Heavy Flavor Physics at CDF

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Fermilab CD/CDF

February 5, 2004

Aspen 2004 Winter Conference on Particle Physics

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- Lifetimes
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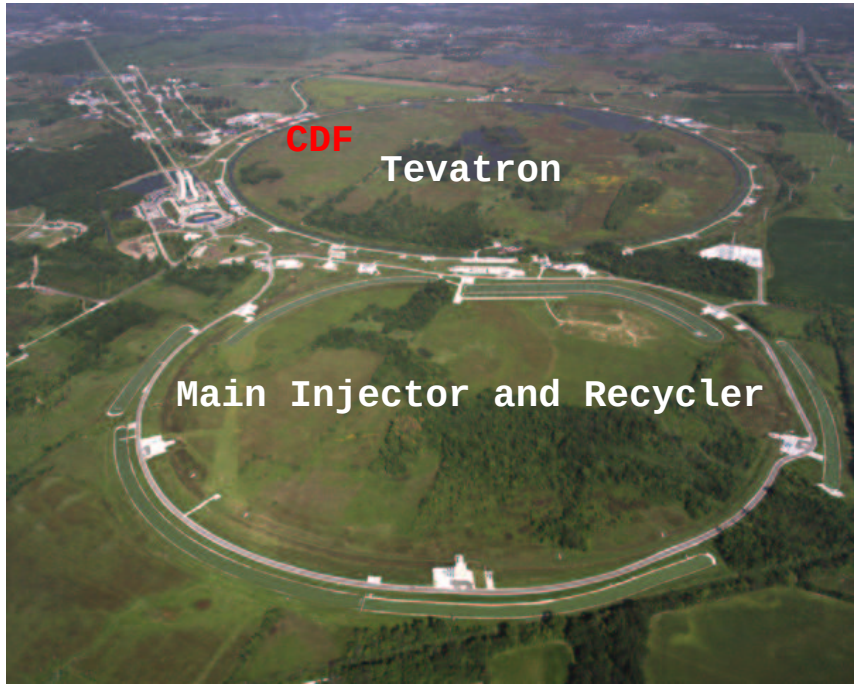
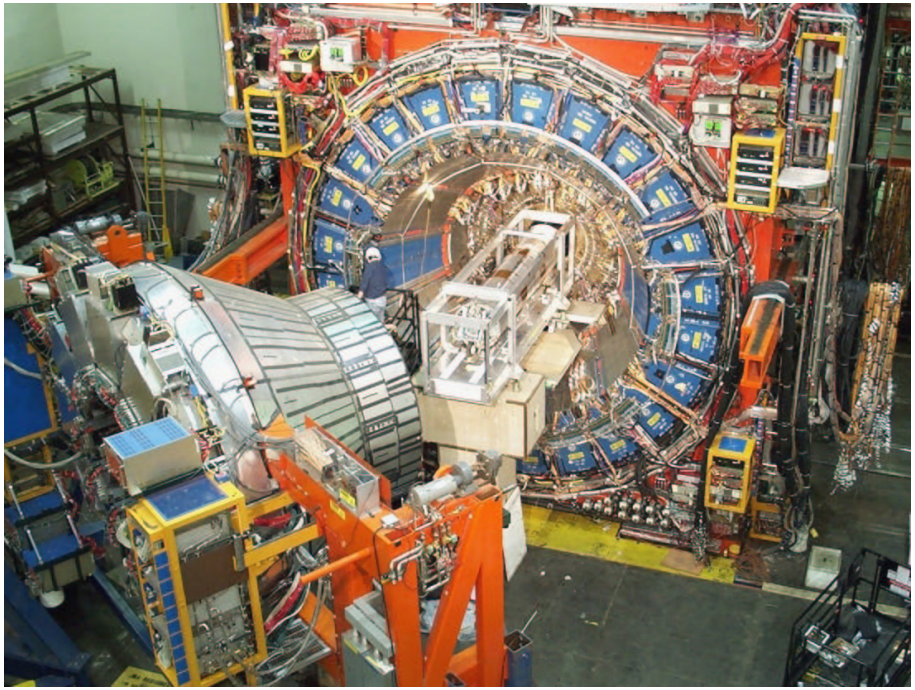
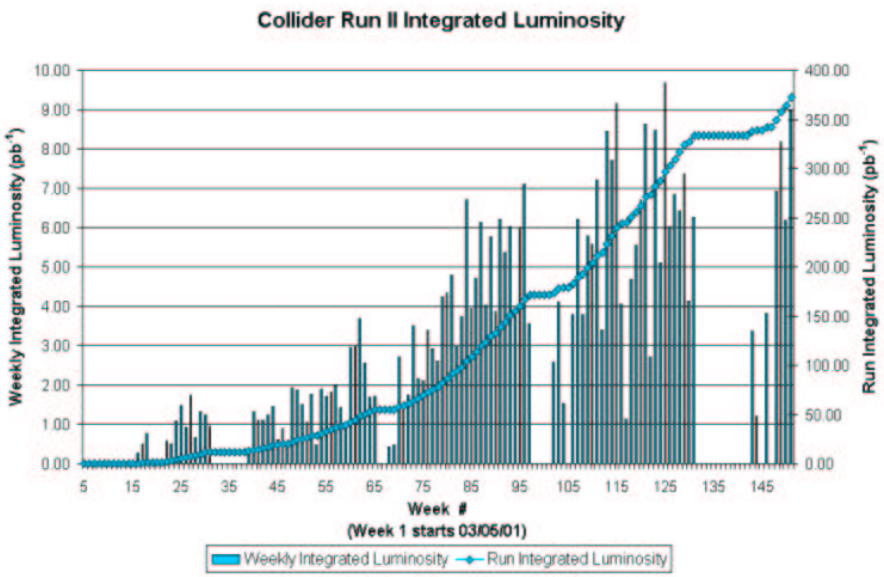
Tevatron at Fermilab

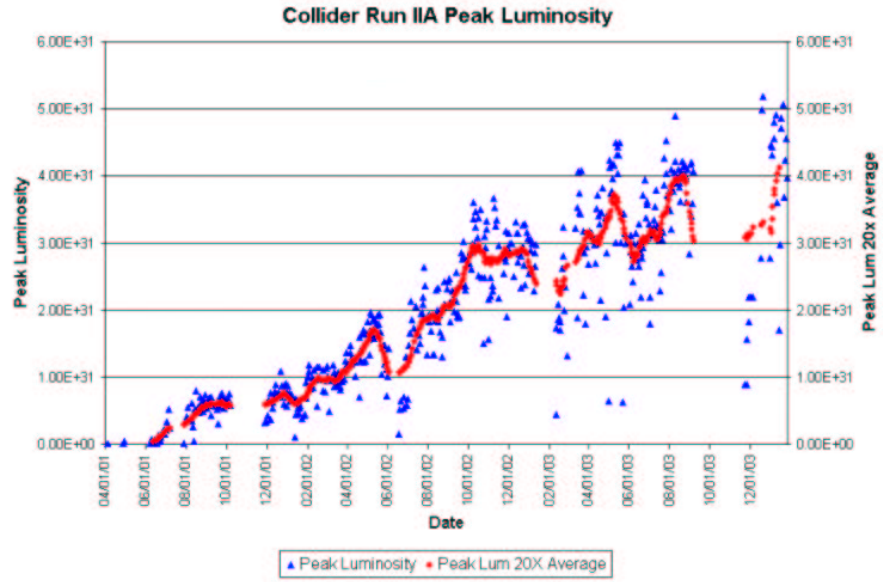


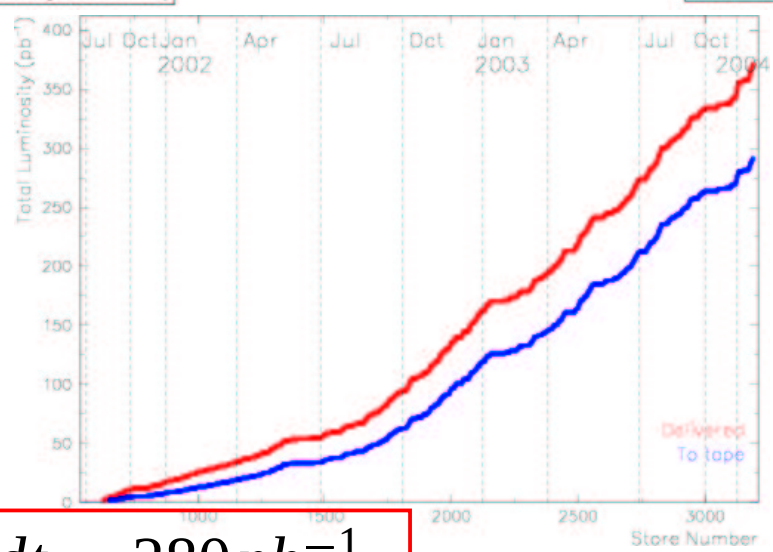


- 1 km ring radius; $p\bar{p}$ collisions, started 1984 $\sqrt{s} = 1.6\ TeV$
- Run I (1992-1995) $\sqrt{s} = 1.8\ TeV$, 6x6 bunches, $\mathscr{L}_{inst} = 1.6 \times 10^{31} cm^{-2} s^{-1}$, $\int \mathscr{L} dt = 110\ pb^{-1}$
- After major upgrade Run II (started 2001):
  - $\sqrt{s} \sim 1.96 TeV$.
  - $10^{11}(10^{10}) p\bar{p}$ per bunch
  - 36x36 colliding $p\bar{p}$ bunches
  - $\mathscr{L}_{inst} = 5.3 \times 10^{31} cm^{-2} s^{-1}$(record) (goal $8.1 \times 10^{31} cm^{-2} s^{-1}$)
  - high beam-beam crossing low pileup

Collider Luminosity

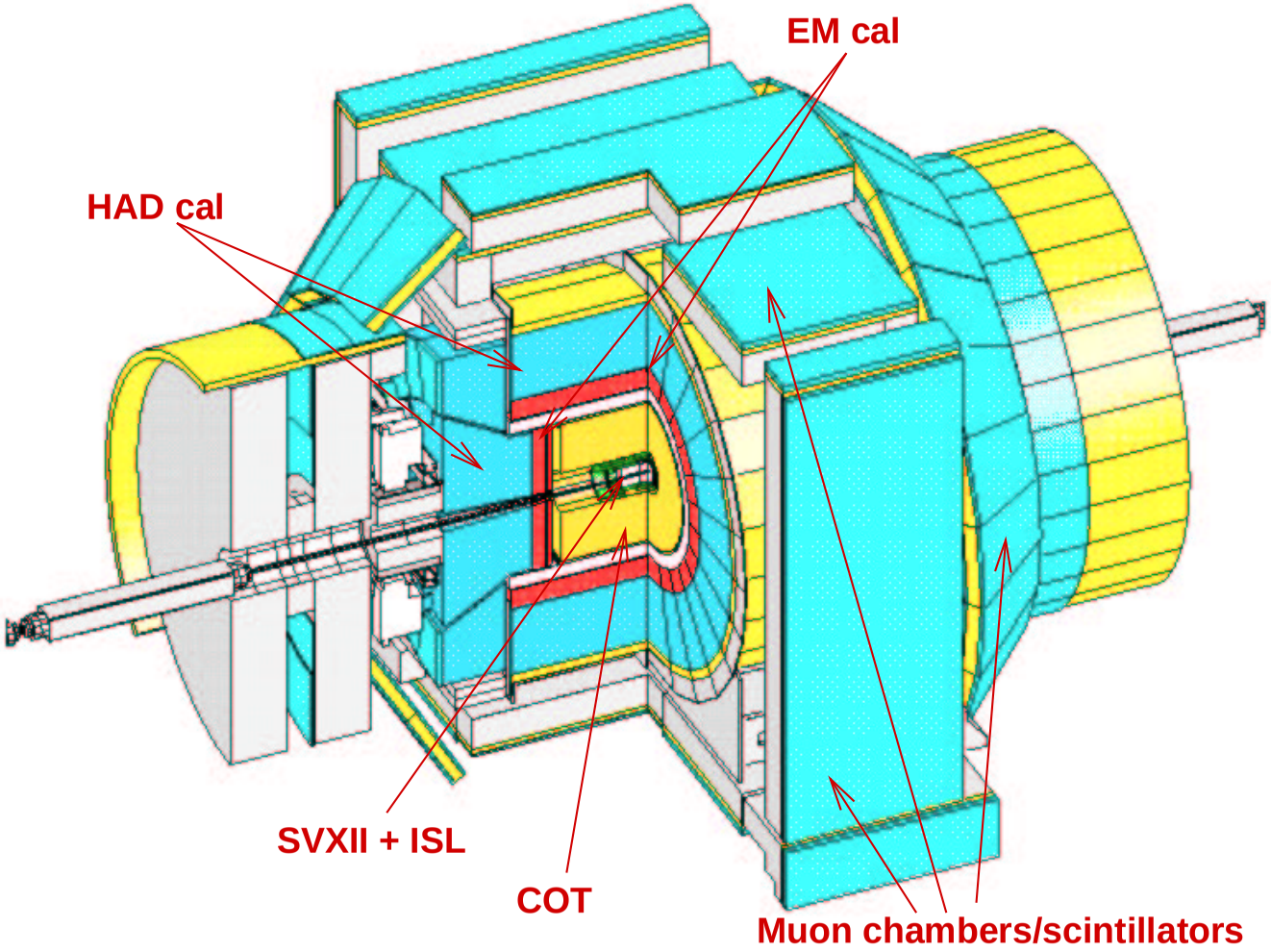






$$\int \mathscr{L} dt = 280 pb^{-1}$$

CDF Run II

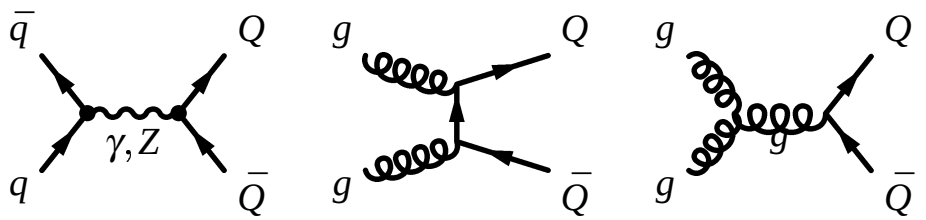


PID using dE/dx and ToF

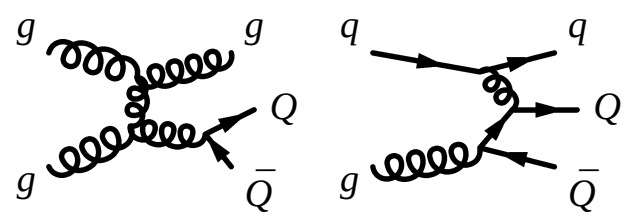
precision vertexing with Layer00

Heavy Flavor Production at Tevatron

LO Heavy quark production



NLO Heavy quark production



Accelerator	PEPII,KEK	Tevatron
$\sigma(b\bar{b})$	1 nb	100 μb
$\sigma(b\bar{b}) : \sigma(had)$	0.26	0.001
Production	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$	$p\bar{p} \to b\bar{b}X$
	coherent production	incoherent production
Environment	clean	messy
Hadrons produced	B^0, B^+	all
Boost	0.5	2-4
Kinematics	forward boost	$b\bar{b}$ not back-to-back, second b usually lost
pile-up	no	yes
Trigger	inclusive	selective
Beam energy constraint	yes	no

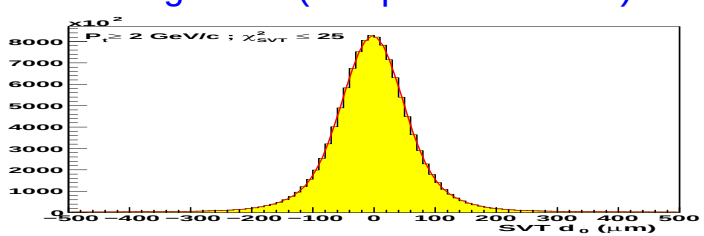
CDF Run II B-triggers

- di-lepton triggers (J/ψ and rare B decays)
- single lepton triggers $p_T > 4\ \mathrm{GeV/c}, \mathrm{p_T} > 8\ \mathrm{GeV/c}$
- New displaced track triggers (two track and ℓ+track):

  - Level 1
    - ✓ XFT tracking in COT $(r-\phi)$
    - ✓ opposite charged track pair with $p_T > 2\ \mathrm{GeV/c}$ each
    - ✓ $\Sigma p_T > 5.5\ \mathrm{GeV/c}$
    - ✓ $\Delta\phi < 135°$
  - Level 2
    - ✓ XFT track seeds SVT boards, that perform fast $(r-\phi)$ track fit
    - ✓ repeat Level 1 cuts
    - ✓ require tracks impact parameter to be $0.012 < |d_0| < 0.1\ \mathrm{cm}$

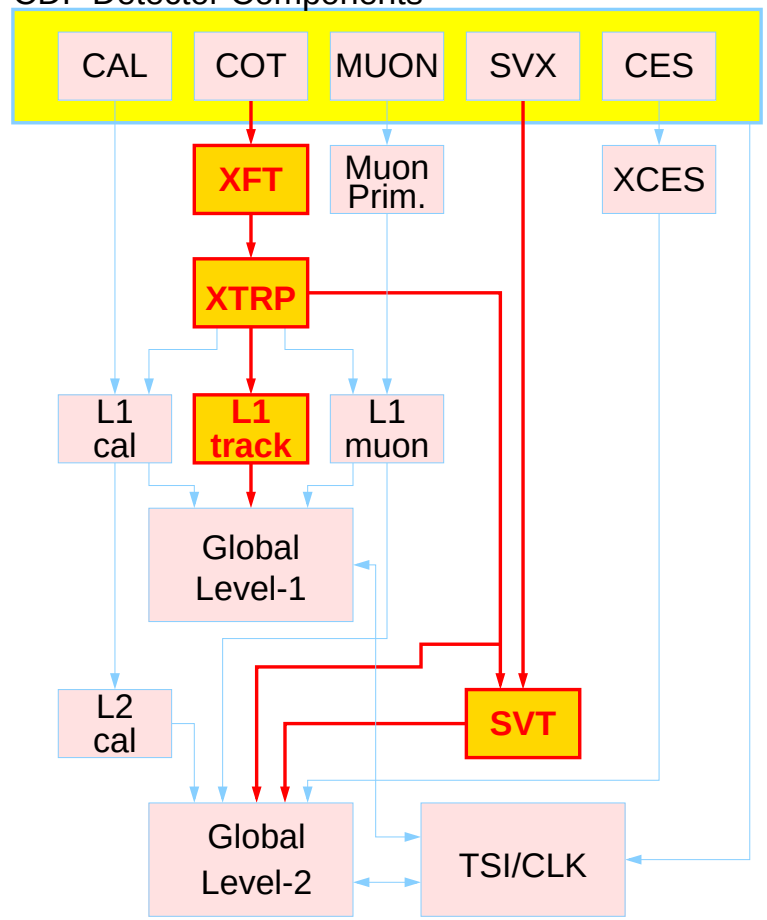
  ℓ+track uses slightly different set of cuts

Hadronic triggers improved B-physics sensitivity by 5 orders of magnitude (compared to Run I)

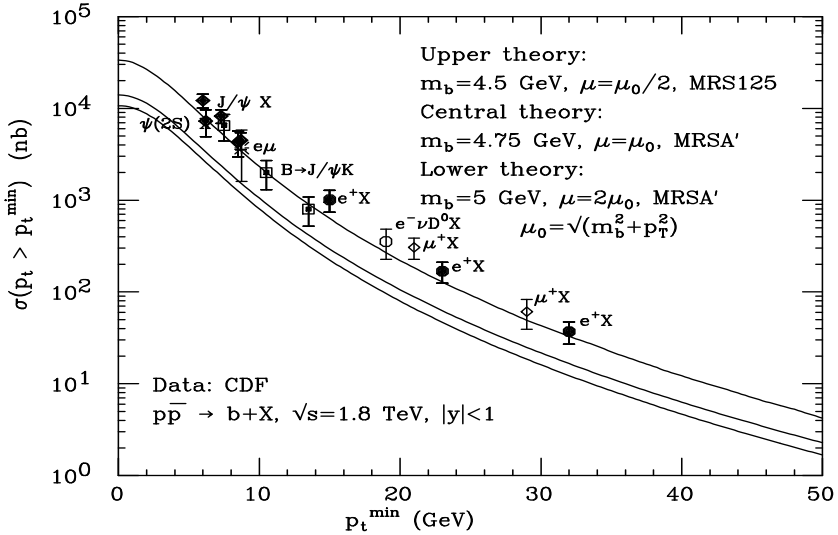


$\sigma(d_0)_{SVT} = 48\ \mu m$ (including $\sigma(beam) = 33\ \mu m$)

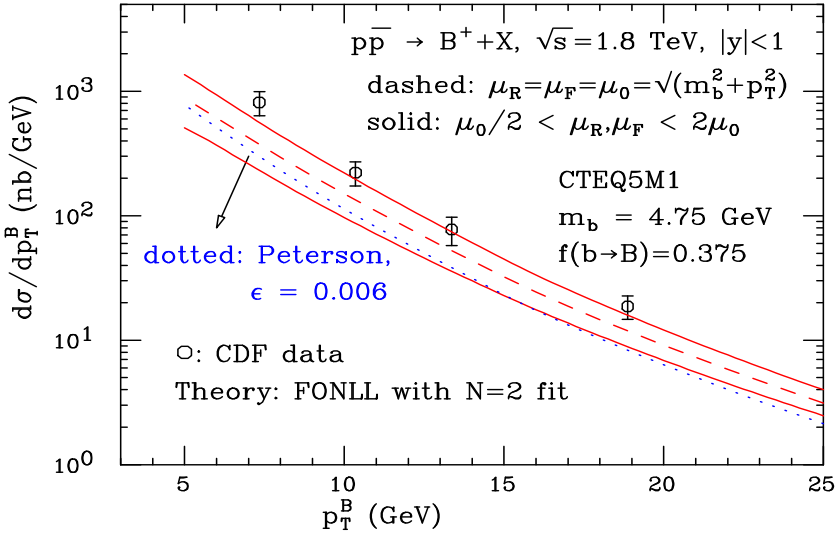
CDF Detector Components



Heavy Flavor Cross-section



e.g. Nucl., Phys., B303 (1988)



Cacciari, Nason PRL 89, 122003 (2002)

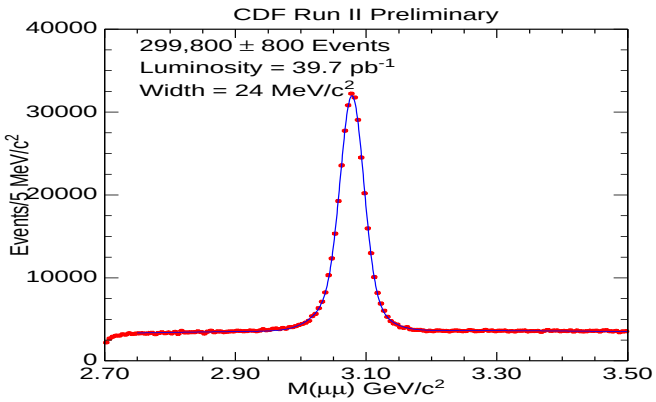
- Tevatron B-hadron cross-sections measured at $\sqrt{s} = 1.8$ TeV for $p_T(B) > 6$ GeV/c consistently higher than NLO QCD calculations (by ≥ 2)
- ongoing theoretical effort to incorporate:
  - Fixed Order (FO) exact NLO calculations for massive quark
  - Resummation of $\log p_T/m_b$ with NLL accuracy
  - Non-perturbative fragmentation functions extracted from LEP and SLC data

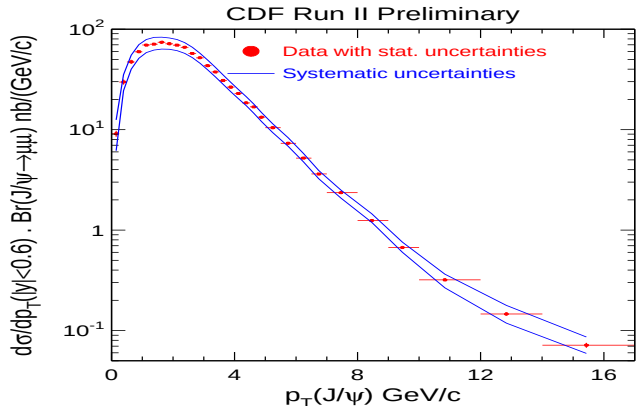
  resulted in greatly improved agreement with Run I b cross-section
- CDF can measure cross-section down to 0 $p_T(B)$

J/ψ Cross-section

- di-muon trigger, $\int \mathscr{L} dt$ = 39.7 pb^{-1}
- central muons
- first measurement down to $p_T(\mu\mu) \geq 0$ GeV/c

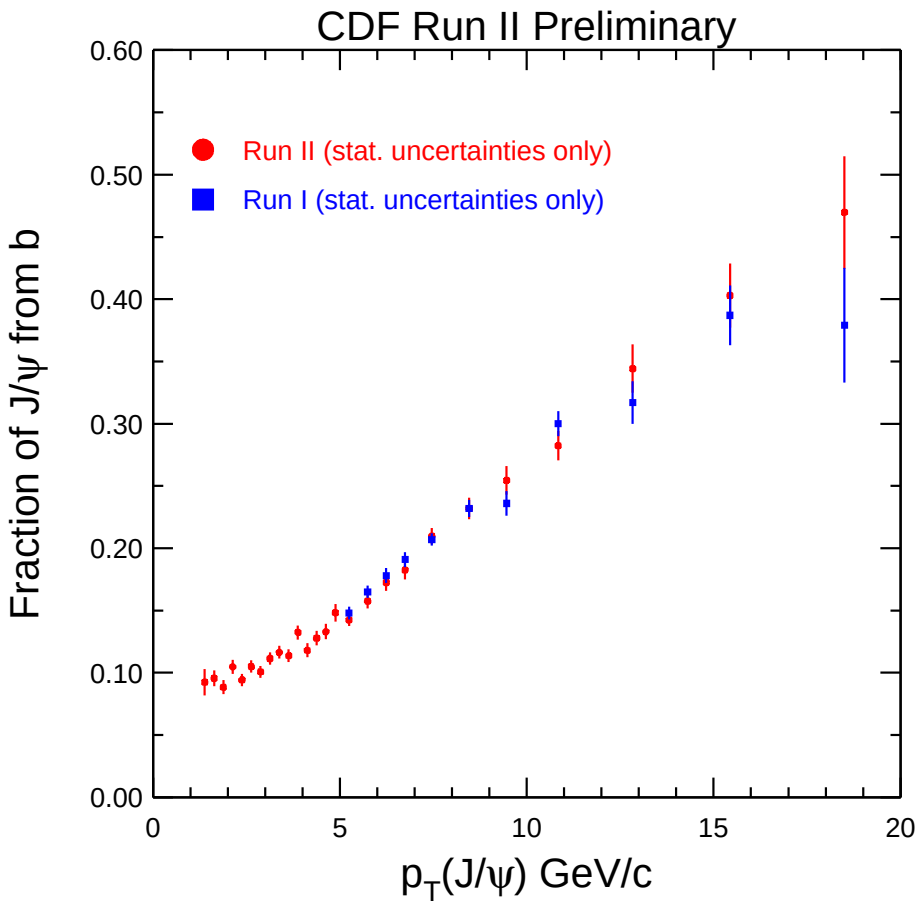
$$\sigma(p\bar{p} \to J/\psi X)|_{|y(J/\psi)|<0.6} = (4.08 \pm 0.02(stat)^{+0.60}_{-0.48}(syst))\ \mu b$$

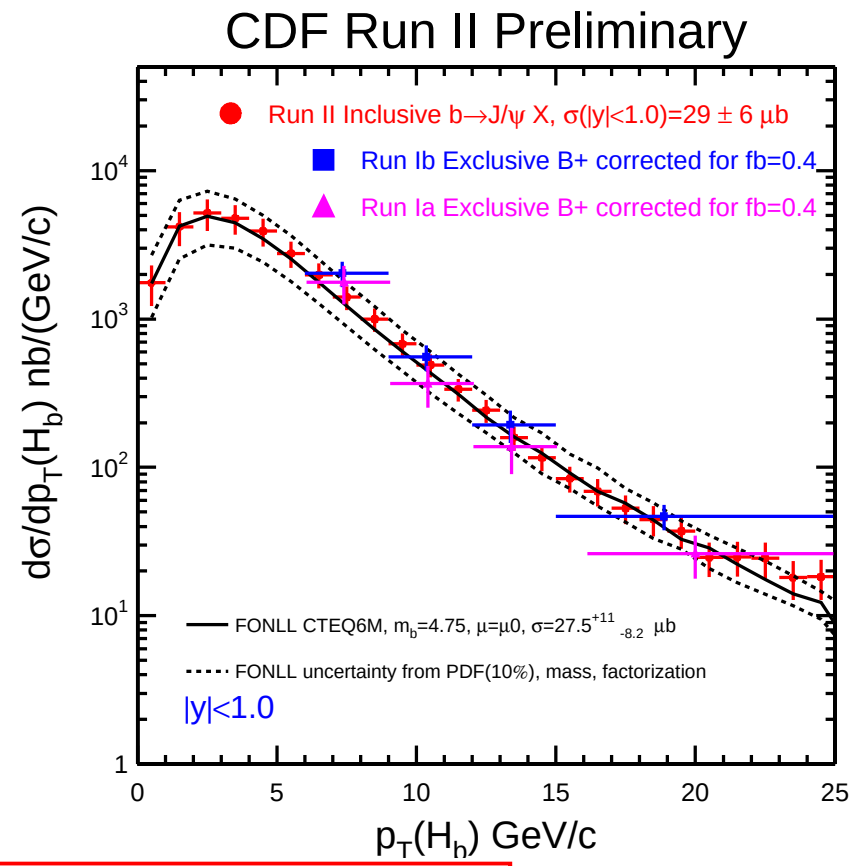




- contains contributions from
  - direct production of J/ψ
  - J/ψ produced in decays of charmonium
  - B-hadron decays 15-20%
- J/ψ from B-hadrons are displaced => fit J/ψ proper time distributions in p_T bins to extract b-fraction.

B-Hadron Cross-section





$$\sigma(p\bar{p} \to bX)|_{|y|<1.0} = (29.4 \pm 0.6(stat) \pm 6.2(sys))\ \mu b$$

FONLL $\sigma(p\bar{p} \to bX)|_{|y|<1.0} = (27.5^{+11}_{-8.2})\ \mu b$

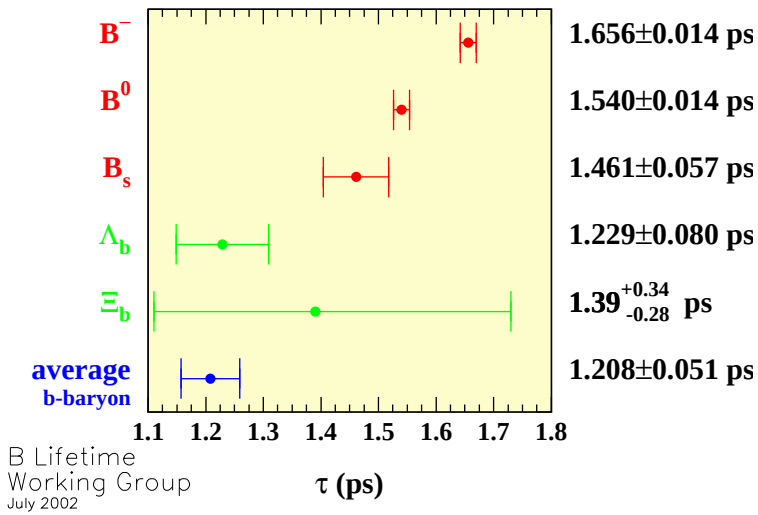
B-Hadron Cross-section

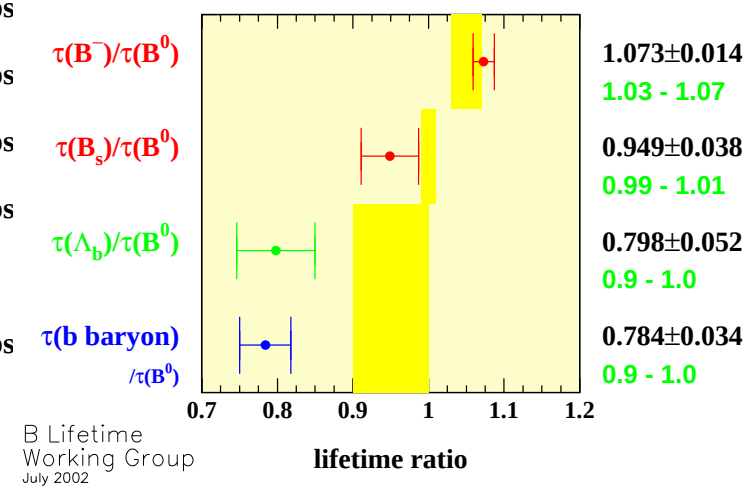
- **Measurement of b cross-section involves inferring b momentum from J/ψ momentum.**
- **Systematic uncertainty is dominated by uncertainty in acceptance calculations. Especially at low muon momentum ($p_T \sim 1.5\ \mathrm{GeV/c}$). Largest single uncertainty is from J/ψ polarization that impacts decay kinematics.**

B-Hadron Lifetimes

- **HQET predicts :**

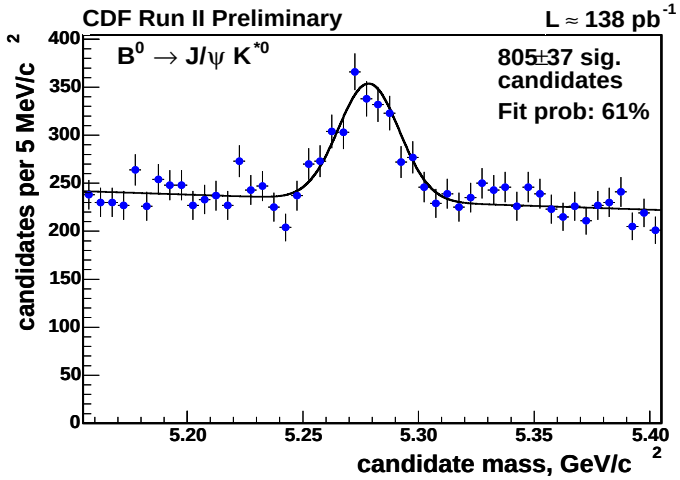
$$\tau_{B^+} \geq \tau_{B^0} \approx \tau_{B_S} > \tau_{\Lambda_b} \gg \tau_{B_c}$$

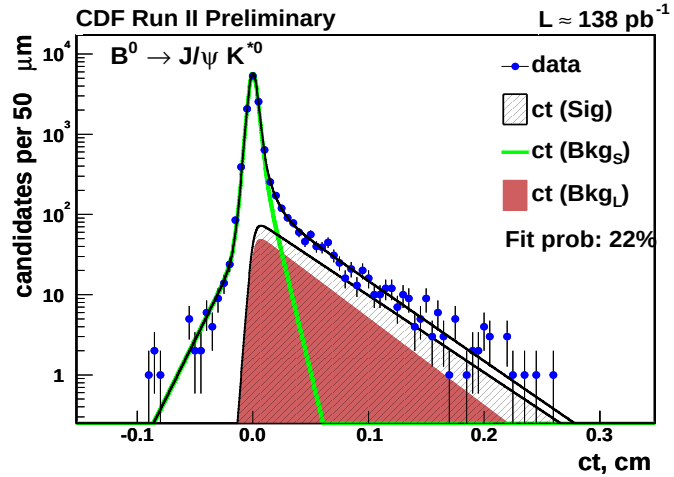




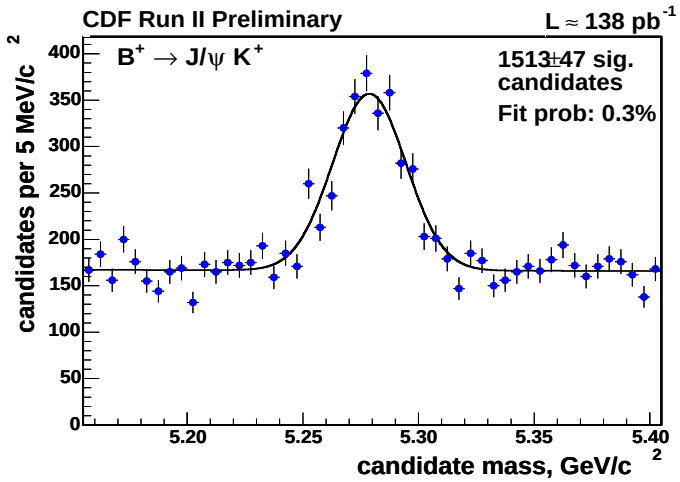
- Λ_b **lifetime lower than predictions**

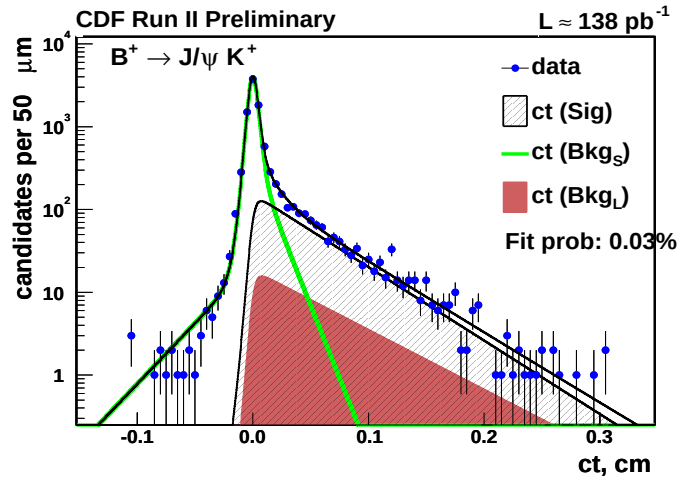
B lifetimes





$$\tau_{B^0} = (1.51 \pm 0.06(stat) \pm 0.02(syst))\ ps$$

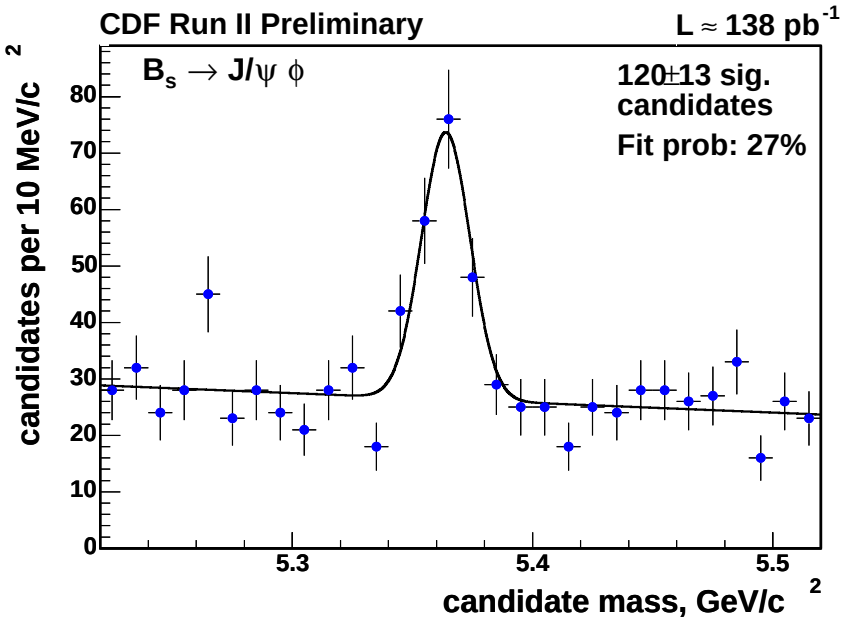


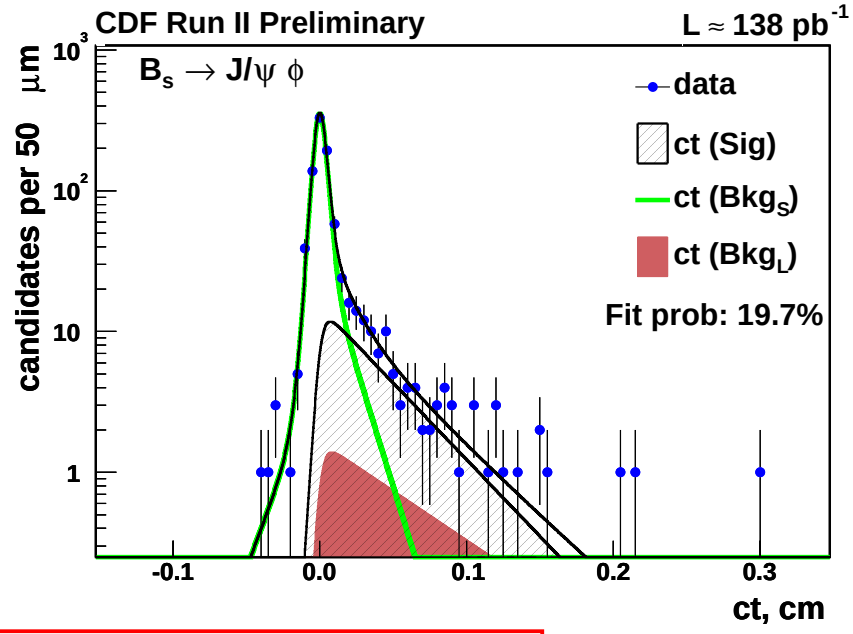


$$\tau_{B^+} = (1.63 \pm 0.05(stat) \pm 0.04(syst))\ ps$$

B_s lifetime

- $B_s \to J/\psi\phi,\ J/\psi \to \mu\mu,\ \phi \to K^+K^-$





$$\tau_{B_s} = (1.33 \pm 0.14(stat) \pm 0.02(syst))\ ps$$

lifetimes summary

Parameter	$B^+ \to J/\psi K^+$	$B^0 \to J/\psi K^+$	$B_s \to J/\psi \phi$	Units
M	5278.7 ± 0.5	5278.5 ± 0.5	5363.9 ± 1.1	$\mathrm{MeV/c^2}$
ct	490 ± 15	453 ± 19	399 ± 43	$\mu\mathrm{m}$
N_{events}	1513 ± 47	805 ± 37	120 ± 13	

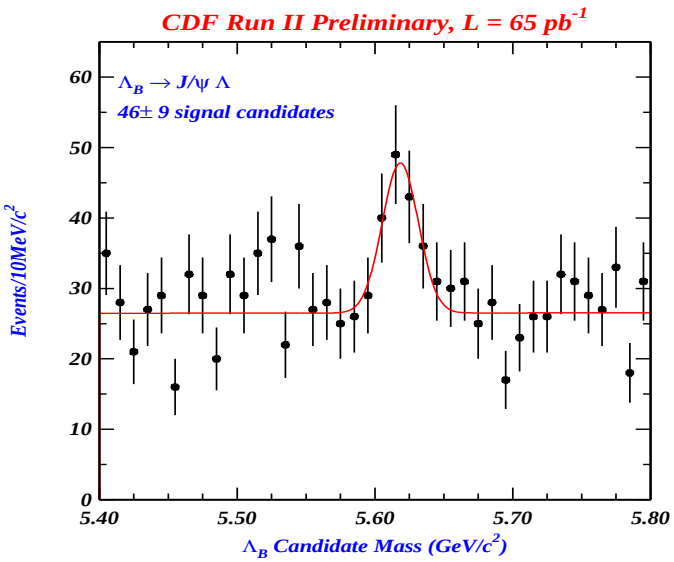
- fit results summary

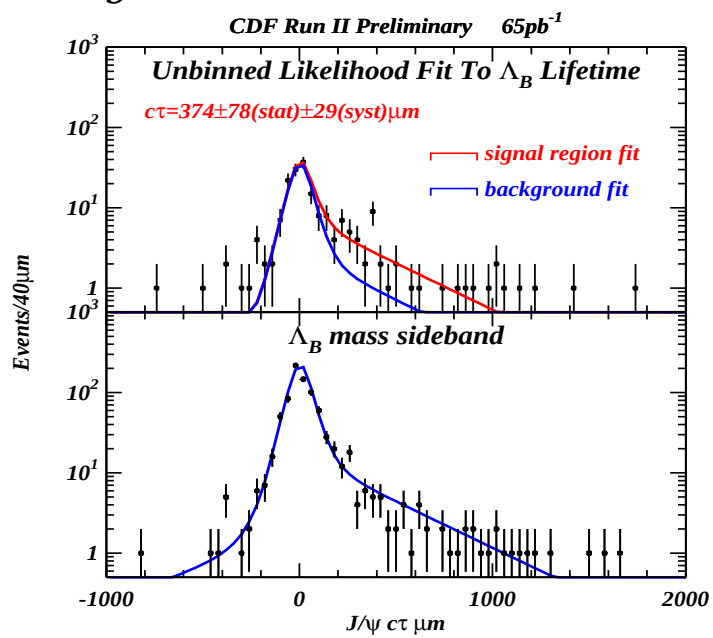
	CDF (ps)	PDG (ps)
B^+	$1.63 \pm 0.05(stat) \pm 0.04(syst)$	1.674 ± 0.018
B^0	$1.51 \pm 0.06(stat) \pm 0.02(syst)$	1.542 ± 0.016
B_s	$1.33 \pm 0.14(stat) \pm 0.02(syst)$	1.461 ± 0.057

- Main sources of systematic uncertainties - SVX detector alignment and modeling of resolution function
- Measurements are still statistically limited but that improves as more data gets analyzed

Λ_b lifetime

- $\Lambda_b \to J/\psi\Lambda, J/\psi \to \mu\mu, \Lambda \to p\pi$
- **first measurement using exclusive Λ_b reconstruction**





$$\tau_{\Lambda_b} = (1.25 \pm 0.26(stat) \pm 0.10(syst))\ ps$$

- **previous measurements (LEP/CDF) used ($\Lambda_c \ell$) - different systematics**

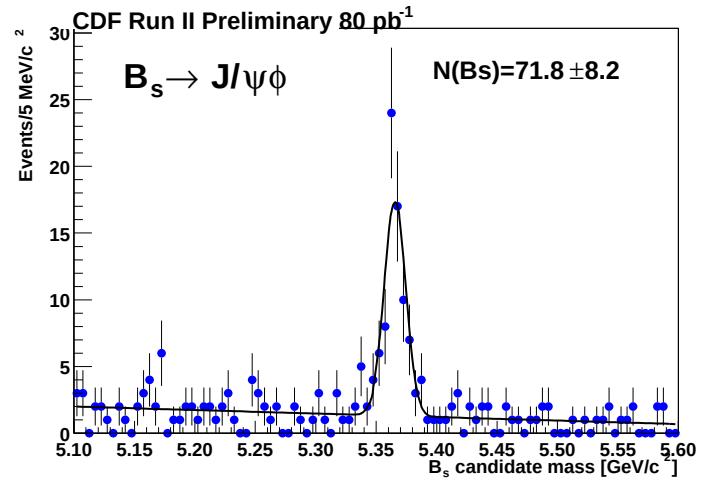
B-Hadron masses

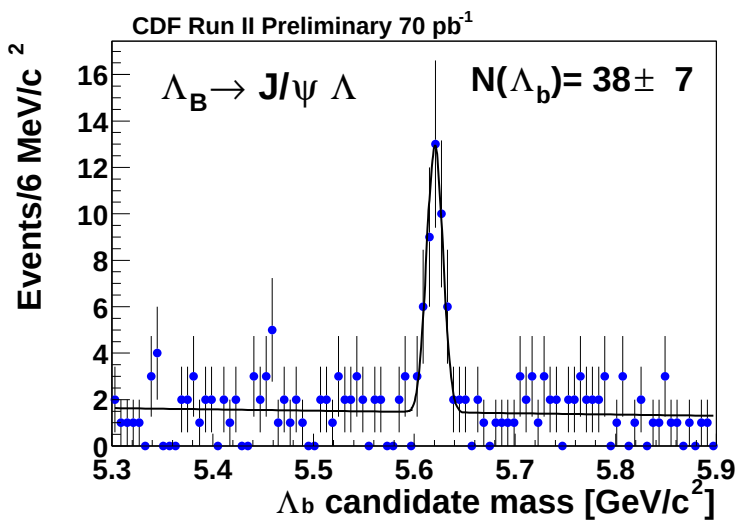
- measure masses in fully reconstructed $B \to J/\psi X$ modes
- use high statistics $J/\psi \to \mu\mu$ and $\psi(2S) \to J/\psi\pi\pi$ to calibrate tracking momentum scale
- systematic uncertainties in tracking momentum scale are due to:
  - magnetic field
  - material description
- results with 80 pb^{-1} of data:

$$m_{B^0} = (5280.30 \pm 0.92 \pm 0.96)\ \mathrm{MeV/c^2}$$
$$m_{B^+} = (5279.32 \pm 0.68 \pm 0.94)\ \mathrm{MeV/c^2}$$

- consistent with PDG average
- B_s and Λ_b are world's best

$$m_{B_s} = (5365.50 \pm 1.29 \pm 0.94)\ \mathrm{MeV/c^2}$$
$$m_{\Lambda_b} = (5620.4 \pm 1.6 \pm 1.2)\ \mathrm{MeV/c^2}$$





X(3870)

- new narrow state observed by Belle using exclusive $B^+ \to J/\psi\pi^+\pi^-K^+$
- charmonium state? or $D^0\bar{D}^{*0}$ molecule?

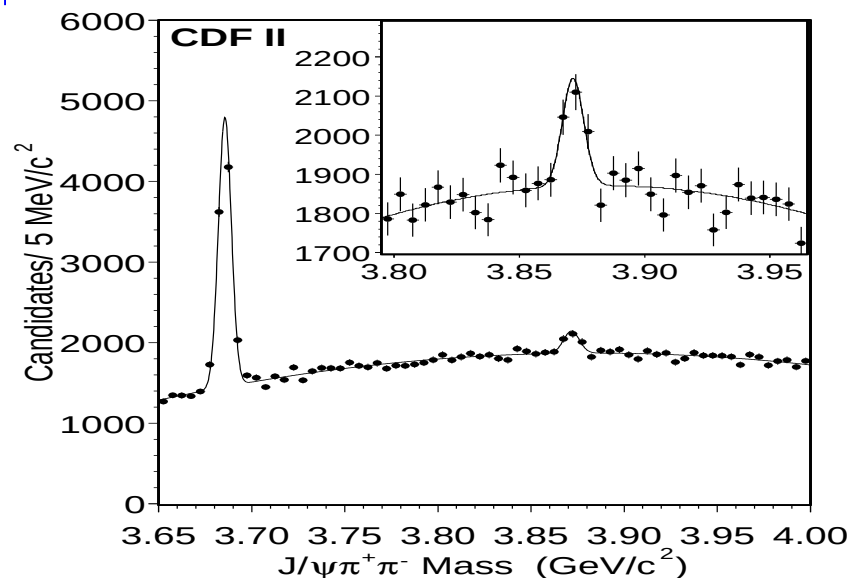
- using 220 pb^{-1} ($\sim$ 2M $J/\psi \to \mu\mu$ decays) CDF produced first confirmation of Belle result in the inclusive $p\bar{p} \to J/\psi\pi^+\pi^-X$ production
- cuts optimized on $\psi(2S)$ signal
- pions required to be in a cone $\sqrt{\Delta\phi^2+\Delta\eta^2} < 0.7$ around $J/\psi\pi\pi$ system momentum direction
- $p_T(J/\psi) > 4$ GeV/c

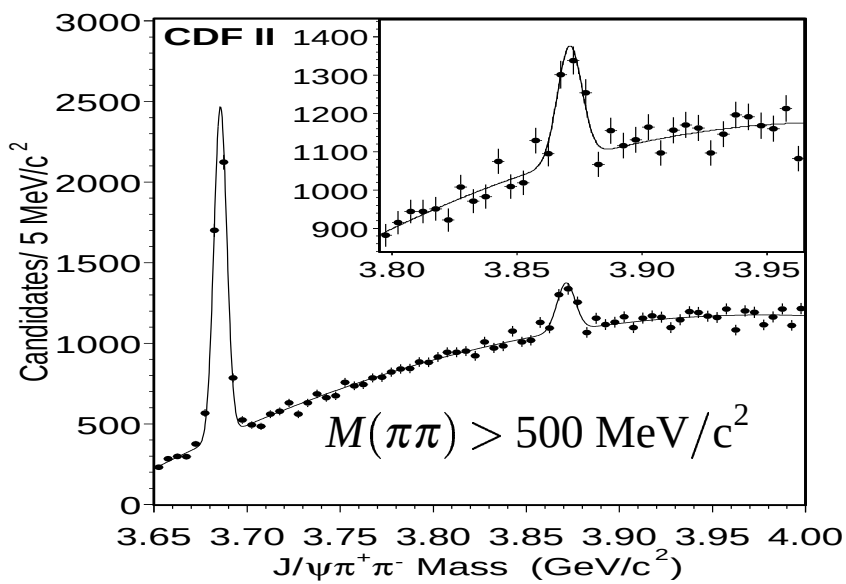
☛ 730 ± 90 around 3870 $\mathrm{MeV/c^2}$

CDF: $m_{X(3870)} = (3871.3 \pm 0.7 \pm 0.4)\ \mathrm{MeV/c^2}$

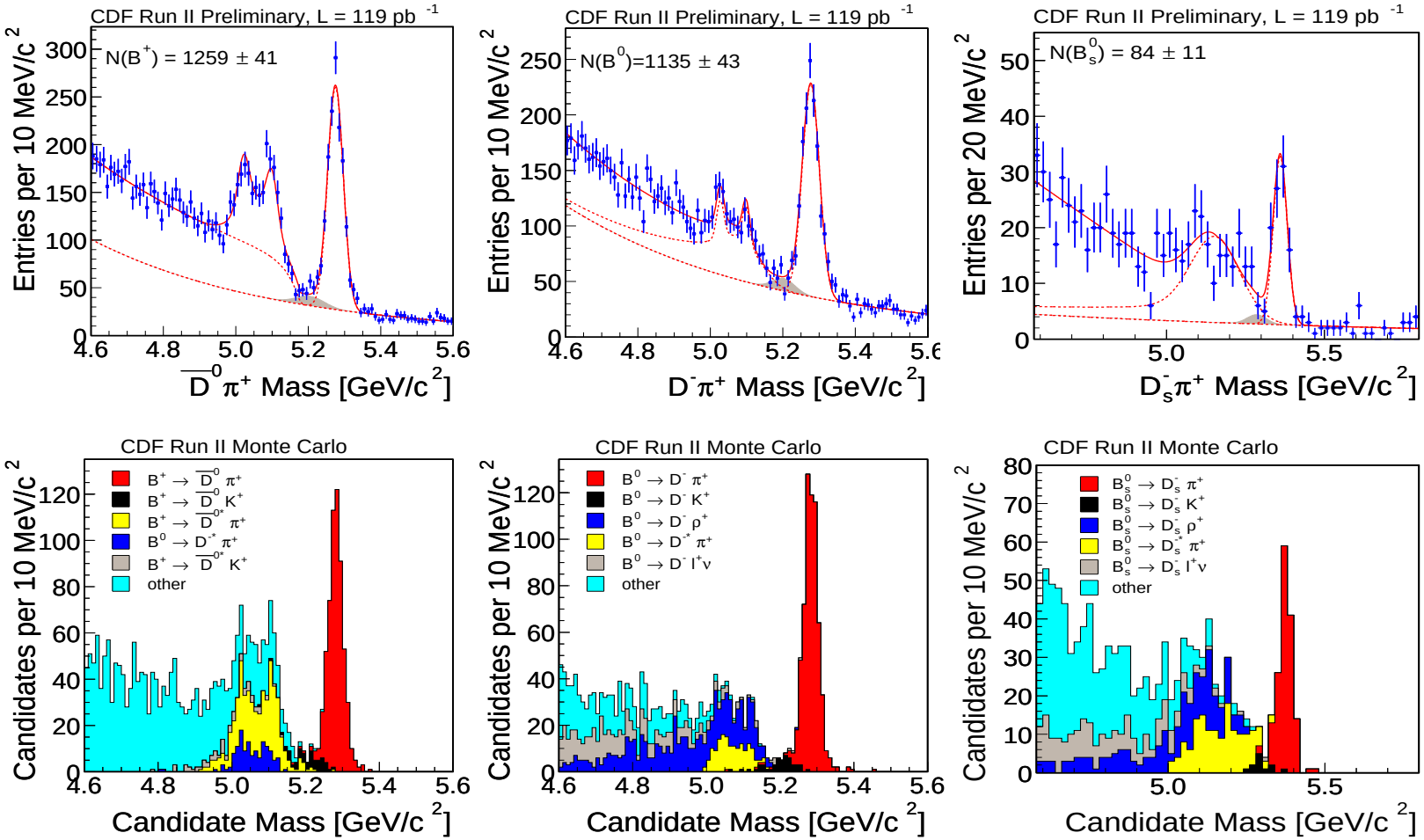
Belle: $m_{X(3870)} = (3872.0 \pm 0.6 \pm 0.5)\ \mathrm{MeV/c^2}$

- Statistically sound sample of X(3870) warrants further studies:
  - lifetime
  - angular analysis
  - $M(\pi\pi)$ analysis





$B_{(s)}^{(0,+)} \to \bar{D}_{(s)}^{(0,-)}\pi^+$



- new measurement

$$Br(B_s \to D_s^+\pi^-) = (4.8 \pm 1.2(stat) \pm 1.8(Br) \pm 0.6(f_s/f_d) \pm 0.8(syst)) \times 10^{-3}$$

$\Lambda_b \to \Lambda_c \pi$

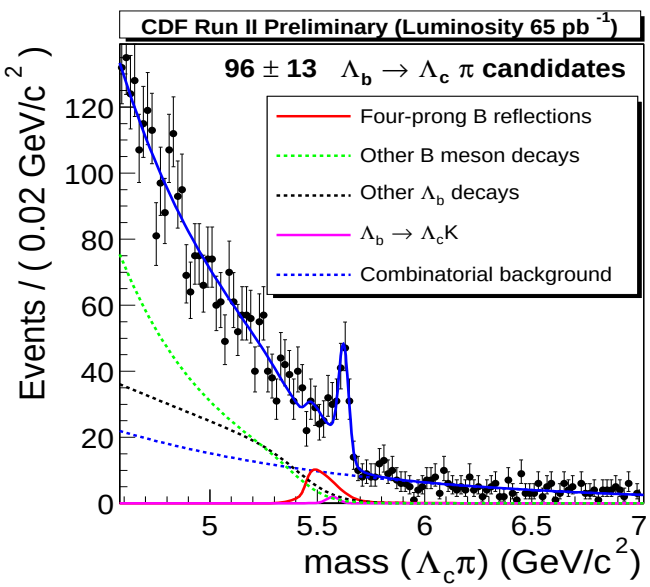
- Backgrounds: real B decays, pion misidentified as proton
- Use MC to parametrized the shape
- Data to normalize the amplitude

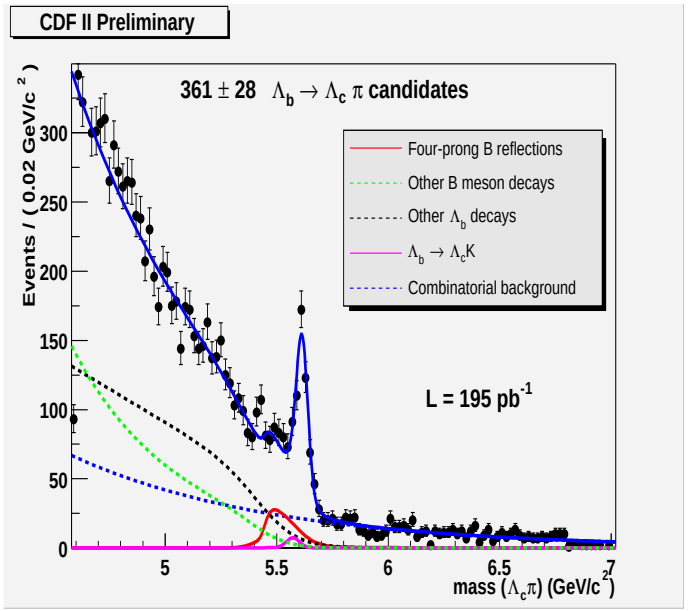
$$N_{\Lambda_b} = (96 \pm 13(stat)^{+6}_{-7}(syst))$$

☛ Measure :

$$\frac{\sigma_b \times f_{baryon} \times Br(\Lambda_b \to \Lambda_c \pi^-)}{\sigma_b \times f_d \times Br(B^0 \to D^- \pi^+)}$$

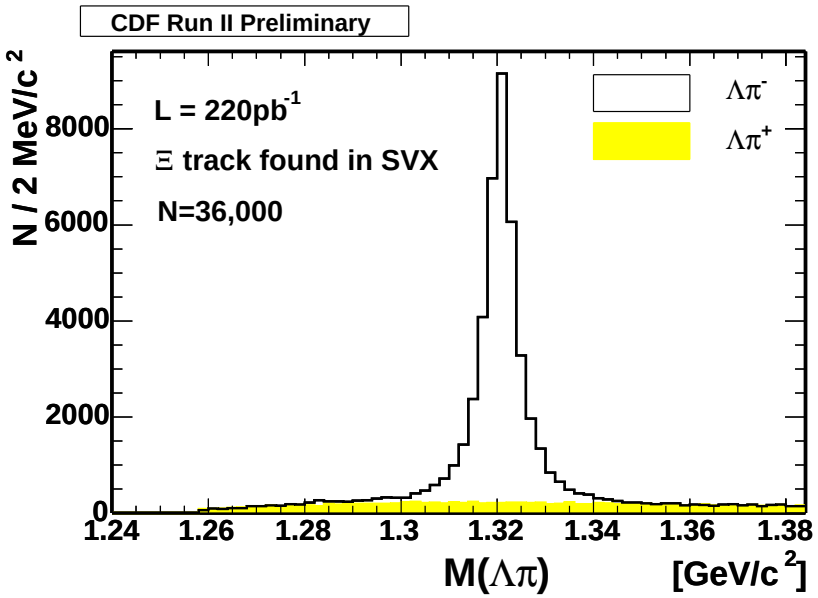
$$\boxed{Br(\Lambda_b \to \Lambda_c \pi^-) = (6.0 \pm 1.0(stat) \pm 0.8(sys) \pm 2.1(Br)) \times 10^{-3}}$$

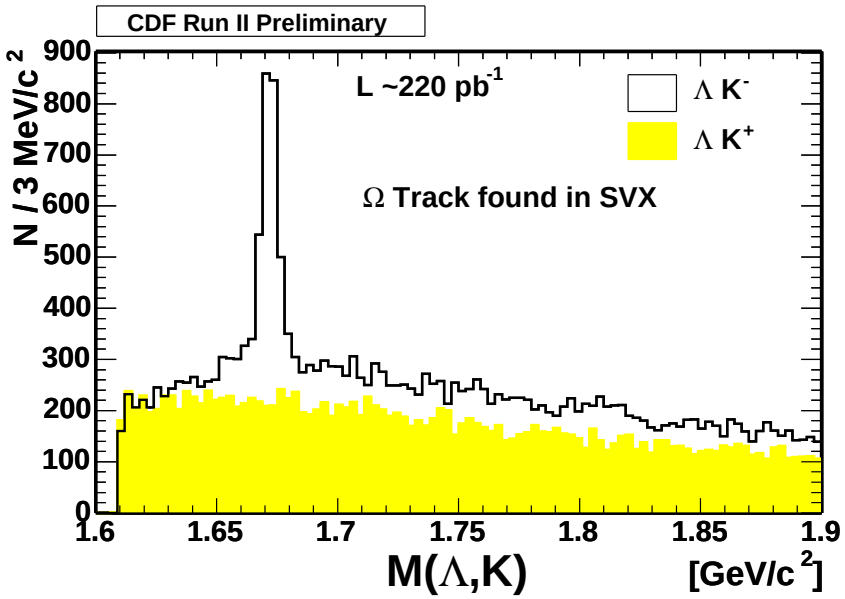




Other Baryons

- CDF has developed tracking of long lived hyperons (Ξ and Ω) in the SVX detector.
- silicon tracking of hyperons improves momentum and impact parameter resolution as well as results in excellent background suppression





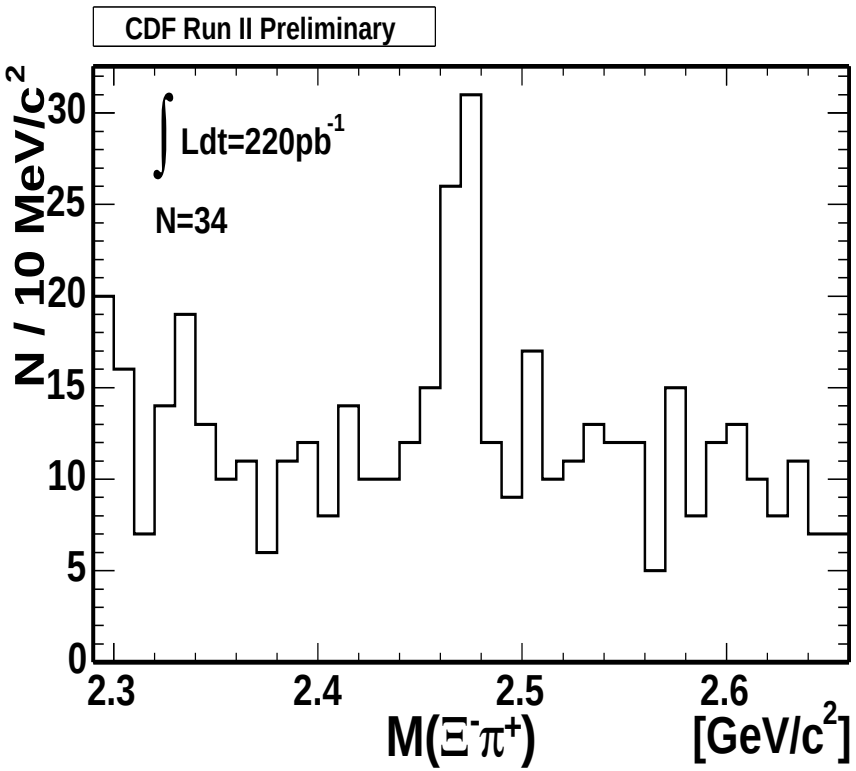
Two Track trigger data

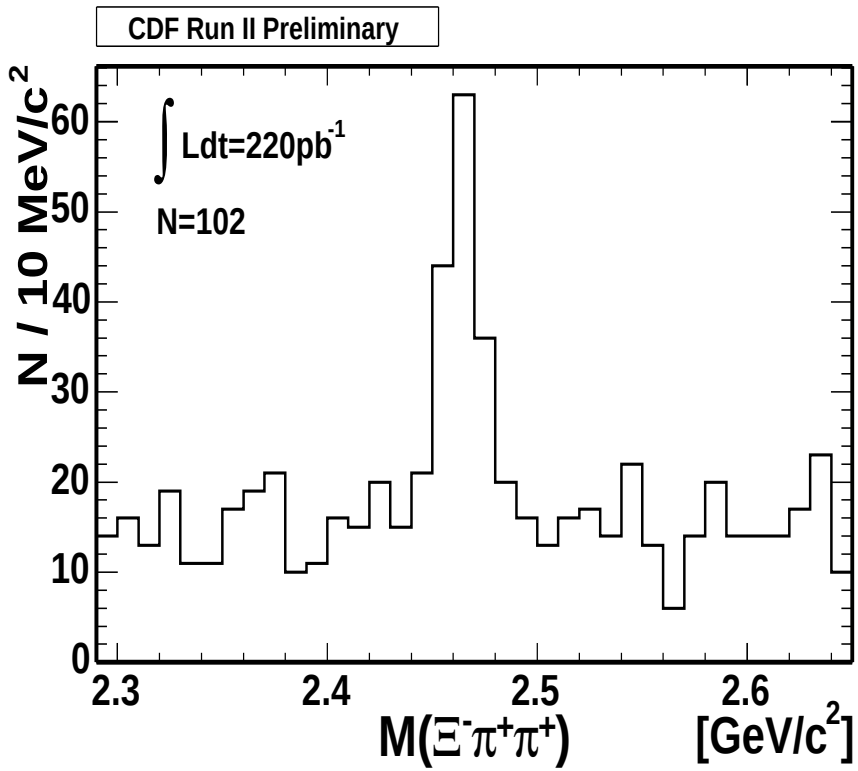
- hyperon tracks reconstructed in SVX are used to probe production of Ξ_b and Ω_b in decays accessible to CDF triggers

charmed-strange baryons

$$\Xi_c^0 \to \Xi^- + \pi^+ \quad , \Xi_c^+ \to \Xi^- + \pi^+\pi^+$$

$$\hookrightarrow \Lambda\pi^- \qquad\qquad \hookrightarrow \Lambda\pi^-$$

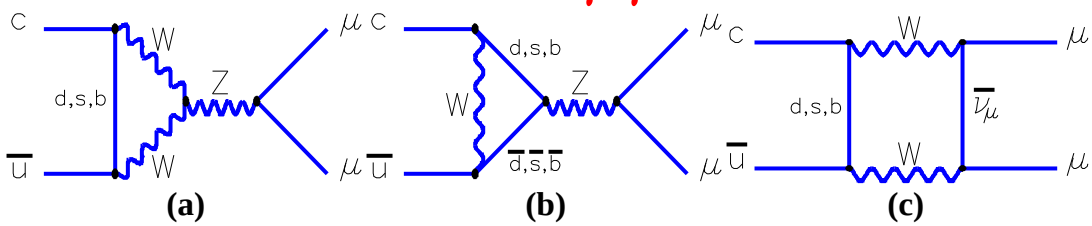




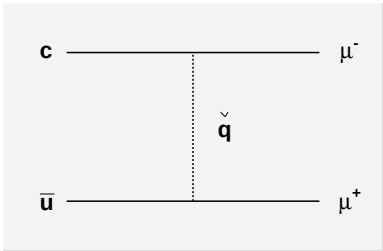
First observation of charmed-strange isodoublet $\left\{\Xi_c^0, \Xi_c^+\right\}$ in $p\bar{p}$

Rare Decays

$D^0 \to \mu\mu$

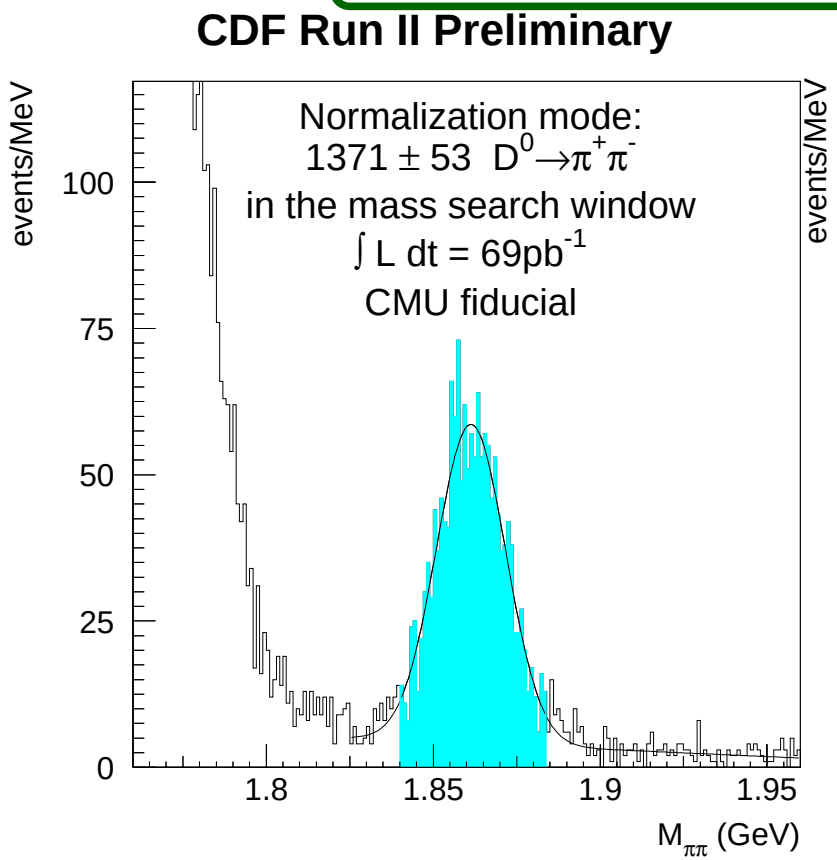


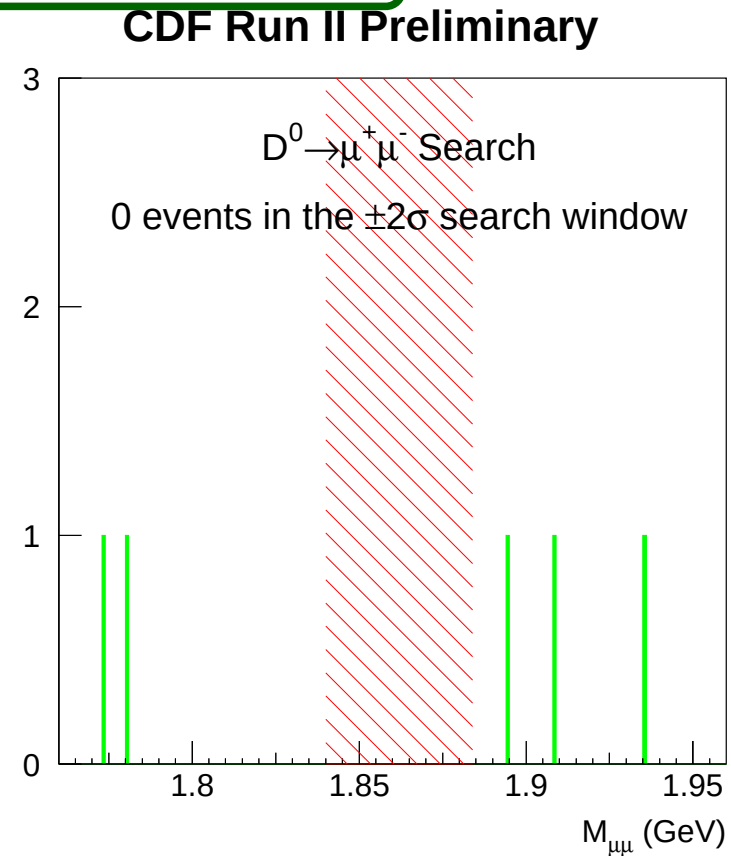
- **SM Br($D^0 \to \mu\mu$)**$\sim 10^{-13}$
- **Non SM physics may enhance the branching to** $\sim 10^{-6}$**. e.g. R-parity violating SUSY:**



- **use** $D^* \to D^0\pi$ **to reduce background**
- **search for** $D^0 \to \mu\mu$ **in two track sample, normalize to** $D^0 \to \pi\pi$ **– systematics and trigger efficiencies cancel**

$D^0 \to \mu\mu$





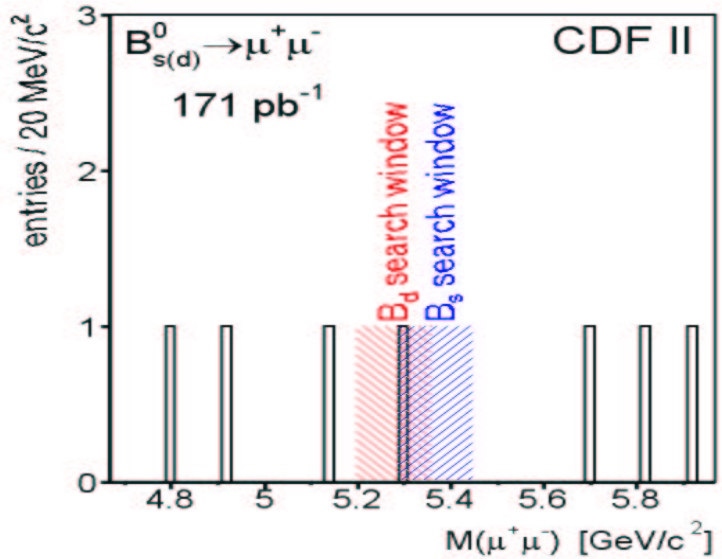
- 1.8 ± 0.7 background events (from high mass sideband)
- "open box" saw 0 events
- $Br(D^0 \to \mu\mu) \leq 2.4 \times 10^{-6}$ @ 90% CL
- about twice better than previous limit!

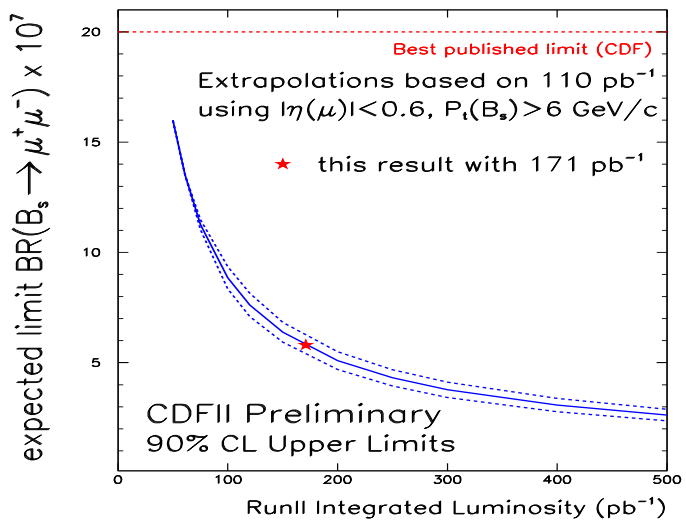
$B_{s,d} \to \mu\mu$

- blind analysis, $171\ pb^{-1}$, rare B trigger di-muon data
- observe 1 event
- expected (backgr) 1.05 ± 0.30 (B_s) and 1.07 ± 0.31 (B_d)
- Branching ratios:

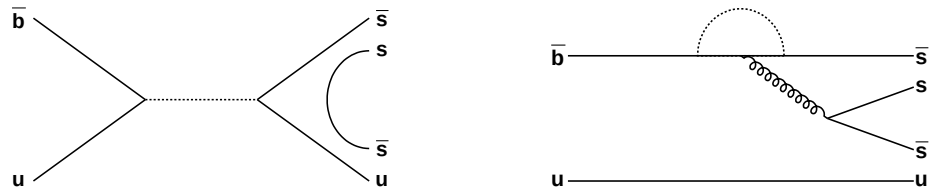
$$B(B_s^0 \to \mu\mu) \leq (5.8 \times 10^{-7}) \text{ @ 90\% CL}$$
$$B(B_s^0 \to \mu\mu) \leq (7.7 \times 10^{-7}) \text{ @ 95\% CL}$$
$$B(B_d^0 \to \mu\mu) \leq (1.5 \times 10^{-7}) \text{ @ 90\% CL}$$
$$B(B_d^0 \to \mu\mu) \leq (1.9 \times 10^{-7}) \text{ @ 95\% CL}$$

- limit on B_s is a factor of 3 better than previously published (CDF).
- limit on B_d is slightly better than Belle's

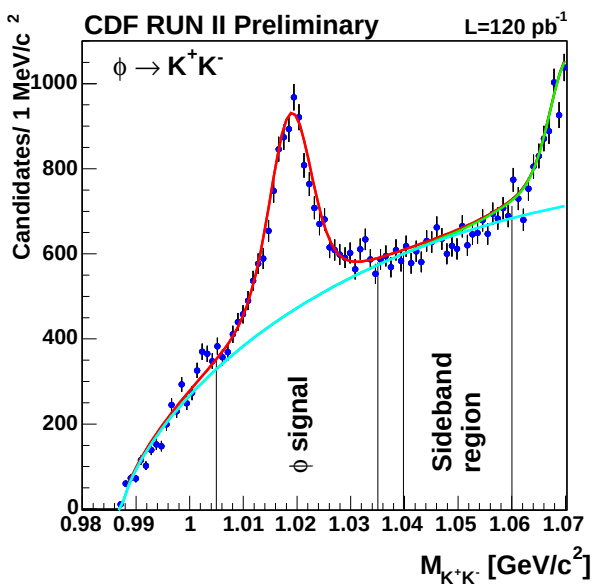


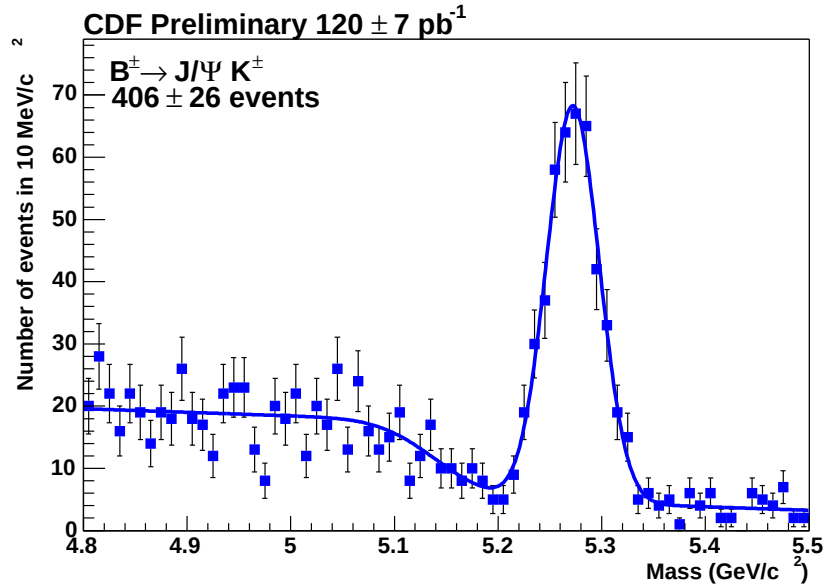


$B^+ \to \phi K^+$

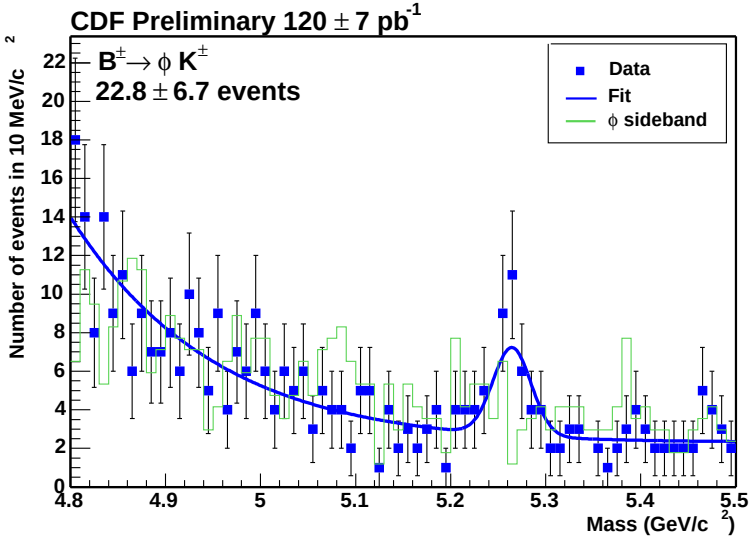


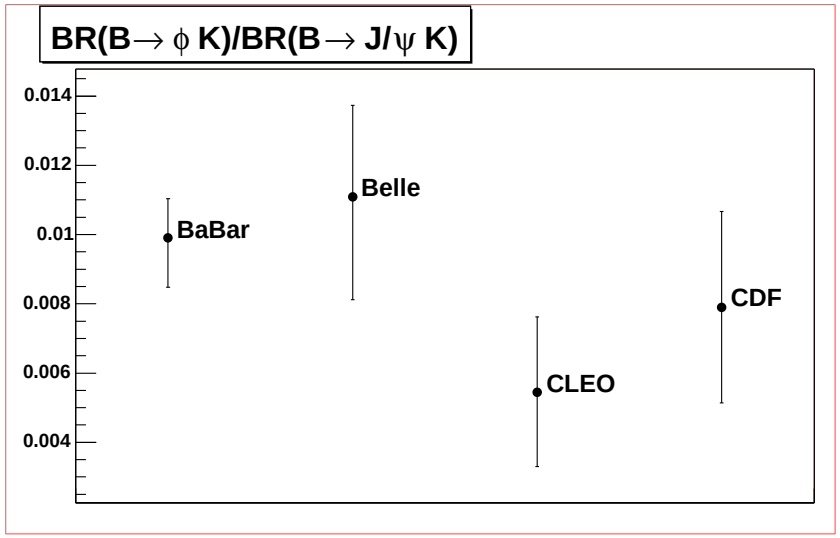
- measure $Br(B^+ \to \phi K^+)/Br(B^+ \to J/\psi K^+)$ ratio using 120 pb^{-1} of two track sample
- $J/\psi \to \ell\ell$, $\ell = \mu, e$; $\phi \to K^+K^-$





$B^+ \to \phi K^+$





$$\frac{Br(B^+ \to \phi K^+)}{Br(B^+ \to J/\psi K^+)} = (0.68 \pm 0.21(stat) \pm 0.07(syst)) \times 10^{-2}$$

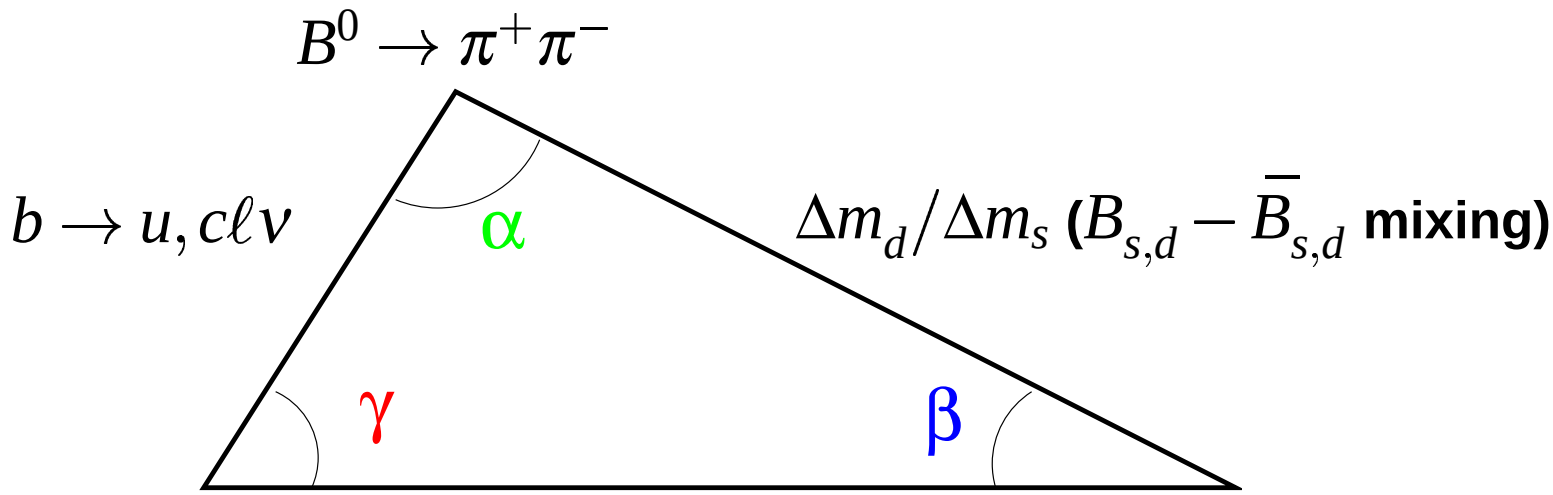
$$Br(B^+ \to \phi K^+) = (6.9 \pm 2.1(stat) \pm 0.8(syst)) \times 10^{-6}$$

PDG'2002 value

$$Br(B^+ \to \phi K^+) = (7.9^{+2.0}_{-1.8}) \times 10^{-6}$$

$B \to hh$

- **angle γ can be extracted from $B_s \to KK$ decay**
- **$\Delta m_d/\Delta m_s$ side of the triangle is extracted from $B_{s,d} - \bar{B}_{s,d}$ mixing measurements**

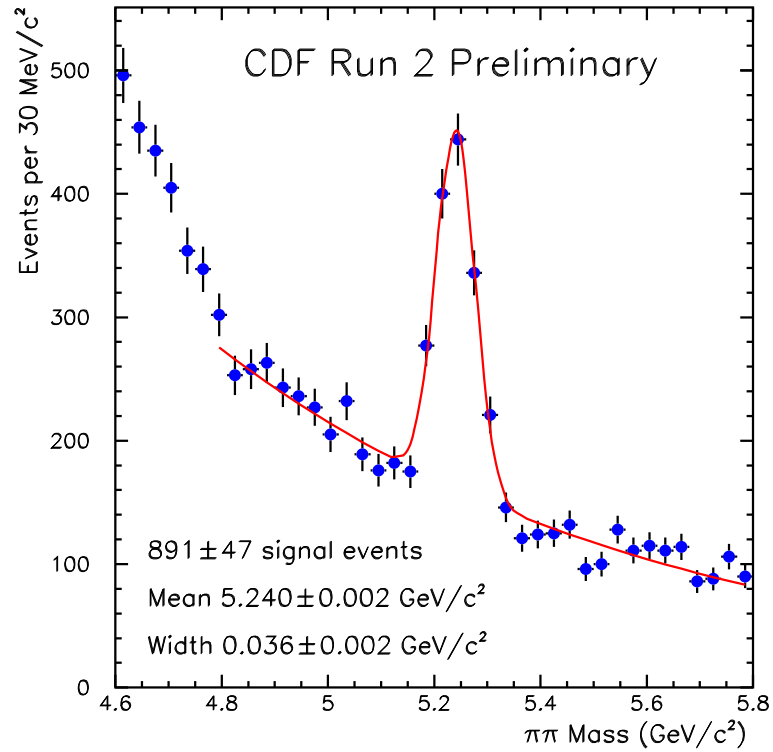


$B^+ \to D^0 K^+$
$B_s \to D_s^- K^+$
$B_s \to K^+ K^-$

$B^0 \to J/\psi K_S^0$
$B^0 \to \phi K_S^0$

$B \to hh$

- **signal is the mixture of:**
  - $B^0 \to K^-\pi^+$
  - $B^0 \to \pi^-\pi^+$
  - $B_s^0 \to K^-K^+$
  - $B_s^0 \to K^-\pi^+$
- **Requirements:**
  - **displaced trigger tracks**
- **ToF does not help (track pt 2 GeV)**
- K/π **separation of dE/dx** $\sim 1.16\sigma$
- ☛ **use kinematics to separate contributions**
- ☛ **numbers presented for** $65\ pb^{-1}$ **(plot shown for** $190\ pb^{-1}$**)**



$B \to hh$ results

mode	Yield ($65 pb^{-1}$)
$B^0 \to K\pi$	$148 \pm 17(stat) \pm 17(syst)$
$B^0 \to \pi\pi$	$39 \pm 14(stat) \pm 17(syst)$
$B_s \to KK$	$90 \pm 17(stat) \pm 17(syst)$
$B_s \to K\pi$	$3 \pm 11(stat) \pm 17(syst)$

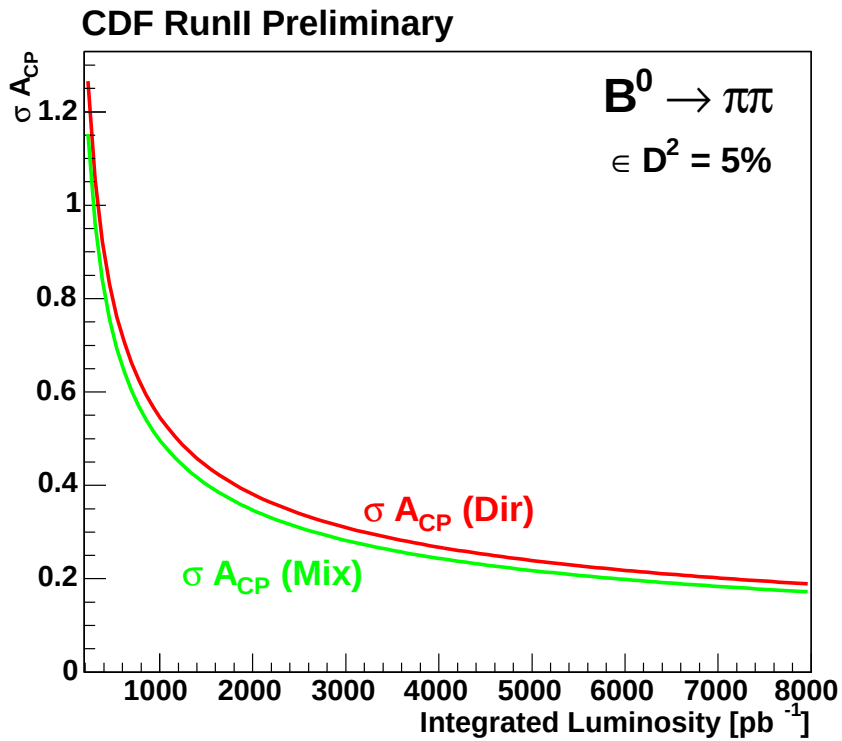
$$\frac{Br(B^0 \to \pi\pi)}{Br(B^0 \to K\pi)} = 0.26 \pm 0.11(stat) \pm 0.06(syst)$$

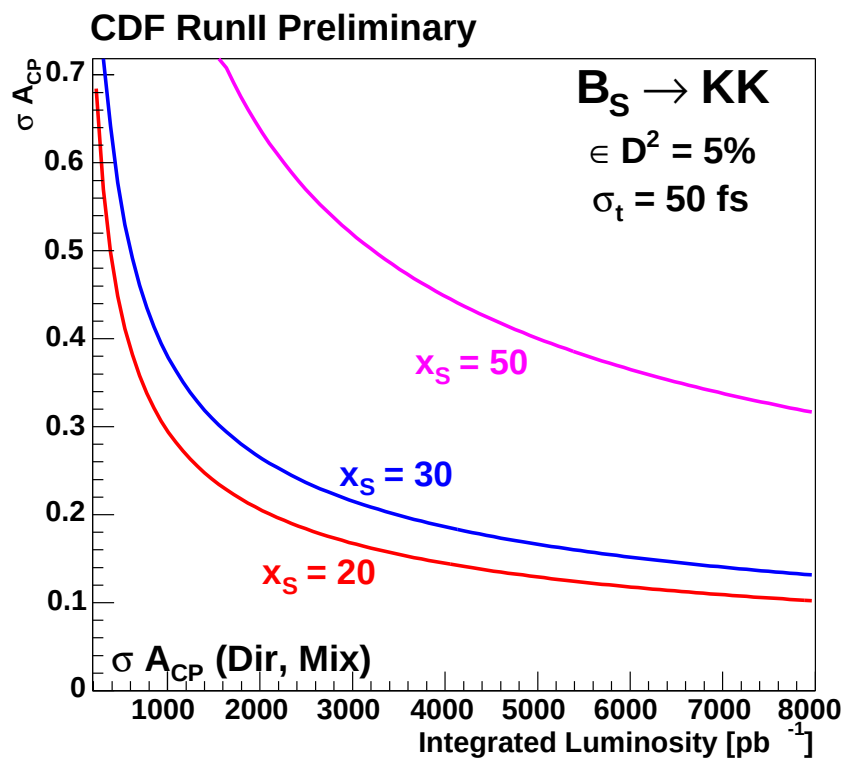
- $$\frac{Br(B_s \to KK)}{Br(B^0 \to K\pi)} = 3.71 \pm 0.73(stat) \pm 0.35(f_s/f_d) \pm 0.81(syst)$$

- $$A_{CP} = \frac{N(\bar{B}^0 \to K^-\pi^+) - N(B^0 \to K^+\pi^-)}{N(\bar{B}^0 \to K^-\pi^+) + N(B^0 \to K^+\pi^-)} = 0.02 \pm 0.15(stat) \pm 0.02(syst)$$

- **BaBar** $A_{CP} = -0.102 \pm 0.05 \pm 0.02$

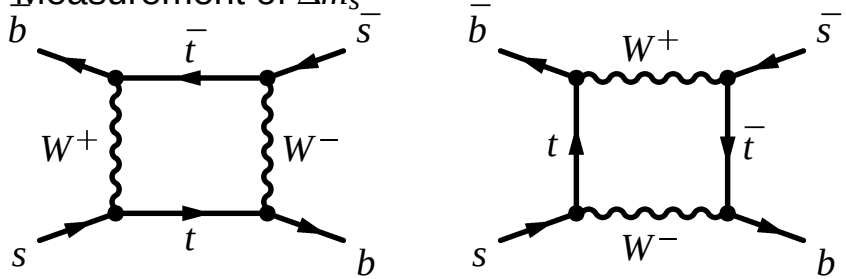
$\sigma_{A_{CP}}$ vs luminosity





B_s mixing

- Measurement of Δm_s

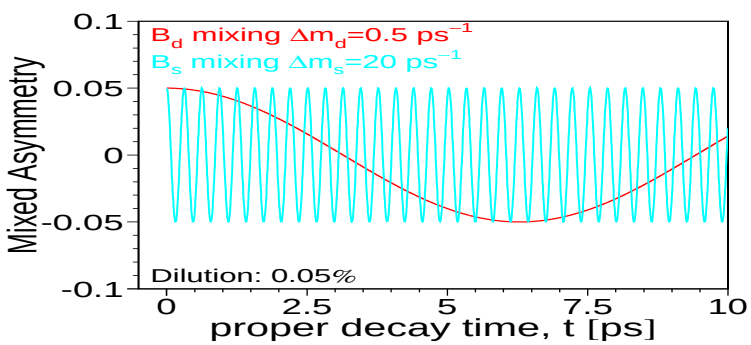


$$P_{unmix}(t) = \frac{1}{2}e^{-\Gamma t}(1 + cos\Delta m_s t)$$

$$P_{mix}(t) = \frac{1}{2}e^{-\Gamma t}(1 - cos\Delta m_s t)$$

$$A_{mix} = \frac{N_{unmixed}(t) - N_{mixed}(t)}{N_{unmixed}(t) + N_{mixed}(t)} = \cos\Delta m_s t$$

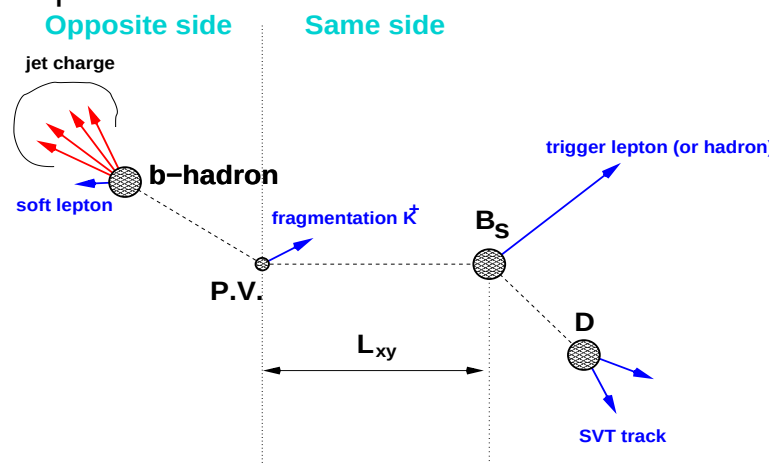
$\Delta m_s \gg \Delta m_d$ as $Re(V_{ts}) \approx 0.04 \gg Re(V_{td}) \approx 0.007$ => B_s fully mixes in 0.15 lifetimes



- In reality

$$A_{mix} = D\cos\Delta m_s t$$

where $D = 2P - 1$ is the dilution of the flavor tag and P is the probability that the flavor tag at production is correct

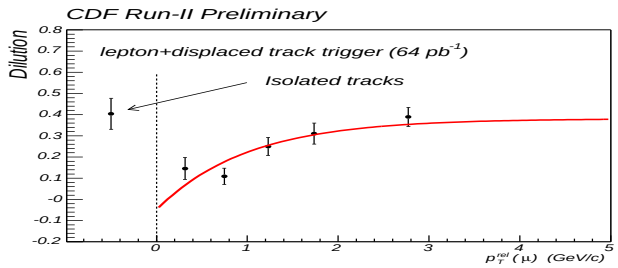


- Opposite Side Tagging (OST):
  - JETQ jet charge of opposite b
  - SLT soft lepton tag
  - OST $b \to c \to s$ => K^- on the other side of B_s
- Same Side Tagging (SST)
  - SST K B_s is likely to be accompanied by K^+ from fragmentation

Taggers performance

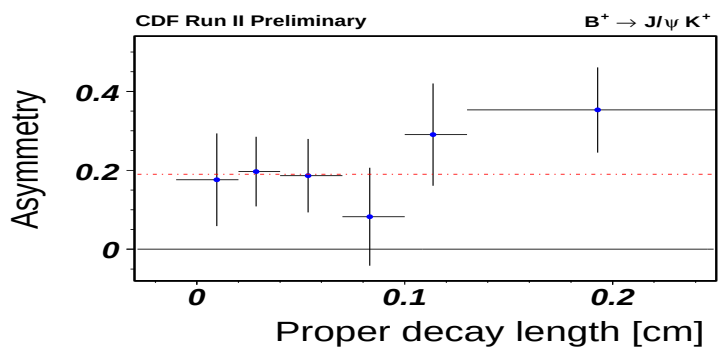
- $\sigma(A_{mix})_{stat} \propto 1/\sqrt{\varepsilon D^2}$, where $\varepsilon = N_{tag}/N_{total}$ – tagger efficiency. The higher εD^2 the better

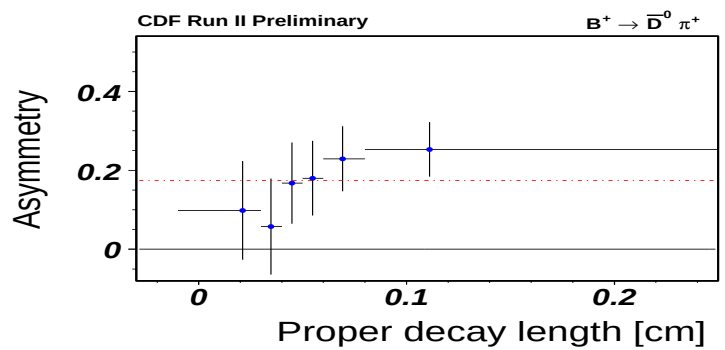
- SMT
  - test SLT using high statistics ℓ+SVT track sample. Trigger ℓ tags initial flavor.
  - identity charge of soft μ
  - verify with partially reconstructed $D\ell$



$$\varepsilon D^2(SMT) = (0.7 \pm 0.1)\%$$

- SST
  - test SST using fully reconstructed modes $B^+ \to J/\psi K^+$ and $B^+ \to \bar{D}^0\pi^+$ no oscillations





$$\varepsilon D^2(SST) = (2.1 \pm 0.1)\%$$

B_s sensitivity

- there is some knowledge of the ingredients needed to measure Δm_s :
  - B_s yield, S
  - Flavor tagging efficiency, εD^2
  - Signal to noise, S/B
  - $c\tau$ resolution, σ_t

$$Significance = \sqrt{\frac{S\varepsilon D^2}{2}} exp\left(-\frac{(\Delta m_s \sigma_t)^2}{2}\right)\sqrt{\frac{S}{B+S}}$$

- Current performance hadronic modes only
  - S=1600 events/fb^{-1}
  - S/B = 2/1
  - εD^2=4% (projecting for SLT-e and JetQ)
  - $\sigma_t = 67\ fs$

2σ sensitivity for $\Delta m_s = 15\ ps^{-1}$ with $\sim 0.5\ fb^{-1}$ of data

- With improvements hadronic modes only
  - S=2000 events/fb^{-1}
  - same S/B
  - εD^2=5% (w/ ToF)
  - $\sigma_t = 50\ fs$ (event by event vertex + L00)

5σ sensitivity for $\Delta m_s = 15\ ps^{-1}$ with $\sim 1.7\ fb^{-1}$ of data
5σ sensitivity for $\Delta m_s = 24\ ps^{-1}$ with $\sim 3.2\ fb^{-1}$ of data

- Additional improvements
  - Trigger and DAQ upgrades in 2004 and 2005

Conclusion

- New B-cross section, precision Heavy hadrons masses, lifetimes and branching ratios measurements from CDF
- Confirmation of Belle's X(3872)
- Best limits on rare B and D decay rates to $\mu\mu$
- First hadronic B-trigger provides wealth of hadronic B and D decays
- Results presented were obtained with (33-80)% of available data. Expect many improvements soon due:
  - Increased statistics
  - Improved silicon stand-alone tracking (coverage up to $|\eta| < 2$
  - Use of L00
  - Event by event vertexing
- CDF remains focused on B_s mixing measurement:
  - DAQ and Trigger upgrades aiming to increase B-hadronic band-width are on the way
  - Work on Kaon SST using ToF
  - Work on jet charge OST
- Expect new results on heavy baryons and low rate modes