B Lifetimes and Mixing at CDF

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Outline

- Overview of B Physics at CDF
- B Triggers
- B lifetimes and masses
- B mixing
- Summary

B Physics at CDF

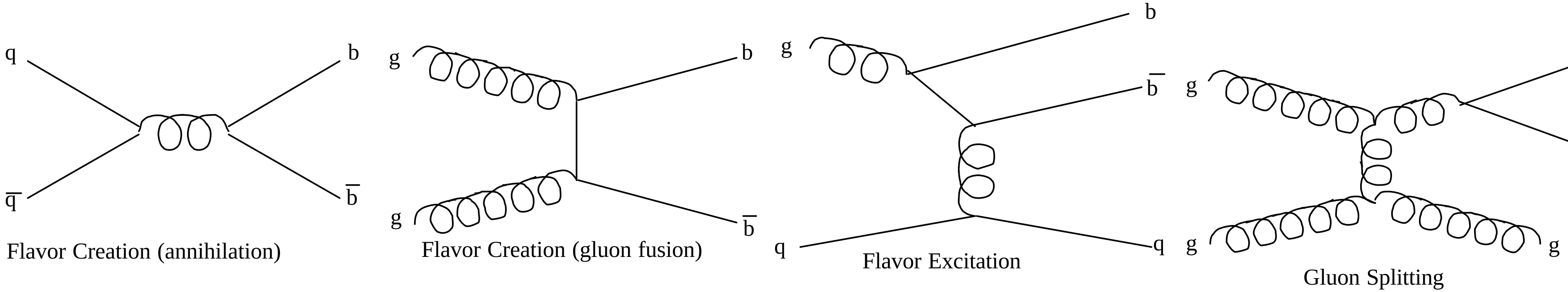
- Bottom Production
  - Cross sections
  - Angular distributions
- Masses and Lifetimes
  - B^0, B^+, B_s, Λ_b, B_c, …
- Rare Decays
  - B → ll, llK…

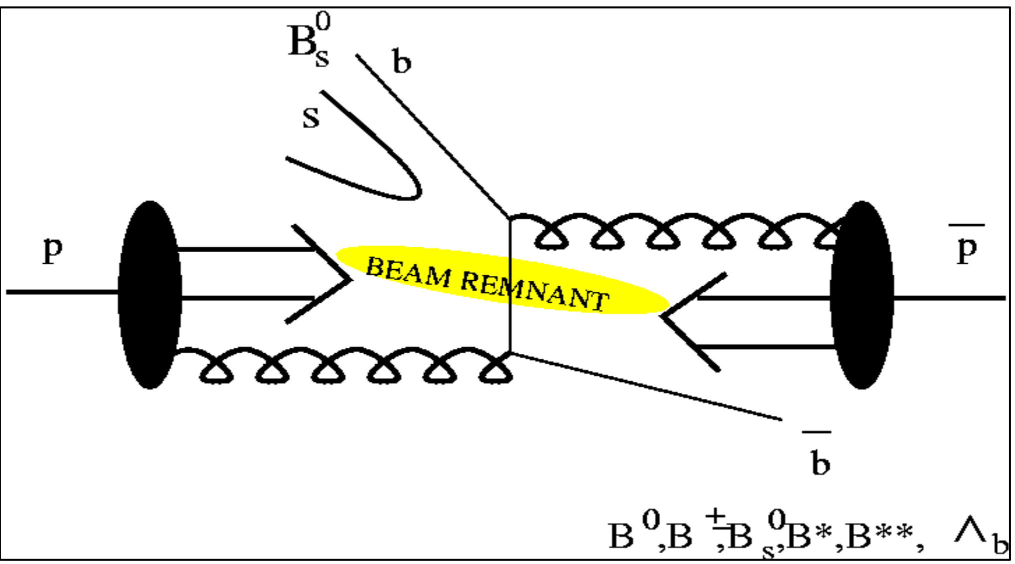
- Studies of CKM mechanism
  - Mixing
    - B^0 ($|V_{td}|$) : $B^0 \rightarrow J/\psi K^{*0}$, $B^0 \rightarrow l\nu D$
    - B_s ($|V_{ts}|$) : $B_s \rightarrow D_s n\pi$, $l\nu D_s$, …
  - $\Delta\Gamma_s$: $B_s \rightarrow J/\psi\phi$, $J/\psi\eta$, $l\nu D_s$, $D_s D_s$
  - CP violation
    - β: $B^0 \rightarrow J/\psi K^0_s$
    - α: $B^0 \rightarrow \pi\pi$
    - γ: $B \rightarrow DK$, $B_s \rightarrow D_s K$
    - γ: B^0, B_s → $K\pi, \pi\pi, KK$
    - "Exotic": $B_s \rightarrow J/\psi\phi$, $D^0 \rightarrow KK, \pi\pi$

- Today's Topics:
  - Lifetimes (and masses)
  - Mixing

B Physics at CDF

BB production mechanics in hadron collider:





- Huge cross-section (~100 µb)
- All *B* species produced:
  - $B_u, B_d, \mathbf{B_s}, \mathbf{B_c}, L_b, \ldots$

BUT s (bb) << s (pp) Þ **B events have to be selected with specific triggers…**

Trigger requirements: large bandwidth, background suppression, deadtimeless

B Triggers at CDF Run II

Di-lepton (J/y) p_T(m/e)>1.5/4.0 GeV/c

- J/y modes at low momentum
- Masses, lifetimes
- Measure x-section
- J/y Yield 2x Run I (low Pt threshold)

l + displaced track

p_T(e/m)>4 GeV/c
p_T(Trk)>2 GeV/c
120 mm<d_0(Trk)<1mm

- Semileptonic decays
- Lifetimes, flavour tagging
- B Yields 3x Run I

NEW!

Two displaced vertex tracks

p_T(Trk)>2 GeV/c
120 mm<d_0(Trk)<1mm
S p_T>5.5 GeV/c

- Hadronic modes!
- Branching ratios
- B^0_s mixing

Data sample: ~220 pb^{-1} on tape (results for ~80-140 pb^{-1})

B hadron Lifetimes

PDG values

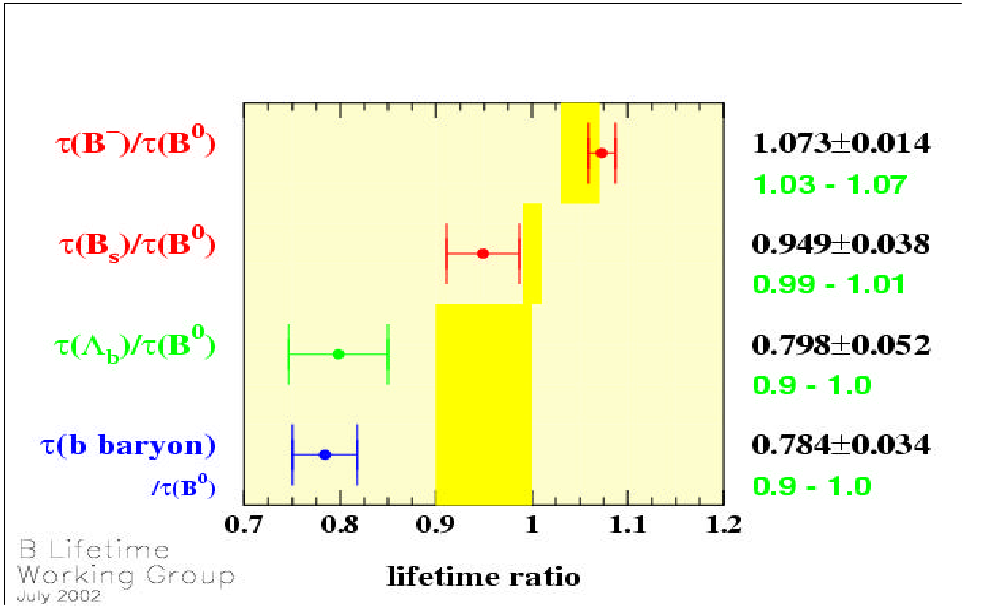
B hadron	Lifetime (ps)	cτ (μm)
B^+	1.674 +/- 0.018	502
B^0	1.542 +/- 0.016	462
B_s	1.461 +/- 0.057	438
B_c	0.460 +/- 0.180	138
Λ_b	1.229 +/- 0.080	368

- All lifetimes are equal in spectator model. Differences come from interference and other nonspectator effects

- *Heavy Quark Expansion* predicts the lifetimes for different B hadron species:

$\tau(B^+) > \tau(B^0) \sim \tau(B_s) > \tau(\Lambda_b) >> \tau(B_c)$

- CDF can be competitive in B_s, B_c and L_b lifetimes



B hadron Lifetimes

Exclusive channels:

J/y trigger

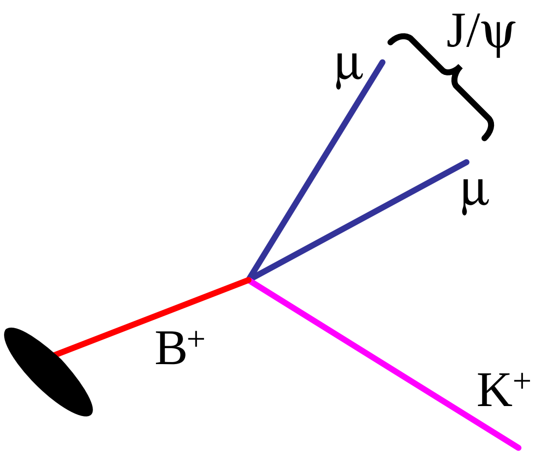
- **Clean**
- **Fully reconstructed**
- **Lifetime unbiased**
- **Low statistics**

B^0 ® J/y K^{0*}

B^+ ® J/y K^+

L_b ® J/y L

B^0_s ® J/y f



Semileptonic channels:

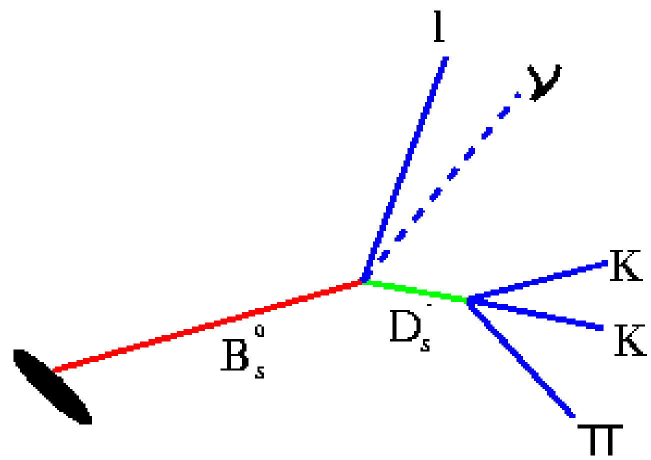
lepton+displaced track trigger

- **Mixed (B^0 <-> B^+)**
- **Only partially reconstructed**
  - **need MC to unfold ct!**
- **Lifetime biased**
- **High statistics**

B^0 ® ln$D^{(*)-}$

L_b ® lnL_c

B^0_s ® ln $D^{\pm}_s$



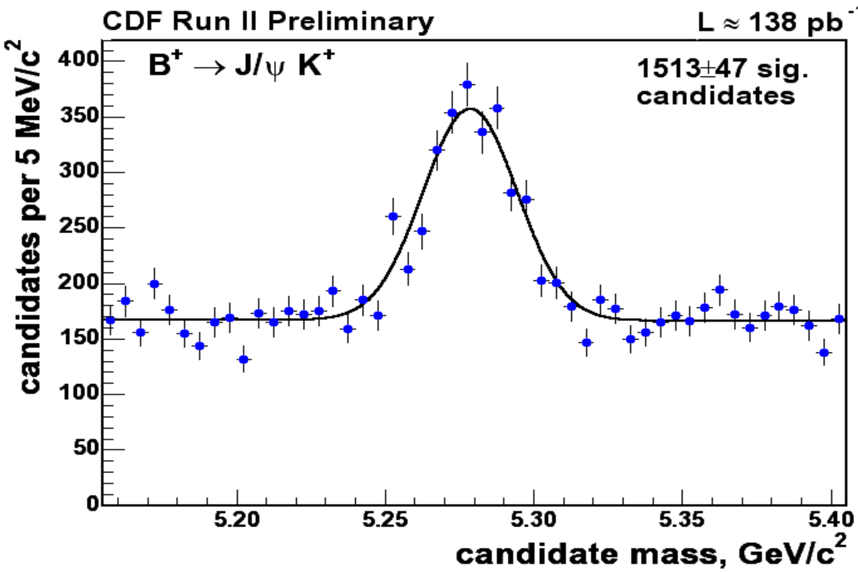
Lifetime measurement:

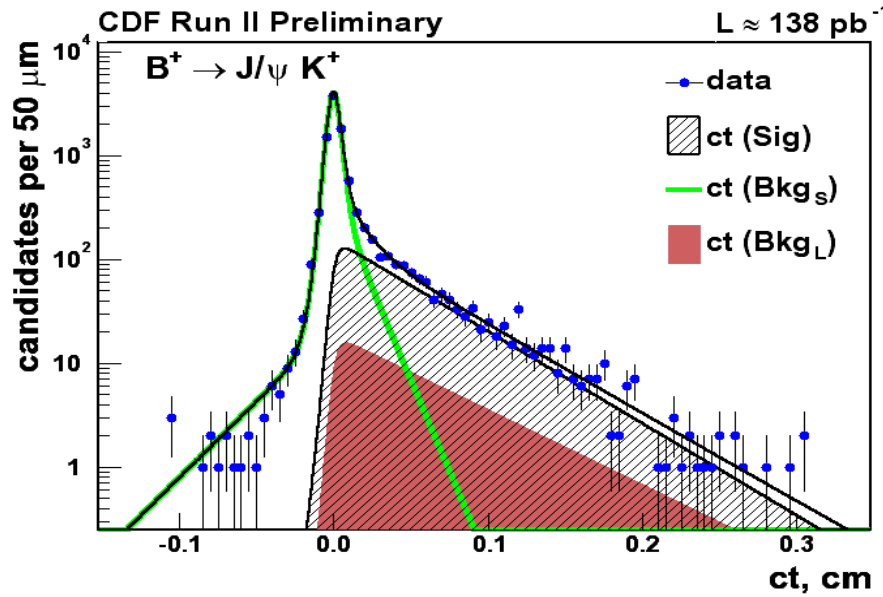
- Reconstruct decay length
- Measure p_T of decay products

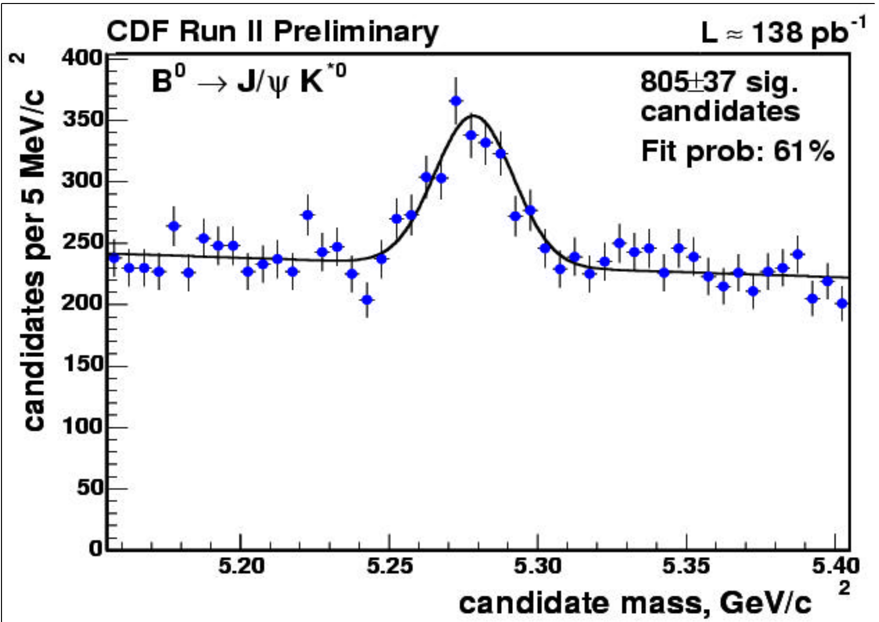
$$ct = \frac{L_{xy}}{b\,g} = \frac{L_{xy}\, m(B)}{P_T(B)}$$

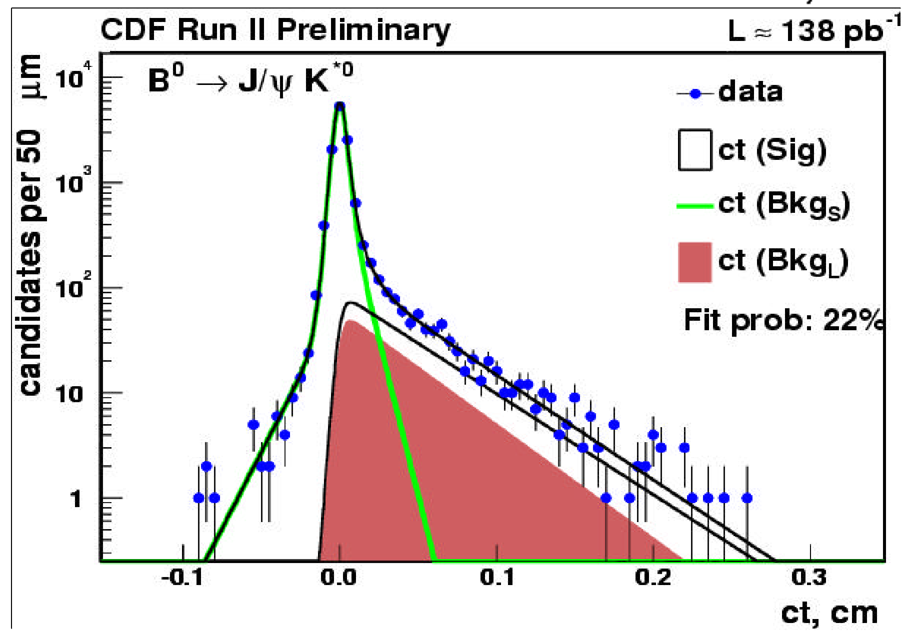
Exclusive B→J/ψX Lifetimes

Simultaneous fit of Mass and ct distributions

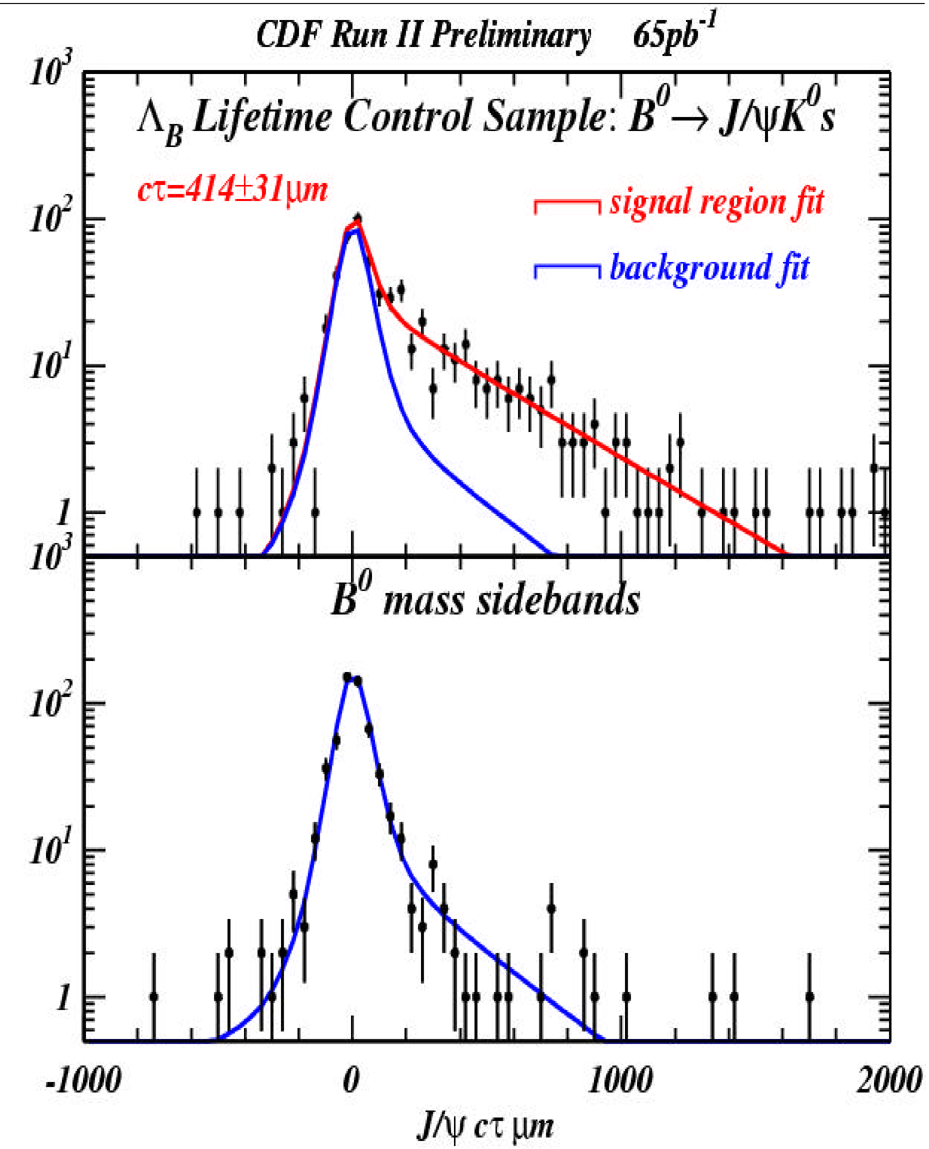


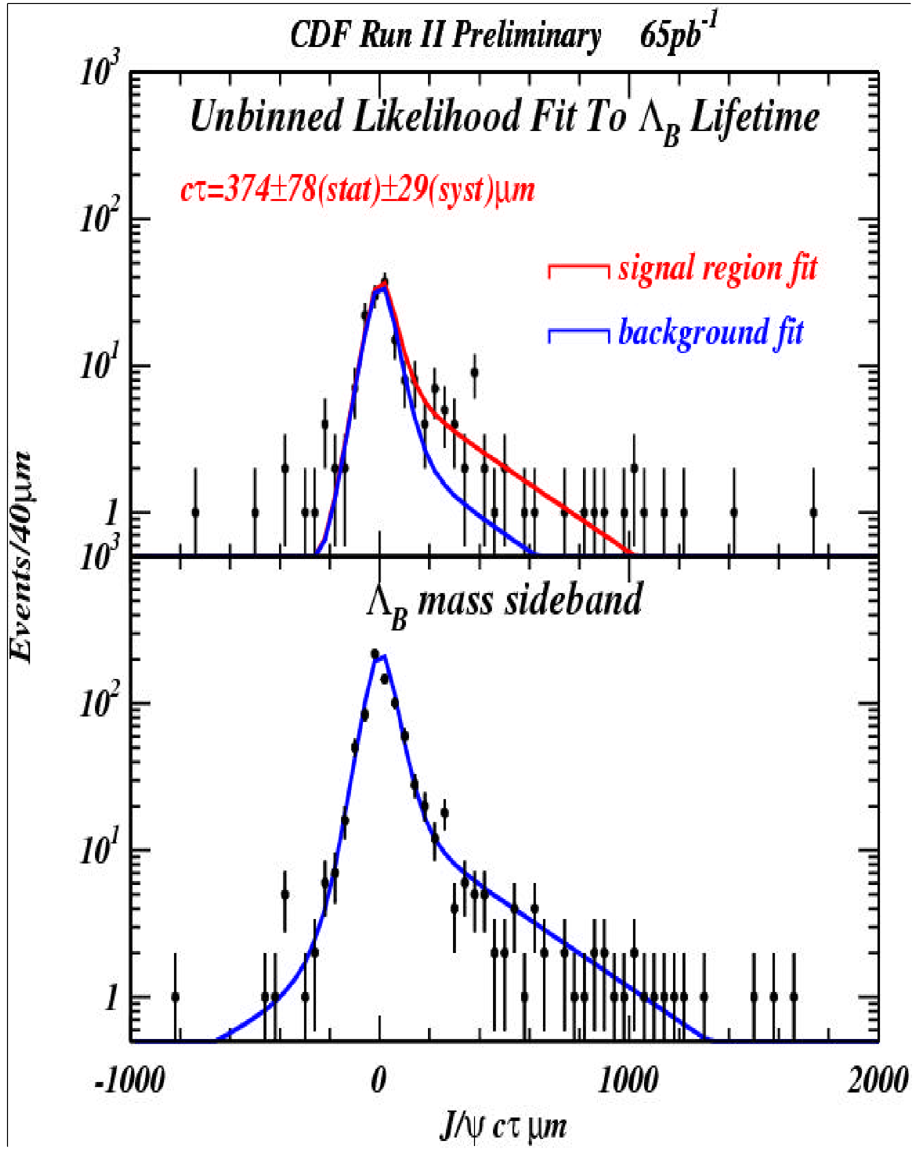






$\Lambda_b \to J/\psi\ \Lambda$ Lifetime

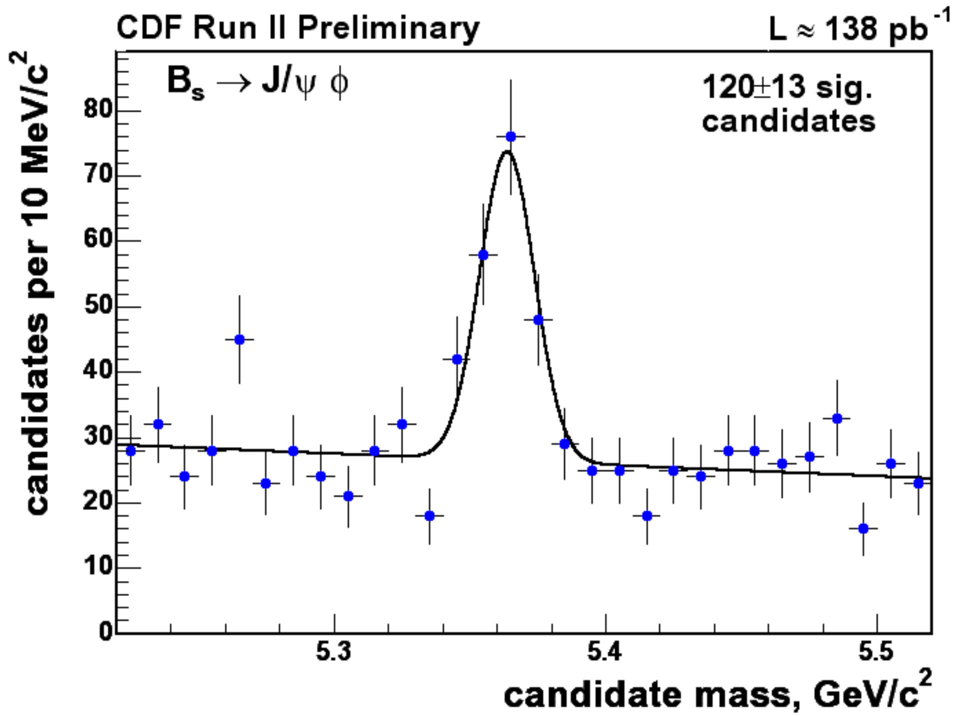


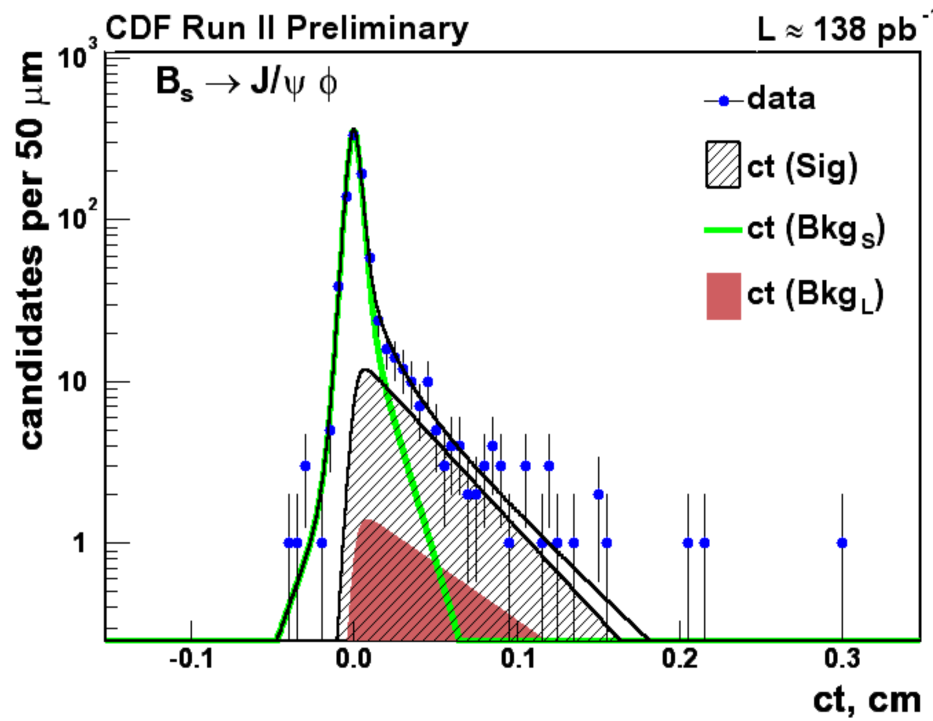


$B^0 \to J/\psi\ K^0_s$

$\Lambda_b \to J/\psi\ \Lambda$

Exclusive B→J/ψφ Lifetimes

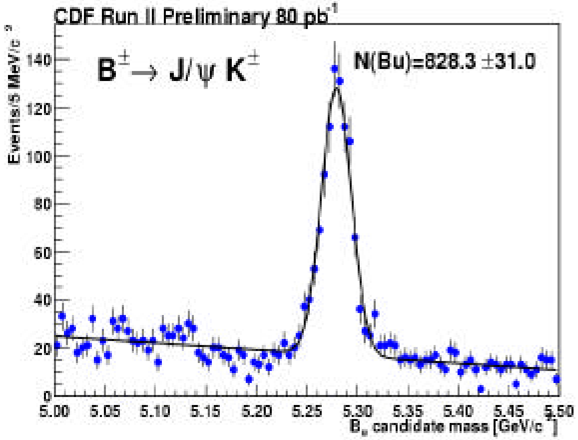


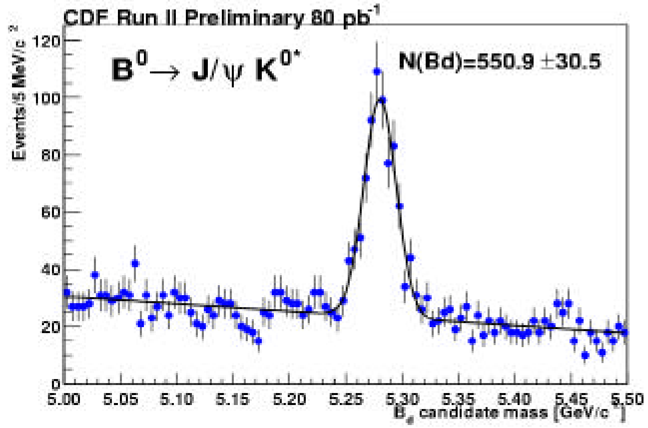


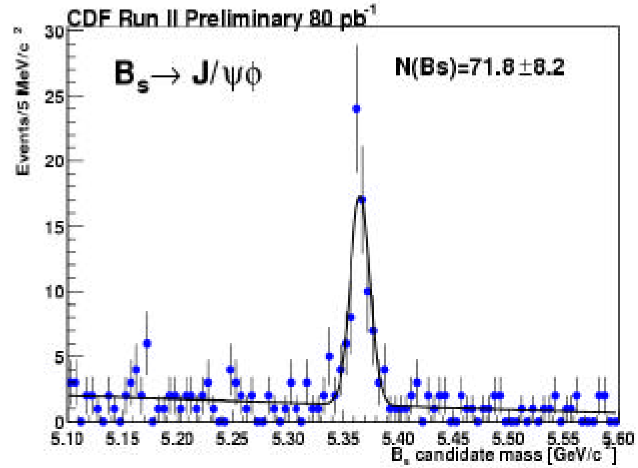
CDF RunII preliminary results (in ps)

B hadron	CDF measurement	PDG value
B^+	1.63 +/- 0.05 +/- 0.04	1.674 +/- 0.018
B^0	1.51 +/- 0.06 +/- 0.02	1.542 +/- 0.016
B_s	1.33 +/- 0.14 +/- 0.02	1.461 +/- 0.057
Λ_b	1.25 +/- 0.26 +/- 0.10	1.229 +/- 0.080

B masses in exclusive J/ψ channels

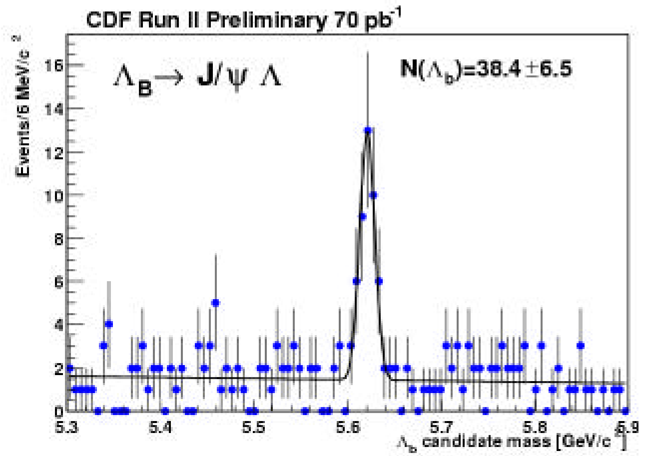






Mass measurements in fully reconstructed B decays:

- Small systematic uncertainties
- Best B_s and L_b in the world



Results in Mev/c^2	CDF preliminary	PDG value
B^+	5279.32 ± 0.68 ± 0.94	5279.0 ± 0.5
B^0	5280.30 ± 0.92 ± 0.96	5279.4 ± 0.5
B_s	**5365.50 ± 1.29 ± 0.94**	5369.6 ± 2.4
L_b	**5620.4 ± 1.6 ± 1.2**	5624 ± 9

Semileptonic Lifetimes

Standard strategy is used:

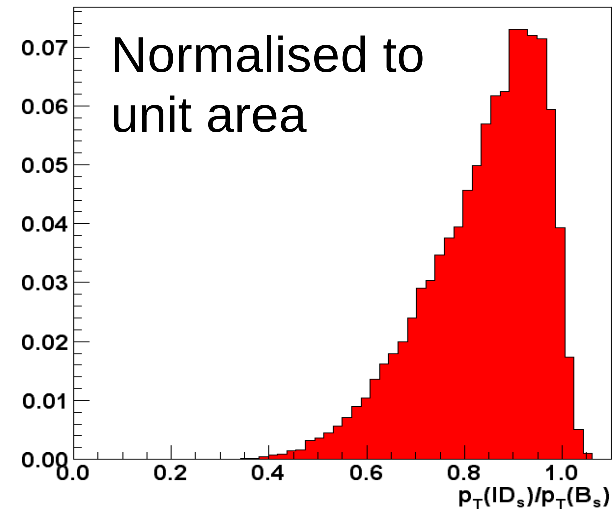
•Reconstruct the D decay close to lepton

•Extract the βγ factor from Monte Carlo

•Extract lifetime from decay length:

$$ct = \frac{L_{xy}}{b\ g} = \frac{L_{xy}\ m(B)}{P_T(lD)} K,\ K = \frac{P_T(lD)}{P_T(B)}$$

K Factor Distribution ($B_s \rightarrow l\ Ds\ X$)

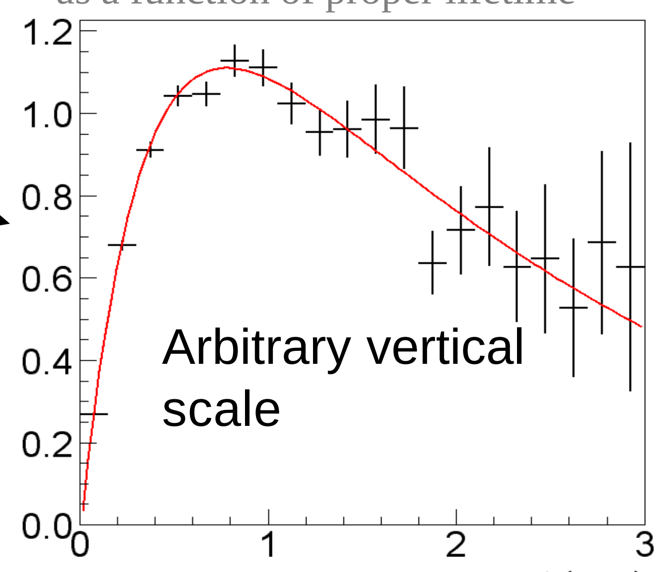


BUT there is one important complication:

Lifetime bias from the displaced vertex trigger

It is crucial emulate trigger with Monte Carlo and model the lifetime bias

Reconstruction efficiency, including trigger bias, as a function of proper lifetime

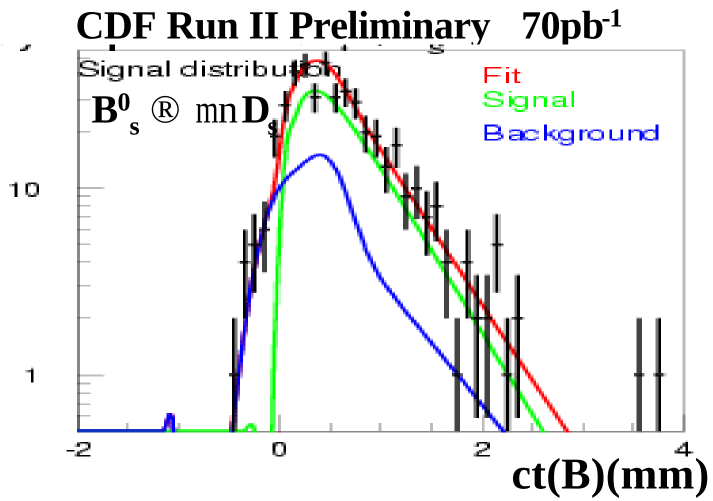


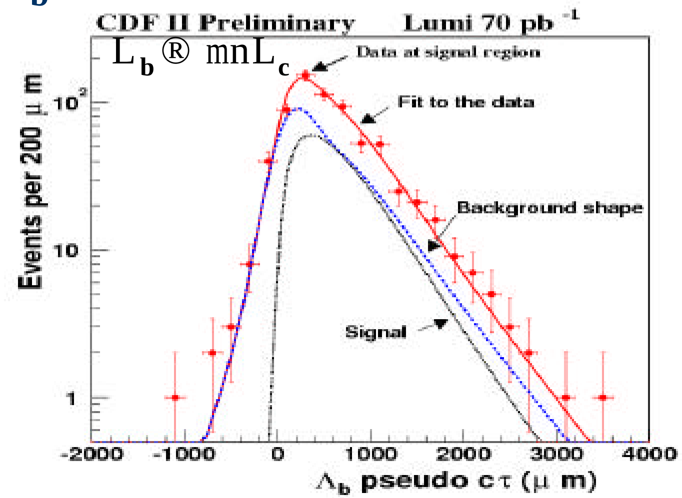
Other issues:

- Sample composition (gluon splitting?)
- Mixture of B's
- Fake leptons

Semileptonic Lifetime Fits

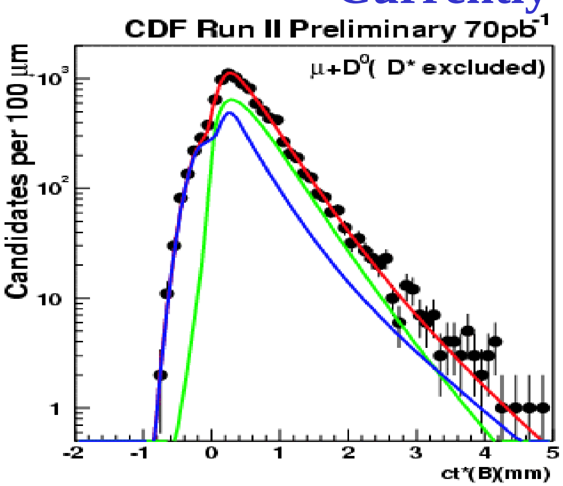
Highest statistical accuracy lifetime fits in B^0_s and L_b:

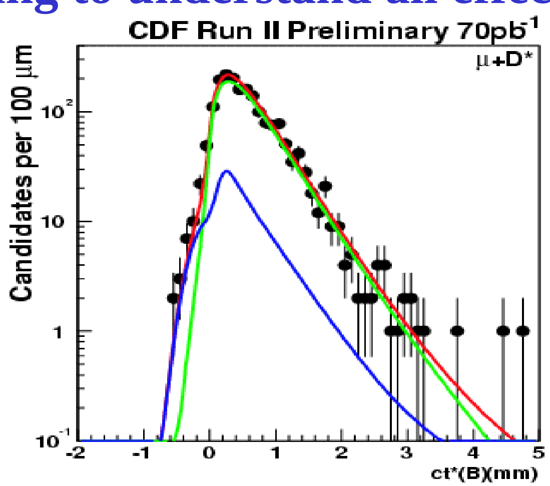




Control Samples:

- **Fit results show discrepancy with PDG world average**
- **Several cross-checks in progress**
- **Currently working to understand all effects.** ***To be continued…***

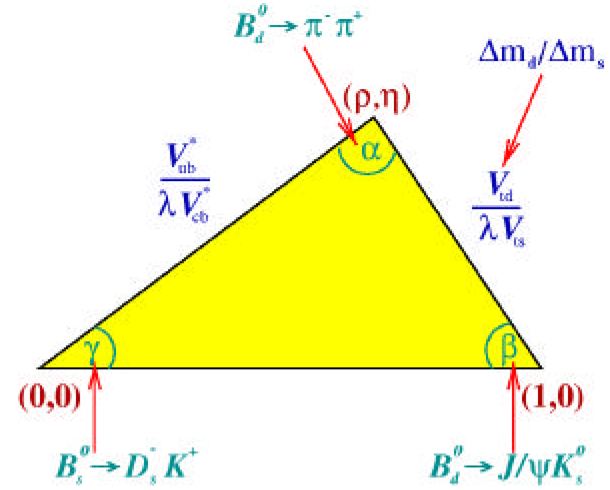


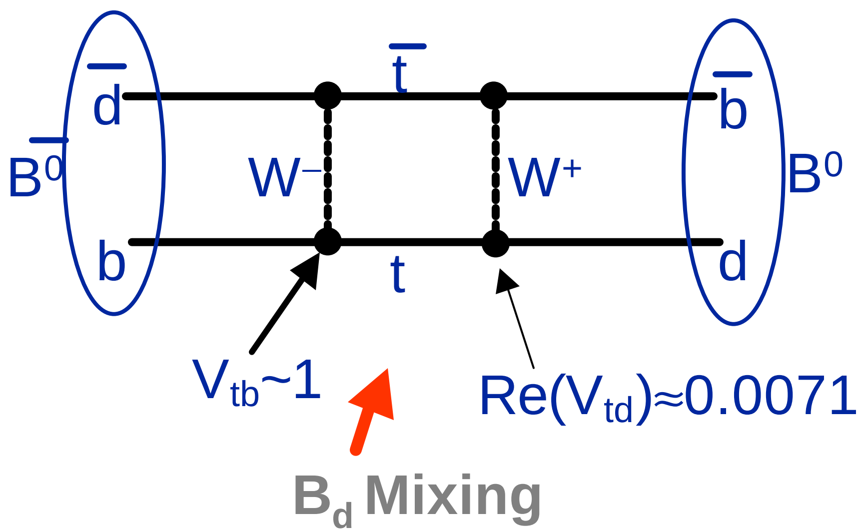


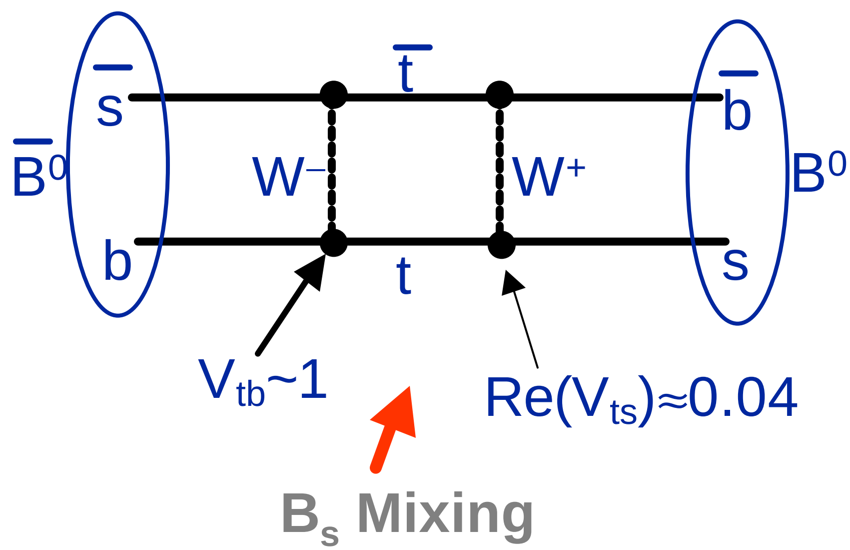
Statistical error is expected to be much better than exclusive modes!

Towards B_s Mixing

- Measurement of Dm_s helps improve our knowledge of CKM triangle
- Combined world limit on B_s mixing
  - –$\Delta m_s > 14.4 ps^{-1}$ @95%C.L.
  - **–B_s fully mixes in < 0.15 lifetime!**
- B_s oscillation much faster than B_d because of coupling to top quark







B Mixing measurement

"Ingredients" to get a $B_{(d,s)}$ mixing measurement:

- Measure proper decay time:

$$ct = \frac{L_{xy}}{b\,g} = \frac{L_{xy}\, m(B)}{P_T(B)} \quad \rightarrow \quad s_{ct} = \frac{m(B)}{P_T(B)} s_{Lxy} \oplus ct \left(\frac{s_{P_T(B)}}{P_T(B)} \right)$$

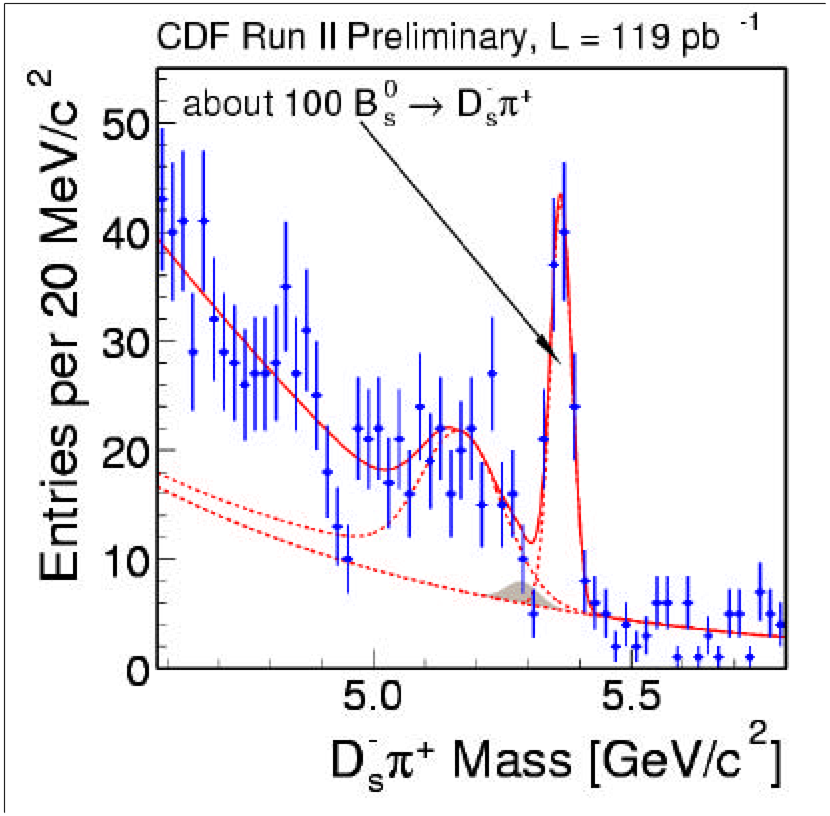
- Identify B flavor at decay:

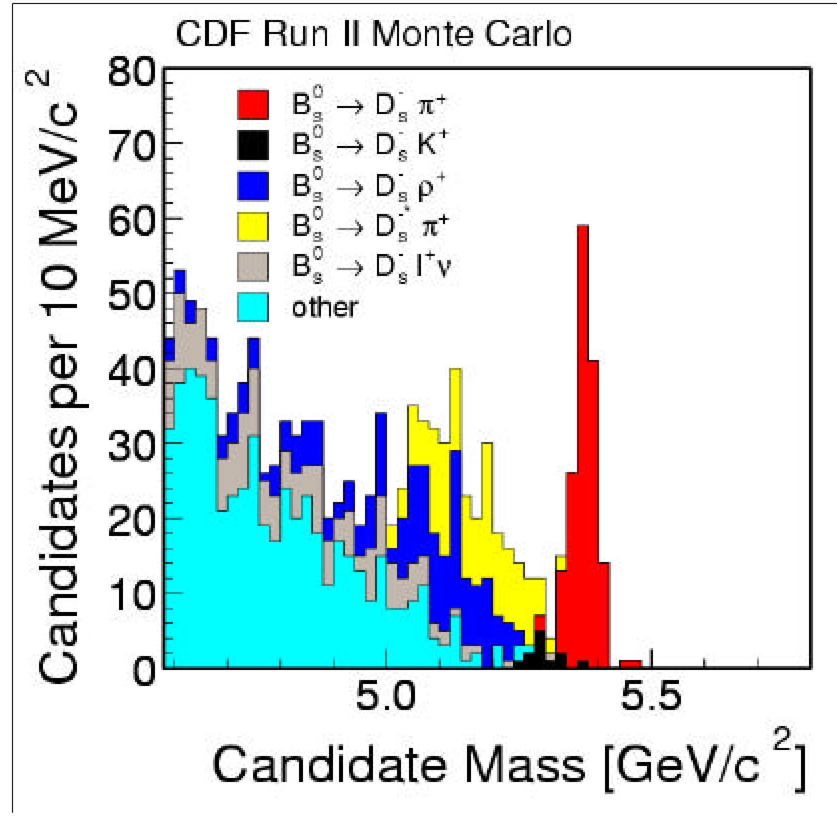
  Reconstruct the final state with good S/B
  (precise tracking, vertexing, particle ID)

- Identify the flavor of B at production:

  B - flavor tagging algorithms

B_s hadronic yields





$\boldsymbol{B^0_s}$ ® $\boldsymbol{D^-_s}$p$^+$ **with** $\boldsymbol{D^-_s}$ ® $f p^-$ **and** f ® $\boldsymbol{K^-K^+}$

$$\frac{f_s\, BR\,(B_s^0 \to D_s^- p^+)}{f_d\, BR\,(B^0 \to D^- p^+)} = 0.35 \pm 0.05\,(stat) \pm 0.03\,(syst) \pm 0.09\,(BR)$$

$$\frac{BR\,(B_s^0 \to D_s^- p^+)}{BR\,(B^0 \to D^- p^+)} = 1.4 \pm 0.2\,(stat) \pm 0.1\,(syst) \pm 0.4\,(BR) \pm 0.2\,(PR)$$

Mixing and Flavor Tagging

Figure of merit: εD^2

- **ε: tag efficiency**
- **D: dilution**

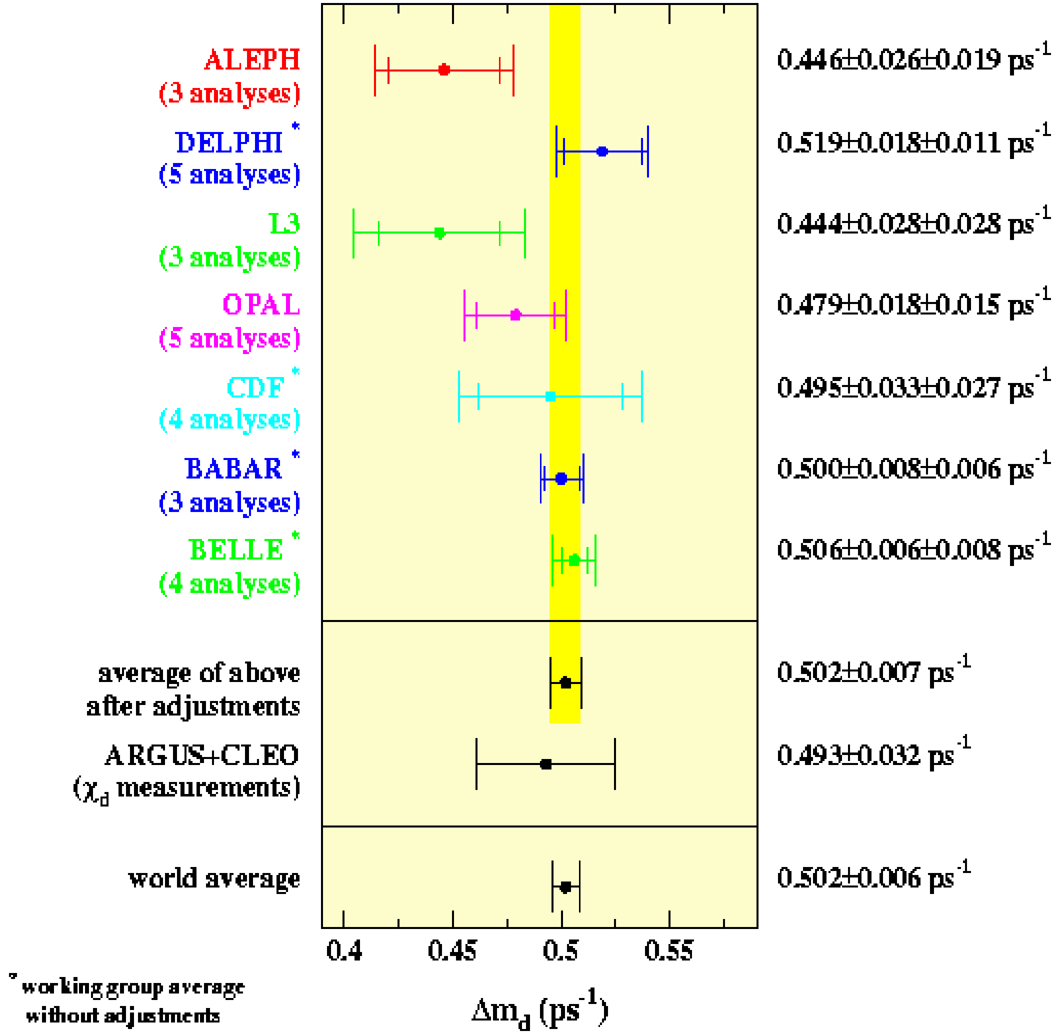
$$A(t) \equiv \frac{N_R(t) - N_W(t)}{N_R(t) + N_W(t)} = D\cos(\Delta m t)$$

$$A \equiv \frac{N_R - N_W}{N_R + N_W} = D = 1 - 2P_{TAG}$$

Strategy:

- use data for calibration (*e.g.* $B^{\pm}\to J/y K^{\pm}$, $B^{\pm}\to D^0\pi^{\pm}$, $B\to$lepton…)
- allows us to measure ε, D and εD^2 in data and optimize the taggers
- can then apply them in any sample without bias

High precision measurement in B_d mixing

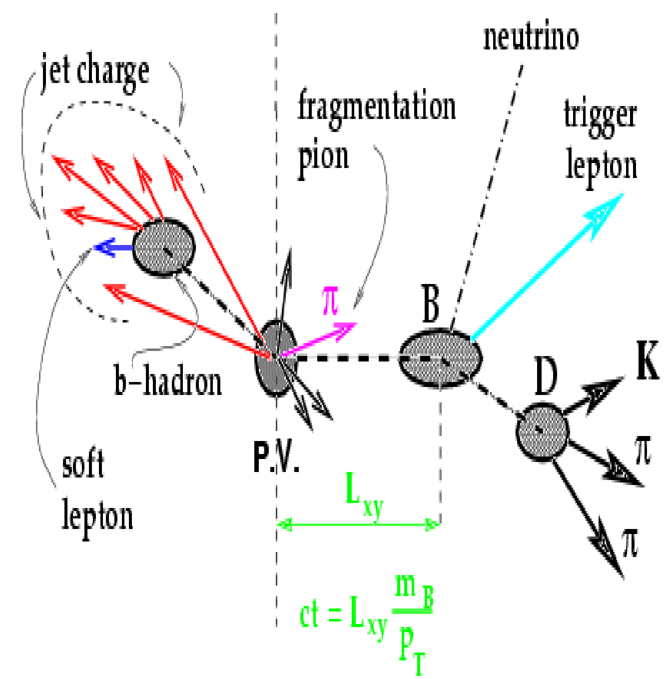


Flavor Tagging algorithms

OST (Opposite Side Tagging):

B's are produced in pairs → measure flavor of opposite B

Opposite side Same side



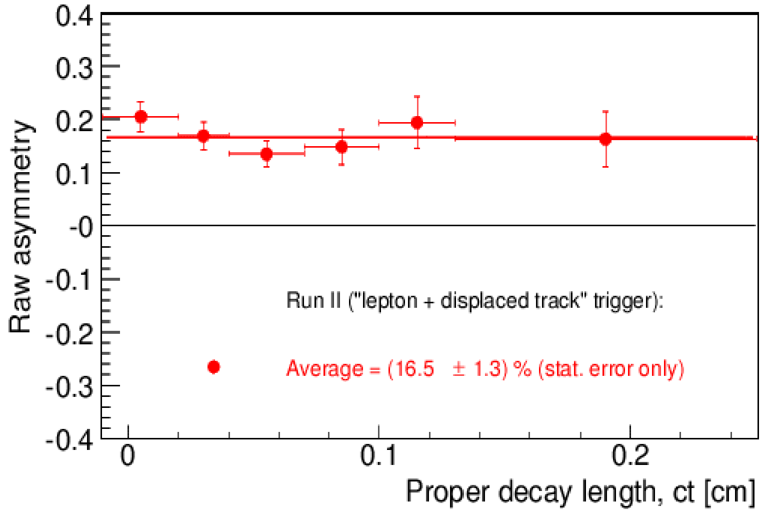
- **JETQ**: sign of the weighted average charge of opposite B-Jet
- **(*) SLT**: identify the soft lepton from semileptonic decay of opposite B
- **Opposite Side K**: due to **b®c®s** it is more likely that a B^0_s meson will contain in final state a K^+ than a K^-. Identify K^- in the opposite side

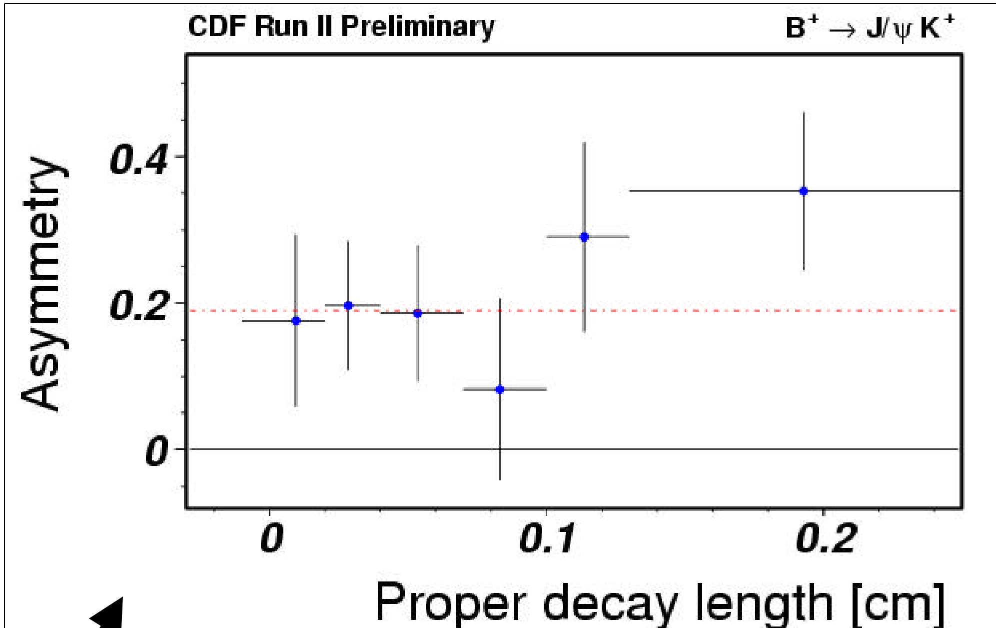
SST (Same Side Tagging):

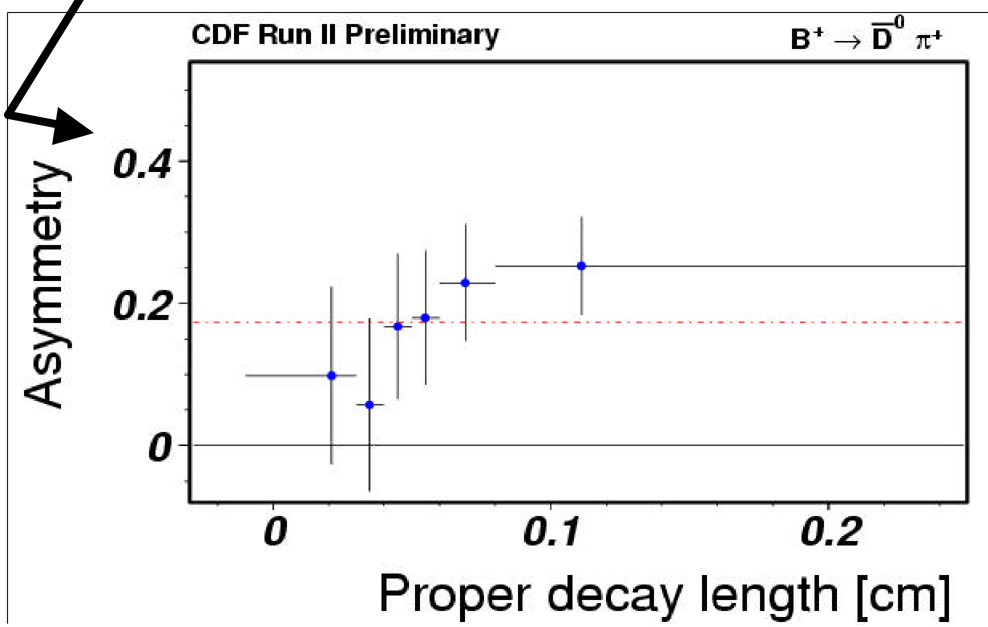
- (*) **SS pion T**: B^0 is likely to be accompanied close by a π^+ from fragmentation
- **SS Kaon T**: B^0_s is likely to be accompanied close by a K^+ from fragmentation

Same Side Tag Asymmetry

B^+ ® l^+nD^0







ϵD^2 (fully reconstructed B^+) = (2.1±0.7)%

Test on B^+ Þ we should see NO oscillations!
Result consistent with RunI

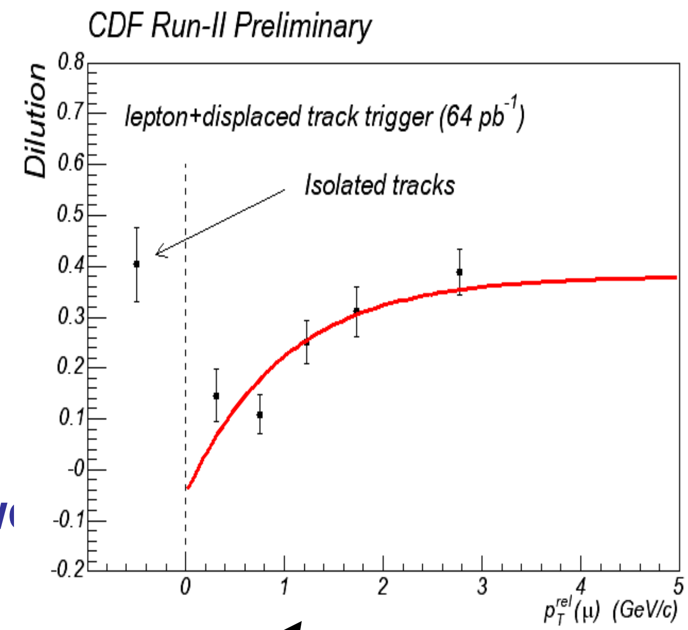
Dilution for **B^0 may be different (~10% lower in RunI)**

Soft Muon Tag in Semileptonic Sample

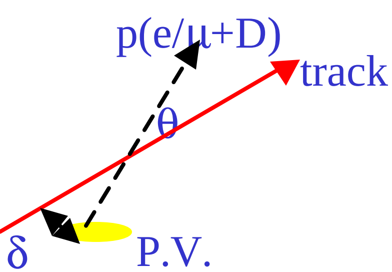
lepton + displaced track trigger provides high statistics sample

Analysis:

- **Trigger lepton used to estimate B flavor at production**
- **Identify m charge on opposite side**
- **Cross check consistency with partially reconstructed lepton+$D^{+,0}$**
- **Remainder: this number is UNBIASED since we are using an independent (and high statistics) control sample**



Consistent with RunI → **ϵD^2 (SMT) = (0.7±0.1)%**



Detailed sample composition studies:

- **Mass cut removes D decays: 2<M(l+track)<4GeV/c²**
- **Background subtraction variable separates B's from background: signed IP of displaced track**

B_s sensitivity

- From data, we have some knowledge of all the pieces that go into measuring Δm_s
- Current CDF performance (only ***B^0_s*** ® ***D^-_s***p$^+$**,** ***D^-_s*** ® *fp*$^-$!):
  - *S = # signal events ~* 1600 events/fb^{-1}
  - *eD^2 = tagging power ~* 4%
  - *S/B = signal/background ~* 2/1
  - *s$_t$ = proper time resolution ~* 67 fs

$$Significance = \sqrt{\frac{S e D^2}{2}} e^{-\frac{(\Delta m_s s_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

2σ sensitivity for Δm_s=15ps^{-1} with ~0.5fb^{-1} of data

It would be better than the current combined averaged limit

B_s sensitivity

- With a "few" improvements:
  - S=2000 events/fb^{-1} (improve trigger, reconstruct more modes)
  - eD^2 = 5% (tagging improvements)
  - S/B = 2/1 (unchanged)
  - s_t = 50 fs (event-by-event vertex + L00)

5σ sensitivity for Δm_s =18ps^{-1} with ~1.7fb^{-1} of data → SM "expected"

5σ sensitivity for Δm_s =24ps^{-1} with ~3.2fb^{-1} of data → To cover SM expectation (indirect fits)

- *We know that B_s Mixing is a difficult measurement, but it is feasible!*

Summary

• **Lifetime and mass measurements performed in $B \rightarrow J/\psi\ X$ channels:**

B hadron	Lifetime (ps)	Ratio (B_x/B^0)
B^+	1.63 +/- 0.05 +/- 0.04	1.08 ± 0.06
B^0	1.51 +/- 0.06 +/- 0.02	-
B_s	1.33 +/- 0.14 +/- 0.02	0.88 ± 0.10
Λ_b	1.25 +/- 0.26 +/- 0.10	0.83 ± 0.19

• **Lifetime measurements using the Lepton + displaced vertex track trigger ongoing: will give best statistical accuracy in B^0_s and Λ_b**

• **Flavor tagging procedure has been established, and it is working in several control samples**

• **First steps towards B^0_s mixing have already been done!**

Work in progress…

Backup Slides…

The CDF Detector in Run II

Inherited from Run I:

Central Calorimeter (|η|<1)

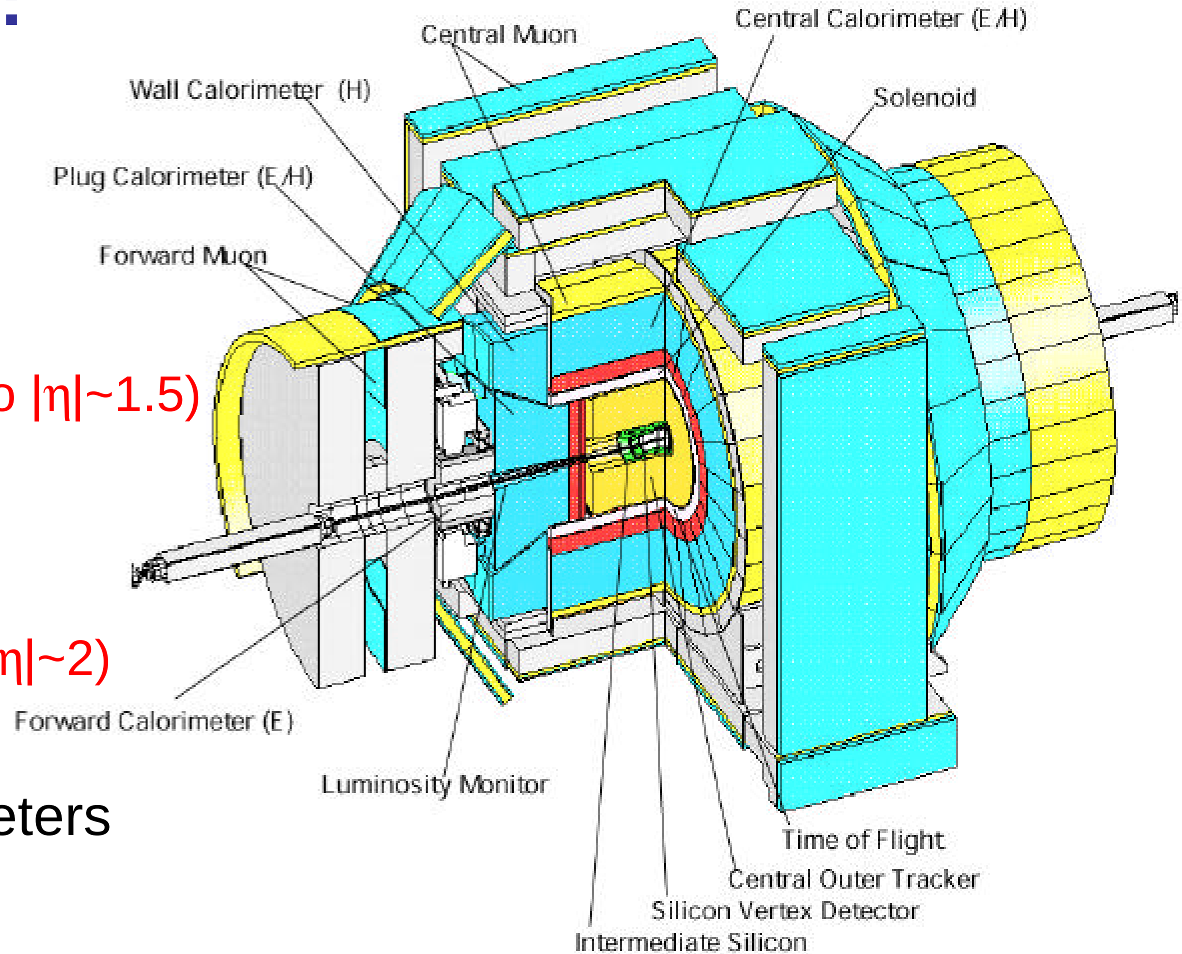
Solenoid (1.4T)

Partially New:

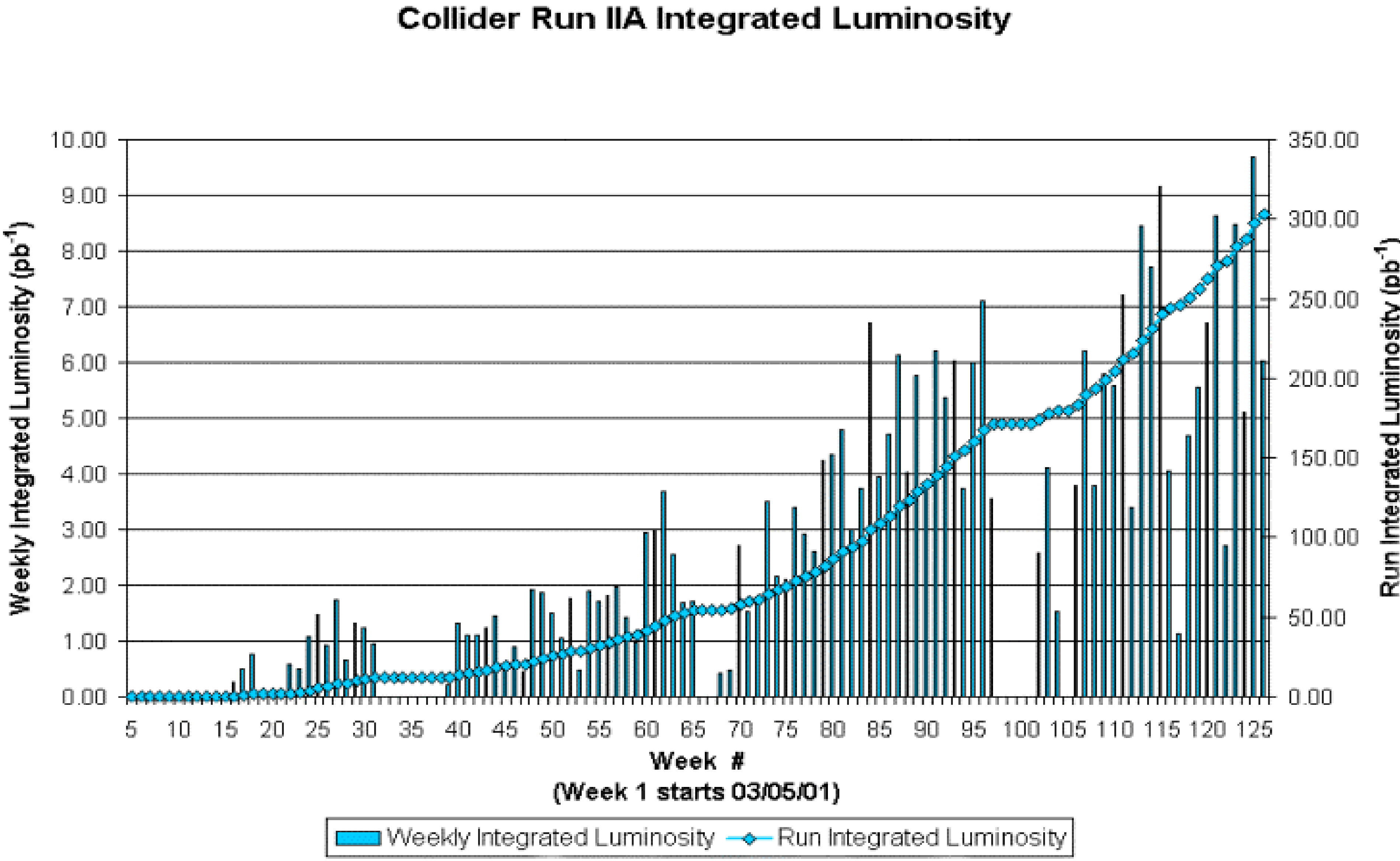
• Muon system (extended up to |η|~1.5)

New:

• Tracking System
  - 3D Silicon Tracker (up to |η|~2)
  - 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!)



Tevatron performance



~220 pb^{-1} on tape, detector efficiency ~85-90%

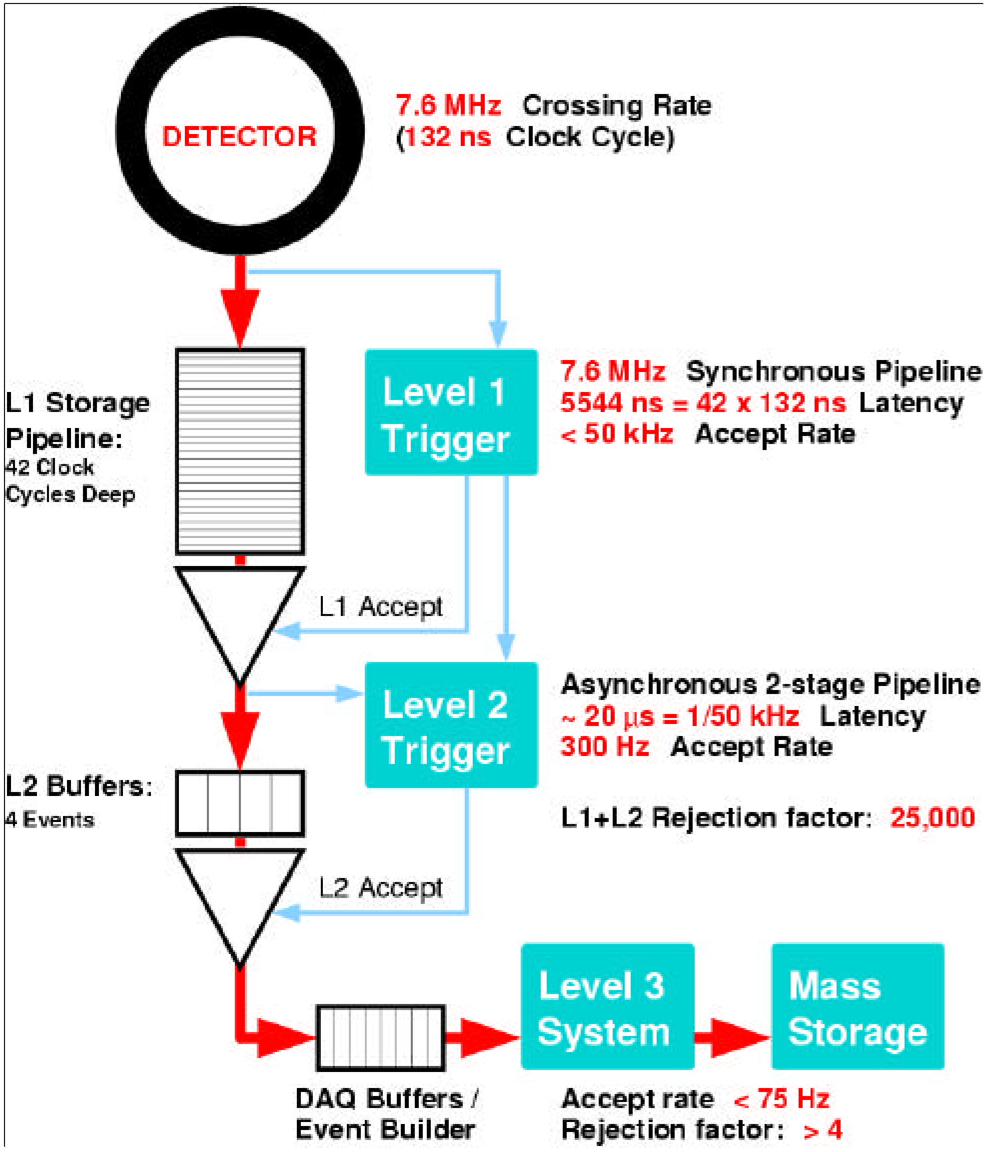
CDF Trigger System Overview

- Crossing: 396 ns, 2.5 MHz

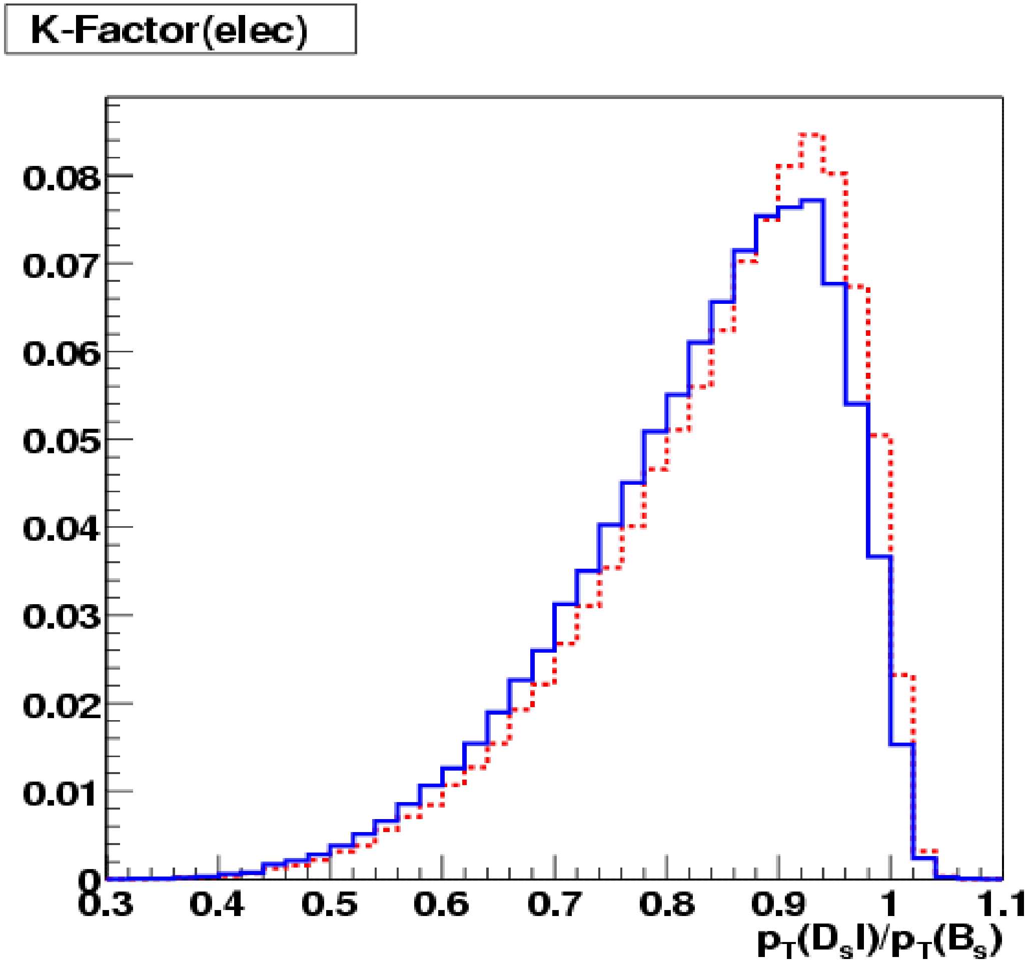
- Level 1: hardware
  - Electron, Muon, track, missing E_t
  - 15-20kHz (reduction ~x200)

- Level 2: hardware
  - Cal. Cluster, jet finding, Silicon track
  - 300-350 Hz (reduction ~x5)

- Level 3: Linux PC farm
  - ~ Offline quantities
  - 50-70 Hz (reduction ~ x6)



K Factor and Bias from MC



RED : Generator Level

BLUE : Reconstructed $p_T(D_s l)$

Semileptonic B Decay Fit Model

Unbinned maximum likelihood fit to ct(B)

- **Background is parameterised by delta function and positive exp convoluted with Gaussian resolution:**

$$F_{bkg} = \left[(1 - f_+) d(t - \Delta_D) + \frac{f_+}{t_+} \exp\left(\frac{\Delta_E - t}{t_+} \right) \right] \otimes G(t, s_G)$$

Free parameters: D_D D_E l_+ f_+ s_G

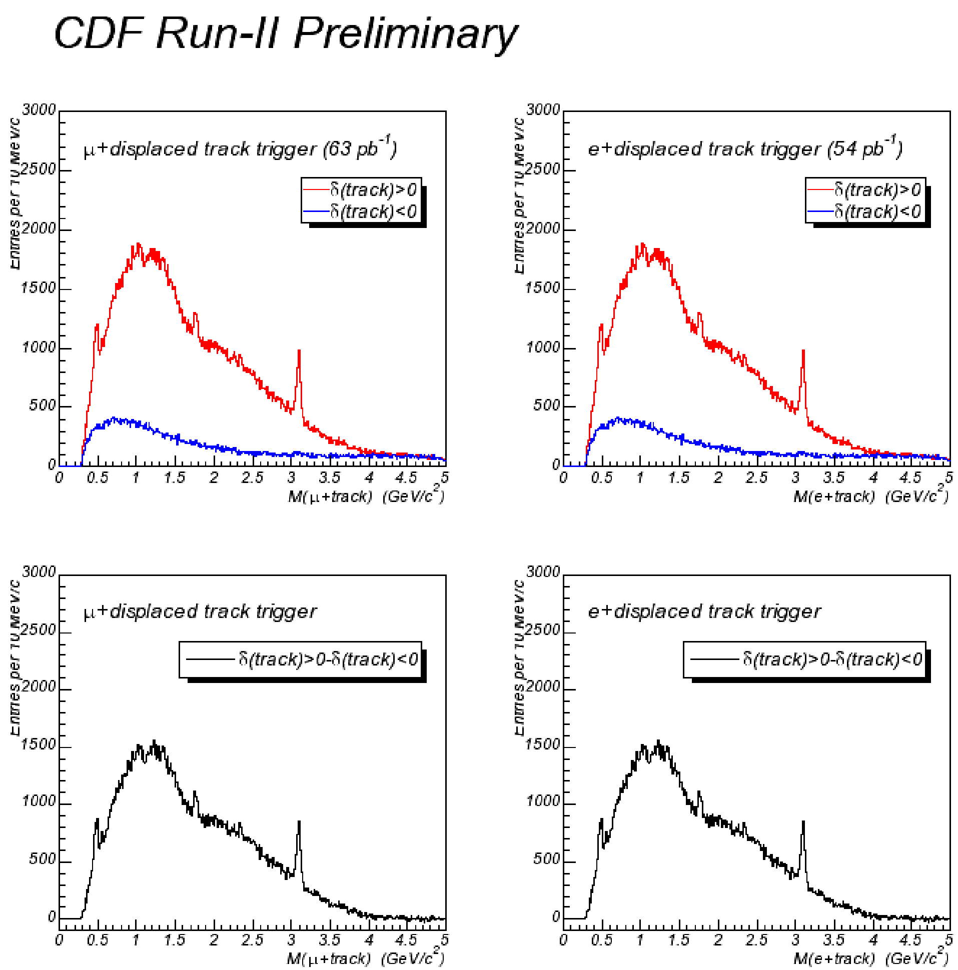
- **Signal: exp convoluted with Gaussian resolution, K factor distribution, P(K), and bias function,** e

$$F_{sig} = N \frac{K}{ct} \exp\left(\frac{-Kt}{t} \right) e(Kt) \otimes G(t, ss_i) \otimes P(K)$$

- **Maximum likelihood function:**

$$L = \prod_i^{N_{sig}} \left[(1 - f_{bkg}) F_{sig}^i + f_{bkg} F_{bkg}^i \right] \cdot \prod_j^{N_{bkg}} F_{bkg}^j$$

Sample composition in Semileptonic B decays



B_s mixing: work in progress

Estimates based current performance plus modest improvements.

Further gain is possible on all of these pieces:

- s_t
  - Event-by-event vertex
  - Layer 00
- Flavor tagging
  - Kaon tagging (same-side and opposite-side)
- Yields
  - Other B_s modes (hadronic and semileptonic)
  - Other D_s modes
  - Triggering
    - Improved use of available bandwidth
    - Improve available bandwidth
    - Improve SVT efficiency

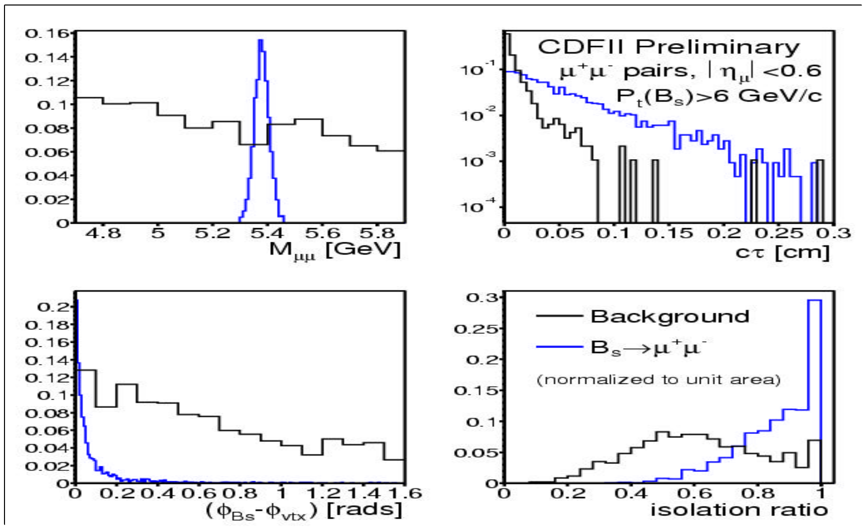
It is important most for going to $D m_s$ > 20 ps^{-1}

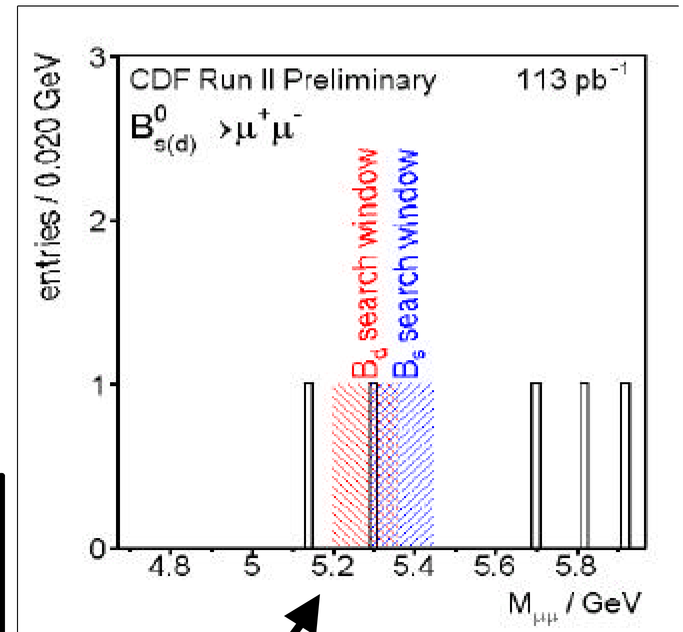
Trigger improvements matter most for yields

Rare B decays: $B_{s(d)} \rightarrow \mu^+\mu^-$

- SM prediction: $BR(B_s \rightarrow \mu^+\mu^-) = (3.8 +/- 1.0)\ 10^{-9}$
- Several extensions to the SM predict an enhancement of this branching ratio by 1 to 3 orders of magnitude
- Any excess would indicate the existence of new Physics

Discriminating variables





Final mass distribution

	$B_s \rightarrow \mu^+\mu^-$	$B_d \rightarrow \mu^+\mu^-$
Background	0.54 +/- 0.20	0.59 +/- 0.22
Data	1	1
BR limit @95% C.L.	1.2×10^{-6}	0.31×10^{-6}

Best world result