B_s Mixing at the Tevatron

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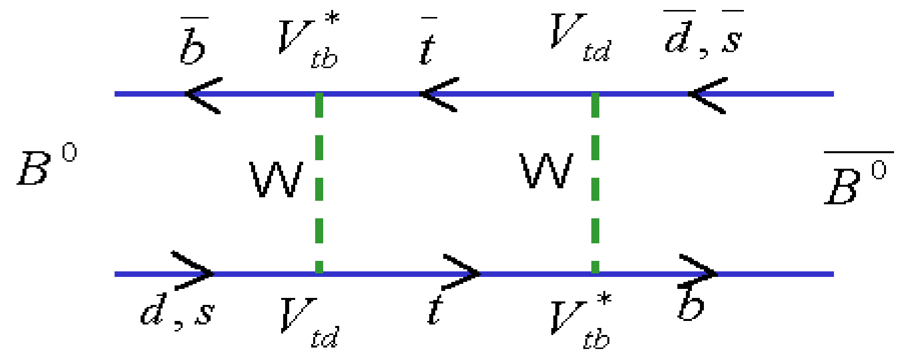
OUTLINE

- Introduction to Mixing
- Why study Mixing
- Fermilab Tevatron
- Data Taking
- CDF and D0 Detectors
- Analysis strategy
- B_s mixing at CDF
- B_s mixing at D0
- Results and Conclusions

Introduction

Mixing: The transition of neutral particle into it's anti-particle, and vice-versa

- First observed in the K meson system.
- In the B meson system, first observed in an admixture of B^0 and B_s^0 by UA1 and then in B^0 mesons by ARGUS in 1987.



These oscillations are possible because of the flavor-changing term of the Standard Model Lagrangian,

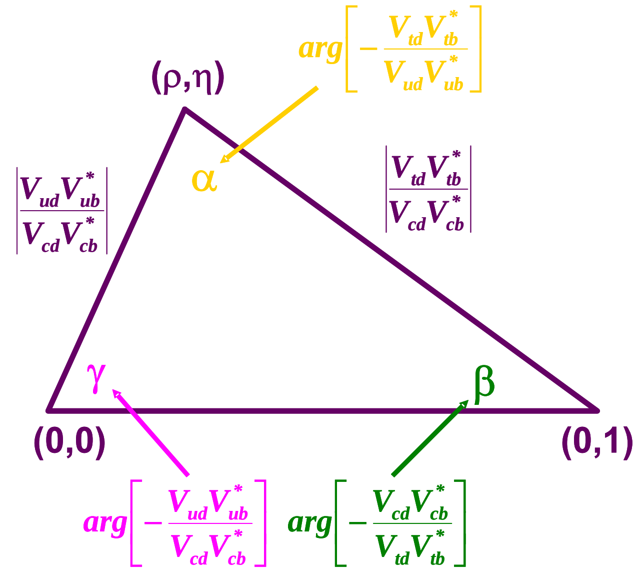
$$\boxed{L = \frac{g}{\sqrt{2}} \left(\overline{u}, \overline{c}, \overline{t}\right)_L V_{CKM} \gamma_\mu \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L W^\mu + h.c.}$$

Introduction

Where V_{CKM} is the CKM matrix;

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

Wolfenstein parametrisation- expansion in $\lambda \sim 0.22$



CP violation in the Standard Model originates due to a complex phase in the CKM matrix (quark mixing).

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

$$V_{ub} = |V_{ub}|\, e^{-i\beta}$$

$$V_{td} = |V_{td}|\, e^{-i\gamma}$$

$$-\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}} - \frac{V_{td}V^*_{tb}}{V_{cd}V^*_{cb}} = 1$$

Mixing in B mesons

Light and Heavy B mesons mass eigenstates differ from flavor eigenstates:

$$|B_L> = p|B> + q|\bar{B}>$$

$$|B_H> = p|B> - q|\bar{B}>$$

$$\sqrt{p^2 + q^2} = 1$$

$$\boxed{m = \frac{M_H + M_L}{2}}$$

$$\boxed{\Gamma = \frac{\Gamma_H + \Gamma_L}{2}}$$

$$\Delta m = M_H - M_L$$

$$\Delta\Gamma = \Gamma_L - \Gamma_H$$

Time evolution of

B^0 and $\overline{B^0}$ states

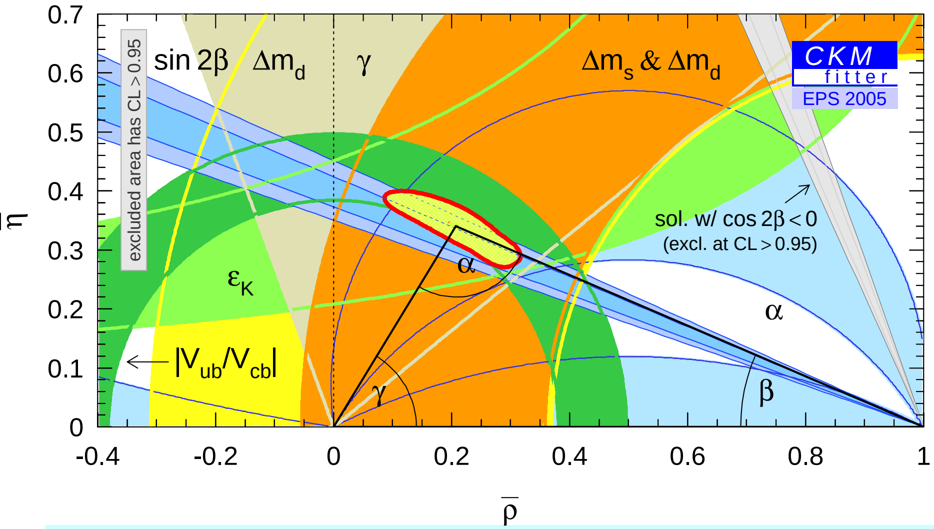
$$P(B \to B) = \frac{e^{-\Gamma t}}{2}\left(\cosh\frac{\Delta\Gamma t}{2} + \cos\Delta m t\right)$$

$$P(B \to \bar{B}) = \frac{e^{-\Gamma t}}{2}\left(\cosh\frac{\Delta\Gamma t}{2} - \cos\Delta m t\right)$$

In case $\Delta\Gamma \to 0$,

$$\boxed{P_{u,m}(t) = \frac{1}{2}\Gamma\, e^{-\Gamma t}(1 \pm \cos \Delta m t)}$$

Why B_s mixing is important



standard model Expectation:

$\Delta m_s = 14 - 28 ps^{-1}$ $\Delta m_d = 0.5 ps^{-1}$

measurement of $\Delta m_s / \Delta m_d$

$\rightarrow V_{ts}/V_{td}$

constrain unitary triangle

$$\Delta m_d = \frac{G_F^2 m_t^2 \eta F(m_t^2 / m_W^2)}{6\pi^2} m_{B_d} f_{B_d}^2 B_{B_d} \left|V_{td}^* V_{tb}\right|^2$$

$f^2_{Bd} B_{Bd} = (228 \pm 30 \pm 10\ MeV)^2$

$|V_{td}|$ from Δm_d limited by ~15%

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

∴ consider ratio

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

Determine $|V_{ts}|/|V_{td}|$ ~ 5% precision

K mixing $\Rightarrow$ direct & indirect CPV

B_d mixing $\Rightarrow$ heavy top mass

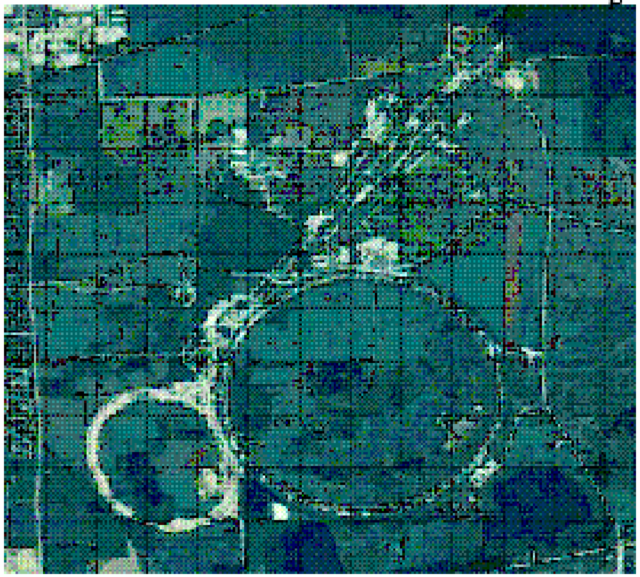
ν mixing $\Rightarrow$ neutrino mass $\neq 0$

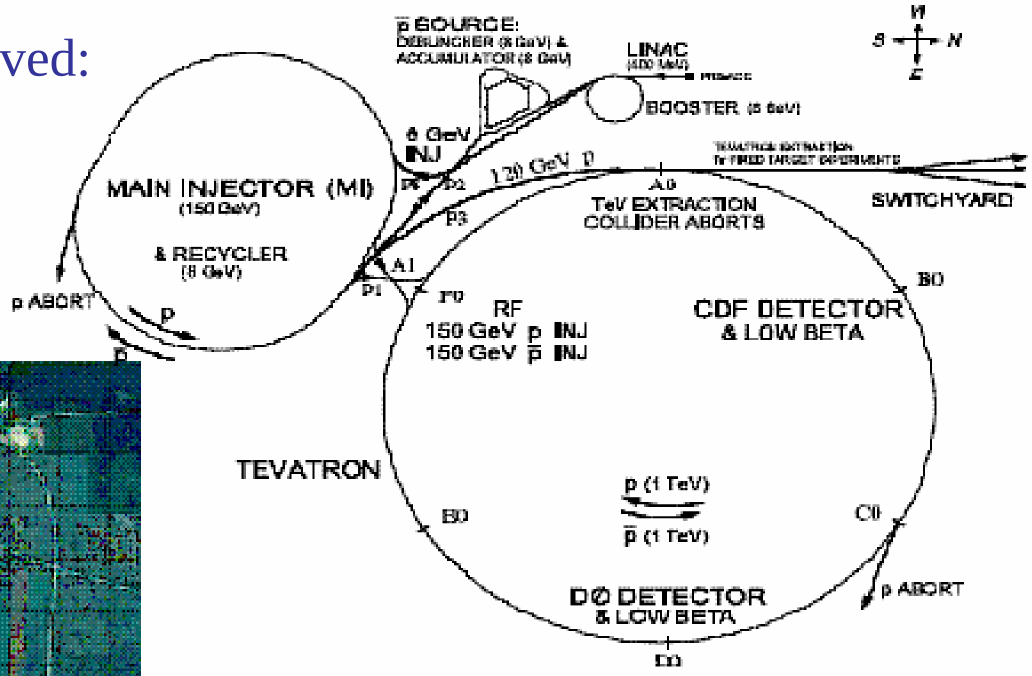
B_s mixing $\Rightarrow$????

Fermilab Tevatron

Highest Luminosity achieved:

1.7×10^{32} cm/s^2





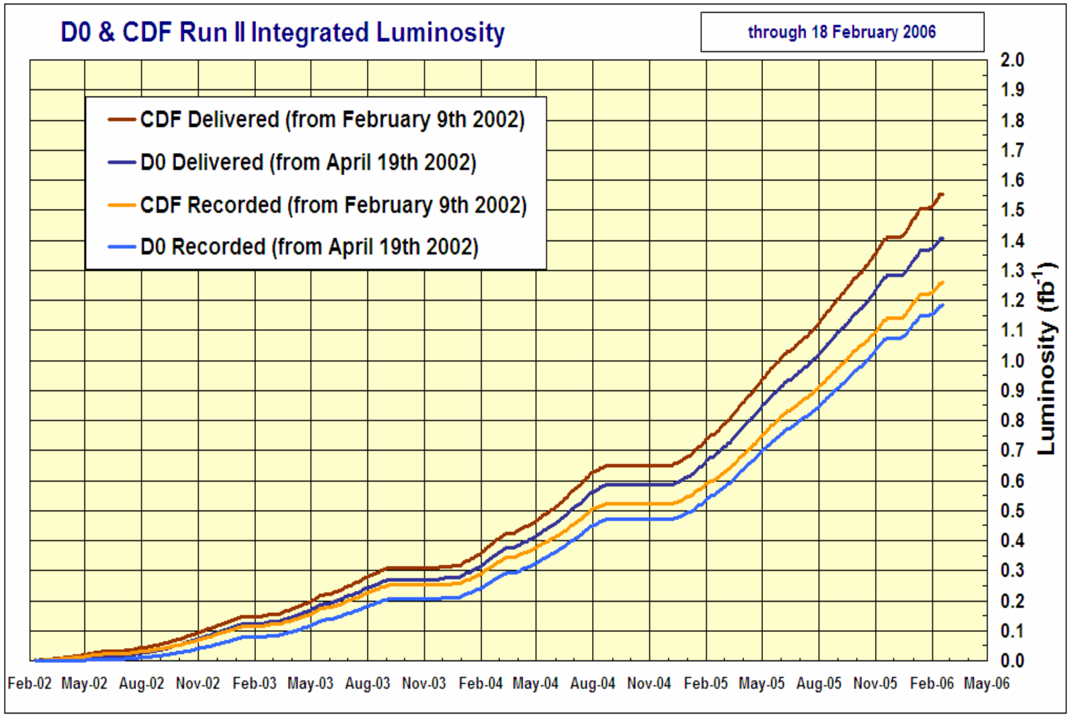
Expected: 2 – 3 x 10^{32} cm/s^2

$\Rightarrow$ 4-8 fb^{-1} before LHC

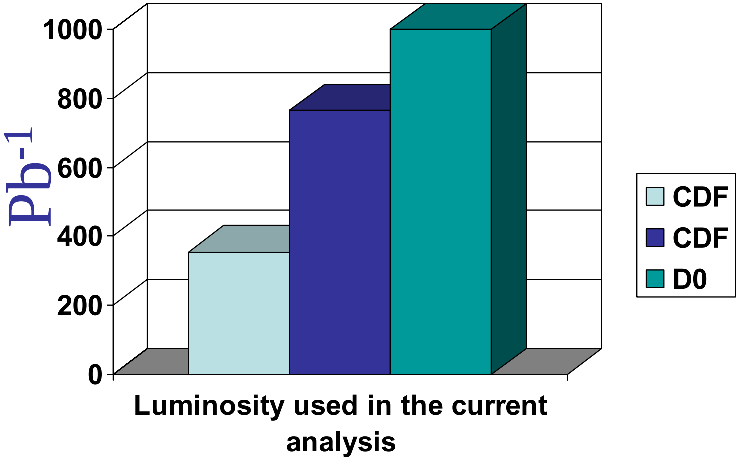
All B species produced including Bs mesons

Data Taking

Excellent performance by the Tevatron and we are doubling our data set every year.



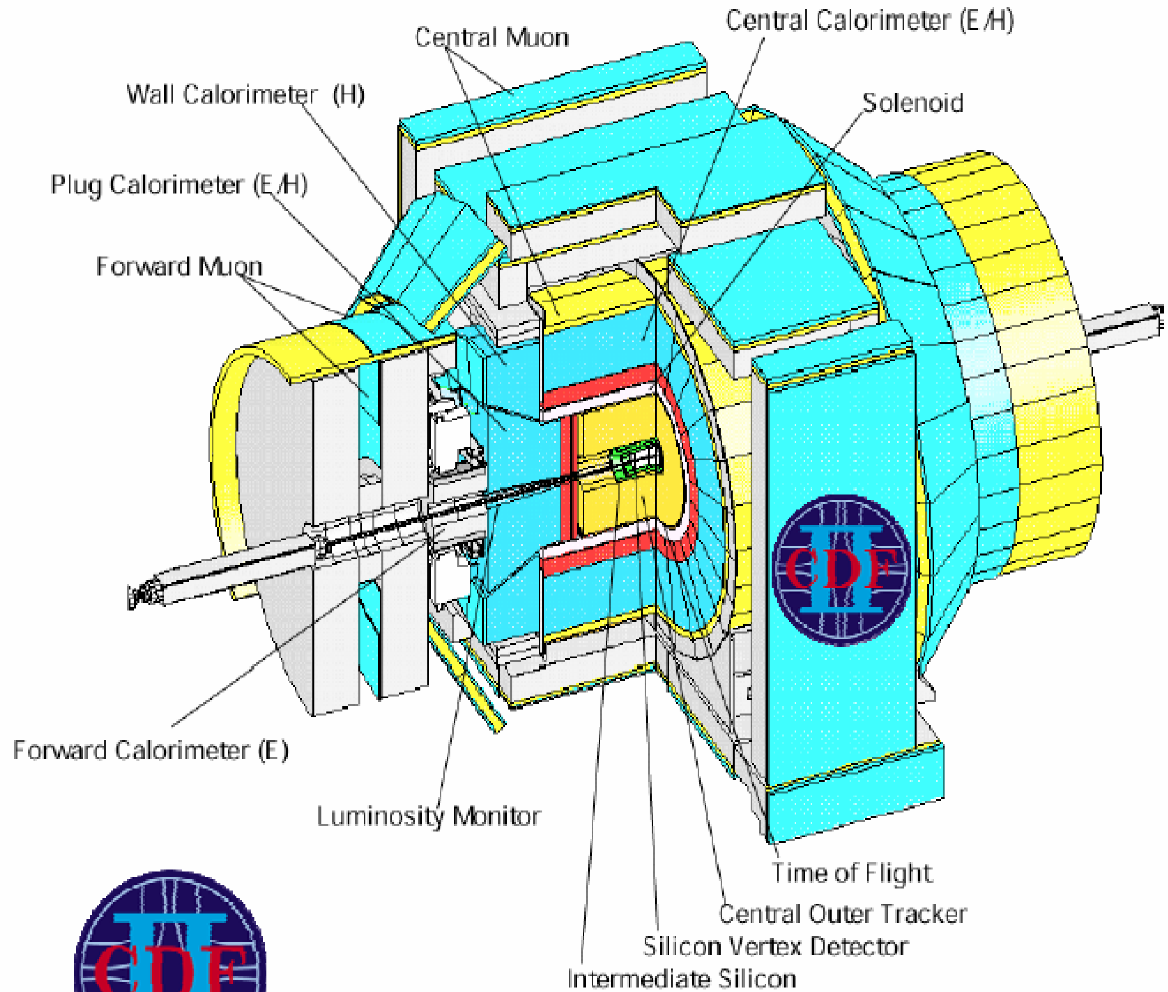
Data taking efficiency is ~ 85%.



We already have collected about 10 times of run 1 data.

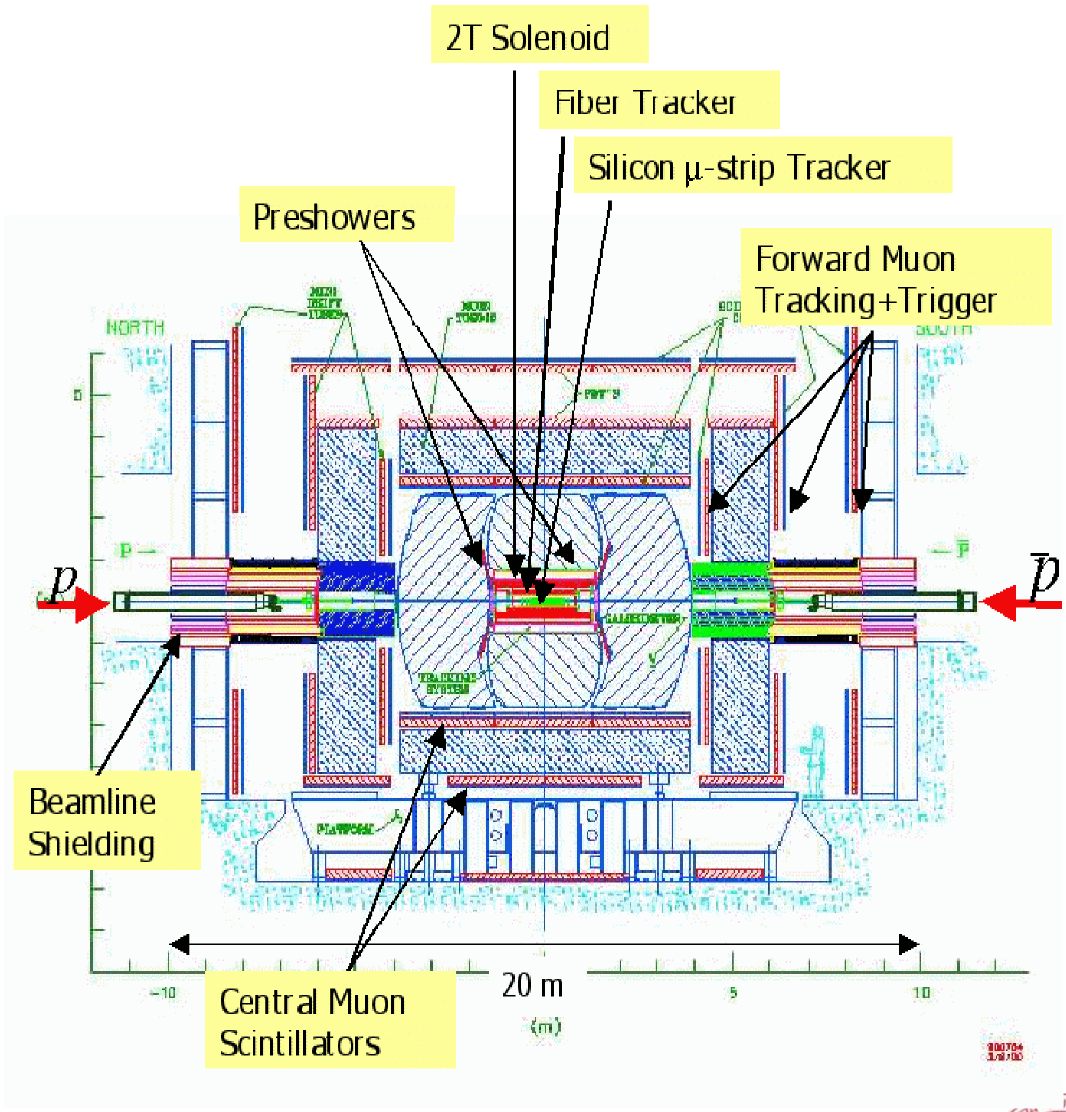
CDF Detector

- Solenoid 1.4T
- Silicon Tracker SVX
  - up to $|\eta|<2.0$
  - SVX fast r-ϕ readout for trigger
- Drift Chamber
  - 96 layers in $|\eta|<1$
  - particle ID with dE/dx
  - r-ϕ readout for trigger
- Time of Flight
  - $\rightarrow$particle ID



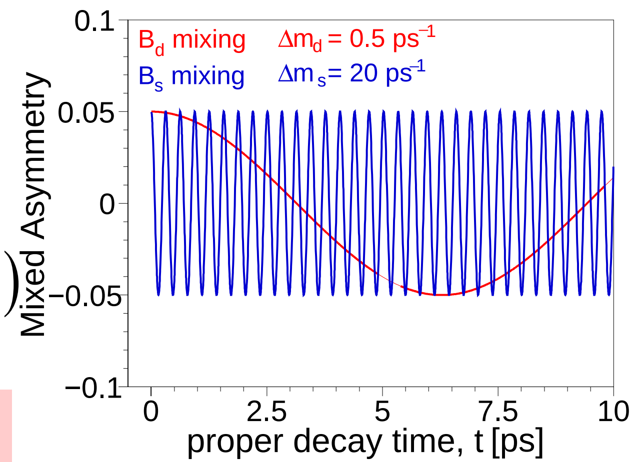
D0 Detector

- 2T solenoid
- Fiber Tracker
  - 8 double layers
- Silicon Detector
  - up to |η|~3
- forward Muon + Central Muon detectors
  - excellent coverage |η|<2
- Robust Muon triggers.



Analysis strategy

❖Measuring B_s oscillations is much more difficult than B_d oscillations because of the fast mixing frequency.



In order to measure,

$$\mathbf{A}_{\mathbf{mix}}(\mathbf{t}) = \frac{\mathbf{N}_{\mathbf{unmix}}(\mathbf{t}) - \mathbf{N}_{\mathbf{mix}}(\mathbf{t})}{\mathbf{N}_{\mathbf{unmix}}(\mathbf{t}) + \mathbf{N}_{\mathbf{mix}}(\mathbf{t})} = \mathbf{D} * \cos(\Delta \mathbf{m}_s \mathbf{t})$$

$$sensitivity \propto \sqrt{\frac{S}{S+B}} \sqrt{\frac{N\varepsilon D^2}{2}} e^{-\frac{(\Delta m_s \sigma_t)^2}{2}}$$

Reconst-ruction

Flavor tagging

Proper time

We need to:

Reconstruct the B_s signal.

Know the flavor of the meson at it's production time (Flavor tagging) and get εD^2

$$\varepsilon = \frac{N_R + N_W}{N}$$

$$D = \frac{N_R - N_W}{N}$$

Proper decay length resolution

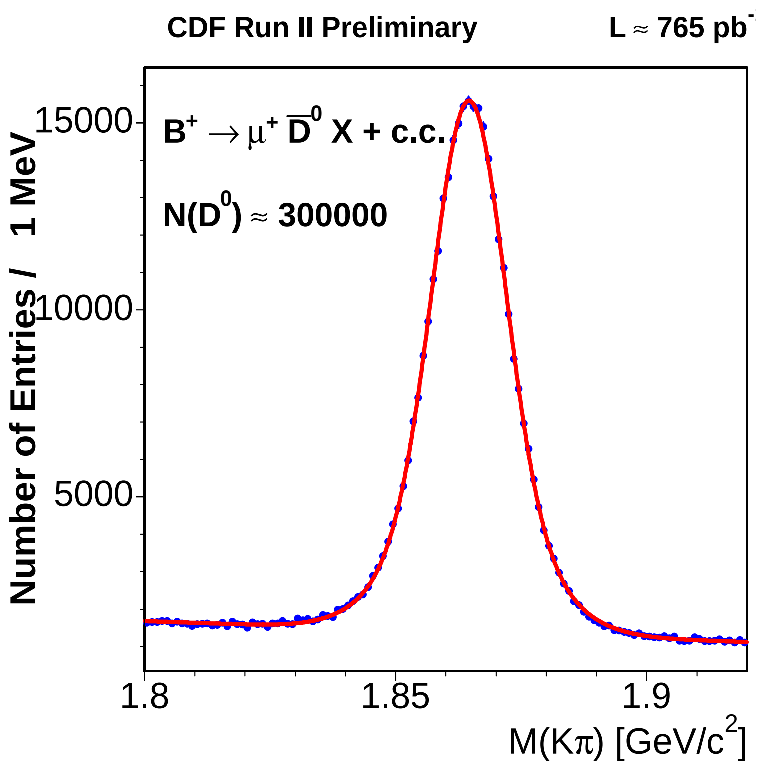
$$sensitivity \propto \boxed{\sqrt{\frac{S}{S+B}}}\sqrt{\frac{N\varepsilon D^2}{2}}e^{-\frac{(\Delta m_s \sigma_t)^2}{2}}$$

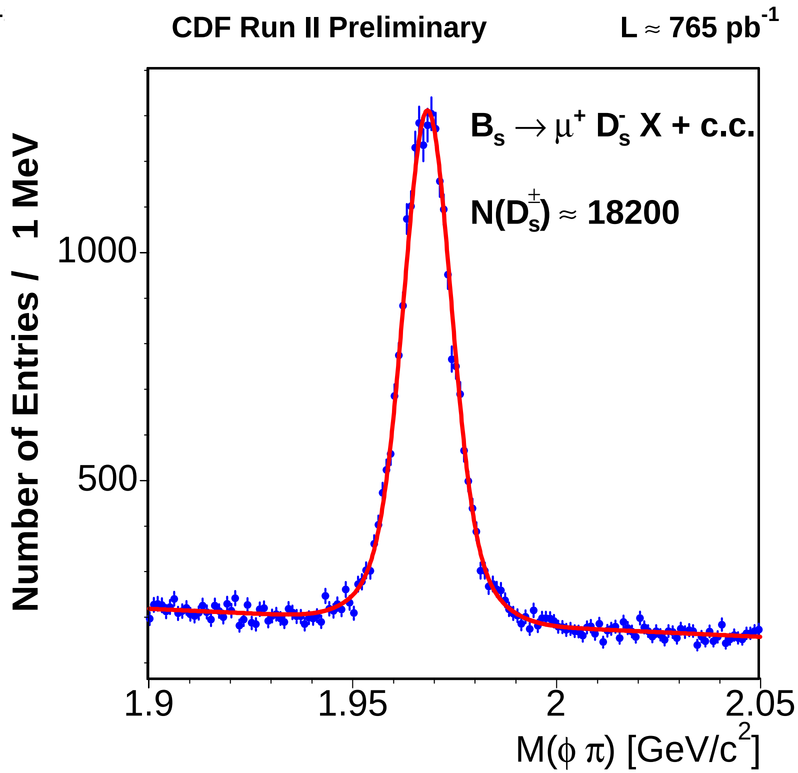
➢ Semileptonic modes collected by the two track trigger

Reconst-ruction

Flavor tagging

Proper time





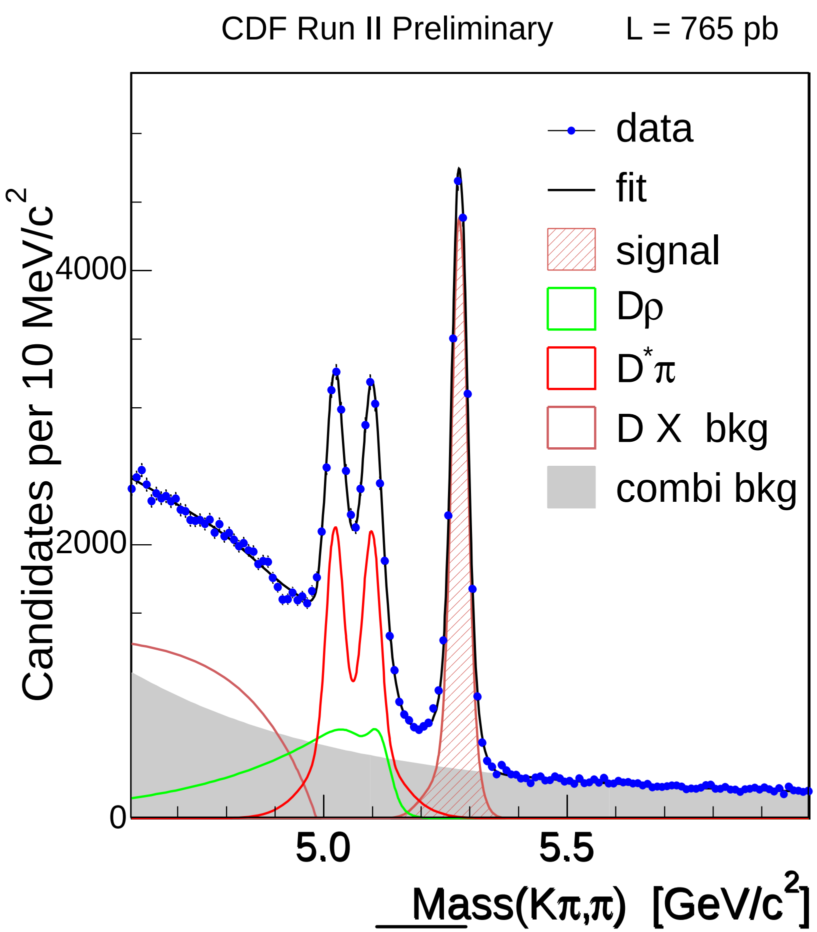
$$sensitivity \propto \boxed{\sqrt{\frac{S}{S+B}}}\sqrt{\frac{N\varepsilon D^2}{2}}e^{-\frac{(\Delta m_s \sigma_t)^2}{2}}$$

- More than 2300 Bs signal candidates in 765 pb^{-1}

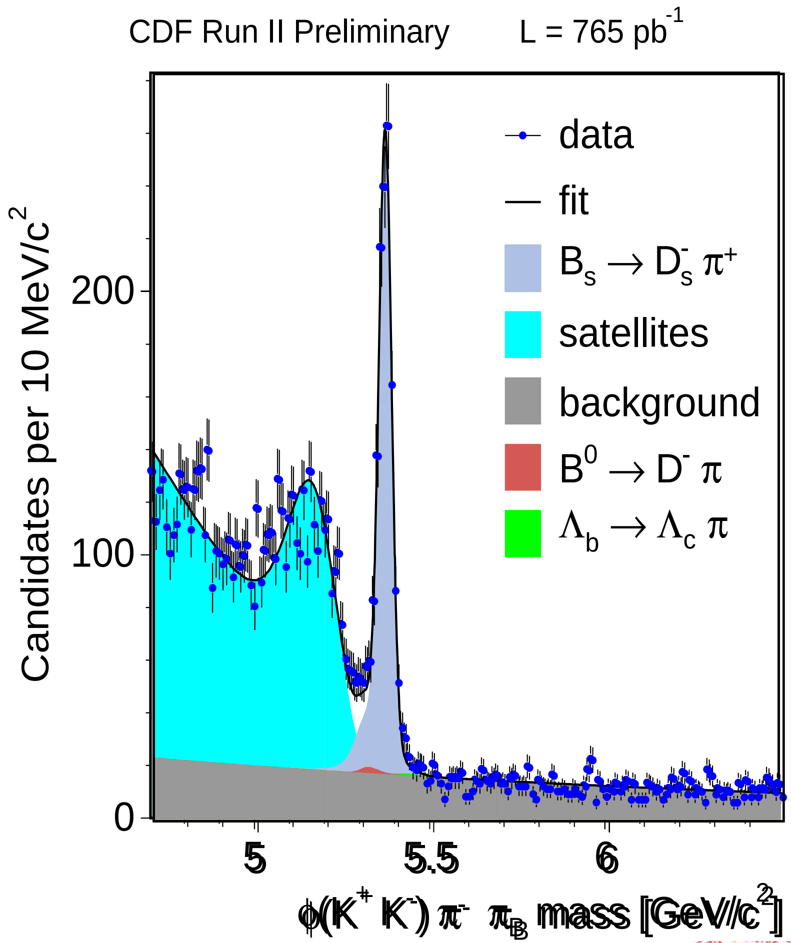
Reconst-ruction

Flavor tagging

Proper time



$B^+ \to D^0(K\pi)\pi^+$



$B_s \to D_s^-(\phi\pi)\pi^+$

$$\text{sensitivity} \propto \boxed{\sqrt{\frac{S}{S+B}}}\sqrt{\frac{N\varepsilon D^2}{2}}\,e^{-\frac{(\Delta m_s \sigma_t)^2}{2}}$$

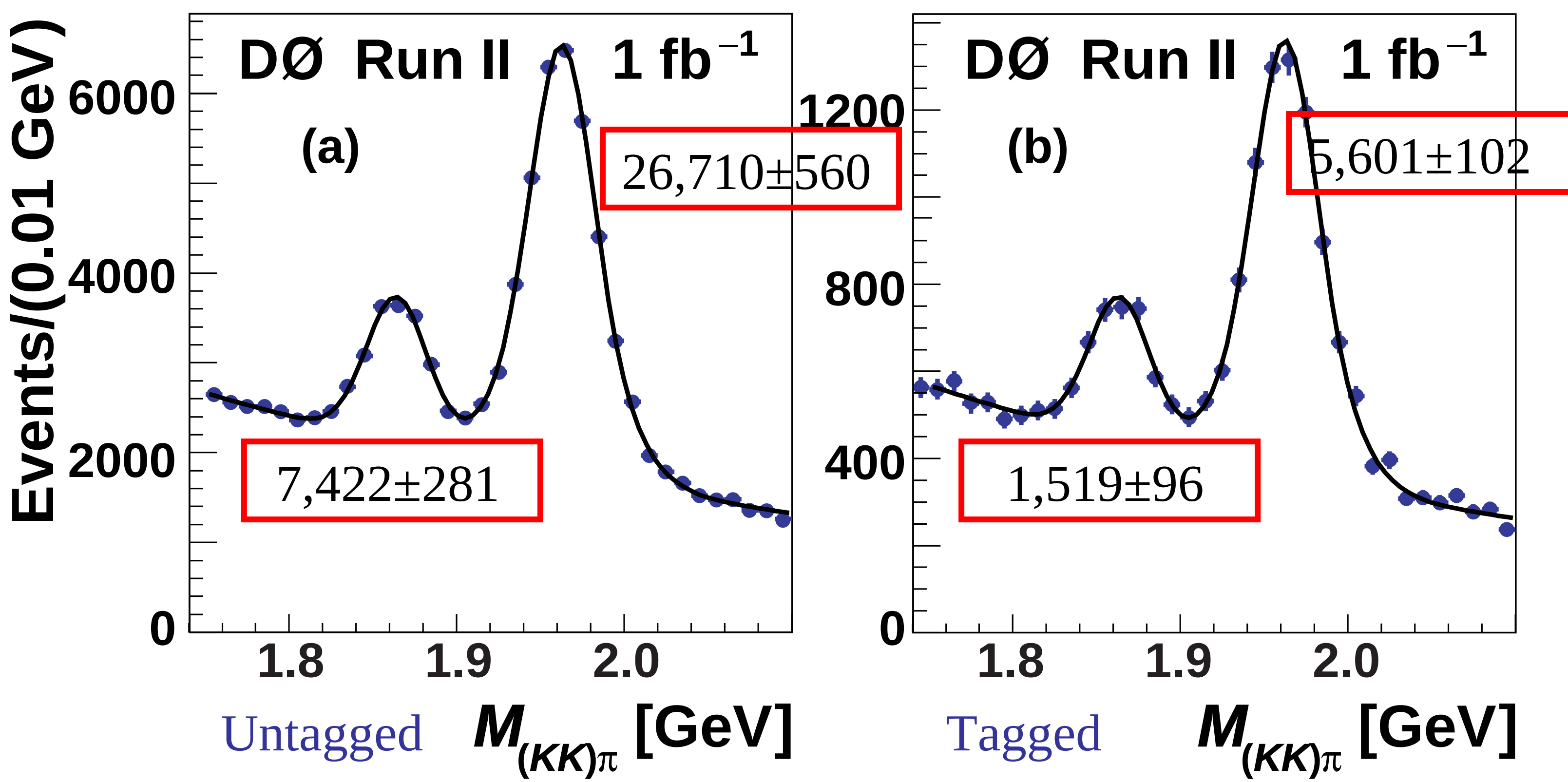
- Currently using only semileptonic decay of the Bs

$B_s \to D_s \mu X$ ($D_s \to \phi \pi$) ($\phi \to K^+K^-$)

Reconst-ruction

Flavor tagging

Proper time



$$sensitivity \propto \sqrt{\frac{S}{S+B}} \boxed{\sqrt{\frac{N\varepsilon D^2}{2}}} e^{-\frac{(\Delta m_s \sigma_t)^2}{2}}$$

Soft Lepton Tagging (μ or e):

- Charge of the leptons provides the flavor of b.

Jet Charge Tagging:

- Sign of the weighted average charge of opposite B jet provides the flavor of b.

Same Side(Kaon) Tagging (New at CDF)

- B meson is likely to be accompanied by a close K/π
- particle Id helps

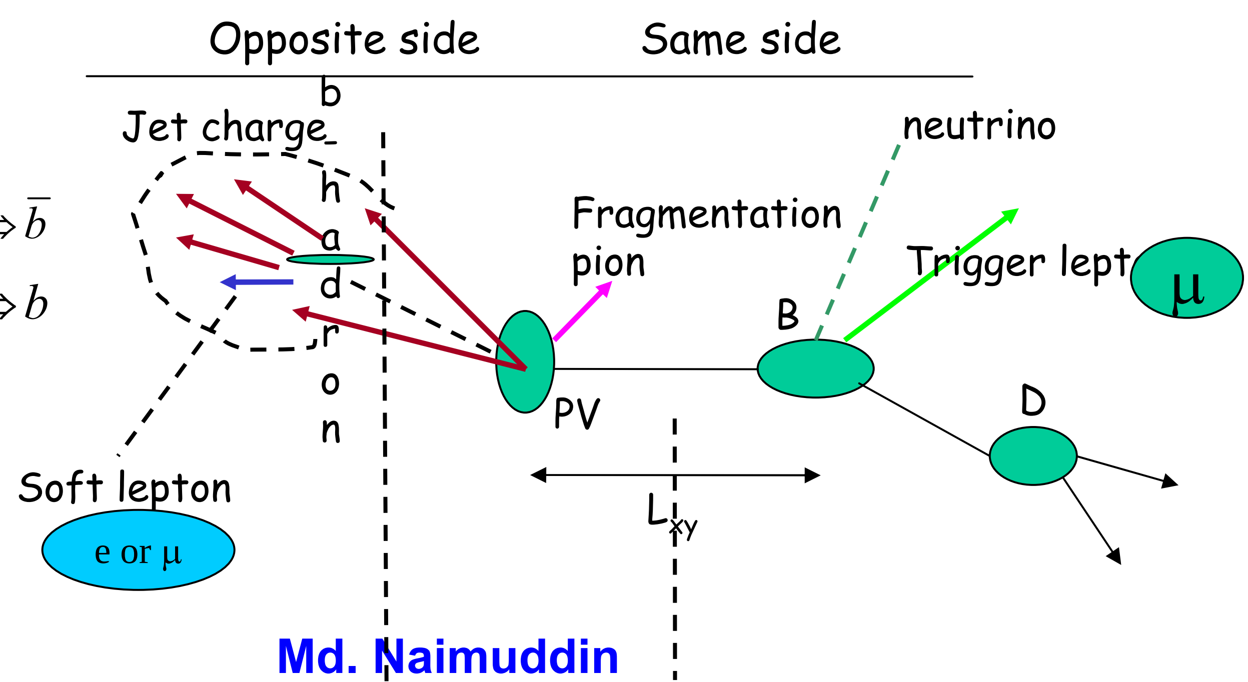
Reconst-ruction

Flavor tagging

Proper time

$jetQ < 0 \Rightarrow \bar{b}$

$jetQ > 0 \Rightarrow b$



$$\text{sensitivity} \propto \sqrt{\frac{S}{S+B}}\boxed{\sqrt{\frac{N\varepsilon D^2}{2}}}e^{-\frac{(\Delta m_s \sigma_t)^2}{2}}$$

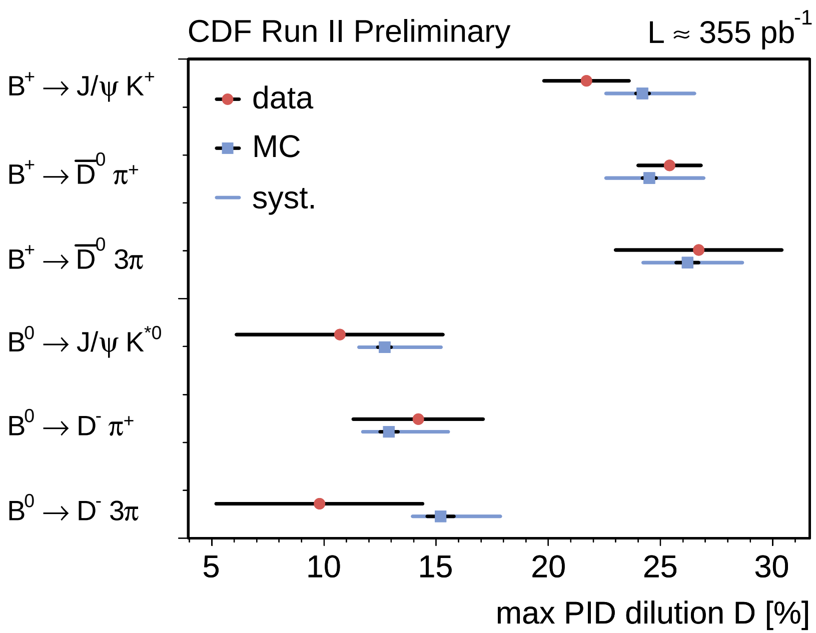
Opposite side Tagging: $\boxed{\varepsilon D^2 = (1.55 \pm 0.020 \pm 0.014)\%}$

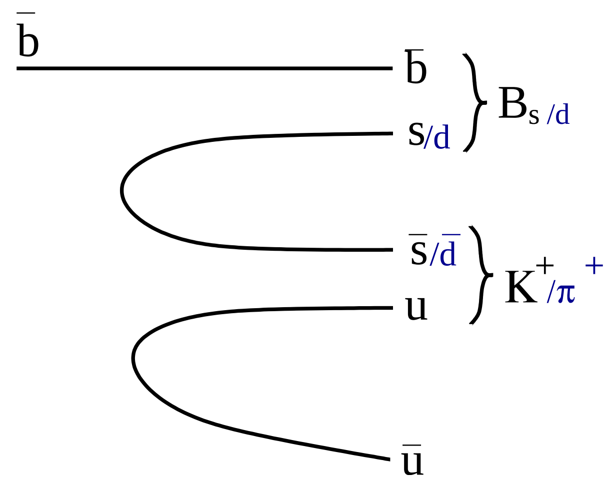
Same side Kaon Tagging:

Reconst-ruction

Flavor tagging

Proper time





$$\boxed{D = 28.3^{+3.2}_{-4.2}\% \qquad \varepsilon D^2 = 4.0^{+0.9}_{-1.2}\%}$$

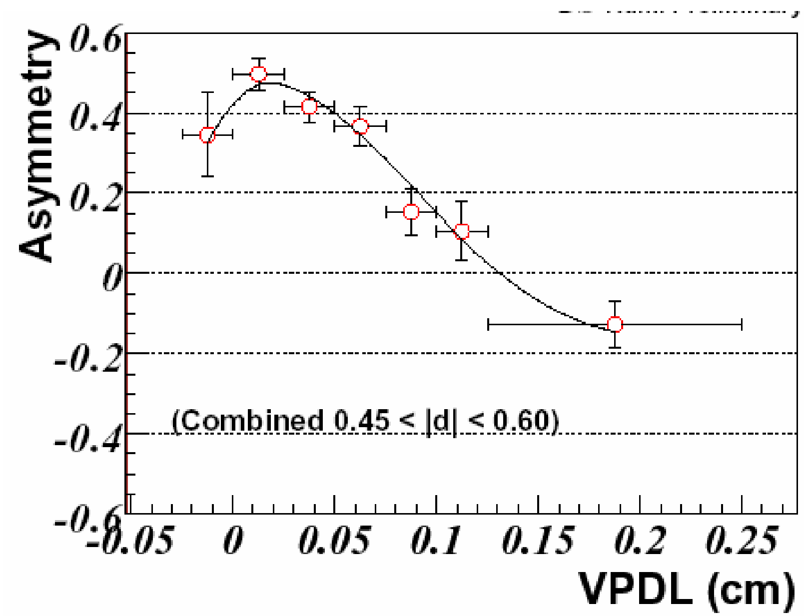
$$\text{sensitivity} \propto \sqrt{\frac{S}{S+B}}\boxed{\sqrt{\frac{N\varepsilon D^2}{2}}}e^{-\frac{(\Delta m_s \sigma_t)^2}{2}}$$

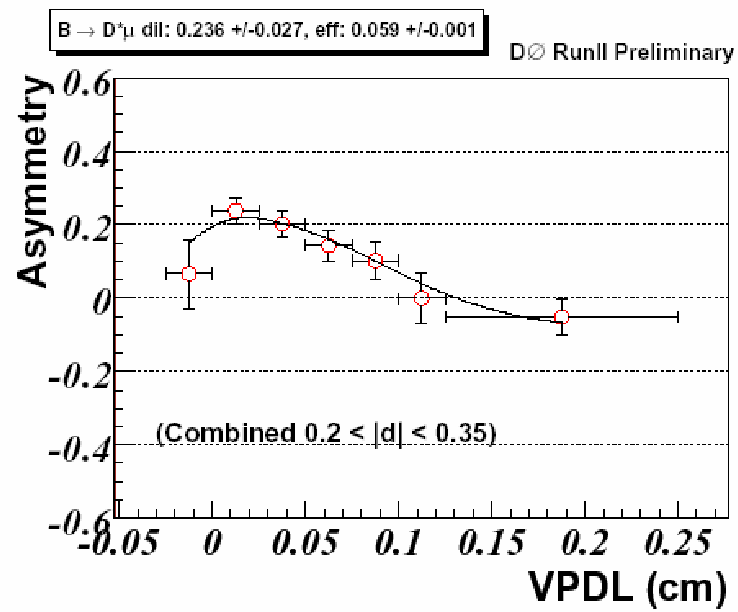
➢ Using only Opposite side e, μ, secondary vertex or jet charge for tagging

Reconst-ruction

Flavor tagging

Proper time





$$\varepsilon D^2 = (2.48 \pm 0.21^{+0.08}_{-0.06})\%$$

Tagger tuned using B_d mixing measurement

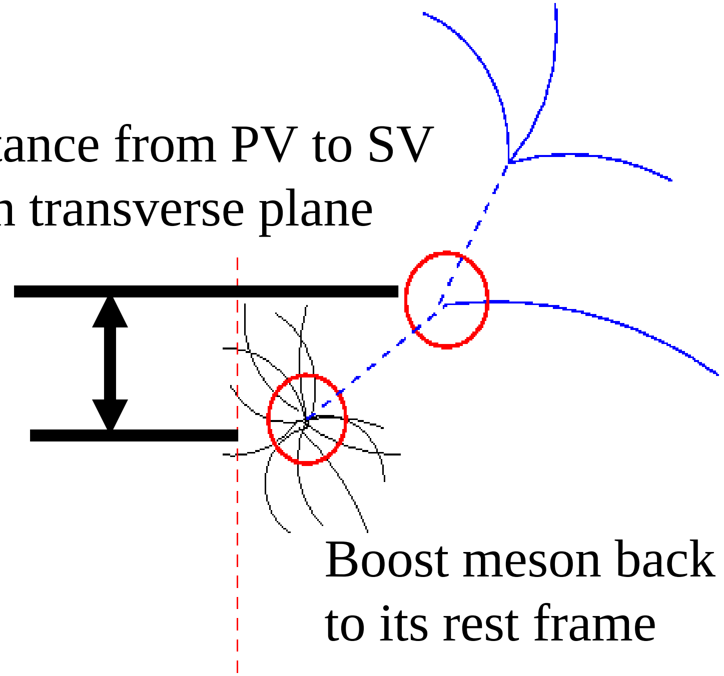
$$\Delta m_d = 0.506 \pm 0.020 \pm 0.014\ \text{ps}^{-1}$$

$$sensitivity \propto \sqrt{\frac{S}{S+B}}\sqrt{\frac{N\varepsilon D^2}{2}}\,e^{-\frac{(\Delta m_s \boxed{\sigma_t})^2}{2}}$$

Easier to calculate for Hadronic decays

Proper decay time given as :

$$ct = L_{xy}\frac{m_B}{P^T}$$



Reconst-ruction

Flavor tagging

Proper time

Due to missing neutrino, it becomes little tricky in semileptonic sample

Missing momentum ⇒ increased ct error (σ_{ct})

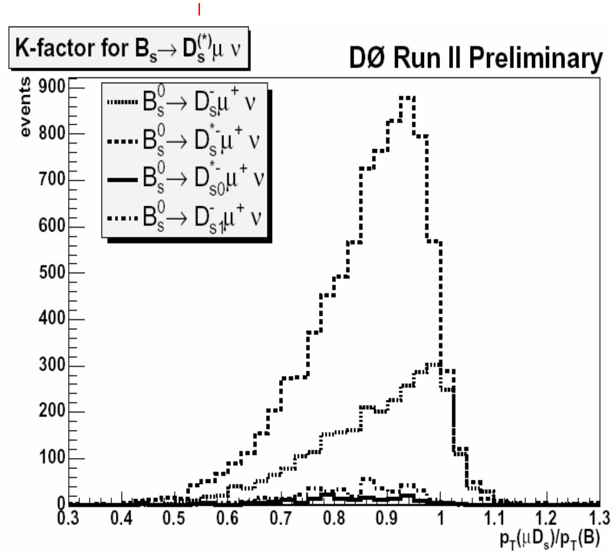
Proper decay time given as:

$$ct = L_{xy}\frac{m_B}{P^T} * K$$

where

$$K = \frac{P^T_{lD_s}}{P^T_B}$$

from MC

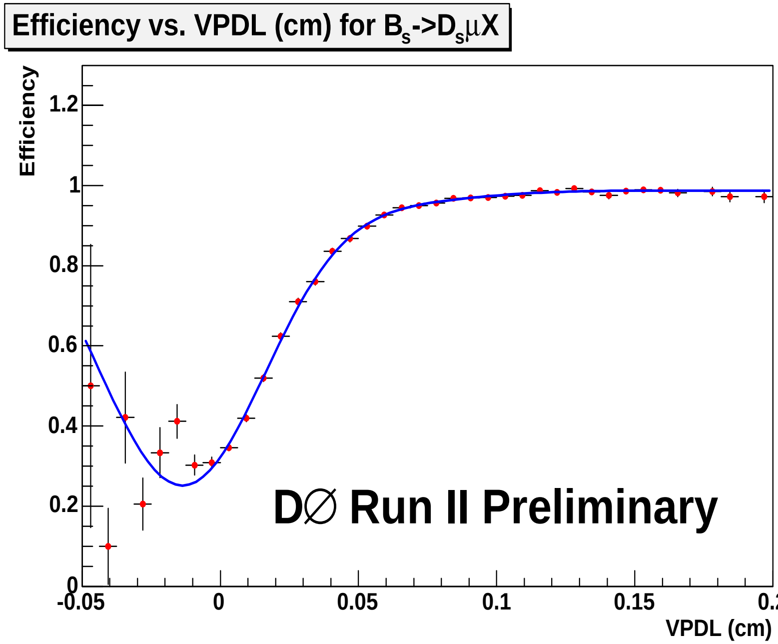


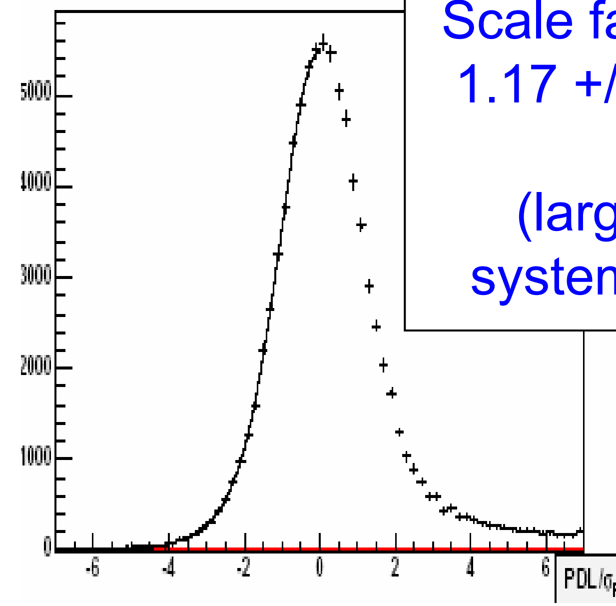
$$sensitivity \propto \sqrt{\frac{S}{S+B}}\sqrt{\frac{N\varepsilon D^2}{2}}e^{-\frac{(\Delta m_s \boxed{\sigma_t})^2}{2}}$$

Reconst-ruction

Flavor tagging

Proper time





Scale factor = 1.17 +/- 0.02

(largest systematic)

Best estimate of errors used in track fitting, any additional scaling determined from data

Pull of J/ψ vertex from the primary vertex for prompt J/ψ s

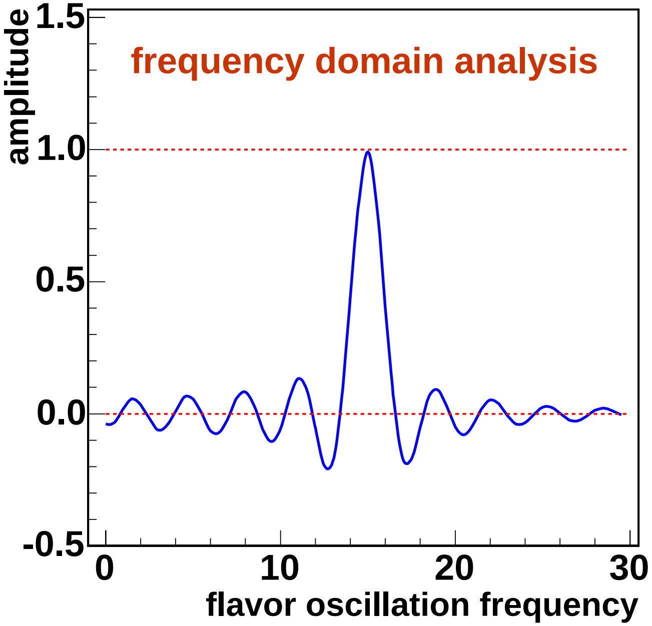
Fitting procedure

Amplitude Fitting approach:

- Introduce amplitude

$$P(t) \sim \left(1 \pm AD\cos \Delta m_s t\right)$$

- Fit for A at different Δm_s
- Traditionally used for B_s mixing search
- Easy to combine experiments



Likelihood approach:

- Search for ν_{min}, which minimizes the –ln(L),

$$\Delta L^{\min}(\nu) = -\ln\left[L(\nu)\right] + \ln\left[L(\nu_{\min})\right]$$

where ν_{min} is the estimator of the true frequency.

- Difficult to combine the results from different experiments.

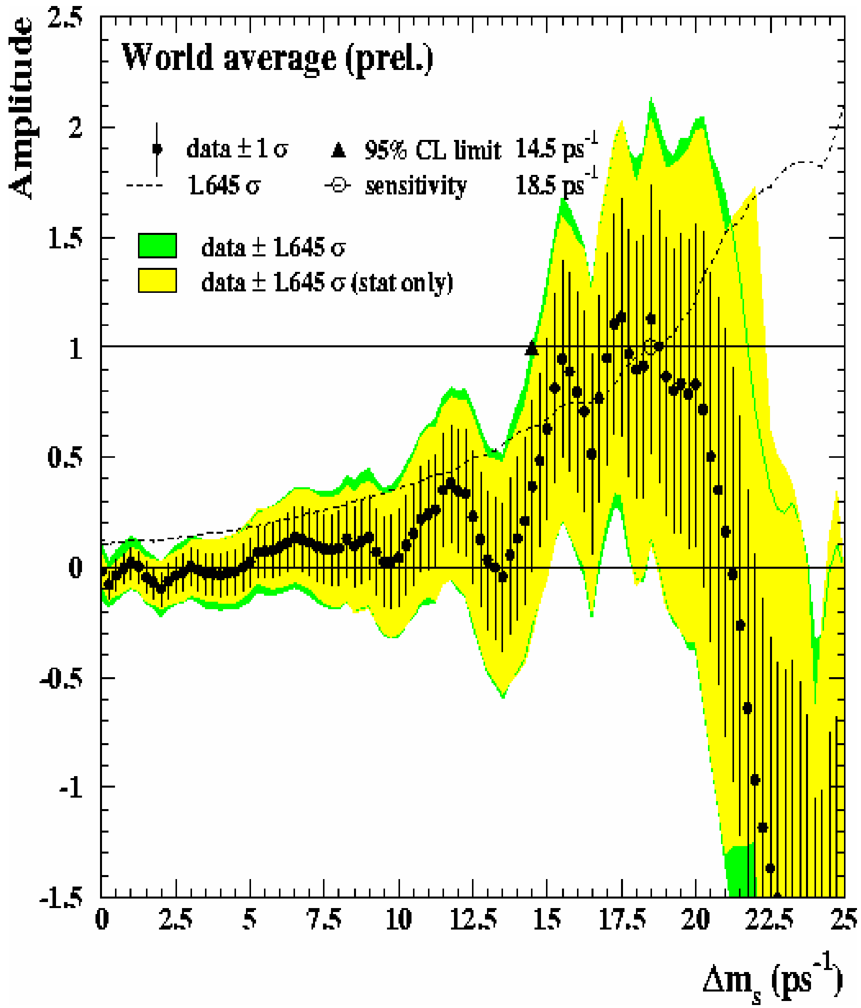
Amplitude fit method

- Fit to data - A free parameter

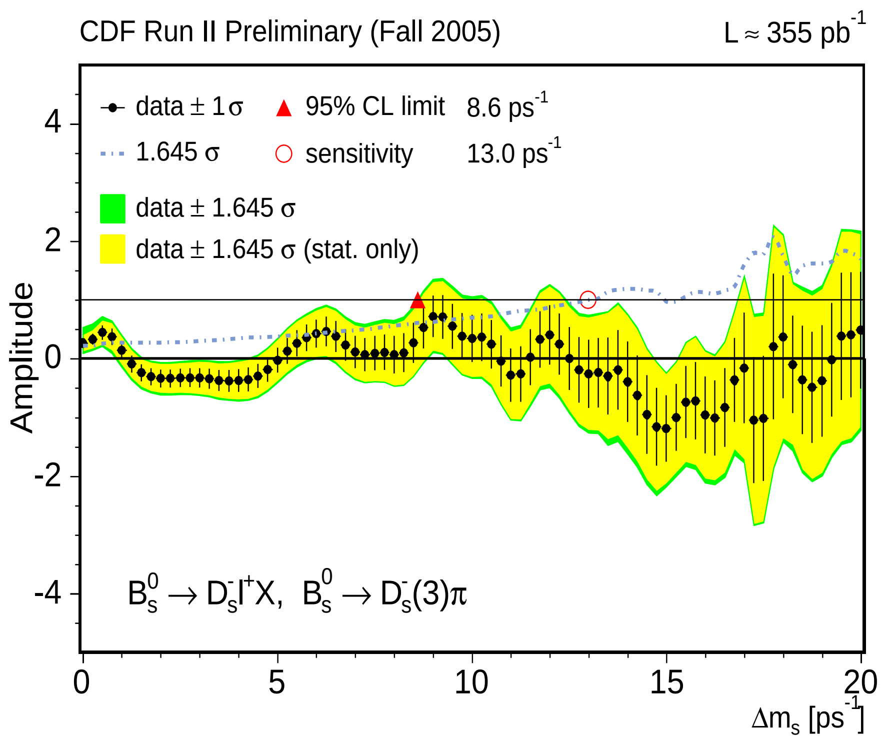
$$p = \frac{1}{2}\Gamma e^{-\Gamma t}[1 \pm A\cos(\Delta m_s t)]$$

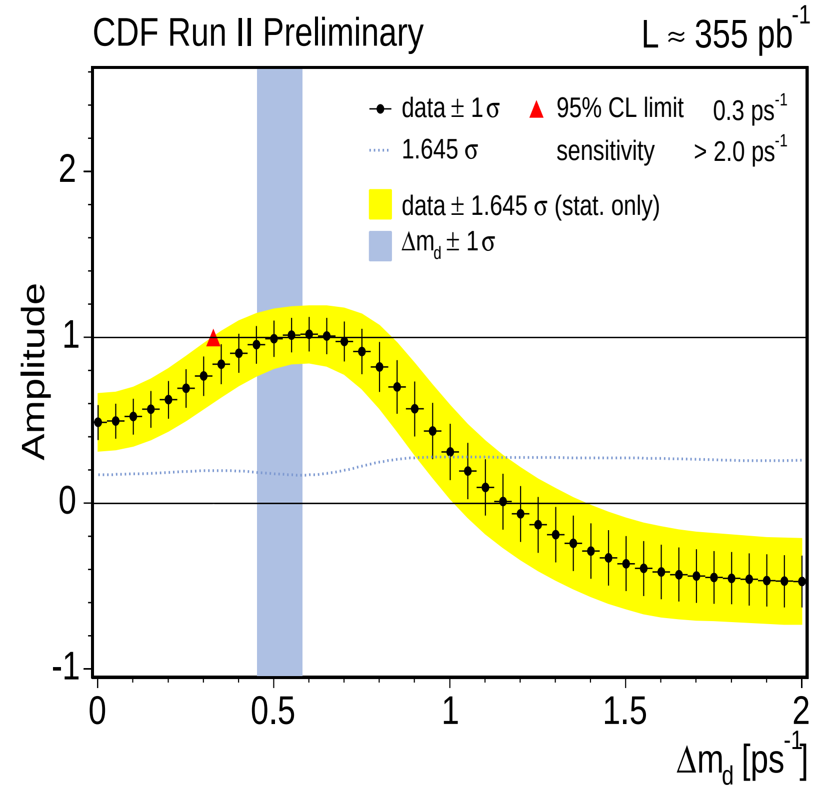
- Obtain A as a function of Δm_s
- Measurement of Δm_s gives $A = 1$ and $A = 0$ otherwise
- At 95% CL
- sensitivity $1.645\sigma_A = 1$
- excluded $A + 1.645\sigma_A < 1$
- Systematics is given by

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



Bs mixing limit

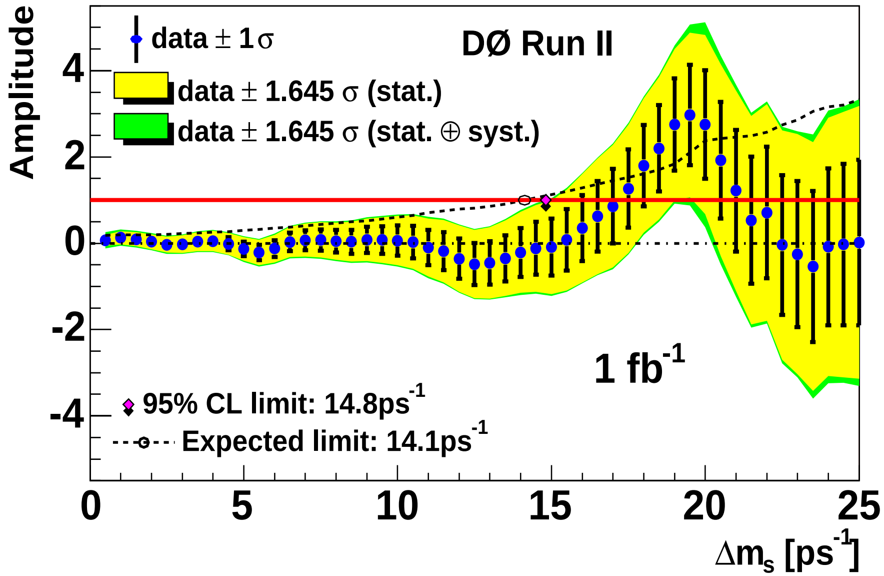


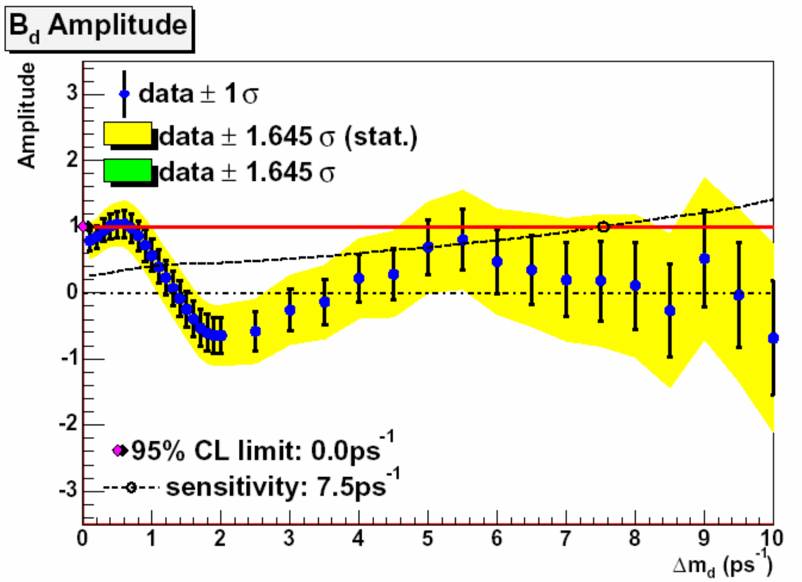


Limit: Δm_s > 8.6 ps^{-1} @ 95% confidence

Sensitivity: 13.0 ps^{-1} @ 95% confidence

Bs mixing limit





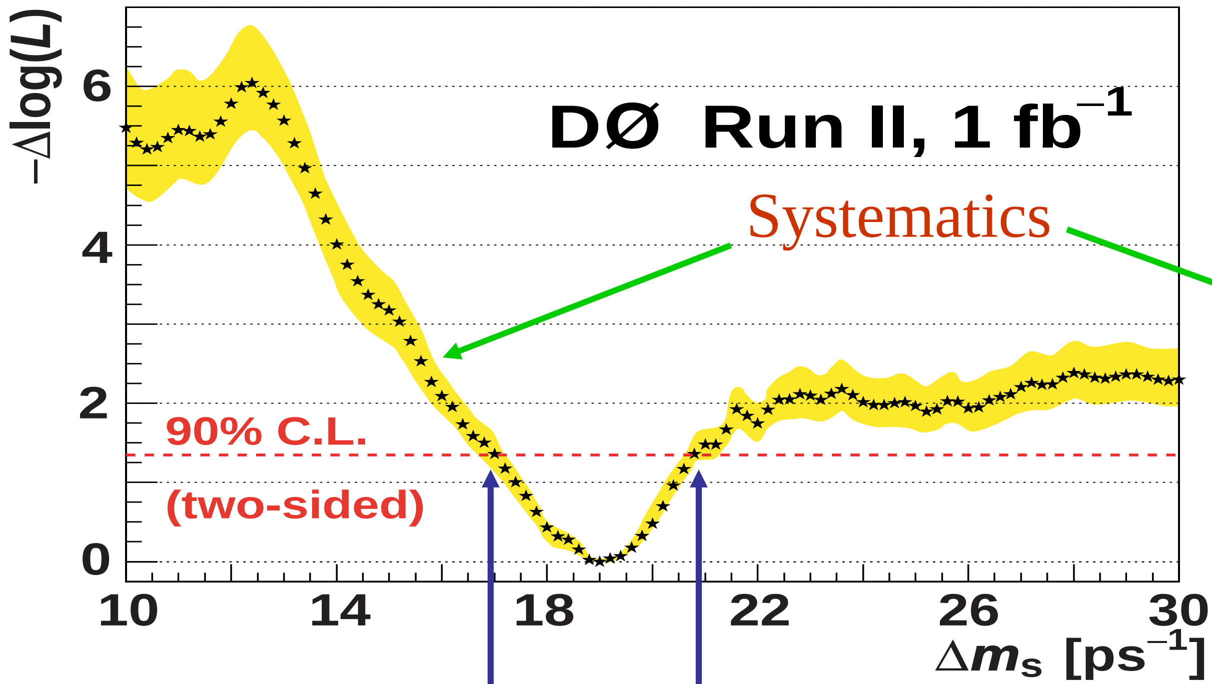
A clear deviation of 2.5 σ from 0 can be seen at Δm_s~19 ps^{-1}

Dominant sources of systematic uncertainty:
Scale factor, K factors and Sample composition

Limit: Δm_s > 14.8 ps^{-1} @ 95% confidence

Expected Limit: 14.1 ps^{-1} @ 95% confidence

Likelihood scan



- Resolution
- K-factor variation by 2%
- BR ($B_s \rightarrow \mu D_s X$)
- ccbar contamination
- BR ($B_s \rightarrow D_s D_s$)

$17 < \Delta m_s < 21\ ps^{-1}$ @ 90% CL

Most probable value of $\Delta m_s = 19\ ps^{-1}$

Significance Test

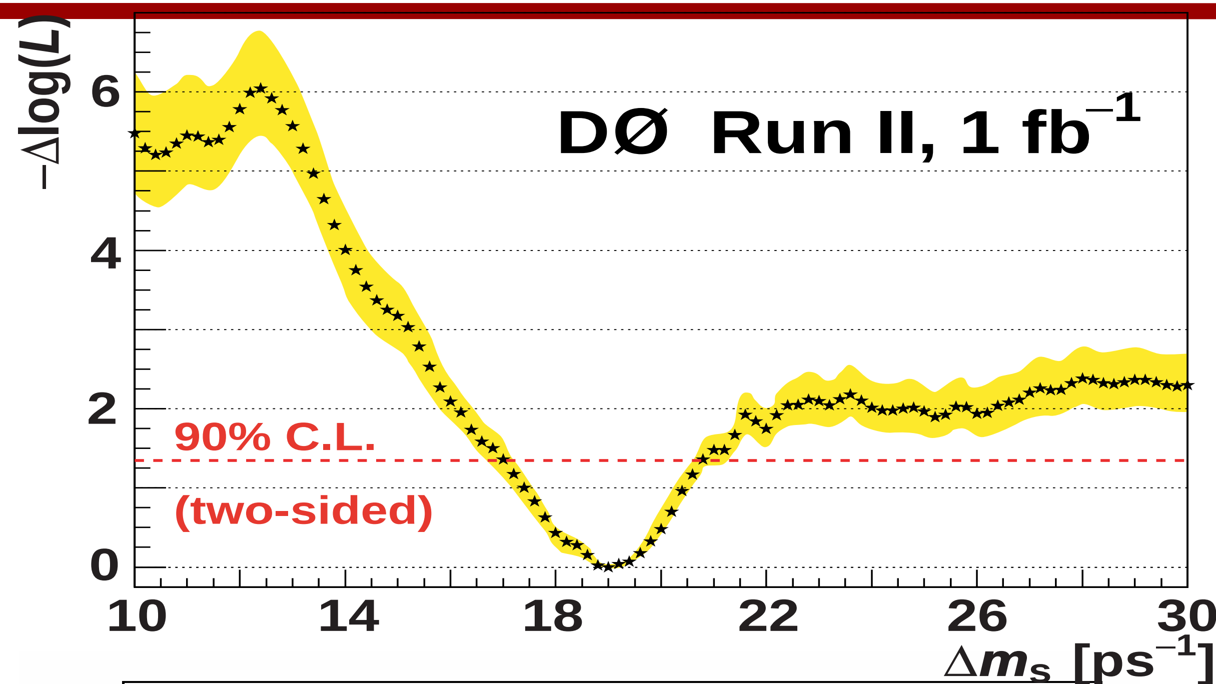
Probability for this measurement to lie in the range

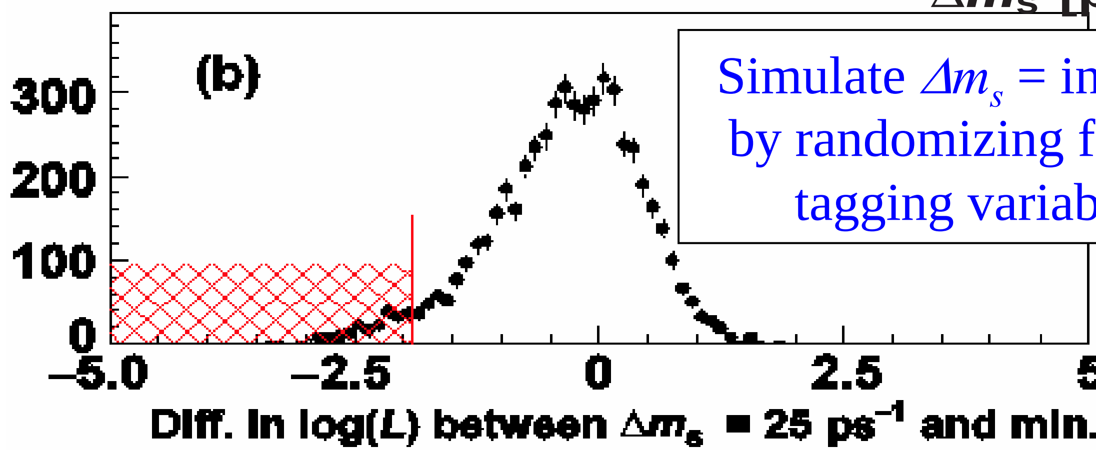
$16 < \Delta m_s < 22 ps^{-1}$

Given a true value:

$\Delta m_s > 22\ ps^{-1}$: 5.0%

$\Delta m_s = 19\ ps^{-1}$: 15%

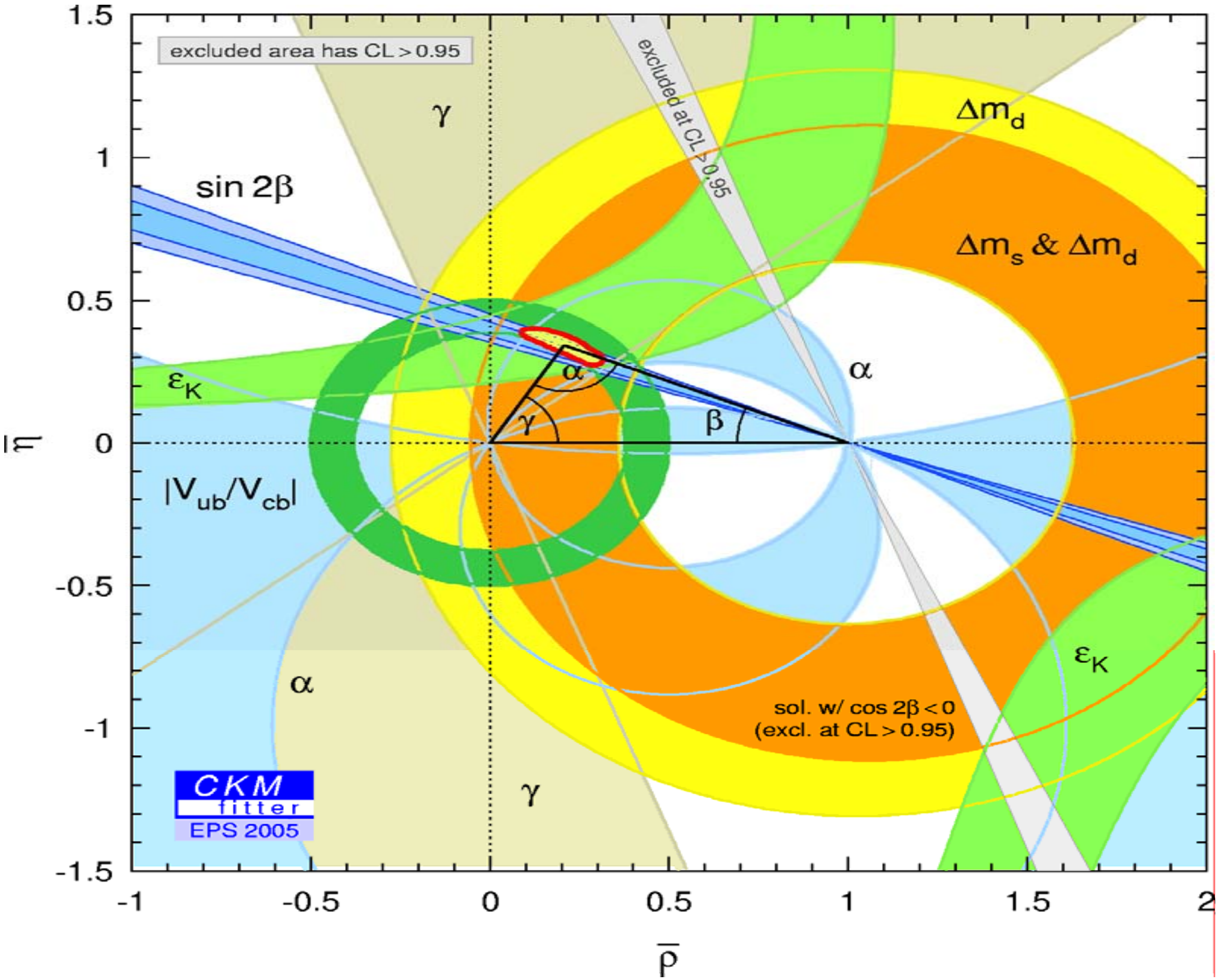




Simulate Δm_s = infinity by randomizing flavor tagging variable

Consistent results from parameterized MC studies

CKM fit without new D0 result



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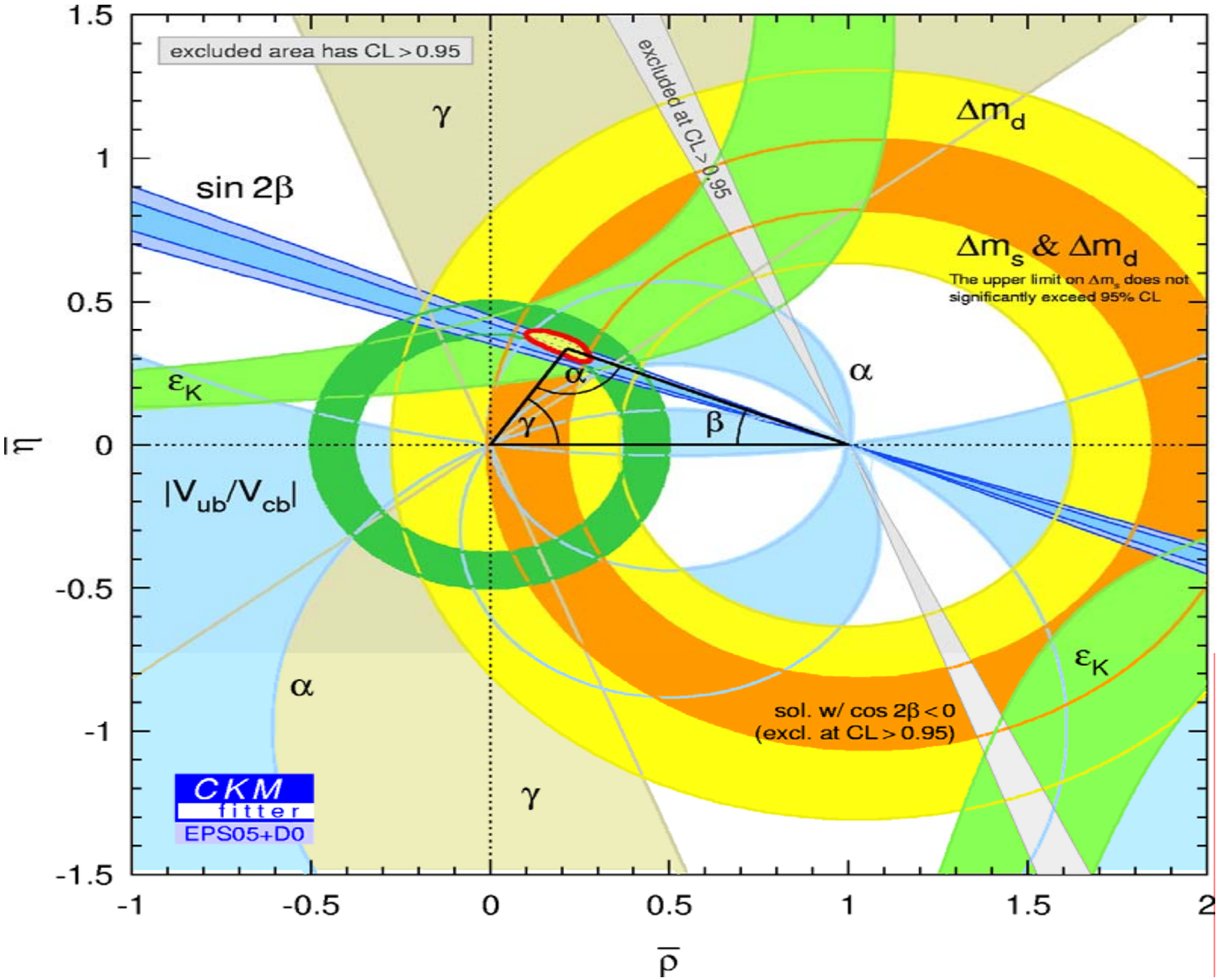
CKM fit with new D0 result



Disclaimer:

Produced only yesterday by CKM group so I don't have much information about the inputs.

CONCLUSIONS

- ✓ Excellent performance of the Tevatron.
- ✓ Development of Same Side Kaon Tagger which will ease the total tagging power by about 2.5 (CDF)
- ✓ D0 has excellent opposite side tagger performance.
- ✓CDF preliminary:

Limit: Δm_s > 8.6 ps^{-1} @ 95% confidence

Sensitivity: 13.0 ps^{-1} @ 95% confidence

- ✓ D0 Final (hep-ex/0603029, submitted to PRL):

Amplitude Scan	**Limit: Δm_s > 14.8 ps^{-1} @ 95% confidence** **Expected Limit: 14.1 ps^{-1} @ 95% confidence**
Likelihood scan	$17 < \Delta m_s <$ **21 ps^{-1} @ 90% CL** **Most probable value of Δm_s = 19 ps^{-1}**

- ✓We are on the edge of B_s mixing measurement and entering into the precision era.

FUTURE IMPROVEMENTS

Several major improvements are expected in the future:

CDF:

✓ Improved selection in hadronic modes using Neural Networks

✓ Use semileptonic events from other triggers.

✓ Improve vertex resolution.

✓ Use same side Kaon tagger.

D0:

✓ More decay modes ($D_s \to K^*K$, 3π, $K_s\pi$, $B_s \to e\, D_s\, X$)

✓ Use of same side tagging.

✓ Use of hadronic modes.

✓ Additional Layer of silicon.

✓ Proposal to increase the bandwidth.

More data: On track for 4-8 fb^{-1} of data by 2009.

- Back-up slides

Backup-1

Time evolution follows from a simple perturbative solution to the schrondinger's equation

$$i\frac{d}{dt}\begin{pmatrix} |B(t)> \\ |\bar{B}(t)> \end{pmatrix} = \begin{pmatrix} M_{11} - i\Gamma_{11} & M_{12} - i\Gamma_{12} \\ M_{21} - i\Gamma_{21} & M_{22} - i\Gamma_{22} \end{pmatrix} \begin{pmatrix} |B(t)> \\ |\bar{B}(t)> \end{pmatrix}$$

Eigenvalues are, $\boxed{\lambda_{H,L} = m_{H,L} - \frac{i}{2}\Gamma_{H,L}}$

In case $\Delta\Gamma \rightarrow 0$,

$$|B_L> = \frac{p+q}{2}\left[\left(|B> + |\bar{B}>\right) + \frac{1-q/p}{1+q/p}\left(|B> - |\bar{B}>\right)\right]$$

$$\boxed{\frac{1-q/p}{1+q/p} \equiv \varepsilon_B}$$

Measure of the amount by which $|B_L>$ and $|B_H>$ differ from CP eigenstates

Backup-2

In the limit of no CP violation in mixing (q/p =1), unmixed and mixed decay probabilities become

$$P_{u,m}(t) = \frac{1}{-}\Gamma\, e^{-\Gamma t}\left(1 \pm \cos \Delta m t\right)$$

These oscillations can be used to measure the fundamental parameters of the standard Model and have other far reaching effects such as breaking the matter anti-matter symmetry of the Universe.

Constraining the CKM matrix redundantly using different measurements of the angles/sides is a sensitive probe of New Physics

Backup-3

$$f_i = P_i^{x^M}(x^M, \sigma_{x^M}, d_{pr}) P_i^{\sigma_{x^M}} P_i^m P_i^{d_{pr}} P_i^y.$$

The following sources, i, were considered:

- $\mu^+ D_s^-(\rightarrow \phi\pi^-)$ signal with fraction $\mathcal{F}_{\mu D_s}$.
- $\mu^+ D^-(\rightarrow \phi\pi^-)$ signal with fraction $\mathcal{F}_{\mu D^\pm}$.
- $\mu^+ D^-(\rightarrow K\pi\pi^-)$ reflection with fraction $\mathcal{F}_{\mu D^\pm_{refl}}$
- Combinatorial background with fraction $(1 - \mathcal{F}_{\mu D_s} - \mathcal{F}_{\mu D^\pm} - \mathcal{F}_{\mu D^\pm_{refl}})$

$$F_n = \mathcal{F}_{\mu D_s} f_{\mu D_s} + \mathcal{F}_{\mu D^\pm} f_{\mu D^\pm} + \mathcal{F}_{\mu D^\pm_{refl}} f_{\mu D^\pm_{refl}}$$

$$+ \left(1 - \mathcal{F}_{\mu D_s} - \mathcal{F}_{\mu D^\pm} - \mathcal{F}_{\mu D^\pm_{refl}}\right) f_{bkg}$$

$$\mathcal{L} = -2 \sum_n \ln F_n$$

Backup-4

$$p_s^{nos}(x, K, d_{pr}) = \frac{K}{c\tau_{B_s}} \exp(-\frac{Kx}{c\tau_{B_s}}) \cdot 0.5 \cdot (1 + \mathcal{D}(d_{pr}) \cos(\Delta m_s \cdot Kx/c))$$

$$p_s^{osc}(x, K, d_{pr}) = \frac{K}{c\tau_{B_s}} \exp(-\frac{Kx}{c\tau_{B_s}}) \cdot 0.5 \cdot (1 - \mathcal{D}(d_{pr}) \cos(\Delta m_s \cdot Kx/c))$$

$$p_{DsDs}^{osc}(x, K) = \frac{K}{c\tau_{B_s^0}} \exp(-\frac{Kx}{c\tau_{B_s^0}}) \cdot 0.5$$

$$p_{DsDs}^{nos}(x, K) = \frac{K}{c\tau_{B_s^0}} \exp(-\frac{Kx}{c\tau_{B_s^0}}) \cdot 0.5$$

$$p_u^{nos}(x, K, d_{pr}) = \frac{K}{c\tau_{B+}} \exp(-\frac{Kx}{c\tau_{B+}}) \cdot 0.5 \cdot (1 - \mathcal{D}(d_{pr}))$$

$$p_u^{osc}(x, K, d_{pr}) = \frac{K}{c\tau_{B+}} \exp(-\frac{Kx}{c\tau_{B+}}) \cdot 0.5 \cdot (1 + \mathcal{D}(d_{pr}))$$

Backup-5

$$p_d^{nos}(x,K,d_{pr}) = \frac{K}{c\tau_{B_d^0}} \exp(-\frac{Kx}{c\tau_{B_d^0}}) \cdot 0.5 \cdot (1 - \mathcal{D}(d_{pr}) \cos(\Delta m_d \cdot Kx/c))$$

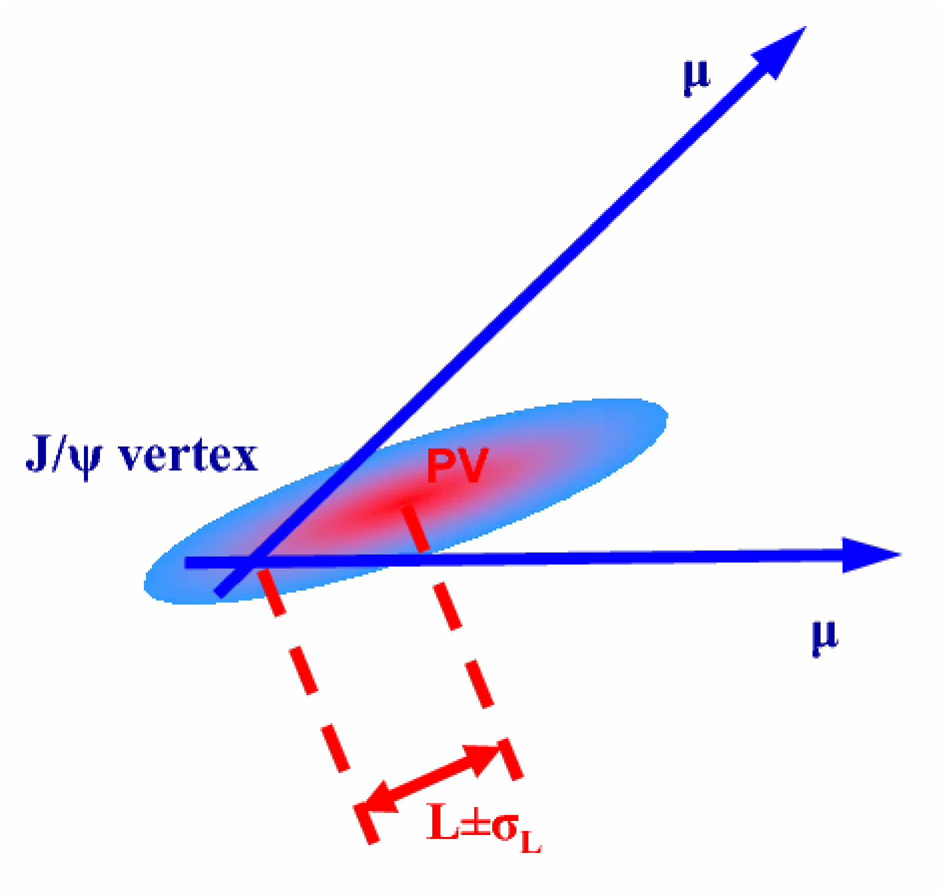
$$p_d^{osc}(x,K,d_{pr}) = \frac{K}{c\tau_{B_d^0}} \exp(-\frac{Kx}{c\tau_{B_d^0}}) \cdot 0.5 \cdot (1 + \mathcal{D}(d_{pr}) \cos(\Delta m_d \cdot Kx/c)).$$

Minimize $\mathcal{L} = -2 \ln f$

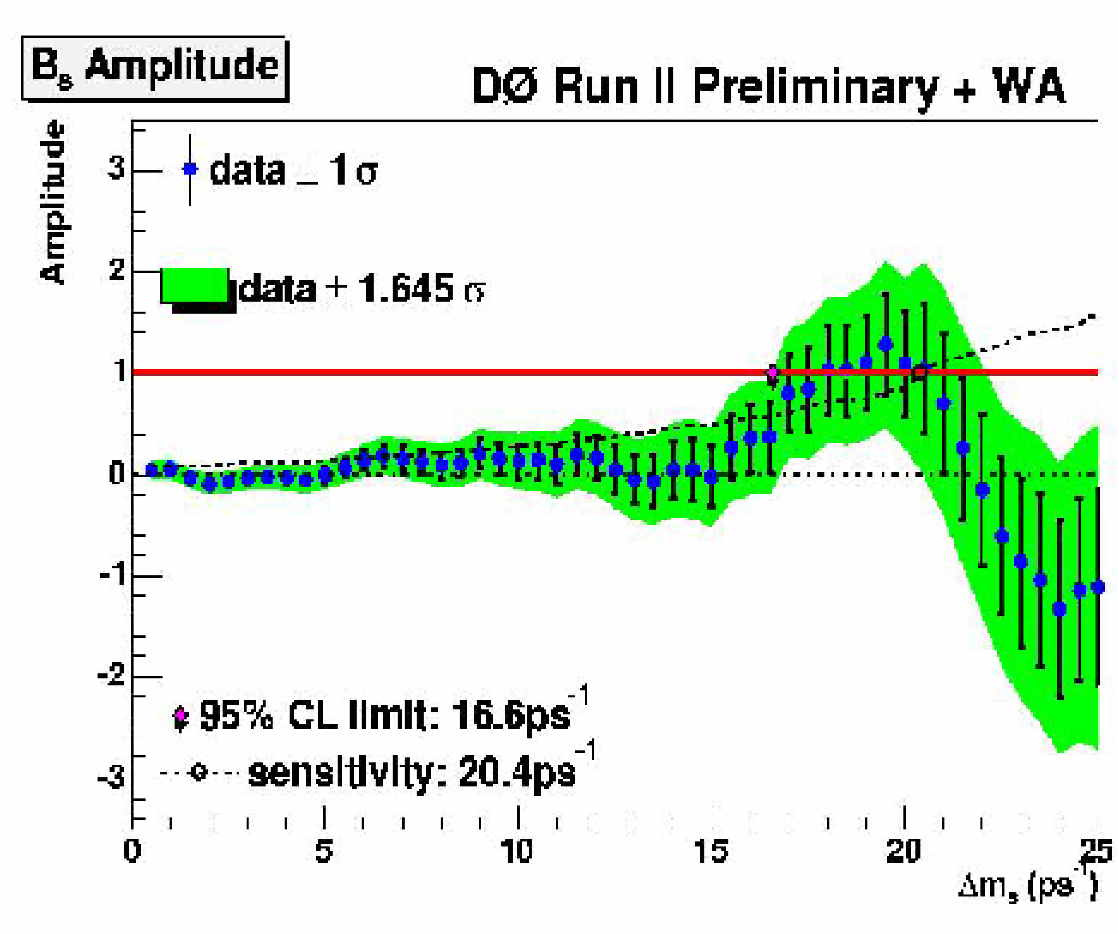
$$f = \prod_{candidates} \left(\left(1 - \mathcal{F}_{sig}\right) f_{i,bg} + \mathcal{F}_{sig} f_{i,sig} \right)$$

$$f_i = P^{VPDL}\left(VPDL, \sigma_{VPDL}, d_{pr}\right) P^{\sigma_{VPDL}} P^{d_{pr}} P^{M_{\phi\pi}} P^{-\log_{10} y}$$

Backup-6



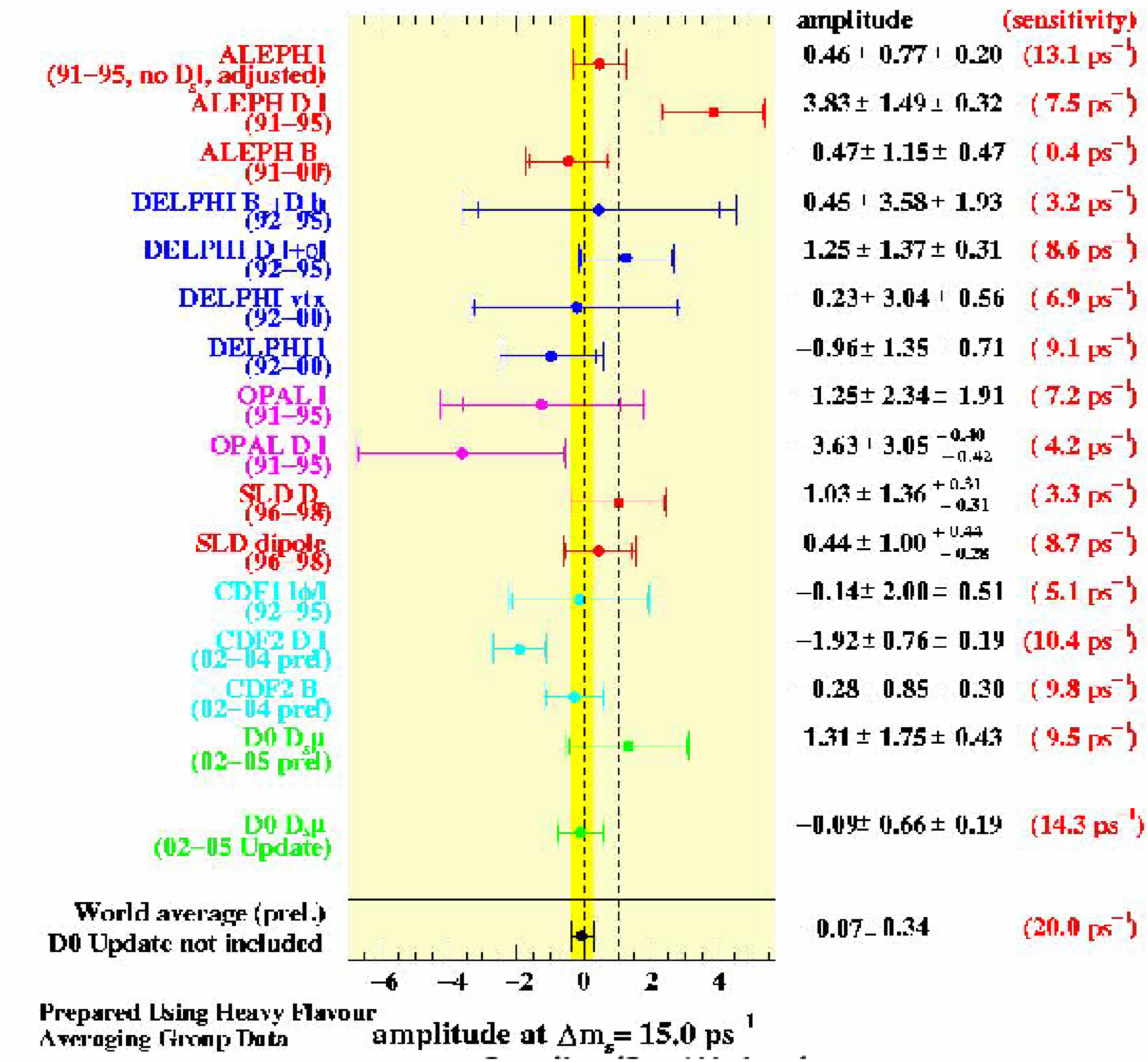
Backup-7



WA+CDF+D0

Backup-8

Comparison with other experiments at Δm_s=15 ps^{-1}



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