B Physics Today

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In this lecture:

- Machine and Detectors review
- b hadron production mechanisms and results
- B hadron lifetimes
- B-$\bar{B}$ mixing
- B meson lifetime differences

Next lecture from Stefano Giagu

- CP Violation
- Rare decays

Introduction

B physics measurements are high precision measurements

High statistic data samples

Dedicated machine or $p\bar{p}$

Dedicated trigger needed

High performances detectors

Tracking, Particle Identification..

How & where b are produced

Accelerator	Beams	Species	$\sqrt{s}$(GeV)	$\sigma_{b\bar{b}}$(nb)	$\sigma_{b\bar{b}}/\sigma_{tot}$
B factories	e^+e^- $\Upsilon(4s)$	B^0 & $B^\pm$	10.5	1.15	0.25
Tevatron	$p\bar{p}$	all	1,960	$1\cdot10^5$	$6\cdot10^{-4}$
LHC	pp	all	14,000	$5\cdot10^5$	?

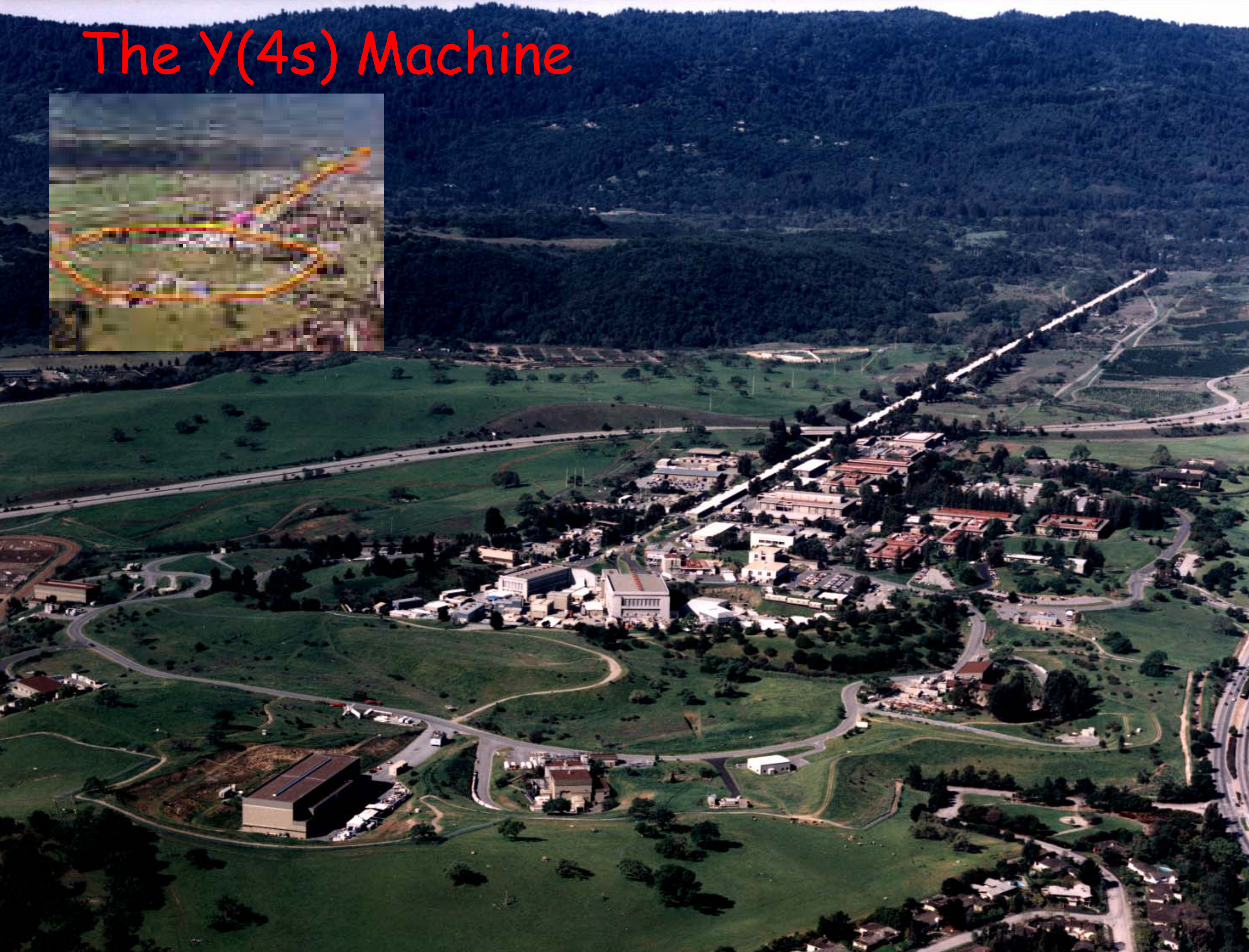
B factories produce only 2 species but very low background

$p\bar{p}$ interactions have all species but high background

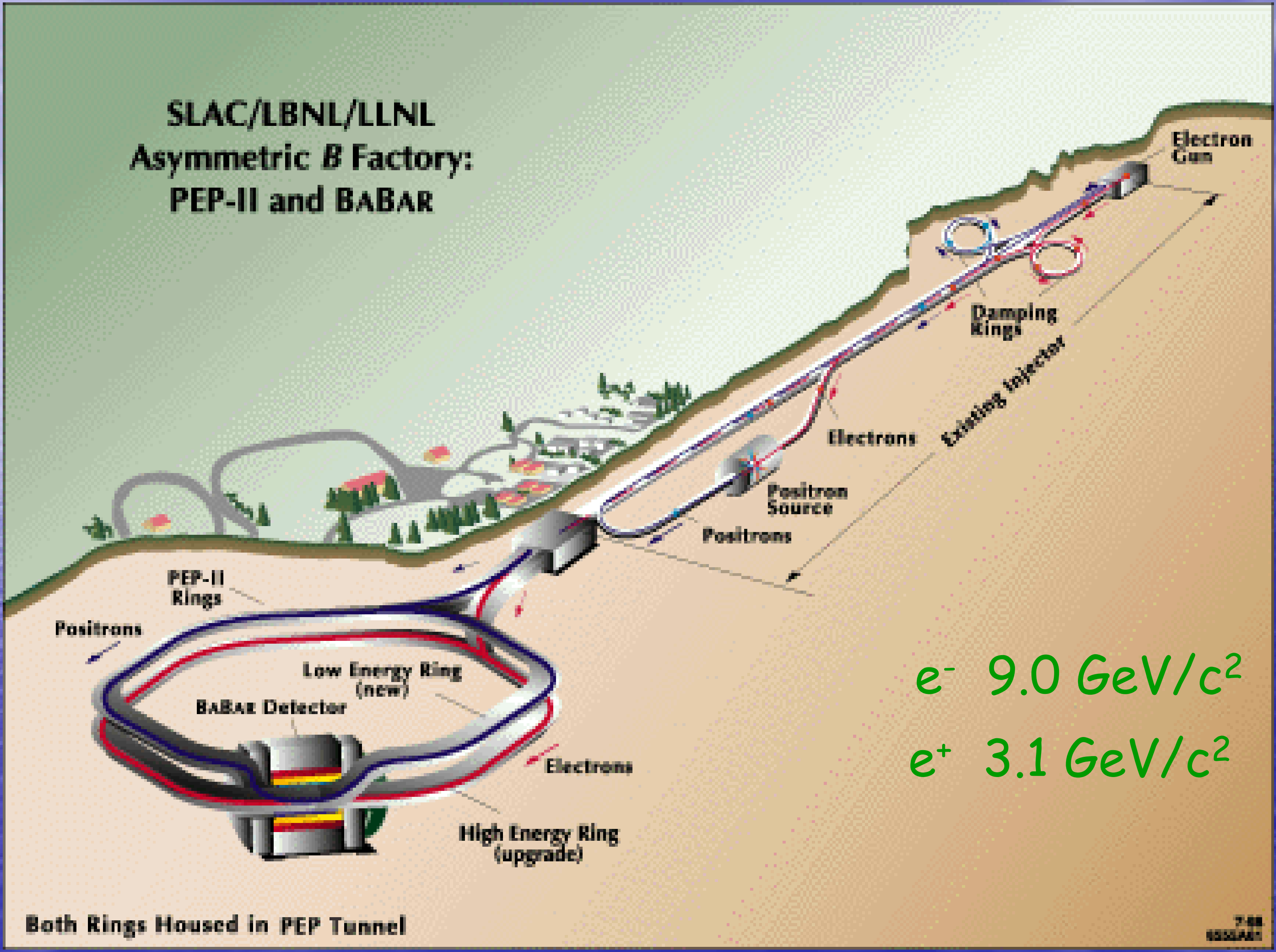
What is needed: detectors

- ✓ Magnetic field
- ✓ Tracking system
  - high space resolution
  - high momentum resolution
- ✓ Calorimeters
  - o fast and efficient to identify e
  - o good energy resolution to reconstruct decays as $\pi^0 \to \gamma\gamma$ or $\eta \to \gamma\gamma$
- ✓ Particle identification:
  - separate K from π
  - identify μ and e

The $\Upsilon(4s)$ Machine



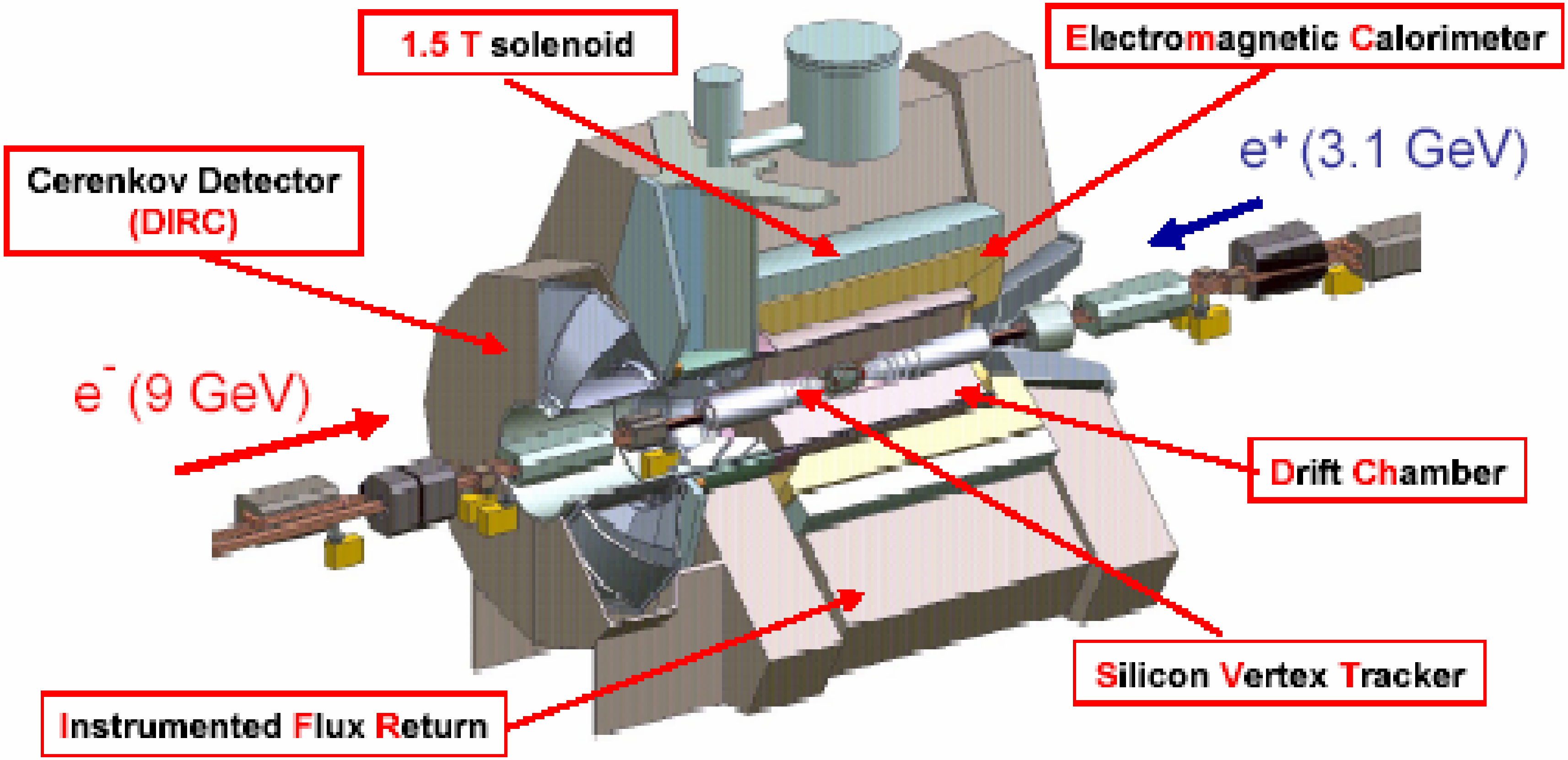
The Υ(4s) Machine



e^- 9.0 GeV/c^2

e^+ 3.1 GeV/c^2

Detectors: Babar



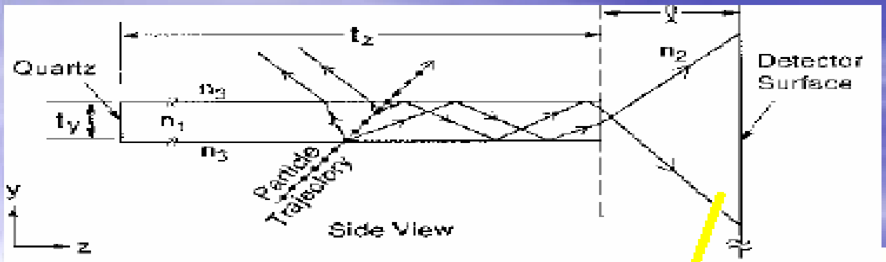
SVT: 97% efficiency, 15 μm z hit resolution (inner layers, perp. tracks)

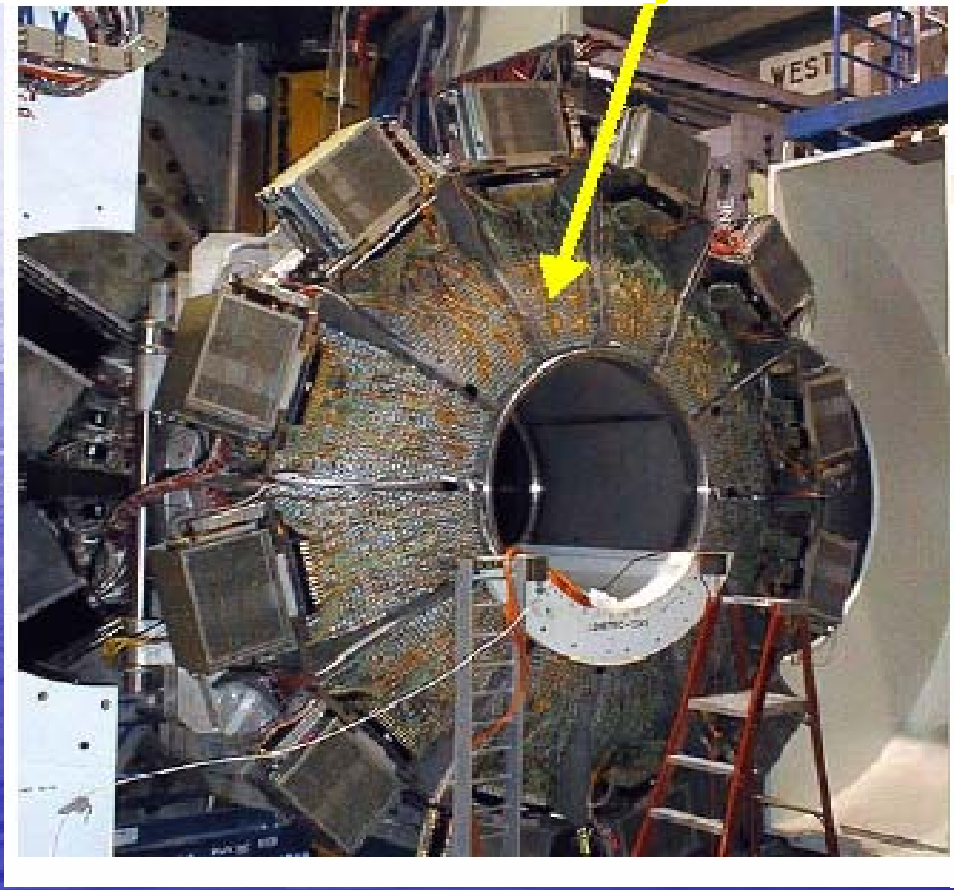
SVT+DCH: $\sigma(p_T)/p_T = 0.13\ \% \times p_T + 0.45\ \%$

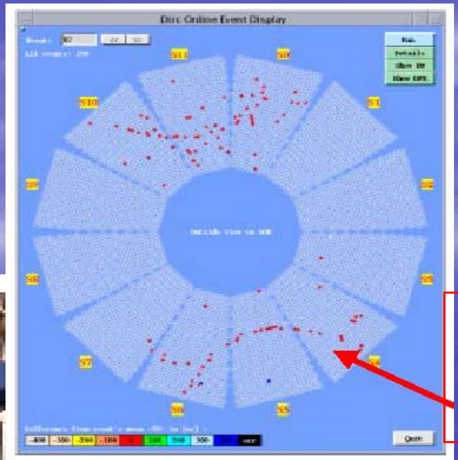
DIRC: K-π separation 4.2 σ @ 3.0 GeV/c → 2.5 σ @ 4.0 GeV/c

EMC: $\sigma_E/E = 2.3\ \% \cdot E^{-1/4} \oplus 1.9\ \%$

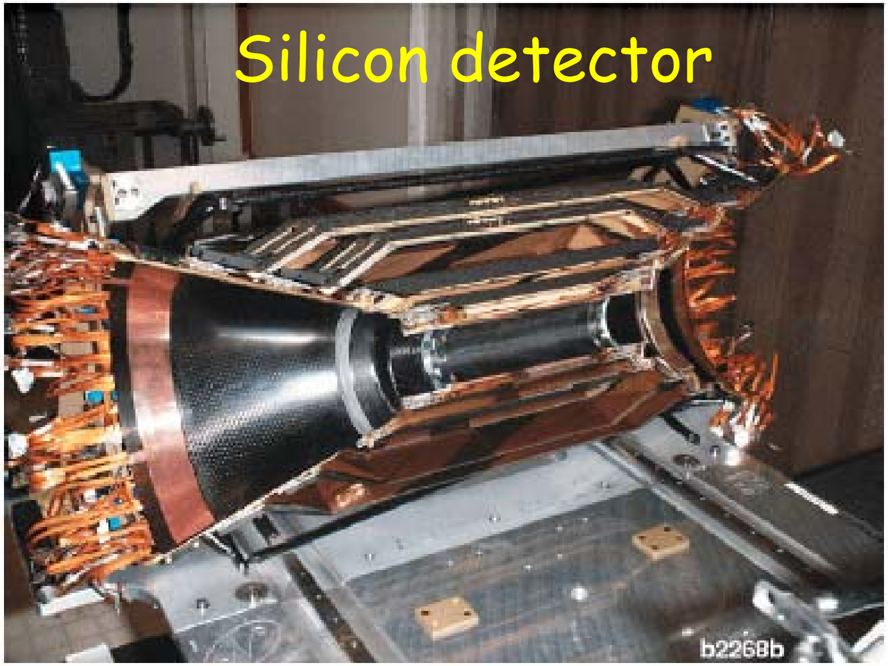
Detectors: Babar some details



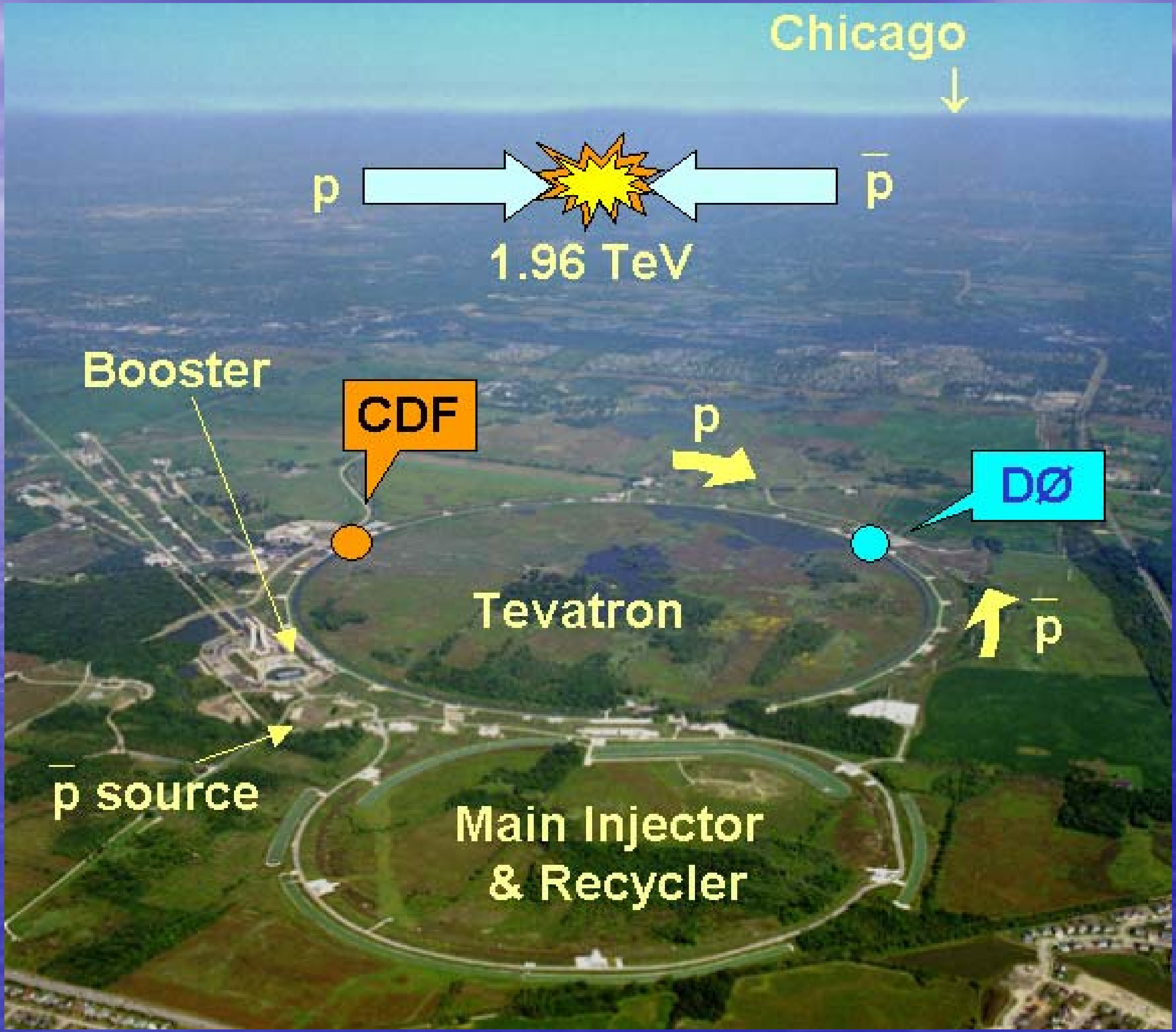




Cherenkov ring



The Tevatron Machine

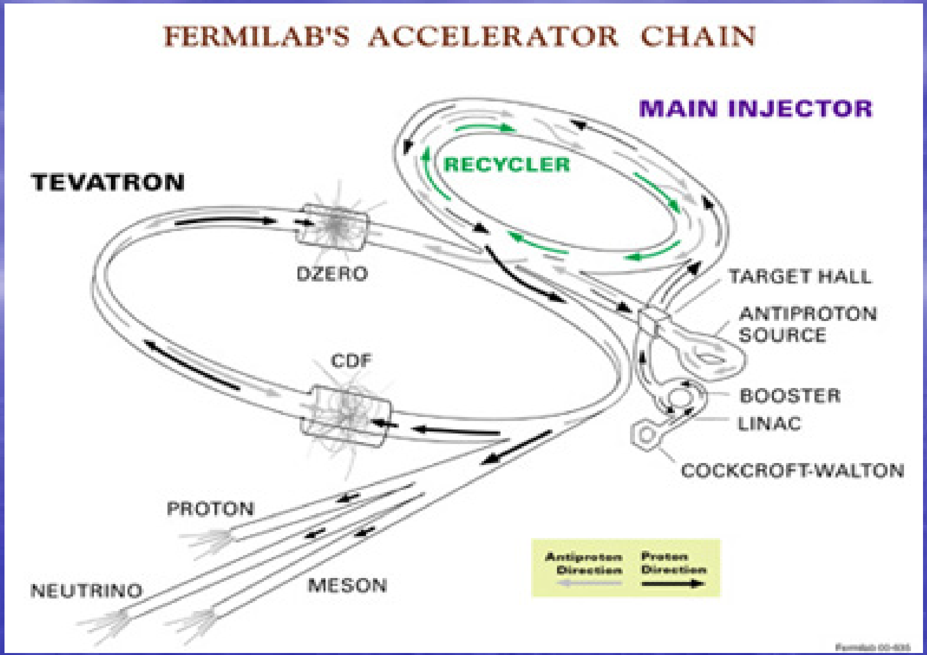


Tevatron Parameter

Substantial upgrades for Run II:

→10% energy increase √s: 1.8 → 1.96

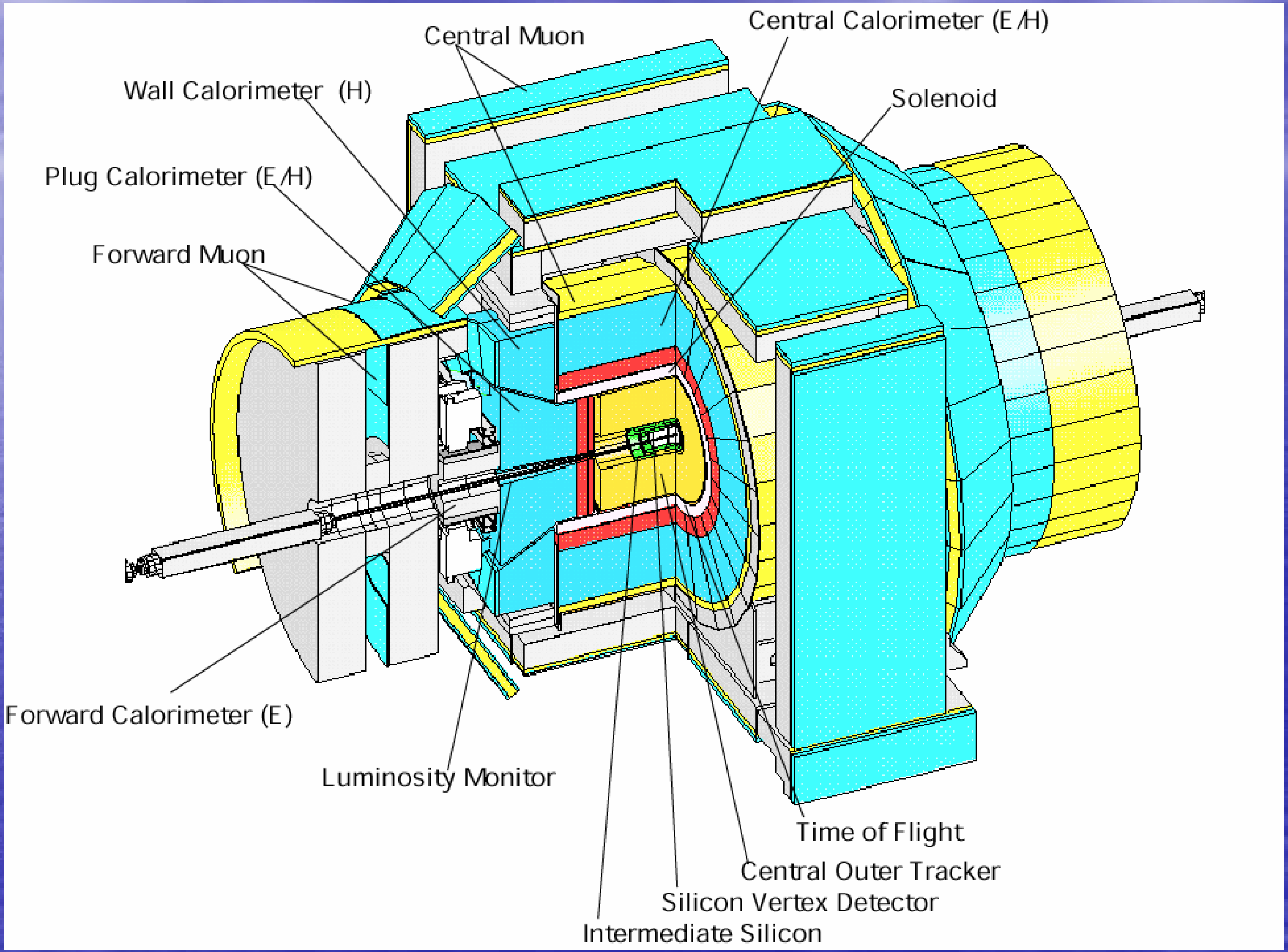
→integrated luminosity increase: x50



	1992-1995 Run I	2001-2009 Run IIa	Run IIb
Bunches in Turn	6 × 6	36 × 36	36 ×36
√s (TeV)	1.8	1.96	1.96
Typical L ($cm^{-2}s^{-1}$)	1.6×10^{30}	9×10^{31}	3×10^{32}
∫ Ldt (pb^{-1}/week)	3	17	50
Bunch crossing (ns)	3500	396	396
Interactions/crossing	2.5	2.3	8

6 km long Tevatron ring

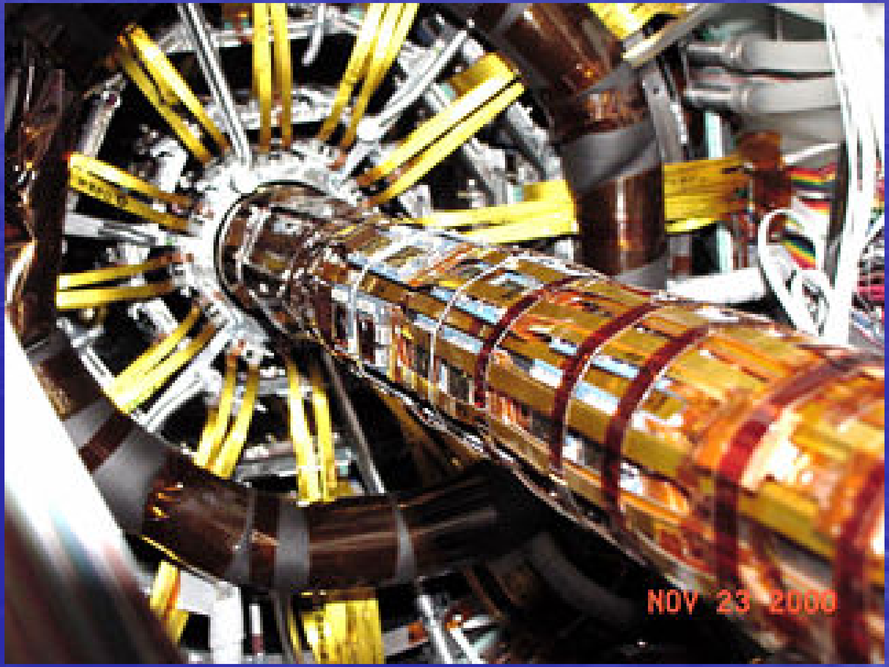
Detectors: CDF



Detectors: CDF some details

Central Outer Chamber:
96 layers
Max drift time 100 ns
Gas: Ar-Et-CF_4 (50:35:15)

Silicon tracker

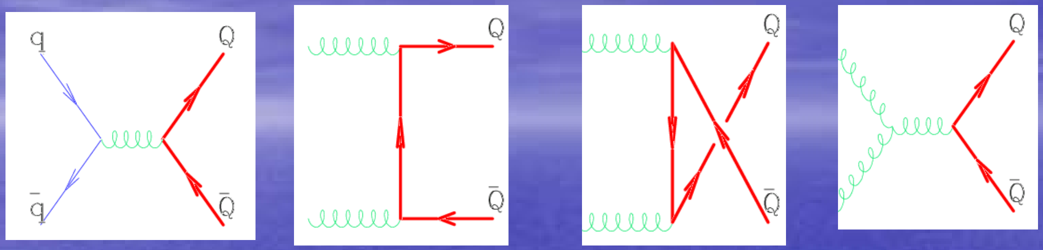


Charm and Beauty production at Tevatron

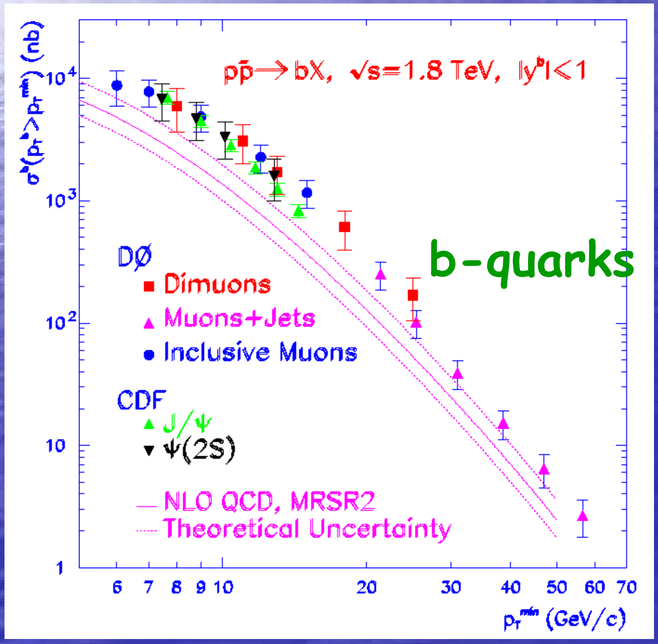
- Since $m_Q \gg \Lambda_{QCD}$ for c and b quarks, heavy quark production at the Tevatron should be well-calculable in QCD.
- Physics objects: hadrons & leptons (NOT quarks & gluons)
- Quarks $\rightarrow$ hadrons: hadronization (fragmentation)
- Fragmentation: phenomenological models non perturbative

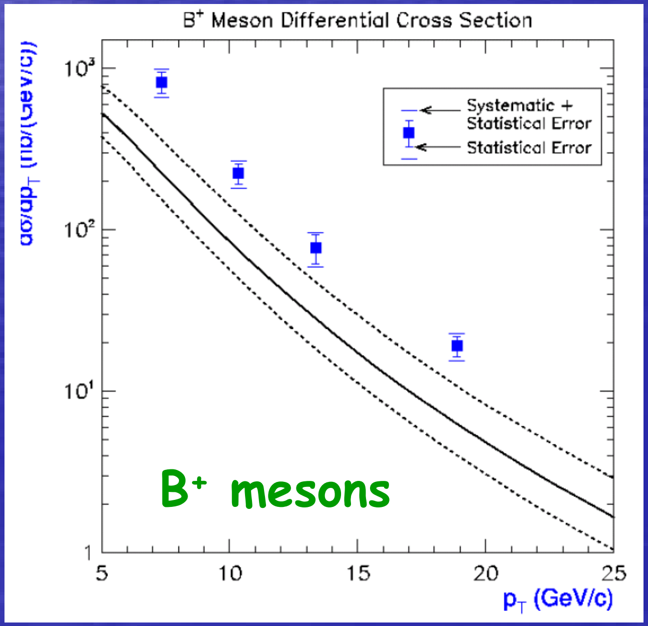
Charm and Beauty production at Tevatron

Diagrams at leading order:



Full calculations have been done up to NLO (and beyond…)
Therefore how do we explain Run 1 Tevatron results?





Experiment wrong?

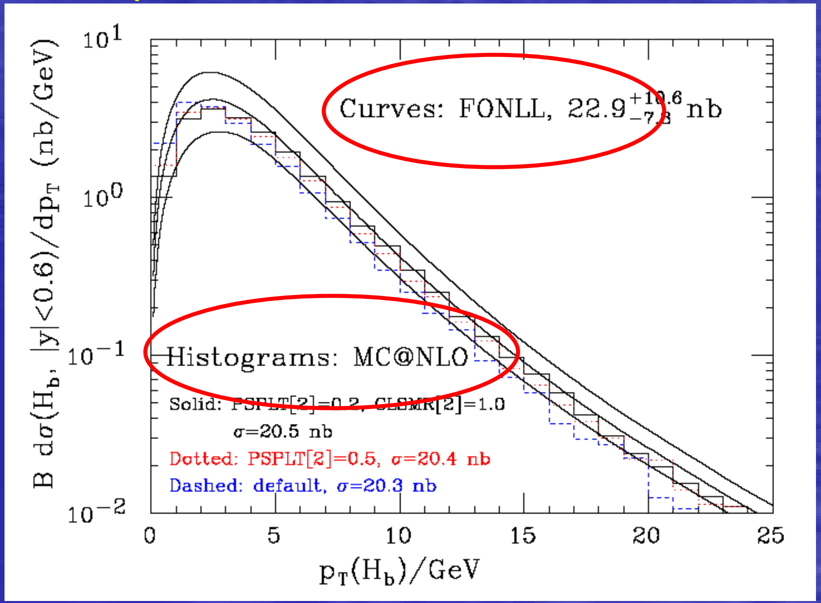
Theory prediction incomplete?

New physics?

Recent developments

In past years many (theoretical) developments:

- Use B meson rather than b-quarks: less dependent on unfolding and fragmentation uncertainties
- Beyond NLO: resummation of log(p_T/m) terms → FONLL (Cacciari et al). Important for medium/high p_T region.
- Extraction of fragmentation function parameters from LEP data in this scheme: substantially different ε_b
- new PDF's
- MC@NLO → match NLO calculation with PS formalism in HERWIG (Frixione, Nason, Webber)



- o Need more B data to compare with theory
- o Charm?

How CDF Collect Data

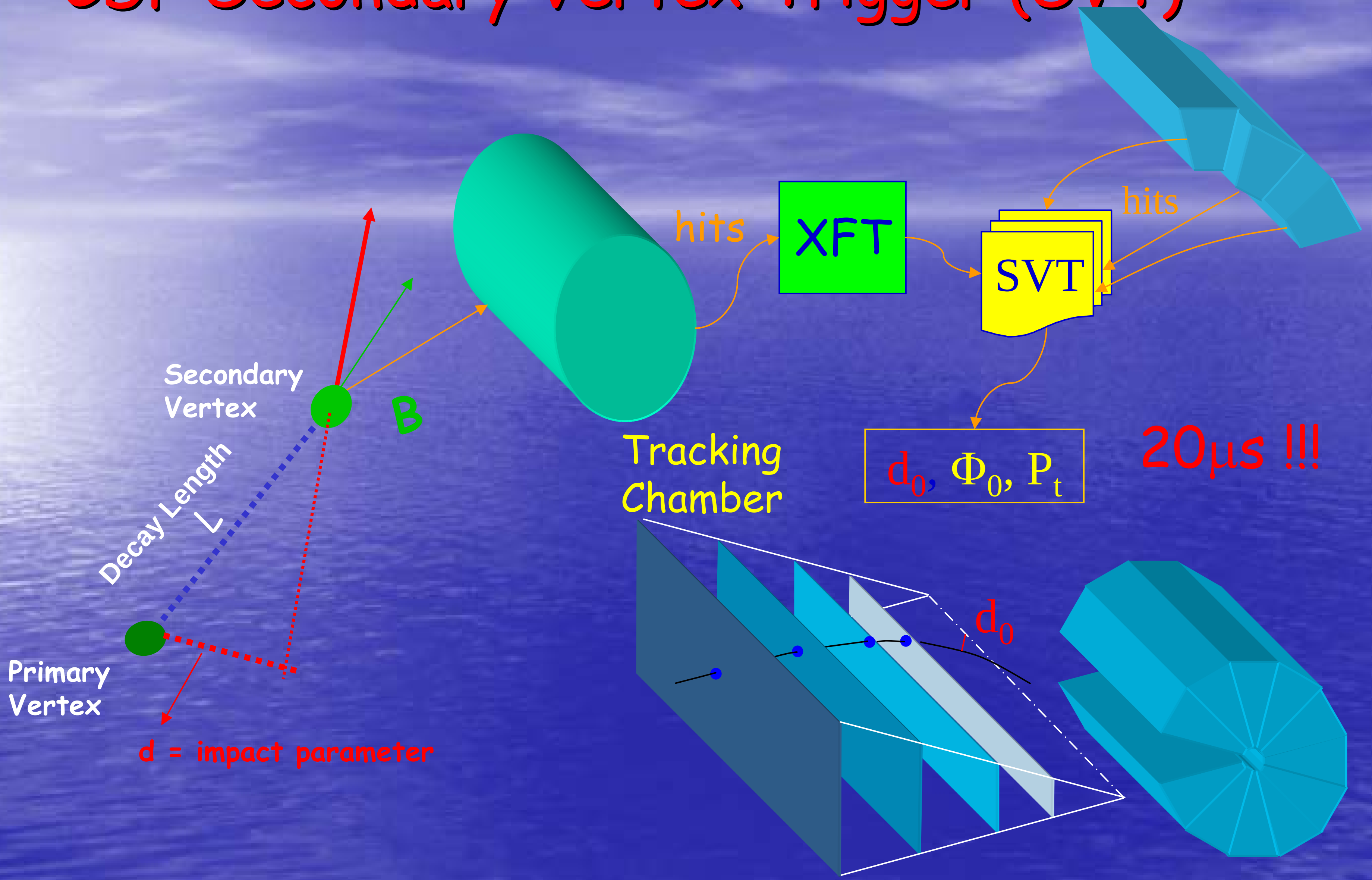
Raw data	Crossing rate 1.7 MHz Inelastic cross Section 56 mb
↓ Level 1 Trigger	Acc. Rate 40 KHz Latency 5.5 μs Pipeline
↓ Level 2 Trigger	Acc. Rate 300 Hz Latency 20 μs Buffer 4 events
↓ Level 3 Trigger	Acc. Rate 75 Hz
↓ Data set	Average size 60 Kbytes/event

Level 1 Synchronous streams:
- Calorimeter
- Fast tracker
- Muons

Level 2 asynchronous systems:
- Calorimeter clustering
- Track parameter available
- electrons

Level 3
- Offline-like

CDF Secondary Vertex Trigger (SVT)



Typical CDF trigger

- Two tracks vertex trigger:

  2 tracks reconstructed by SVT with:
  - pt>2 GeV/c
  - 120 μm < d_0 < 1 mm
  - pt1+pt2> 5.5 GeV/c

- Lepton + displaced track trigger:
  - Lepton (e or μ) with pt>4 GeV/c
  - Track reconstructed by SVT with pt>2 GeV/c

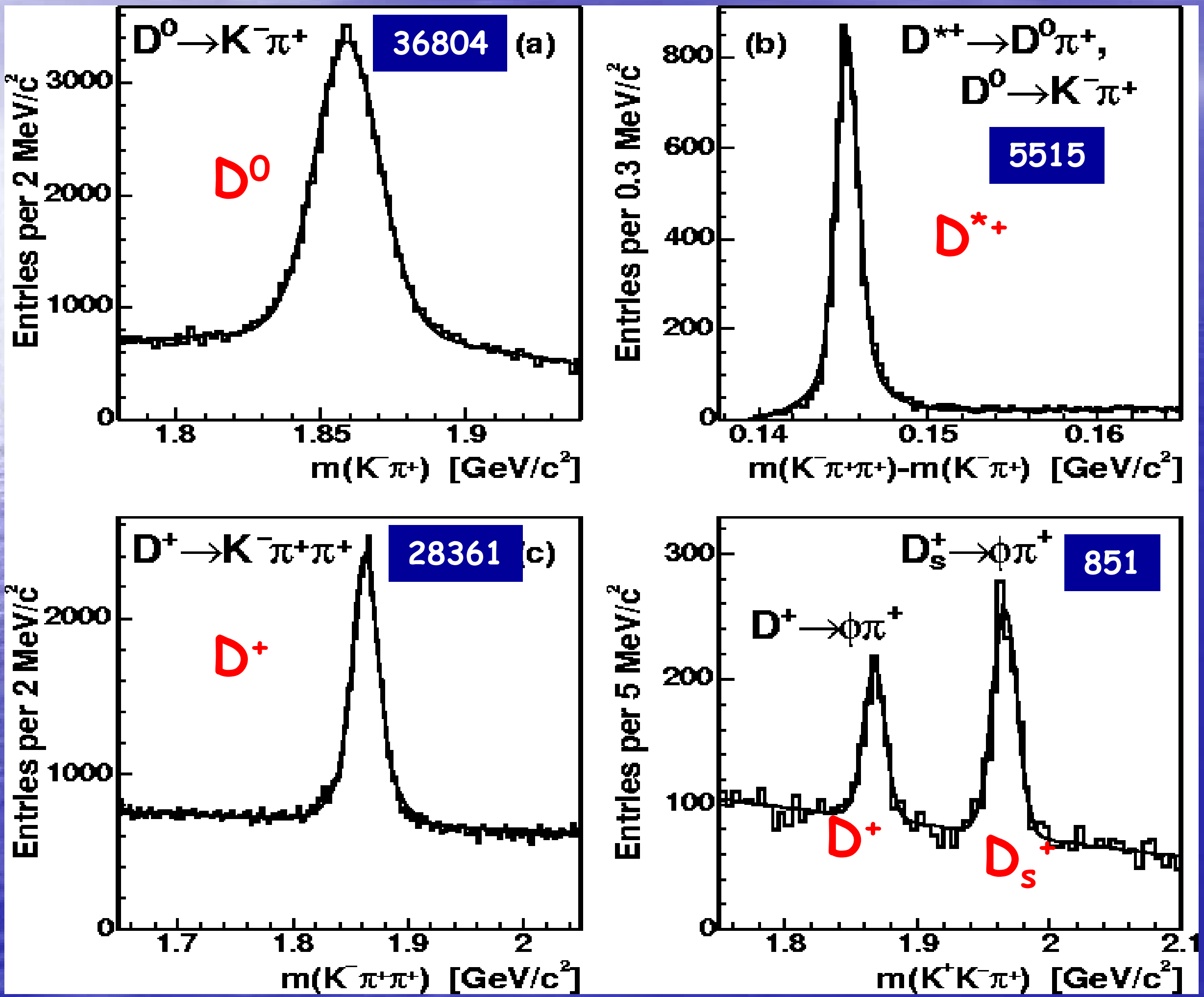
    120 μm < d_0 < 1 mm

- Di-muon trigger :

  2 muons pt>1.5 GeV/c

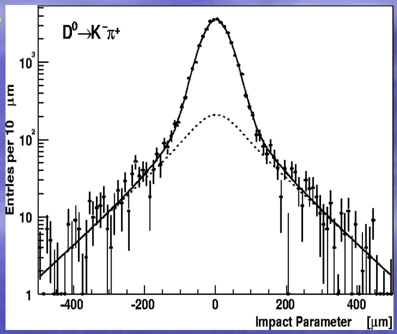
Charm Production: Open Charm meson

CDF: 5.8 pb^{-1}
taken with displaced track trigger.
>80% prompt production

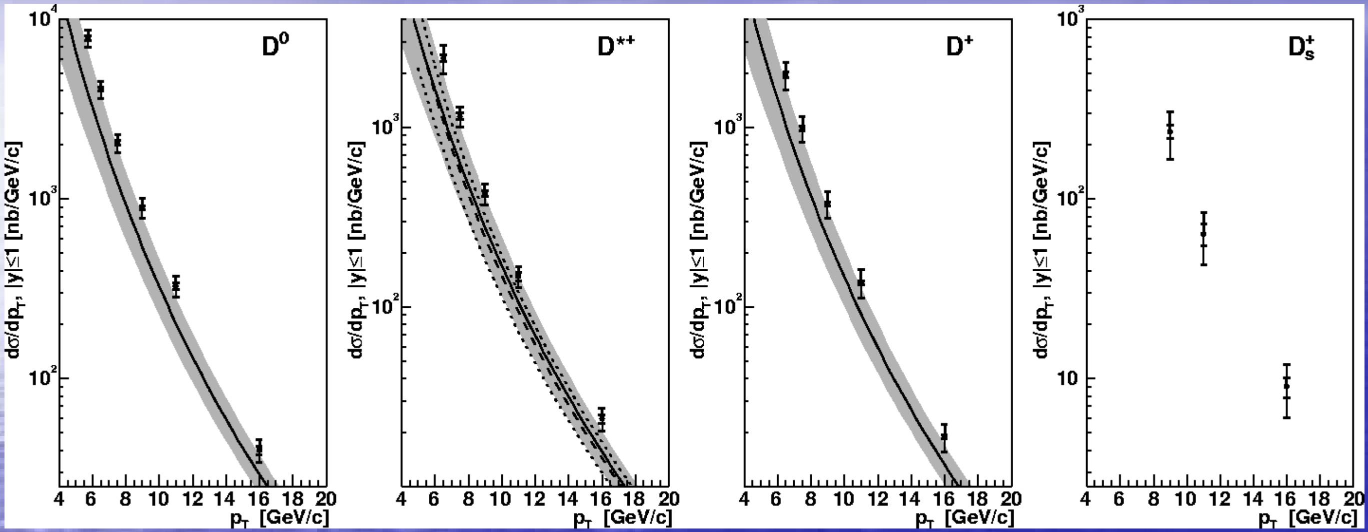


Open Charm Cross Section at CDF

Prompt charm production component extracted looking at impact parameter of reconstructed D meson

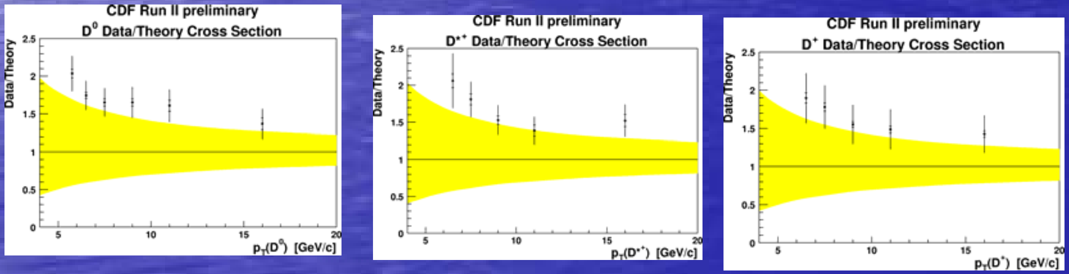


Compare to FONLL theory (Cacciari and Nason):



Prompt fraction:
- D^0: 86.6 ± 0.4%
- D^{*+}: 88.1 ± 1.1%
- D^+: 89.1 ± 0.4%
- D_s^+: 77.3 ± 3.8%

(±3-4% syst. err.)



Cross sections for $|y|<1$:
- $D^0(p_T>5.5$ GeV$)$: 13.3 ± 1.5 μb
- $D^{*+}(p_T>6.0$ GeV$)$: 5.2 ± 0.8 μb
- $D^+(p_T>6.0$ GeV$)$: 4.3 ± 0.7 μb
- $D_s^+(p_T>8.0$ GeV$)$: 0.75 ± 0.23 μb

Theory uncertainty: vary renormalization/factorization scales
data at upper limits of theory prediction

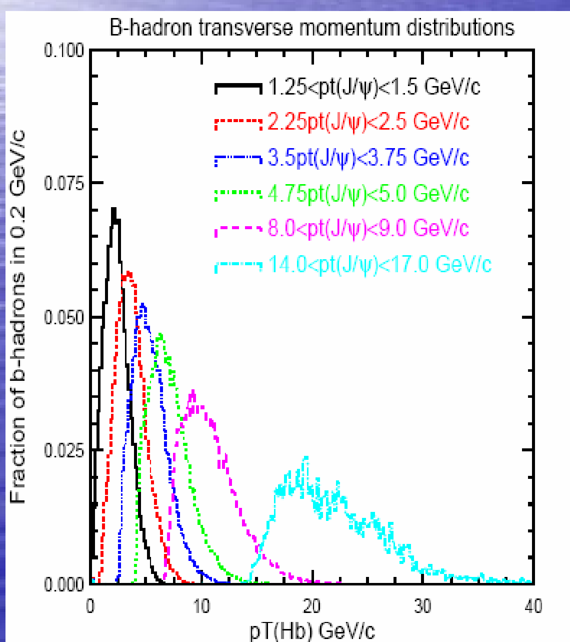
b-hadron from J/ψ Production at CDF

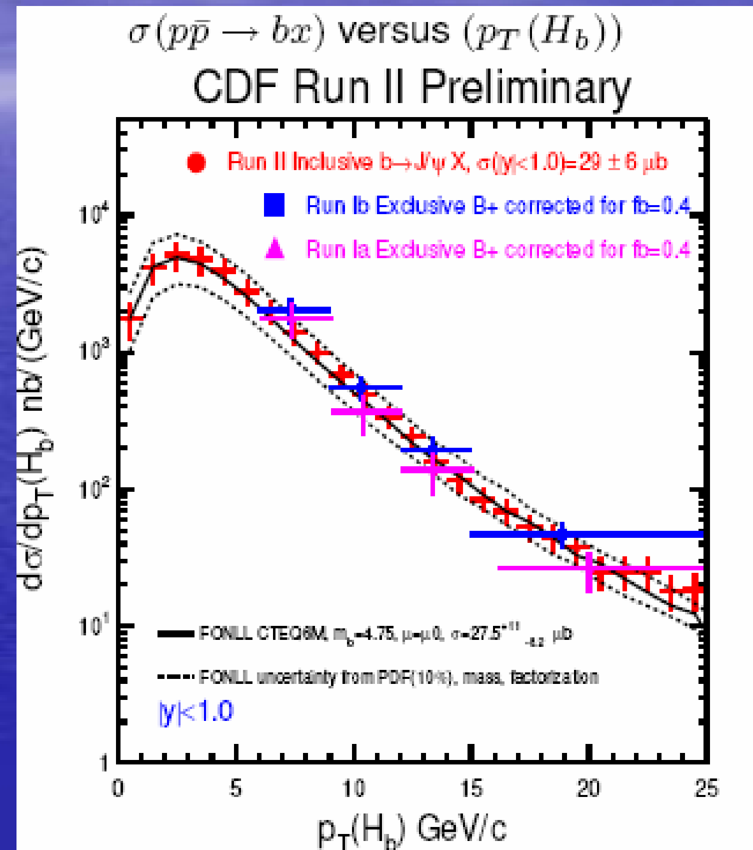
$J/\psi \rightarrow \mu\mu$ collected with di-muons trigger

To extract $d\sigma/dp_T(H_b)$:
Count the observed number of b-hadrons in a given $p_T(H_b)$ bin:

$$N_i^b = \sum_{j=1}^{N} w_{ij} N_j^{J/\psi}$$

w_{ij} is the fraction of b events in the i^{th} $p_T(H_b)$ from the j^{th} $p_T(J/\psi)$ b in obtained from MC





$\sigma(J/\psi \text{ from } H_b) = 19.9 \pm 3.8$ nb

$\sigma(H_b \rightarrow J/\psi, |y|<0.6) = 24.5 \pm 4.7$ nb

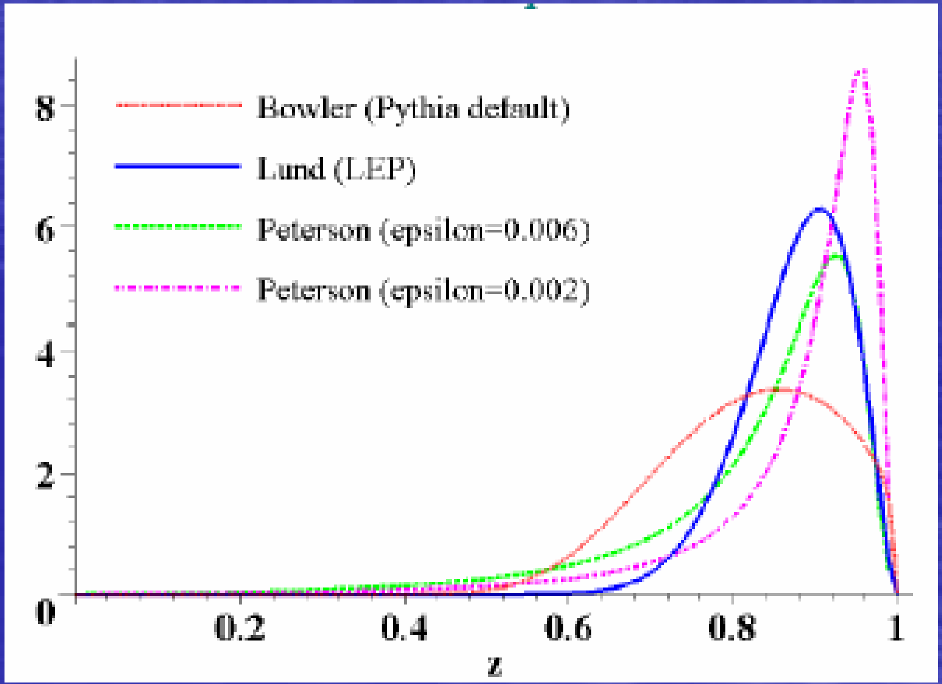
Fragmentation Function Studies at CDF

Due to QCD factorization fragmentation is supposed to be independent of the initial state.

Possible fragmentation functions models studied:

- Bowler
- Lund; favored by e^+e^- collider fragmentation analysis
- Peterson (soft ε=0.006, hard ε=0.002) widely used by experiments. It does not describe well e^+e^- data.

$$z = \frac{(E + p_L)_B}{(E + p)_b}$$



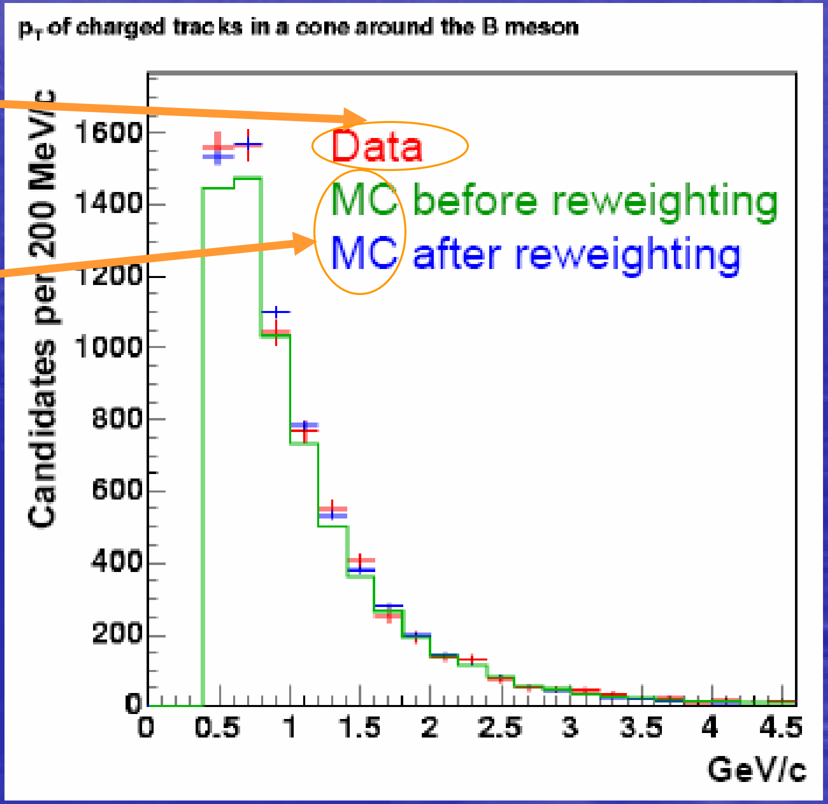
Fragmentation Function Studies: Plan

1. Find more sensitive variables
2. Compare data/Monte Carlo changing fragmentation model
   1. Fit the chosen variables
   2. Change the hadronization parameters

   } Iterative process

$B^+ \to J/\psi K^+$

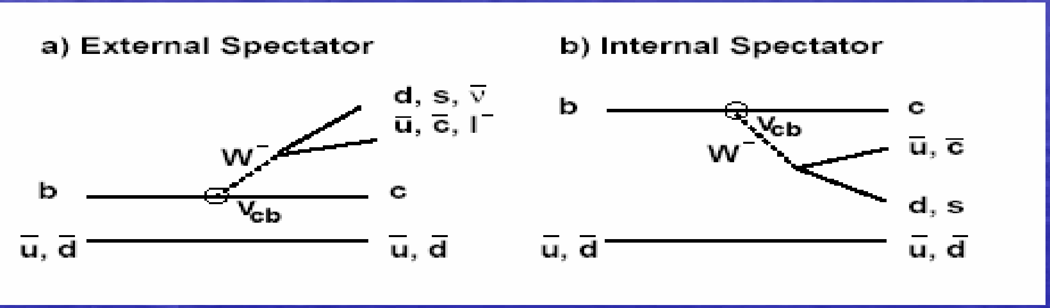
Pythia: all process



Reweighting tracks Pt In a cone (R=0.7) around B using Lund Model

Lifetimes Determination: Theory

- Important for:
  - Mixing measurements
  - Test decay dynamics information on non perturbative QCD effects
- Described by HQET:
- LO: spectator model $\tau(Bu)/\tau(Bd)=\tau(B_s)/\tau(B_d)=\tau(\Lambda b)/\tau(Bd)=1$



- NLO:

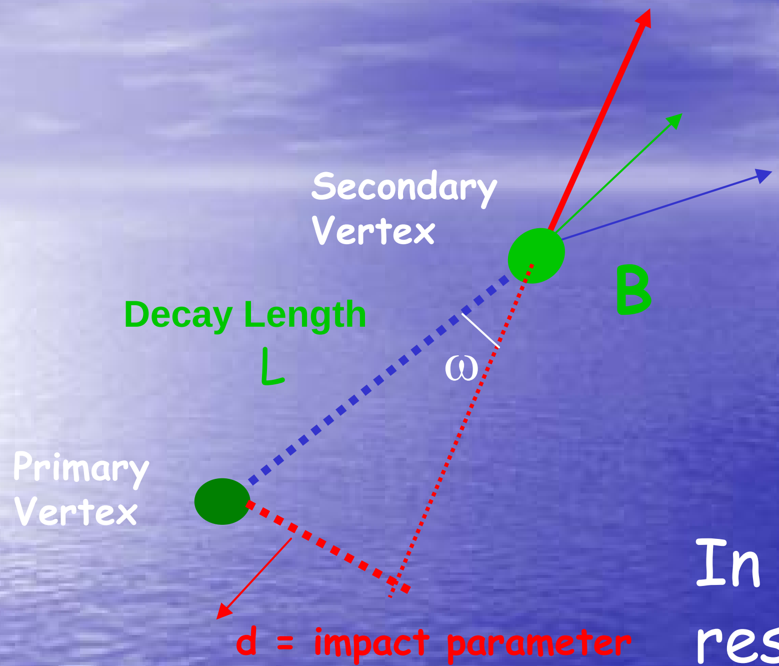
$$\frac{\tau(B^+)}{\tau(B_d)} = 1.09 \pm 0.03$$

$$\frac{\tau(\Lambda_b)}{\tau(B_d)} = 0.87 \pm 0.05$$

$$\frac{\tau(B_s)}{\tau(B_d)} = 1.00 \pm 0.01$$

hep-ph/0407004

Lifetimes: experimental techniques



Proper time

$L = \gamma\beta c t$

$\gamma\beta = p_B/m_B$

$$ct = \frac{L \cdot m_B}{p_B}$$

Needs:

1) Decay length
2) momentum

In the transverse plane respect to the beam line

$$ct = \frac{L^{xy} \cdot m_B}{p^t_B}$$

First measurements done by using impact parameter:

$d^{xy} = \gamma\beta ct \cdot \sin\omega$ $\quad \sin\omega \sim \gamma^{-1}$ $\quad d^{xy} \approx ct$ (relativistic approx)

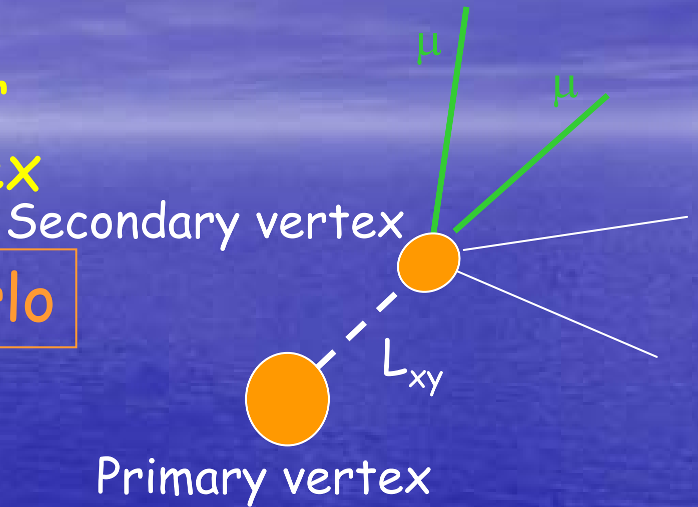
Finally fit the t distribution to extract τ_B

Lifetimes Measurements at CDF

- Inclusive and semi-exclusive measurements: $B \to J/\psi X$, $J/\psi \to \mu\mu$ and $B \to lDX$
  - $J/\psi \to \mu\mu$ collected with muon trigger
  - The J/ψ vertex is the B decay vertex

$$ct = \frac{Lxy\, m_B}{P_t^{J/\psi}} F^{corr}$$

F^{corr} → from Monte Carlo



  - Fit ct to extract the B lifetime

- Exclusive measurements: $B \to D\pi$
  - Data collected mainly with lepton + displaced track or displaced tracks
  - Fit the secondary decay products to find secondary vertex

$$ct = \frac{Lxy\, m_B}{P_t^{B}}$$

Exclusive life time measurement

Decay modes:

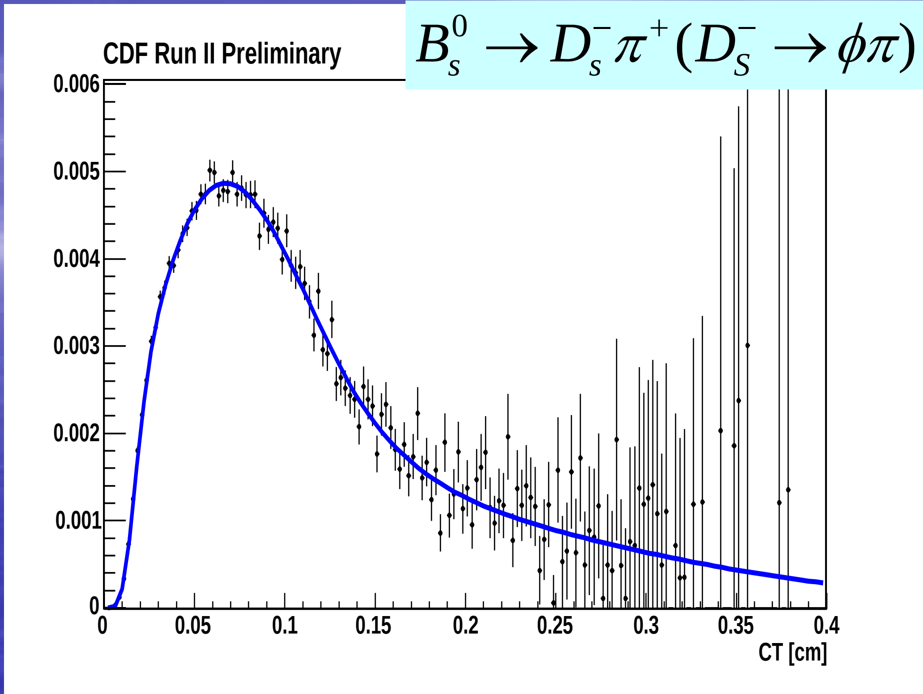
$B^{\pm}$: $D^0\pi^{\pm}$ [8380 ev.] ($D^0 \to K\pi$)

B^0: $D^{\pm}\pi^{\mp}$ [5280 ev.] ($D^{\pm} \to K\pi\pi$)

$D^{\pm}\,3\pi$ [4173 ev.] ($D_{\pm} \to K\pi\pi$)

B_s: $D_s\,\pi^{\pm}$ [465 ev.] ($D_s \to \phi\pi$)

$D_s\,3\pi$ [133 ev.] ($D_s \to \phi\pi$)

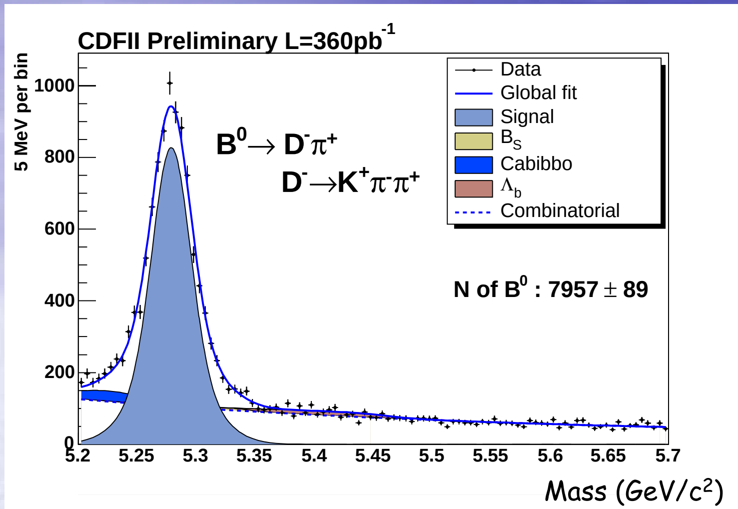


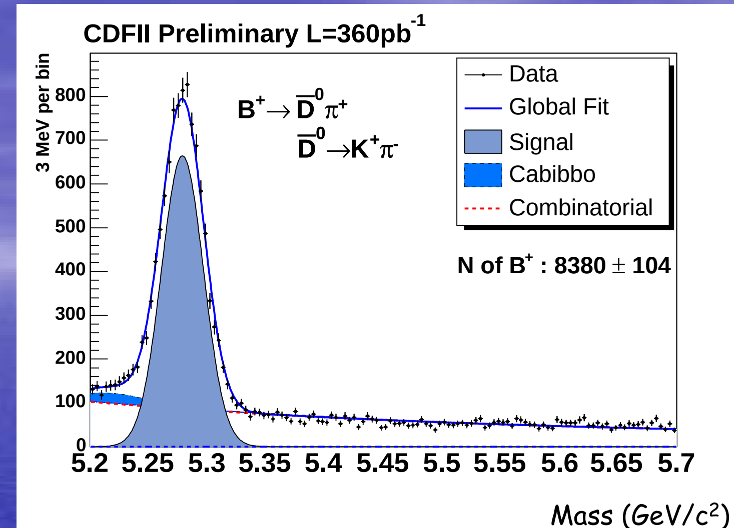
- Events selected with displaced tracks trigger
- Trigger and reconstruction requirements affect L_{xy}:
  - Impact parameter cuts at low ct
  - SVT acceptance at high ct

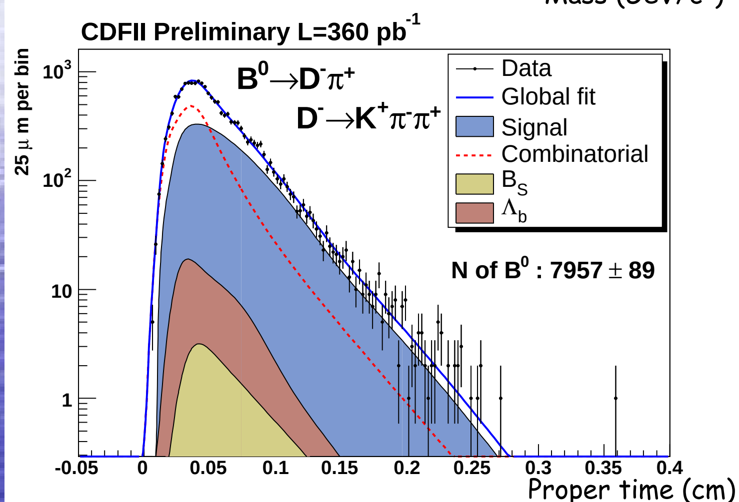
"ct" efficiency from Monte-Carlo, needed:

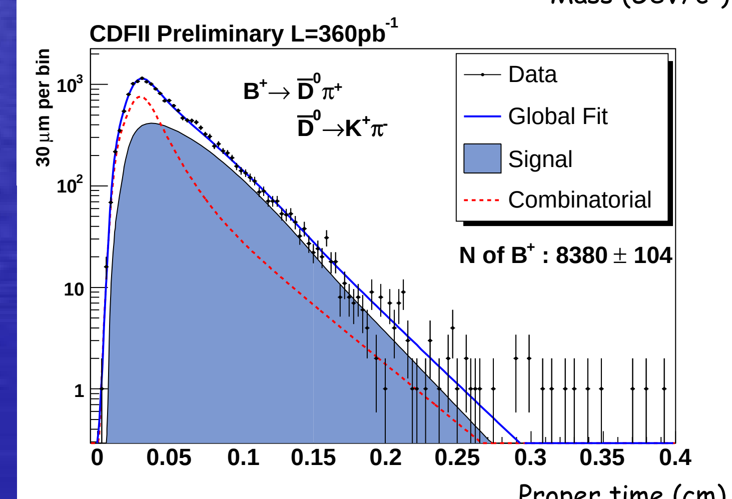
- B production/decay model
- detailed Trigger/Detector simulation

Hadronic B^0 and B^+ Lifetime Results









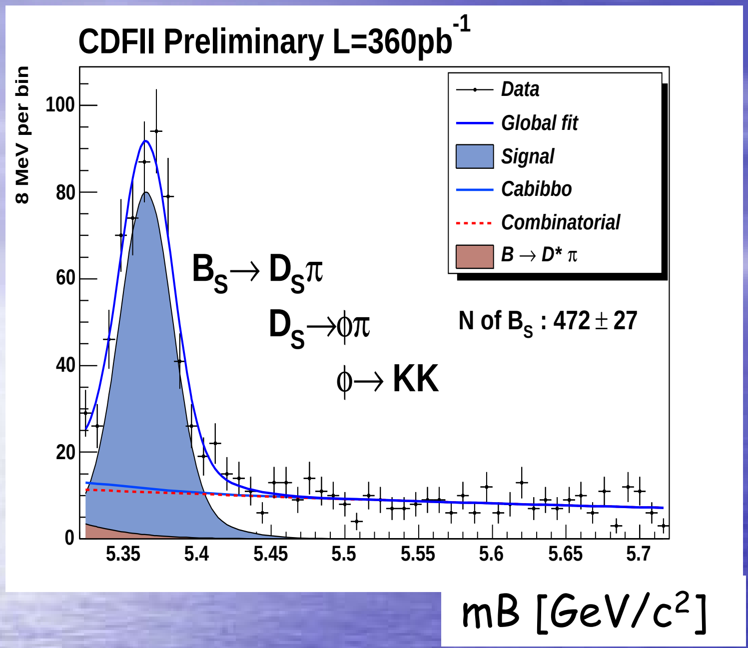
τ_{B0}=1.511±0.023(stat)±0.013(syst) ps

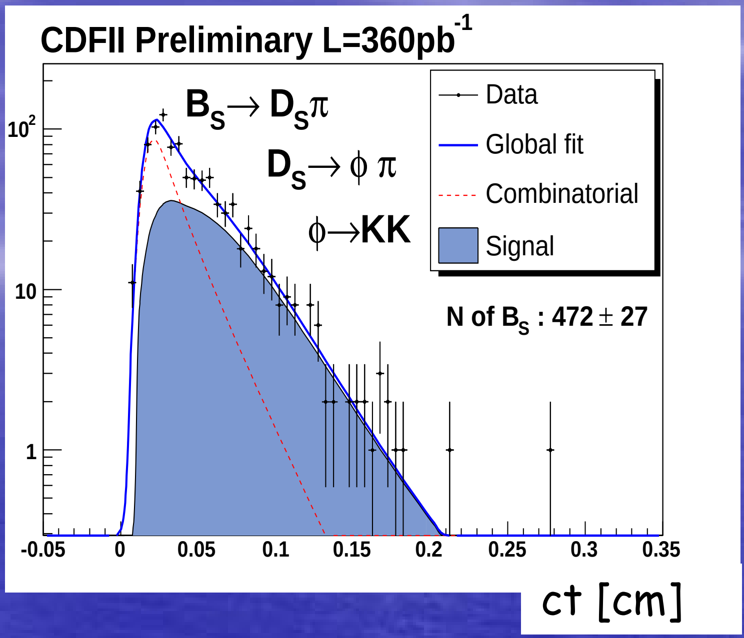
τ_{B0}=1.528±0.009 World Average

τ_{B+}=1.661±0.027(stat)±0.013(syst) ps

τ_{B0}=1.643±0.010 World Average

Hadronic B_s Lifetime Results





$\tau(B_s)$ =1.598±0.097(stat)±0.017(syst) ps

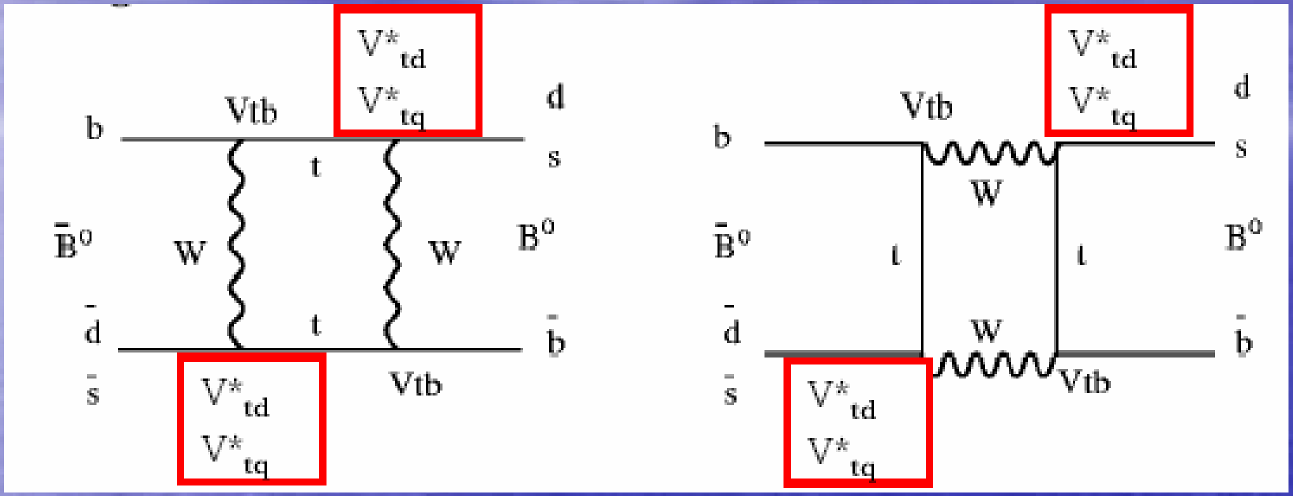
W.A.: $\tau(B_s)$ = 1.469 ± 0.059 ps

Systematic error Summary on ct

Effect	Variation
Pt re-weight	1.9
Kg ct description	1.1
Bkg fraction	2.0
I.P. correlation	2.2
Eff. Parameterization	1.5
Alignm. + others	2.6
Total	4.7

Decay Rates of neutral B meson

- Contribution at lowest order in the standard Model:



- Time evolution:

$$i\frac{d}{dt}\begin{pmatrix}|B^0\rangle \\ |\overline{B}^0\rangle\end{pmatrix} = H\begin{pmatrix}|B^0\rangle \\ |\overline{B}^0\rangle\end{pmatrix} \quad \text{with } H = M - i\frac{\Gamma}{2} \equiv \begin{pmatrix}M_{11} & M_{12} \\ M_{21} & M_{22}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22}\end{pmatrix}$$

Decay Rates of neutral B meson

- Mass eigenstates $|B_1\rangle$, $|B_2\rangle$ with masses $m_1^{(q)}$ $m_2^{(q)}$ and decay widths $\Gamma_1^{(q)}$, $\Gamma_2^{(q)}$:

  $\Delta m_q \equiv m_1^{(q)} - m_2^{(q)}$ $\quad \Delta\Gamma_q \equiv \Gamma_1^{(q)} - \Gamma_2^{(q)}$ $\quad \Gamma_q \equiv \frac{1}{2}(\Gamma_1^{(q)} + \Gamma_2^{(q)})$

$$\left|B_1^0\right\rangle = \frac{\left|B^0\right\rangle - \left|\overline{B}^0\right\rangle}{\sqrt{2}} \quad \text{and} \quad \left|B_2^0\right\rangle = \frac{\left|B^0\right\rangle + \left|\overline{B}^0\right\rangle}{\sqrt{2}}$$

- Time evolution with $\Delta\Gamma = 0$:

$$P_{B^0 \to B^0}(t) = P_{\overline{B}^0 \to \overline{B}^0}(t) = \frac{e^{-t/\tau}\left(1 + \cos\left(\Delta m t\right)\right)}{2\tau}$$

$$P_{B^0 \to \overline{B}^0}(t) = P_{\overline{B}^0 \to B^0}(t) = \frac{e^{-t/\tau}\left(1 - \cos\left(\Delta m t\right)\right)}{2\tau}$$

Mixing frequency

- Inside the Standard Model:

$$\Delta m_q = \frac{G_F^2}{6\pi^2} |V_{tb}|^2 |V_{tq}|^2 M_W^2 M_{B_q^0} f_{B_q^0}^2 B_{B_q^0} \eta_{B_q^0} S\left(\frac{M_t^2}{M_W^2}\right)$$

non perturbative QCD ($f_{B_q^0}^2 B_{B_q^0}$)

perturbative QCD ($\eta_{B_q^0}$)

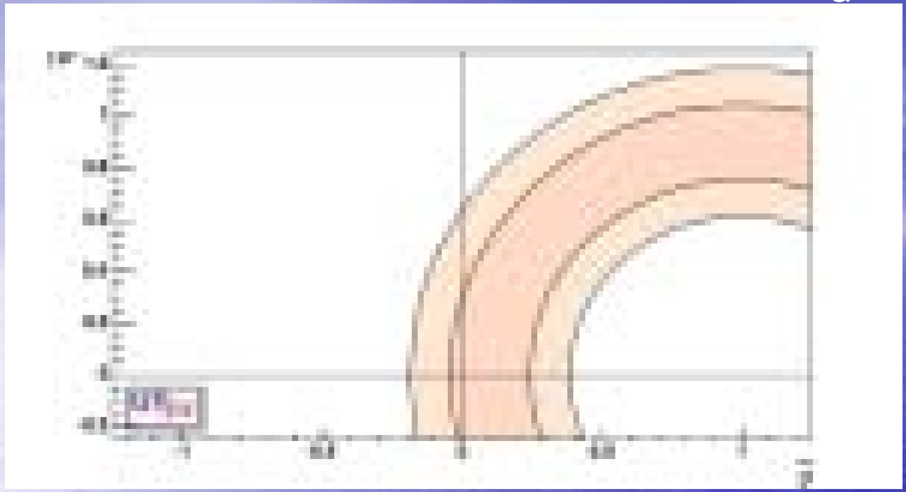
$$\frac{\Delta m_d}{\Delta m_s} = \frac{|V_{td}|^2}{|V_{ts}|^2} \frac{M_{B_d^0}}{M_{B_s^0}} \frac{\eta_{B_d^0}}{\eta_{B_s^0}} \frac{f_{B_d^0}^2 B_{B_d^0}}{f_{B_s^0}^2 B_{B_s^0}}$$

$\frac{\eta_{B_d^0}}{\eta_{B_s^0}} \cong 1$

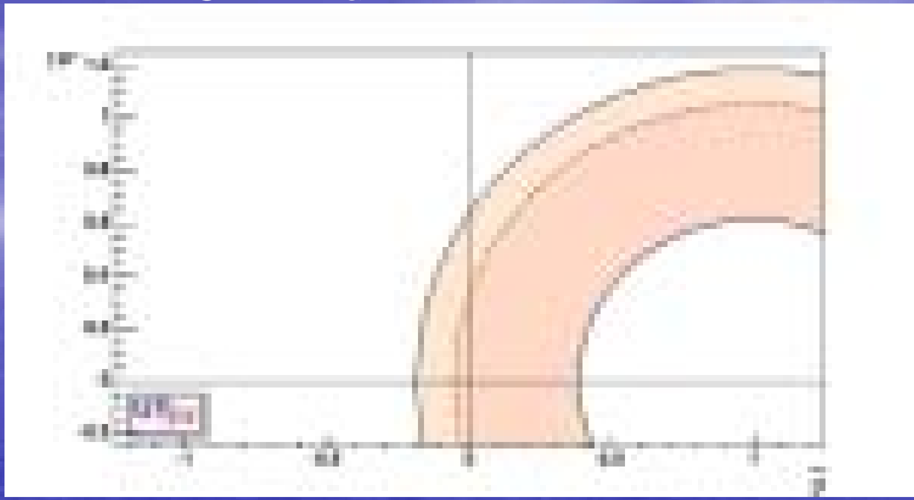
SU(3) Flavor breaking theoretical uncertainties <5%

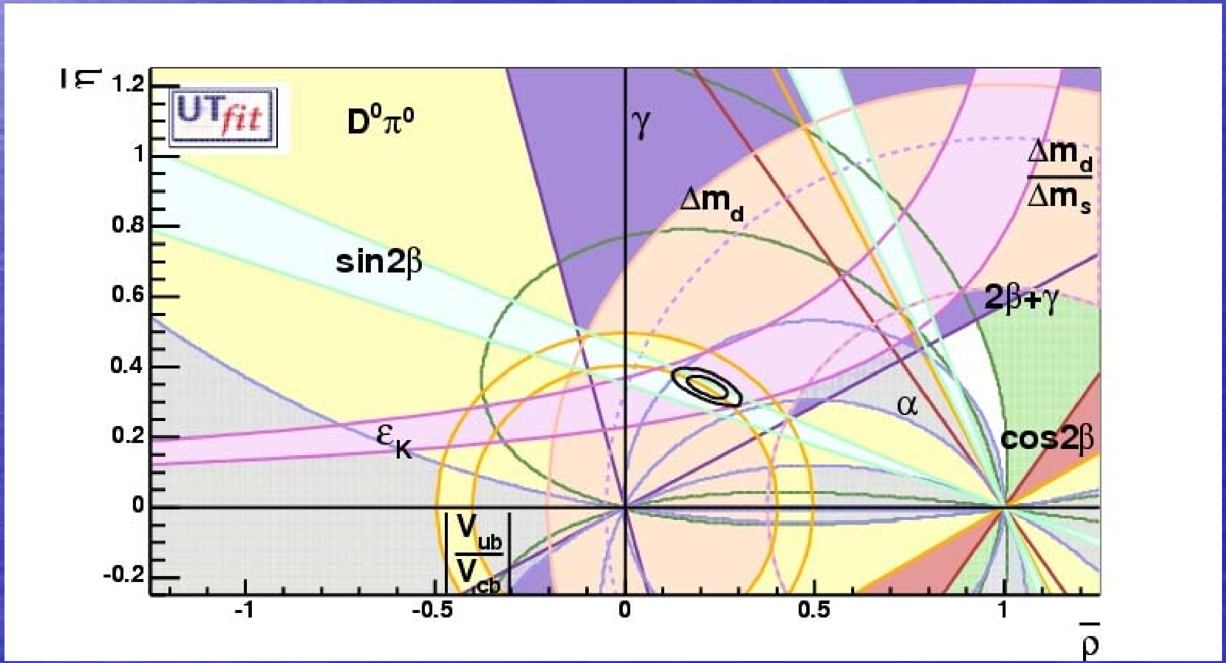
CKM constraint

Δm_d

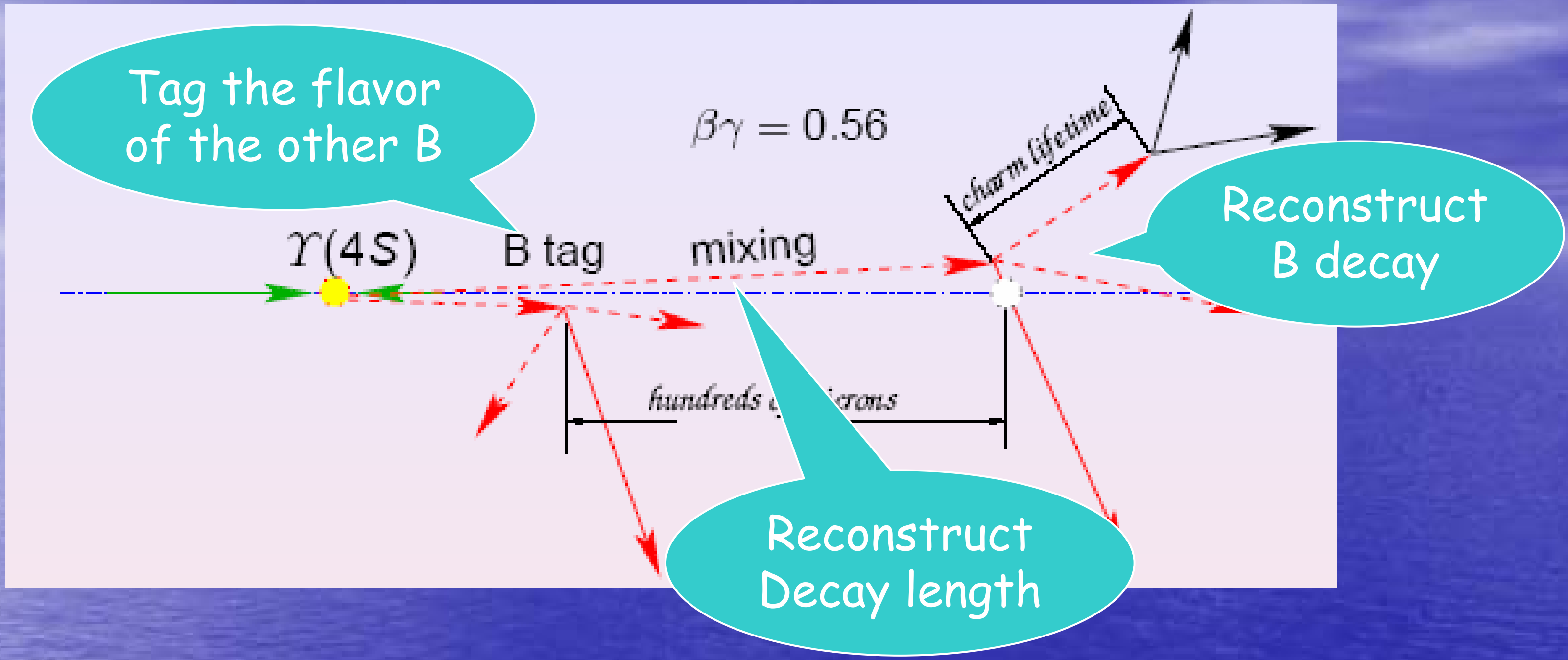


$\Delta m_s/\Delta m_d$





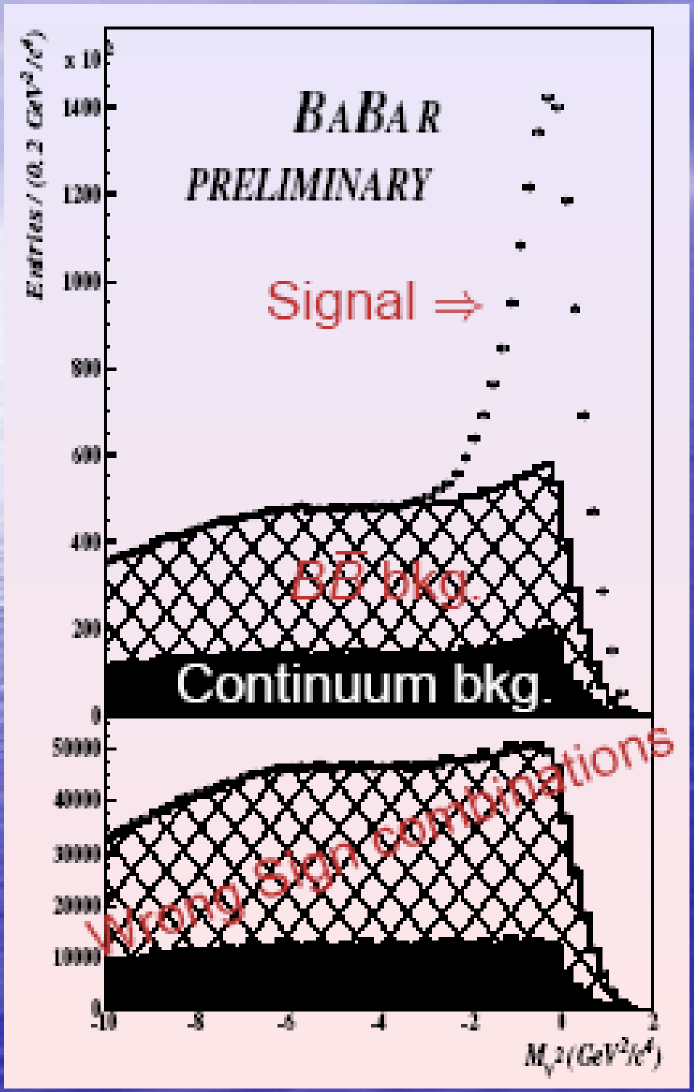
ΔM_d and lifetime measurement at Babar



Probabilities of observing mixed (S^-) or unmixed (S^+) as function of proper time difference:

$$S^{\pm} = \frac{e^{-\Delta t/\tau_{B^0}}}{4\tau_{B^0}}(1 \pm D\cos(\Delta m_d \Delta t))$$

Partial $B^0 \rightarrow D^{*-} l^+ \nu$ reconstruction



$B^0 \rightarrow D^{*-} l \nu \quad D^{*-} \rightarrow \pi^-_{soft} \bar{D}^0$

Reconstruction cuts:

- Lepton: $1.3 < p < 2.4$ GeV/c
- Soft pion: $60 < p < 200$ MeV/c
- D^0 : not reconstructed.

Limited phase space in D^{*-} decay:

- π^-_{soft} ~ at rest in D^{*-} frame
- $p_{D^*} \sim \parallel p_{\pi\text{-}soft}$
- $E_{D^*} \sim f(E_{\pi\text{-}soft})$ from Monte Carlo

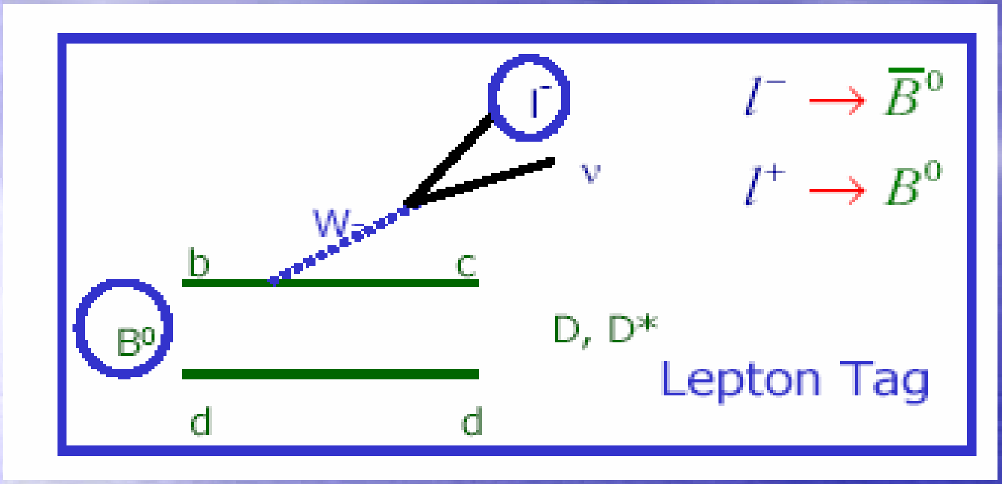
Since B^0 ~ at rest in $\Upsilon(4s)$ frame:

$$M^2_\nu = \left(\frac{\sqrt{s}}{2} - E_{D^{*+}} - E_l\right)^2 - (p_{D^{*+}} + p_l)^2$$

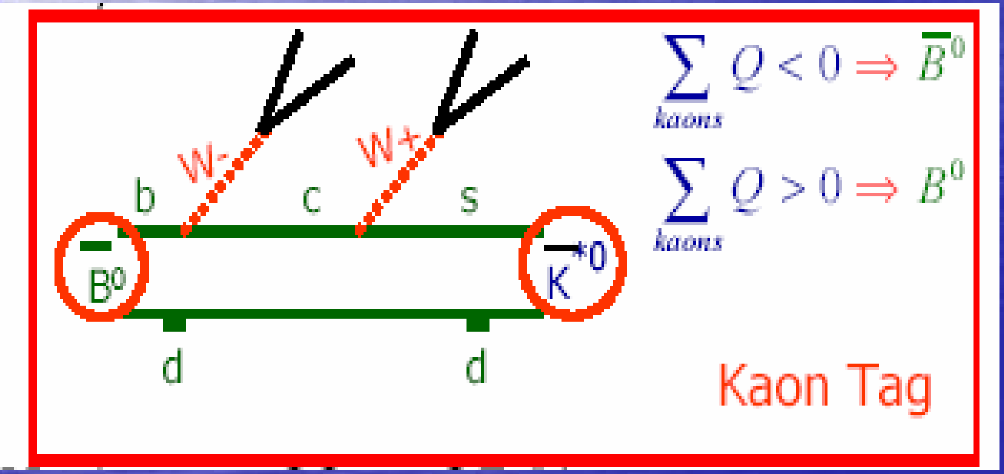
$M_\nu^2 > -2.5$ GeV/c2

Initial state tagging

Identify the flavor of the other B: opposite side tagging



search for a lepton or kaon coming from B decay



reconstruct the "other b" charge

$\varepsilon = N_{tag}/N_{total}$ efficiency

$D = N_{tag}^{W} - N_{tag}^{R}/N_{tag}$ dilution

D=1 D=0

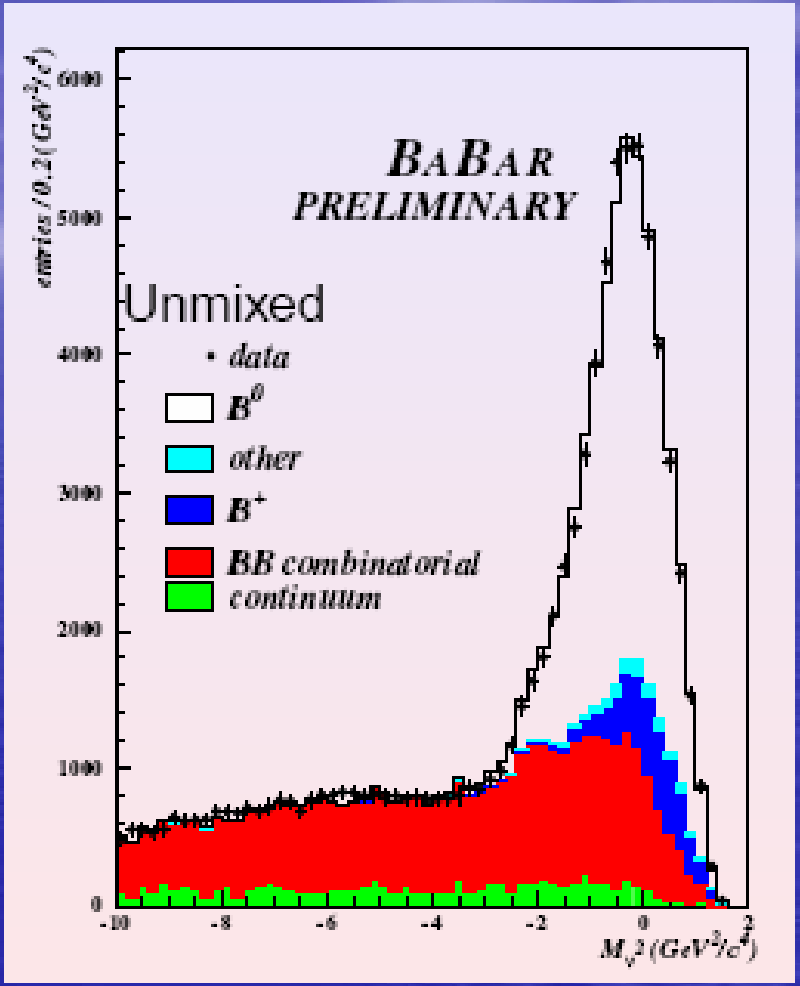
εD^2=figure of merit

B^0 flavor tag

A second stiff (p>1.0 GeV/c) lepton required to:

- Reduce continuum background
- Have a precise Δz reconstruction
- Tag the reconstructed B flavor

Data sample:
88×10^6 BB events
$\sim50\times10^3$ $B^0 \rightarrow D^{*-}l\nu$ candidates
$\sim27\times10^3$ background events



Sample composition and background evaluation from M_ν^2 fit

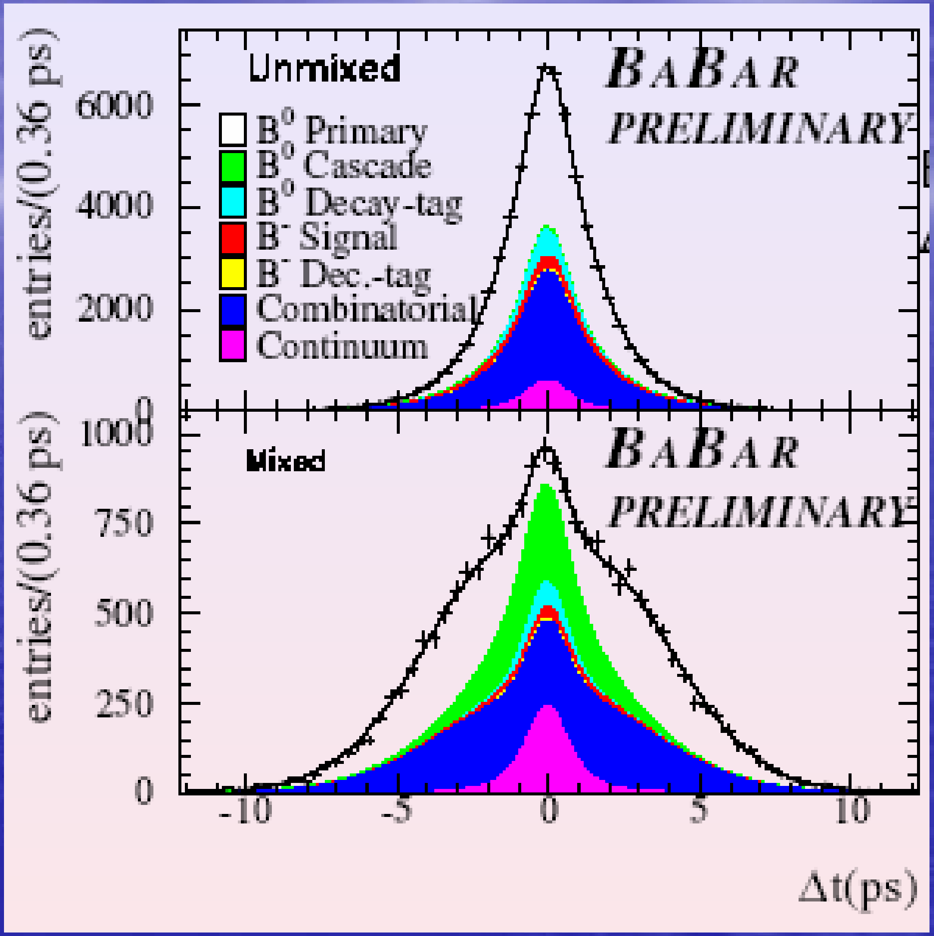
Fit procedure

- Binned maximum likelihood fit to Δt [-18 ps, 18 ps] and σ(Δt) [0 ps, 3 ps]
- Signal fitting function:

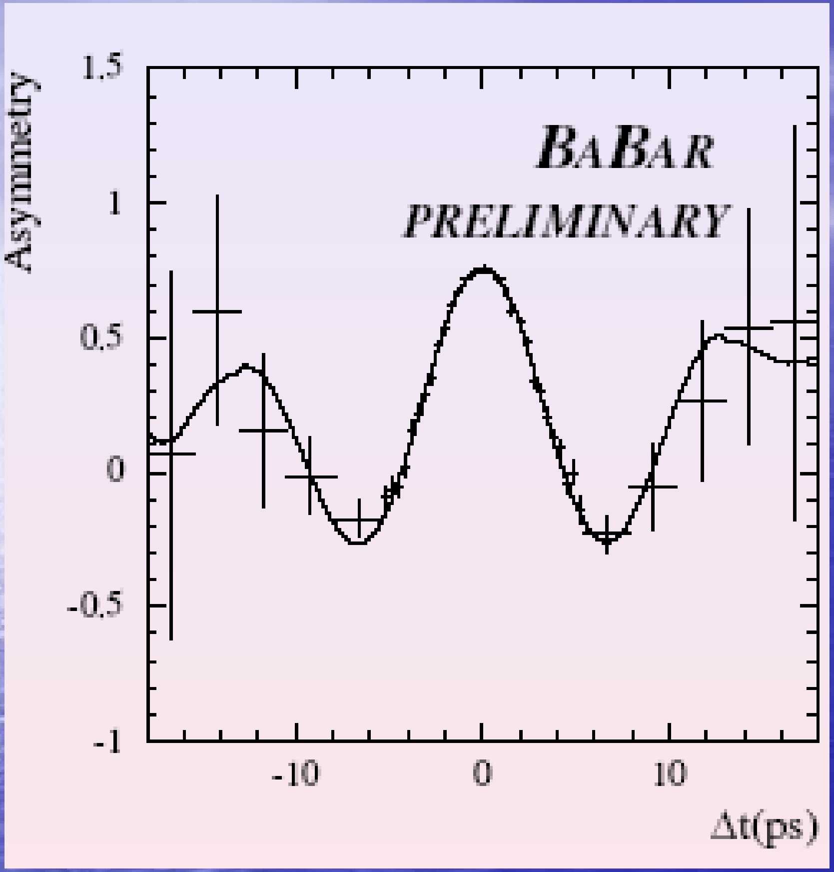
$$S^{\pm} = \frac{e^{-\Delta t/\tau_{B^0}}}{4\tau_{B^0}}(1 \pm D\cos(\Delta m_d \Delta t))$$

~1 for signal

- Detector response on Δt: Gaussian parameterization
- Cascade lepton tag: D evaluated from semileptonic BR
- Fit free parameters:
  a) Gaussian parameters for detector response
  b) $\tau(B^0)$ & Δm_d



Fit results



Main systematic errors:

- Analysis bias
- Misalignment of the silicon vertex detector

τ_{B0} = 1.501±0.008(stat)±0.030(syst) ps

Δm_d = 0.523 ± 0.004(stat) ± 0.007(syst) ps^{-1}

Δm_d = 0.509 ± 0.004 ps^{-1} World Average

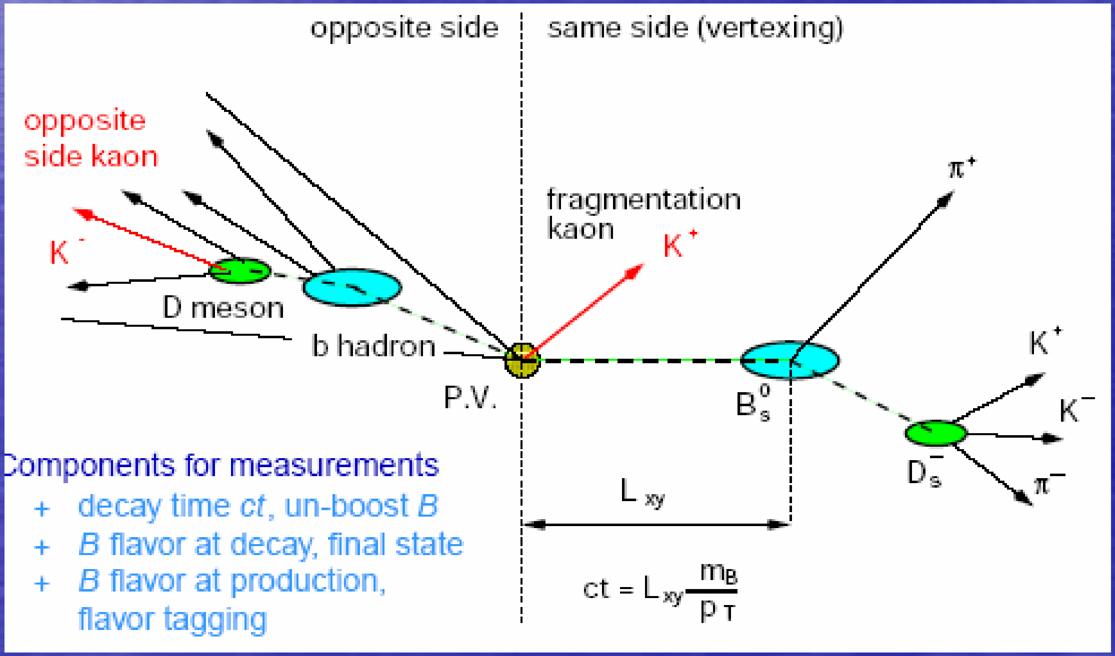
How is measured at Tevatron

Production time: $b\bar{b} \rightarrow$ one B^0_d/B^0_s and b-hadron

Decay time: B^0_d/B^0_s decays

Needs:

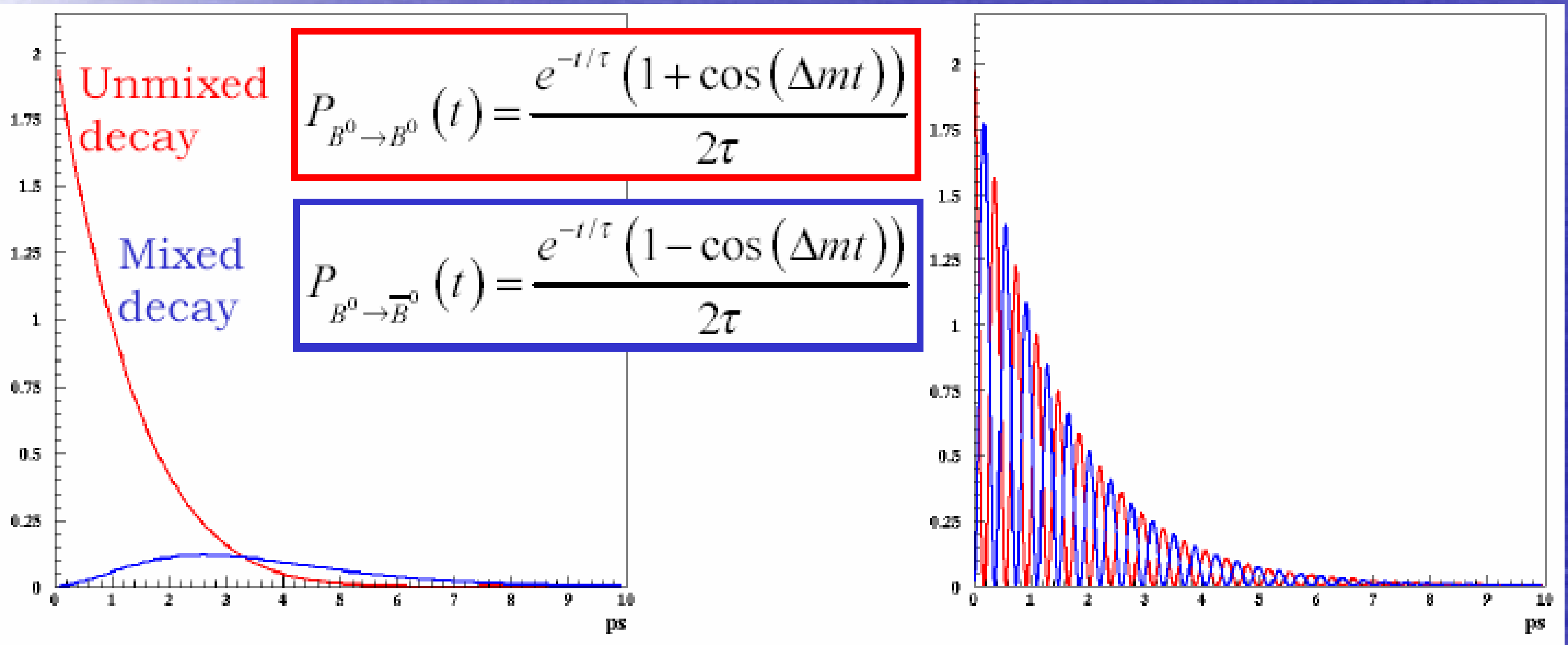
- Identify B flavor at the decay time and at the production time
- Proper decay time (ct) determination with high resolution



B_d and B_s Mixing differences

Due to the different size of CKM matrix elements B_d and B_s mixing frequencies are very different

B_d Δm_d= 0.47 ps^{-1} B_s Δm_s= 17 ps^{-1}

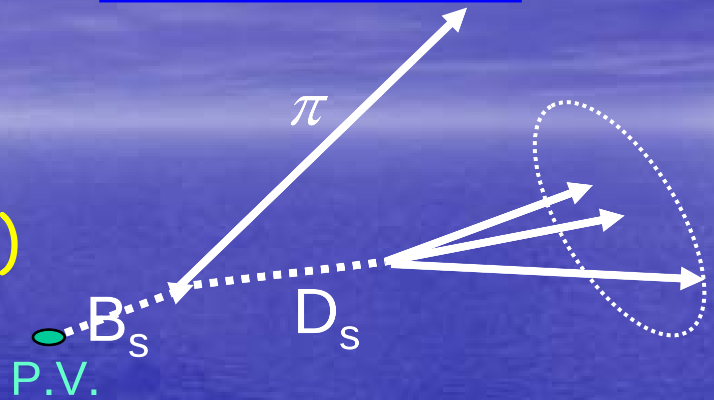


B_s collection

Fully reconstructed hadronic modes:

$$B_s^0 \rightarrow D_s^- \pi^+$$

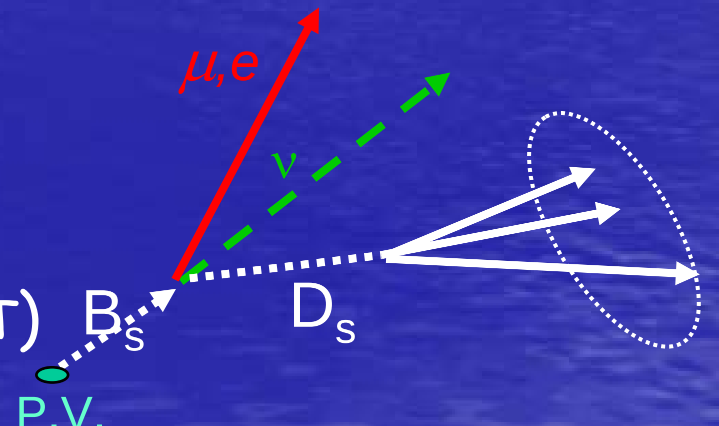
- Complete momentum reconstruction
- Good proper time resolution
- High B_s mass resolution → high S/B
- Selected by Two Track Trigger (SVT)
- Two displaced tracks
- Low statistics



Partially reconstructed semileptonic modes:

$$B_s^0 \rightarrow D_s^- l^+ \nu_l X$$

- Missing momentum carried by the ν
- Visible proper time corrected from MC (K factor)
- Proper time resolution diluted by missing momentum
- Selected by dedicated trigger (l+SVT)
- High statistics



B_s hadronic decays

$B^0_s \rightarrow D_s^- \pi^+$

$D_s^- \rightarrow \phi\pi^-$ ($\phi \rightarrow K^+K^-$)

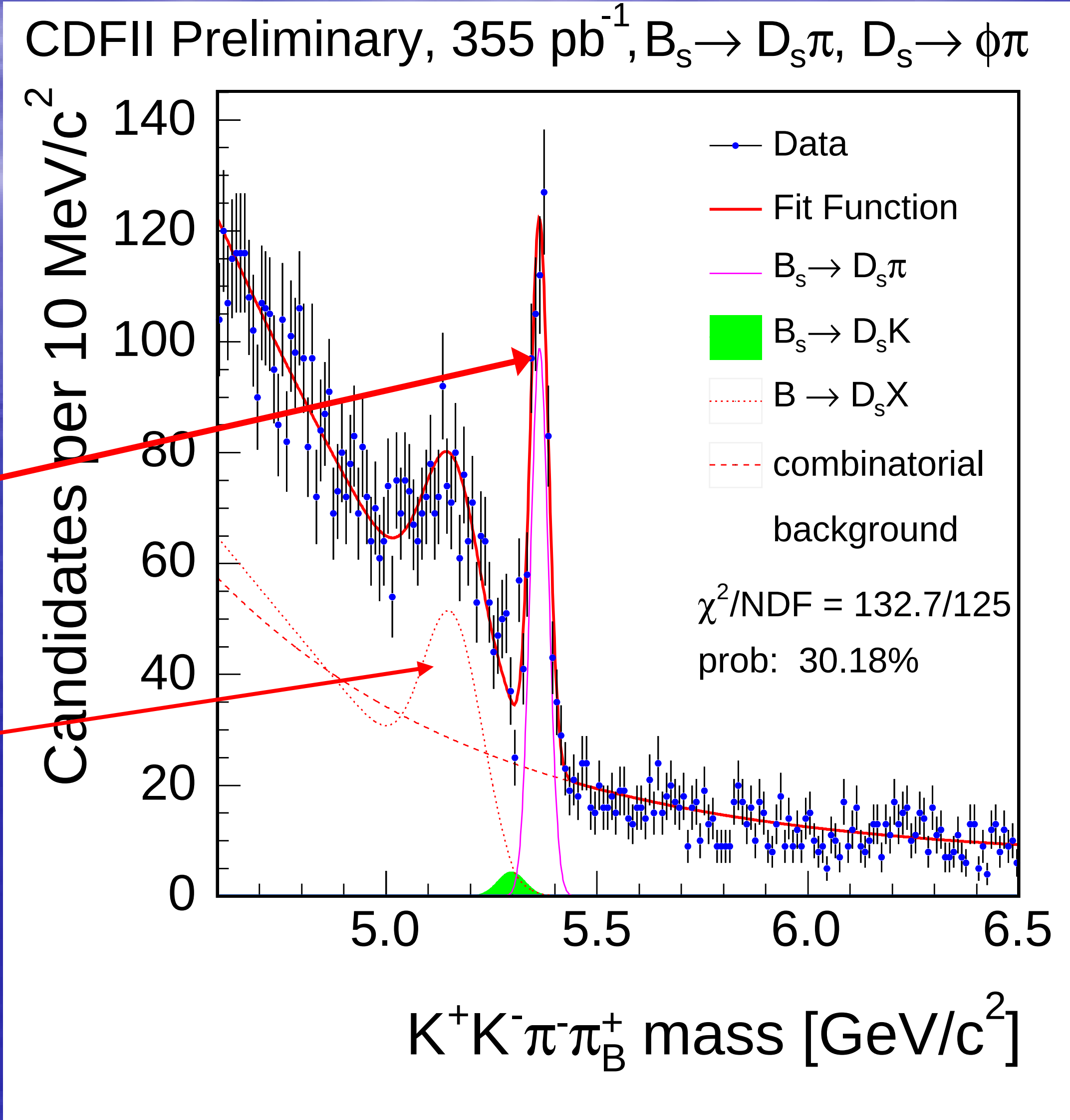
$D_s^- \rightarrow K^{*0}K^-$

$D_s^- \rightarrow \pi^+ \pi^- \pi^-$

$N_{B_s} = 526 \pm 33$

$S/B \sim 2$

$\sigma_M \approx 15$ MeV



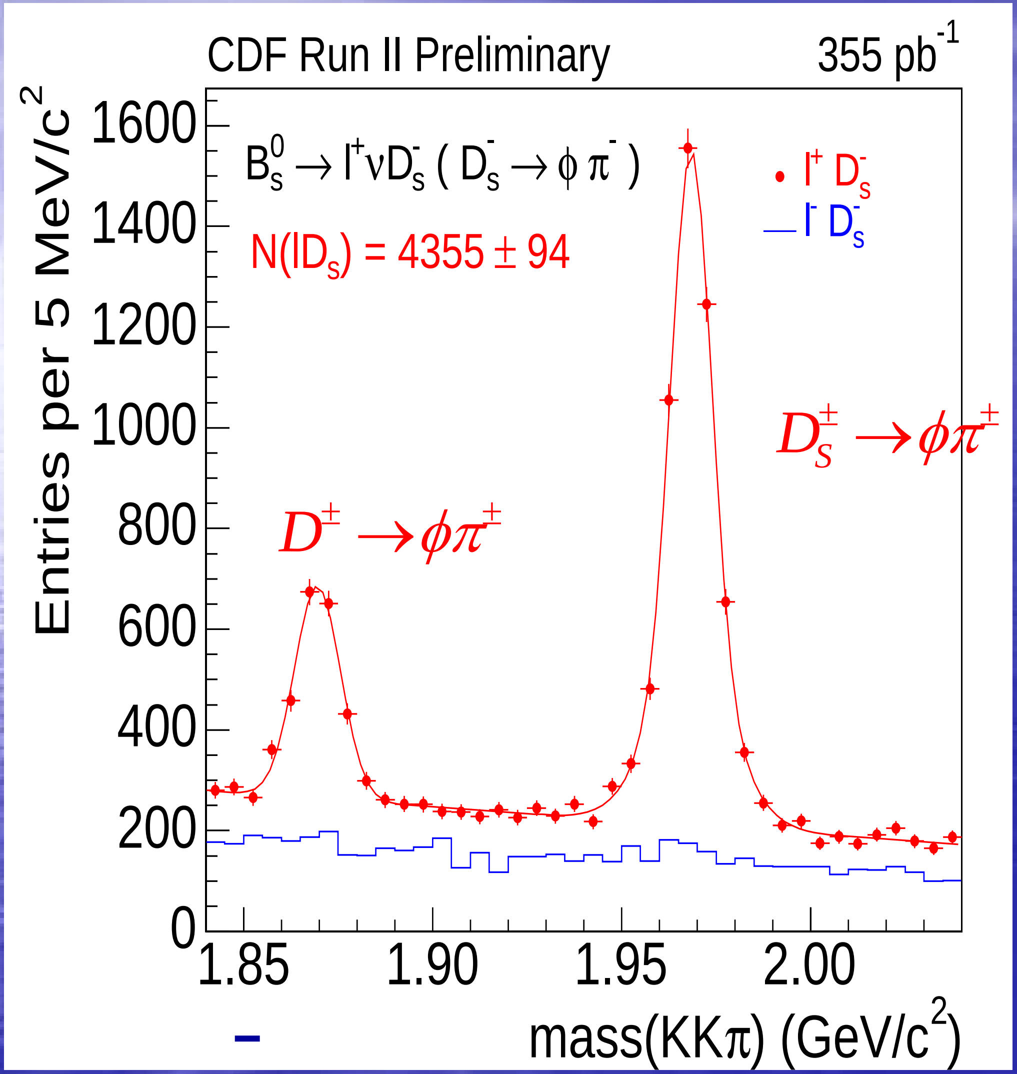
Partially reconstructed:

$B^0_s \rightarrow D_s^{*-}\pi^+$ $D_s^{*-} \rightarrow D_s^-\gamma$

$B^0_s \rightarrow D_s^-\rho^+$ $\rho^+ \rightarrow \pi^+\pi^0$

(not used)

B_s semileptonic decays



$B^0_s \rightarrow D_s^- l^+ \nu X$

$D_s^- \rightarrow \phi\pi^- \; (\phi \rightarrow K^+K^-)$

$D_s^- \rightarrow K^{*0}K^-$

$D_s^- \rightarrow \pi^+ \pi^- \pi^-$

- No B_s mass peak: missing particles
- Use D_s invariant mass
- Charge correlation l-D_s :
  - signal: $l^+D_s^-$
  - background: $l^-D_s^-$
- $l^+D_s^-$ peak not pure signal ~20% background:
  - D_s+fake lepton from PV
  - $B^0, B^+ \rightarrow D_s \, D \, X$, $D \rightarrow l\nu X$
  - c-c backgrounds

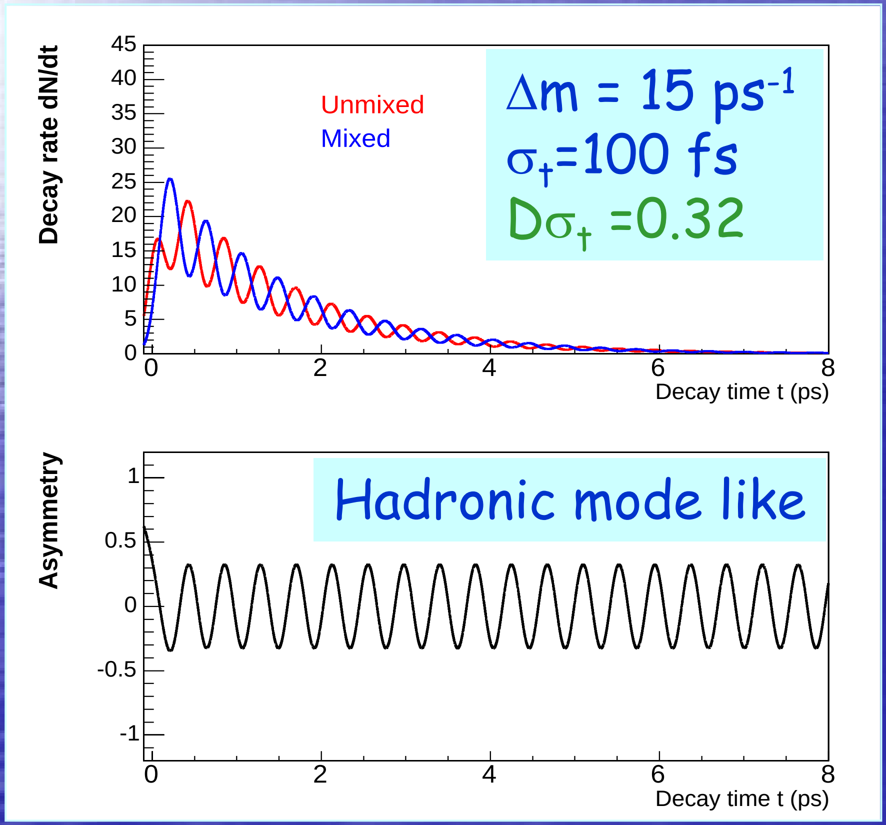
Proper time resolution

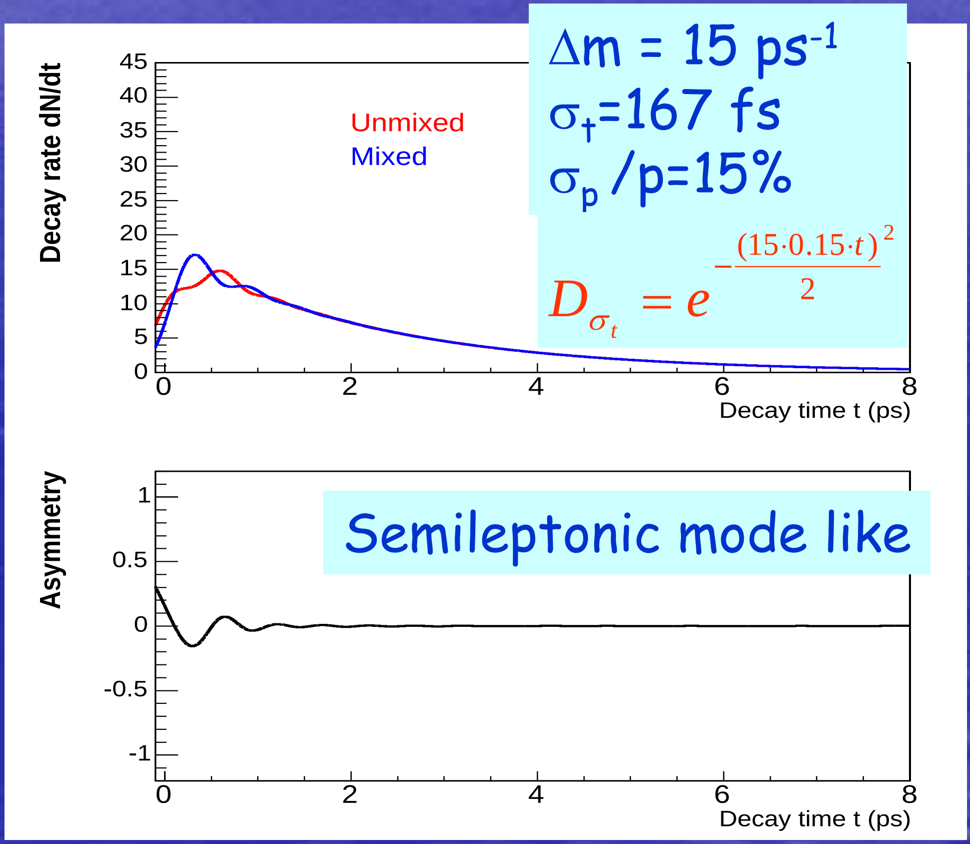
The amplitude of mixing asymmetry is diluted by a factor $D_{\sigma_t} = e^{-\frac{(\Delta m\,\sigma_t)^2}{2}}$

$$\sigma_{ct} = \sqrt{\left(\sigma_{ct}^{0}\right)^2 + \left(ct \times \frac{\sigma_p}{p}\right)^2}$$

Vertex resolution (constant)

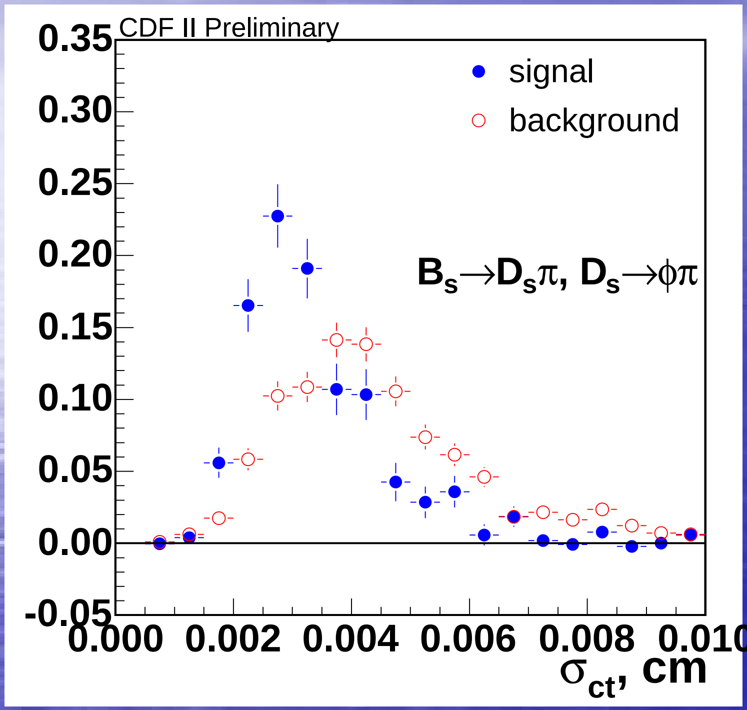
Momentum resolution (proportional to ct)

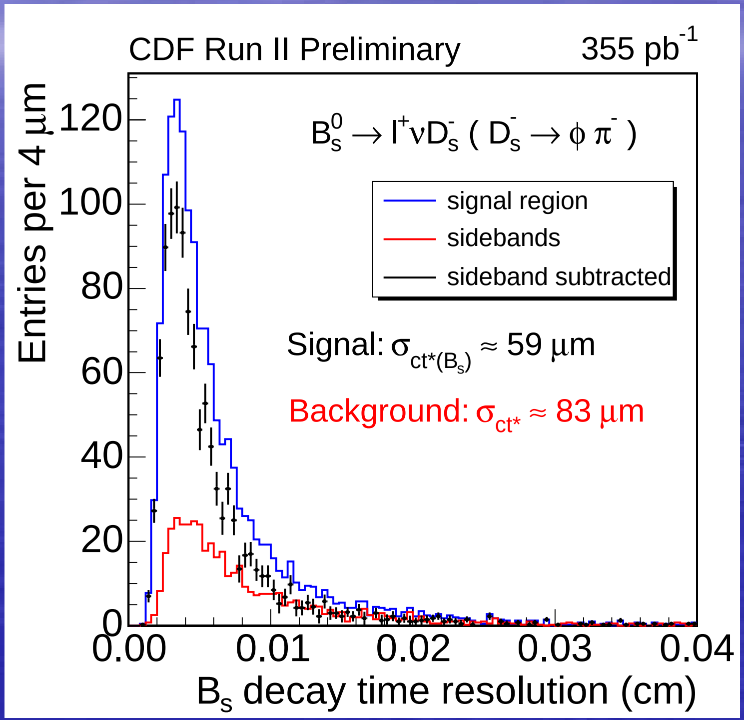




B_s decay time resolution

D_s + track: sample of prompt events used to correct σ_{ct} and parameterize σ_{ct} as a function of several variables.





Hadronic Decays:

$\langle\sigma_{ct}^0\rangle$: ~ 30 μm (100 fs)

$\sigma p/p < 1\%$

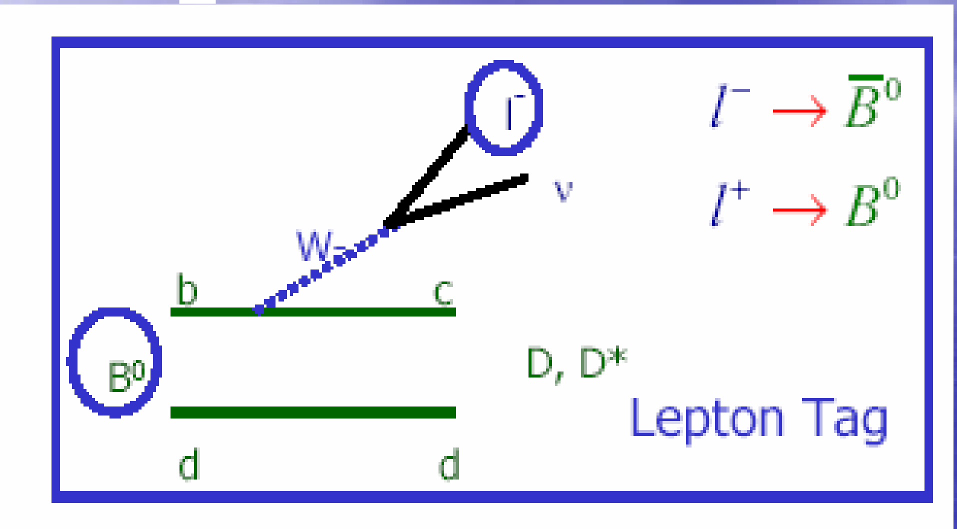
Semileptonic Decays:

$\langle\sigma_{ct}^0\rangle$: ~ 50 μm (167 fs)

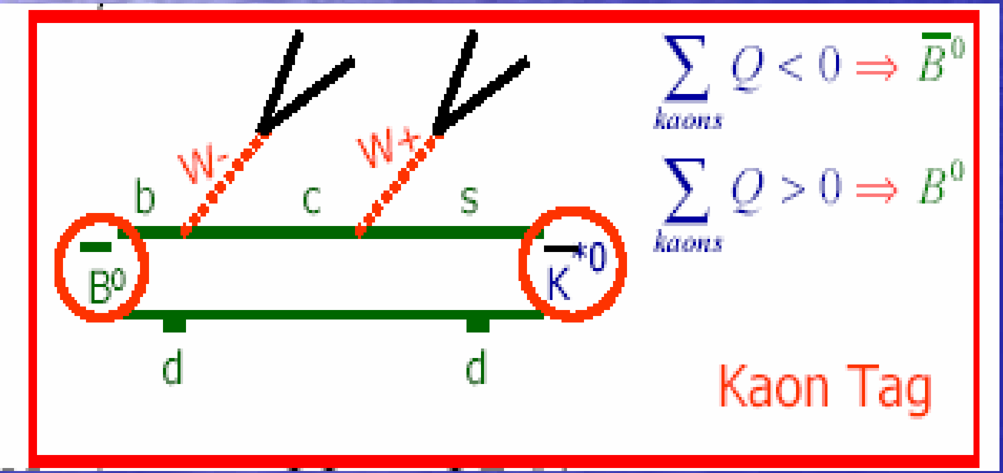
$\sigma p/p$ ~ 15% (K factor for missing neutrino)

Initial state tagging: Opposite side

Identify the flavor of the other B: opposite side tagging



search for a lepton or kaon coming from B decay



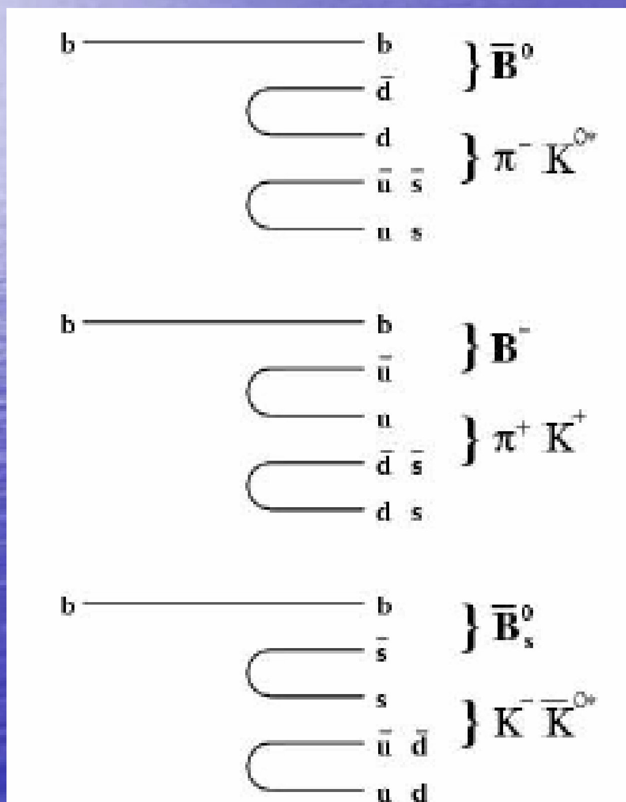
reconstruct the "other b" charge

$\varepsilon = N_{tag}/N_{total}$ efficiency
$D = N_{tag}^{W} - N_{tag}^{R}/N_{tag}$ dilution
D=1 D=0
εD^2=figure of merit

Initial state tagging: Same Side

Same side tagging: infer the production B flavor from particle produced "close" to the B:

- fragmentation tracks
- B^{**} production and $B^{**} \to B^0 \pi$



Same side Bs tagger performances can not be measured from data if setting a limit.
Must be understood in Monte Carlo.
other way?

εD^2=2.33(1.0)±0.34(0.35) % $B^+(B^0)$

Opposite Side Tagging: lepton

Find event with Opposite side $B \rightarrow \mu(e)X$

- Low momentum lepton
- Use likelihood method to combine calorimeter muon detector, dE/dx info
- High purity
- Low efficinecy
- Performances and calibration on SVT +lepton data

εD^2 Muon: (0.70 ± 0.04) %

εD2 Electron: (0.37 ± 0.03)%

D_{max}~0.4 → 30% mistag rate

Opposite Side Tagging: jet charge

Cone based jet algorithm: compute
Jet Charge of

- Secondary Vertex tagged jets
- Jet Probability tagged jet
- Highest P jet

D_{max}~0.4 → 30% mistag rate

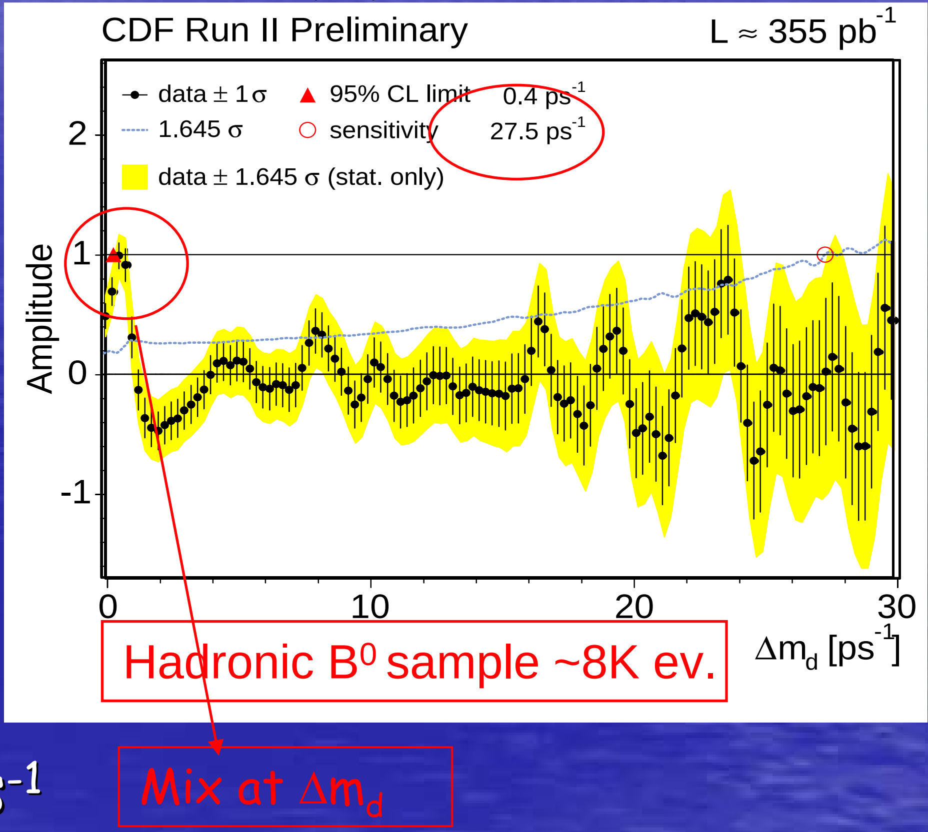
εD^2 secondary vertex: (0.36 ± 0.02) %
εD^2 displaced track: (0.36 ± 0.03) %
εD^2 highest p jet: (0.15 ± 0.01) %

Amplitude Scan for $B^0_{d(s)}$

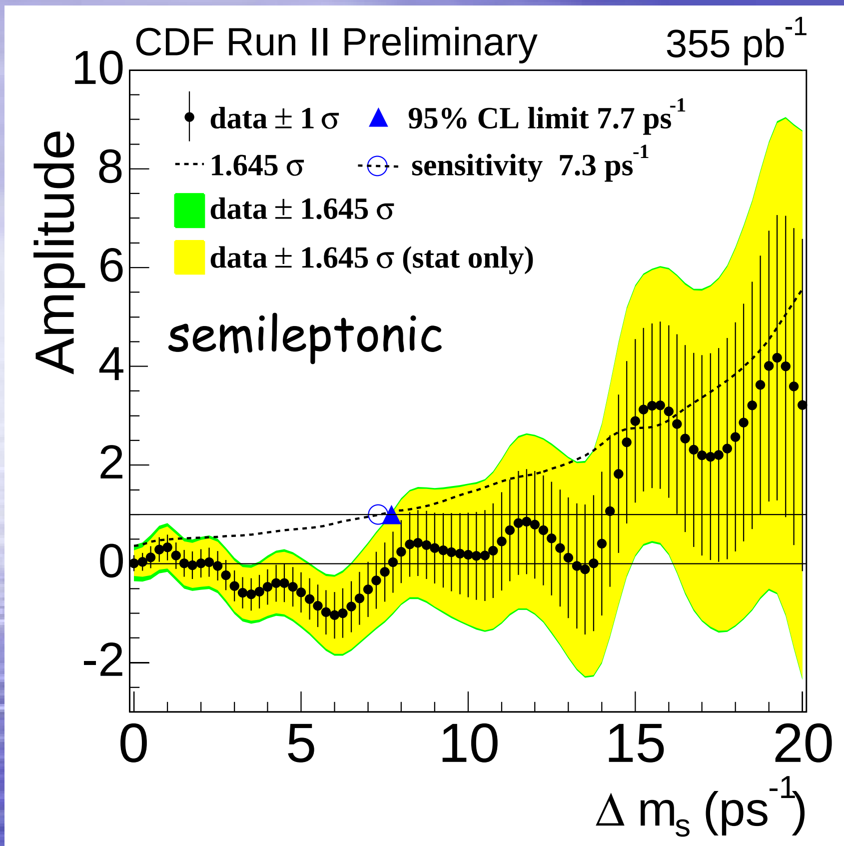
- Introduce "Amplitude" A in the Likelihood

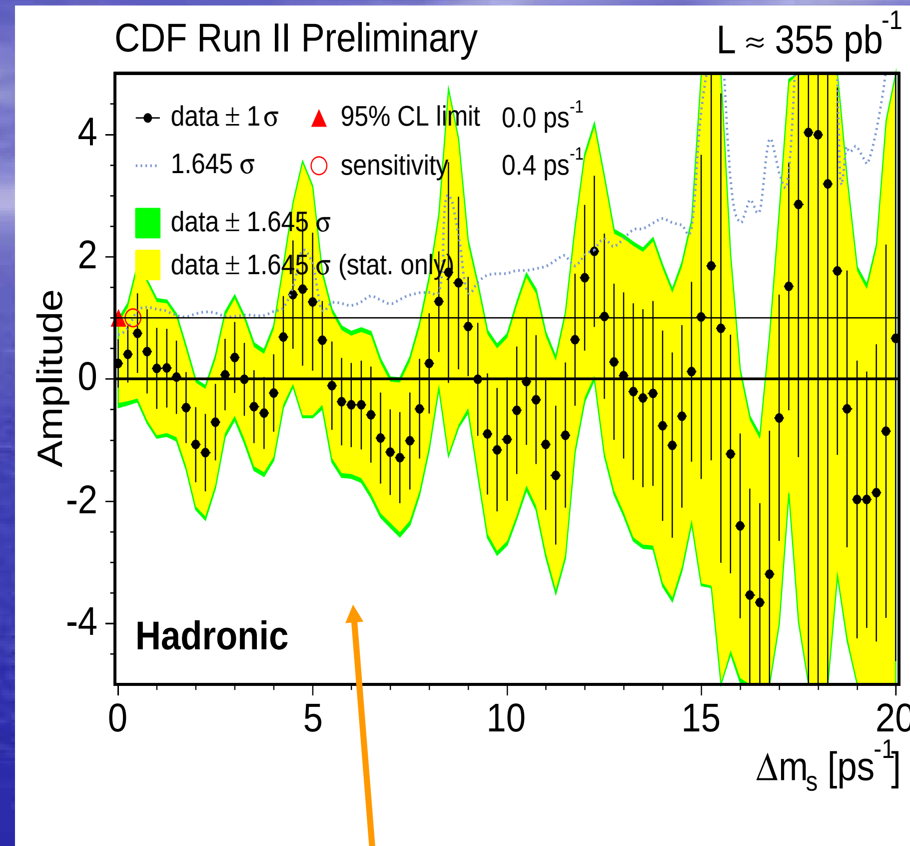
$$L_{sig}^{t} = \frac{1}{\tau} e^{-t/\tau} \left(1 \pm A \cdot D \cdot cos(\Delta m \cdot t)\right)$$

- Amplitude scan:
  - Fit for the amplitude A and its error σ(A) at fixed Δm
  - Repeat the fit for different Δm
- Amplitude consistent with:
  - 1 if mixing present at the frequency Δm
  - 0 if there is no mixing
- Example B^0 Hadronic decays
  - Amplitude = 1 at Δm =0.5 ps^{-1}
  - Amplitude = 0 at Δm » 0.5 ps^{-1}



Amplitude Scan result



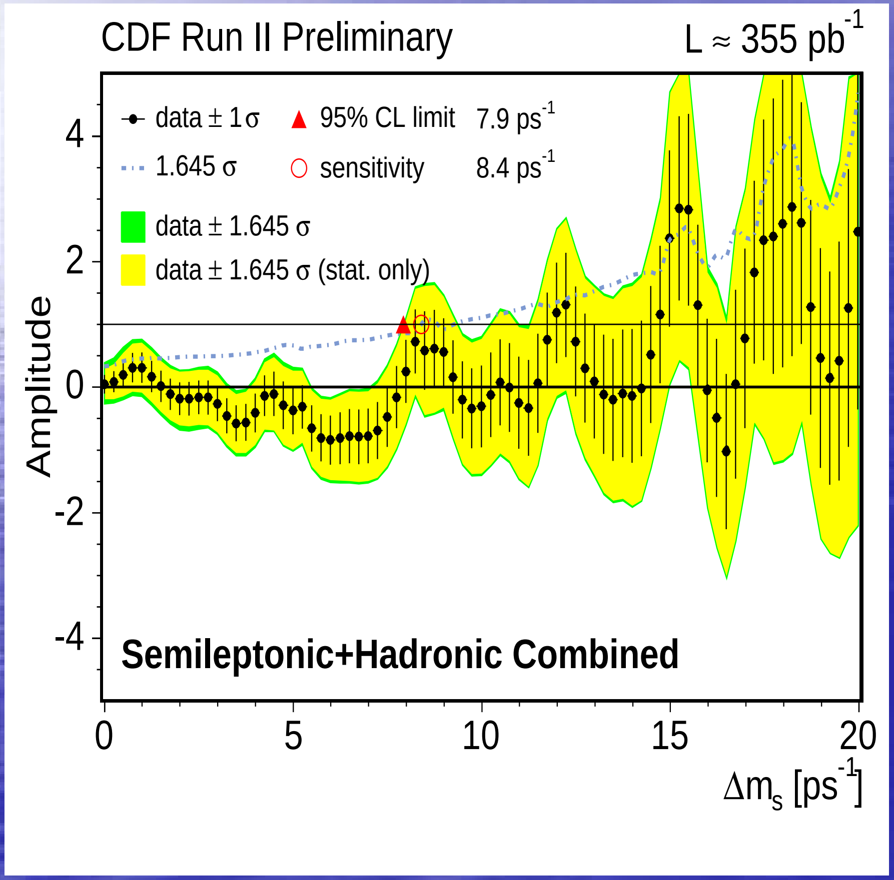


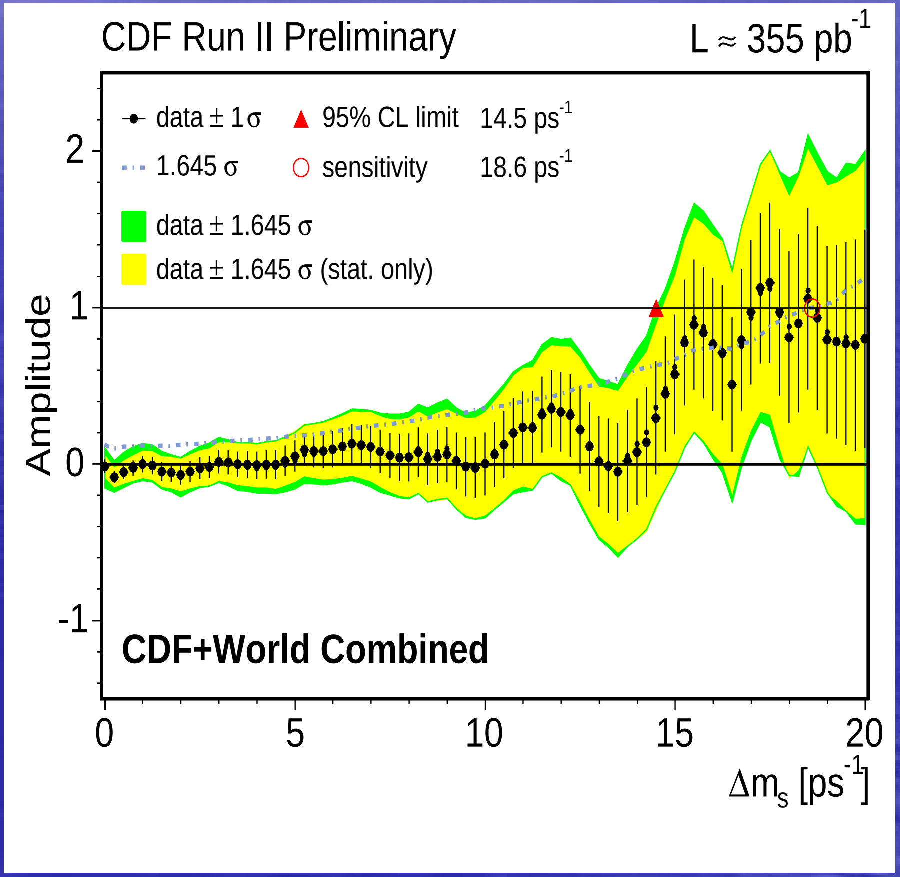
No sensitivity (yet) but better behaved at high Δms

CDF + World Combined Result

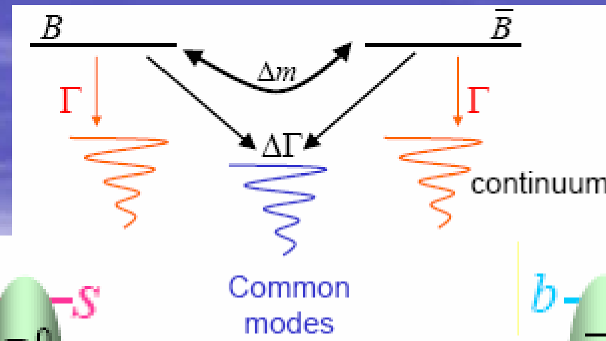
CDFII combined result
- Sensitivity: 8.4 ps^{-1}
- Limit: $\Delta m_s > 7.9\ ps^{-1}$ @ 95% CL

World Average + CDF Run II
- Sensitivity: 18.6 ps^{-1}
- Limit >14.5 ps^{-1} @ 95% CL

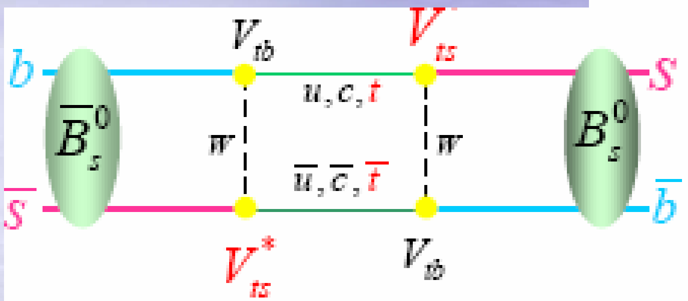




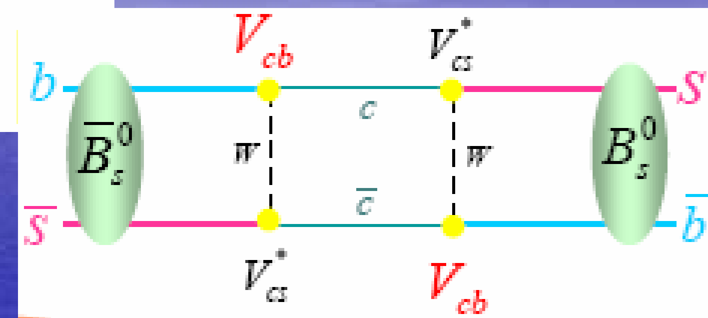
$B_{s,d}$ Lifetime differences: $\Delta\Gamma/\Gamma$



Off-shell transition contributes to Δm



On-shell transition contributes to $\Delta\Gamma$



Standard Model expectation:

$$\Delta\Gamma_d/\Gamma_d = (3.0^{+0.9}_{-1.4}) \times 10^{-3}$$

If bigger $\Rightarrow$ new physics

$$\Delta\Gamma_{Bs}/\Gamma_{Bs} \sim (7\text{-}14)\text{x}10^{-2}$$

Indirect Δm_s measurement (model dependent):

$$\frac{\Delta\Gamma_{B_s}}{\Delta m_s} = 3.9^{+0.8}_{-1.5}\, x10^{-3}$$

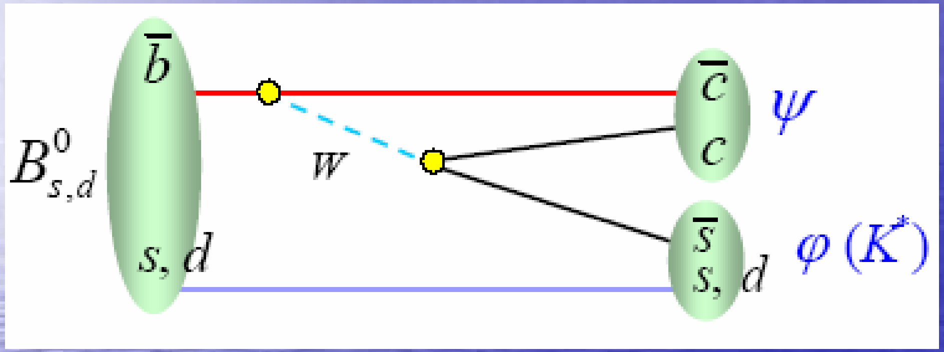
Fermilab-Pub-01, 197

$B_{s,d}$ $\Delta\Gamma/\Gamma$ at Tevatron

Definition:

$$\Gamma = (\Gamma_{long} + \Gamma_{short})/2$$
$$\Delta\Gamma = (\Gamma_{long} - \Gamma_{short})$$
$$\tau = 1/\Gamma$$

Look for evidence of two lifetimes in B decays



Examine two similar decay

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

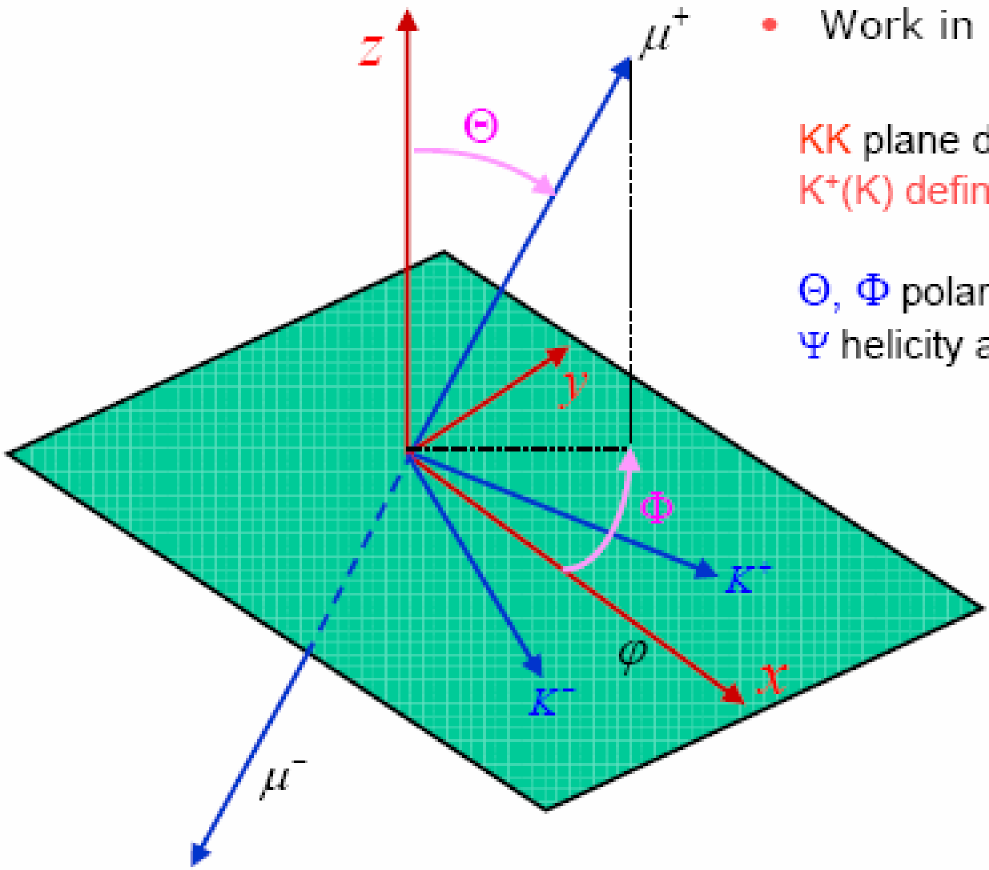
$J/\psi \to \mu\mu$
$\phi \to KK$
$K^{*0} \to K^-\pi^+$

Total J=0 final state
Two spin-1 J=0,1,2
Orbital L=0,1,2 ⇒ 3 Different decay amplitudes

$B_{s,Light}$≈CP even, $B_{s,Heavy}$≈CP odd
Disentangle different L-components of decay amplitude
⇒ isolate two B states

$B_{s,d}$ $\Delta\Gamma/\Gamma$ at Tevatron

Transversity angle analysis



- Work in J/Ψ rest Frame

KK plane defines (x,y) plane
$K^+(K)$ defines +y direction

Θ, Φ polar & azimuthal angles of μ^+
Ψ helicity angle of ϕ (K^*)

Decay Angular Distributions

$$\frac{d^4\mathcal{P}}{d\vec{\rho}\,dt} \propto |A_0|^2 \cdot g_1(t) \cdot f_1(\vec{\rho}) + |A_{||}|^2 \cdot g_2(t) \cdot f_2(\vec{\rho}) + |A_\perp|^2 \cdot g_3(t) \cdot f_3(\vec{\rho}) \pm Im(A_{||}^* A_\perp) \cdot g_4(t) \cdot f_4(\vec{\rho}) + Re(A_0^* A_{||}) \cdot g_5(t) \cdot f_5(\vec{\rho}) \pm Im(A_0^* A_\perp) \cdot g_6(t) \cdot f_6(\vec{\rho}) \equiv \sum_{i=1}^{6} A_i \cdot g_i(t) \cdot f_i(\vec{\rho})$$

$$f_1(\vec{\rho}) = 2\cos^2\psi(1-\sin^2\theta\cos^2\phi)$$

$$f_2(\vec{\rho}) = \sin^2\psi(1-\sin^2\theta\sin^2\phi)$$

$$f_3(\vec{\rho}) = \sin^2\psi\sin^2\theta$$

$$f_4(\vec{\rho}) = -\sin^2\psi\sin 2\theta\sin\phi$$

$$f_5(\vec{\rho}) = \frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\phi$$

$$f_6(\vec{\rho}) = \frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\phi$$

$g_i(t)$ different for B_d and B_s and are rather non-trivial

A_0 = longitudinal pol. amplitude

$A_{||}, A_\perp$ = transverse pol. amplitudes

A. Dighe et. al., Eur. Phys. J. C6, 647-662

Fitting functions:

B_s:

$$\frac{d^4\mathcal{P}}{d\vec{\rho}\,dt} \propto |A_0|^2 \cdot e^{-\Gamma_L t} \cdot f_1(\vec{\rho}) + |A_{\|}|^2 \cdot e^{-\Gamma_L t} \cdot f_2(\vec{\rho}) + |A_{\perp}|^2 \cdot e^{-\Gamma_H t} \cdot f_3(\vec{\rho}) + Re(A_0^* A_{\|}) \cdot e^{-\Gamma_L t} \cdot f_5(\vec{\rho})$$

$\Gamma_L = CP-\text{even}$

$\Gamma_H = CP-\text{odd}$

B_d:

$$\frac{d^4\mathcal{P}}{d\vec{\rho}\,dt} \propto \Big\{ |A_0|^2 \cdot f_1(\vec{\rho}) + |A_{\|}|^2 \cdot f_2(\vec{\rho}) + |A_{\perp}|^2 \cdot f_3(\vec{\rho}) \pm Im(A_{\|}^* A_{\perp}) \cdot f_4(\vec{\rho}) + Re(A_0^* A_{\|}) \cdot f_5(\vec{\rho}) \pm Im(A_0^* A_{\perp}) \cdot f_6(\vec{\rho}) \Big\} \cdot e^{-\Gamma_d t}$$

Fit simultaneously mass, lifetime and angular distribution convoluted with resolution function

mB, τ_L, τ_H and A_0, $A_{||}$ $A_{\perp}$

Resuslts

Perform two fits

1. Unconstrained: Fit data as described

2. Constrained: Invoke SM constraint $\Gamma_s = \frac{1}{2}(\Gamma_H + \Gamma_L) = \Gamma_d$
   (Expected true to ~1%)

   Since $\tau_d = 1.54 \pm 0.014\,\text{ps}$

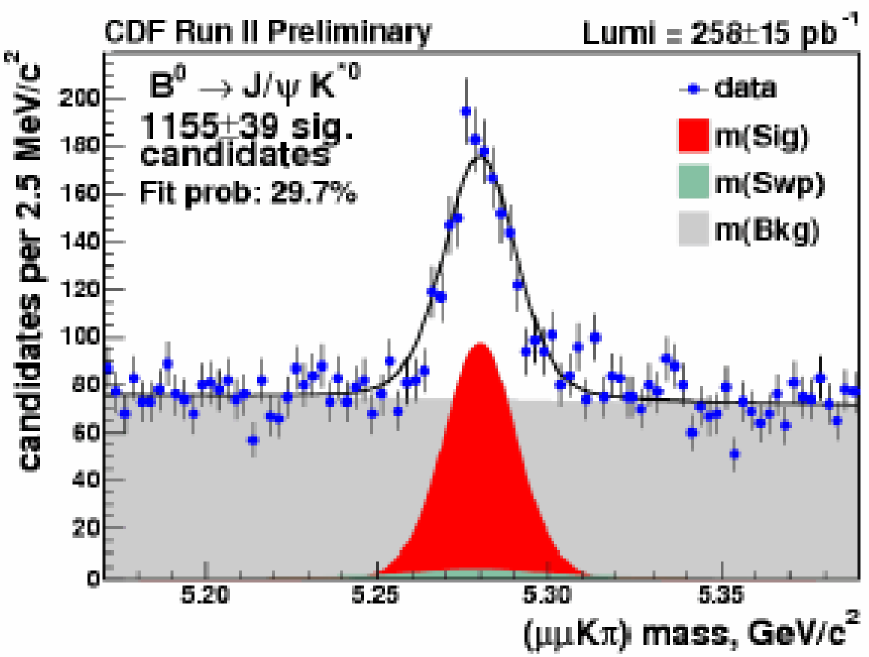
   set

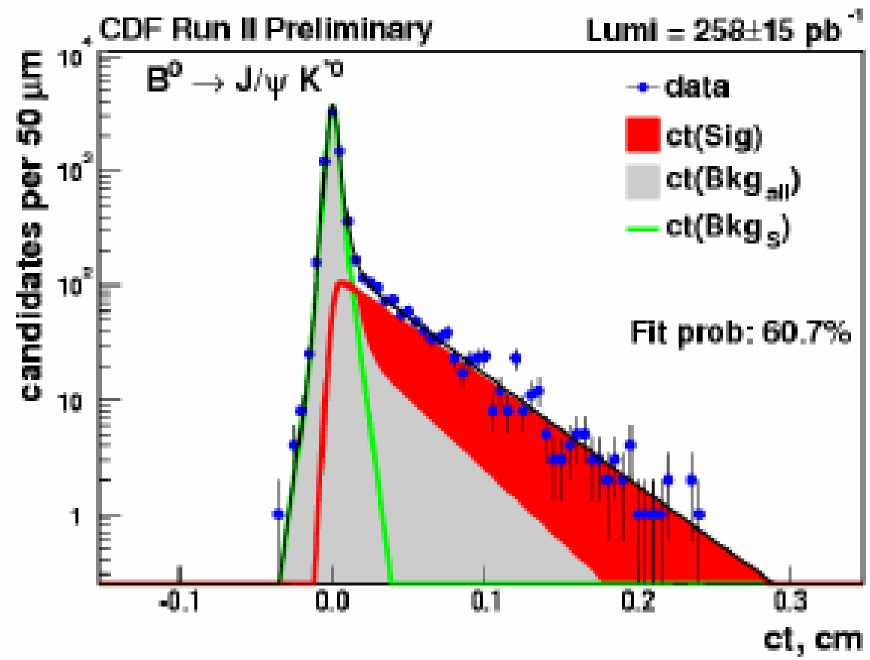
$$\frac{1}{\Gamma_s} = \frac{2\tau_L \tau_H}{\tau_L + \tau_H} = 1.54 \pm 0.021\,\text{ps}$$

B_d Results

$A_0 = 0.750 \pm 0.017 \pm 0.012$ $A_{||} = (0.473 \pm 0.034 \pm 0.006) e^{(2.86 \pm 0.22 \pm 0.07)i}$

$|A_\perp| = (0.464 \pm 0.035 \pm 0.007) e^{(0.15 \pm 0.15 \pm 0.04)I}$





$\frac{\Delta\Gamma_d}{\Gamma_d} \leq .01$ is small in SM

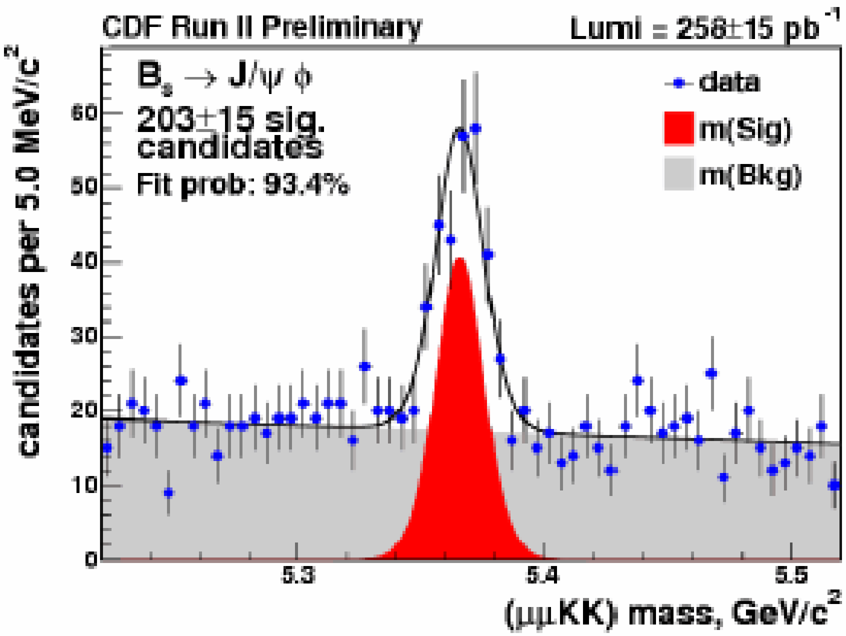
=>Fit to 1 lifetime

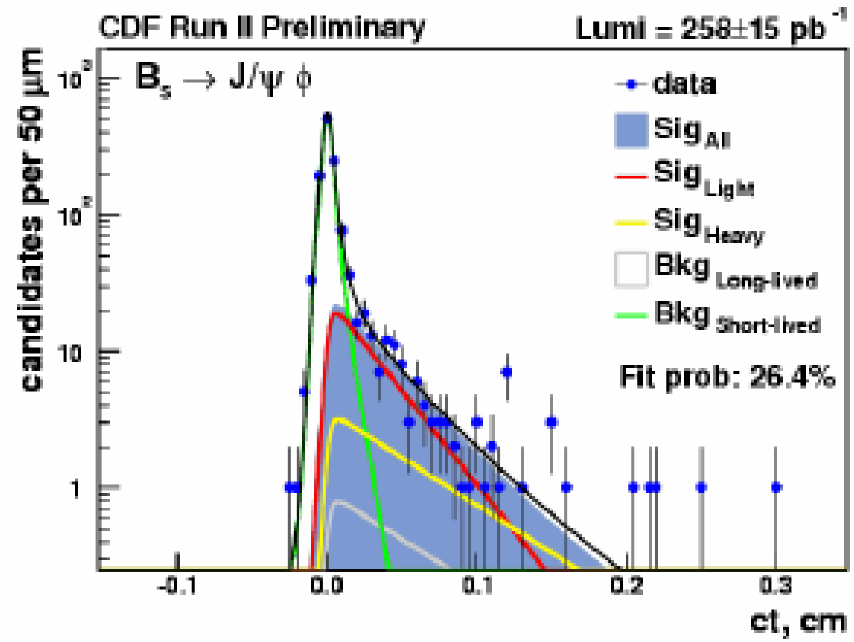
$c\tau_{B^0} = 462 \pm 15 \pm 4 \mu m$

$PDG = 460.8 \pm 4.2 \mu m$

Consistent with B factories results

B_s Lifetime difference: unconstrained fit





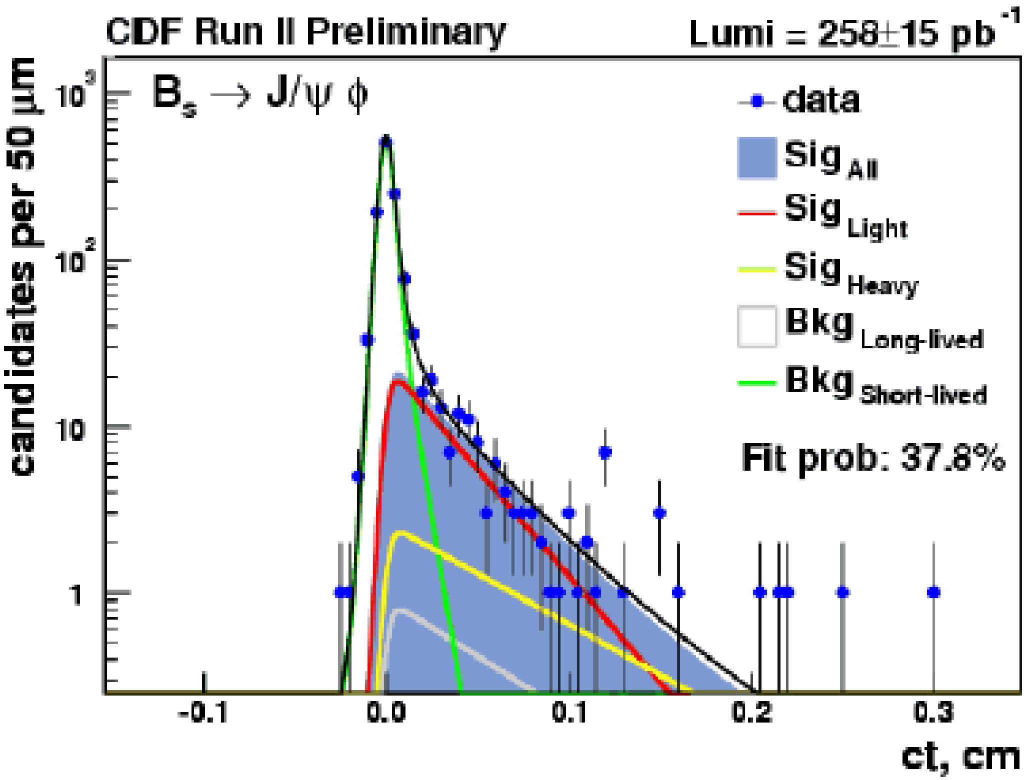
$$\tau_L = 1.05^{+0.16}_{-0.13} \pm 0.02\,\text{ps}$$
$$\tau_H = 2.07^{+0.58}_{-0.46} \pm 0.03\,\text{ps}$$

$$\Delta\Gamma_s = 0.47^{+0.19}_{-0.24} \pm 0.01\,\text{ps}^{-1}$$
$$\frac{\Delta\Gamma_s}{\Gamma_s} = 0.65^{+0.25}_{-0.33} \pm 0.01$$

CP-odd fraction (τ_H) ~ 22%

$\Delta\Gamma_s$ results $\Delta m_s = 125^{+69}_{-55}$

B_s Lifetime difference: $B_s^0 \to J/\psi\phi$ constrained fit



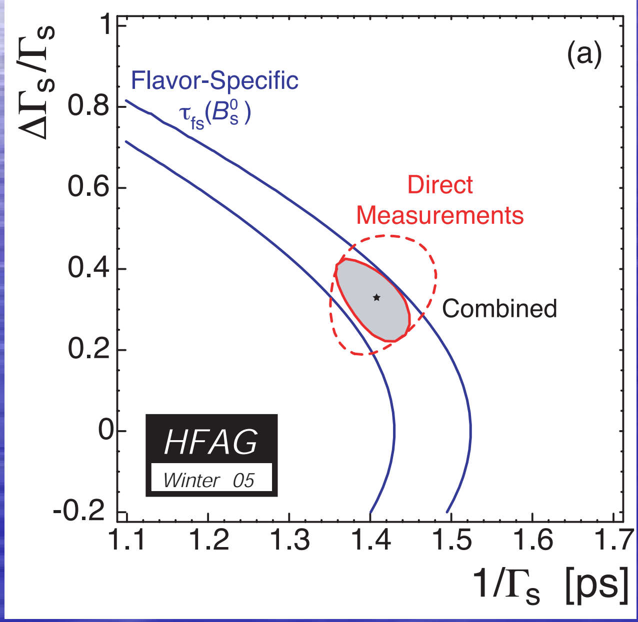
- SM Predicts $\Gamma_s = \Gamma_d$ to ~1% : constrain in fit
- Remember, can't see angular separation of CP eigenstates in projection

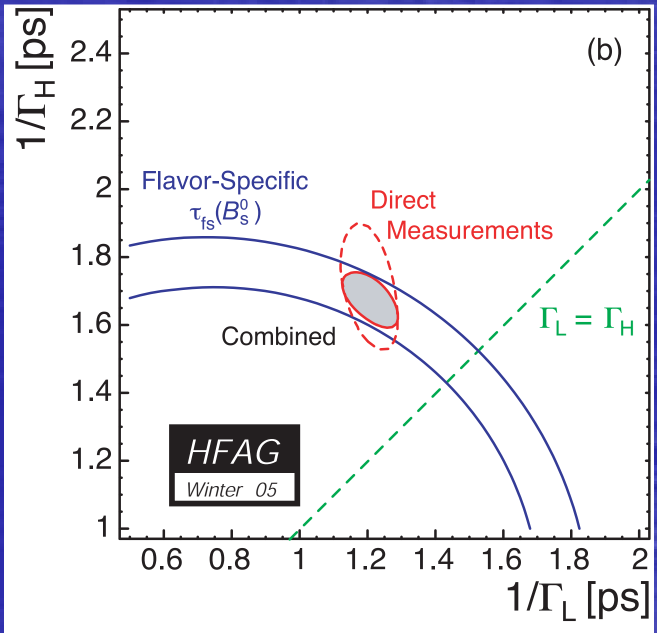
$$\tau_L = 1.13^{+0.13}_{-0.09} \pm 0.02\,\text{ps}$$
$$\tau_H = 2.38^{+0.56}_{-0.43} \pm 0.03\,\text{ps}$$

$$\Delta\Gamma_s = 0.46 \pm 0.18 \pm .01\,\text{ps}^{-1}$$
$$\frac{\Delta\Gamma_s}{\Gamma_s} = 0.71^{+0.24}_{-0.28} \pm 0.01$$

B_s $\Delta\Gamma/\Gamma$ Combined

Fit results from ALEPH, CDF and DELPHI data	without constraint	with constraint
$\Delta\Gamma s/\Gamma s$ (95% CL range)	[+0.01 ; +0.59]	[+0.01 ; +0.59]
$\Delta\Gamma s/\Gamma s$	$+0.35^{+0.12}_{-0.16}$	$+0.33^{+0.09}_{-0.11}$
$\Delta\Gamma s$	$+0.25^{+0.09}_{-0.11}$ ps^{-1}	$+0.23 \pm 0.08$ ps^{-1}
$1/\Gamma s$	$1.42^{+0.06}_{-0.07}$ ps	$1.405^{+0.043}_{-0.047}$ ps
tau(short) = $1/\Gamma L$	$1.21^{+0.08}_{-0.09}$ ps	1.21 ± 0.08 ps
tau(long) = $1/\Gamma H$	1.72 ± 0.19 ps	$1.68^{+0.08}_{-0.09}$ ps





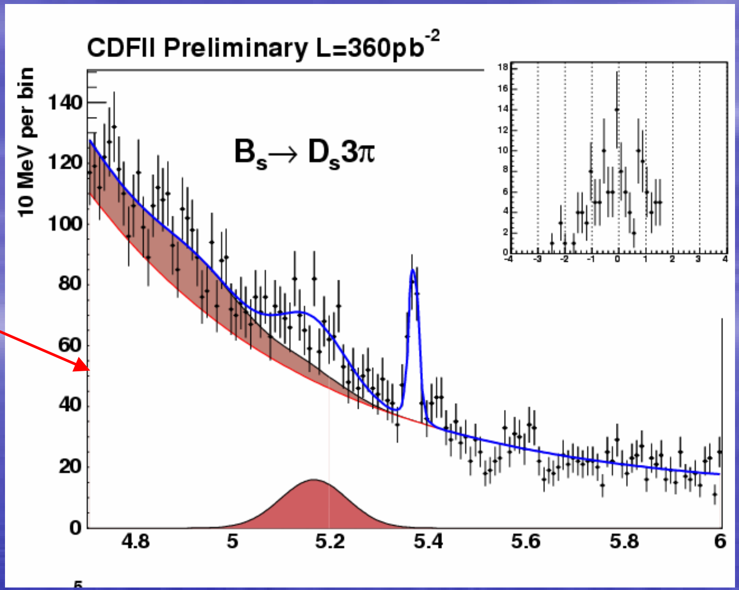
Summary

I hope I convinced you that B system is a nice and important "laboratory" where precisely test the Standard Model.

For more tests and for probes for physics beyond Standard Model listen to the next talk

Backup

Future perspectives

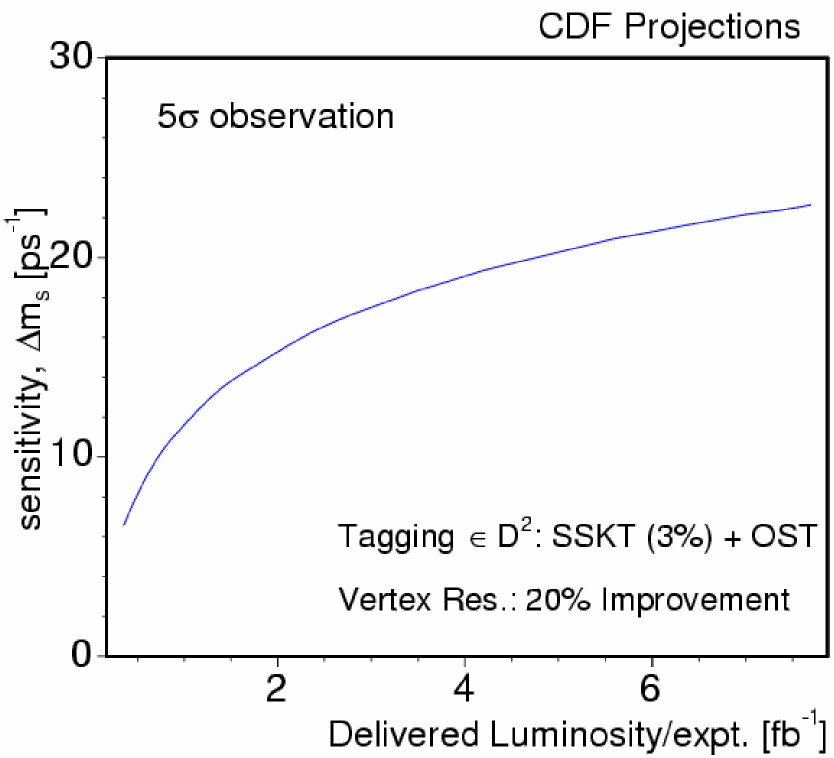


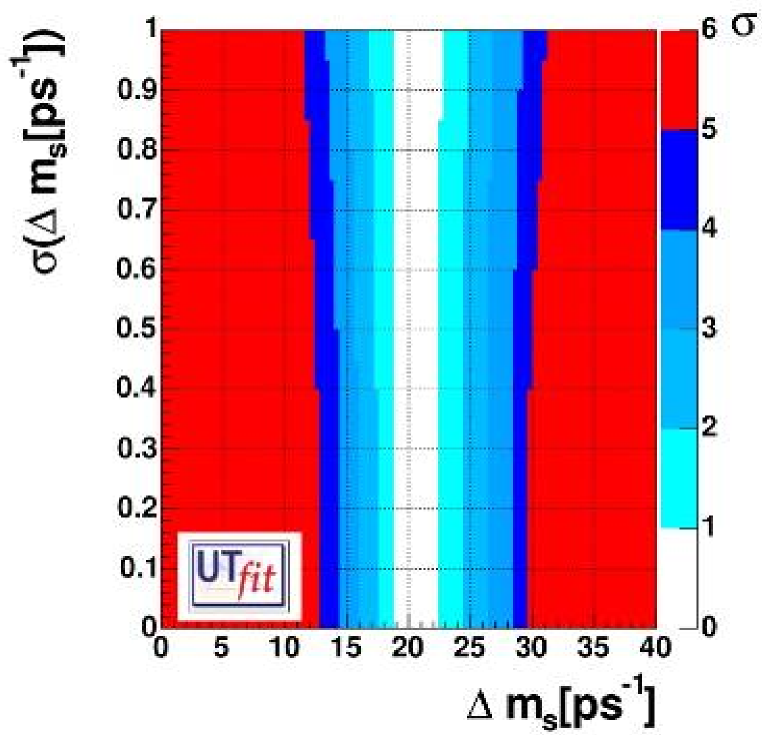
- Add more channels
  - $B_s \to D_s 3\pi$ (130 events +20%)
  - $B_s \to D_s^* p$
- Add semileptonic B_s decays from the hadronic trigger
X2 semileptonic statistic

- Improve decay time resolution with PV event by event (detail)
- Incremental changes in existing algorithm (new Jet Charge +20% eD^2)
- Add new tagging algorithm Same Side Kaon Tag

- New data rolling in, but increasingly peak luminosity:
  - Keep alive as much as possible present triggers → SVT upgrade
  - Use new trigger strategies
    - 2 SVT Tracks + opposite side muon (pt>1.5 GeV) at trigger level (already in place since summer 2004 can survive at higher luminosity)

B_s mixing sensitivity projection





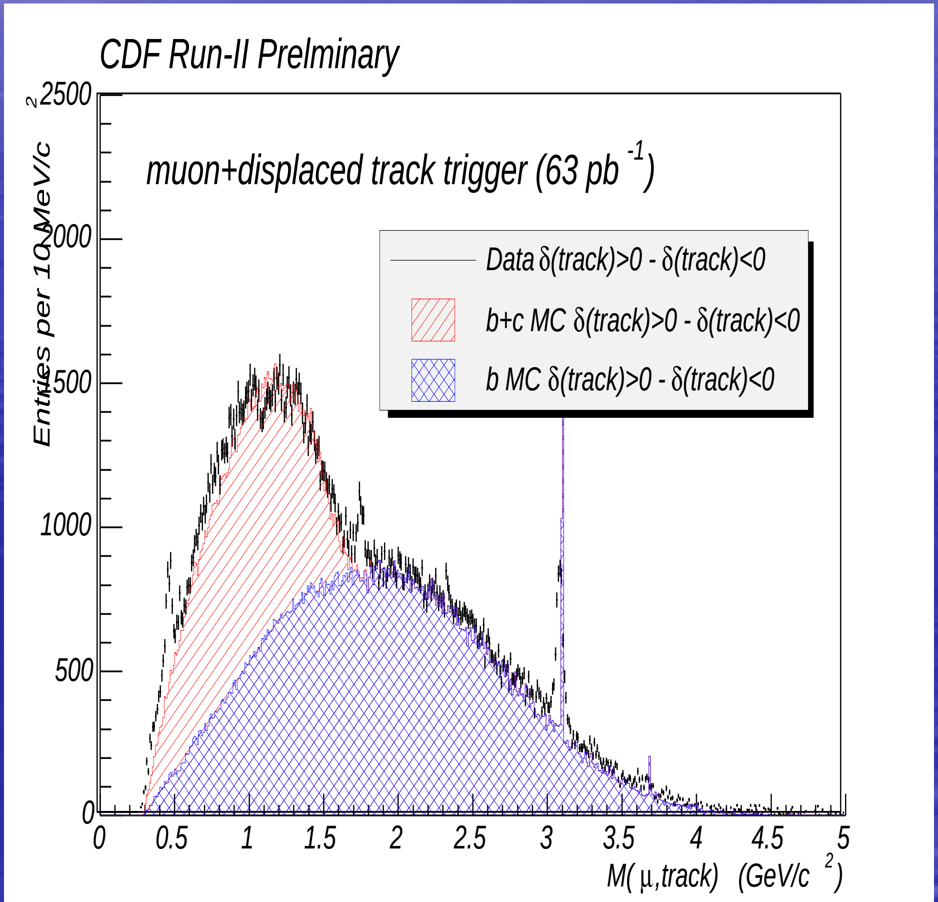
- Analytic extrapolation, reproduce present result with current inputs
- Prediction include a reduced (50%) effective luminosity usable for B-physics from 2007 onwards
- Sensitivity to the favorite CKM range
- In case of no signal 95% C.L. up to 30 ps^{-1} with 4 fb^{-1}
- CKM fit will imply New Physics if Δm_s>28 ps^{-1} by then…

Calibration Sample for Taggers

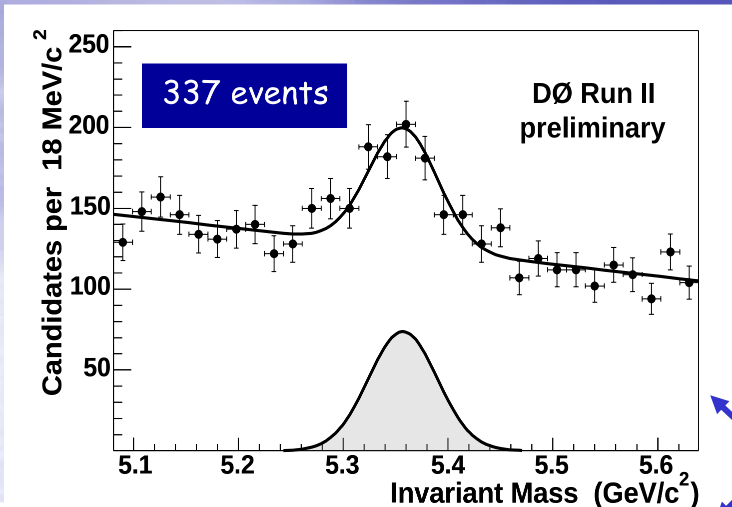
- Need high stat. sample to develop and calibrate tagging algorithm:
- High purity reached after lepton+track mass cut applied
- Statistical Power of a tag: eD^2
  - Tagging efficiency (e)
  - Tagging dilution (D = 1-2w)
    - w = mistag rate
- Parameterize dilution as a function of relevant variables and wheight events with their event-by-event dilution
- Dividing events into different classes based on tagging power improves combined eD^2
- Calibration of the tagger performance requires high statistics!

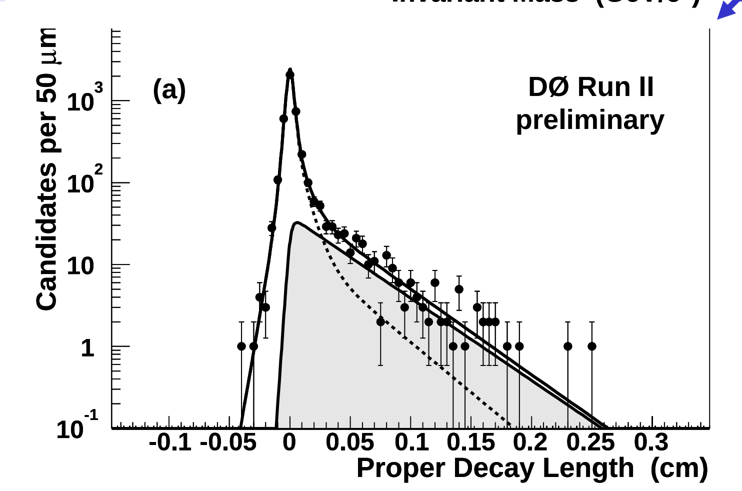
Use inclusive semileptonic decays from the lepton+track trigger (>10^6 events)

- Lepton charge gives "true" B flavour
- Tag the other b

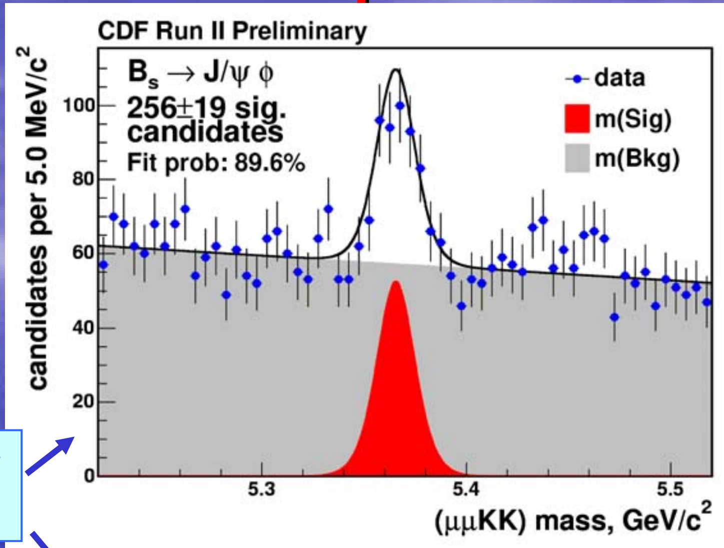


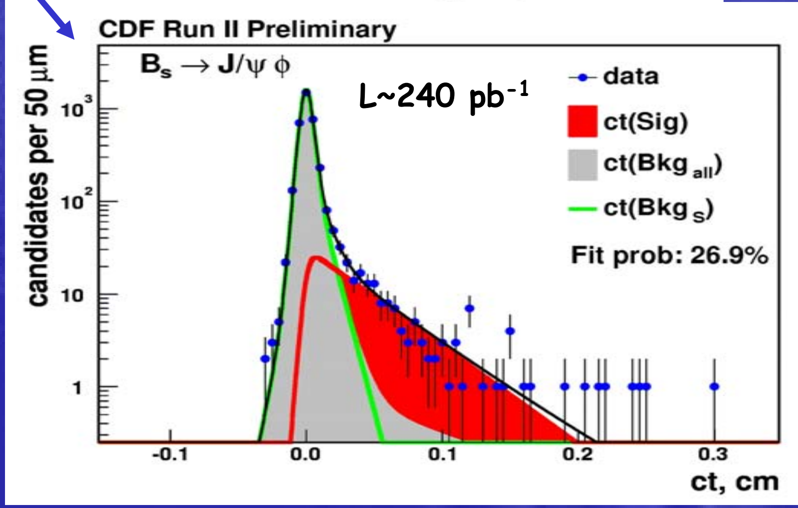
B^0_s Lifetime: $B_s^0 \to J/\psi\phi$ one component





D0 CDF

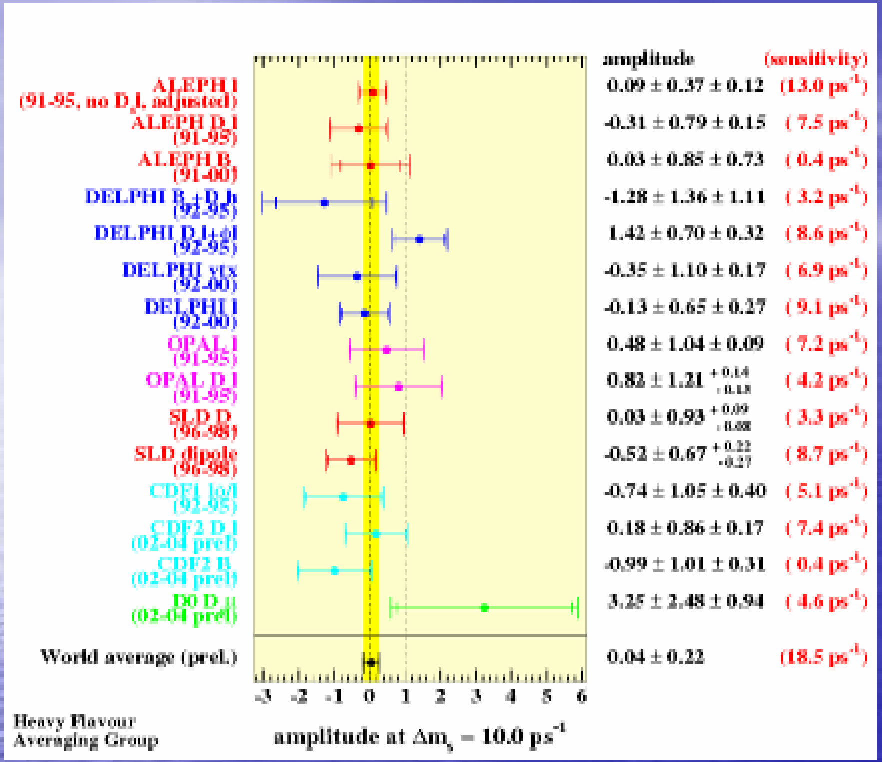


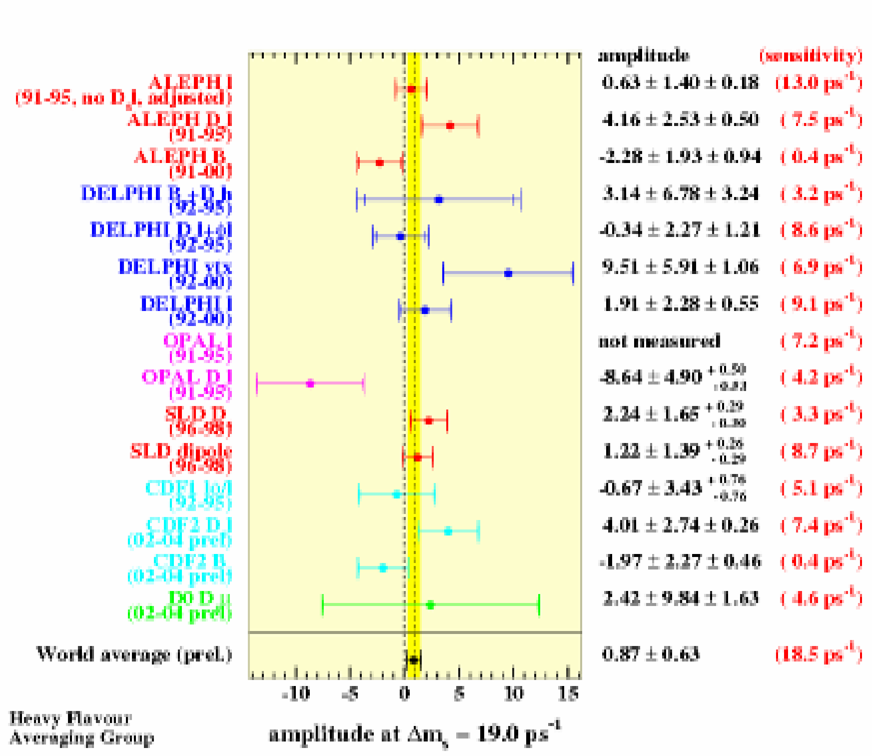


Ratio respect to $B_d^0 \to J/\psi K^{*0}$

$\tau_s/\tau_d = 0.980^{+0.075}_{-0.070}(\text{stat.}) \pm 0.003(\text{syst.})$ $\tau_s/\tau_d = 0.890 \pm 0.072(\text{tot.})$

CDF/World Comparison





B_d Lifetime difference

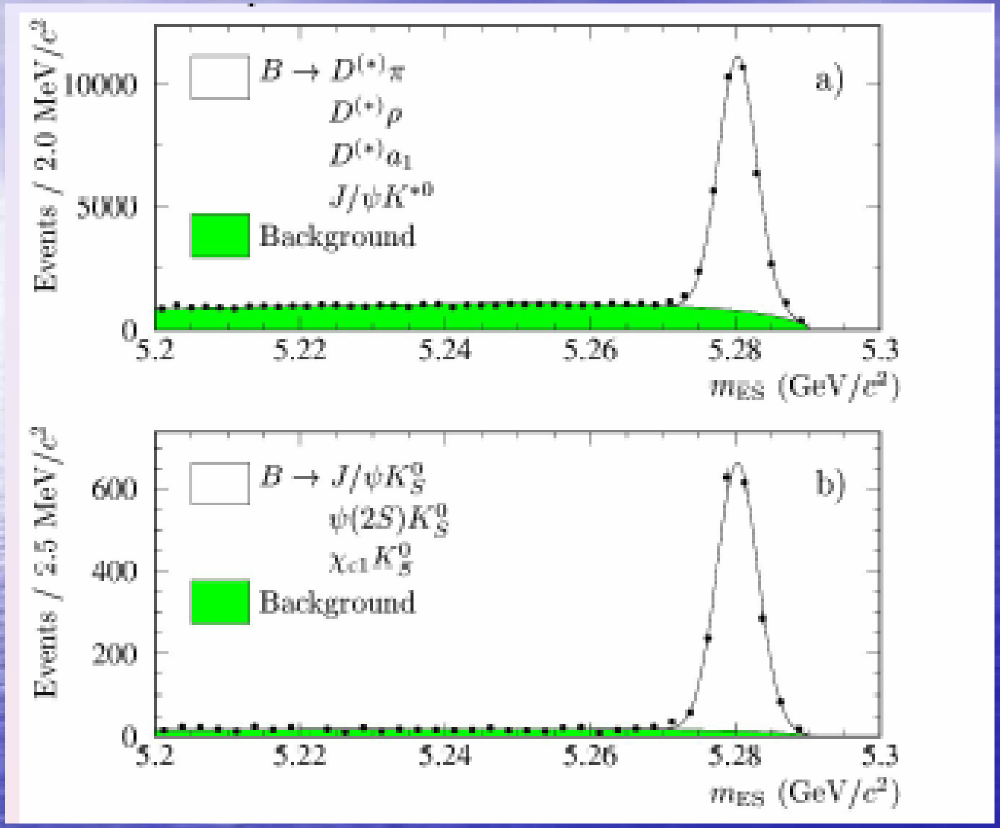
Fully reconstruct on Bboth in CP and flavor eigenstate decay modes
Tag the other B
Fit the proper time distribution with:

$$\frac{dN(\Upsilon(4S) \to B_{tag}, B_{rec} \text{ after } t)}{dt} \propto$$

$$e^{-\Gamma|t|}\left\{\frac{1}{2}c_{+}\cosh\Delta\Gamma t/2+\frac{1}{2}c_{-}\cos\Delta mt-\Re s\sinh\Delta\Gamma t/2+\Im s\sin\Delta mt\right\}$$

$\Delta\Gamma$ explicitly appears in the hyperbolic term

Data sample



Luminosity =82fb^{-1}

B_{flavor} 31027 events

$B^0 \to D^{*-}\pi^+(\rho^+, a_1^+)$

$B^0 \to D^-\pi^+(\rho^+, a_1^+)$

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

B_{CP} 2603 events

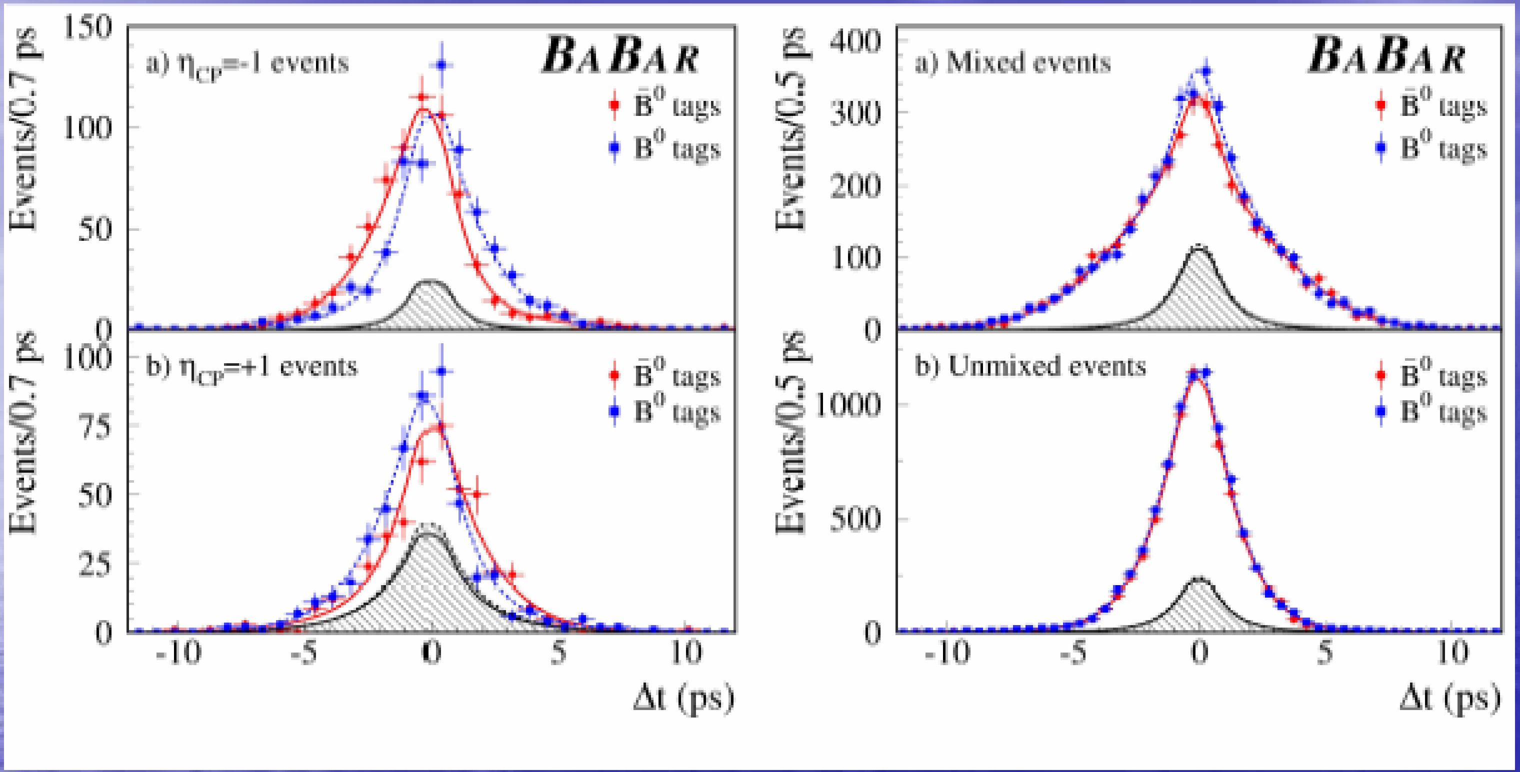
$B^0 \to J/\psi K^0_s$

$B^0 \to \psi(2s)K^0_s$

$B^0 \to J/\psi K^0_L$

$B^0 \to \chi_{c1}K^0_s$

Results



$\mathrm{sgn}[\Re(\lambda_{CP})]\Delta\Gamma/\Gamma$=-0.008±0.037 ±0.018

The 90% confidence level interval for $\Delta\Gamma/\Gamma$

$\mathrm{sgn}[\Re(\lambda_{CP})]\Delta\Gamma/\Gamma \in$ [-8.4%, 6.8%]

$-s^*\Delta\Gamma_d/\Gamma_d$ = -0.009 +- 0.037 (BABAR and DELPHI)