B mixing and lifetimes at the Tevatron

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Jónatan Piedra
LPNHE-University Pierre et Marie Curie / CNRS-IN2P3
on behalf of the DØ and CDF Collaborations

Outline

- Precision *B* Lifetimes
  - motivation
  - L_b
  - B_c
  - B_s
  - $B_s \rightarrow KK$
  - B_s lifetime difference

- *B* Mixing
  - current status
  - ingredients
  - yields and lifetime
  - flavor taggers
  - amplitude scans

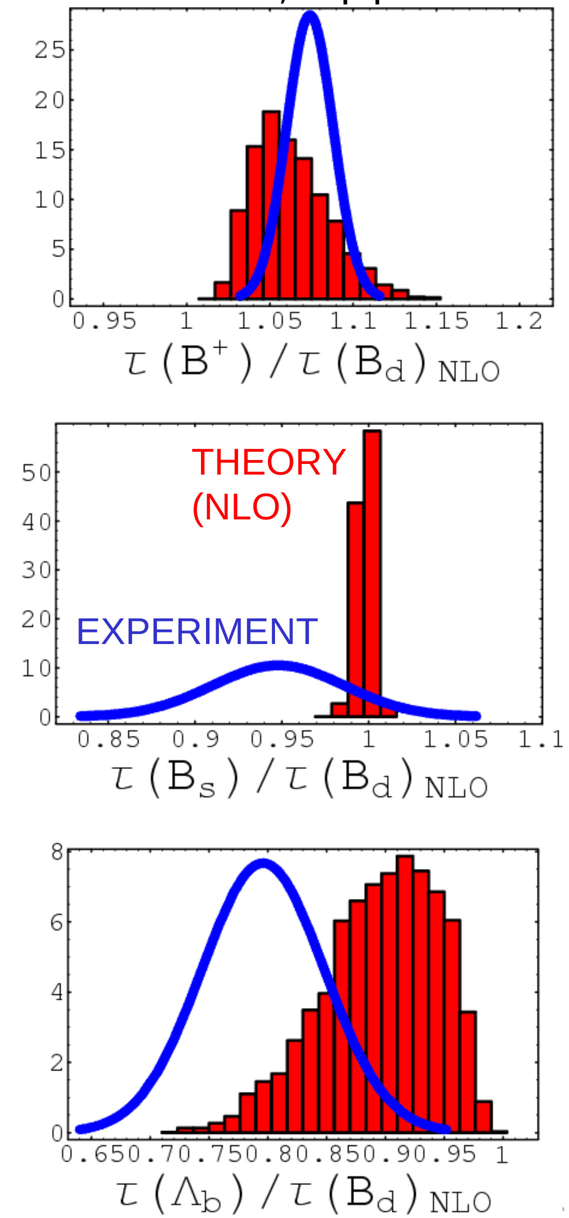
- Summary

Precision *B* Lifetimes

Motivation

- *b*-hadron decays dominated by *b*-quark
- Light quarks are included with $1/m_b$ perturbative expansions (HQE)
  - expect small differences between lifetimes of different species
  - lifetime ratios reduce theory uncertainties

C. Tarantino, hep-ph/0310241

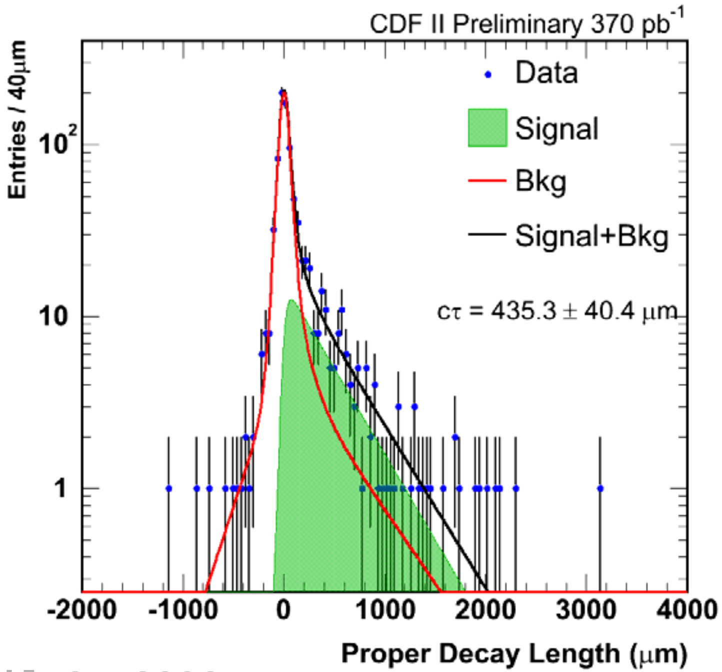


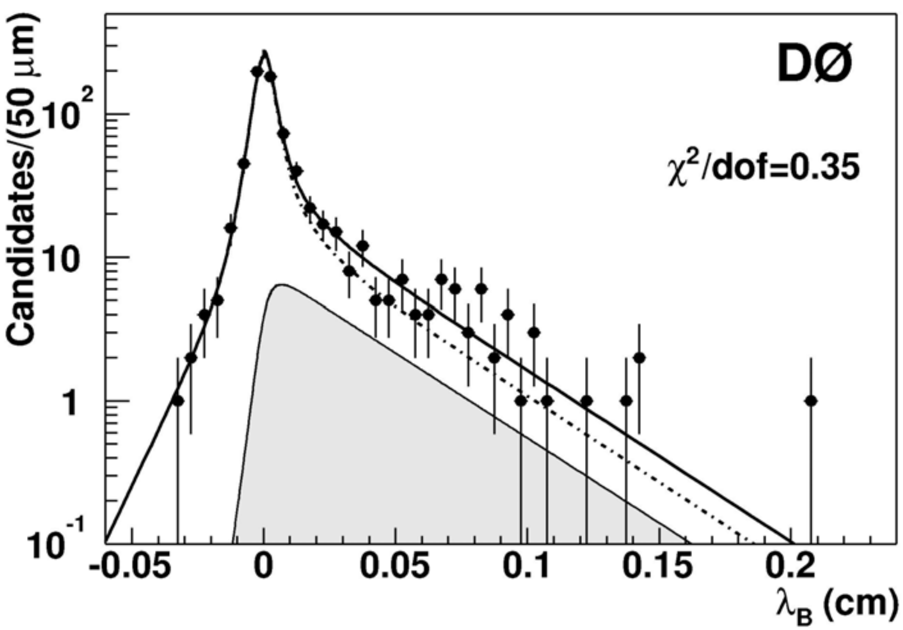
Λ_b Lifetime

- CDF and DØ have measured $\Lambda_b \rightarrow J/\psi\ \Lambda$ lifetime
- Better proper time resolution than $\Lambda_b \rightarrow \Lambda_c\ l\nu$ (world average)
- New result by CDF agrees better with theory

CDF *370 pb^{-1}*	DØ *250 pb^{-1}*
$\tau_{\Lambda_b} = 1.45^{+0.14}_{-0.13}\,(stat) \pm 0.02\,(syst)\,\text{ps}$	$\tau_{\Lambda_b} = 1.22^{+0.22}_{-0.18}\,(stat) \pm 0.04\,(syst)\,\text{ps}$

PRL 94 102001 (2005)





B_c Lifetime

- Expected $\tau(B_u^+) \sim 3 \times \tau(B_c^+)$ assuming 3 decay subprocesses
  - *b*(*c*) quark decays, *c*(*b*) quark is spectator
  - *bc* annihilation decays
- Lifetime extracted from $B_c^+ \to J/\psi e^+ \nu_e$ decay
  - electron ID using energy loss and calorimeter shower information

CDF *360 pb⁻¹*

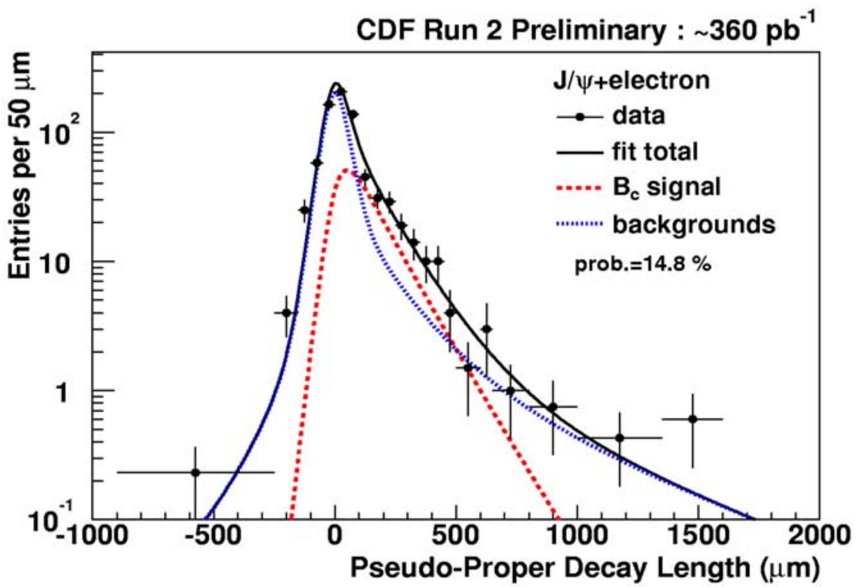
$$\tau_{B_c^+} = 0.463^{+0.073}_{-0.065}\,(stat) \pm 0.036\,(syst)\,\text{ps}$$

best in the world

theory prediction

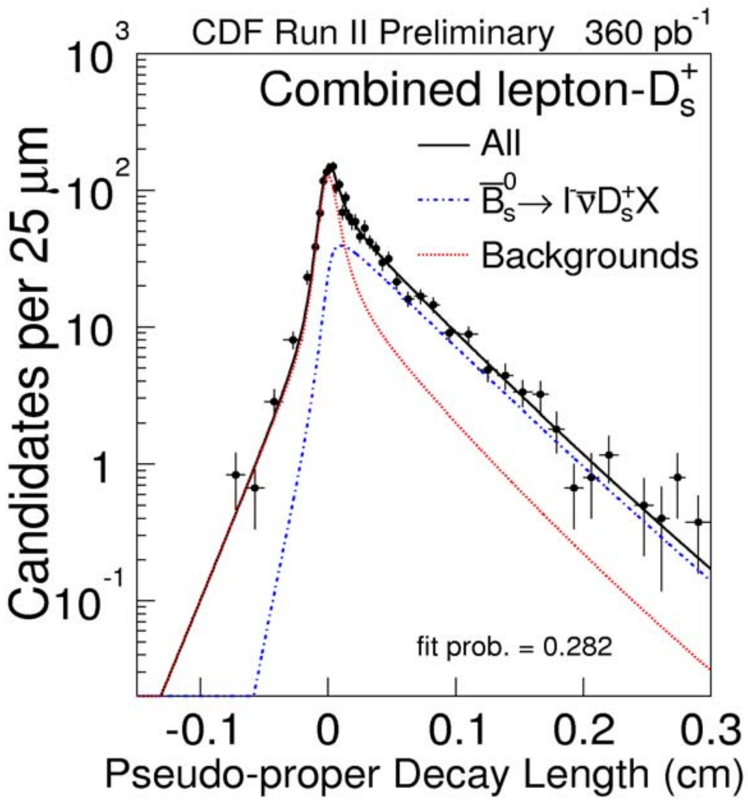
$$\tau_{B_c^+} = 0.55 \pm 0.15\,\text{ps}$$

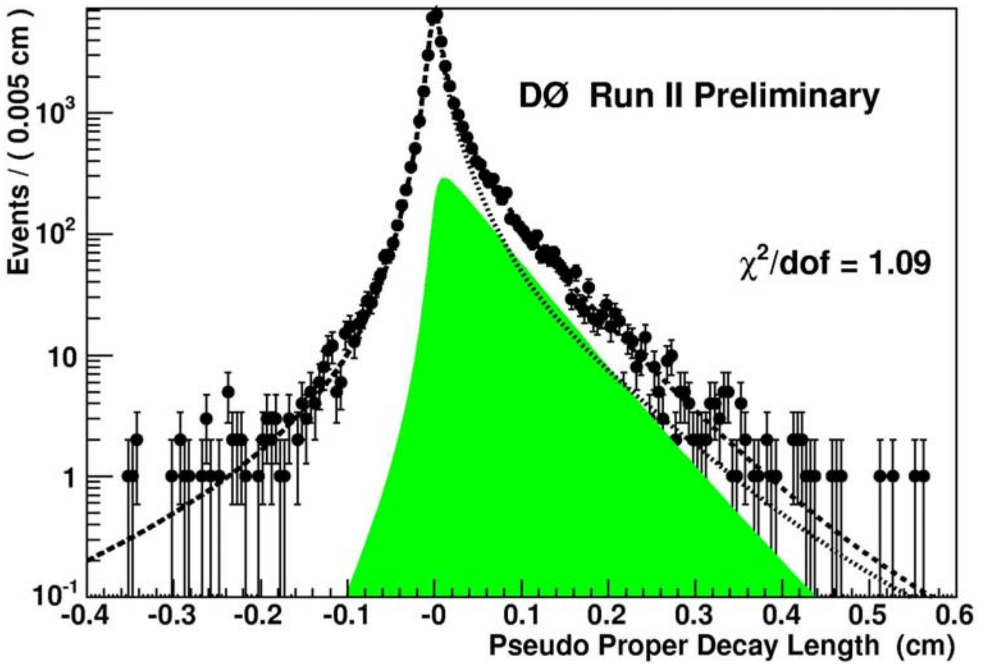
V. Kiselev, hep-ph/0308214



B_s Lifetime

- DØ and CDF measure B_s^0 lifetime in $B_s^0 \to D_s^- l^+ \nu\ X$





CDF *360 pb-1*

$$\tau_{B_s^0} = 1.381 \pm 0.055\,(stat)^{+0.052}_{-0.046}\,(syst)\,\text{ps}$$

DØ *400 pb-1*

$$\tau_{B_s^0} = 1.420 \pm 0.043\,(stat) \pm 0.057\,(syst)\,\text{ps}$$

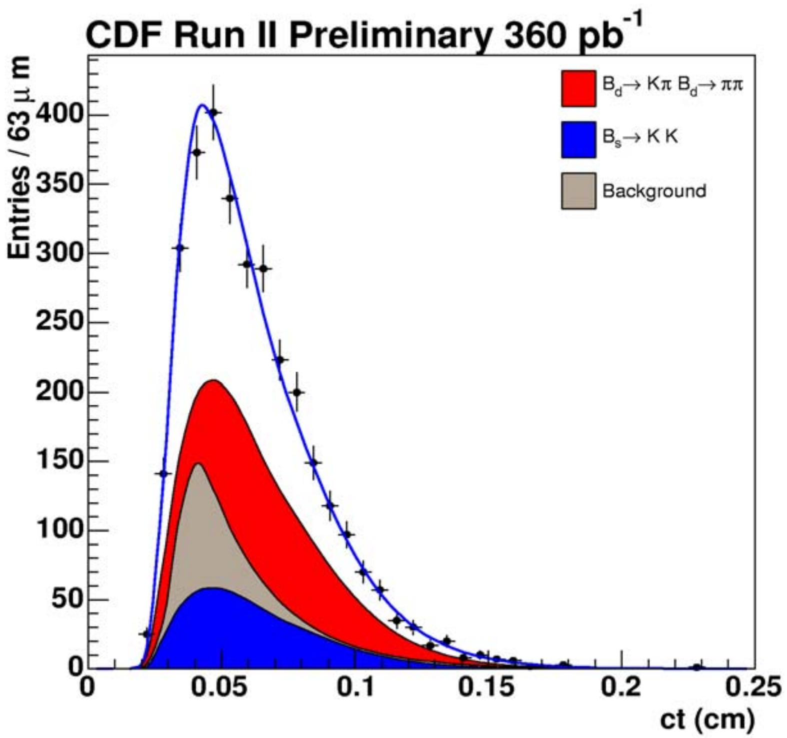
best in the world

$B_s \to K^+K^-$ Lifetime

- First $\tau_{B_s \to K^+K^-} (\approx \tau_L)$ measurement
- $B \to h_1^+ h_2^-$ is a mixture of

$$B_d^0 \to \pi^+\pi^- \qquad B_d^0 \to K^+\pi^-$$
$$B_s^0 \to K^+K^- \qquad B_s^0 \to \pi^+K^-$$

- Separate decays statistically
  - kinematics
  - particle ID (dE/dx)



CDF 360 pb^{-1} | HFAG flavor specific

$\tau_L = 1.53 \pm 0.18\,(stat) \pm 0.02\,(syst)$ ps | $\tau_{B_s} = 1.454 \pm 0.040$ ps

$$\frac{\Delta\Gamma_{CP}(B_s \to K^+K^-)}{\Gamma_{CP}(B_s \to K^+K^-)} = -0.08 \pm 0.23\,(stat) \pm 0.03\,(syst)$$

B_s Lifetime Difference

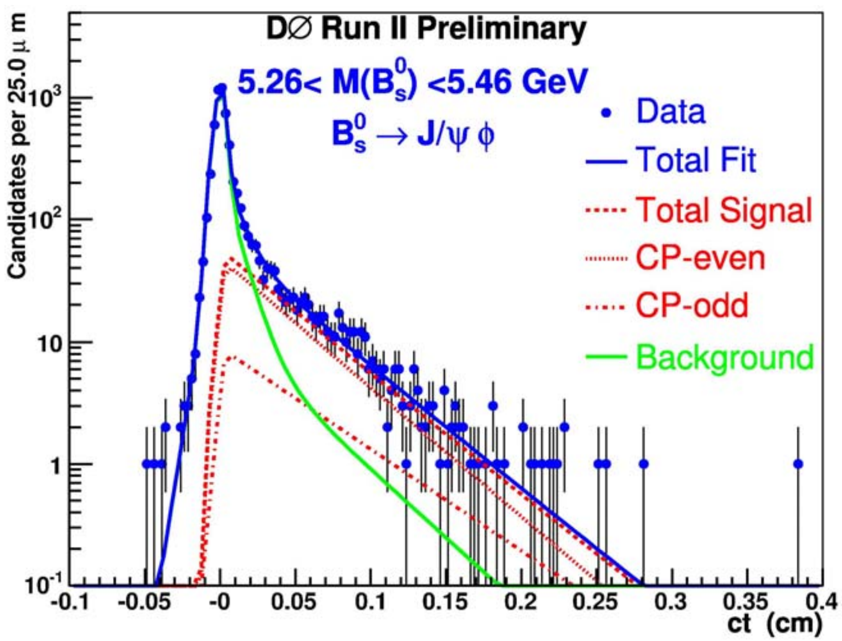
- $B_s \to J/\psi\ \phi$

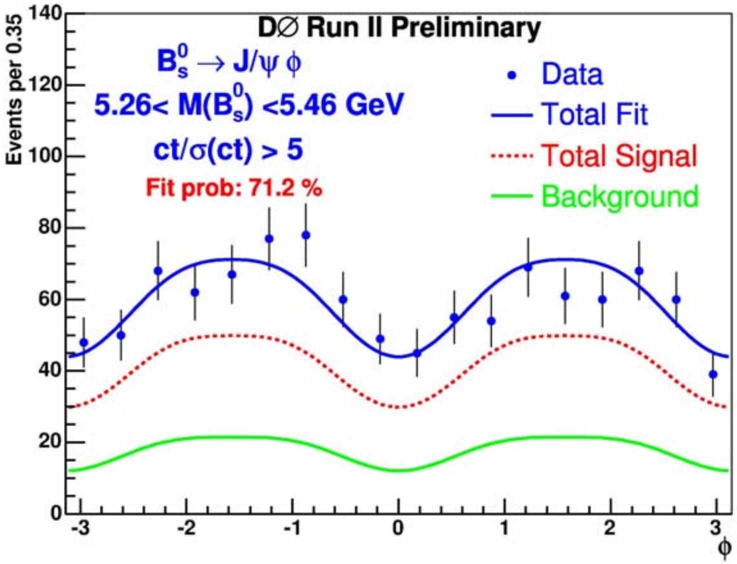
Pseudoscalar $\to$ Vector - Vector

- Decay amplitude decomposed into 3 linear polarization states
  - A_0 = S + D wave $\Rightarrow$ P even
  - $A_{||}$ = S + D wave $\Rightarrow$ P even
  - $A_{\perp}$ = P wave $\Rightarrow$ P odd
- If CP violation neglected
  - $B_{s,\text{Light}} \approx$ CP even
  - $B_{s,\text{Heavy}} \approx$ CP odd
  - angular distributions are different
- Angular analysis separates CP eigenstates $\Rightarrow$ measure two lifetimes

B_s Lifetime Difference

- Results consistent with SM
- Consistent with no CP violation





DØ *0.8 fb^{-1}*

$$\Delta\Gamma = 0.15 \pm 0.10^{+0.03}_{-0.04}\ \mathrm{ps}^{-1}$$

$$\bar{\tau}\left(B_s^0\right) = 1.53 \pm 0.08^{+0.01}_{-0.04}\ \mathrm{ps}^{-1}$$

$$R_\perp = \left|A_\perp(0)\right|^2 = 0.19 \pm 0.05 \pm 0.01$$

$$\left|A_\perp(0)\right|^2 - \left|A_\parallel(0)\right|^2 = 0.35 \pm 0.07 \pm 0.01$$

$$\delta_1 - \delta_2 = 2.5 \pm 0.4 \pm 0.02$$

B Mixing

B Mixing Theoretical Prediction

- SM prediction for the ratio of B_s and B^0 mixing frequencies

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

$$\xi^2 = 1.21 \pm 0.02^{+0.035}_{-0.014}$$

- Δm_d precisely measured

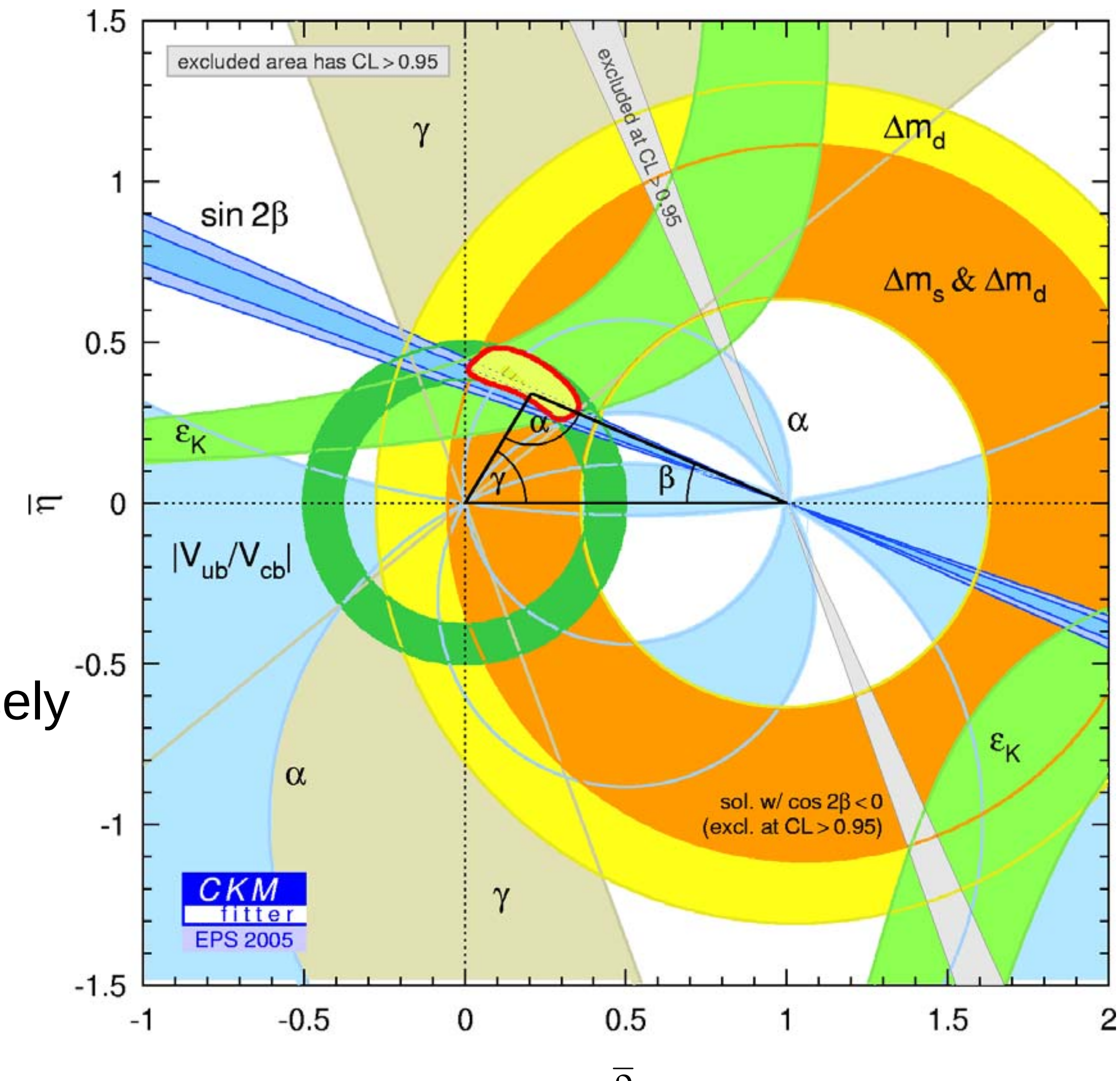
$$\Delta m_d = 0.508 \pm 0.004\ \mathrm{ps}^{-1}$$

- Δm_s not yet measured precisely

CKM fit

$$\Delta m_s = 18.3^{+6.5}_{-1.5}\ \mathrm{ps}^{-1}$$

- Potential NP discovery

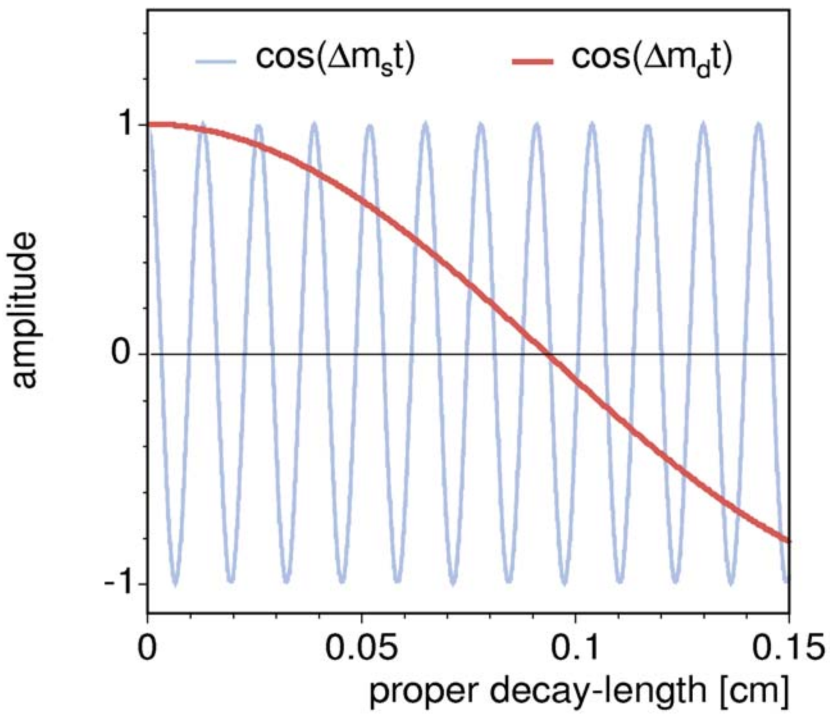


B_s Mixing

- Δm_s challenge, fast oscillations
  - precise vertex
  - precise momentum
  - tagging essential
  - many signal events
  - low background

$\Delta m_d = 0.5\ \text{ps}^{-1}$

$\Delta m_s \equiv 14.4\ \text{ps}^{-1}$



- Sensitivity to mixing

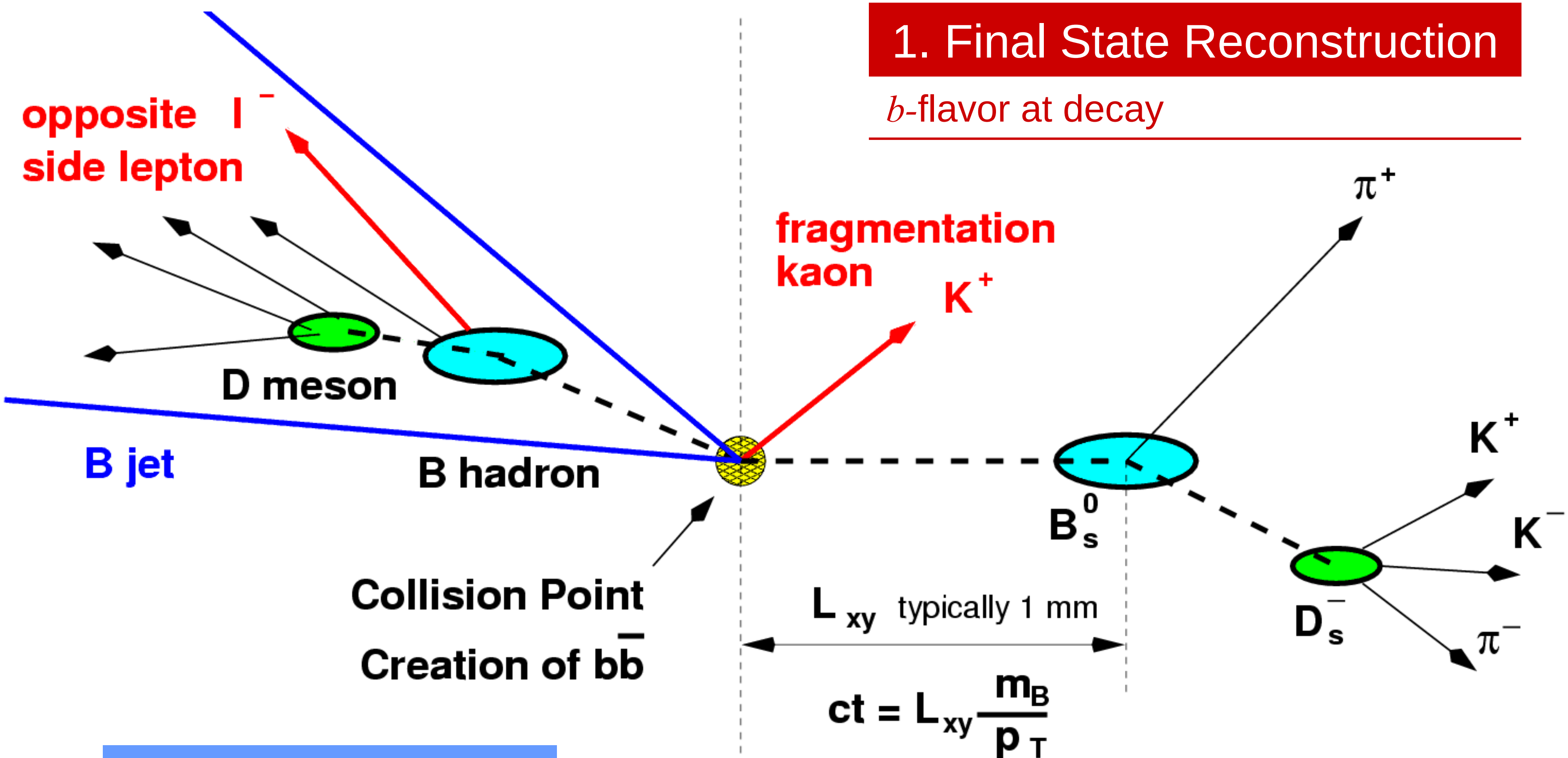
NIM A 384 491, Moser & Roussarie

$$significance = \sqrt{\frac{S}{S+B}}\sqrt{\frac{\varepsilon\mathcal{D}^2}{2}}e^{-\frac{1}{2}\sigma_{ct}^2\Delta m_s^2}$$

B Mixing Ingredients

1. Final State Reconstruction

b-flavor at decay



3. *b*-Flavor Tagging

b-flavor at production

2. Proper Decay Time

In *B* rest frame

4. Amplitude Scan for B_s Mixing

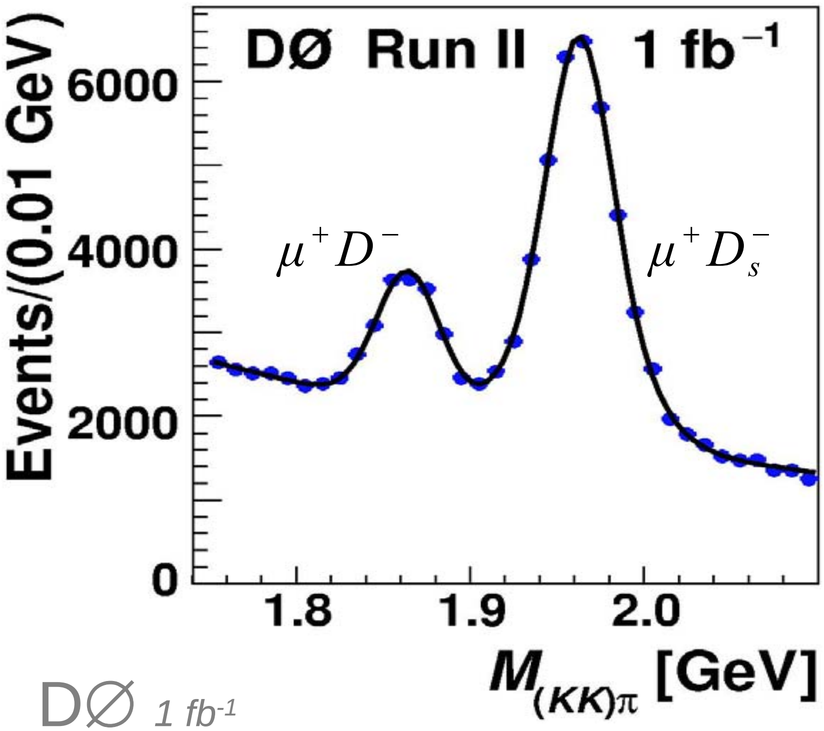
Set a lower limit on Δm_s

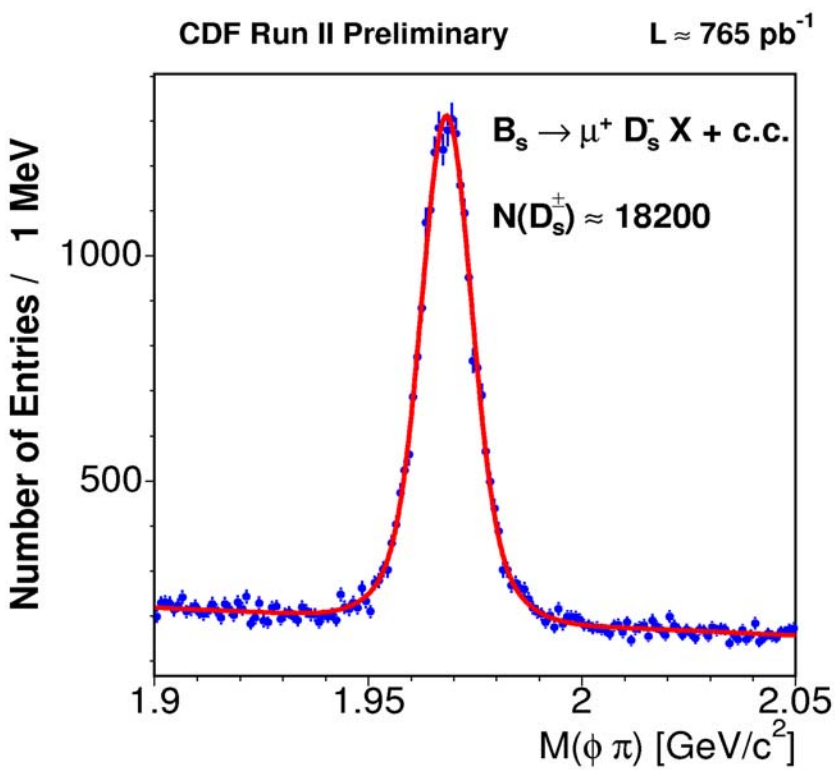
Opposite Side

Trigger Side

Reconstructed $B_s \to l^+ D_s^- X$

- Worse proper time resolution but high statistics
- DØ exploits semileptonic decays from μ trigger
- CDF uses both electrons and muons





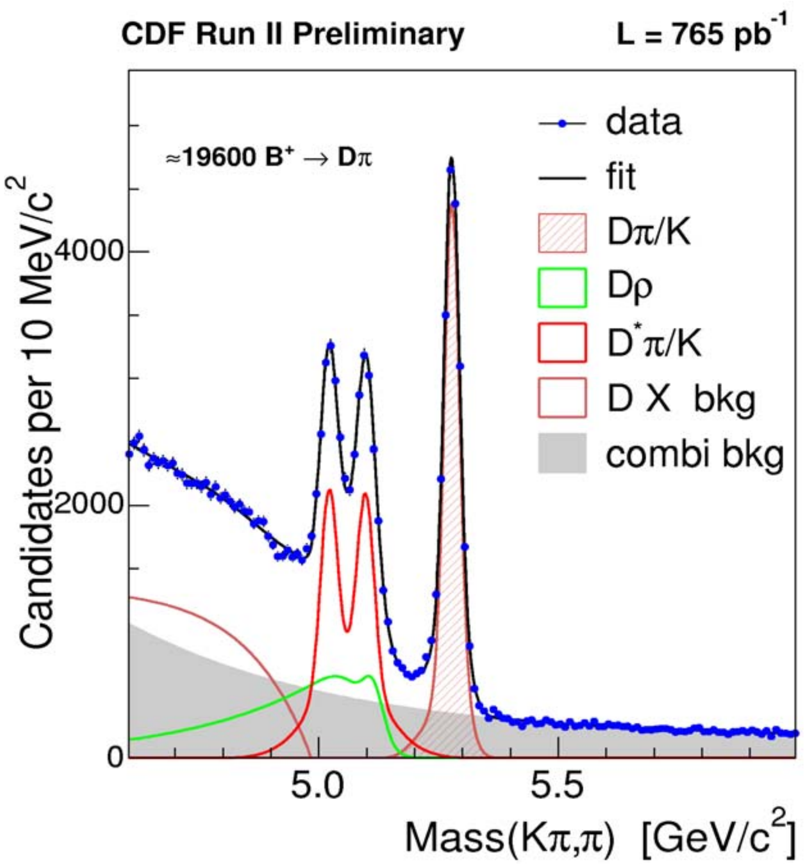
DØ 1 fb^{-1}

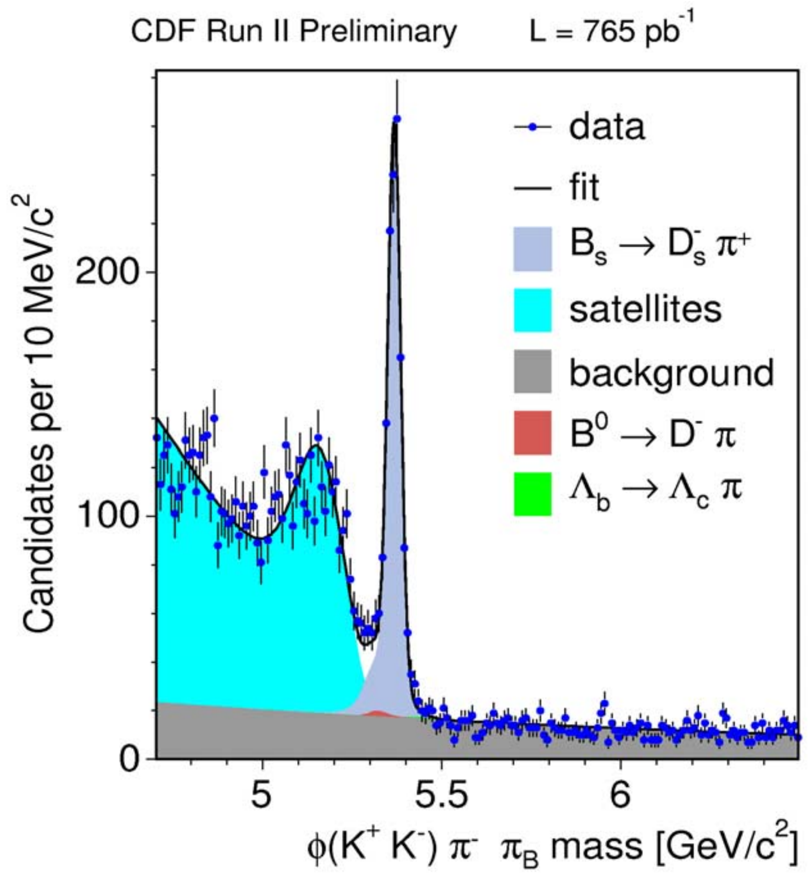
$$N_{\mu^+ D_s^-} = 26710 \pm 556\,(stat)$$

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

Reconstructed $D_s^-(\pi^+\pi^-)\pi^+$

- CDF collects hadronic *B* decays by triggering on impact parameter
- More than 2300 B_s signal candidates





B Mixing Proper Decay Time

- Procedure
  - measure p_T of B daughter tracks
  - measure the decay length L_{xy}
  - boost B back to its rest frame

$$ct = \frac{L_{xy}}{\gamma\beta}$$

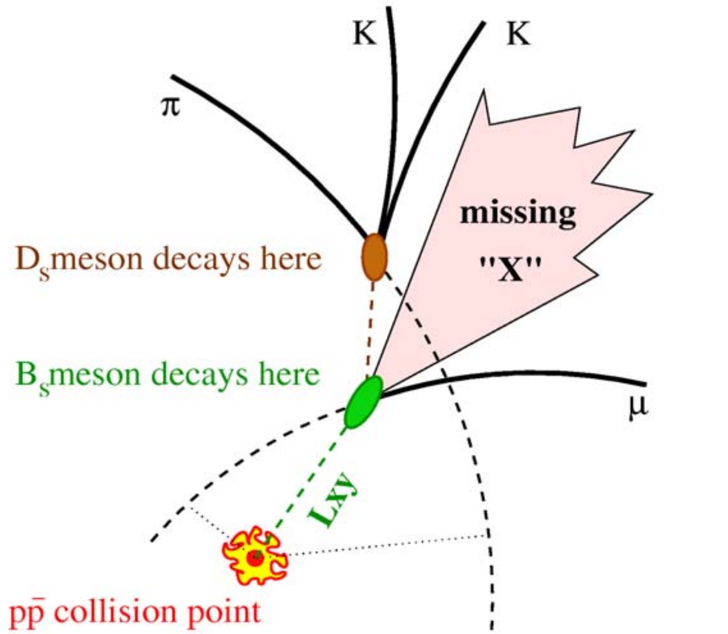
$$k_{MC} \equiv \left\langle \frac{p_T^{lD}}{p_T^B} \right\rangle_{MC}$$

$$\gamma\beta = \frac{p_T^B}{m_B} \approx \frac{p_T^{lD}}{m_B}\frac{1}{k_{MC}}$$

- Fully reconstructed decays
  - all daughters reconstructed

- Partially reconstructed decays
  - some tracks escape detection

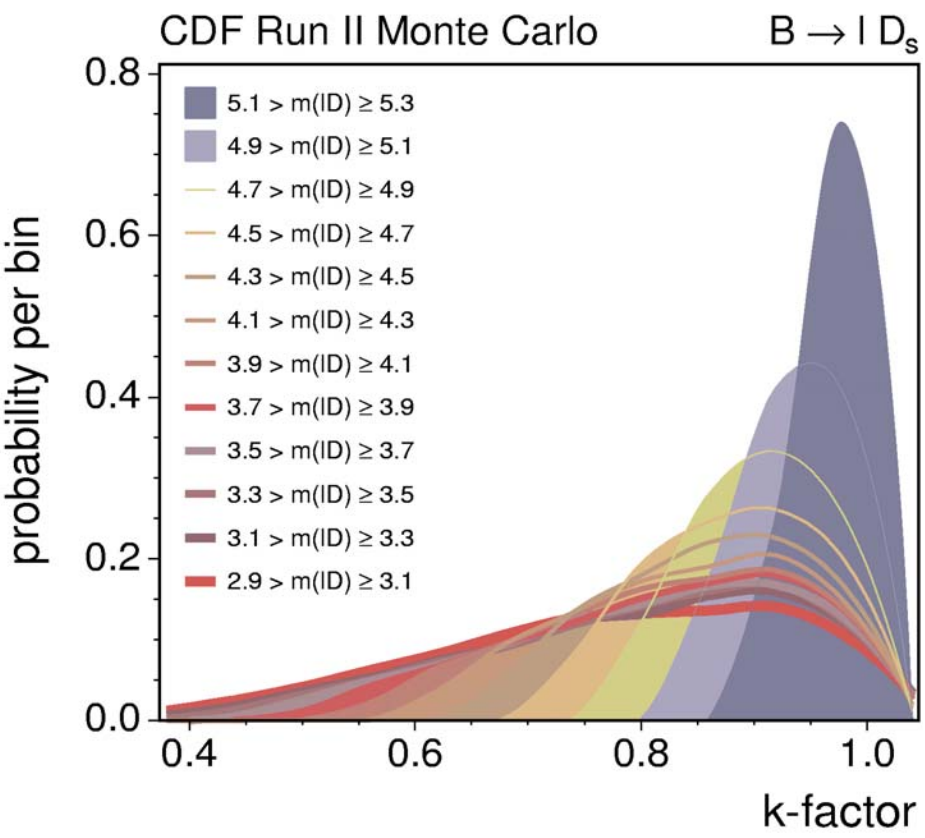
$\Rightarrow$ need simulation *(next slide)*



Semileptonic Decay Time

- Missing particles ⇒ missing p_T
- Determine pseudo-ct from data

$$ct^* = L_{xy} \frac{m_B}{p_T^{lD}}$$



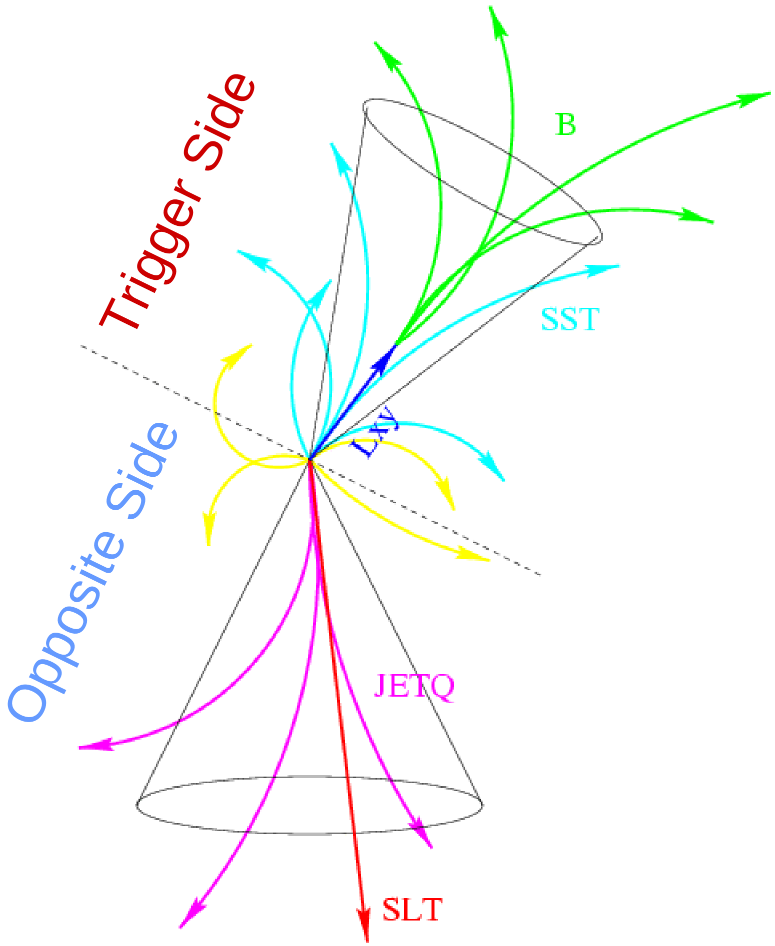
- $ct = ct^* K$, estimate K from MC
  - include K effect in signal PDF

$$P(ct^*) = \frac{K}{2c\tau} e^{-\frac{ct^* K}{c\tau}} \theta(ct^*) \otimes Gauss \otimes F(K)\, \xi(ct^*)$$

- Use different $F(K)$ for different $m(lD)$ ranges

b-Flavor Tagging

- A flavor tagger determines the b-flavor at production time
- $b\bar{b}$ production $\Rightarrow$ flavor tagging on the Trigger Side or the Opposite Side



- Soft Lepton Tagger **SLT**
  - look for $B \to l\nu DX$ decay on the OS
  - lepton charge indicates b-flavor
- Jet Charge Tagger **JQT**
  - look for a jet from OS b-hadron
  - jet charge indicates b-flavor
- Same Side (Kaon) Tagger **SS(K)T**
  - look for a fragmentation track on the TS
  - it is charge correlated with the b-flavor

Opposite Side Taggers

- A flavor tagger not always can be applied $\varepsilon \equiv \frac{correct\ \ tags + incorrect\ \ tags}{N}$
- It can give a wrong answer. The dilution $\mathcal{D}$ measures the purity

$$\mathcal{D} \equiv \frac{correct\ \ tags - incorrect\ \ tags}{correct\ \ tags + incorrect\ \ tags}$$

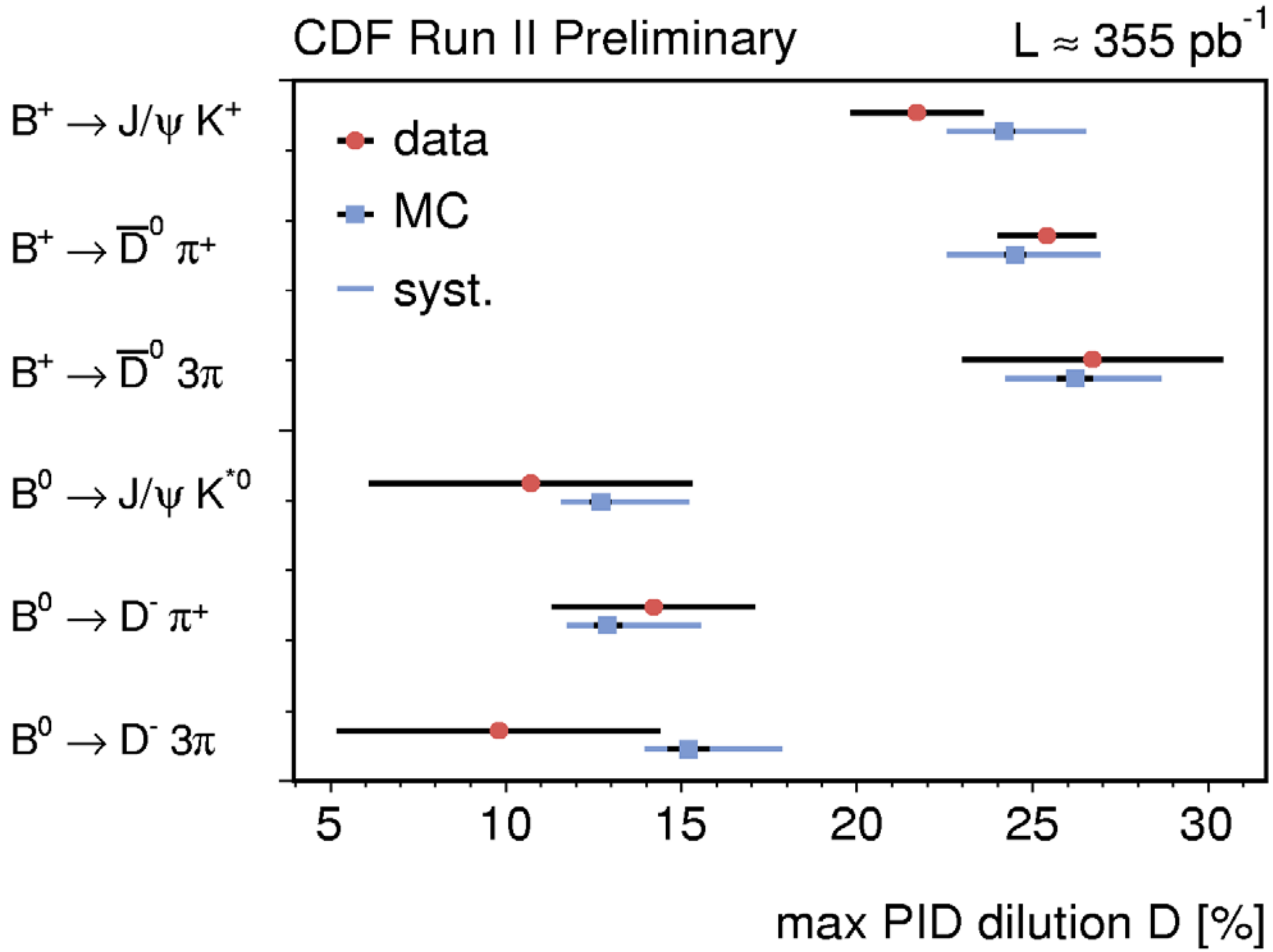
- The dilution attenuates the observed oscillations

$$P(t)_{B^0 \to B^0, \overline{B}^0} \cong \frac{1}{2\tau} e^{-\frac{t}{\tau}} \left[1 \pm \mathcal{D} \cos(\Delta m t)\right]$$

$\varepsilon\mathcal{D}^2$ (%)	DØ	CDF
muons	1.48 ± 0.17	0.55 ± 0.05
electrons	0.21 ± 0.07	0.30 ± 0.03
jets	0.50 ± 0.11	0.70 ± 0.06
combined	2.48 ± 0.22	1.55 ± 0.08

SSKT at CDF

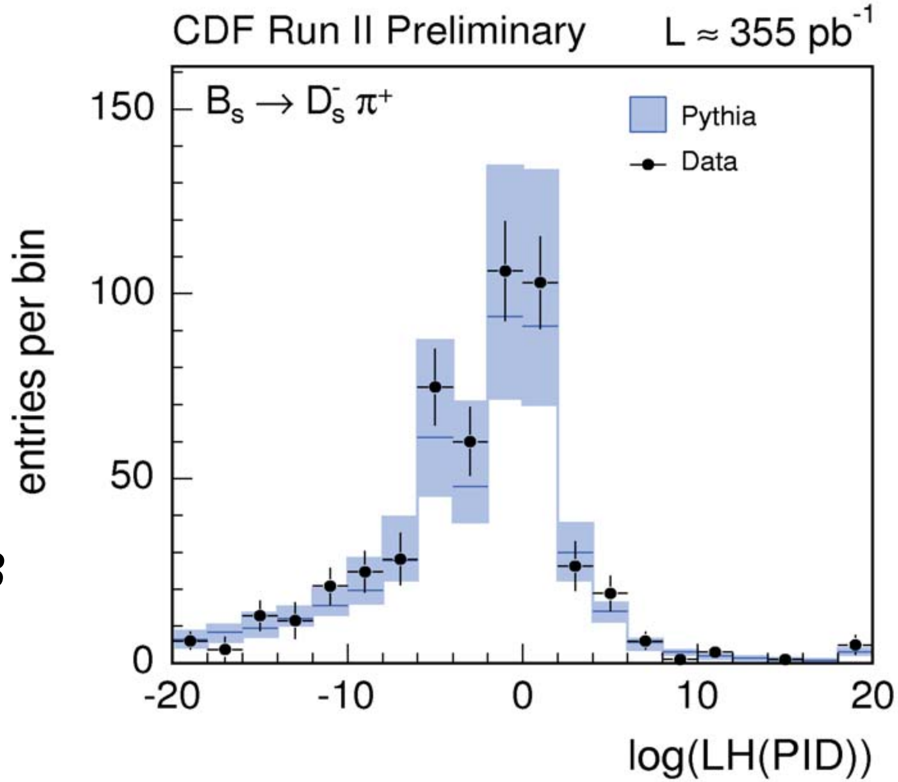
- Must rely on MC prediction of SSKT performance for B_s decays
  - Extensive data/MC comparisons on all tagging related quantities



EXCELLENT AGREEMENT IN HIGH STATISTICS B^+ AND B^0 MODES

B Mixing SSKT at CDF

- Systematic studies cover
  - quark fragmentation model
  - $b\bar{b}$ production mechanisms
  - excited *B* mesons content
  - detector / PID resolution
  - particle species content around *B*
  - data / MC agreement



- Select using PID the most likely kaon track
  - LH(PID) ≡ TOF and *dE/dx* combined likelihood

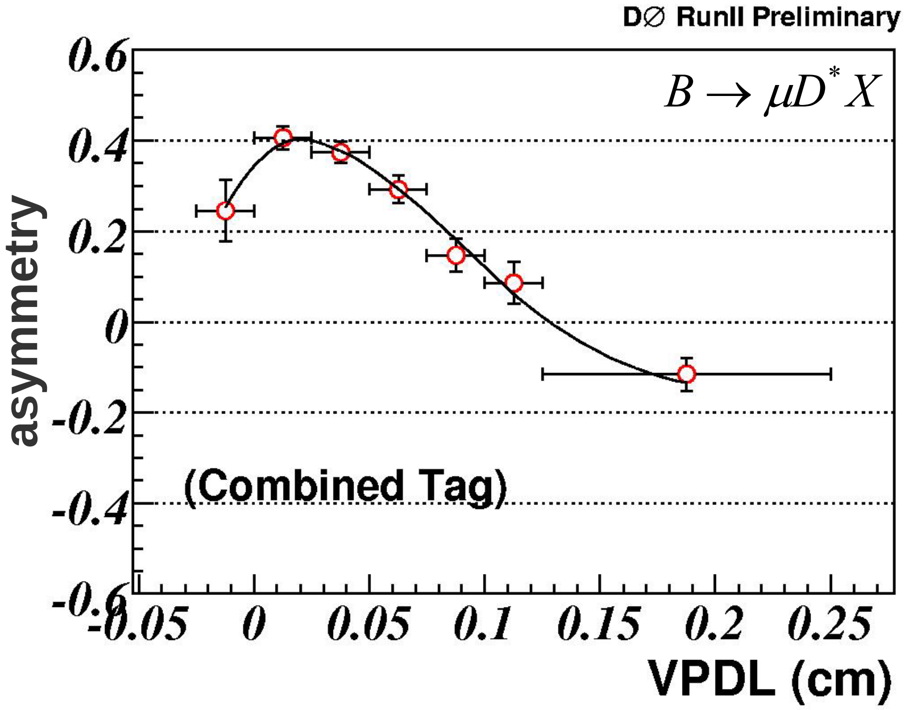
CDF *MC*

$$\varepsilon \mathcal{D}^2_{SSKT}\left(B_s^0 \rightarrow D_s^- \pi^+\right) = 4.0^{+0.8}_{-1.2}\ \%$$

Flavor Analysis on B^+ and B^0

- Calibrate opposite side flavor taggers prior to Δm_s analysis
  - combine several $B^{+,0}$ decays
  - combine all taggers
- Direct Δm_d measurement
  - crosscheck for B_s mixing
  - 'easy' slow oscillations

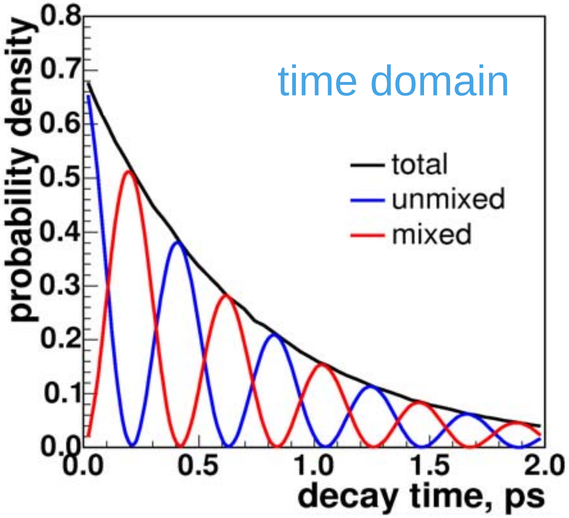
$$\mathcal{A} = \frac{P(ct)_{unmix} - P(ct)_{mix}}{P(ct)_{unmix} + P(ct)_{mix}} \sim \mathcal{D}\cos(\Delta m_d t)$$



DØ semileptonic	Δm_d = 0.506 ± 0.020 (syst) ± 0.016 (stat) ps^{-1}
CDF semileptonic	Δm_d = 0.511 ± 0.020 (syst) ± 0.014 (stat) ps^{-1}
CDF hadronic	Δm_d = 0.536 ± 0.028 (syst) ± 0.006 (stat) ps^{-1}
world average	Δm_d = 0.508 ± 0.004 ps^{-1}

Fourier Analysis

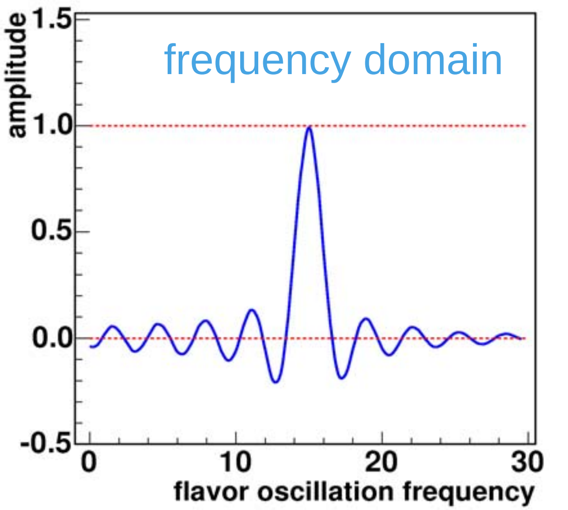
- Two domains to fit for oscillations
  - time $\rightarrow$ fit for a cosine wave
  - frequency $\rightarrow$ examine f-spectrum



- Time domain approach
  - fit for Δm_s in $P(t) \sim 1 \pm \mathcal{D}\cos(\Delta m_s t)$

- Frequency domain approach
  - introduce amplitude, $P(t) \sim 1 \pm \mathcal{A}\mathcal{D}\cos(\Delta m_s t)$
  - fit for $\mathcal{A}$ at different Δm_s

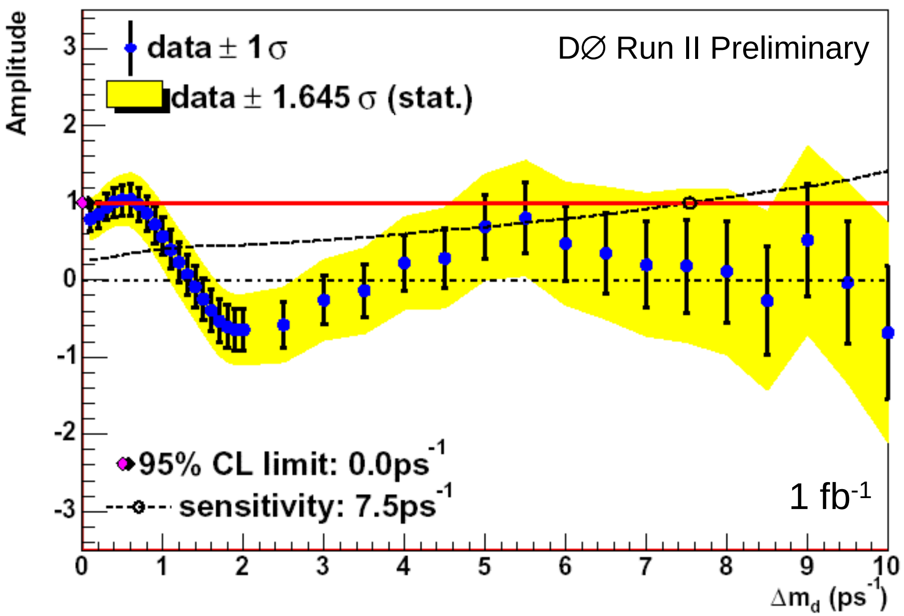
  $\Rightarrow$ obtain frequency spectrum $\mathcal{A}(\Delta m_s)$
  - method is called amplitude scan



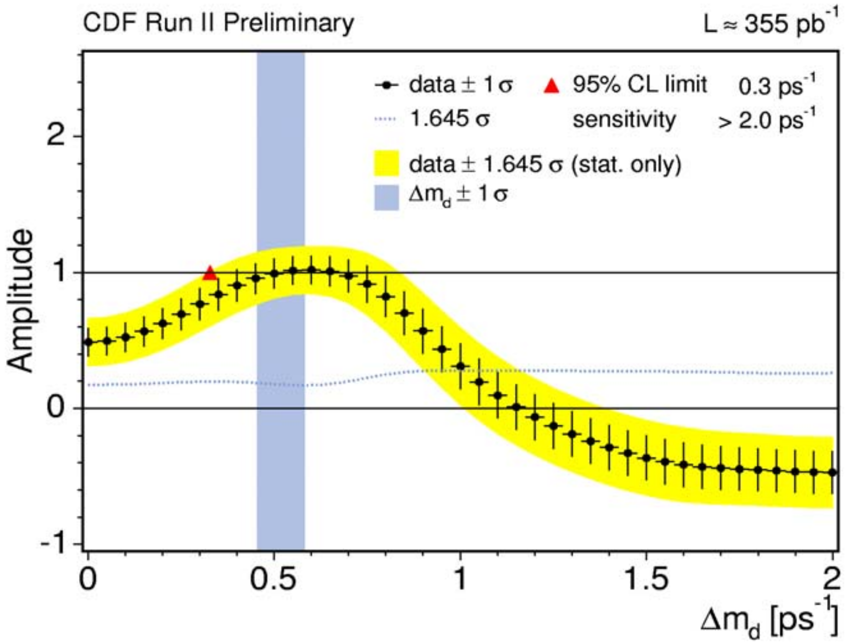
  - with flavor taggers calibrated $\mathcal{A} = 1$ for the true Δm_s else $\mathcal{A} = 0$

Amplitude Scans on Δm_d

- The yellow band is $\pm 1.645\sigma_{\mathcal{A}}$ around data points
- Δm values where $\mathcal{A} + 1.645\sigma_{\mathcal{A}} < 1$ are excluded at 95% CL
- Sensitivity is where $1.645\sigma_{\mathcal{A}} = 1$



$B \to \mu^+ D^- X$

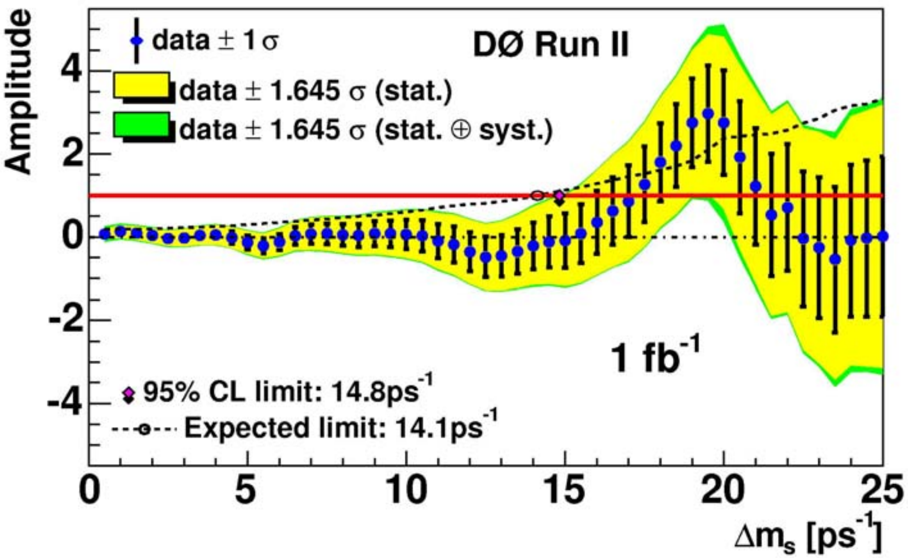


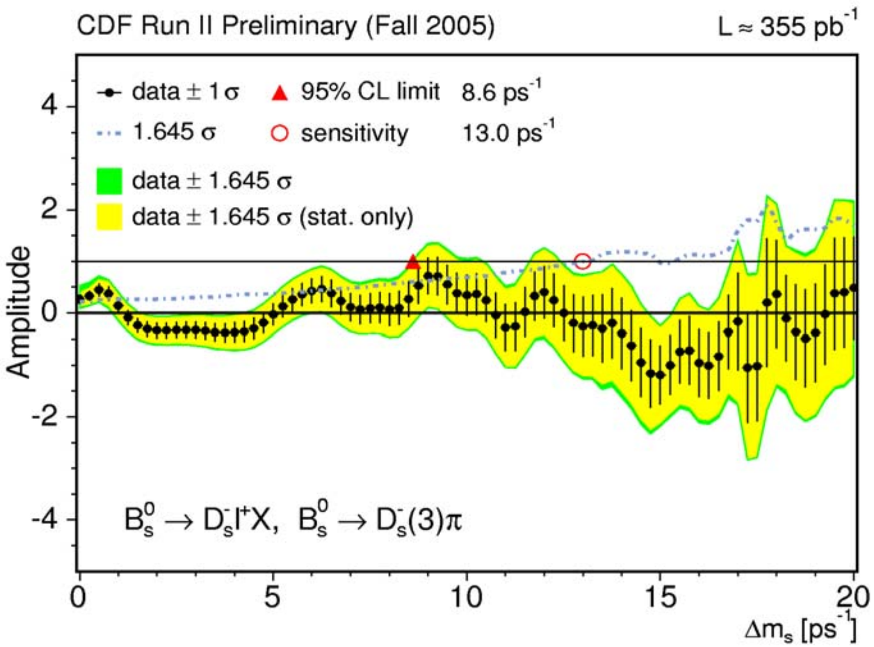
$B^0 \to J/\psi K^{*0}, B^0 \to D^- \pi^+$

Amplitude scan works on B^0 decay modes

Amplitude Scans on Δm_s

$A/\sigma_A(\Delta m_s = 19\ ps^{-1}) = 2.5 \rightarrow$ 5% p-value





DØ *1 fb^{-1}*

95% CL limit	14.8 ps^{-1}
sensitivity	14.1 ps^{-1}

CDF *355 pb^{-1}*

95% CL limit	8.6 ps^{-1}
sensitivity	13.0 ps^{-1}

Summary

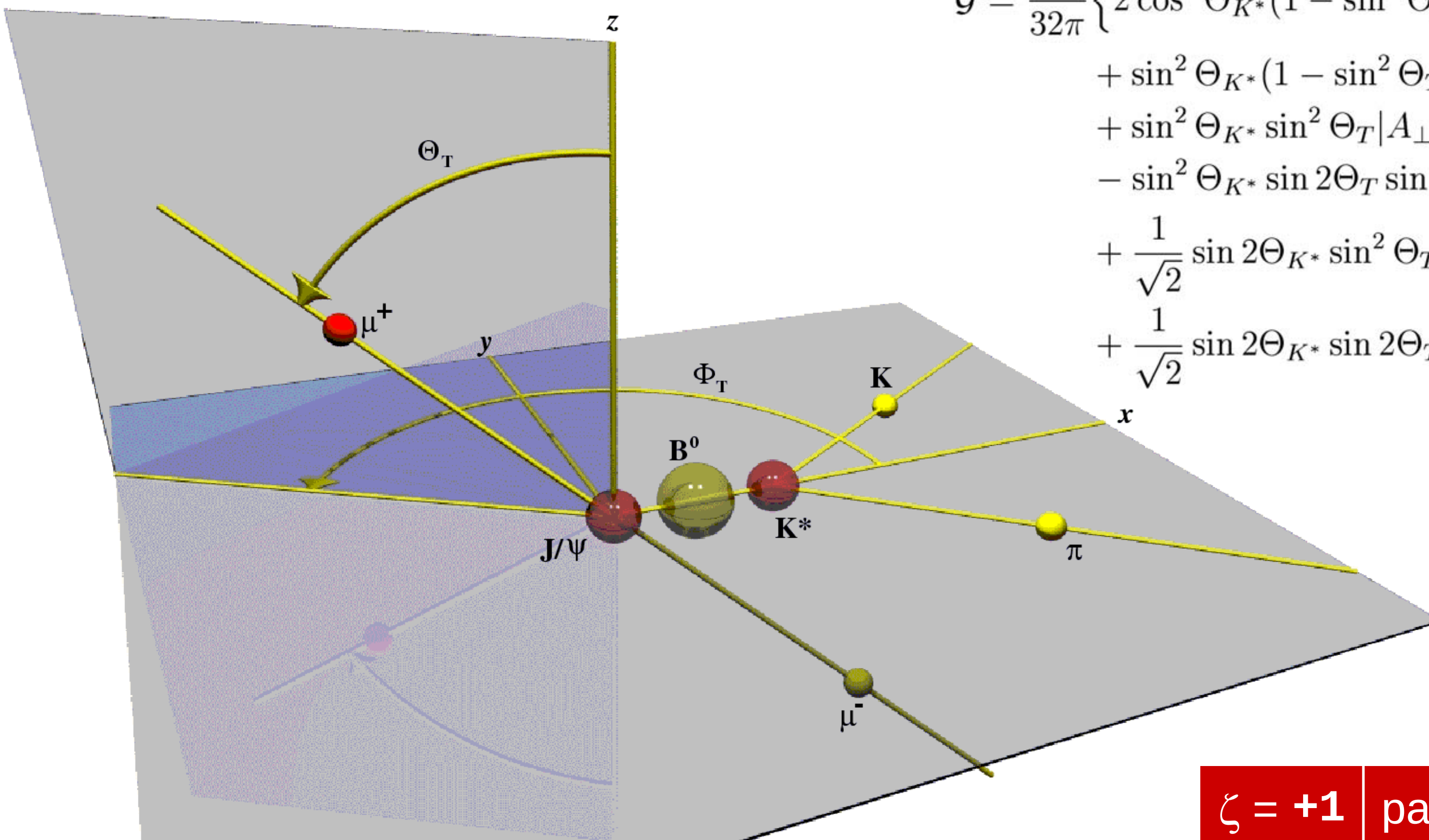
- New CDF Λ_b lifetime reduces distance with theory
- Best B_c lifetime in the world at CDF
- Best B_s lifetime in the world at D∅
- CDF measures by the first time $B_s \to KK$ lifetime
- D∅ finds B_s lifetime difference within SM *(0.8 fb^{-1})*

- D∅ mixing squeezes their semileptonic decays
  - $\Delta m_s > 14.8$ ps^{-1} @ 95% CL *(1 fb $^{-1}$)*
- CDF mixing expected to be probing SM soon
  - $\Delta m_s > 8.6$ ps $^{-1}$ @ 95% CL *(355 pb $^{-1}$)*


Backup

Transversity Basis

$$\mathcal{G} = \frac{9}{32\pi}\Big\{2\cos^2\Theta_{K^*}(1-\sin^2\Theta_T\cos^2\Phi_T)|A_0|^2$$
$$+\sin^2\Theta_{K^*}(1-\sin^2\Theta_T\sin^2\Phi_T)|A_{||}|^2$$
$$+\sin^2\Theta_{K^*}\sin^2\Theta_T|A_\perp|^2$$
$$-\sin^2\Theta_{K^*}\sin 2\Theta_T\sin\Phi_T Im(A_{||}^*A_\perp)\zeta$$
$$+\frac{1}{\sqrt{2}}\sin 2\Theta_{K^*}\sin^2\Theta_T\sin 2\Phi_T Re(A_0^*A_{||})$$
$$+\frac{1}{\sqrt{2}}\sin 2\Theta_{K^*}\sin 2\Theta_T\cos\Phi_T Im(A_0^*A_\perp)\zeta\Big\}$$



ζ = **+1**	particle
ζ = **-1**	antiparticle
ζ = **0**	untagged B_s

- Transversity basis ≡ J/ψ rest frame
- ϕ flight direction ≡ $+x$
- KK plane ≡ xy plane