B_s Oscillations and Prospects for Δm_s at the Tevatron

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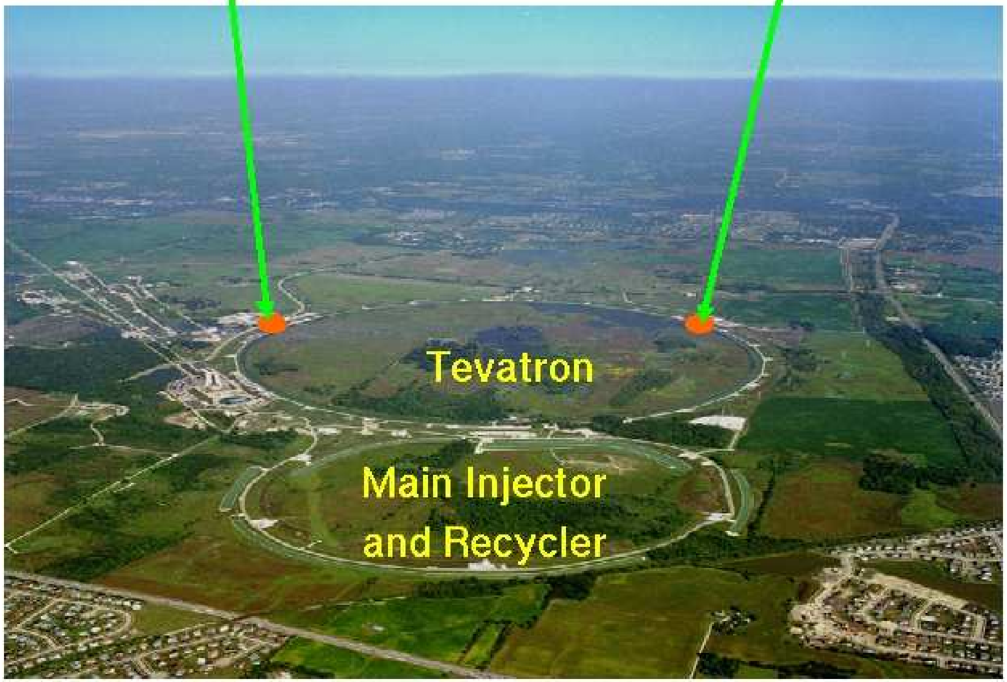
Tevatron



- Observe $p\bar{p}$ collisions with two detectors: CDF & D0
- First data taking period (Run I) 1992-1996
- Restarted data taking (Run II) in 2001 with major detector and accelerator upgrades

B-Physics at Hadron Colliders

- Large production rates

  $\sigma(p\bar{p} \to bX, |y| < 0.6) \approx 18\mu b$

  10^3 higher than at $\Upsilon(4S)$

- Heavy and excited B states currently uniquely at Tevatron:

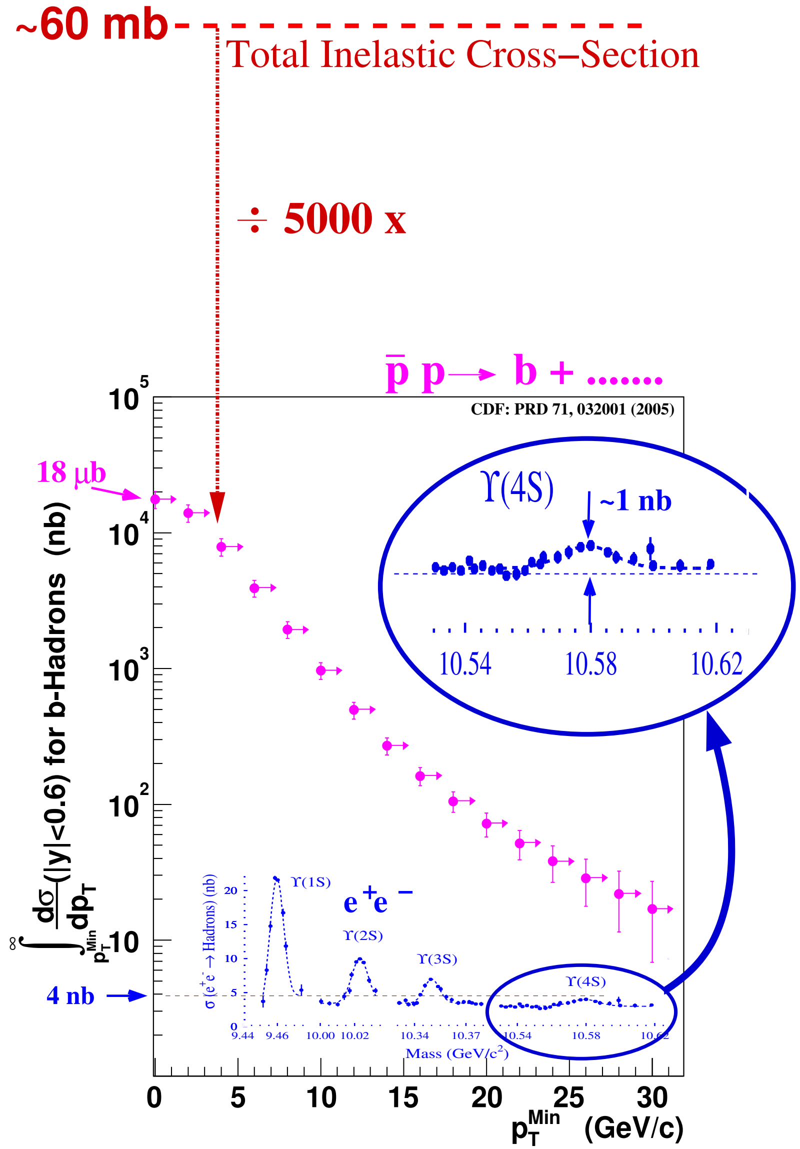
  $B_s, B_c, \Lambda_b, \Xi_b, B^{**}, B_s^{**}, ...$

- But QCD background is 10^3 higher than signal

  Triggers are critical.

- Event signature polluted by many fragmentation tracks;

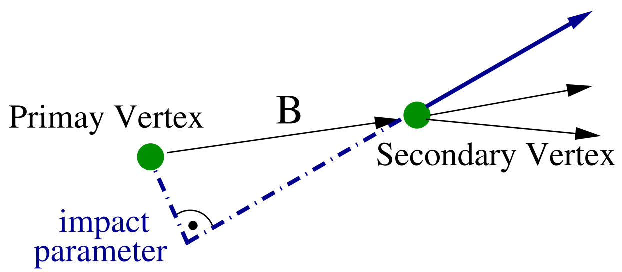
  High precision vertex tracker + dedicated reconstruction algorithms needed

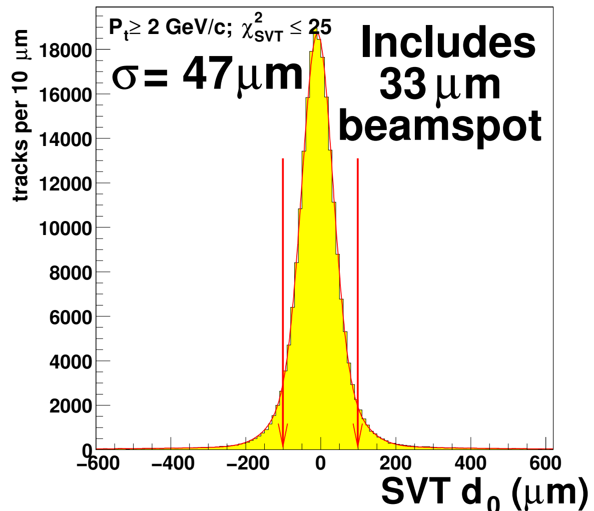


B-Triggers

Trigger signatures: lepton (e, μ) and displaced tracks

- B decays to $J/\Psi \to \mu^+\mu^-$ $\Rightarrow$ Di-Muon Trigger (CDF+D0)
  - + muon provides easy trigger
  - – small branching fraction
- Semi-leptonic B decays $\Rightarrow$ Lepton Trigger (D0), + Displaced Track (CDF)
  - + large branching rations ($\approx$ 20%)
  - – missing neutrino
- Fully hadronic B decays $\Rightarrow$ Two Track Trigger (CDF)
  - + $\approx$ 80% of branching fraction
  - – requires displaced track trigger



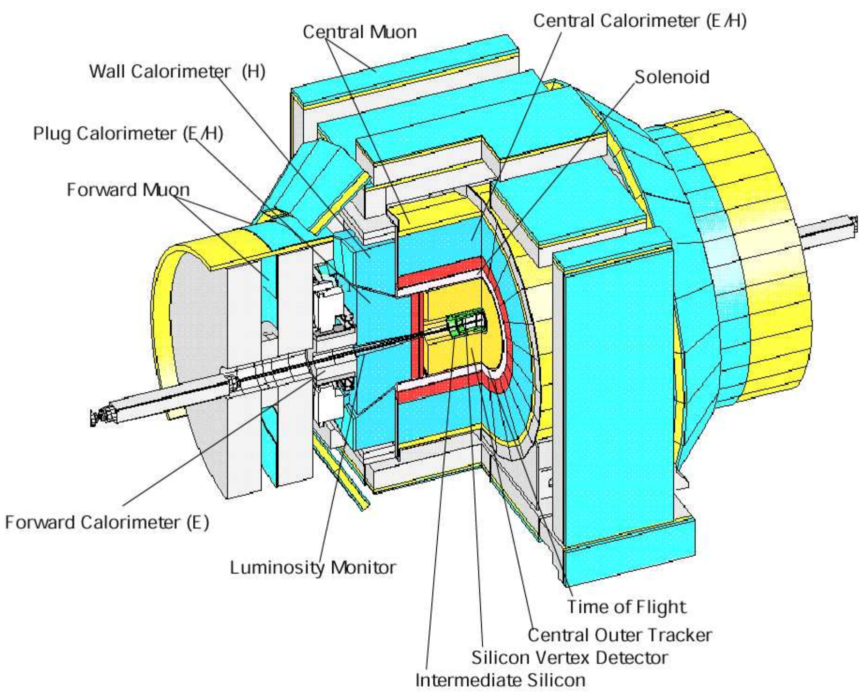


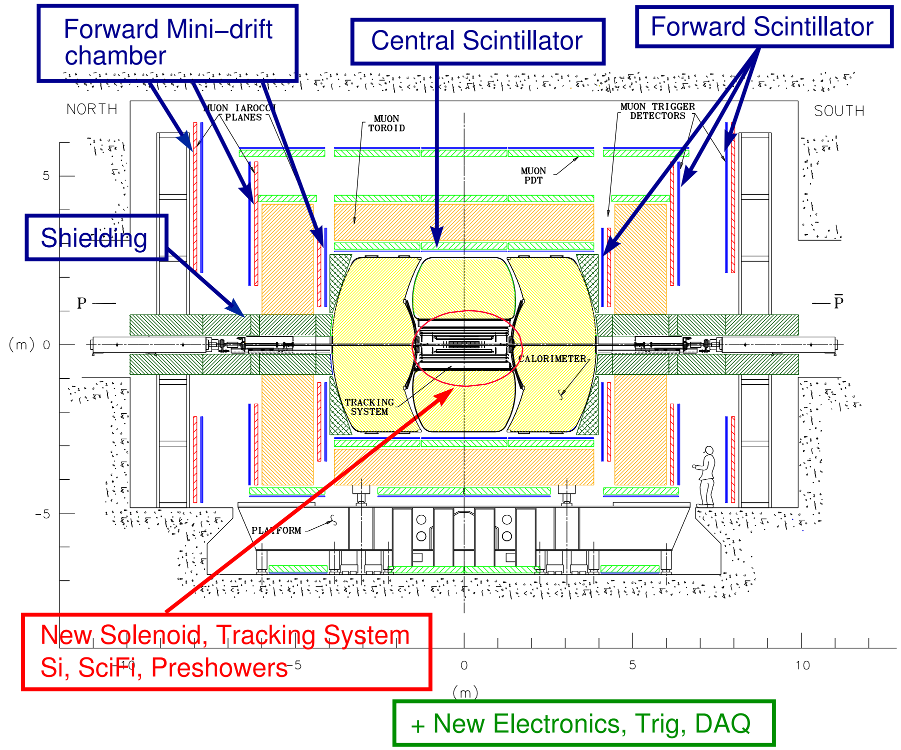
CDF versus D0 Detector

CDF

- Displaced track trigger
- PID: TOF and dE/dx
- Excellent mass resolution

Strong in fully hadronic modes





D0

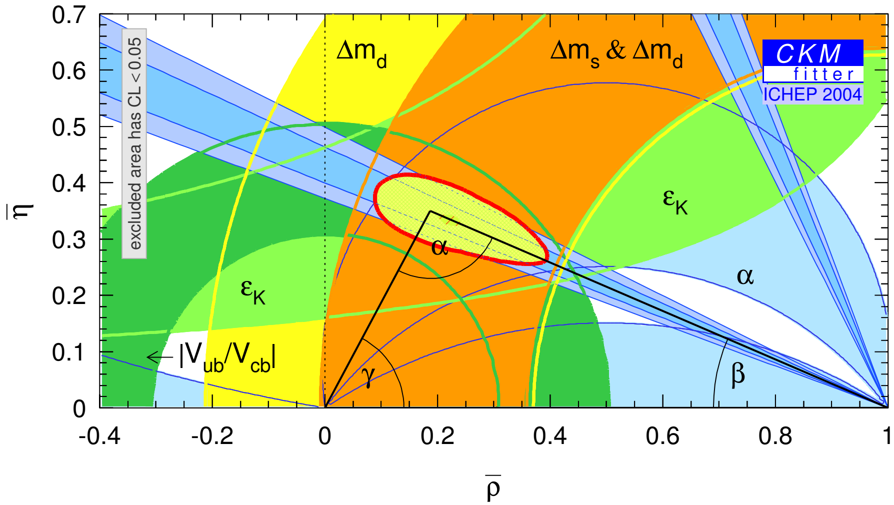
- Large muon coverage
- Very good forward tracking

Strong in J/ψ modes

Strong in semileptonic modes

Δm_s Measurements

- So far $V_{td}V_{tb}^*$ measured via Δm_d, suffers from large theoretical uncertainties, but $\Delta m_d/\Delta m_s$ related to CKM elements with 5% uncertainty only
- Δm_s required for measuring time dependent CPV in B_s system ($\rightarrow \gamma$)
- New physics may affect $\Delta m_s/\Delta m_d$



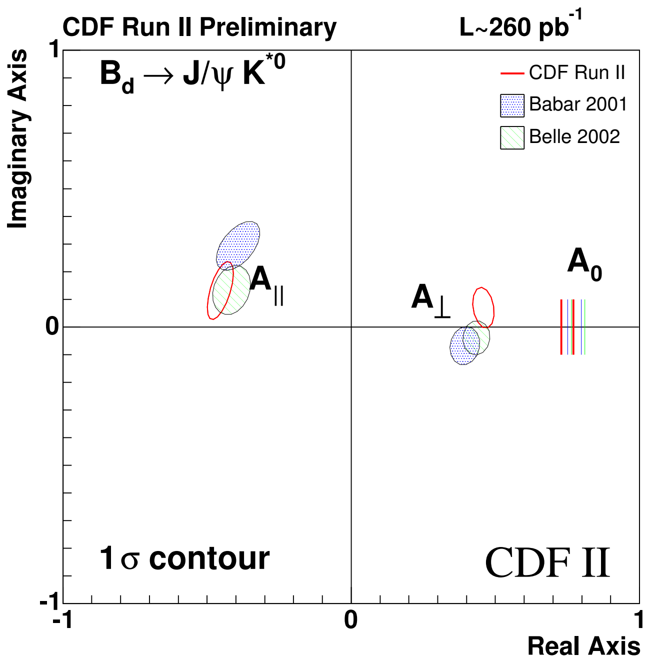
B_s, uniquely available at Tevatron, provide 2 independent handles on Δm_s.

- Measuring B_s oscillation frequency: $\mathcal{A}_{mix}(t) \sim \mathcal{D} * cos(\Delta m_s t)$
- Measuring decay width difference $\Delta\Gamma_s$, clean relation with Δm_s (in SM):

$$\frac{\Delta m_s}{\Delta\Gamma_s} \approx \frac{2}{3\pi}\frac{m_t^2}{m_b^2}\left(1 - \frac{8}{3}\frac{m_c^2}{m_b^2}\right)^{-1} h\left(\frac{m_t^2}{M_W^2}\right)$$

$\Delta\Gamma_s$: Polarization Amplitudes

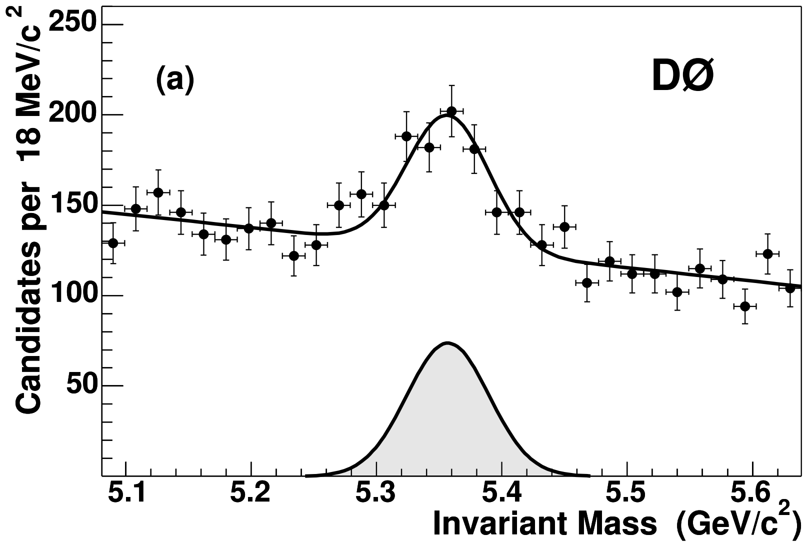
- In B_s system CP violation is small ($\delta\Phi_s \approx 0$)
  $\Rightarrow B_{s,light}$ = CP even
  $\Rightarrow B_{s,heavy}$ = CP odd
- Generally final states mixture of CP even and odd states but for Pseudoscalar $\rightarrow$ VV, we can disentangle them.
  Has been already done for $B_d \rightarrow J/\psi K^{*0}$, apply same analysis now to $B_s \rightarrow J/\psi\phi$:

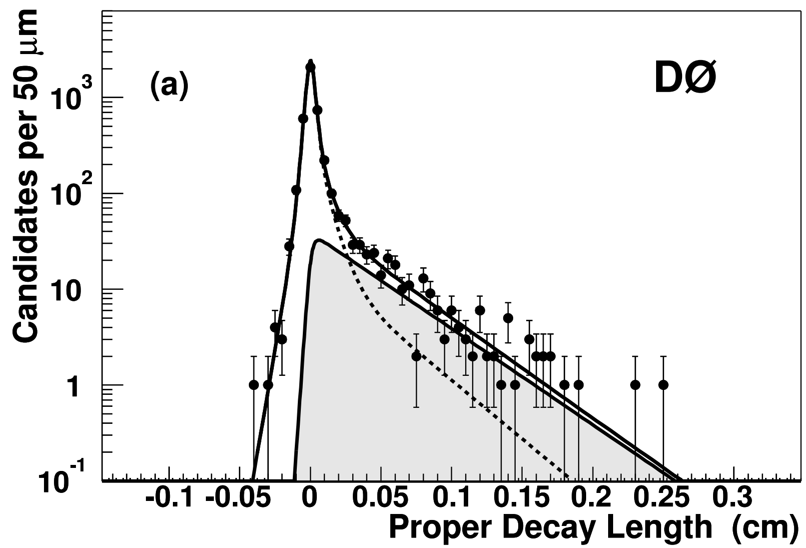


- Decay amplitudes decompose into 3 linear polarization states
  $|A_0|^2 + |A_{||}|^2 + |A_{\perp}|^2$=1
  - $A_0, A_{||}$ = S+D wave $\Rightarrow$ CP even
  - $A_{\perp}$ = P wave $\Rightarrow$ CP odd
- Together with lifetime measurement, angular analysis can separate heavy and light mass eigenstates and determine $\Delta\Gamma_s \rightarrow \Delta m_s$

Mass and Lifetime Projections

First have to reconstruct events, measure mass and lifetime:





hep-ex/0409043

Relative average lifetime of $B_s \rightarrow J/\psi\phi$ with respect to topological similar mode $B_d \rightarrow J/\psi K^*$:

$$\tau_s/\tau_d = 0.980^{+0.075}_{-0.070}\ \text{(stat)} \pm 0.003\ \text{(syst)}\ \text{(D0)}$$

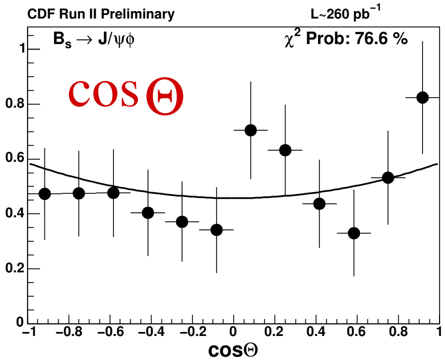
$$\tau_s/\tau_d = 0.890 \pm 0.072\ \text{(total)}\ \text{(CDF)}$$

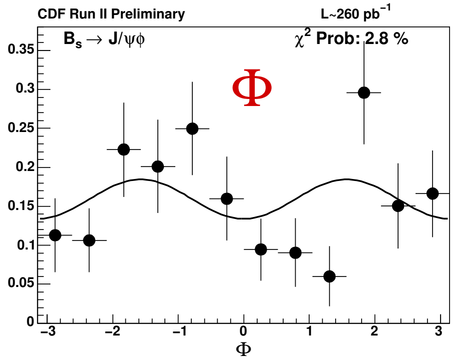
Angular Distributions

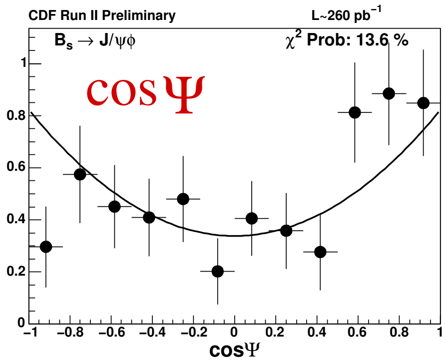
CDF - Results

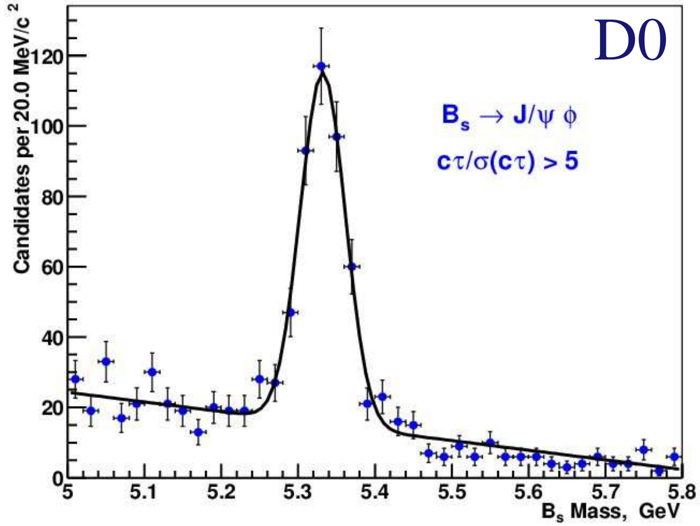
Then fit for angular distribution in transversity* frame:

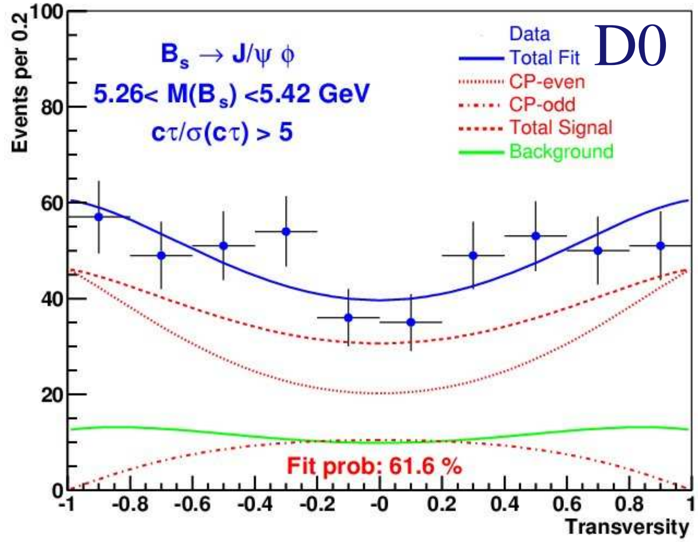
$$B_s \to J/\psi\phi$$











* See definition of transversity angles in backup slides

Angular Amplitudes: Results

$A_{\|} = (0.473 \pm 0.034 \pm 0.006)e^{(2.86\pm0.22\pm0.07)i}$

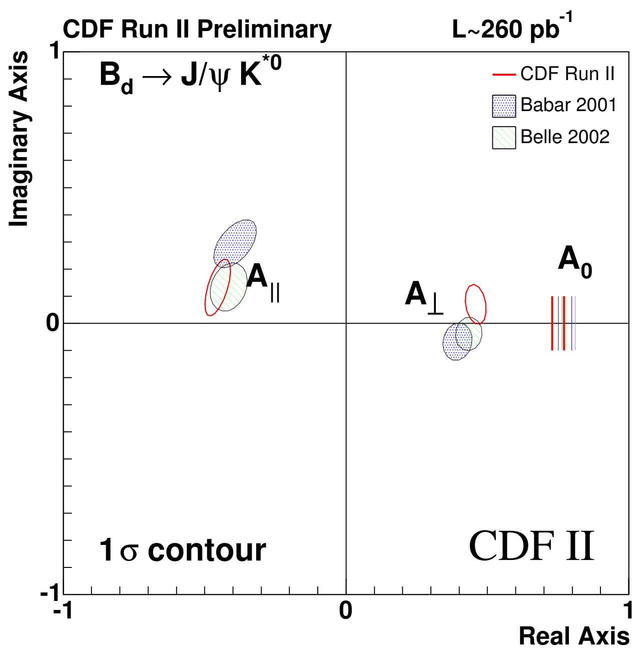
$A_{\perp} = (0.464 \pm 0.035 \pm 0.007)e^{(0.15\pm0.15\pm0.06)i}$

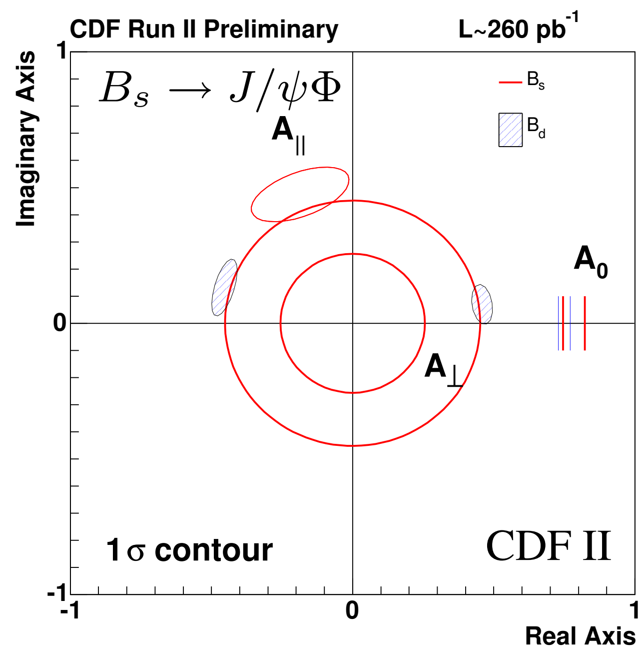
$A_0 = 0.750 \pm 0.017 \pm 0.012$

Cross check:

$B_d \to J/\psi K^{*0}$

B_d amplitude compare well with BABAR/BELLE





CDF - Results

$B_s \to J/\psi\phi$

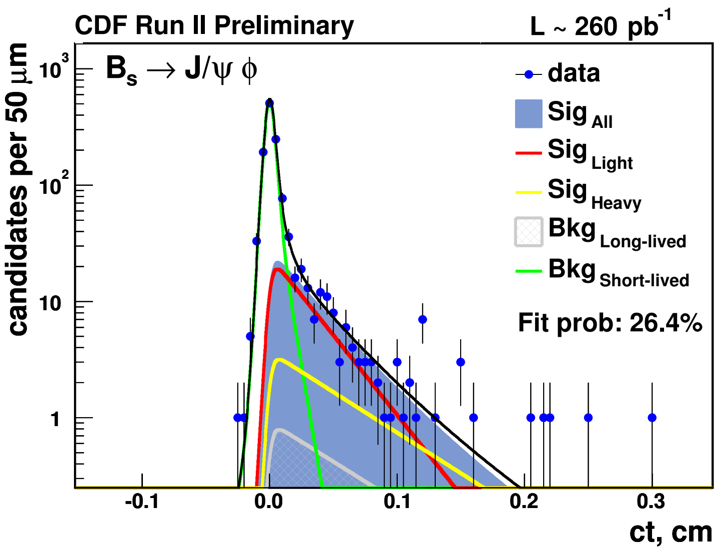
$A_{\|} = (0.510 \pm 0.082 \pm 0.013)e^{(1.94\pm0.36\pm0.03)i}$

$|A_{\perp}| = 0.354 \pm 0.098 \pm 0.003$

$A_0 = 0.784 \pm 0.039 \pm 0.007$

$\Delta\Gamma_s$: Results

CDF II: hep-ex/0412057



$$\tau_L = 1.05^{+0.16}_{-0.13} \pm 0.02 \text{ ps}$$

$$\tau_H = 2.07^{+0.58}_{-0.40} \pm 0.03 \text{ ps}$$

$$\Delta\Gamma_s/\Gamma_s = 0.65^{+0.25}_{-0.33} \pm 0.01$$

$$\Delta\Gamma_s = 0.47^{+0.19}_{-0.24} \pm 0.01 \text{ ps}^{-1}$$

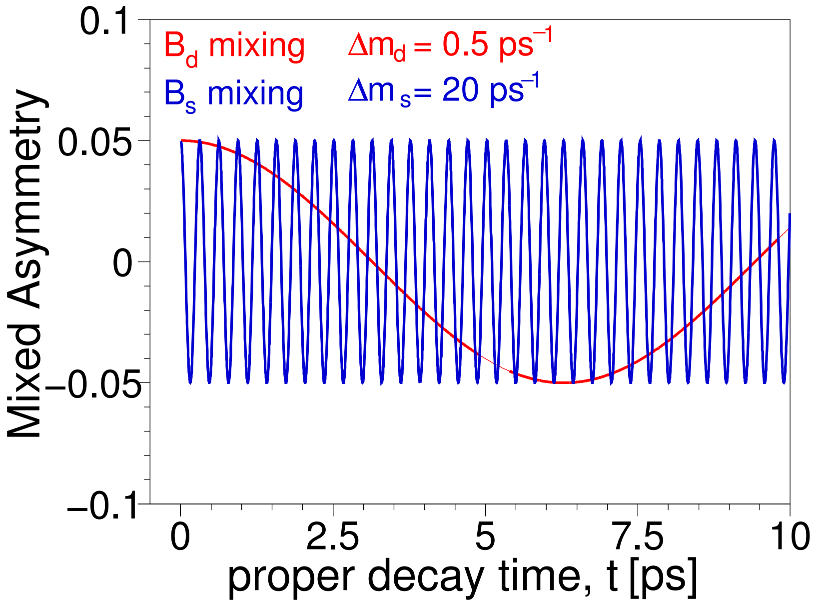
$$\tau_{PDG} = 1.461 \pm 0.057 \text{ ps}$$

- With $\approx$ 200 signal events CDF finds a large value for the lifetime difference, $\approx 2.5\ \sigma$ away from $\Delta\Gamma_s = 0$
- About 2σ away from $\Delta\Gamma_s/\Gamma_s = 0.12$ (SM).
- $\Delta\Gamma_s$ results in $\Delta m_s = 125^{+65}_{-55}$ ps
- New Physics - or just fluctuation?
- Tiny systematics! more data $\rightarrow$ beautiful measurement
- Waiting for D0 result, soon to be released publicly

Towards B_s Mixing

Why is it so difficult?

B_s mixing is very fast!



In order to measure:

$$\mathcal{A}_{mix}(t) = \frac{N_{unmix}(t) - N_{mix}(t)}{N_{unmix}(t) + N_{mix}(t)}$$
$$= \mathcal{D} * cos(\Delta m_s t)$$

We need to:

- Reconstruct B_s signal
  - hadronic modes: good p_T resolution but fewer events
  - semileptonic modes: high statistics, poor p_T ($\rightarrow c\tau$) resolution
- Tag the production flavor: tagging power ϵD^2

  Efficiency: $\epsilon = \frac{N_{wrong}+N_{right}}{N}$

  Dilution: $\mathcal{D} = 1 - 2\frac{N_{wrong}}{N_{wrong}+N_{right}}$

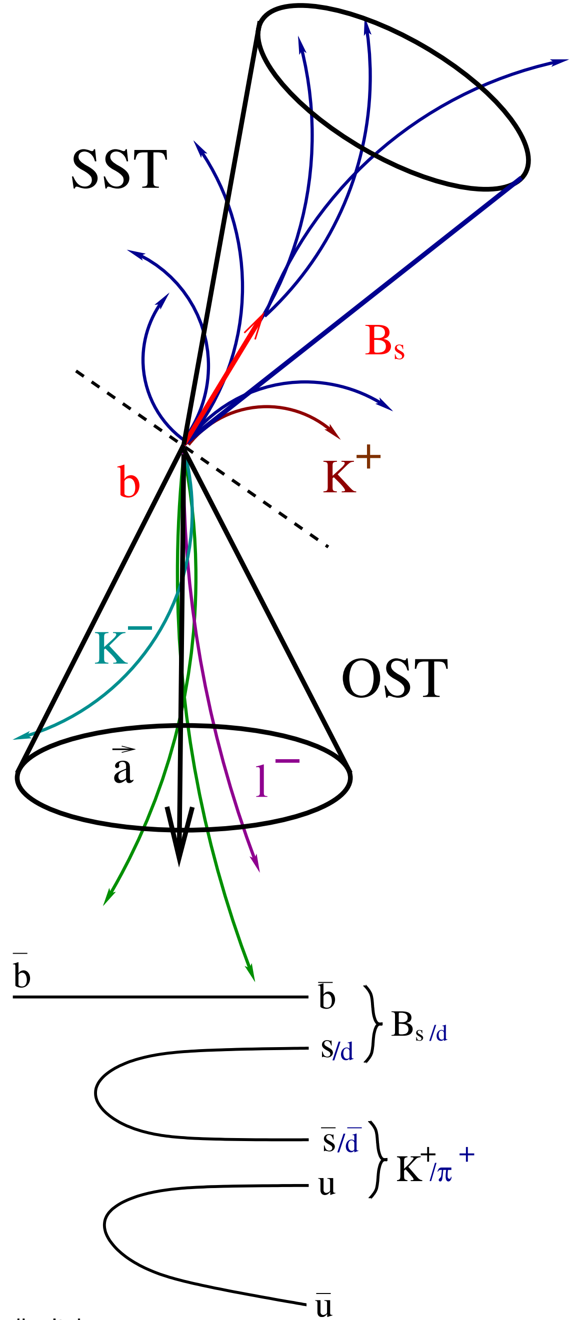
B Flavor Tagging

Opposite Side Tagging:

- Jet-Charge-Tagging:
  sign of the weighted average charge of opposite B-Jet
- Soft-Lepton-Tagging:
  identify soft lepton (e, μ) from semileptonic decay of opposite B: $b \to l^- X$ (BR $\approx 20\%$),
  Dilution due to $\bar{b} \to \bar{c} \to l^- X$ and oscillation
- Kaon-Tagging:
  due to b→c→s it is more likely that a $\bar{B}$ meson contains a K^- than a K^+ in the final state (particle ID)

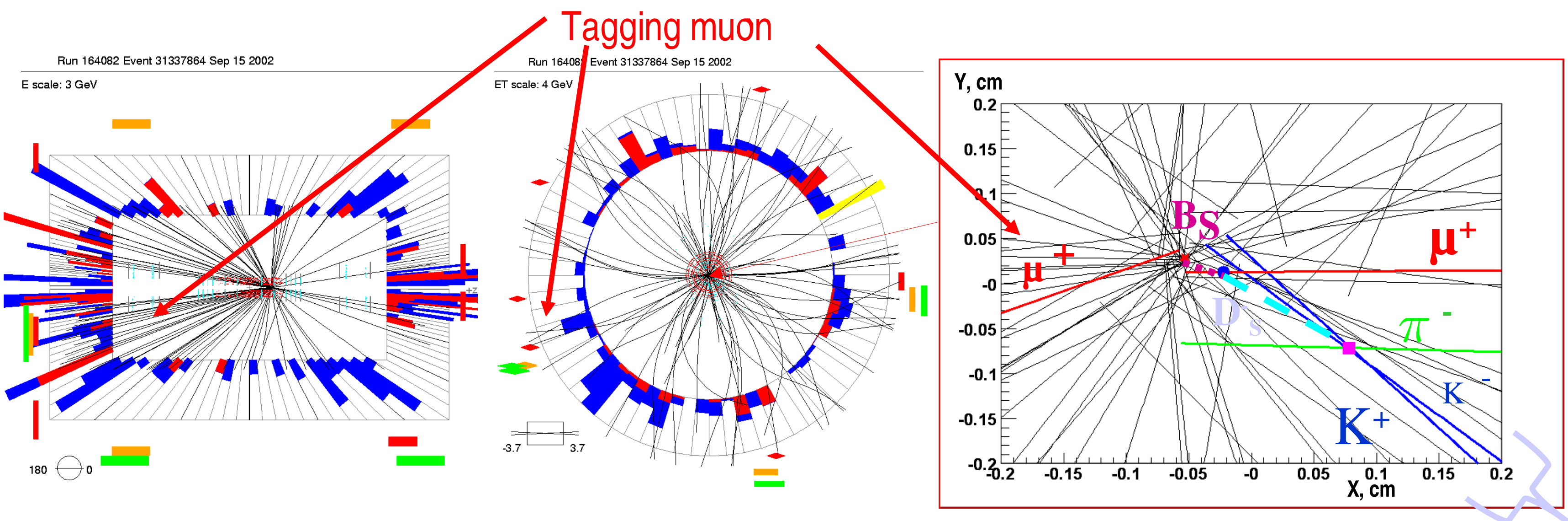
Same Side Tagging:

- $B_{s/d}$ is likely to be accompanied close by a K^+/π^+ (particle ID)



Example of Tagged B_s Candidate

- Two same sign muons are detected: $B_s \rightarrow D_s \mu X, (D_s \rightarrow \phi(KK)\pi)$
- $M_{KK} = 1.019$ GeV, $M_{KK\pi} = 1.94$ GeV
- $p_T(\mu_{B_s}) = 3.4$ GeV, $p_T(\mu_{tag}) = 3.5$ GeV



About half of the B_s detected, have same flavor at production and decay.

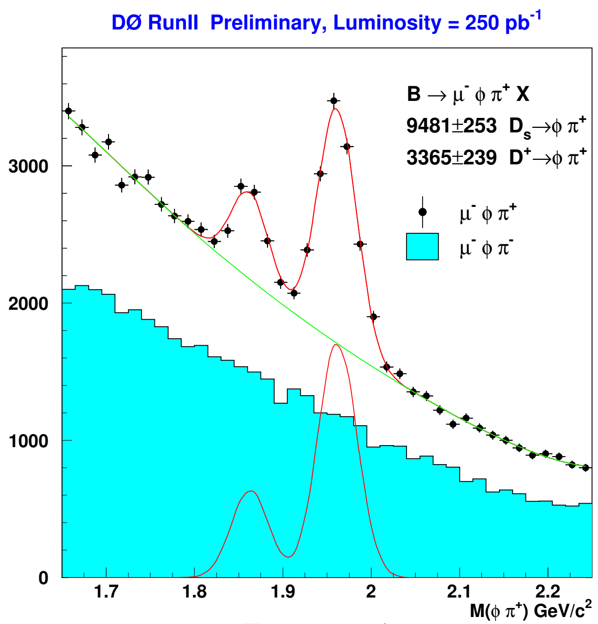
Reconstructed B_s Candidates

D0 exploits high statistics muon trigger

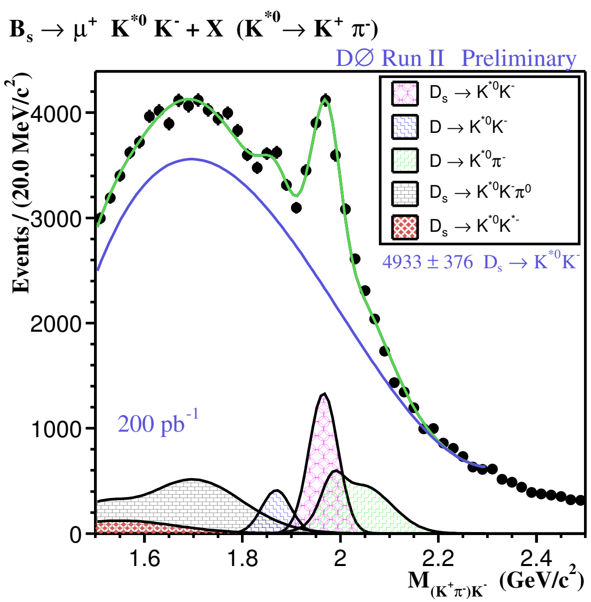
semileptonic decays: worse proper time resolution, but high statistics

$c\tau = \frac{L_{xy}}{\gamma\beta}$; $\gamma\beta = \frac{p_T(B)}{M(B)} = \frac{p_T(\ell D)}{M(B)} * K$ (K from MC);

$\sigma_{c\tau} = (\frac{\sigma_{L_{xy}}}{\gamma\beta}) \oplus (\frac{\sigma_{\gamma\beta}}{\gamma\beta}) * c\tau$



$D_s \rightarrow \phi\pi$



$D_s \rightarrow K^*K(K^* \rightarrow K\pi)$

D0 uses trigger muon in combination with other flavor tagging variables

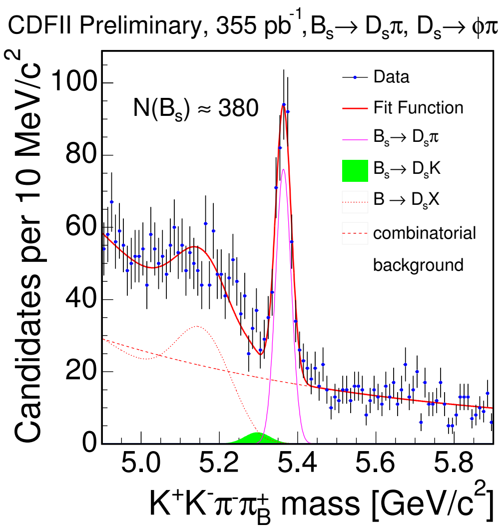
→ fully reconstructed decays.

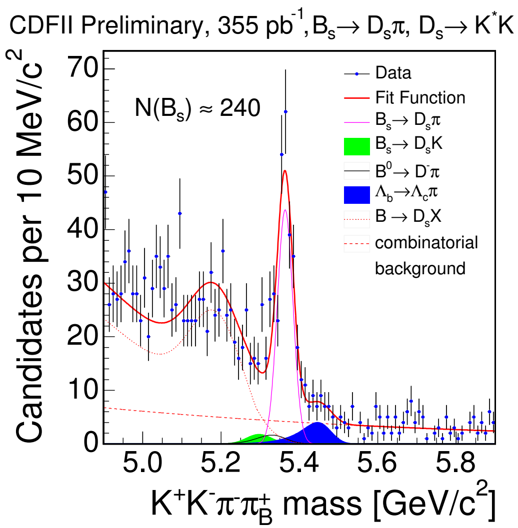
Reconstructed B_s Candidates

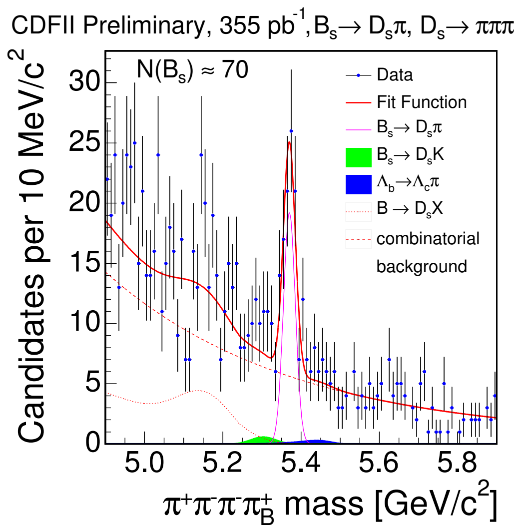
CDF uses hadronic modes: $B_s \to D_s\pi$

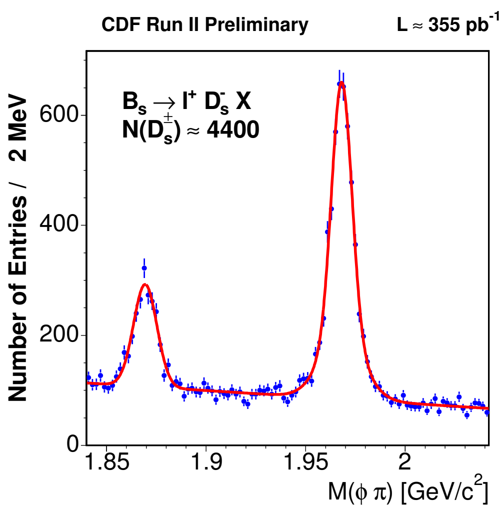
& semileptonic modes: $B_s \to \ell D_s X$

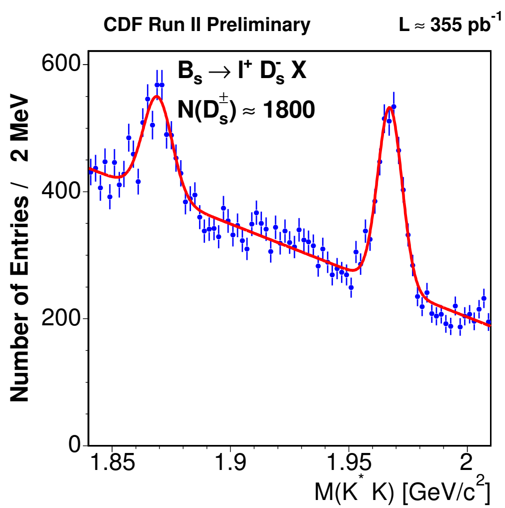
where $D_s \to \Phi\pi, K^*K, 3\pi$

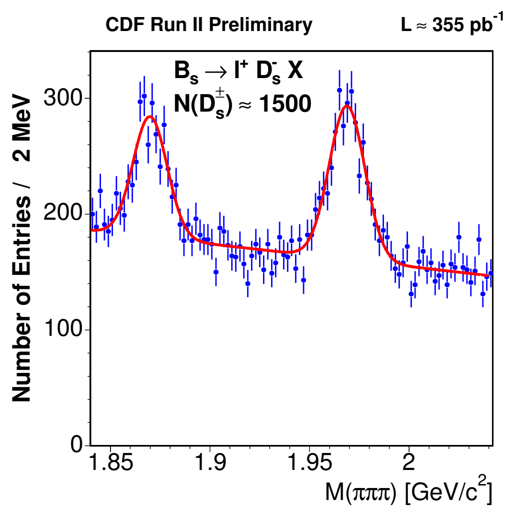








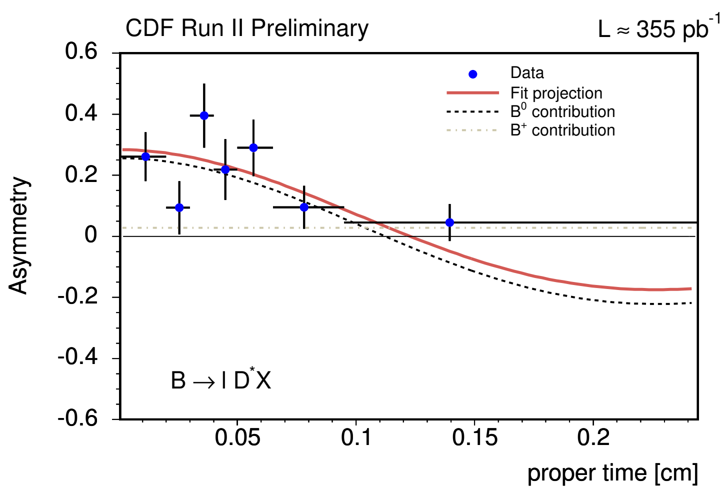




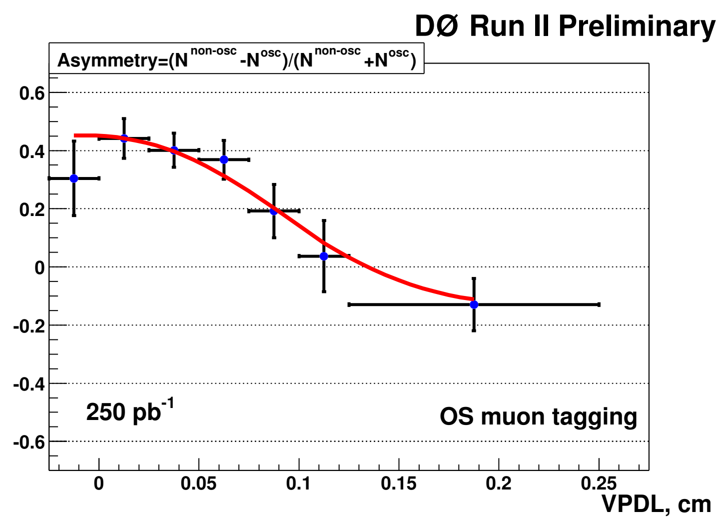
Proof of Principle: B_d Mixing

- For setting limit on Δm_s, knowledge of tagger performance is crucial
  $\rightarrow$ measure tagging dilution in kinematically similar B^0/B^+ samples
- Δm_d and Δm_s fit is very complex, up to 500 parameters
  - combining several B flavor and several decay modes
  - combining several taggers
  - mass and lifetime templates for various backgrounds

  Δm_d measurement is very important to test the fitter



CDF: Soft Muon Tagger



D0: Soft Muon Tagger

Δm_d Measurement

Combined taggers (semileptonic channels) D0 (250pb $^{-1}$):

$\Delta m_d = 0.456 \pm 0.034$(stat)$\pm 0.025$(syst) ps^{-1}

Combined opposite side taggers (semileptonic channels) CDF (355 pb^{-1}):

$\Delta m_d = 0.497 \pm 0.028$(stat) ± 0.015(sys) ps^{-1}; total ϵD^2 : 1.43 ± 0.09 %

Combined opposite side taggers (hadronic channels) CDF (355 pb^{-1}):

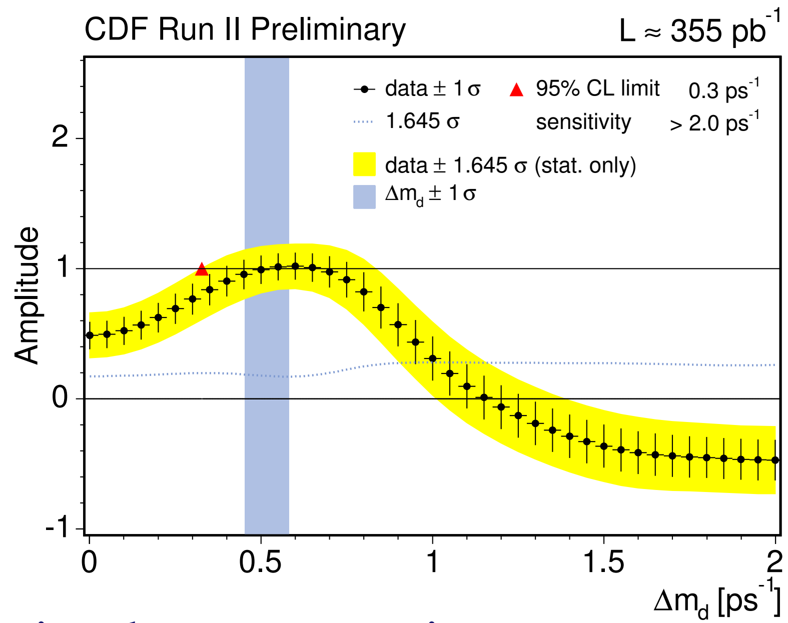
$\Delta m_d = 0.503 \pm 0.063$(stat)$\pm 0.015$(sys) ps^{-1}; total ϵD^2 : 1.12 ± 0.18 %

$\epsilon D^2 (\%)$	CDF semileptonic channels*	D0
SST(B_d)	$1.04 \pm 0.35 \pm 0.06$	1.00 ± 0.36
Soft μ	0.56 ± 0.05	1.00 ± 0.38
Soft e	0.29 ± 0.03	-
Jet-Q	0.57 ± 0.06	~ 1 (measured combined with SST)

* OST measured exclusively

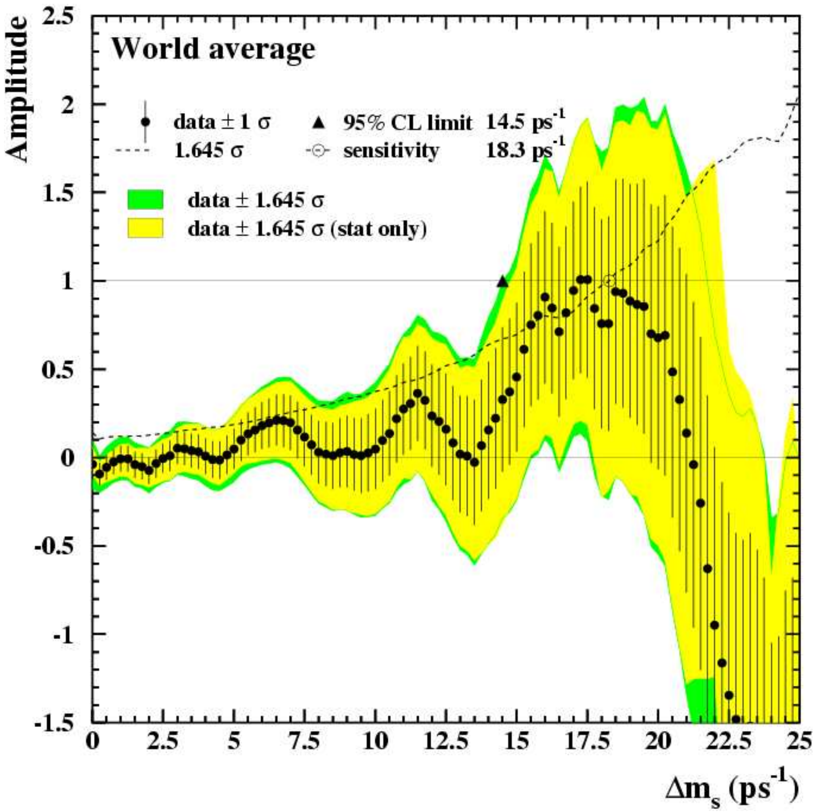
For SST(B_s) have to understand MC before it can be used for Δm_s limit.

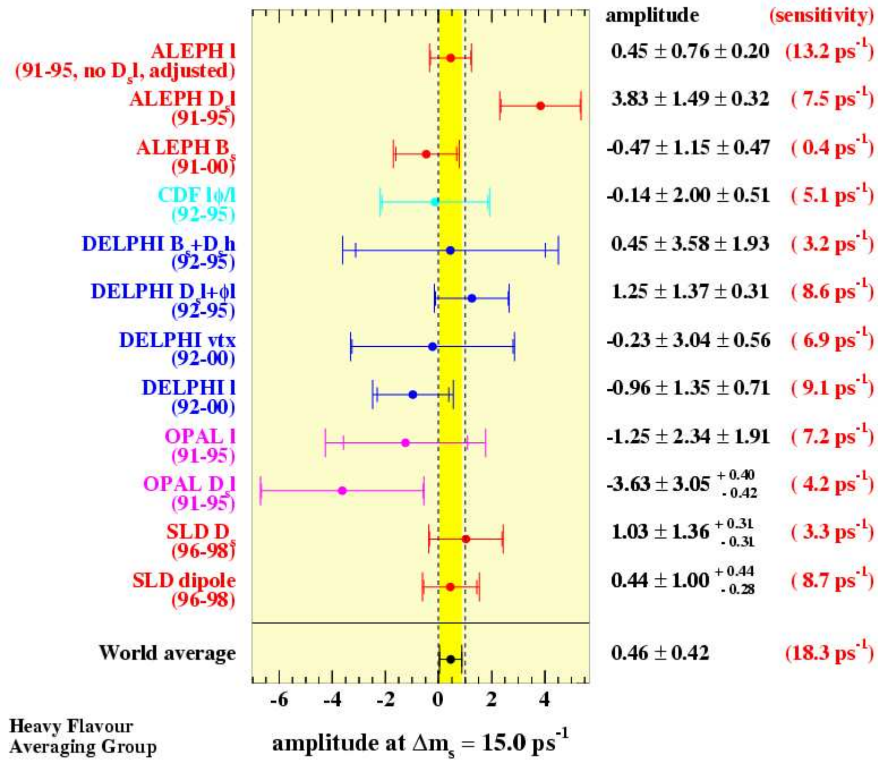
Amplitude Scan



- introduce new parameter, amplitude A
  $\mathcal{L} \sim \frac{1 \pm A \cdot D \cdot \cos(\Delta m_s t)}{2}$
- fit for A for each Δm_s hypothesis
- For infinite statistics, perfect taggers, optimal reconstruction, A should be zero for all Δm_s values but the correct one.
- Limit: a given value Δm_s is excluded @ 95% C.L., if $A(\Delta m_s) + 1.645 \cdot \sigma[A(\Delta m_s)] \leq 1$
- Sensitivity: smallest Δm_s value for which $1.645 \cdot \sigma[A(\Delta m_s)] = 1$
- Amplitude scan method allows easy combination among different measurements/experiments.

Current Experimental Results on Δm_s





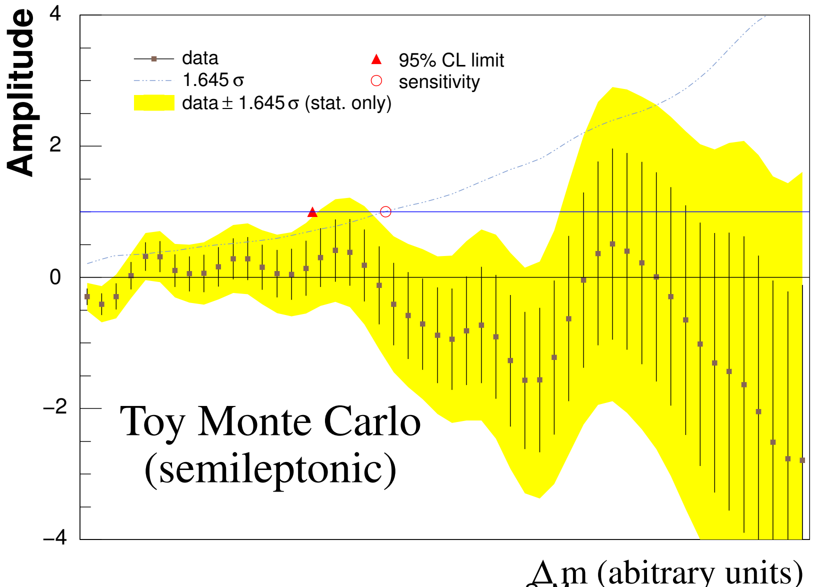
Winter 2004 summary (world average):

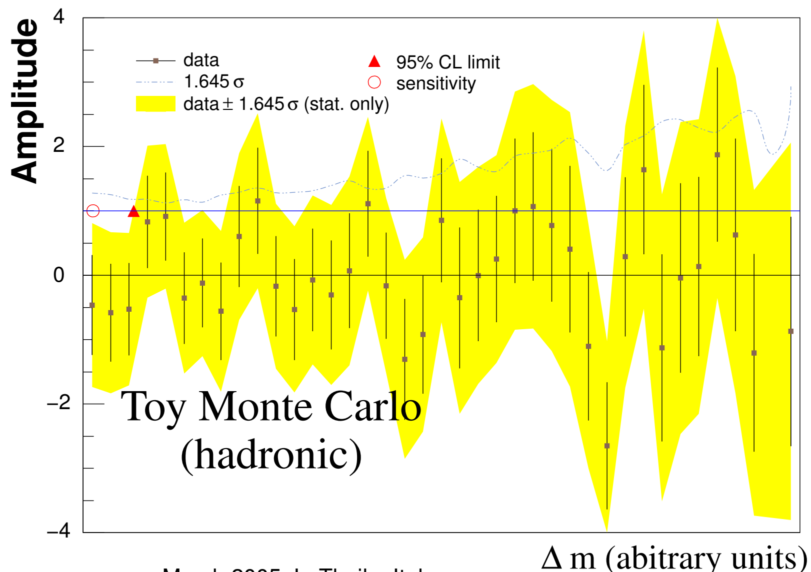
- Limit: $\Delta m_s \geq 14.5\ \text{ps}^{-1}$
- Sensitive up to $\Delta m_s = 18.3\ \text{ps}^{-1}$

MC Studies on Δm_s Sensitivity

What do we have to expect ...

- The limit can be lower or higher than the sensitivity reach
- Tevatron results will improve the sensitivity of the world average
- But if we are very unlucky, we might worsen the limit
- At lower luminosity the semileptonic modes will contribute more to limit/sensitivities at lower values of Δm_s
- The lower statistics hadronic modes will contribute more at higher values of Δm_s due to better proper time resolution.



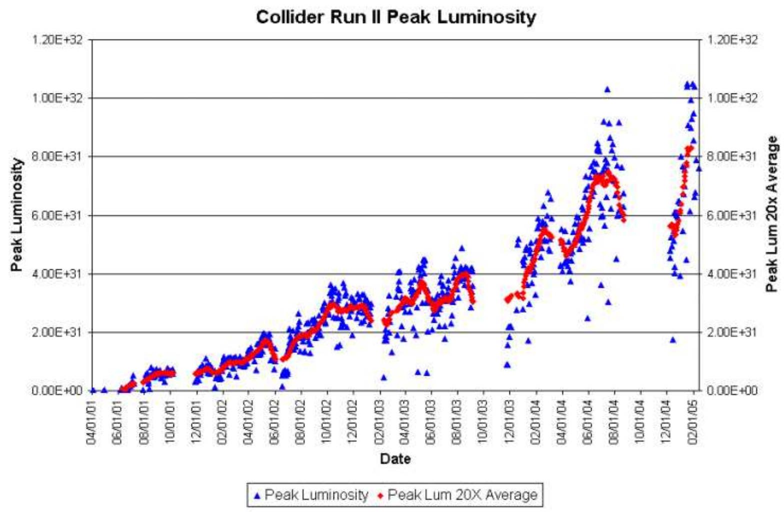


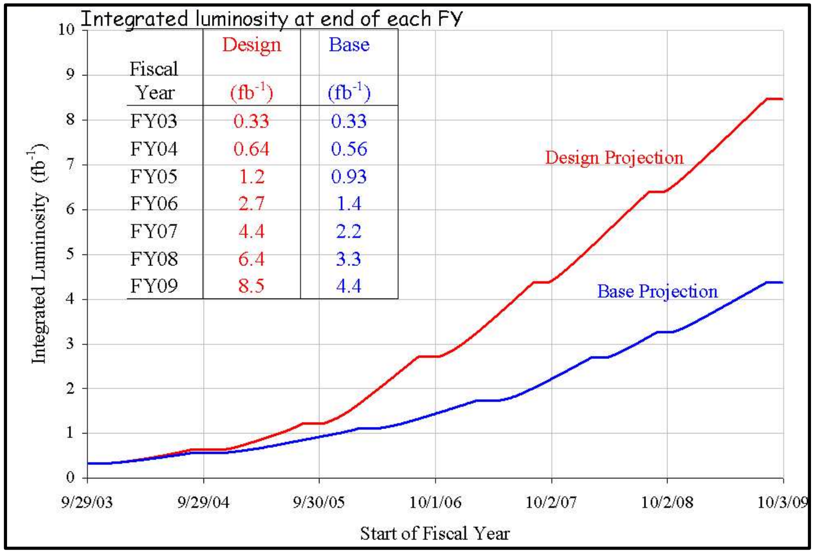
Summary

- Tevatron experiments are in unique position to exploit B_s system to constrain/measure CKM elements
- First measurement of $\Delta\Gamma_s$ from CDF available, favors large values of Δm_s, but with large uncertainties
- $\Delta\Gamma_s$ measurement from D0 expected soon
- Δm_s mixing measurement/limit is a very complex analysis, CDF/D0 are almost ready
- Δm_d results are available
- Δm_s limits are coming soon

Backup

Luminosity and Data Taking





Tevatron performed very well in 2004:

- Peak lumi above $1 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$

  (Run I peak lumi: $1 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$)
- Recorded integrated lumi: 0.5 fb^{-1}, 350-400 pb^{-1} good run data

  (all important detector subsystems working)
- Data taking efficiency about 80%

Luminosity Projections:

- Expected peak lumi $3 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ by 2007
- Delivered luminosity $\approx$ 4-8 fb^{-1} by end of 2009 (30-60 $\times$ more than Run I)

CKM Matrix

What is the origin of flavor symmetry breaking?

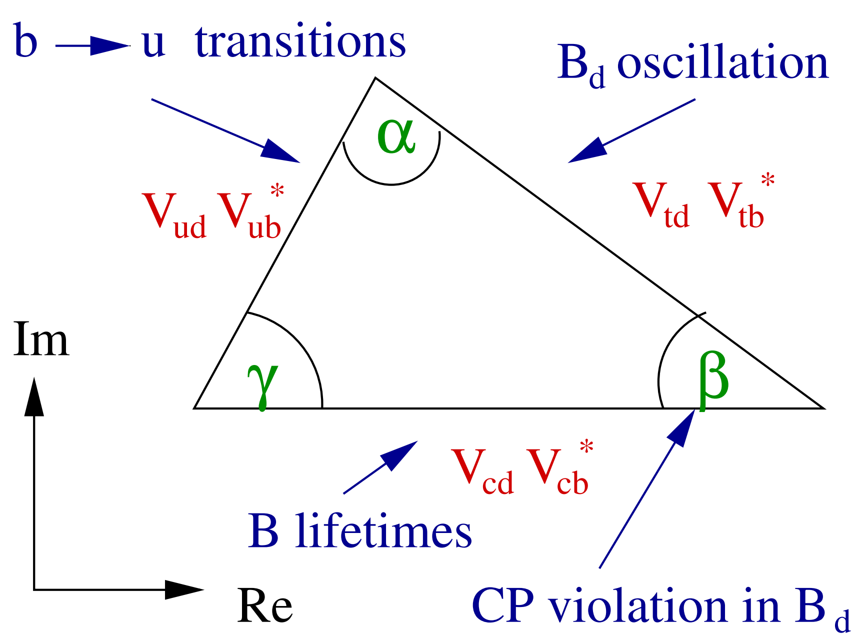
$\longrightarrow$ quark mixing, CKM matrix

quark mass eigenstates

$\neq$ weak interaction eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$V * V^{\dagger} = 1$



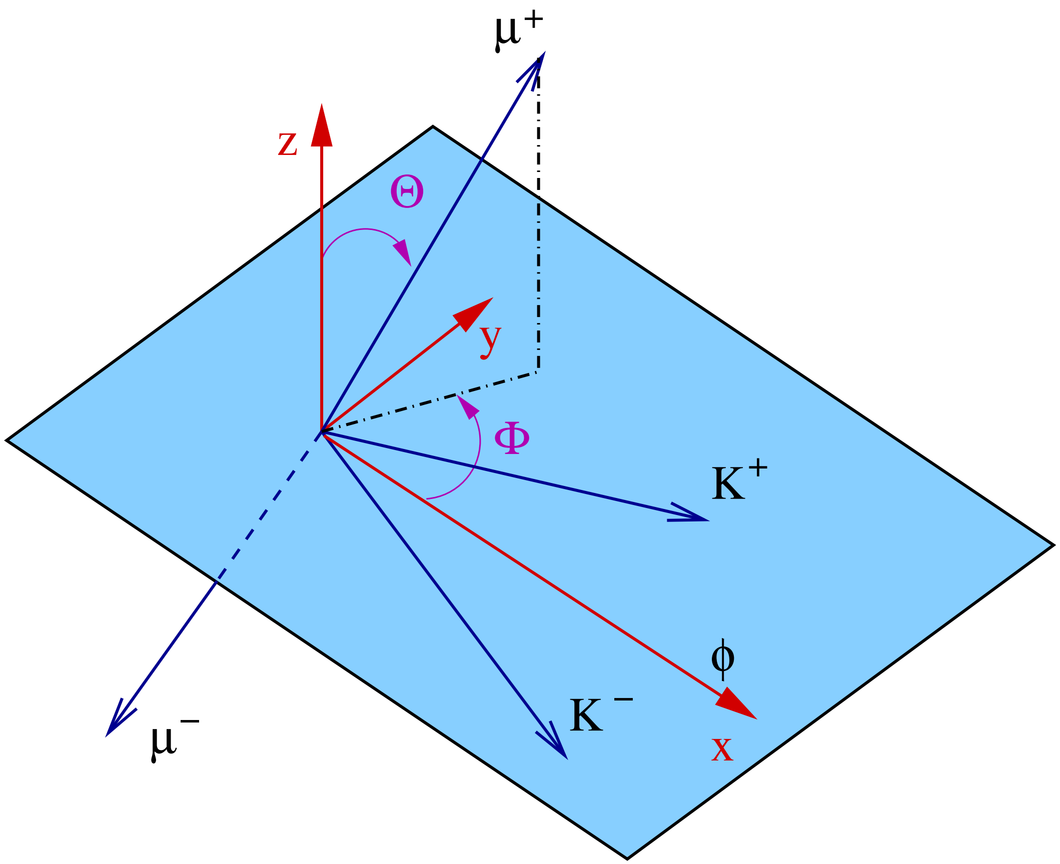
CKM elements not predicted by SM

B decays measure 5 CKM elements

Goal: Measure sides/angles of CKM triangle sides in all possible ways

Transversity Angles

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



Work in J/ψ rest frame

KK plane defines (x,y) plane

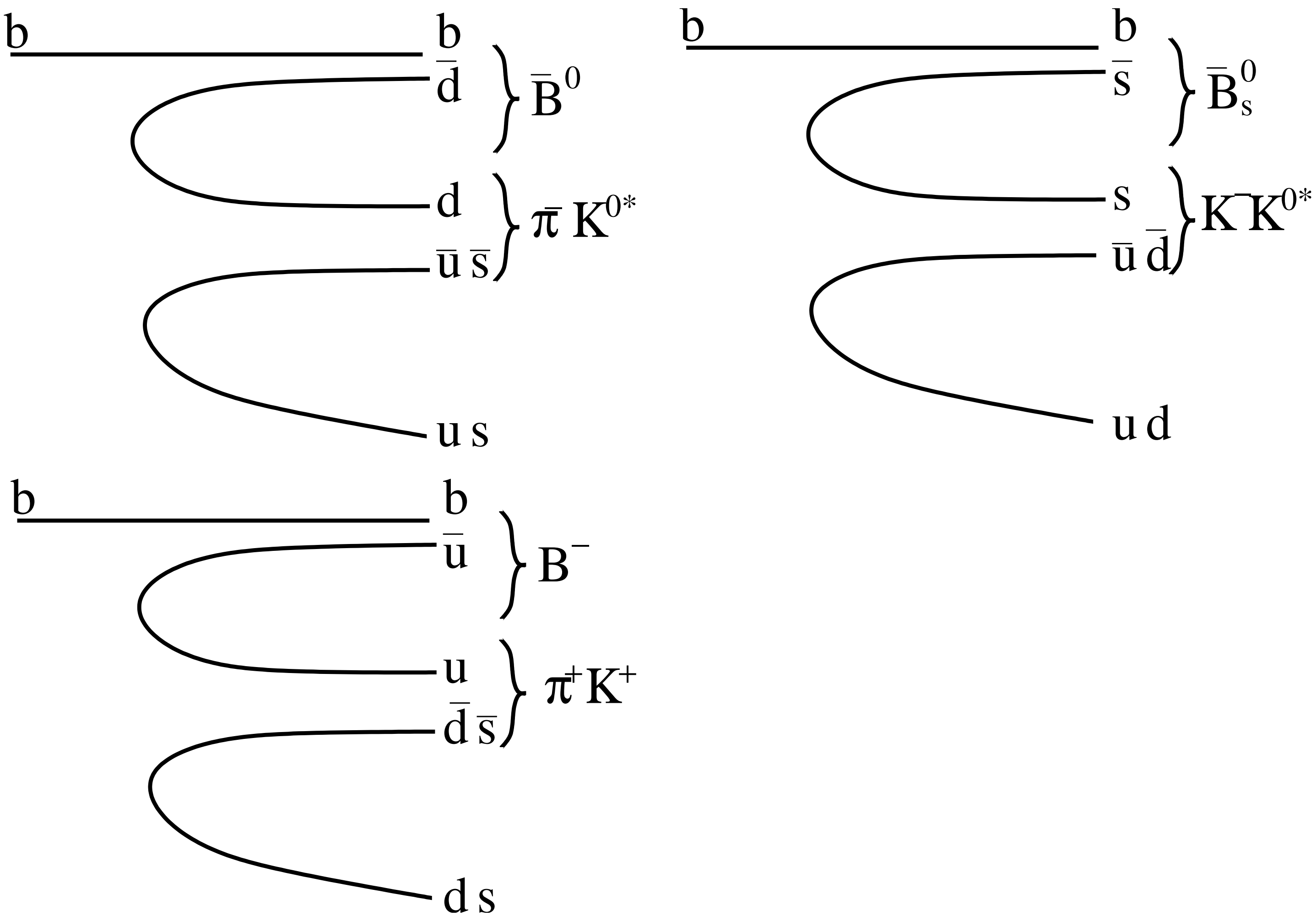
ϕ defines x axis

K^+ defines +y direction

Θ, Φ polar azimuthal angles of μ^+

Ψ helicity angle of ϕ

Same Side Tagging



some of the possible species of particles produced in the fragmentation of a b quark to a B meson.

B_s Mixing Sensitivity

CDF baseline:

$\epsilon D^2 = 1.6\%$

$\sigma_t = 67$ fs

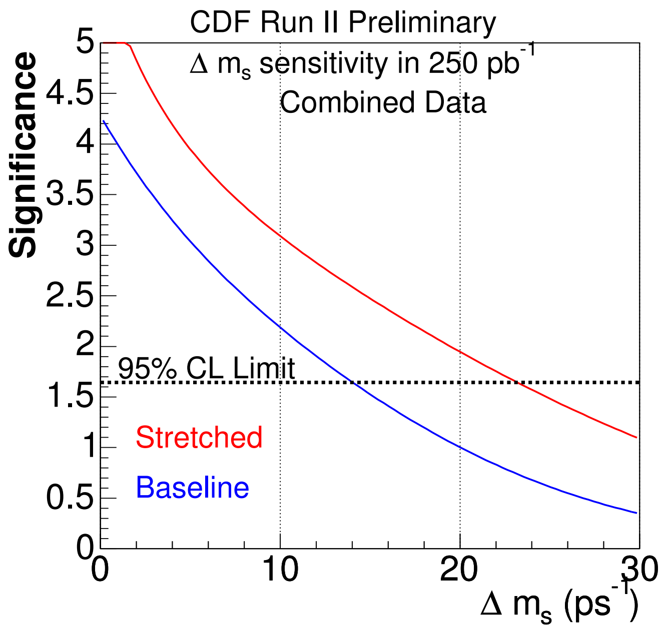
$\Delta m_s = 14$ ps^{-1}

CDF stretch:

$\epsilon D^2 = 2.6\%$

$\sigma_t = 47$ fs

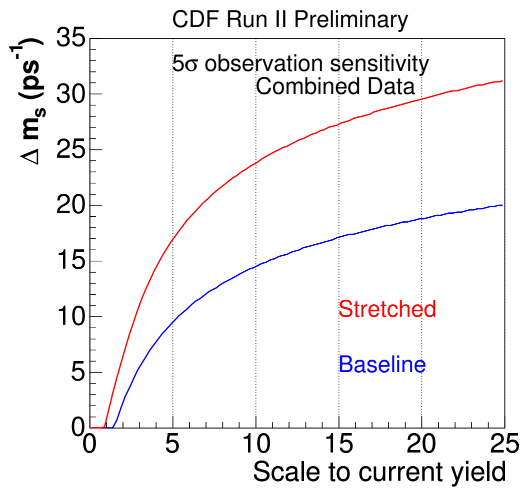
$\Delta m_s = 23$ ps^{-1}



Modes used for projection:

- hadronic modes:
  - $B_s \to D_s\pi(D_s \to \phi\pi)$
  - $B_s \to D_s 3\pi(D_s \to \phi\pi)$
  - $B_s \to D_s\pi(D_s \to K^*K)$
  - $B_s \to D_s\pi(D_s \to 3\pi)$
- semileptonic mode:
  - $B_s \to l\nu D_s X(D_s \to \phi\pi)$

A little bit further away ...



Further improvements ongoing:

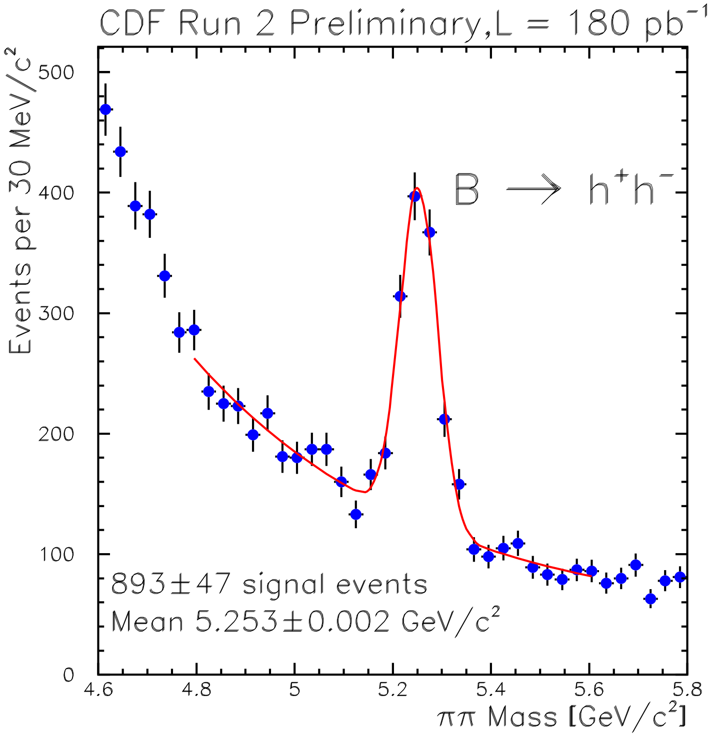
- add more modes
- improve taggers (PID for SST)

$B \to h^+h^-$

$B \to h^+h^-$: Ingredient for measurement of CP asymmetry and CKM angle γ

Need to measure many modes to get rid of hadronic uncertainties.

- Exploit Two Track Trigger sample
- 4 major expected modes overlap to form a single bump
  - $B_d \to K^+\pi^-$
  - $B_s \to K^+K^-$
  - $B_d \to \pi^+\pi^-$
  - $B_s \to \pi^+K^-$



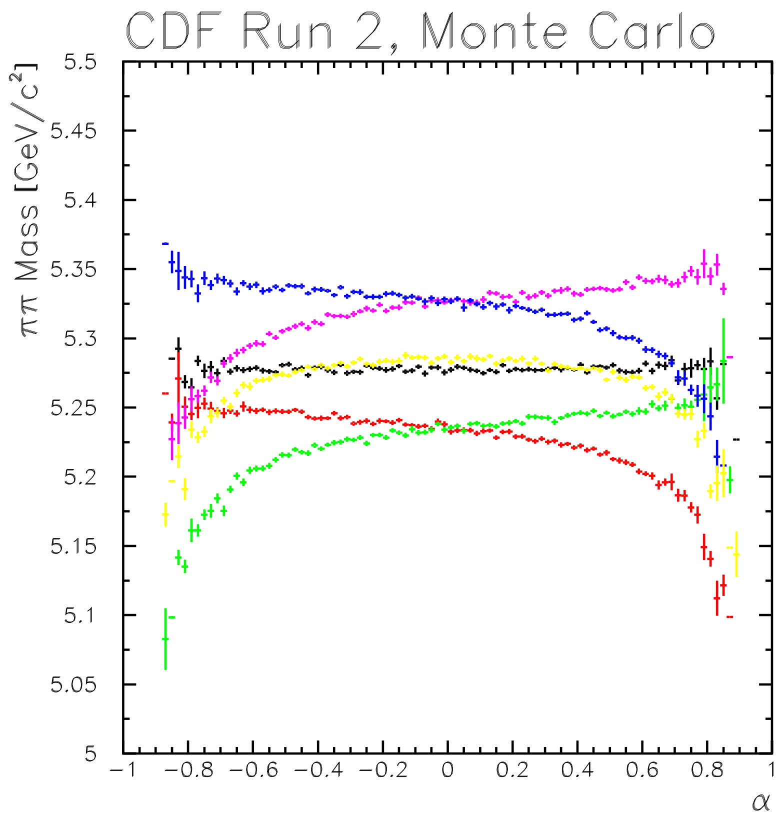
Signal: 893 ± 47, S/B>2

$B \to h^+h^-$: Separation of Modes

Approach: use mass + kinematic variable + track PID in an unbinned Maximum Likelihood fit $\to$ extract the fraction of each component

Mass ($\pi\pi$ hypothesis) versus signed momentum imbalance

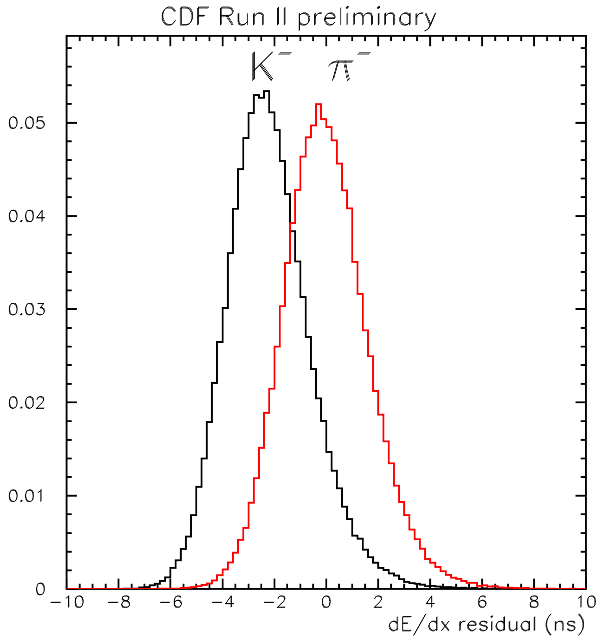
$\alpha = (1 - \frac{p_1}{p_2}) * q_1$; p: momentum, q: charge, index 1/2 refer to the low/high momentum track



- $\bar{B}_s \to K^+\pi^-$
- $B_s \to K^-\pi^+$
- $\bar{B}_d \to K^-\pi^+$
- $B_d \to K^+\pi^-$
- $B_s \to K^+K^-$
- $B_d \to \pi^+\pi^-$

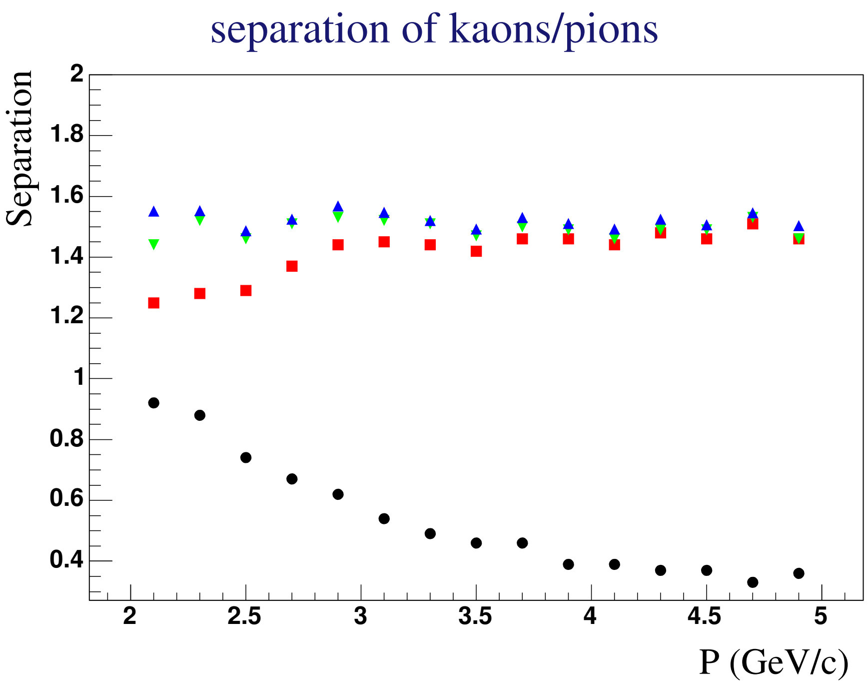
$B \rightarrow h^+h^-$: Separation of Modes

Kaon/Pion separation from dE/dx in the drift chamber: 1.4σ ($p_T \geq 2$ GeV/c)



calibration via $D^* \rightarrow \pi D^0 \rightarrow \pi h^+ h^-$

Improvement expected by including time-of-flight as well: $1.4\sigma \rightarrow 1.6\sigma$



TOF separation

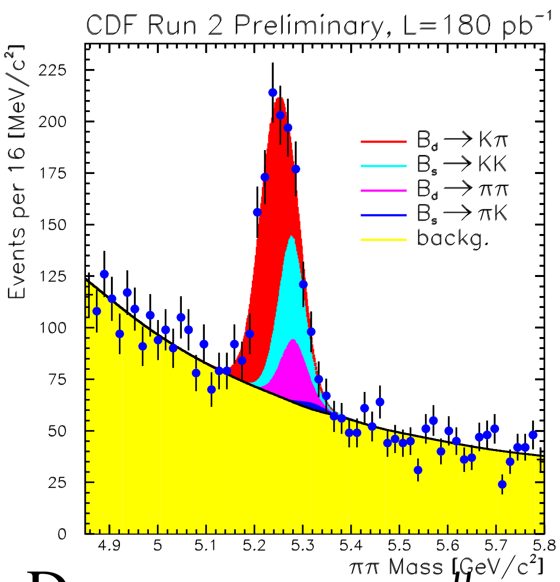
dE/dx separation

combined TOF+dE/dx separation

$\sqrt{(TOF\ sep)^2 + (dE/dx\ sep)^2}$

$B \rightarrow h^+h^-$: Results

Fit Result



Decay	# events
$B_d \rightarrow K^+\pi^-$	509
$B_s \rightarrow K^+K^-$	232
$B_d \rightarrow \pi^+\pi^-$	134
$B_s \rightarrow \pi^+K^-$	0

B_d sector

- $\frac{BR(B_d \rightarrow \pi^+\pi^-)}{BR(B_d \rightarrow K^+\pi^-)} = 0.24 \pm 0.06 \pm 0.04$
  Ratio of B_d BR consistent with other experiments
- $A_{CP}(B_d \rightarrow K^+\pi^-) = -0.04 \pm 0.08 \pm 0.01$
  $A_{CP} = -0.133 \pm 0.03 \pm 0.009$ (Babar),
  $A_{CP} = -0.088 \pm 0.03 \pm 0.013$ (Belle)
  A_{CP} results compatible with Babar/Belle.
  Analysis is still statistically limited.

B_s sector (unique to Tevatron):

- $BR(B_s \rightarrow K^+K^-) =$
  $0.50 \pm 0.08 \pm 0.07 * BR(B_d \rightarrow K\pi) * (f_s/f_d)$
- $BR(B_s \rightarrow K\pi) < 0.11 * BR(B_d \rightarrow Kpi) * (f_s/f_d)$

Next steps

- Measure CP asymmetry in B_s system
- Measure CKM angle γ