CDF Results on B Physics

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The Tevatron Connection

June 24th, 2005

Bottom/Charm Physics in CDF

- "B Physics" at Tevatron covers wide variety of the physics
  - Test of CKM
  - Indirect NP search
  - Test of QCD models …

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

- Rare Decays
  - $B \to ll$, llK, γX
  - $D \to ll$, $ll\pi$, …

- Mass/Br/Lifetime
  - D^0, D^+, D_s, Λ_c, …
  - B^0, B^+, B_s, Λ_b, B_c, …
  - X(3782), D_{sJ}, pentaquark…

- Heavy flavor production
  - Onium Production (ψ, Υ)
    - Cross section
    - Polarization
  - Charm production
  - Bottom Production

- Today's presentation,
  - New results for LP2005

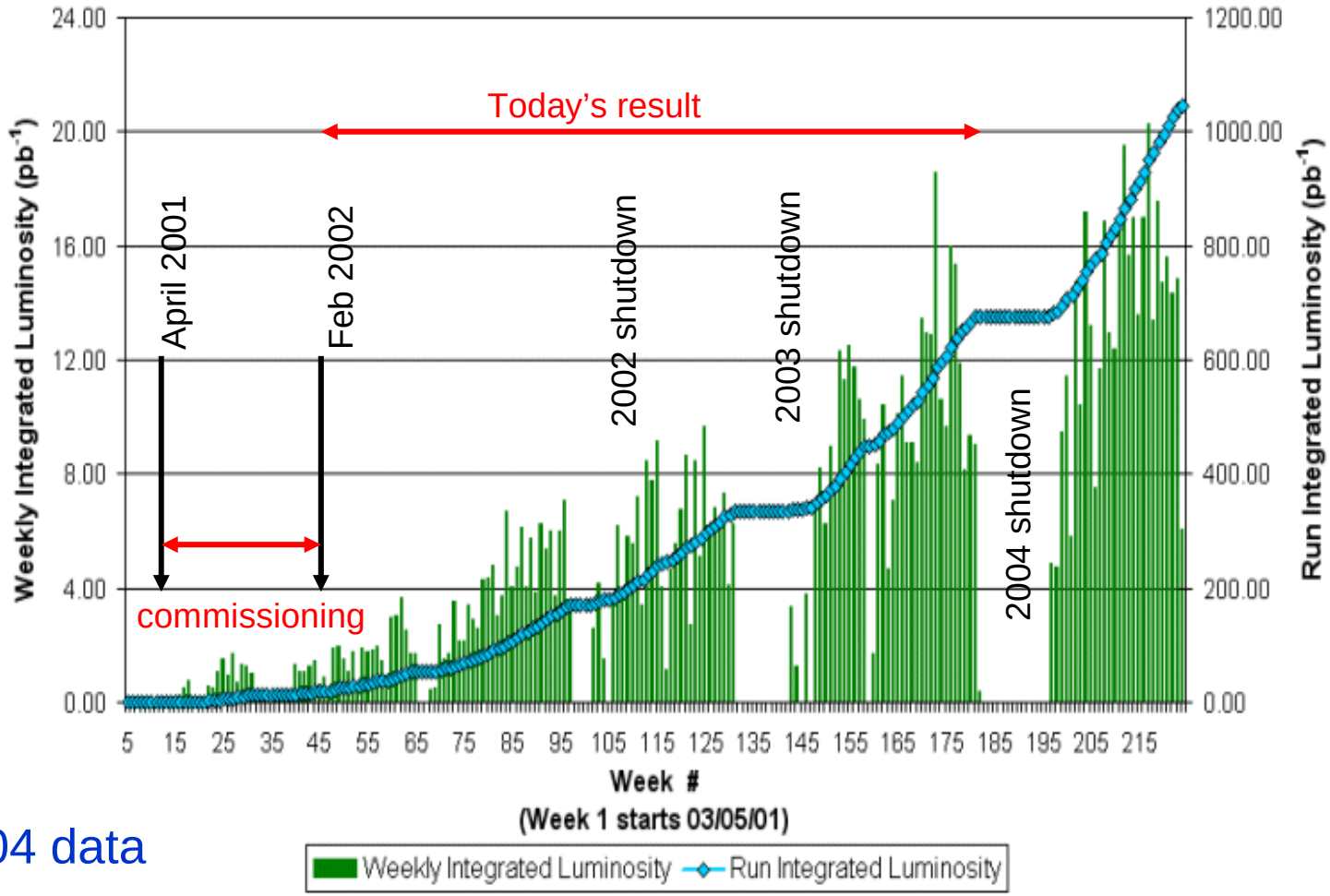
Outline

- Introduction
  - Tevatron Status
  - CDF Detector and Trigger
  - Signals Examples
- Recent Results
  - J/ψ Spin Alignment
  - Λ_b Branching Fractions
  - B_c Meson Studies
  - Rare $B_s \rightarrow \mu\mu$ decay
- B_s Mixing
  - Winter 04 analysis
  - Future Prospects

Backup slides:
X(3872) Properties
B_s branching fraction

- Summary

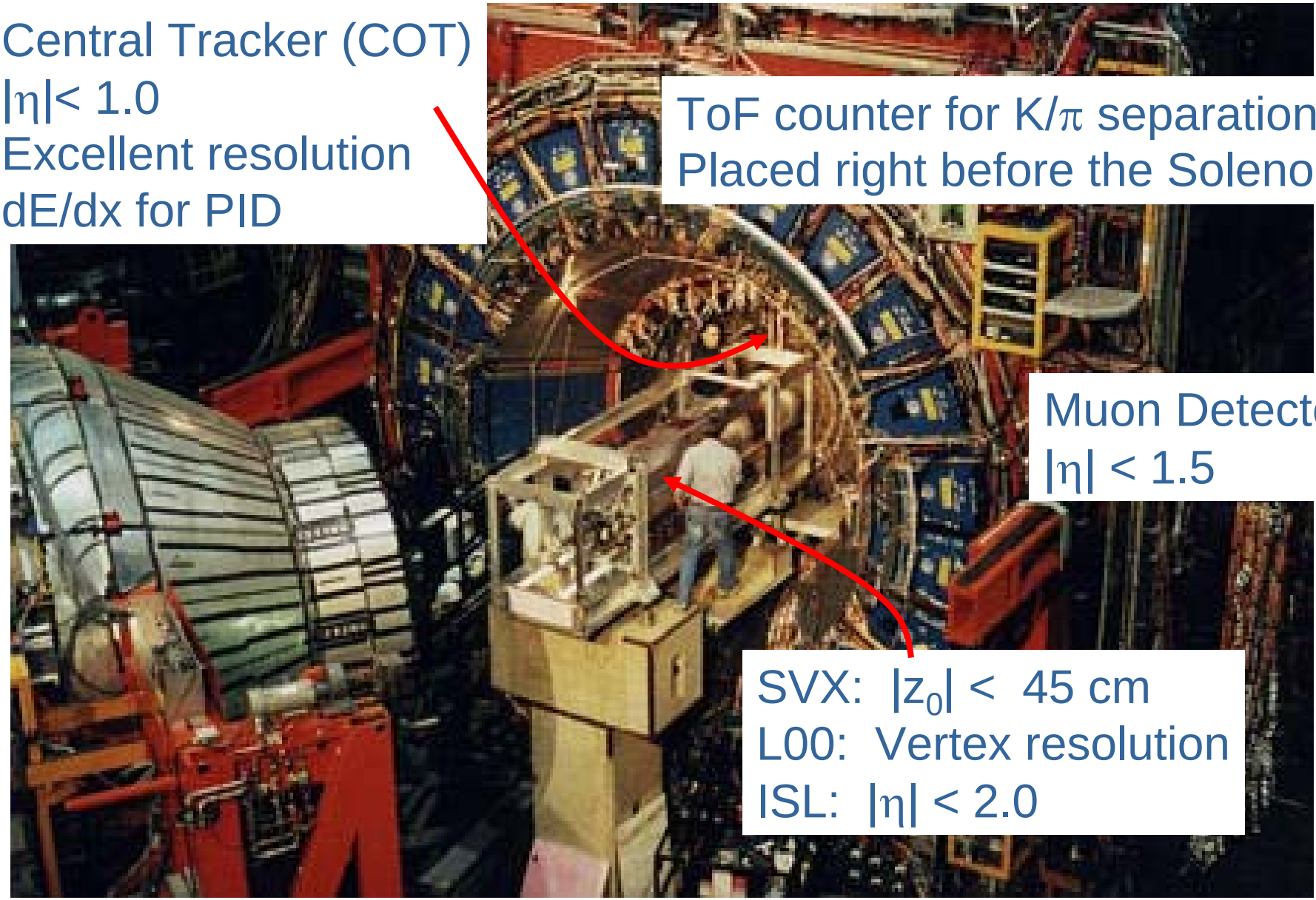
Integrated Luminosity



- 2002—2004 data
  - 700 pb^{-1} delivered
  - 350 pb^{-1} good for physics

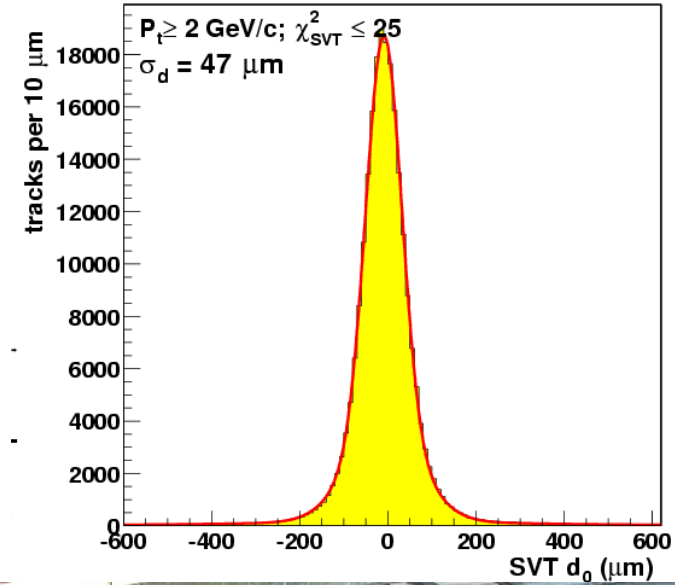
- 2005 data
  - 300 pb^{-1} delivered so far
  - much better efficiency

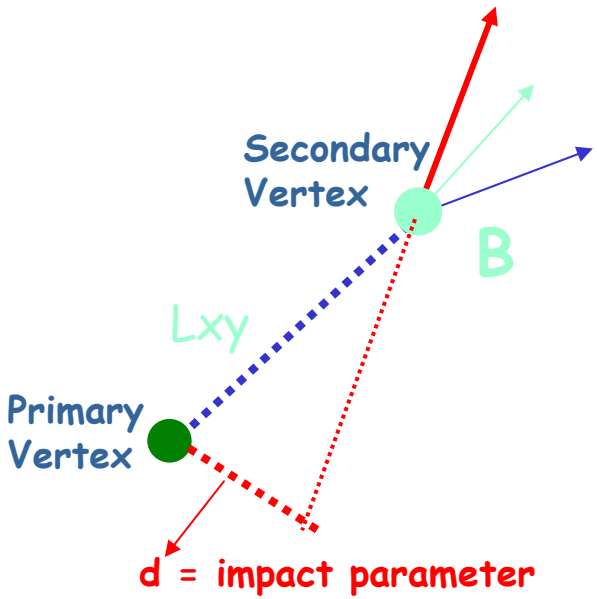
CDF Detector Overview

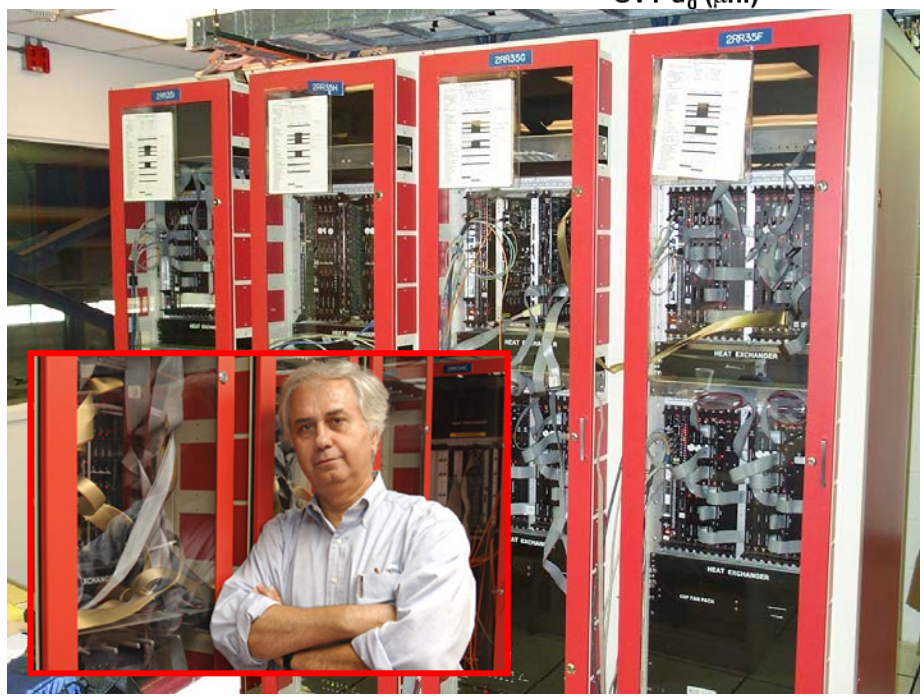


Silicon Vertex Trigger (SVT)

- Level 2: Silicon Vertex Trigger
  - –Use silicon detector information
    - Good IP resolution
    - Trigger on displaced track
  - – beamline reconstruction
    - update every ~ 30 seconds
  - –IP resolution: ~ 50 μm
    - 35μm beam size + 35μm SVT





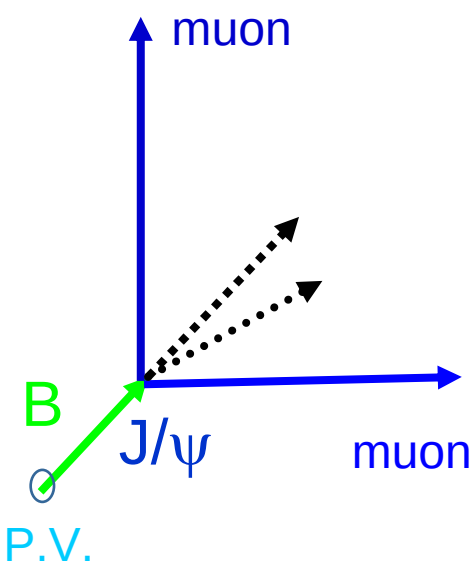


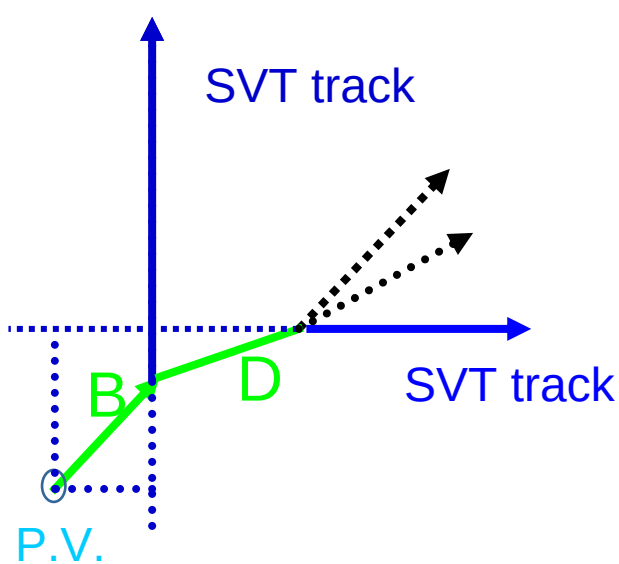
Triggers for B Physics

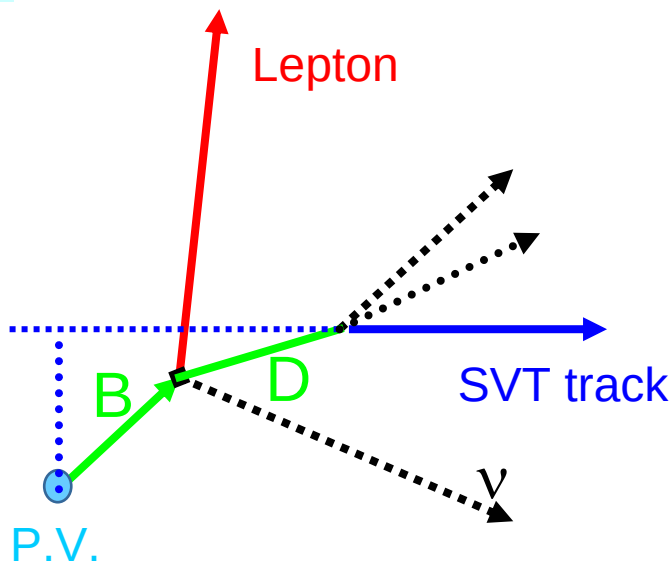
- $J/\psi \rightarrow \mu\mu$
- Two muons
  - p_T>1.5~2GeV
  - Opposite charge

- Hadronic
- Two SVT tracks
  - p_T>2GeV
  - $p_{T1}+p_{T2}$ > 5.5 GeV
  - Opposite charge
  - 120μm<d_0<1 mm
  - L_{xy} > 200 μm

- Semileptonic
- 1 Lepton + 1 SVT
  - 1 μ/e p_T> 4 GeV
  - 1 Additional SVT
    - p_T > 2 GeV
    - 120μm<d_0<1mm



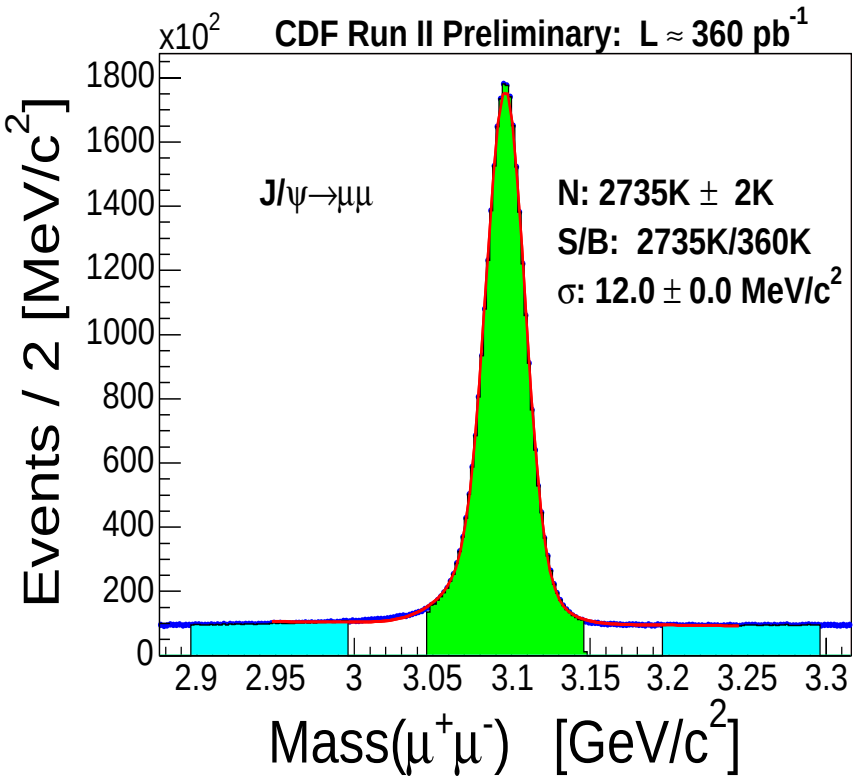


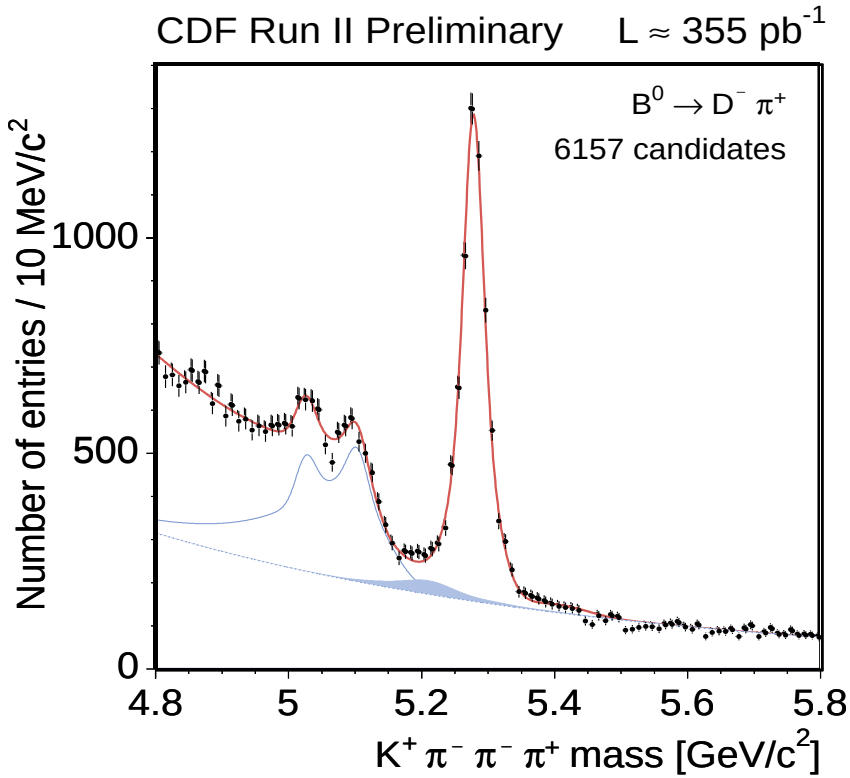


Signal Example

- $J/\psi \rightarrow \mu\mu$
  - 2.7M candidates in 360 pb^{-1}
    - Dimuon trigger sample
  - Mass resolution ~ 12 MeV
  - ~85%: prompt charm production
  - ~15%: B decay

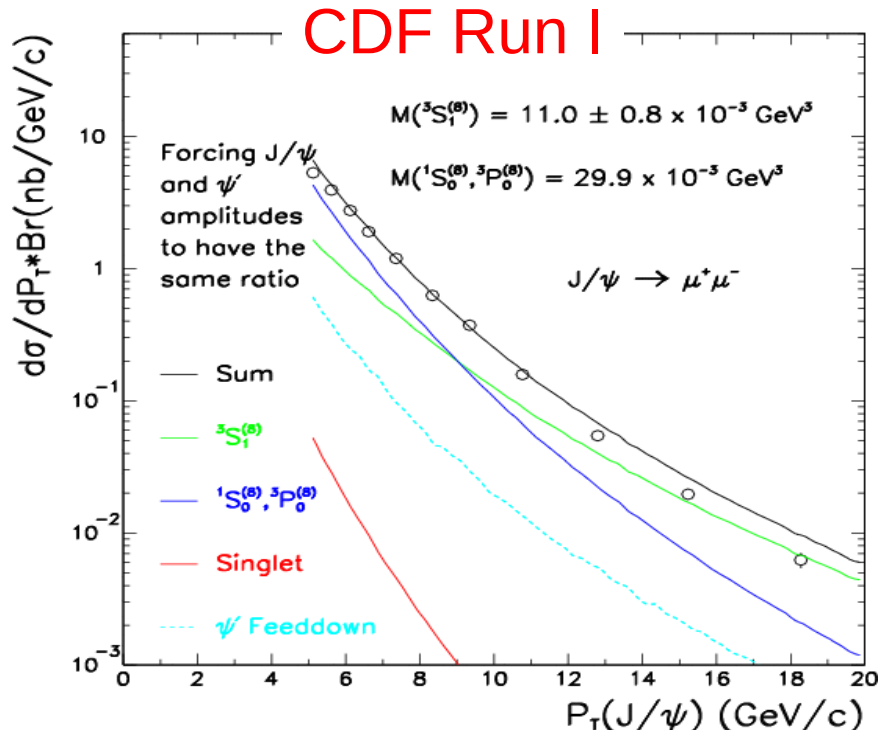
- $B^0 \rightarrow D^- \pi^+$
  - 6k candidates in 360 pb^{-1}
    - Two track trigger sample
  - Mass resolution ~ 20 MeV

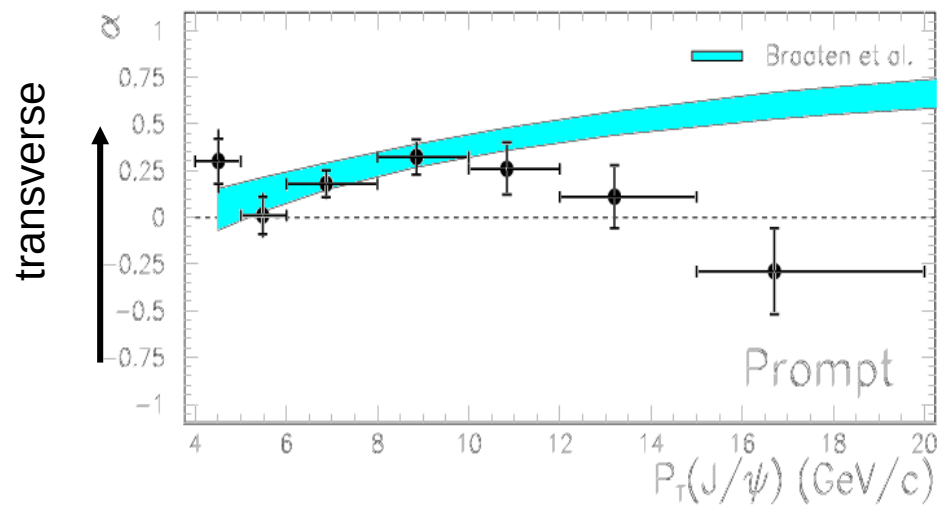




Direct J/ψ Production

- Direct J/ψ production cross section
  - LO calculation: 1/ 100 x CDF
- Non-relativistic QCD
  - J/ψ production is dominated by the color octet mechanism
  - J/ψ is positive polarized at high p_T
    - positive polarized = transverse
- CDF Run I measurement (100 pb^{-1})
  - good agreement at low p_T
  - Disagreement at high p_T
    - Theory: positive polarization
    - CDF data: negative polarization



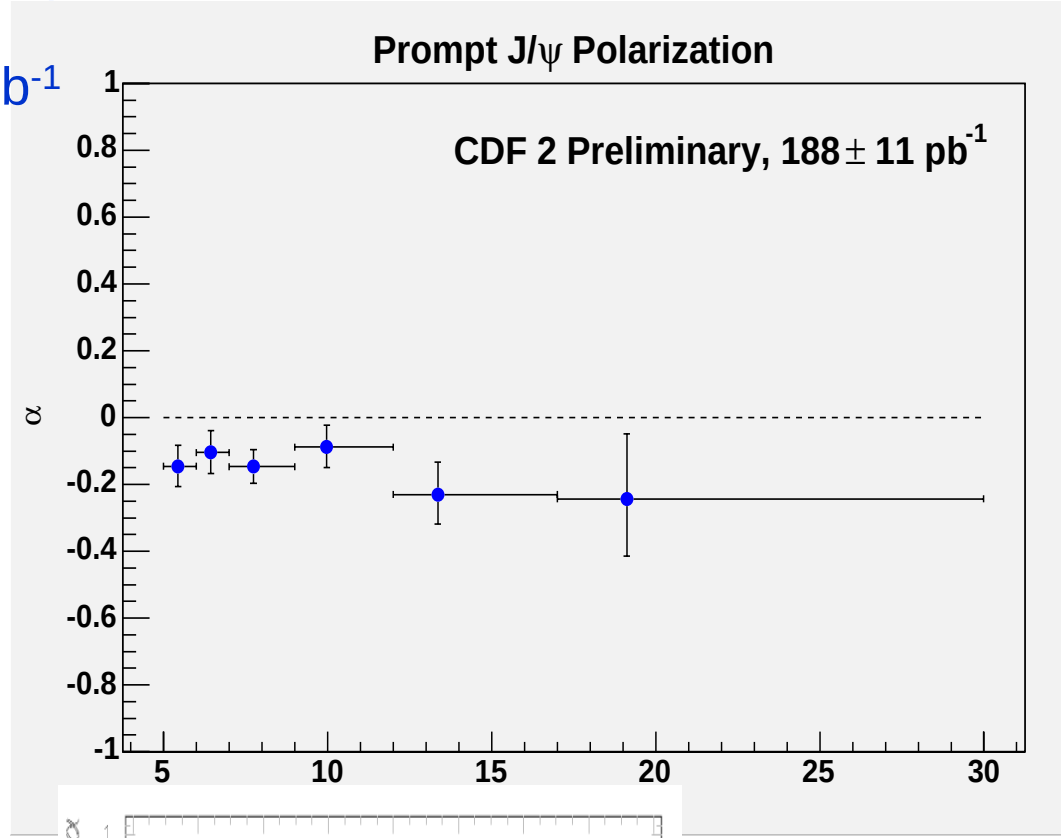


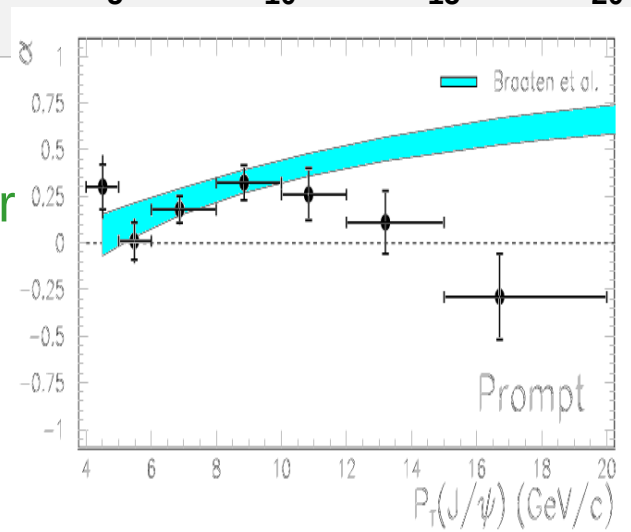
Prompt J/ψ Polarization

- Run II Dimuon trigger data 190 pb^{-1}
  - x2 luminosity
  - better acceptance for muons
  - extend p_T region to <30 GeV

- ~ constant negative polarization
  - Slight disagreement (~ 2σ) between Run I and Run II measurement at low p_T.

- Still need more statistics
  - CDF data does not favor the color octet model





Λ_b Branching Fractions

- Current knowledge of Λ_b property is very limited

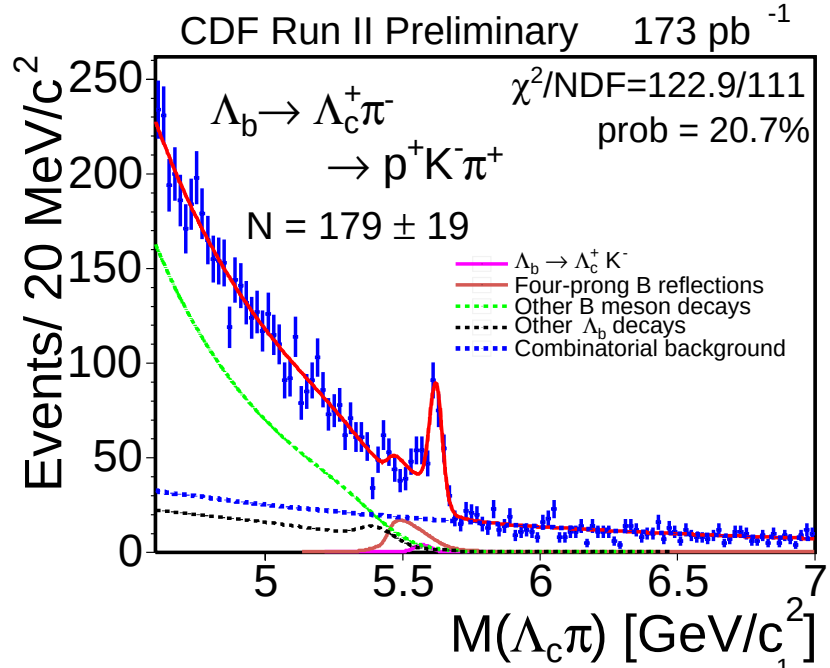
Λ_b^0 DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$J/\psi(1S)\Lambda$	$(4.7\pm2.8)\times10^{-4}$		1744
$\Lambda_c^+\pi^-$	seen		2345
$\Lambda_c^+ a_1(1260)^-$	seen		2156
$\Lambda_c^+\ell^-\overline{\nu}_\ell$ anything	[τ] (9.2 ± 2.1) %		–
$p\pi^-$	$< 5.0 \times10^{-5}$	90%	2732
pK^-	$< 5.0 \times10^{-5}$	90%	2711
$\Lambda\gamma$	$< 1.3 \times10^{-3}$	90%	2701

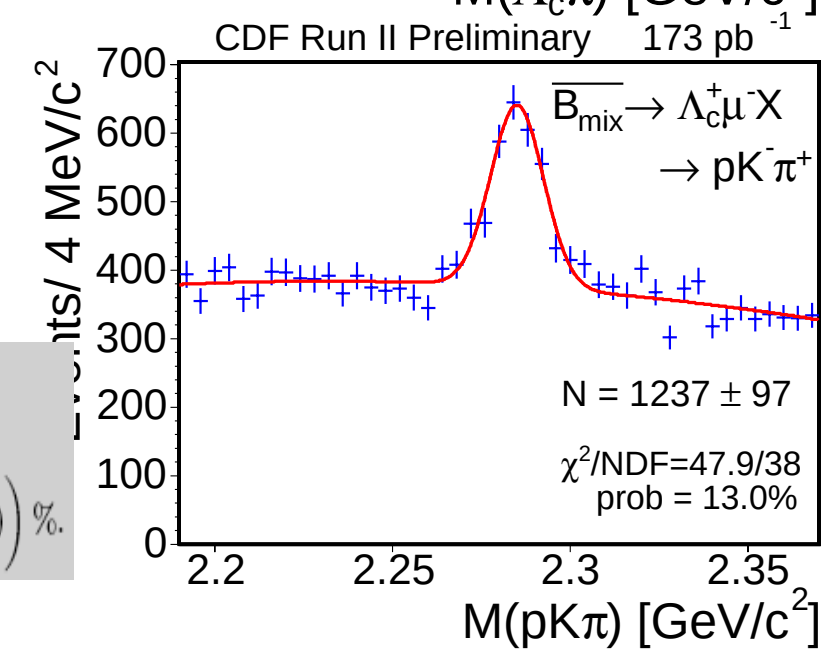
- 170 pb^{-1} two track trigger sample
  - Hadronic $\Lambda_b\to\Lambda_c\pi$ Decay
  - Semileptonic $\Lambda_b\to\Lambda_c l\nu$ Decay

$$\frac{Br(\Lambda_b\to\Lambda_c l\nu)}{Br(\Lambda_b\to\Lambda_c\pi)} = 20.0\pm3.0(stat.)\pm2.5(syst.)$$

$$\mathcal{B}(\Lambda_b\to\Lambda_c^+\pi^-) = \left(0.41\pm0.19\ (stat\oplus syst)\ ^{+0.06}_{-0.08}\ (P_T\ \text{spectrum})\right)\%,$$

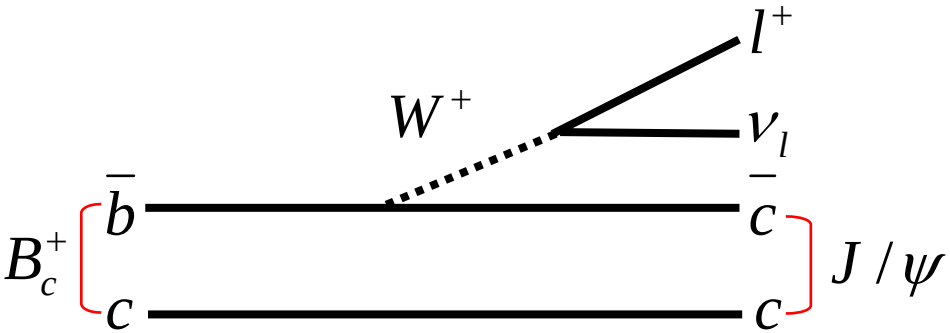
$$\mathcal{B}(\Lambda_b\to\Lambda_c^+\mu^-\overline{\nu}_\mu) = \left(8.1\ \pm1.2\ (stat)\ ^{+1.1}_{-1.6}\ (syst)\pm4.3\ (\mathcal{B}(\Lambda_b\to\Lambda_c^+\pi^-))\right)\%.$$

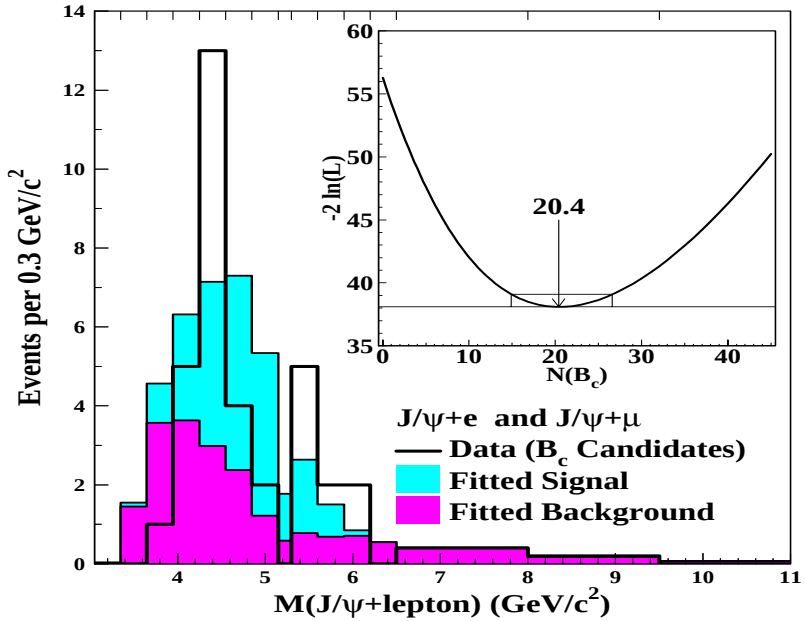




B_c Properties

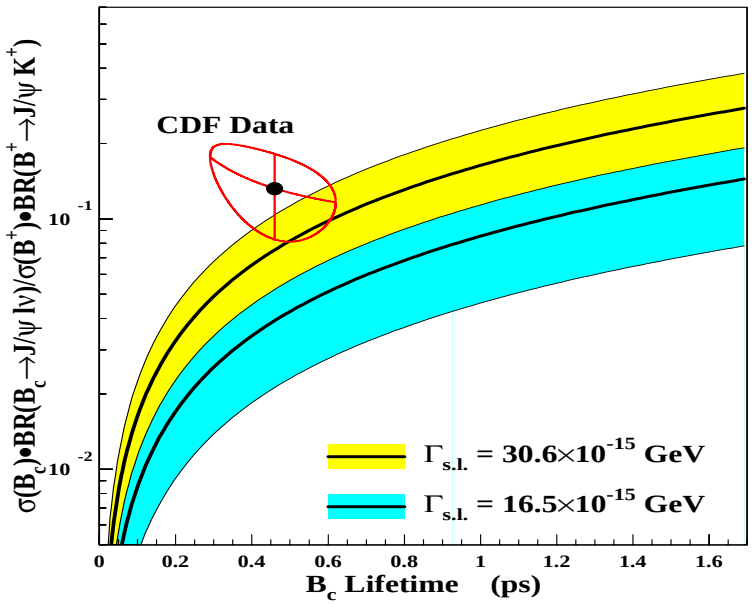
- Semileptonic $B_c \rightarrow J/\psi l \nu$ decay
  - $J/\psi \rightarrow \mu\mu$, l = e or μ
  - 3 muons / 2 muons + 1 electron





- First "obervation": Semileptonic B_c
  - Run I CDF : 100 pb^{-1}
  - Significance: 4.8 σ
- Measurement
  - Mass : (6.4±0.39±0.13) GeV
  - Lifetime: (0.46±0.17±0.03) ps

$$\frac{\sigma_{B_c} \cdot BR(B_c \rightarrow J/\psi l \nu)}{\sigma_{B^\pm} \cdot BR(B^\pm \rightarrow J/\psi K^\pm)} = 0.132 \pm 0.041(stat.) \pm 0.045(syst.)$$



Run II CDF B_c Studies

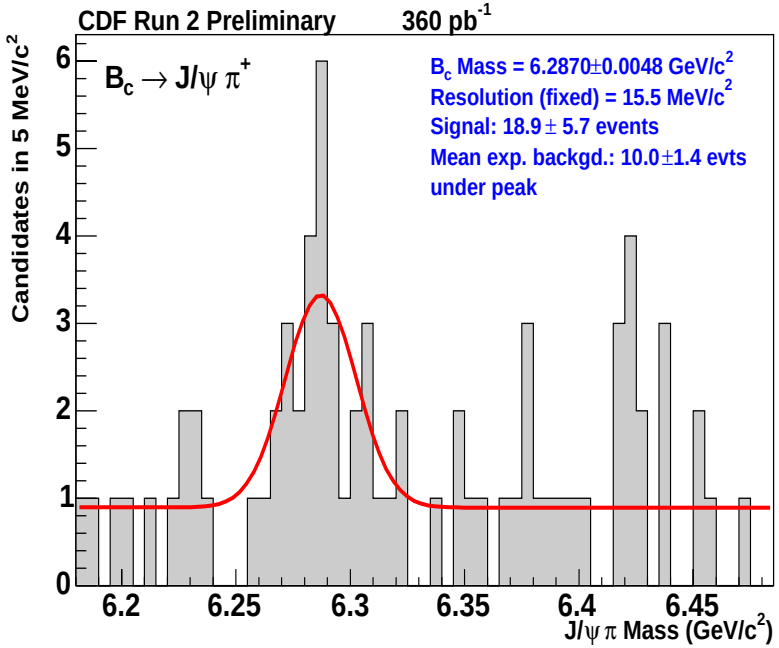
- "Evidence" of Hadronic $B_c \rightarrow J/\psi\pi$
  - ~ 350 pb^{-1}
  - Significance: 3.5 σ
  - $M(B_c) = 6287.0 \pm 4.8 \pm 1.1$ MeV
    - Good agreement with recent theory
    - 6307 ± 17 MeV
    - (N. Brambilla et.al PRD65 034001)
- Semileptonic analysis
  - ~ 350 pb^{-1}
  - Muon channel

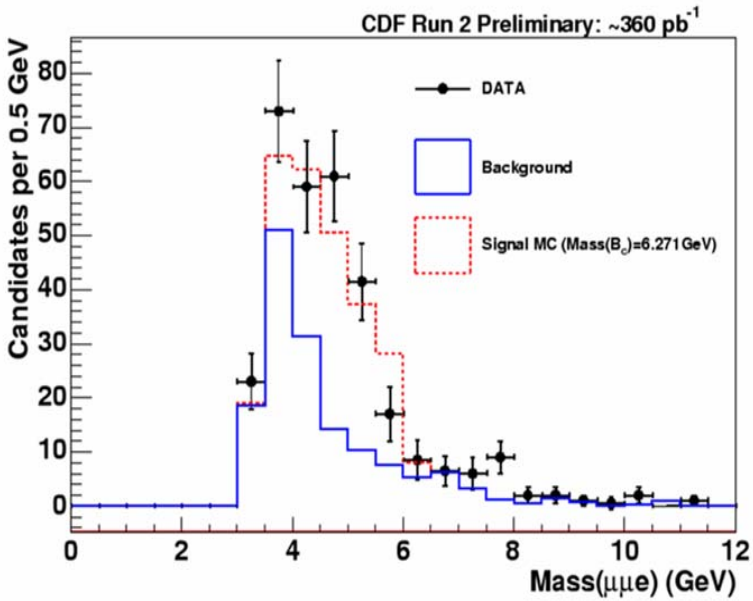
$$\frac{\sigma_{B_c} \cdot BR(B_c \rightarrow J/\psi\mu\nu)}{\sigma_{B^\pm} \cdot BR(B^\pm \rightarrow J/\psi K^\pm)} = 0.249 \pm 0.045(stat.) \pm 0.107(syst.)$$

  - Electron channel

$$\frac{\sigma_{B_c} \cdot BR(B_c \rightarrow J/\psi e\nu)}{\sigma_{B^\pm} \cdot BR(B^\pm \rightarrow J/\psi K^\pm)} = 0.282 \pm 0.038(stat.) \pm 0.074(syst.)$$

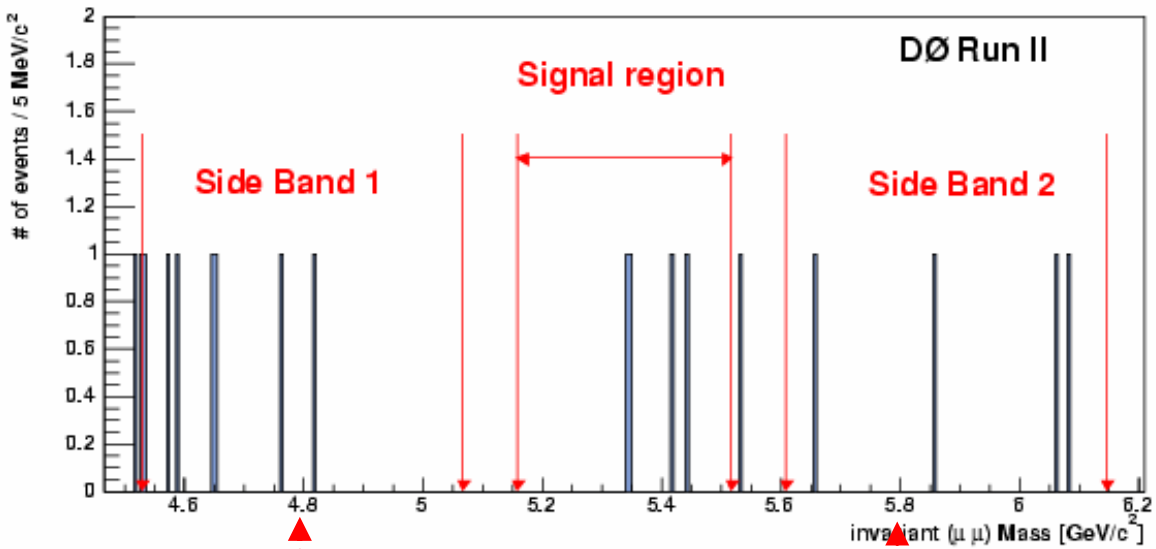
  - Main systematics
    - Background (fake lepton, bb)
    - $p_T(B_c)$ spectrum
  - High statistic signal good for precise lifetime measurement

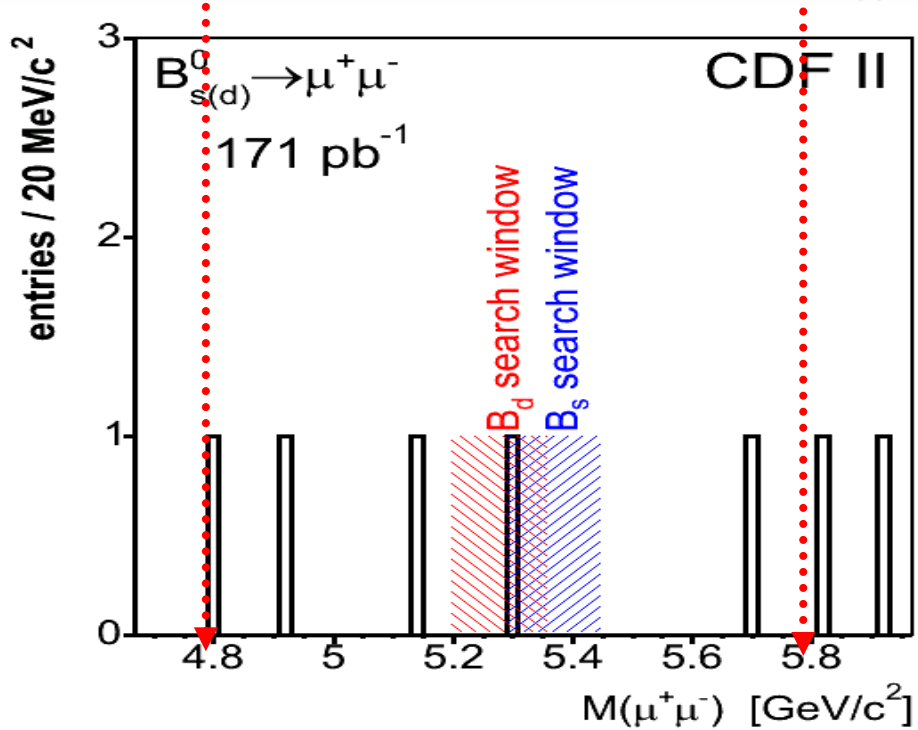




Rare Decay Search: $B_s \rightarrow \mu\mu$

- SM prediction: ~ 4×10^{-9}
  - Enhanced by NP
    - mSUGRA at high tanβ
    - SO(10) unification
    - RPV SUSY
    - …
- D0 Run II: 300 pb^{-1}
  - < 3.7×10^{-7} @95%CL
  - 4 observed events
  - 4.3 expected background
  - B mass resolution ~90 MeV
- CDF Run II: 170 pb^{-1}
  - < 7.5×10^{-7} @95%CL
  - 1 observed events
  - 1.1 expected background
  - B mass resolution ~25 MeV



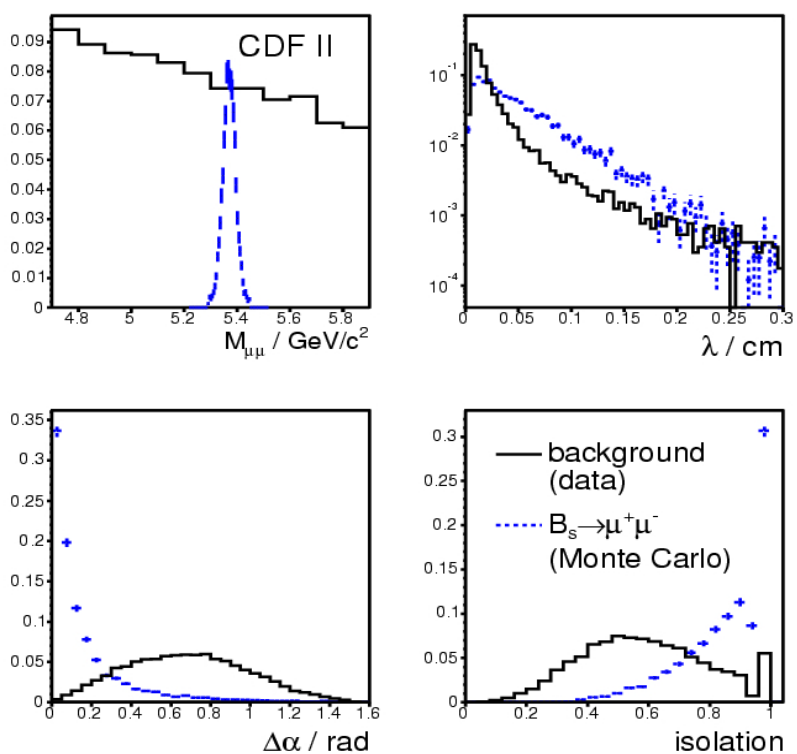


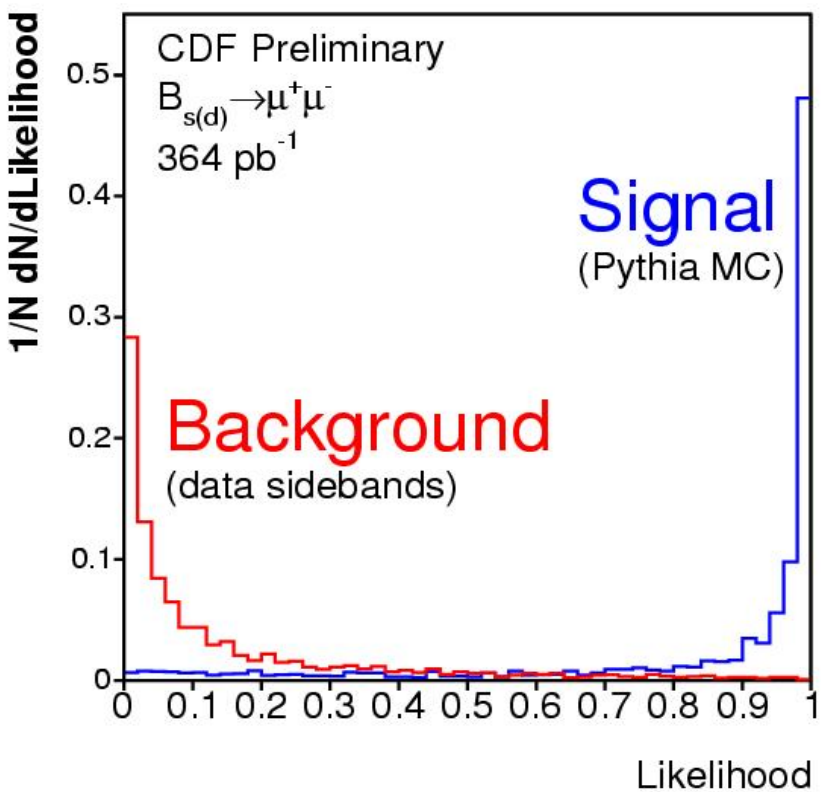
Update CDF $B_s \rightarrow \mu\mu$ Search

- ~360 pb^{-1} dimuon trigger data
  - x2 luminosity
  - Increase muon acceptance
    - CMU: $|\eta| < 0.6$: previous analysis
    - CMX: $0.6 < |\eta| < 1.0$
  - multivariate Likelihood

- Selection Optimization
  - Minimize the expected limit
  - LH and $p_T(B)$

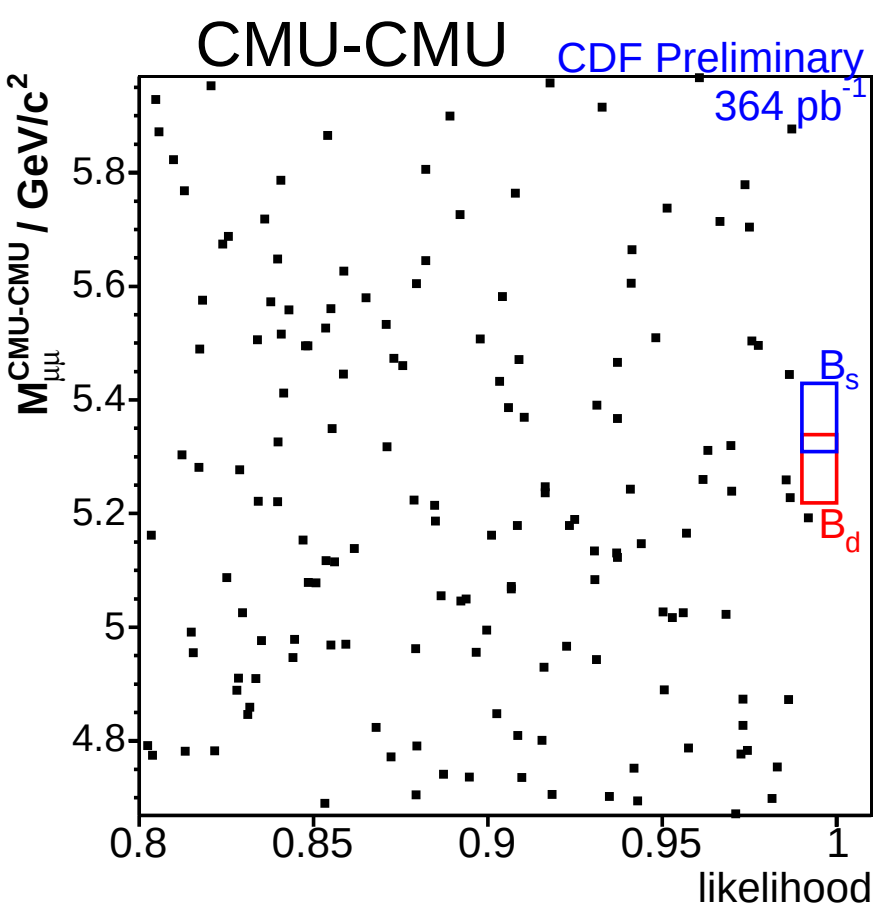
$$LH = \frac{\prod_i P_s(x_i)}{\prod_i P_s(x_i) + \prod_i P_b(x_i)}$$

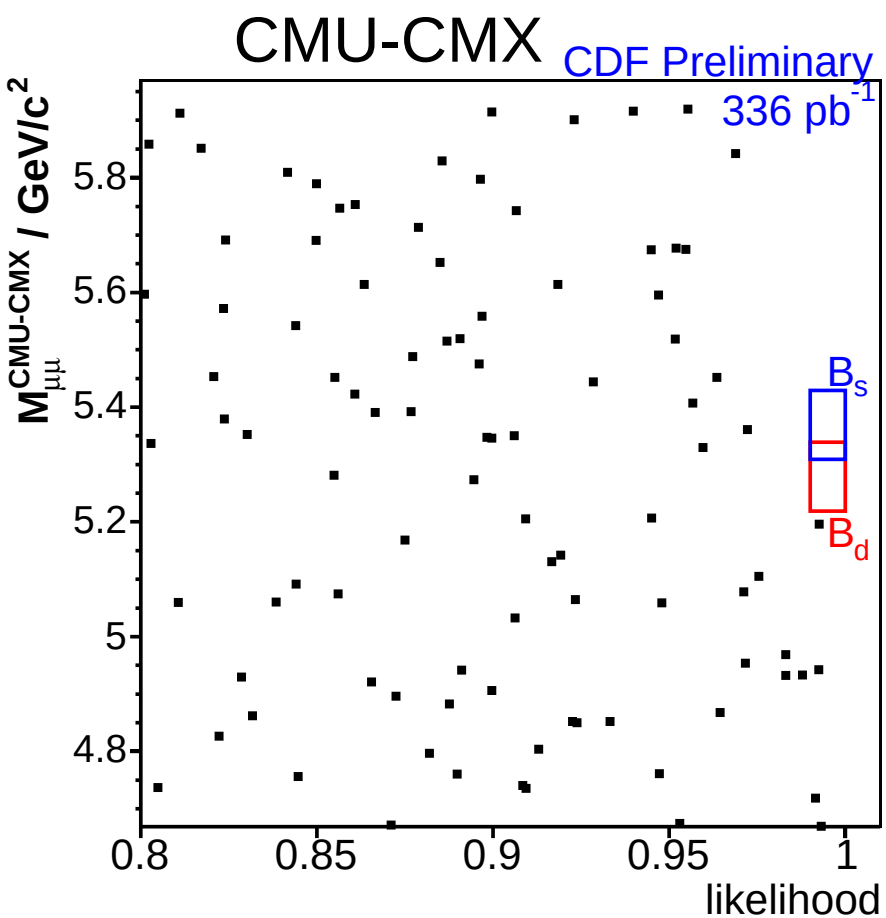




$B_s \rightarrow \mu\mu$ Result

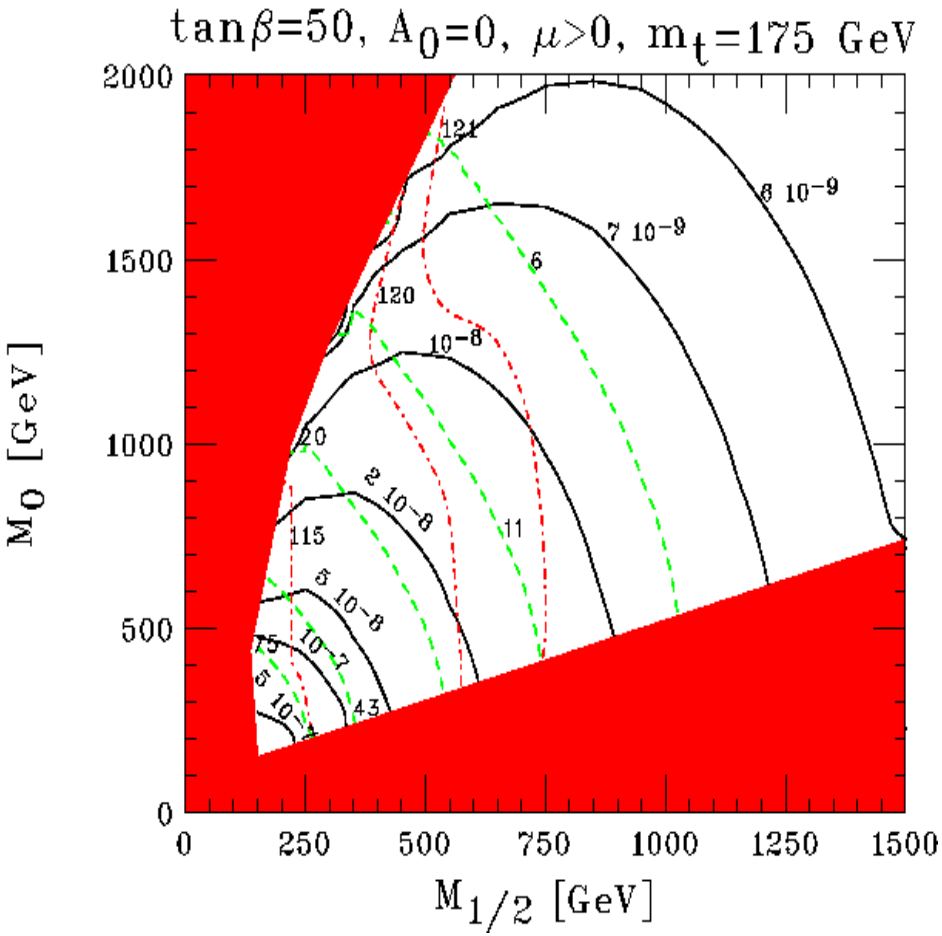
- No events observed in signal box
  - 1.5 expected background
  - $<2.0 \times 10^{-7}$ @95%CL
- CDF+D0 combined limit
  - $< 1.6 \times 10^{-7}$ @95% CL





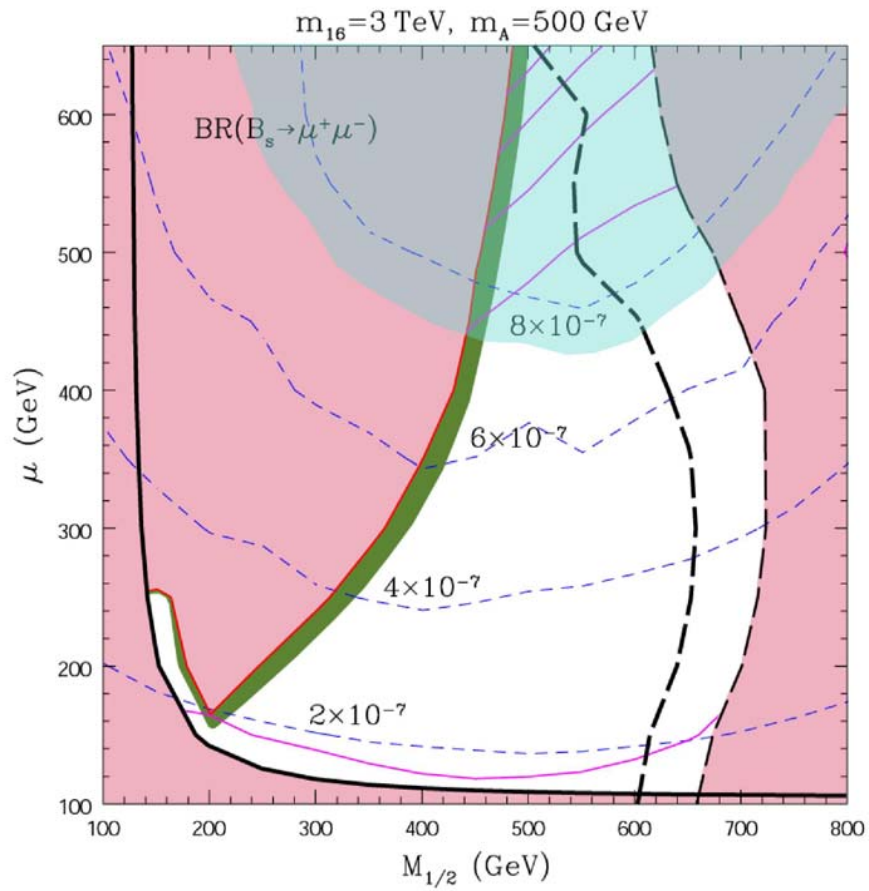
Constrain to new physics models

- mSUGRA



Dedes, Dreiner, Nierste, PRL 87(2001) 251804

- SO(10) Unification



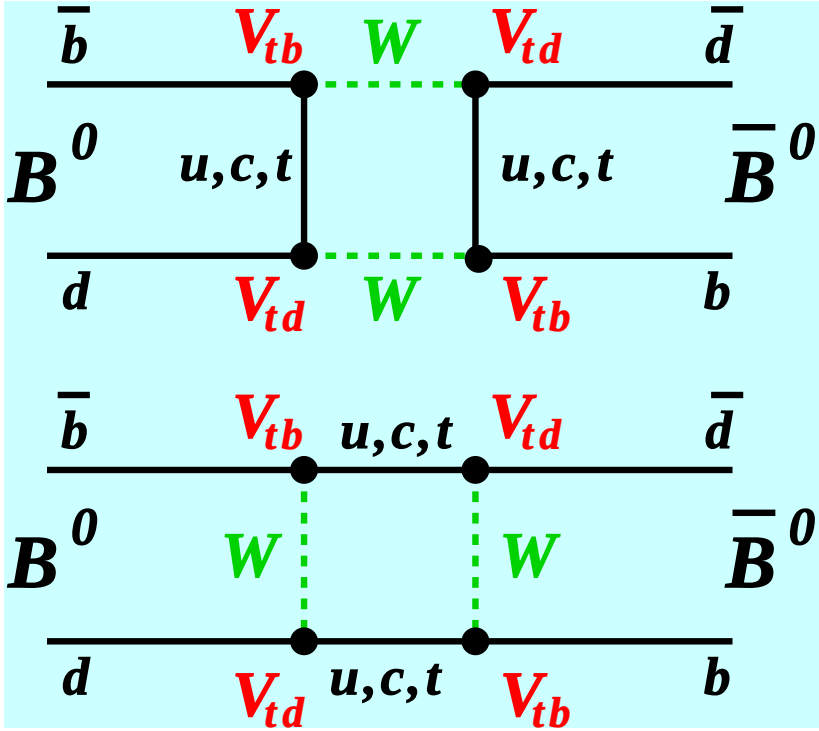
R. Dermisek *et al.*, hep-ph/0304101

B Mixing in Standard Model

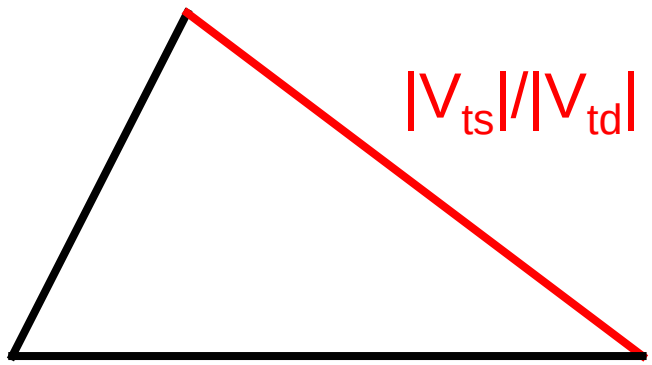
- Within the SM
  - B mixing: Box diagram
  - $\Delta m_d \sim |V_{td}|^2$, $\Delta m_s \sim |V_{ts}|^2$
- Ratio between Δm_s and Δm_d

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{Bs}}{m_{Bd}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

  - Many theoretical uncertainties are cancelled in the ratio
    - $\xi = 1.21 \pm 0.04 \pm 0.05$
    - Determine $|V_{ts}|/|V_{td}|$ 5% precision

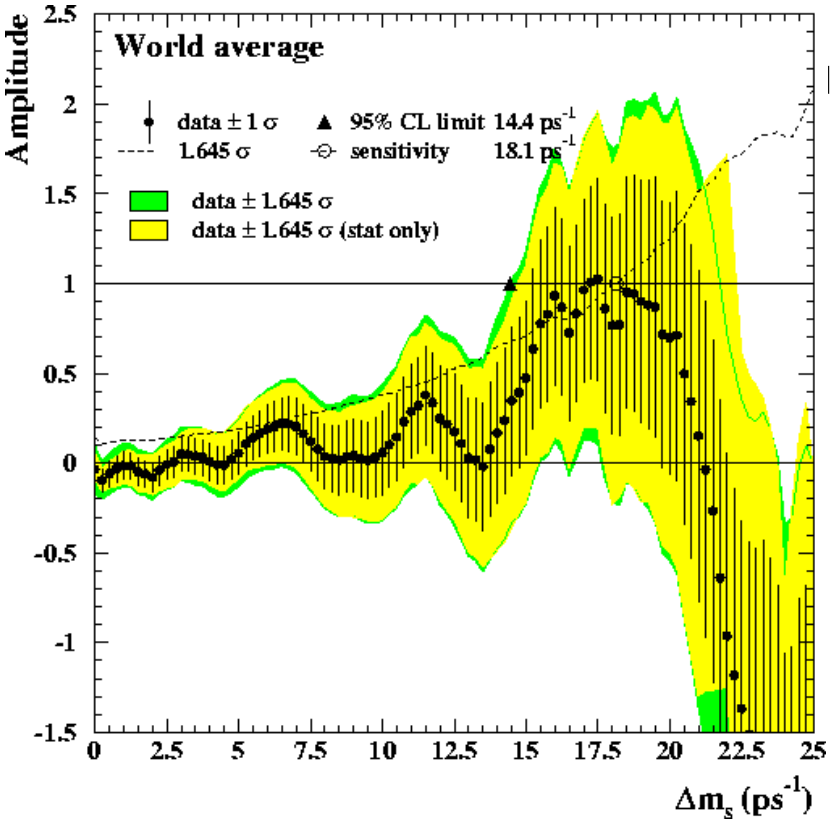


- $|V_{ts}|/|V_{td}|$ is propotional to one side of the unitarity triangle

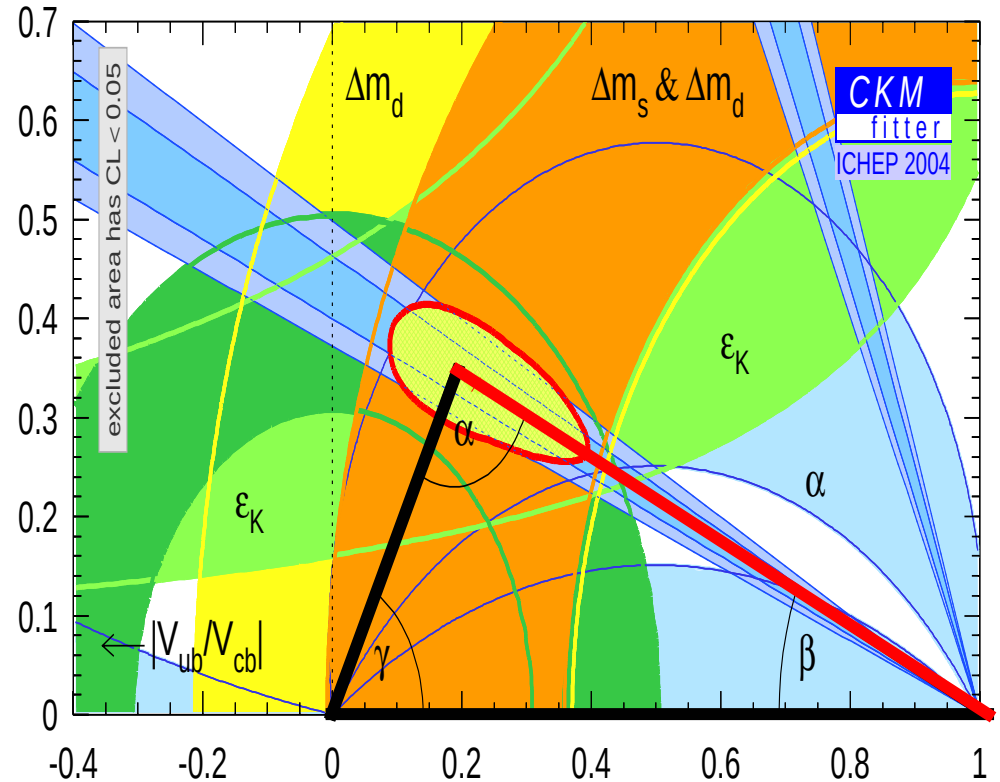


Current Experimental Result

- 95% CL limit on Δm_s
  - LEP, SLD, CDF Run I
  - Sensitivity: 18.3 ps^{-1}
  - Limit: 14.5 ps^{-1}



- Constrain to Unitarity triangle



Δm_d only

Δm_s and Δm_d

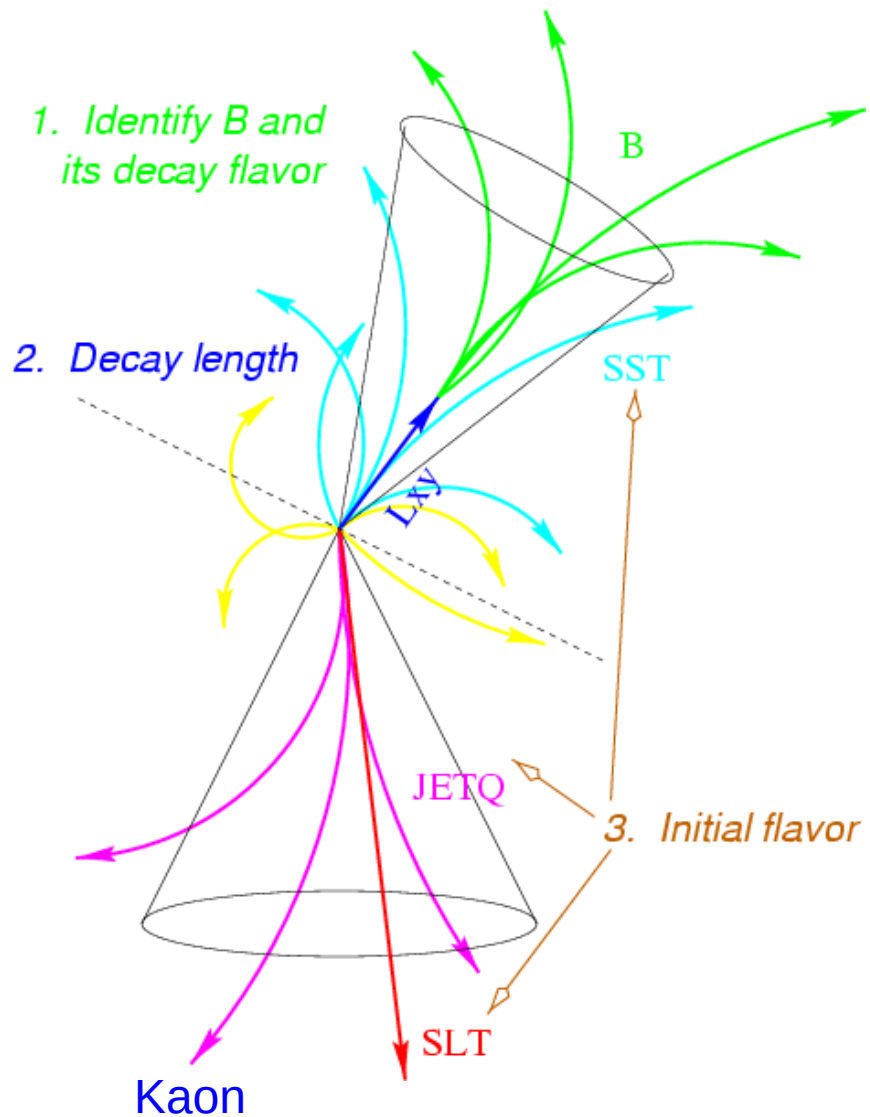
Analysis Strategy

- Mixing

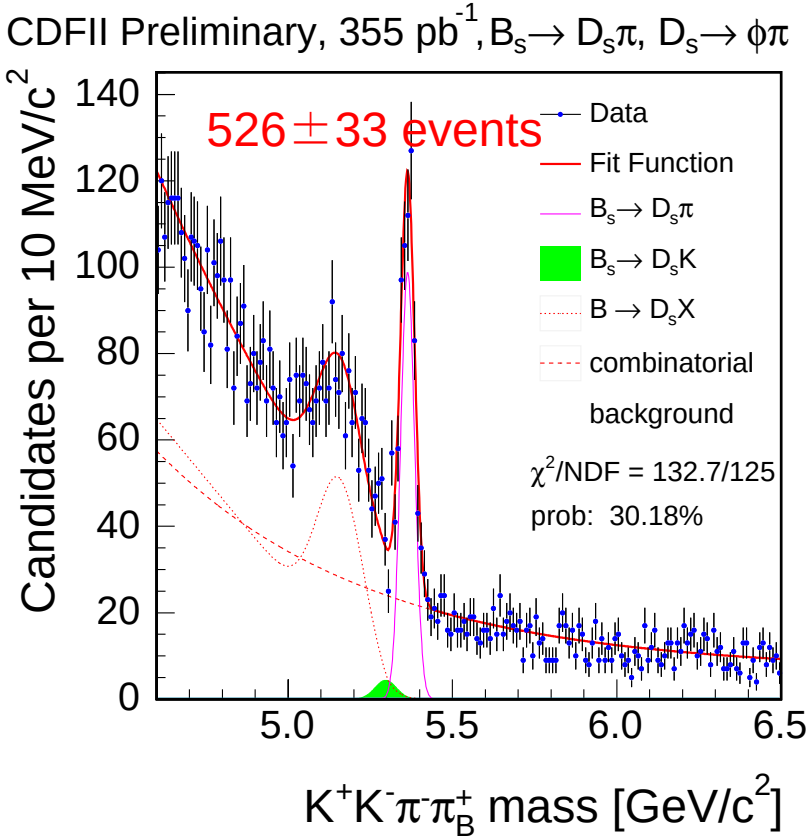
$$\frac{dN}{dt}\left(B^0 \to B^0\right) = \frac{N_0}{2\tau} e^{-t/\tau}\left(1+\cos\Delta m t\right)$$

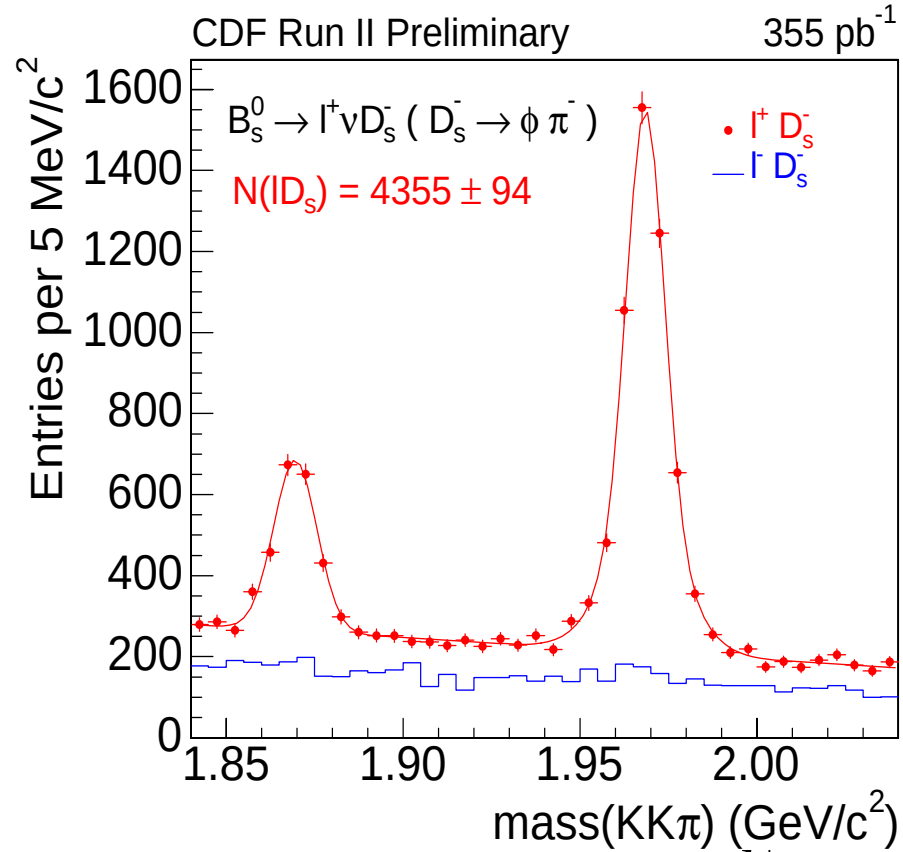
$$\frac{dN}{dt}\left(B^0 \to \overline{B^0}\right) = \frac{N_0}{2\tau} e^{-t/\tau}\left(1-\cos\Delta m t\right)$$

- (1) Reconstruct Signal
  - Flavor eigenstate
- (2) Determine B decay time
  - Decay time reconstruction
  - Lifetime measurement
- (3) Identify the initial flavor of B meson
  - Flavor tagging
  - B^0 mixing
- (4) B_s Mixing
  - Amplitude scan

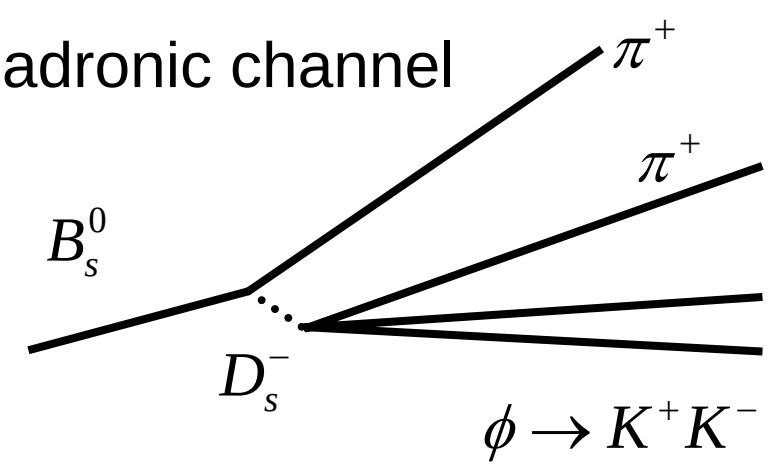


Signal Reconstruction

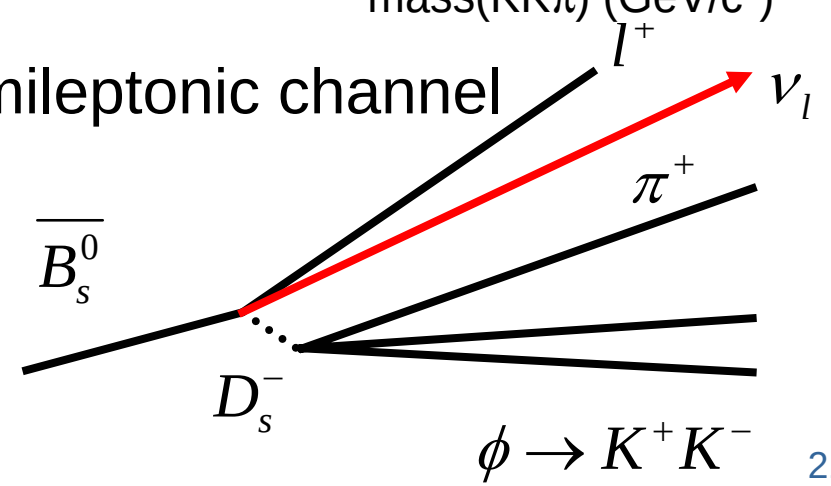




Hadronic channel



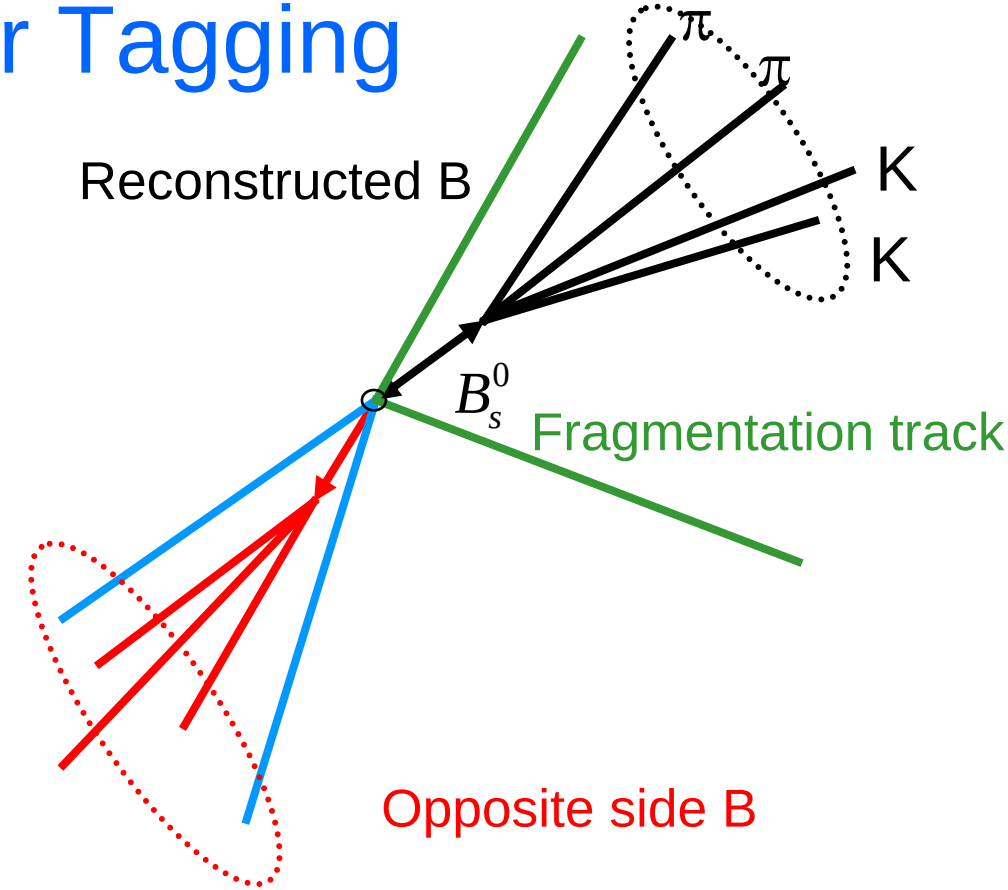
Semileptonic channel



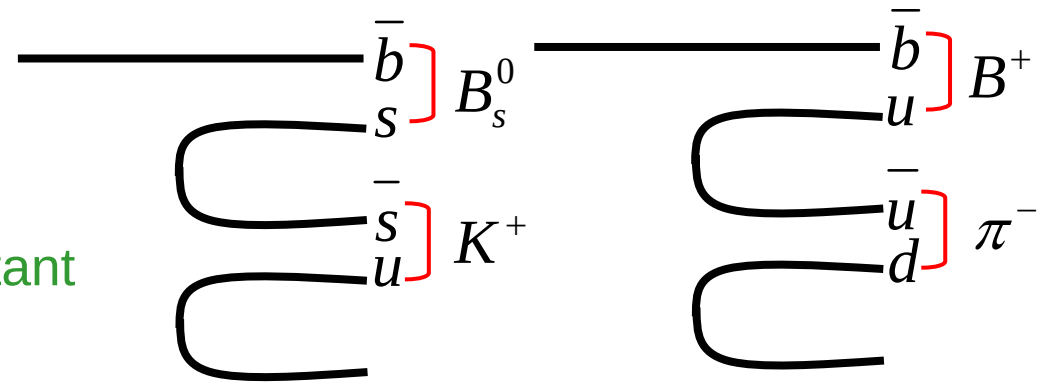
Flavor Tagging

- Today's result:
  - Opposite side tag only

- Opposite side tagging
  - Use the other B in the event
  - Semileptonic decay ($b \rightarrow l^-$)
    - (1) Muon, (2) Electron
  - Use jet charge ($Q_b = -1/3$)
    - (3) Jet has 2ndary vertex
    - (4) Jet contains displaced track
    - (5) Highest momentum Jet



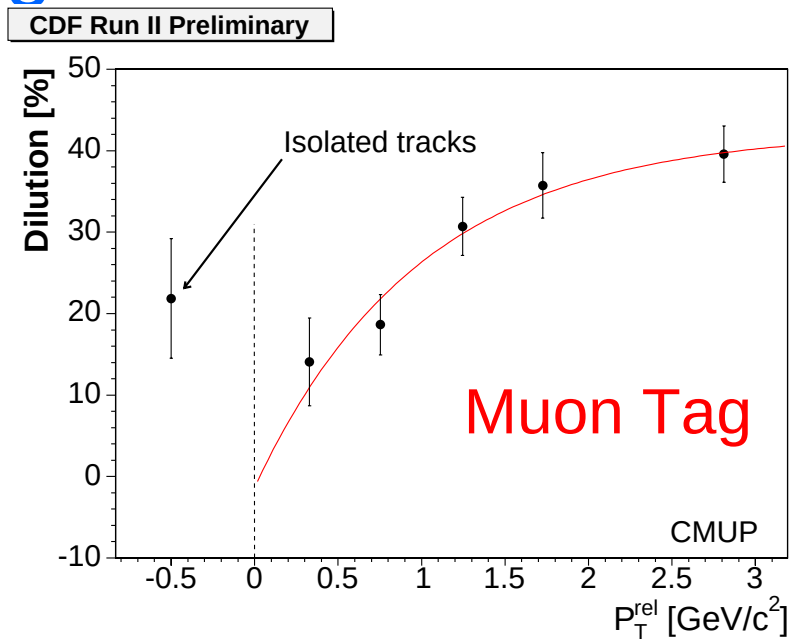
- Same side tagging
  - Use fragmentation track
  - B^0, B^+, and B_s are different
  - Kaon around B_s: PID is important

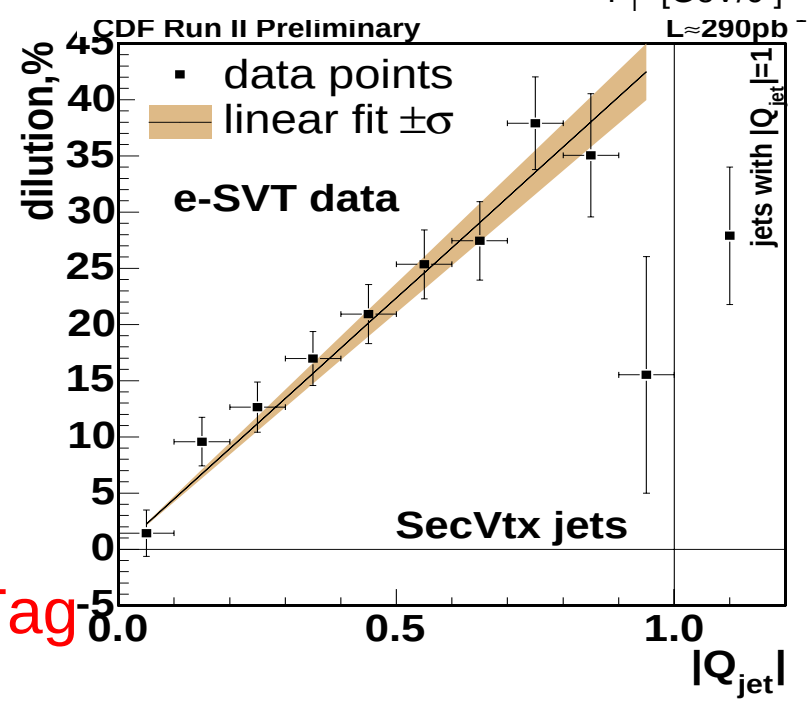


Flavor Tagging Calibration

- Opposite side taggers are calibrated using the inclusive lepton samples

Tag type	εD^2 (%)
Muon	(0.70±0.04)%
Electron	(0.37±0.03)%
2ndary vtx	(0.36±0.02)%
Displaced track	(0.36±0.03)%
Highest p jet	(0.15±0.01)%
Total	~1.6%

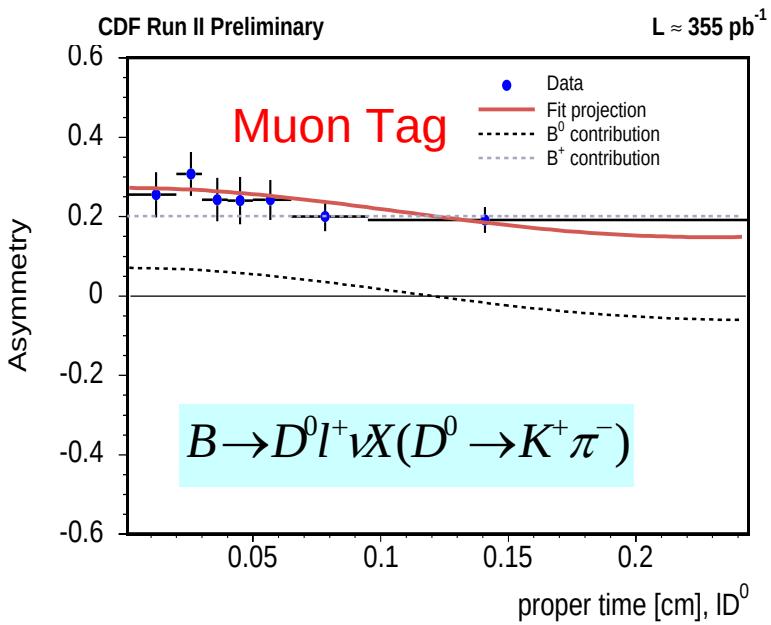


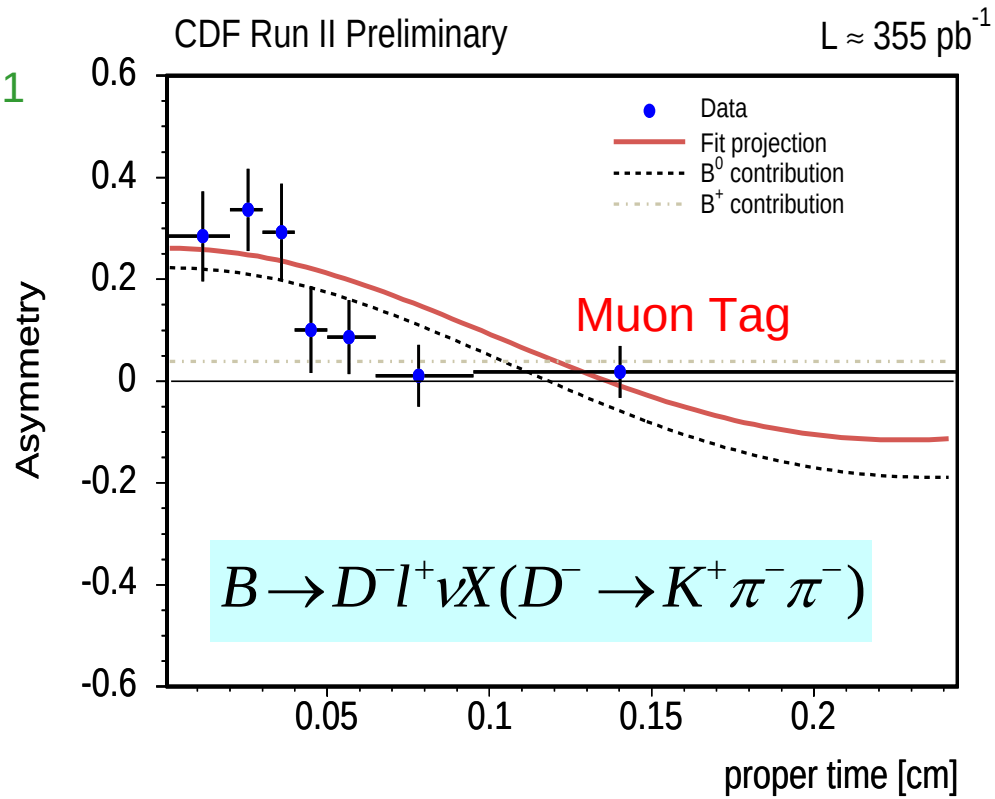


2ndary vertex Tag

B^0_d Mixing (Semileptonic)

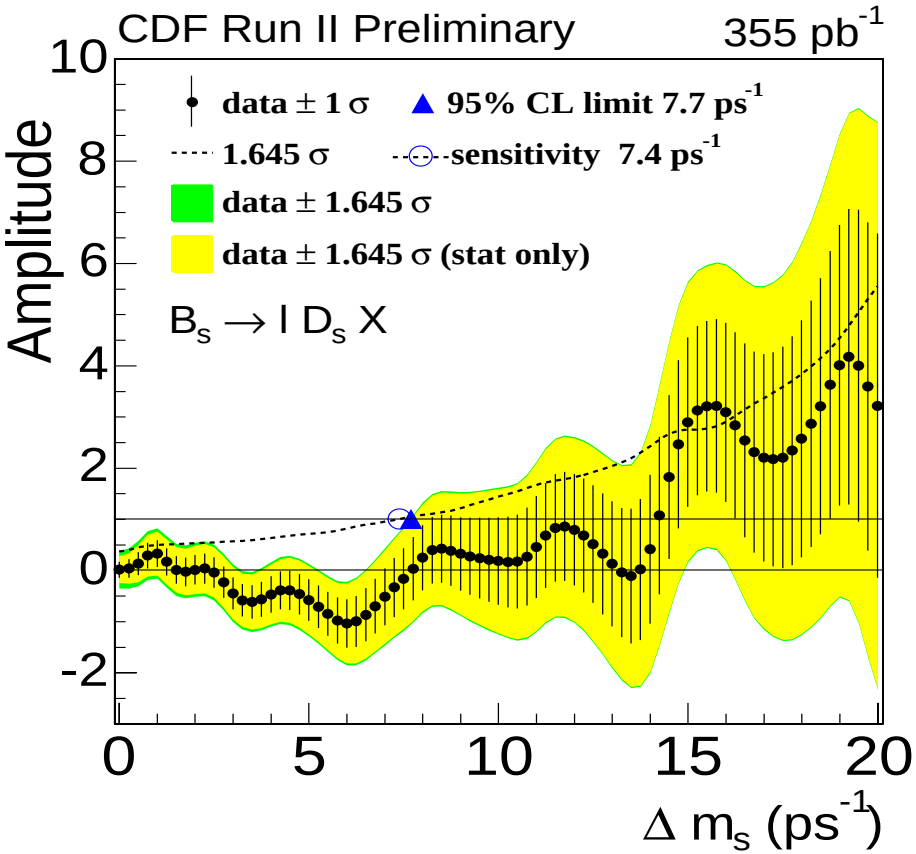
- Validation of the flavor tag calibration using B^0 and B^+ sample
  - $B^0 \rightarrow D^- l \nu$, $B^+ \rightarrow D^0 l \nu$
- Measured Δm_d
  - $(0.498 \pm 0.028 \pm 0.015)$ ps^{-1}
  - WA: (0.510 ± 0.005) ps^{-1}

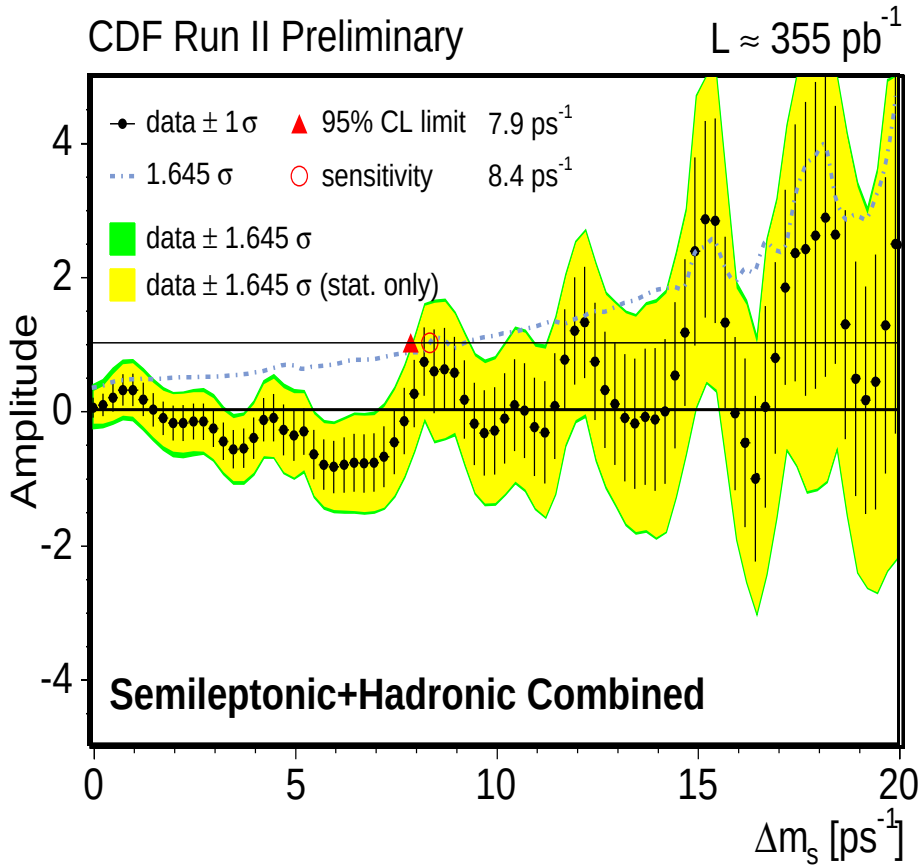




CDF B_s Mixing Result

- Semileptonic Channel
  - Sensitivity = 7.4 ps^{-1}
  - Limit: 7.7 ps^{-1}
- Semileptonic + Hadronic
  - Sensitivity: 7.4 → 8.4 ps^{-1}
  - Limit: 7.7 → 7.9 ps^{-1}

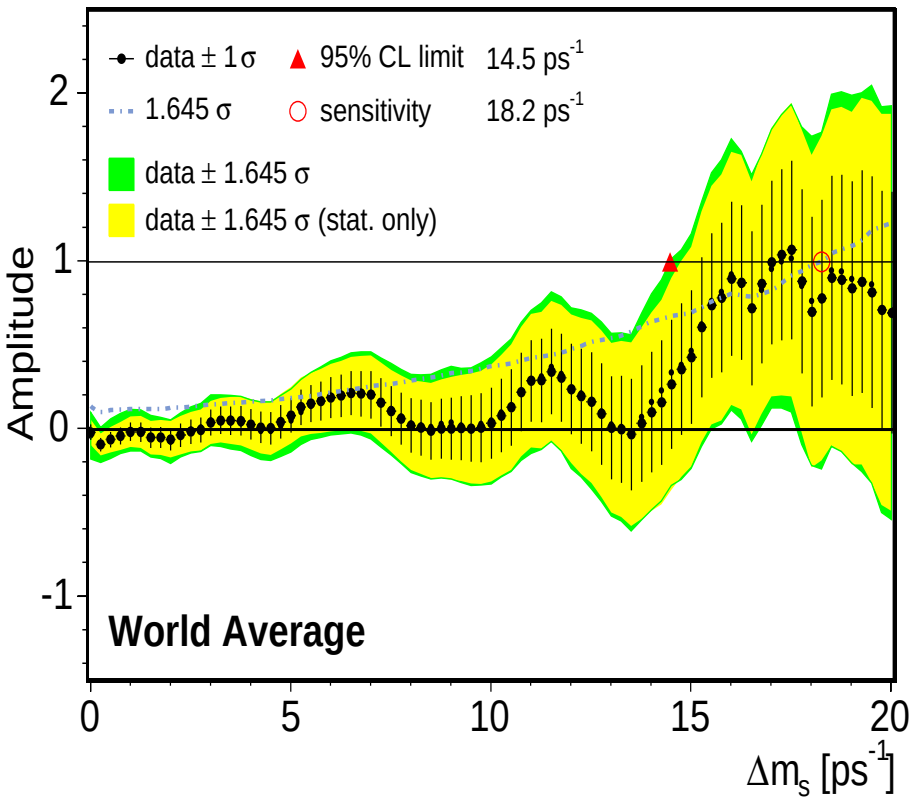


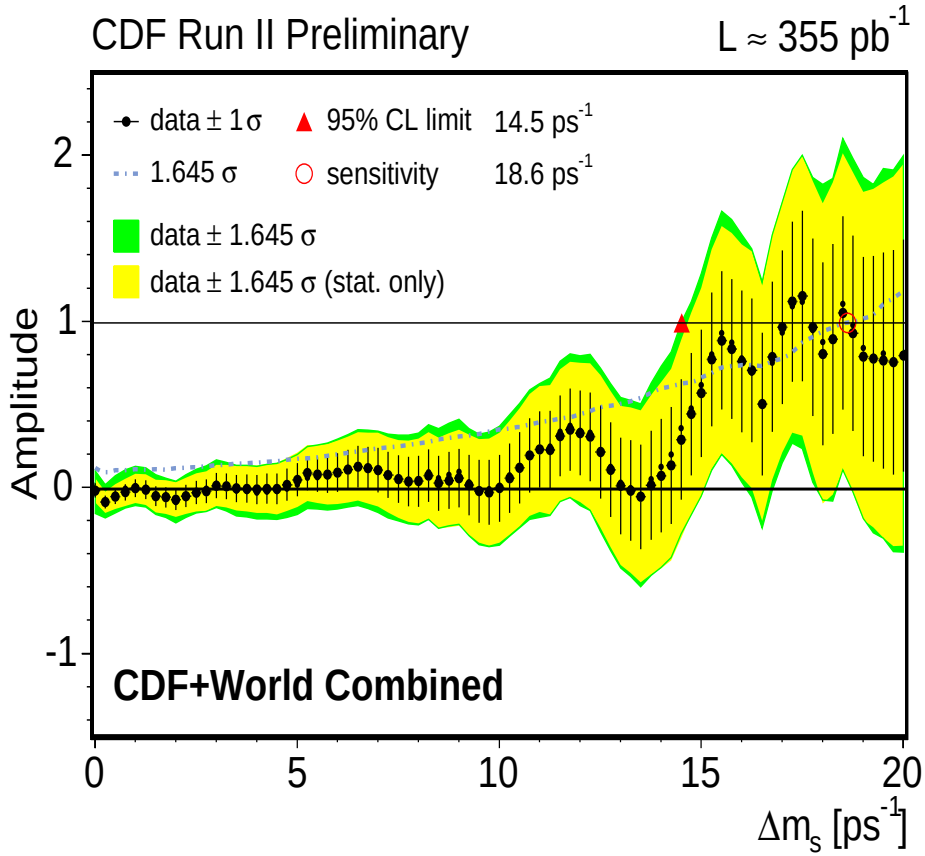


CDF+World Combined Result

- World Average
  - LEP, SLD, CDF run I
  - Sensitivity: 18.2 ps^{-1}
  - Limit: 14.5 ps^{-1}

- World Average + CDF Run II
  - Sensitivity: 18.6 ps^{-1}
  - Limit 14.5 ps^{-1}

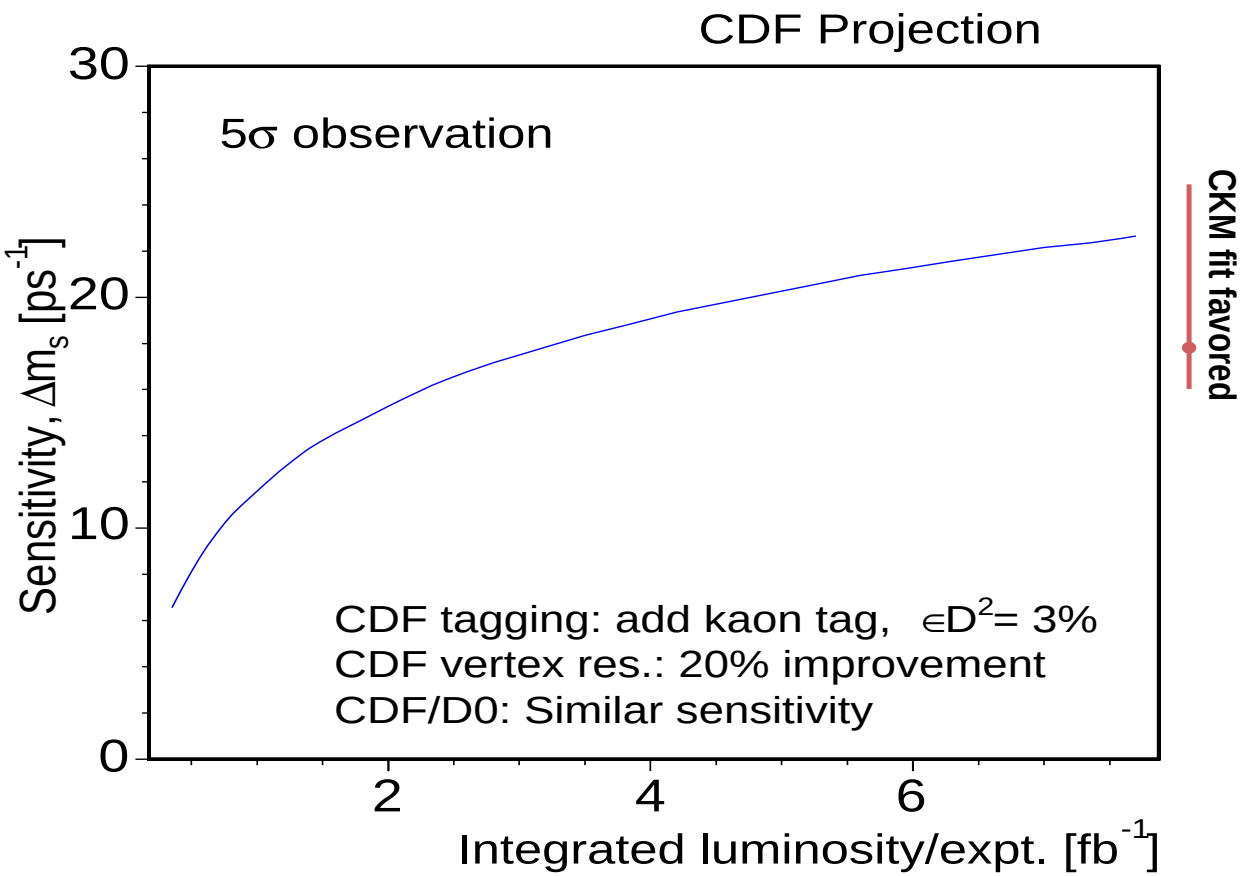




Future Prospects

- Sensitivity for 5σ observation for Δm_s
  - Keep the same signal yield
  - Flavor tagging (SSKT) 1.6%→ 3%
  - 20% improvement in vertex resolution

- Reasonable chance to observe B_s mixing in 5 fb^{-1} of data
  - Trigger strategy at high luminosity
  - Better understanding of detector



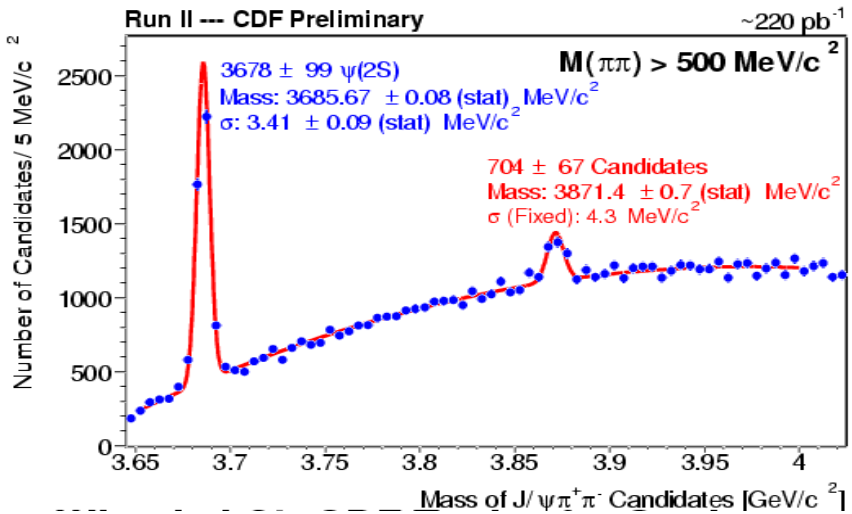
Summary

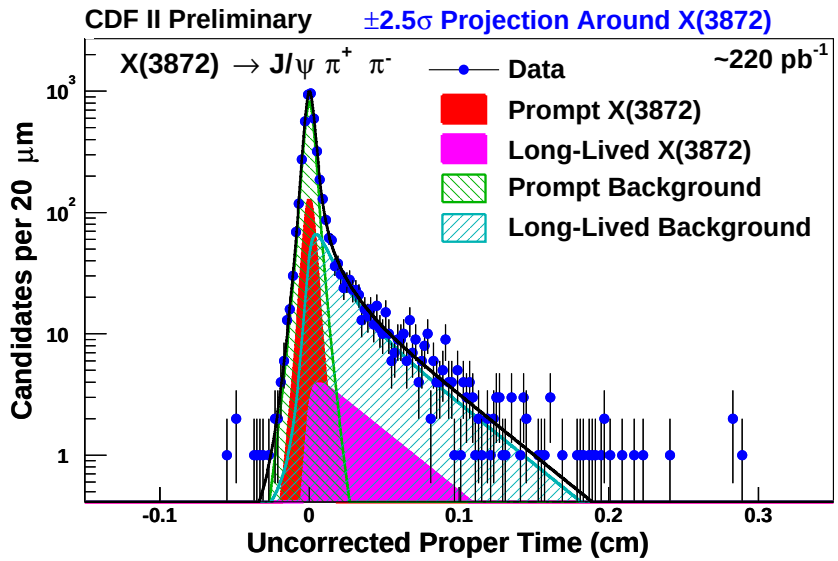
- CDF has analyzed 2002—2004 data
  - 700 pb^{-1} delivered, 350 pb^{-1} good run for physics
  - Additional +300 pb^{-1} in 2005 data (Better efficiency)
- Three specific trigger for B physics
  - Dimuon for $B \rightarrow J/\psi$ decays
  - Lepton + track for B semileptonic decays
  - Two track for hadronic B decays
- Quick review of new results for LP2005
  - J/ψ spin alignment, B_c semileptonic decays
  - $B_s \rightarrow \mu\mu$, B_s mixing
- Lots of Interesting physics in the near future
  - B_s mixing update, $\Delta\Gamma_s$ update
  - $B \rightarrow hh$
  - $B_s/B_c/\Lambda_b$ Lifetime measurement
- Long term plan
  - Two "Flagship" analyses: Δm_s and $B_s \rightarrow \mu\mu$
  - Effort to evaluate/maximize the sensitivity
  - More discussion on Saturday session "Tevatron Future"

Backup Slides

Property of X(3872) State

- Belle: new J/ψππ state at LP2003
  - 3872 MeV, narrow width
  - Seen only in B decays
- Confirm by CDF and D0
- CDF: 220 pb^{-1}
  - M = 3871.4±0.7±0.4 MeV
    - Belle: 3872±0.6±0.5 MeV
  - Separate the direct production and B decays
    - B fraction: (16.1±4.9 ±2.0)%
    - Dominated by direct production





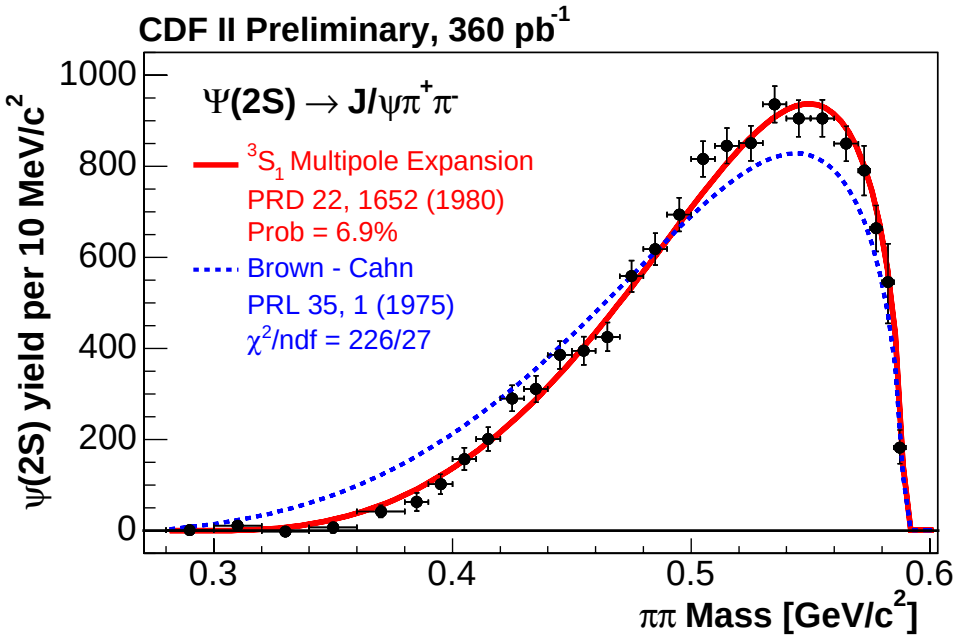
M(ππ) Distribution

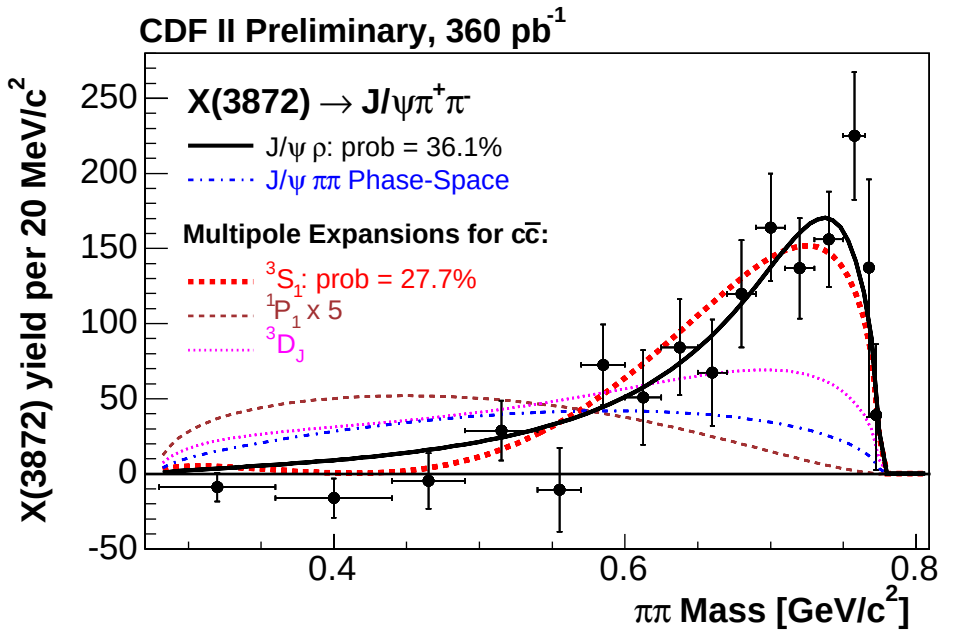
- Compare M(ππ) distribution between the data and predictions

- ψ(2S): control sample
  - consistent with $^3S_1$ Charmonium

- X(3872):
  - Favor J/ψρ state (38%)
  - Consistent with $^3S_1$(28%)
  - Inconsistent with other models

- Recent progress at Belle
  - Evidence of X(3872)→J/ψγ
  - Angular analysis
  - Favor $J^{PC} = 1^{++}$
  - Favor D^0D^{*0} bound state

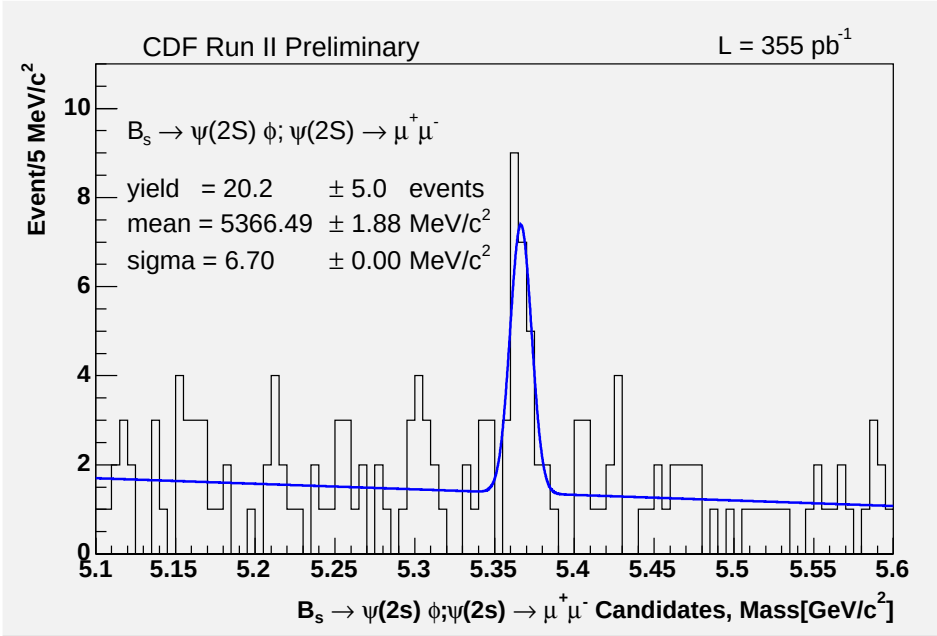


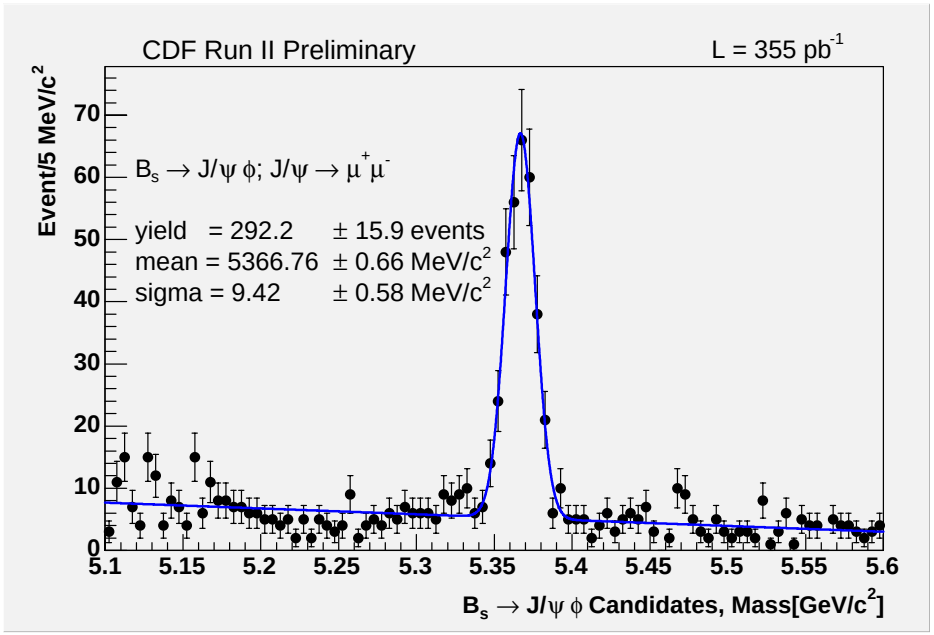


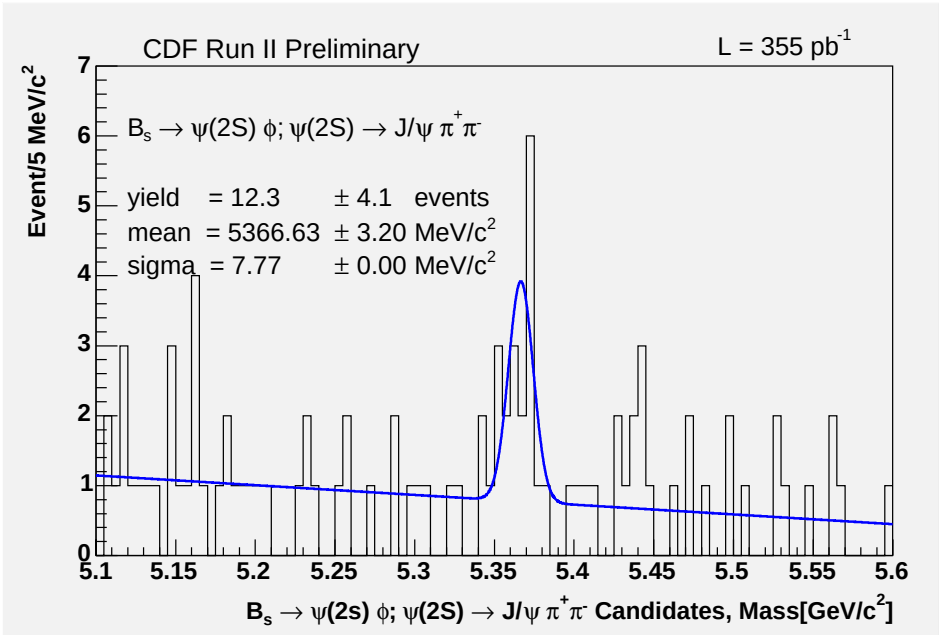
Observation of $B_s \to \psi(2S)\phi$

- Two decay modes
  - $\psi(2S) \to \mu\mu$
  - $\psi(2S) \to J/\psi\pi\pi$ ($J/\psi \to \mu\mu$)
- 350 pb^{-1} Dimuon trigger data
  - 6.5 sigma significance
- Ratio of branching fractions

$$\frac{Br(B_s \to \psi(2S)\phi)}{Br(B_s \to J/\psi\phi)} = 0.52 \pm 0.13(stat.) \pm 0.07(syst.)$$

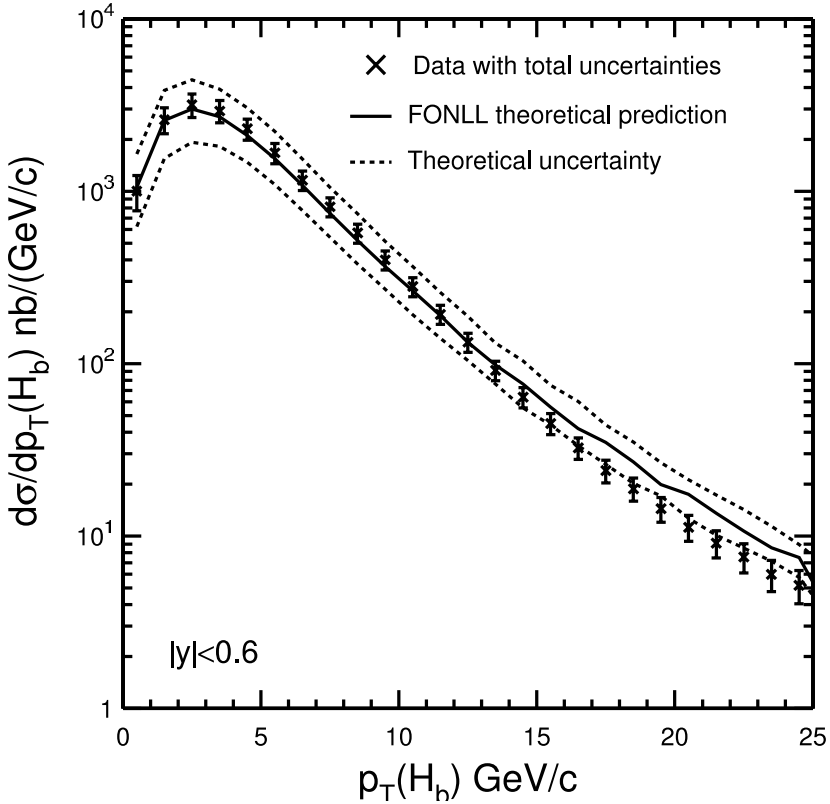


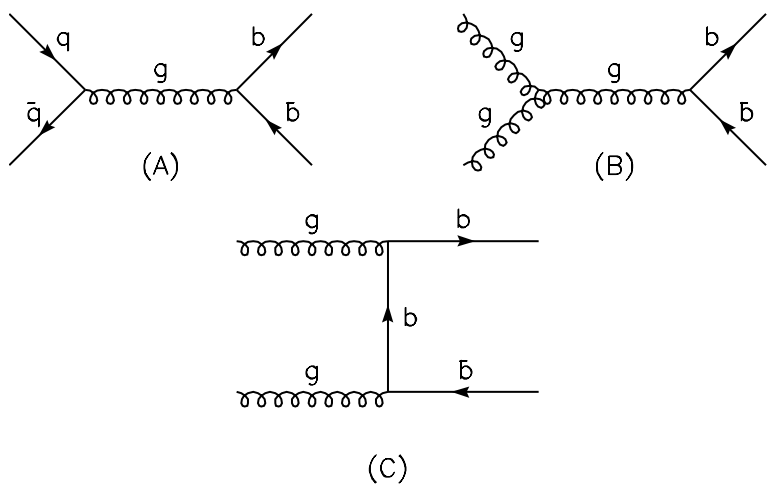


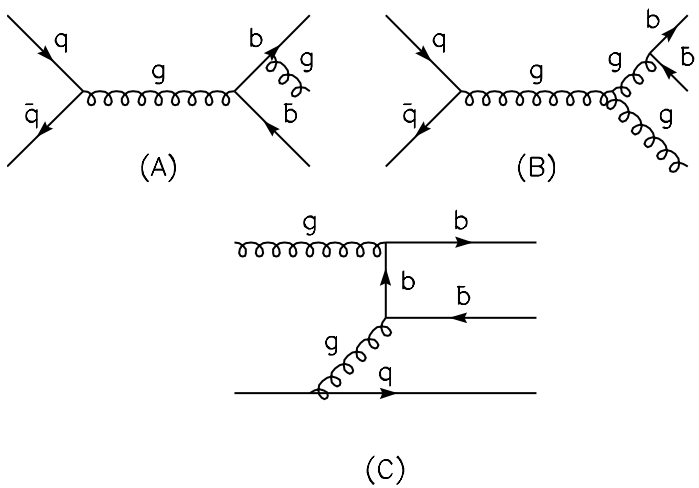


b-quark Production at Hadron Collider

- Leading order
  - $b\bar{b}$ pair production
  - back to back (in ϕ, not in η)
- Higher order
  - gluon splitting
  - flavor excitation
- Run II CDF cross section
  - total cross section ~ 30 μb
  - good agreement with theory

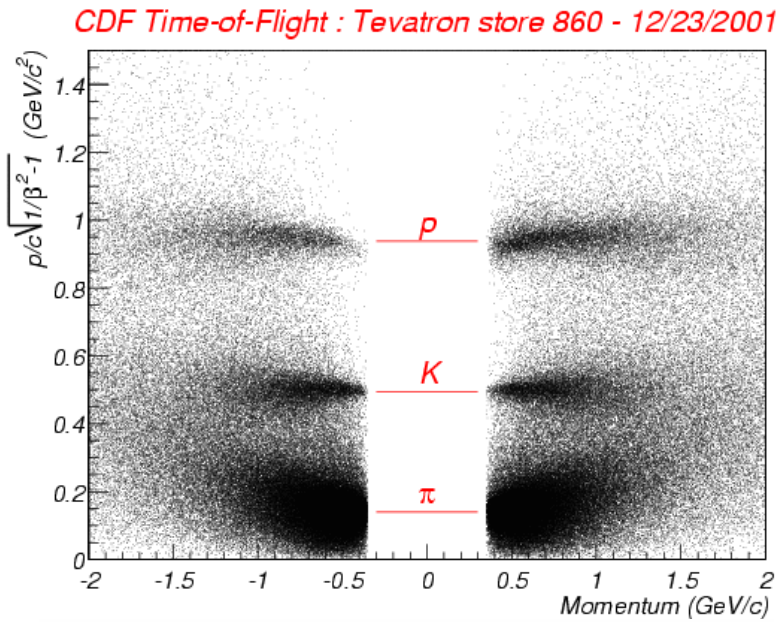


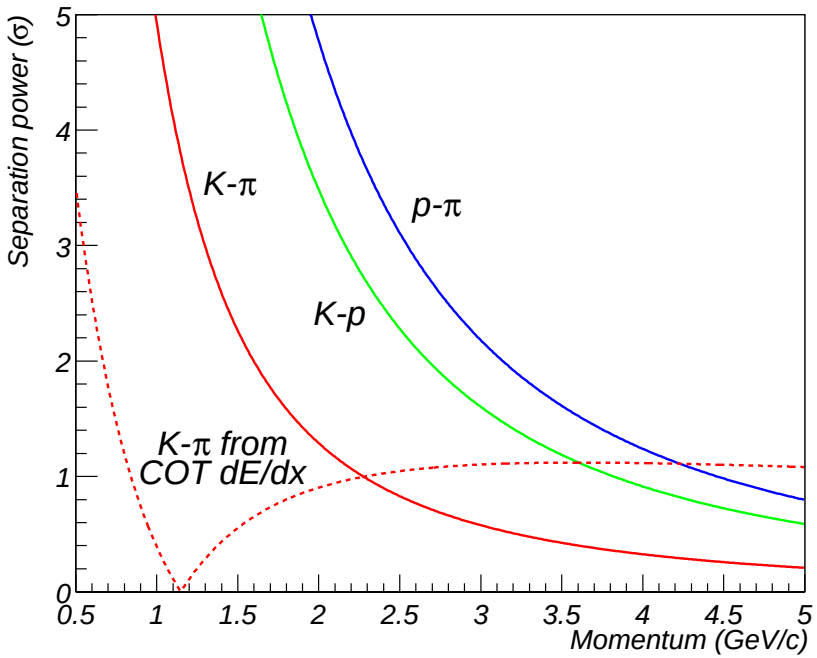


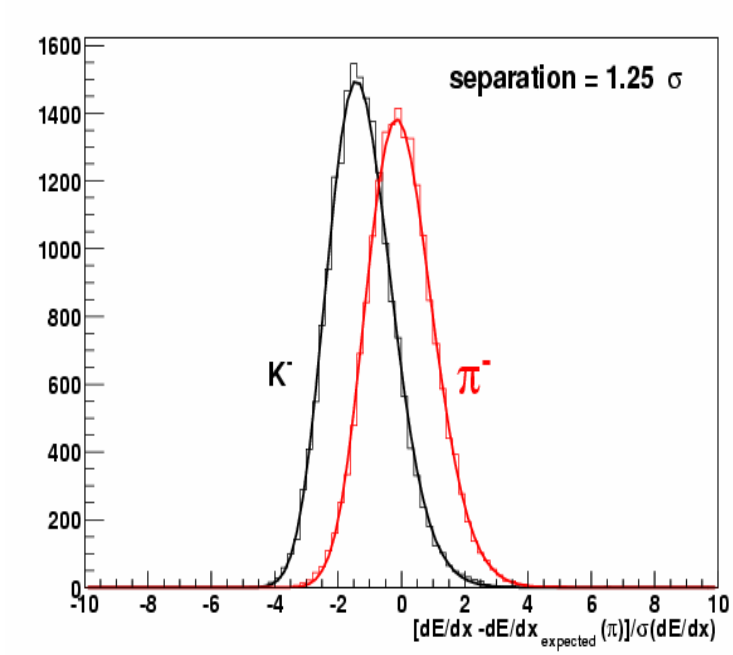


Particle ID

- K/π/p separation is important to improve S/B for B signal and B flavor tagging
- Time of Flight
  - σt ~100 ps, L ~ 1.5 m
  - 2σ K/π separation for p~1.5 GeV
- COT dE/dx
  - 1.3σ K/π separation for p > 2GeV

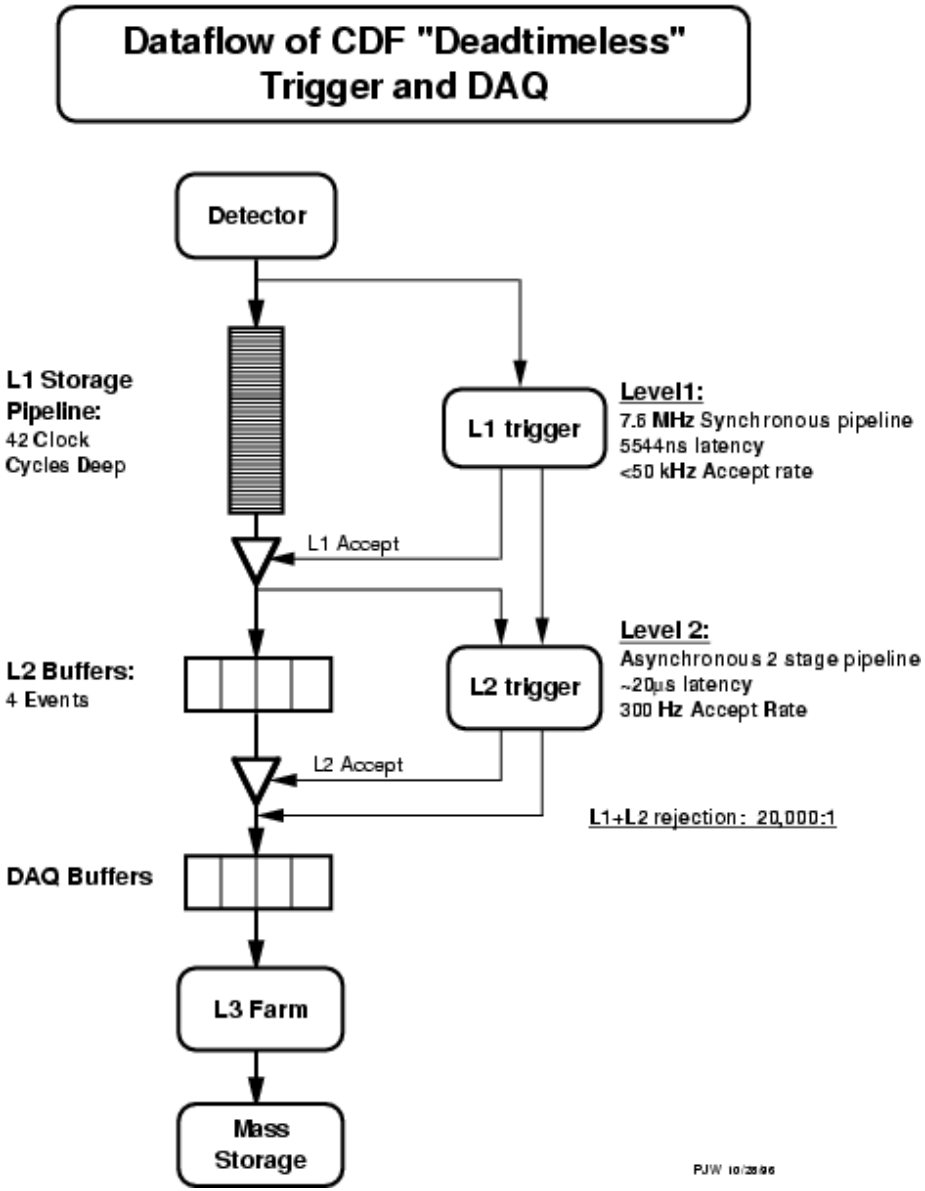






CDF Trigger System Overview

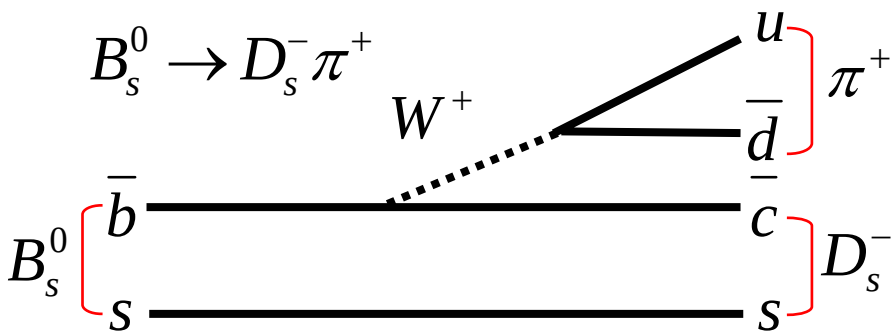
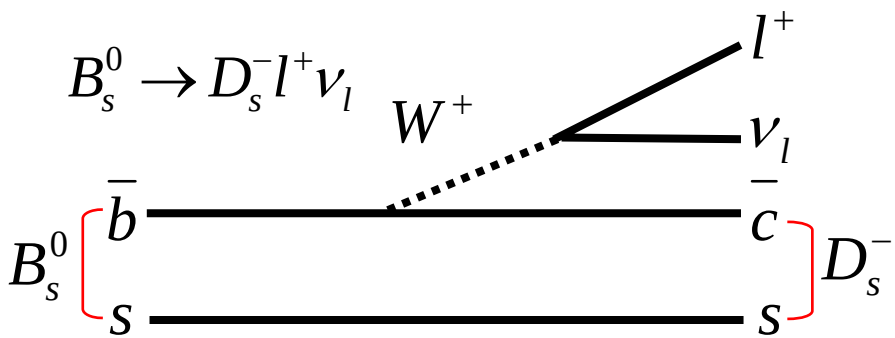
- Crossing: 396 ns: 2.5 MHz
- Level 1: hardware
  - Calorimeter, Muon, Track
  - 25kHz (reduction ~x100)
- Level 2: hardware + CPU
  - Cal cluster, Silicon track
  - 400 Hz (reduction ~x6)
  - Run IIB upgrade: 1k Hz
- Level 3: Linux PC farm
  - ~ Offline quantities
  - 100 Hz (reduction ~ x5)



Hadronic and Semileptonic

- Reconstruct two different signatures
  - "Hadronic" = "Exclusive"
  - "Semileptonic" = "Inclusive"
- These are different
  - Trigger, signal yield
  - Background
  - Missing momentum
  - Sensitivity for B_s mixing
- Hadronic:
  - Less signal yields
  - Good sensitive at higher Δm_s
- Semileptonic:
  - Higher signal yield
  - good sensitivity at lower Δm_s
- These two signatures are treated differently, and the results are combined together.

"Hadronic"



"Semileptonic"