Heavy Flavor Hadrons at CDF

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Outline

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  - Lifetime measurement method
  - Discussion
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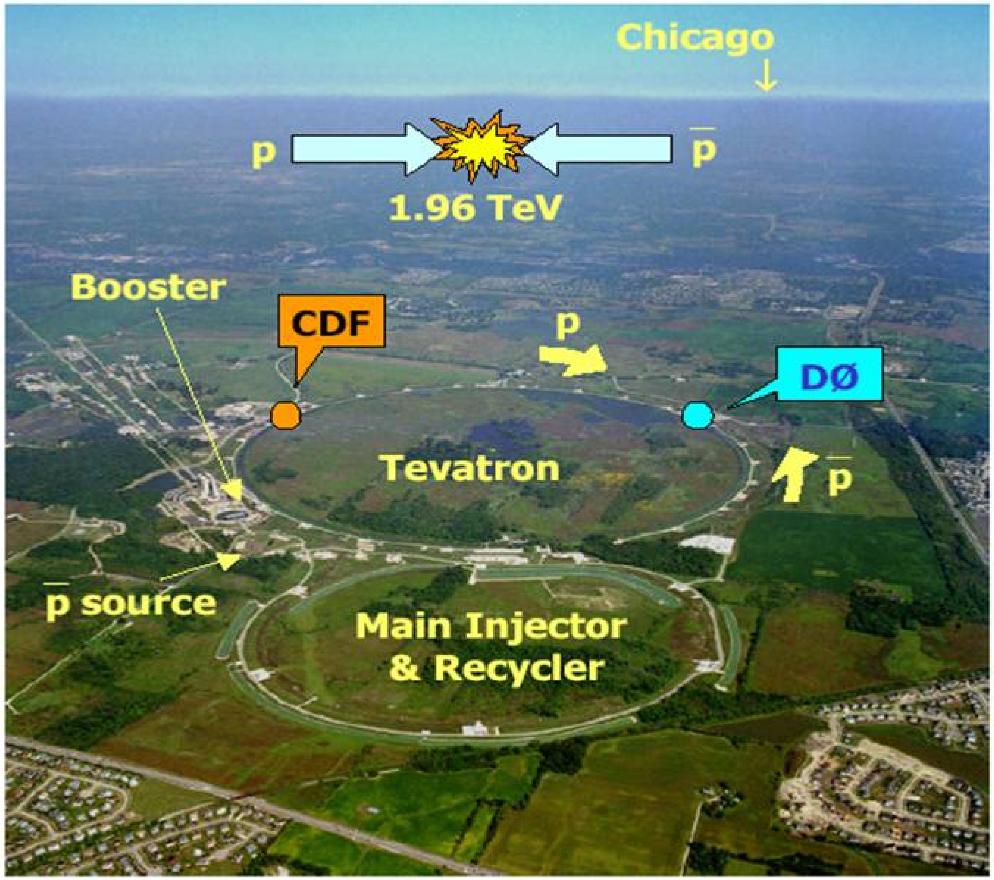
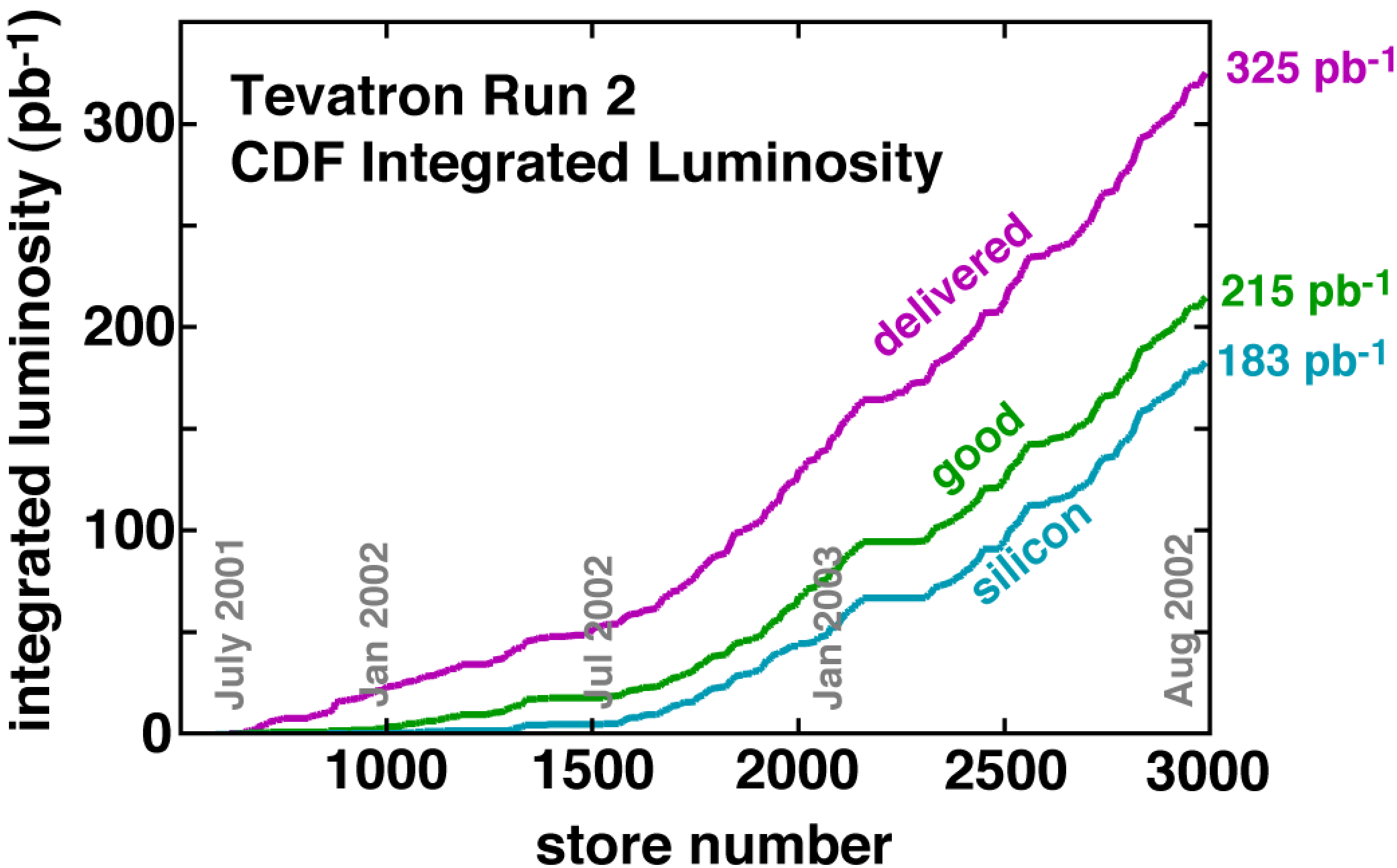
The Tevatron



- C.M.E.: 1.96 TeV
- 2.5M Hz Collision
- Peak Lum.($10^{32} cm^{-2} s^{-1}$):
  - Run I Avg: 0.16
  - Run II Record: 0.52
  - Until 2005: 0.8
  - Before LHC: 2-4
- Int. Luminosity:
  - Run I: $\sim$ 110 pb^{-1} (92-95)
  - Run II: 220 pb^{-1} to tape
  - $\sim$ 2 fb^{-1} by 2005 (Run II)
  - $\sim$ 6 fb^{-1} before LHC (Run II)

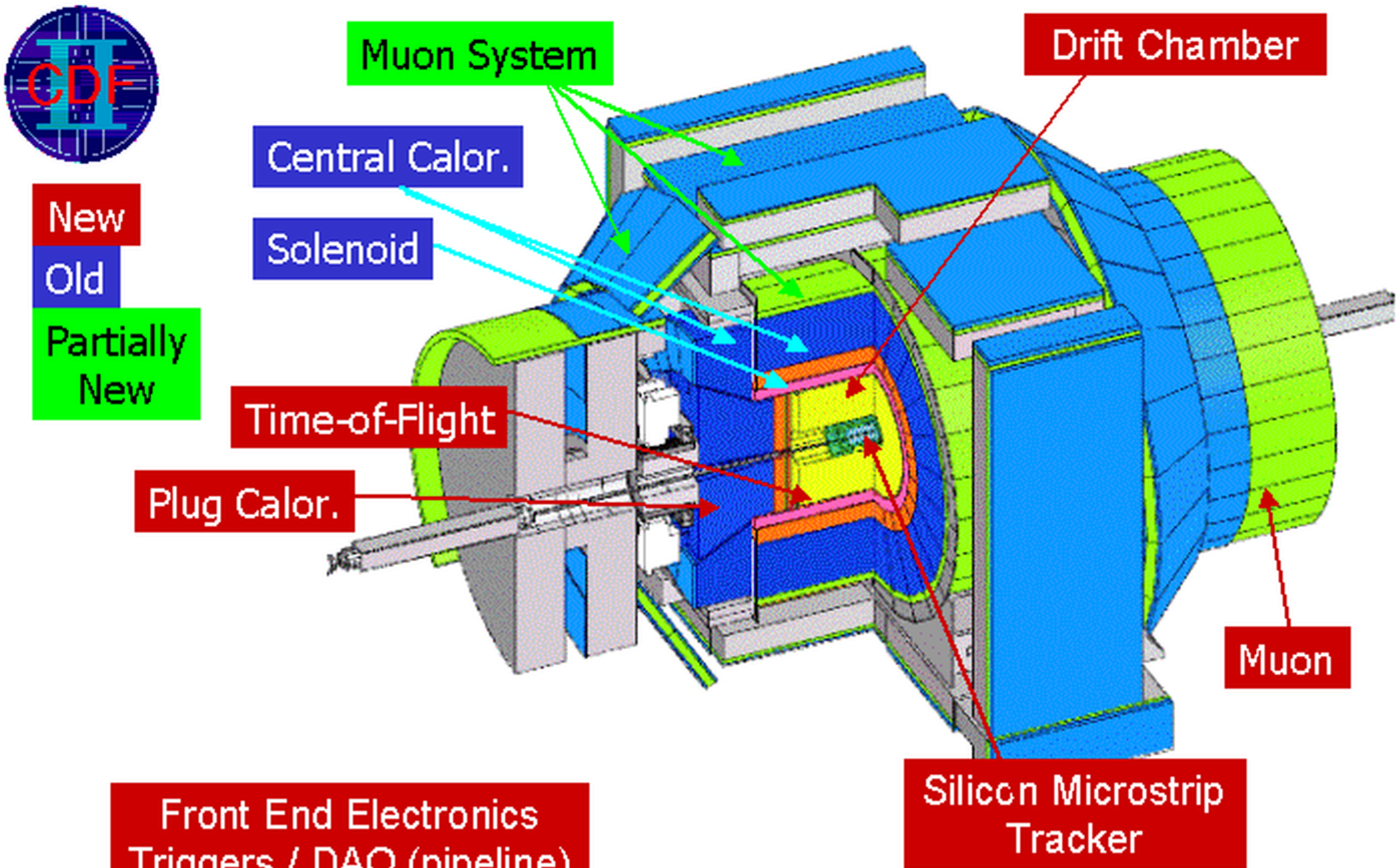
The Tevatron–Luminosity



Tevatron Heavy Flavor Physics

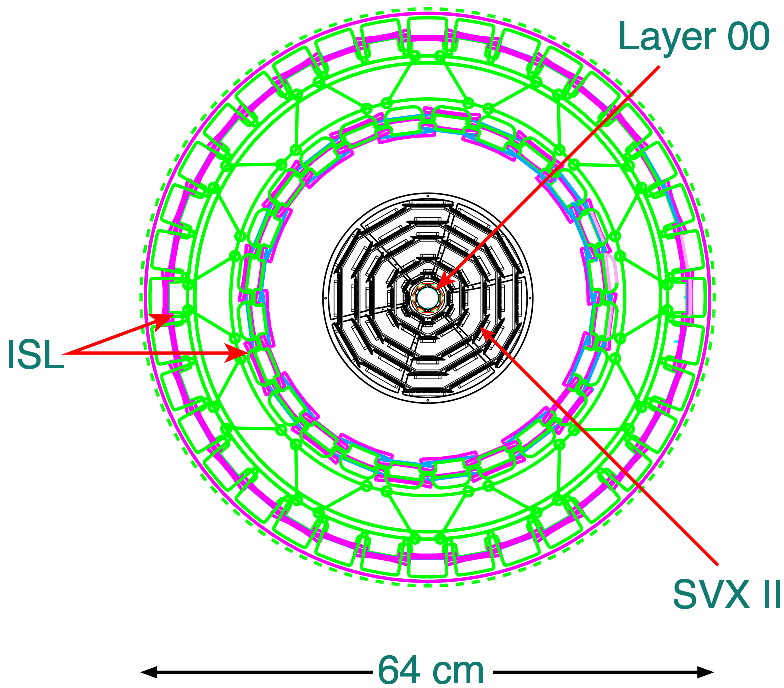
- CDF I(110 pb^{-1}) successful!
  b hadron mass, lifetime,mixing...
  sin2β
- Run II goals
- b Hadron spectroscopy
  - B_s, B_c, B^{**}, B^*_{sJ}
  - Λ_b, Ξ_b, Ω_b? ...
- Other competitive
  hadron spectroscopy
  - X(3872)
  - ...
- Precision measurements
  - B_s mixing,
    No. 1 B measurement!
  - B_s, Λ_b, B_c ... lifetime.
  - Branching ratio, polarization
  - ...
- Rare decays
  - $B_s \rightarrow \mu^+\mu^-$, $B_s \rightarrow K^{*0}\gamma$,
  - $\Lambda_b \rightarrow \Lambda\gamma$
  - ...

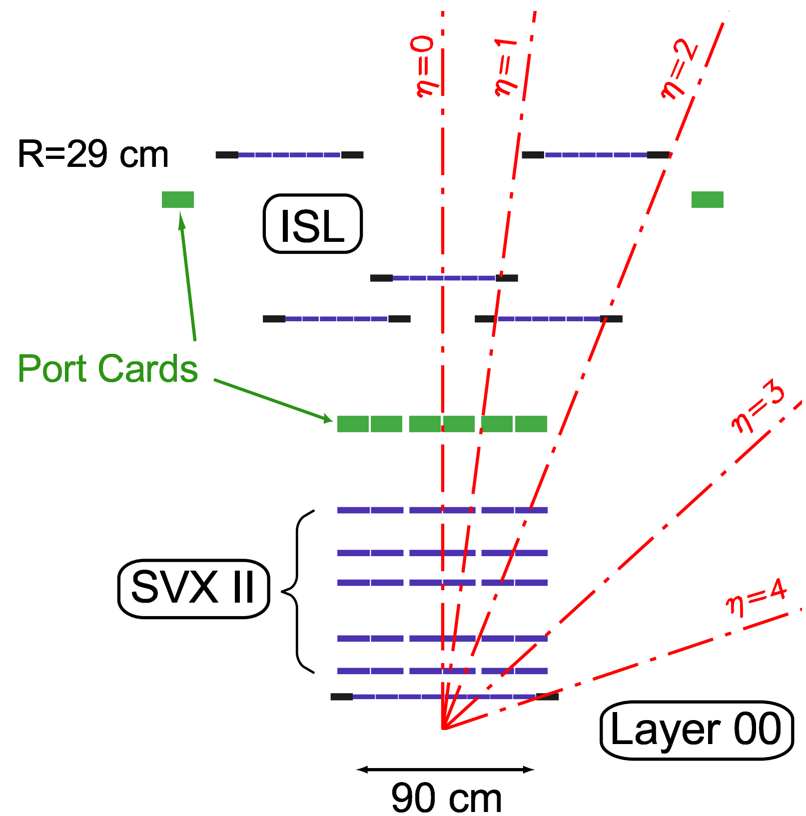
The CDF Detectors



Front End Electronics
Triggers / DAQ (pipeline)
Online & Offline Software

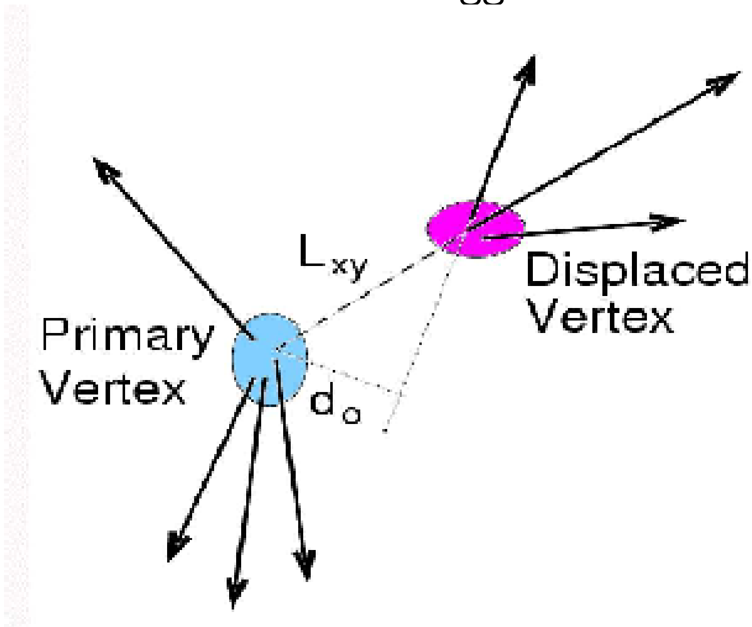
The CDF Detectors





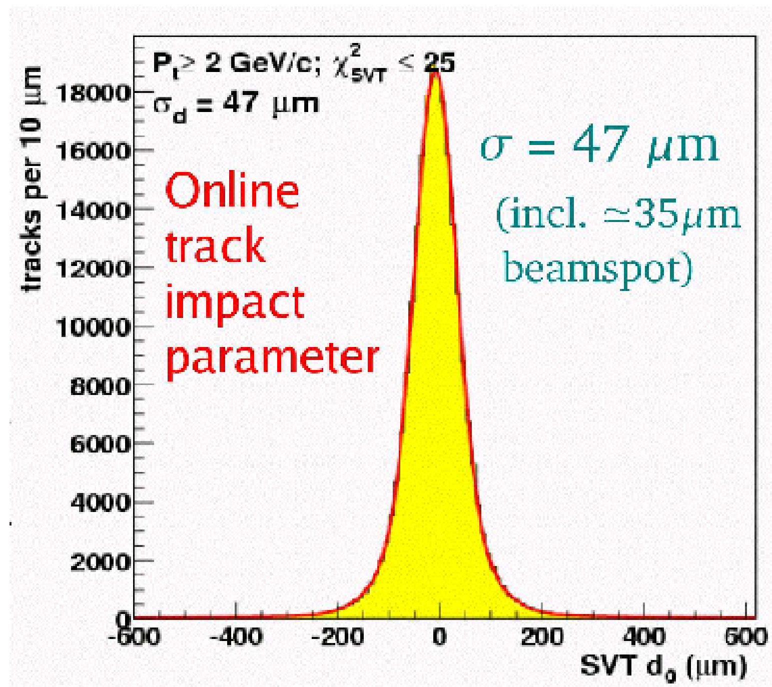
Triggers: Revolutionary Silicon Vertex Tracker(SVT)

- Collision rate: 2.5M Hz
- Bandwidth: L1/L2/L3: 20k/350/75 Hz
- Never had hadronic B trigger at Hadron collider



- Significantly reduce L2 trigger rate

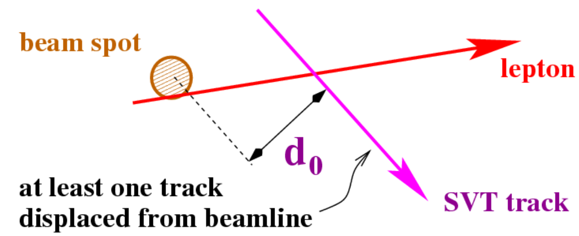
- Increase physics sensitivity
  - CDF as "Charm Factory"
  - Hadronic B trigger. $B \to hh$, $B_s \to D_s\pi$
  - Increased yield for semileptonic decays
  - new particles decaying into b/c quarks

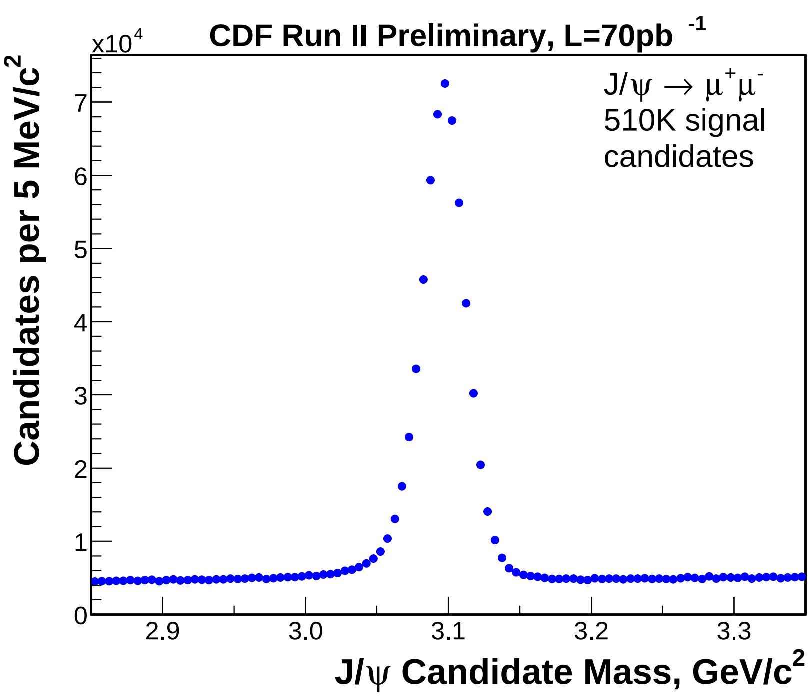


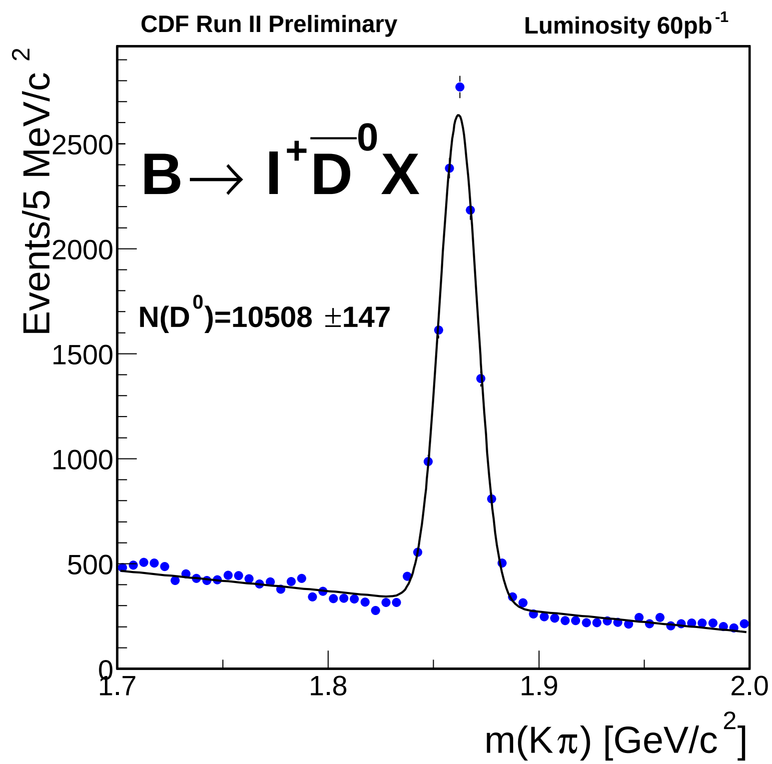
Triggers for B/Charm Physics

- CDF Di-muon-Trigger
  - $J/\psi \to \mu\mu$
  - Two central μ ($|\eta| < 1.0$)
  - $p_T > 1.5$ GeV

- Lepton+Track-Trigger(ℓ+SVT)

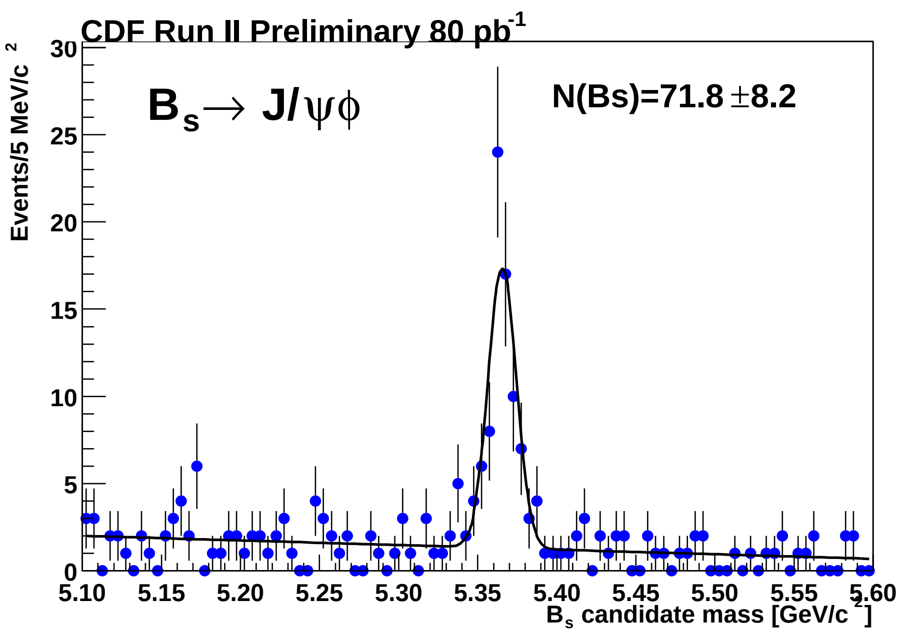




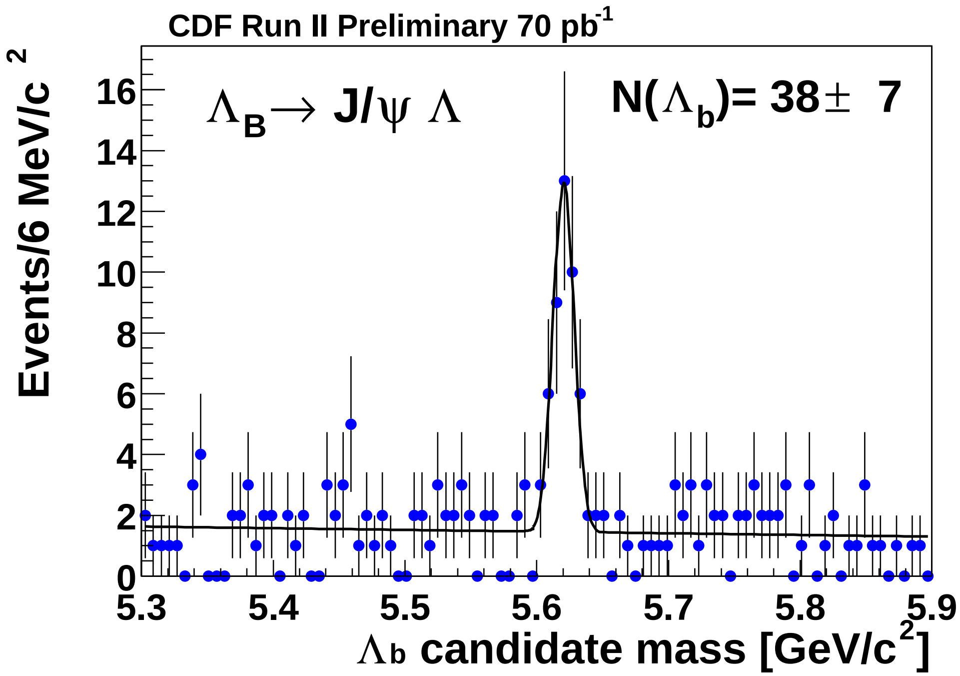


Hadron Spectroscopy

- B_s:



- Λ_b:

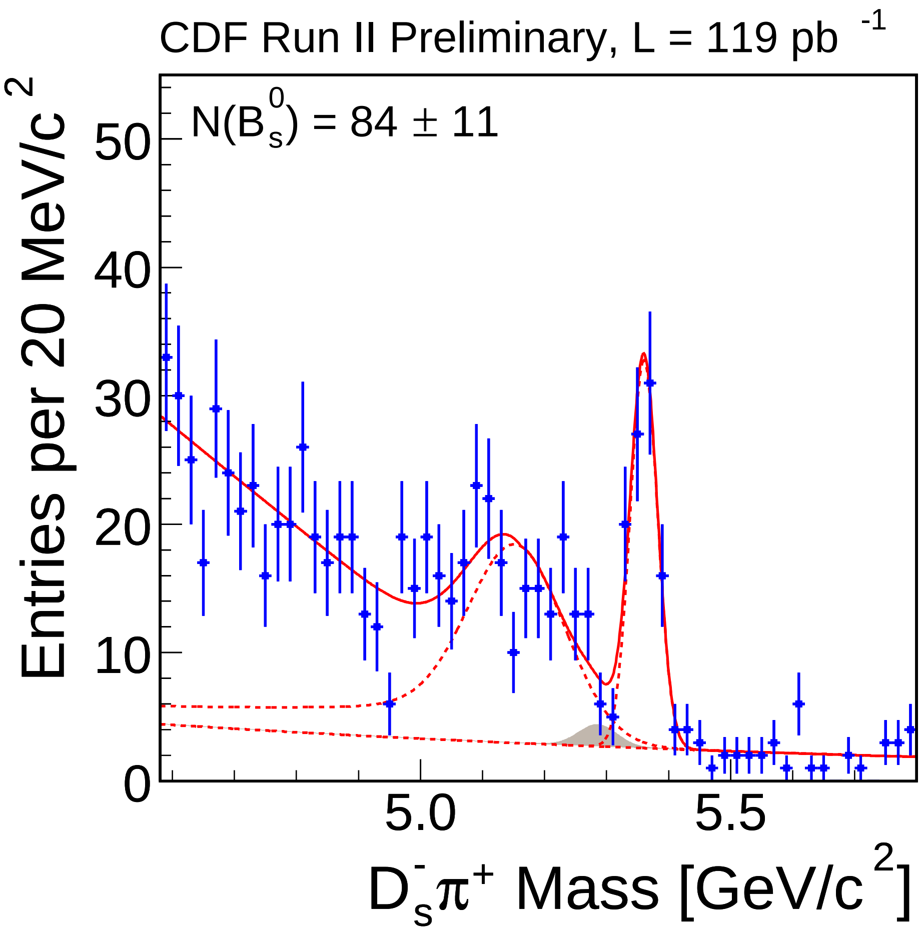


- $m(B_s^0)$ from $B_s^0 \to J/\psi\phi$:
  $5365.50 \pm 1.29(stat) \pm 0.94(sys)$ MeV/c^2
  5369.6 ± 2.4MeV/c^2 (2002 PDG)

- $m(\Lambda_b)$ from $\Lambda_b \to J/\psi\Lambda$:
  $5620.4 \pm 1.6(stat) \pm 1.2(sys)$ MeV/c^2
  5624 ± 9MeV/c^2 (2002 PDG)

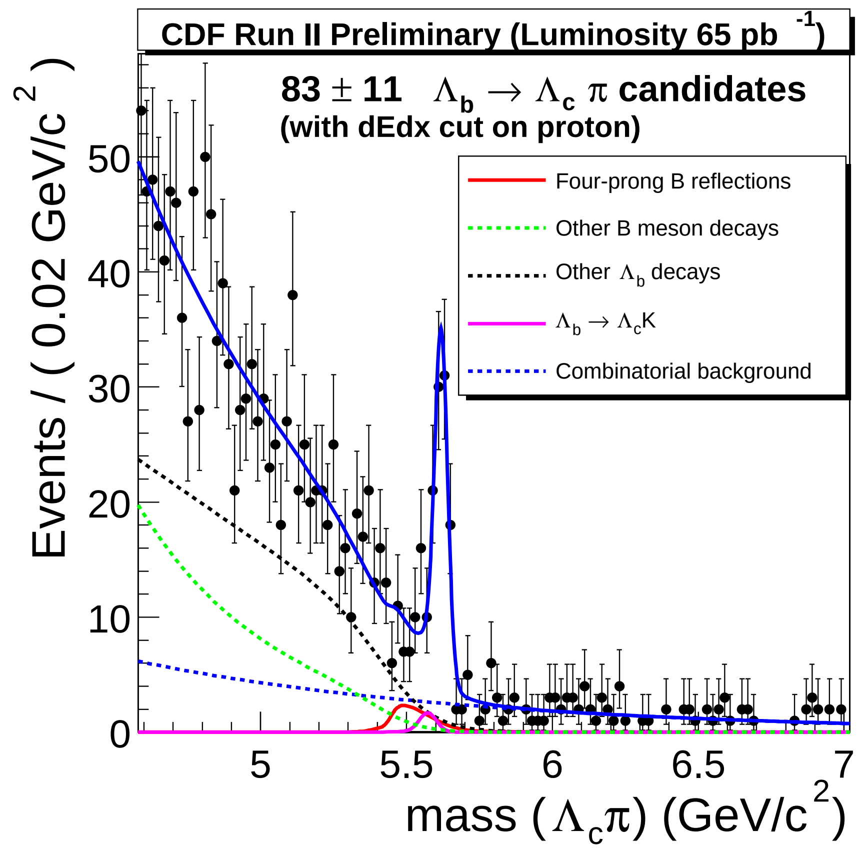
Hadron Spectroscopy(Other decay channels–SVT!!)

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



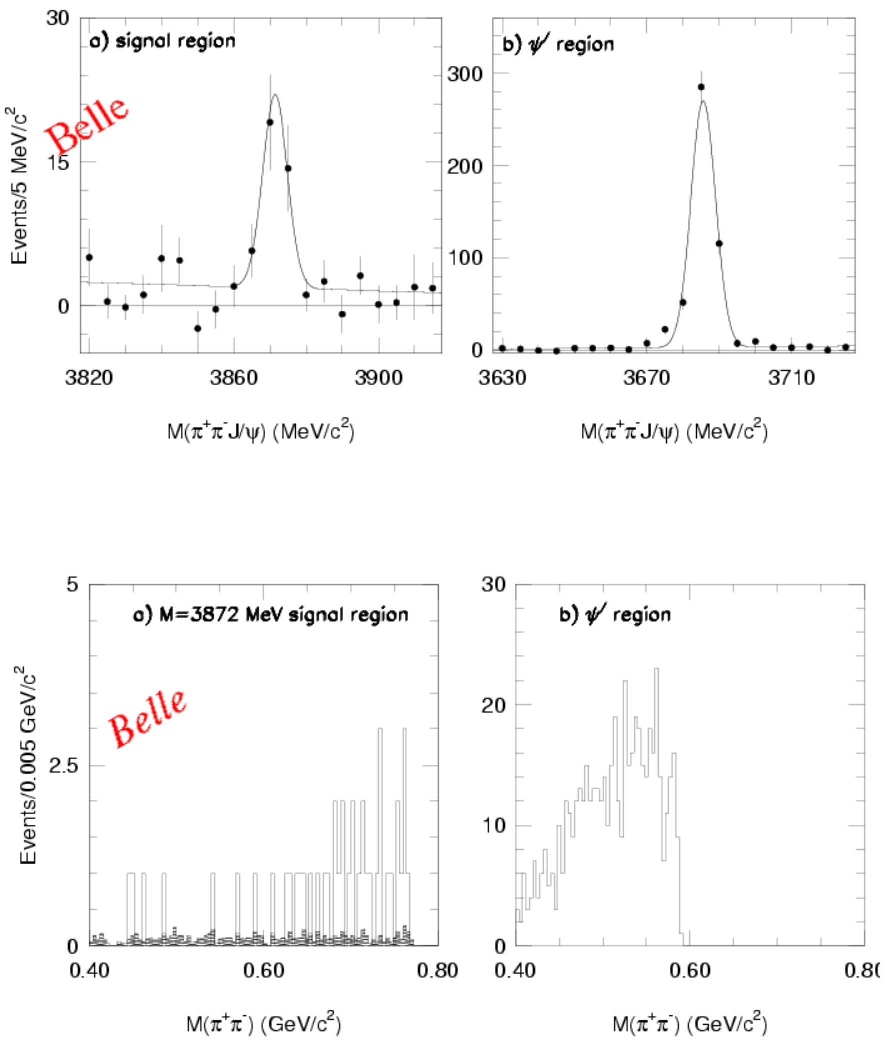
- Will be used for B_s mixing

- $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$:



- Largest fully reconstructed Λ_b sample in existence!

X(3872)$\rightarrow J/\psi\pi\pi$ Mystery –Introduction



- New narrow state – Belle (Aug. 10) $J/\psi\pi^+\pi^-$
- Using exclusive $B^+ \rightarrow J/\psi\pi^+\pi^-K^+$
- 35.7 ± 6.8 signal events(10.3 σ)
- Mass= $3872.0 \pm 0.6 \pm 0.5$ MeV
- $\Gamma < 2.3$ MeV, 90% CL
- A new Charmonium? or something else?

$\mathbf{X}$(3872) Mystery –Introduction

PDG Quark Model:

$c\bar{c}$

$L = 2$

$N\,^{2S+1}L_J$	J^{PC}	$u\bar{d}, u\bar{u}, d\bar{d}$ $I=1$	$u\bar{u}, d\bar{d}, s\bar{s}$ $I=0$	$c\bar{c}$ $I=0$	$b\bar{b}$ $I=0$	$s\bar{u}, s\bar{d}$ $I=1/2$	$c\bar{u}, c\bar{d}$ $I=1/2$	$c\bar{s}$ $I=0$	$b\bar{u}, b\bar{d}$ $I=1/2$	$b\bar{s}$ $I=0$	$b\bar{c}$ $I=0$
$1\,^1S_0$	0^{-+}	π	η, η'	$\eta_c(1S)$	$\eta_b(1S)$	K	D	D_s	B	B_s	B_c
$1\,^3S_1$	1^{--}	ρ	ω, ϕ	$J/\psi(1S)$	$\Upsilon(1S)$	$K^*(892)$	$D^*(2010)$	D_s^*	B^*	B_s^*	
$1\,^1P_1$	1^{+-}	$b_1(1235)$	$h_1(1170)$, $h_1(1380)$	$h_c(1P)$		$K_{1B}{}^\dagger$	$D_1(2420)$	$D_{s1}(2536)$			
$1\,^3P_0$	0^{++}	$a_0(1450)^*$	$f_0(1370)^*$, $f_0(1710)^*$	$\chi_{c0}(1P)$	$\chi_{b0}(1P)$	$K_0^*(1430)$					
$1\,^3P_1$	1^{++}	a_1[illegible]	[illegible]5), $f_1(1420)$	$\chi_{c1}(1P)$	$\chi_{b1}(1P)$	$K_{1A}{}^\dagger$					
$1\,^3P_2$	2^{++}	a_2[illegible]	[illegible]0), $f_2'(1525)$	$\chi_{c2}(1P)$	$\chi_{b2}(1P)$	$K_2^*(1430)$	$D_2^*(2460)$				
$1\,^1D_2$	2^{-+}	$\pi_2(1670)$	$\eta_2(1645)$, $\eta_2(1870)$			$K_2(1770)$					
$1\,^3D_1$	1^{--}	$\rho(1700)$	$\omega(1650)$	$\psi(3770)$		$K^*(1680)^\ddagger$					
$1\,^3D_2$	2^{--}			??		$K_2(1820)$					
$1\,^3D_3$	3^{--}	$\rho_3(1690)$	$\omega_3(1670)$, $\phi_3(1850)$			$K_3^*(1780)$					
$1\,^3F_4$	4^{++}	$a_4(2040)$	$f_4(2050)$, f_4([illegible]220)			$K_4^*(2045)$					
$2\,^1S_0$	0^{-+}	$\pi(1300)$	$\eta(129$[illegible]$)$, $\eta(1440)$	$\eta_c(2S)$		$K(1460)$					
$2\,^3S_1$	1^{--}	[illegible](1450)	$\omega(1420)$, $\phi(1680)$	$\psi(2S)$	$\Upsilon(2S)$	$K^*(1410)^\ddagger$					
$2\,^3P_2$	[illegible]	[illegible]	$f_2(1950)$, $f_2(2010)$		$\chi_{b2}(2P)$	$K_2^*(1980)$					
$3\,^1S_0$	0^{-+}	$\pi(1800)$	$\eta(1760)$			$K(1830)$					

$J/\psi\,\pi^+\pi^-$

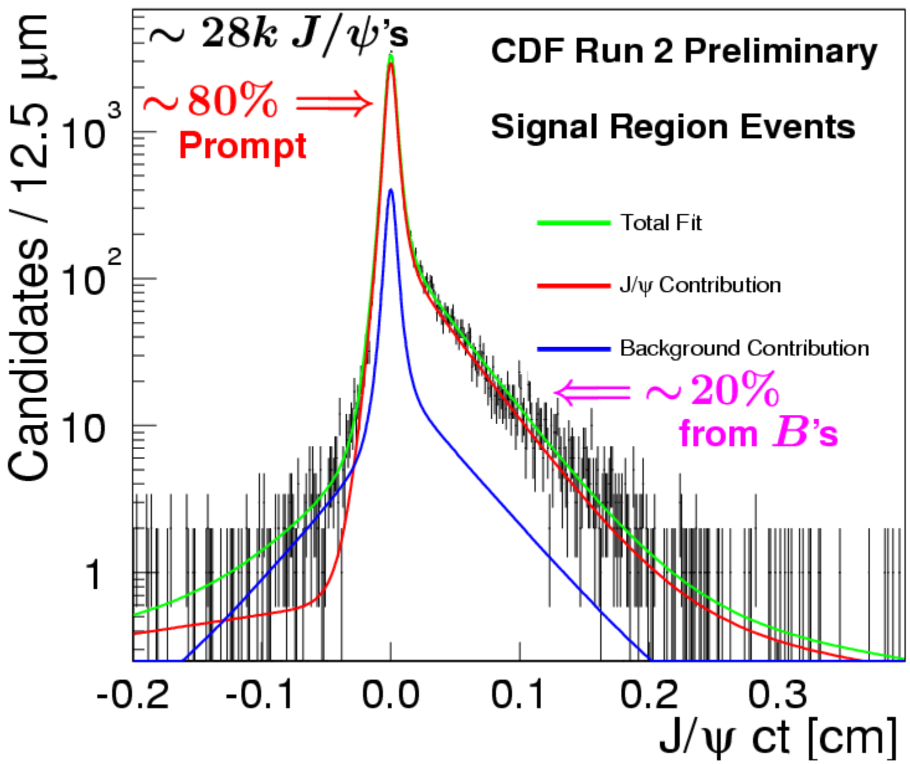
X(3872) Mystery –Introduction

- Choice 1: $^3D_2$
  - $^3D_2$ expected around 3820 MeV
  - 3872 MeV too heavy!
  - No observation $\chi_c\gamma$ at Belle!
    $\Gamma(\chi_{c1}\gamma)/\Gamma(J/\psi\pi\pi) < 0.89$
- Choice 2: $D\bar{D}^*$ molecule
  - Mass(3872 MeV) $\sim D\bar{D}^*$
- Choice 3: P wave, F wave states?
- Choice x: $c\bar{c}g^*$ Hybrids ?
- Whatever, interesting!
- hep-ph/0309294,...

- First Confirmation of Belle's result
- Complementary Information?
- The Tevatron Comparison:
  - The Good:
    * Various production mechanisms
      →Open to all states
    * Large production cross sections
  - The Bad:
    * Even larger total cross section
    * Selective triggers needed! ℓ, SVT
  - The Ugly:
    * Large Combinatorial background!

X(3872) Mystery –Introduction

- Example: Production Mechanism:
  J/ψ Prompt & B Production



- B fraction depends on
  - kinematics

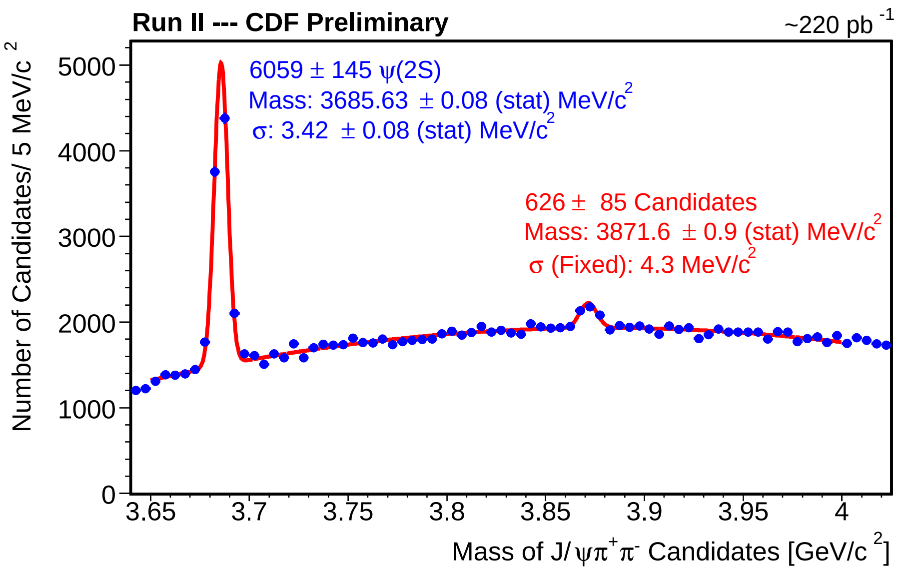
- CDF Search:
  - $\sim$2M $J/\psi(220\ pb^{-1})$ at CDF
  - Use inclusive $J/\psi\pi^+\pi^-X$

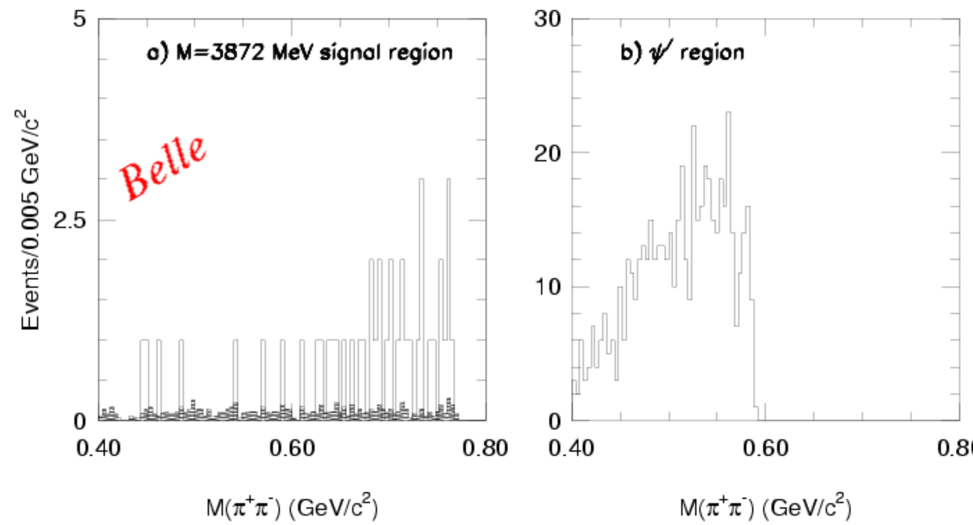
- Background suppression strategies:
  - minimum p_T's
  - good silicon tracks
  - only tracks in fixed cone

- optimize $\psi(2s) \rightarrow J/\psi\pi^+\pi^-$
  Scale to X signal

X(3872) Mystery –CDF Observation of X(3872)

- $\sim$ 600 candidates around 3872 MeV
- $\sim$ 6k $\psi(2s)$ candidates

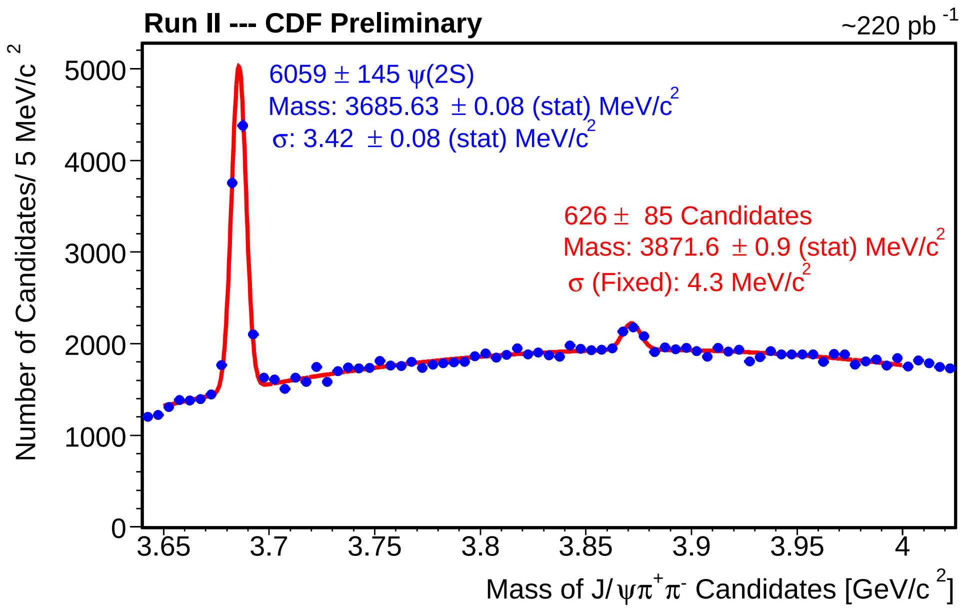




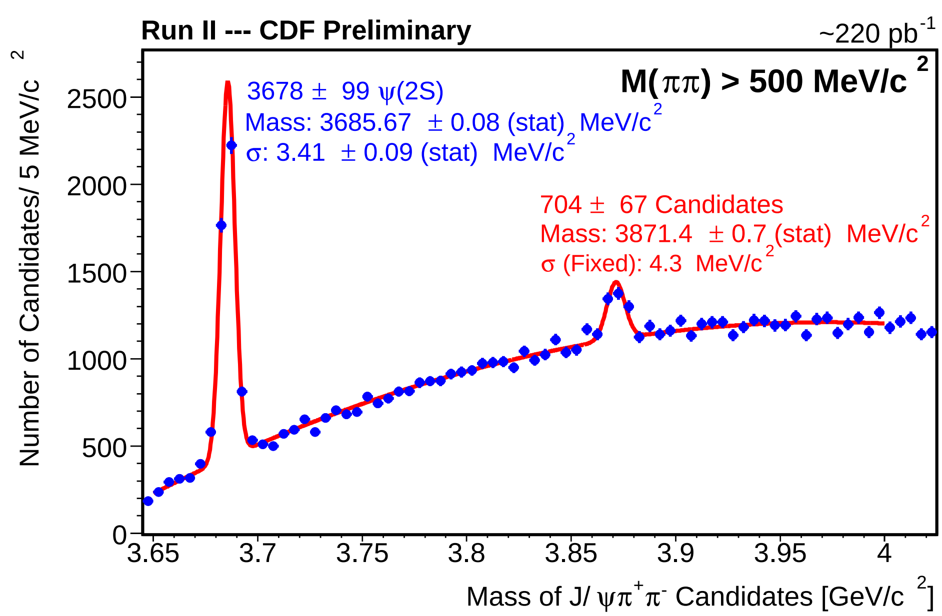
- Width fixed from $\psi(2S)$ extrapolation
  - help stabilize yield
  - no effect on mass

- Belle's signal favor high $m(\pi\pi)$
- What happens if apply $m(\pi\pi) > 500$ MeV/c?

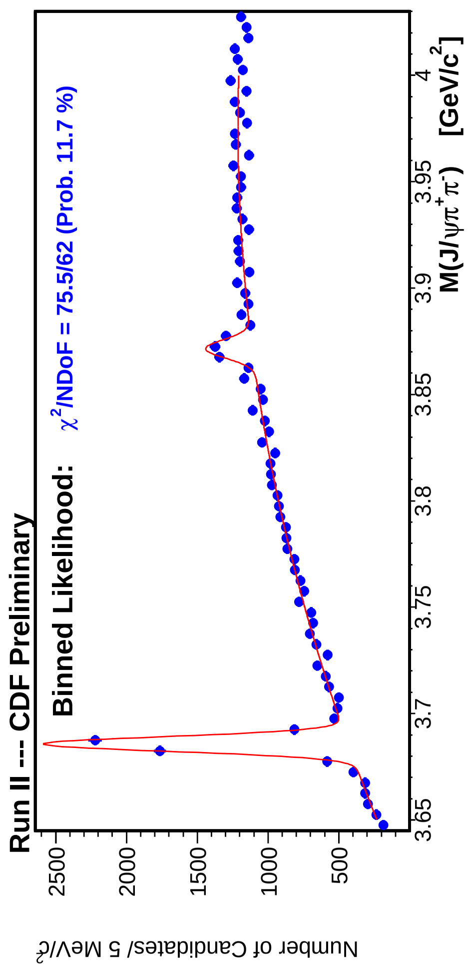
X(3872) Mystery – CDF Observation of X(3872)



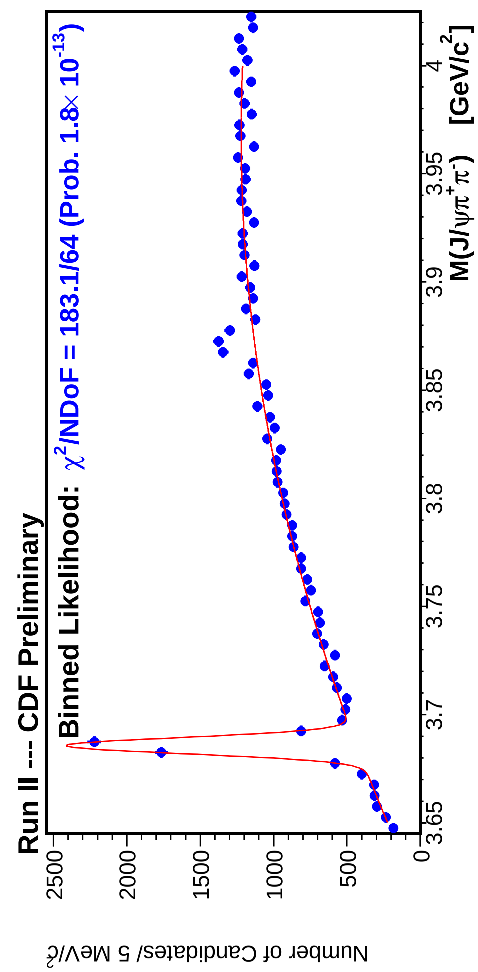
Significantly improve signal!



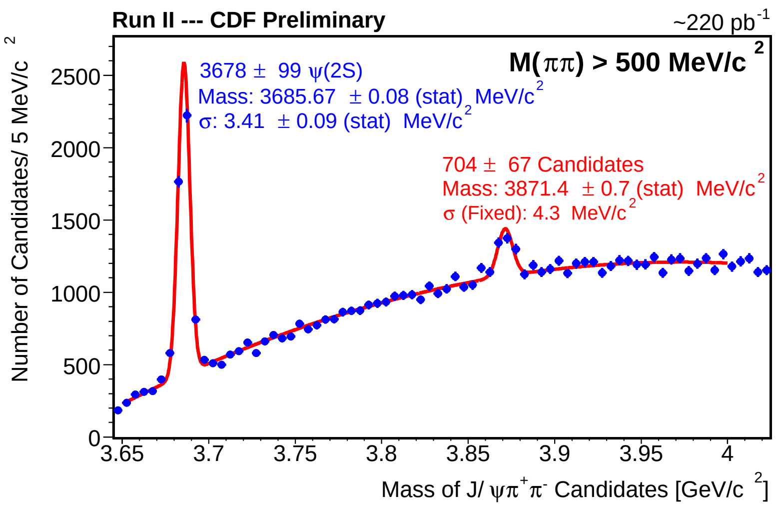
X(3872) Mystery –CDF Observation of X(3872)



$$\text{Significance} = \sqrt{-2ln(\mathcal{L})_0/(\mathcal{L})_{max}}$$
$$= 10.9\ \sigma$$



X(3872) Mystery –Prospects



- $M = 3871.4 \pm 0.7 \pm 0.4$ MeV
  Belle: $3872.0 \pm 0.6 \pm 0.5$ MeV

- first error–stat, second–sys

- Good agreement, CDF $\longleftrightarrow$ Belle

- $M(\psi') = 3685.67 \pm 0.08(stat)$ MeV
  PDG 02: 3685.96 ± 0.09 MeV

- Use $\psi(2s)$ to estimate sys: 0.4 MeV

- Belle: < 2.3 MeV. 90% C.L.
  Width: <CDF detector Resolution.

- Yield: 704 ± 67 inclusive
  Belle: 35.7 ± 6.8 exclusive

X(3872) Mystery –Prospects

- What is THIS??
- Hints:
  - Charmonium does not decay to $J/\psi\rho$
  - $J/\psi\pi^0\pi^0$, $J/\psi\pi^+\pi^0$
  - Measure Spin–Angular distribution analysis
  - Production mechanism
  - ...
- CDF working on:
  - m$(\pi\pi)$ – Is it a ρ, probably not conclusive!
  - Trying angular distribution? Difficult!?
  - Prompt vs Long lived production mechanism? lifetime fit.
- Note: $X/\psi(2s)$ rate is large! like D-state?

Λ_b Lifetime–the Puzzle

- Heavy Quark Expansion:
- $\Gamma = \Gamma_0 + \frac{\Lambda^2}{m_b^2}\Gamma_2 + \frac{\Lambda^3}{m_b^3}\Gamma_3 + ...$
- $\frac{\Lambda}{m_b} \simeq \frac{M_B - m_b}{m_b} \simeq 0.1$
- Γ_0: *spectator model*
  All b-hadrons have same lifetime!
- No $1/m_b$ corrections
- Γ_2(due to isospin): *Fermi Motion* and *chromomagnetic interaction*
- Γ_3: *Weak annihilation* and *Pauli interference*

- Theoretical prediction for b-hadrons until the end of 2001

$$\tau_{\Lambda_b}/\tau_{B_d} = 0.90...1.00 \text{ ps}$$

- Experimental results for b-hadrons, Heavy Flavor Averaging Group, 2003

$$\tau_{\Lambda_b}/\tau_{B_d} = 0.789 \pm 0.034 \text{ ps}$$

- A puzzle – Λ_b lifetime

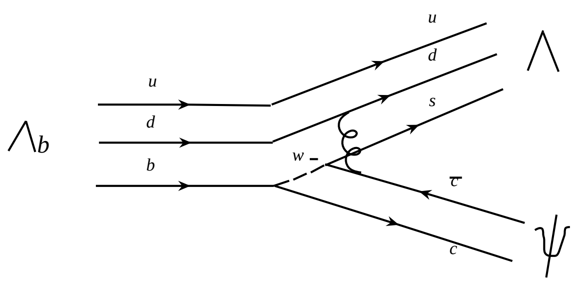
Current Λ_b Lifetime Measurements(before CDF II)

Experiment	DataSet	#event	Channel	$\tau_{\Lambda_b}(ps)$
ALEPH	91-95	$705 \pm 32 \pm 62$	$\Lambda\ell$	$1.20 \pm 0.08 \pm 0.06$
	$4 \times 10^6 Z$	137 ± 2	$\Lambda_c\ell$ $\Lambda_c \to pK\pi$ $\Lambda_c \to pK_s^0$ $\Lambda_c \to \Lambda\pi$ $\Lambda_c \to \Lambda\pi\pi\pi$	$1.18^{+0.13}_{-0.12} \pm 0.03$
DELPHI	91-94 $3.6 \times 10^6 Z$	82 ± 9	$\Lambda_c\ell$ $\Lambda_c \to pK\pi$ $\Lambda_c \to pK_s^0$ $\Lambda_c \to pK_s^0\pi\pi$	$1.11^{+0.19}_{-0.18} \pm 0.05$
		235 ± 25	$p\ell$	$1.19 \pm 0.14 \pm 0.07$
OPAL	90-94	490	$\Lambda\ell$ I.P.	$1.21^{+0.15}_{-0.13} \pm 0.10$
	$3.6 \times 10^6 Z$	356	$\Lambda\ell$ vtx	$1.15 \pm 0.12 \pm 0.06$
	90-95 $4.4 \times 10^6 Z$	129 ± 25	$\Lambda_c\ell$ $\Lambda_c \to pK\pi$	$1.29^{+0.24}_{-0.22} \pm 0.06$
CDF I	92-95 110 pb^{-1}	197 ± 25	$\Lambda_c\ell$ $\Lambda_c \to pK\pi$	$1.32 \pm 0.15 \pm 0.06$

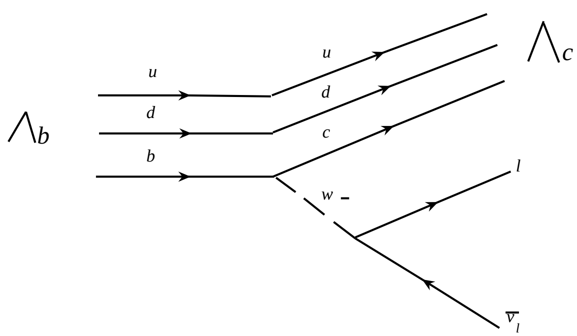
- Dominated by statistical error!

Λ_b Lifetime–at CDF

- CDF Situation
  - Exclusive decays: $\Lambda_b \to J/\psi \Lambda$

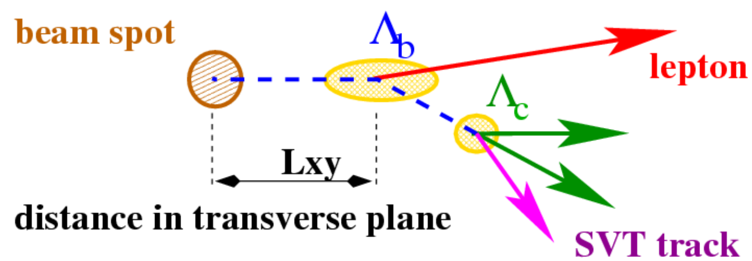


  - Semileptonic decays: $\Lambda_b \to \ell \bar{\nu}_\ell \Lambda_c$



- Lifetime measurement: proper time

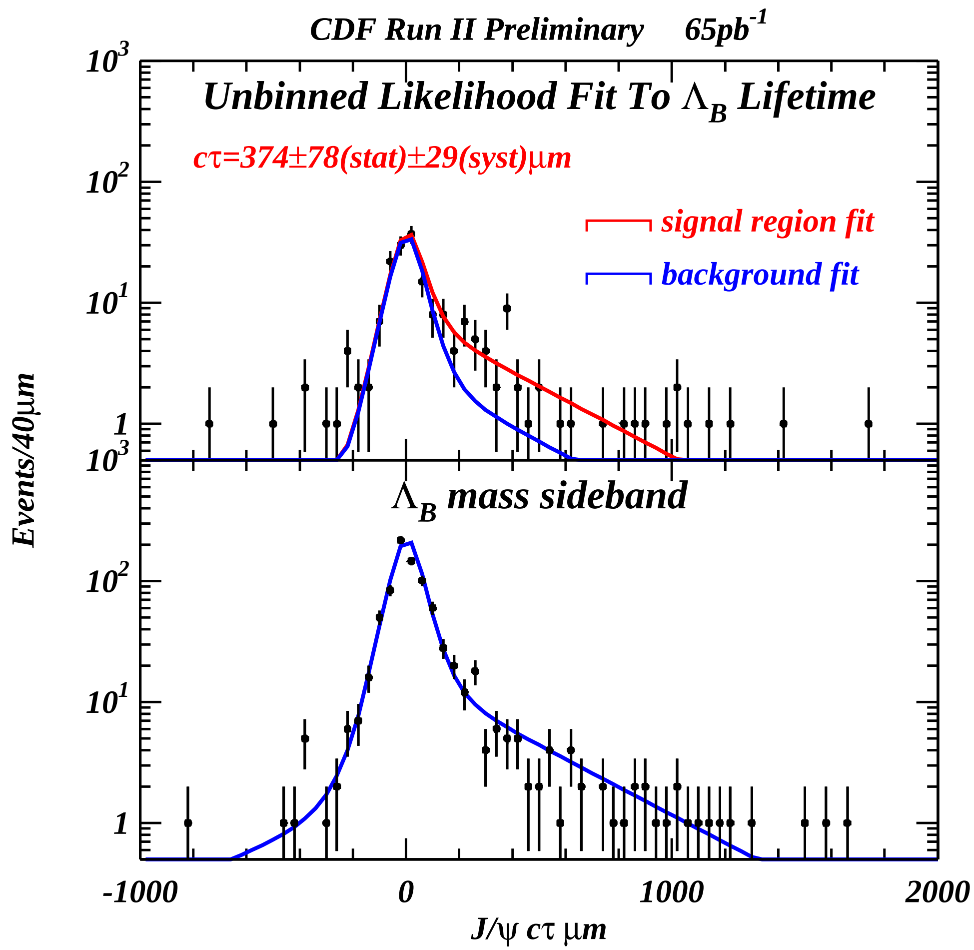
$$c\tau = \frac{L}{\beta\gamma} = L_{xy} \cdot \frac{m_{\Lambda_b}}{p_T(\Lambda_b)}$$

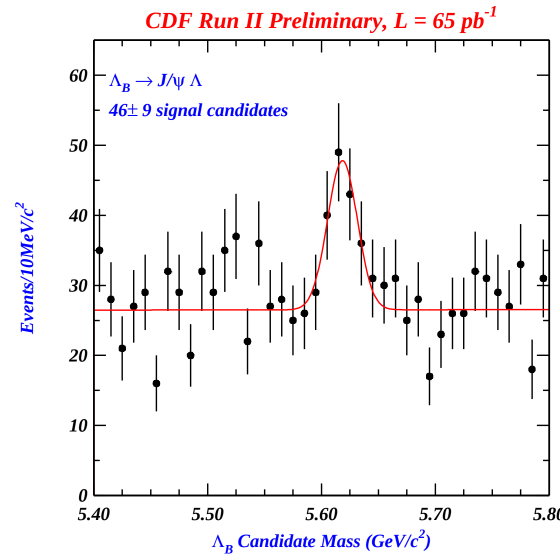


- Exclusive: m_{Λ_b}, $p_T(\Lambda_b)$ reconstructed
- Inclusive: m_{Λ_b}, $p_T(\Lambda_b)$ missing due to ν
- Exclusive $\to$ low systematic uncertainty
- Inclusive $\to$ low statistic uncertainty
- Complementary!

Λ_b Lifetime–at CDF

- Preliminary result from $\Lambda_b \to J/\psi\Lambda$





- $c\tau(\Lambda) = 374 \pm 78 \pm 29\mu m$
  $1.25 \pm 0.26 \pm 0.10$ ps
  $369 \pm 24\mu m$ PDG 2002
  1.229 ± 0.08 ps
- Sys. uncertainty $\to$ current V0 tracking
- Statistics too low!
- $\Lambda_c\pi$ channel, unknown$\leftarrow$trigger bias

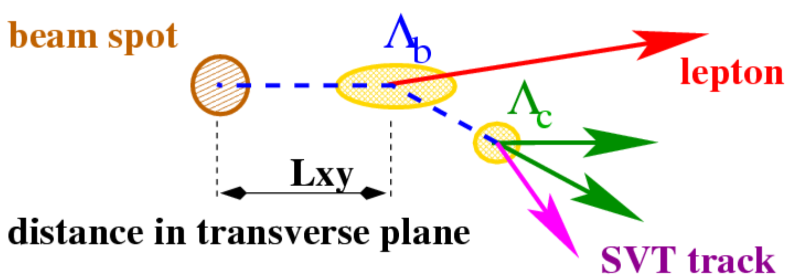
Λ_b Lifetime–$\Lambda_b \to \ell \bar{\nu}_\ell \Lambda_c, \Lambda_c \to pK\pi$ Reconstruction

- Trigger confirmation:
  $p_T(\ell) > 4$ GeV + SVT track with
  $p_T > 2$ GeV, $d_0 > 120\mu m$

- Good silicon tracks

- Fixed cone size around lepton$\leftarrow \Lambda_C$

- Λ_b vertex$\leftarrow$ intersection of ℓ and Λ_c



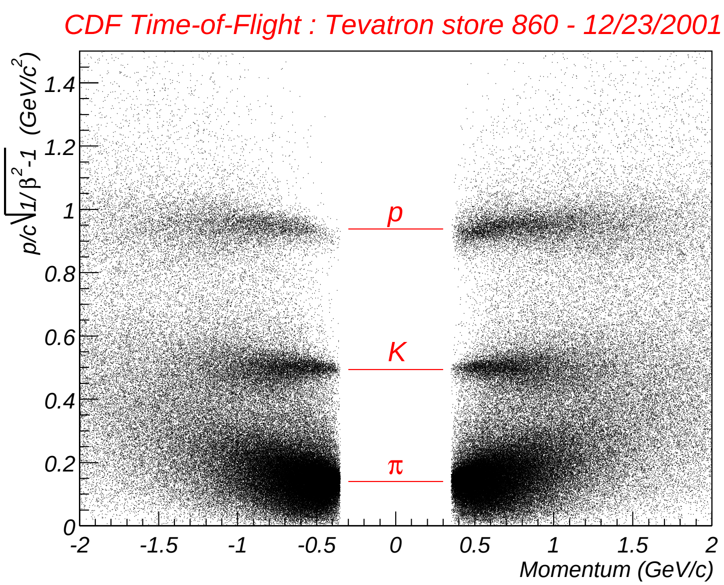
- Large background:
  - Combinatorial background! Always
  - $X\ell^- D^+(K\pi\pi)$, $X\ell^- D_s^+(KK\pi) \leftarrow$ B
  - Identify proton/pion is the solution!

- Small background:
  - $\Lambda_b \to \Lambda_c^{+*}\ell\nu, \Lambda_c^{+*} \to \Lambda_c \pi^+\pi^-$
  - $\bar{B} \to \Lambda_c^+ D_s^- \bar{N} X, D_s^- \to \ell^- X$
  - $\Lambda_b \to \Lambda_c^+ D_s^- X, D_s^- \to \ell^- X$
  - $3.5 < m_{\ell+\Lambda_c} < 5.6$ GeV$/c^2$
    $p_T(\Lambda_c) > 5$GeV

- Other background:
  - Monitor $\ell^+\Lambda_c^+$ and $\ell^-\Lambda_c^-$

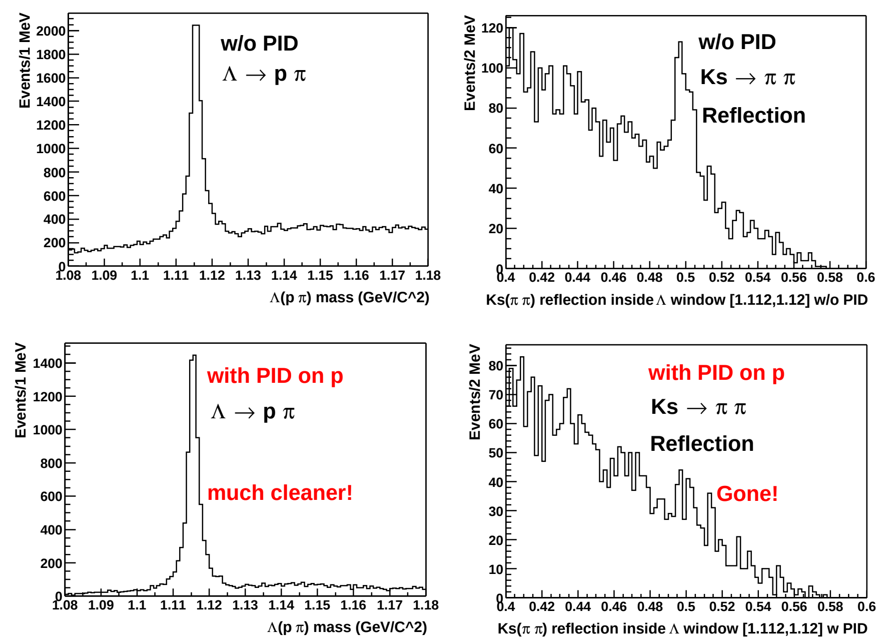
Λ_b Lifetime–$\Lambda_b \to \ell \bar{\nu}_\ell \Lambda_c, \Lambda_c \to pK\pi$ Reconstruction

- Particle ID(PID) on proton
  - New Time-of-Flight(ToF)
    Excellent resolution,$_{d}$ $\sim 60\%$ Efficiency



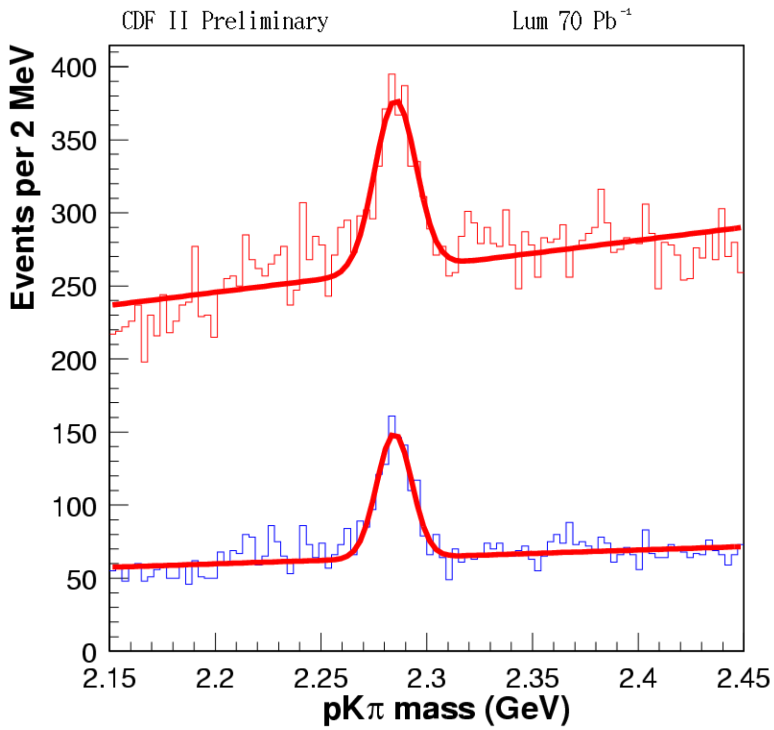
  - dE/dx, $\sim 100\%$ Efficiency
    Need recalibration
  - Combined χ^2 prob. of ToF and dE/dx
  - First analysis used ToF for PID at CDF

- PID control sample: $\Lambda \to p\pi$
  - $\Lambda \to p\pi^-$, good sample to test $p\pi$ ID
    $K_s \to \pi^+\pi^-$ reflection



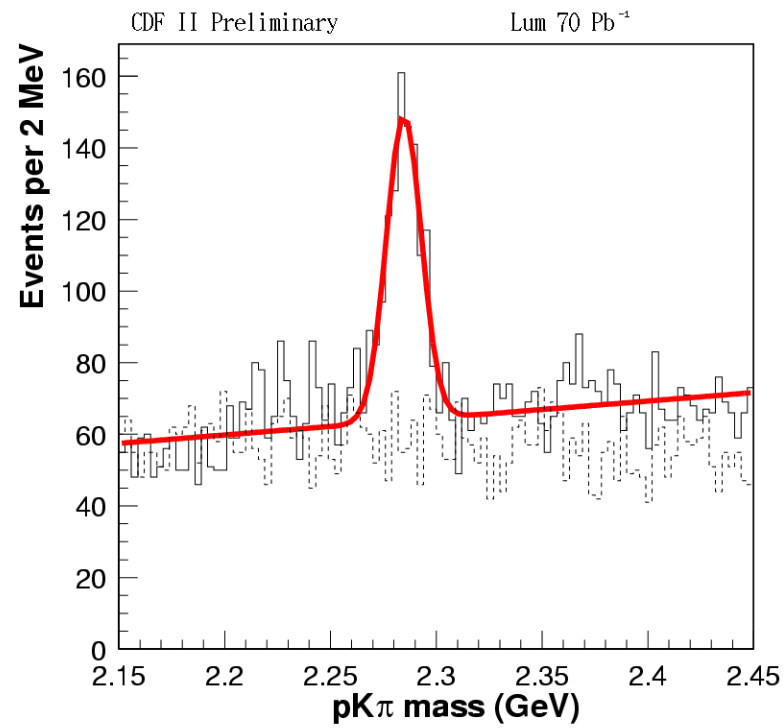
Λ_b Lifetime–$\Lambda_b \to \ell \bar{\nu}_\ell \Lambda_c, \Lambda_c \to pK\pi$ Reconstruction

- 586 events in $e/\mu + SVT$ sample, Largest Λ_b sample



- Upper–no PID, lower–PID on proton
- Reduce bkg $\div 4$, keep $\sim 60\%$ signal

- $\ell^+\Lambda_c^-$ compare with wrong charge combinations $\ell^+\Lambda_c^+$, $\ell^-\Lambda_c^-$

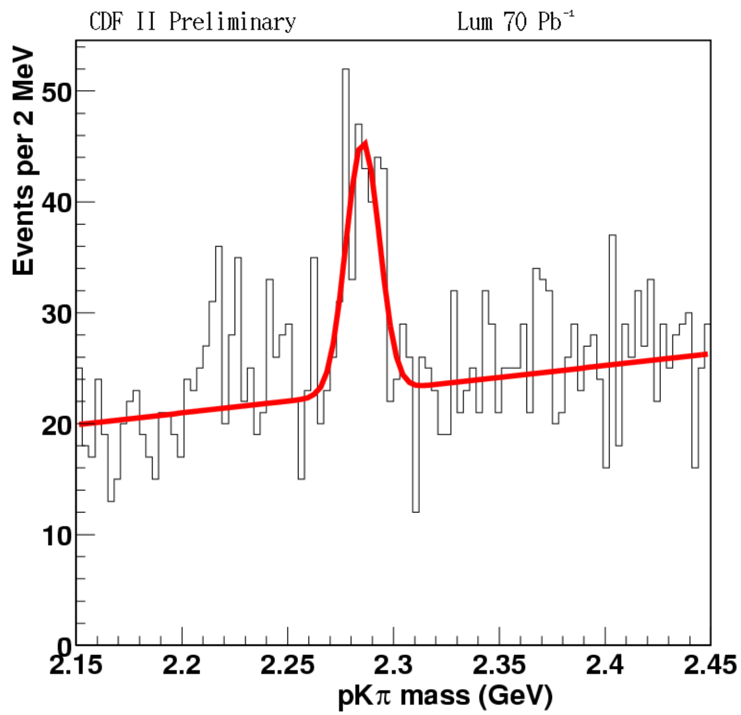


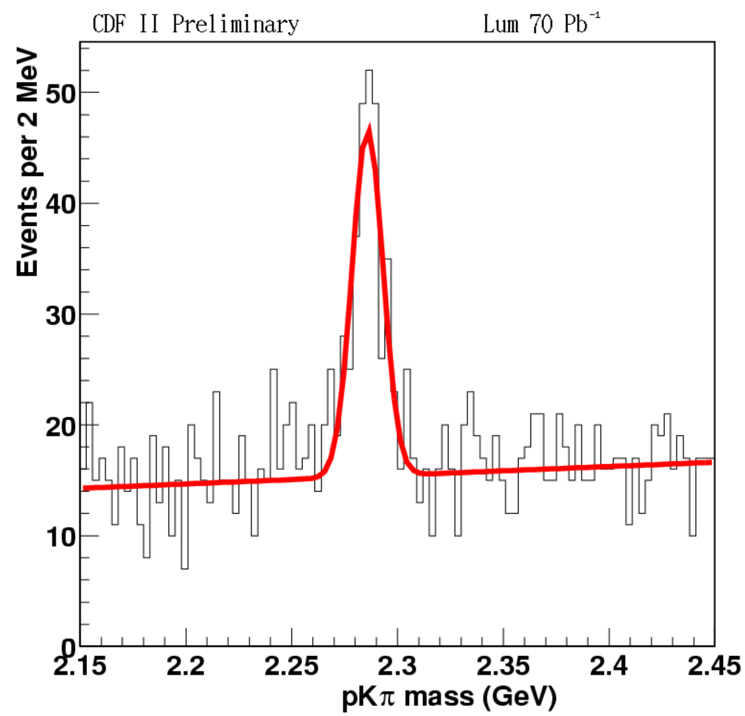
- Solid line–right charge combinations
- Dash line–wrong charge combinations

Λ_b Lifetime–$\Lambda_b \to \ell\bar{\nu}_\ell\Lambda_c$ Reconstruction

- Currently for lifetime only fit 345 evts
  μ+SVT sample
  e+SVT coming soon

- Two proton PID scenarios:
  proton track has dE/dx only
  proton track has both dE/dx and ToF





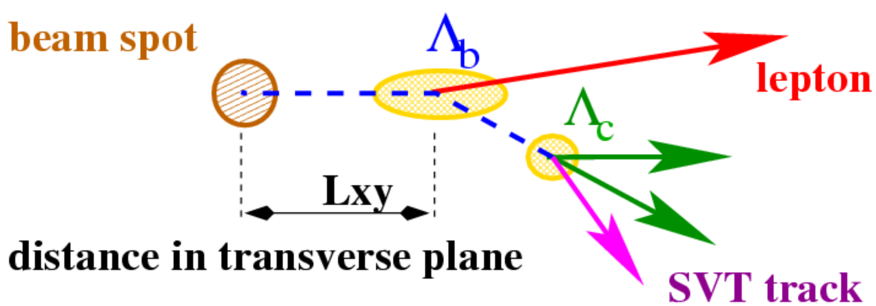
- Proton track has dE/dx only

- Proton track has both dE/dx and ToF

Λ_b Lifetime–Lifetime Measurement Method

- Lifetime←proper time distribution
- Proper decay length:

$$c\tau = \frac{L}{\beta\gamma} = L_{xy} \cdot \frac{m_{\Lambda_b}}{p_T(\Lambda_b)}$$



- m_{Λ_b}?, $p_T(\Lambda_b)$? ← missing ν

- m_{Λ_b} from PDG
- Define:

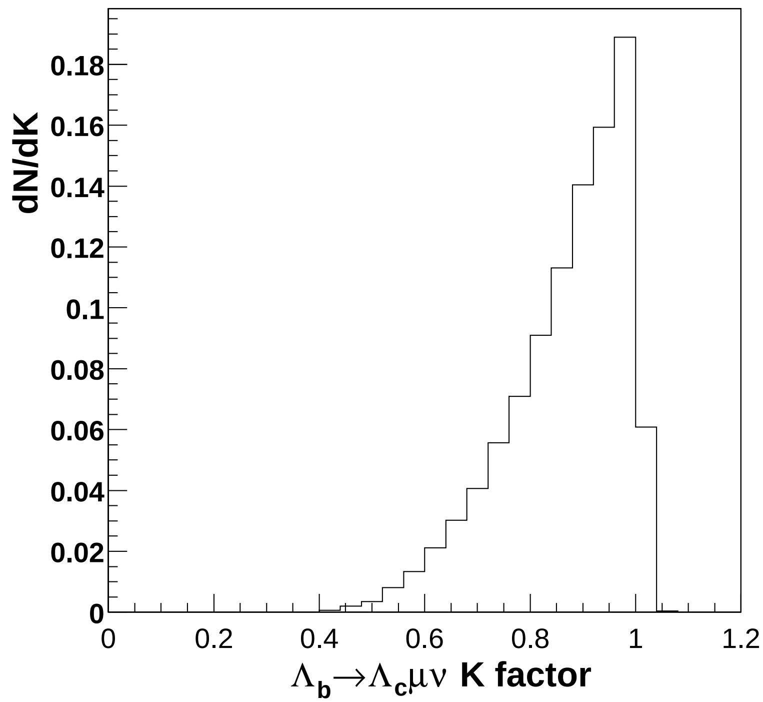
$$K = \frac{p_T(\Lambda_c \ell)}{p_T(\Lambda_b)}$$

$$\Longrightarrow c\tau = L_{xy} \cdot \frac{m_{\Lambda_b}}{p_T(\Lambda_c \ell)} . K = XK$$

- X–pseudo proper time
- K from Monte Carlo
  Large uncertainty source

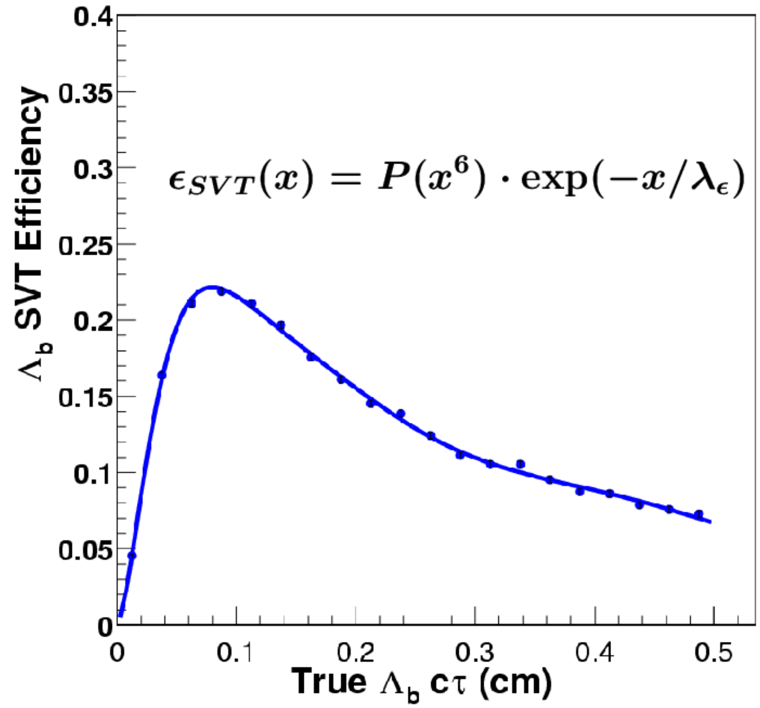
Λ_b Lifetime–Lifetime Measurement Method

- Momentum correction due to missed ν



- K factor shape used in convolution of likelihood fit

- Λ_b SVT efficiency vs true proper time



- Parametric MC for SVT, $p_T > 2$GeV $d_0 > 120\mu m$
- Validate MC on high stat. ℓD sample

Λ_b Lifetime–Lifetime Measurement Method

- Unbinned likelihood fit
  Event by Event
- Total likelihood

$$ln\mathcal{L} = \sum_{i=1}^{N_s} ln\mathcal{F} + \sum_{i=1}^{N_b} ln\mathcal{F}_b$$

$$\mathcal{F} = (1 - f_b)\mathcal{F}_s + f_b\mathcal{F}_b$$

- Sig. Prob. Density Function(P.D.F)

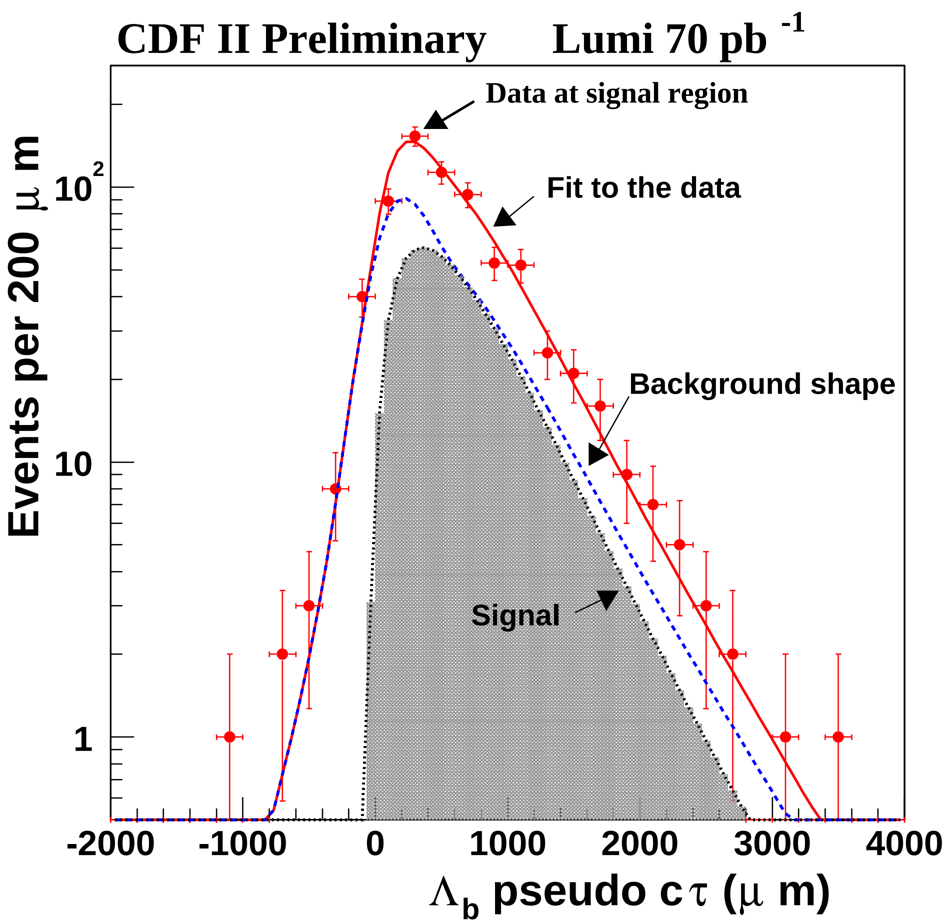
$$\mathcal{F}_s = [\epsilon_{SVT}(KX')e^{-\frac{KX'}{c\tau_{\Lambda_b}}}]$$
$$\otimes G(X' - X, s\sigma) \otimes H(K)$$

- Background P.D.F: parametric

- ϵ_{SVT}–the correction due to SVT track
- G(x-x',sσ)–Gaussian resolution function
- σ–the measurement error
- s–scale factor due to our imperfect modeling of the measurement error in reconstruction.
- s–determined from an independent control data sample(has no SVT bias) inclusive lepton sample

Λ_b Lifetime–Lifetime Measurement Method

- Simultaneous fit:
  signal+background(both float)



- Fitting result in 70 pb^{-1}μ+SVT sample:

  $\sigma_{c(\tau_{\Lambda_b})}$ (stat) : $\sim 40\mu m(0.13ps)$

  $\sigma_{c(\tau_{\Lambda_b})}$ (stat, CDF II)
  $(\Lambda_b \to J/\psi\Lambda)$: $\sim 78\mu m(0.26ps)$

  $\sigma_{c(\tau_{\Lambda_b})}$ (PDG, 2002) : $\sim 24\mu m(0.08ps)$

- Adding e+SVT sample, $\times 2$
  Using 220 pb^{-1}, $\times 3$
  Potential $\sigma_{c(\tau_{\Lambda_b})}$(stat) in this channel :
  $40(0.13)/\sqrt{6} \sim 16\mu m(0.05ps)$

- Central value pending completion of $B^+ \to \ell^+\nu D^0$ control sample studies
  - New trigger to be understood
  - $B^0 \to \ell^+ D^{-*}$ cross talk
  - In progress

Λ_b Lifetime–Discussion

- Systematic uncertainties:

source	value
SVT bias	$15\ \mu$m
Λ_c^* (30% contribution)	11μm
event selection bias	$9\ \mu$m
PID bias	$3\ \mu$m
background normalization	3μm
fitting procedure	$2\ \mu$m
$L_{xy}(\Lambda_b)$ error scale factor	$2\ \mu$m
total	$21\ \mu$m

- Leading errors: SVT bias, Λ_c^*

- Reduce stat error:
  - more data
  - more channels

- Reduce sys error:
  - SVT, more studies from high stat sample: $B \to \ell \nu D^0$ studies, $\sim 5\mu m$?
  - Λ_c^* uncertainty, possible ways:
    increase $p_T(\Lambda_C)$, lose stat.
    increase $m(\ell\Lambda_c)$, lose stat.
    spectroscopy studies

- Combine exclusive and inclusive channels

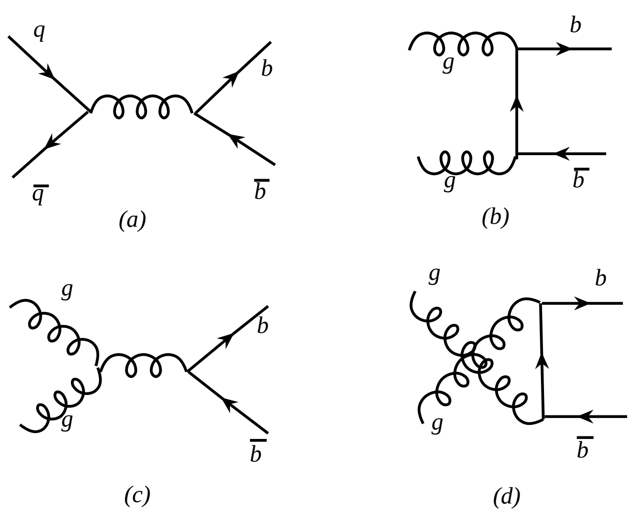
Summary and Outlook

- Many results in heavy hadron spectroscopy: B_s, Λ_b masses, ...
- First result for heavy baryon lifetime from $\Lambda_b \to J/\psi\Lambda$ exclusive channel:
  $c\tau = 374 \pm 78(sta) \pm 29(sys)\ \mu m$
- Confirmed X(3872) discovered by Belle, measured its mass at CDF as:
  $M = 3871.4 \pm 0.7(stat) \pm 0.4(sys)$ MeV
  New studies in progress
- More data coming soon
- Prepare for mixing:
  B^0 as test case, have seen $B_s \to D_s\pi$
  preparing B_s mixing
- More excitement in the future!

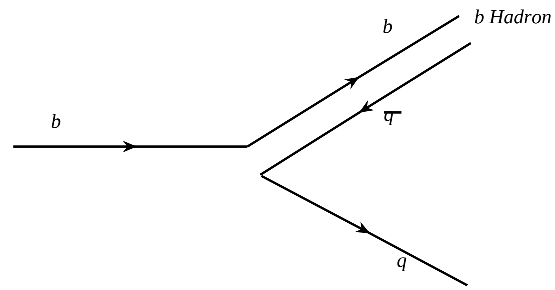
Tevatron B/Charm Physics

- Heavy Flavor(c, b, t) Production
  - Interactions of partons from p and $\bar{p}$
  - Fragmentation thereafter, separately
  - LO: $q\bar{q}$ annihilation (a)$+$ gluon fusion(b,c,d)
  - $q\bar{q}$ dominate, $2M_q/\sqrt{s} \geq 0.1$, t quark
  - Others dominate, $2M_q/\sqrt{s} << 1$, b, c

- Leading order production



- Schematic of fragmentation process



- Higher order b(c,t) production