Heavy quarks *(s, c, b, t)* are unstable.

Transitions across the generations are possible:

→ Quark flavors are not conserved in the C.C. weak int's.

Mass and flavor eigenstates connected by the CKM matrix.

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

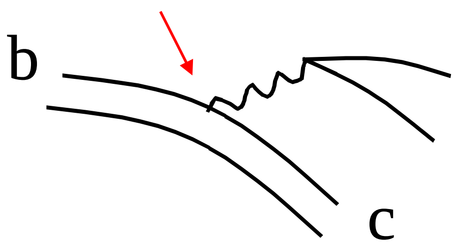
$$L \quad W_\mu \bar{U}_i \gamma^\mu V_{ij} D_j$$

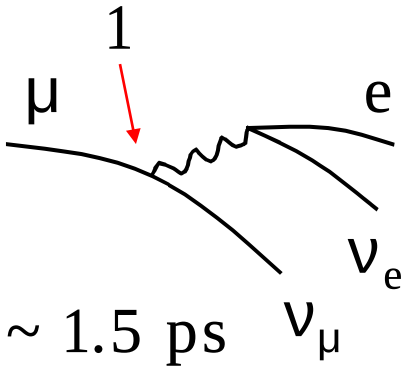
Need to determine the elements V_{ij} experimentally.

B decays: Can probe five elements of V_{CKM}

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

1: V_{cb}

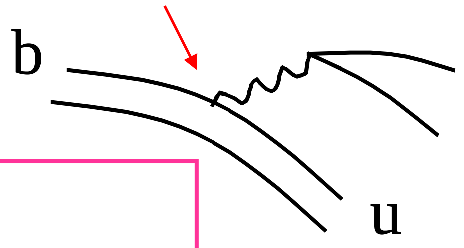




$\tau_b \sim 1.5$ ps

→ $|V_{cb}| \sim 0.04$

2: V_{ub}



$|V_{ub}|/|V_{cb}| \sim 0.1$

V_{tb}, V_{ts}, V_{td} : *t* quark couplings.
In principle from *t* decays,
but hard in practice.
Can use *B* decay processes where
the *t* quark is involved in the loop,
e.g. particle-antiparticle oscillations
of the neutral *B* mesons.

Introduction

Why *B* Physics at a Hadron Machine ?

Because the production rates are high.

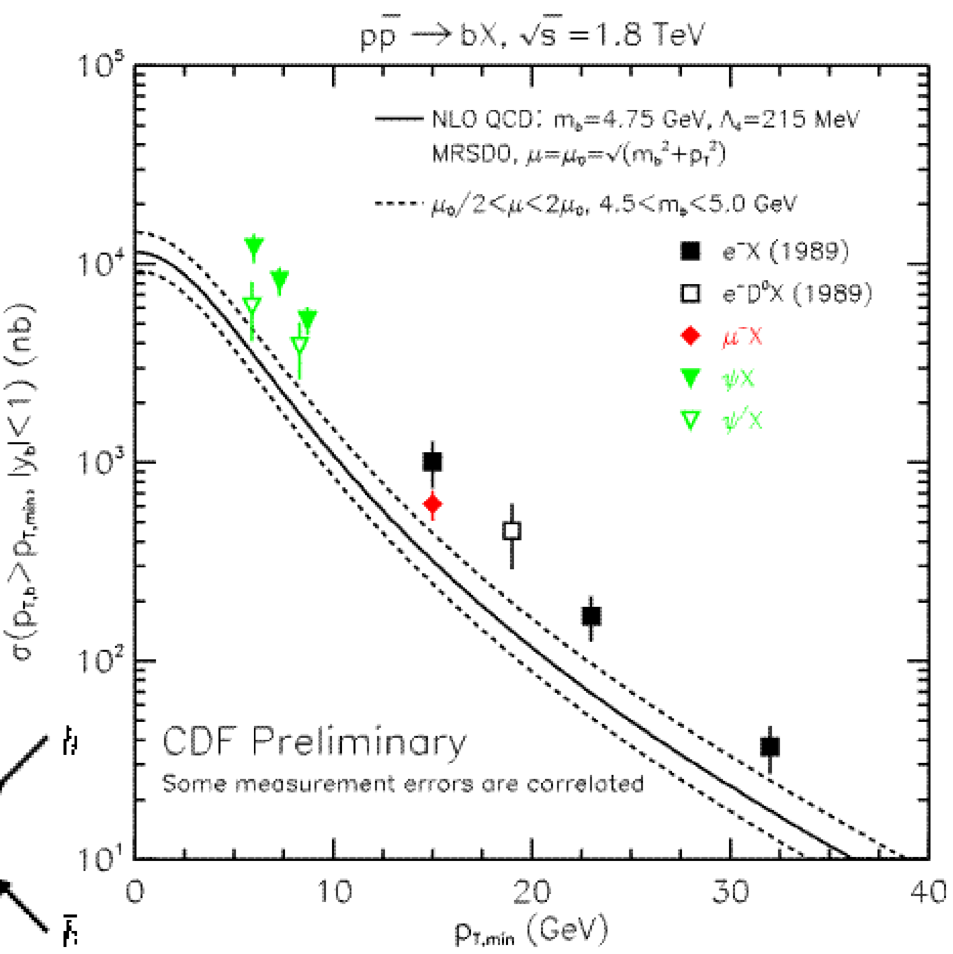
$e^+e^- \rightarrow b\bar{b}$ ~ 1 nb at $\Upsilon(4S)$

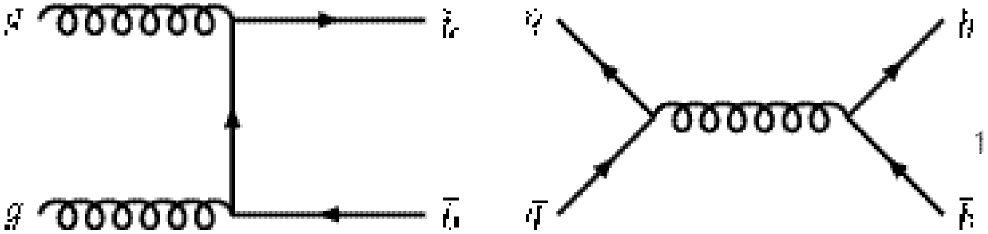
~ 6 nb at Z^0

$p\bar{p} \rightarrow b\bar{b}$ x via

strong interaction

σ ~ 10 μb at 1.8 TeV





- Not only B^0, B^+, but also B^0_s, baryons, B_c
- Lorentz boost, $\beta\gamma \sim 2 - 4$.

Vertex resolution not an issue.

Need to trigger on B decays, though.

So far relied on leptons:

- Single leptons (e, μ)
  - $B \rightarrow l^+ \nu X$

$p_T > 8$ GeV/c

$\langle p_T(B) \rangle \sim 20$ GeV/c

purity ~ 40%

- Di-leptons (μμ, eμ)
  - $B \rightarrow J/\psi\, X$, $J/\psi \rightarrow \mu^+\mu^-$
  - $b \rightarrow e\, \nu\, X$, $\bar{b} \rightarrow \mu\, \nu\, X'$

$p_T > 2$ GeV/c

$\langle p_T(B) \rangle \sim 10$ GeV/c

purity ~ 20% (J/ψ)

CDF Detector (Run I)

- Silicon micro-strip detector

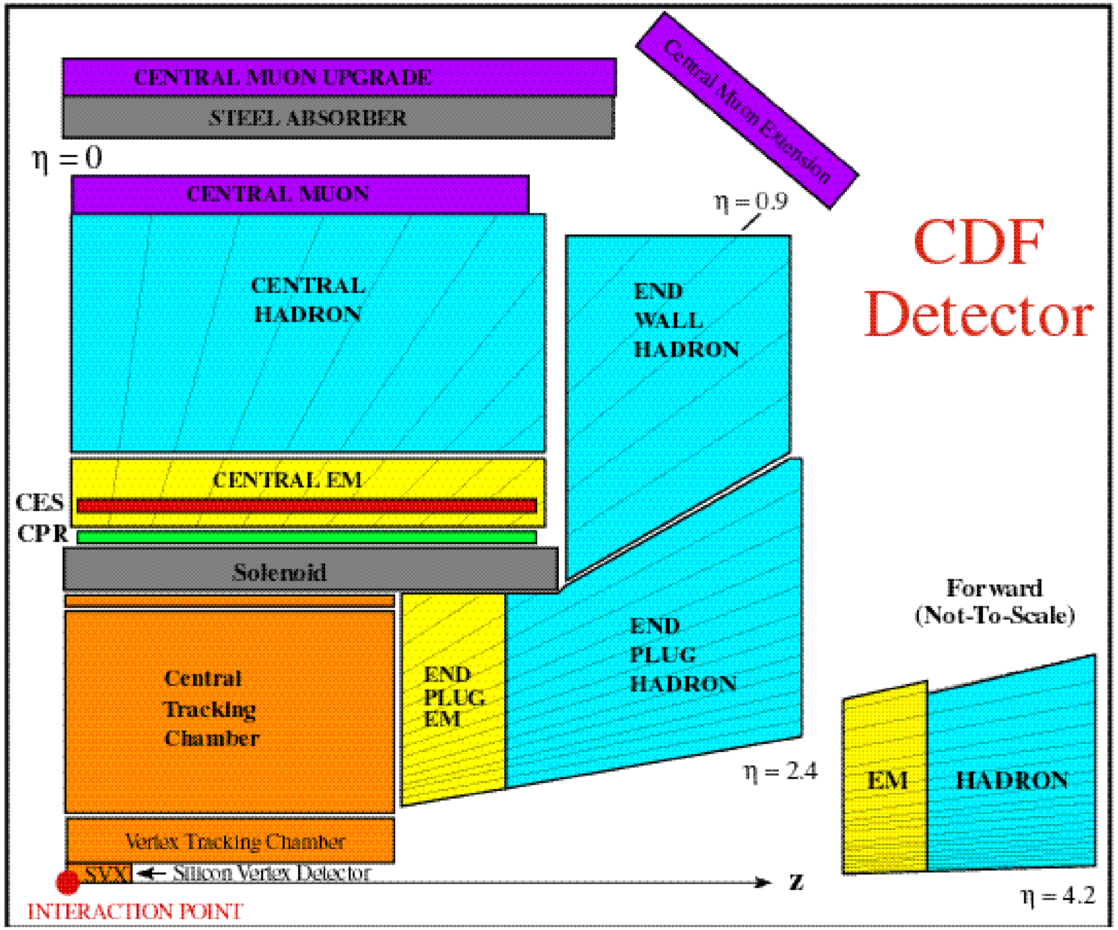
  Impact parameter

  $\sigma = (13+40/p_T)\ \mu m$

- Central tracking chamber

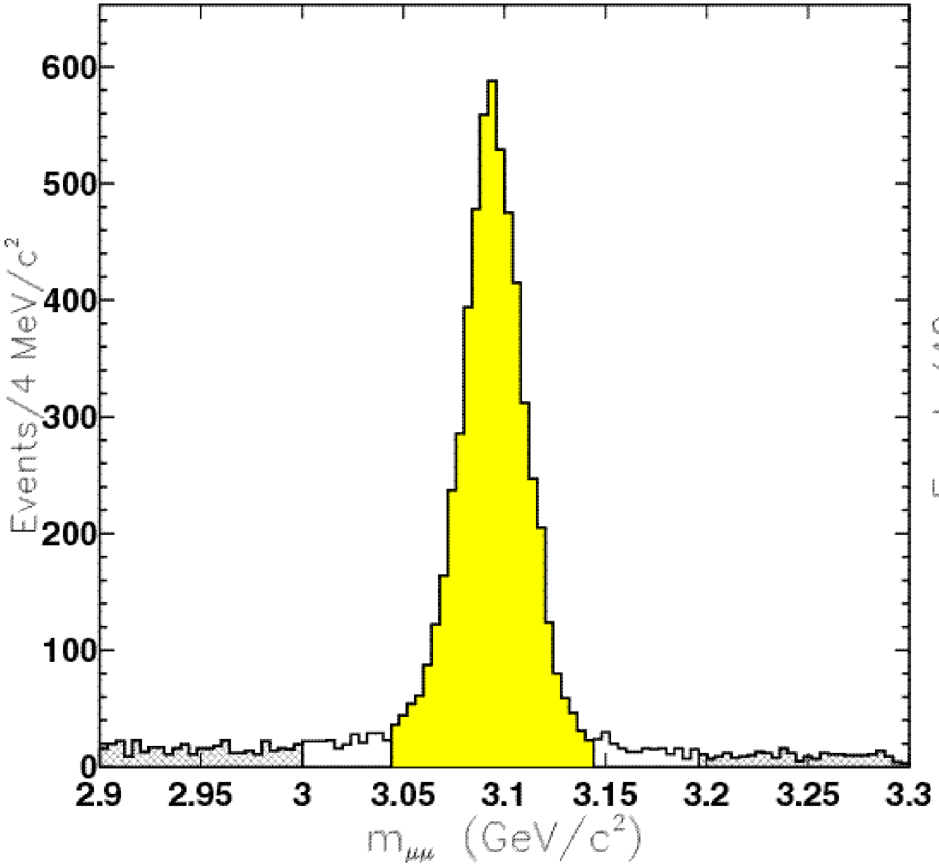
  $\sigma(p_T)/p_T \sim 0.001\ p_T$

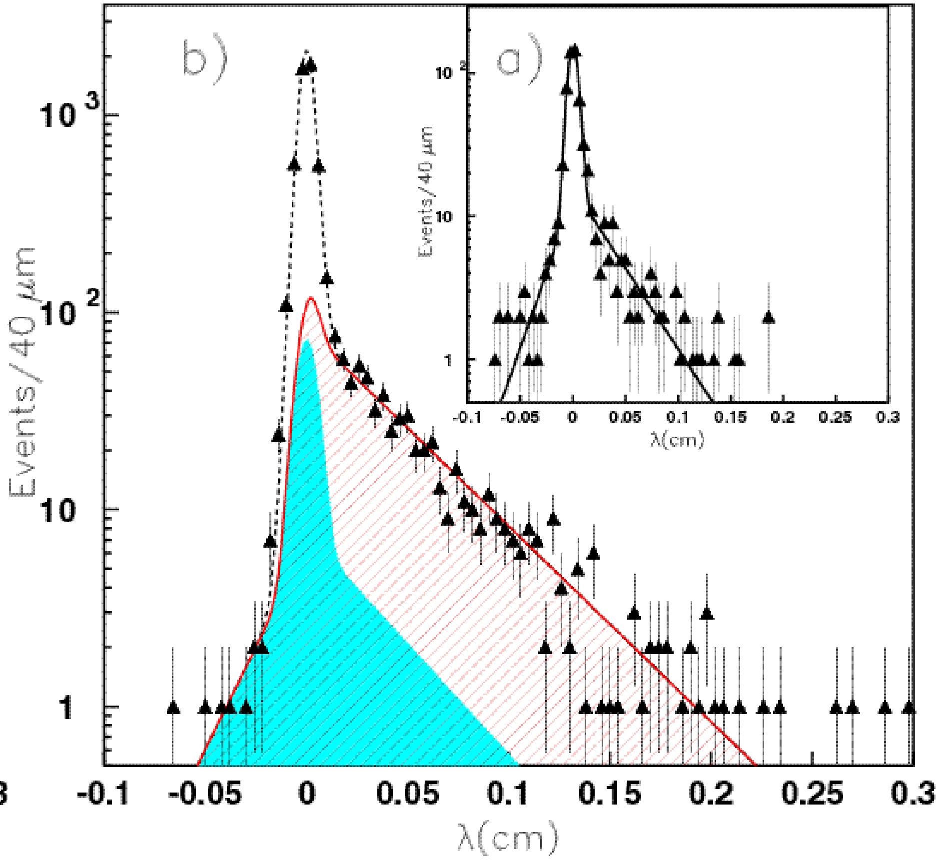
- Lepton detection



Collected ~ 110 pb^{-1} in 1992 - 96.

Signal $J/\psi \rightarrow \mu^+\mu^-$ Decay length dist.





- ~ 240 k $J/\psi \rightarrow \mu^+\mu^-$.
- Mass resolution ~ 16 MeV/c².
- ~ 20% from *B* decays, others direct / $\chi_c \rightarrow J/\psi\ \gamma$.

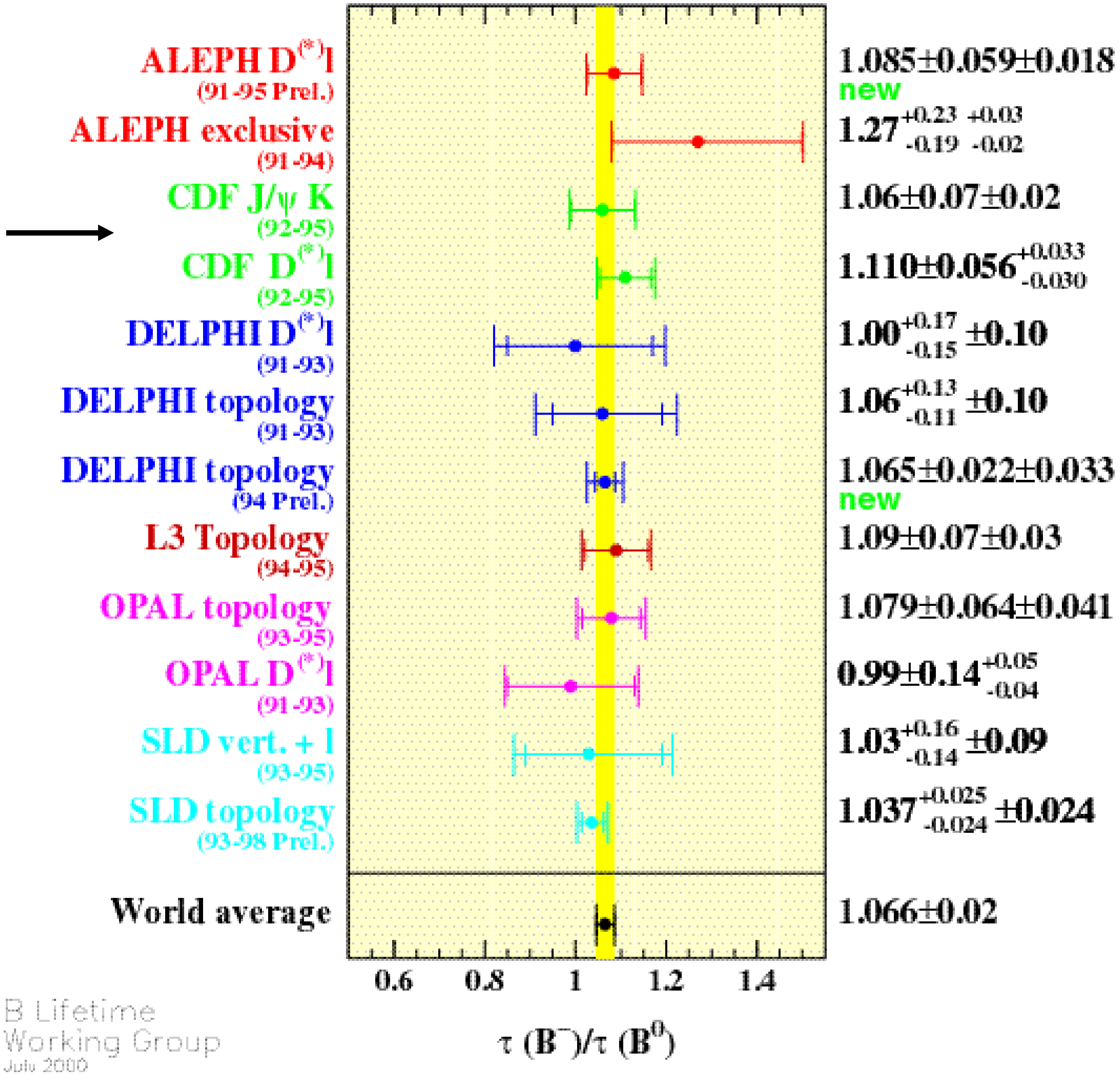
Run-I CDF *B* physics results

- Mass measurements of B^+, B^0, B^0_s and Λ_b.
- Lifetime measurements of B^+, B^0, B^0_s, Λ_b.
- B^0-$\overline{B}^0$ oscillations and flavor tagging.
- $\sin(2\beta)$ from $B^0/\overline{B}^0 \rightarrow J/\psi\, K^0_S$.
- B_c meson.
- Rare decay searches (FCNC decays)

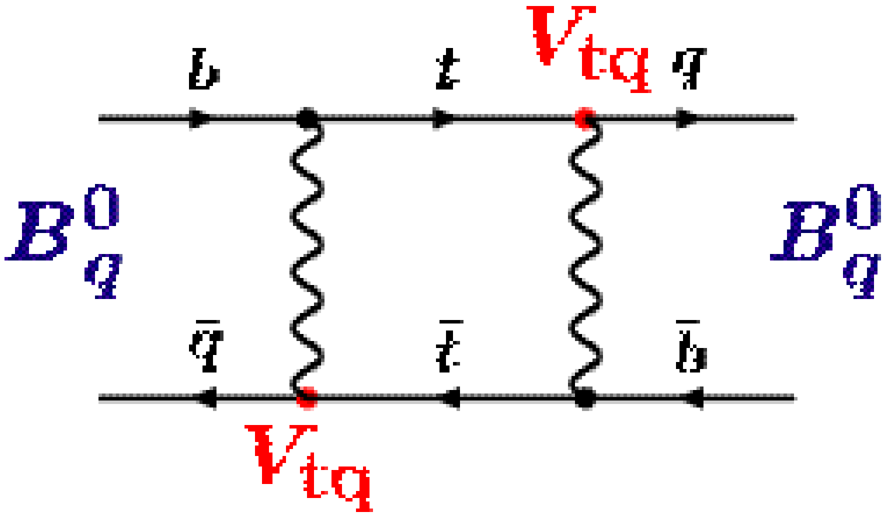
- Inclusive b and B production.
- $b\overline{b}$ production correlations.
- b-quark fragmentation fractions, f_u, f_d, f_s …
- Onium production (J/ψ, Υ)
  - Prompt and non-prompt (from B, χ_c) production
  - Production polarization

Lifetime Ratio $\tau(B^+) / \tau(B^0)$

CDF →



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



- 2nd order weak interaction.
- Decay probability:

$$P_{B^0\to B^0}(t) = \frac{1}{2\tau} e^{-t/\tau}(1+\cos\Delta mt)$$ Unmixed

$$P_{B^0\to \bar{B}^0}(t) = \frac{1}{2\tau} e^{-t/\tau}(1-\cos\Delta mt)$$ Mixed

- Oscillation frequency = $\Delta m = m_H - m_L$:

$$\Delta m_q \propto |V_{tq}|^2$$

- Eventually $\Delta m_s / \Delta m_d \rightarrow |V_{ts}| / |V_{td}|$

with less theory uncertainty

Ingredients for B^0-$\bar{B}^0$ Oscillation Measurements

- Proper decay time
- Decay flavor ($B^0 \rightarrow l^+ \nu X$ vs $\bar{B}^0 \rightarrow l^- \nu X$)
- Production flavor, b or $\bar{b}$? Flavor tagging

Flavor tagging is the hardest part (for CDF).

Conventional approach: *b* and $\bar{b}$ *are produced in pairs.*

identify the flavor of the other *B*

semileptonic decay leptons,

kaons, jet charge

infer the flavor of the signal *B*

Flavor Tagging (cont'd)

Exploit charge-flavor correlation with a nearby pion (Gronau, Nippe, Rosner).

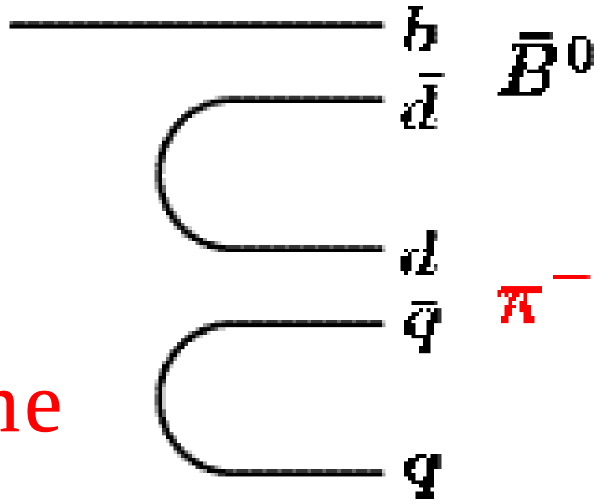
Example: $D^{*+} \rightarrow D^0 \pi^+$.

Since $B^* \not\rightarrow B\,\pi$, use pions from

$B^{**} \rightarrow B\,\pi$ (resonant) or

Fragmentation $b \rightarrow B\,\pi$

(non-resonant).



The correlations are the same if it is resonant or not.

Tagging Dilution

No tag is perfect. e.g. for lepton tag:

- Leptons from $b \rightarrow c \rightarrow l^{+} \nu s$
- B^{0}, B^{0}_{s} mixes.
- Fakes.

Probability of misidentification W

Dilution $D = 1 - 2W$.

Oscillation amplitude reduced by a factor D.

(unmixed - mixed) / total = $\cos(\Delta m\ t)$

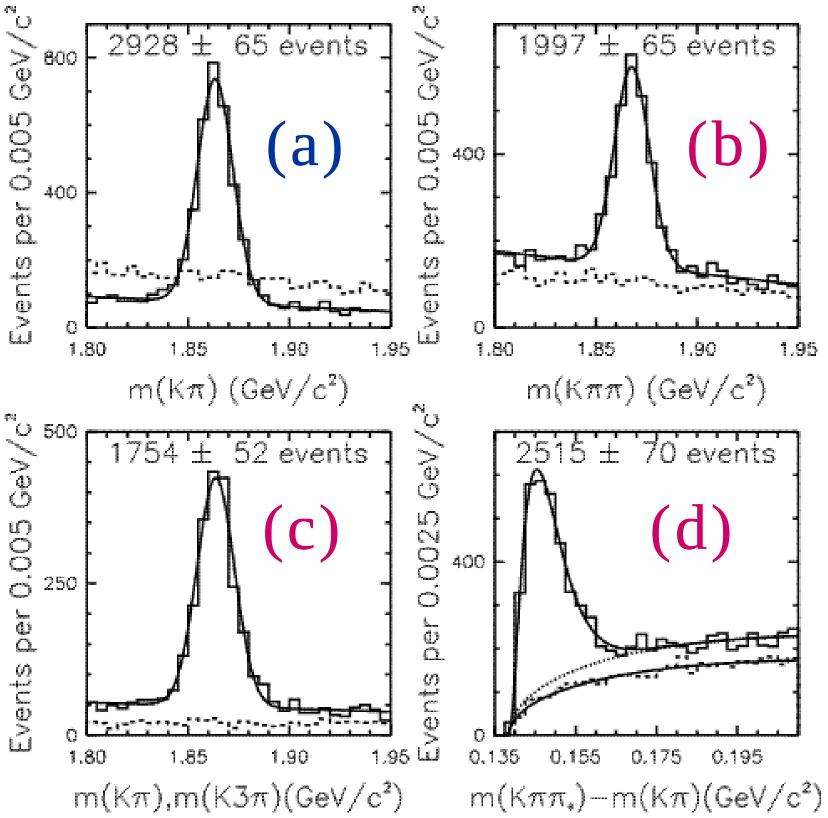
$\rightarrow D \cos(\Delta m\ t)$

Tag effectiveness = εD^{2},

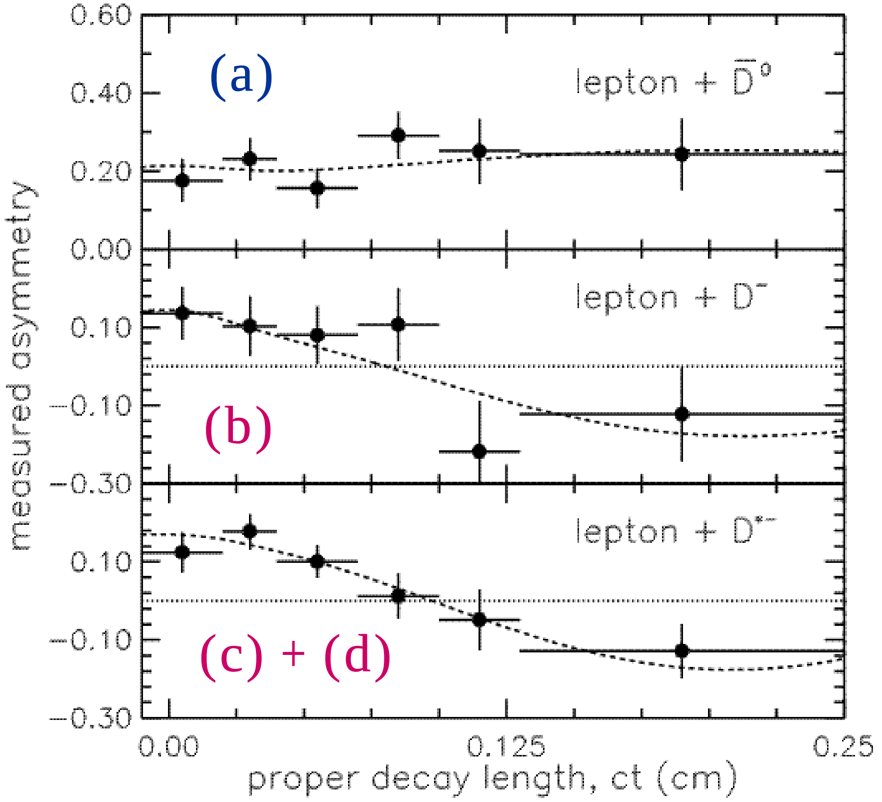
ε is the efficiency of the tag.

Mixing from l^- $D^{(*)}$ and same-side pion tag

Charm signal near l^-



Asymmetry = (RS-WS) / Total



(a) $D^0 \rightarrow K^- \pi^+$. (b) $D^+ \rightarrow K^- \pi^+ \pi^+$.

(c) $D^{*+} \rightarrow D^0 \pi^+$,

$D^0 \rightarrow K^- \pi^+, K^- \pi^+ \pi^+ \pi^-$.

(d) $D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow K^- \pi^+ \pi^0$.

$$\boxed{\Delta m = 0.471^{+0.078}_{-0.068} \pm 0.034\, ps^{-1}}$$

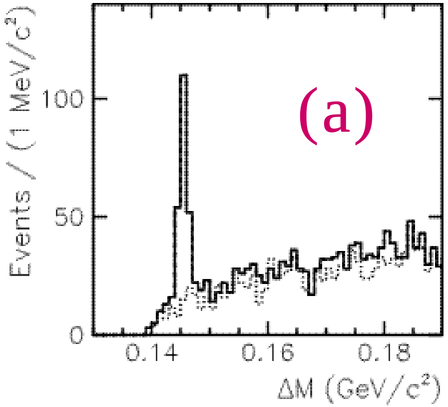
$D(B^+) = 0.27 \pm 0.03 \pm 0.02$

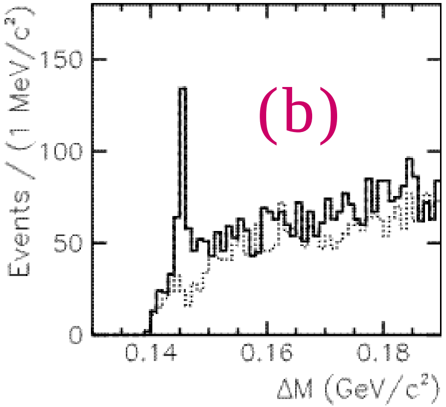
$D(B^0) = 0.18 \pm 0.03 \pm 0.02$

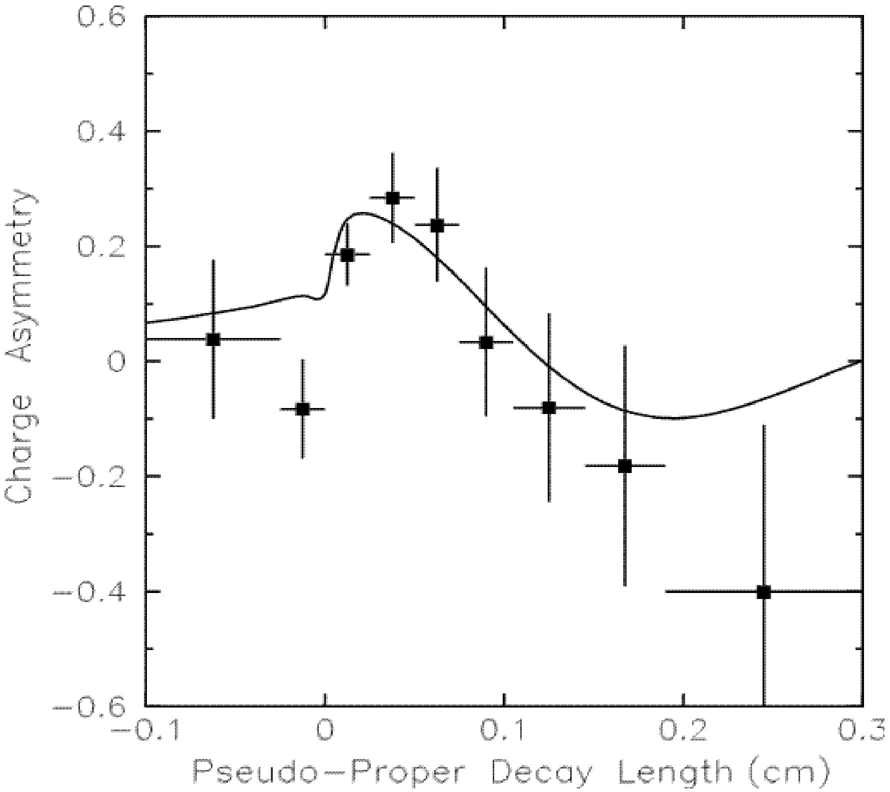
Mixing from l^- D^{*+} and lepton tag

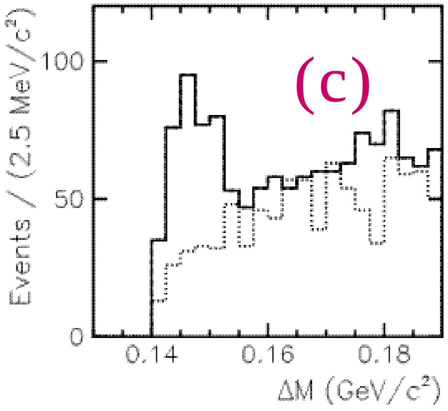
Charm signal near l^-

Asymmetry = (RS-WS) / Total









$m(D^0\pi^+) - m(D^0)$

$D^{*+} \rightarrow D^0 \pi^+$, followed by

(a) $D^0 \rightarrow K^- \pi^+$,

(b) $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$.

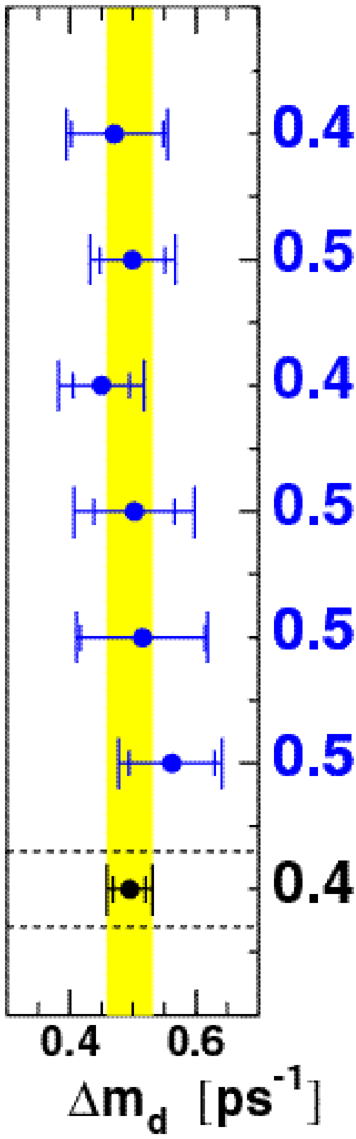
(c) $D^0 \rightarrow K^- \pi^+ \pi^0$.

$$\boxed{\Delta m = 0.516 \pm 0.099^{+0.029}_{-0.035}\, ps^{-1}}$$

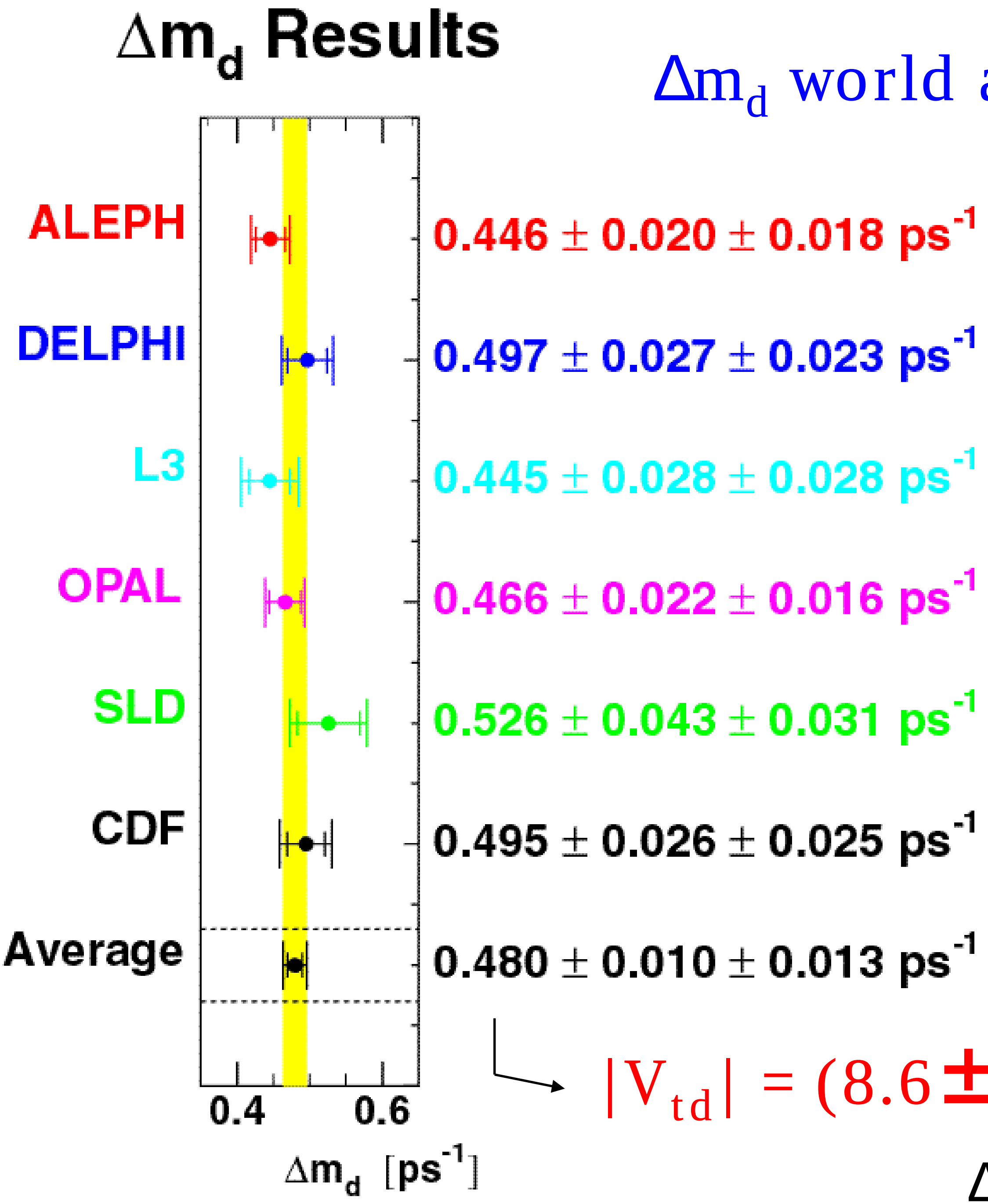
$W = 0.325 \pm 0.033 \pm 0.012$

$\rightarrow D = 0.350 \pm 0.070.$

CDF Δm_d Results



D*lep / SST	$0.471 ^{+0.078}_{-0.068} \pm 0.034$ ps^{-1}	PRL 80, 2057 (1998)
lep / Q^{jet},lep	$0.500 \pm 0.052 \pm 0.043$ ps^{-1}	PRD 60, 072003 (1999)
e / μ	$0.450 \pm 0.045 \pm 0.051$ ps^{-1}	Preliminary
μ / μ	$0.503 \pm 0.064 \pm 0.071$ ps^{-1}	PRD 60, 051101 (1999)
D*lep / lep	$0.516 \pm 0.099 ^{+0.029}_{-0.035}$ ps^{-1}	PRD 60, 112004 (1999)
$D^{(*)}$ / lep	$0.562 \pm 0.068 ^{+0.041}_{-0.050}$ ps^{-1}	Preliminary
Average	$0.495 \pm 0.026 \pm 0.025$ ps^{-1}	



Δm_d world ave. now very precise.

Need better theory to improve precision in $|V_{td}|$.

Or, measure Δm_s.

m_{top}:
Another CDF contribution to *B* physics

$$|V_{td}| = (8.6 \pm 0.2 \pm 0.2 \pm 1.7) \text{ X } 10^{-3}$$

Δm_d ↑ theory ↑

CP Violation in $B^0/\overline{B}^0 \rightarrow J/\psi\, K^0{}_S$

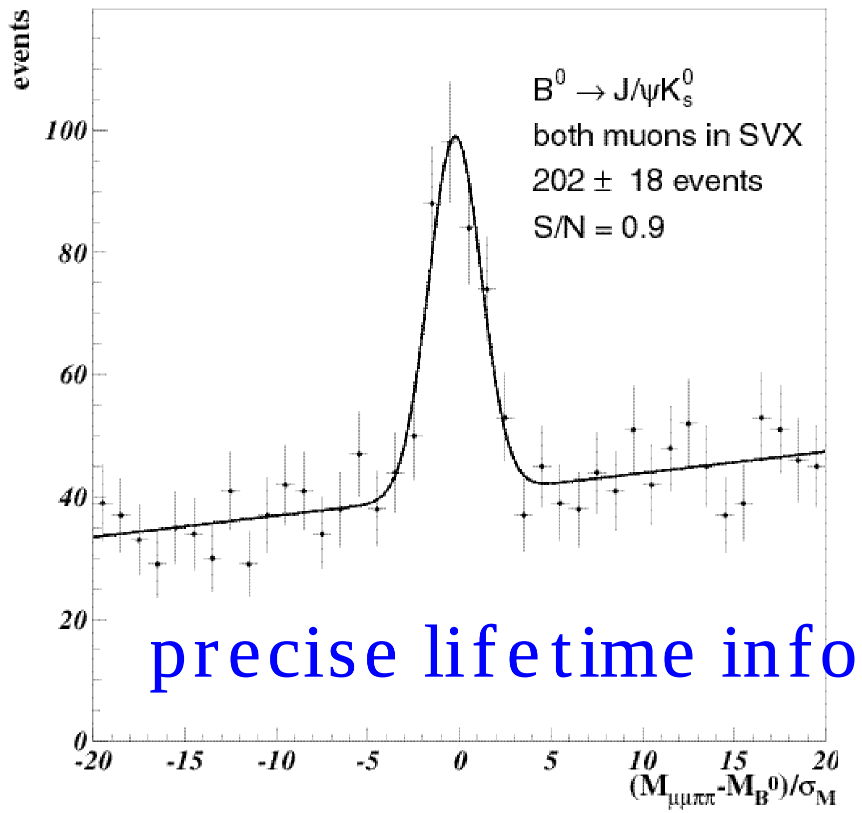
CP viol. ⇔ $\Gamma(\, i \rightarrow f\,) \neq \Gamma(\, \bar{i} \rightarrow \bar{f}\,)$

$$A(t) \equiv \frac{\Gamma(B^0 \rightarrow J/\psi K^0{}_S) - \Gamma(\overline{B}^0 \rightarrow J/\psi K^0{}_S)}{\Gamma(B^0 \rightarrow J/\psi K^0{}_S) + \Gamma(\overline{B}^0 \rightarrow J/\psi K^0{}_S)}$$

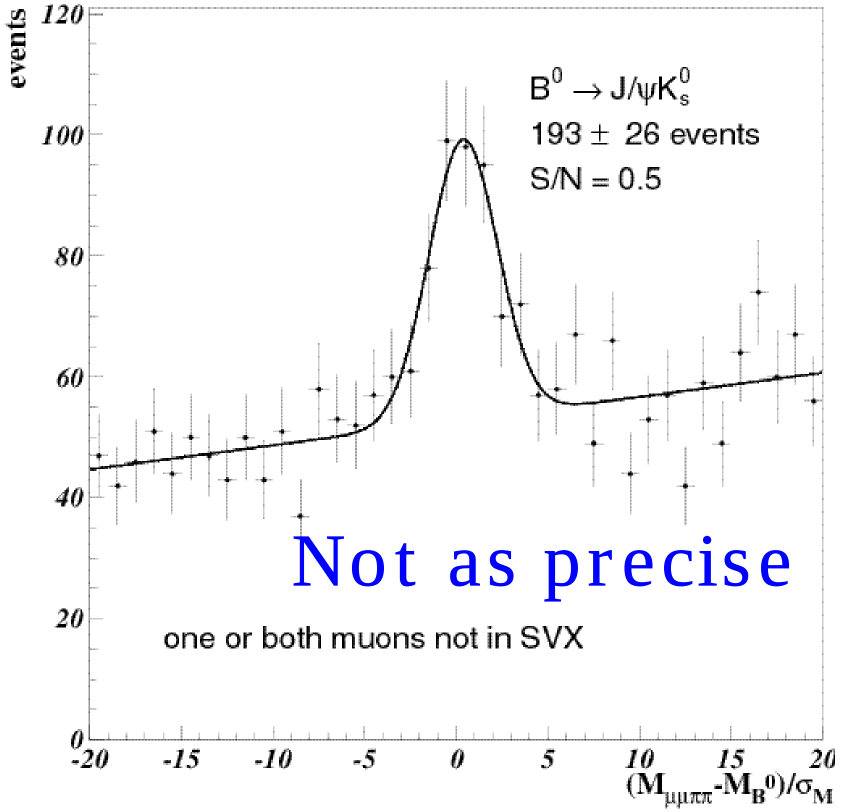
$$= -\sin(2\beta)\sin(\Delta m t)$$

- Now the amplitude is the quantity of interest.
- Final state = $J/\psi\, K^0{}_S \rightarrow \mu^+\mu^-\,\pi^+\pi^-$ "Trivial"
- Initial state, B^0 or $\overline{B}^0$? Flavor Tagging
- Decay time: Not necessary at CDF, but helps.

$B^0/\bar{B}^0 \rightarrow J/\psi\, K^0_S$ ~ 400 signal ev. / 110 pb^{-1}



precise lifetime info



Not as precise

$[\ \mathrm{Mass}(J/\psi\, K^0_S) - M(B^0)\ ]\ /\ \sigma_M$

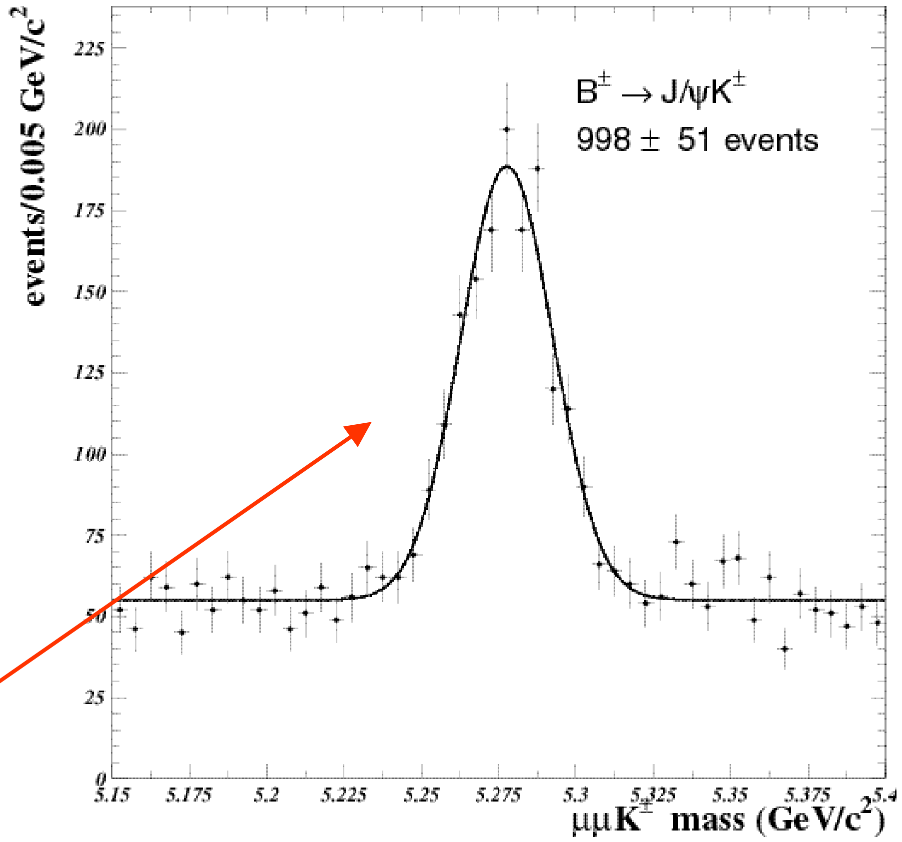
Apply 3 flavor tags, count B^0 vs $\bar{B}^0$.

Extract raw asymmetry = $D \sin(2\beta)$

Divide it by tag dilution → $\sin(2\beta)$

Apply 3 Flavor Tagging Methods

- Same-side "pions"
- Leptons
- Jet charge



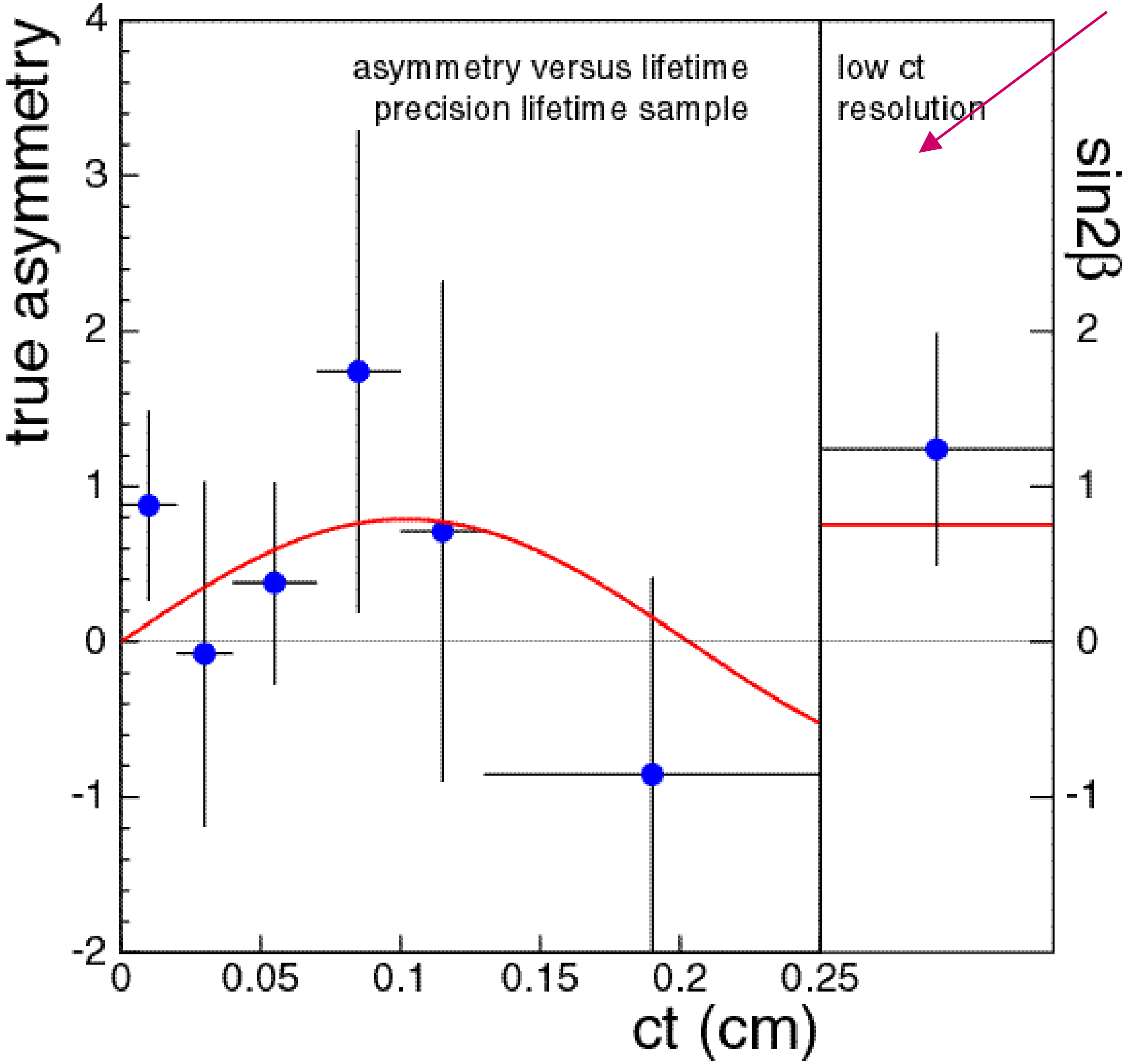
Measure tag dilution from ~ 1000 $B^+ \to J/\psi\, K^+$ decays.

(For SST, extrapolation of *lepton-D* meas.)

Tag	ε(%)	D(%)	εD^2(%)
SST	70	17±3	2.1±0.5
Lepton	6.5	63±15	2.2±1.0
Jet Q	45	22±7	2.2±1.3
Total			6.3±1.7

Asymmetry

Precise lifetime sample:
Asymmetry vs. time.



$\text{Asymmetry} = [\, N(\bar{B}^0) - N(B^0) \,] / \text{tot}$

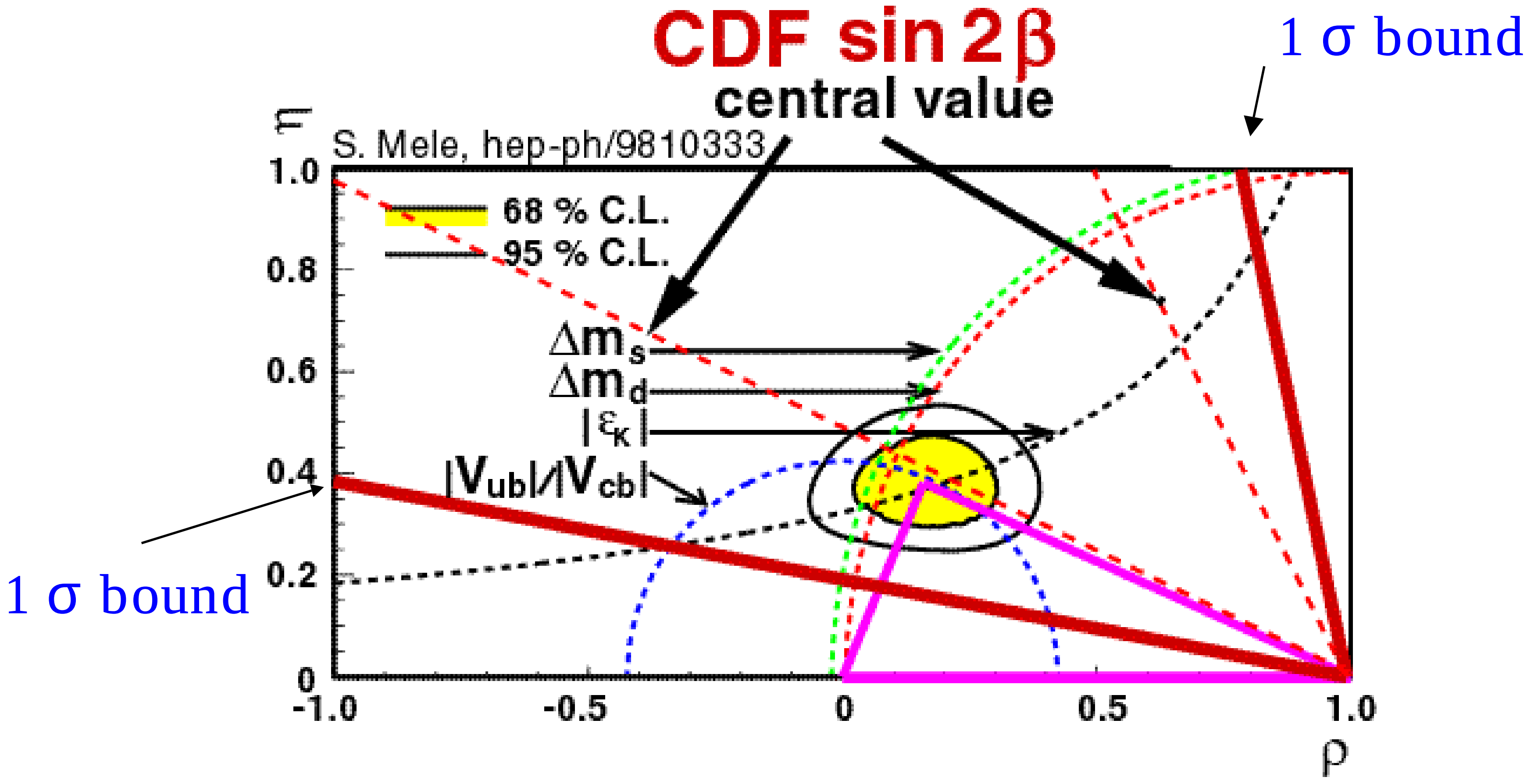
Less precise
lifetime sample:
Time-integrated
Asym x $(1+x_d^2) / x_d$
= sin (2β)

$$\sin(2\beta) = +0.79 \begin{smallmatrix} +\,0.41 \\ -\,0.44 \end{smallmatrix} \text{ (stat + syst).}$$

PRD 61, 072005 (2000)

Constraints on the unitarity triangle

$\sin(2\beta) \rightarrow \beta$: four solutions, β_1, β_2, $\beta_1+\pi$, $\beta_2+\pi$ ($\beta_2=\pi/2-\beta_1$).



CDF sin 2β
central value

1 σ bound

1 σ bound

Not much constraint now, but should be interesting in Run-II.

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

PRL 83, 3378 (1999)

- $b \to s$ FCNC transition
- Z^0 penguin and box diagram

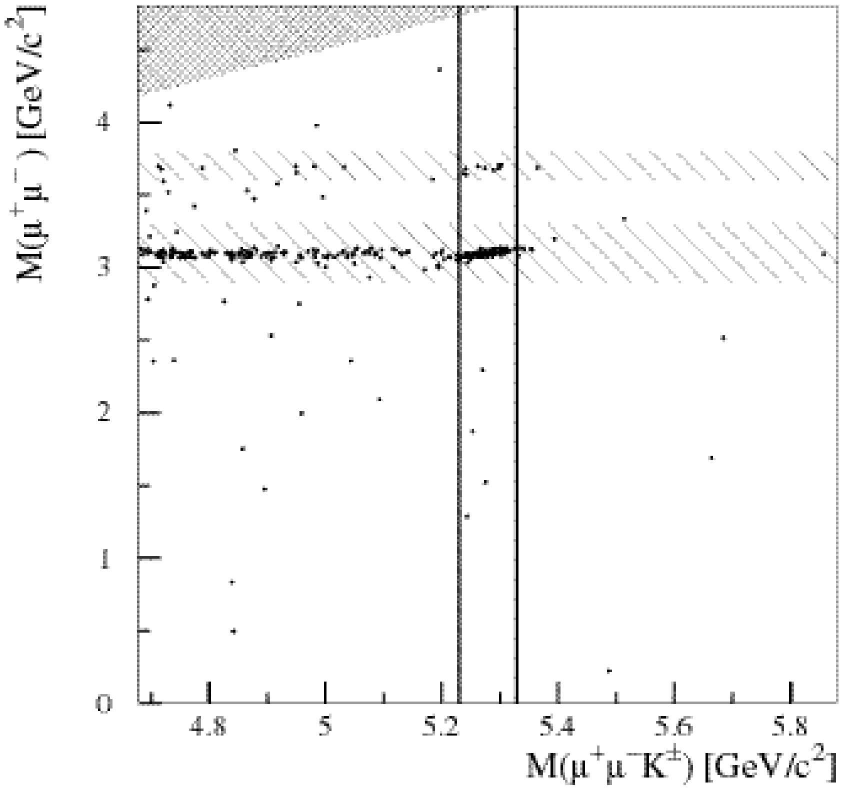
  in addition to EM penguin.
- $|V_{ts}|$
- SM predicts B.R. ~ 10^{-7} to 10^{-6}.
- New physics could enhance it.
- Has yet to be observed.

$l^+ l^-$ can be resonant, e.g. J/ψ, $\psi(2S)$.

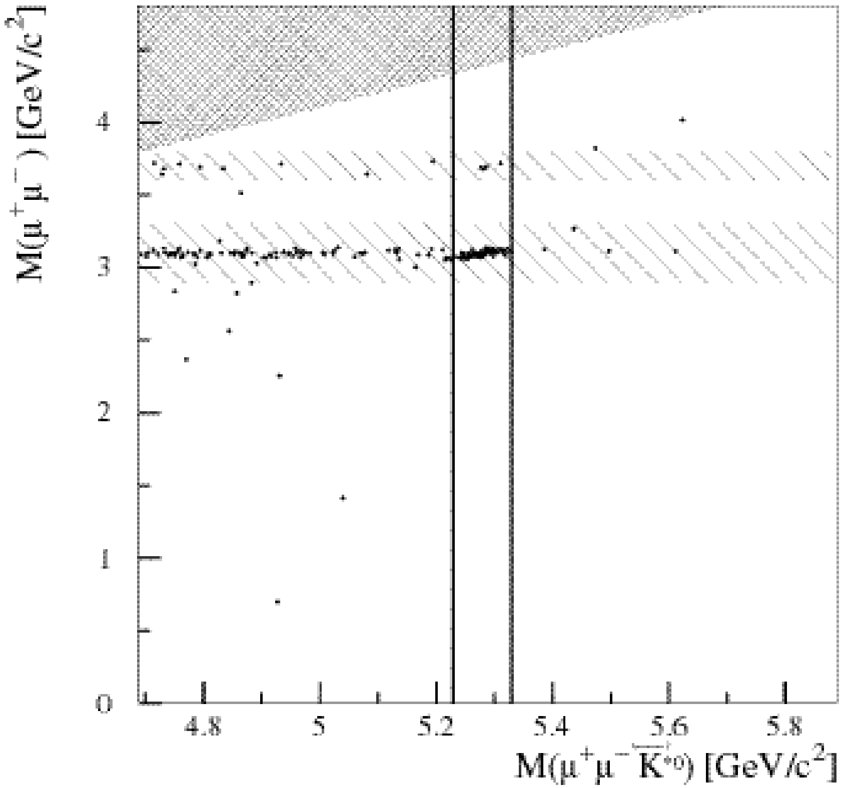
→ Indistinguishable from $b \to c\bar{c}s$

Look at non-resonant mass region.

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



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



- 4 candidates
- BR < 5.2 X 10^{-6} @90% CL
- SM: (5.9 ± 2.1) X 10^{-7}

- 0 candidate
- BR < 4.0 X 10^{-6} @90% CL
- SM: (2.0 ± 0.7) X 10^{-6}

Expected signal ~ 0.5 event each.

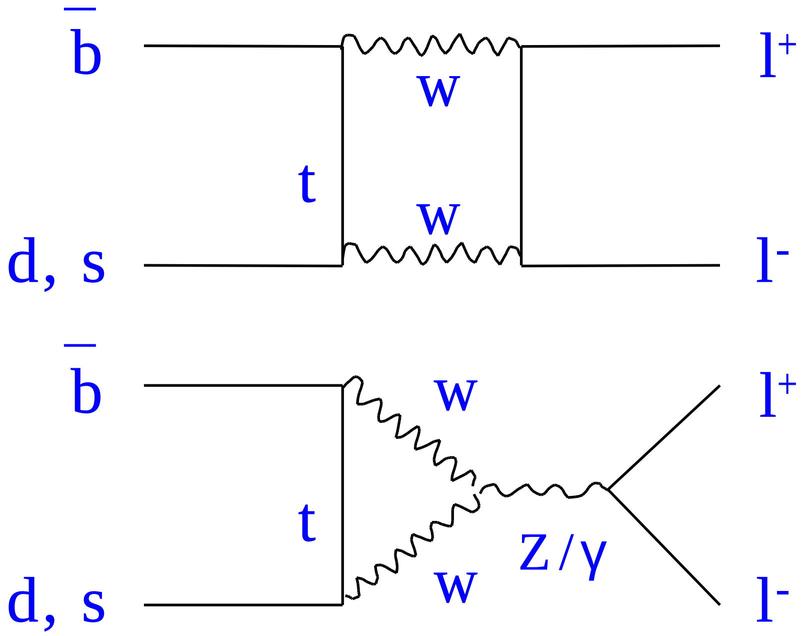
Should see a handful of signal events in Run II.

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

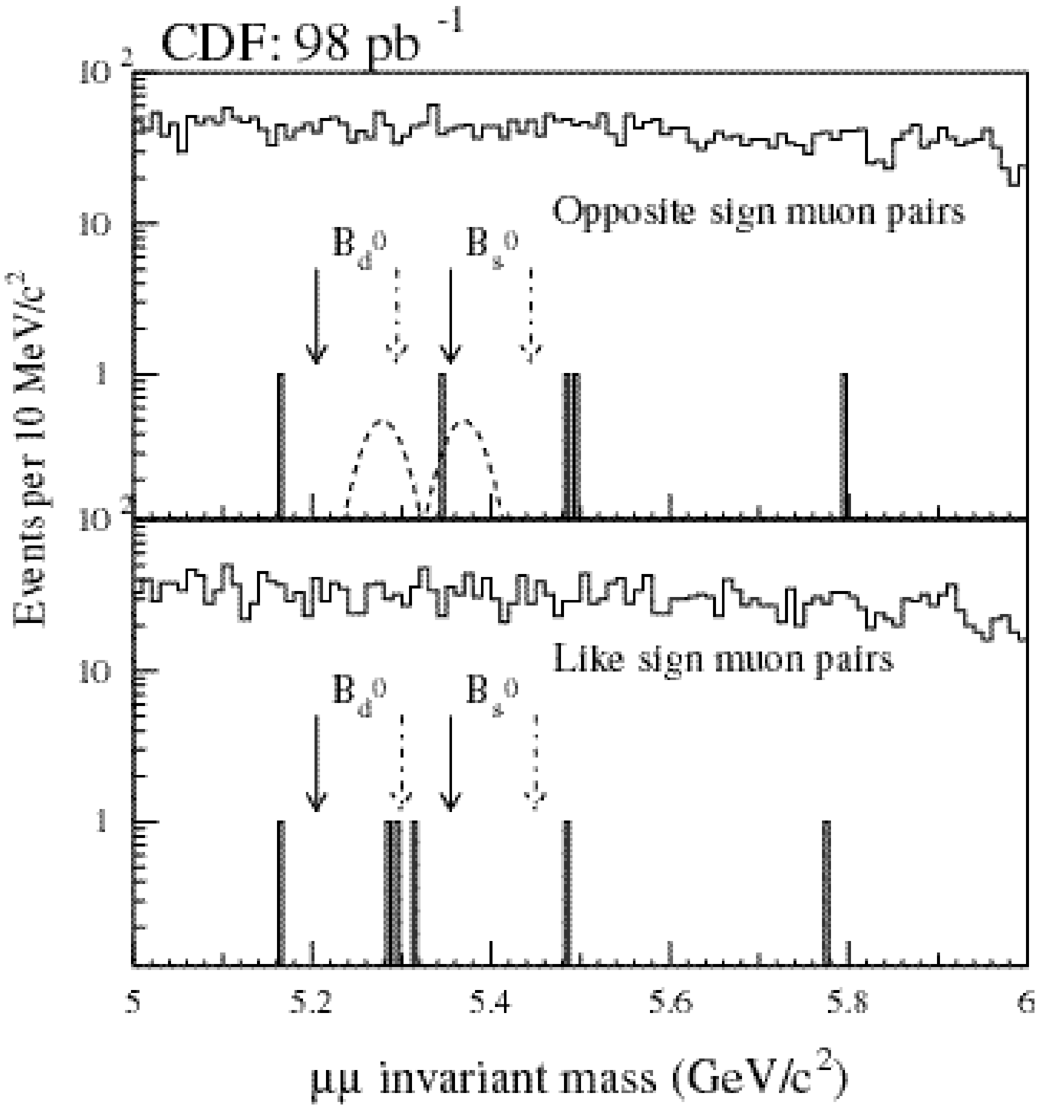
- V_{td} for B^0, V_{ts} for B^0_s
- Helicity suppressed.
- B.R. very small.

SM predictions:

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



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



Still long way to go...

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.

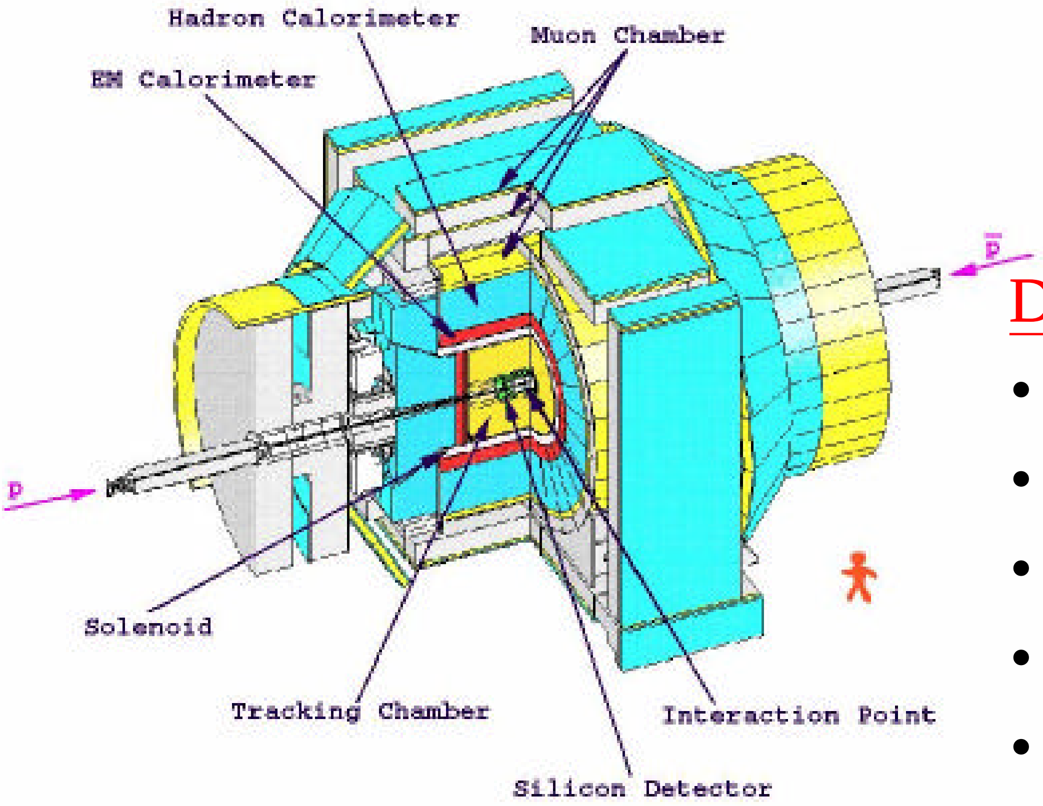
Also looked for decays to $e^+\mu^-$, $e^-\mu^+$

B.R. < 4.5×10^{-6} for B^0

B.R. < 8.2×10^{-6} for B^0_s

PRL 81, 5742 (1998)

B Physics and CDF Run I I



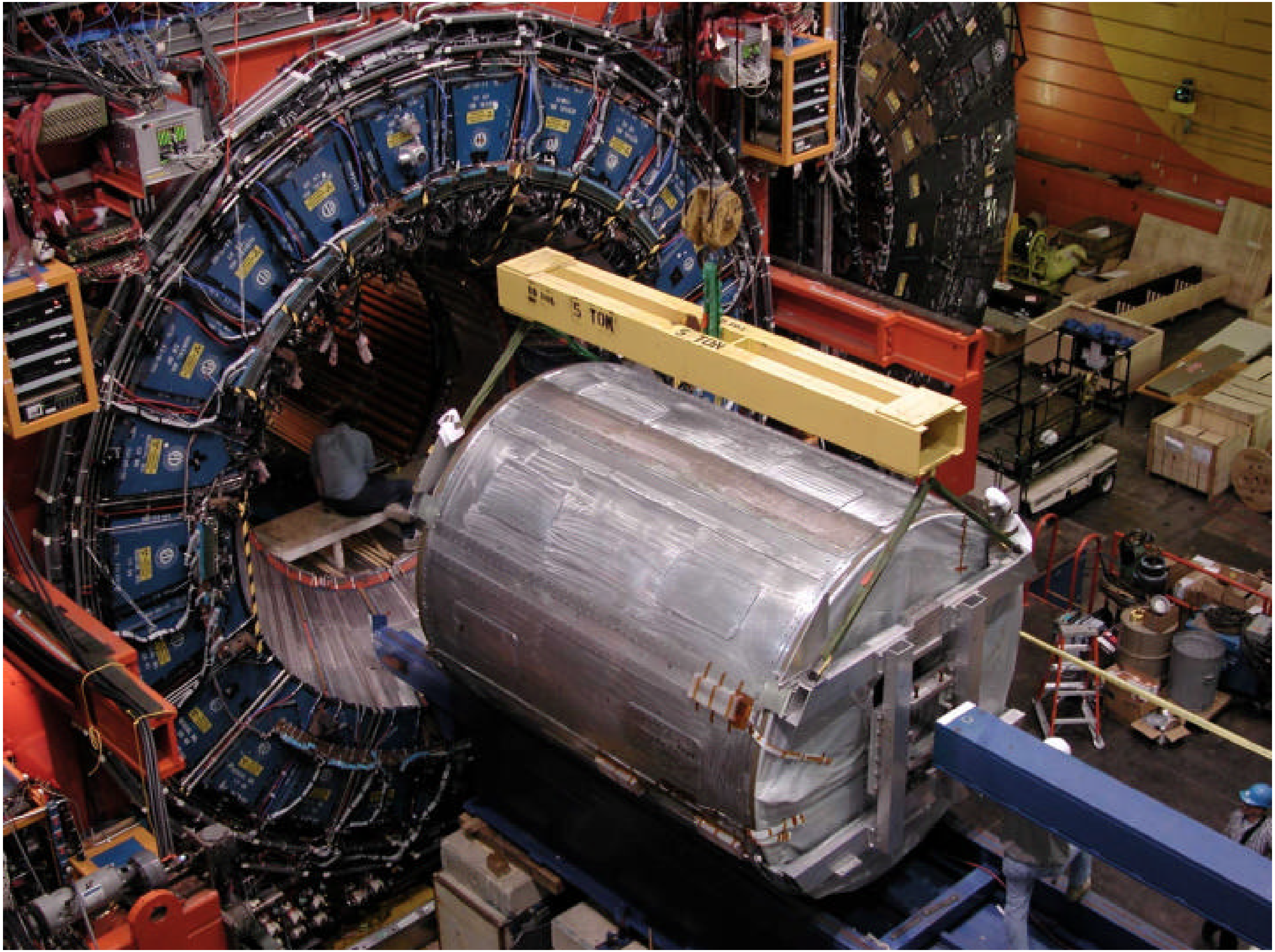
Accelerator

- $\sqrt{s}$ = 2000 GeV
- 6 bunches → 36, 108.
- New 120 GeV Main Injector
- Luminosity = 10^{32} $cm^{-2}s^{-1}$
- $\int L\,dt$ = 2 fb^{-1} (2 years)

Detector

- Tracking system
- FE electronics
- Trigger/DAQ
- Plug calorimeter
- Extended muon coverage

Retained good momentum resolution & lepton ID.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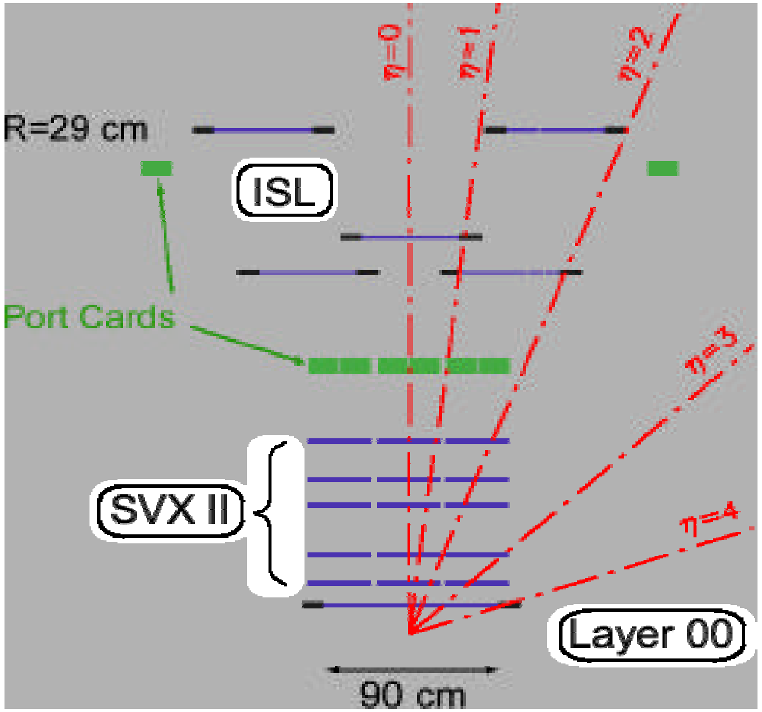
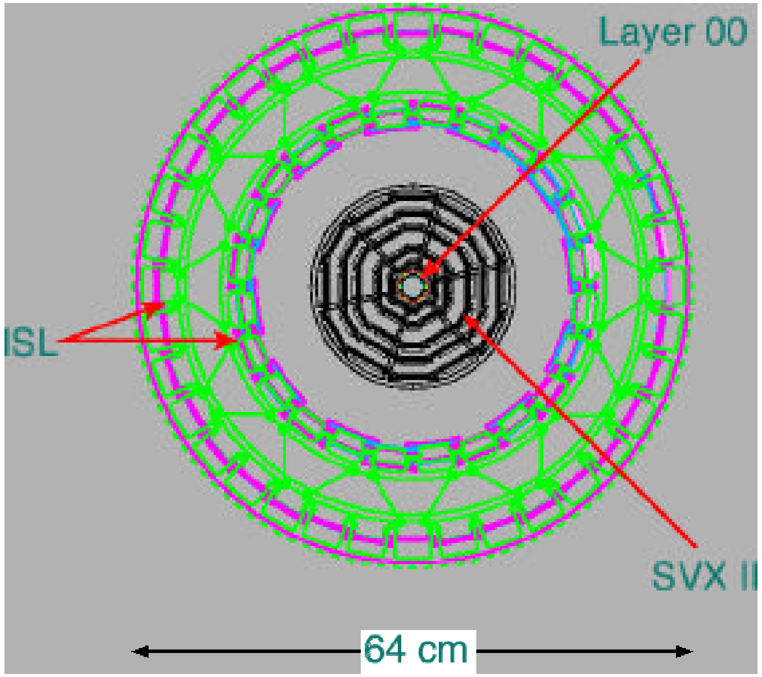




CDF-II silicon detectors

SVX II

- Radii 2.5 cm to 11 cm
- 5 layers
- Double-sided, 90° and 1.2° stereo
- Main vertex detector

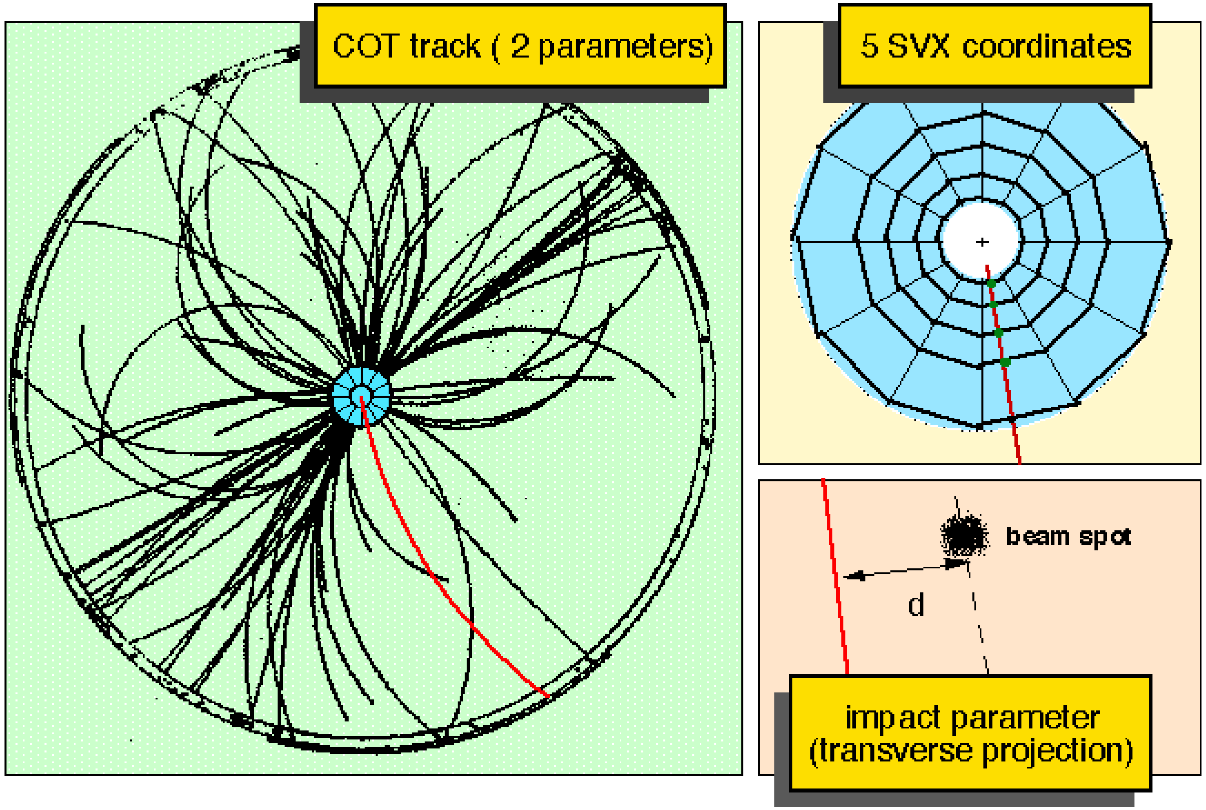
Intermediate silicon layers (ISL)

- 3 more layers at R = 20 - 29 cm
- Construction similar to SVX II
- Precision tracking to higher eta.
- Aid linking from COT to SVX.

Significant Japanese contributions :

SVX II	Hiroshima, Okayama
ISL	Osaka City, Tsukuba

Silicon Vertex Trigger : SVT



Use silicon information at the 2nd level trigger

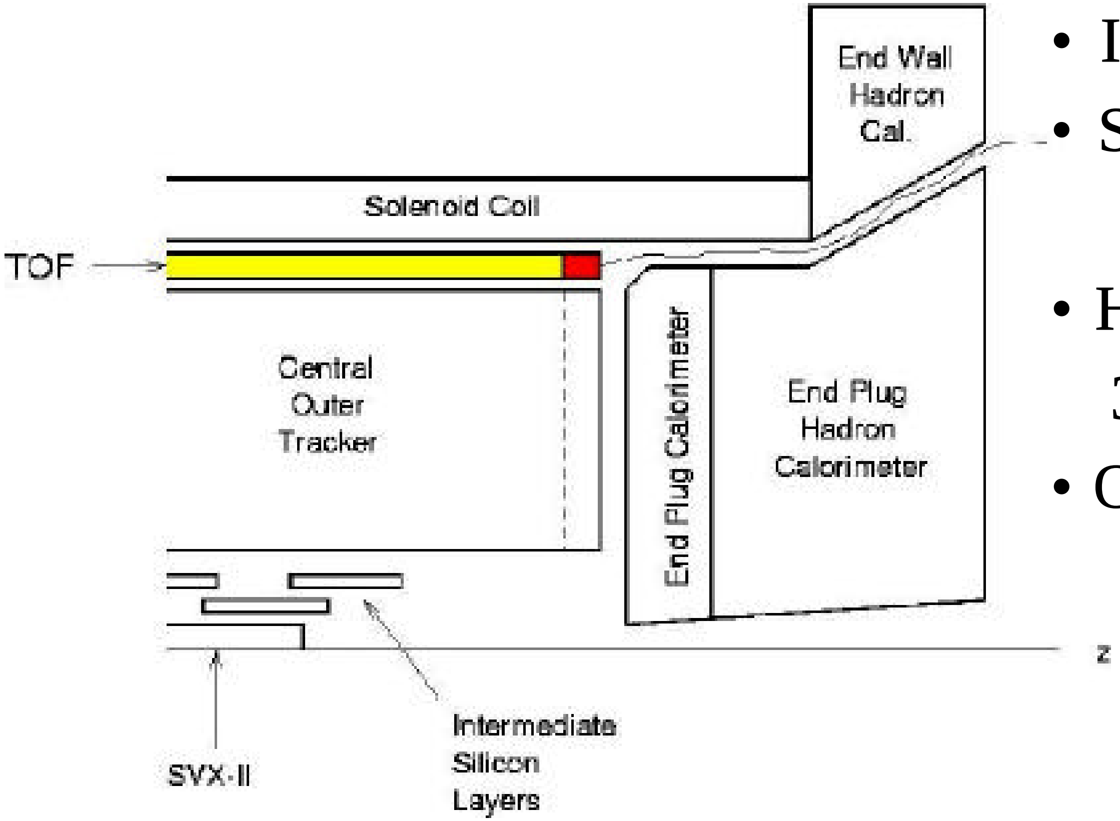
- Find a track in the main tracker COT.
- Extrapolate toward the SVX.
- Find SVX hits along the road.
- Calculate impact parameter wrt the primary vertex (beam spot).
- Resolution ~ 40 μm at 1 GeV/c.

Can trigger on all-hadronic final states such as

$B^0 \rightarrow \pi^+\pi^-$, $B^0_s \rightarrow D_s^- \pi^+$.

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
  $4 \times 4 \times 270$ cm^3
- Hamamatsu R7761 PMTs
  38 mm, 19-stage fine mesh
- Goal: $\sigma_T \sim 100$ ps

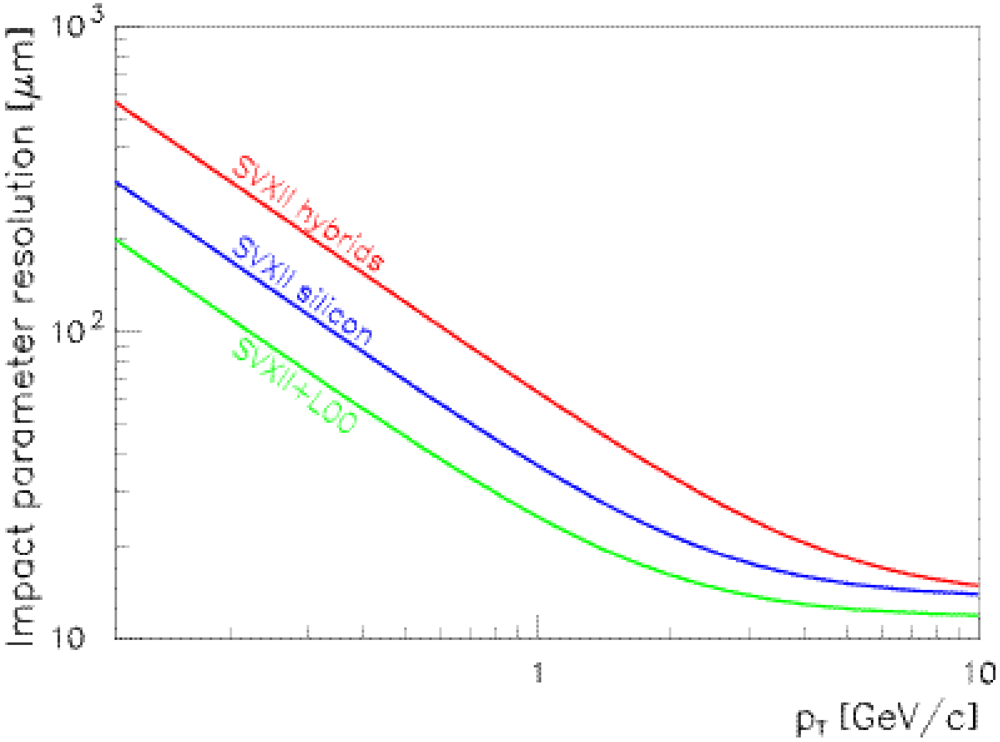
Purpose

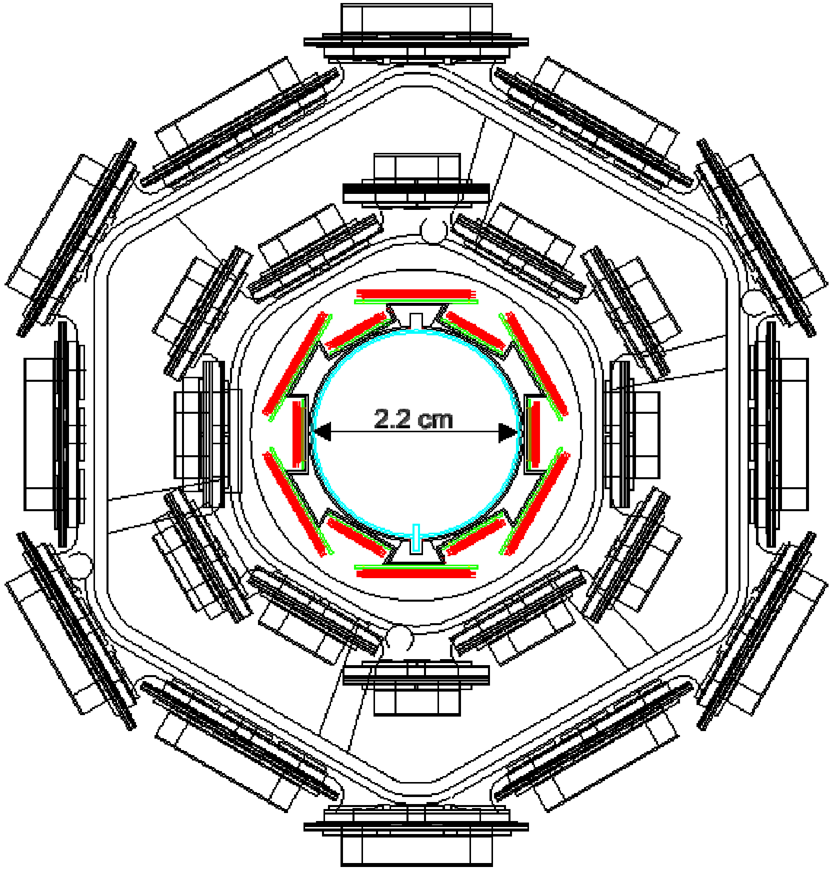
- 2σ K/π separation
  up to 1.6 GeV/c
- *B* flavor tagging

Layer 00

Detector

- Single-sided
- At radius ~ 1.6 cm, minimize effect of multiple scattering.
- Can operate up to ~ 5 fb^{-1}





Purpose

Improve impact parameter resolution :

$\sigma \sim$ 9 μm for high p_T

10 μm alignment

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

Signal

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

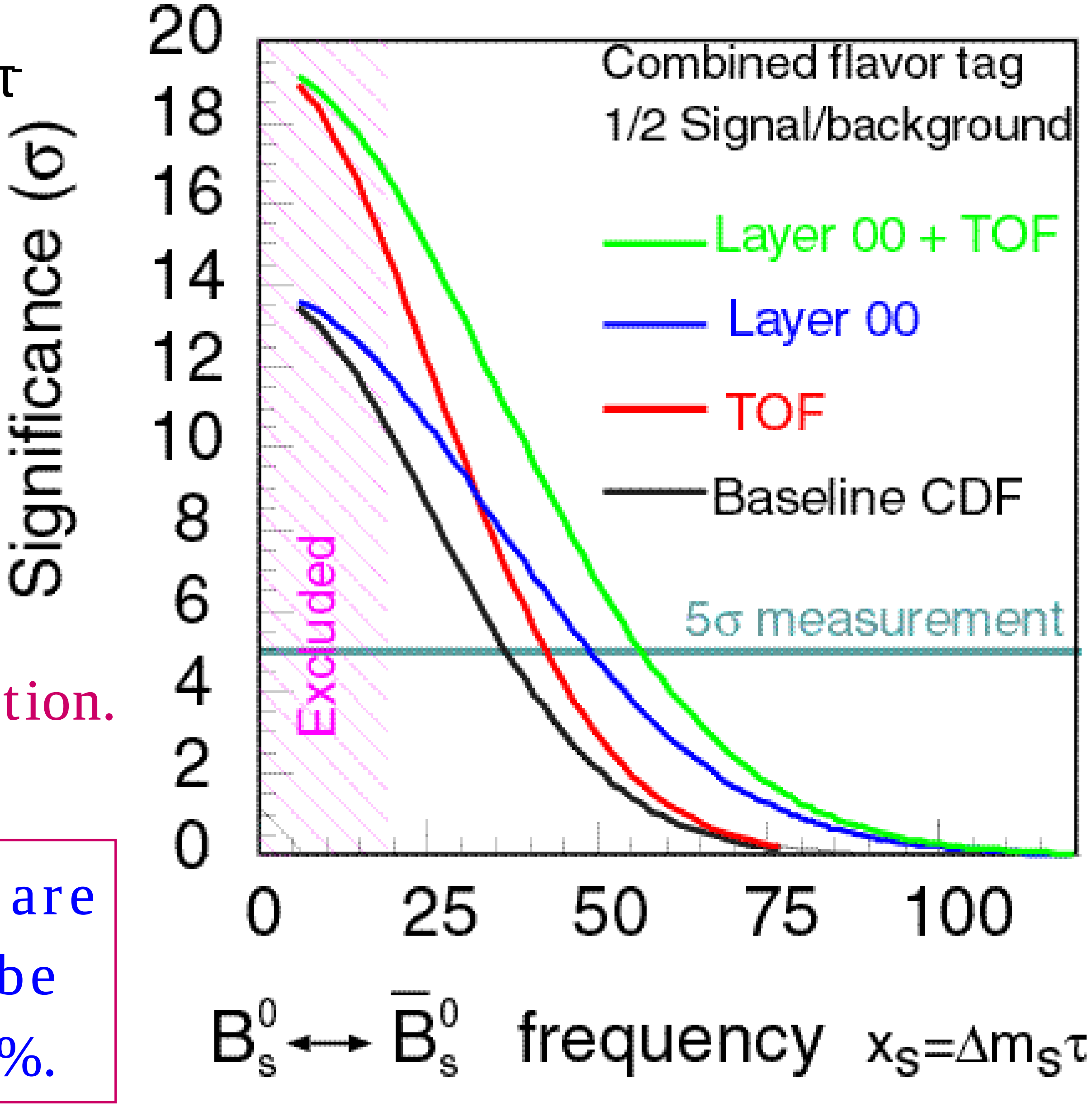
TOF

- 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 %.

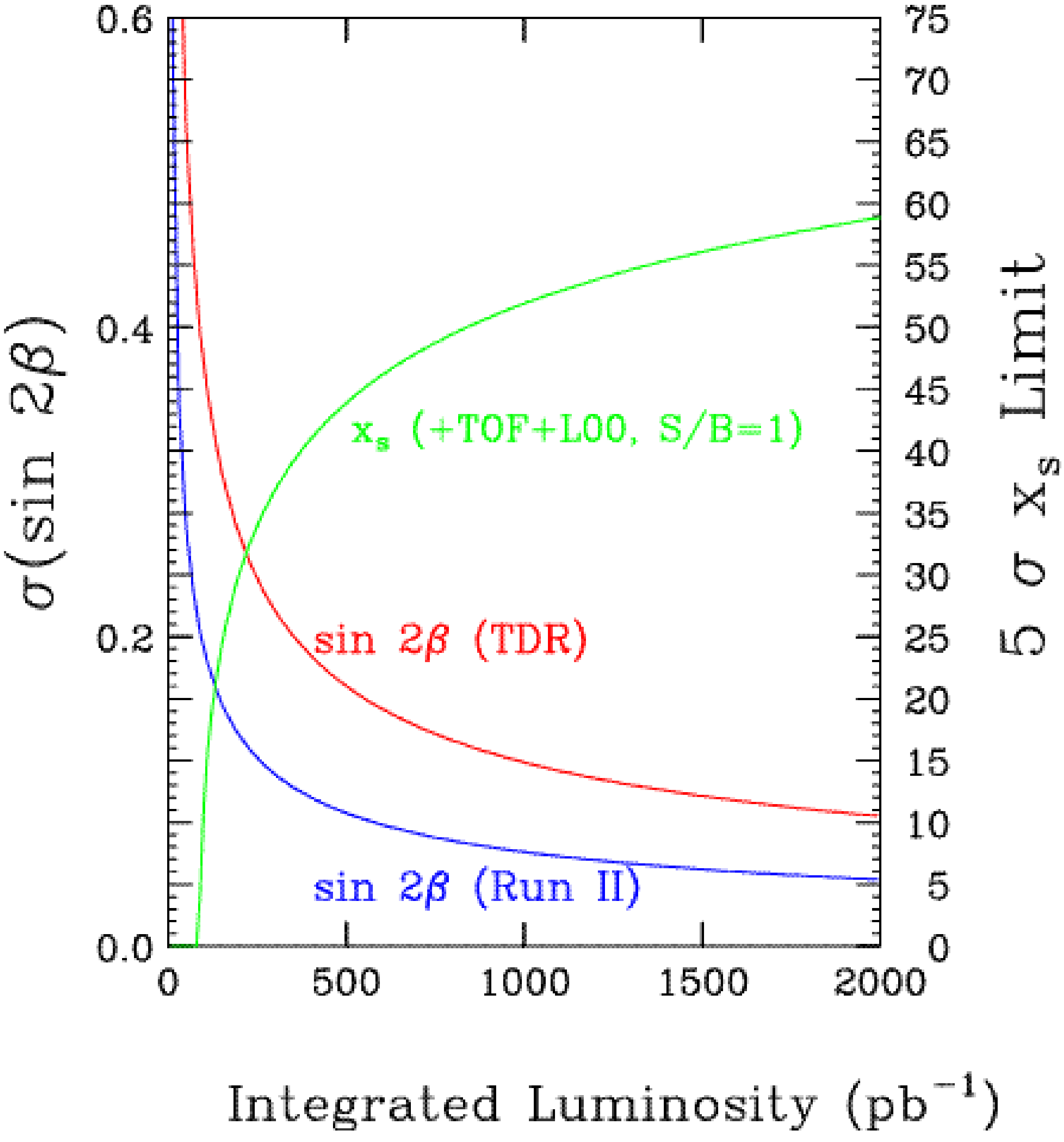


Run II projections

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

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

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

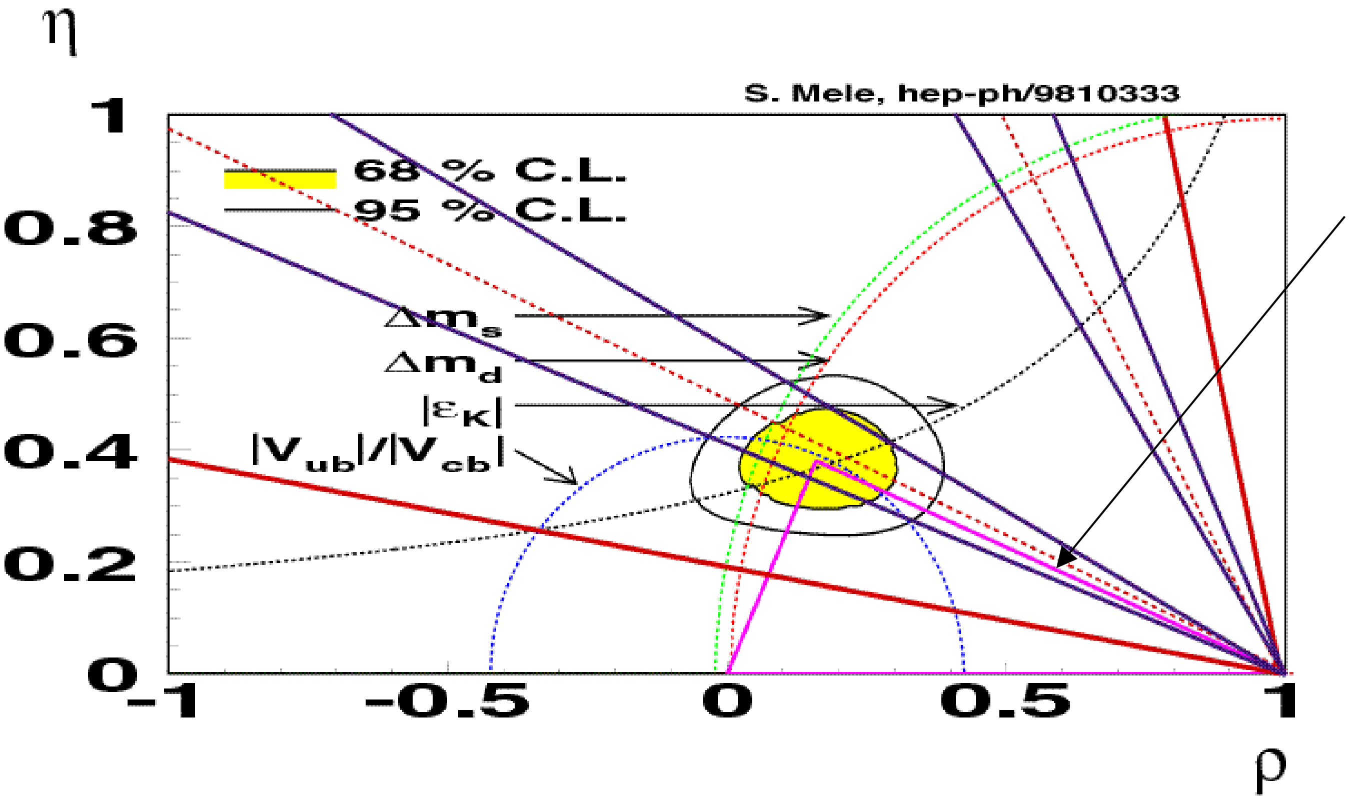


B Physics in CDF Run II

Two Major Goals:

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

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



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

Can be the first meaningful test of the unitarity triangle.

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

- $B^0 \rightarrow \pi^+ \pi^-$ once thought to be the mode for sin2(π-γ-β).

  (assuming $b \rightarrow u$ tree dominance over penguin)
- CLEO finds much larger $K^- \pi^+$ and tiny $\pi^+ \pi^-$.
- Not just small rates, but also means penguin pollution.

  → Relation to sin(2α) less clear.
- Strategies proposed, but are challenging experimentally...

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

In general, for a decay $B^0 \rightarrow f$ (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 $B^0 \rightarrow \pi^+ \pi^-$ and $B^0_s \rightarrow K^+K^-$.

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

Angle γ (phase of V_{ub}) continued

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

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

If no penguin,

$A^{dir} = 0 \qquad (B^0, B^0_s)$

$A^{mix} = \sin 2(\beta+\gamma) \ (B^0)$

$A^{mix} = \sin(2\gamma) \quad (B^0_s)$

Four unknowns to extract :

- β, γ = angles of the unitarity triangle.
- d = ratio of penguin (P) to tree (T) decay amplitudes,

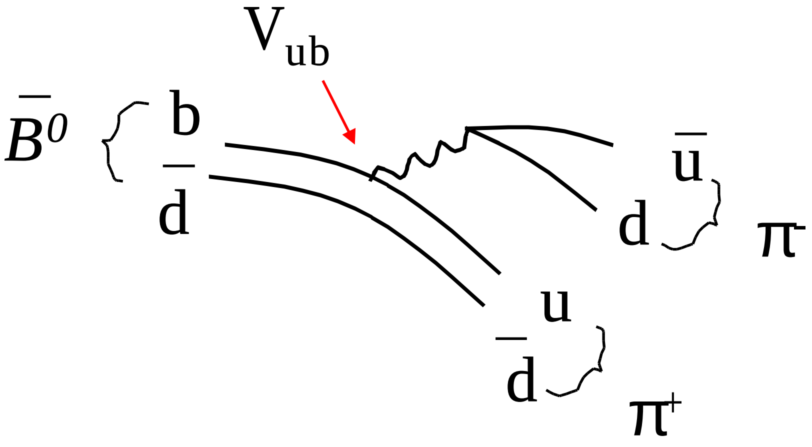
  θ = phase of "P/T"

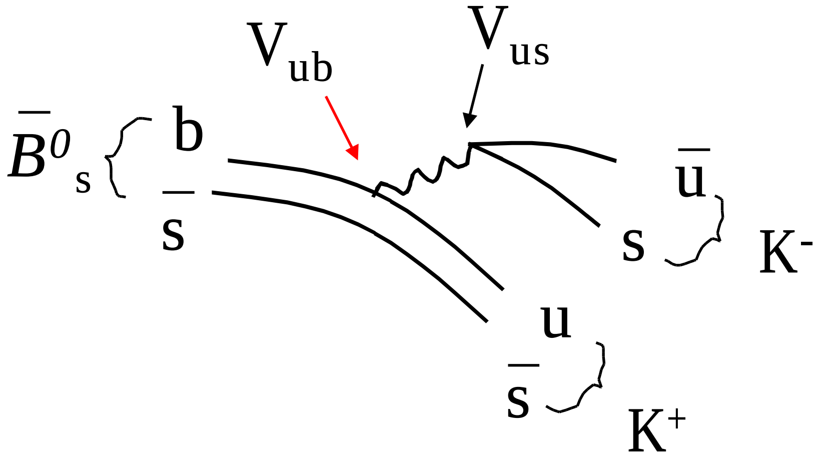
  $d\, e^{i\theta} \equiv \lambda |V_{cb}/V_{ub}| / (1-\lambda^2/2) [P / (T+P)]$

Expect ~5 k $B^0 \rightarrow \pi^+\pi^-$, ~10 k $B^0_s \rightarrow K^+K^-$

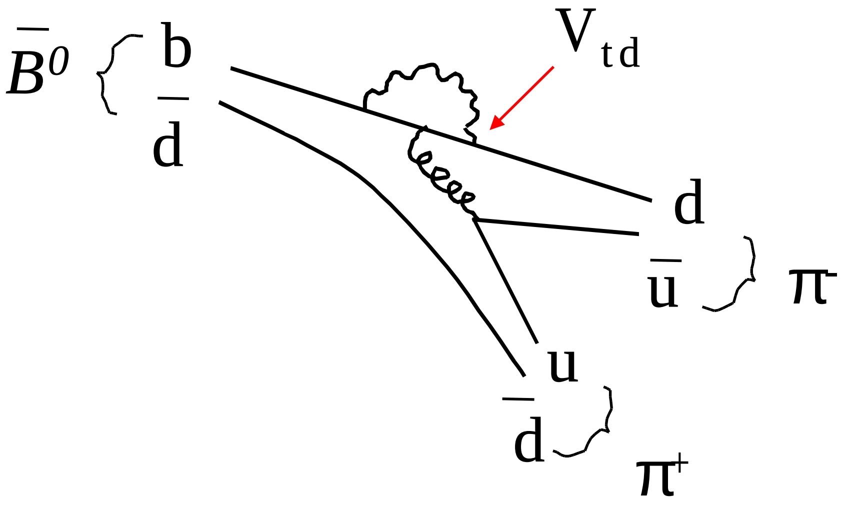
→ angle γ to ~10°.

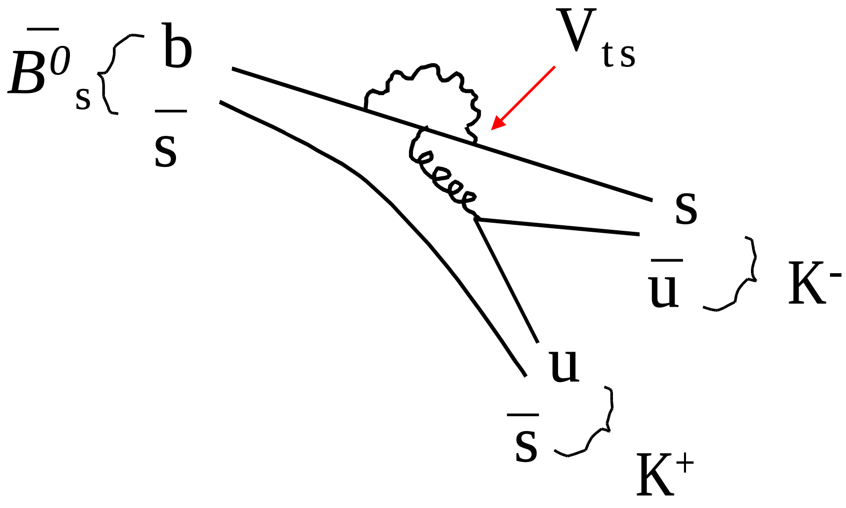
Tree





Penguin





Summary

- CDF does *B* physics pretty well.
- Run-I results cover virtually all aspects of *B* physics.
- Run II should produce further interesting results, in particular
  - sin(2β) precision of ±(0.043 to 0.084).
  - Δm_s up to ~ 40 ps^{-1}.
  - angle γ to ±10 degrees.