Experimental Results on Lifetimes, Width and Mass Differences from the Tevatron

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for the CDF and DØ collaborations

Overview

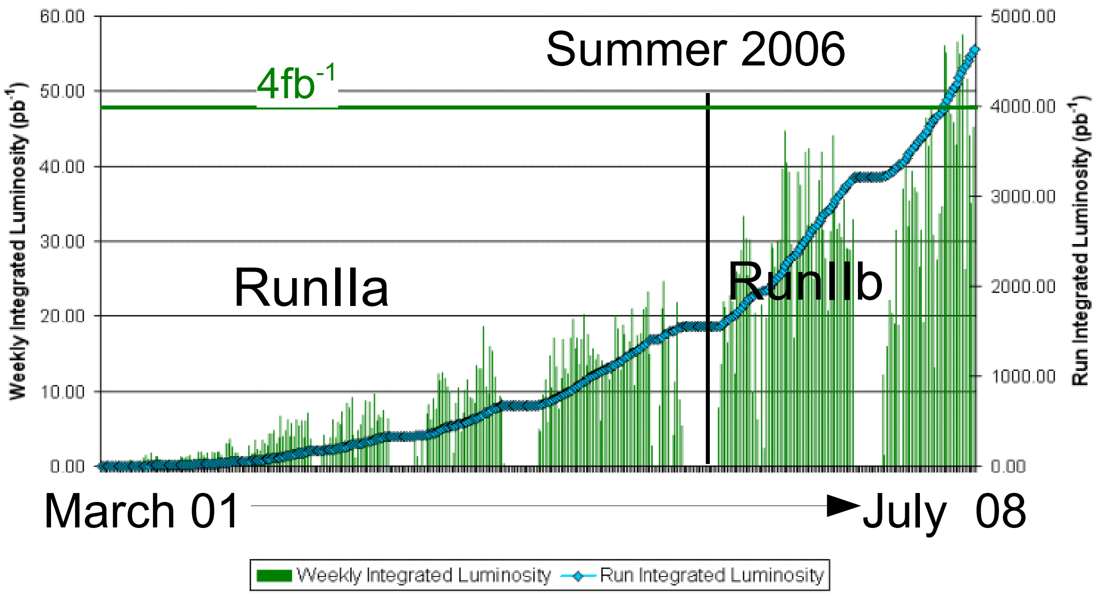
- Introduction
  CDF and DØ detectors
- The B_s system
  $\Delta\Gamma$
  Δm_s
  flavour specific lifetime
- Lifetimes
  Λ_b, B_c
- Conclusions

The Tevatron Collider at Fermilab

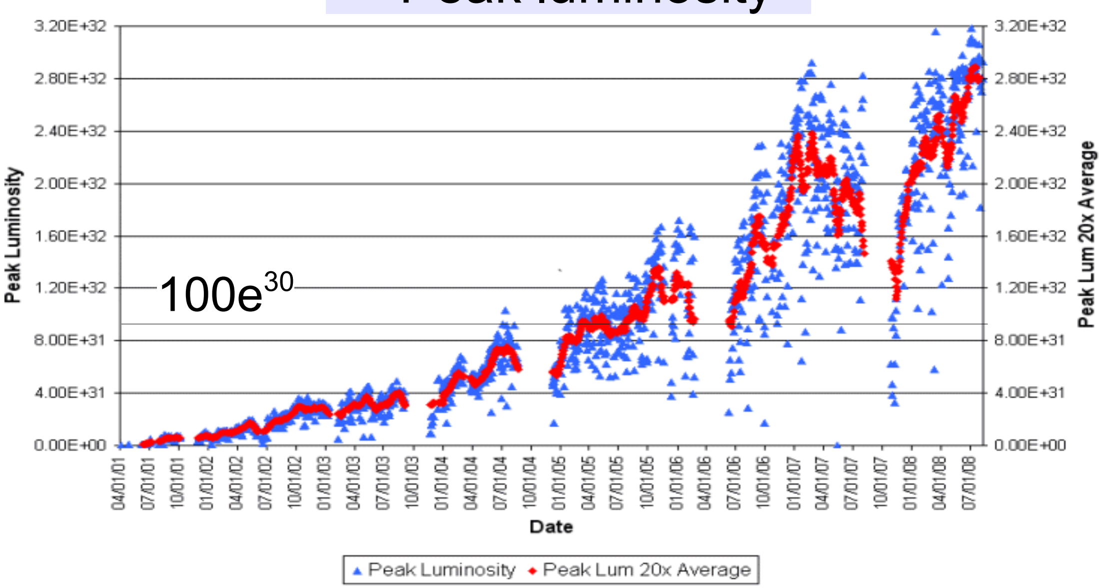
Run I 1992-1995
E_{CM} = 1.8 TeV
125 pb^{-1}

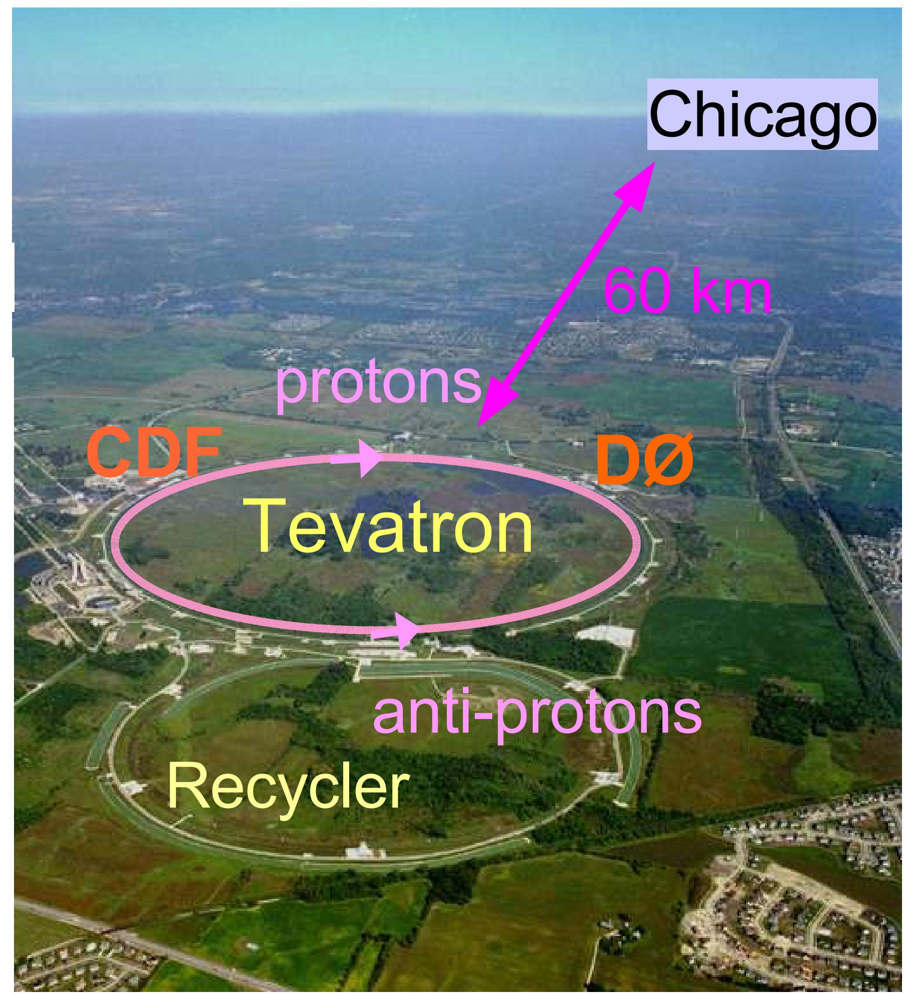
Run II
E_{CM}= 1.96 TeV
4 fb^{-1}

Integrated Luminosity



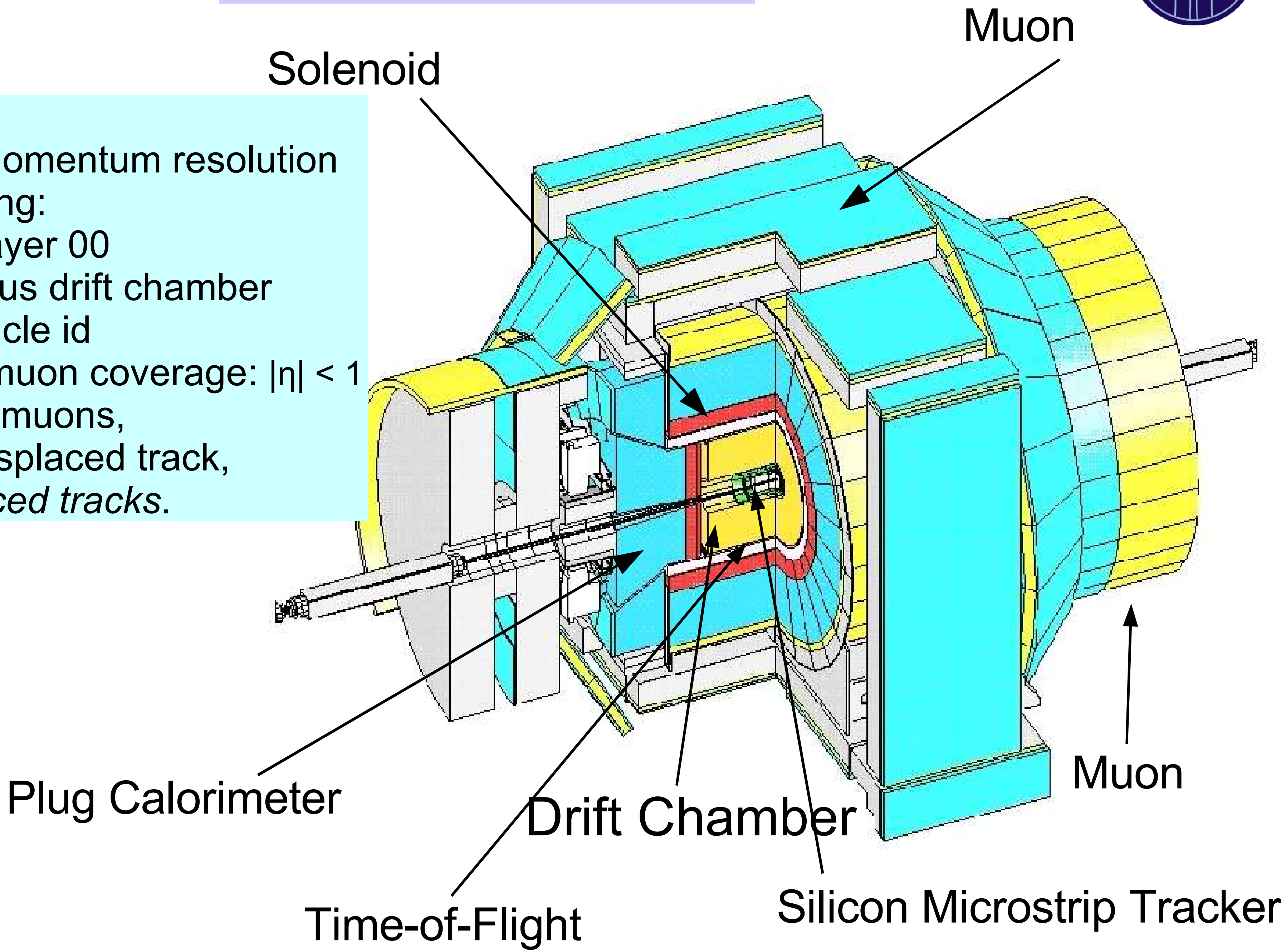
Peak luminosity





The CDF detector

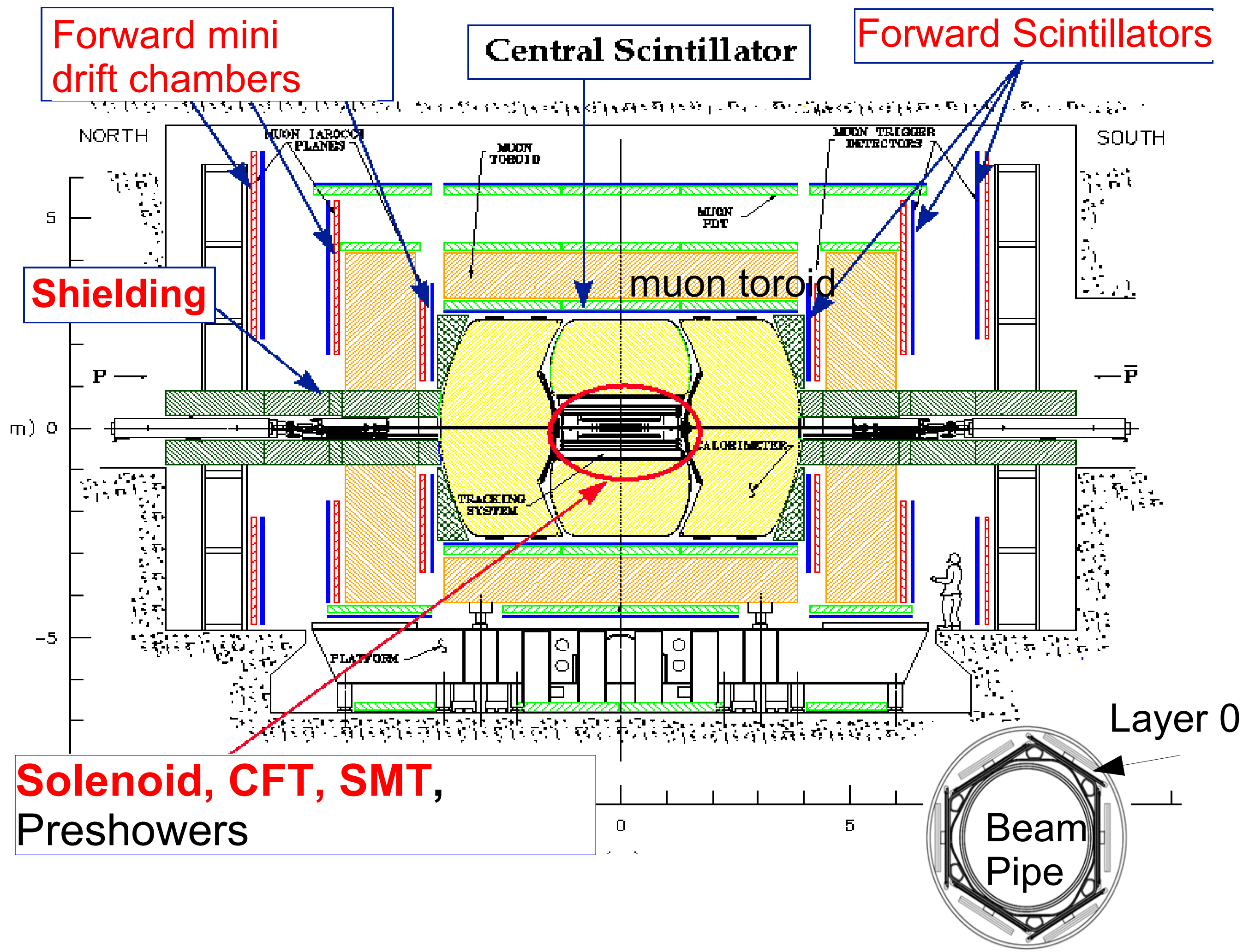
b-physics:
- excellent momentum resolution and vertexing:
  - Silicon, Layer 00
  - large radius drift chamber
- dE/dx: particle id
- Triggered muon coverage: $|\eta| < 1$
- Triggers: dimuons, lepton + displaced track, *two displaced tracks*.



The DØ Detector

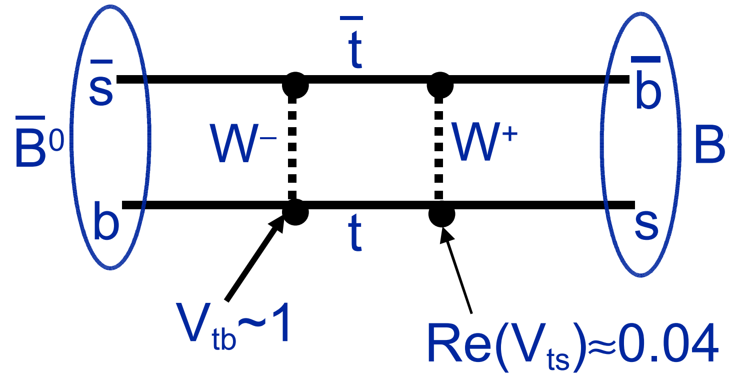
b-physics:

- Tracking: small radius, but coverage up to |η| < 2 Layer 0
- Triggered muon coverage up to |η| < 2
- Triggers: dimuons, single muons, (track displacement at second trigger level)



The B_s^0 System

B_s Mixing



Two flavour eigenstates:

$$\bar{B}_s^0 = \left| b\,\bar{s} \right\rangle$$

$$B_s^0 = \left| \bar{b}\, s \right\rangle$$

Mass eigenstates are an admixture of B_s^0 flavour eigenstates:

$$\left| B_s^H \right\rangle = p\left| B_s^0 \right\rangle - q\left| \bar{B}_s^0 \right\rangle \qquad \left| B_s^L \right\rangle = p\left| B_s^0 \right\rangle + q\left| \bar{B}_s^0 \right\rangle \qquad \frac{q}{p} = \frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}$$

Assuming no CP violation: mass eigenstate = CP eigenstate

Γ_L ~ CP even (short lived), Γ_H ~ CP odd (long lived)

B_s Mixing

Time evolution of the eigenstates is described by

$$i\frac{d}{dt}\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} = \Bigg[\underbrace{\begin{pmatrix} M_0 & M_{12} \\ M_{12}^* & M_0 \end{pmatrix}}_{\text{mass matrix}} - \frac{i}{2}\underbrace{\begin{pmatrix} \Gamma_0 & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_0 \end{pmatrix}}_{\text{decay matrix}}\Bigg]\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix}$$

Experimental observables describing the system:

$\Delta m_s = m_H - m_L \sim 2|m_{12}|$ Oscillations between B_s^0 and $\bar{B}_s^0$

$\Delta\Gamma = \Gamma_L - \Gamma_H \sim 2\,|\Gamma_{12}|\cos(\Phi_s)$ Lifetime/width difference

$\Phi_s = \arg(-M_{12}/\Gamma_{12})$ CP phase (→ tomorrows session)

Measuring Δm_s

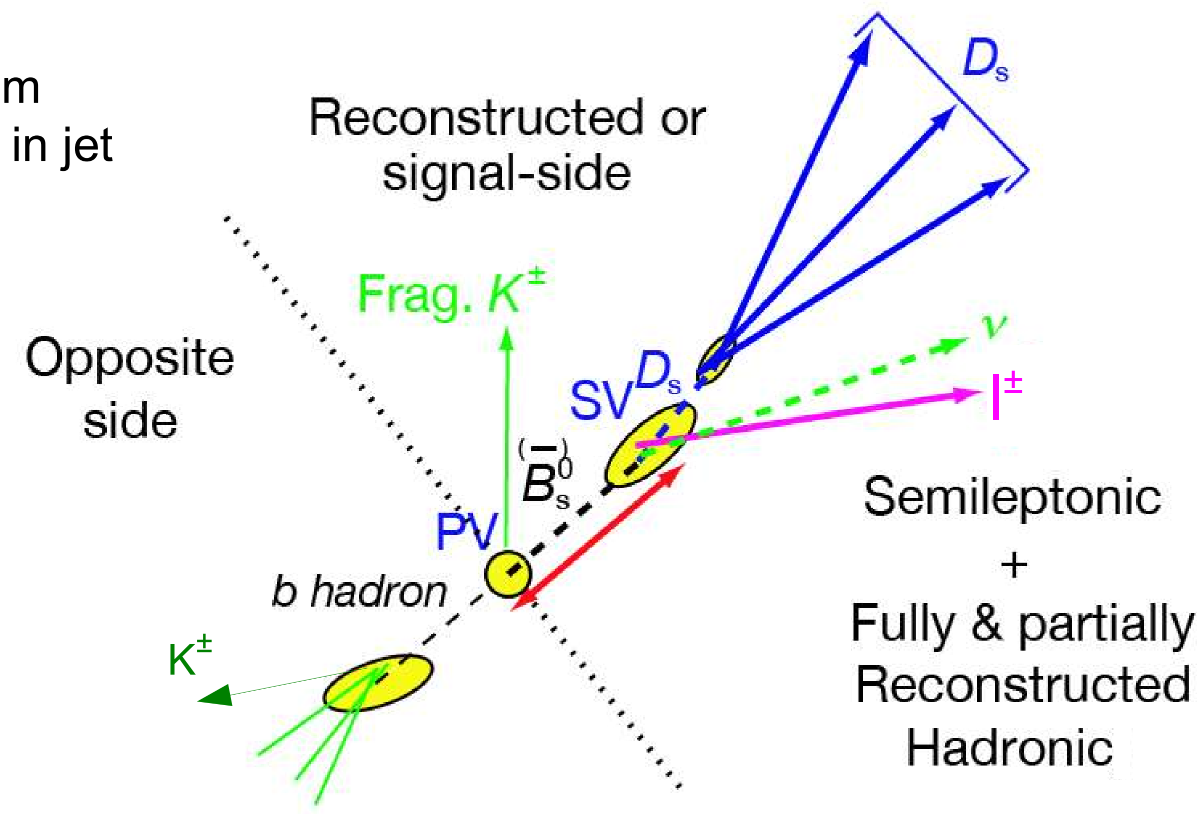
$$\mathrm{Prob}^{\text{non-osc}}_{\text{osc}}(x) \sim 1 \pm (1 - 2\eta)\, A \cos(\Delta m_s\, Kx/c)$$

true visible decay length   purity of flavour tag   Amplitude

- jet charge tagging:
  sign of *b*-quark ~ sign of momentum weighted sum of particles charges in jet

- lepton tagging:
  from semileptonic *b*-decays
  ($b \leftrightarrow l^-$, bbar $\leftrightarrow l^+$)

- same side tagging:
  charge of 'nearby' track correlated with b-quark flavour
  ($b \leftrightarrow K^-/\pi^+$, bbar $\leftrightarrow K^+/\pi^-$)



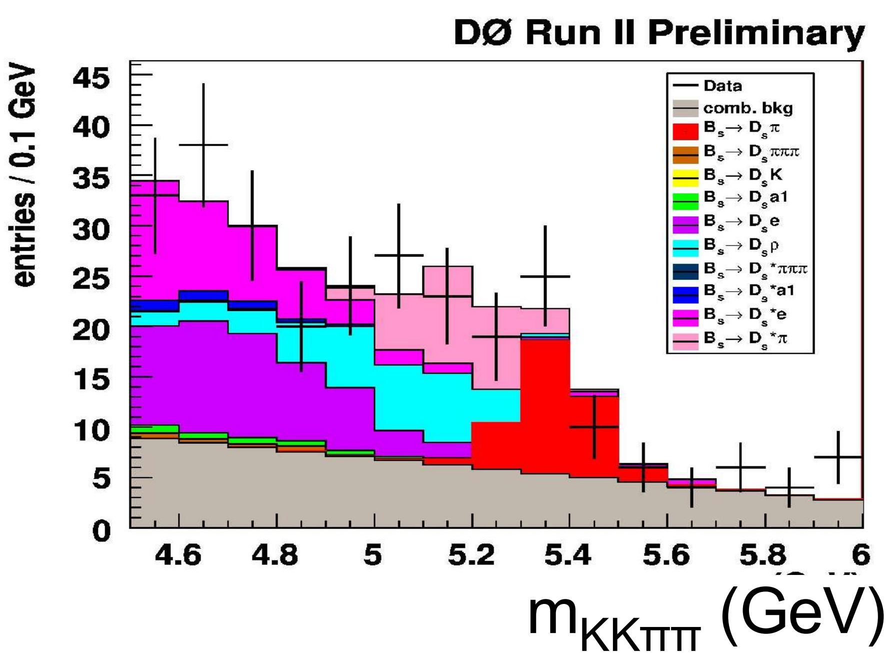
Δm_s at DØ

First two-sided limit $17 < \Delta m_s < 21\ ps^{-1}$ at 90% CL ($1\ fb^{-1}$)

PRL 97, 021802 (2006)

Updated measurement in 2008 ($2.4\ fb^{-1}$)

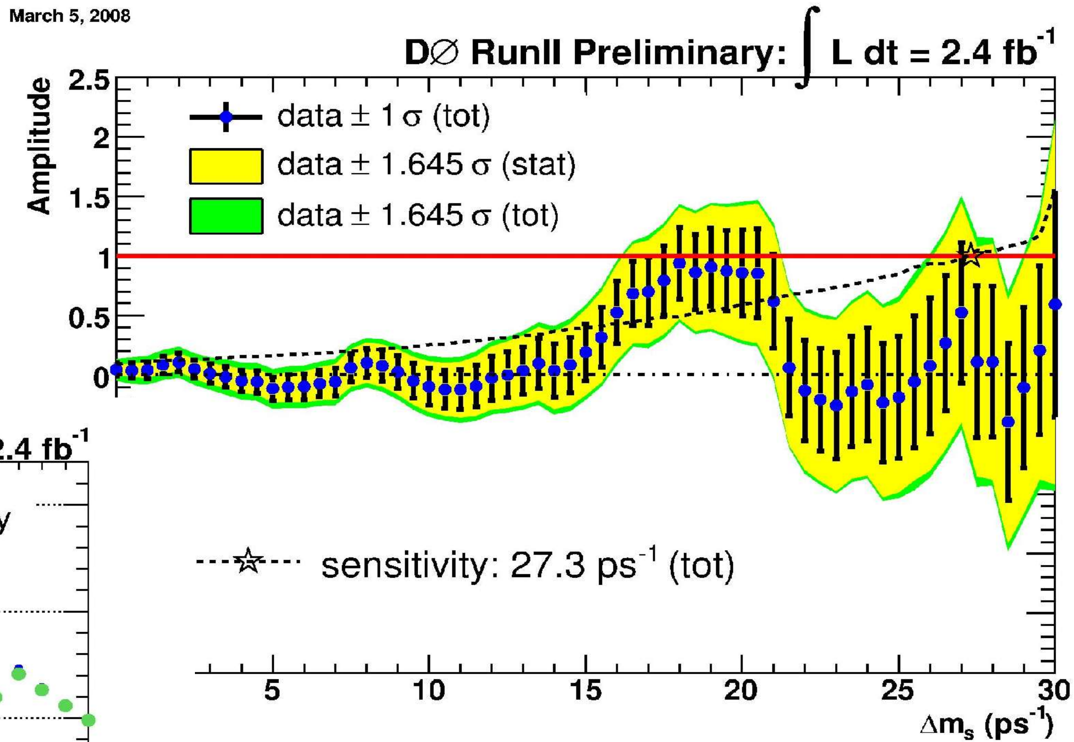
- Individual amplitude vs probe Δm_s for each channel
- RunIIa and RunIIb considered separately (Layer 0)
- Event-by-event scale factor to correct for impact parameter resolution
- Improved modeling of trigger effects & missing particles correction
- Hadronic modes included

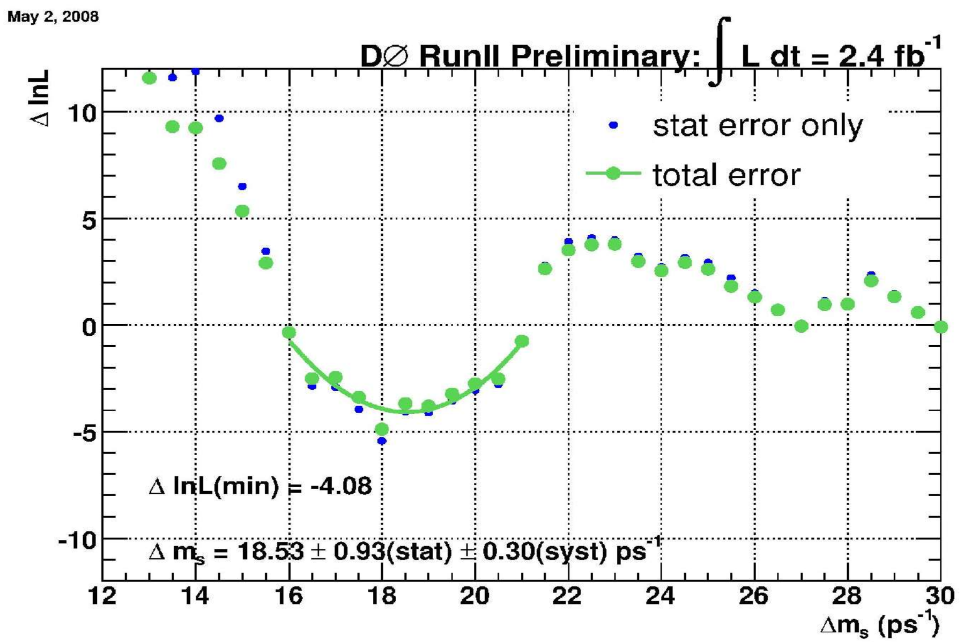


Data Sample

$B_s \to D_s \mu \nu X,\ D_s \to \Phi \pi$	44000
$B_s \to D_s \mu \nu X,\ D_s \to K^{*0} K$	18000
$B_s \to D_s \mu \nu X,\ D_s \to K_s K$	600
$B_s \to D_s^{(*)} e \nu X,\ D_s \to \Phi \pi$	1600
$B_s \to D_s \pi,\ D_s \to \Phi \pi$	200
Total	64400

Δm_s at DØ





$\Delta m_s = 18.53 \pm 0.93 \text{ (stat)} \pm 0.30 \text{ (sys) ps}^{-1}$

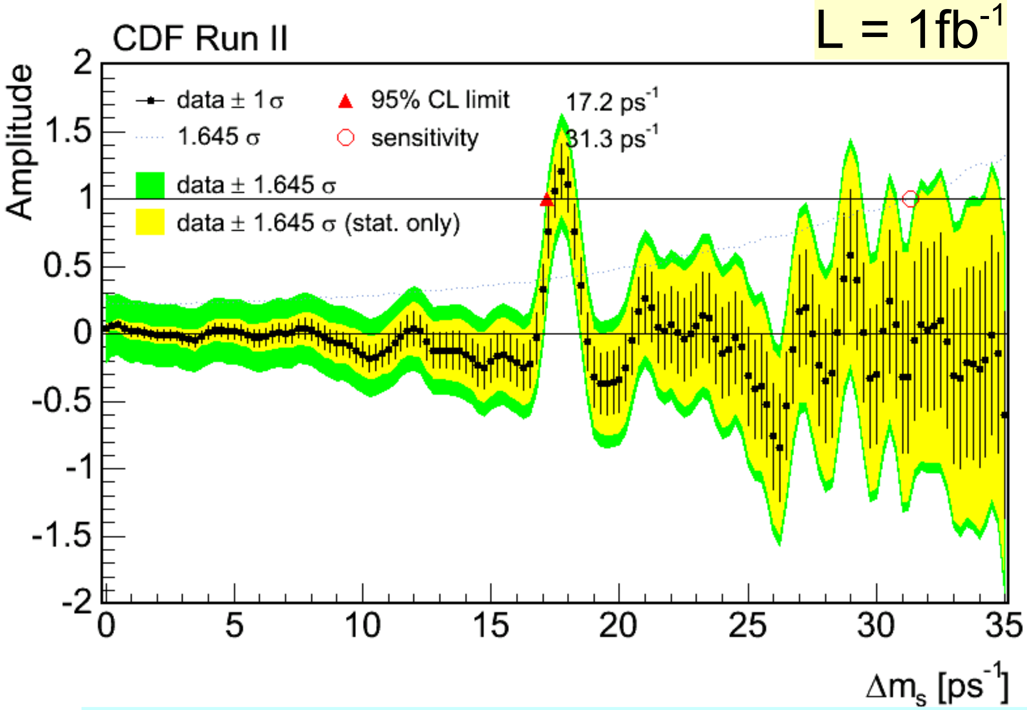
2.9 σ significance (3.0 σ statistical only)

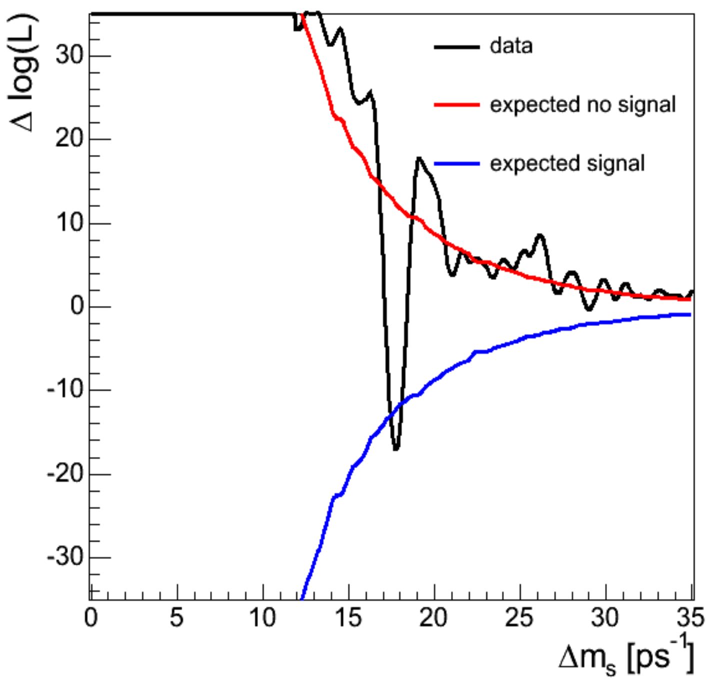
Δm_s at CDF

2000 fully reconstructed decays
3100 partially reconstructed decays

Phys. Rev. Lett. 97, 242003 (2006)

L = 1fb^{-1}

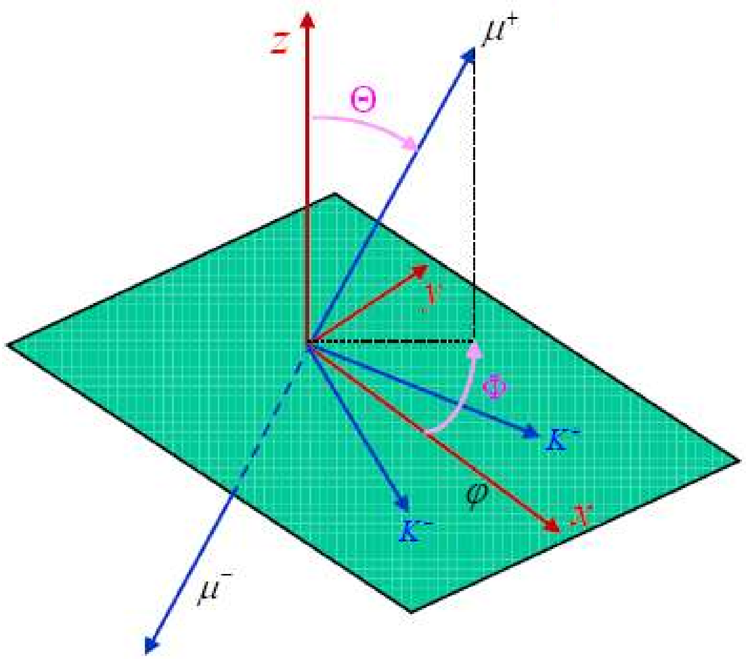




$\Delta m_s = 17.77 \pm 0.10$ (stat) ± 0.07 (syst) ps^{-1}

(5.4σ significance)

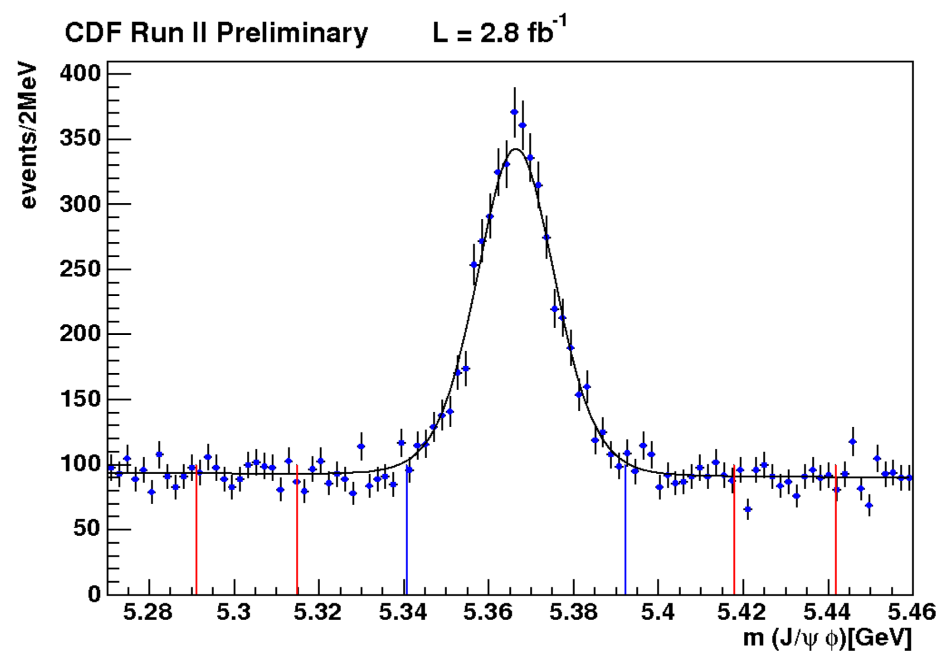
Measuring $\Delta\Gamma$ in the decay $B_s \rightarrow J/\psi\ \Phi$



Pseudo-scalar → Vector Vector

Different angular distributions for CP even and odd components

Simultaneous fit to
mass, lifetime and angular distributions



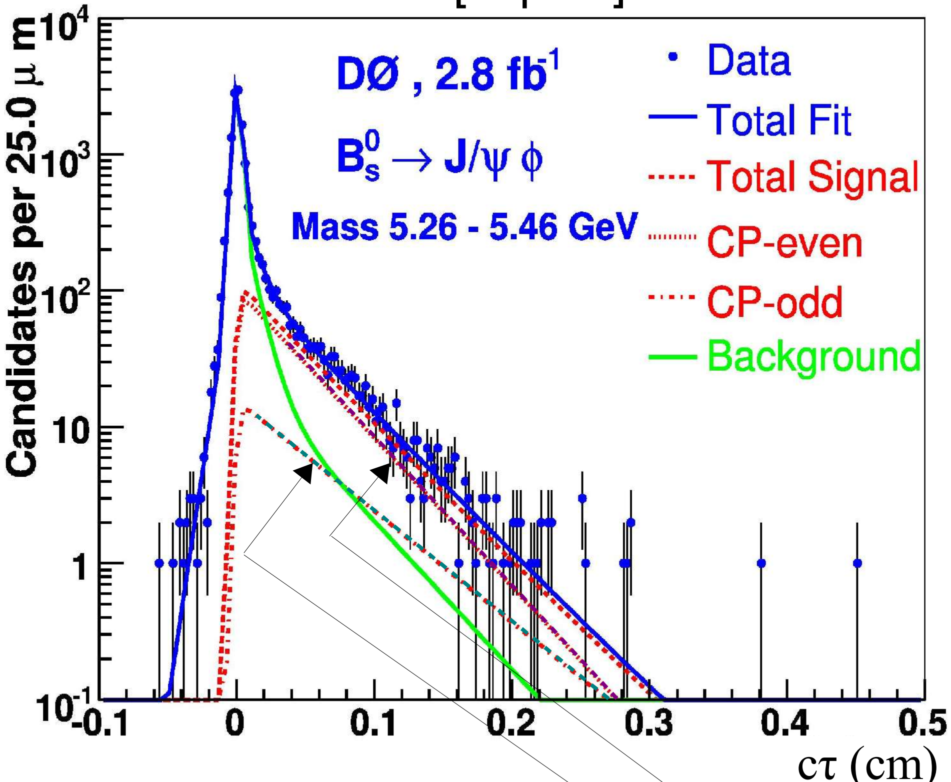
In J/ψ restframe:
K^+K^- plane defines (x,y) plane
K^+ defines +y direction
Θ, Ψ polar and azimuthal angles of
φ in Φ restframe: angle(K^+, -J/ψ)

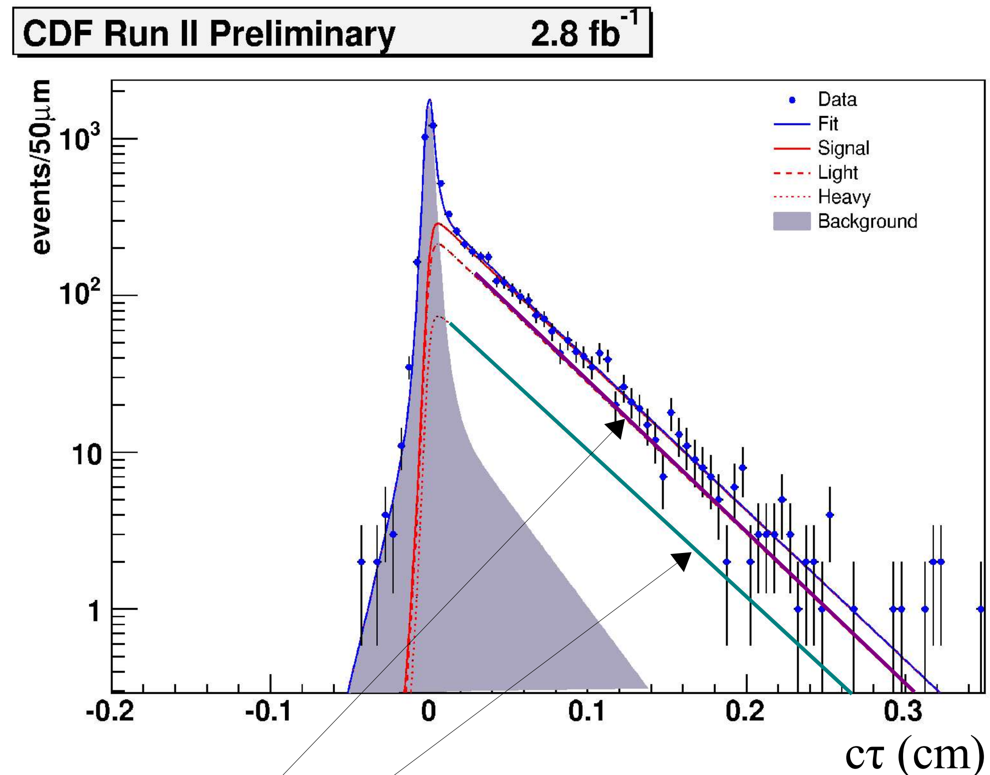
Measuring ΔΓ in the decay $B_s \rightarrow J/\psi\ \Phi$

Both experiments have now analysed 2.8 fb^{-1}.

Results below are for $\Phi_s = \Phi_s^{SM}$

arXiv:0802.2255[hep-ex]





-- CP even (light)

-- CP odd (heavy)

$\Delta\Gamma = 0.14 \pm 0.07 \pm 0.02\ ps^{-1}$

$\tau_s = 1.53 \pm 0.05 \pm 0.01$ ps

$\Delta\Gamma = 0.02 \pm 0.05 \pm 0.01\ ps^{-1}$

$\tau_s = 1.53 \pm 0.04 \pm 0.01$ ps

A different approach to $\Delta\Gamma$

- $B_s \to D_s^{(*)} D_s^{(*)}$ (~ CP even)

Neglecting small CP odd component: $\Delta\Gamma/\Gamma = 2\,BR\,(B_s \to D_s^{(*)} D_s^{(*)})$

CDF: $BR\,(B_s \to D_s D_s)$ measured relative to $B^0 \to D_s D^-$

0.36 fb^{-1}: $\Delta\Gamma/\Gamma \geq 2\,BR\,(B_s \to D_s D_s) > 0.012$ at 95 % CL

DØ: $BR\,(B_s \to D_s^{(*)} D_s^{(*)})$ measured relative to $B_s \to D_s^{(*)} \mu\nu$

2.8 fb^{-1}: $\Delta\Gamma/\Gamma = 0.088 \pm 0.030$ (stat) ± 0.036 (sys)

- $B_s \to K^+ K^-$ (CP even)

CDF: Displaced track trigger and good mass resolution

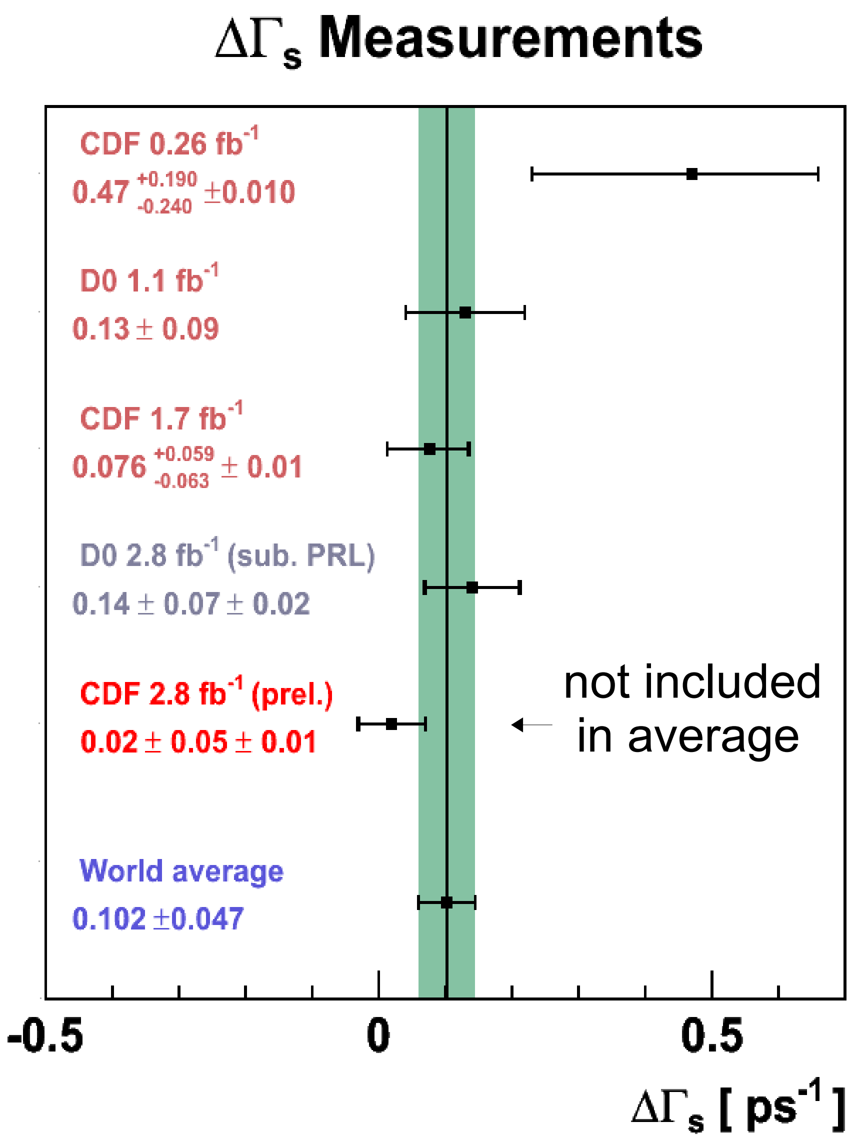
Assuming flavour specific $c\tau(B_s) = 1.454 \pm 0.040$ ps

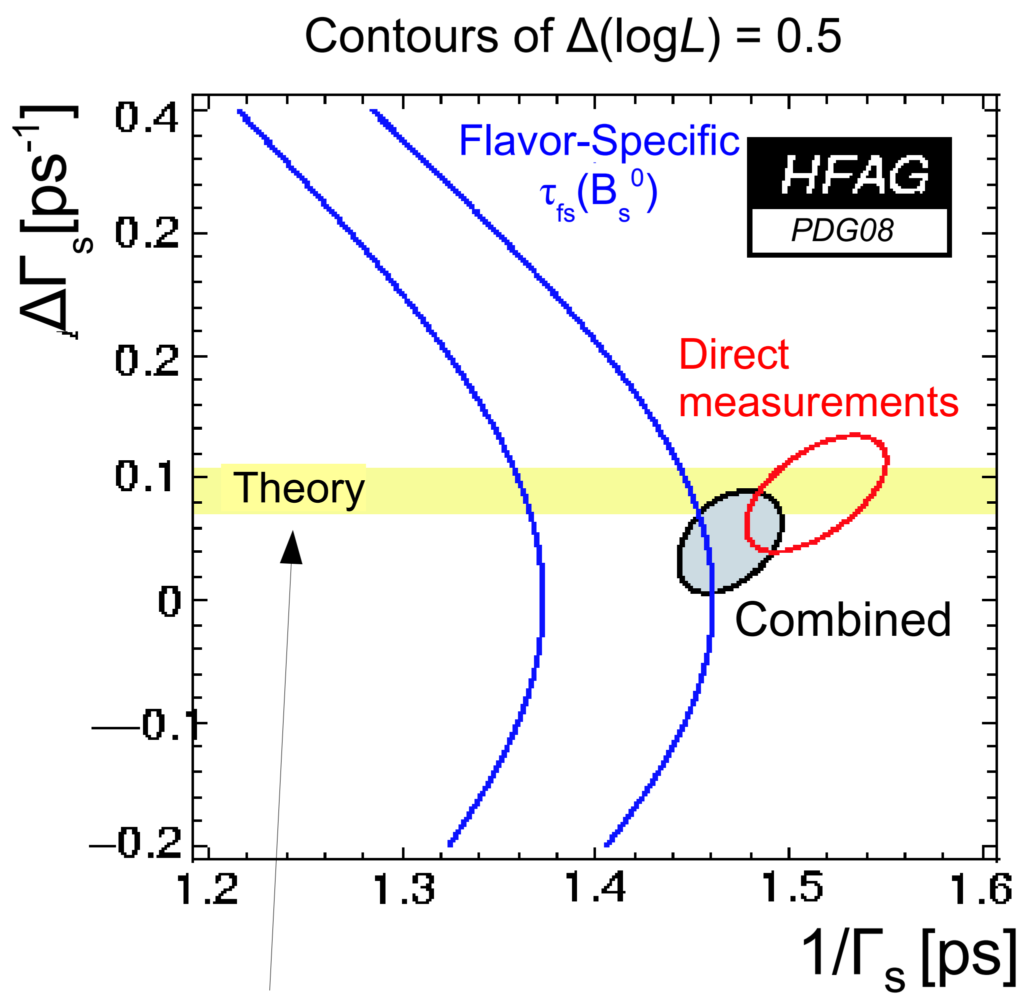
$\Delta\Gamma/\Gamma = -0.08 \pm 0.23$ (stat) ± 0.03 (sys) using 0.36 fb^{-1}

Update to > 2fb^{-1} in progress.

$\Delta\Gamma_s$ Summary

$$\Gamma_s = (\Gamma_L + \Gamma_H)/2 = 1/\tau_s$$





JHEP 06(2007) 072: $\Delta\Gamma_s = 0.088 \pm 0.017$ ps^{-1}

B_s^0 lifetimes

$\Delta\Gamma \neq 0 \rightarrow$ specific measurements

- Flavour specific lifetime

  Equal mix of B_s^H and B_s^L at t = 0
  e.g. semileptonic decays

- *CP* specific lifetime

  Assumed to be either *CP* even or odd
  $B_s \rightarrow D_s^+ D_s^-$ assumes to be *CP* even $\rightarrow$ measures Γ_L

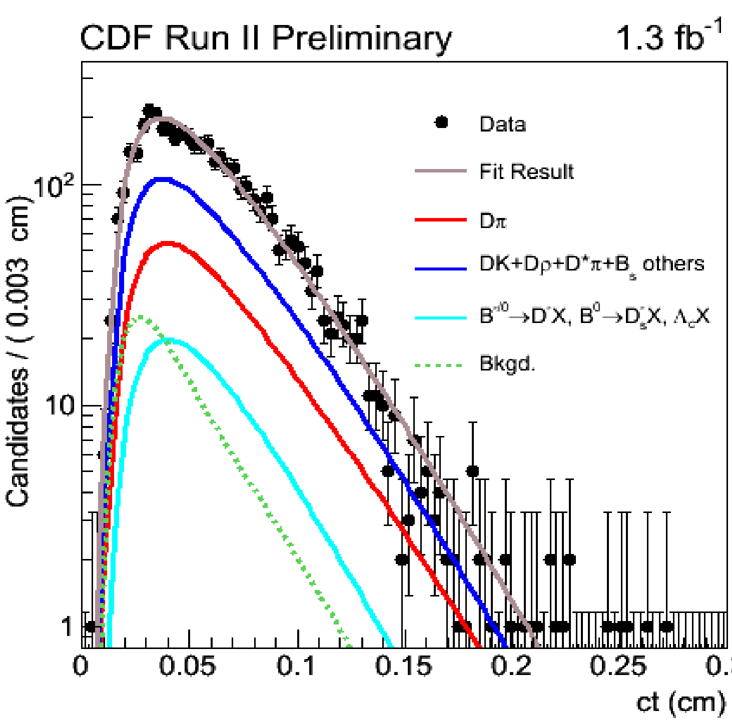
- Mixed CP states

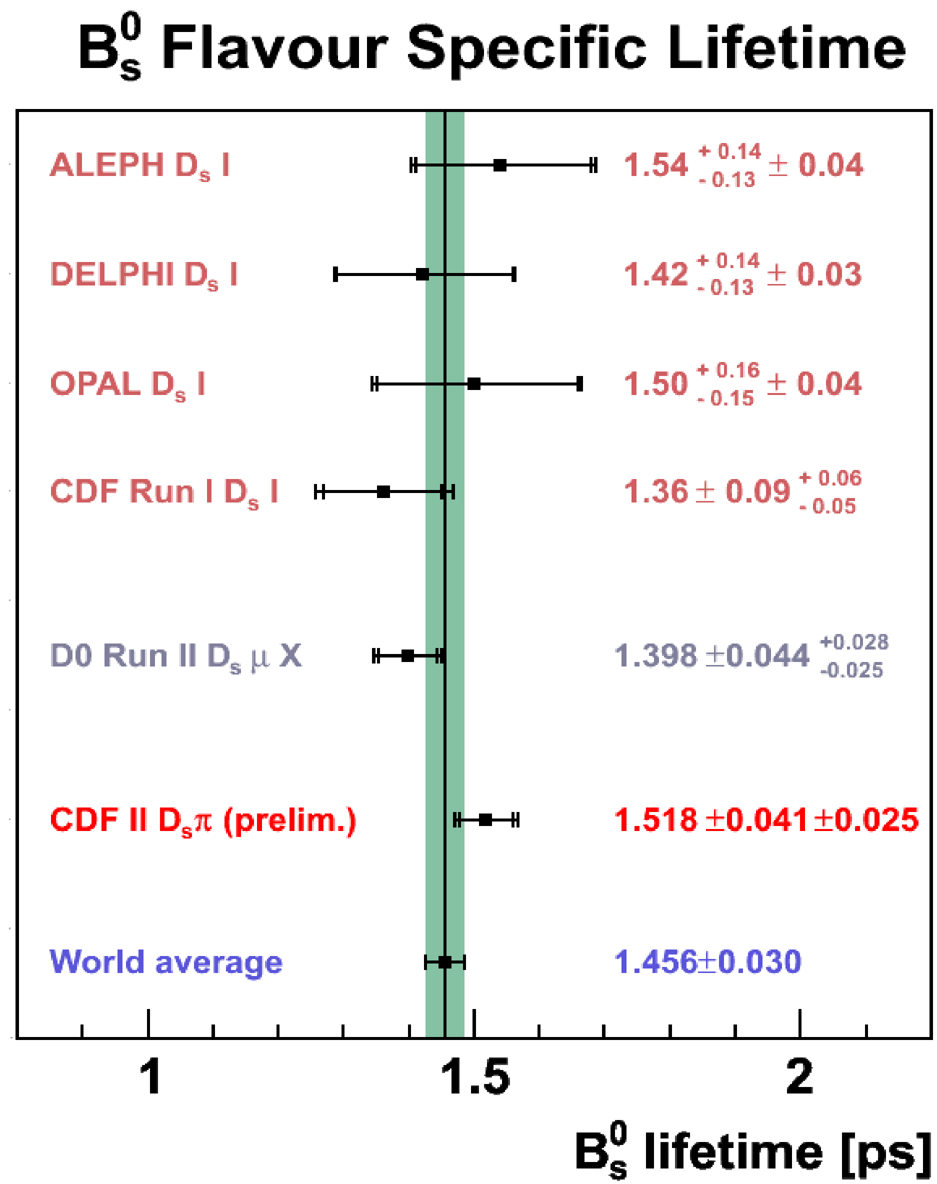
  $B_s \rightarrow J/\psi\ \Phi$

B_s^0 flavour specific lifetime

DØ: $1.398 \pm 0.044^{+0.028}_{-0.025}$ ps
semilep, 0.4 fb
PRL 97, 241801 (2006)

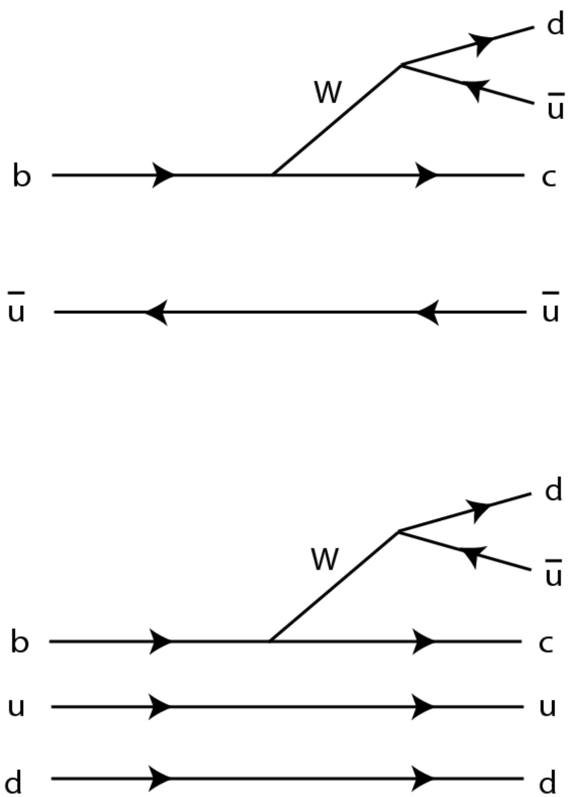
CDF (new in 2008):
$1.518 \pm 0.041 \pm 0.025$
$B_s \rightarrow D_s\ (\Phi\pi)\ \pi\ X$





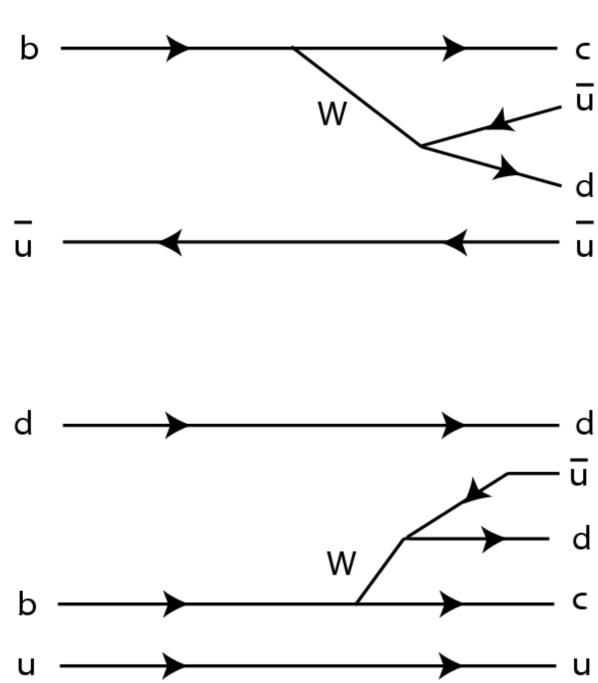
B Hadron Lifetimes

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3} \left|V_{cb}\right|^2 \cdot \left[A_0 + A_2 \left(\frac{\Lambda_{QCD}}{m_b}\right)^2 + A_3 \left(\frac{\Lambda_{QCD}}{m_b}\right)^3 \right]$$



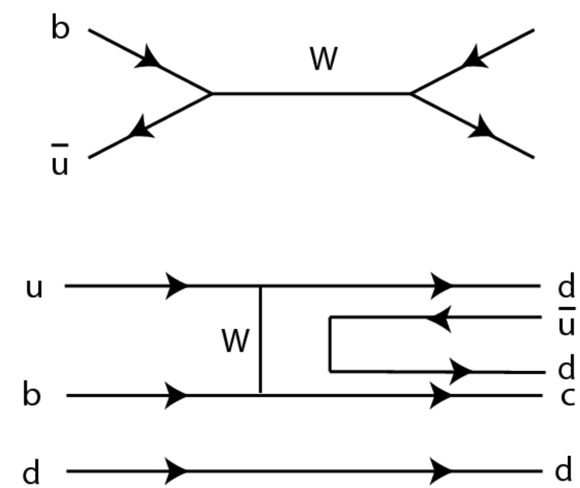
Spectator model

b hadron lifetimes are equal



Pauli Interference

prolongs lifetimes (+3% Λ_b)



Weak Annihilation and Exchange

reduces lifetime (-7% Λ_b)

B Hadron Lifetimes

- The B^+ and B^0 lifetimes are precisely measured at *B*-factories.
- Tevatron gives access to B_s, B_c and Λ_b.

Expected: $\tau(B^+) \geq \tau(B^0) \approx \tau(B^0{}_s) > \tau(\Lambda_b) >> \tau(B_c)$

Theoretical prediction for lifetime ratios:

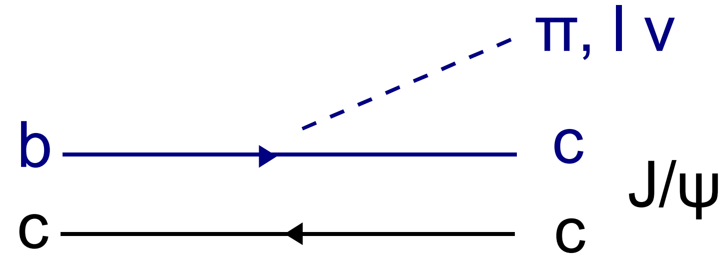
$\tau(B^+)/\tau(B^0) = 1.06 \pm 0.02$

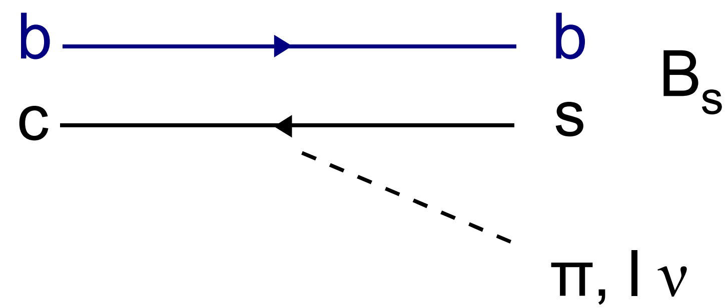
$\tau(B_s)/\tau(B^0) = 1.00 \pm 0.01$

$\tau(\Lambda_b)/\tau(B^0) = 0.88 \pm 0.05$

The B_c meson: A double heavy bound state

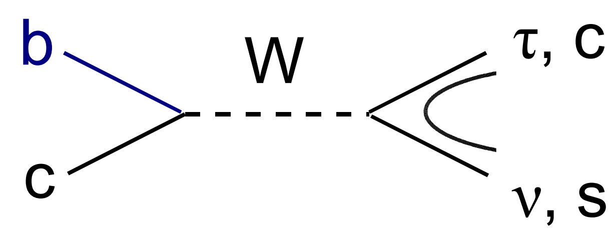
B_c meson decays via weak decays of *b* **or** *c* quark or via weak annihilation
→ considerably shorter lifetimes than light *B* mesons.





B_c lifetime is measured in semileptonic decays ($B_c \rightarrow J/\psi\, l\nu$)
(large branching fraction wrt hadronic channel)

B_c mass measured in hadronic decays ($B_c \rightarrow J/\psi\, \pi$), lifetime is used to reject background

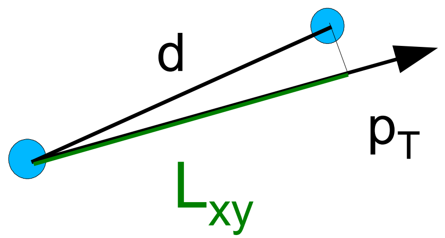


B_c lifetime in semileptonic decays

measured variables:

$\vec{d}_{xy} = \vec{x}_{primary\_vertex} - \vec{x}_{secondary\_vertex}$

$\vec{p}_T(J/\psi, l)$



transverse decay length $L_{xy} = (\vec{d}_{xy} * \vec{p}_T)/p_T^2 * m$

$c\tau_{B_c} = m\, L_{xy}/p_T(B_c)$

B_c momentum cannot be fully reconstructed
→ correction factor (K) derived from Monte Carlo

pseudo(CDF)/visible(DØ) proper decay length
$c\tau_{B_c}/K = m\, Lxy(J/\psi\ l)/pT(J/\psi\ l)$

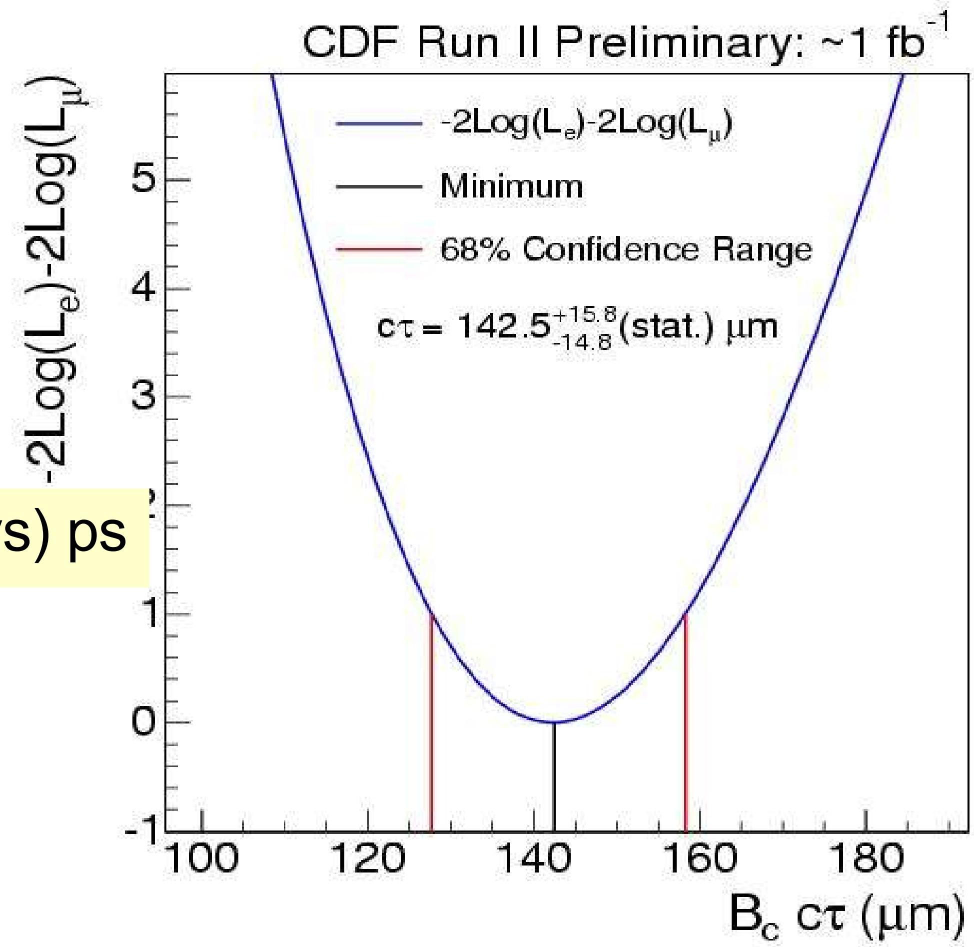
B_c lifetime in semileptonic decays

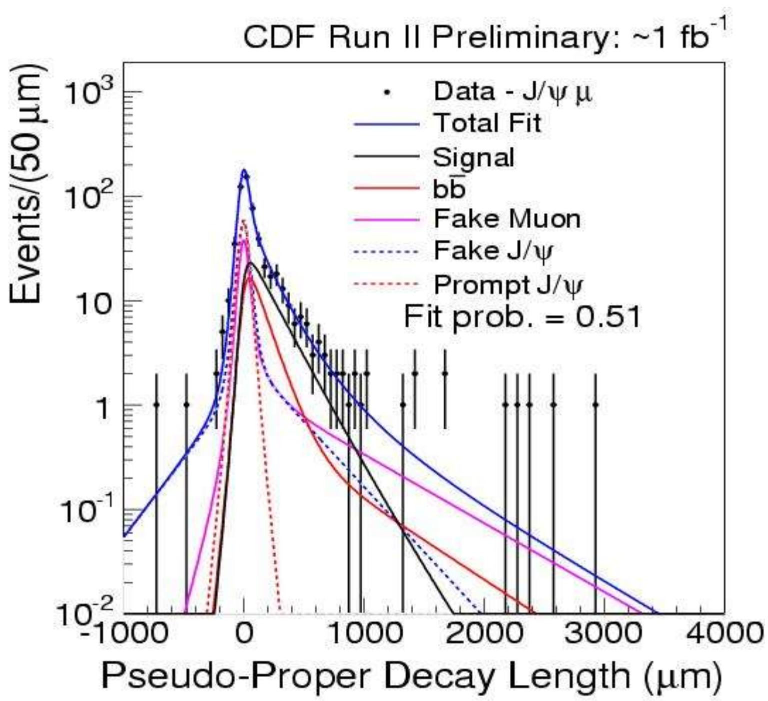
$c\tau_\mu = 179.1^{+32.6}_{-27.2}$ (stat) μm

$c\tau_e = 121.7^{+18.0}_{-16.3}$ (stat) μm

Combined lifetime from likelihood scan of B_c lifetimes ($-2\mathrm{Log}(L_e)-2\mathrm{Log}(L_\mu)$)

$\tau(B_c) = 0.475^{+0.053}_{-0.049}$ (stat) ± 0.018 (sys) ps

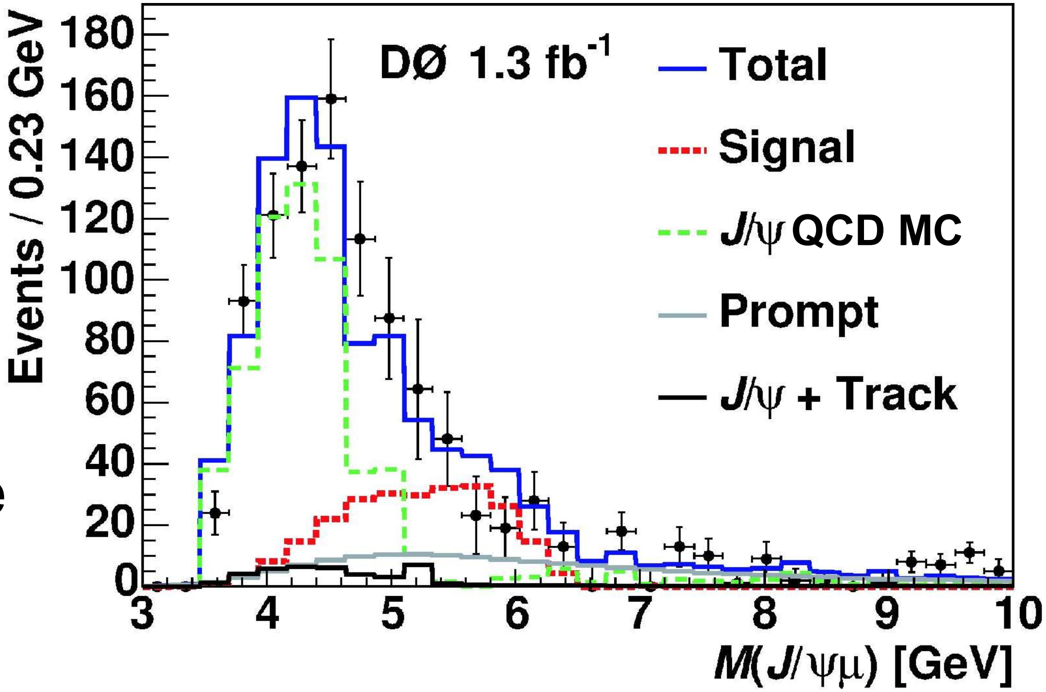


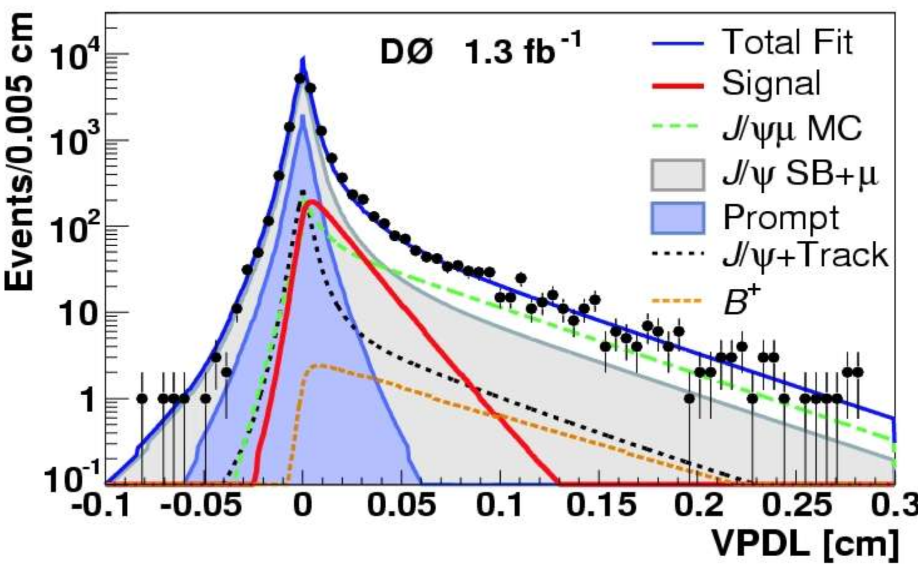


B_c lifetime in semileptonic decays

- Tri-muon invariant mass used to characterize each of the components contributing to J/ψ μ sample.

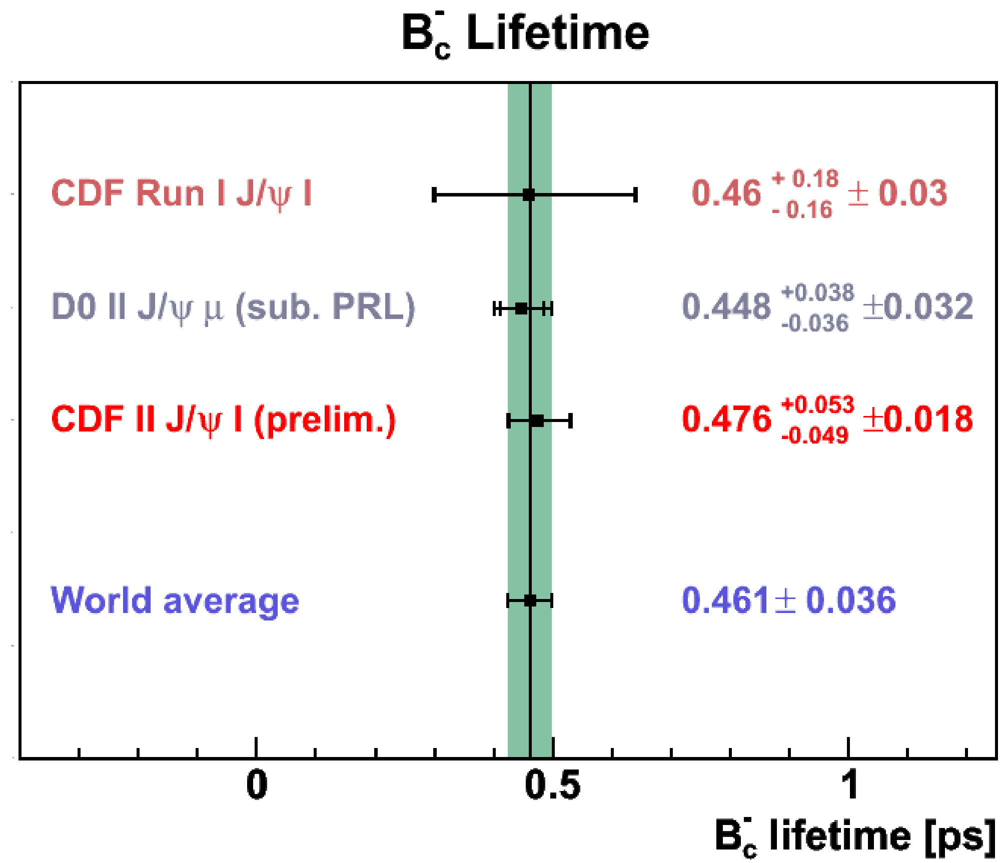
- Use mass only fits to demonstrate signal, then simultaneous fit to mass and lifetime.





$\tau(B_c) = 0.448\ ^{+0.038}_{-0.036}$ (stat) $\pm$ 0.032 (sys) ps

B_c Overview



Theoretical predictions*: 0.48 – 0.55 ps

*V.V. Kiselev airXiv:hep-ph/0308214

Λ_b lifetime

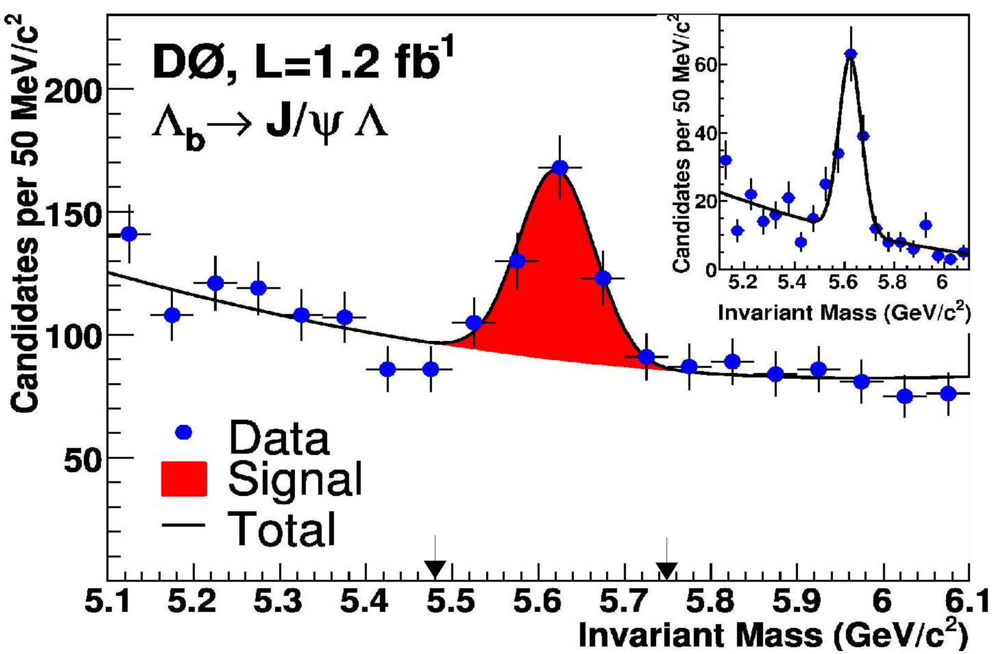
Λ_b (udb)
Λ_c (udc)
Λ (uds)

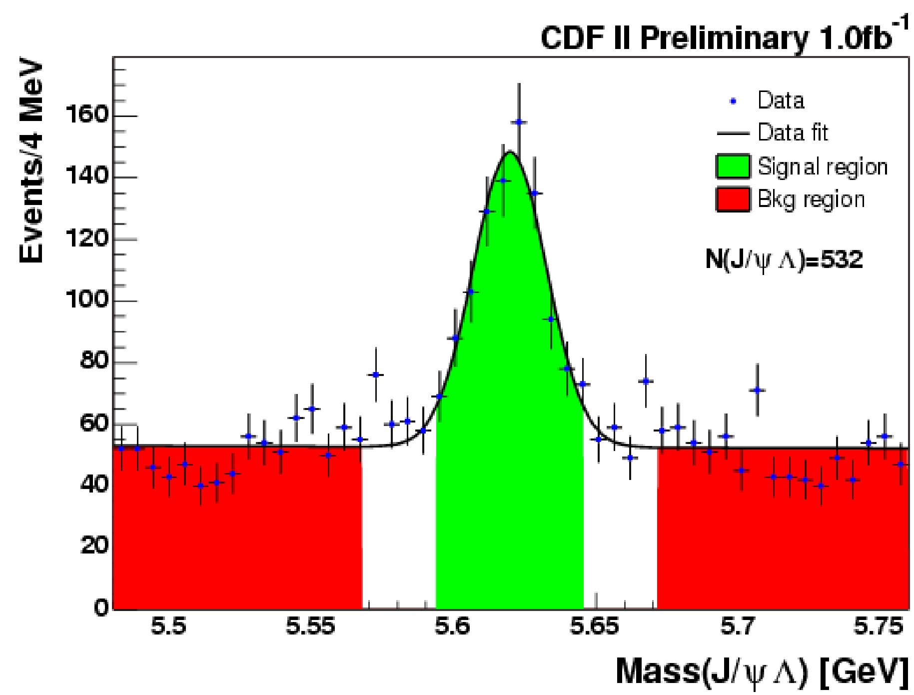
DØ: $\Lambda_b \to \Lambda_c \mu\nu X$ 1.3 fb^{-1} (4437 decays) $\tau(\Lambda_b) = 1.290^{+0.119}_{-0.110}\,(stat)^{+0.087}_{-0.091}\,(sys)$ ps

$\Lambda_b \to \Lambda\, J/\psi$ 1.2 fb^{-1} (171 decays) $\tau(\Lambda_b) = 1.218^{+0.130}_{-0.115}\,(stat) \pm 0.042\,(sys)$ ps

CDF: $\Lambda_b \to \Lambda\, J/\psi$ 1.0 fb^{-1} (557 decays) $\tau(\Lambda_b) = 1.580 \pm 0.077\,(stat) \pm 0.012\,(sys)$ ps

$\Lambda_b \to \Lambda_c\, \pi$ 1.0 fb^{-1} (2904 decays) $\tau(\Lambda_b) = 1.410 \pm 0.046\,(stat) \pm 0.029\,(sys)$ ps





Λ_b lifetime

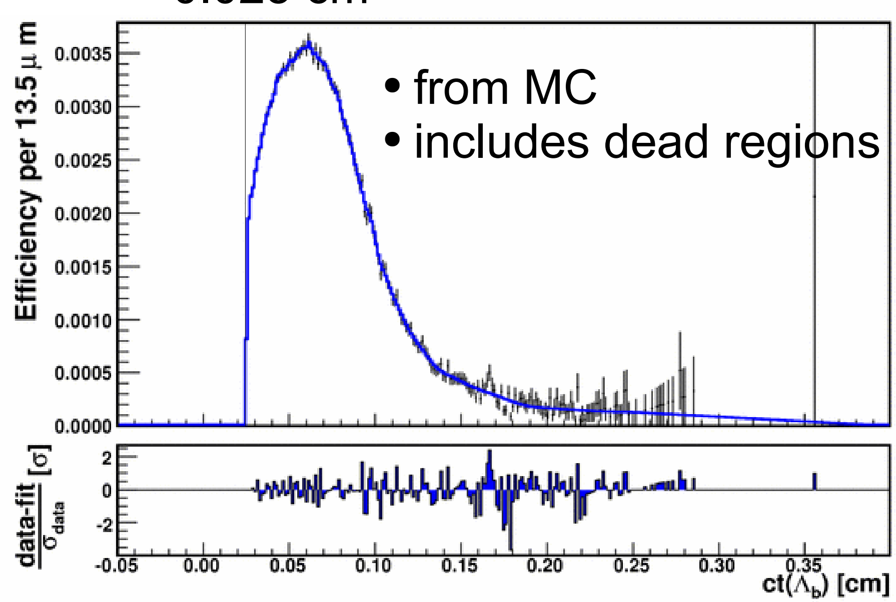
Most recent update:

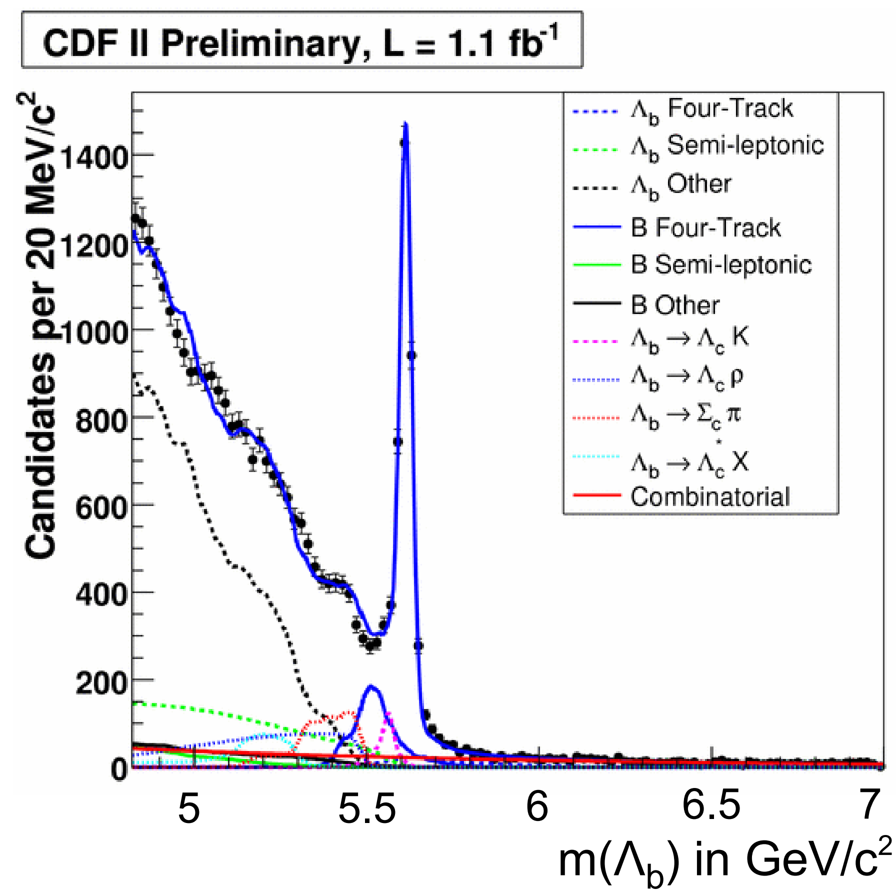
CDF: $\Lambda_b \to \Lambda_c\ (\to p\ K\ \pi)\ \pi$ using a displaced track trigger

- Two step fit: mass, lifetime for signal region only
- Trigger efficiency from MC
- Using current world average for B^0 lifetime: $\tau(\Lambda_b)/\tau(B^0) = 0.922 \pm 0.039$

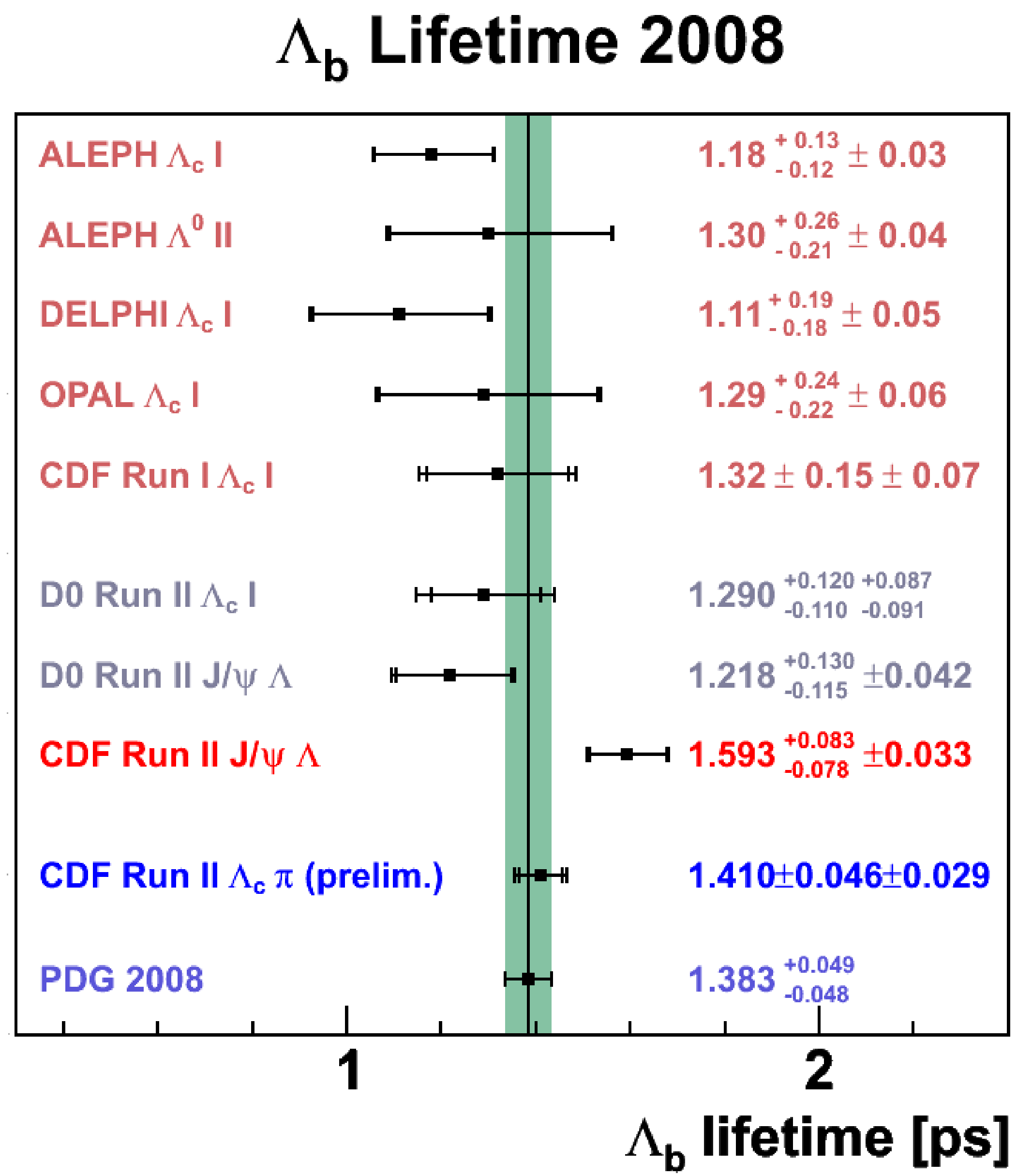
Efficiency Two Track Trigger

0.025 cm





Λ_b lifetime 2008



Conclusions

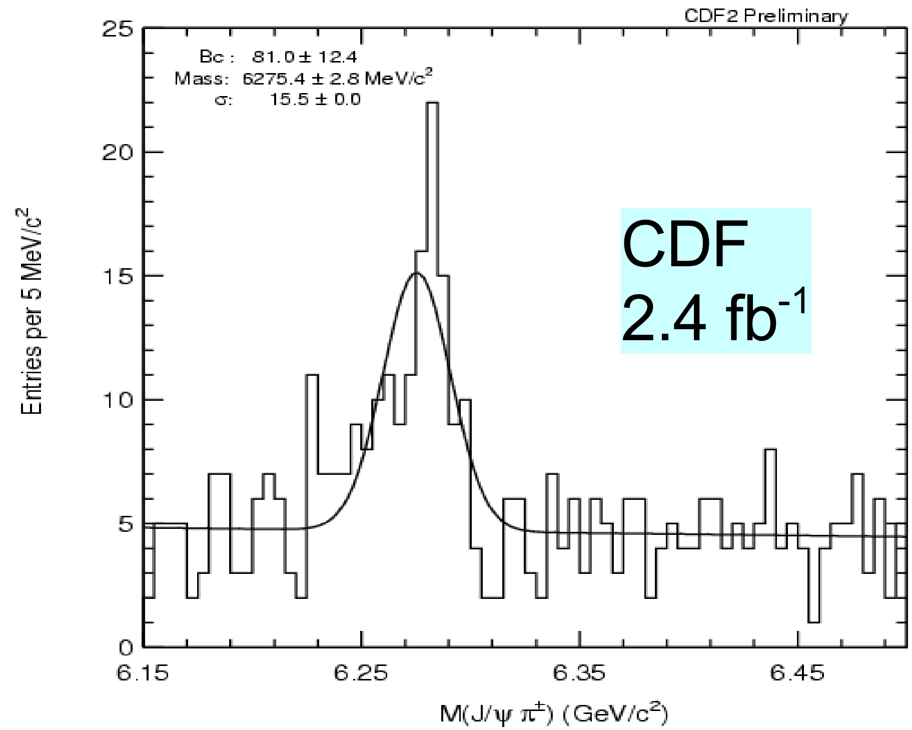
Reviewed **recent** Tevatron measurements of the B_s system and *b*-hadron lifetimes.

The Tevatron experiments continue to produce precision heavy flavour measurements that are complementary to and competitive with the *b*-factories.

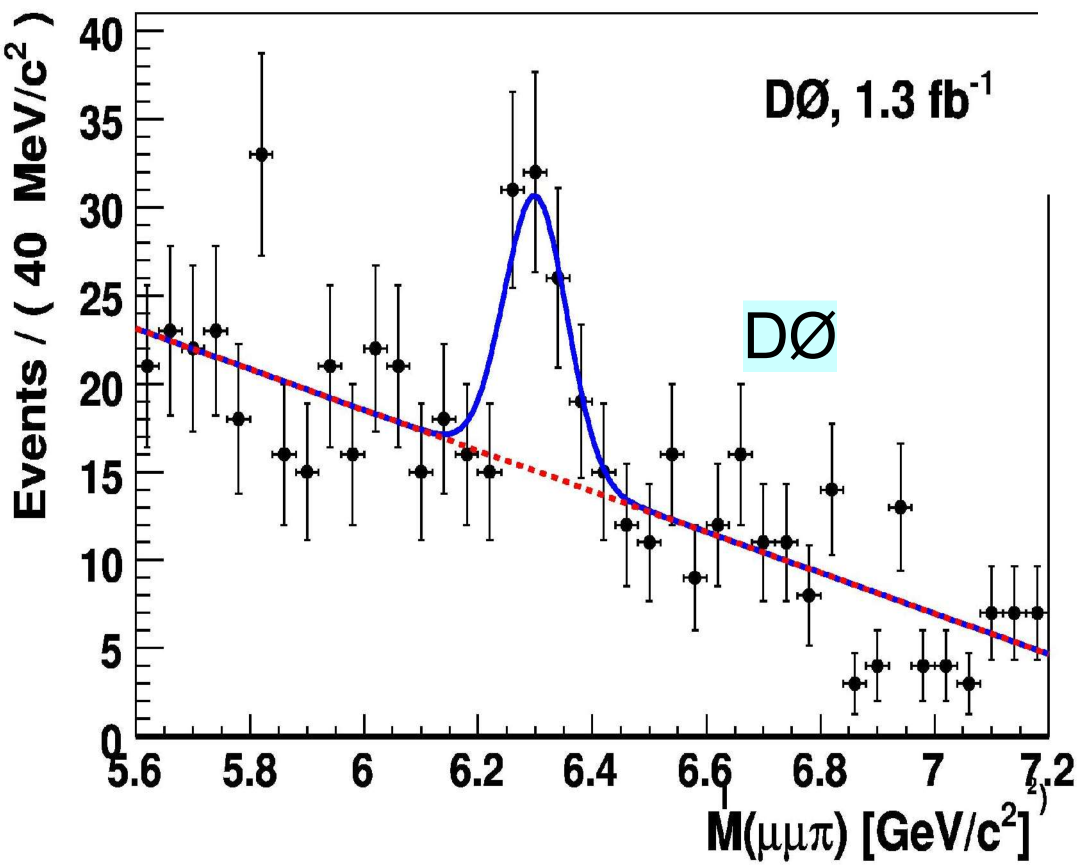
With ongoing data taking and a doubling of the data set further improvements to be expected before the LHC takes over.

Backup slides

B_c mass

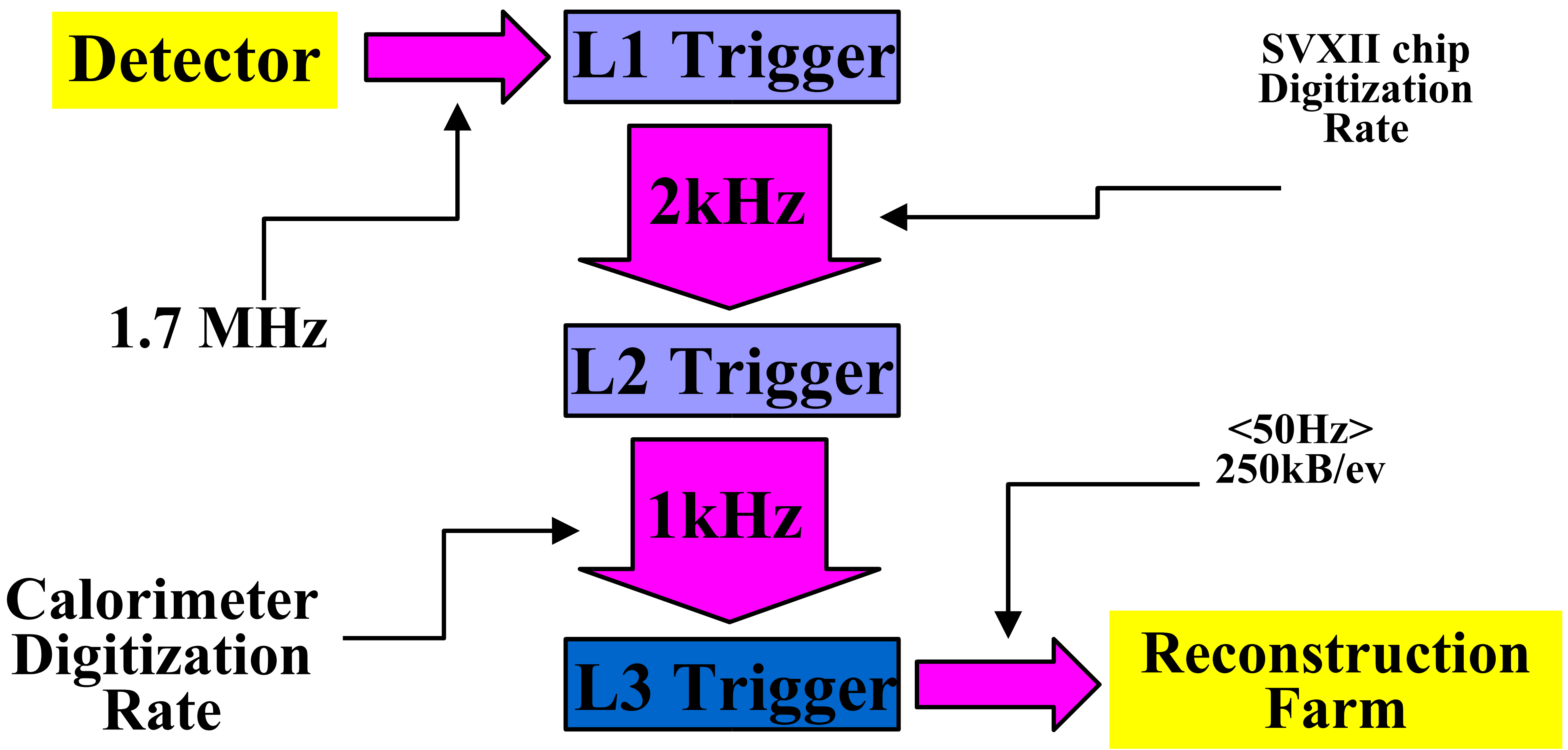


CDF2 Preliminary
Bc : 81.0 ± 12.4
Mass: 6275.4 ± 2.8 MeV/c²
σ: 15.5 ± 0.0
Entries per 5 MeV/c²
M(J/ψ π±) (GeV/c²)
CDF
2.4 fb⁻¹

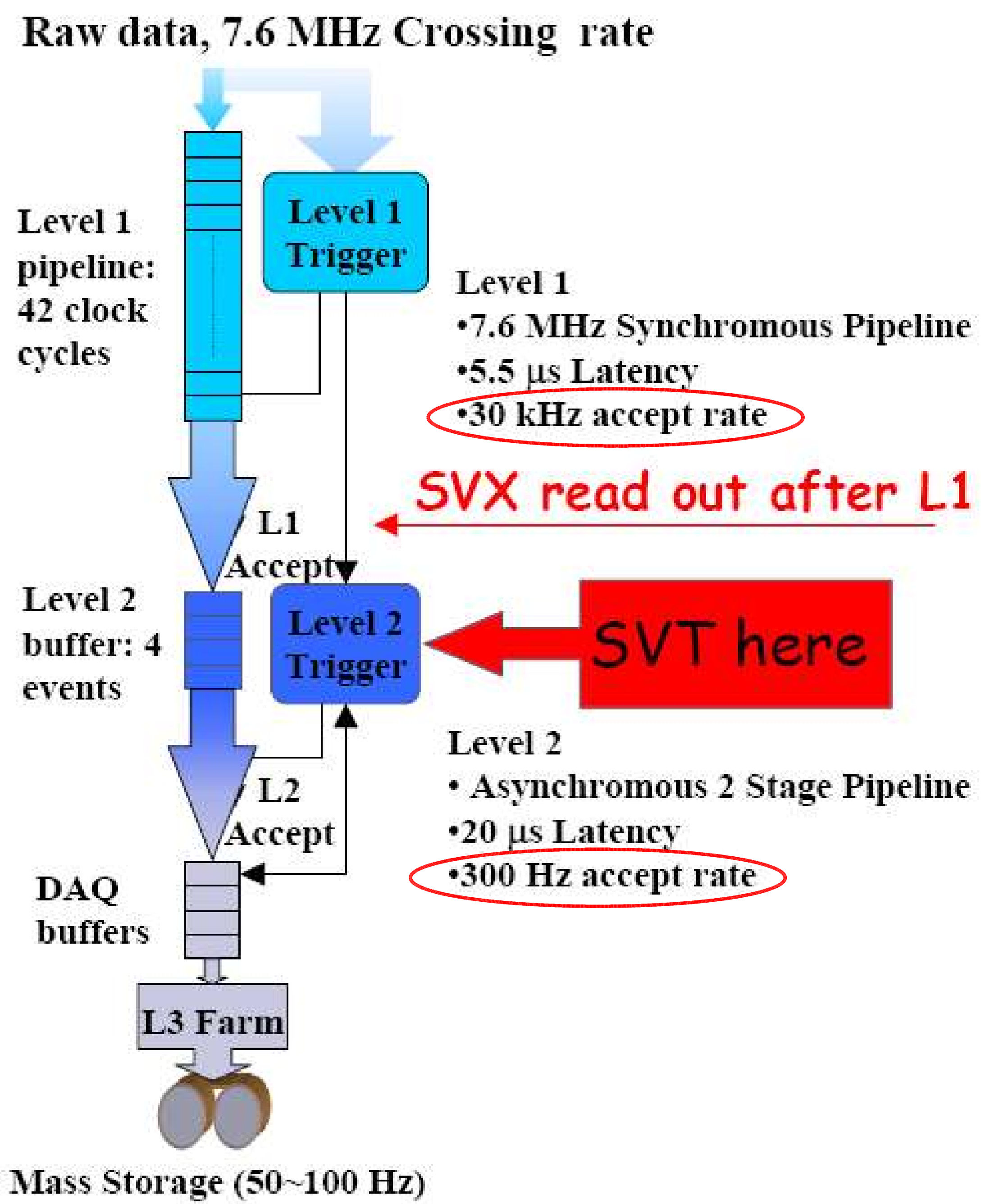


Events / (40 MeV/c²)
DØ, 1.3 fb⁻¹
DØ
M(μμπ) [GeV/c²]

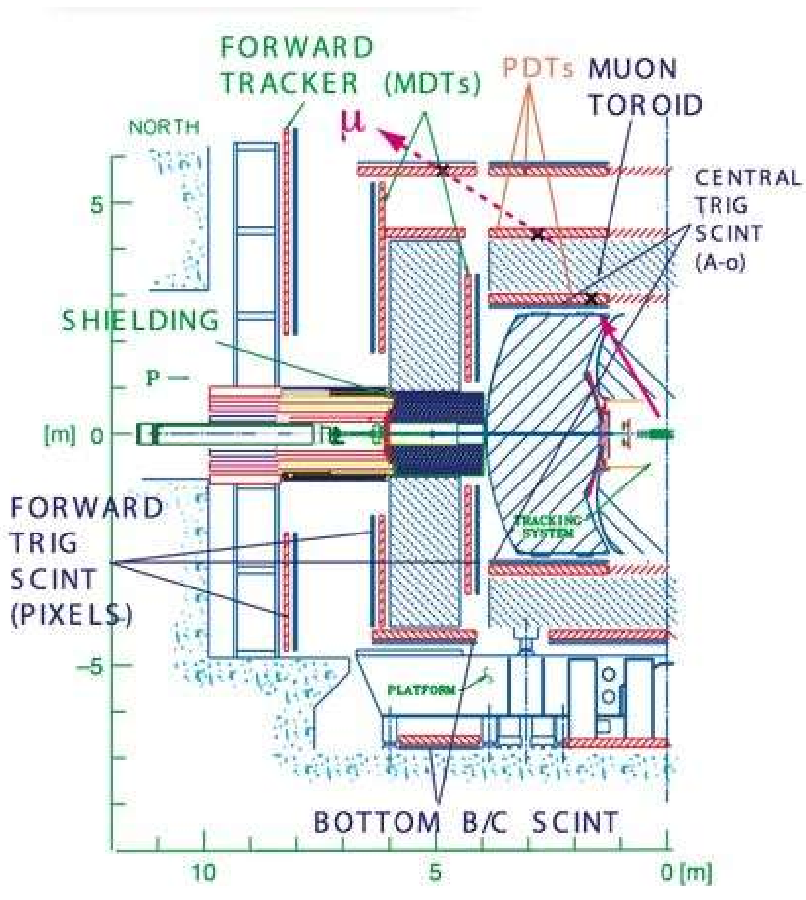
DØ Trigger System

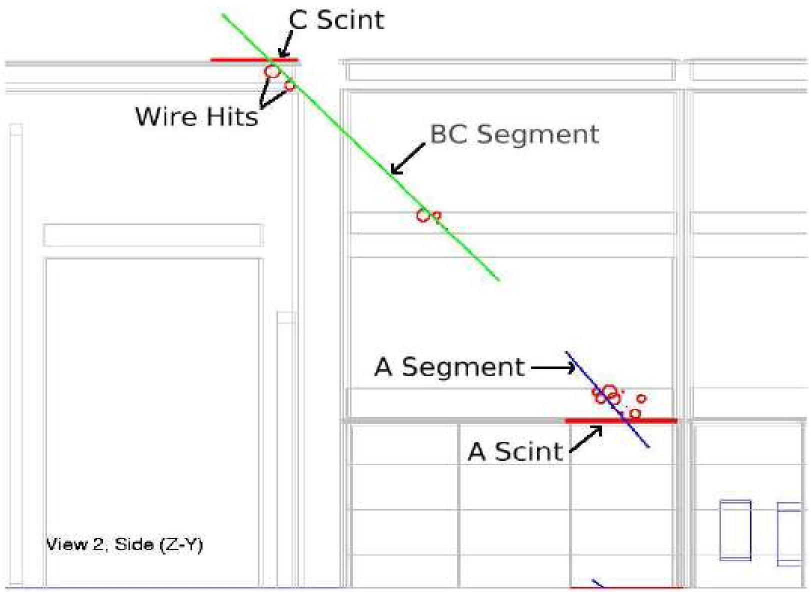


CDF Trigger System



Muon system



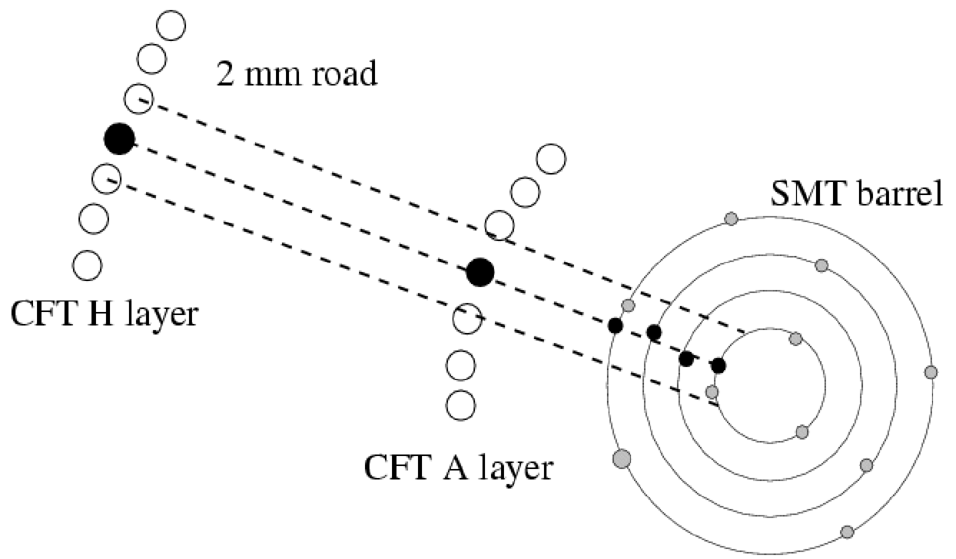


Main features:

- 3 layers of drift tubes.
- 3 layers of scintillators: triggering, improved resolution in wire direction, rejection of cosmics
- Toroid magnet (1.8 T) after the first layer: local p_T measurement (trigger).
- Toroid and solenoid polarities reversed on regular basis.
- Track matched muons up to $|\eta| < 2.2$

Silicon Track Trigger

- L1 CTT tracks are used to define roads into the SMT.
- SMT hits are clustered in these roads.
- Track is refit within the road.



→ Improved p_T measurement wrt L1.

→ Impact parameter measurement.

Under-used by *b*-physics in RunIIa:

- Impact parameter bias difficult to model/analyze.
- (Planned) late commissioning: Triggers already well established with sufficient rate reduction.
- No displaced track only trigger due to L1 bandwidth limitations.

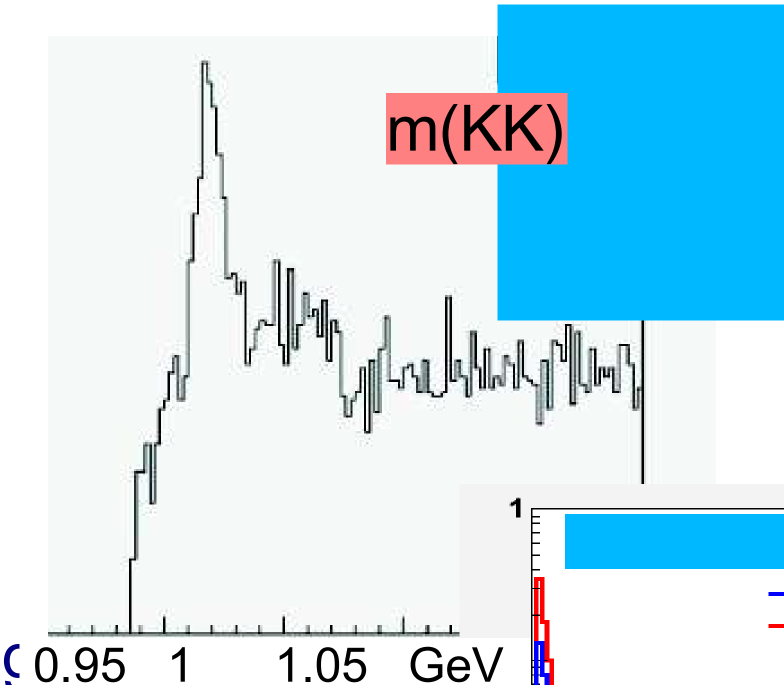
RunIIb: *b*-physics and Higgs group are the main users of the STT.

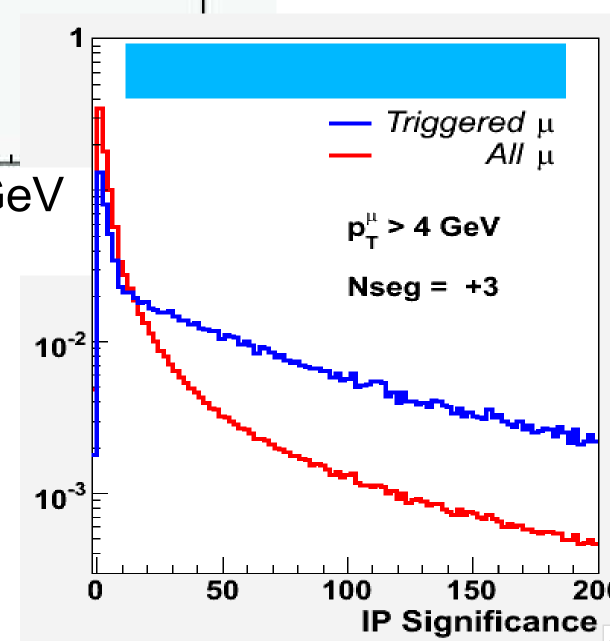
Trigger System: Level 3

- Software based.
- Goal: To perform a (partial) reconstruction of the event.

Tools of the trade:

- muons
- electrons
- tracking
- taus
- jets
- missing E_T
- primary & secondary vertexing
- isolation (muons, electrons)
- impact parameter (tracks, muons)
- invariant mass





... and almost any combination thereof