B_s Properties at the TeVatron

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HCP2005

The ”Expected” Outline

- Brief introduction
- Tevatron
- D0 and CDF detectors
- *B* Triggers
- Masses and Lifetimes
- $B_{(s)} \to h^+h^-$
- Rare B_s decays
- B_s Mixing:
  - $\Delta\Gamma_s$
  - Δm_s
- Summary

The ”Real” Outline

- + Brief introduction
- + Tevatron (see previous D0/CDF talks)
- + D0 and CDF detectors (see previous D0/CDF talks)
- + *B* Triggers (see previous talk, H. Castilla-Valdez)
- + Masses and Lifetimes (see previous talk, H. Castilla-Valdez)
- + $B_{(s)} \to h^+h^-$
- + Rare B_s decays (see next talk, S. Dugad)
- + B_s Mixing:
  - $\Delta\Gamma_s$
  - Δm_s
- + Summary

B-Physics at Hadron Colliders

- Large production rates

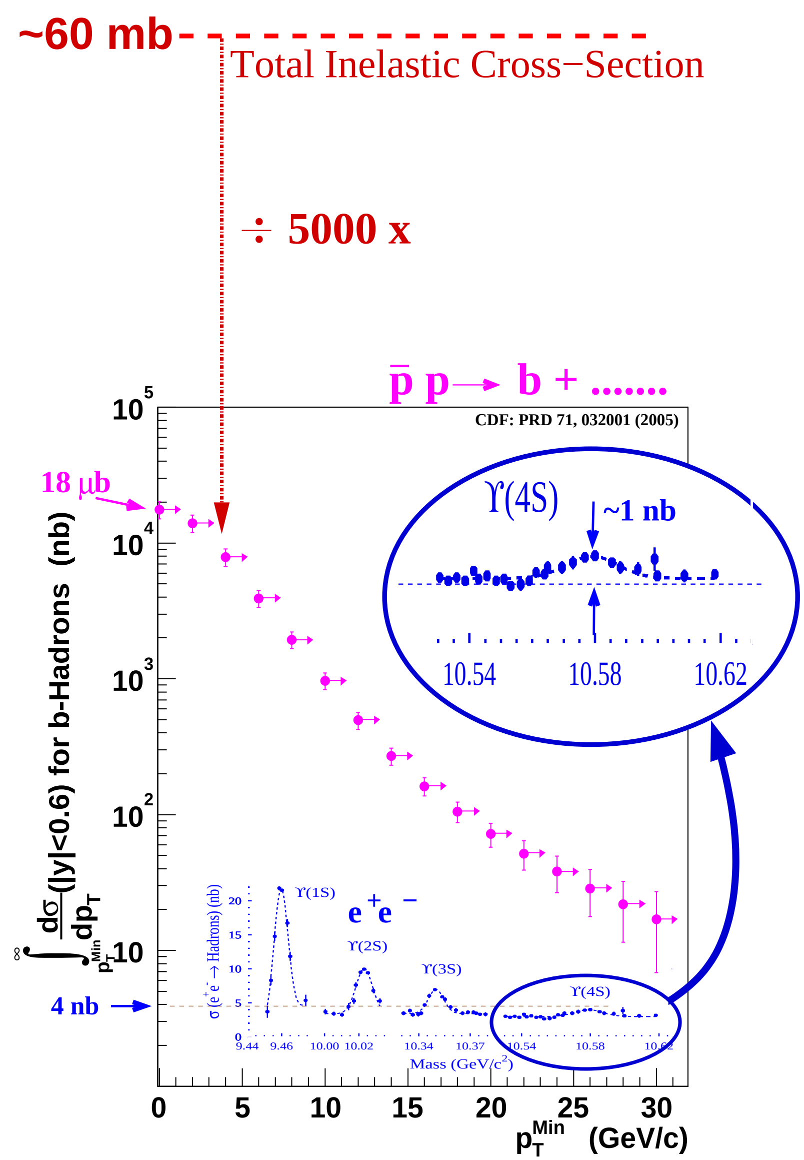
  $\sigma(p\bar{p} \to bX, |y| < 0.6) \approx 18\mu b$

  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



A lot of Topics...

A large variety of unique *B*-Physics can be made at the Tevatron

...in my talk:

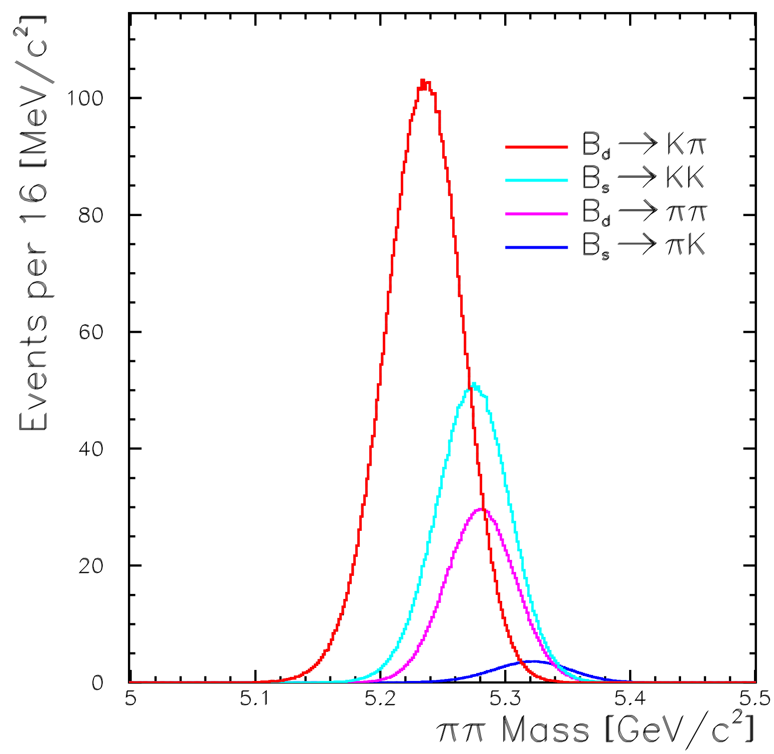
- $B_{(s)} \to h^+h^-$
- $\Delta\Gamma_s$
- Δm_s

$B \to h^+h^-$

Ingredient for measurement of CP asymmetry, analysis related to the CKM angle γ

Need to measure several modes to cancel the hadronic uncertainties in ratio

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



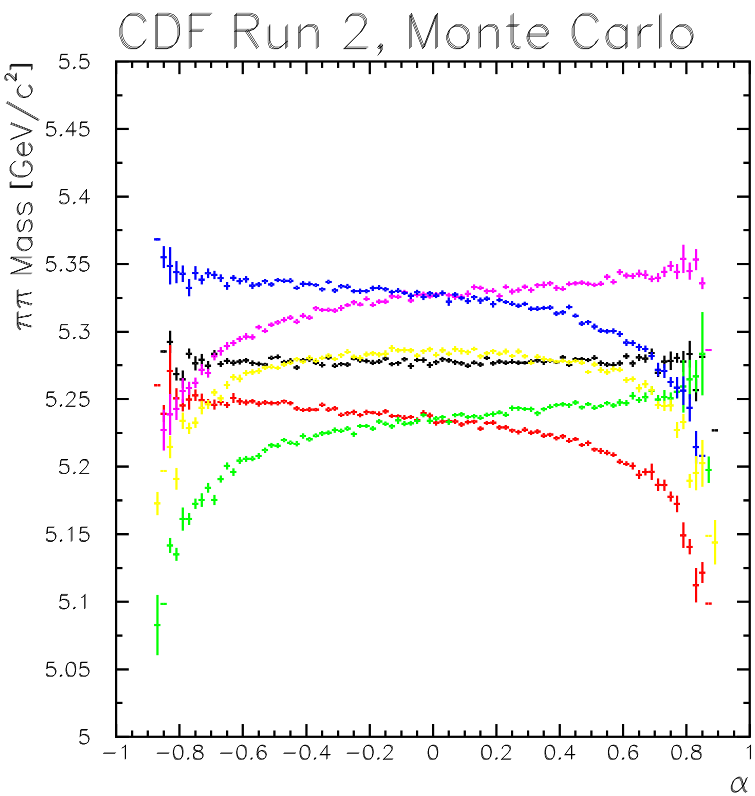
$B \to h^+h^-$

Signal Monte Carlo

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

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

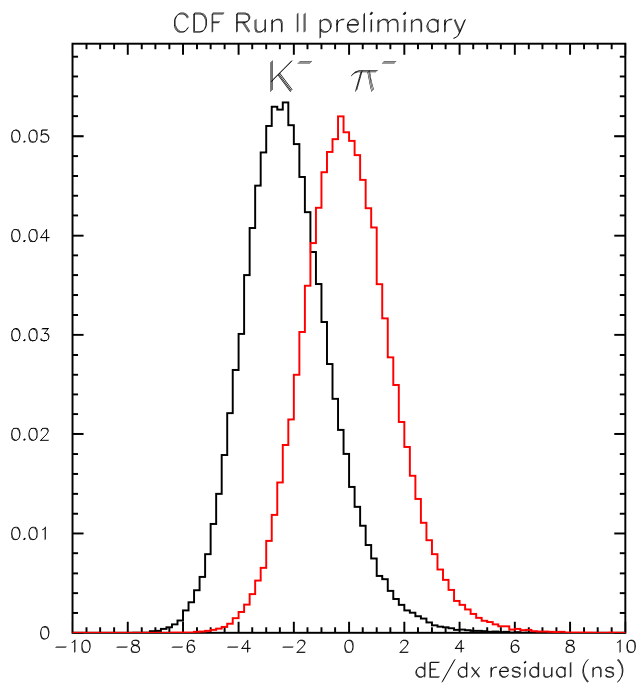
Mass ($\pi\pi$ hypothesis) versus signed momentum imbalance $\alpha = (1 - \frac{p_1}{p_2}) * q_1$; p: momentum, q: charge, index 1/2 refer to the lowest/highest momentum track



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

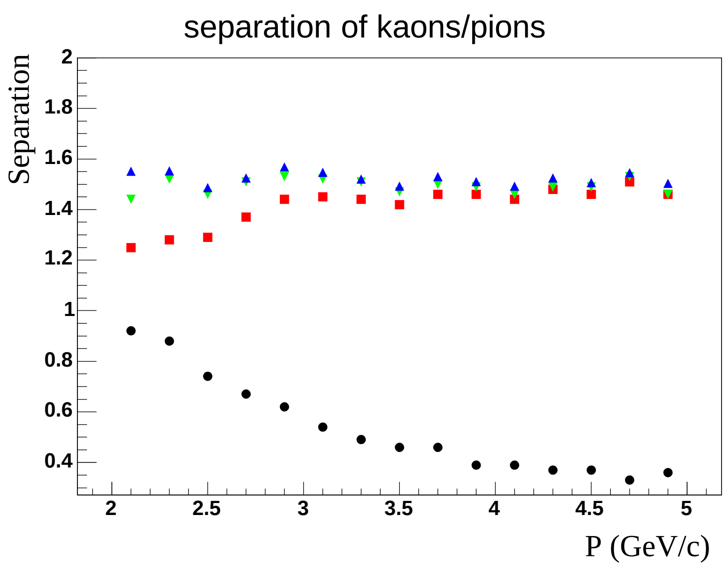
$B \to h^+h^-$: Separation of Modes (II)

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



$D^* \to \pi D^0 \to \pi k^+ \pi^-$ used to calibrate dE/dx

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



TOF separation

dE/dx separation

combined TOF+dE/dx separation

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

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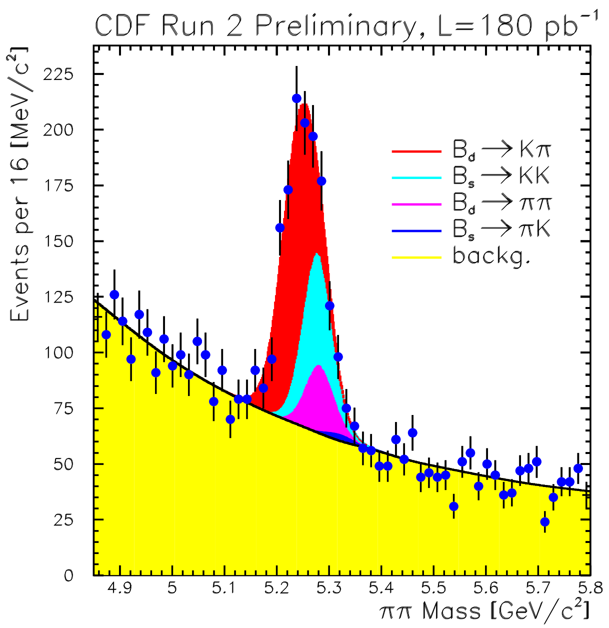
$B \to h^+h^-$ Results

Fit Result



Decay	# events
$B_d \to K^+\pi^-$	~510
$B_s \to K^+K^-$	~230
$B_d \to \pi^+\pi^-$	~140
$B_s \to \pi^+K^-$	~0

B_s sector (unique at the Tevatron):

- $\frac{f_s}{f_d}\frac{R(B_s \to K^+K^-)}{BR(B_d \to K\pi)} = 0.46 \pm 0.08 \pm 0.07$ (first observation!)
- $BR(B_s \to K\pi) < 0.08 * BR(B_d \to K\pi) * (f_s/f_d)$ @90% C.L. (a factor 100 improvement w.r.t. PDG!)

B_d sector

- $A_{CP}(B_d \to K\pi) = \frac{N(B_d \to K^+\pi^-) - N(\overline{B}_d \to K^-\pi^+)}{N(B_d \to K^+\pi^-) + N(\overline{B}_d \to K^-\pi^+)} = -0.022 \pm 0.078 \pm 0.012$

  $A_{CP} = -0.133 \pm 0.03 \pm 0.009$ (Babar), $A_{CP} = -0.088 \pm 0.03 \pm 0.013$ (Belle)

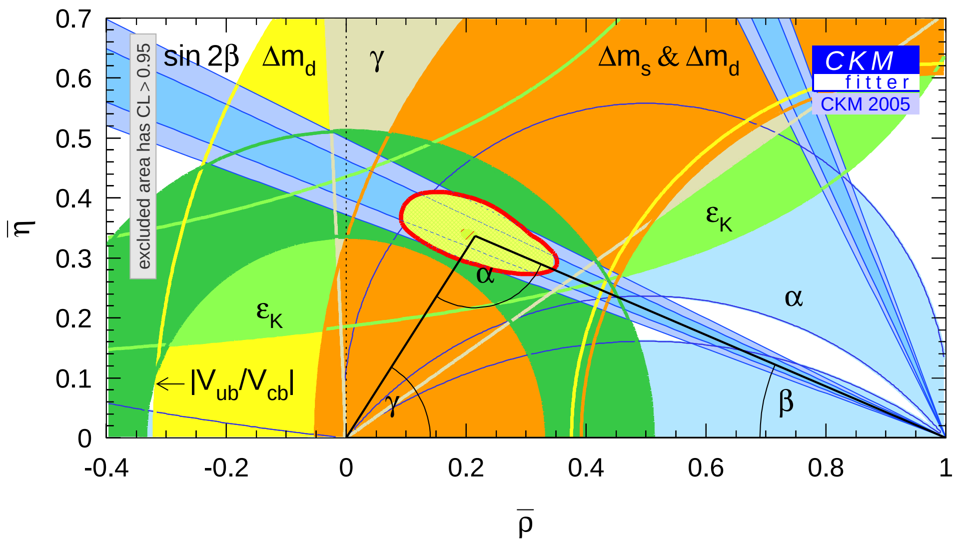
  A_{CP} systematics at the level of Babar/Belle. With the current sample on tape we expect to reach Y(4S) precision on the statistical uncertainty as well!
- $\frac{BR(B_d \to \pi^+\pi^-)}{BR(B_d \to K^+\pi^-)} = 0.21 \pm 0.05 \pm 0.03$

Next to follow:

- Measure CP asymmetry in B_s system
- Observe $BR(B_s \to K\pi)$
- $B_d \to \pi\pi$ time dependent analysis
- ...

B_s Mixing

- 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, provides 2 independent handles on Δm_s

+ Measuring B_s oscillation frequency: $\mathcal{A}_{mix}(t) \sim cos(\Delta m_s t)$
+ Measuring decay width difference $\Delta\Gamma_s$, clean relation with Δm_s (in SM)
+ $\frac{\Delta m_s}{\Delta\Gamma_s} \approx \frac{2}{3\pi}\frac{m_t^2}{m_b^2}(1-\frac{8}{3}\frac{m_c^2}{m_b^2})^{-1}h(\frac{m_t^2}{M_W^2})$

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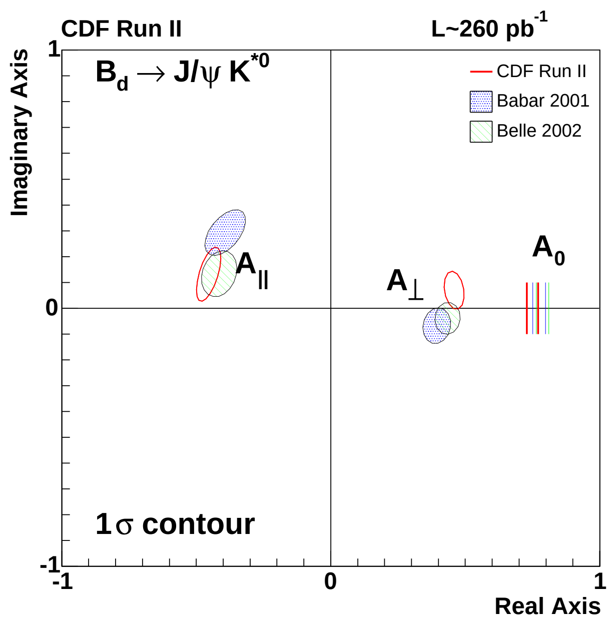
$\Delta\Gamma_s$: Polarization Amplitudes

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

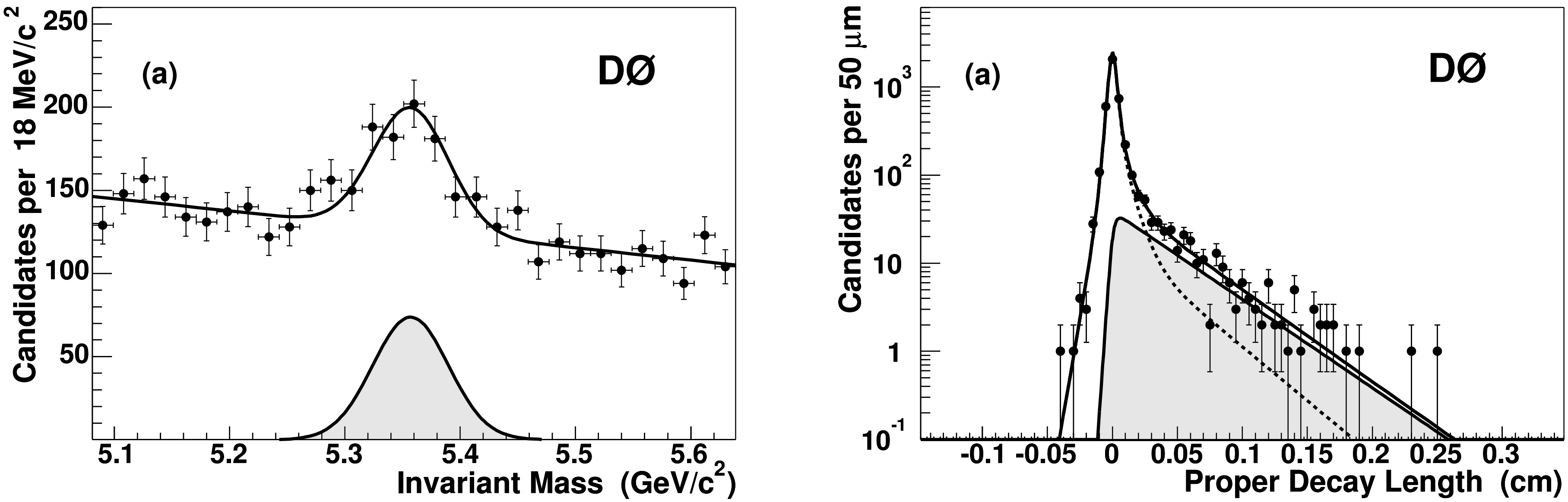


- Decay amplitudes decompose into 3 linear
- polarization states
- $|A_0|^2 + |A_{||}|^2 + |A_\perp|^2 = 1$
- $A_0, A_{||}$ = S+D wave $\Rightarrow$ CP even
- $A_\perp$ = P wave $\Rightarrow$ CP odd

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

First have to reconstruct events, measure mass and lifetime:



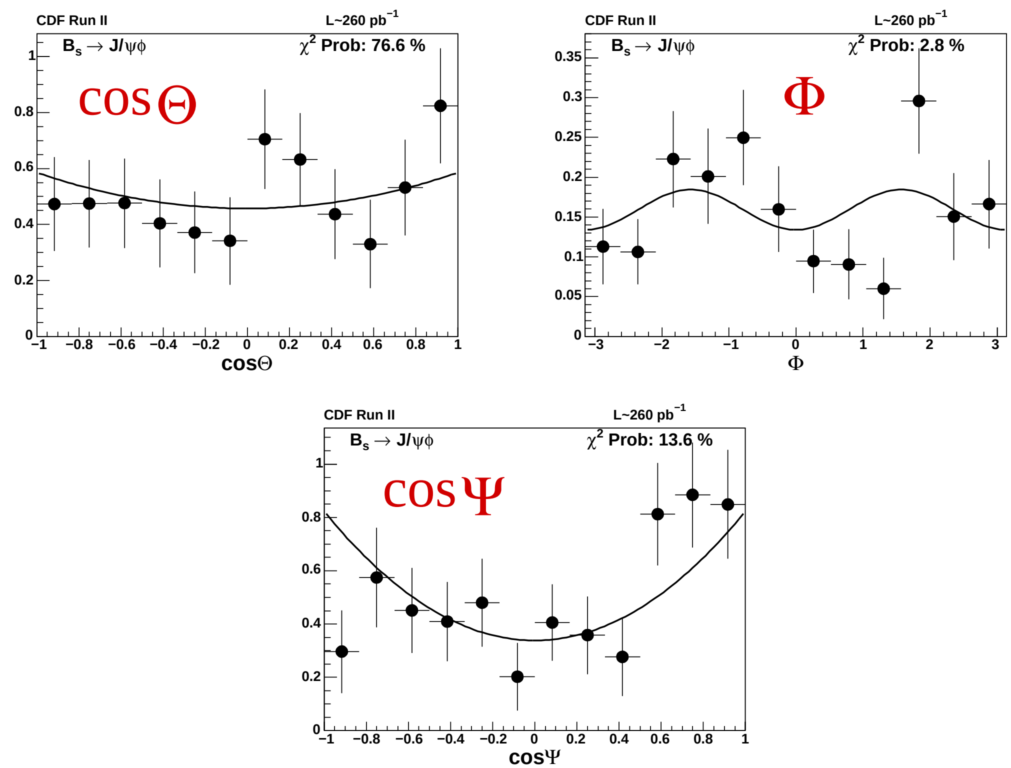
Relative average lifetime of $B_s \to J/\psi\phi$ with respect to topological similar mode $B_d \to J/\psi K^*$:

$$< \tau_s > / \tau_d = 0.910 \pm 0.090 \text{ (D0)}$$
$$< \tau_s > / \tau_d = 0.890 \pm 0.072 \text{ (CDF)}$$

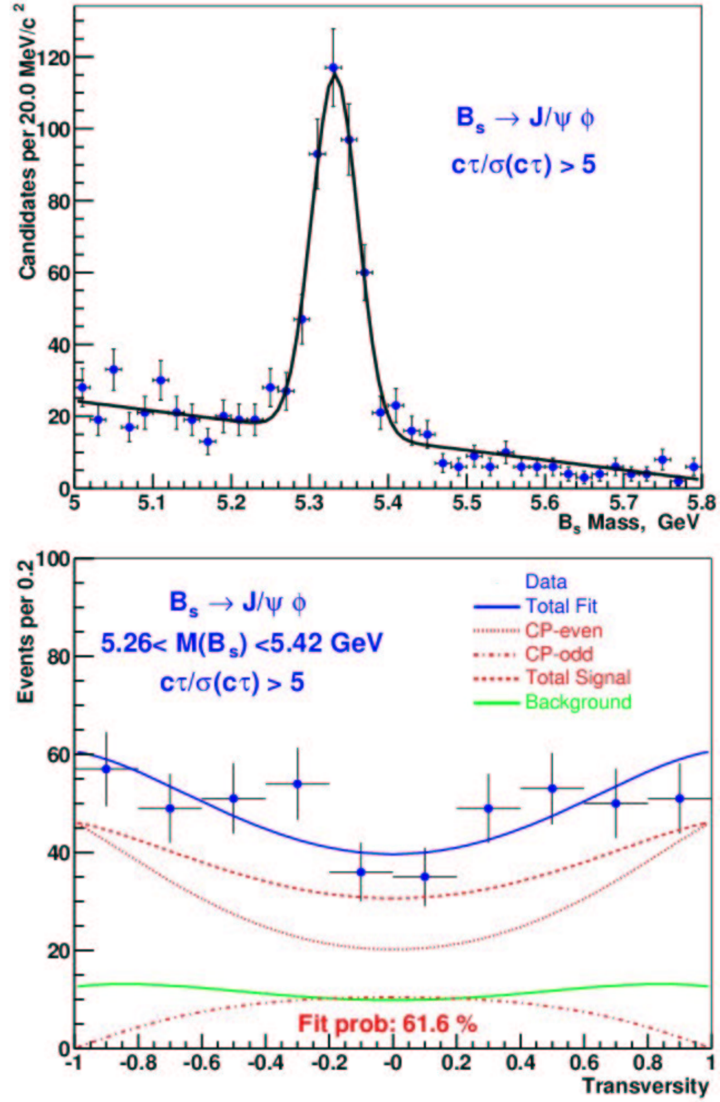
Angular Distributions

Then fit for angular distribution in transversity* frame:

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



CDF Projections



D0 Projections

* See definition of transversity angles in backup slides

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Angular Amplitudes at CDF

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

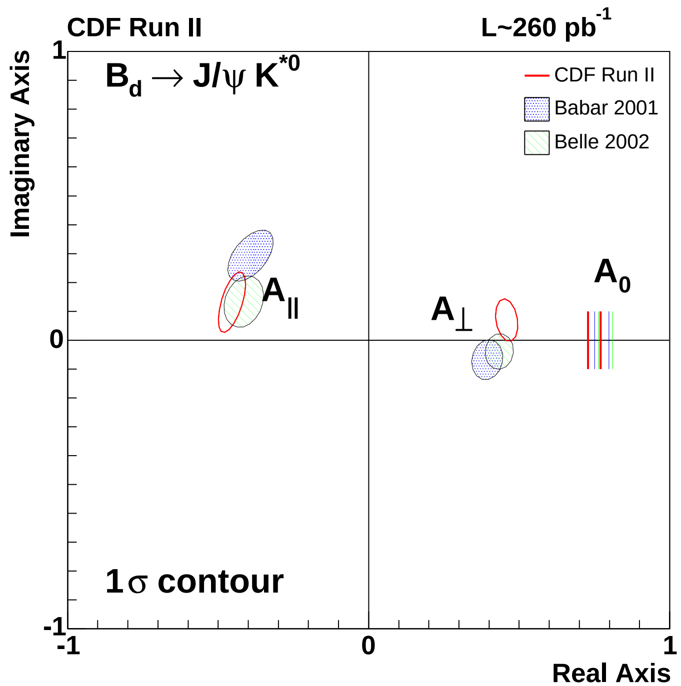
$A_{\perp} = (0.464 \pm 0.035 \pm 0.007)e^{(0.15\pm0.15\pm0.06)i}$

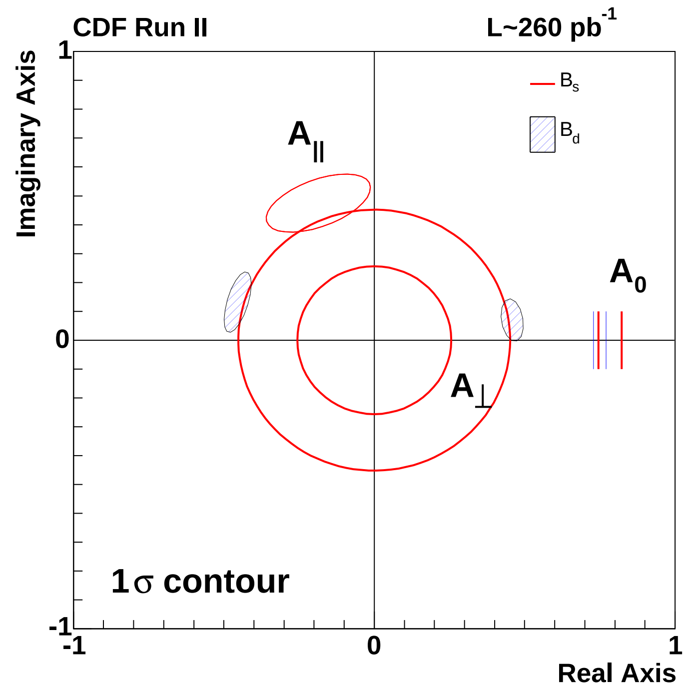
$A_0 = 0.750 \pm 0.017 \pm 0.012$

B_d amplitude compare well with Babar/Belle

Cross check:

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





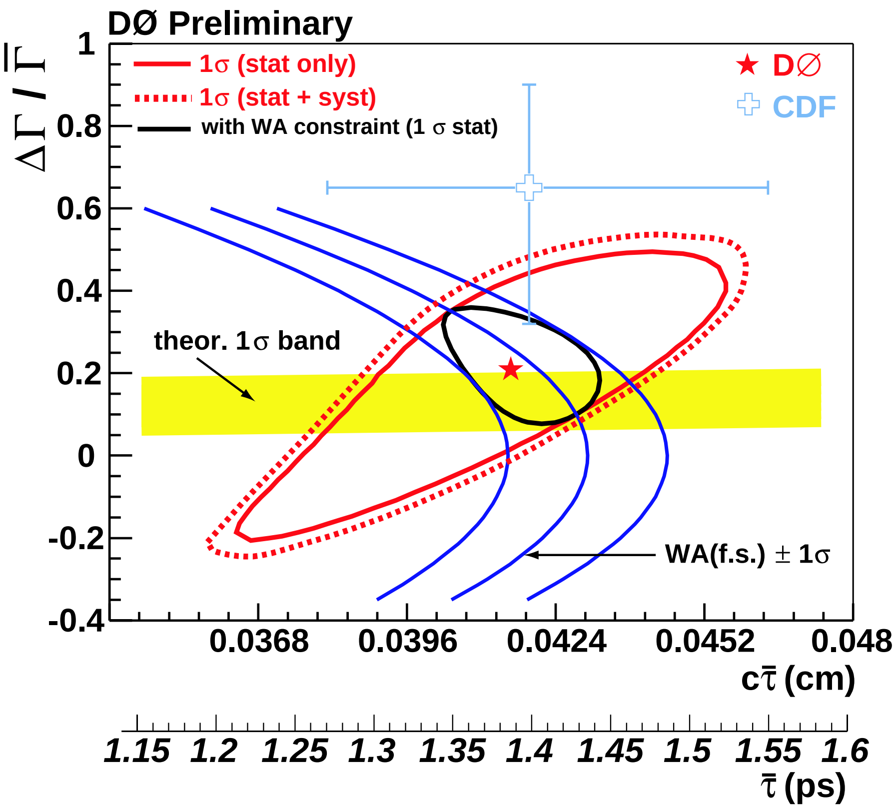
$B_s \to J/\psi\phi$

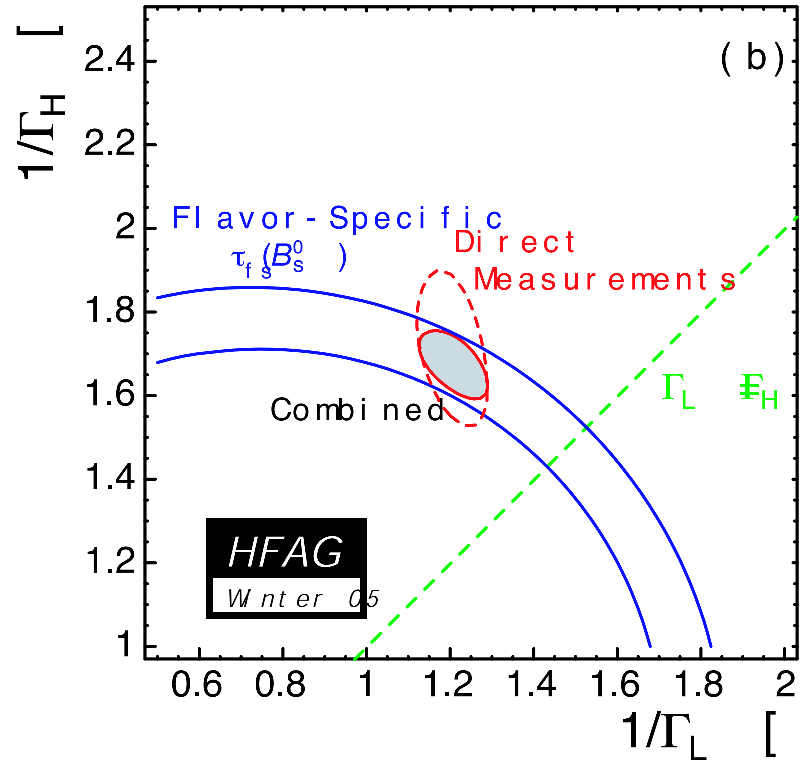
$A_{||} = (0.510 \pm 0.082 \pm 0.013)e^{(1.94\pm0.36\pm0.03)i}$

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

$A_0 = 0.784 \pm 0.039 \pm 0.007$

$\Delta\Gamma_s$ Results





CDF/D0 combined results consistent with SM

Tiny systematics!

Experiment	$\Delta\Gamma_s/\Gamma_s$	$<\tau>$ (ps)	τ_L (ps)	τ_H (ps)
CDF	$0.65^{+0.25}_{-0.33}$	$1.40^{+0.15}_{-0.13}$	$1.05^{+0.16}_{-0.13}$	$2.07^{+0.58}_{-0.46}$
D0	$0.21^{+0.33}_{-0.45}$	$1.39^{+0.15}_{-0.16}$	$1.23^{+0.16}_{-0.13}$	$1.52^{+0.39}_{-0.43}$

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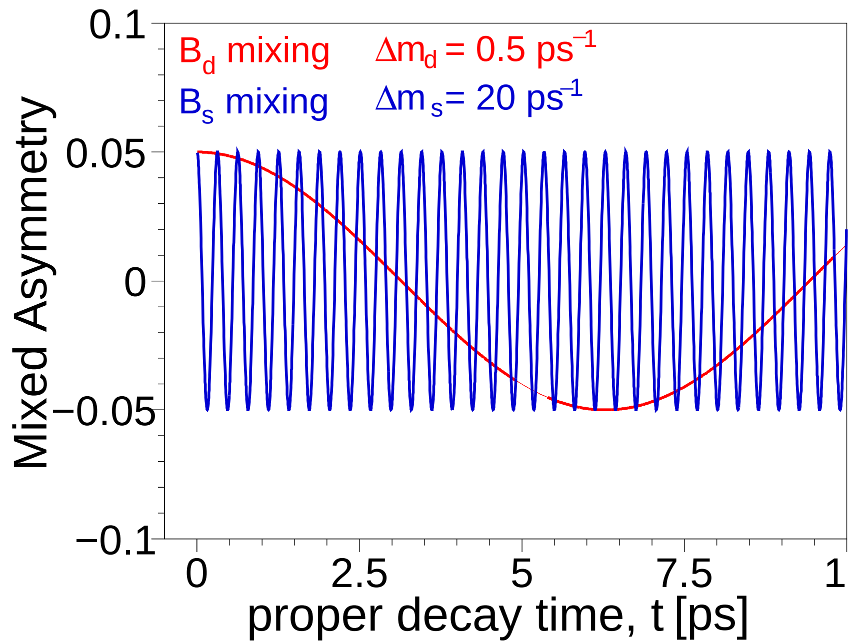
Δm_s

Why is this measurement so difficult?:

B_s Mesons Mix much faster than B_d Mesons!

In order to measure:

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



Sensitivity $\propto \varepsilon\mathcal{D}^2\sqrt{\frac{S}{S+B}}e^{-\Delta m_s^2\sigma_t^2/2}$

We need to:

- Reconstruct B_s signal in:
  - hadronic modes
  - semileptonic modes
- Proper decay length resolution: fully reconstructed modes provide better accuracy
- Tag the production flavor (the -key- problem in a hadron collider!): tagging power $\varepsilon\mathcal{D}^2$

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

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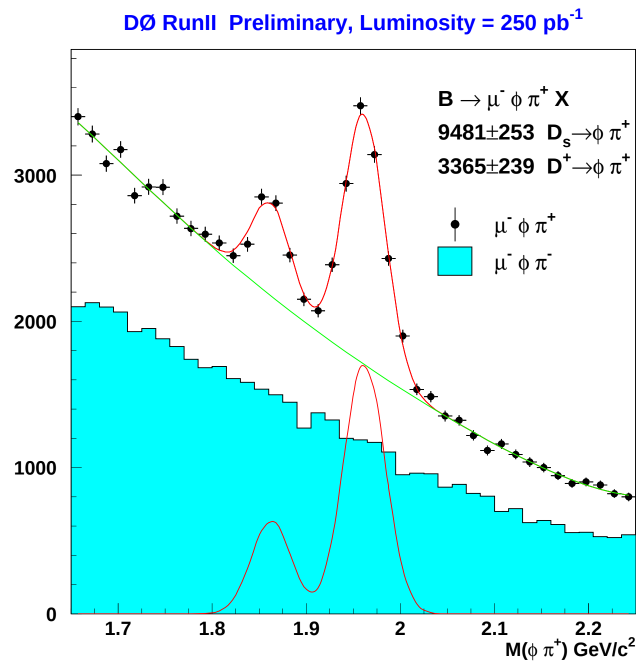
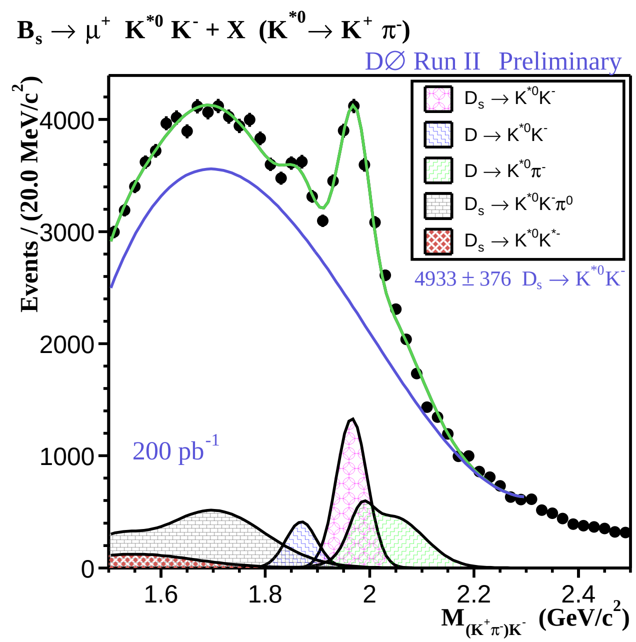
Reconstructed B_s Candidates (D0)

D0 exploits high statistics μ trigger semileptonic decays: worse proper time resolution, but high statistics

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



$D_S \to \phi\pi$



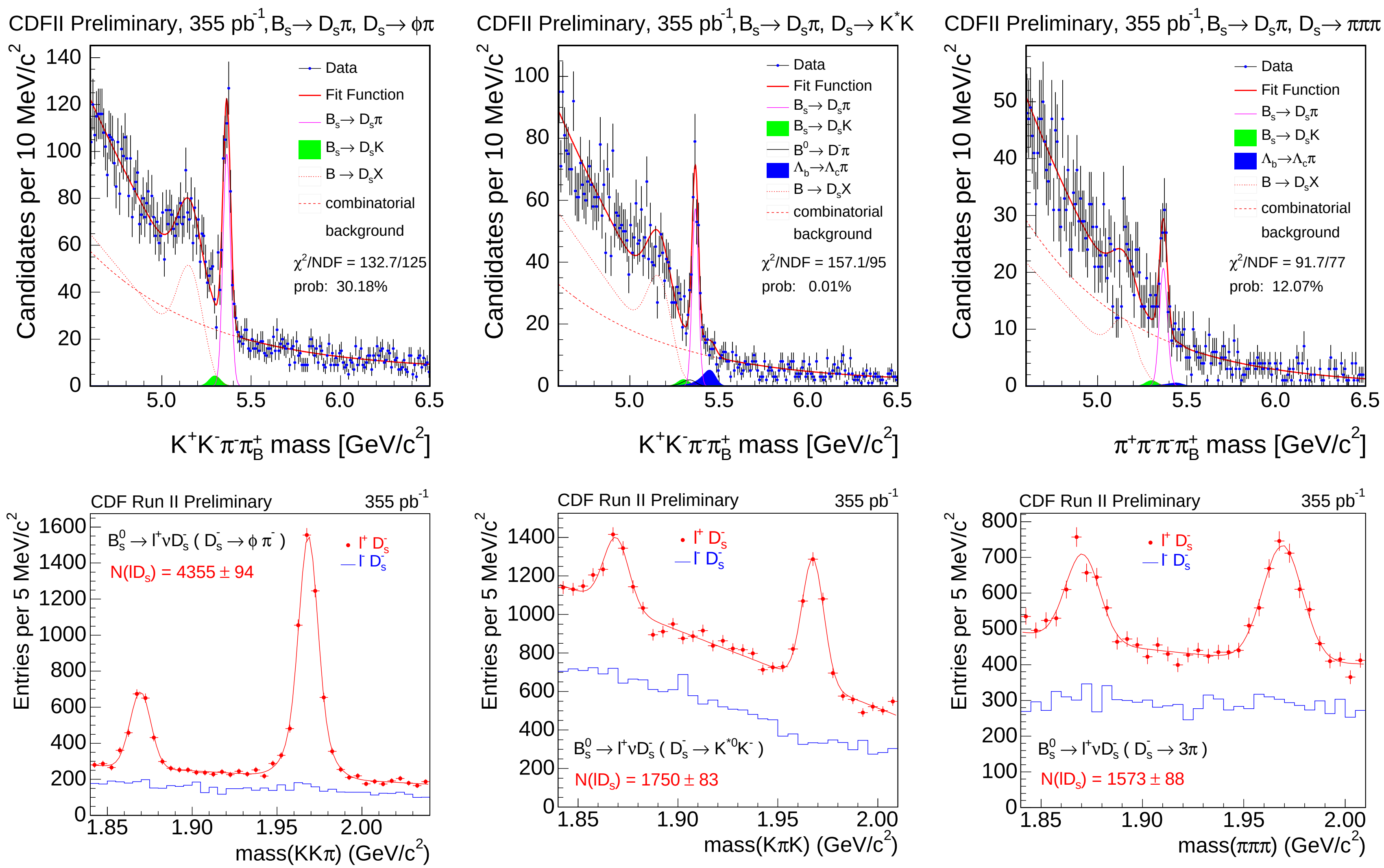
$D_S \to K^* K (K^* \to K\pi)$

Reconstructed B_s Candidates (CDF)

Uses hadronic modes: $B_s \to D_s \pi$

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

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



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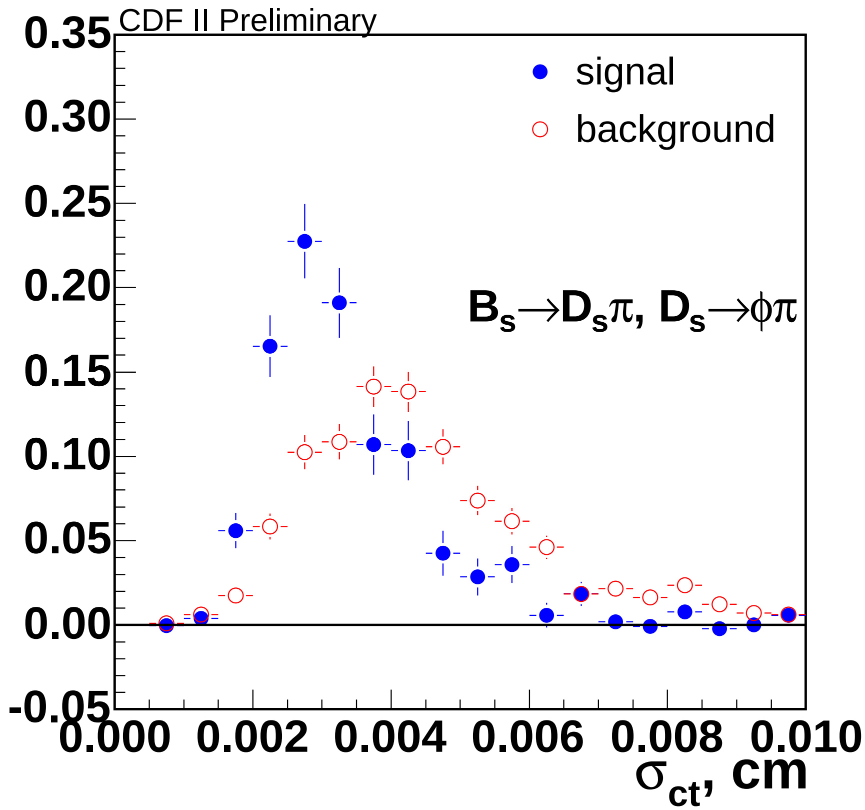
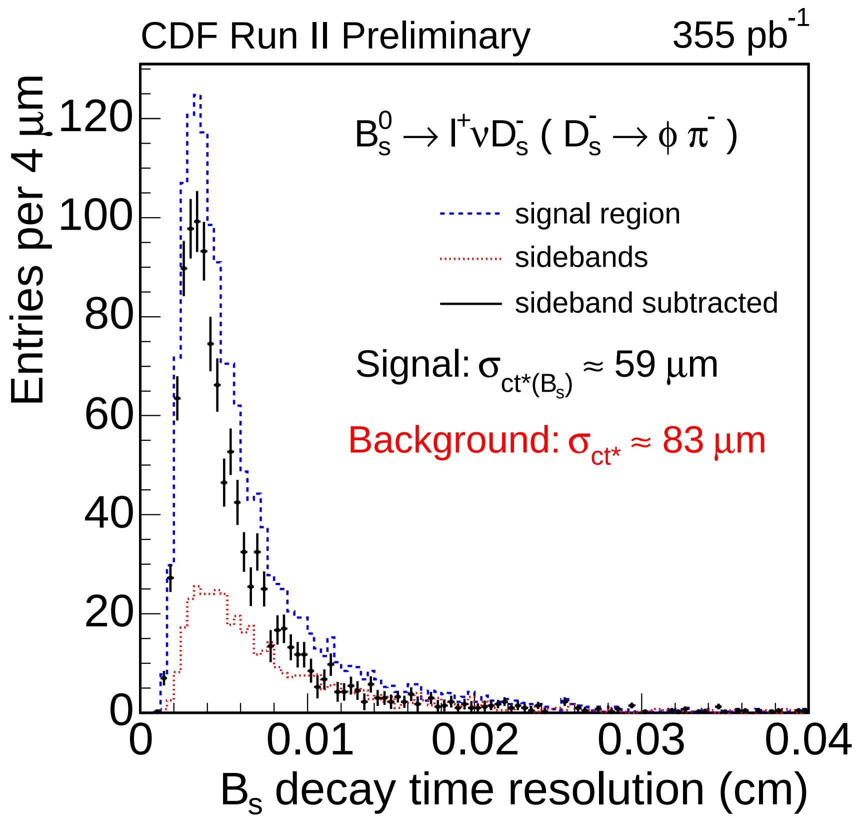
ct Resolution Studies (CDF)

The proper decay length resolution is the limiting factor at high Δm_s
Studies on this topic play a very important role!





B Flavor Tagging

Opposite Side Tagging:

- Jet-Charge-Tagging:
  sign of the weighted average charge of opposite B-Jet

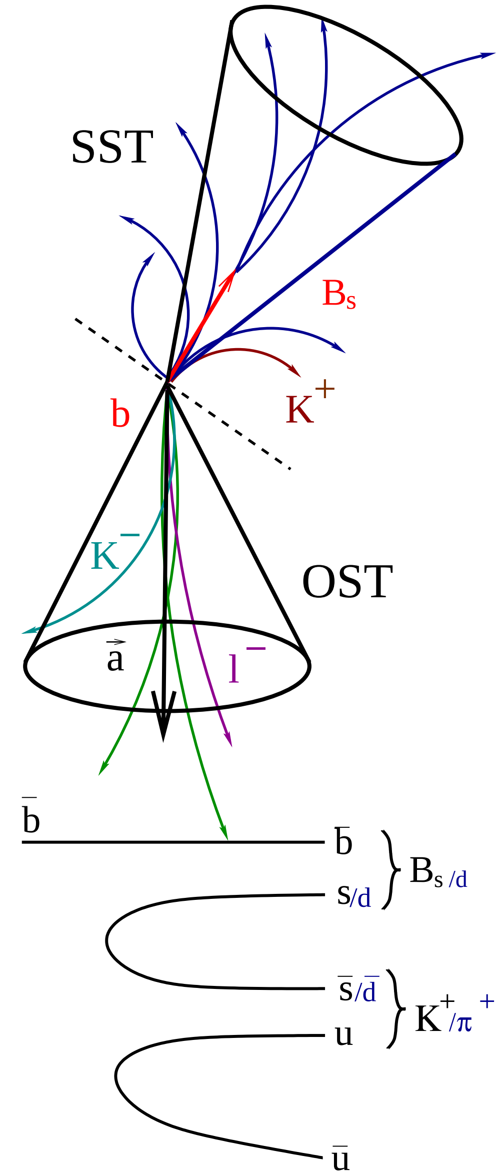
- Soft-Lepton-Tagging:
  identify soft lepton (e, μ) from semileptonic decay of opposite B: $b \to l^- X$ (BR $\approx$ 20%),

  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 is mandatory)

Same Side Tagging:

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



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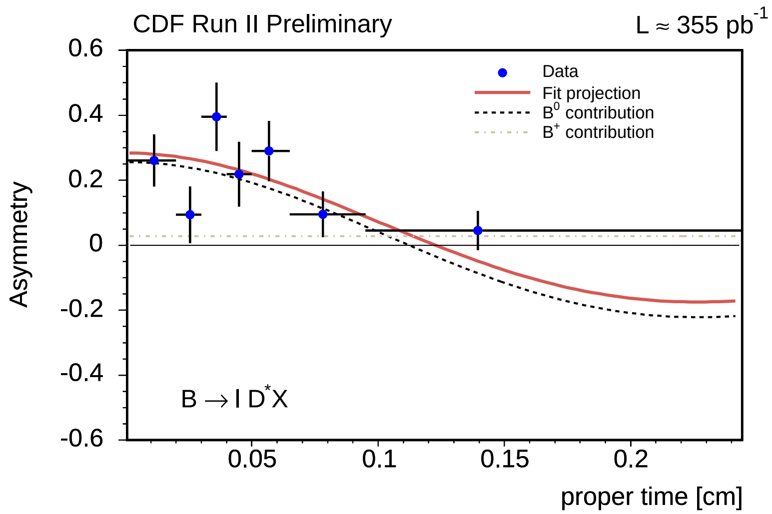
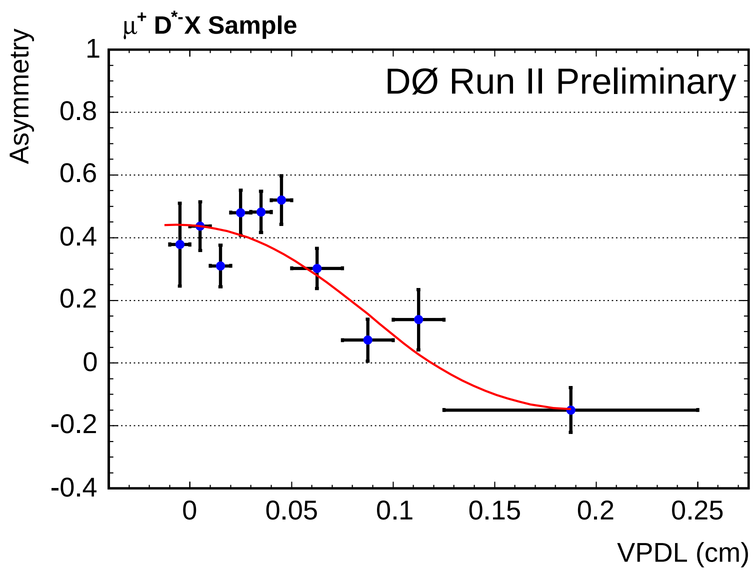
Crucial Test of the Whole "Machinery": B_d Mixing

+ 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 and Tagging Performance

Combined taggers (semileptonic channels) D0:

$$\Delta m_d = 0.558 \pm 0.048(\text{stat})\ \text{ps}^{-1}$$

Combined opposite side taggers (semileptonic channels) CDF:

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

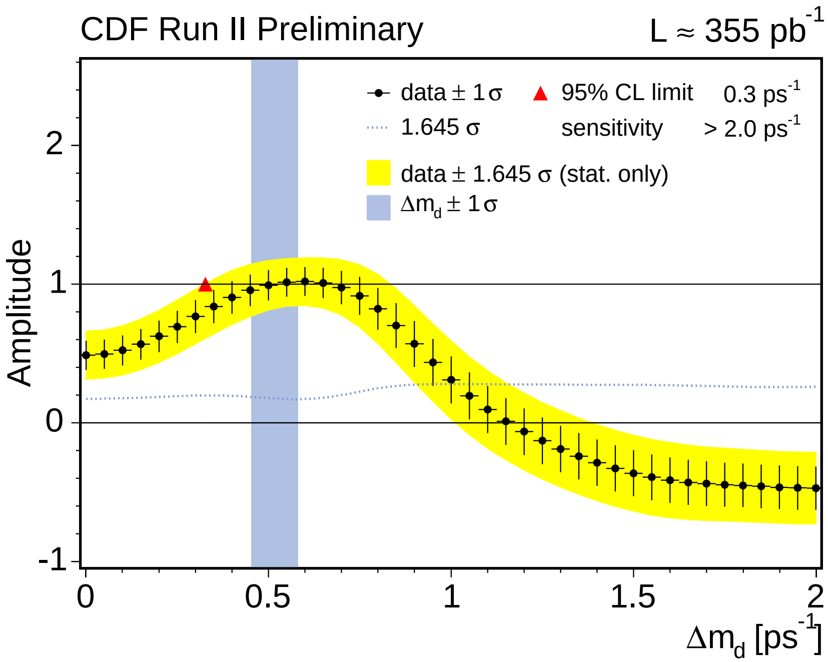
Combined opposite side taggers (hadronic channels) CDF:

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

εD^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

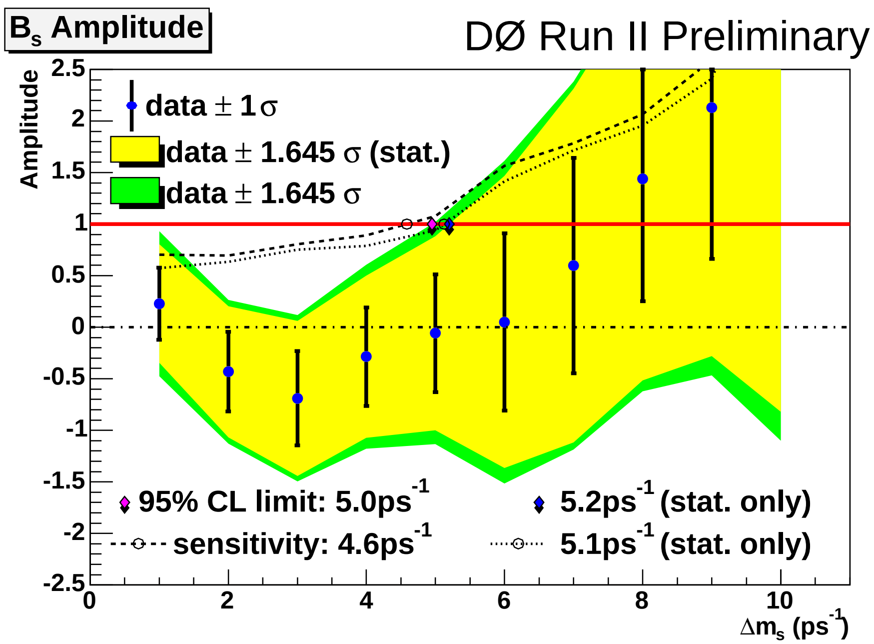
Amplitude Scan Method

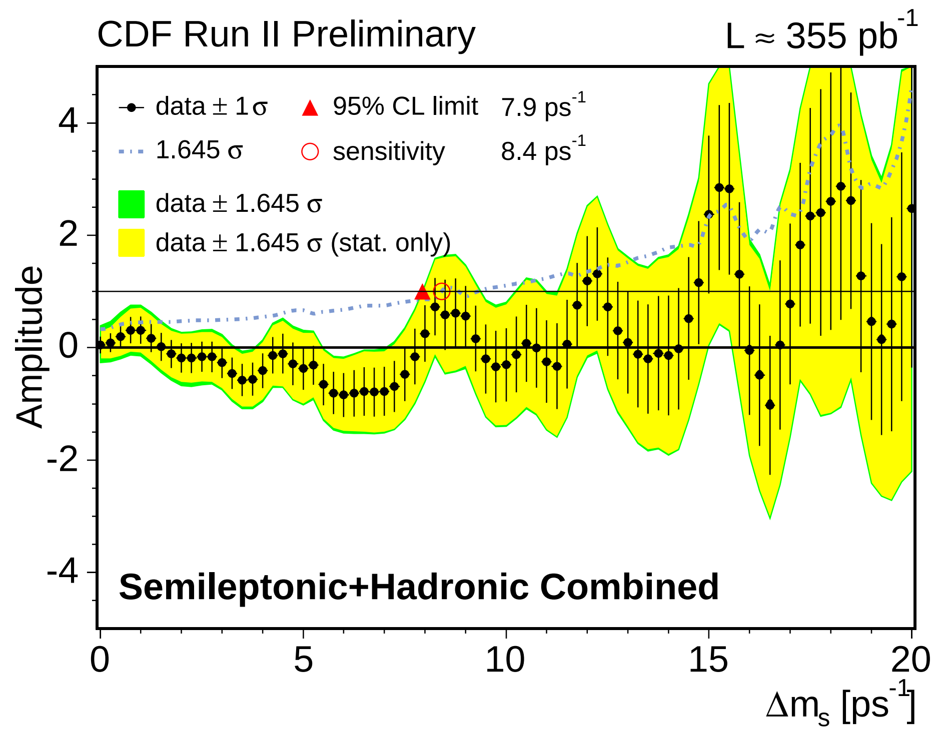


- introduce new parameter, amplitude A
  $\mathcal{L} \sim \frac{1 \pm A \cdot D \cdot \cos(\Delta m_s t)}{2}$
- fit for A for each Δm_s hypothesis

* 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.

First B_s Mixing Limits in Run II





D0:
Observed Limit at 95% C.L.: 5.0 ps^{-1}
(Sensitivity: 4.6 ps^{-1})

CDF:
Observed Limit at 95% C.L.: 7.9 ps^{-1}
(Sensitivity: 8.4 ps^{-1})

World Average:
Observed Limit at 95% C.L.: 14.5 ps^{-1} (Sensitivity: 18.5 ps^{-1})

Coming Improvements and Projections

Short term improvements (a few months scale)

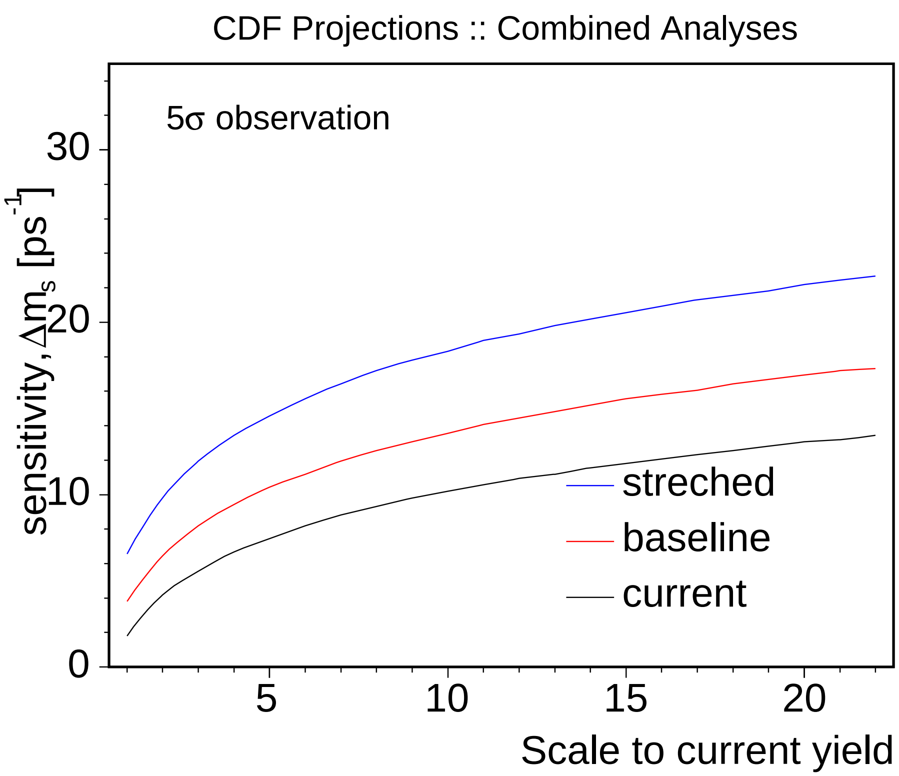
D0:

- Unbinned fitting procedure
- Addition of other taggers
- Use of other semileptonic decay modes
- Use of hadronic decay modes (!)

CDF:

- Use additional hadronic modes
- Use semileptonic events from other triggers
- Improve vertex resolution
- Use an improved version of the Jet Charge tagger
- Use Same-Side Kaon tagger (!)

Long term projections: Δm_s Measurement

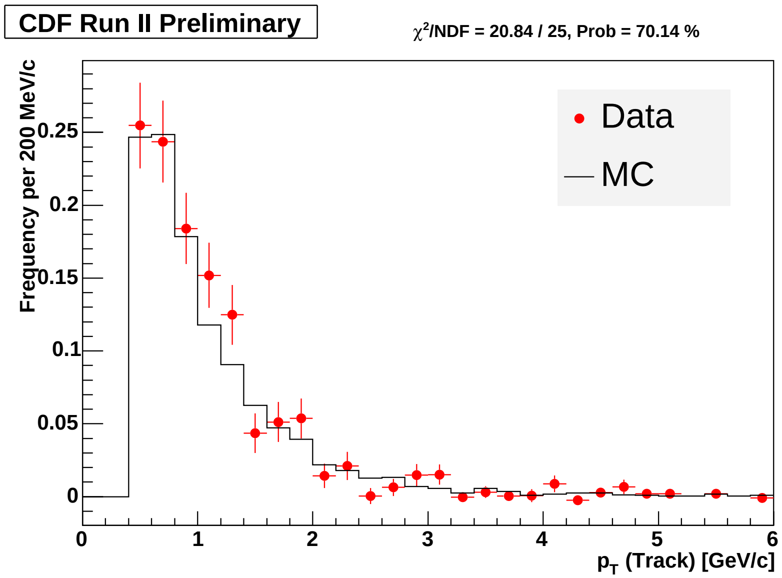


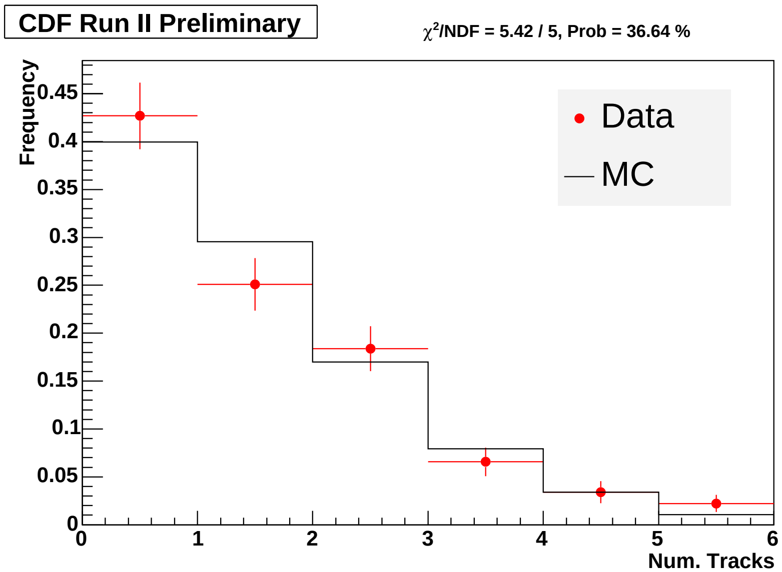
SSKT: Work in Progress (CDF)

- + There is no straightforward way to measure the tagger dilution on data unless we observe Mixing
- + On the other hand to set a limit we must know the dilution of the taggers

Therefore, we need to believe the SSKT MC prediction

Tune in progress!: we need to convince ourselves that MC is reproducing the charge correlation for B_s Mesons





Summary

- Tevatron experiments are in unique position to exploit B_s system

- A lot of new results on B_s decays in the last year
- First measurements of $\Delta\Gamma_s$ from D0 and CDF available
- Δm_d results are quite robust and consistent with world average
- First Δm_s Mixing limits in Run II from both D0 and CDF since last March, a huge room for improvements is still possible!
- We are working very hard to give both experiments very important contributions to the B_s Mixing world average as soon as possible!

Back Up Slides

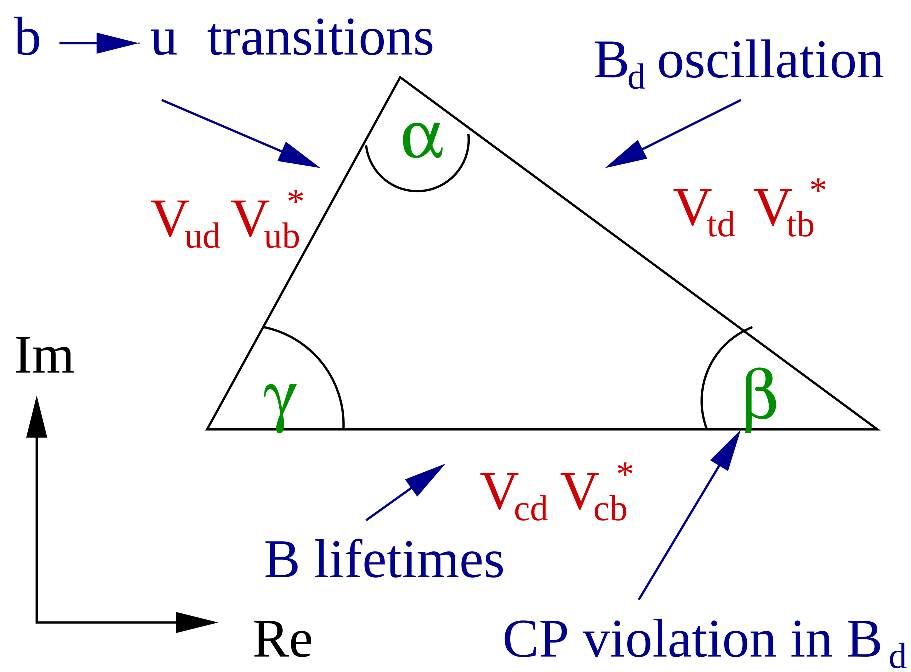
CKM Matrix

What is the origin of flavor symmetry breaking?
$\rightarrow$ quark mixing, CKM matrix

quark mass eigenstates
$\neq$ weak interaction eigenstates

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

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

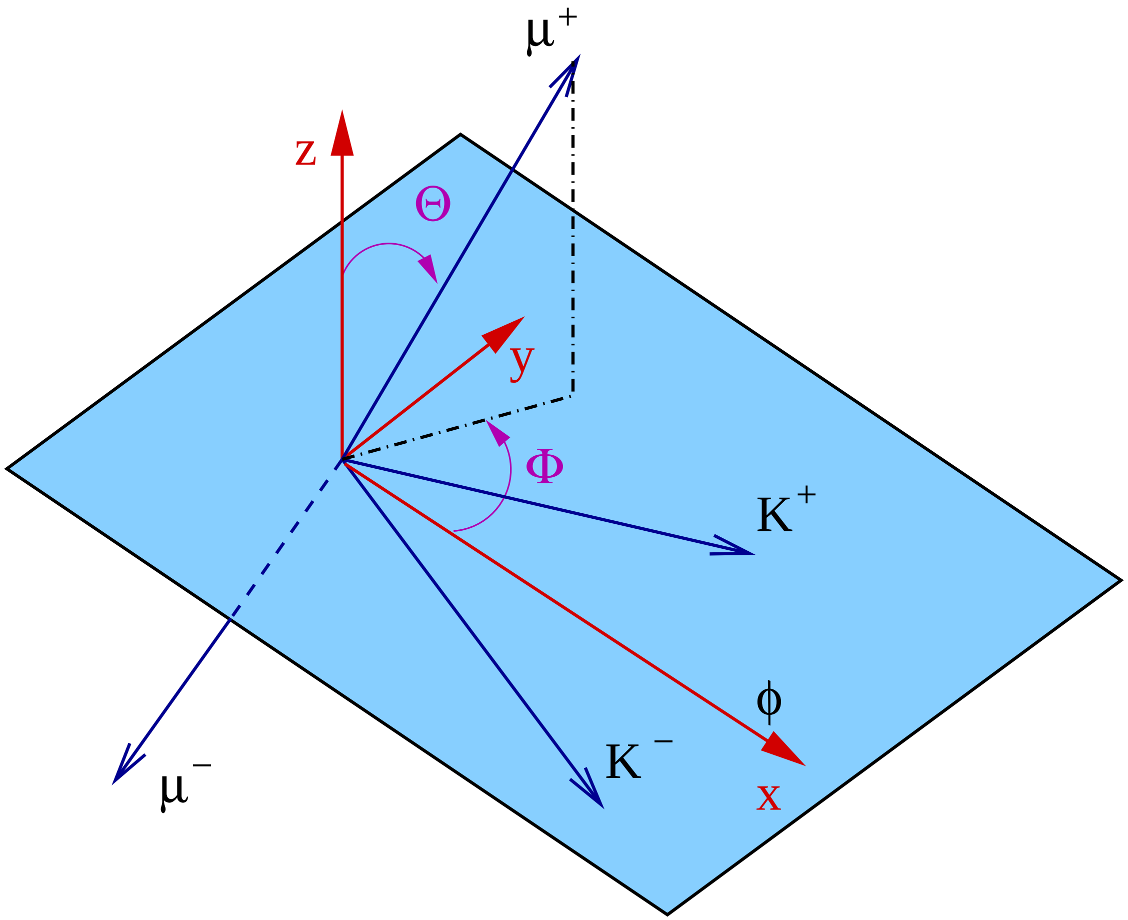


CKM elements not predicted by SM
B decays measure 5 CKM elements

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

Transversity Angles

$B_s \to J/\psi\phi$

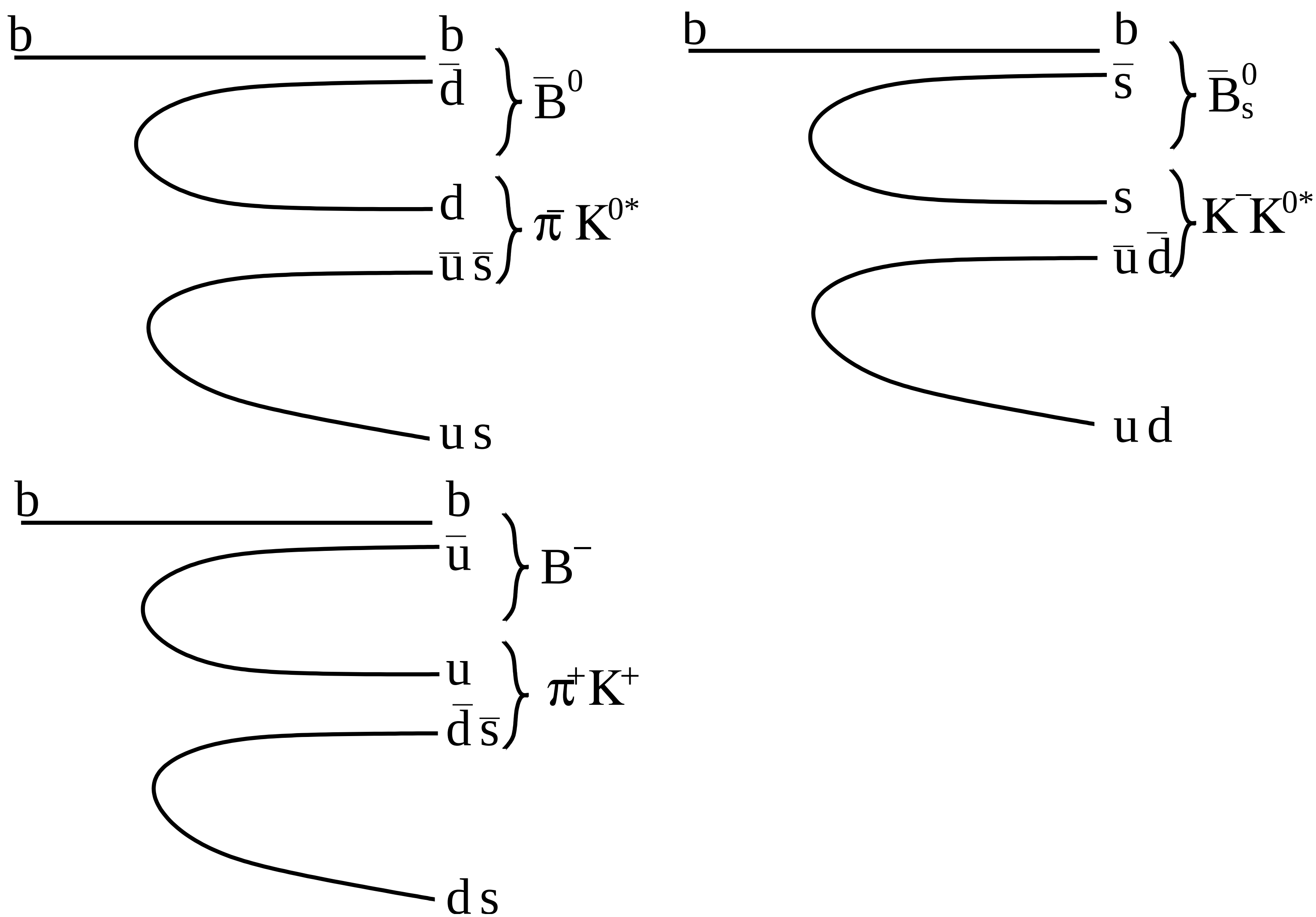


Work in J/ψ rest frame

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.

Δm_s: World Average