B physics at Tevatron

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Before starting…

- Speaker background:
  - Member of CDF since 1999 (CDF “biased”)
  - My current work Bs meson mixing.
- A myriad of B physics analysis at the Tevatron:
  - Picked up a very reduced sample as illustration.
  - In great detail: out of the oven Bs mixing result.

Outline

- Introduction
  - Hadronic b physics motivation
  - Tevatron – CDF and D0
  - Event selection…or why CDF and D0 are two separate “B worlds”
- 1001 Analysis
  - Lifetimes, CKM physics, CPV, Spectroscopy…
- A detailed case: Bs mixing
- Summary and Conclusions

Introduction

- Why B physics ?
- Why in a “messy” hadron collider?
- Event selection…the hadronic path at CDF

Intro – B physics motivation

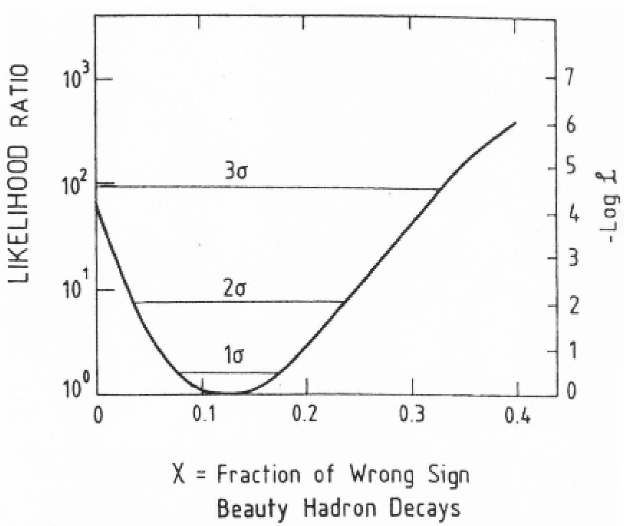
- Excellent benchmark for flavor physics
  - Improve our knowledge of the SM
  - Determine constrain CKM matrix elements.
- New Physics probe, additional contribution in loop and tree diagram
  - Rare decays (Tree level suppress in SM)
  - B decays with dominant s-penguin type amplitudes.
  - Bs oscillations
  - ...
- We see hadrons not free quarks
  - Non perturbative QCD playground
  - Non perturbative methods/computations valiation
  - Mass, exclusive lifetimes,... QCD probes at low Q **2

Why in a hadron collider ?

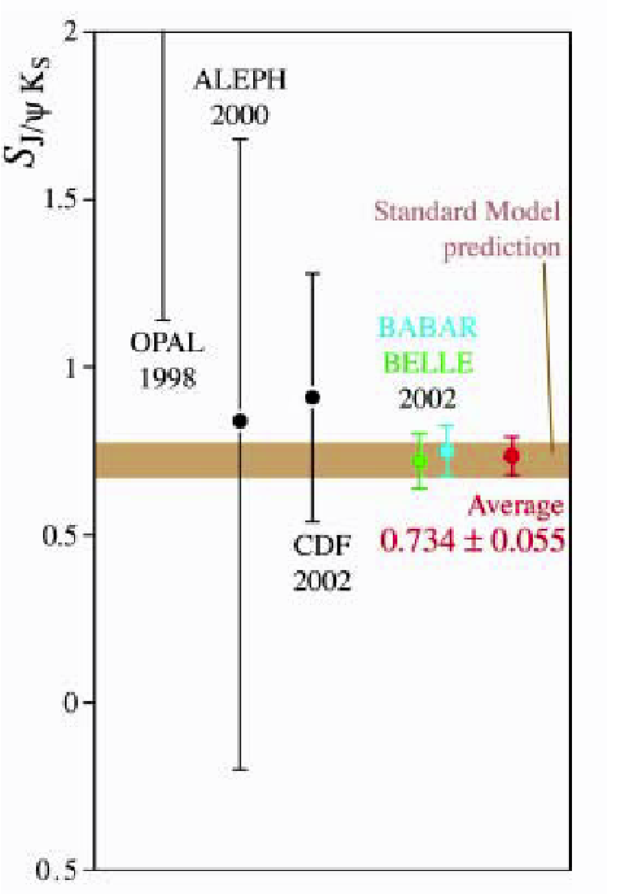
History of Brilliant predecessors

UA1 (1987) primera medida inclusiva mixing en hadrones B

Signatura: carga de pares de leptones de alto momento transverso



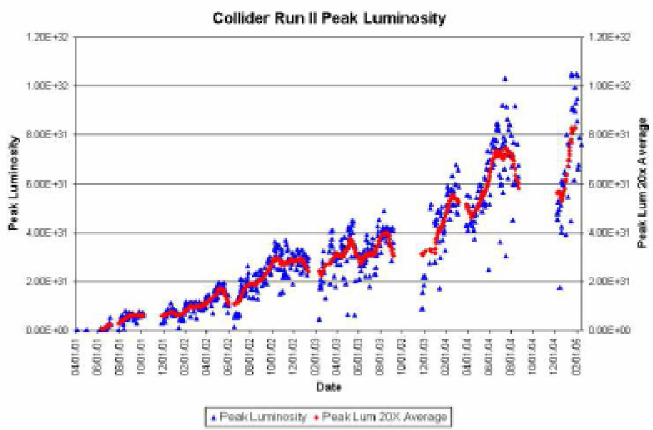
CDF RunI

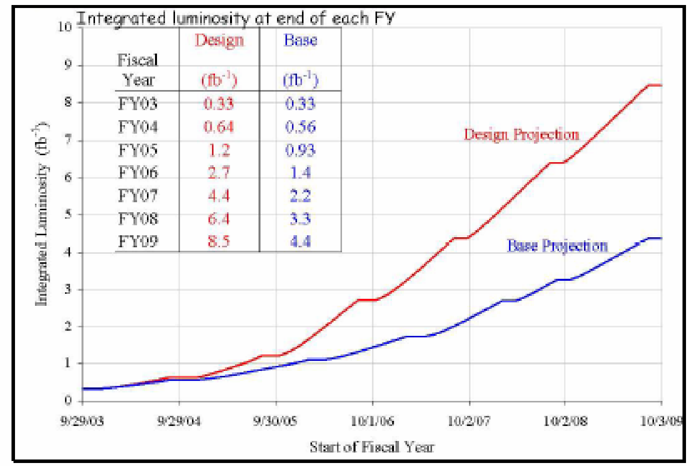


Intro – Why B physics at Tevatron?

- Large b production cross-section
  - $\sigma(bb)$ ~ 50μb (5kHz @ E32, sqrt(s)=1.96 TeV)
  - $\sigma(bX, |y(b)|\leq 1)$ ~ 30μb (3000Hz @ E32)
  - compare: $\sigma(bb)$ ~ 1nb at $\Upsilon(4S)$ (10Hz @ E34)
- Many B hadrons states produced:
  - B^0, B^+, B_s, Λ_b, B_c, Ξ_b
- But… HUGE inelastic cross section ~ 100mb
- A dedicated **selective** trigger needed vs. B factories inclusive trigger.

Introduction – Tevatron





Tevatron performed very well in 2004:

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

  (Run I peak lumi: $1 \times 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)

- Recorded integrated lumi: 0.5 fb^{-1}, 350-400 pb^{-1} good run data

  (all important detector subsystems working)

- Data taking efficiency about 80%

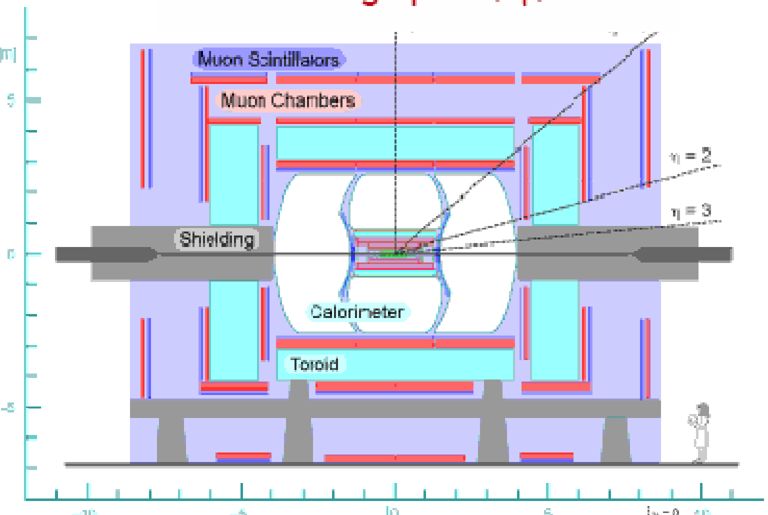
Luminosity Projections:

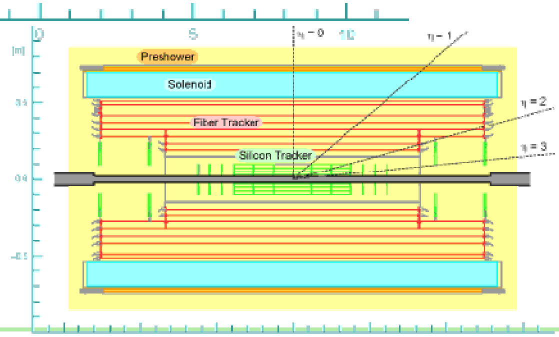
- Expected peak lumi $3 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ by 2007
- Delivered luminosity $\approx$ 4-8 fb^{-1} by end of 2009 (30-60 $\times$ more than Run I)

Introduction - Experiments

Excellent muon and tracking coverage ⇒ high yields

- Extended muon system $|\eta|<2.0$
- Tracking up to $|\eta|<3.0$





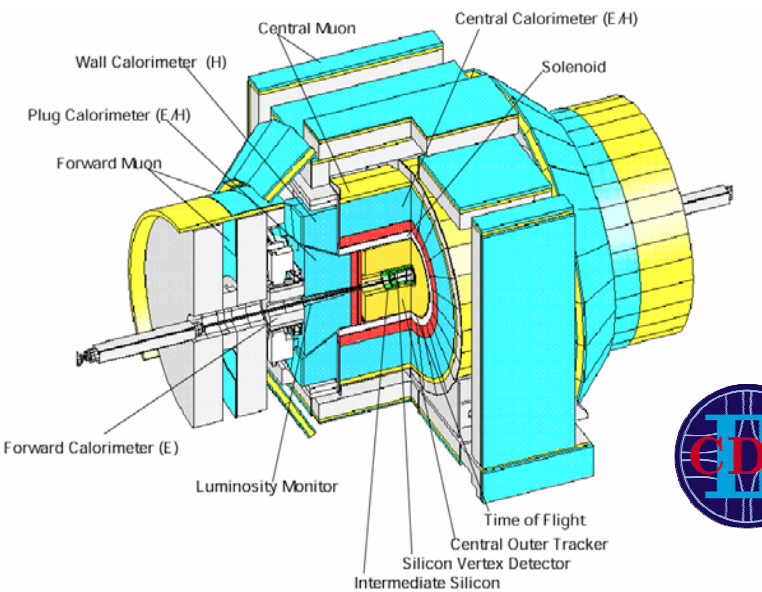
Muon system (extended up to $|\eta|\sim1.5$)

Tracking System

3D Silicon Tracker (up to $|\eta|\sim2$)

Time-of-Flight (particle ID)

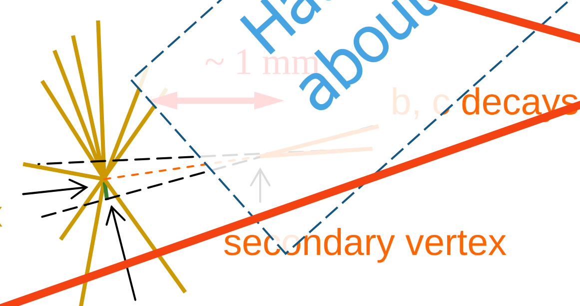
Trigger system (on displaced vertices!)

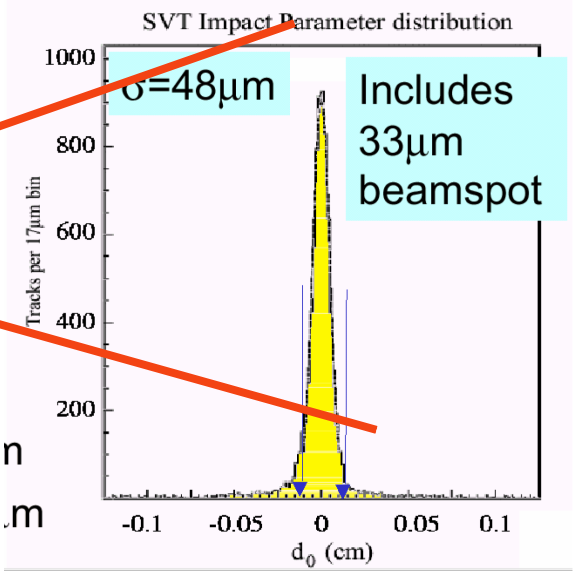


Introduction - B Triggers

- Di-lepton - dilepton sample
  - pT(μ/e)>1.5/4.0 GeV/c
  - J/ψ modes, masses, lifetime, x-section
  - Yield 2x Run I (low Pt threshold, increased acceptance)
- lepton + displaced track - semileptonic sample
  - pT(e/μ)>4 GeV/c 120 μm<d0(Trk)<1mm, pT(Trk)>2 GeV/c
  - Semileptonic decays, Lifetimes, flavor tagging.
  - B Yields 3x Run I
- Two displaced vertex tracks - hadronic sample
  - pT(Trk)>2 GeV/c, 120 μm<d0(Trk)<1mm, Σ pT>5.5 GeV/c
  - Branching ratios, Bs mixing ...

Hadronic mode sensitivity increased about five orders of magnitude !





B physics analysis

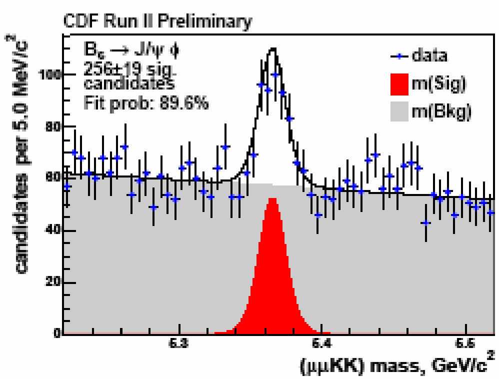
- B hadron lifetimes, mass and branching ratios
- CP Violation
- Mixing
- Spectroscopy (excited and exotic states)
- Quarkonium production
- Other flavor and "track-oriented" physics
  - Charm physics
  - Pentaquark searches

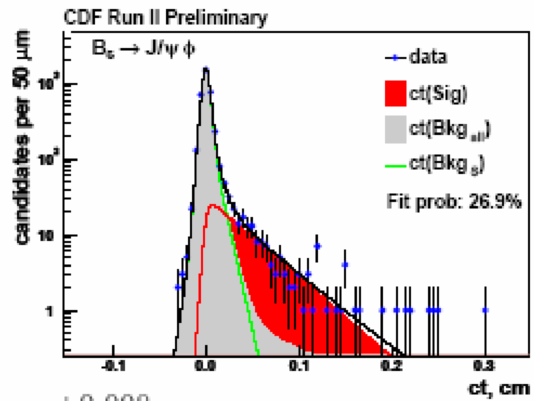
The old good way
Lifetimes in exclusive charmonium decays

- Very well understood di-muon trigger. $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$

240 pb^{-1}

~ 250 Evt.

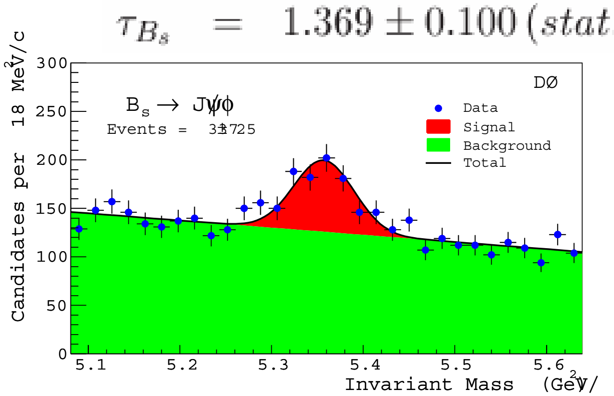


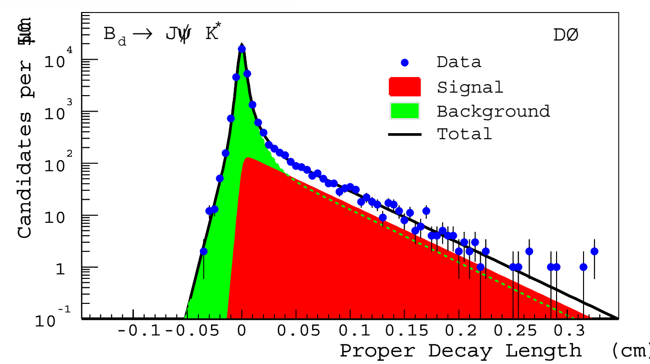


$$\tau_{B_s} = 1.369 \pm 0.100\,(stat.)^{+0.008}_{-0.010}(syst.)\,\mathrm{ps}$$

220 pb^{-1}

~ 350 Evt





$$\tau(B_s^0) = 1.444^{+0.098}_{-0.090}\,(\mathrm{stat}) \pm 0.020\,(\mathrm{sys})\ \mathrm{ps}$$

- D0 higher yield, future CPV meas. (sensible to NP)

CPV - Two body charmless decays B → h^+h^-

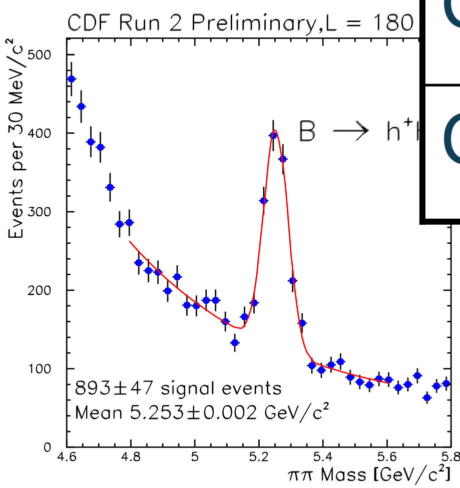
CDF only

- Time dependent asymmetry Bd → ππ (α angle) and Bs → KK (γ angle)
- Direct CP asymme… d Bs → Kπ

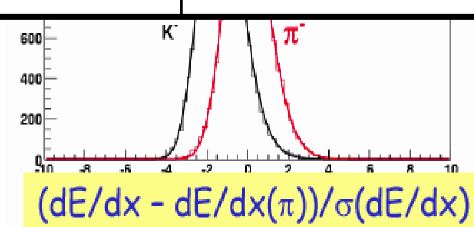
1. extracting the si…

Online hadronic selec…
+ B pointing prim. ve…
displaced & isolated

…ding
…1-p1/p2)q1



Bd → πK	Direct CPV Acp
BaBar	$-0.133 \pm 0.030 \pm 0.009$
Belle	$-0.101 \pm 0.025 \pm 0.005$
CLEO	$-0.04 \pm 0.16 \pm 0.02$
CDF	$-0.04 \pm 0.08 \pm 0.006$



	…ction (180 pb^{-1})
	…±0.03(stat.)
	… ± 0.03(stat)
B_s → KK	0.26±0.03(stat.)
B_s → Kπ	0.02±0.03(stat.)

Bd & Bu – Tevatron vs. B Factories

- $B_{d,u}$ limitations:
  - No neutral reconstruction
  - Lower flavor tagging efficiency

Υ(4s)	Tevatron
Coherent $\bar{B}B$ production the other b always tags the flavor	No Coherent $\bar{B}B$ production mixing dilutes de flavor tagging $D_{max} = 2(1 - f_d \cdot \chi_d - f_s \chi_s) - 1 \sim 0.7$
Geom. acceptance ~ 100%	Geometrical acceptance ~ 20-40%

- Competitive $B_{d,u}$ program:
  - Selftagging modes
  - Charged final states
  - Rare decays
- Wait for the next generation: LHCb

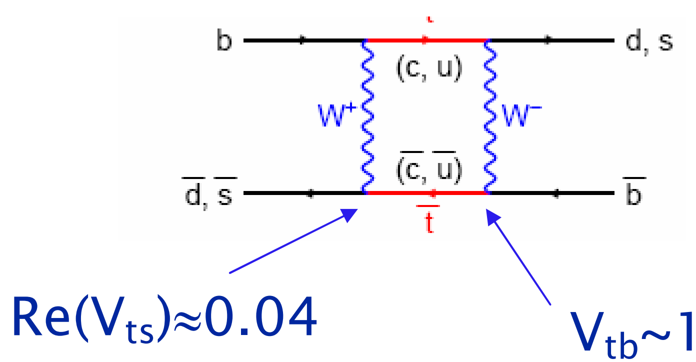
A detailed analysis: B_s mixing

- Introduction
  - Why ? How? Status?
- Ingredients:
  - Final State reconstruction (semilep. & hadro.)
  - Flavor tagging
  - Proper time measurement (lifetime and mass)
- Blind amplitude vs. Δm_s scan

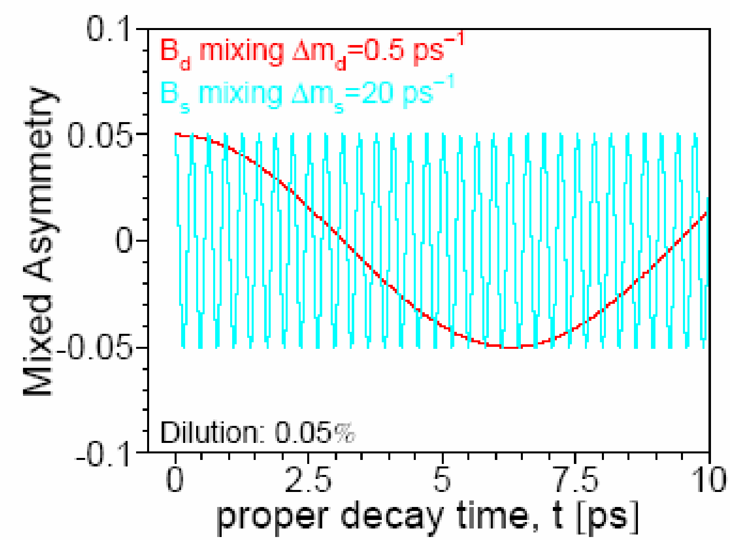
Introduction – Why Δm_s ?

- Measurement of Δm_s constrains the CKM triangle.
- Sensible to new physics via virtual intermediate states
- Very fast oscillations !!

  Experimental challenge !!



$Re(V_{ts}) \approx 0.040 > Re(V_{td}) \approx 0.007$



Intro - Who?

- Plan A, direct Δms measurement:
  A. Flavor defined final state reconstruction
  B. B Flavor tagging at production
  C. Proper decay time measurement.
- Plan B, indirect measurement, decay width difference $\Delta\Gamma_s$ of two CP(mass) eigenstates:

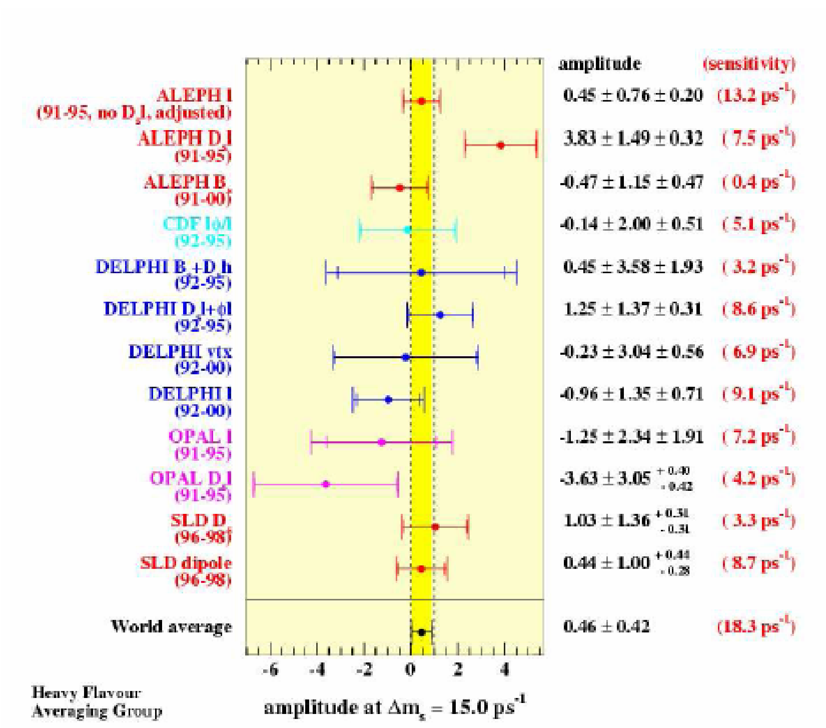
hep-ex/0412057

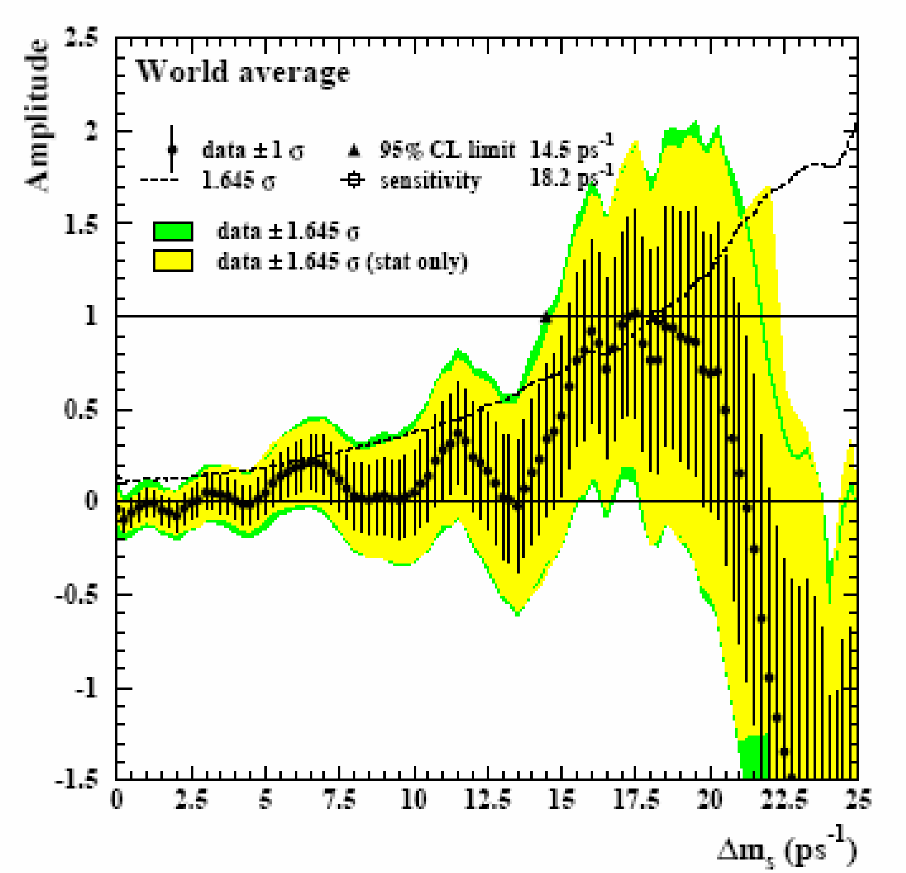
$$\Delta\Gamma_s/\Gamma_s = 0.65^{+0.25}_{-0.33} \pm 0.01$$

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

$$\frac{\Delta m_s}{\Delta\Gamma_s} \approx \frac{2}{3\pi}\frac{m_t^2}{m_b^2}\left(1 - \frac{8}{3}\frac{m_c^2}{m_b^2}\right)^{-1} h\left(\frac{m_t^2}{M_W^2}\right) \quad \Delta m_s = 125^{+65}_{-55} \text{ ps}$$

Intro – Δm_s Status





- Combined limit from LEP, SLD and CDF Run I
  - Comb. Sensitivity ~ 18 ps^{-1}
  - Comb. Limit ~ 14.5 ps^{-1}

Overall analysis strategy

- Observable:

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

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

- The sensitivity approx. by:

$$\mathcal{S} = \frac{S}{\sqrt{S+B}}\sqrt{\frac{\varepsilon D^2}{2}}\exp(-\sigma_{ct}^2 \Delta m_s^2/2)$$

Signal optimization

Flavor Tagger "effectiveness"

Proper time uncertainty

$$c\tau = \frac{L_{xy}}{\beta\gamma} = \frac{L_{xy}\, m(B)}{P_T(B)} \rightarrow \sigma_{ct} = \frac{m(B)}{P_T(B)}\sigma_{Lxy} \oplus c\tau\left(\frac{\sigma_{P_T(B)}}{P_T(B)}\right)$$

For semileptonic decays $\left(\frac{\sigma_{P_T(B)}}{P_T(B)}\right) \approx 15\%$

Fully reconstructed decays $\left(\frac{\sigma_{P_T(B)}}{P_T(B)}\right) \approx 0.5\%$

FINAL STATE RECONSTRUCTION

$$\mathcal{S} = \boxed{\frac{S}{\sqrt{S+B}}} \sqrt{\frac{\varepsilon D^2}{2}} \exp(-\sigma_{\mathrm{ct}}^2 \Delta m_s^2 / 2)$$

Signal Reconstruction

- 355 pb^{-1} from April 2001 – August 2004
- Hadronic and semileptonic channels:

$B_s \to D_s\pi$ $\quad B_s \to \ell D_s X$ with $D_s \to \Phi\pi, K^*K, 3\pi$

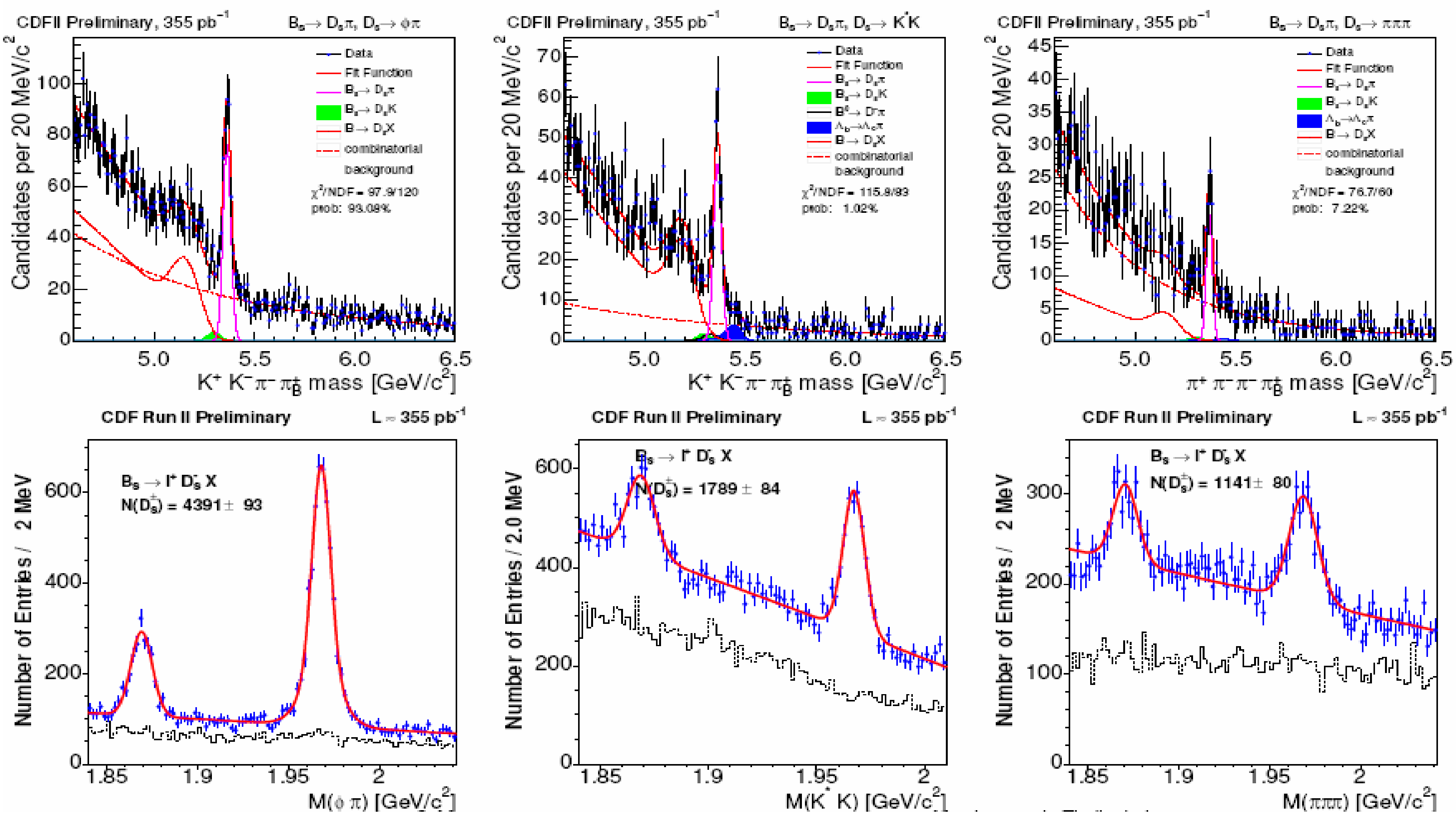
- Maximize $\dfrac{S}{\sqrt{S+B}}$

- Long lived backgrounds (reflections, missreconstructed cand.) modeled using realistic full detector simulations. Trigger efficiency sculpting is critical.
- Combinatorial background from upper side band.

Channel	Yield	$\frac{S}{B}$	$\frac{S}{\sqrt{S+B}}$
$B \to l^+ D_s(D_s \to \phi\pi)$	4391 ± 93	2.49	55.5
$B \to l^+ D_s(D_s \to K^*K)$	1811 ± 82	0.47	24.0
$B \to l^+ D_s(D_s \to \pi\pi\pi)$	1489 ± 85	0.34	19.5

Subsample	Yield	S/B
$D_s^- \to \phi\pi$	378.8 ± 25.5	1.833
$D_s^- \to K^*K$	235.3 ± 18.8	2.395
$D_s^- \to \pi\pi\pi$	72.9 ± 11.7	1.833

Signal Reconstruction



FLAVOR TAGGING

$$S = \frac{S}{\sqrt{S+B}} \sqrt{\frac{\varepsilon D^2}{2}} \exp(-\sigma_{\mathrm{ct}}^2 \Delta m_s^2 / 2)$$

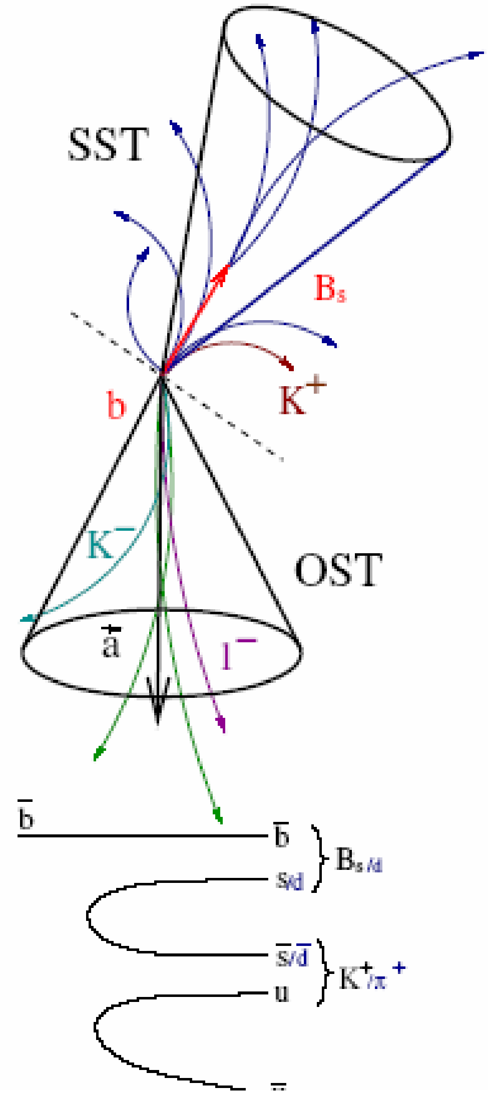
Flavor Tagging 101

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)

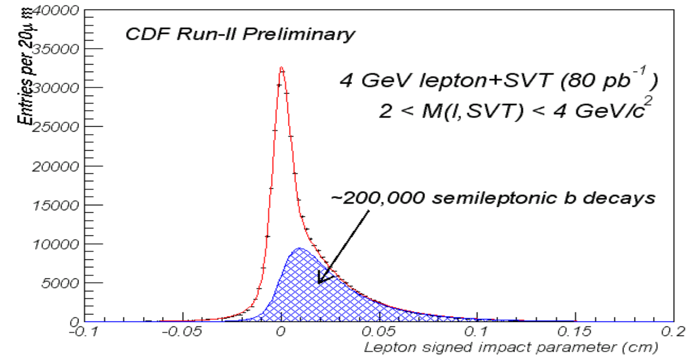


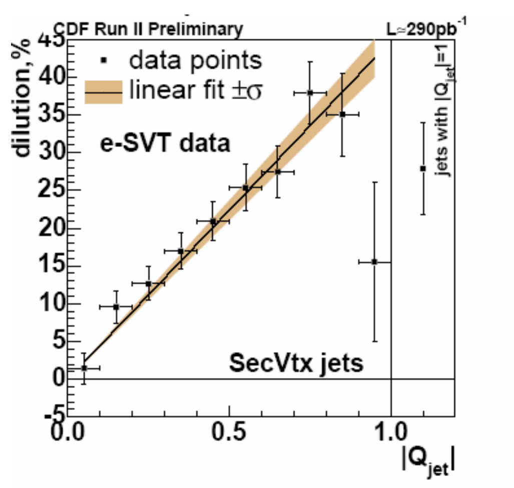
Opposite Side Tagger Calibration

Opposite site taggers (SLT,JQT):

- Dilution and efficiency determined with data

  (high statistics lepton + disp. Track sample)
- Dilution as a function of relevant parameters (Ptrel, L, JetQ)
- Big improvement agreement data vs. MC for away side quatities BUT still MC (runI tunned pythia msel=1) does not reproduce flavor tagging results (outstanding issue since runI)
- OSKT (powerful tagger in B factories) is still in progress





Same Side Tagger Calibration

- Same Side (Kaon) Taggers
  - SS(K)T really critical to increase sensitivity
  - Can not use lepton+SVT sample
  - Dilution inferred from the amplitude of mixing asymmetry oscillation. (only Δmd)
  - MC NEEDED for determining the Dilution and its parameterization vs. the relevant variables.
  - SST RunI (Δmd, $\sin 2\beta$) succeeded.
  - Very recent and encouraging progress on SSKT with predicted overall $\varepsilon D^2 \sim 3.26 \pm 0.88$!!!

OST Dilution scale factors

- Lepton+SVT sample D parameterization vs. relevant variables.
- D absolute scale depends on kinematics of event samples ⇒ trigger bias predicted dilution.
- Scaling of the predicted dilution using samples with similar kinematics required
  - Bd calibration samples: lepton+D, $J/\psi K$, $D\pi$
- Dilution not fitted in Bs mixing likehood ⇒ understanding of this scale factor is a critical issue

Flavor Tagging - Status

- Current Δms analysis oposite side taggers only (ICHEP04)
- D parameterization (l+SVT)
- Scale factor hadronic modes (Bd,u$\rightarrow$Dπ,J/ψK)
- Scale factor semileptonic modes (Bd,u $\rightarrow$ lepton + D)

Parameter	Result
Δm_d	$0.503 \pm 0.063 \pm 0.015$ ps^{-1}
SMT	$0.83 \pm 0.10 \pm 0.03$
SET	$0.79 \pm 0.14 \pm 0.04$
JVX	$0.78 \pm 0.19 \pm 0.05$
JJP	$0.76 \pm 0.21 \pm 0.03$
JPT	$1.35 \pm 0.26 \pm 0.02$

variable	fit result
$S_D(Smt)$ [%]	92.6 ± 3.9
$S_D(Set)$ [%]	98.0 ± 5.6
$S_D(Jvx)$ [%]	97.1 ± 6.4
$S_D(Jjp)$ [%]	90.3 ± 7.9
$S_D(Jpt)$ [%]	108.2 ± 9.3
Δm_d	0.497 ± 0.029
$c\tau(B_d)$ [μm]	448.5 ± 2.8
$c\tau(B_u)$ [μm]	475.9 ± 3.1

Hadronic sample fitted scaled εD^2

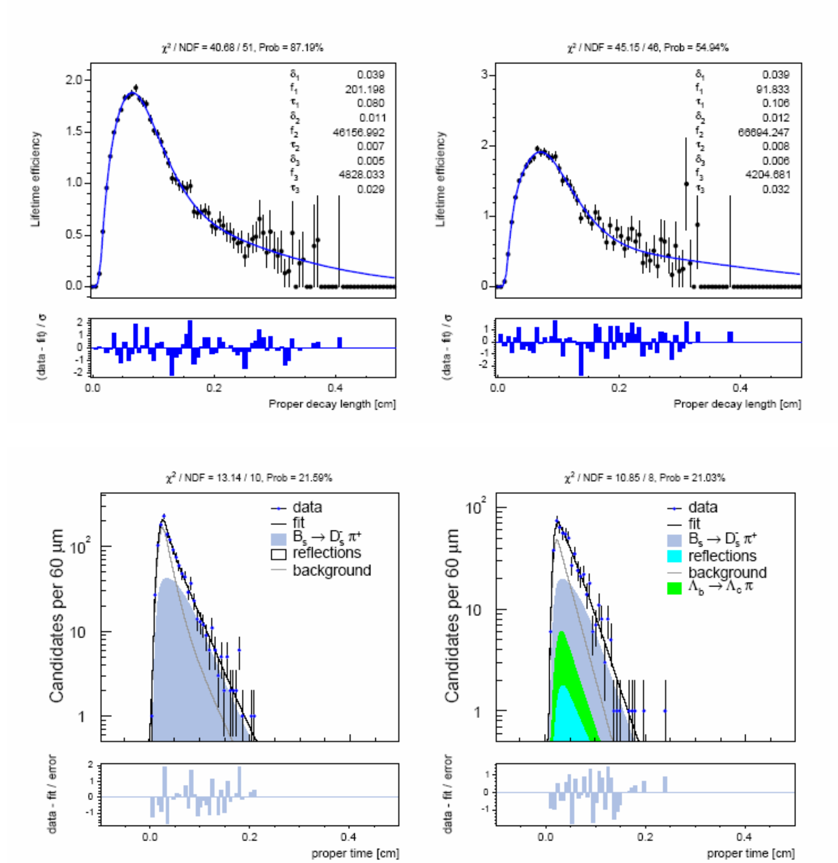
Tagger	Dilution	Est. Error	Sys. Error
SMT	0.409	0.030	0.1
SET	0.170	0.017	0.061
JVX	0.153	0.008	0.075
JJP	0.141	0.007	0.078
JPT	0.403	0.006	0.0155
Total	1.276	0.222	0.036

PROPER TIME MEASUREMENT

$$S = \frac{S}{\sqrt{S+B}}\sqrt{\frac{\varepsilon D^2}{2}}\exp(-\sigma_{\mathrm{ct}}^2 \Delta m_s^2/2)$$

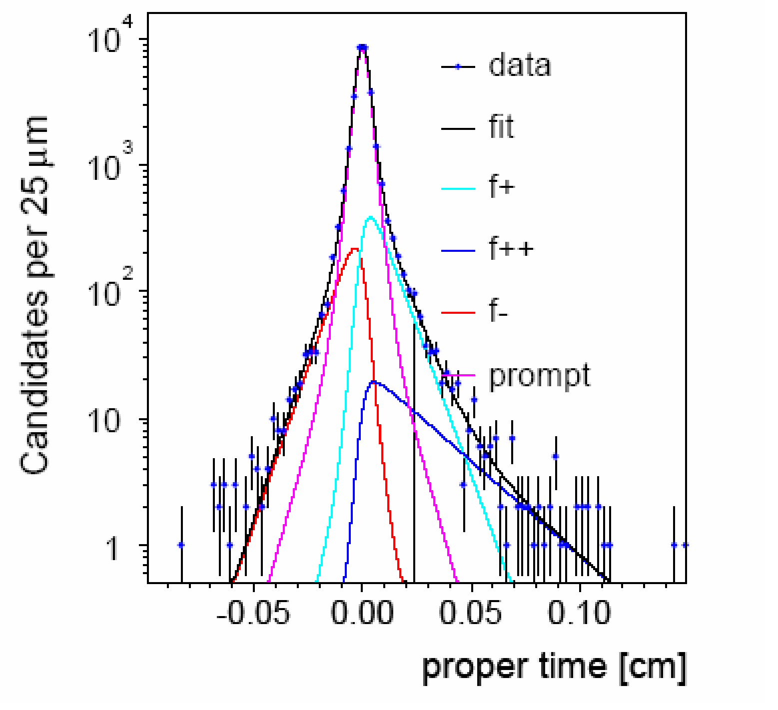
Lifetime - IP biased sample

- Displace track trigger $\Rightarrow$ Lxy bias
- Simultaneous lifetime and mass fit.
- Bkg templates from data & mc.
- Inclusion of the innermost silicon layer "L00" still open issue (mainly in mc).



Lifetime - cτ scale factor

- Measured cτ error out of the vertexing algorithm (CTVMFT) are underestimate true value.
- Ad-hoc scale factor to achieve the "real" uncertainty.
- In this case, extracted from prompt D meson hadronic sample + plus primary track.
- In Semileptonic sample is not a issue.
- Vertex topology and kinematics dependence also corrected.



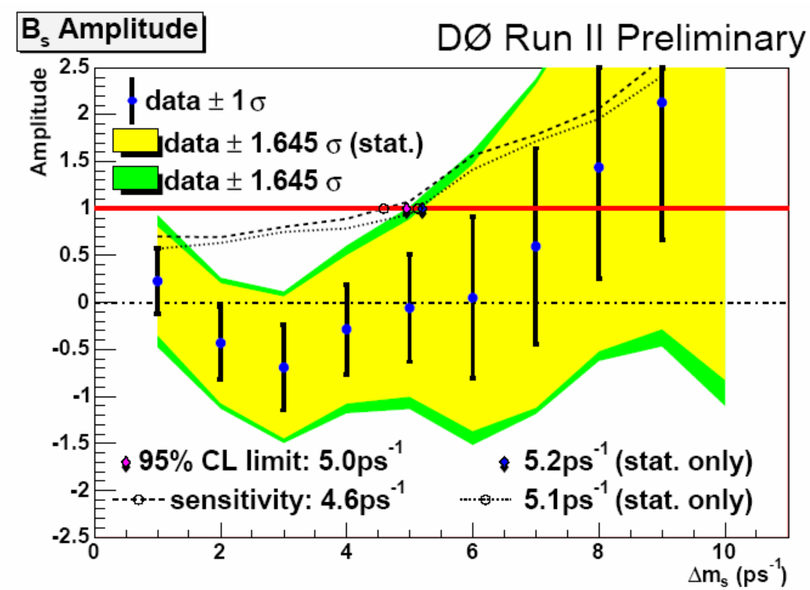
Sensitivity - Δm_s Amplitude Scan

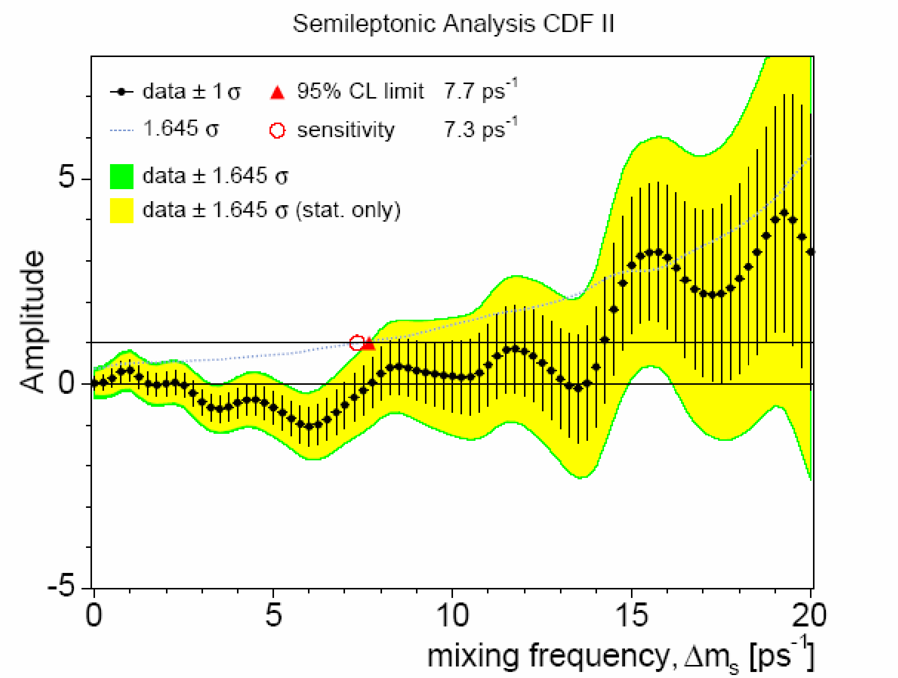
- Introduce a new parameter (A the amplitude) in the fitter.

$$\mathcal{L} \sim \frac{1 \pm A \cdot D \cdot \cos(\Delta m_s t)}{2}$$

- Fit for each Δm_s hypothesis
- Ideal conditions: A=0 for all Δm_s but the correct one ($A_{correct}=1$)
- 95 C.L. exclusion limit: $A(\Delta m_s) + 1.645 \cdot \sigma[A(\Delta m_s)] \leq 1$
- Sensitivity smallest value that: $1.645 \cdot \sigma[A(\Delta m_s)] = 1$
- Detailed method Moser, Roussarie NIM A384 (1997) 491-505
- For avoiding any human bias, the tagging dilutions are **randomized** $\Rightarrow$ sensitivity unchanged , limit changed

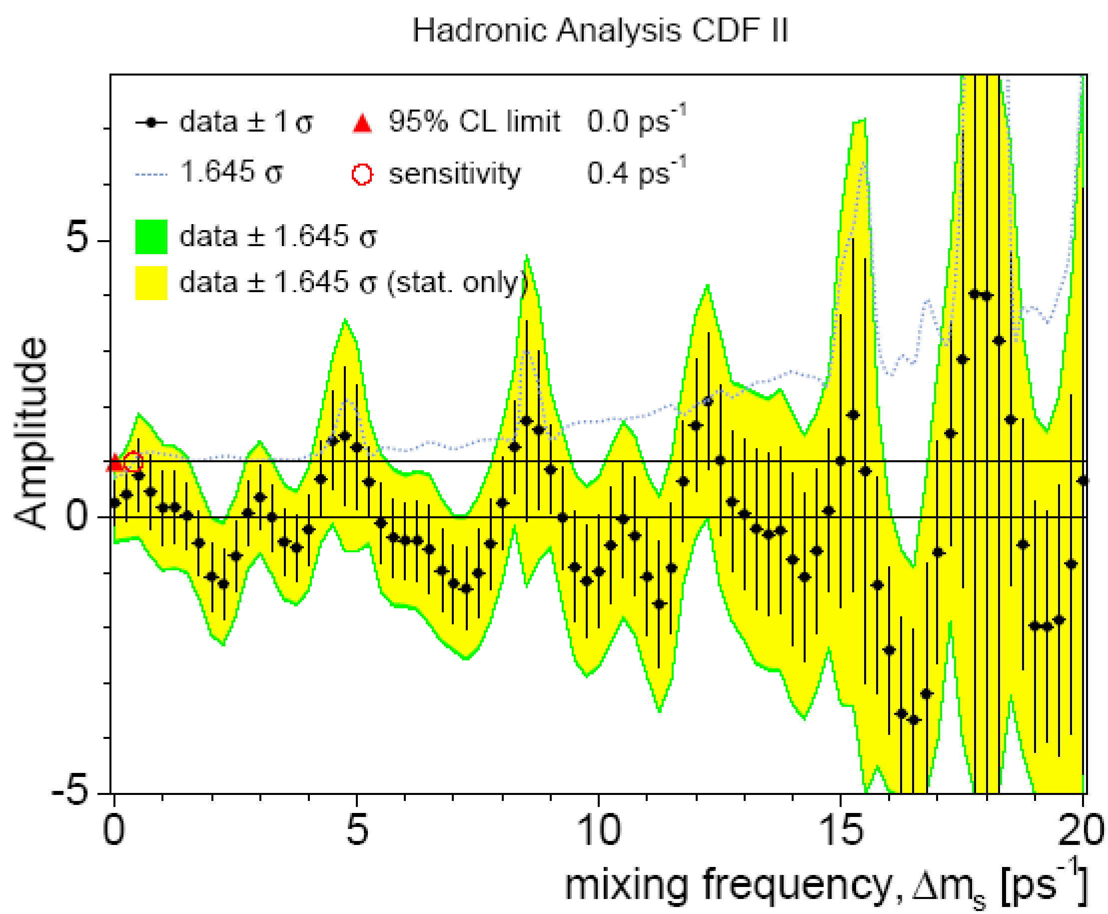
Sensitivity – Δm_s semileptonic



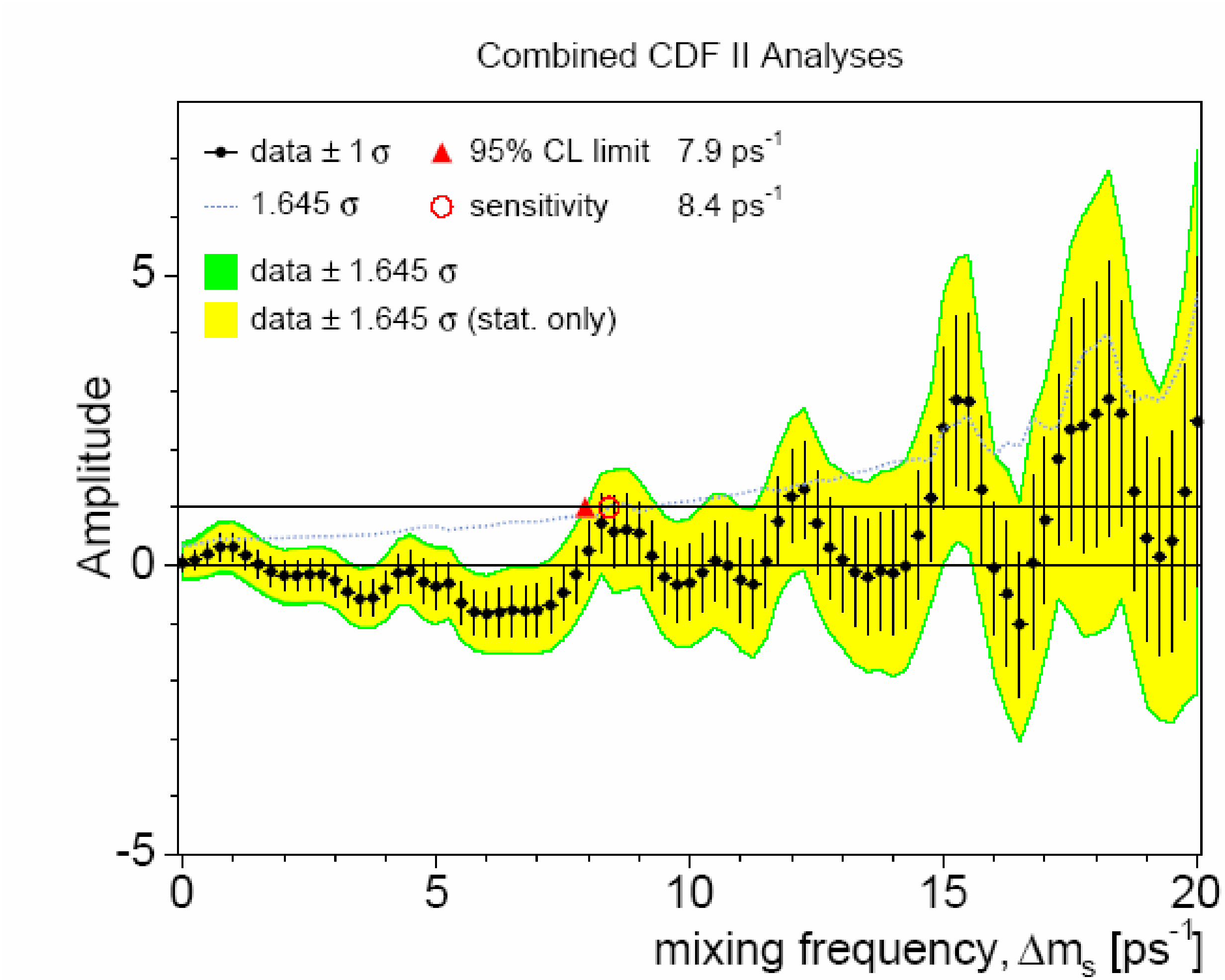


Sensitivity - Δm_s hadronic

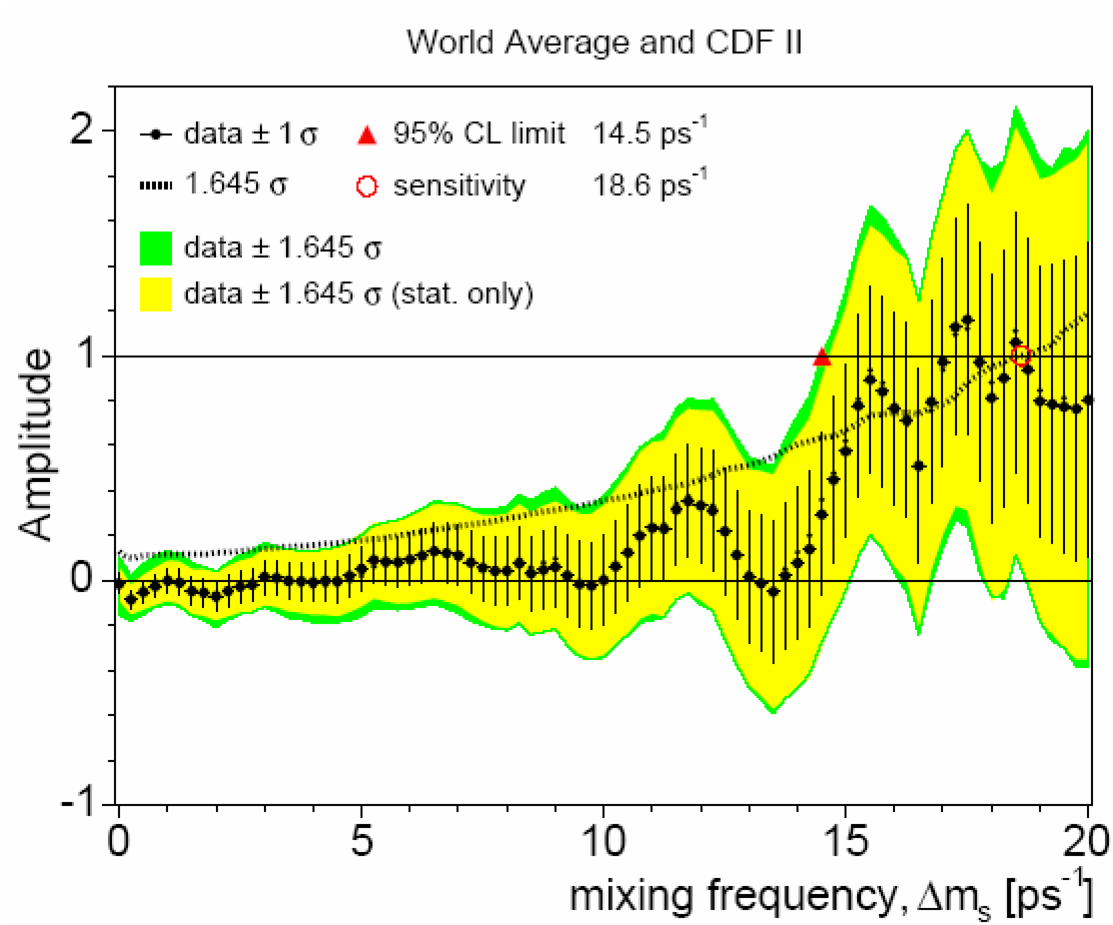
CDF only



Sensitivity - Δm_s hadr + semilep



Sensitivity - Δm_s naïve global comb.



Short term improvements

- Results are still statistical limited we may be lucky or… unlucky setting the limit.
- More data already available
- Flavor tagging:
  - Improved JQT
  - Add Kaon based taggers
    - SSKT expect soon a factor of two increase
    - OSKT will take more time.
- Time resolution:
  - Proper time error scaling very conservative, expect better understanding with better time resolution.

Conclusions

- Tevatron is back in business of producing world class results with more that 400 pb^{-1} "physics quality" data on tape (x4 RunI)
- D0 and CDF excellent performance DAQ ε~80%.
- CDF's L2 trigger processor on displaced track has been a big success.
- For the first time, both experiments have completed the whole analysis sequence of the "El Dorado" for B hadronic physics: Bs mixing
  - Combined global limit increased ~ 1-2 ps^{-1}
  - There are many know handles for improving

Back-up

- Results are still statistical limited we may be lucky or… unlucky setting the limit.
- Semileptonic sensitivity matches summer 04 expectation.
- Lower hadronic limit compare to semileptonics

Sensitivity – hadronic sample

	Summer 2004 Projected	Observed
Yield	725	~700
avg S/B	3.3:1	2:1
εD^2	1.6 %	> 1.5 % ?
σ(ct)	67 fs	100 fs ?

- yield is Ok (more luminosity compensates for Ds 3pi)
- S/B got worse – adding L00 hits increases bg by 50%
- εD2 confirmed 1.5% using average dilution
- Vertexing algorithm errors only – ct resolution consistent 67 fs
- but the scale factor is 1.3, so really: 100 fs!

CDF

Inherited from Run I

Central Calorimeter ($|\eta|<1$)

Solenoid (1.4T)

Partially New

Muon system (extended up to $|\eta|\sim1.5$)

New

Tracking System

- 3D Silicon Tracker (up to $|\eta|\sim2$)
- faster Drift Chamber

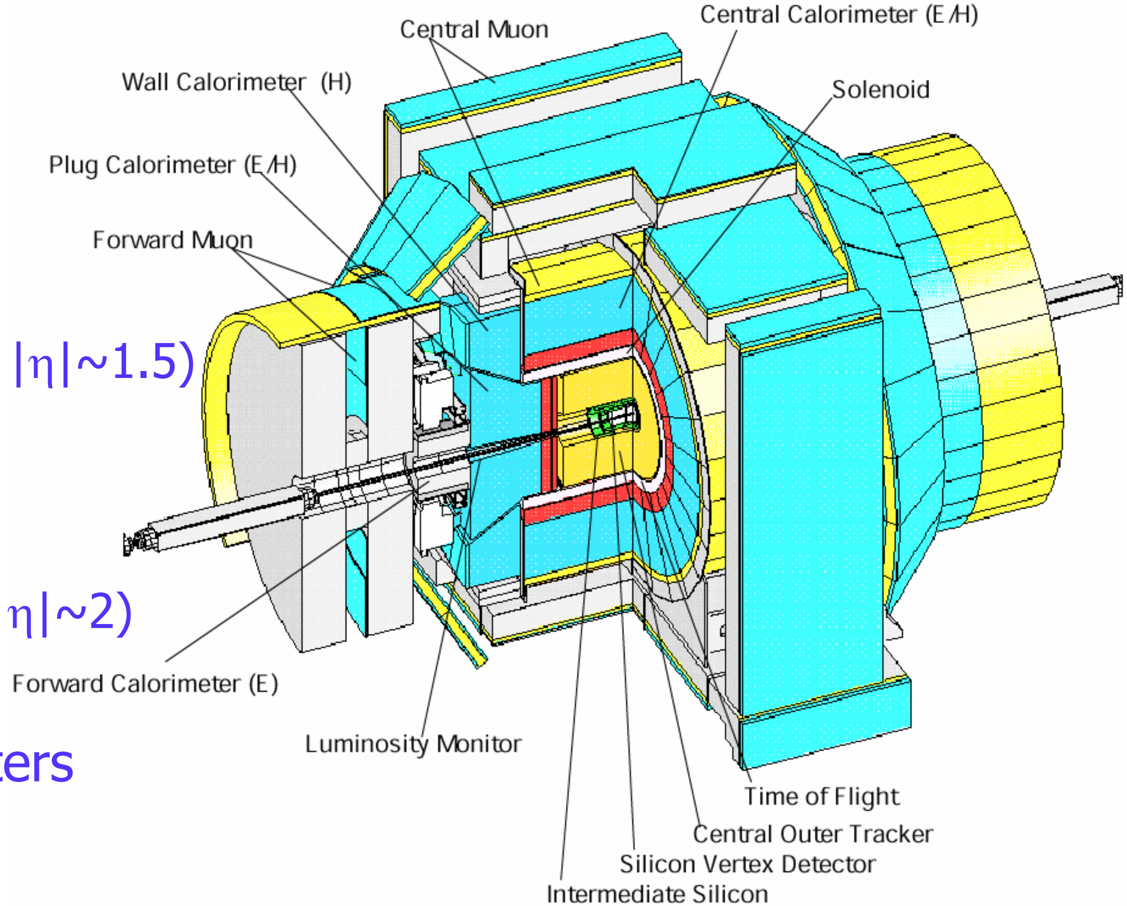
Plug and Forward Calorimeters

Time-of-Flight (particle ID)

Luminosity monitor

DAQ system, front end electronics

Trigger system (new trigger on displaced vertices!)



"Physics" backgrounds

Decay	$\phi\pi$	K^*K	3π
$B_s \to D_s^{(*)} D^{(*)} X,\ D^{(*)} \to \ell X$	3.1	3.4	3.1
$B_s \to D_s^{(*+)} D_s^{(*-)} X,\ D^{(*-)} \to \ell X$	3.2	3.4	2.8
$B_u \to D_s^{(*)} D^{(*)} X,\ D^{(*)} \to \ell X$	2.4	2.3	2.2
$B_s \to D_s^{(*)} D^{(*)} X,\ D^{(*)} \to \ell X$	1.7	1.7	1.3

Table 4: Fraction (in %) of each physics background with respect to the signal for each selected decay mode.

	$B_s \to D_s^- \pi$ $D_s^- \to \phi\pi$	$B_s \to D_s^- \pi$ $D_s^- \to K^*K$	$B_s \to D_s^- \pi$ $D_s^- \to \pi\pi\pi$
$B_s \to D_s^- \pi, \phi\pi$	100 %	$3.35 \pm 0.34\%$	$0.10 \pm 0.02\%$
$B_s \to D_s^- \pi, K^*K$	0.24 ± 0.02 %	100%	$0.09 \pm 0.02\%$
$B_s \to D_s^- \pi, \pi\pi\pi$	0 %	0%	100%
$B^0 \to D^- \pi, K\pi\pi$	1.70 ± 0.32 %	$7.33 \pm 1.44\%$	$0.65 \pm 0.23\%$
$B^0 \to D^{*-} \pi, D^0\pi$	0 %	$0.09 \pm 0.03\%$	$0.12 \pm 0.05\%$
$\Lambda_b \to \Lambda_c \pi, pK\pi$	1.50 ± 0.36 %	$33.63 \pm 8.41\%$	$1.19 \pm 0.36\%$
$\Lambda_b \to \Lambda_c \pi, p\pi\pi$	0.01 ± 0.01 %	$0.07 \pm 0.04\%$	$5.62 \pm 3.30\%$

Table 2: Table of reflection ratios for different decays. The values in the different columns correspond to the ratio of reflected decays that are found in the narrow mass range relative to the signal decay.