The CDF-II Time-Of-Flight Detector and Impact on Flavor Tagging

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On behalf of:

The CDF-II TOF Group

Outline

- CDF-II TOF System Overview
  - Basic Principles of the TOF method
  - The CDF TOF detector
  - Mechanics, photomultipliers
  - Front End electronics and signal path
- The Time measurement
  - System stability and calibrations status
  - Measuring the interaction time (t0) of the event
  - Initial performances and first Particle ID applications
- Flavor Tagging in CDF with TOF
  - Physics Motivations
  - Opposite side Flavor Tagging with TOF
  - Same Side Flavor tagging with TOF
  - Projections for the Bs mixing reach in Run-II

Related Presentations at BEAUTY-2002

D.Lucchesi: *Secondary Vertex Trigger*

M.Paulini: *CDF Run-II Status and Prospects*

The CDF-II TOF Group

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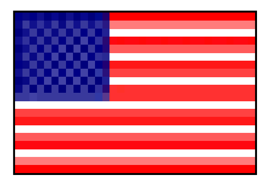
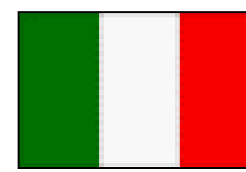
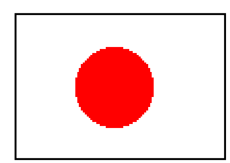
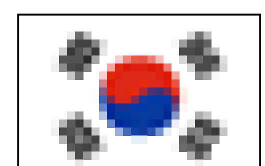


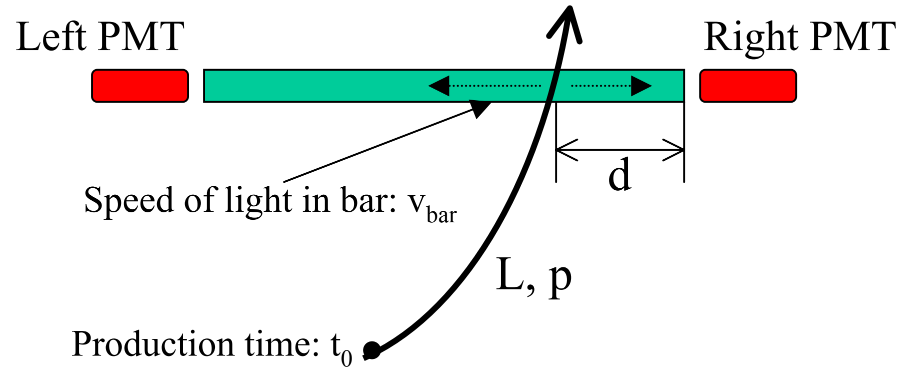






The TOF Technique

- Speed of charged particle determined by flight time t across known distance L
- Using the particle momentum p, measured with the central tracking system, is then possible to determine the particle mass m
- Mass resolution in CDF dominated by the time resolution of the detector



$$t = t_{hit} - \frac{d}{v_{bar}} - t_0$$

~ 5 ns for fastest particles

$$m = \frac{p}{c}\sqrt{\frac{c^2 t^2}{L^2} - 1}$$

$$\frac{\sigma_m}{m} = \frac{\sigma_p}{p} \oplus \gamma^2 \left(\frac{\sigma_t}{t} \oplus \frac{\sigma_L}{L} \right)$$

$\sigma_p / p \cong 1\%$

$\sigma_L / L \cong 0.1\%$

$\sigma_t / t \cong 2\%$

$\gamma^2 >> 1$

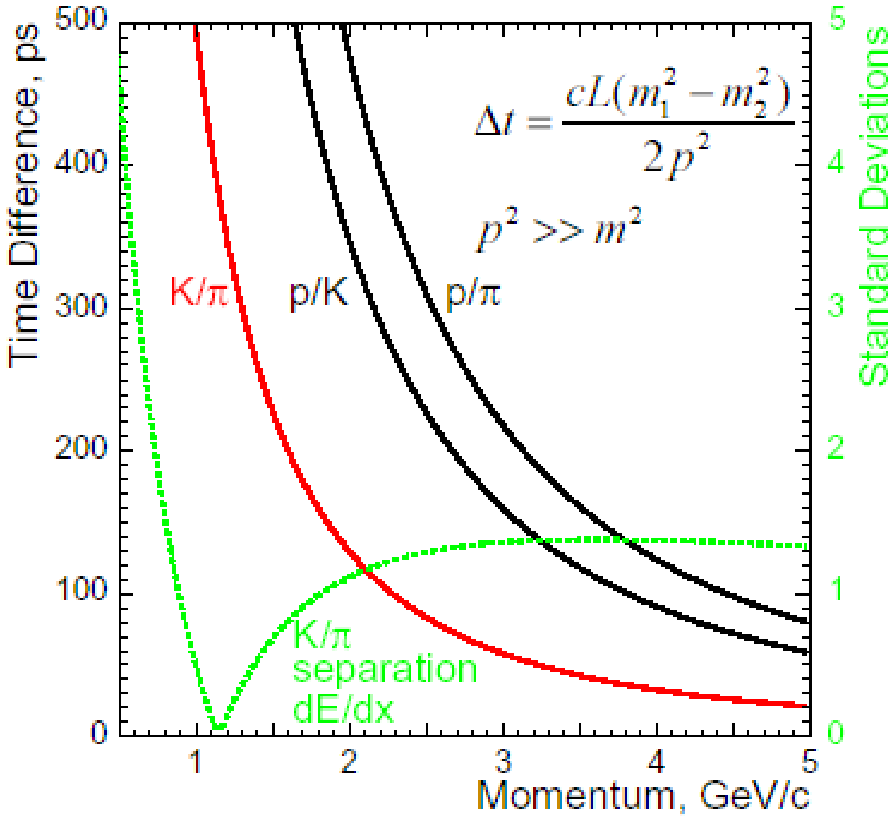
Particle Identification in CDF

- Time resolution goal for the CDF TOF detector: 100 ps

- With that resolution:

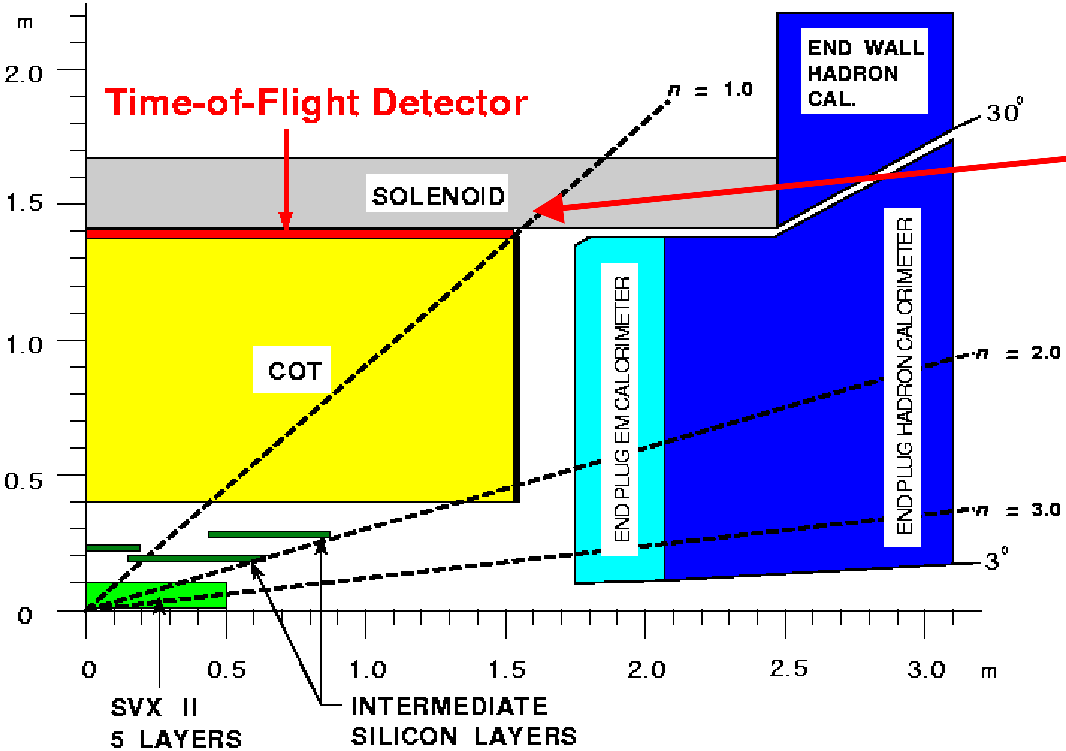
  2σ K/π separation for p < 1.6 GeV/c
  2σ K/p separation for p < 2.7 GeV/c
  2σ K/π separation for p < 3.2 GeV/c
  1.2σ K/p separation over all p

- TOF will complement the particle ID based on dE/dX measured on the central drift chamber (used in RunI)



- L = 140 cm ~ R_{TOF}
- Assuming 100 ps timing resolution for TOF

The CDF-II TOF Detector

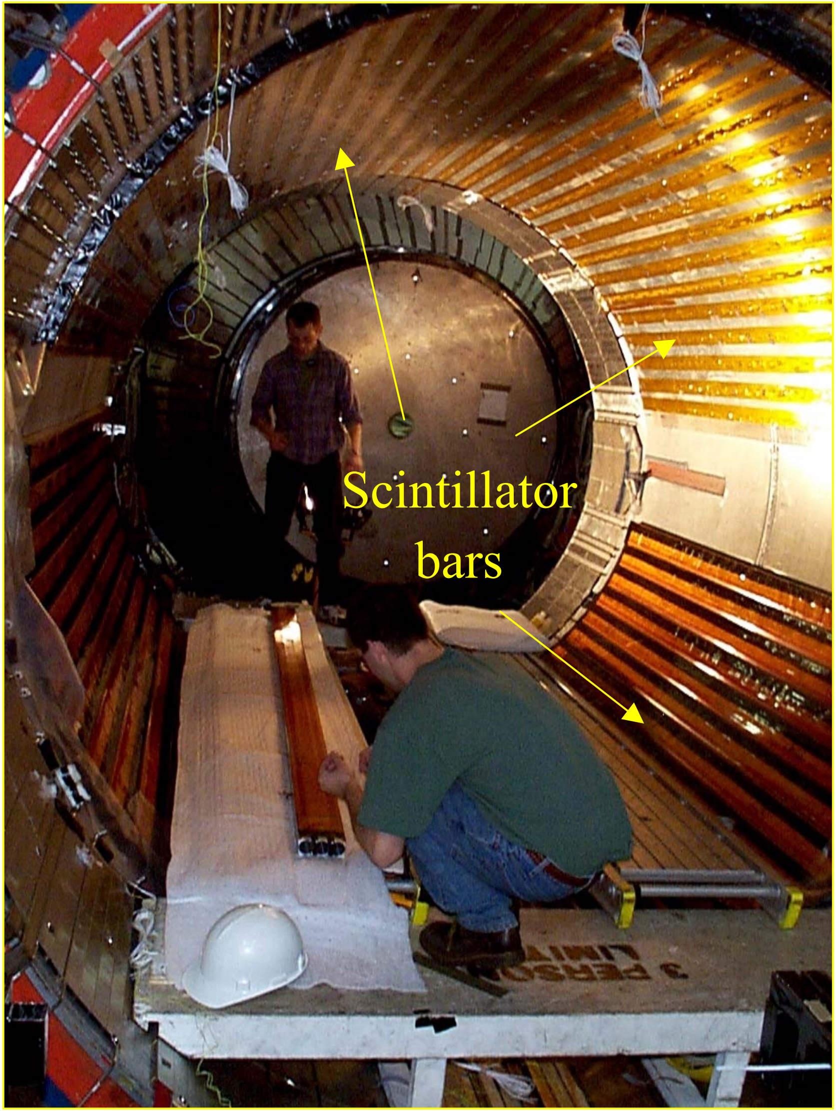


R_{TOF} ~ 1.4 m
Coverage: $|\eta| < 1$

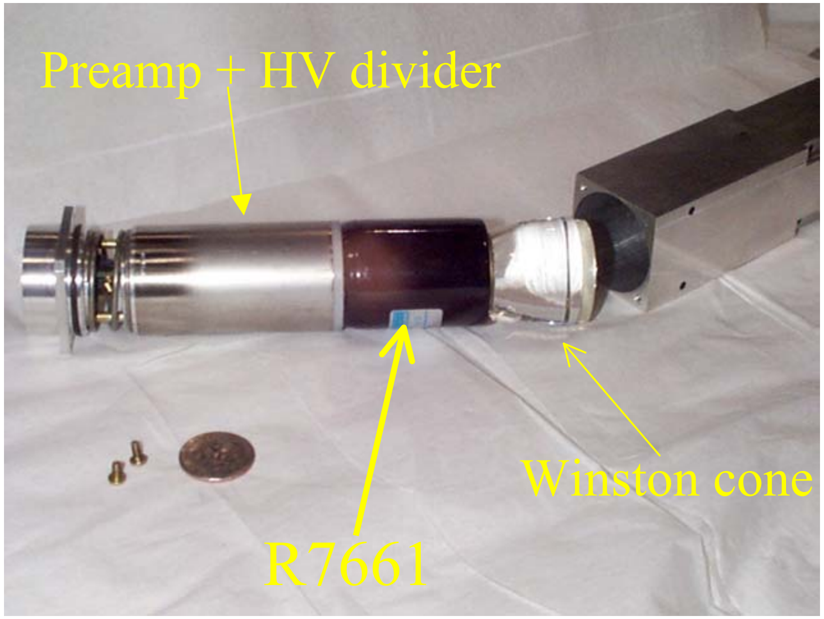
- 216 scintillator bars
  - Bicron BC-408
  - Λ_{att} ~ 2.5 m
  - Fast rise time ~ 0.9 ns
  - 2.8 m with ~ 4×4 cm^2 cross section
- Hammamatsu R7761 PMT on both ends
  - Fine-mesh, 19 stage
  - Gain reduction 500 @ 1.4 T
  - Small TTS: 250÷400 ps

Test run (5% "full-scale") in 1995
Approved January 1999
Fully installed in August, 2000
electronics - August, 2001
Stable data taking from October 2001

TOF Mechanics and PMTs

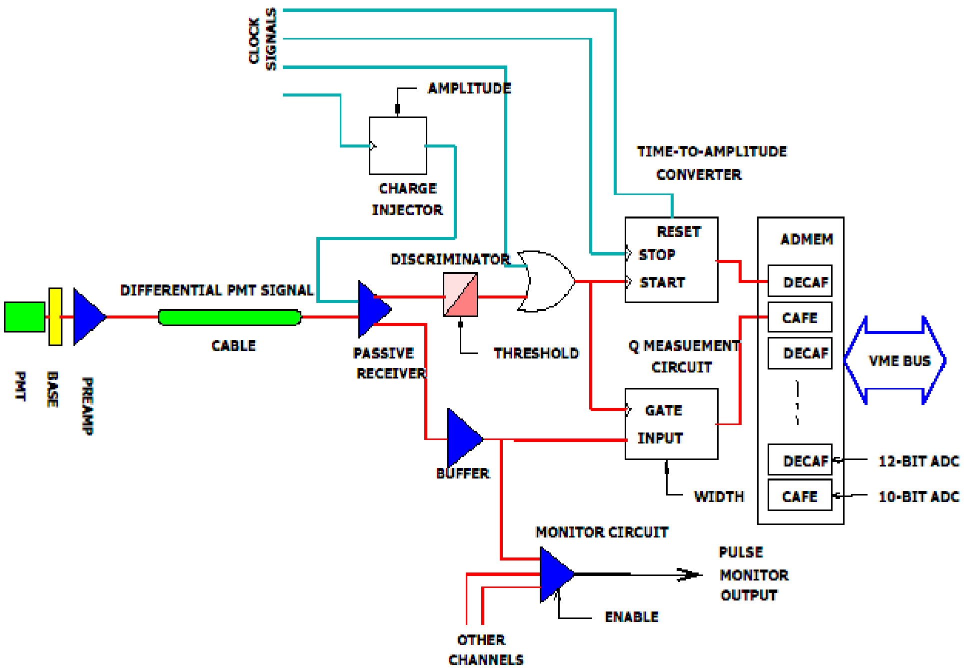


- Scintillator bars assembled in 72 triplets
- 100 μm fibers for laser calibration
- Few millimeters radial clearance



- Light concentrator, Hammamatsu PMT, HV divider and preamplifier held together in Aluminum holders.
- Not glued for staged installation

Front End electronics and Signal Path



✓864 channels in 8 FE crates
✓Slightly modified CDF Calorimeter FE electronics (ADMEM) used
✓Clock cycle 7.58 MHz (132 ns bunch crossing)

- Differential PMT signal from anode and last dynode fed into preamplifier to recover PMT gain reduction due to B field
- Signals from preamplifier driven to readout into two paths:
  - Timing path:
    - $t = t_{stop} - t_{start}$ with TAC
    - t_{stop}: from clock distribution system (jitter < 25 ps)
    - t_{start}: from threshold discriminator
    - TAC output digitized (12 bits)
  - Charge path:
    - Gated current integration (10 bits)
    - Used for time slewing corrections

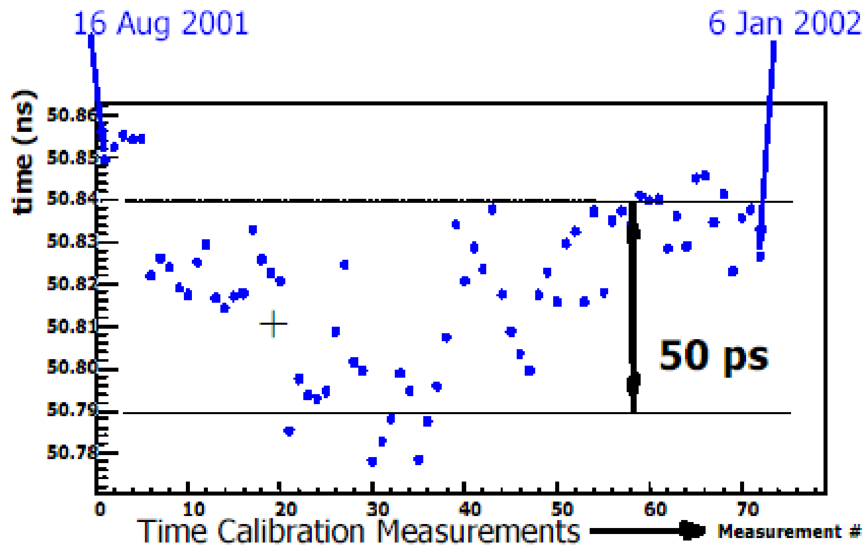
The Time Measurement

- TOF TAC measures $t = t_{stop} - t_{start}$ (common stop)
  - t_{start} from the PMT signal
  - t_{stop} from clock distribution system synchronized with the bunch crossing
- For a track hitting a bar at z and Q being the charge read by the channel:
  - $t_{start} = t_0 + t_{tof} + t_{scint} + t_{cable} + F(Q)$

  Where:
    - t_0: collision time
    - t_{tof}: travel time from collision point to scintillator
    - $t_{scint} = (L_{bar}/2 \pm z)/v$: scintillator light propagation to PMT ($v \sim 15$ cm/ns)
    - t_{cable}: signal propagation, through PMT and cables, to discriminator
    - $F(Q)$: effect of the time slewing (walk), which depends on Q
- All these effect must be controlled better than few tens of ps to achieve the desired 100 ps timing resolution!

Calibrations

- Essential to achieve the 100 ps goal
- Includes:
  - online calibrations:
    - TAC/ADC calibrations
    - Electronics Stability



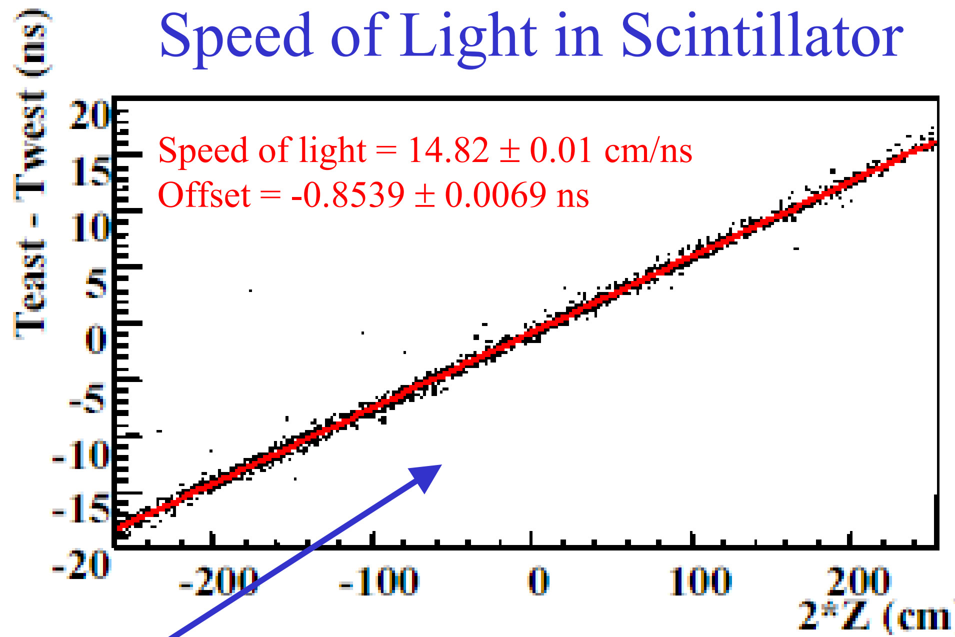
  - offline calibrations:
    - Speed of light measurement bar by bar
    - Attenuation length studies
    - Time Slewing (Walk) corrections
    - Cable length analysis
  - event t0 measurement with TOF

TAC routinely calibrated
Good Stability
Difference subtracted by the calibration (residual effect < 17 ps)

Time Difference Analysis

- Compare track to time difference between z<0 and z>0 PMTs (east-west)
- $\Delta t \equiv t_E - t_W = 2z/v + t_{offset}$
- t_0, t_{TOF} cancel in difference
- t_{offset} is residual walk corr. and cable diff.

Speed of Light in Scintillator



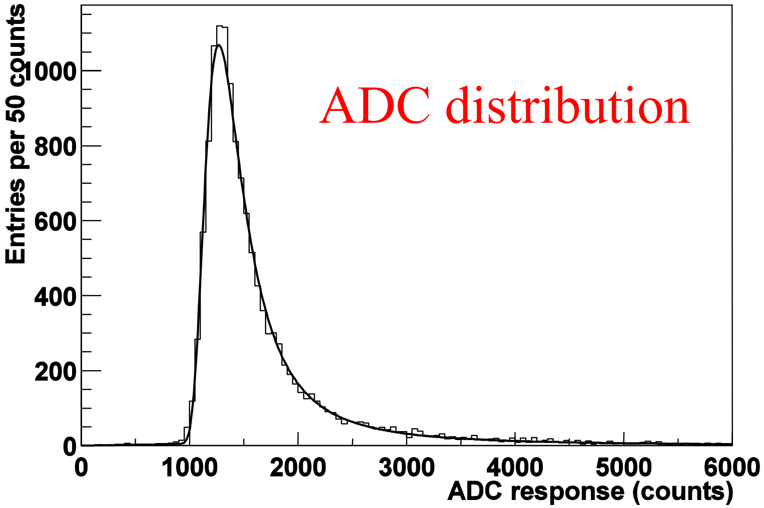
Width of residuals from the straight line fit is a measure of the timing resolution of the two PMT added in quadrature:

Averaged over all bars: better than 250 ps $(\sigma_{\Delta t} \approx 2\sigma_{TOF})$

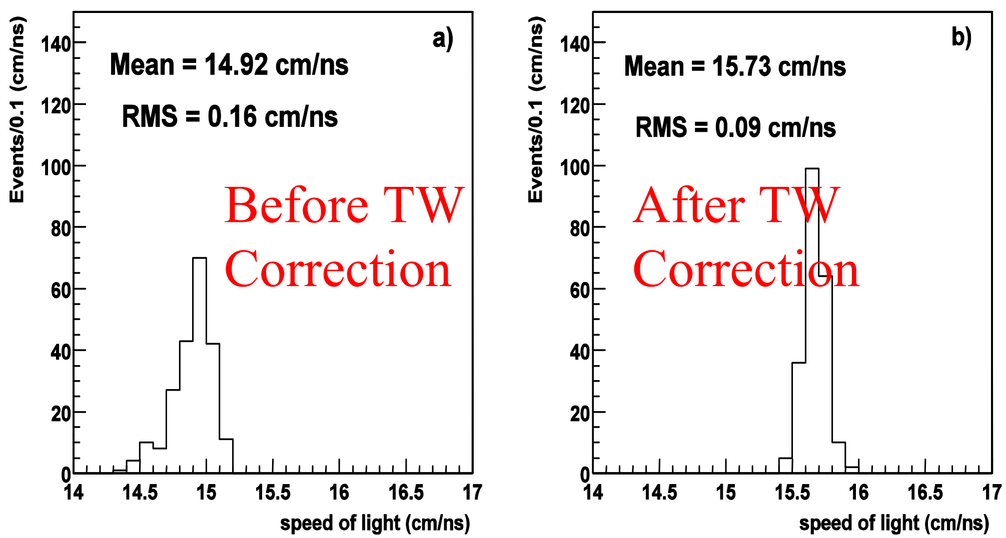
CAVEAT: Systematic effects that cancel in the time difference not necessarily would cancel in the calculation of TOF

Charge Distribution and Walk Correction

- Used for time slewing correction.
- ADC response studied selecting tracks passing through a single bar.
- Landau charge distribution after correcting for attenuation.
- Measure of the attenuation length bar by bar



- <u>Time slewing (walk) effect:</u>
- Leading edge time pick-off method: larger pulse fire the discriminator earlier than smaller pulses
- Substantial effect: ~ 2ns (full ADC range)
- Studied comparing Δt between same side channels of adjacent bars:
  - Same z entrance point → $\Delta t = t_A - t_B$ depends mainly from the walk effects
  - Parameterization: $\propto 1/\sqrt{Q}$

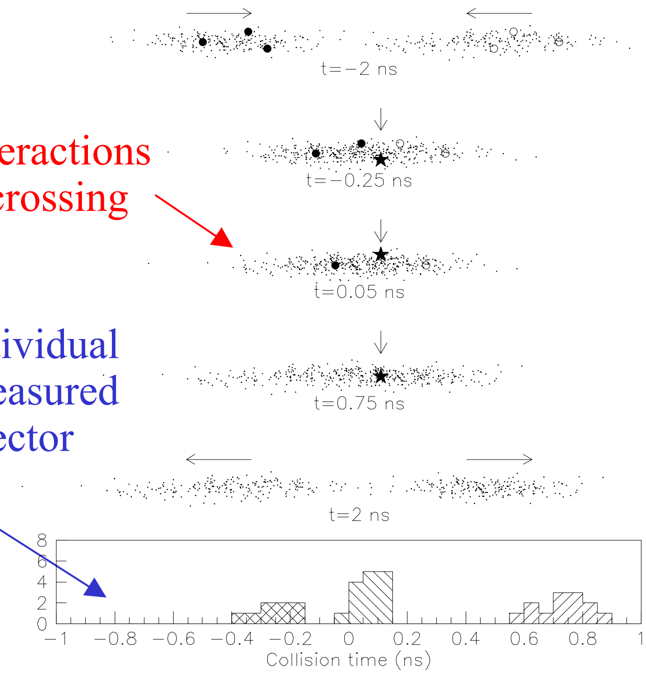


Measuring the t_0 of the event

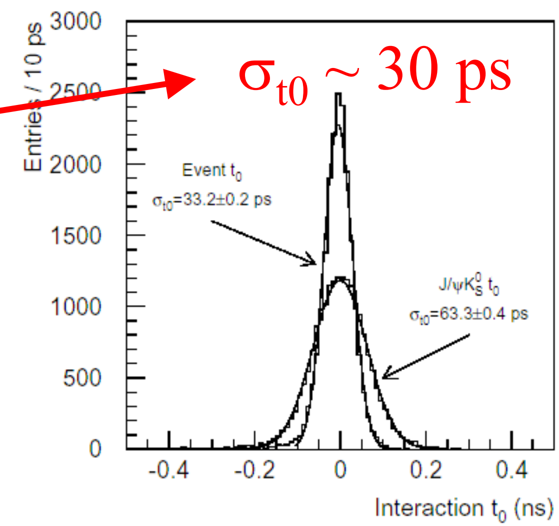
- Operation of a TOF detector in the CDF-II environment is a unique challenge
  - Long bunches: $\sigma_z \sim 30$ cm → $\Delta t_0 = \sigma_z/c \sim 1$ ns >> σ_{tof}
  - Multiple interactions in the same bunch crossing

Three $p\bar{p}$ interactions in one bunch crossing at the same z

Times of individual collisions measured with TOF detector



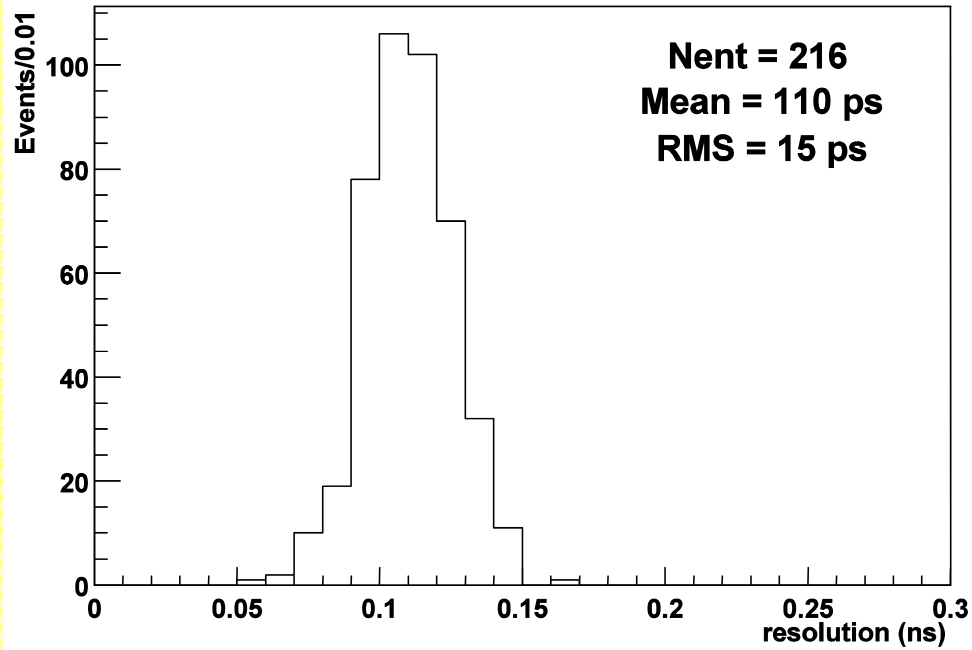
- For analysis in which a B decay is fully reconstructed is sufficient to consider only tracks associated to its primary interaction vertex:
  - –Reconstruct B decay ($B^0 \to J/\psi K^0_S$, $B^0_S \to D^{\pm}\pi$, …)
  - –Find other tracks in primary vertex (<n> ~ 13)
  - –Perform likelihood fit for t_0



Time Resolution Estimate

- First estimate of the time resolution of the complete TOF system
- all calibrations and corrections applied
- Compare measured TOF versus expected value using pion hypothesis as a function of *z* position
- Measure TOF resolution at PMT face from the sigma of the measured distributions
- Calibrations and event t_0 determination are still preliminary!

Time resolution at the PMT face

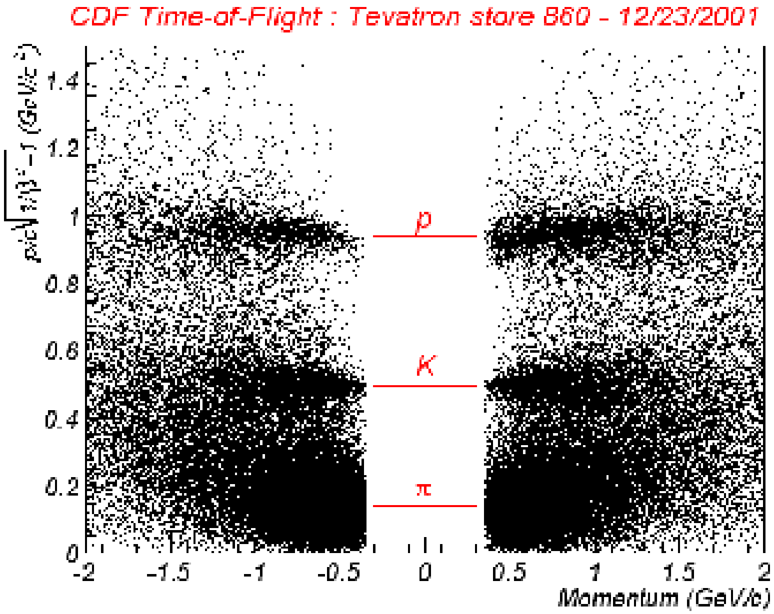


$\sigma_{TOF} \approx 110$ ps

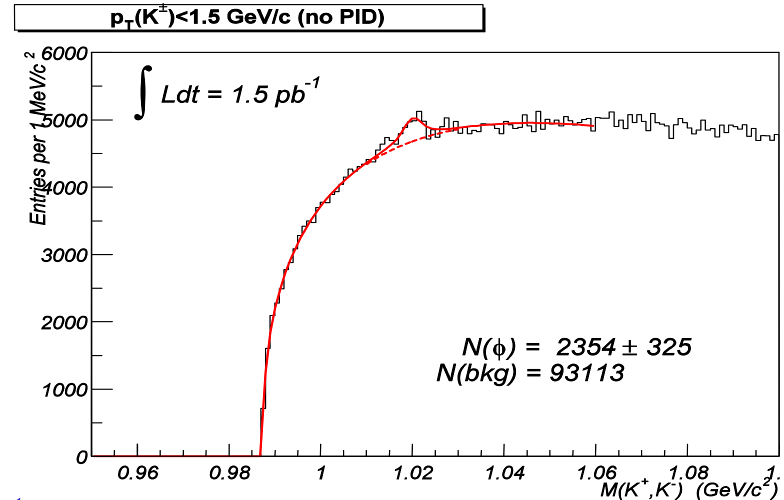
We are approaching the design goal!

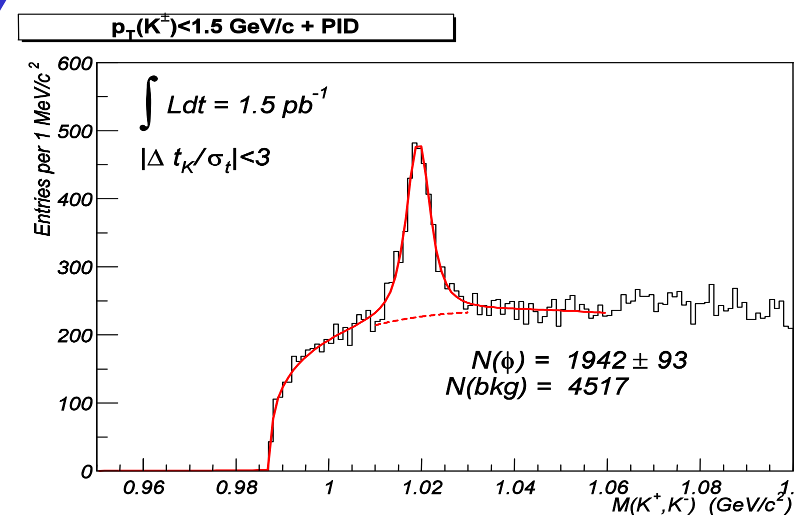
Preliminary Performances

TOF Reconstructed mass VS momentum



$\phi(1020) \rightarrow K^+K^-$





Particle ID: $\phi(1020) \rightarrow K^+K^-$
with Pt < 1.5 GeV/c

BG reduced by a factor 20

Signal reduced by 17%

Using TOF to enhance flavor tagging in CDF

- The measure of the flavor oscillations is one of the main goal for the B physics program at Run-II
- Basic ingredients for the measurements are:
  - Trigger on tracks from displaced vertex (see D.Lucchesi's talk)
  - B mesons reconstruction in the appropriate final state:
    - Ex. $B^0 \rightarrow J/\psi K^0_S$, $B^0_S \rightarrow D_S^{\pm}\pi^{\mp}$
  - Measuring the proper-time of the B meson decay ($c\tau$)
  - Determining the flavor of the B meson at the production (and decay for the mixing analysis)

- CDF TOF detector was designed to substantially improve the ability of CDF to study the B^0_S system, and to increase the statistical power of the $J/\psi K^0_S$ sample for the measurement of $\sin 2\beta$

B Flavor tagging in a nutshell

Determine whether the reconstructed B meson contains a b quark or a $\bar{b}$ antiquark

Given a pure signal: $S = N + \overline{N}$ (no background) → asymmetry: $A = \dfrac{N - \overline{N}}{N + \overline{N}}$

⇨ Flavor tag is always imperfect ⇦

Can't always deduce production flavor: $\varepsilon N + \varepsilon \overline{N} = \varepsilon S$ → ε ≡ tag efficiency

Sometime the tag is wrong: (if P is the probability that the tag is correct):

$$A_{meas} = \frac{\left(\varepsilon P N + \varepsilon(1-P)\overline{N}\right) - \left(\varepsilon P \overline{N} + \varepsilon(1-P)N\right)}{\varepsilon(N + \overline{N})} = (2P-1)A$$

→ ≡ D (dilution)

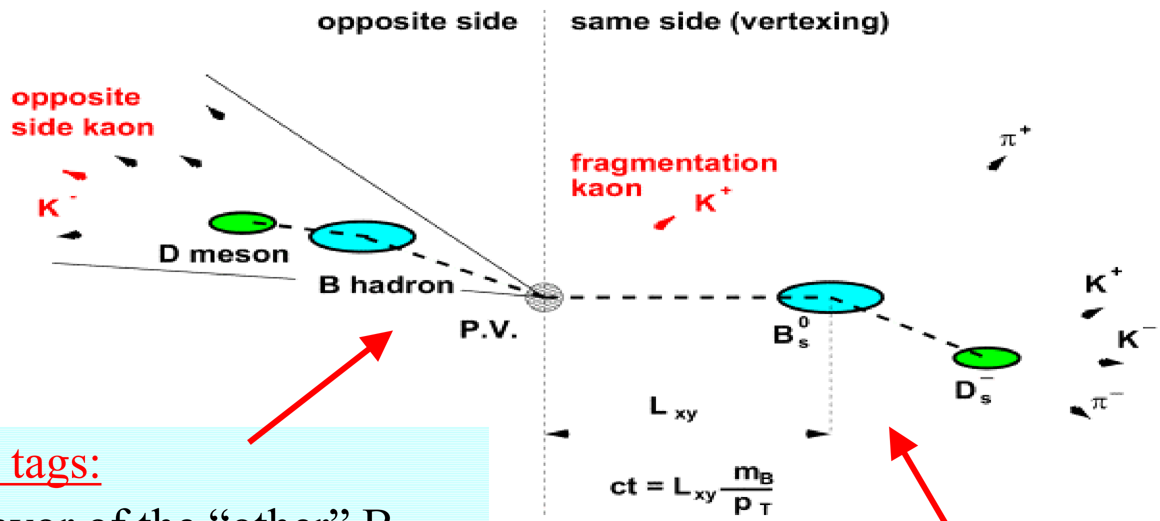
Figure of merit: εD^2 ← total tagging effectiveness

εD^2 determines the effective statistic of the sample: $S \rightarrow \varepsilon D^2 S$

$$\delta A = \sqrt{\frac{1 - D^2 A}{\varepsilon D^2 (N + \overline{N})}} \propto \frac{1}{\sqrt{\varepsilon D^2 S}}$$

B Flavor tagging in a nutshell (2)

Several B flavor tagging methods studied in CDF:



Opposite side tags:

Identify the flavor of the "other" B

- opposite side lepton tagging* (RunI)
- jet charge tagging* (RunI)
- opposite side kaon tagging (TOF)

reduced acceptance → ε

flavor oscillations (B^0/B^0_S) → D

* Successfully implemented in RunI

Same side tags:

Tag particles produced in the hadronization of the reconstructed B

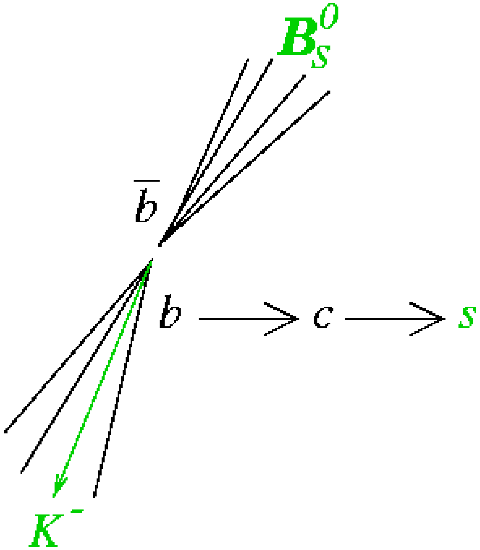
- same side tagging* (B^0) (RunI + TOF)
- same side kaon tagging (B^0_S) (TOF)

better acceptance → ε

εD2 diff. for $B^0/B\pm/B^0_S$ and Pt dependent

Opposite Side Tag with TOF

- Idea: exploiting B weak decay: $b \to c \to s$
- B-mesons containing a b quark will contain likely a K^- in the final state than a K^+: $b \to K^- X$ but $\bar{b} \to K^+ X$
- Require TOF, dE/dX and SVX to identify displaced kaons
- Can be applied equally to B^0 and B^0_S
- CDF-II potential estimated using Montecarlo simulations and assuming 100 ps resolution for the TOF

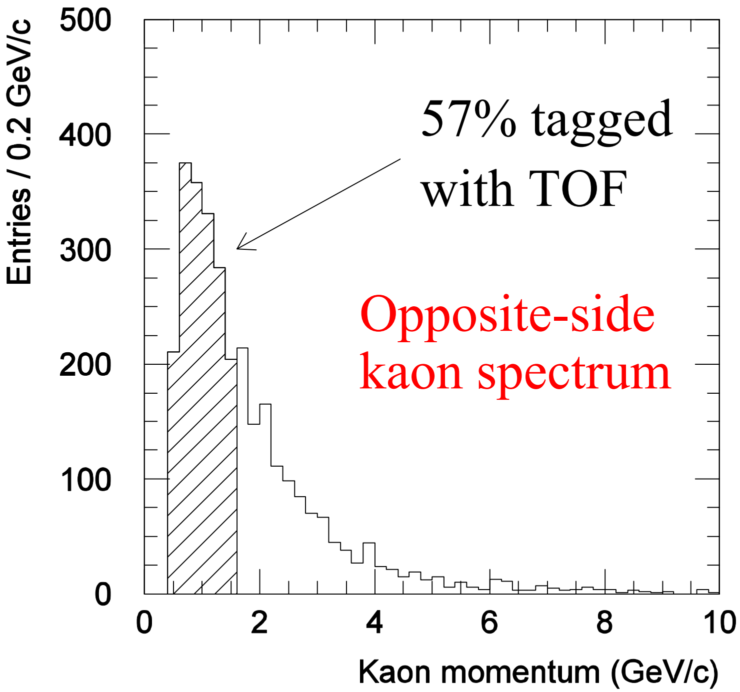


$\varepsilon = 11.2\ \%$

$D = 46.1\ \%$

$\varepsilon D^2 = 2.4\%$

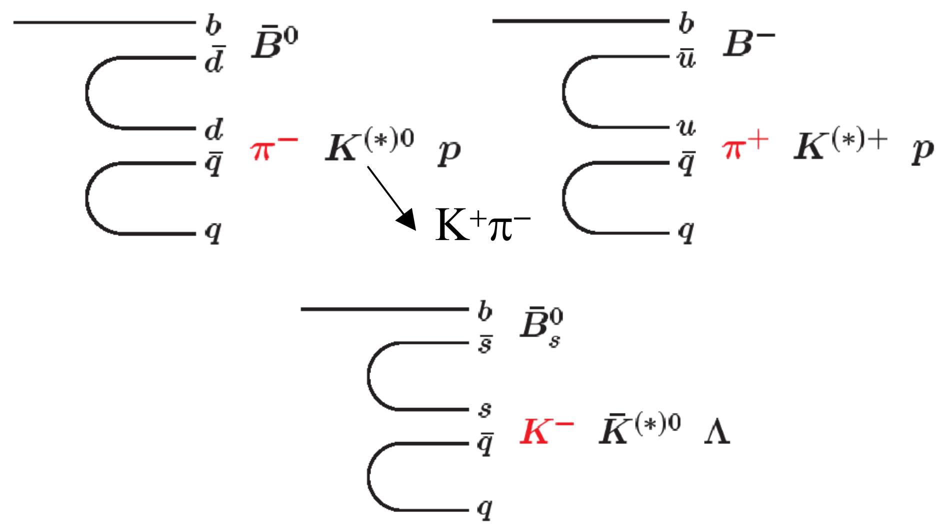
Run-I $\leq 1\%$



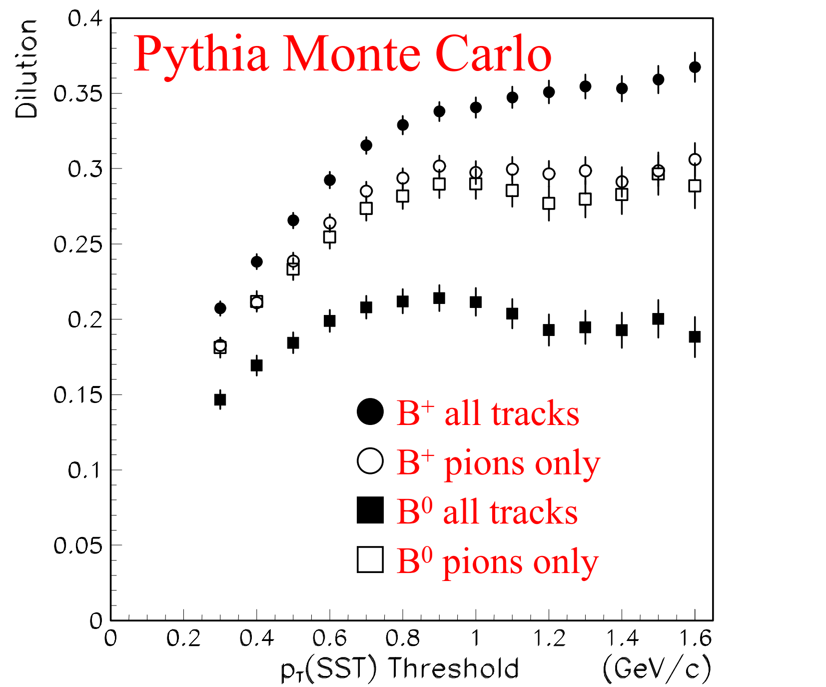
Same Side Tag with TOF

- Exploit correlation between b-flavor and particles produced in the hadronization of the quark
- $\pi^+ \rightarrow B^0$, $\pi^- \rightarrow \overline{B}^0$ and $K^+ \rightarrow B^0_S$

- Reduced effectiveness for B^0 due to opposite charge correlations of associated π and K/p → different dilution for B^+ and B^0
- The TOF ability to identify π, K (and p!) double the εD^2 for B^0 and make possible in CDF same side tagging for B^0_S

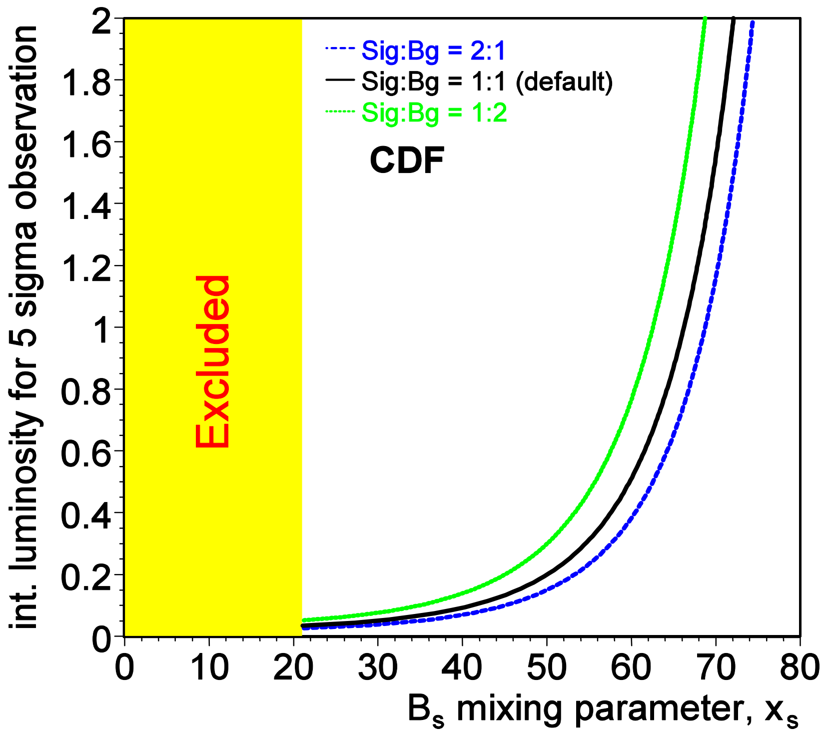


εD^2	w/o TOF	with TOF
B^0s	1.0%	4.2%
B^0	1.8%	2.4%



B_s mixing parameter x_s projections

- Combining all the b-flavor tag methods:
  - $\varepsilon D^2 = 5.7\ \%$ (w/o TOF)
  - $\varepsilon D^2 = 11.3\ \%$ (with TOF)
- Substantial impact on the sensitivity for the Bs mixing parameter x_s
- x_s reach estimated using Montecarlo assuming:
  - Only Bs hadronic decay: $B^0_s \to D_s^-\pi^+$, $D_s^-\pi^+\pi^-\pi^+$ with $D_s^- \to \phi\pi^-$, $K^{*0}(892)K^-$, $\pi^-\pi^-\pi^+$
  - 100 ps TOF resolution
  - A completely commissioned and fully operational detector and trigger system
  - Signal to Noise: 2:1, 1:2



Sensitive up to $x_s \approx 70$
Test SM prediction (~30) with
< 200 pb^{-1} integrated luminosity

Outlook and Conclusion

- The new CDF-II TOF detector is fully installed and in stable operations since Fall 2001
  - Calibrations are actively going on, as are the development/optimization of reconstruction algorithms
  - Basic Particle ID functionality start to be available
  - 100 ps time resolution goal seems reachable
- We expect substantial improvements using TOF in the effectiveness of CDF flavor tagging, particularly relevant for B^0_s
- We can explore Standard Model predictions for x_s with ~ 100÷200 pb^{-1} … first result expected for Summer 2003!