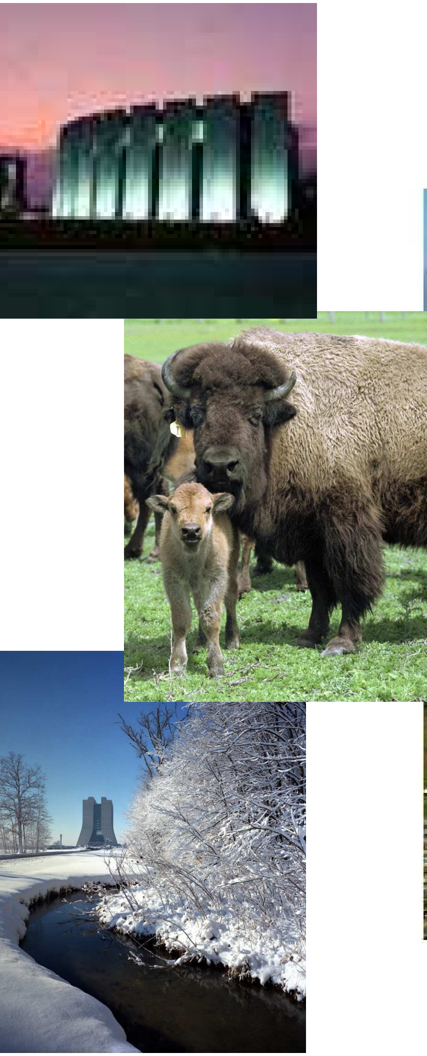
B_s Lifetime Difference and Mixing @ the Tevatron

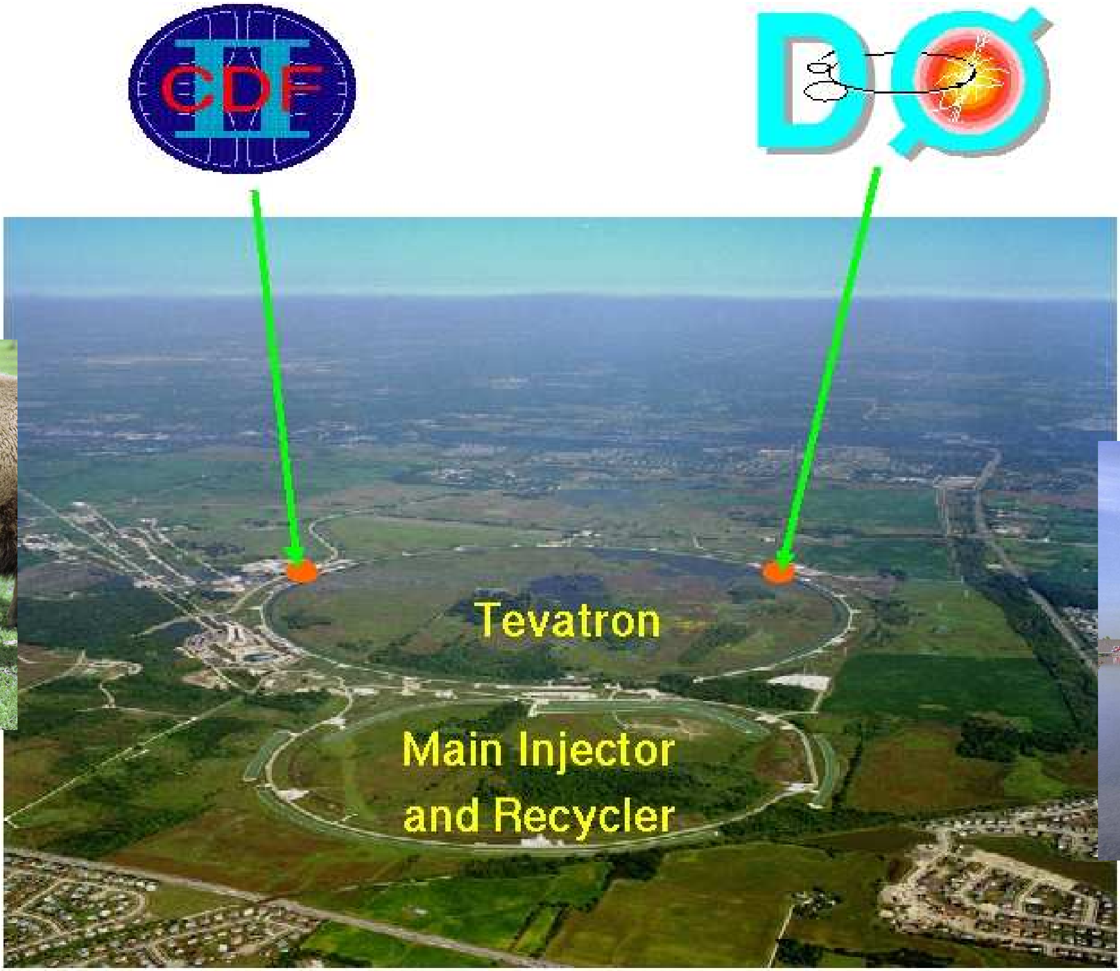
Stephanie Menzemer

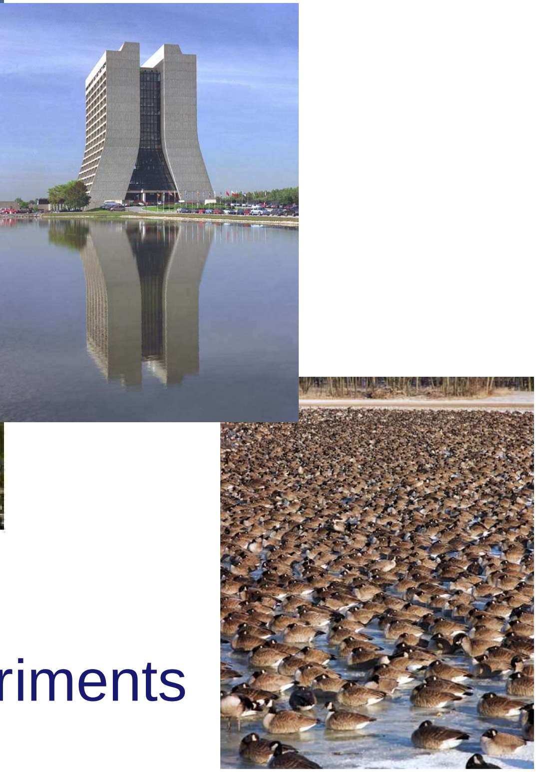
Physikalisches Institut,
Ruprecht-Karls-Universität Heidelberg

Munich, 17^{th} of October 2006

Tevatron







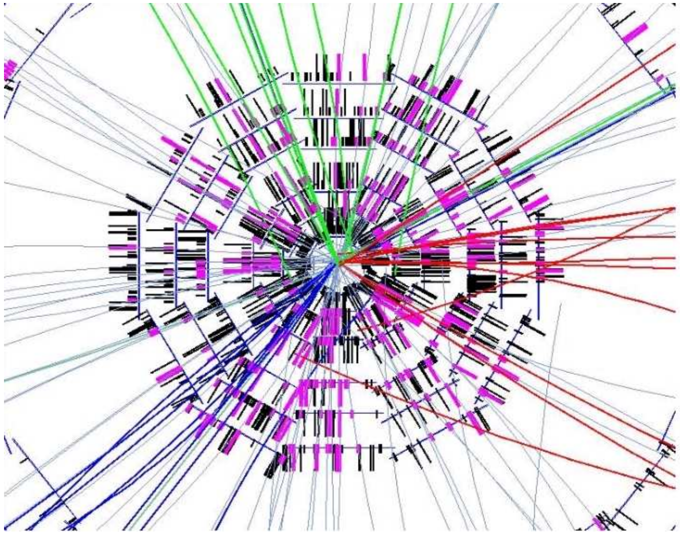
$p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV observed by two experiments

CDF & D0

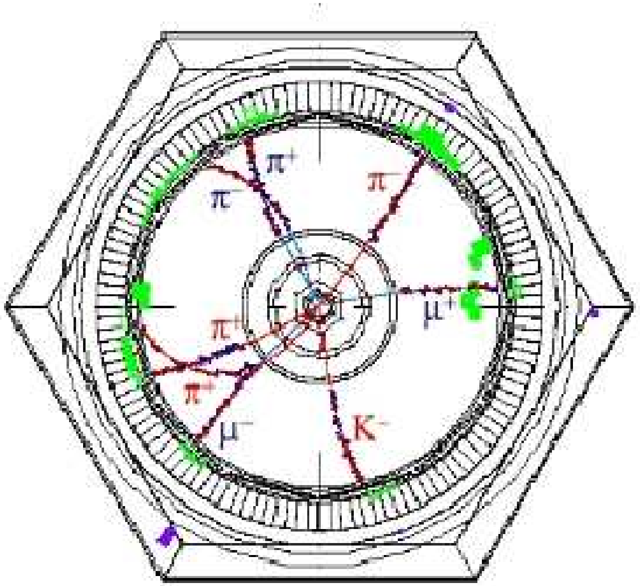
B Physics @ Hadron Colliders

- **+** Large cross section
  $\sigma(p\bar{p} \rightarrow bX) \approx 100\ \mu b$
  $\leftrightarrow$ B factories: $\approx$ 1 nb
- **+** High center-of-mass energy
- **+** Heavy & excited B's,
  e.g. B_s, $B_c, \Lambda_b, \Xi_b, B^{**}, B_s^{**}$, ...

- **-** $\sigma(p\bar{p} \rightarrow X)$ O(10^3) higher
  $\longrightarrow$ require excellent trigger
- **-** High track density
  $\longrightarrow$ require dedicated algorithms



event @ CDF



event @ BABAR

Tevatron unique place to study large amounts of B_s Mesons.

Selected B_s Topics

Many exciting B analysis going on at the Tevatron

today ...

- $\Delta\Gamma_s$ and CP violation
- $B_s - \bar{B}_s$ oscillations

for more Tevatron B physics results see:

- B Lifetimes, CP Violation and Rare Decays
  (Monday, 16th of October; Cano Ay)
- Spectroscopy and Decays of B Hadrons
  (Thursday, 19th of October; Manfred Paulini)

$\Delta\Gamma_s$ and CP violation

Different Approaches to $\Delta\Gamma_s$

$\Delta\Gamma_s$: decay-width difference between heavy (CP odd) and light (CP even) mass eigenstate:

$$\Delta\Gamma_s = \Delta\Gamma_s^{SM,CP} \times \cos(\phi_s^{SM} + \phi_s^{NP}); \qquad \phi_s^{SM} \approx 0.0$$

$$\left(\frac{\Delta\Gamma_s}{\Delta m_s} \approx \frac{3}{2}\pi\frac{m_b^2}{m_t^2} = 3.7^{+0.8}_{-1.5} 10^{-3}\right)$$

Many orthogonal measurements ongoing:

- Directly measure lifetimes in $B_s \rightarrow J/\psi\phi$
  separate CP states by angular distribution, measure lifetimes
- Measure lifetime in $B_s \rightarrow K^+K^-$ (CP even);
  compare to PDG lifetime for flavor specific states (see Cano Ay's talk)
- Measure BR($B_s \rightarrow D_s^{(*)}D_s^{(*)}$) $\propto$ $\Delta\Gamma_s/\Gamma_s$, (CP even);
  account for most of lifetime difference (see Manfred Paulini's talk)
- Measure time-integrated untagged decay rate asymmetry
  $A_{SL}^s = \frac{\Delta\Gamma_s}{\Delta m_s}\tan(\phi_s)$ (see Cano Ay's talk)

D0: $\Delta\Gamma_s$ via $B_s \longrightarrow J/\psi\phi$

$B_s \longrightarrow J/\psi\phi$: Pseudoscalar ⟶ Vector Vector decay

Simultaneous fit for angular distributions and short and long B_s lifetime

A_0: S + D wave ⟶ P even

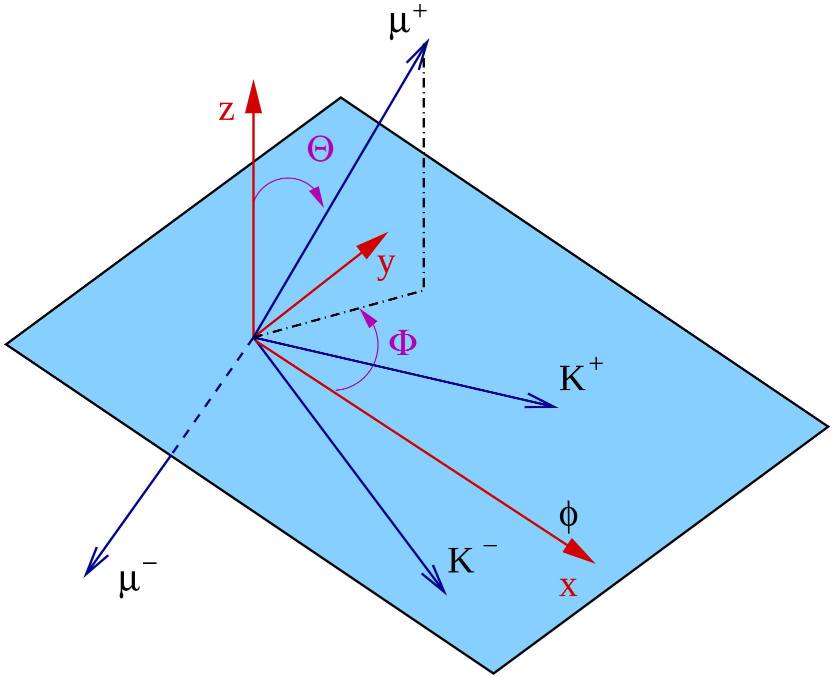
$A_\parallel$: S + D wave ⟶ P even

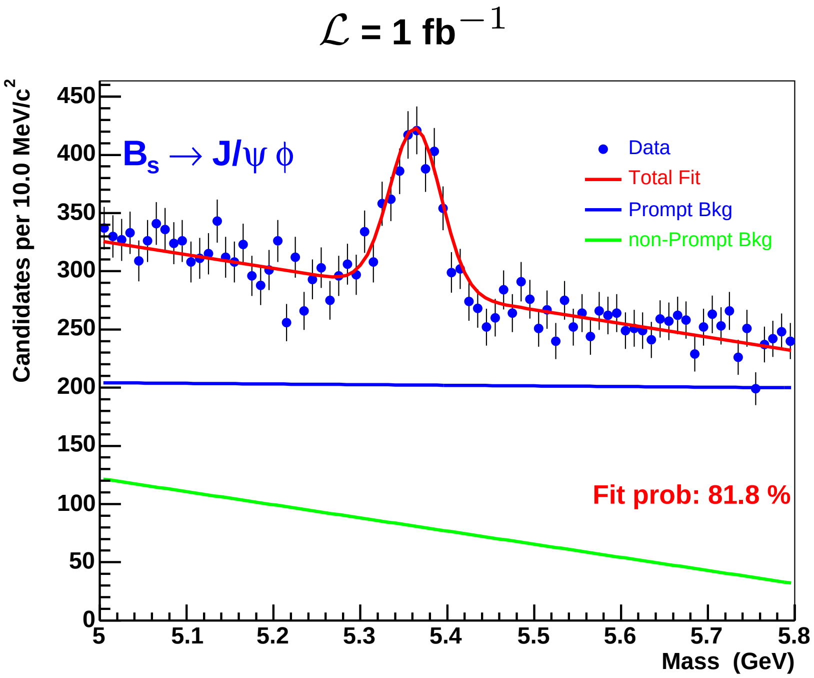
$A_\perp$: P wave ⟶ P odd

without CP violation:

$B_{s,Short,Light} \longrightarrow CP$ even

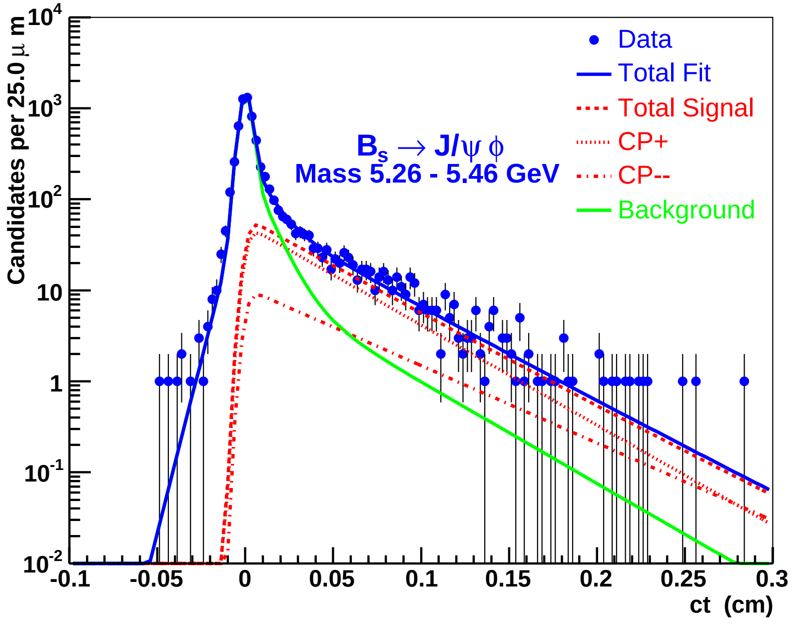
$B_{s,Long,Heavy} \longrightarrow CP$ odd

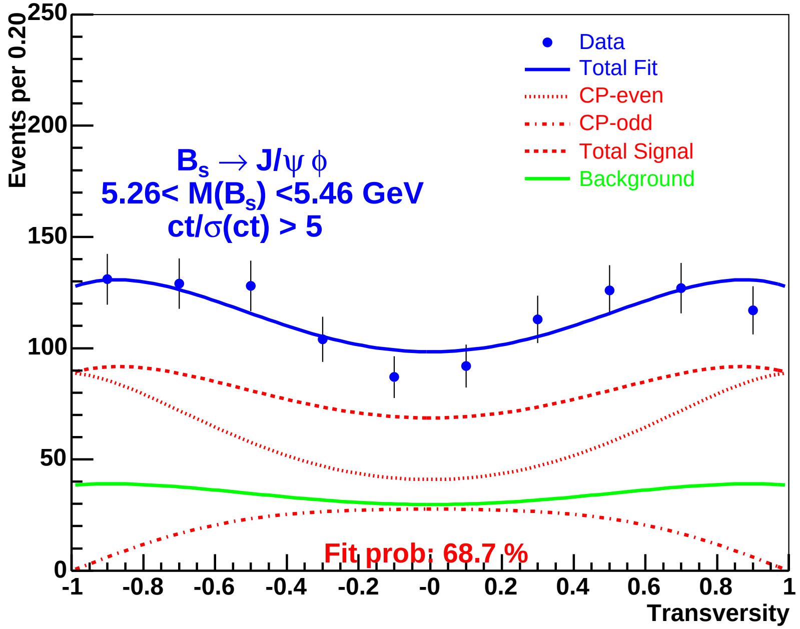




Use transversity basis to resolve angular dependencies

D0: Results on $\Delta\Gamma_s$



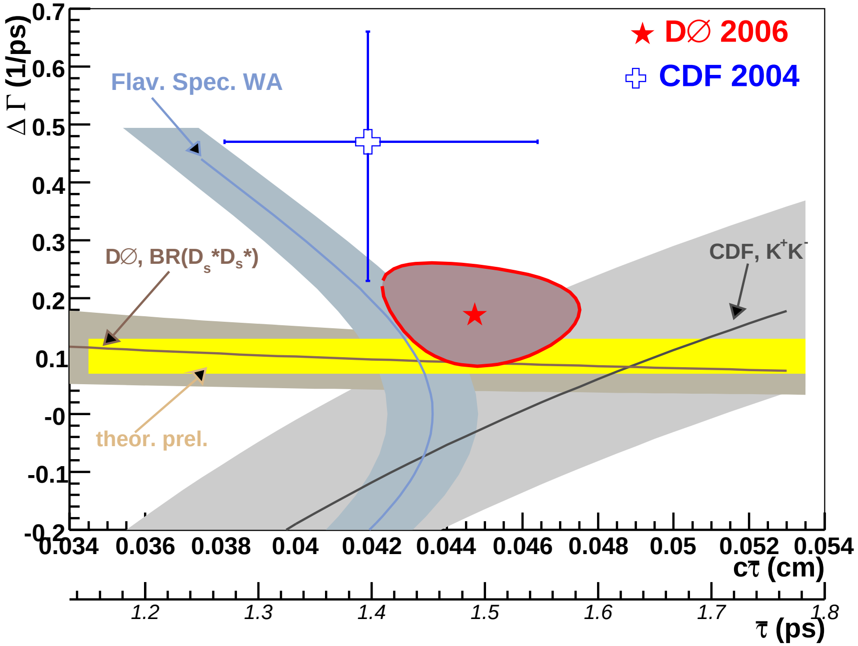


Assuming no CP violation:

$\Delta\Gamma_s$ = 0.12 ± 0.08 ± 0.03 ps^{-1}

Non 0 $\Delta\Gamma_s$!

Putting all measurements together ...



D0: $\Delta\Gamma_s$ CP Violation Results

- Allowing for CP violation

$$\Delta\Gamma_s = \Delta\Gamma_s^{SM,CP} \times \cos(\phi_s)$$

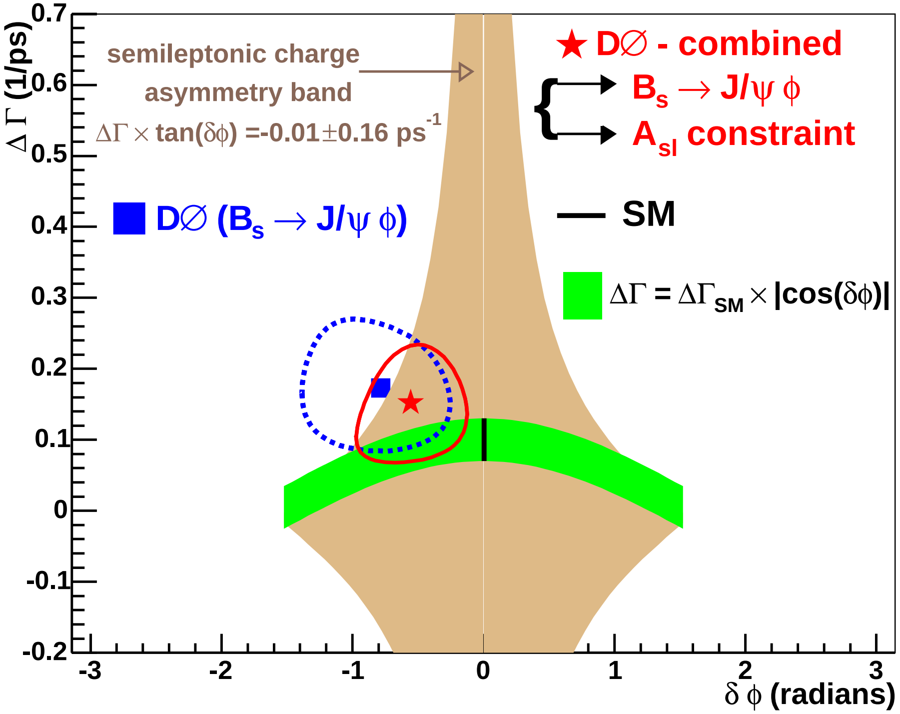
$\Delta\Gamma_s$ = 0.17 ± 0.09 ± 0.03 ps^{-1}

ϕ_s = -0.79 ± 0.56 ± 0.01

- Combine with time-integrated search for CP violation in untagged $B_s \to D_s(\phi\pi)\mu X$ decays

$\Delta\Gamma_s$ = 0.15 ± 0.08 ± 0.03 ps^{-1}

ϕ_s = -0.56 ± 0.40 ± 0.01



- Consistent with SM (U. Nierste hep-ph/0406300)

$\Delta\Gamma_s$ = 0.10 ± 0.03 ps^{-1}; ϕ_s = -0.03 ± 0.005

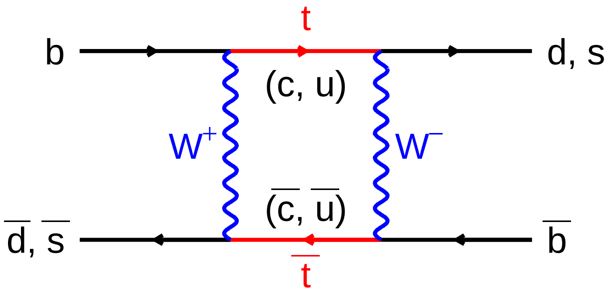
$B_s - \bar{B}_s$ Mixing

- First double sided limit on Δm_s (D0) (Phys. Rev. Lett. **97** (2006) 021802)
- First precision measurement of Δm_s (CDF) (Phys. Rev. Lett. **97**, (2006) 062003)
- Observation of Δm_s (CDF) (hep-ex/0609040)

Motivation

- Access to fundamental SM parameters

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



- Hadronic uncertainties cancel in ratio:

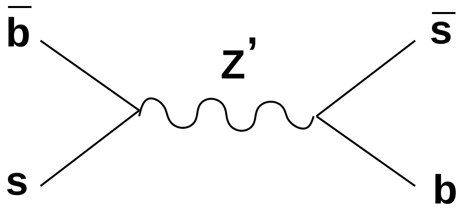
$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

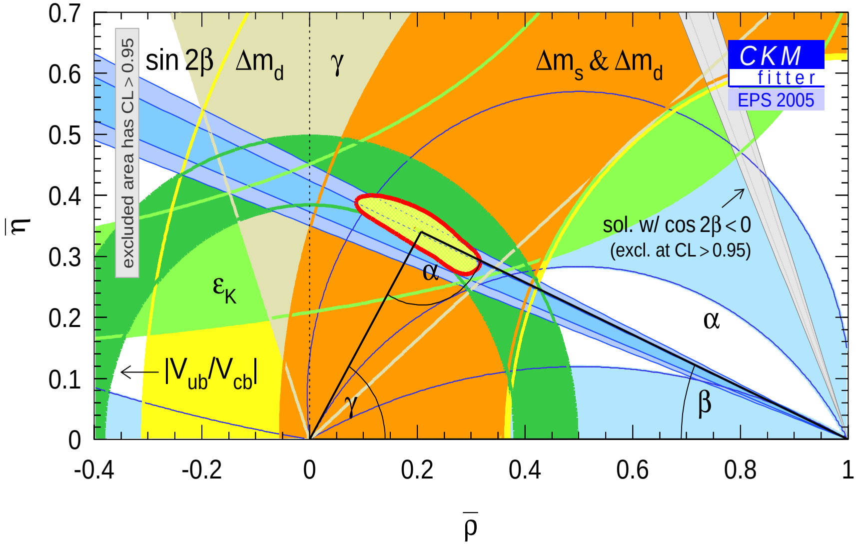
improved lattice (Okamoto, Lattice 05):

$$\xi = 1.21\ {}^{+0.047}_{-0.035}$$

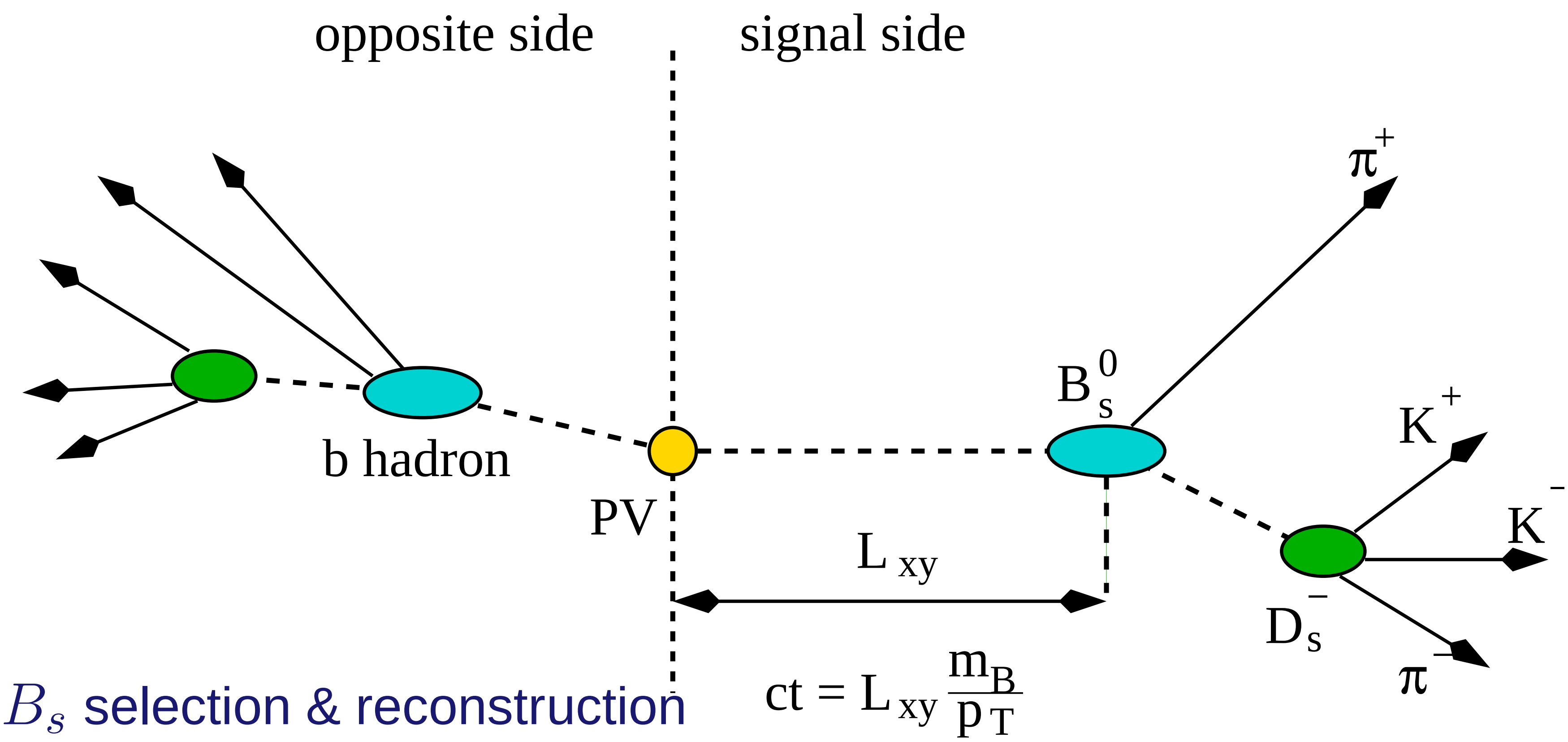
- Prerequisite for time dependent CPV
- New Physics may affect $\Delta m_s/\Delta m_d$

E.g. new particles in loop, ...





$B_s^0 - B_s^0$ Mixing Analysis



1) B_s selection & reconstruction

2) Measurement of proper decay time ct & ct resolution

3) Flavor tagging (main challenge at hadron colliders)

Time dependent asymmetry measurement:

$$\mathcal{A}(t) \equiv \frac{N(t)_{unmixed} - N(t)_{mixed}}{N(t)_{unmixed} + N(t)_{mixed}} = \mathcal{D} \cos(\Delta m_s t), \qquad \mathcal{D} = 1 - 2P_{mistag}$$

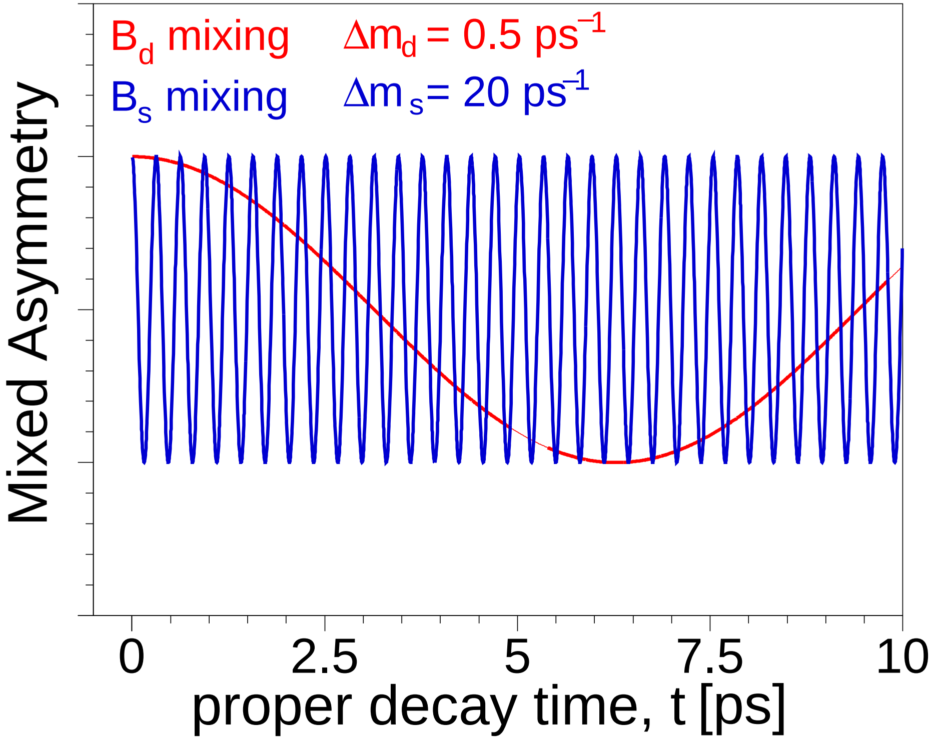
Why is it so difficult?

B_s Mixing is very very fast!

Challenges:

- Large statistics
- High vertex resolution
- High momentum resolution
- Good tagging

Very complex analysis!



For high Δm_s, $\sigma(ct)$ is crucial:

$$\text{significance} = \sqrt{\frac{S\epsilon D^2}{2}}\sqrt{\frac{S}{S+B}}e^{-\frac{(\Delta m_s \sigma_{ct})^2}{2}}$$

Signal Reconstruction

$$\sqrt{\frac{S\epsilon D^2}{2}}\sqrt{\frac{S}{S+B}}e^{-\frac{(\Delta m_s \sigma_{ct})^2}{2}}$$

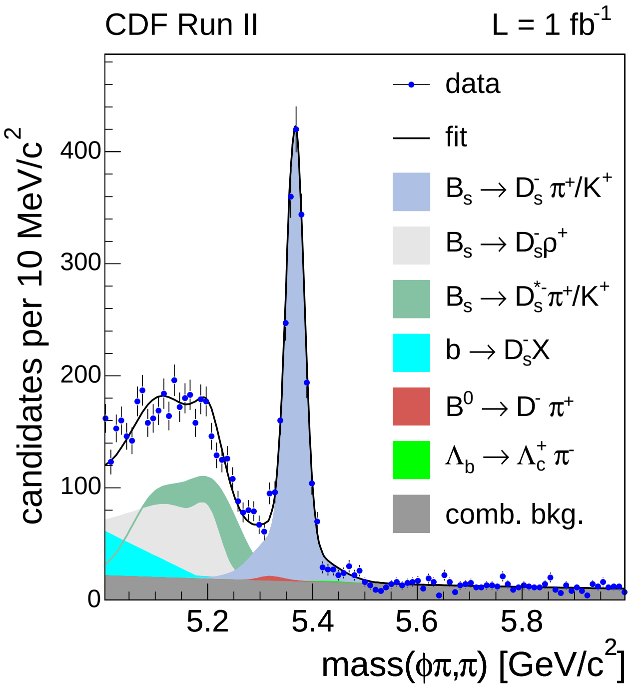
Hadronic B_s Modes (CDF)

Hadronic Modes selected by Two Track Trigger

- 2000 fully reconstructed $B_s \to D_s(\phi\pi)\pi$ (golden mode)
- 3200 partially reconstructed

  $B_s \to D_s^*(\phi\pi)\pi$ and $B_s \to D_s^*(\phi\pi)\rho$ decays

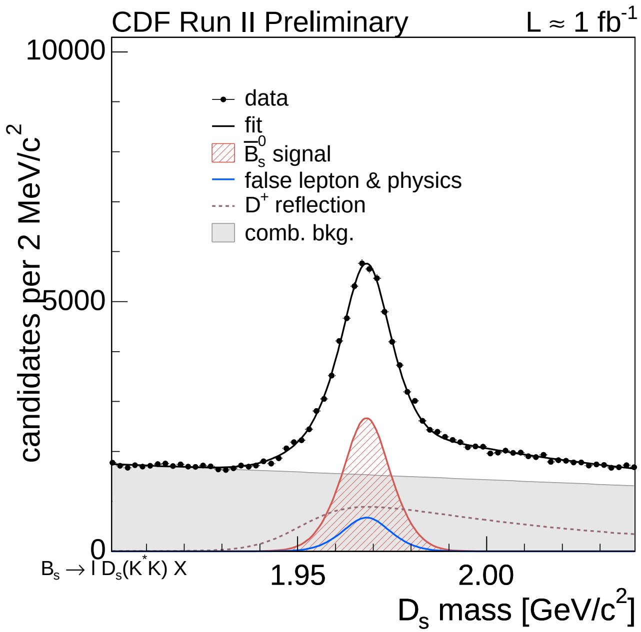
  slightly worse ct resolution due to lost γ or π^0
- 3600 fully reconstructed B_s candidates in add. modes

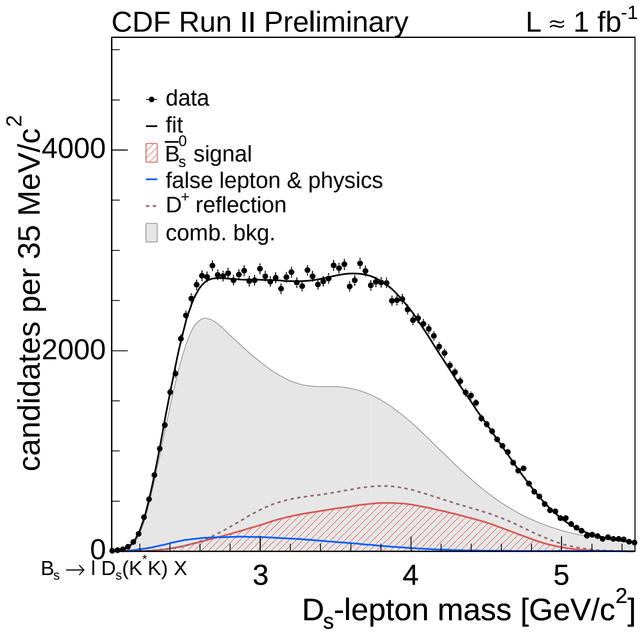


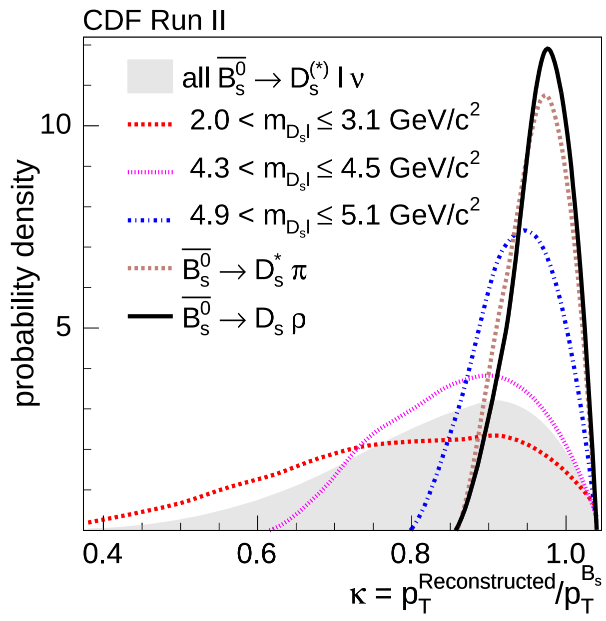
decay	#
$B_s \to D_s(K^*K)\pi$	1400
$B_s \to D_s(3\pi)\pi$	700
$B_s \to D_s(\phi\pi)3\pi$	700
$B_s \to D_s(K^*K)3\pi$	600
$B_s \to D_s(3\pi)3\pi$	200

NN for candiate selection

$B_s \to \ell D_s X$ Decays (CDF)







$\sim$ 61.500 semileptonic B_s candidates

High statistic, but worse ct-resolution:

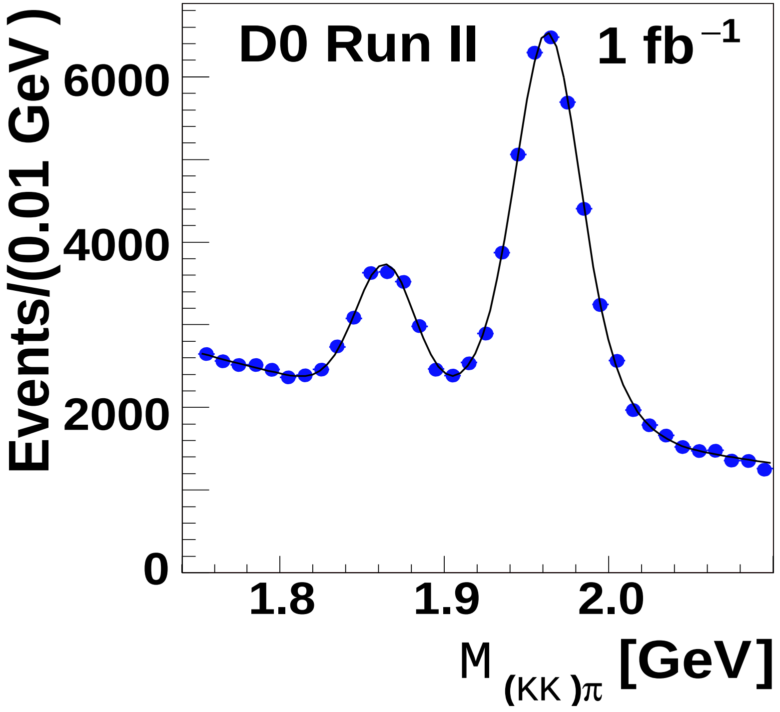
$$ct = \frac{L_{xy}}{\gamma\beta} = \frac{L_{xy}M(B)}{p_T(B)} = \frac{L_{xy}M(B)}{p_T(\ell D)} * K \text{ (K from Monte Carlo);}$$

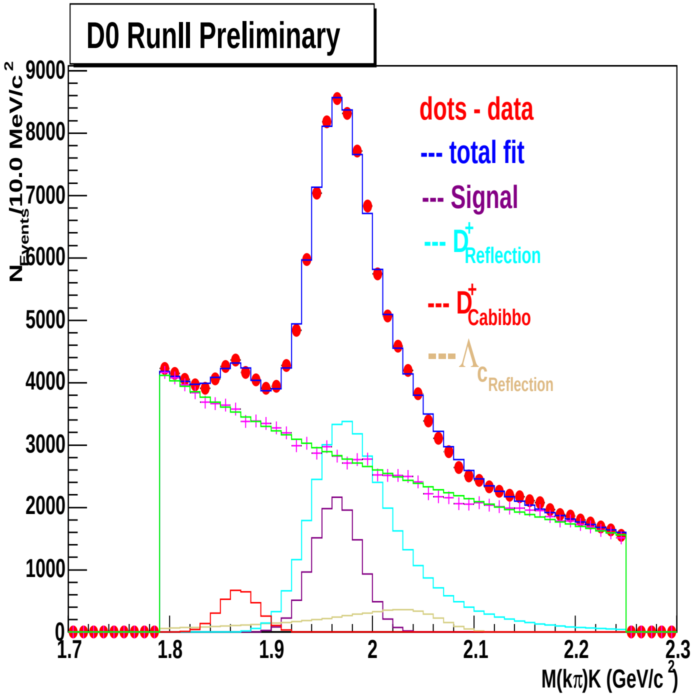
$$\sigma_{ct} = \sqrt{\left(\frac{\sigma_{L_{xy}}}{\gamma\beta}\right)^2 + \left(\frac{\sigma_{\gamma\beta}}{\gamma\beta} * ct\right)^2}$$

Sensitivity driven by high ℓD mass candidates $\longrightarrow$ exploit in the fit

B_s Decays (D0)

Large statistic in semi-muonic decays





$\sim$ 27.000 $B_s \to \mu D_s(\phi\pi)X$

& $\sim$ 2.000 $B_s \to e D_s(\phi\pi)X$

$\sim$ 12.600 $B_s \to \mu D_s(K^* K)X$

Plan: trigger muon as opposite side tag + fully reconstructed B_s candidate on the other side

Proper Decay Time Resolution

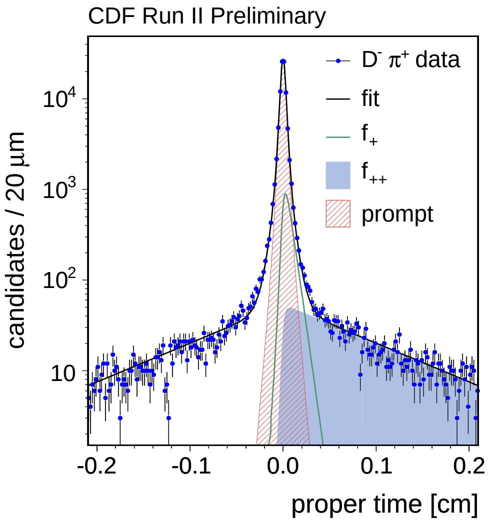
$$\sqrt{\frac{S\epsilon D^2}{2}}\sqrt{\frac{S}{S+B}}e^{-\frac{(\Delta m_s \sigma_{ct})^2}{2}}$$

Proper Time Resolution

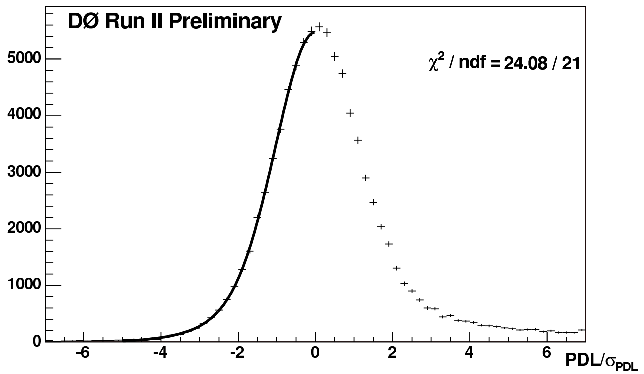
Critical aspect of the analysis, limiting factor at high Δm_s

σ_{ct} is determined from data

CDF: prompt D + track(s)
mimics B decay topology



D0: prompt J/Ψ



+ exploit event-by-event predicted resolution, take into account dependence on several variables: isolation, vertex χ^2, ...

Mode	$<\sigma(ct)>$ [μm]
$B_s \rightarrow D_s(3)\pi$ (CDF)	26
$B_s \rightarrow \ell D_s X$ (CDF)	45
$B_s \rightarrow \mu D_s X$ (D0)	50-60*

(Δm_s = 18 ps^{-1} $\approx$ 100μm)

* Add. silicon layer currently being commissioned

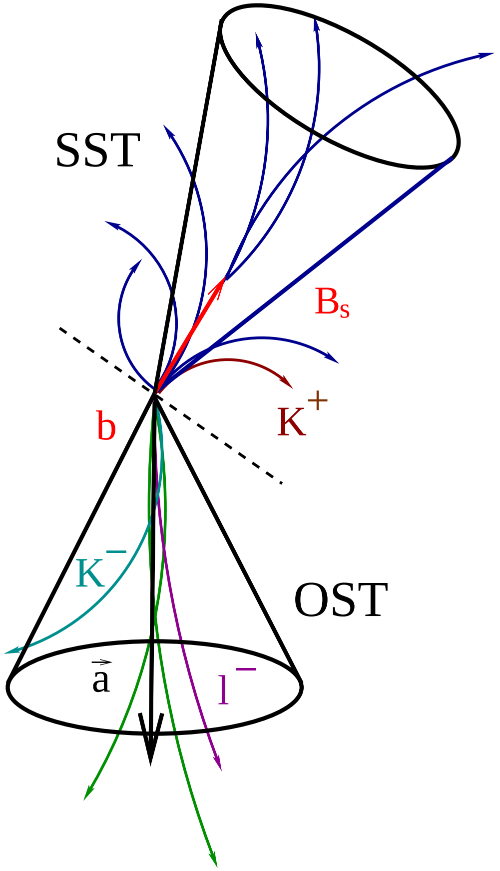
Flavor Tagging

$$\sqrt{\frac{S\epsilon D^2}{2}}\sqrt{\frac{S}{S+B}}e^{-\frac{(\Delta m_s \sigma_{ct})^2}{2}}$$

Opposite Side Tagging

B mesons produced in pairs $\longrightarrow$ production flavors correlated

- Jet Charge Tagging (high efficiency, low purity)
  Weighted sum of fragmentation and decay tracks of the opposite side B
- Lepton Tagging (high purity, low efficiency)
  Semileptonic decay of opposite side B
  ($\approx 20\%$ B's mix before the decay)
- Kaon Tagging (high efficiency, low purity)
  Favored transition: $b \longrightarrow c \longrightarrow s$



Often opposite side B not in detector acceptance

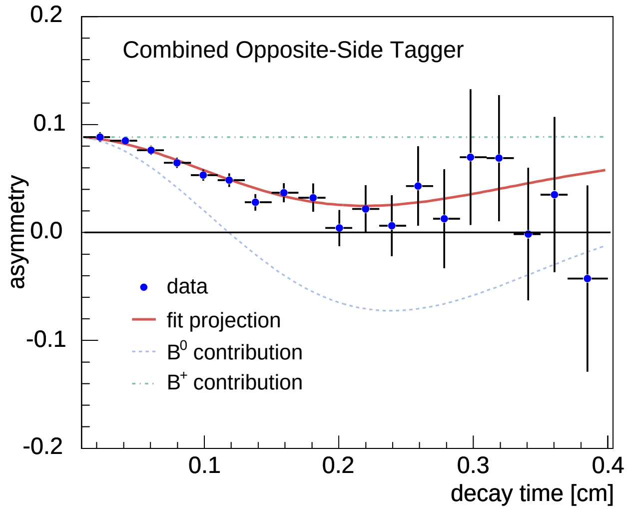
Additional gain in tagging performance:

\+ Classification of events (dilution parameterization)

\+ Combination of all opposite side tagging information

OST in B^+ & B_d

- Important test of the fitter (complex unbinned likelihood fit)
- Calibration of opposite side taggers
  (opposite side B independent of signal side)

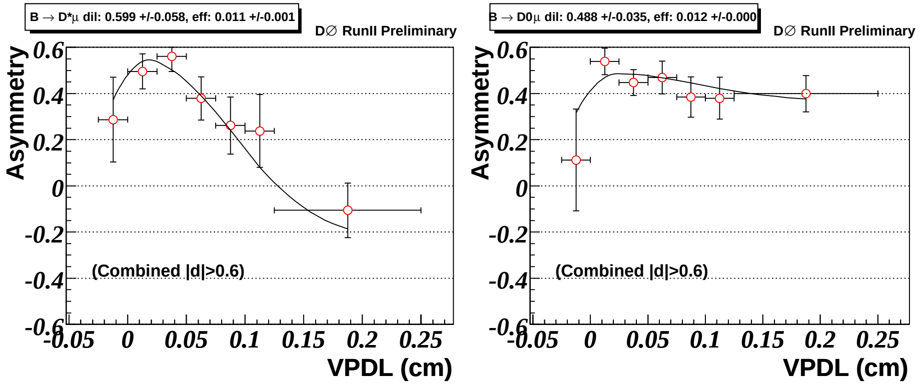


ϵD^2 = 1.8 %

Δm_d = 0.509 $\pm$ 0.010 $\pm$ 0.016 ps^{-1}

ϵD^2 = 2.5 %

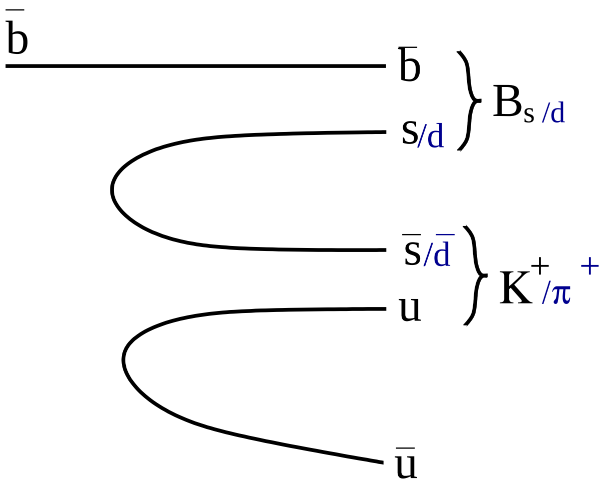
Δm_d = 0.506 $\pm$ 0.020 $\pm$ 0.016 ps^{-1}

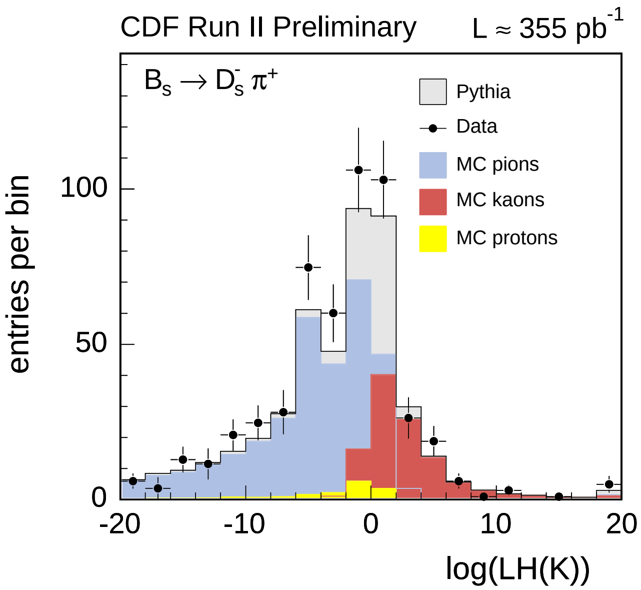


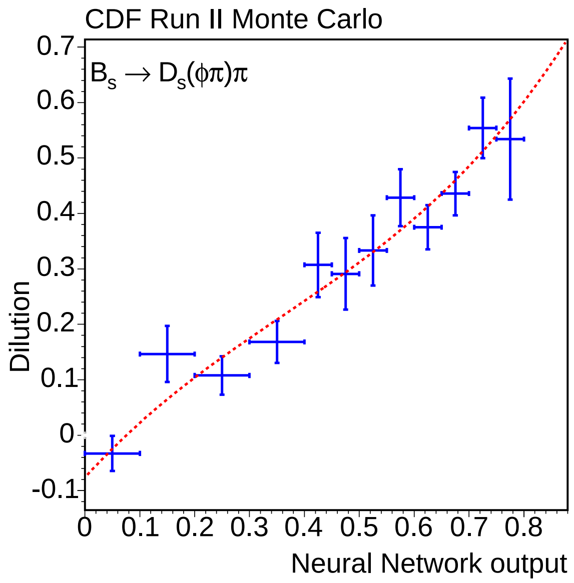
Δm_d (PDG) = 0.507 $\pm$ 0.005 ps^{-1}

to be compared with $\epsilon D^2 \approx$ 30% from B factories

Same Side Tagger @ CDF







- Charge of closest fragmentation track correlated to B production flavor
- SSKT performance can NOT be determined on data

  Understanding of Monte Carlo (PYTHIA) crucial!

Final algorithm: NN combination of kaon probability and kinematical variables

ϵD^2(hadronic modes) = 3.5 %; ϵD^2 (semileptonic modes) = 4.8 %

Tagging performance enlarged by $\times$ 3-4!

Analysis Methods & Results

Fourier Analysis

Two domains to fit for oscillation:

Time domain:

- Fit for Δm_s in
  $P(t) \sim (1 \pm D \cos \Delta m_s t)$

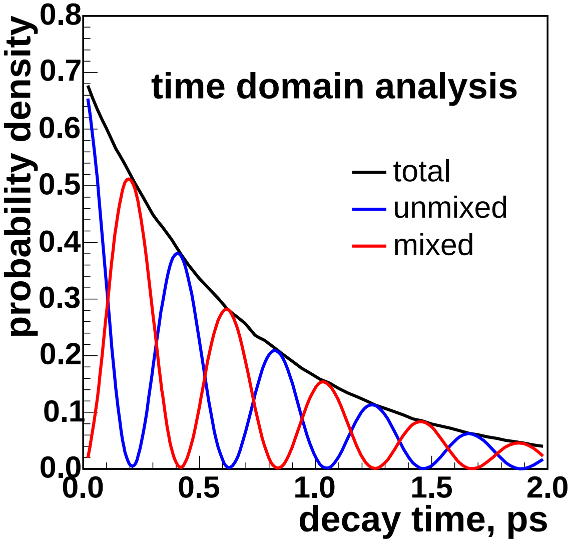
Frequency domain: amplitude scan

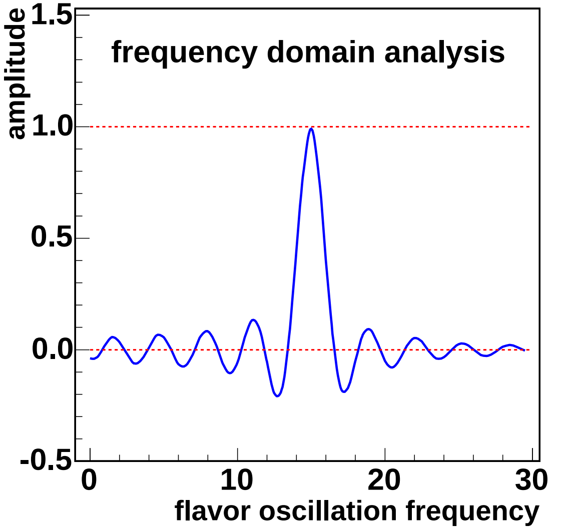
- Introduce amplitude:
  $P(t) \sim (1 \pm \mathcal{A} D \cos \Delta m_s t)$
- Fit for $\mathcal{A}$ at different Δm_s

$\Rightarrow$ Obtain frequency spectrum

- True $\Delta m_s \Rightarrow \mathcal{A} = 1$, else $\mathcal{A} = 0$
- Traditionally used for B_s mixing search

$\Rightarrow$ Easy to combine experiments

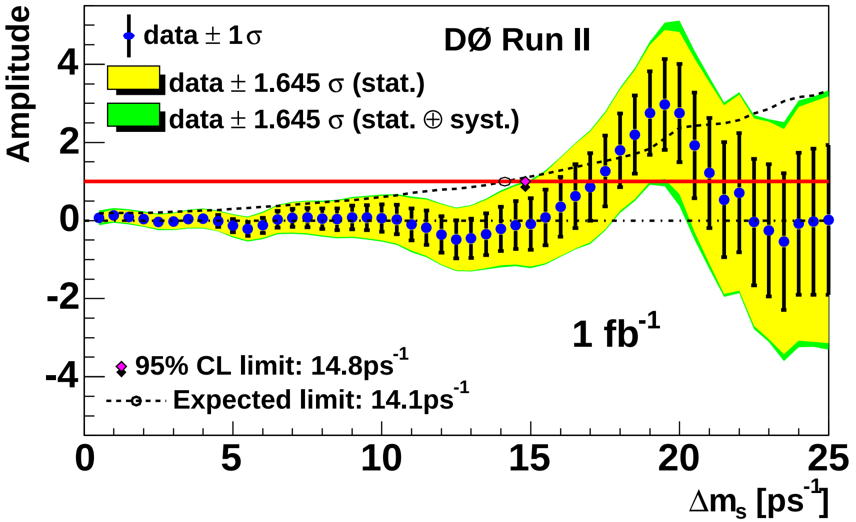


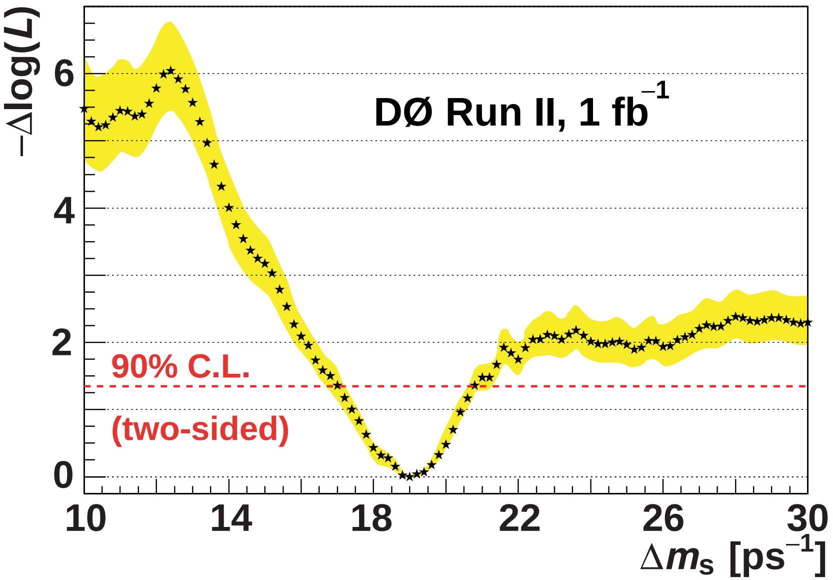


Published D0 Result

based on $B_s \to D_s(\phi\pi)\mu X$ sample (Phys. Rev. Lett. **97** (2006) 021802)

One experiment sets same exclusion limit as all combined ones!





First double sided limit: 17 $< \Delta m_s <$ 21 ps^{-1} @ 90% CL

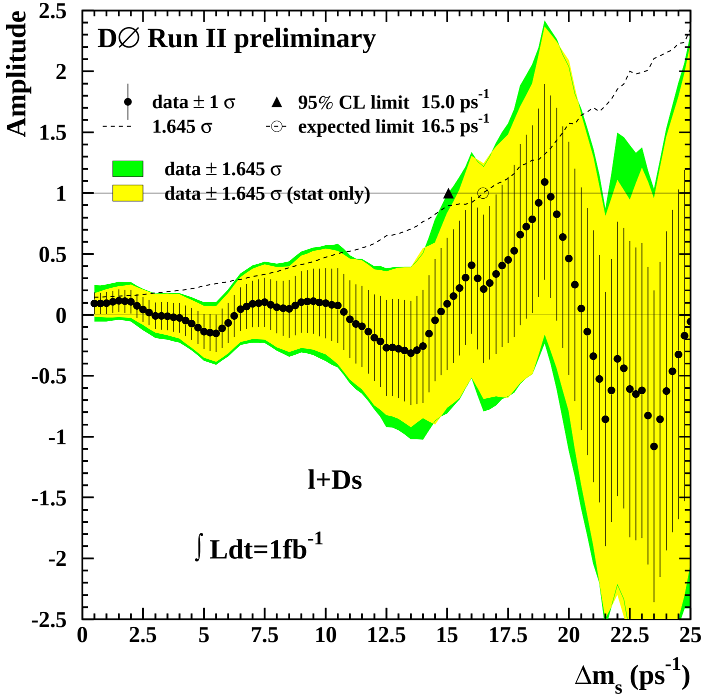
$\Delta m_s <$ 21 ps^{-1} @ 95% CL

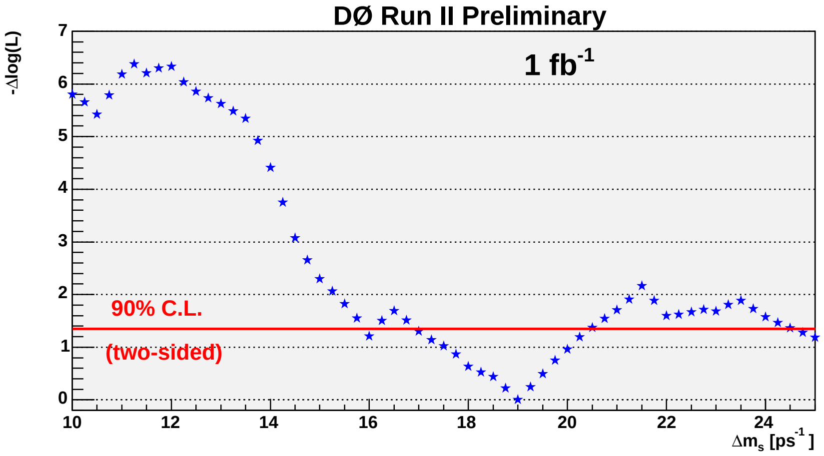
false probability at 17-21 ps^{-1} $\approx$ 5%

Updated D0 Result

include additionally $B_s \to D_s(K^*K)\mu X$ & $B_s \to D_s(\phi\pi)eX$

Amplitude consistent with 1 around Δm_s = 19 ps^{-1}





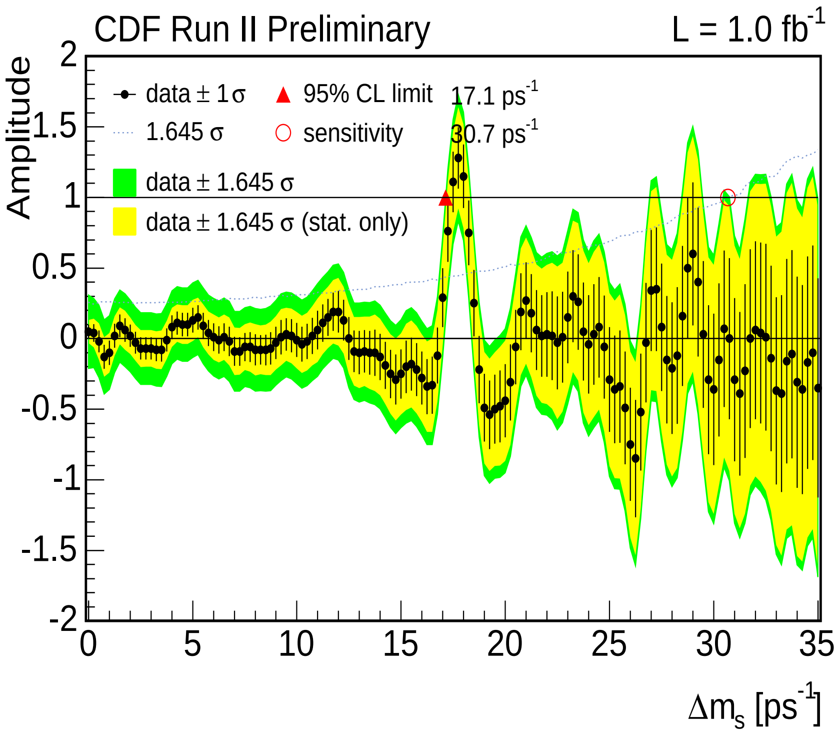
double sided 90% CL limit: 17 $< \Delta m_s <$ 21 ps^{-1}

$\Delta m_s >$ 15 ps^{-1} @ 95% CL

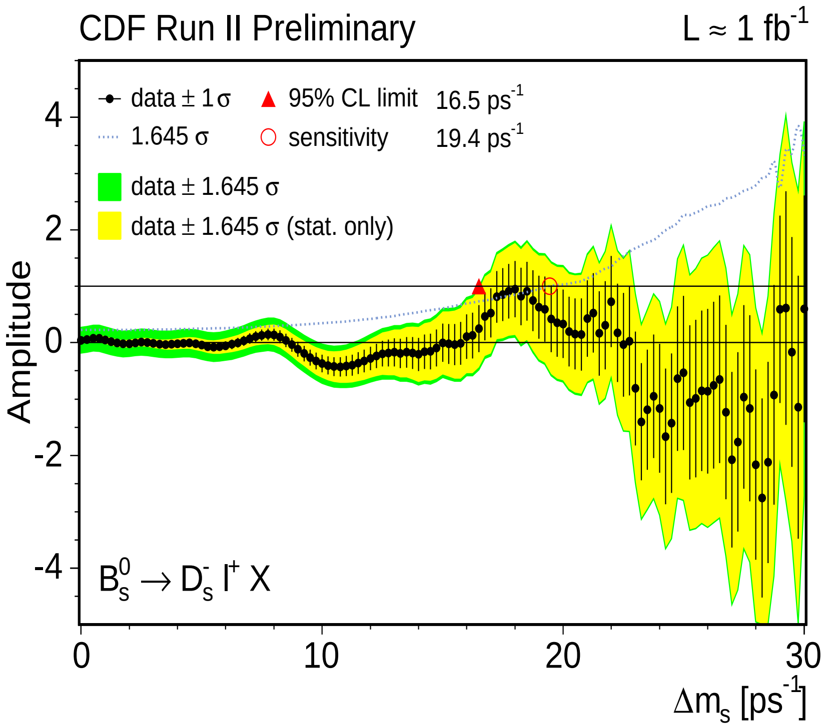
false probability at 17-21 ps^{-1} $\approx$ 8.0%

Amplitude Scans (CDF)

hadronic



semileptonic

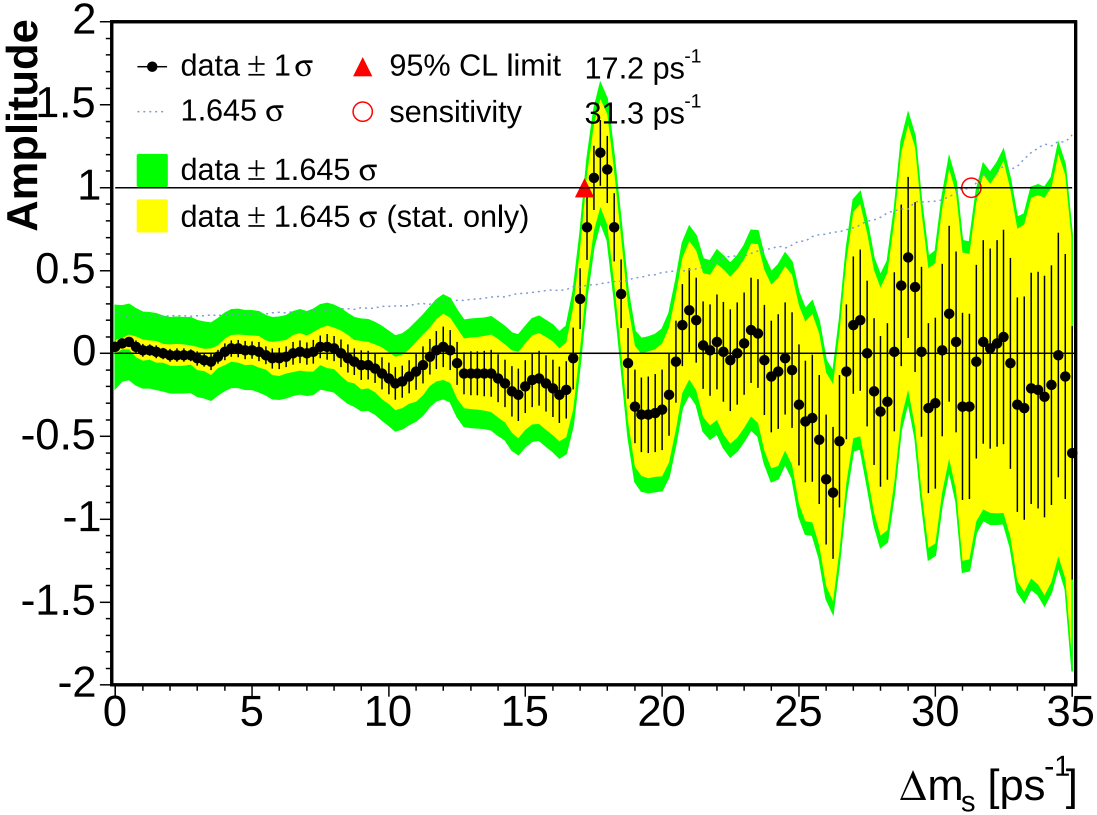


$\mathcal{A}$ consistent with 1 for $\Delta m_s \sim$ 17.75 ps^{-1} for both samples

Hadronic sensitivity $\geq$ 30 ps^{-1} !

Combined Amplitude Scan (CDF)

$\mathcal{A}$ compatible with 1 for $\Delta m_s \sim$ 17.75 ps^{-1}!

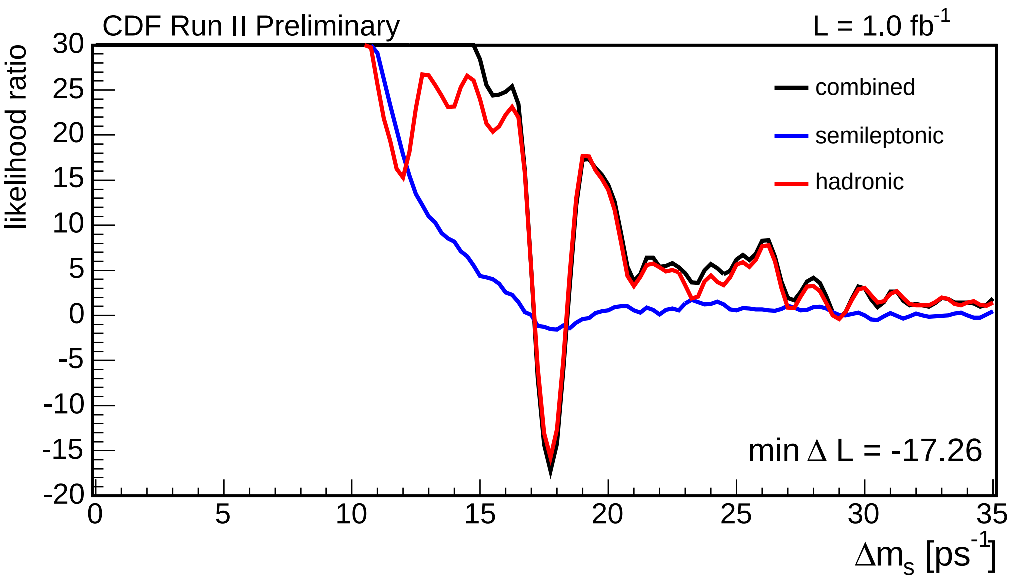


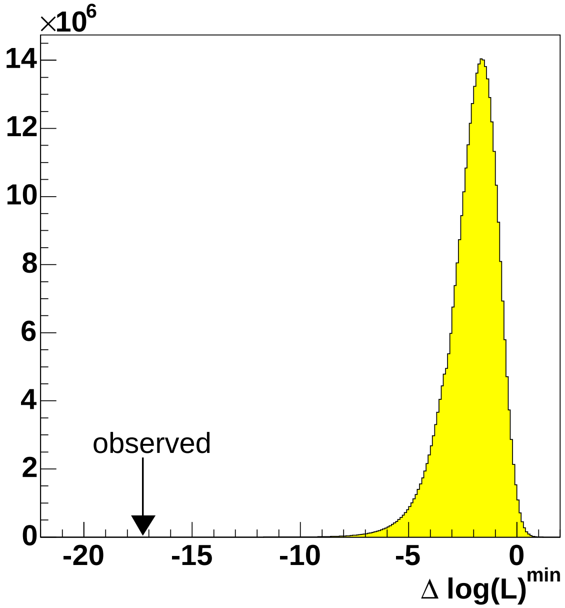
$$\mathcal{A}/\sigma_{\mathcal{A}}(\Delta m_s = 17.75\ \text{ps}^{-1}) \sim 6.05$$

What is the probability for background to fake such a signal?

Likelihood Scan (CDF)

Figure of merit: $\log(L) = \log[L(A=1,\Delta m_s)/L(A=0)]$





How often can random tags produce a LH minimum this deep?

P-value: 8× 10^{-8}; we are in 5 σ land!

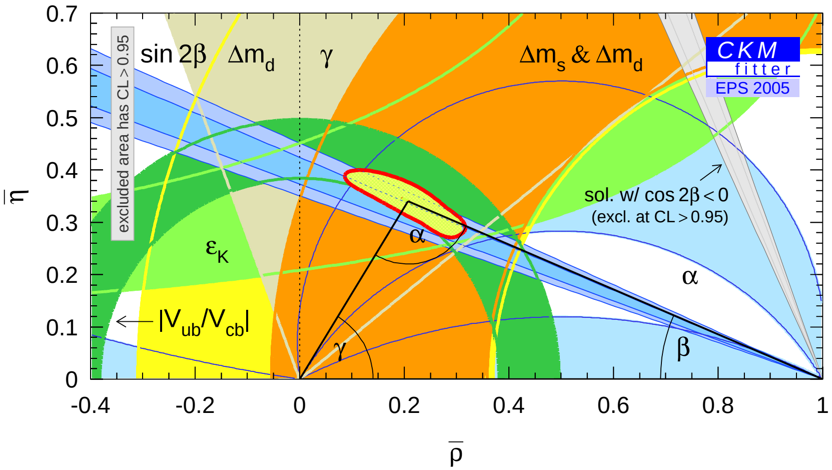
Δm_s = 17.77±0.10(stat.)±0.07(syst.) ps^{-1}

Systematic dominated by uncertainties on ct scale

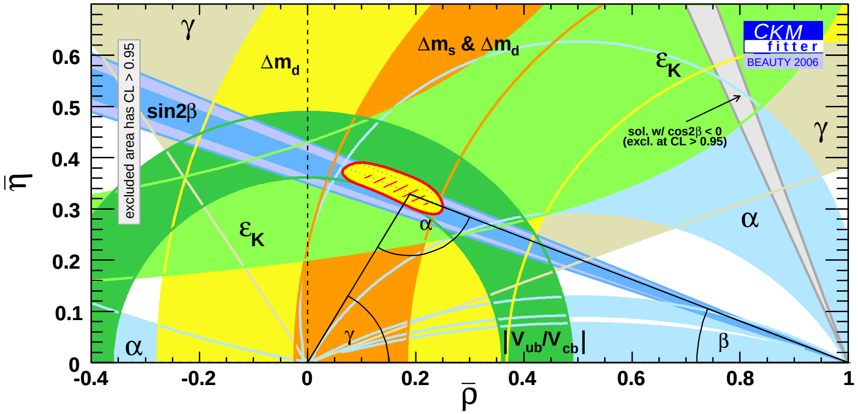
consistent with indirect SM fits: Δm_s = 18.3$^{+6.5}_{-1.5}$ps^{-1}

$|V_{td}|/|V_{ts}|$ Measurement (CDF)

status summer 05

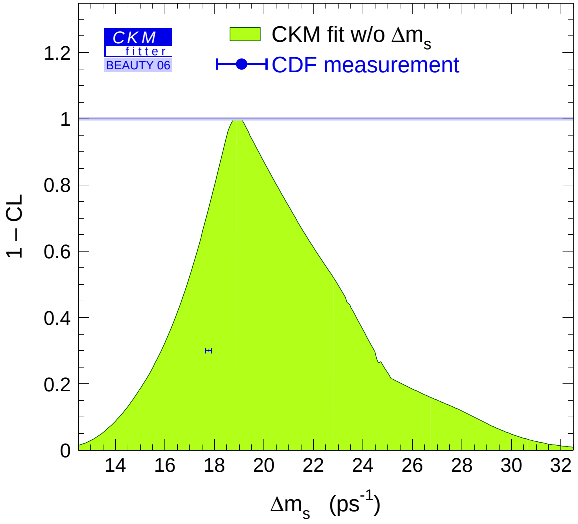


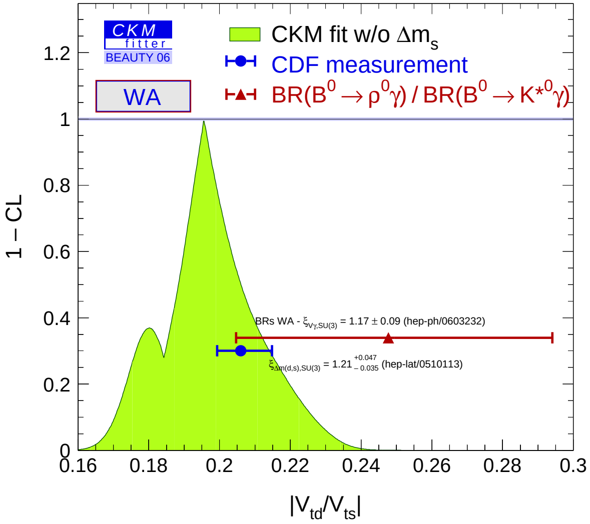
status autumn 06



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

Measurement no longer determined by experimental uncertainties





Summary

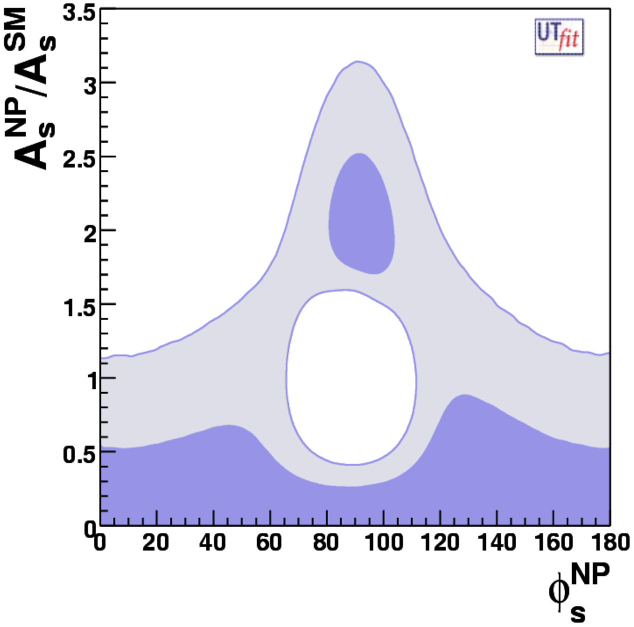
- Tevatron significantly improved understanding of B_s physics
- Precision measurements on $\Delta\Gamma_s$

  $\Delta\Gamma_s$ = 0.12 $\pm$ 0.08 $\pm$ 0.03 ps^{-1}

  (and first look at CP violating phase)
- First measurement of Δm_s:

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

  Signal at 5 σ level & seen by both experiments!
- CDF & D0 keep on testing the Standard Model and constraining New Physics Models



Backup

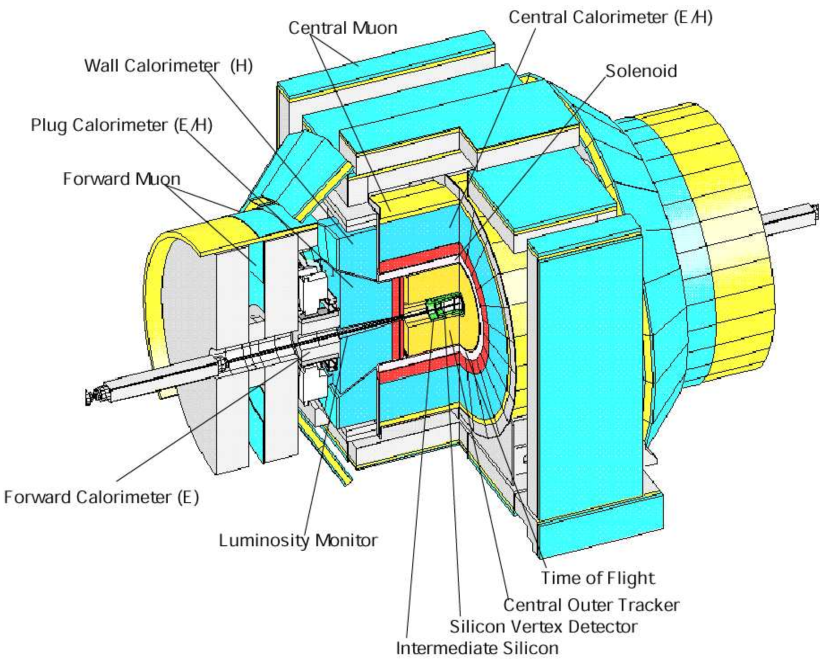
CDF versus D0

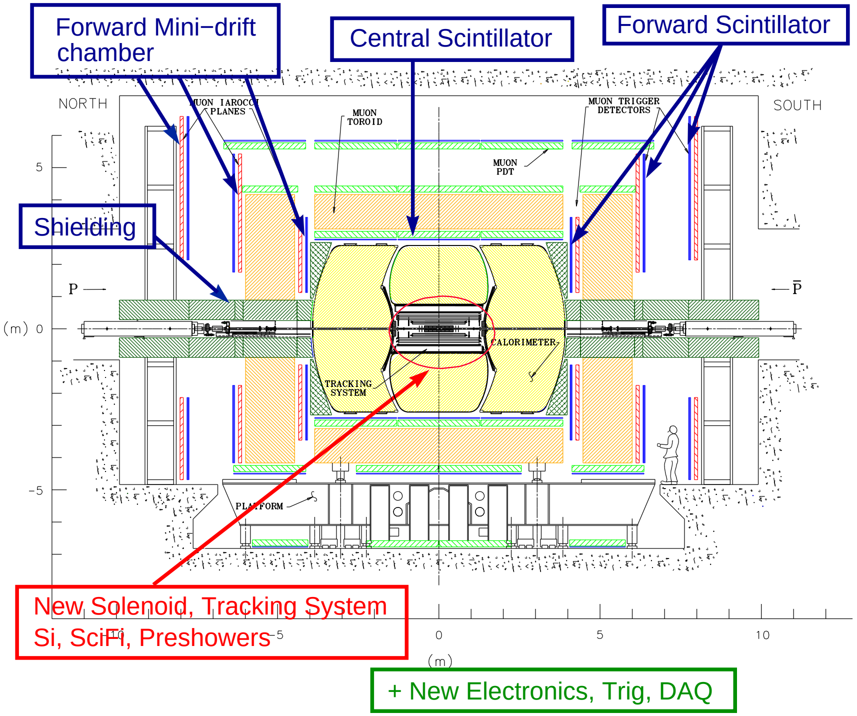
CDF

- Two displaced Track Trigger (TTT)
- Particle ID (dE/dx & TOF)
- Silicon layer close to interaction

strong in hadronic decays

good kaon tagging





Forward Mini−drift chamber

Central Scintillator

Forward Scintillator

Shielding

New Solenoid, Tracking System
Si, SciFi, Preshowers

\+ New Electronics, Trig, DAQ

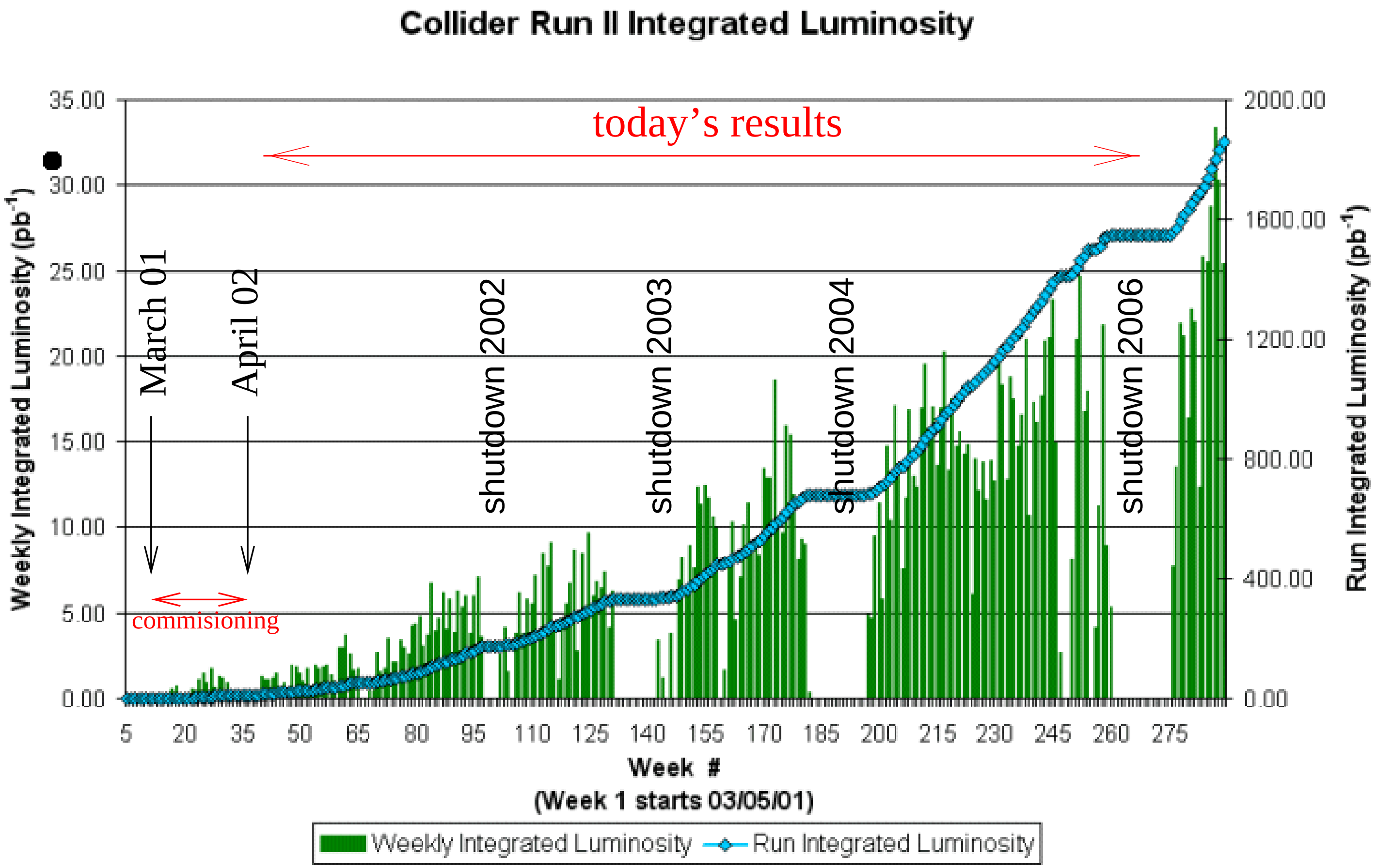
D0

- Excellent Muon coverage
- High forward acceptance

strong in semi-muonic decays

excellent muon tagging

Tevatron Performance



Delivered luminosity (2002 - now): 1.8 fb^{-1}, (on tape: 1.6 fb^{-1})

Used for following analysis: 1 fb^{-1}; (unless explicitly stated)

Short Reminder on CKM Physics

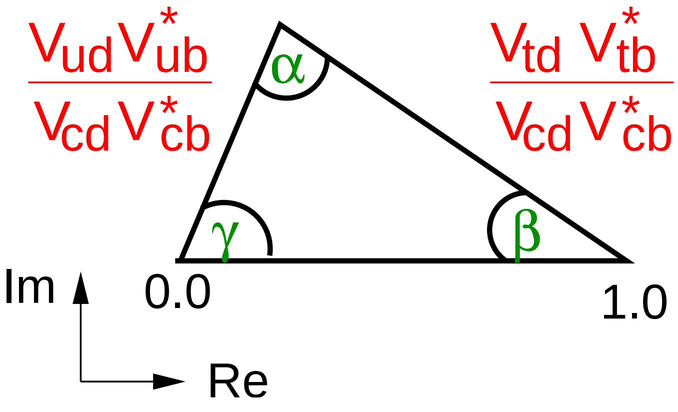
Our knowledge of flavor physics can be expressed in the CKM matrix

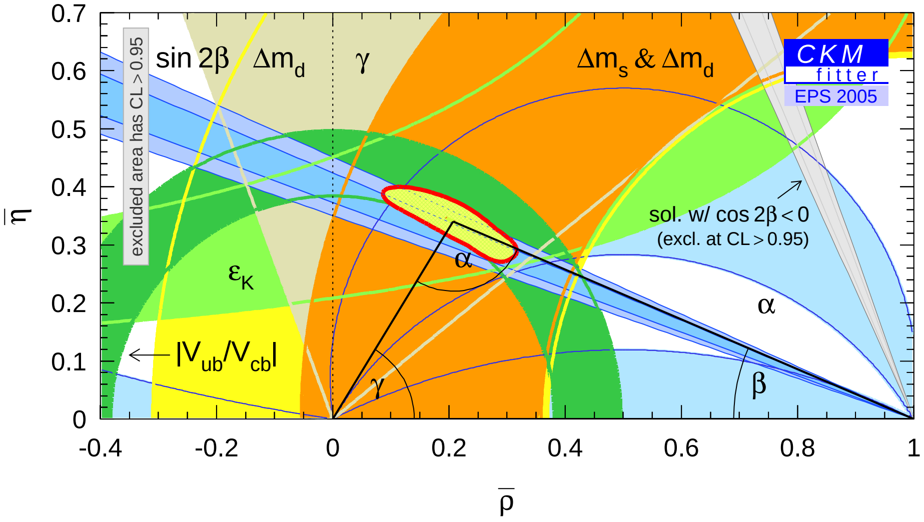
basis transformation between mass (strong) and flavor (weak) eigenstates

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

3 real parameters & one complex phase → CP violation $\lambda \approx 0.22$

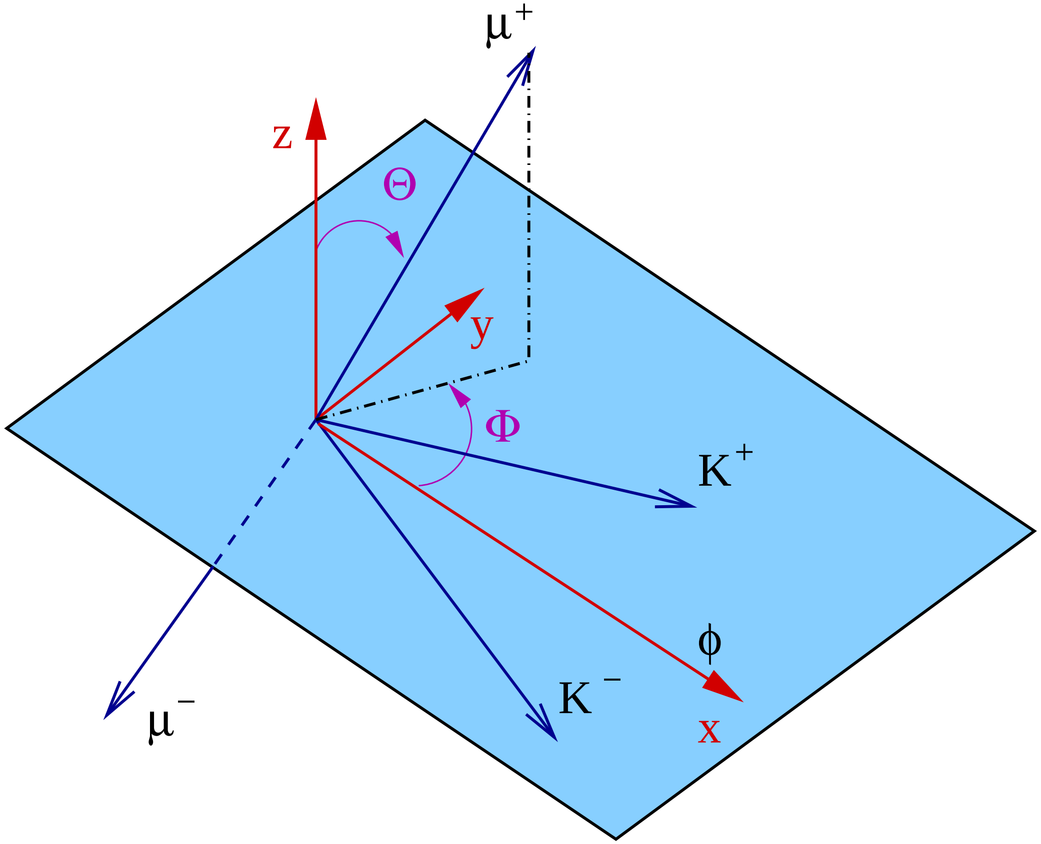
Unitarity relation for b quarks: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$





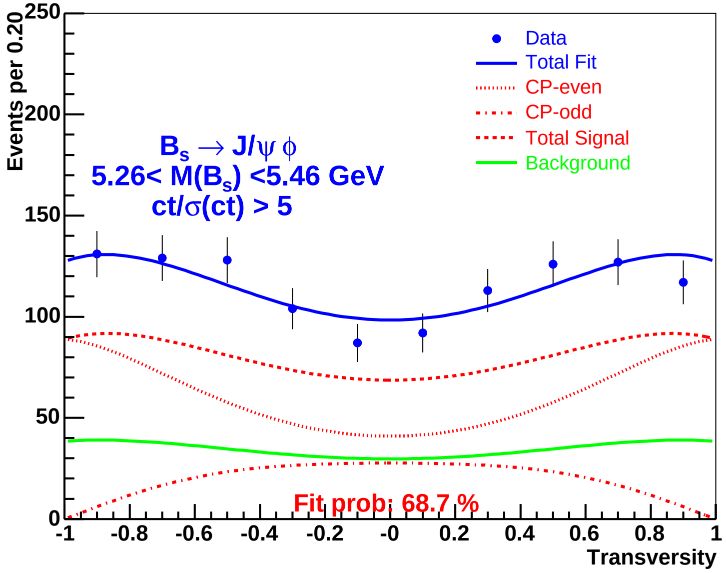
Many constraints on CKM parameters come from B system

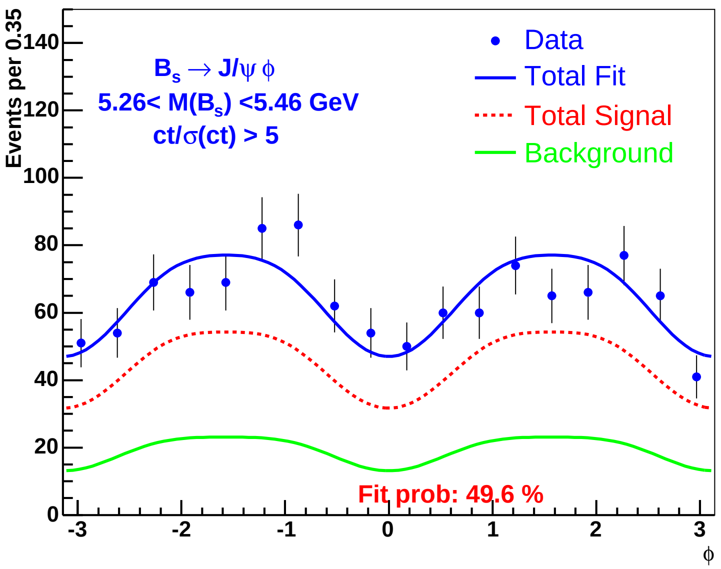
Transversity Base

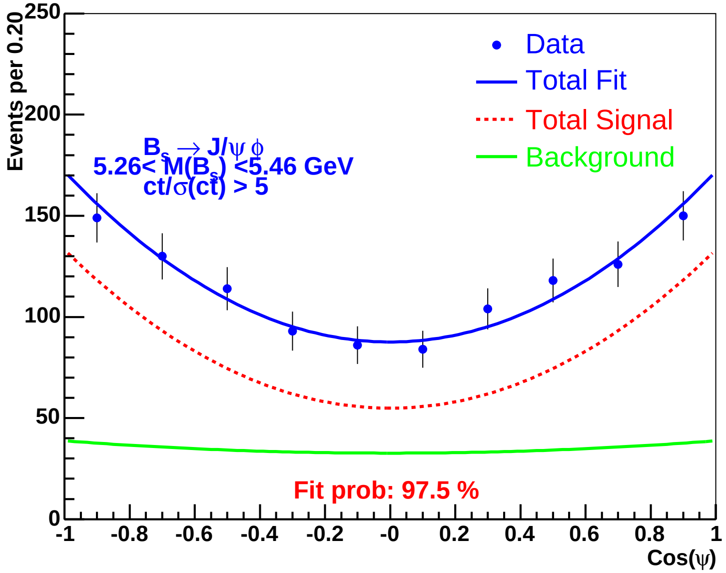


- work in J/ψ rest frame
- K^+K^- plane defines x/y plane, K^+ defines positive y axis
- θ, ϕ polar and azimuthal angle of μ^+
- Ψ helicity angle of ϕ

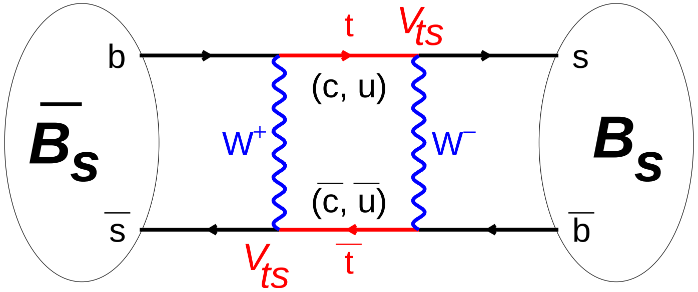
$\Delta\Gamma_s$: Angular Distributions

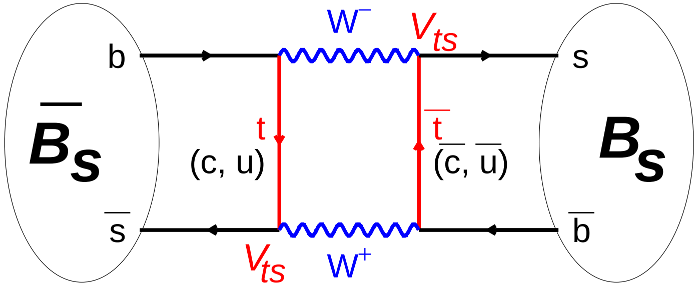






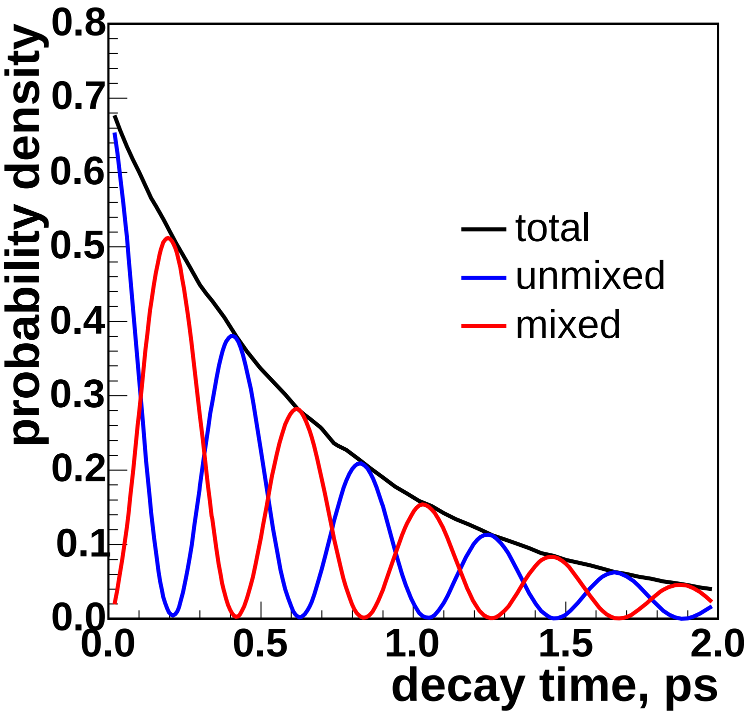
Neutral B Meson Mixing



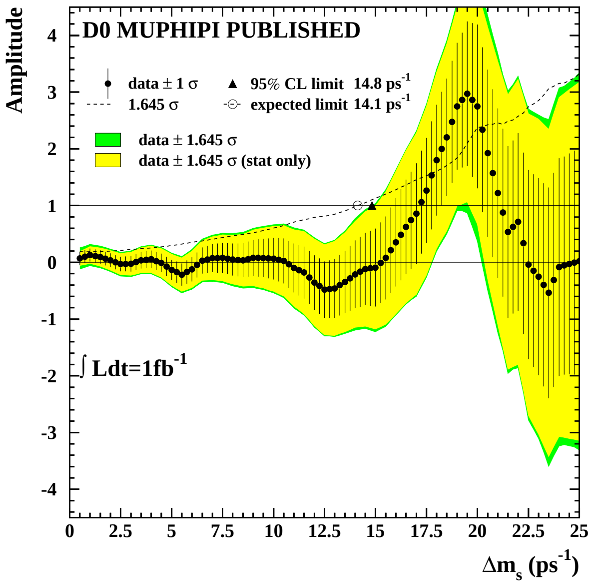


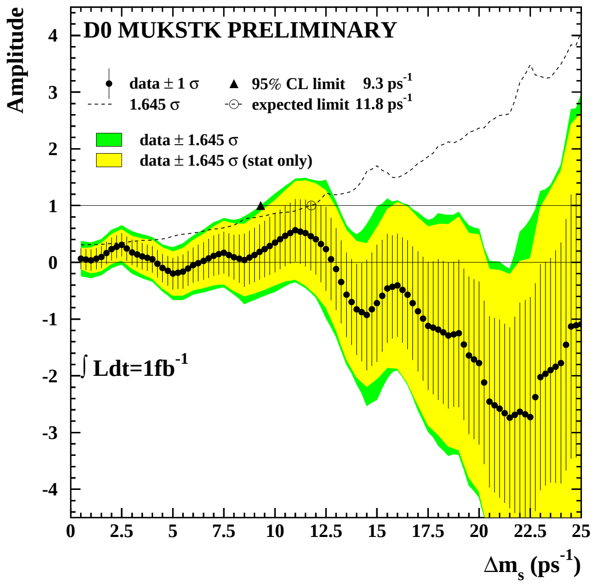
Two-state mixing system

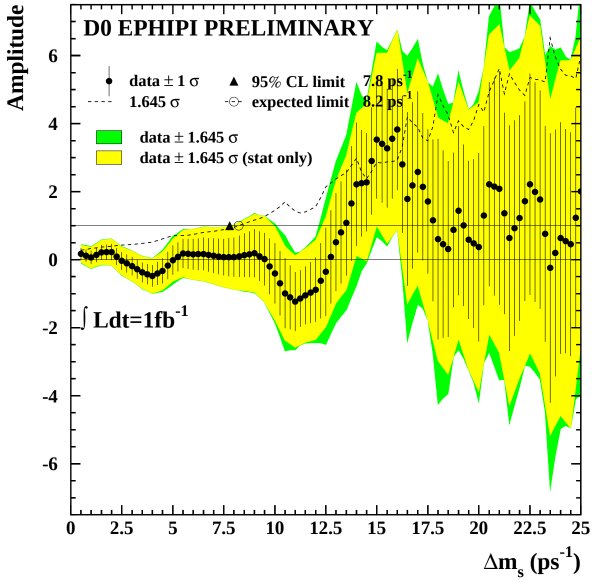
- “heavy” and “light” mass eigenstates
- B and $\overline{B}$ weak eigenstates:
  $$|B_s^0\rangle = \frac{1}{\sqrt{2}}(|B_{s,H}\rangle + |B_{s,L}\rangle)$$
  $$|\overline{B}_s^0\rangle = \frac{1}{\sqrt{2}}(|B_{s,H}\rangle - |B_{s,L}\rangle)$$
- Solution in proper time
  $$P(t)_{B_s^0\to B_s^0} = \frac{1}{2\tau}e^{-t/\tau}(1+\cos\Delta m_s t)$$
  $$P(t)_{B_s^0\to \overline{B}_s^0} = \frac{1}{2\tau}e^{-t/\tau}(1-\cos\Delta m_s t)$$
- mixing frequency $\Delta m_s = m_H - m_L$



Mixing Results (D0)







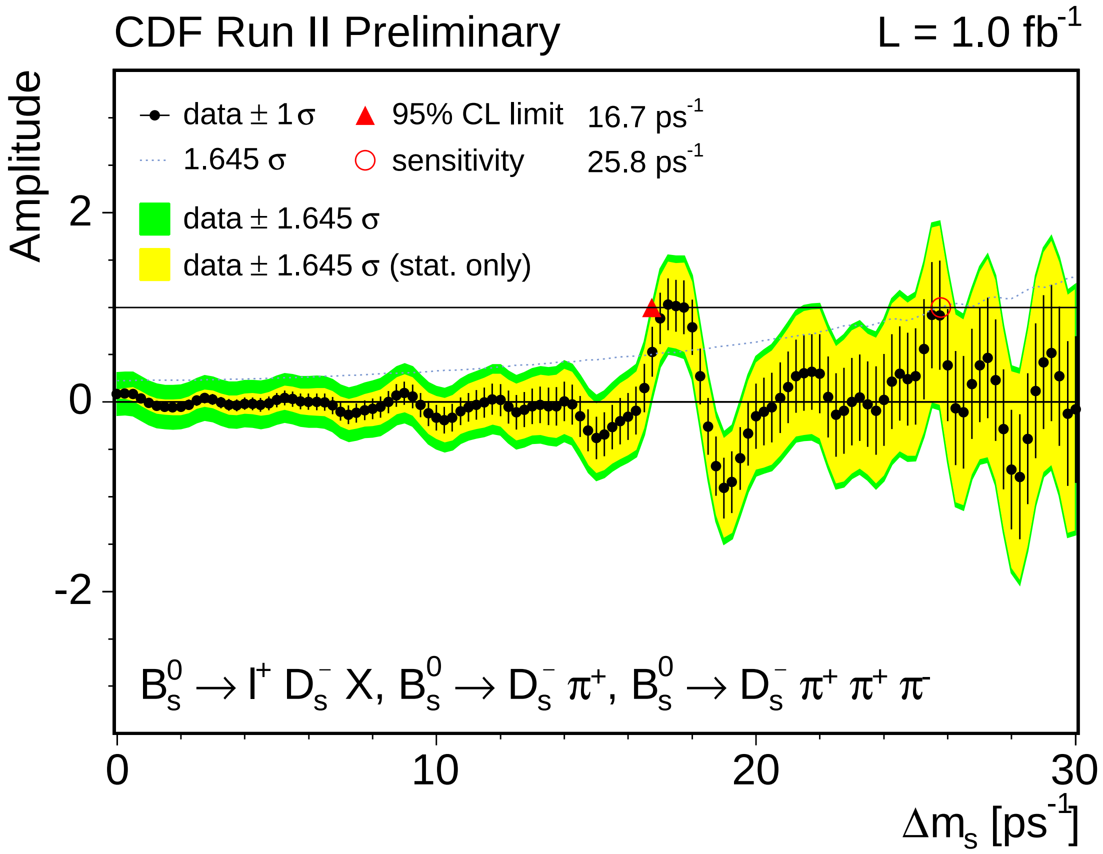
Update of Δm_s Analysis (CDF)

- partial reconstructed golden modes (+ 3.200 B_s candidates)
- NN selection for additional hadronic modes (2.100 $\longrightarrow$ 3.600 B_s candidates & better S/N)
- improvement in tagging performance:
  - addition of opposite side kaon tagger
  - NN combination of opposite side taggers
  - combination of kinematical and PID variables for SST
- PID selection for semileptonic modes, $m(\ell D)$ included in fit

False probability went down from 0.5 $\times$ 10^{-2} to 8 $\times$ 10^{-8} on the same data sample!

Spring ’06 Result (CDF)

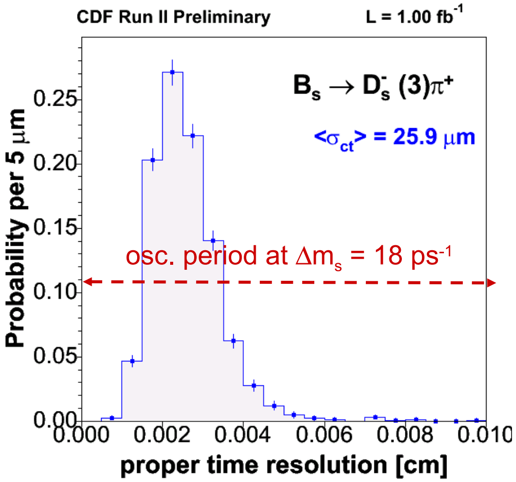
(Phys. Rev. Lett. **97**, (2006) 062003)

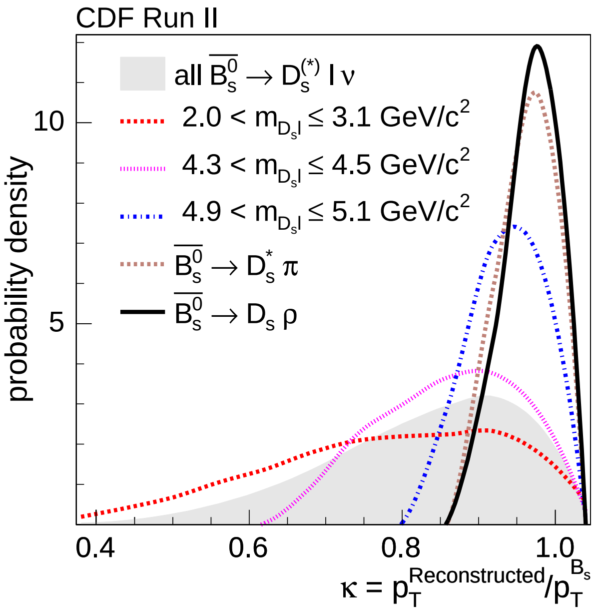


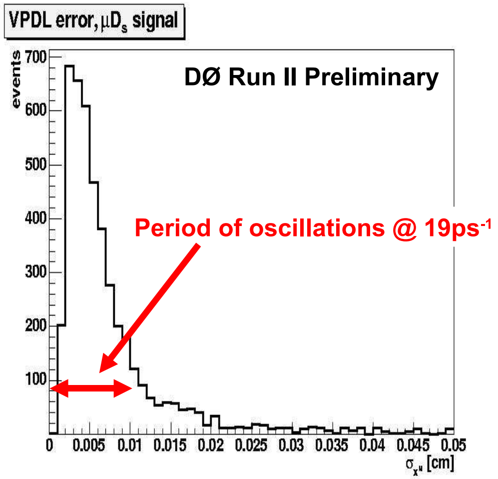
$$\Delta m_s = 17.31^{+0.33}_{-0.18}(stat.) \pm 0.07(syst.)\text{ps}^{-1}$$

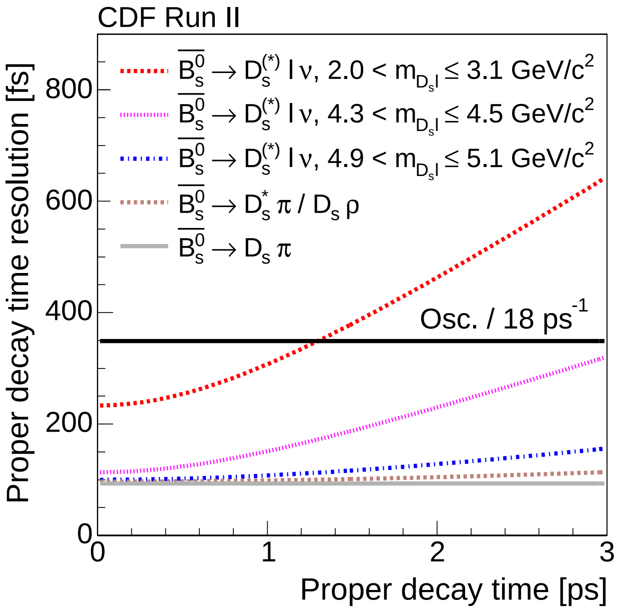
Proper Time Resolution

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

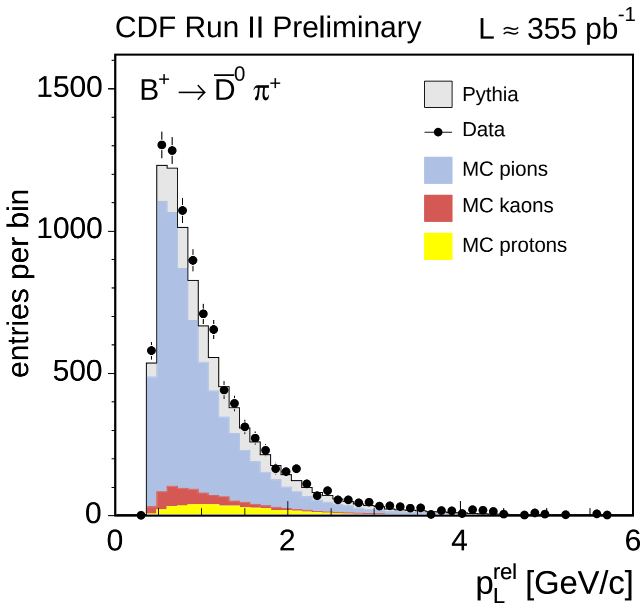


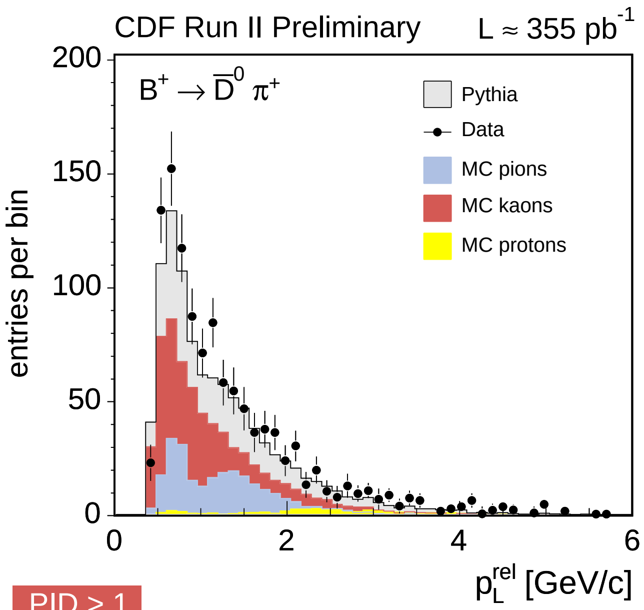




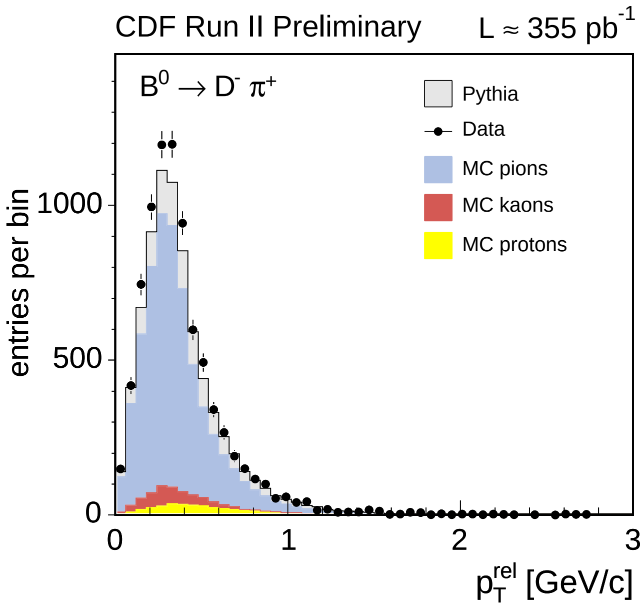


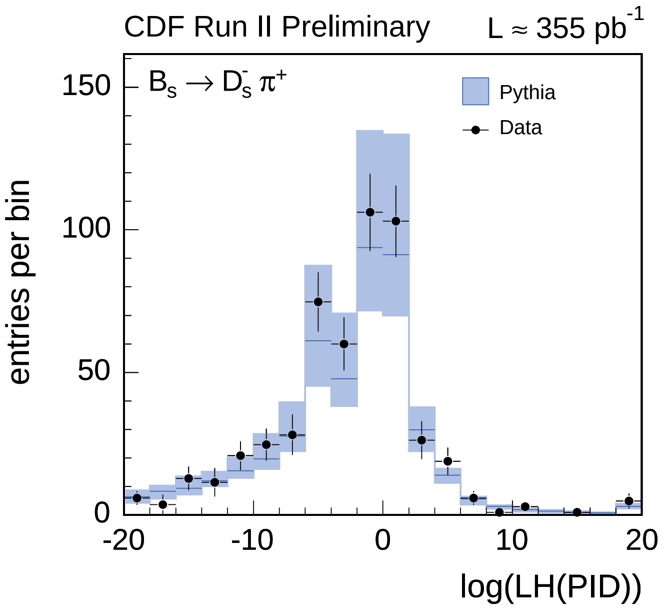
Same Side Tagger @ CDF (II)





PID > 1

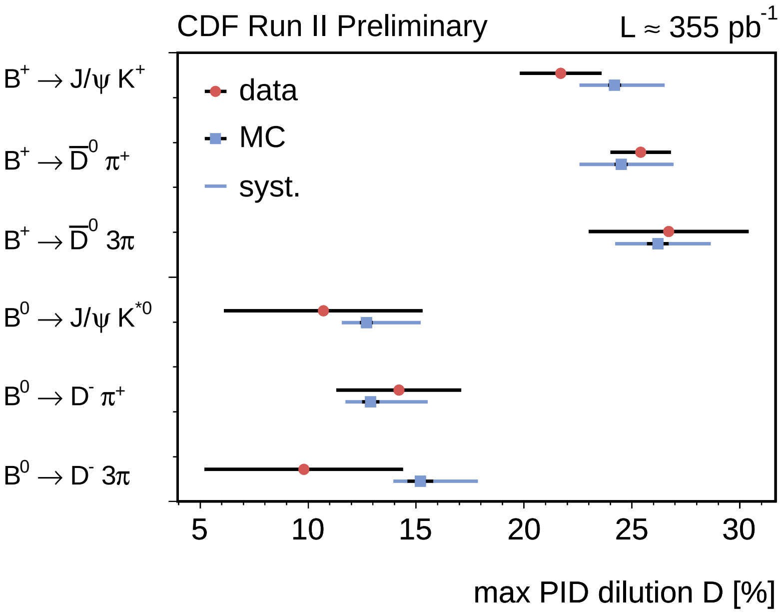




Same Side Tagger @ CDF (III)

Systematic studies:

- Fragmentation
- Production mechanisms
- Particle ID resolution
- kaon/proton/pion rates
- B^{**} rates (for B^+, B^0)
- Data/Monte Carlo agreement

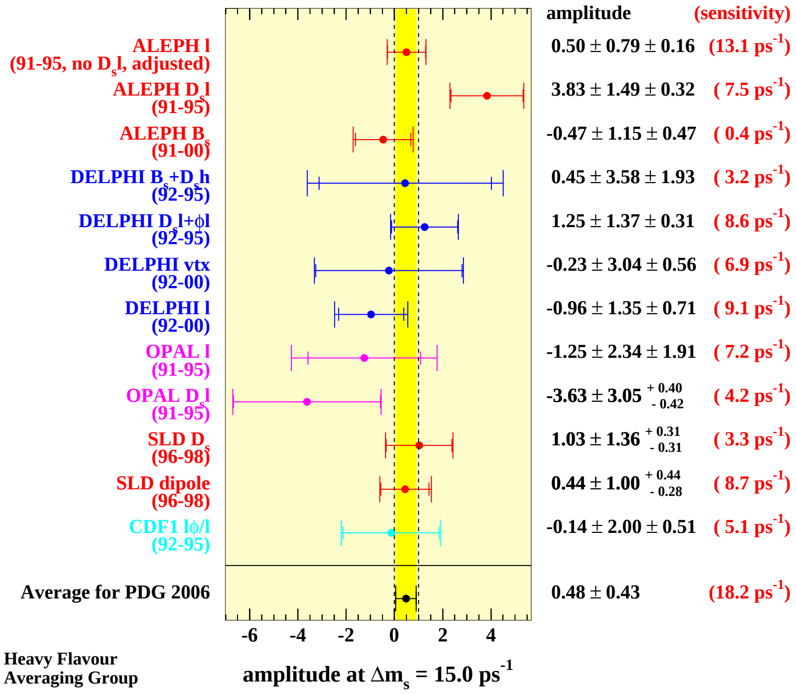


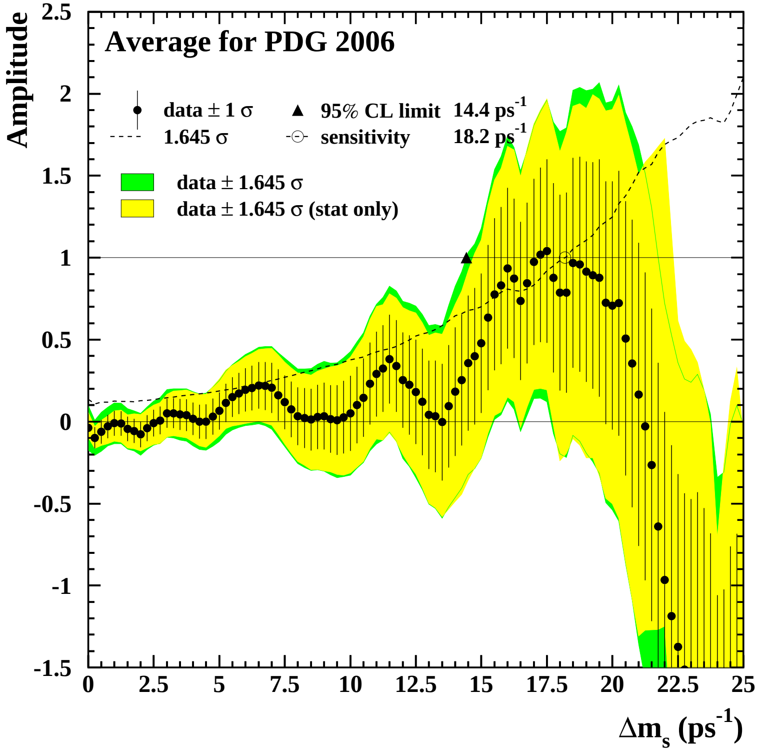
Very good data MC agreement for B^+ and B_d modes!

Status w/o Tevatron Run II Results

$\Delta m_s > 14.4\, ps^{-1}$ 95% CL

LEP + SLD + CDF Run I





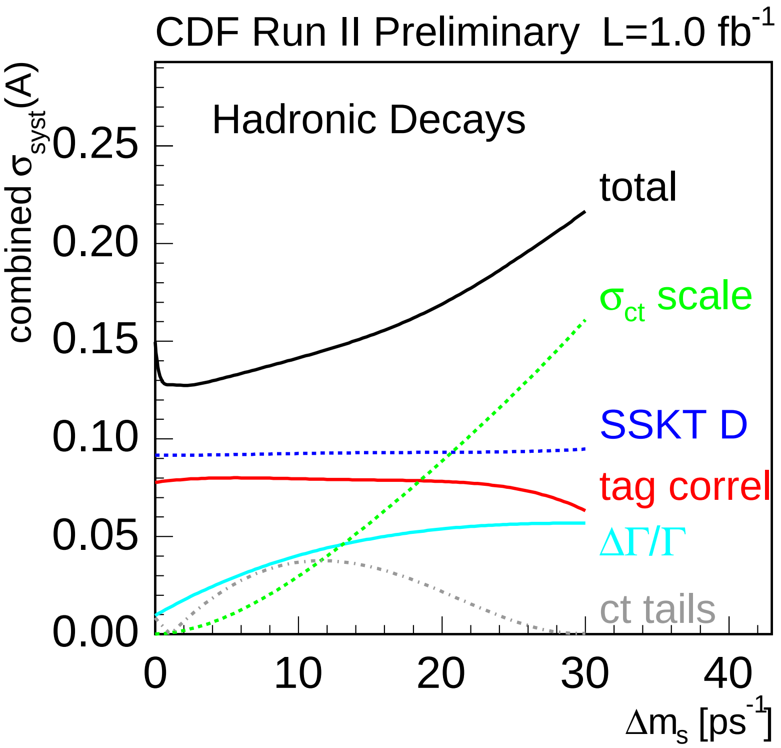
$$A(\Delta m_s = 15\, ps^{-1}) = 0.48 \pm 0.43$$

Sensitivity: $18.2\, ps$

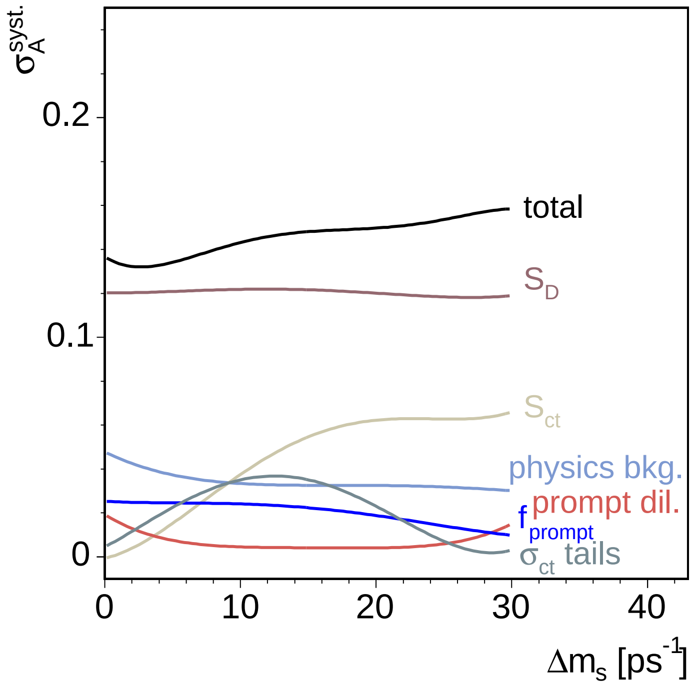
Amplitude method: H-G. Moser, A. Roussaire, NIM **A384**, 491 (1997)

Systematic Uncertainties (CDF) (I)

Hadronic



Semileptonic



Systematic uncertainties ∼0.15-0.20 at high Δm_s

Analysis limited by statistics

Systematic Uncertainties (CDF) (II)

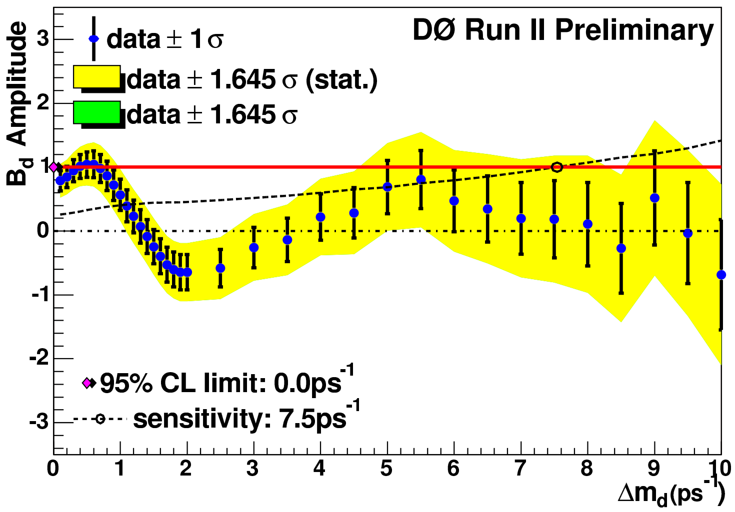
Source	Value (ps^{-1})
Silicon detector alignment	0.04
Track fit bias	0.05
Primary vertex bias	0.02
Hadronic k-factors	0.03
Amplitude scan systematic effects	$<$ 0.01
Total	0.07

All relevant systematic uncertainties:

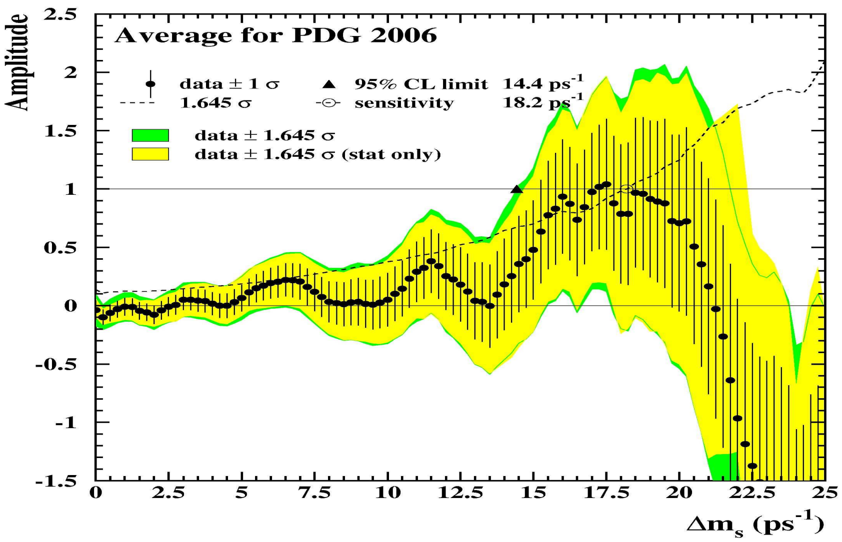
- related to ct scale
- common between hadronic and semileptonic samples

Amplitude Scan Notation

Test of amplitude scan on B_d data



2006 world combined B_s scan

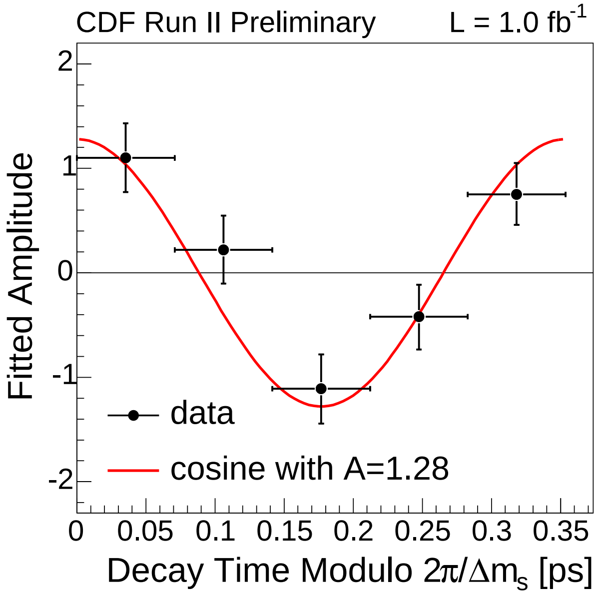


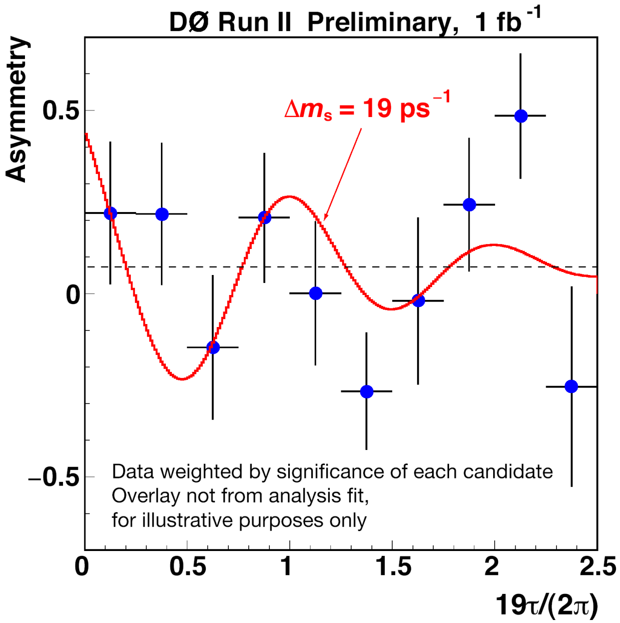
H.G. Moser, A. Roussarie, Nucl Instr. Meth. A **384**

- Amplitude uncertainties from unbinned likelihood fit
- Yellow: 1.645σ around data points defines 95% CL region
- Δm values, where $\mathcal{A} + 1.645\sigma < 1$ are excluded at 95% CL
- Dashed line: 1.645σ as a function of Δm
- Sensitivity: Δm, where $1.645\sigma = 1$ first
- On average, we expect to observe mixing within sensitivity

Can we SEE the Asymmetrie?

CDF: Asymmetry modulo 17.77 ps^{-1} for hadronic modes





Unbinned LH fit, exploiting

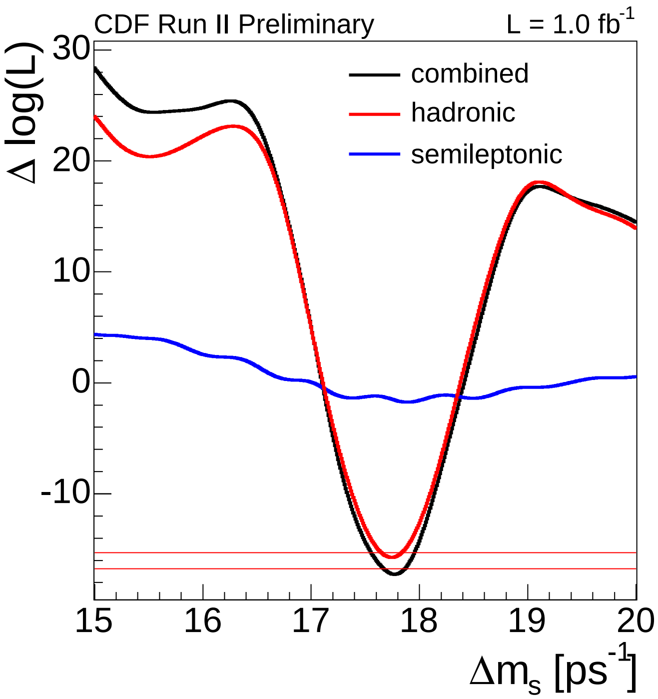
event-by-event σ_{ct} & D

D0: data points weighted by significance

Δm_s Measurement (CDF)

Δm_s in [17.00, 17.91] ps^{-1} @ 90% C.L.

Δm_s in [16.94, 17.97] ps^{-1} @ 95% C.L.



Δm_s = 17.77±0.10(stat.)±0.07(syst.) ps^{-1}

Systematic dominated by uncertainties on ct scale

consistent with indirect SM fits: Δm_s = $18.3^{+6.5}_{-1.5}$ps^{-1}

$|V_{td}|/|V_{ts}|$ Measurement (CDF)

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

Input	Value	Source
$\frac{m(B^0)}{m(B_s)}$	0.98390	CDF 2006
ξ	$1.21^{+0.047}_{-0.035}$	Lattice 2005
Δm_d	0.507 ± 0.005	PDG 2006
Δm_s	$17.77 \pm +0.10 \pm +0.07$	this analysis

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

Measurement no longer determined by experimental uncertainties.

Belle measurement $b \to d\gamma$: $|V_{td}|/|V_{ts}| = 0.199^{+0.026}_{-0.025}$(exp.)$^{+0.018}_{-0.015}$(theo.)