B_s Mixing at CDF

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on behalf of the CDF Collaboration

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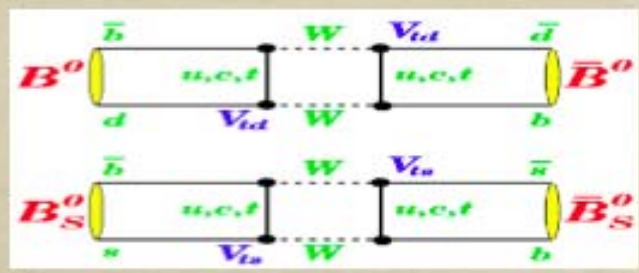
Motivation

- Neutral B mesons flavor-oscillate
- Measure fundamental SM parameters

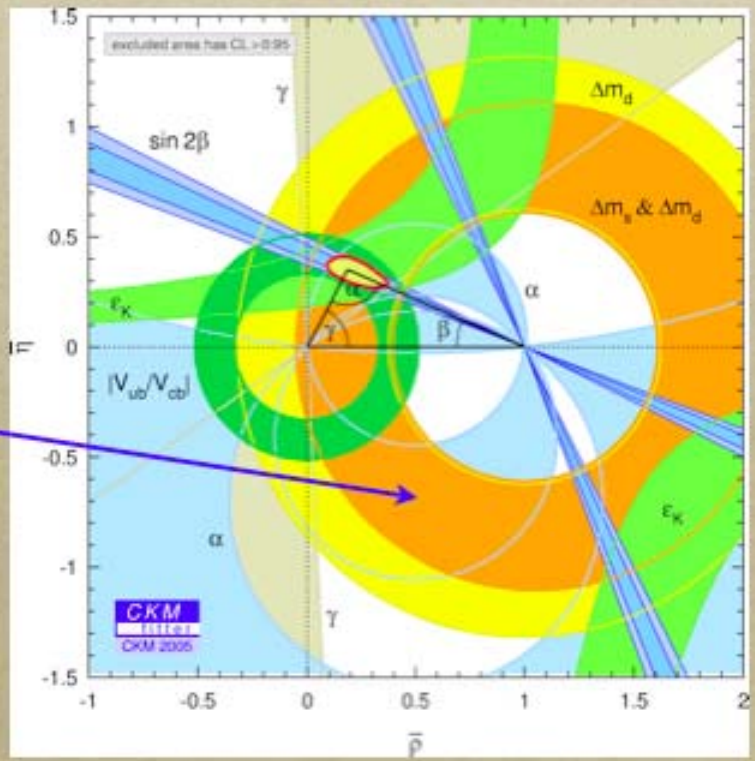


$$\Delta m_s = \frac{G_F^2 m_W^2 \eta S(m_t^2/m_W^2)}{6\pi^2} m_{B_s} f_{B_s}^2 B_{B_s} |V_{ts}^* V_{tb}|^2$$

- Hadronic uncertainties cancel in ratio

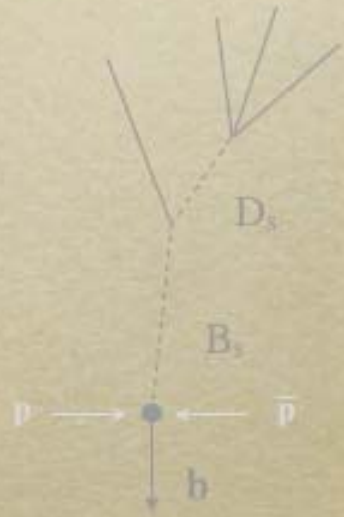
$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_{B_s}}}{m_{B_{B_d}}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

- New Physics may have sizeable effect
- Prerequisite for time dependent CPV



Mixing ingredients

- **B samples**
  - collect events with displaced tracks - SVT trigger
  - reconstruct decay modes: $B_s \rightarrow D_s \pi$ and $B_s \rightarrow l D_s X$
- **B proper decay time**
  - measure distance between production and decay
  - determine B_s meson's momentum
- **B flavor at production**
  - established by flavor tagging methods
  - determine probability that tag is correct
- **Likelihood description for unbinned fitting**
  - signal and background components in mass and ct space
  - trigger and selection bias in proper decay time



Contributions to mixing

Signal yield Tagging Purity ct-resolution

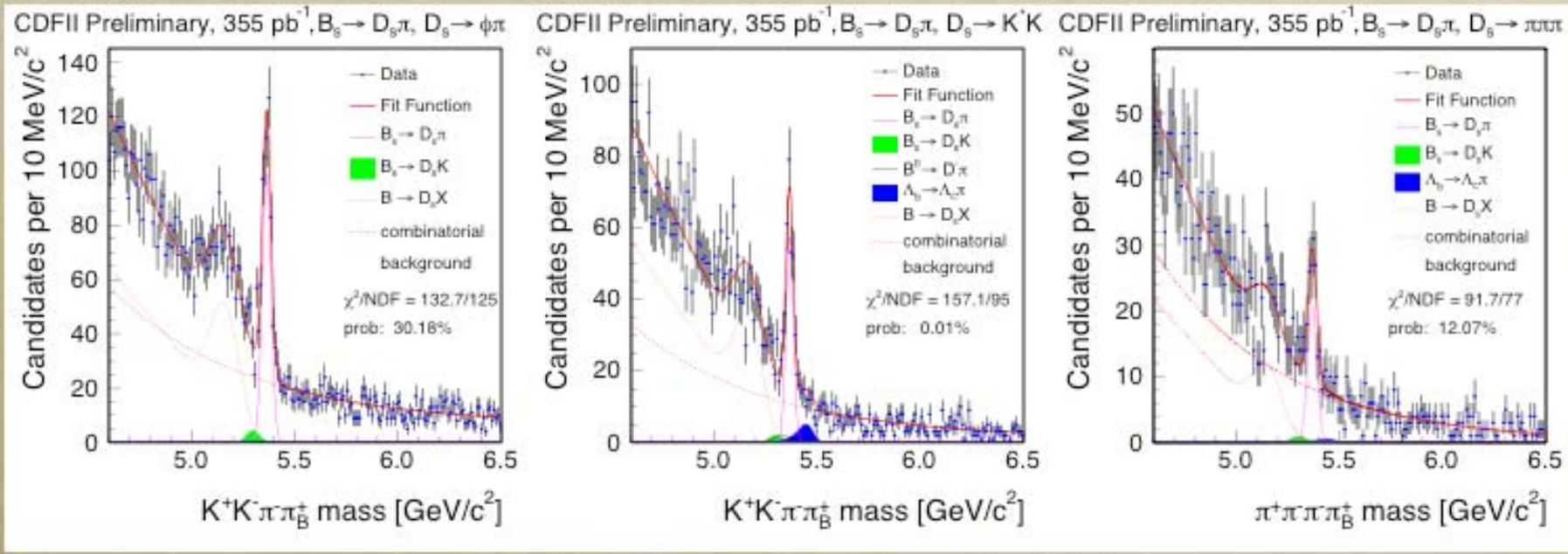
$$S_{\text{significance}} \sim \sqrt{\frac{S \cdot \epsilon D^2}{2}} \cdot \sqrt{\frac{S}{S+B}} \cdot e^{-\frac{(\Delta m\ \sigma_t)^2}{2}}$$

- ct-resolution $\sigma_t = \sigma_l \oplus t\sigma_p$
- vertex resolution (σ_l), measured per-event
- momentum resolution (σ_p): scales with ct
  - negligible for fully reconstructed modes
  - important effect in partially reconstructed decays

Samples

Hadronic samples $B_s \to D_s \pi$

$D^-_s \to \Phi \pi^-$ $D^-_s \to K^* K^-$ $D^-_s \to \pi^- \pi^- \pi^+$



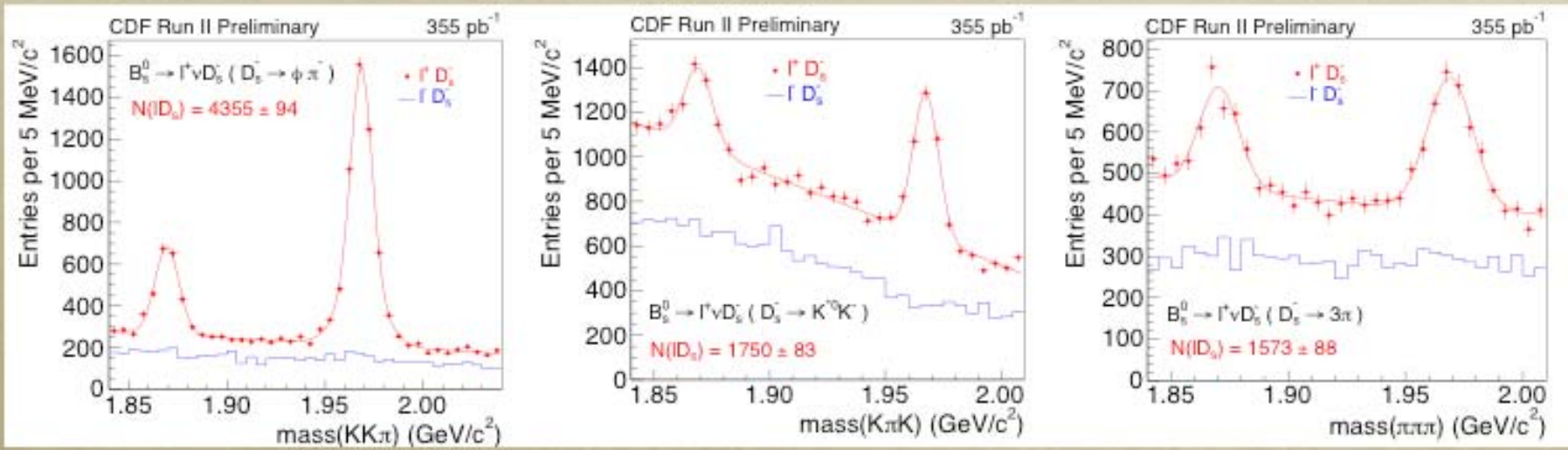
$S=526\pm33$, $S/B=1.8$ $S=254\pm21$, $S/B=1.7$ $S=115\pm18$, $S/B=1.0$

Exclude mass region of partially reflected B mesons in the fit

Smaller statistics, better ct resolution

Semileptonic samples $B_s \rightarrow l D_s X$

$D^-_s \rightarrow \Phi \pi^-$ $D^-_s \rightarrow K^{*} K$ $D^-_s \rightarrow \pi^- \pi^- \pi^+$



S=4355±94, S/B=3.1 S=1750±83, S/B=0.42 S=1573±88, S/B=0.32

B_s is only partially reconstructed

use D_s mass together with $l^- D_s$ charge correlation

Larger statistics, worse ct resolution

Decay time

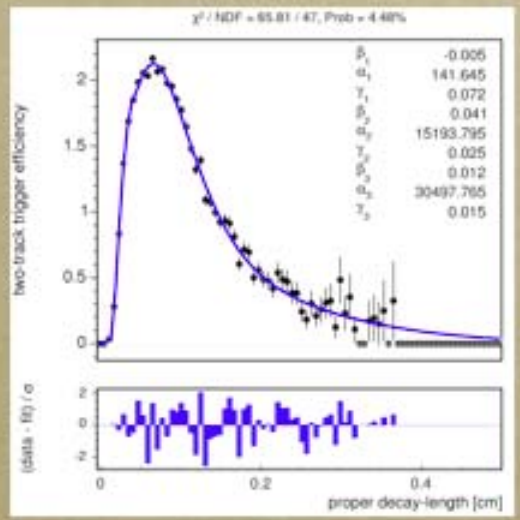
Proper decay time $t = L\, m/p$

ct-efficiency

Trigger and event selection sculpt lifetime distribution

Effect is described by ct-efficiency curve obtained from Monte Carlo:

$$\epsilon(ct) = \frac{\text{reconstructed } ct \text{ AFTER trigger + cuts}}{\text{reconstructed } ct \text{ BEFORE trigger + cuts}}$$



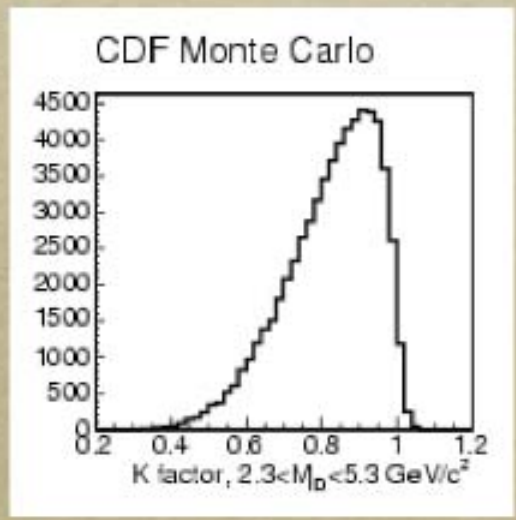
k-factor

Determination of B_s momentum is incomplete in semileptonic modes

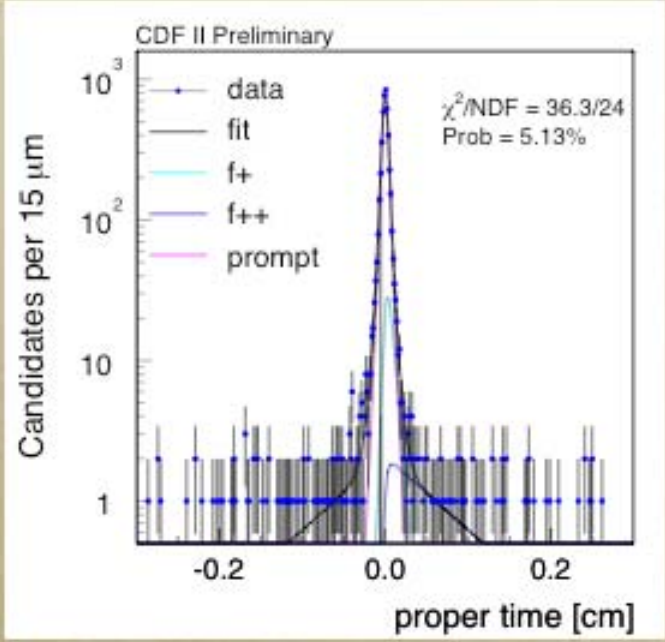
Worsens resolution in ct space

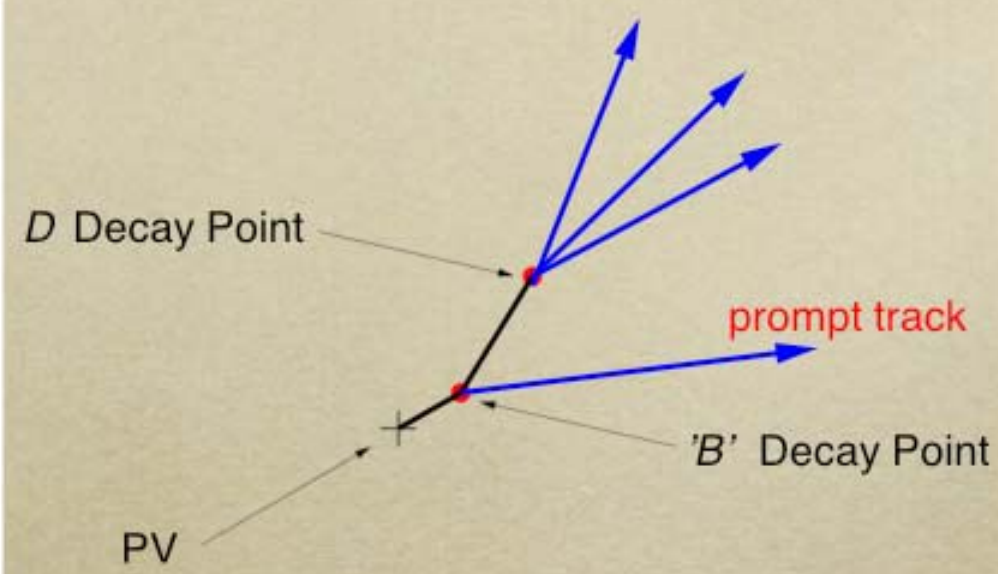
Include $k_{inematical}$-factor from MC:

$$k = \langle \frac{p_t(lD_s)}{p_t(B_s)} \rangle_{MC}$$



Vertex resolution calibration

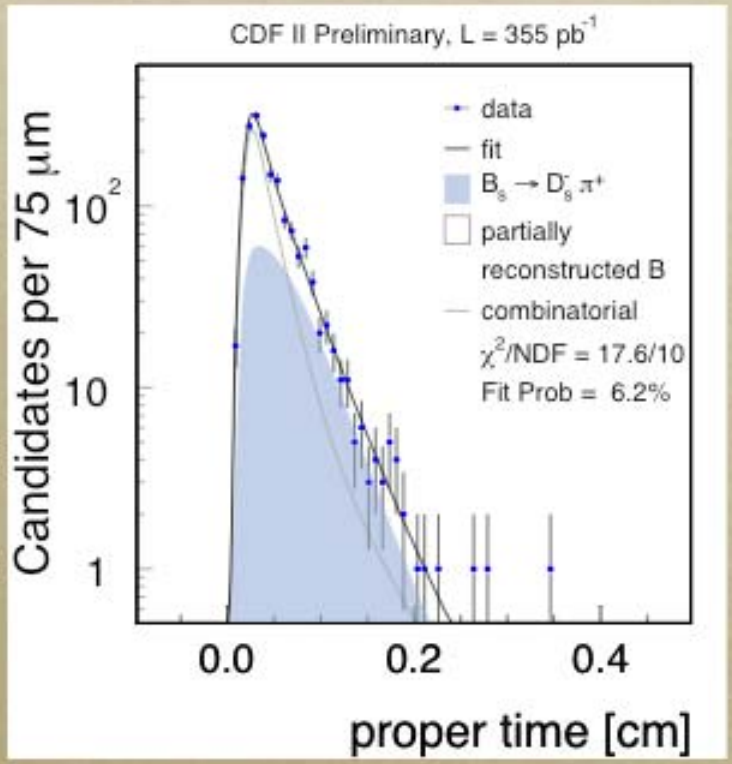




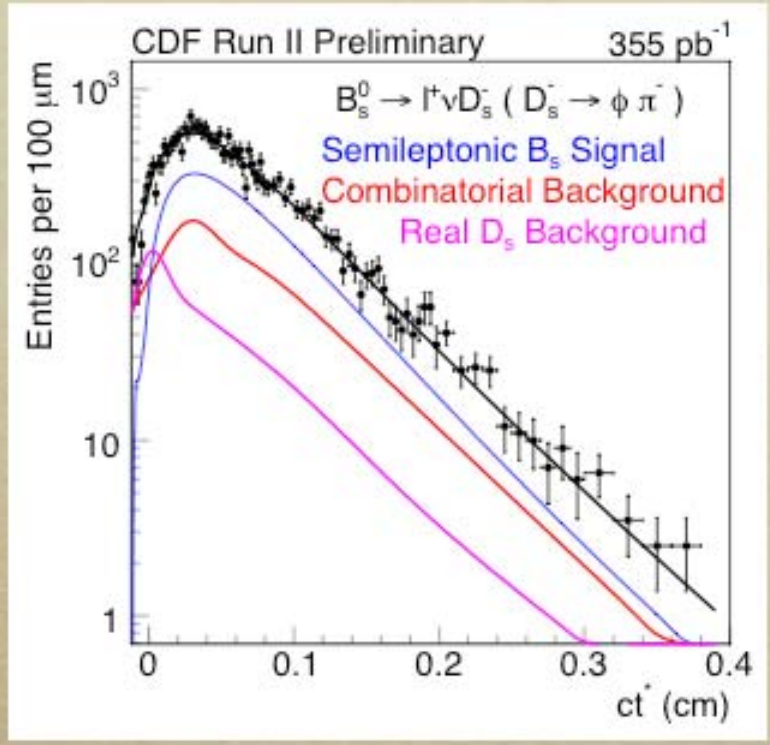
- Vertex fitter errors need to be corrected - scale factors
- Create unbiased calibration sample
  - require D to trigger and add unbiased track (not triggered)
- PV position has to be zero :: extract scale factor per event
- Fit: prompt unit Gaussian + negative tail + long-lived component

Lifetime fit

Hadronic



Semileptonic



$c\tau$ (B_s) = 479 ± 29 (stat) ± 5 (syst) μm

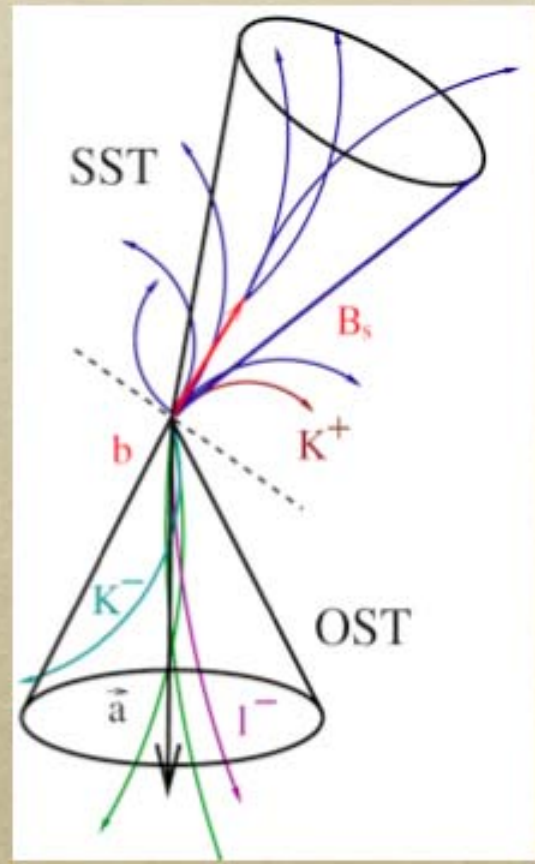
$c\tau$ (B_s) = 442.7 ± 9.5 (stat) μm

$c\tau$ (B_s) = 439.5 ± 17.7 μm [PDG 2005]

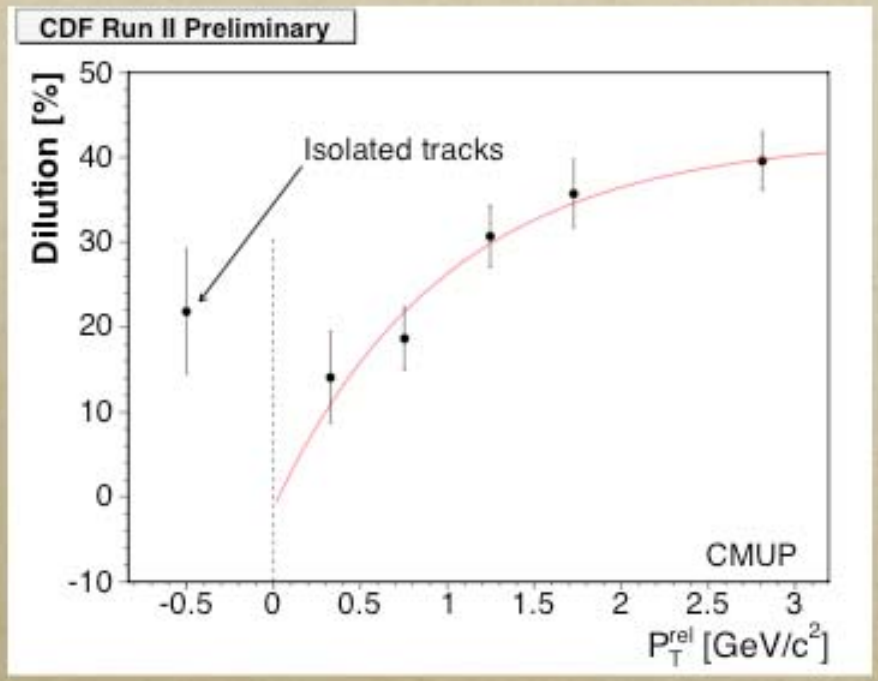
Flavor tagging

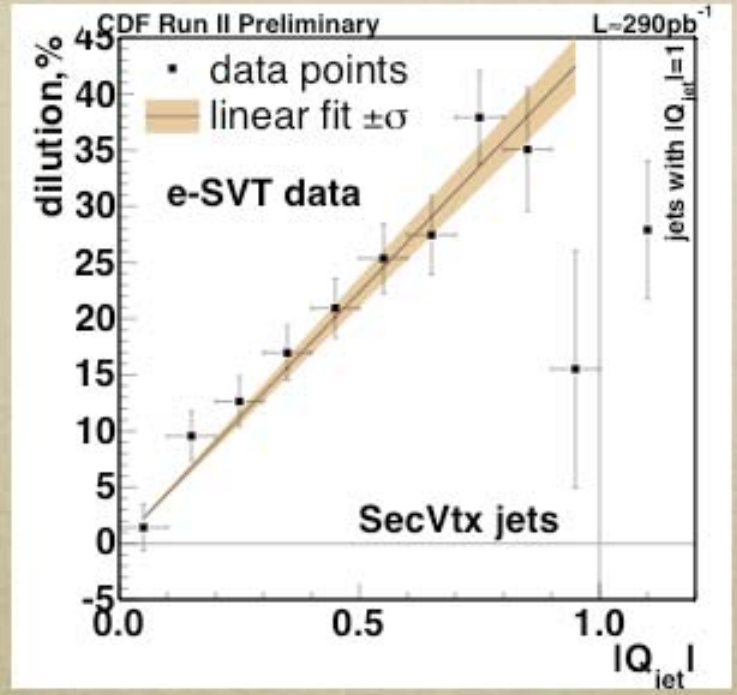
Tagging B production flavor

- Establish whether B originated from b or $\bar{b}$
- Two classes of flavor taggers:
  - Opposite-Side (based on properties of the non-reconstructed b-hadron)
  - Same-Side (dependent on B type)
    - *SST not used at current stage of the analysis*
- Use exclusive combination of OSTs:
  - Lepton taggers: muon, electron
  - Jet charge taggers: displaced vertex, jet probability, highest p_T
- Tagging power: ϵD^2
  - Efficiency, ϵ = fraction of tagged events
  - Dilution, $D = 1 - 2\,P_{mistag}$
  - Effective statistics for mixing is $N\,\epsilon D^2$



Dilution calibration





- OSTs tuned in lepton + SVT track high statistics sample
- Dependences: lepton likelihood and p_T w.r.t. jet axis, charge of jet
- Overall dilution scale factors measured in Dπ and lDX samples
- knowledge of per-event dilutions necessary input for B_s analysis

Tagger performance and Δm_d

	ϵD^2 Hadronic (%)	ϵD^2 Semileptonic (%)
Muon	$0.46 \pm 0.11 \pm 0.03$	$0.577 \pm 0.047 \pm 0.034$
Electron	$0.18 \pm 0.06 \pm 0.02$	$0.293 \pm 0.033 \pm 0.017$
JQ/Vertex	$0.14 \pm 0.07 \pm 0.01$	$0.263 \pm 0.035 \pm 0.021$
JQ/Prob.	$0.11 \pm 0.06 \pm 0.01$	$0.150 \pm 0.026 \pm 0.015$
JQ/High p_T	$0.24 \pm 0.09 \pm 0.01$	$0.157 \pm 0.027 \pm 0.015$
Total	$1.12 \pm 0.18 \pm 0.04$	1.429 ± 0.093
Δm_d [ps^{-1}]	$0.503 \pm 0.063 \pm 0.015$	$0.497 \pm 0.028 \pm 0.015$

$\Delta m_d = 0.505 \pm 0.005$ ps^{-1} [PDG 2005]

Likelihood Fitting

Likelihood model

Perform unbinned likelihood fit using event information:

mass, proper decay-time t and σ_t, tagging decision and dilution

Introduce PDFs describing all signal and background components

Example: signal PDF in ct-space for tagged events (for hadronic modes k=1, F(k)=1):

Normalization **Lifetime** **Tagging** **Mixing** **ct-resolution** **ct-efficiency** **k-factor**

$$\mathcal{P}(t) = \frac{1}{N}\,\Gamma k\, e^{-\Gamma k t'}\,\{\frac{1 \pm AD\ cos(\Delta m_s k t')}{2}\} \otimes G(t-t';\sigma_t)\cdot \epsilon_{ct}(t) \otimes \mathcal{F}(k)$$

Amplitude (A,σ_A)

$$N = \int \Gamma k e^{-\Gamma k t'} \otimes G(t-t';\sigma_t)\cdot \epsilon_{ct}(t) \otimes \mathcal{F}(k)\ dt$$

(PDF normalization, analytical calculations)

Amplitude method

Introduce Amplitude into likelihood: $P \sim 1 \pm A\, D \cos(\Delta m_s\, t)$

Perform Amplitude fit for spectrum of Δm_s probed values

expect: A~1 for true Δm_s value and A~0 away from true value

Apply method to B^0 mixing case

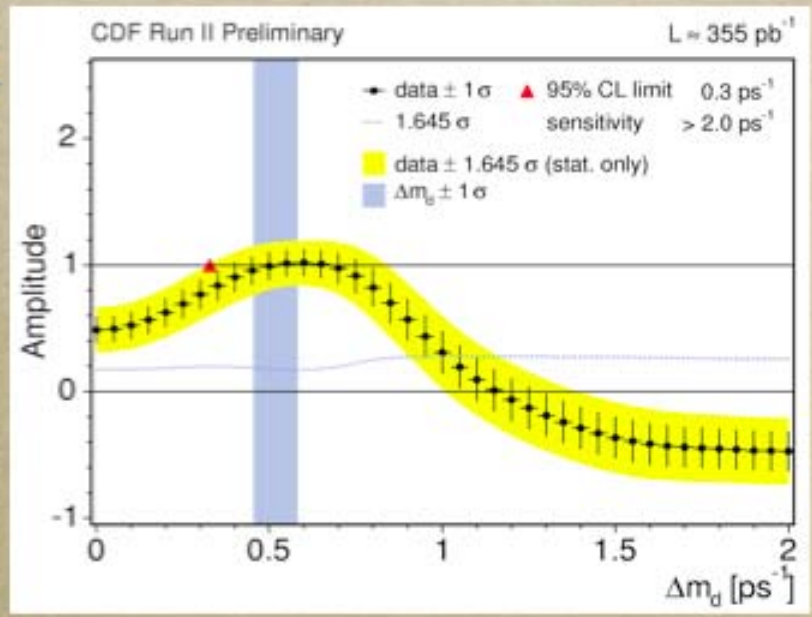
- 95% CL exclusion condition

$$A + 1.645\, \sigma_A < 1$$

- 95% CL sensitivity condition

$$1.645\, \sigma_A = 1$$

H.G. Moser, A. Roussarie, NIM **A384** (1997)

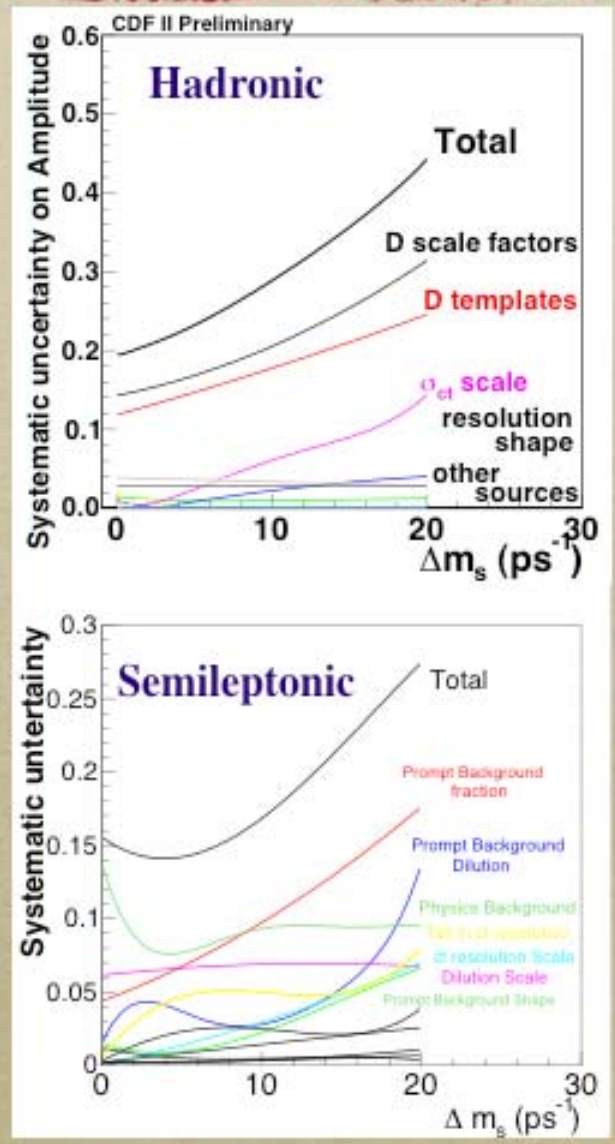


Summary of Systematic uncertainties

- Dominant contributions :: **Hadronic**
  - absolute dilution calibration
  - shape of dilution templates
  - statistical effects feed in systematics
- Dominant contributions :: **Semileptonic**
  - prompt background fraction + asymmetry
  - physics backgrounds fractions
- Analysis is statistics dominated
- Evaluate by fitting toy MC samples
  - with modified likelihood configurations
  - take shifts in A and in statistical error σ_A

  [H.G. Moser, A. Roussarie, NIM **A384** (1997)]

$$\sigma_A^{syst} = \Delta A + (1 - A)\frac{\Delta\sigma_A}{\sigma_A}$$

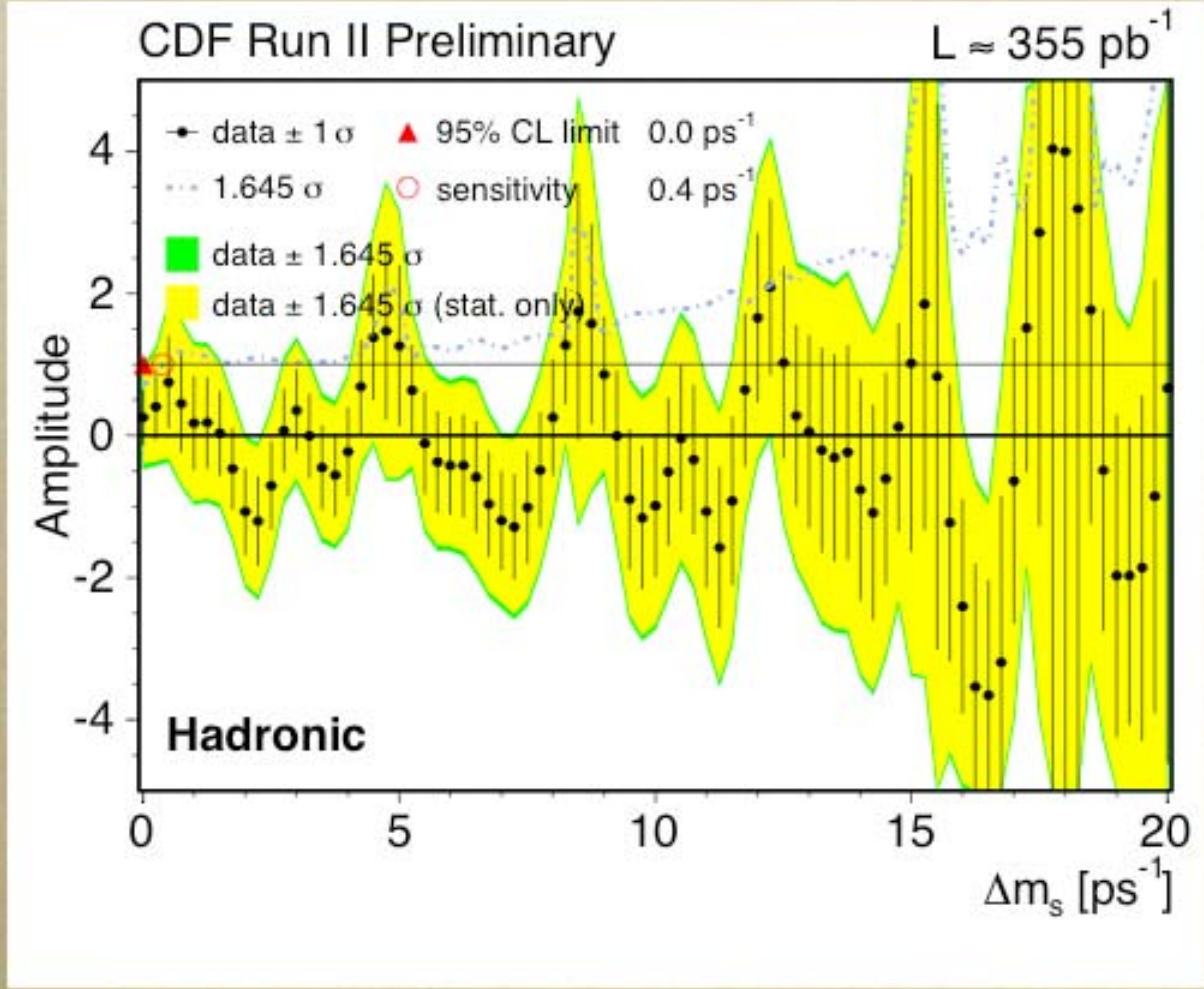


Amplitude scan (i)

Hadronic modes

95% CL Limit
0.0 ps^{-1}

Sensitivity
0.4 ps^{-1}

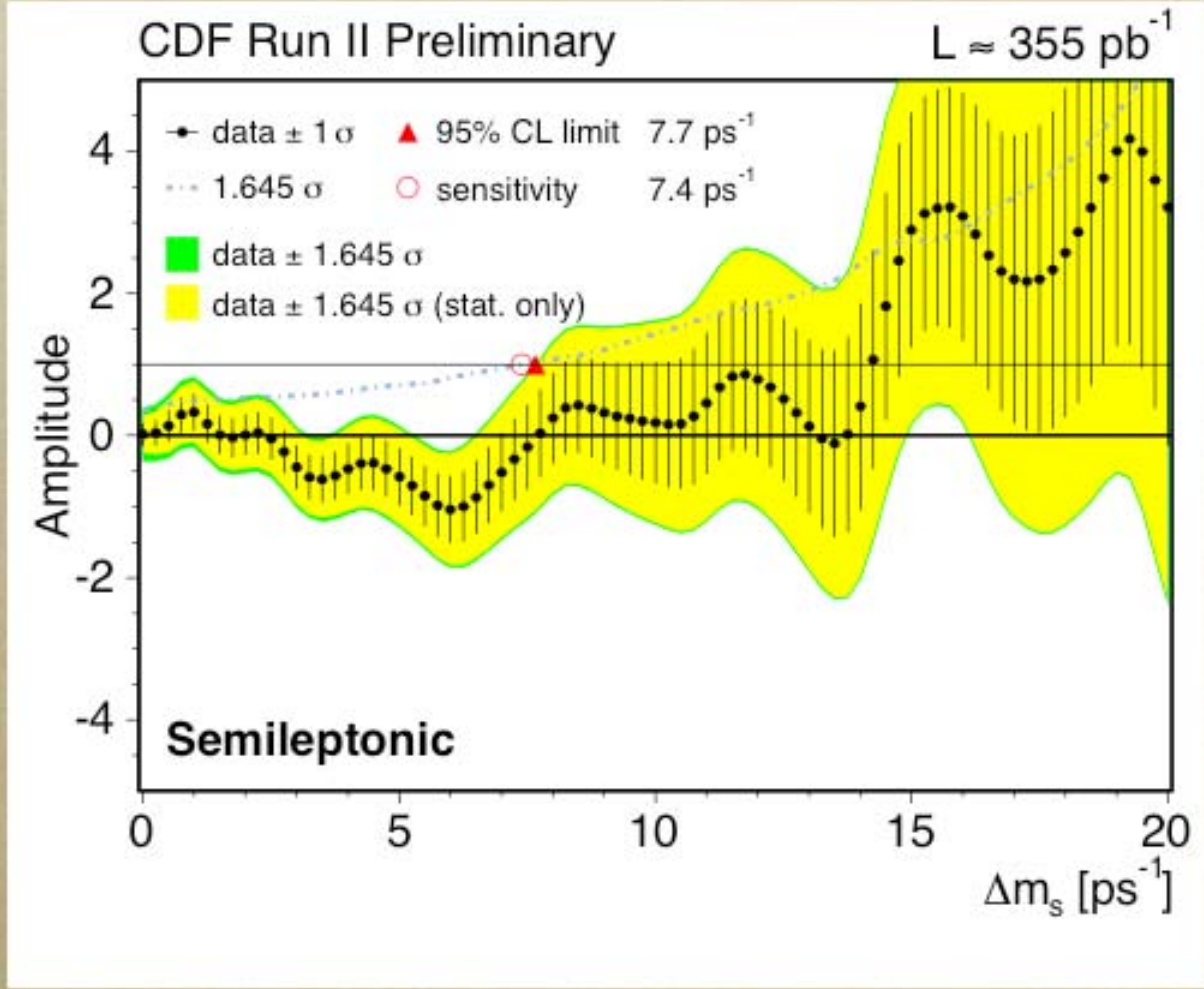


Amplitude scan (ii)

Semileptonic modes

95% CL Limit
7.7 ps^{-1}

Sensitivity
7.4 ps^{-1}

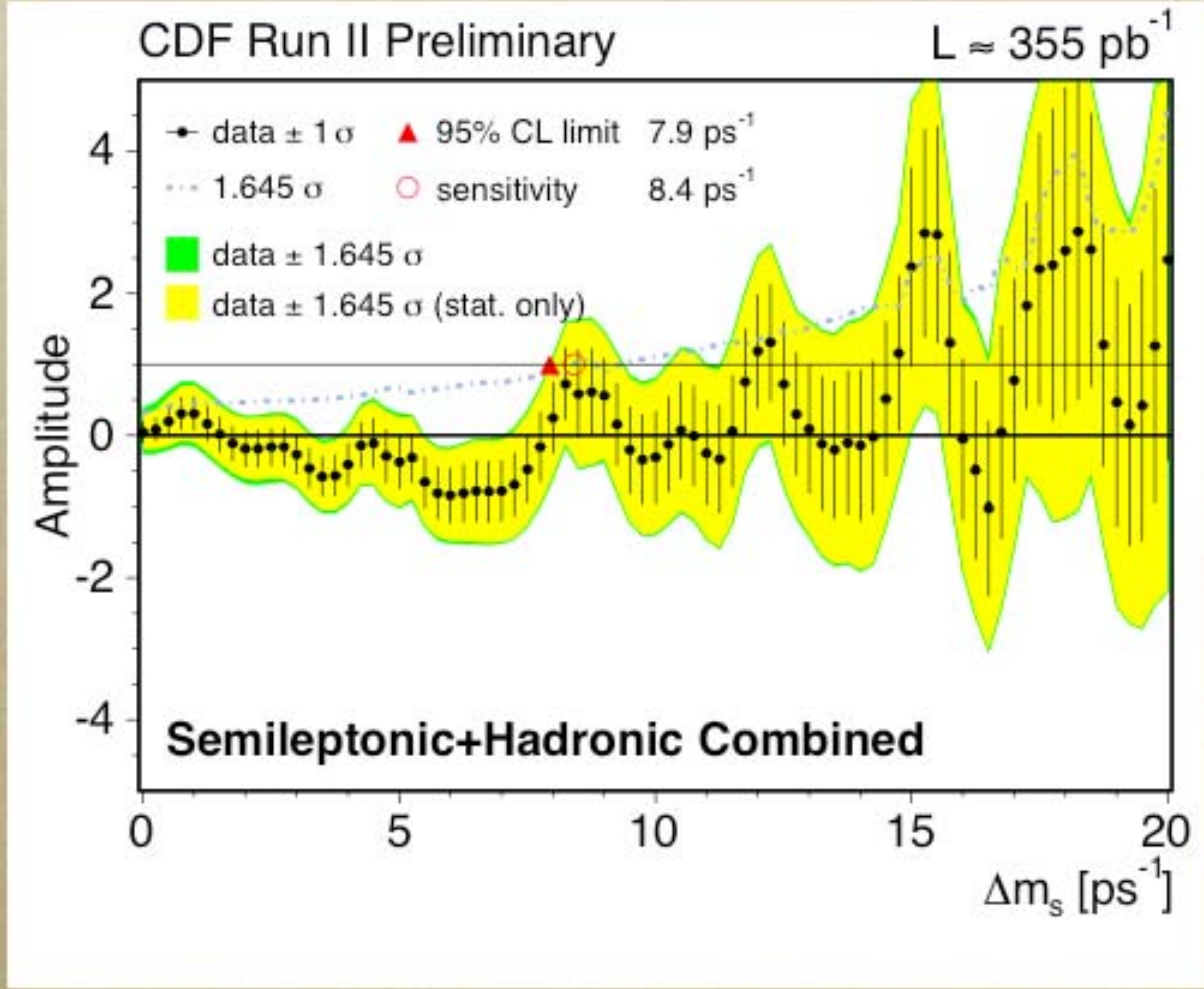


Amplitude scan (iii)

Combined
semileptonic+hadronic
modes

95% CL Limit
7.9 ps^{-1}

Sensitivity
8.4 ps^{-1}



Amplitude scan (iv)

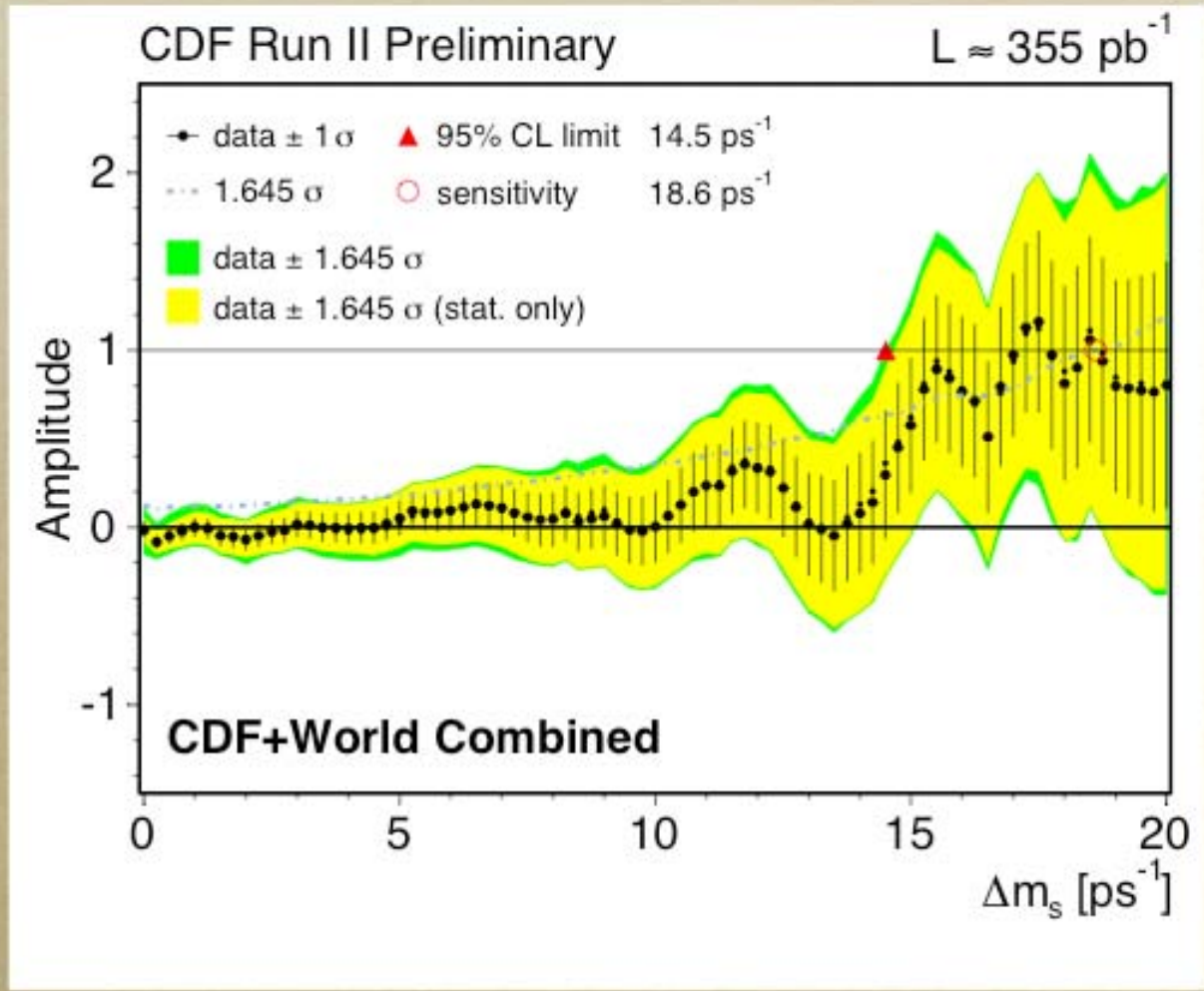
Combined CDF&World

95% CL Limit

14.5 ps^{-1} → **14.5 ps^{-1}**

Sensitivity

18.2 ps^{-1} → **18.6 ps^{-1}**



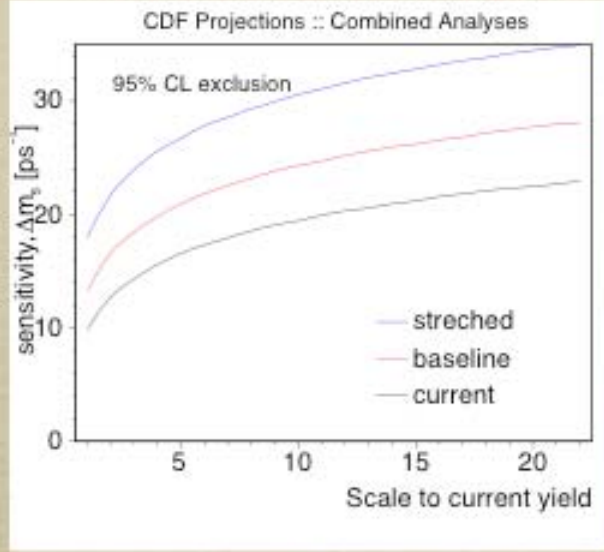
Improvements

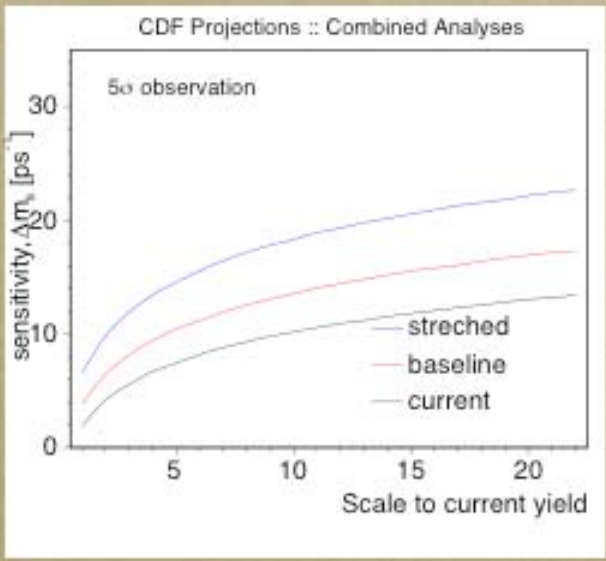
Measurement improvements

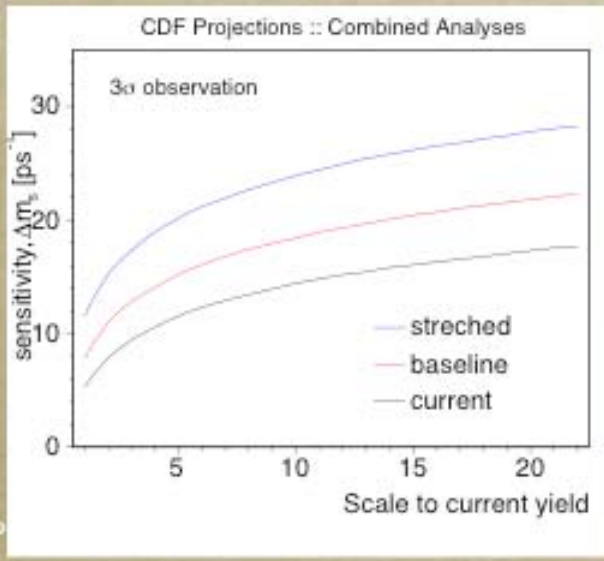
- Tagging: include SST to combine with OSTs
- Vertex resolution: use per-event primary vertex determination instead of beamline; track fitting
- Sample statistics: collect and analyze more data, new modes and triggers (+e.g. semileptonic signals from hadronic trigger)
- Projections made for following scenarios
  (based on analytical description of significance curves)
  - current
  - baseline: additional 0.01 in ϵD^2 and 10% in vertex resolution
  - stretched: additional 0.03 in ϵD^2 and 20% in vertex resolution

Sensitivity projections

- Projections shown for multiples of B_s yield currently analyzed
- In near/medium term should be able to contribute to improve exclusion limit
- Observation is a longer term objective







Conclusions

- Performed first B_s mixing analysis at CDF Run II
  - exclusion limit **7.9 ps^{-1}** and sensitivity **8.4 ps^{-1}** at 95% CL
- Hadronic and Semileptonic B_s decays
  - best probe complementary regions of Δm_s spectrum
- Established lifetime and mixing analysis techniques
  - trigger biases, likelihood model, sample backgrounds
- Measurement will further benefit from improvements soon
  - flavor tagging, decay time resolution, sample size

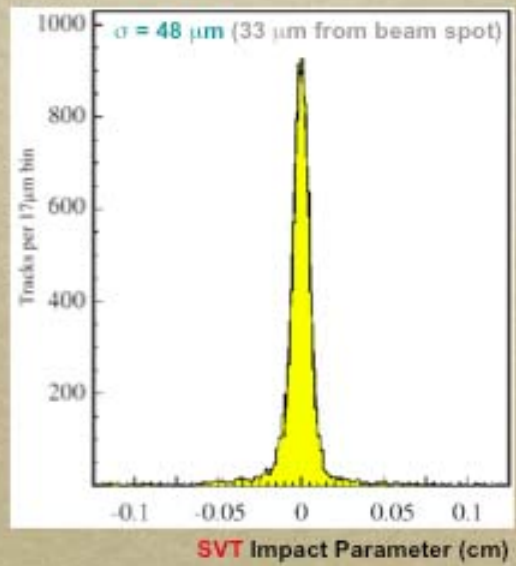
Backup

B physics in $p\bar{p}$ collisions

- Huge B production cross section
  - $\sigma(pp \rightarrow bX, |y| < 0.6) = 17.6 \pm 0.4\ (stat) \pm 2.5\ (syst)\ \mu b$
  - 3 orders of magnitude higher than at $e^+e^- \rightarrow \Upsilon(4s)$
- Various b-hadron species are produced
  - $B^+, B^0, B_s, B_c, \Lambda_b, \Xi_b, B^*, B^{**}$
- Immersed in large inelastic background
  - inelastic cross section ~100 mb
  - challenge: pick 1 B decay from ~10^3 QCD events

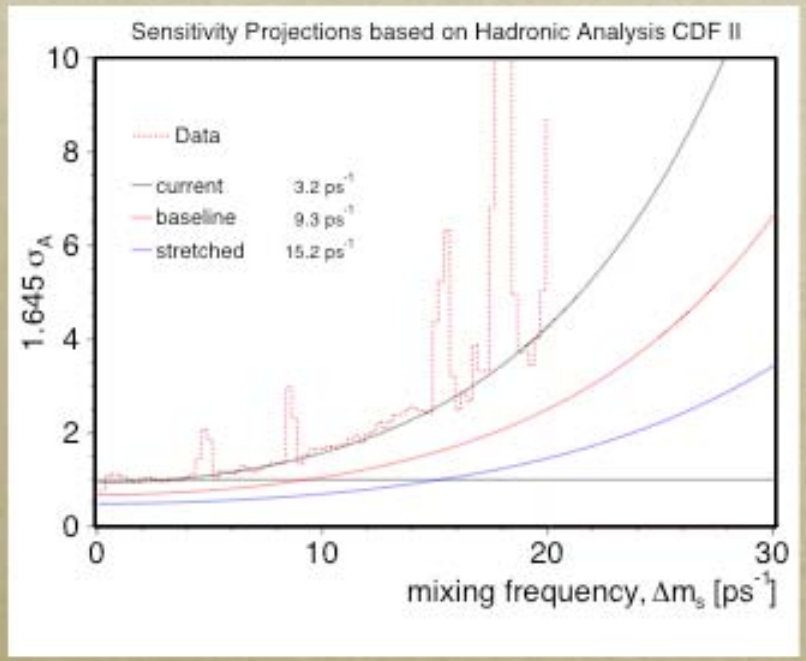
Trigger

- Two displaced-tracks trigger
  - $p_T > 2$ GeV/c, 120 μm $< d_0 <$ 1 mm, $\Sigma\ p_T > 5.5$ GeV/c
- Lepton + displaced-track trigger
  - $p_T > 2$ GeV/c, 120 μm $< d_0 <$ 1 mm, $p_T(\mu,e) > 2$ GeV/c

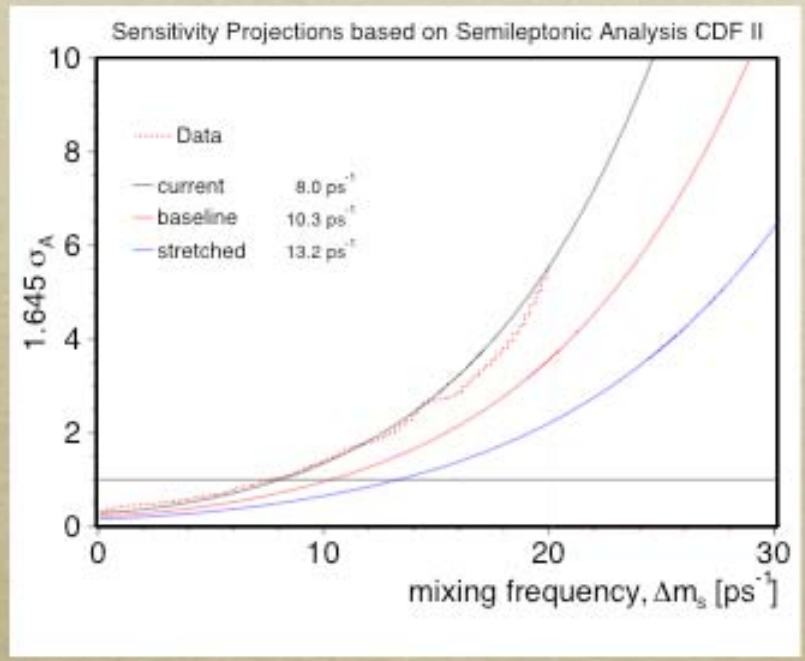


Significance curves

Hadronic modes



Semileptonic modes



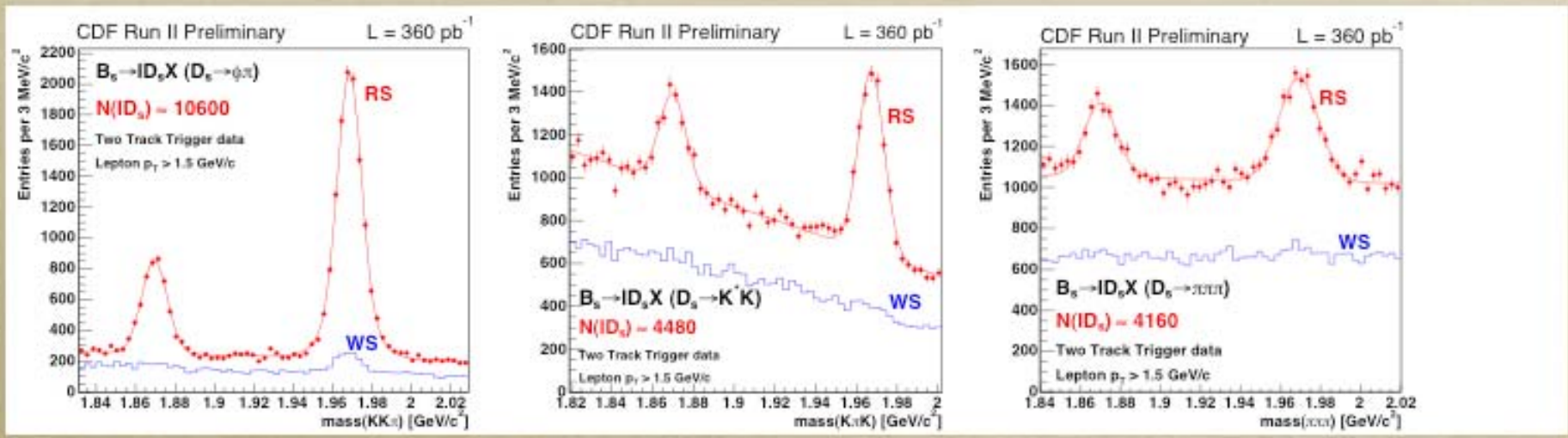
semileptonic and hadronic — semileptonic modes only

$$\sigma_A \sim \sqrt{\frac{2}{\epsilon D^2}} \cdot \frac{\sqrt{S+B}}{S} \cdot e^{\frac{\sigma_t^2 \Delta m_s^2}{2}} \cdot \frac{\sqrt{2}\sigma_p \Delta m_s}{\sqrt{\pi}\Gamma} e^{-\left(\frac{\Gamma}{\sqrt{2}\sigma_p \Delta m_s}\right)^2}$$

Analytical description of significance curves [H.G. Moser, A. Roussarie, NIM **A384** (1997)]

Semileptonic signals from two-track trigger

$D^-_s \rightarrow \Phi\,\pi$ $D^-_s \rightarrow K^* K$ $D^-_s \rightarrow \pi\,\pi\,\pi^+$



S~10600 S~4480 S~4160

Important sample of semileptonic Bs mesons to be included in next round of mixing analysis!