Observation of B_s^0-$\bar{B}_s^0$ Oscillations in Hadronic Decays at CDF

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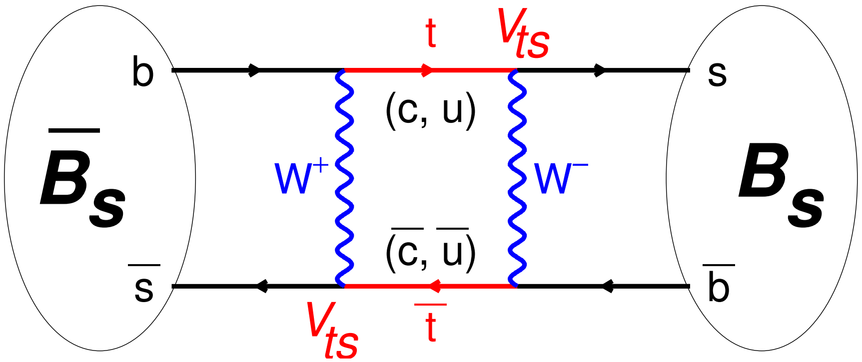
DPF MEETING – October 30, 2006

Neutral B Mixing



Hamiltonian connecting $|B\rangle$,$|\bar{B}\rangle$:

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

Diagonalize ⇒ 2 energy e'states:

$$\Delta m \equiv m_H - m_L$$
$$\Delta\Gamma \equiv \Gamma_L - \Gamma_H$$

Ratio of frequencies for B^0, B_s:

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

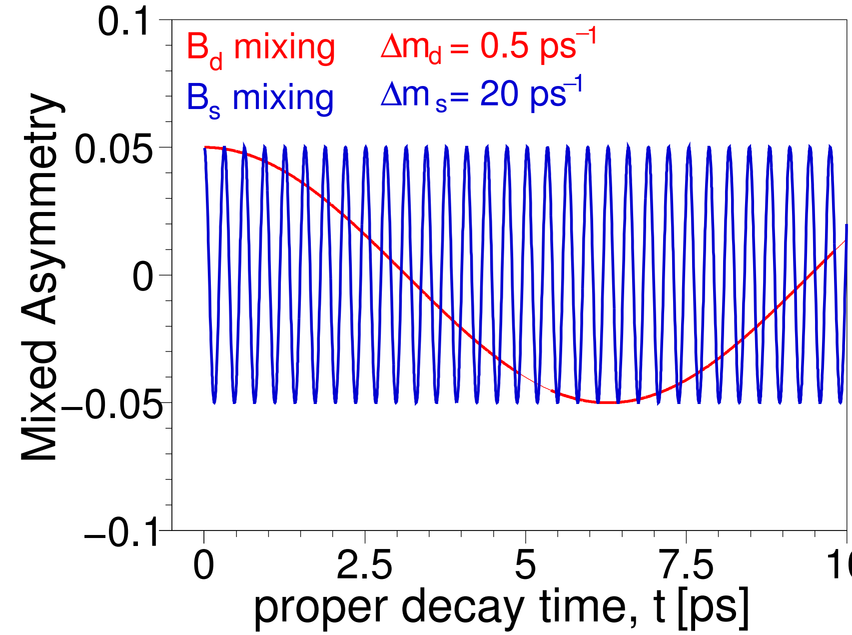
Many QCD uncertainties cancel!

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

(hep/lat-0510113)

...But emphasis today is
DEFINITIVE OBSERVATION,
not just measurement!

B_s oscillates *rapidly!*



Historic Steps

1987

- First evidence of B^0 mixing from UA1 C. Albajar *et al.*, PLB **186**, 247 (1987)
- Argus observes B^0 mixing $\Rightarrow$ UA1 result points to large B_s mixing ($m_t > 50$ GeV$/c^2$) H. Albrecht *et al.*, PLB **192**, 245 (1987)

1990's

- Inclusive measurements of B mixing from LEP establish B_s mixing

1993

D. Buskulic *et al.*, PLB **313**, 498 (1993)

- First time dependent measurement of Δm_d from Aleph
- First lower limit on Δm_s from Aleph: $\Delta m_s > 12 \cdot 10^{-4}$ eV$/c^2$ CDF 06: 0.011 eV$/c^2$ D. Buskulic *et al.*, PLB **322**, 441 (1994)

1999

- CDF Run I result on Δm_s: $\Delta m_s > 5.8$ ps^{-1} F. Abe *et al.*, PRL **82**, 3576 (1999)

2000's

- CDF Run II first result on Δm_s: $\Delta m_s > 7.9$ ps^{-1}
- D0 reports interval: $\Delta m_s \in [17, 21]$ ps^{-1} at 90% CL

The point is: Decades of attempts at this result!

Ingredients for Statistical Significance

$$\frac{1}{\sigma_A} = \sqrt{\frac{S}{S+B}} \cdot e^{-\frac{\Delta m_s^2 \sigma_{ct}^2}{2}} \cdot \sqrt{S\frac{\epsilon D^2}{2}}$$

Signal statistics

- Hadronic modes: $B_s \rightarrow D_s\pi,\ D_s 3\pi,\ D_s\rho,\ D_s^*\pi$
- Good $\mathcal{S}/\mathcal{B}$ separation

Proper decay time resolution

- Exponential dependence $\Rightarrow$ Hadronics' main asset!
- Fully reconstructed signal provides best precision

b-flavor tagging

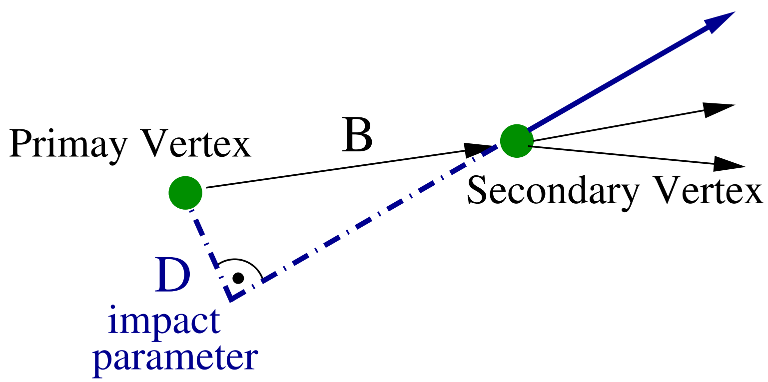
- Effective statistics scale with ϵD^2

Hadronic Sample Overview

Displaced track trigger:

→ decisions at 25 kHz

→ unique Tevatron capability

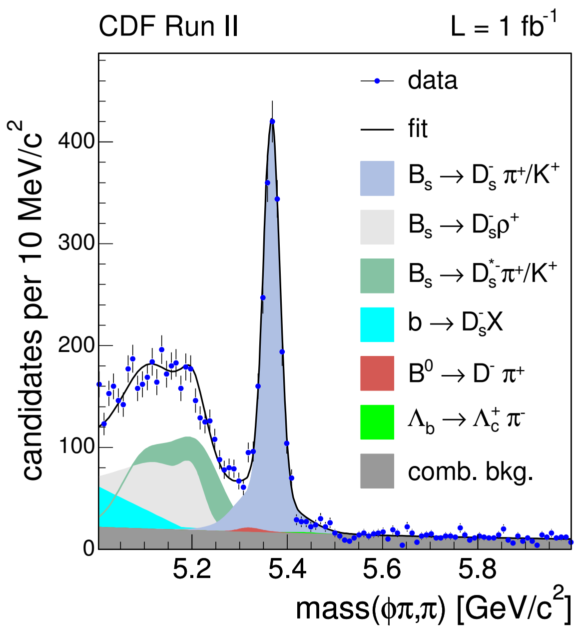


Recent upgrades:

- Partially reconstructed channels
- Neural network for selection
- Particle ID in selection
- Additional 6π channel

General attributes:

- Excellent proper time resolution!
- Good $\mathcal{S}/\mathcal{B}$
- Small branching fractions
  $\Rightarrow$ smaller yields than ℓD_s



Reconstructed Channels

Fully reconstructed:

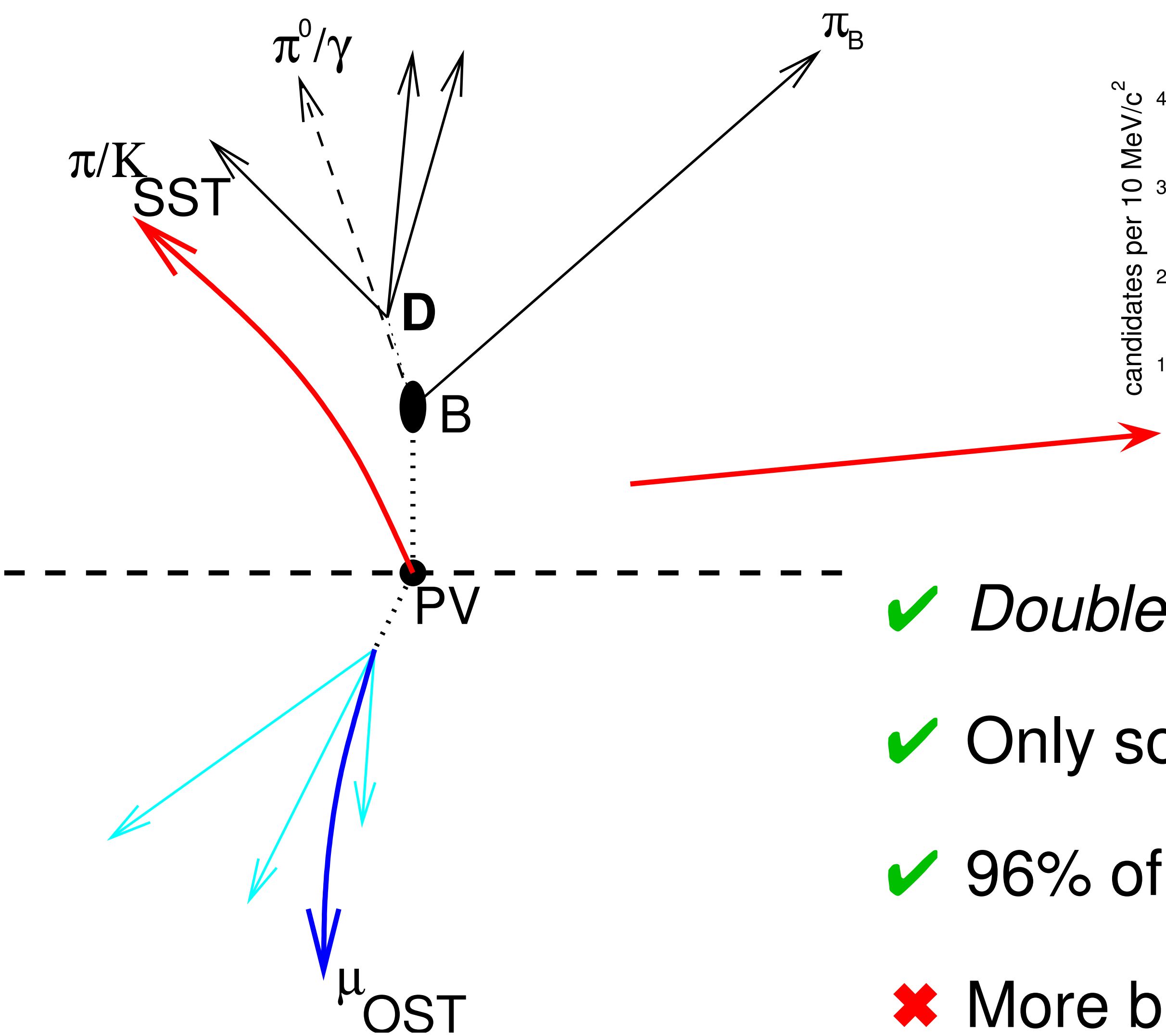
$$\left.\begin{array}{l} \mathrm{B_s} \to \mathrm{D_s^-}\pi^+ \\ \mathrm{B_s} \to \mathrm{D_s^-}(3\pi)^+ \end{array}\right\} \otimes \left\{\begin{array}{l} \mathrm{D_s^-} \to \phi\pi^- \\ \mathrm{D_s^-} \to \mathrm{K^{*0}K^-} \\ \mathrm{D_s^-} \to \pi^-\pi^+\pi^- \end{array}\right.$$

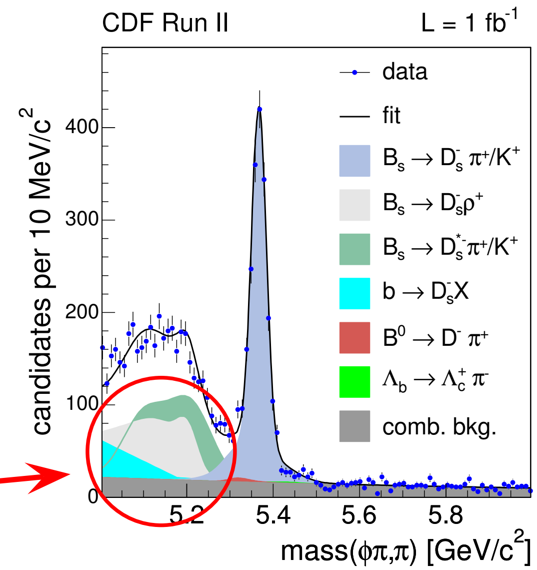
Partially reconstructed:

$$\left.\begin{array}{l} \mathrm{B_s} \to \mathrm{D_s^-}\rho^+ \\ \mathrm{B_s} \to \mathrm{D_s^{*-}}\pi^+ \end{array}\right\} \otimes \left\{\ \mathrm{D_s^-} \to \phi\pi^- \right.$$

$\Rightarrow$ both in same sample as $B_s \to D_s\pi$, $D_s \to \phi\pi$

Addition of Partially Reconstructed Signals

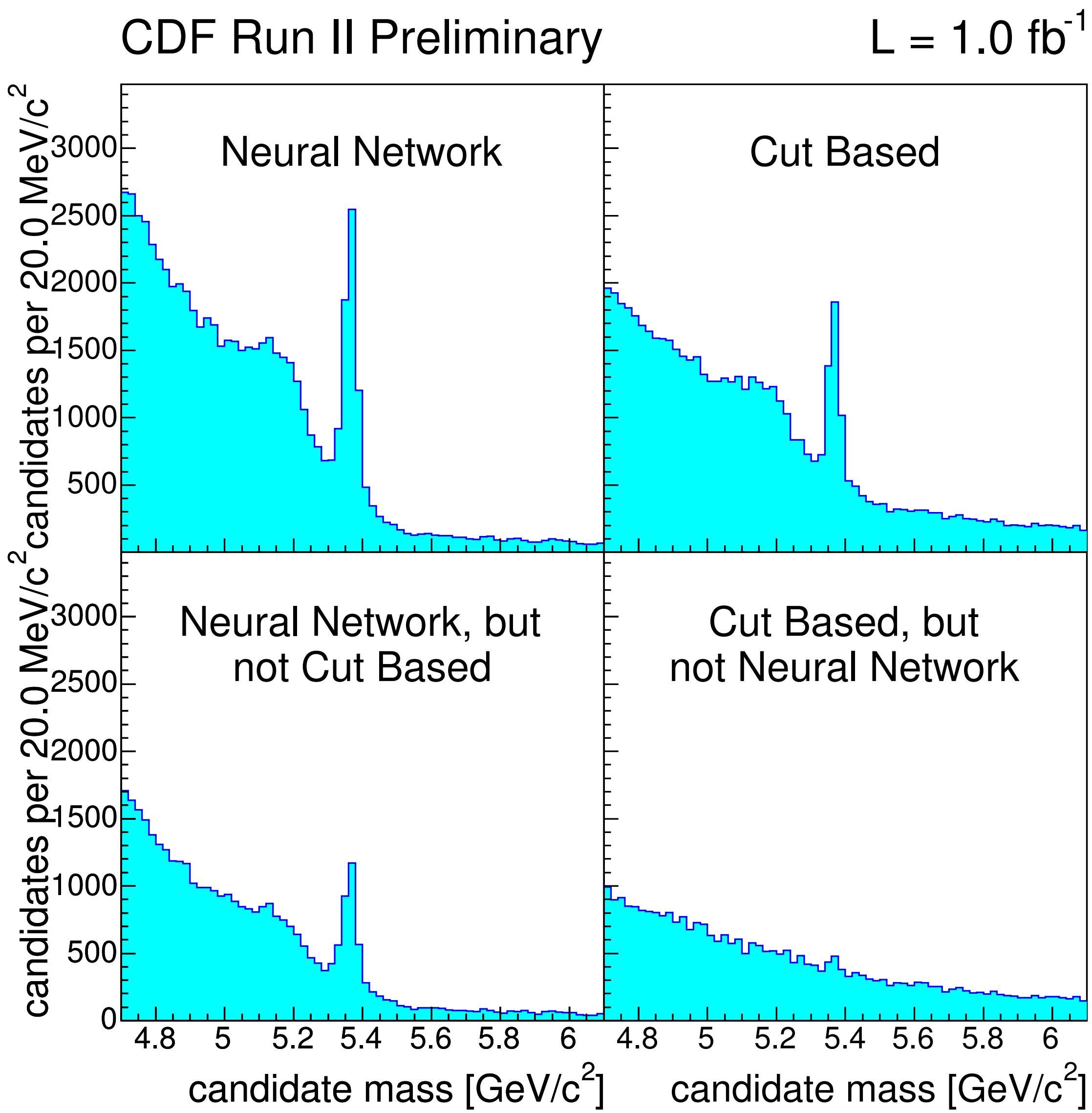




- ✔ *Double* signal yield in $D_s(\phi\pi)\pi$
- ✔ Only soft π^0 or γ lost
- ✔ 96% of p_T reconstructed
- ✖ More bkg to understand

$\Rightarrow$ Developed in B^0/B^+ samples

Performance of Neural Network Selection



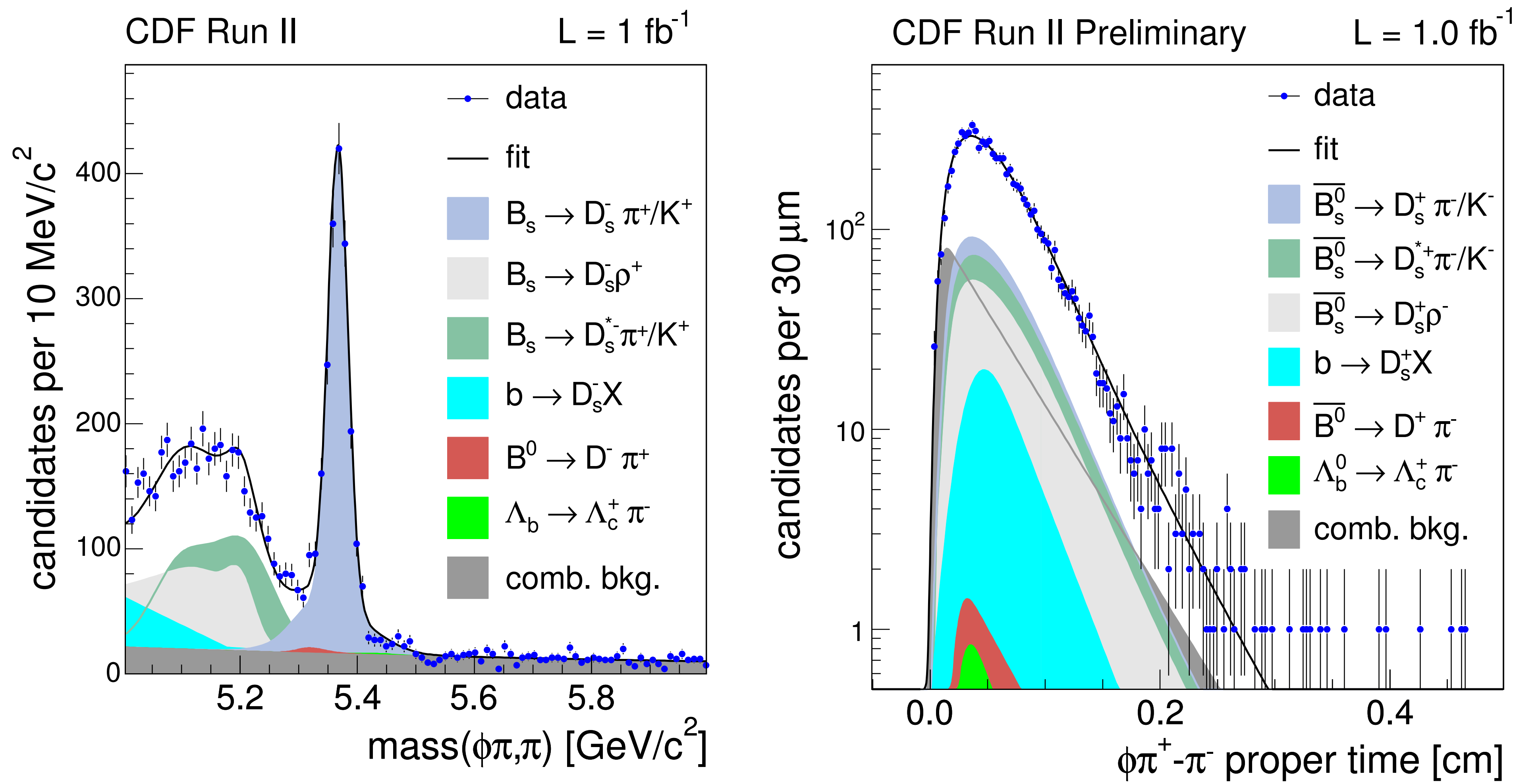
- Trained to accept "signal-like" events
- Admits more signal than cut-based
- No inefficiency!

$\Rightarrow$ Smarter selection

$\Rightarrow$ Major upgrade across hadronic sample

"Golden" Sample

$B_s \to D_s^- \pi^+$, $D_s^- \to \phi\pi^-$



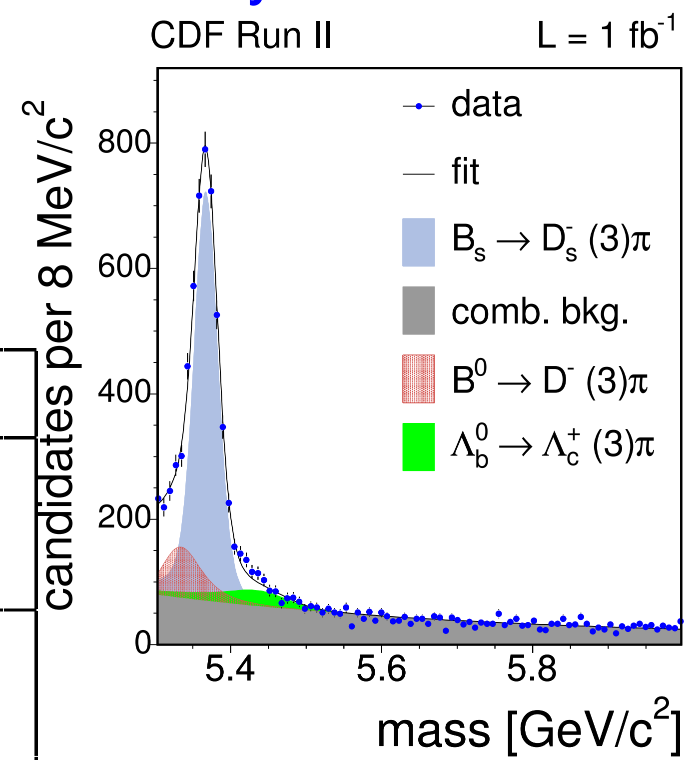
Most powerful *individual* sample

Other Hadronic Channels

- NN important for non-golden modes
- Particle ID suppresses B^0 contamination in K^*K modes

Decay	Yield	S/B	Gain
$B_s \to D_s(\phi\pi)\pi$	2000	11.3	13%
Partially Reco'd	3100	3.4	n.a.
$B_s \to D_s(K^*K)\pi$	1400	2.0	35%
$B_s \to D_s(3\pi)\pi$	700	2.1	22%
$B_s \to D_s(\phi\pi)3\pi$	700	2.7	92%
$B_s \to D_s(K^*K)3\pi$	600	1.1	110%
$B_s \to D_s(3\pi)3\pi$	200	2.6	n.a.
Total	8700		

5 fully reconstructed:



Combined 5 modes more powerful than golden alone

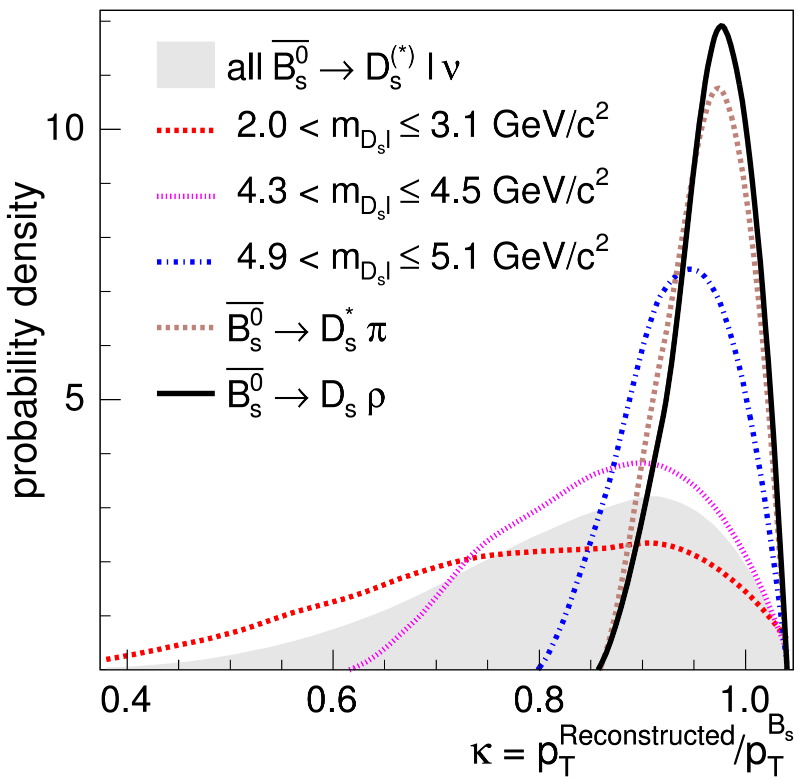
Reconstruction of Proper Time

$$ct = \frac{L_{xy} \cdot M}{p_T}$$

Critical to Δm_s sensitivity:

$$\sigma_{ct} = \sigma^0_{ct} \oplus ct \cdot \frac{\sigma_p}{p}$$

vertex res. momentum res.



Fully reconstructed:

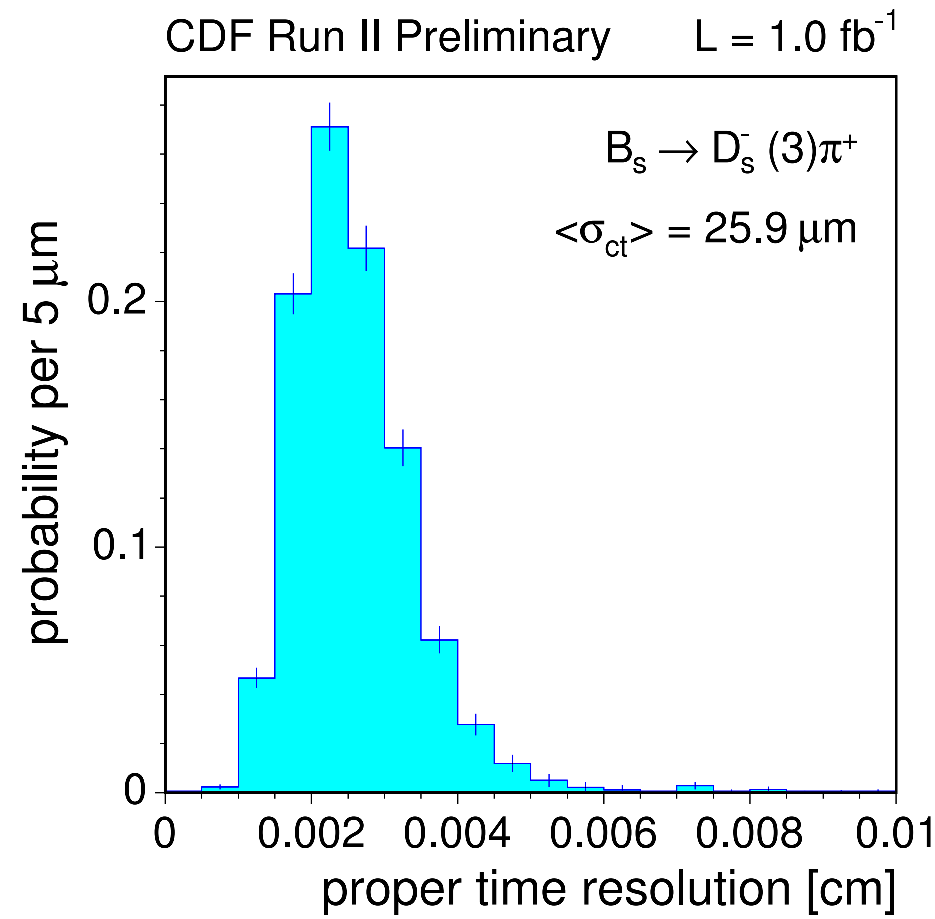
- $\rightarrow$ negligible $\frac{\sigma_p}{p}$
- $\rightarrow$ excellent $\sigma_{ct} = \sigma^0_{ct}$

Partially reconstructed:

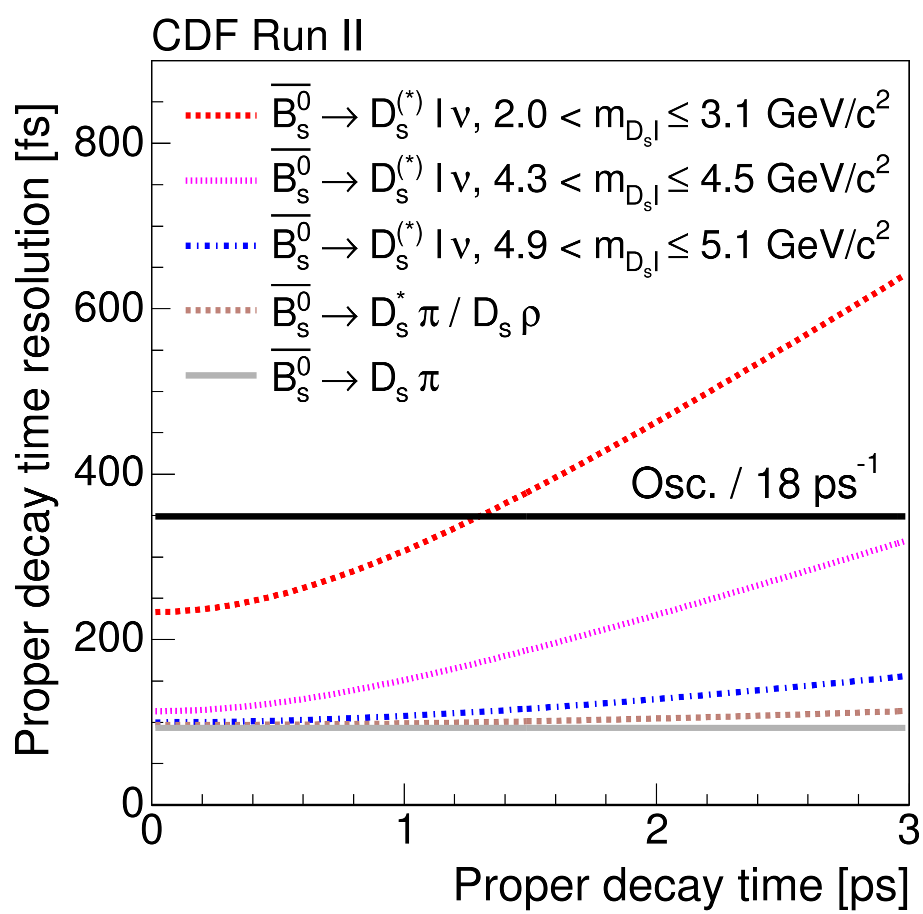
- $\rightarrow$ $\frac{\sigma_p}{p}$ quantified by κ *width*
- $\rightarrow$ indicates σ_{ct} rise vs. ct
- $\rightarrow$ hadronic:
  narrow κ; still valuable!

Proper Time Resolution

$$\sigma_{ct} = \sigma_{ct}^{0} \oplus ct \cdot \frac{\sigma_p}{p}$$



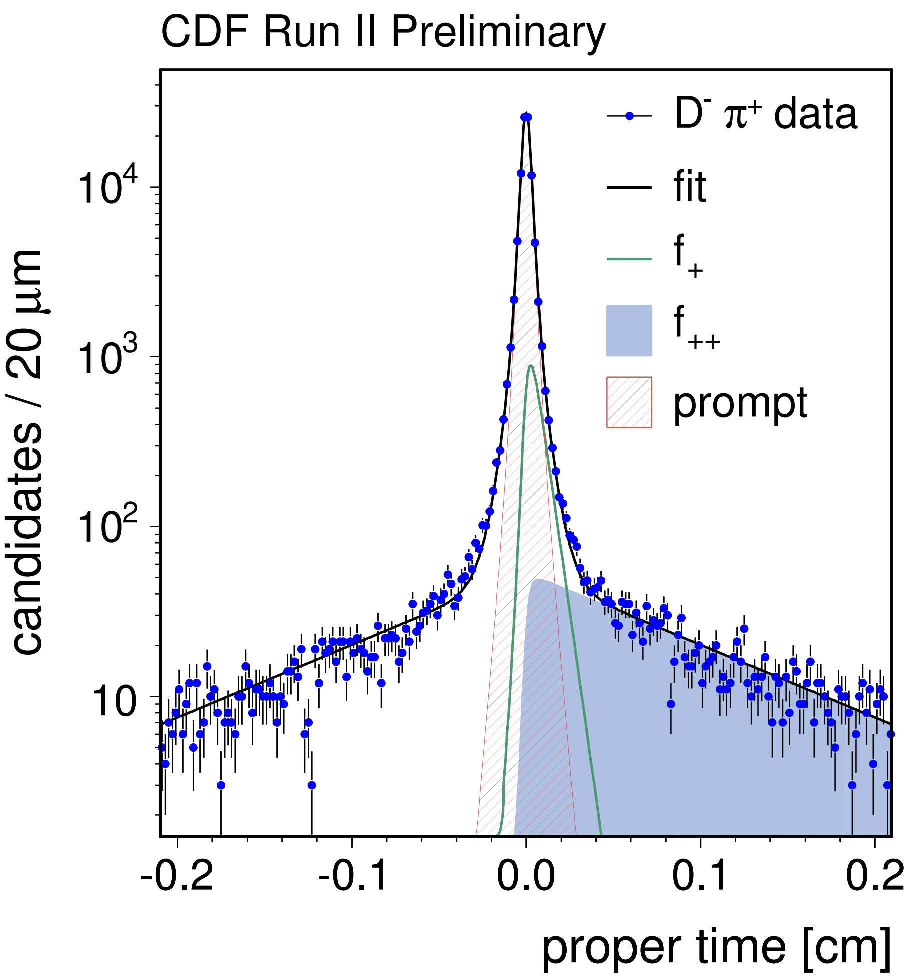
Hadronic σ_{ct} small fraction of oscillation period

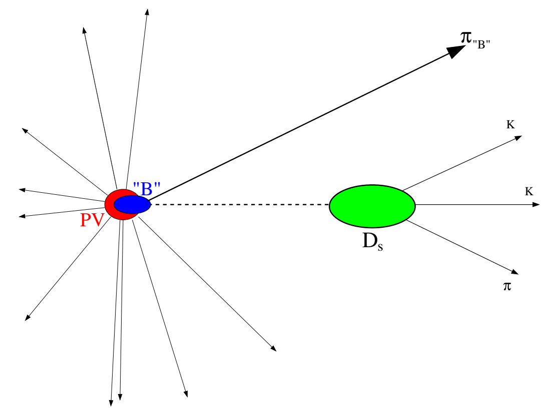


Excellent detector-based σ_{ct}^{0}

Calibration of Proper Time Measurement

Must have accurate knowledge of σ^0_{ct}





Construct calib sample:

- prompt D^+ plus track
- unbiased w.r.t. primary vertex
- same topology as signal
- examine variation of σ_{ct} pulls

σ^0_{ct} correction parameterized by event kinematics

b-Flavor Tagging

Opposite side algorithms:

- Soft lepton tagger
- Jet charge tagger
- Opp. side kaon tagger

$\rightarrow$ Combined via NN into single OST

$\rightarrow$ $\epsilon\mathcal{D}^2 = 1.8\%$ (20% relative increase)

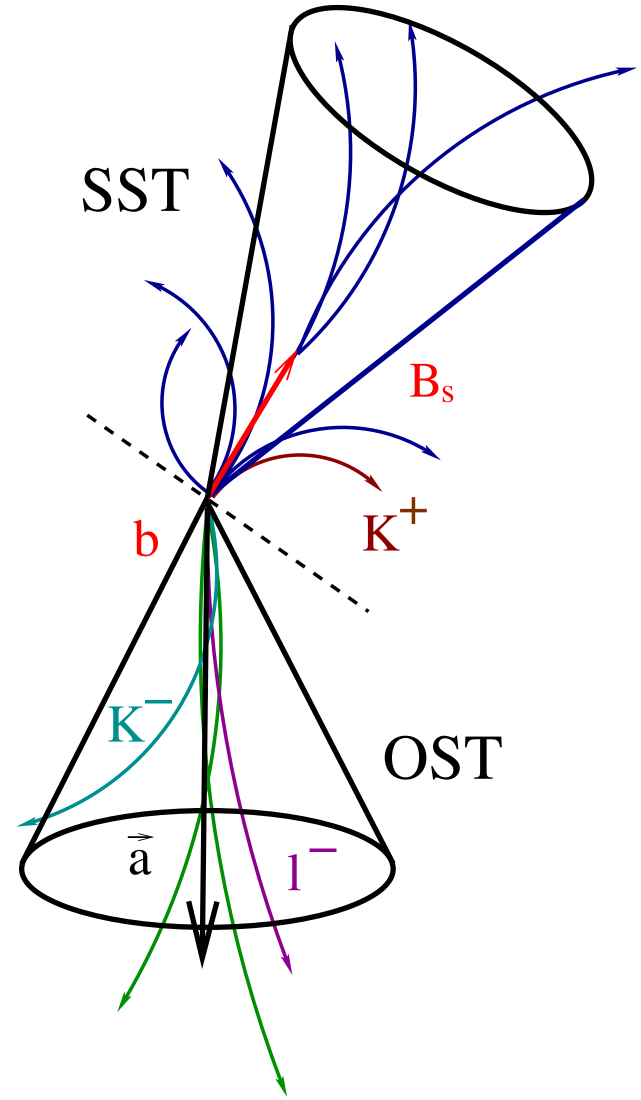
$\Rightarrow$ Identical to semileptonics

Same side tagger:

$\rightarrow$ NN combines particle ID and kinematics

$\rightarrow$ $\epsilon\mathcal{D}^2 = 3.7\%$

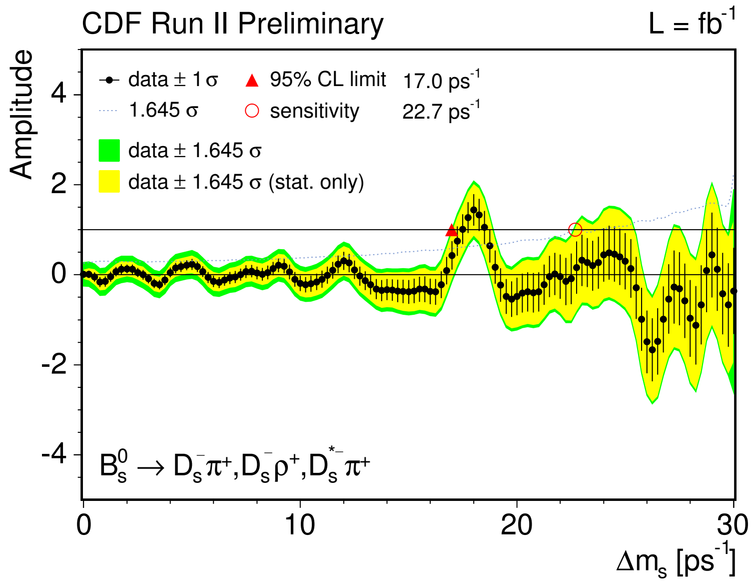
$\Rightarrow$ Slightly less than semi-ℓ due to triggers



OST and SST independently combined

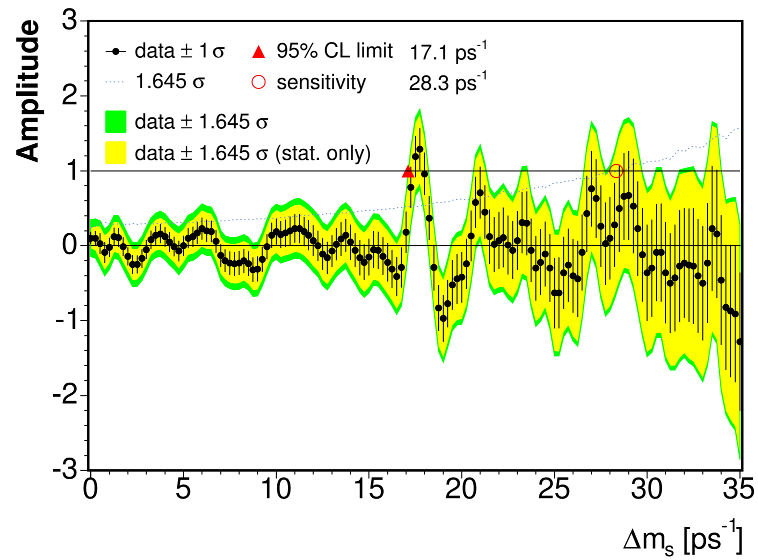
Amplitude Scans by Sample

Golden Hadronic
Fully & part'ly reconstructed



$$\mathcal{A} = 1.27 \pm 0.34$$

Other Hadronic
Fully reconstructed

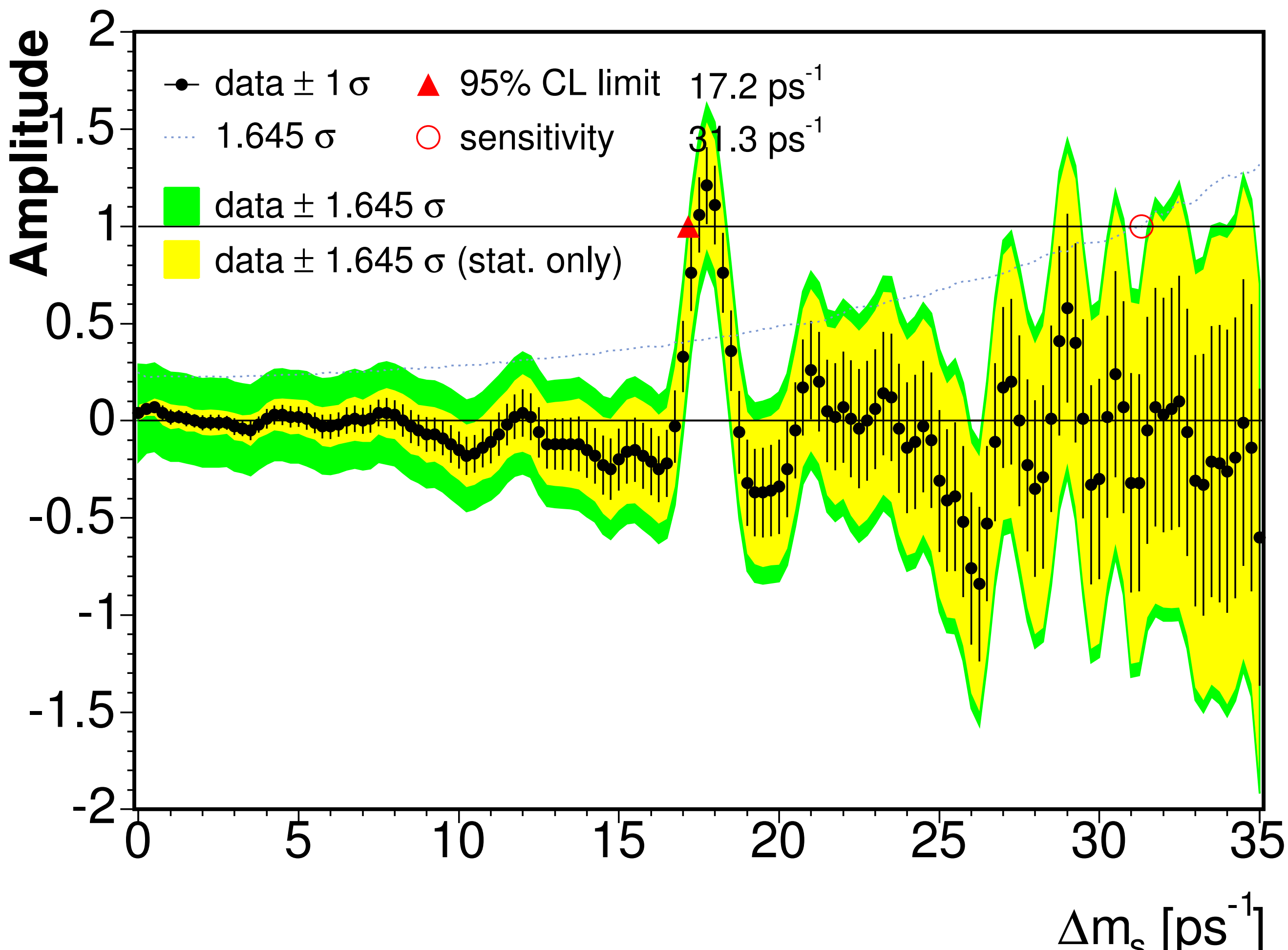


$$\mathcal{A} = 1.29 \pm 0.29$$

- Focus here on $\mathcal{A}(\Delta m_s = 17.75)$
- Consistent with signal! $(\mathcal{A} = 1)$
- *In*consistent with bkg! $(\mathcal{A} = 0)$

Combined Amplitude Scan

Combine hadronic and semileptonic scans:

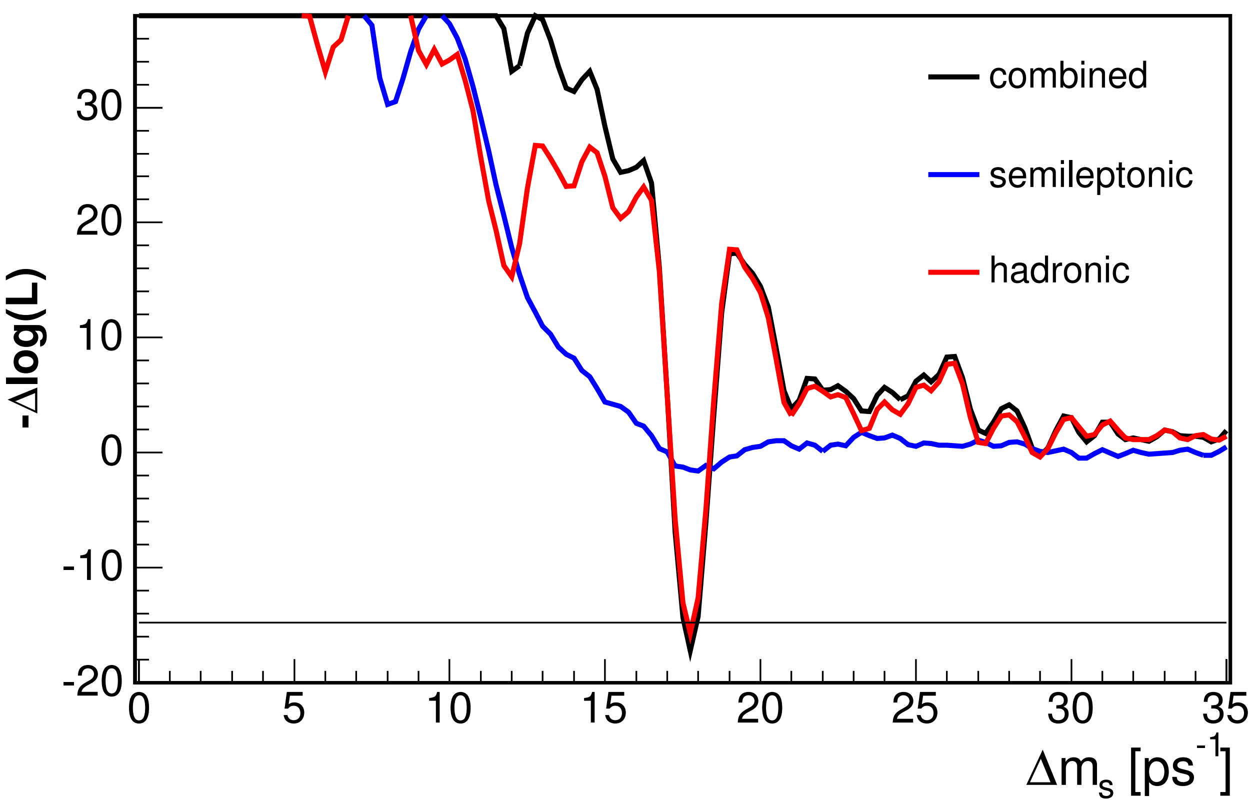


$$\mathcal{A} = 1.21 \pm 0.20 \quad \Longrightarrow \quad \mathcal{A}/\sigma_{\mathcal{A}} \sim 6 \quad (!)$$

How significant is this signal?

Likelihood Profile

- Ratio of combined analysis likelihood at:
  $\rightarrow \mathcal{A} = 1$ (hypothesis of signal); and
  $\rightarrow \mathcal{A} = 0$ (hypothesis of random tags)
- Used to extract significance and Δm_s measurement

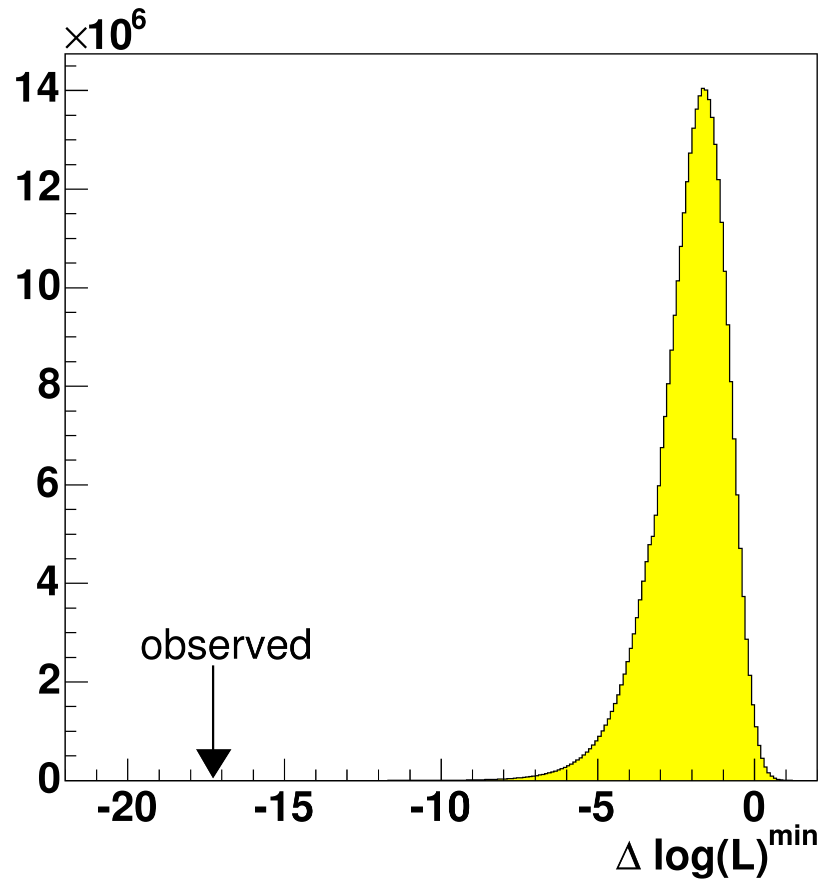


Extremum
$\Lambda = -17.26$

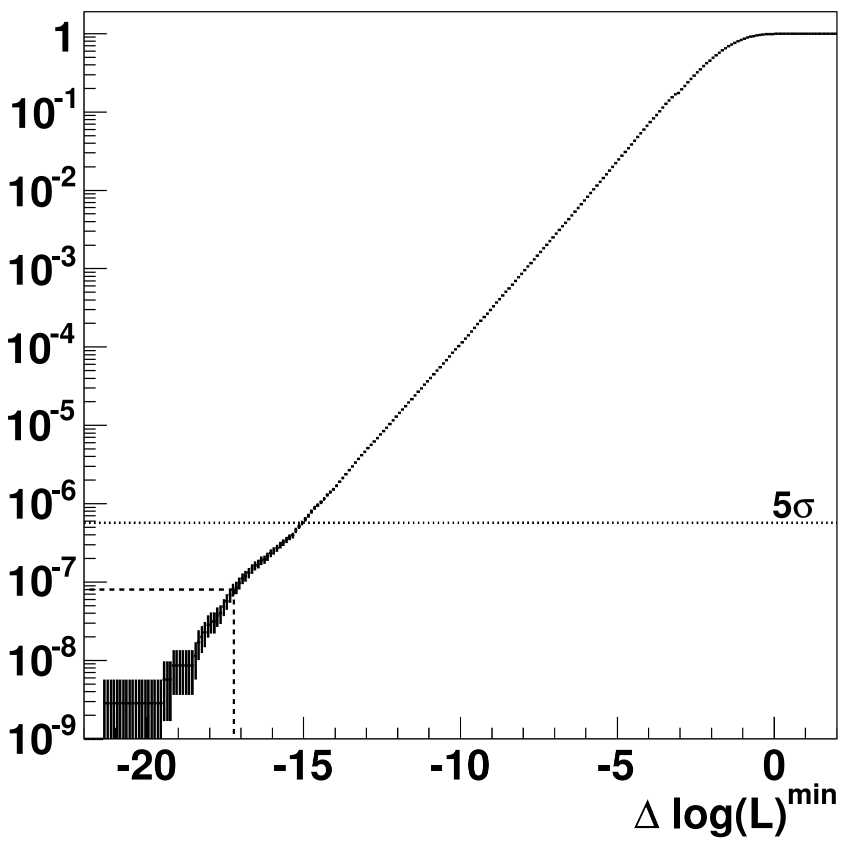
How often can random tags exceed this mininum value?

P-value Estimation

- Randomize tags $\times 3.5 \cdot 10^8$
- Collect $\Delta log(\mathcal{L})$ minimum for each scan $\Longrightarrow$



$\Downarrow$ Plot probability vs. minimum



$\Rightarrow$ Probability of fluctuation: 8×10^{-8}

5.4σ significance

Δm_s Measurement

Limits

- $[17.56, 17.96]$ps^{-1} @ 90% C.L.
- $[16.51, 18.00]$ps^{-1} @ 95% C.L.

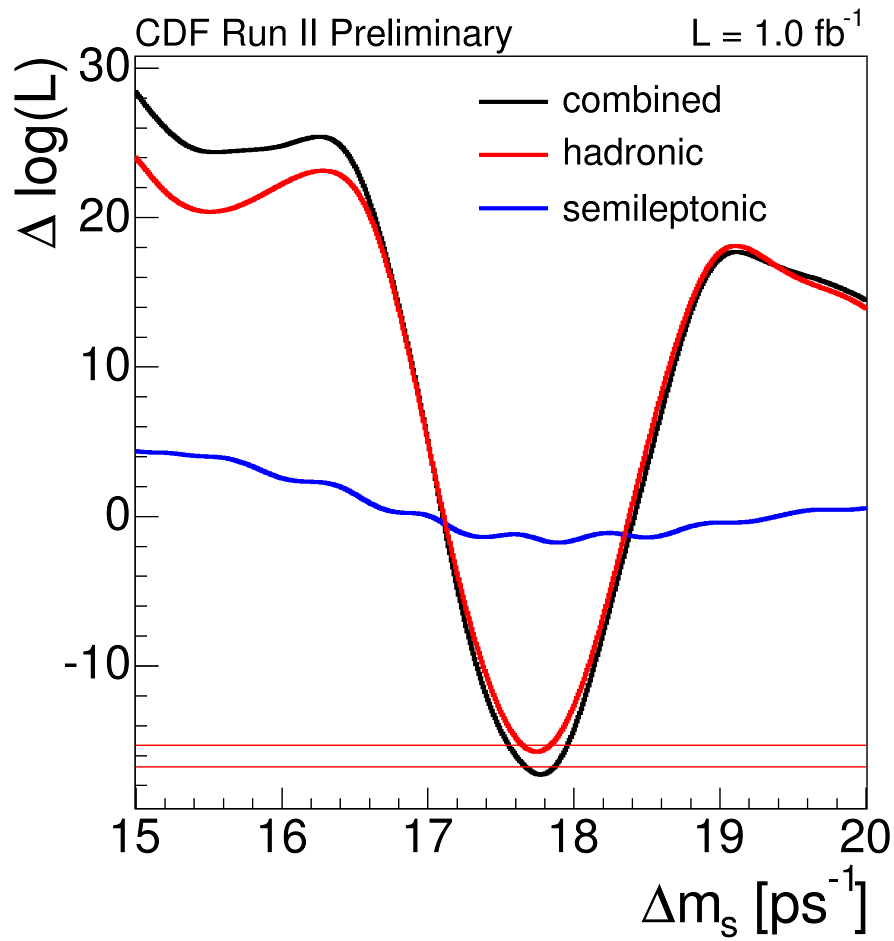
Consistent with SM

- $18.3\ ^{+6.5}_{-1.5}$ ps^{-1} EPS 2005

Agrees with 1^{st} measurement

- $17.31\ ^{+0.33}_{-0.18} \pm 0.07$ ps^{-1}

PRL **97**, 062003 (2006)



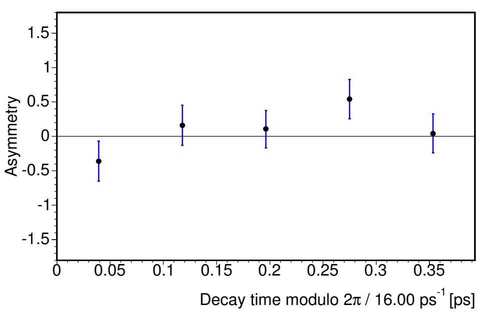
$$\Delta m_s = 17.77 \pm 0.10(stat.) \pm 0.07(syst.) \text{ ps}^{-1}$$

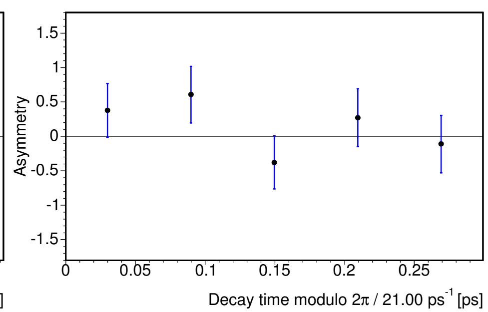
Systematics dominated by ct scale; all other effects small

Visualizing the Oscillation

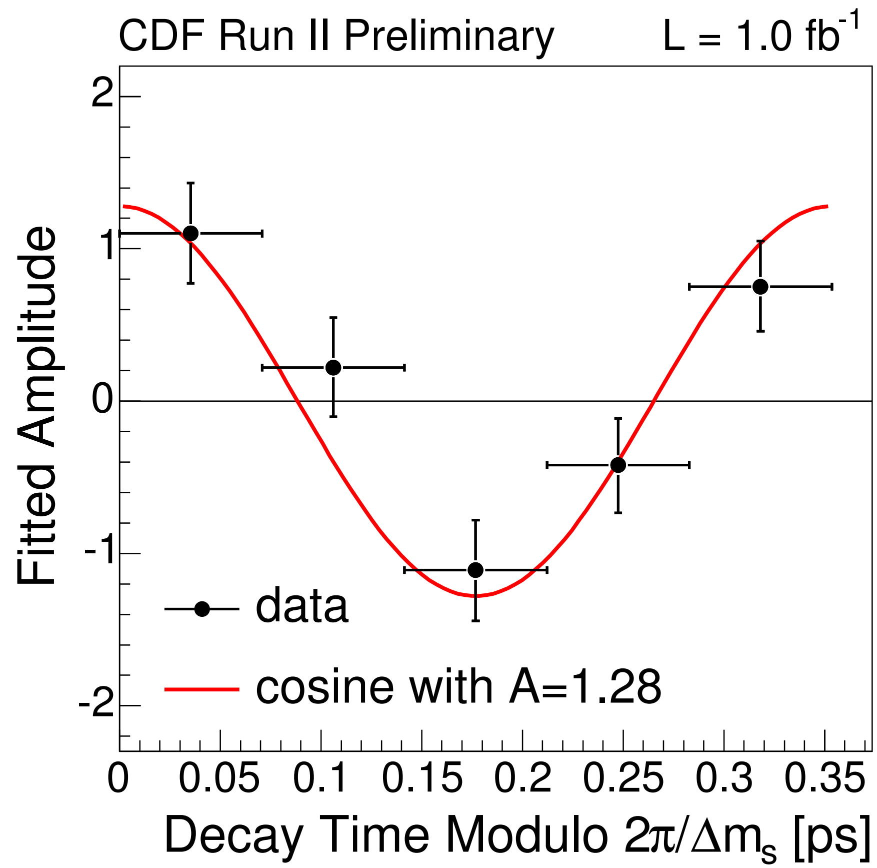
- Use fitter to de-transform data
- Oscillations folded modulo $2\pi/\Delta m_s$

Fitted $\mathcal{A}$ closely matches result of amplitude scan





at $\Delta m_s = 16$ or 21 ps^{-1}
$\Rightarrow$ no oscillations!



binned $\chi^2 = 4.77$

NDF = $5(3) \rightarrow$ Prob = $44\%(19\%)$

flat line: $\chi^2 = 30.5$

Measurement of CKM Parameters

- $$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$
  - $\frac{m_{B_s}}{m_{B_d}} = 0.98390$ CDF 2006
  - $\Delta m_d = 0.507 \pm 0.005$ ps^{-1} W.-M. Yao *et al.* 2006
  - $\Delta m_s = 17.77 \pm 0.10(stat.) \pm 0.07(syst.)$ ps^{-1} CDF 2006
  - $\xi = 1.210^{+0.047}_{-0.035}$ Okamoto, Lattice 2006

$$\Longrightarrow |V_{td}|/|V_{ts}| = 0.2061 \pm 0.0007(exp.)\ ^{+0.0081}_{-0.0060}(th.)$$

No longer limited by experimental precision

Summary

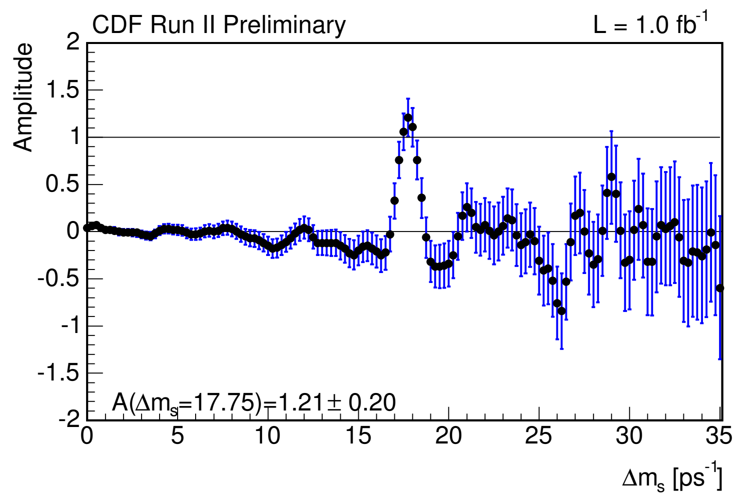
- Historic observation of B_s^0-$\bar{B}_s^0$ Oscillations

$$5.4\sigma$$

- Most precise measurement of oscillation frequency:

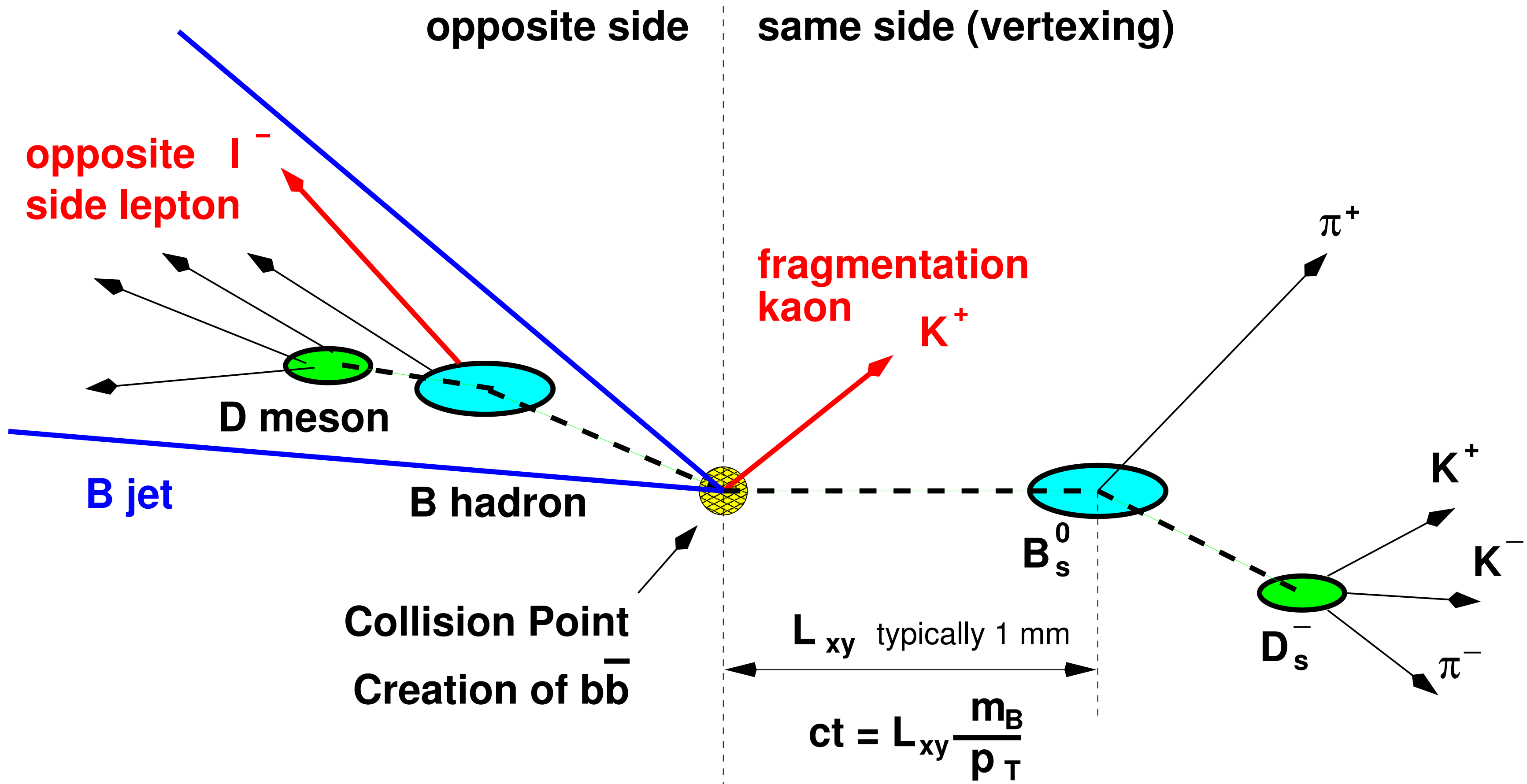
$$\Delta m_s = 17.77 \pm 0.10(stat.) \pm 0.07(syst.)\ \text{ps}^{-1}$$

- Accepted to PRL (hep-ex/0609040)



Back-up Slides

Reconstruction of Mixing Candidates



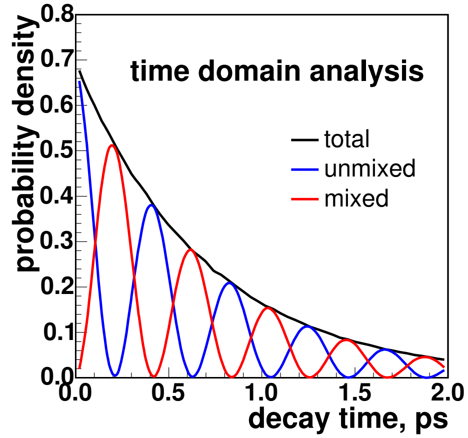
Must determine 3 properties of every B_s event:

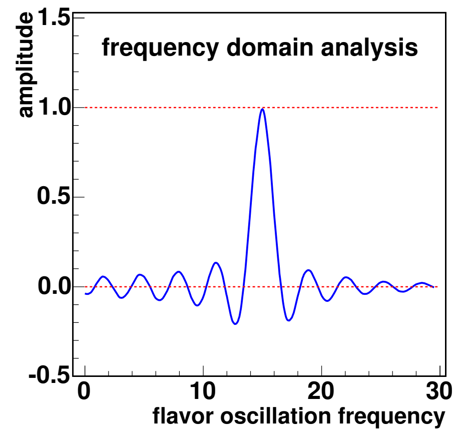
- Proper decay length ct, in B rest frame
- *Final* flavor of B at decay
- *Initial* flavor of B at production

All incorporated in simultaneous likelihood fit

Fourier Analysis

Can fit for oscillations in two domains





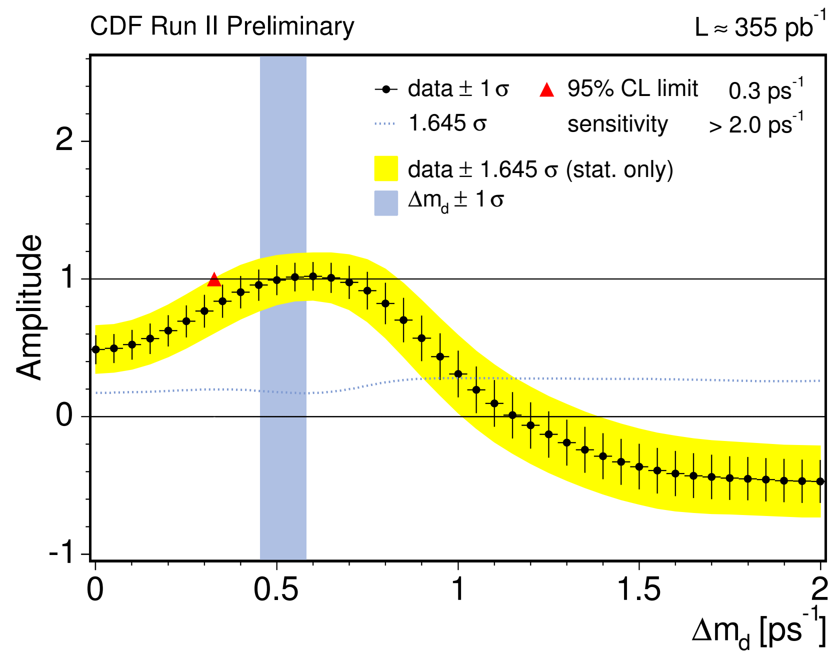
Time domain

- Fit for Δm in
  $\mathcal{P}(t) \sim 1 \pm \mathcal{D} \cdot cos(\Delta m t)$
  For mistag probability q,
  "dilution" $\mathcal{D} = 1 - 2q$
- Possible if direct observation

Frequency domain

- Introduce amplitude,
  $\mathcal{P}(t) \sim 1 \pm \mathcal{A} \cdot \mathcal{D} \cdot cos(\Delta m t)$
- Fit $\mathcal{A}$ for different Δm
  $\Rightarrow$ frequency spectrum $\mathcal{A}(\Delta m)$
- $\mathcal{A} = 1$ for true Δm, else $\mathcal{A} = 0$
- $\frac{1}{\sigma_A} \sim \sqrt{S \epsilon \mathcal{D}^2} \sqrt{\frac{S}{S+B}} e^{-\Delta m_s^2 \sigma_t^2 / 2}$

Amplitude scan for B^0 mixing:



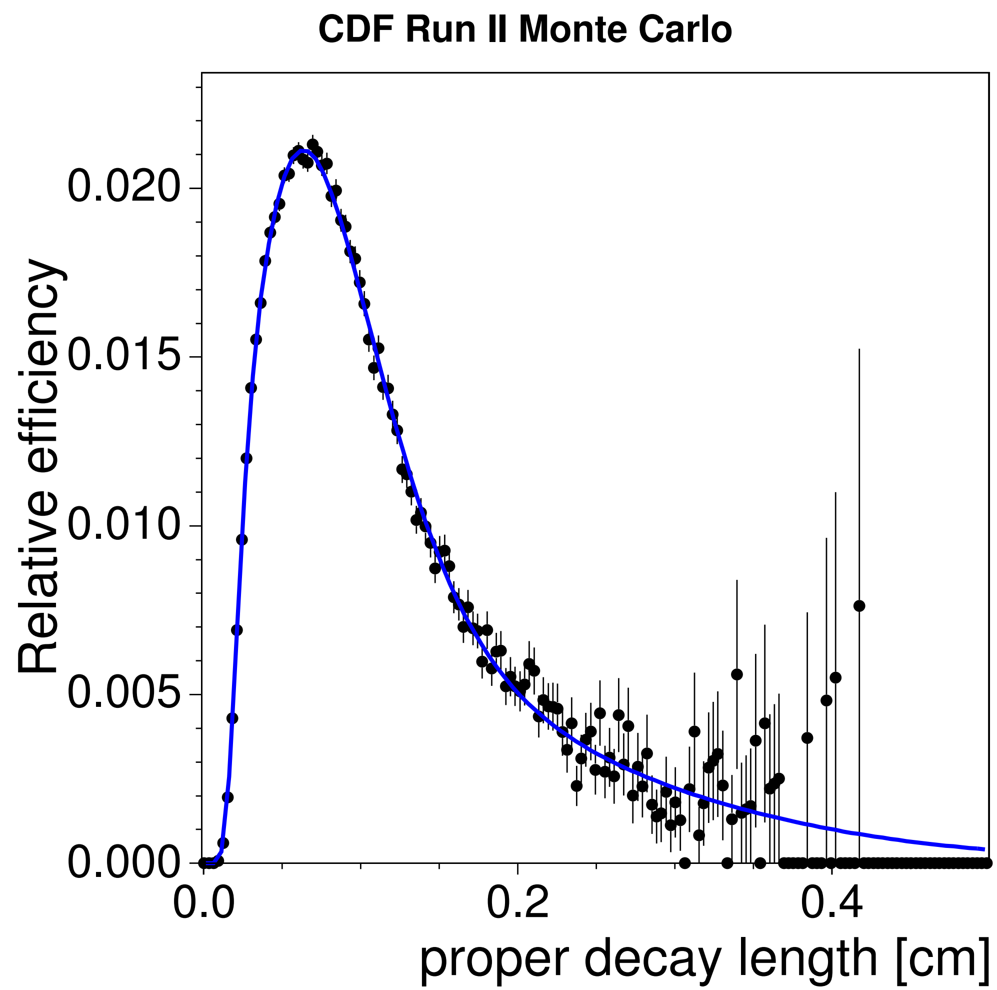
CDF II Detector

Relevant components for getting those ingredients:

- B_s **reconstruction**: low background, high statistics
  - Displaced track trigger
  - SVX/ISL/L00: vertexing
  - COT: momentum resolution
  - Muon Chambers and Calorimeters: lepton ID
- **Proper decay time resolution**:
  - L00: 10-20% improvement in track d_0 resolution
- b**-flavor tagging**: separation of kaons versus pions
  - dE/dx information from COT
  - Time-Of-Flight:
    $\rightarrow$ essential for Same-Side Kaon Tagging

Trigger Sculpting

- Displaced track trigger sculpts proper time distribution
- Modeled by efficiency $\epsilon(t)$ in PDFs
- Derived from realistic Monte Carlo



Validated in high statistics B lifetime measurements

Crucial Test of the fitter: B_d Mixing

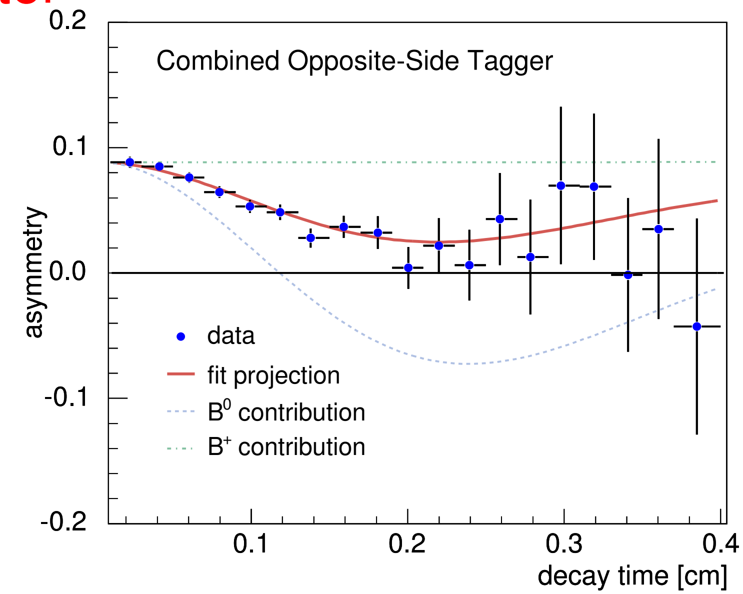
To set limits on Δm_s, knowledge of tagger performance is crucial

- ☞ measure tagging dilution in kinematically similar B^0/B^+ samples (for OST)

Δm_d and Δm_s fits are very complex

- ☞ combining several B flavor and several decay modes
- ☞ combining several taggers
- ☞ mass and lifetime templates for various backgrounds

Δm_d measurement also important to test the fitter



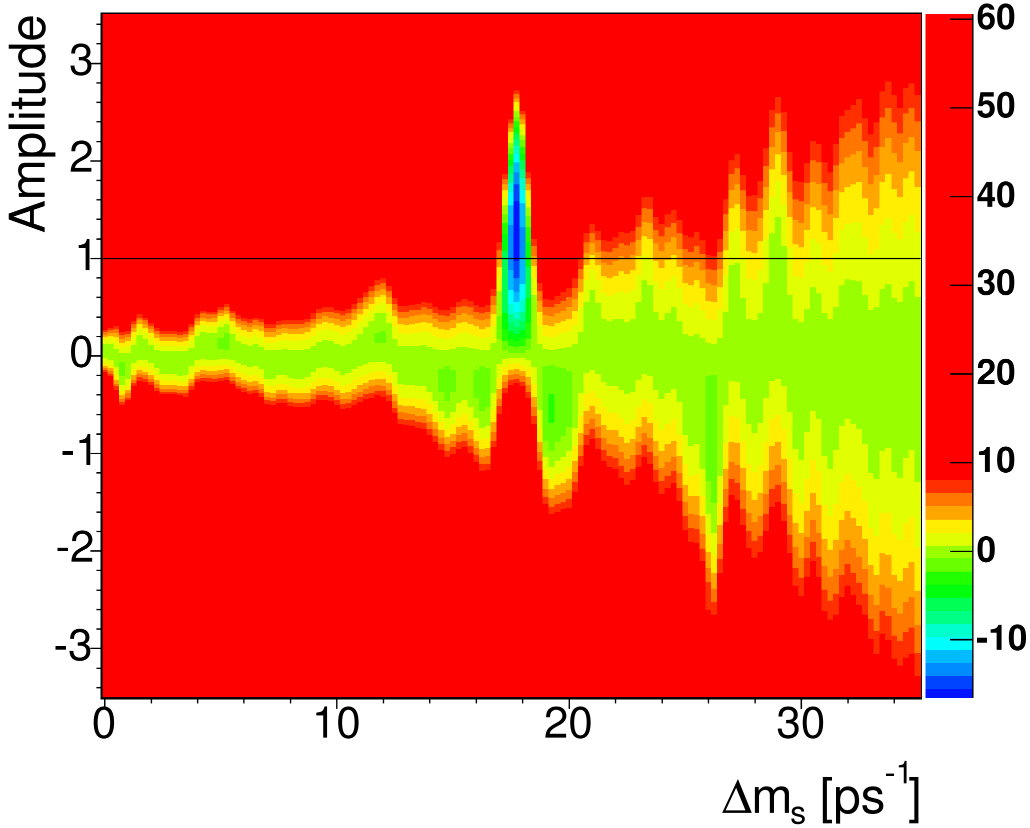
CDF measurement:

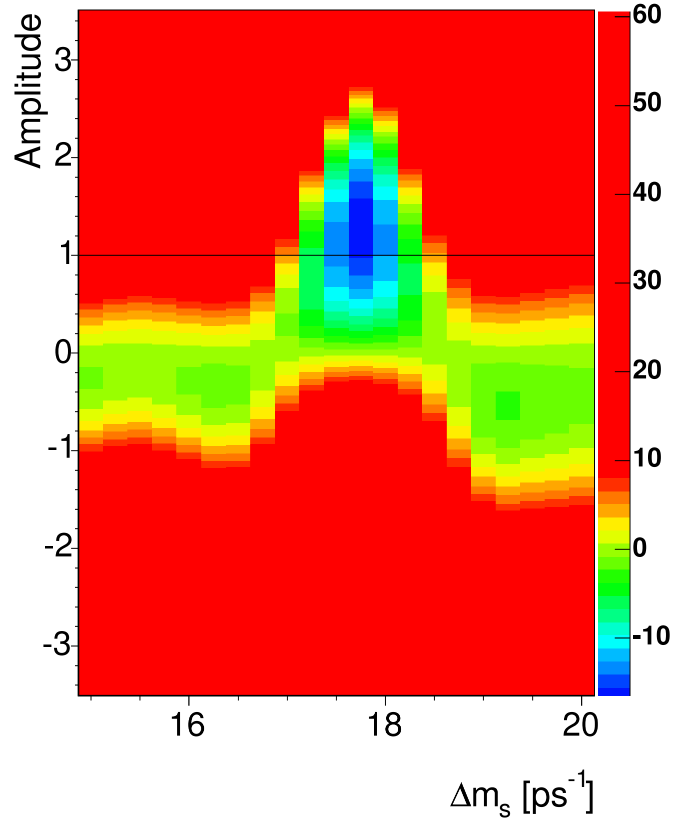
- ☞ $\Delta m_d = 0.509 \pm 0.010 \pm 0.016\ \text{ps}^{-1}$

World average:

- ☞ $\Delta m_d = 0.507 \pm 0.005$

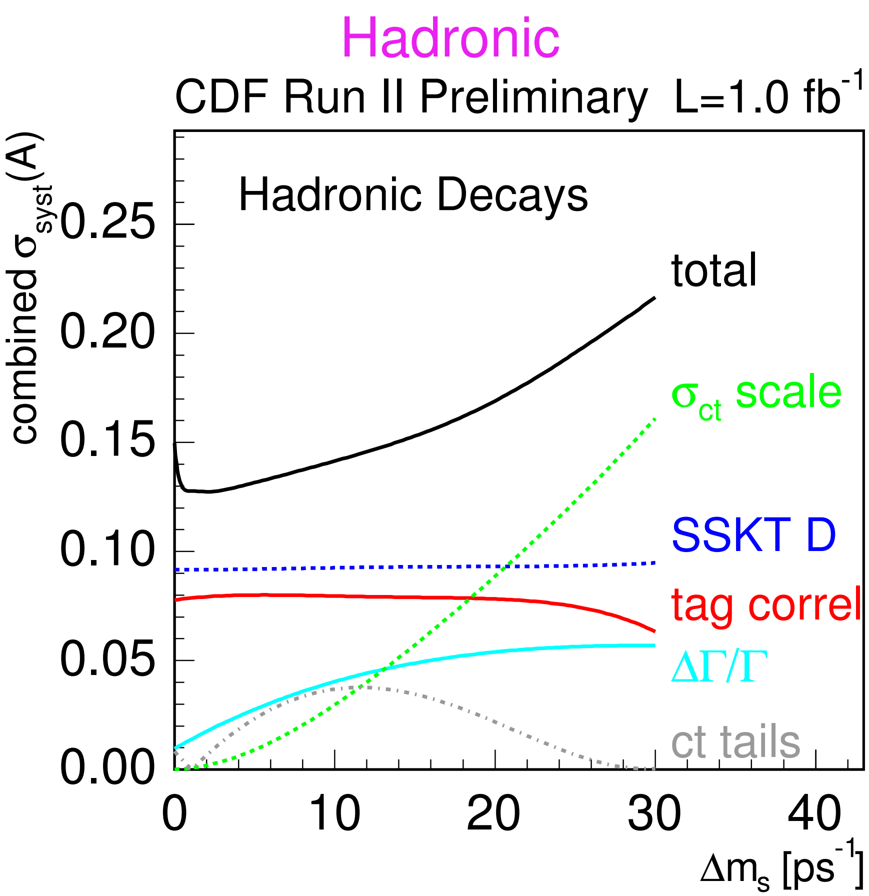
Amplitude vs. Δm_s

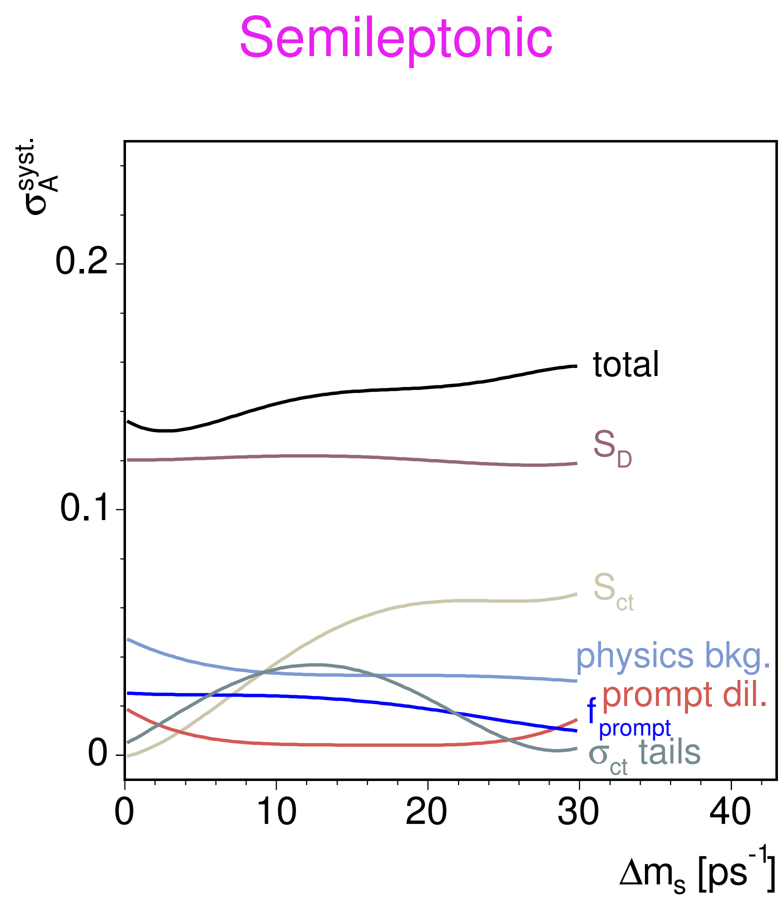




Clear minimum at $\mathcal{A} \sim 1$ and $\Delta m_s \sim 17.75$ ps^{-1}

Systematic Uncertainties on $\mathcal{A}$





Systematic uncertainties ~0.15-0.20 at high Δm_s
Analysis limited by statistics

Systematic Uncertainties on Δm_s

Source	Value (ps^{-1})
Silicon detector alignment	0.04
Track fit bias	0.05
Primary vertex bias	0.02
Hadronic k-factors	0.03
Amplitude scan systematic effects	< 0.01
Total	0.07

All relevant systematic uncertainties:

- ☞ related to ct scale
- ☞ common between hadronic and semileptonic samples

Probability of Δm_s uncertainty