Measurement of B_s oscillations at CDF

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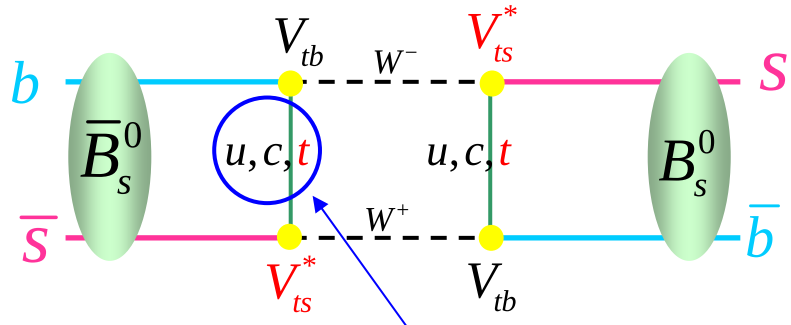
Outline

- Motivations: ΔM_s and the Unitarity Triangle
- Analysis details:
  - Trigger and reconstruction
  - Lifetime measurements and biases
  - Flavour tagging
- (Some) Statistical details and expected significance
- Results for ΔM_s
- Interpretation and derived constraints

- Paper submitted to PRL: hep-ex/0606027

Why ΔM_s

Observation of a quantum phenomenon: flavour oscillations via a $\Delta F = 2$ *Box* diagram



$$\Delta M_q = \frac{G_F^2 m_W^2 \eta S(x_t^2)}{6\pi^2} m_{B_q} f_{B_q}^2 B_{B_q} |V_{tq}^* V_{tb}|^2$$

- The only relevant diagram has b coupling with top
- New (s)particles in the loop..?

Form factors and B-parameters from Lattice calculations have high uncertainty → V_{td} known *only* at ~15% level

Mixing involves CKM elements → measuring ΔM_q constraints the unitarity triangle

UT and constraint from mixing

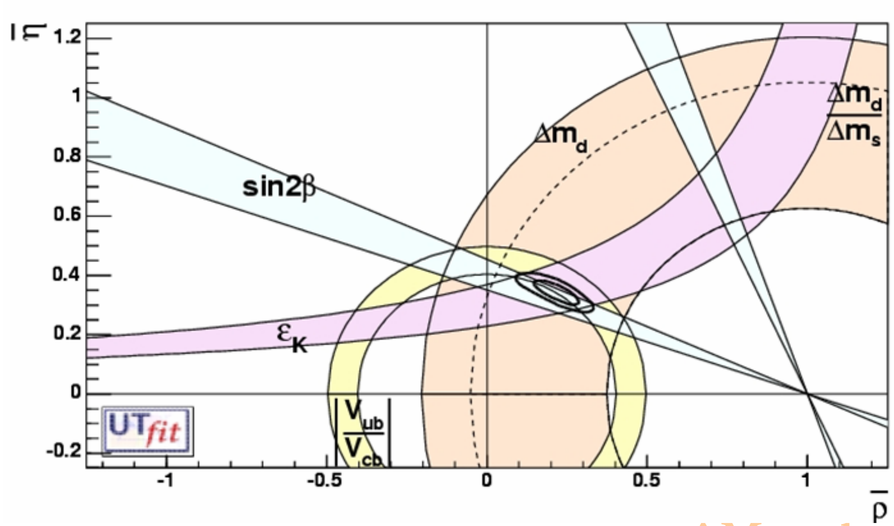
From lattice:

- **Ratio** $\frac{f_d^2 B_d}{f_s^2 B_s} \equiv \xi^2$ **is better calculated than single factors**

- $\xi = 1.210^{+0.047}_{-0.035}$

(M.Okamoto, hep-lat/0510113)

♣ **Measuring $\Delta M_s / \Delta M_d$ returns V_{ts} / V_{td} with ~4% error from theory**



ΔM_d only

Limit on ΔM_s ··········· $\Delta M_s / \Delta M_d$

UP TO WINTER '06:

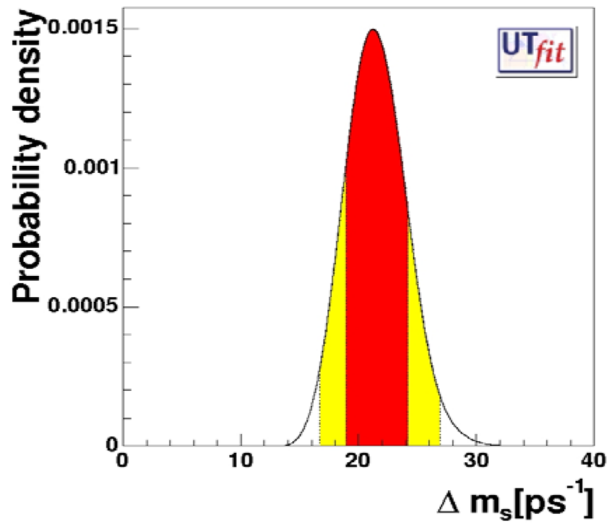
•$\Delta M_s \geq 16.6\ ps^{-1}$ (LEP+SLD+Tevatron I and II)

•**Expected value** (UT fit, utfit.roma1.infn.it) :

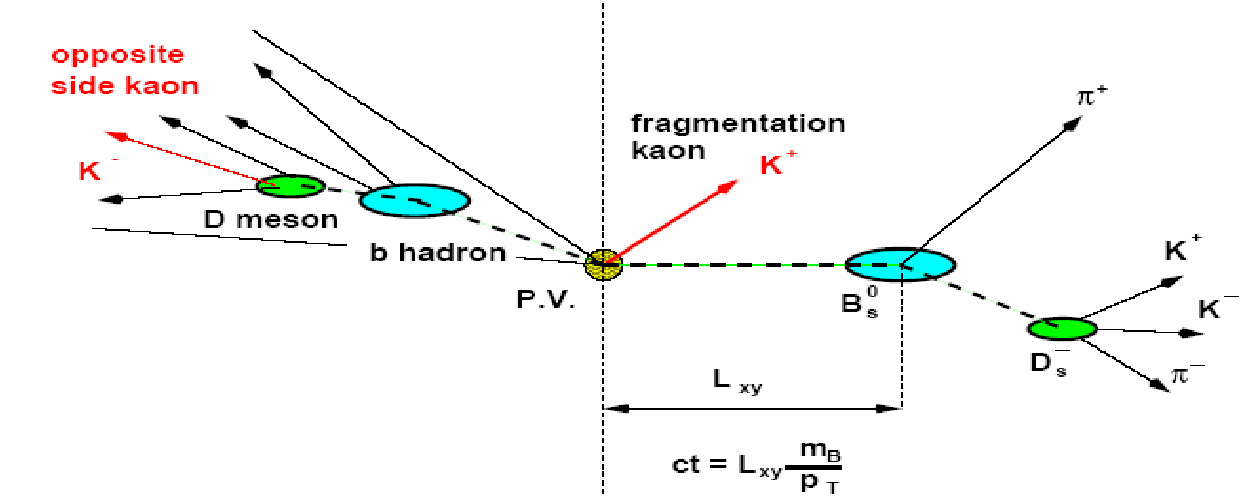
ΔM_s (SM) = 21.5 ± 2.6 ps^{-1}

ΔM_s in [16.7, 26.9] @ 95% CL

♣ **LARGER ΔM_s could indicate NP contrib's**



Want to measure…so, how?



- **Final state:**
  - **Reconstruct final states from both *Semileptonic* (high statistics, *but* missing kinematics) and *Hadronic* (fully reconstructed, best ct resolution)**
- **Lifetime measurement**
  - **Hadronic decay length measured with better resolution than Semileptonic**
- **Flavour tagging**
  - **Tag the flavour of the mixing B candidate using both:**
    - **correlation with fragmentation tracks AND**
    - **flavour of other *b* (*incoherent* b-$\bar{b}$ production)**

Amplitude Scan

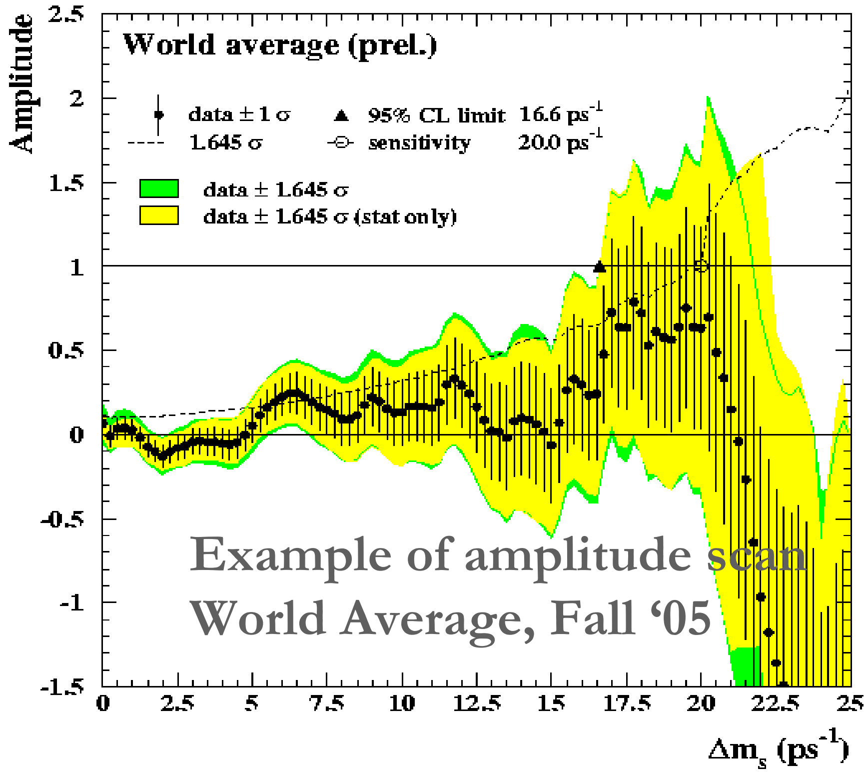
Introduce "Amplitude" in Likelihood

$$L_{sig}^{t} = \frac{1}{\tau} e^{-t/\tau} \left(1 \pm A \cdot D \cdot \cos\left(\Delta M \cdot t\right)\right)$$

- **Fit A for fixed ΔM**

- **A consistent with:**
  1 if mixing detected at a given ΔM
  0 if no mixing at a given ΔM

- **Limit where A+1.645σ_A = 1**
- **Sensitivity: 1.645σ_A = 1**



Measurement significance

- **The expression of the statistical Significance of a mixing measurement is given by:**

Trigger-challenge to collect S *suppressing B*

$$1/\sigma_A = \sqrt{\frac{S\varepsilon D^2}{2}}\, e^{-\frac{(\Delta M_s \cdot \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

Signal

(*b*-flavour at decay tagged)

Fraction of S with info *also* on flavour at creation

Experimental time resolution *exponentially* dilutes a measurement

- **Significance exponentially reduced at higher ΔM_s …**


…$|V_{ts}|$ >> $|V_{td}|$ $\Rightarrow$ $\Delta M_s \sim 40 \cdot \Delta M_d$

Final states selection and yields

Hadronic signals

L = 1 fb^{-1}
N(B_s) ≈ 3600

•Fully reconstructed decays triggered on **at CDF only**; requiring 2 tracks with
• $d_0 > 120\ \mu m$ ($\tau(B) \approx 1.5 ps$)
• $P_t > 5.5$ GeV/c

$B_s^0 \to D_s^-$ (3)π^+ ($D_s^- \to \varphi\pi^-$, $\varphi \to K^+ K^-$)

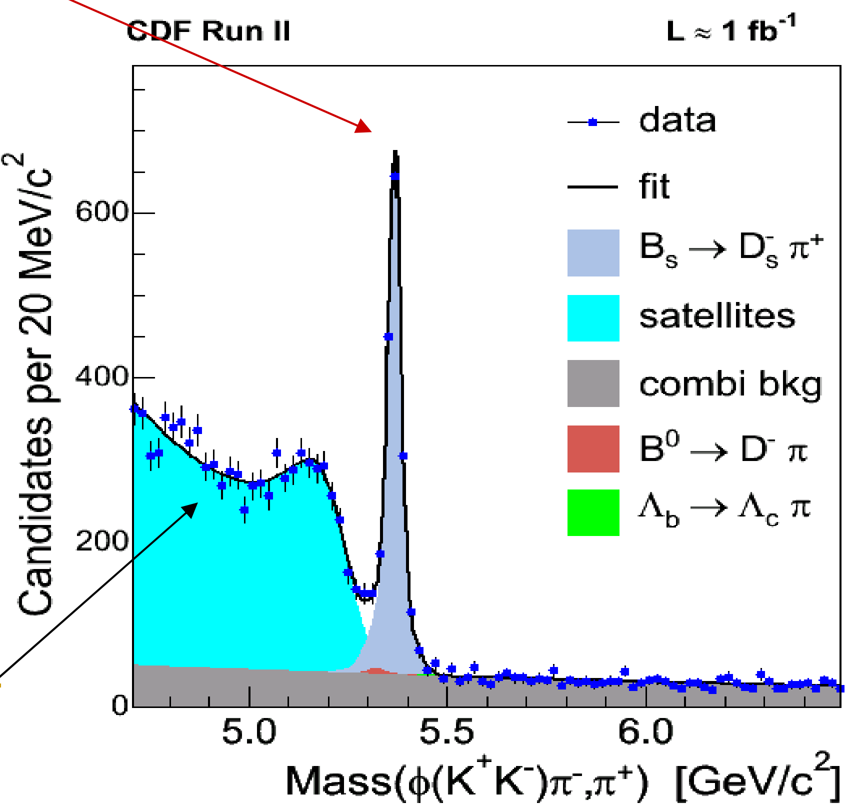
$B_s \to D_s \pi$, $D_s \to \varphi \pi$	1570 ± 43
$B_s \to D_s \pi$, $D_s \to K^{*0} K^-$	857 ± 32
$B_s \to D_s \pi$, $D_s \to 3\pi$	612 ± 37
$B_s \to D_s 3\pi$, $D_s \to \varphi \pi$	493 ± 37
$B_s \to D_s 3\pi$, $D_s \to K^{*0} K^-$	204 ± 26

"Satellites":

$B_s^0 \to D_s^{*-}\pi^+ (D_s^{*-} \to D_s^- \gamma)$

$B_s^0 \to D_s^- \rho^+ (\rho^+ \to \pi^+ \pi^0)$

(Not used in this analysis)

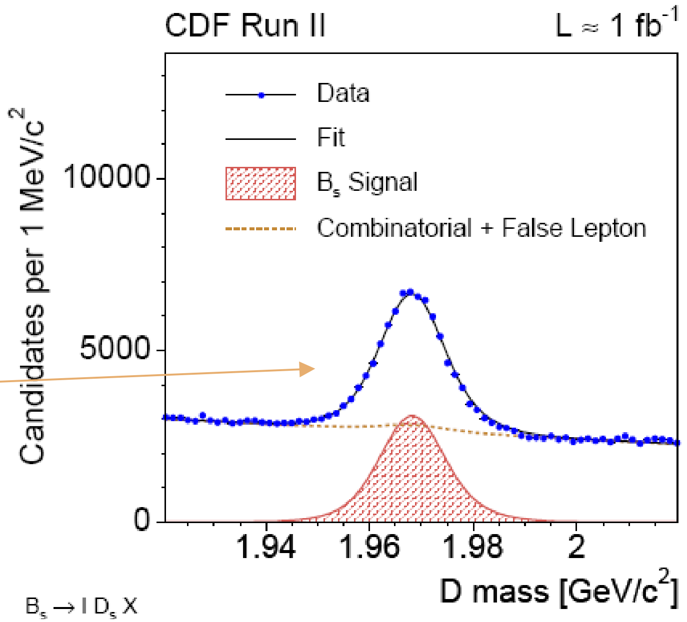


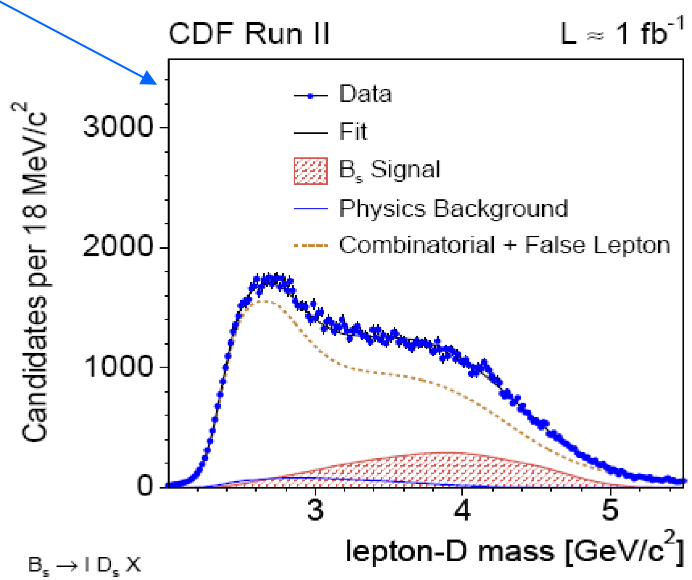
Semileptonic signals

$B_s^0 \rightarrow D_s^{-(*)} \ell^+ \nu X \; (D_s^- \rightarrow \varphi \pi^-)$

- Missing $P_t \rightarrow$ No B_s mass peak
- Use D_s mass signals
- Using $M(lD_s)$ helps bkg rejection
- Charge correlation between ℓ and D_s:
- Bkg also from Right Sign (~15%):
  - D_s + fake lepton from PV
  - $B_{s,d}$ to D_sDX, D to $\ell\,\nu X$
  - $c\bar{c}$ background

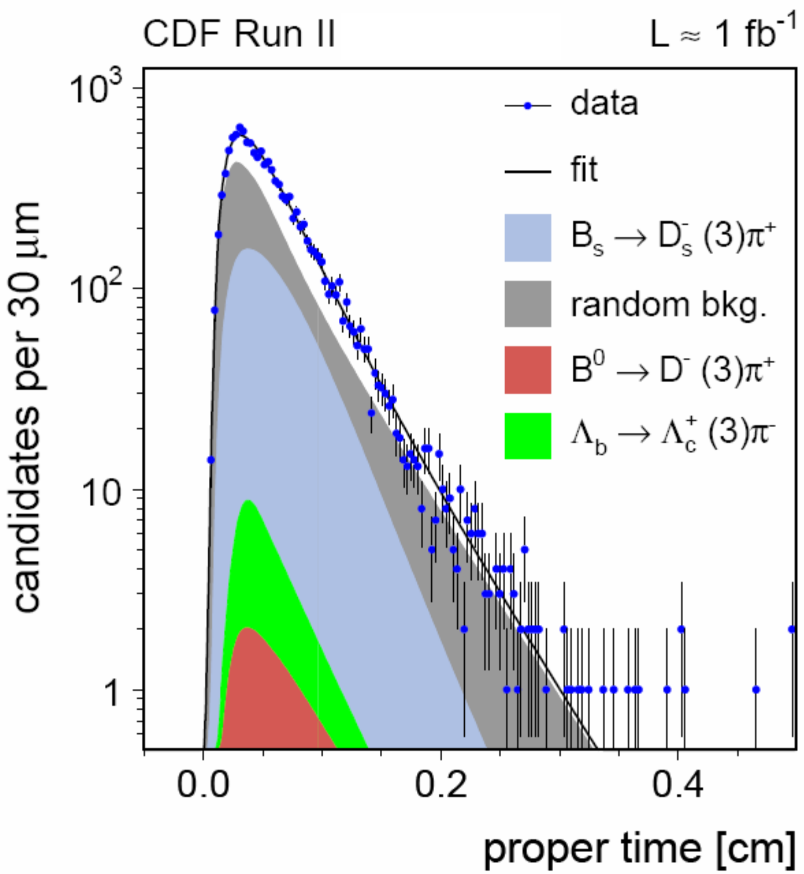
~37000 semileptonic B_s candidates





Lifetime measurement

Hadronic Lifetime Results



Mode	$c\tau$ [μm] (stat. only)
$B^0 \to D^- \pi^+$	491.1 ± 5.1
$B^- \to D^0 \pi^-$	452.1 ± 5.1
$B_s \to D_s(\phi\pi)\ \pi$	461 ± 12

- World Average (HFAG06)

$c\tau(B^+) = 491.1 \pm 3.3(\text{stat})$ μm

$c\tau(B_d) = 458.7 \pm 2.7$ μm

$B_s \to$ Flavour specific:

$c\tau(B_s) = 432 \pm 20$ ps

Excellent agreement !

•Detailed simulation to correct for trigger bias on the selection of the B decay length

•Syst. on trigger efficiency negligible for mixing measurements

Effect of proper time resolution

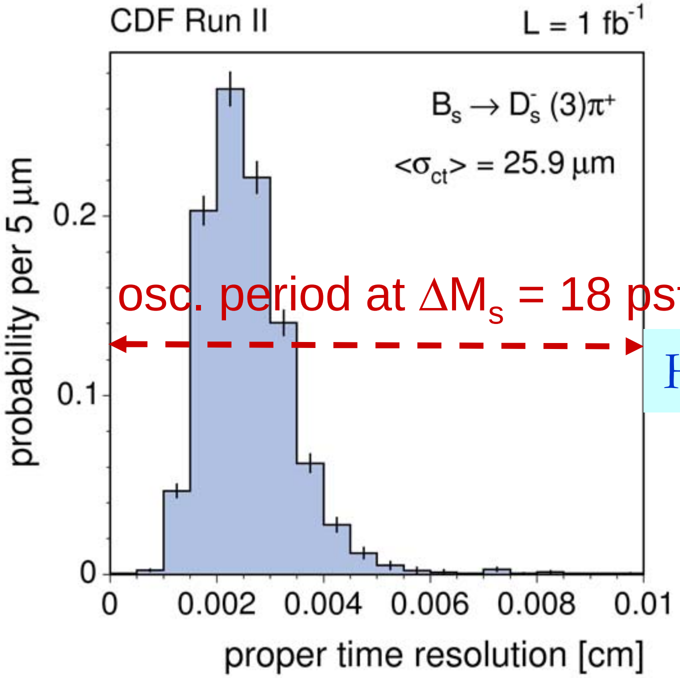
Amplitude of mixing asymmetry diluted by a factor

$$D_{\sigma_t} = e^{-\frac{(\Delta M \cdot \sigma_t)^2}{2}}$$

$$\sigma_{ct} = \sqrt{(\sigma^0_{ct})^2 + \left(ct \times \frac{\sigma_p}{p}\right)^2}$$

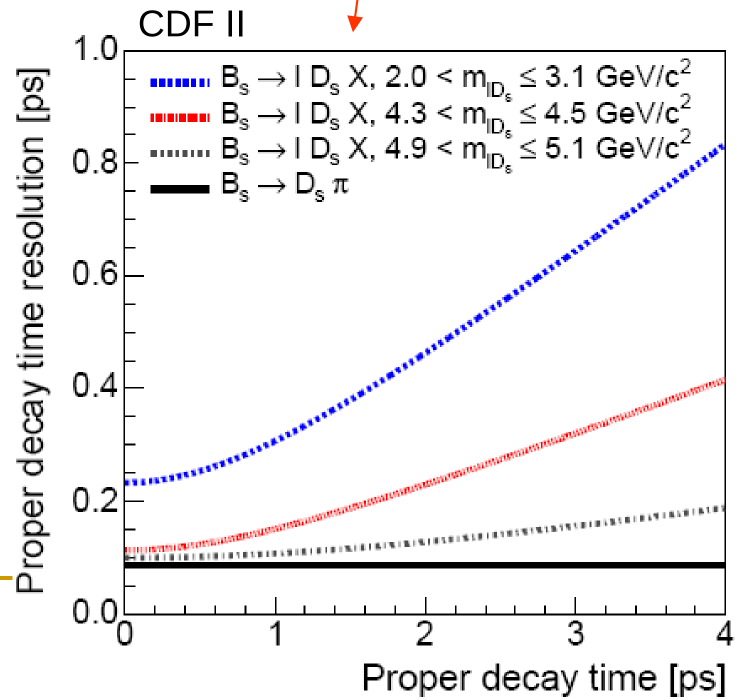
Vertex resolution (constant)

Momentum resolution (~ct)



Hadronic-like

Semileptonic-like $\langle\sigma_p/p\rangle \approx 15\%$



- Calibrated on large D^+ data samples combined with prompt tracks to mimic B^0-like topologies
- Calibrate by fitting for lifetime of B^0-like decays

Flavour tagging

Combined tagging power

- Opposite Side Taggers (OST) tag the other b-hadron in the event using e and μ from decay and jet charge
- Combine OST exclusively
- Calibrate Combined OST on samples of B^+ and B_d (by measuring ΔM_d)
- **Add Same Side Kaon Tagger independently**

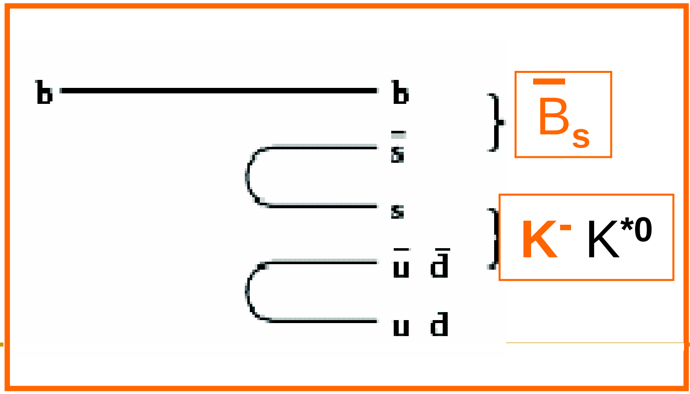
Dilution = 1-2•mistag rate

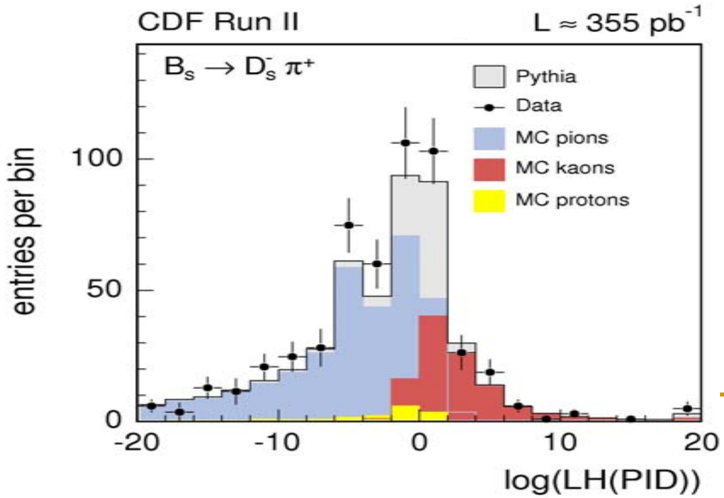
Efficiency

	εD^2 Hadronic (%)	**εD^2 Semileptonic (%)**
Muon	**0.48 ± 0.06 (stat)**	**0.62 ± 0.03 (stat)**
Electron	**0.09 ± 0.03 (stat)**	**0.10 ± 0.01 (stat)**
JQ/SecVtx	**0.30 ± 0.04 (stat)**	**0.27 ± 0.02 (stat)**
JQ/Displ'd trk	**0.46 ± 0.05 (stat)**	**0.34 ± 0.02 (stat)**
JQ/High p_T	**0.14 ± 0.03 (stat)**	**0.11 ± 0.01 (stat)**
Total OST	**1.47 ± 0.10 (stat)**	**1.44 ± 0.04 (stat)**
SSKT	**3.5 ± 0.5 (syst)**	**4.0 ± 0.6 (syst)**

Main "boost" is from SSKT

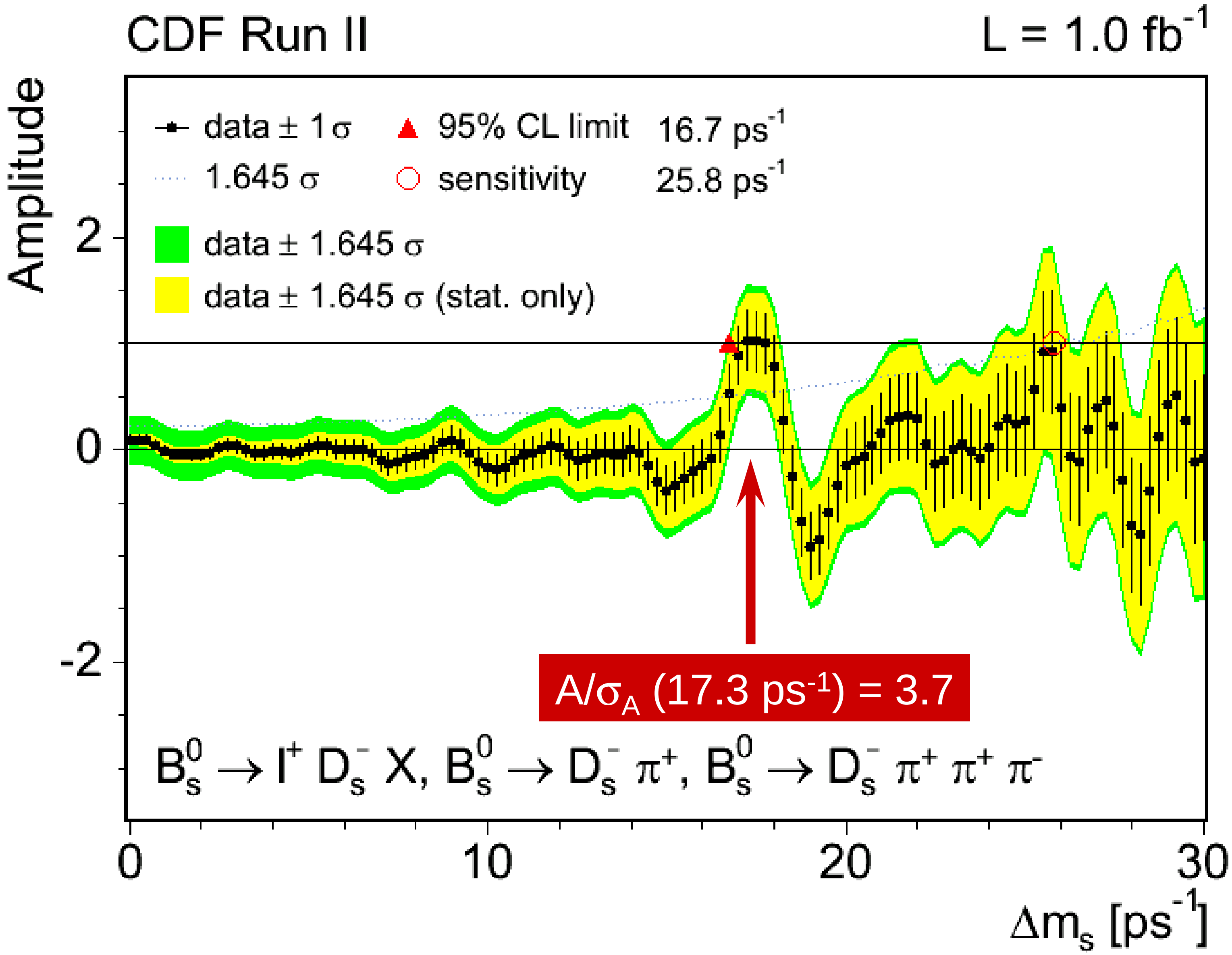
- Exploits the charge correlation between the ***b* flavour** and the leading product of ***b* hadronization**
- Close to trigger B: large **acceptance!**
- SS **Kaon** Tagging *exploits PID over wide momentum range* → use a combined TOF+dE/dx **likelihood ratio**
- Dilution depends on the fragmentation process → cannot calibrate using B_d and B^+ → Need to estimate **D from MC**
- Extended MC-data comparison on quantities related to fragmentation
- Then test predictions on data for other species (B^+ and B_d) and add systematics on agreement accordingly for usage with B_s





RESULTS

Amplitude Scan (hadronic+semileptonic)



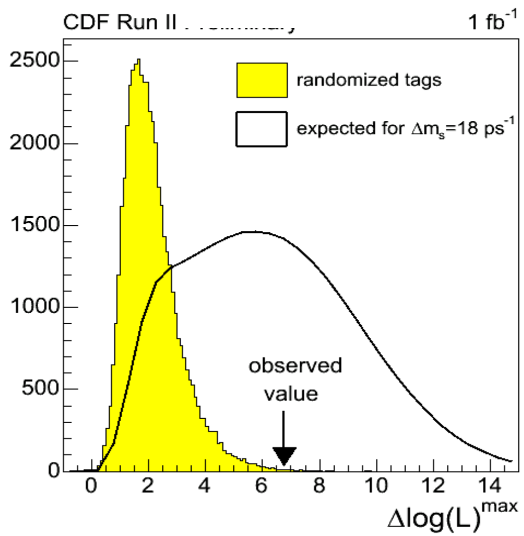
Sensitivity

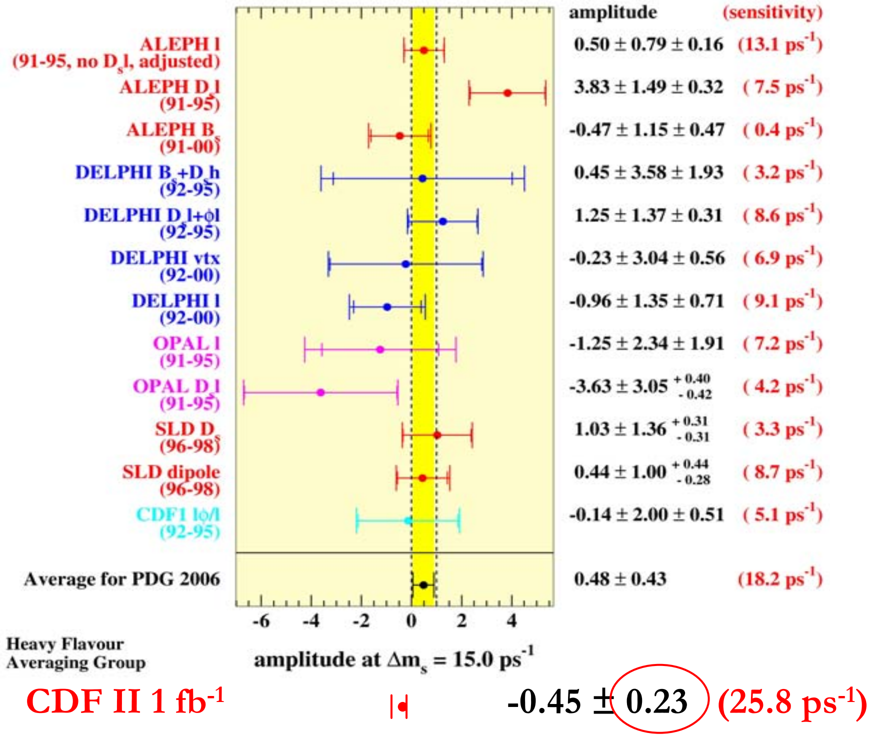
- CDF sensitivity compared to WA

- Use the Likelihood Ratio:

  $-\Delta\log(L) = -\log[\, L(A=1) \,/\, L(A=0) \,]$

  to evaluate the probability **p** of null experiment (bkg fluctuations)

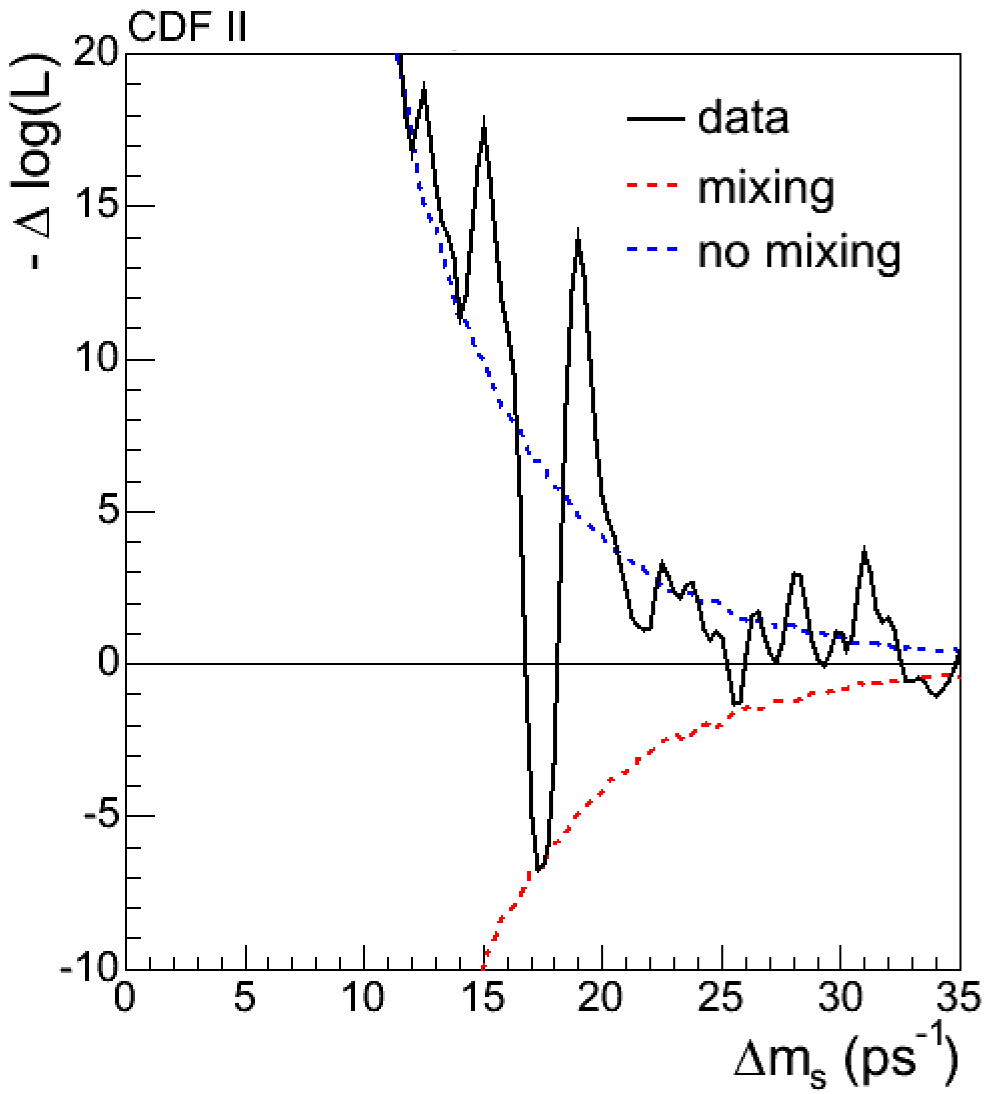




This sensitivity reached with:

- $1\ fb^{-1}$
- Addition of SSKT
- Improved σ_{ct} fitting model

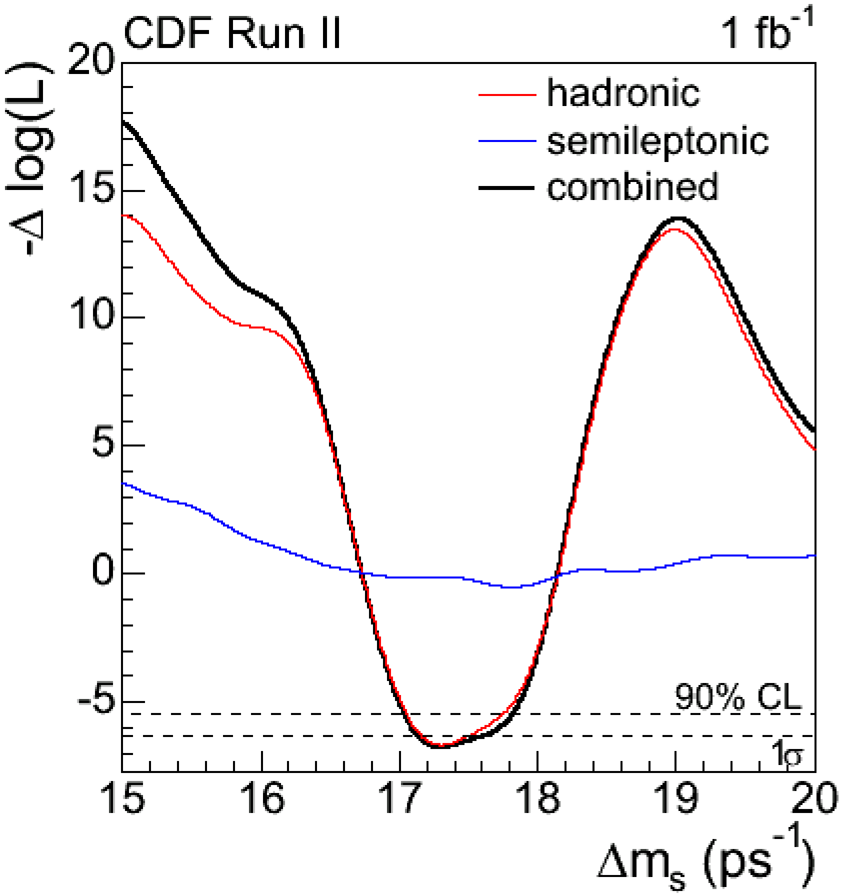
Significance of the peak



- From data
  $-\Delta \log(L)_{MIN} = -6.75$
- Randomize tags ~50k times on data and calculate….
- **P-value = 0.2%**
- **Significance > 3σ**

→ assume that peak IS real mixing signal

Finally….ΔM_s



- Contribution of hadronic modes essential due to better ct resolution at high ΔM_s

$\sigma(\Delta M_s)/\Delta M_s \sim 0.02$

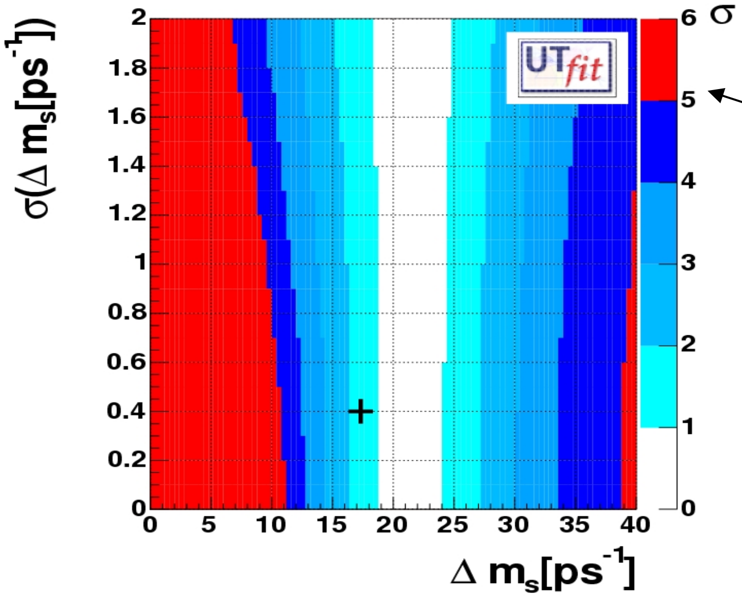
Δm_s in [17.01, 17.84] ps^{-1} at 90% CL

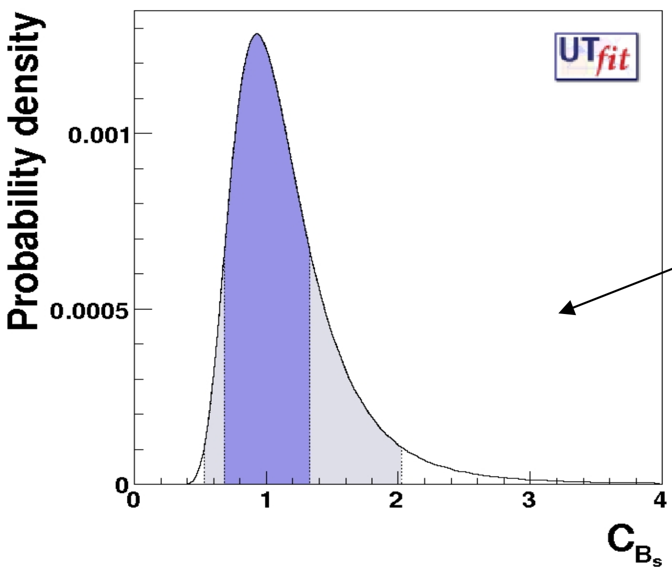
Δm_s in [16.96, 17.91] ps^{-1} at 95% CL

- Systematics low and under control: dominated by uncertainty on the absolute scale of the decay-time measurement

$$\Delta M_s = 17.31\,^{+0.33}_{-0.18}(stat) \pm 0.07(syst)\ \ ps^{-1}$$

From ΔM_s : information on UT





•Compatible with SM within 1σ

•From measurement and chosen inputs

($m(B0)/m(Bs) = 0.9830$, $\Delta M_d = 0.505 \pm 0.005\ ps^{-1}$ from PDG06 and $\xi = 1.210^{+0.047}_{-0.035}$, hep-lat 0510113)

we infer the value:

$$|V_{td}|/|V_{ts}| = 0.208\ ^{+0.001}_{-0.002}\ (exp)\ ^{+0.008}_{-0.006}\ (th)$$

•Constraint on C_{Bs}:

$C_{Bs} = \Delta M_s^{SM+NP} / \Delta M_s^{SM} = 1.01 \pm 0.33$

[0.33,2.04] @ 95% CL (UTFit, utfit.roma1.infn.it)

Conclusions…

- CDF finds signature consistent with B_s oscillations
- Probability of fluctuation from random tags is 0.2%
- Constraints to UT:

$$\bar{\rho} = 0.193 \pm 0.029 \text{ (was } 0.240 \pm 0.037\text{)}$$
$$\bar{\eta} = 0.355 \pm 0.019 \text{ (was } 0.333 \pm 0.022\text{)} \text{ (UTFit)}$$

…and perspectives

- Inclusion of partially reconstructed decays
- Refinement of fully reconstructed mode selections to gain events
- New OS Kaon Tagger in place: $\varepsilon D^2 = 0.23 \pm 0.02$ %

$$\Delta M_s = 17.31^{+0.33}_{-0.18}(stat) \pm 0.07(syst)\ ps^{-1}$$