Mixings, Lifetimes, Spectroscopy and Production of *b*-quarks

(*mostly hadron collider results*)

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Outline

- Introduction- *B* physics at hadron machines
- Heavy flavor production
  - ➔ charm cross section
- Lifetimes
- *B* hadron masses
- Branching ratios
  - ➔ $B_s \rightarrow K^+K^-$, $\Lambda_b \rightarrow \Lambda_c \pi^-$, $B_s \rightarrow D_s \pi^+$
- Mixing
  - ➔ B_d , B_s
- Summary

Notation:

$B_d = B^0 = |\bar{b}d\rangle$

$B_u = B^+ = |\bar{b}u\rangle$

$B_s = |\bar{b}s\rangle$

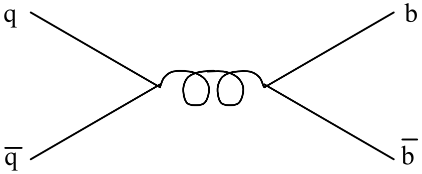
$B_c = |\bar{b}c\rangle$

$\Lambda_b = |udb\rangle$

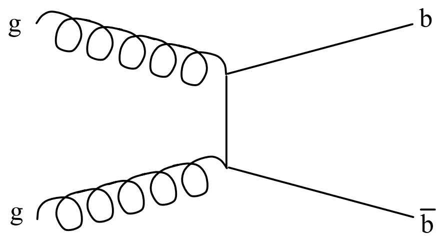
B Physics at Hadron Machines

b's produced by strong interaction, decay by weak interaction

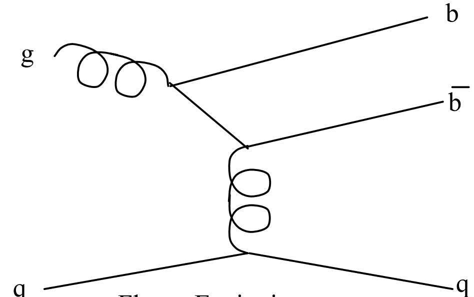
Production:



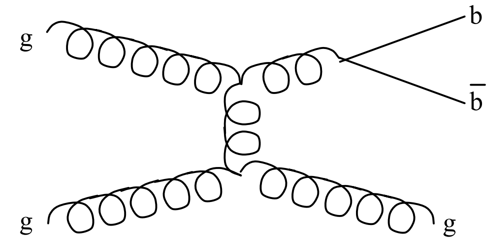
Flavor Creation (annihilation)



Flavor Creation (gluon fusion)



Flavor Excitation



Gluon Splitting

Pros

- Enormous cross-section
  - ~100 μbarn total
  - ~3-5 μbarn "reconstructable"
  - **At 4×10^{31}cm^{-2}s^{-1} ⇒ ~150Hz of reconstructable $\bar{B}B$!!**
- All *B* species produced
  - B_u,B_d,$\mathbf{B_s}$,$\mathbf{B_c}$,Λ_b,…
- Production is incoherent
  - Measure of *B* and $\bar{B}$ not required

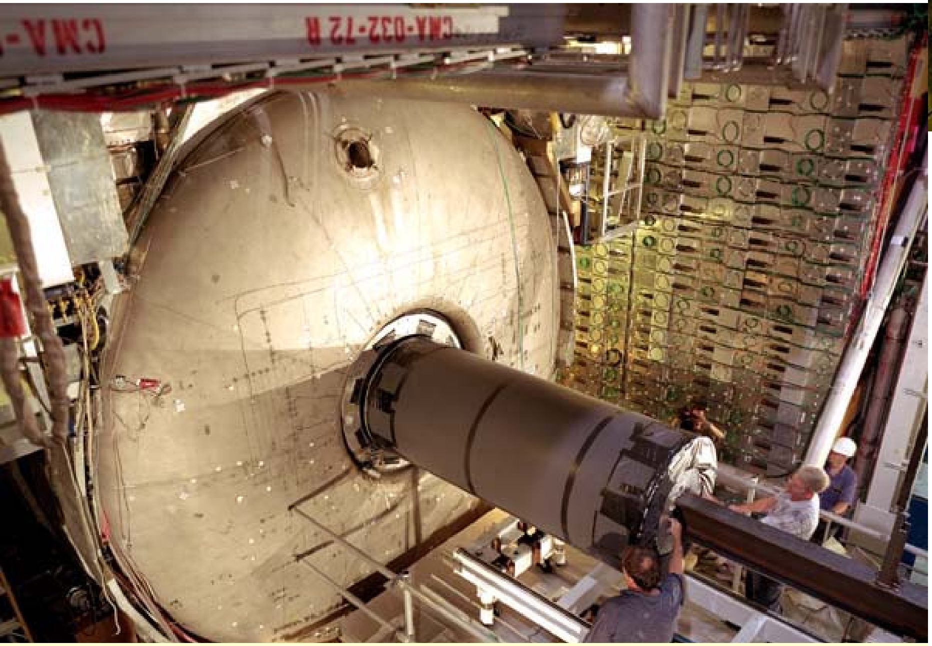
Cons

- Large inelastic background
  - Triggering and reconstruction are challenging
- Reconstruct a *B* hadron, ~20-40% chance 2nd *B* is within detector acceptance
- p_T spectrum relatively soft
  - **Typical $p_T(B)$~10-15 GeV for trigger+reconstructed *B*'s**
    …softer than *B*'s at LEP!

Disclaimer: acceptance comments relevant to "central" detectors like DØ and CDF

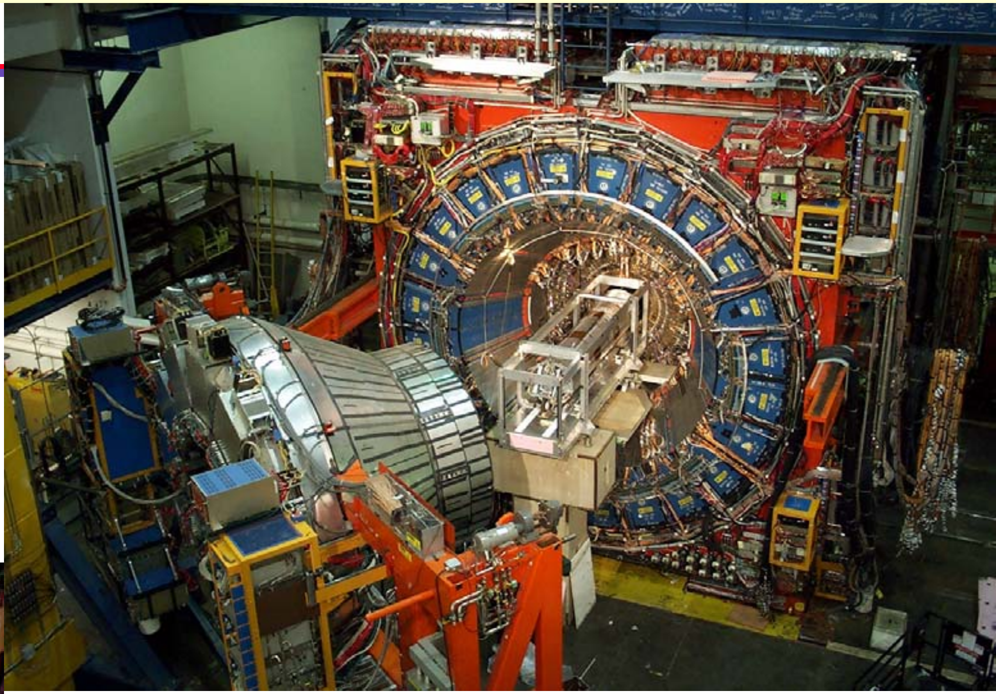
Detectors

- Both detectors
  - ➔ silicon microvertex detectors
  - ➔ axial solenoid
  - ➔ central tracking
  - ➔ high rate trigger/DAQ system
  - ➔ calorimeter & muon systems



DØ fiber tracker installation

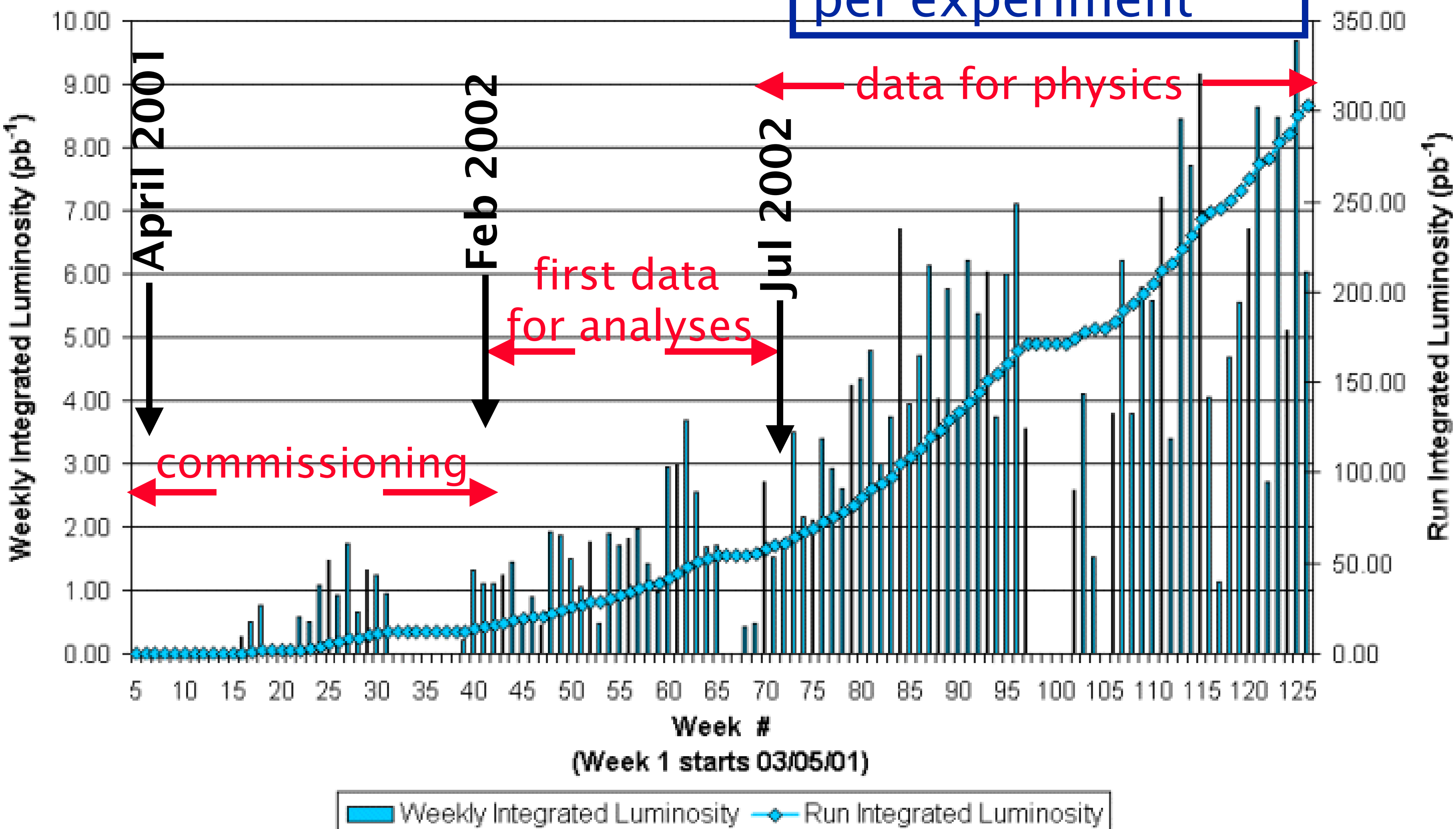
CDF silicon detector installation



- DØ
  - ➔ Excellent electron & muon ID
  - ➔ Excellent tracking acceptance
- CDF
  - ➔ Silicon vertex trigger
  - ➔ Particle ID (TOF and dE/dx)
  - ➔ Excellent mass resolution

Collider Run IIA Integrated Luminosity

~220 pb^{-1} on tape per experiment

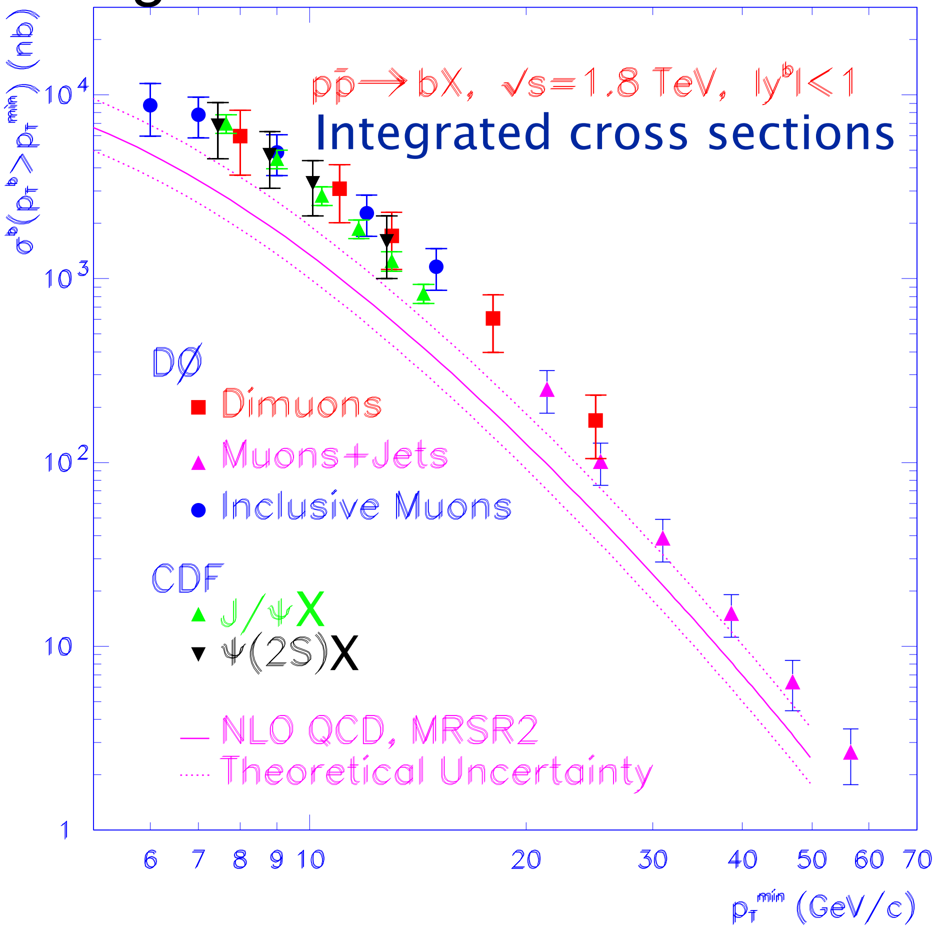


Typical detector efficiency ~85-90%

Luminosity used for HF analyses 6–140 pb^{-1}

Heavy Flavor Cross Sections

- Tevatron *B* Cross sections measured at sqrt(s)=1.8TeV (1992-1996) consistently higher than NLO calculation

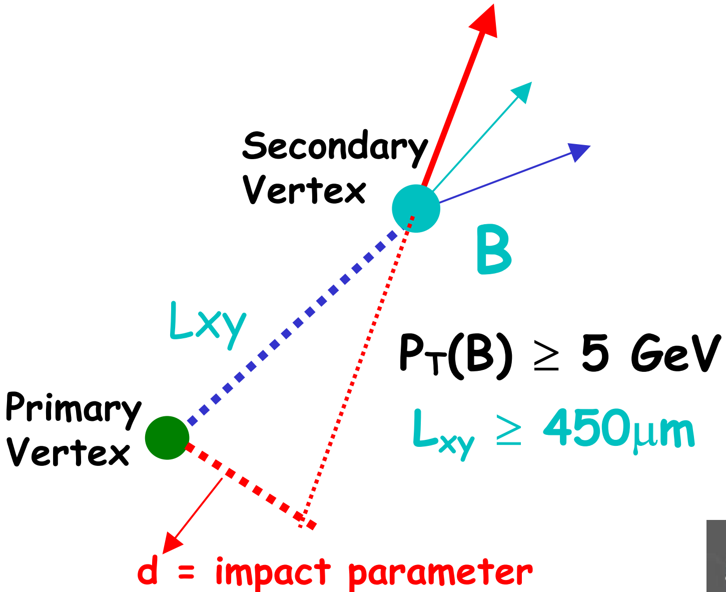


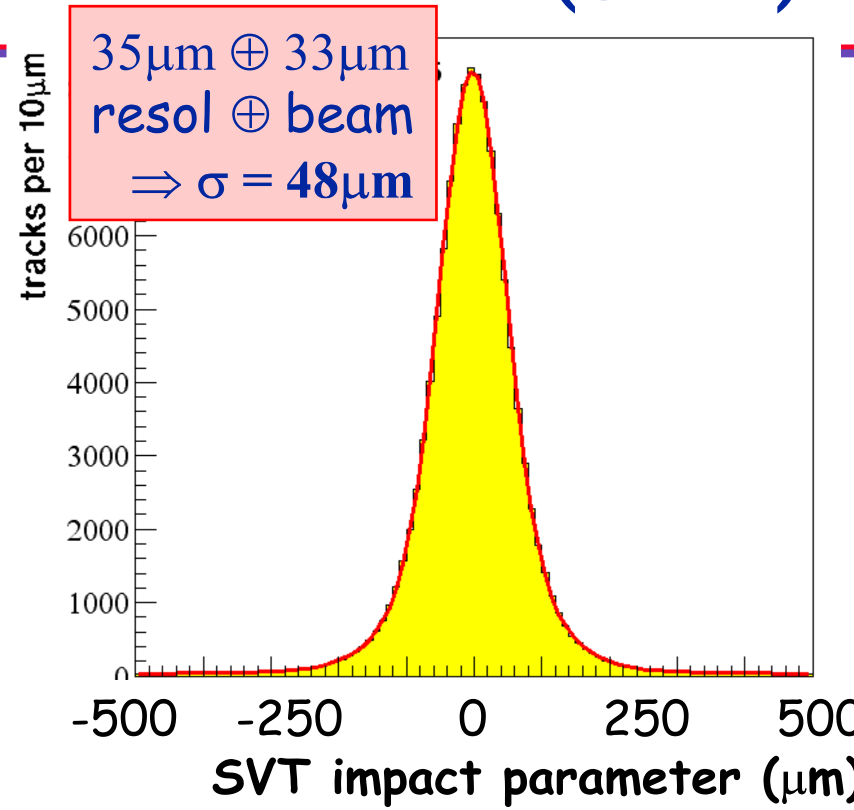
- Theoretical work is ongoing
  - Fragmentation effects
  - Small *x*, threshold effects
  - Proposed beyond SM effects

- What can experiments do?
  - Measure more cross sections
    - sqrt(s)=1.96 TeV
    - go to lower $p_T(B)$
  - Look at $b\bar{b}$ correlations
  - Measure the charm cross section

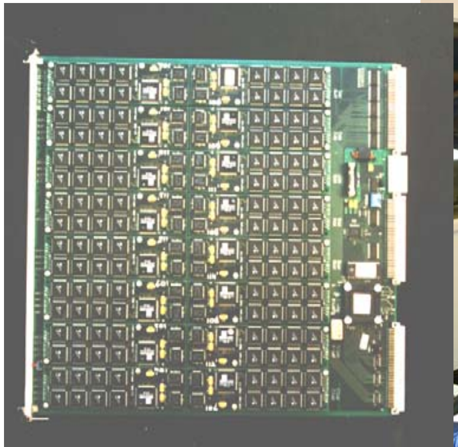
CDF Silicon Vertex Tracker (SVT)

- SVT incorporates silicon info in the Level 2 trigger… select events with large impact parameter!





- Uses fitted beamline
- impact parameter per track
- System is deadtimeless:
  - ➔ ~25 μsec/event for readout + clustering + track fitting

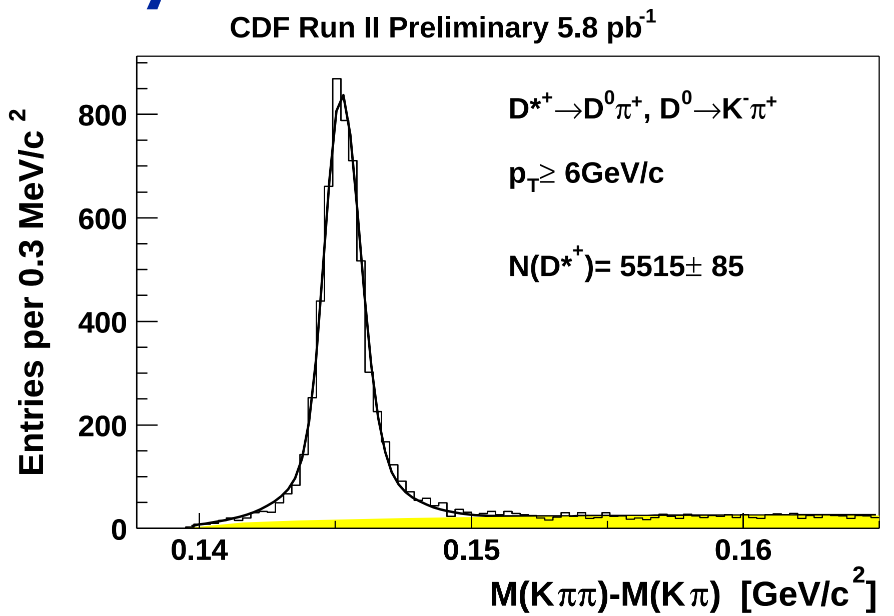


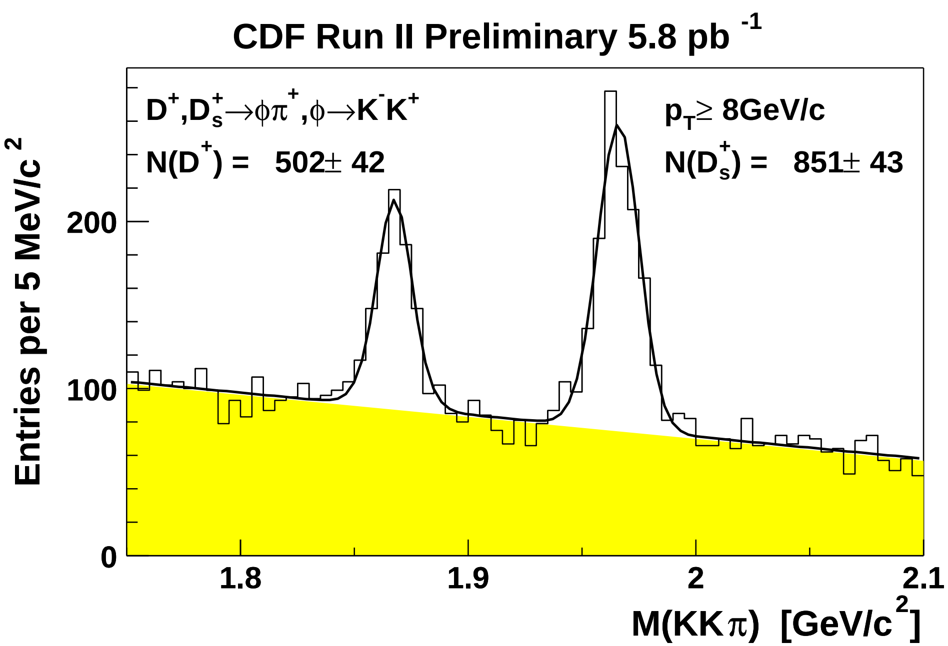
CDF charm yields

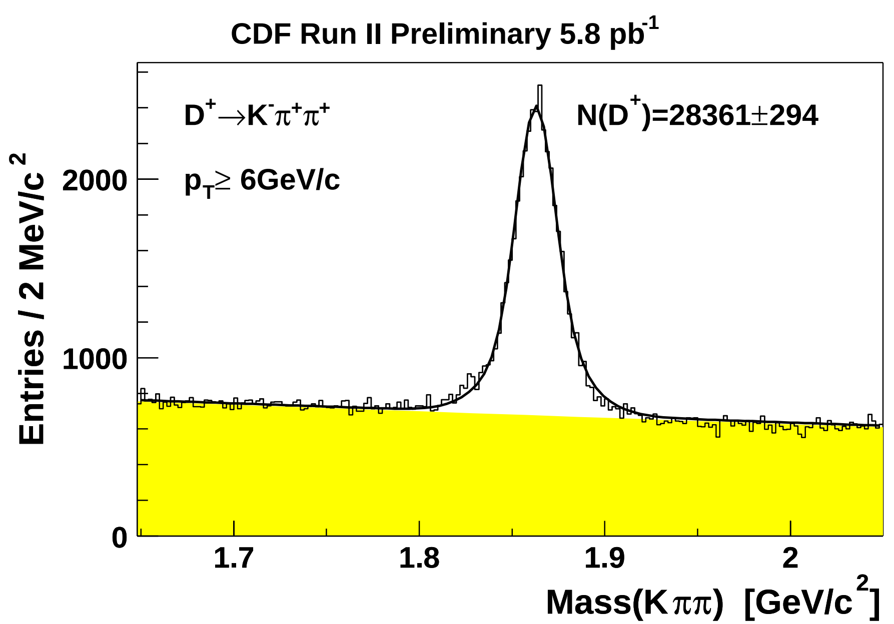
- Trigger on displaced tracks, accepts both bottom & charm.
- Reconstruct large samples of charm hadrons

  >85% prompt charm!

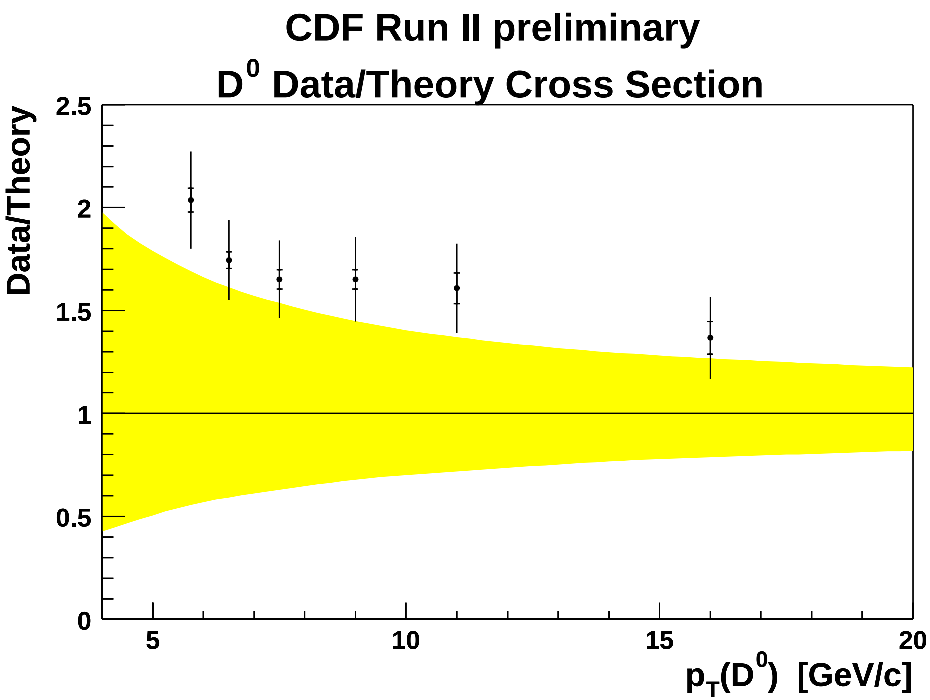
Yields shown for $5.8 pb^{-1}$



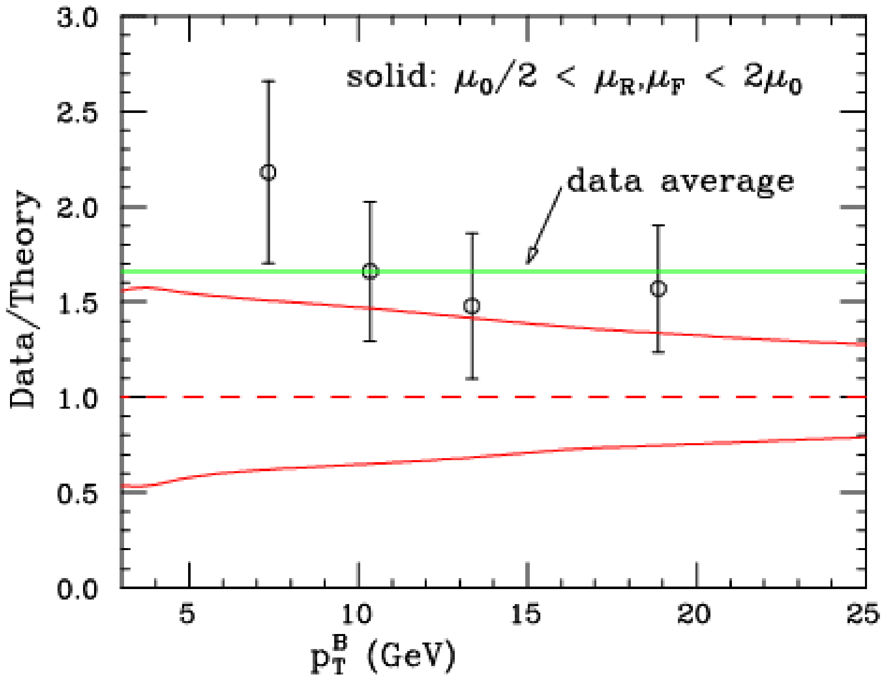




CDF Prompt charm Cross Section



data/theory for D^0



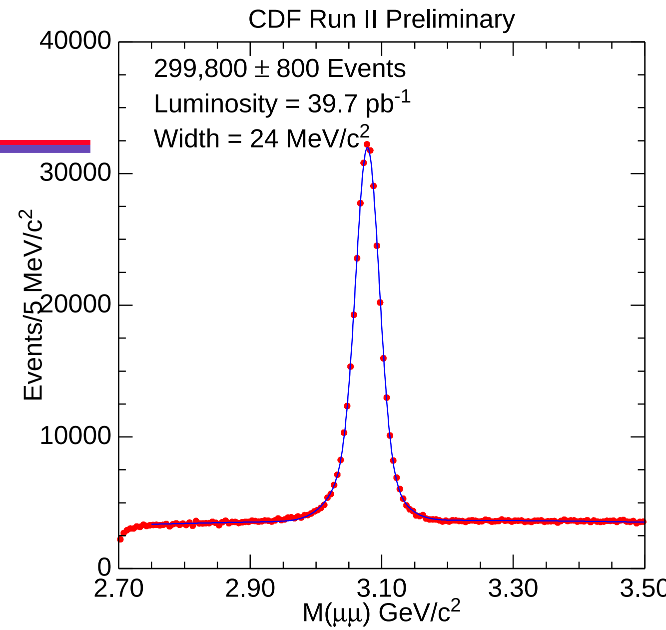
data/theory for *B*

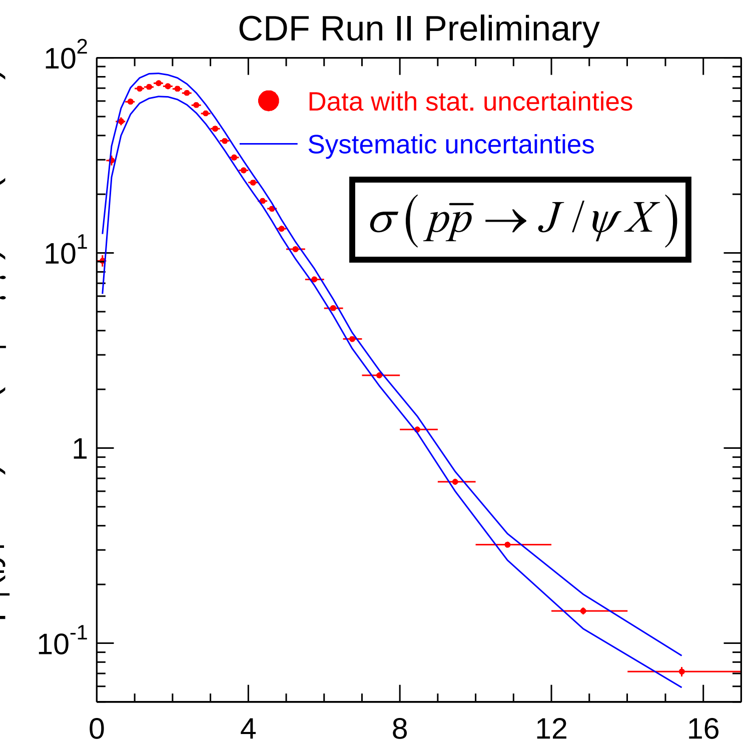
- **Prompt charm cross section result submitted to PRL hep-ex/0307080**
  - ➔ See poster by Chunhui Chen
- **Calculations shown are Cacciari & Nason hep-ph/0306212**
- **Observations:**
  - ➔ Data on the "upper edge" of theory for D^0 (shown), D^+ and D^*.
  - ➔ Trend similar to that seen in *B* cross section measurements.

Inclusive J/ψ

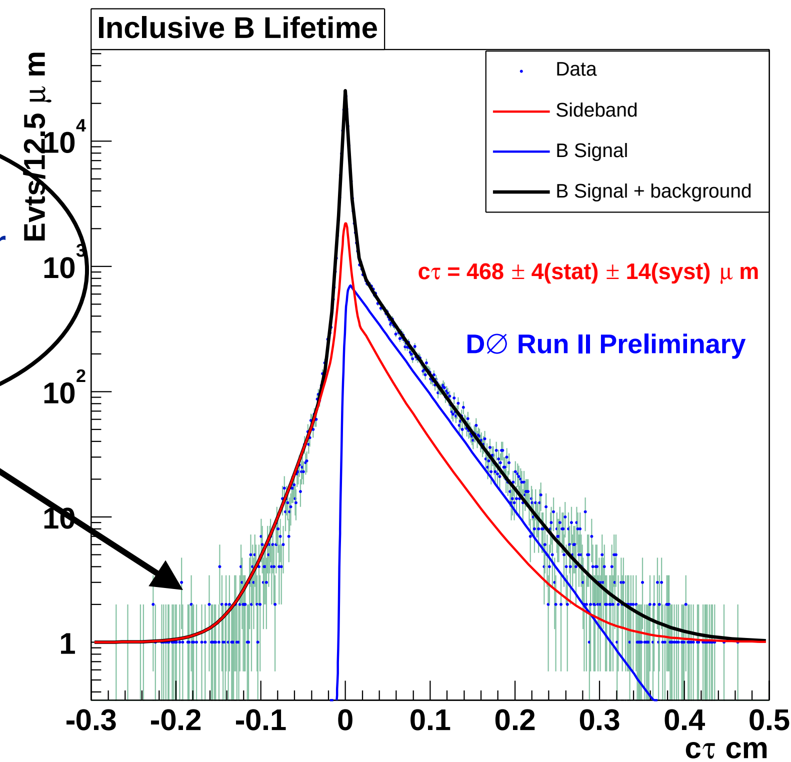
Large yield, clean signals

- Acceptance down to p_T=0 GeV!
  - χ_c signals also observed
- Inclusive lifetime shows $B \to J/\psi X$ fraction to be 15-20% (>80% direct charm)
- See Tomasz Skwarnicki's quarkonia talk





Inclusive lifetime also important for understanding lifetime systematics



B Hadron Lifetimes

- All lifetimes equal in spectator model.
  - Differences from interference & other nonspectator effects
- Heavy Quark Expansion predicts the lifetimes for different B hadron species

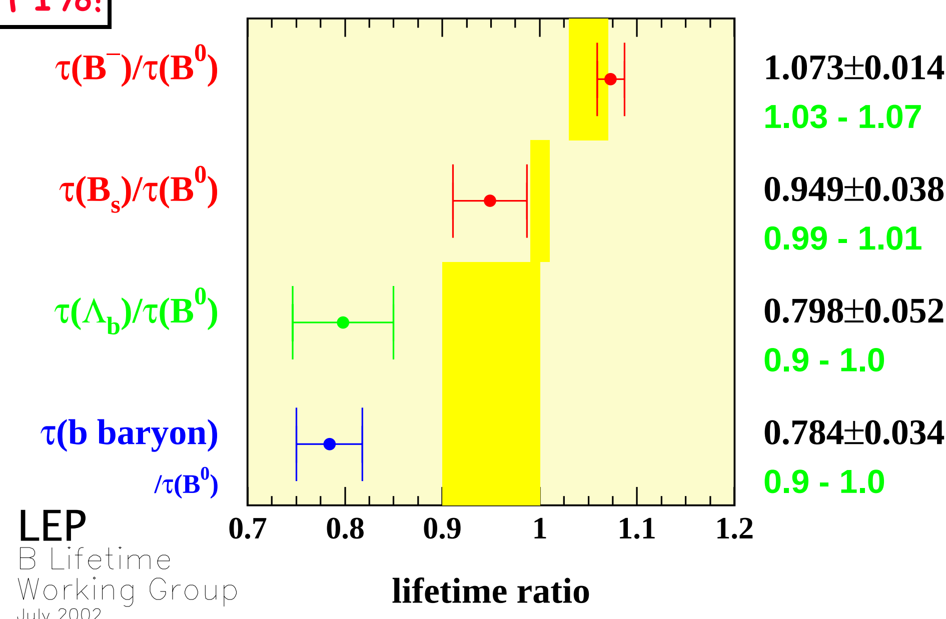
$$\tau\left(B^{+}\right) \geq \tau\left(B^{0}\right) \approx \tau\left(B_{s}\right) > \tau\left(\Lambda_{b}\right) \gg \tau\left(B_{c}\right)$$

- Measurements:
  - B^0,B^+ lifetimes measured to better than 1%!
  - B_s known to about 4%
  - LEP/CDF (Run I) Λ_b lifetime lower than HQE prediction

Heavy Flavor Averaging Group
http://www.slac.stanford.edu/xorg/hfag/index.html

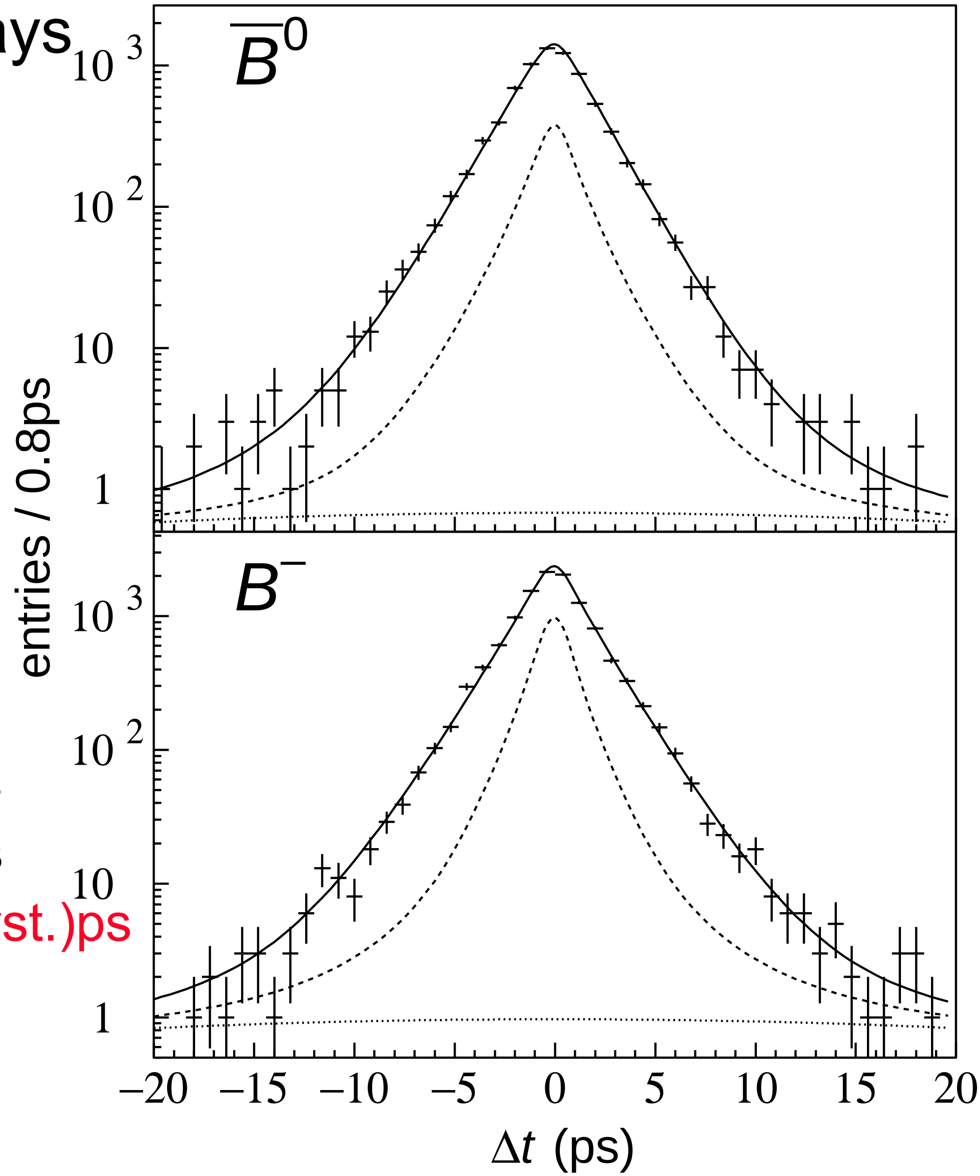
B hadron	Average lifetime (ps)
B^0	1.534 ± 0.013
B^+	1.653 ± 0.014
B_s	1.439 ± 0.053
B_c	$0.46^{+0.18}_{-0.16}$
Λ_b	$1.233^{+0.078}_{-0.076}$

- Tevatron can contribute to B_s,B_c and Λ_b (and other *b*-baryon) lifetimes.



Belle B^+ & B^0 Lifetime

- 29 fb^{-1} fully reconstructed decays
  - ➔ 7863 B^0
  - ➔ 12047 B^+
- Lifetime measured in Δt
  (see Tom Browder's talk)



- Results:

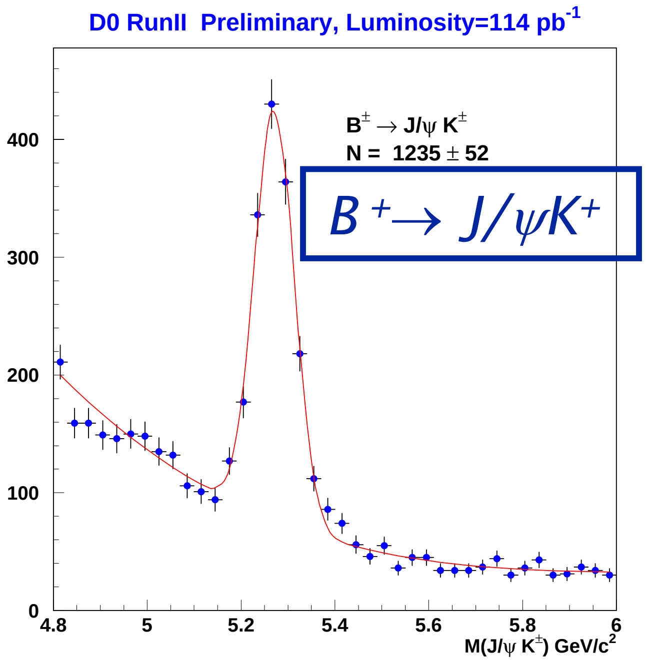
$\tau(B^0)=1.554\pm0.030(\text{stat.})\pm0.019(\text{syst.})\text{ps}$

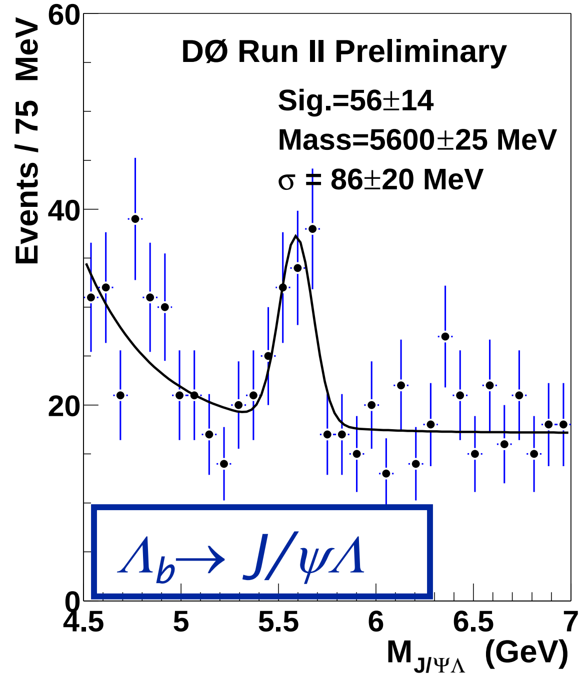
$\tau(B^+)=1.695\pm0.026(\text{stat.})\pm0.015(\text{syst.})\text{ps}$

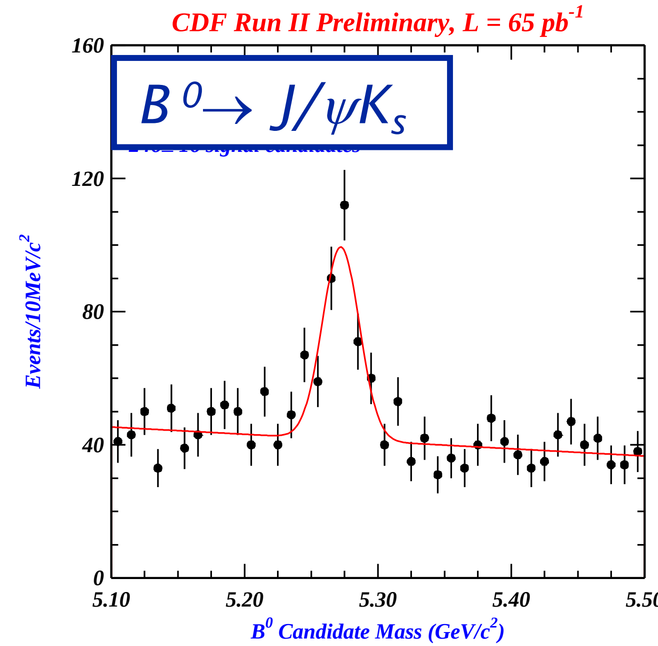
$\tau(B^+)/\tau(B^0)=1.091\pm0.023(\text{stat.})\pm0.014(\text{syst.})\text{ps}$

- Tails are well-modeled

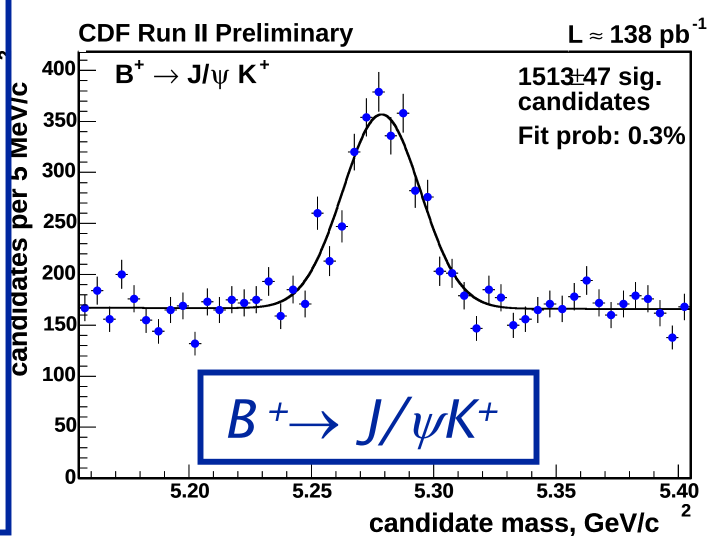
Yields in $B \rightarrow J/\psi X$ Modes

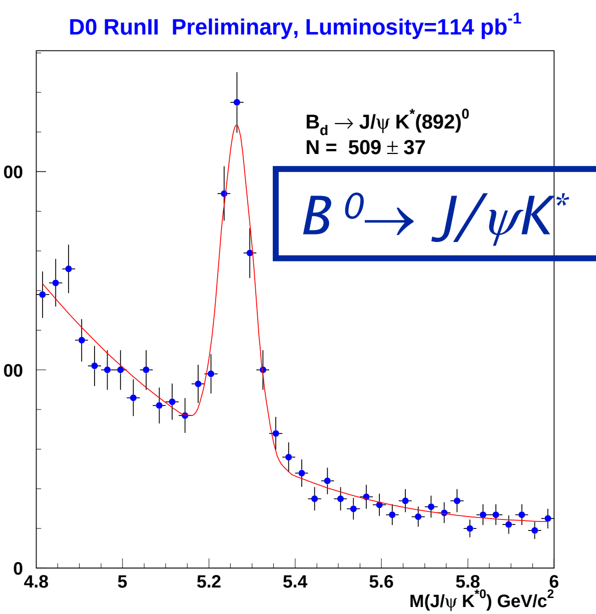






- Trigger on low p_T dimuons (1.5-2GeV/μ)
- Fully reconstruct
  - ✓ J/ψ, $\psi(2s) \rightarrow \mu^+\mu^-$
  - ✓ $B^+ \rightarrow J/\psi K^+$
  - ✓ $B^0 \rightarrow J/\psi K^*$, $J/\psi K_s$
  - ✓ $B_s \rightarrow J/\psi \phi$
  - ✓ $\Lambda_b \rightarrow J/\psi \Lambda$



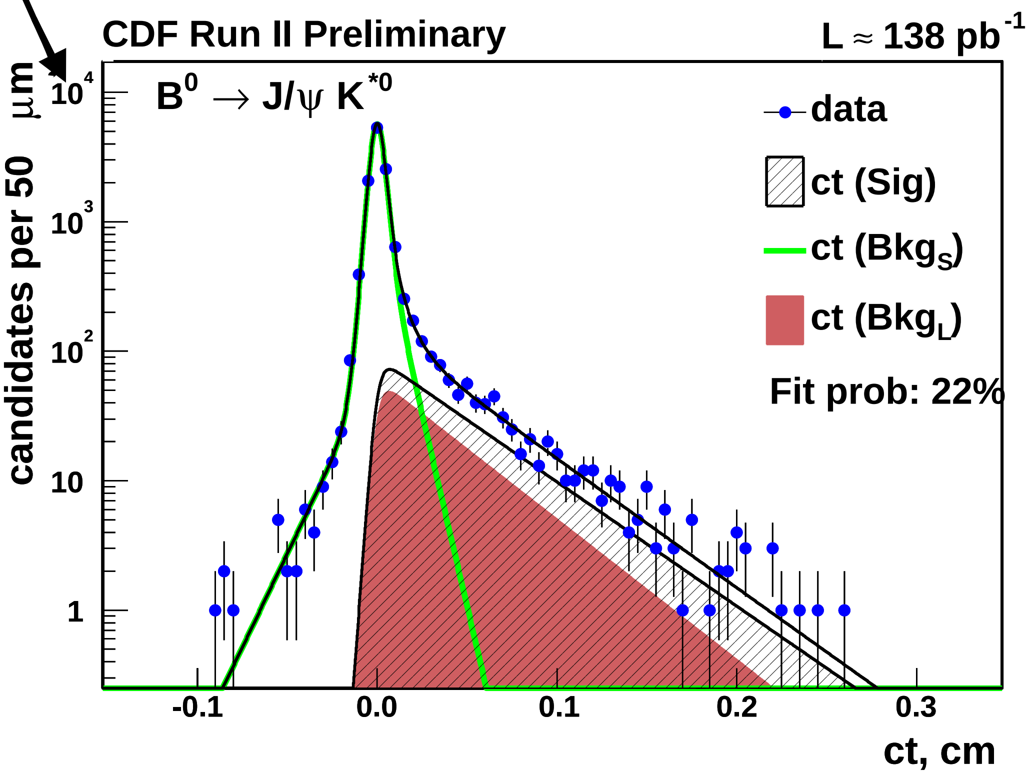


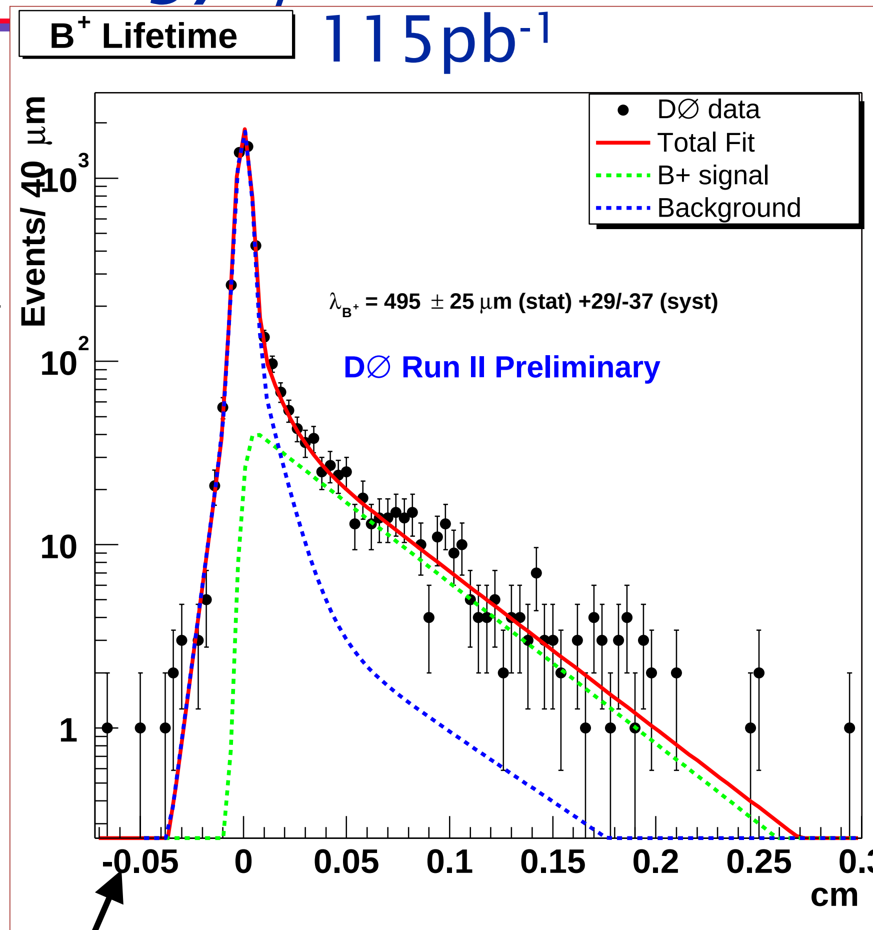
B^+, B^0 Lifetimes in J/ψ Modes

$\tau(B^0)$

DØ **1.51** $^{+0.19}_{-0.17}$ **(*stat.*) ± 0.2 (*syst.*) ps**

CDF **1.51 ± 0.06(*stat.*) ± 0.02 (*syst.*) ps**





Proper decay length:

$$ct = \frac{L_{xy}}{\beta\gamma} = \frac{L_{xy} m_B}{p_T}$$

$\tau(B^+)$

DØ **1.65 ± 0.08(*stat.*)** $^{+0.10}_{-0.12}$ **(*syst.*) ps**

CDF **1.63 ± 0.05(*stat.*) ± 0.04 (*syst.*) ps**

B_s Lifetime

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

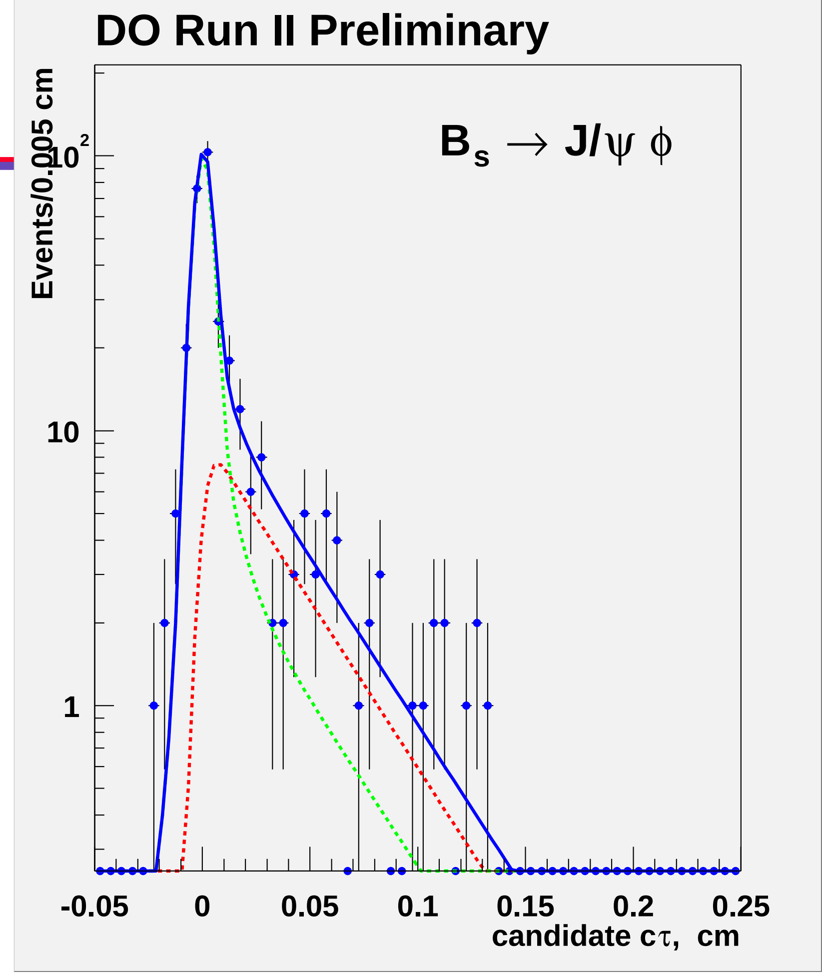
DØ (115pb^{-1}): *(shown here)*

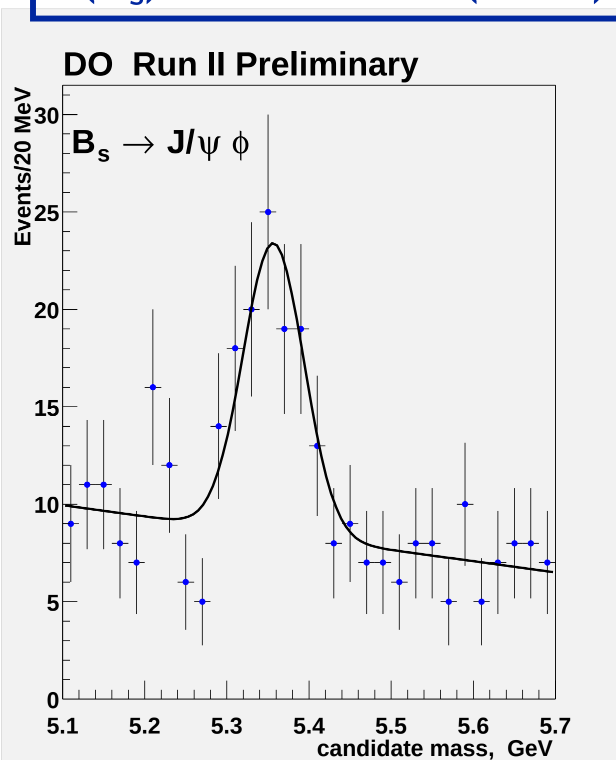
$\tau(B_s)=1.19^{+0.19}_{-0.16}$ (stat.) ±0.14(syst.) ps

$\tau(B_s)/\tau(B^0)$ $=0.79\pm0.14$ *(uncorrected for CP composition)*

CDF (138pb^{-1}):

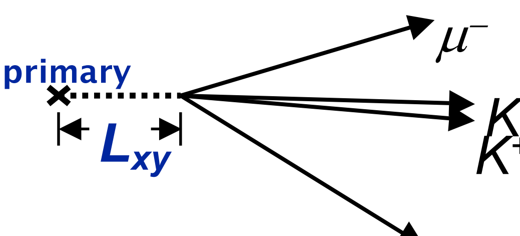
$\tau(B_s)=1.33\pm0.14$(stat.) ±0.02(syst.) ps





Interesting B_s physics:

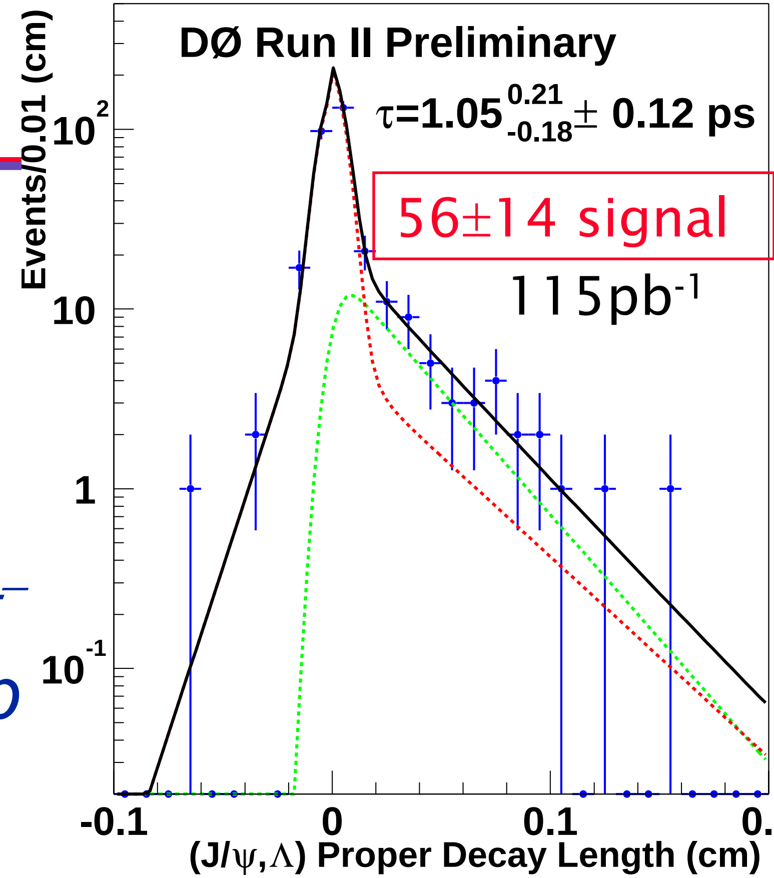
- **Search for CPV in $B_s \to J/\psi\phi$** ***…sensitive to new physics***
- **Width difference $\Delta\Gamma$**
- ***B_s mixing* *(later in talk)***

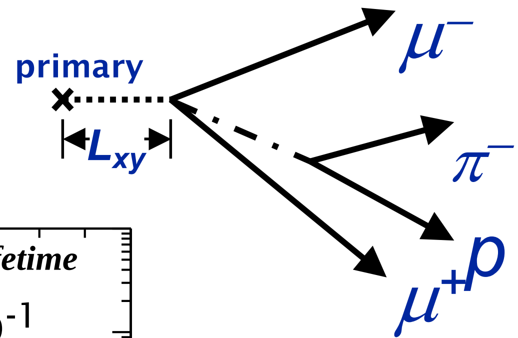


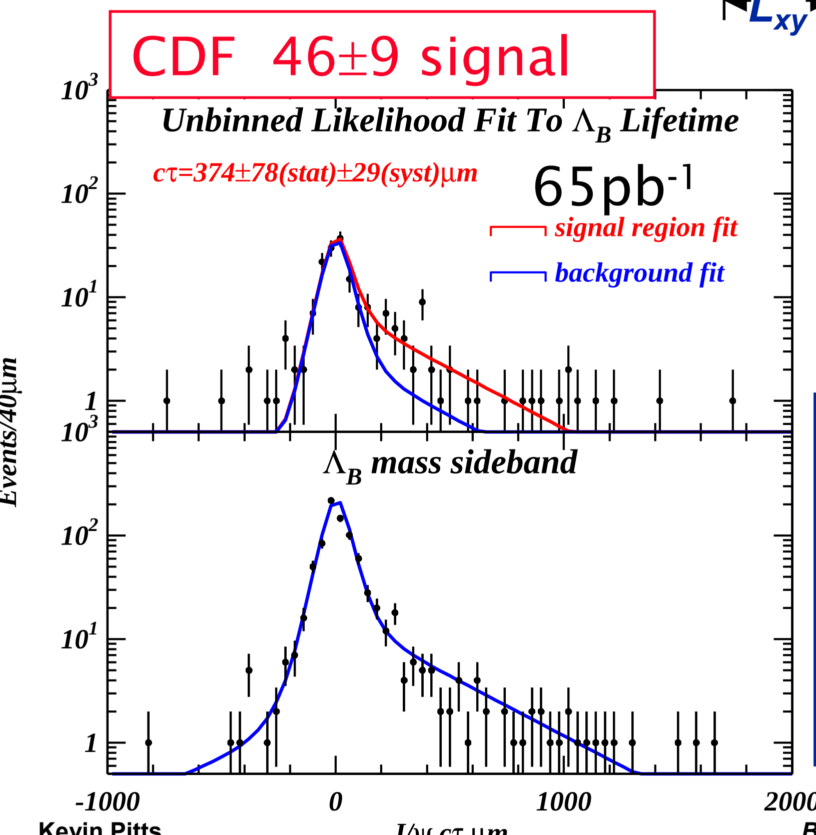
$$ct = \frac{L_{xy}}{\beta\gamma} = \frac{L_{xy} m_B}{p_T}$$

Λ_b Lifetime

- Use <u>fully reconstructed</u> $\Lambda_b \to J/\psi \Lambda$ with $J/\psi \to \mu^+\mu^-$ and $\Lambda \to p\pi^-$
  - ➔ *Previous LEP/CDF measurements used semileptonic* $\Lambda_b \to \Lambda_c l \nu$
    - *Systematics different*







CDF

$$\tau(\Lambda_b) = 1.25 \pm 0.26(stat.) \pm 0.10(syst.)\,\mathrm{ps}$$

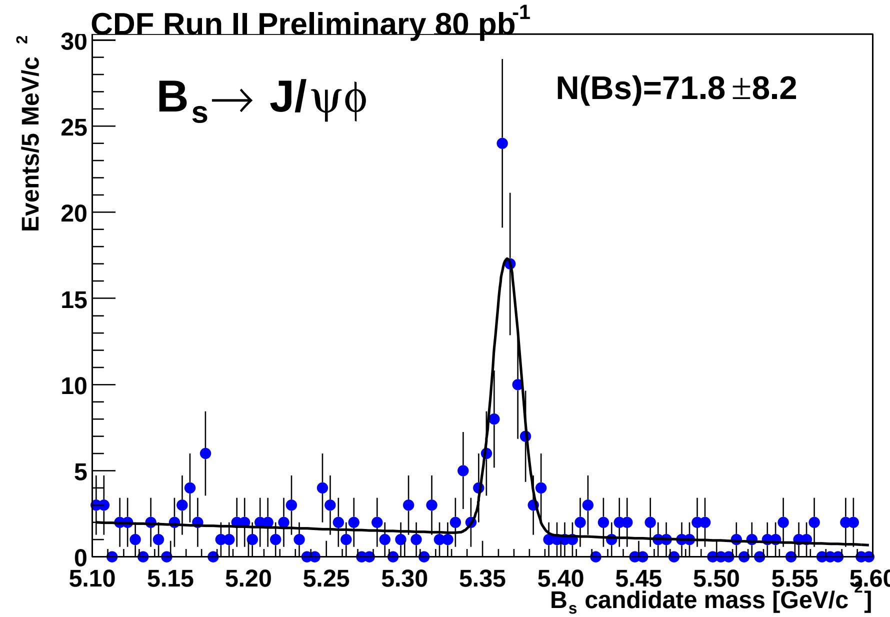
DØ

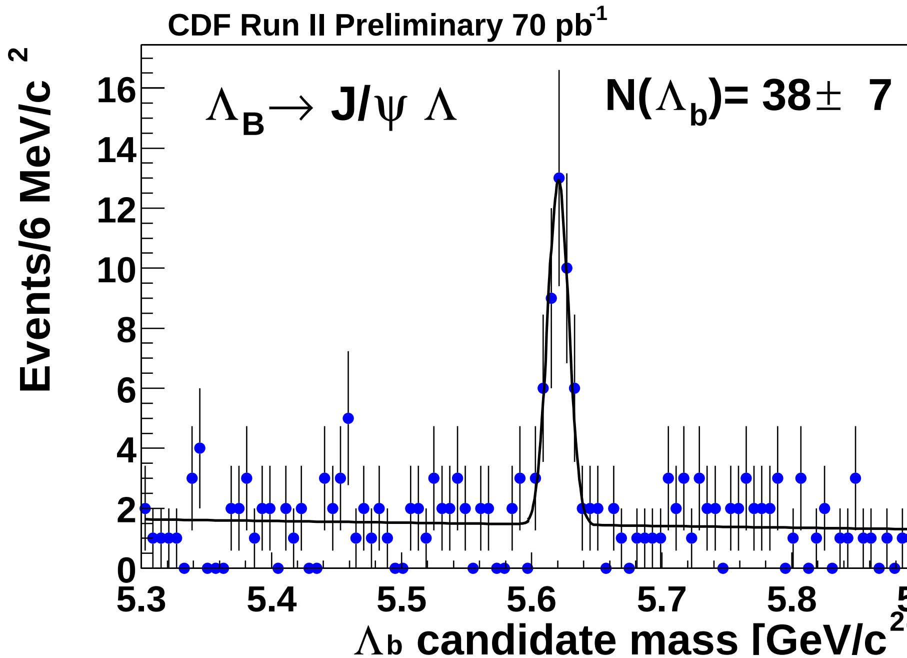
$$\tau(\Lambda_b) = 1.05^{+0.21}_{-0.18}(stat.) \pm 0.12(syst.)\,\mathrm{ps}$$

B Hadron Masses

- Measure masses using fully reconstructed $B \to J/\psi X$ modes
- High statistics $J/\psi \to \mu^+\mu^-$ and $\psi(2s) \to J/\psi \pi^+\pi^-$ for calibration.
- Systematic uncertainty from tracking momentum scale
  - ➔ *Magnetic field*
  - ➔ *Material (energy loss)*
- *B^+ and B^0 consistent with world average.*
- ***B_s and Λ_b* measurements are world's best.**

CDF result:	$M(B_s)$=5365.50 ±1.60 MeV
World average:	$M(B_s)$=5369.6 ±2.4 MeV
CDF result:	$M(\Lambda_b)$=5620.4 ±2.0 MeV
World average:	$M(\Lambda_b)$=5624 ±9 MeV





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  - ➔ $B_s \rightarrow K^+K^-$, $\Lambda_b \rightarrow \Lambda_c \pi^-$, $B_s \rightarrow D_s \pi^+$
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  - ➔ B_d , B_s
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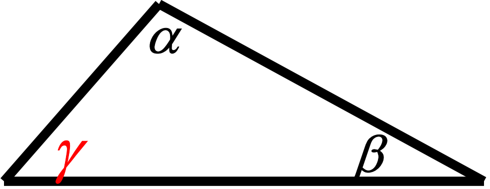
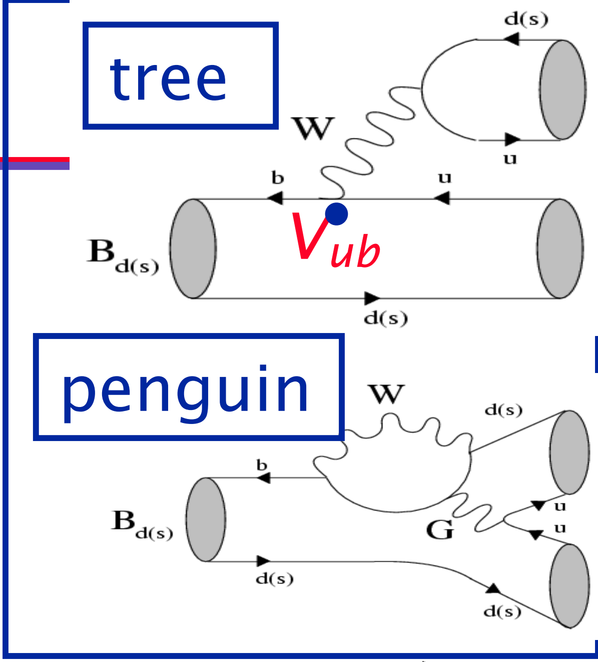
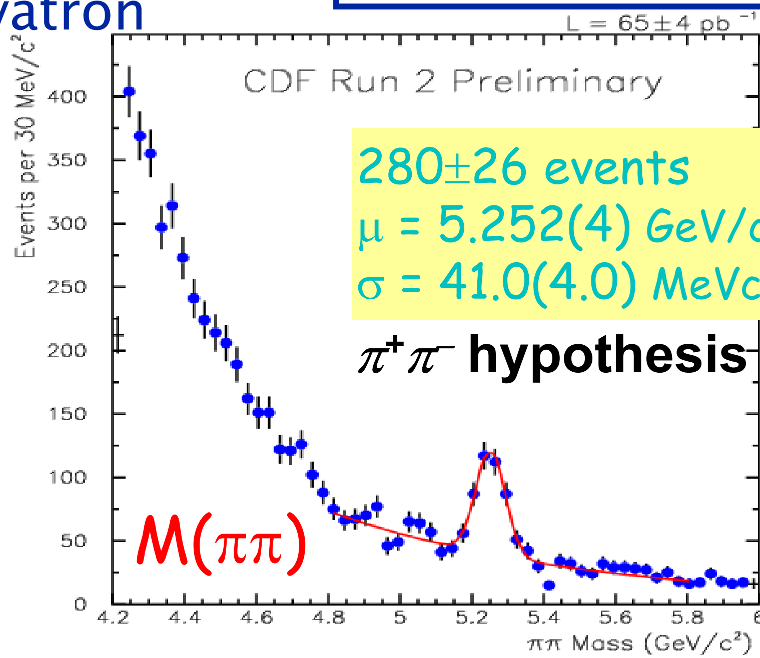


CDF $B \to h^+ h^-$

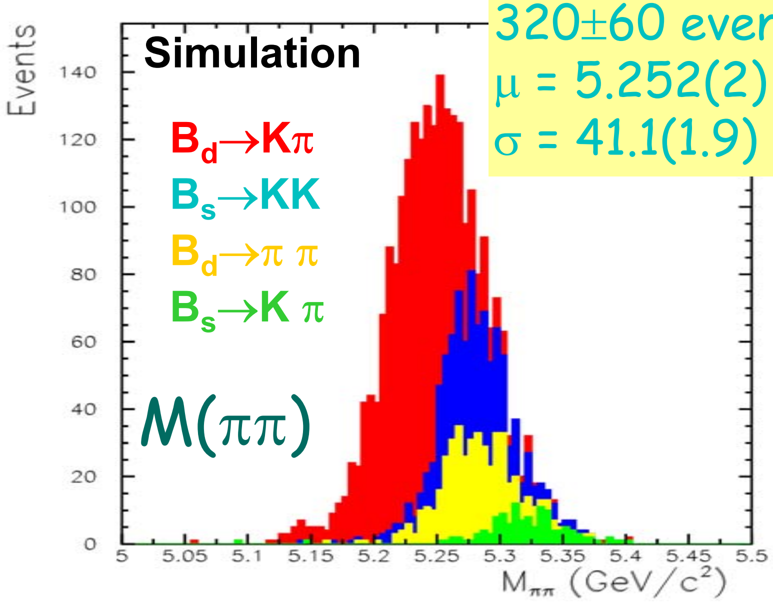


- charmless two-body decays
  - longer term B_s modes help extract unitarity angle γ (see Hassan's talk)
- Signal is a combination of:
  - $B^0 \to \pi^+\pi^-$ BR~5x10^{-6}
  - $B^0 \to K^+\pi^-$ BR~2x10^{-5} } Υ(4s),Tevatron
  - $B_s \to K^+K^-$ BR~5x10^{-5}
  - $B_s \to \pi^+K^-$ BR~1x10^{-5} } Tevatron
- Requirements
  - Displaced track trigger
  - Good mass resolution
  - Particle ID (*dE/dx*)



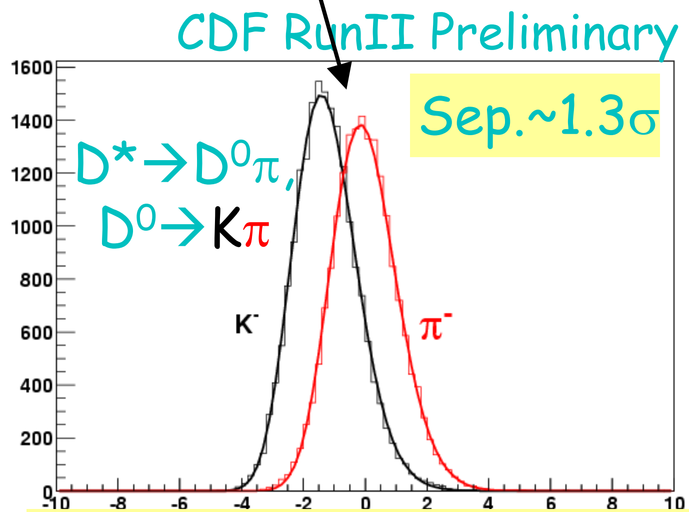
Did you ever think this physics could be done at a hadron collider?

$BR(B_s \to K^+K^-)$



320±60 events
$\mu = 5.252(2)$ GeV/c^2
$\sigma = 41.1(1.9)$ MeV/c^2

kinematics & *dE/dx* to separate contributions



Fitted contributions:

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

First observation of $B_s \to K^+K^-$!!

Result: $$\frac{BR(B_s \to K^\pm K^\mp)}{BR(B_d \to K^\pm \pi^\mp)} = 2.71 \pm 1.15$$

includes error on f_s/f_d

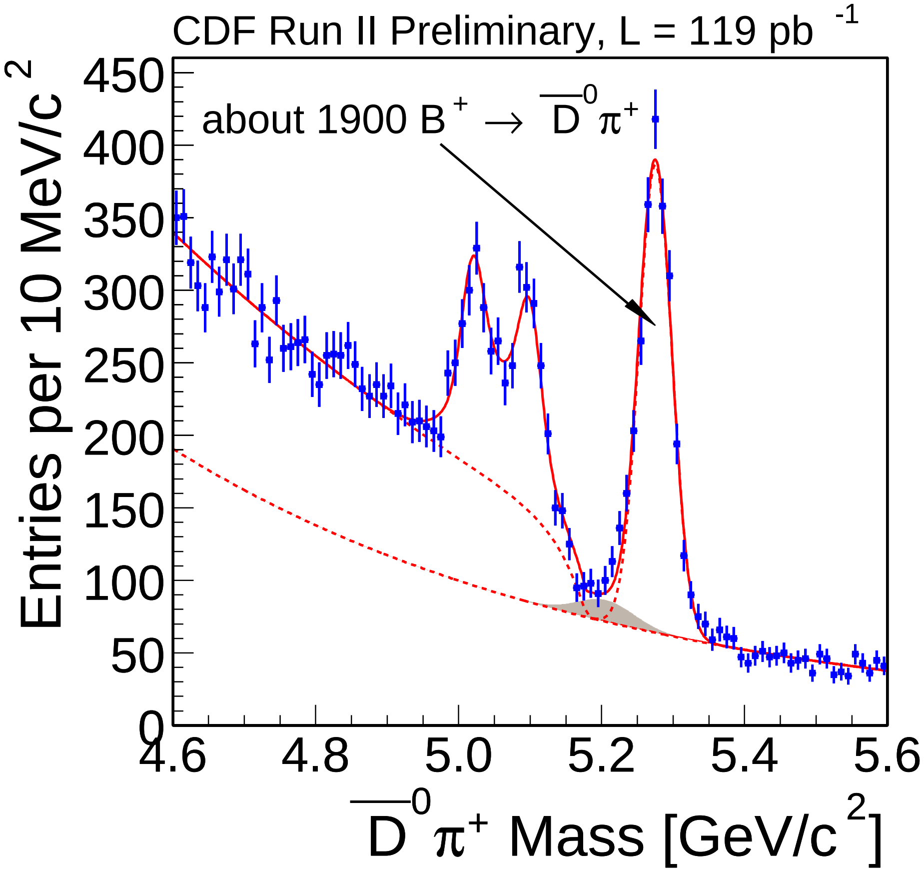
see poster by Diego Tonelli

Reflections, Satellites and All That

Vertex trigger sample

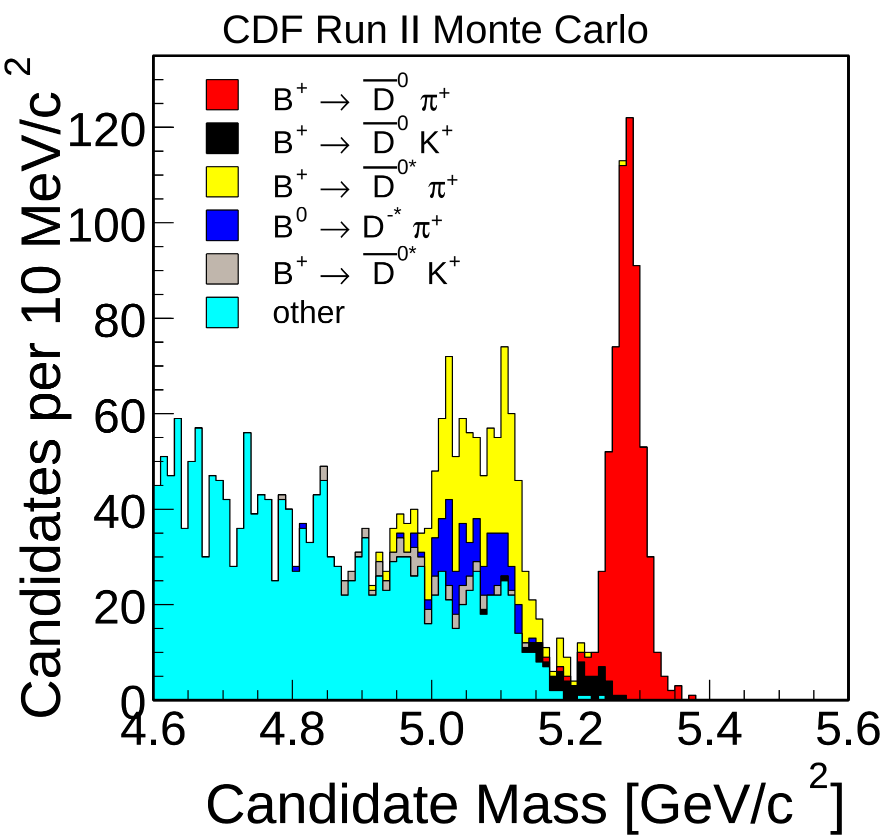
reconstruct: $B^- \to D^0 \pi^-$

Clear peak seen, sidebands have interesting structure



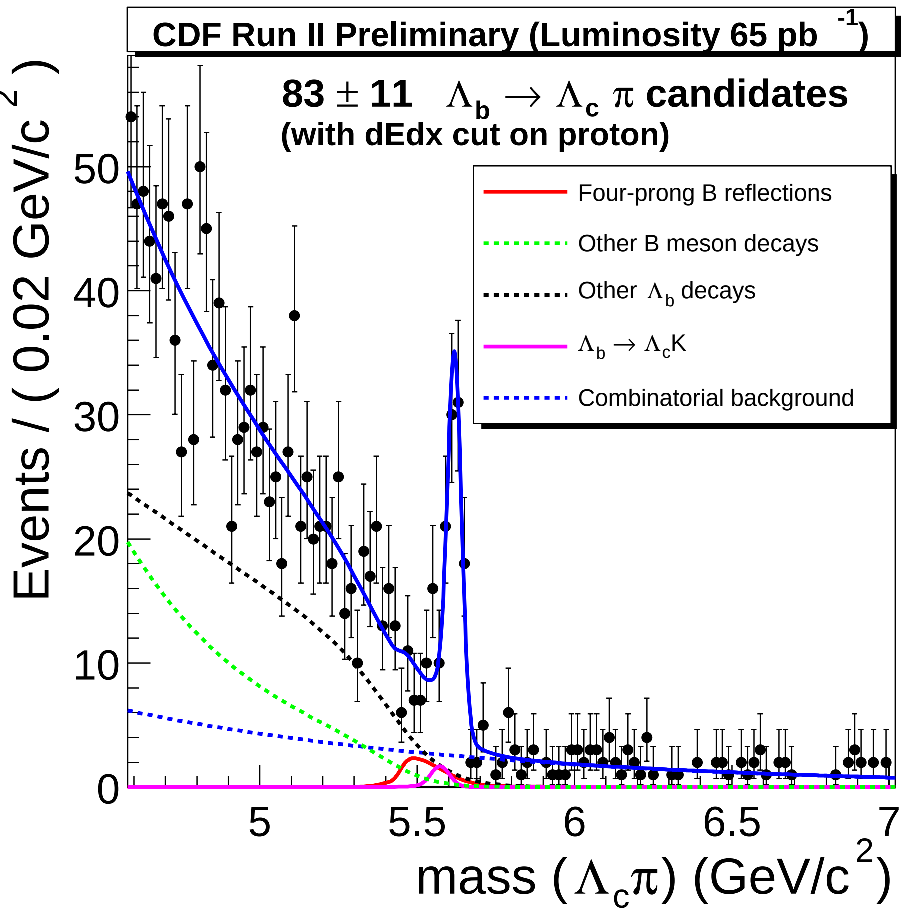
-"horns" coming from D^*

-Reflection from $B^- \to D^0 K^-$ (reconstruct K as π)



Work in progress, must understand these contributions to extract BR

CDF $\Lambda_b \to \Lambda_c \pi$ with $\Lambda_c \to pK\pi$



Backgrounds: real B decays

Reconstruct π as p: $B_d \to D^-\pi^+ \to K^+\pi^-\pi^-\pi^+$

- Use MC to parametrize the shape.
- Data to normalize the amplitude
- Dominant backgrounds are real heavy flavor
- proton particle ID (*dE/dx*) improves S/B

Fitted signal:

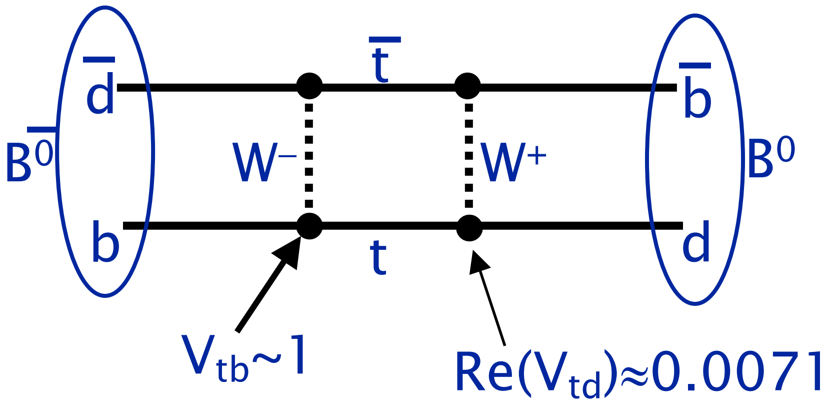
$$N_{\Lambda_b} = 96 \pm 13(stat.)^{+6}_{-7}(syst.)$$

Measure: $$\frac{\sigma_b \times f_{baryon} \times BR(\Lambda_b \to \Lambda^+_c \pi^-)}{\sigma_b \times f_d \times BR(B^0 \to D^- \pi^+)}$$

New Result !

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

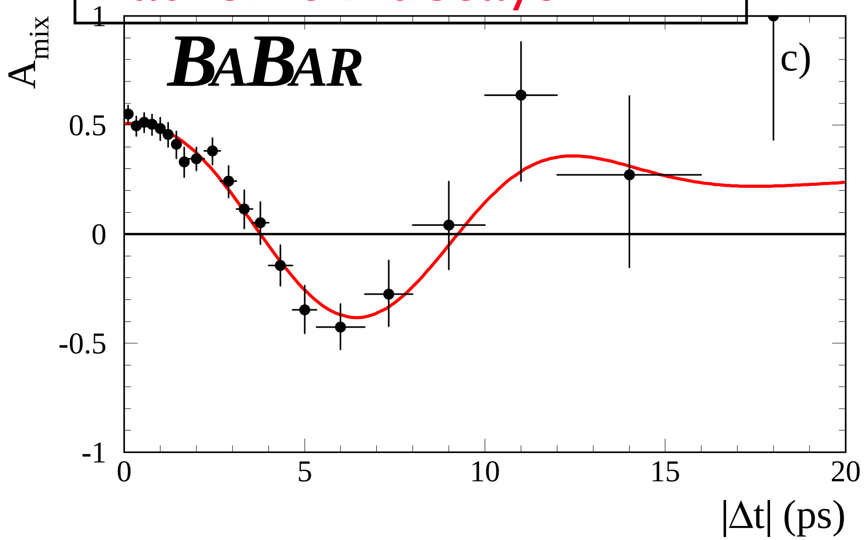
B_d Mixing

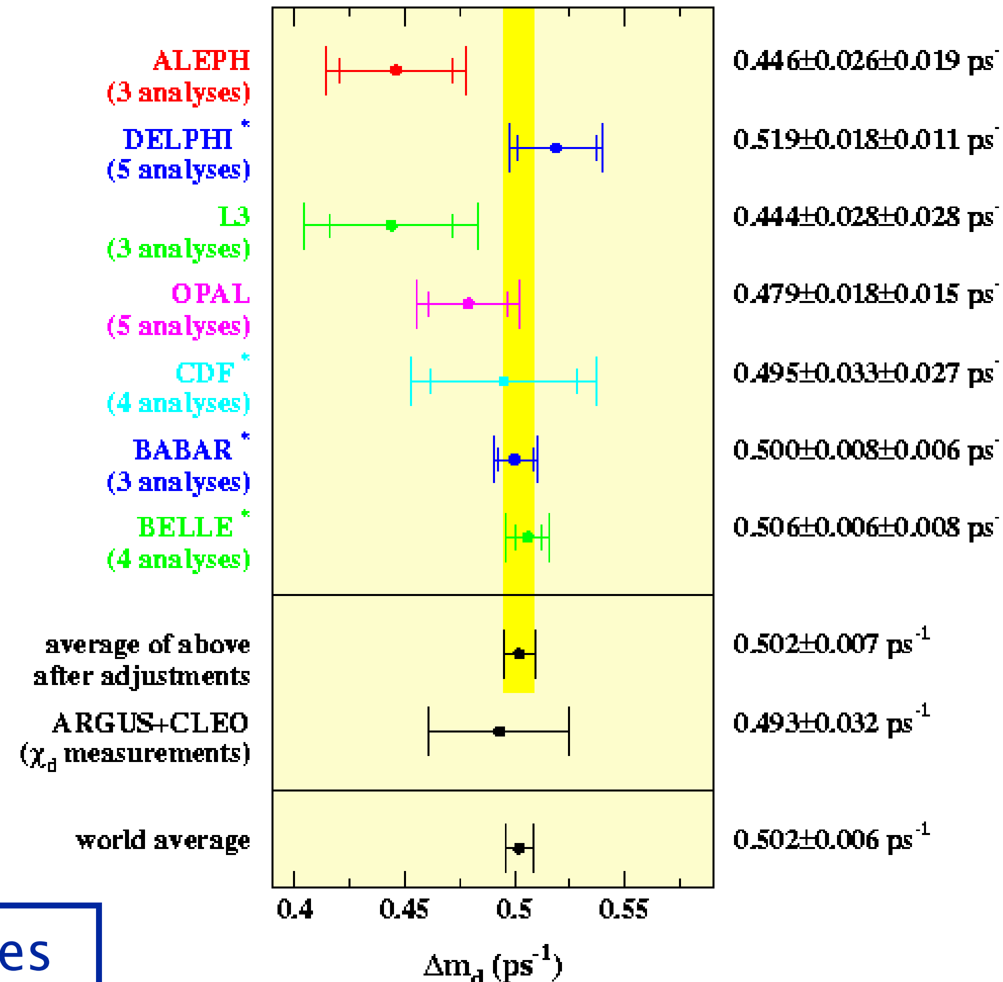


B_d mixing measured with great precision

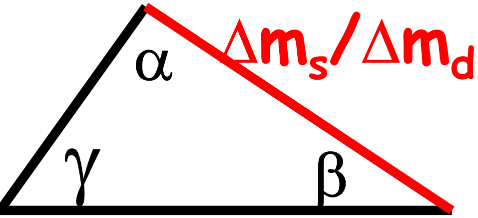
- World average now dominated by Babar and Belle

Babar Δm_d result using hadronic B decays





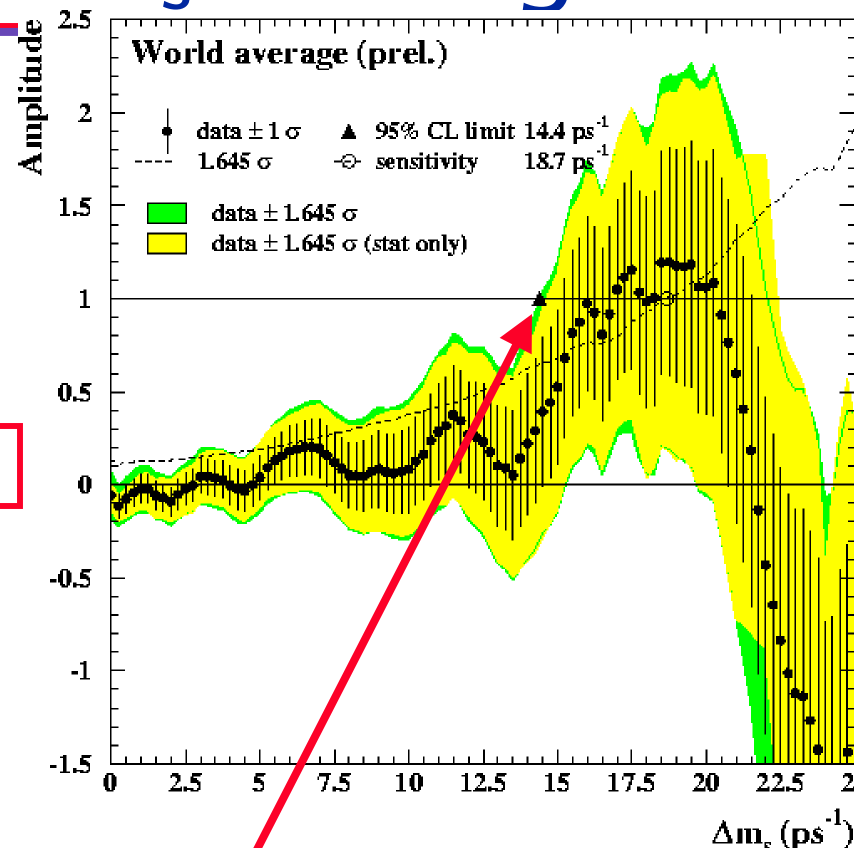
B_d fully mixes in about 4.1 lifetimes

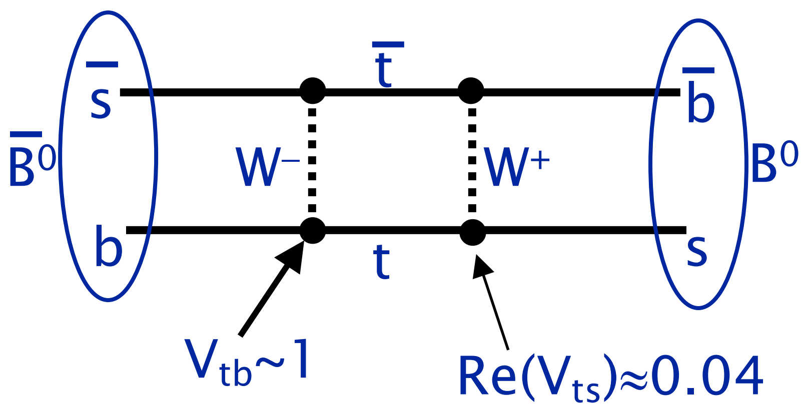


Towards B_s Mixing

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

$$\mathrm{Re}(V_{ts}) \approx 0.040 > \mathrm{Re}(V_{td}) \approx 0.007$$





Combined limit comes from 13 measurements from LEP, SLD & CDF Run I

Measuring Mixing

- **B_s or $\overline{B}_s$ at the time of production?**
  - Initial state flavor tagging
  - Tagging "dilution": D=1-2w
  - Tagging power proportional to: εD^2

Typical power (one tag):
$\varepsilon D^2 = \mathcal{O}(1\%)$ at Tevatron
$\varepsilon D^2 = \mathcal{O}(10\%)$ at PEPII/KEKB

- **B_s or $\overline{B}_s$ at the time of decay?**
  - Final state flavor tagging
  - Can tell from decay products (e.g. $B_s \to D_s^- \pi^+$)
- **Yields**
  - Need lots of decays (because flavor tagging imperfect)
- **Proper decay time**

$$ct = \frac{L_{xy}}{(\beta\gamma)} = \frac{L_{xy} m_B}{p_T}$$

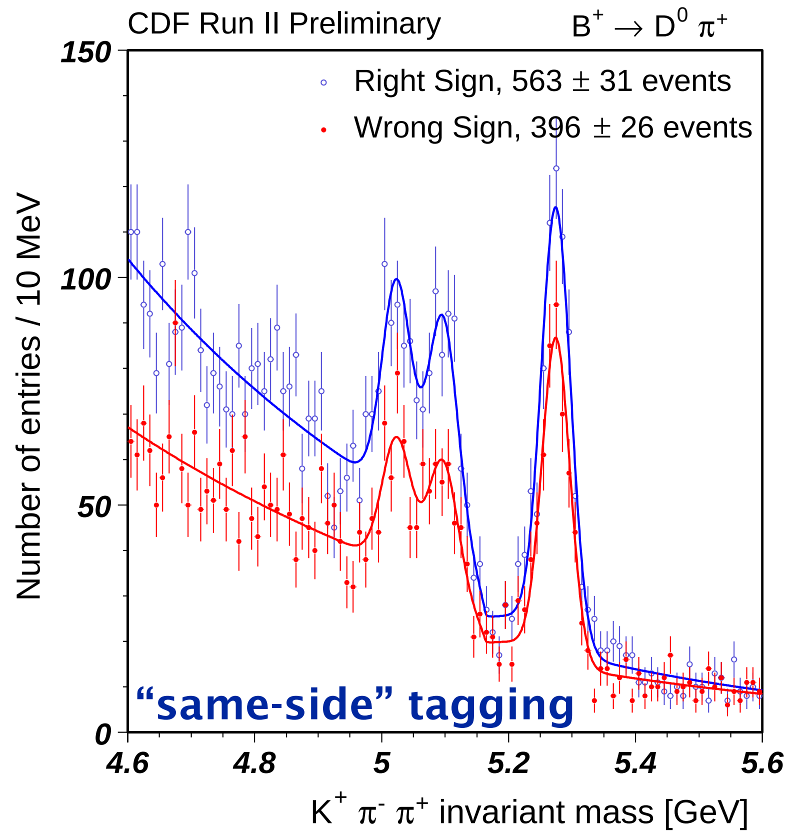
uncertainty →

$$\sigma_{ct} = \frac{m_B}{p_T}\sigma_{L_{xy}} \oplus ct\left(\frac{\sigma_{p_T}}{p_T}\right)$$

  - Need decay length (L_{xy}) and time dilation factor ($\beta\gamma = p_T/m_B$)
  - Crucial for fast oscillations (i.e. B_s)

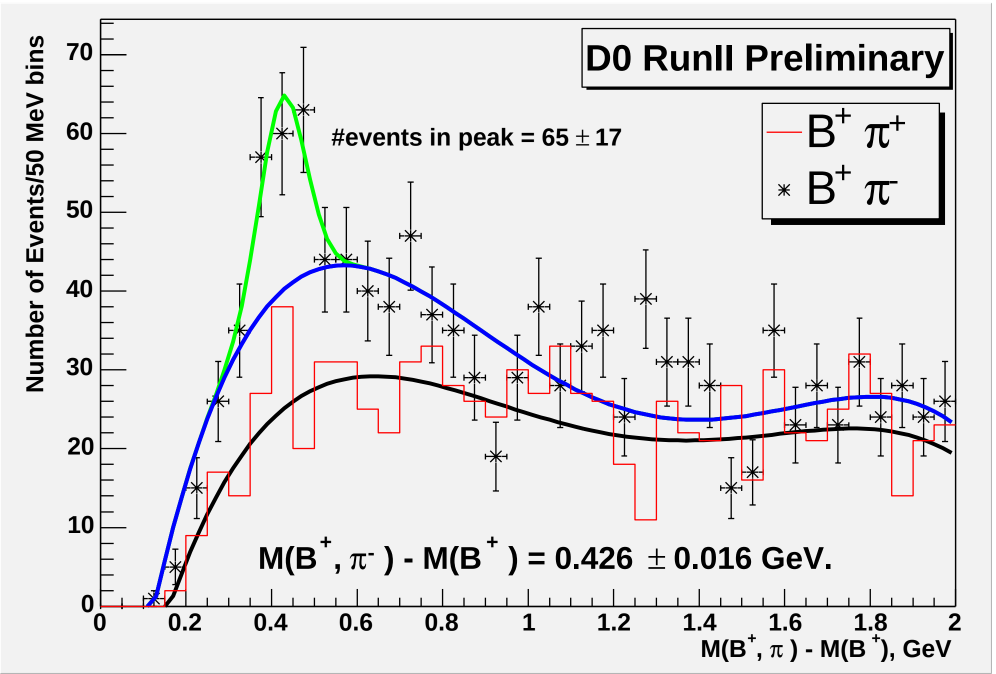
Flavor Tagging

- Strategy: use data for calibration (*e.g.* $B^{\pm}\rightarrow J/\psi K^{\pm}$, $B\rightarrow$lepton)
  - "know" the answer, can measure right sign and wrong sign tags.



DØ Results:

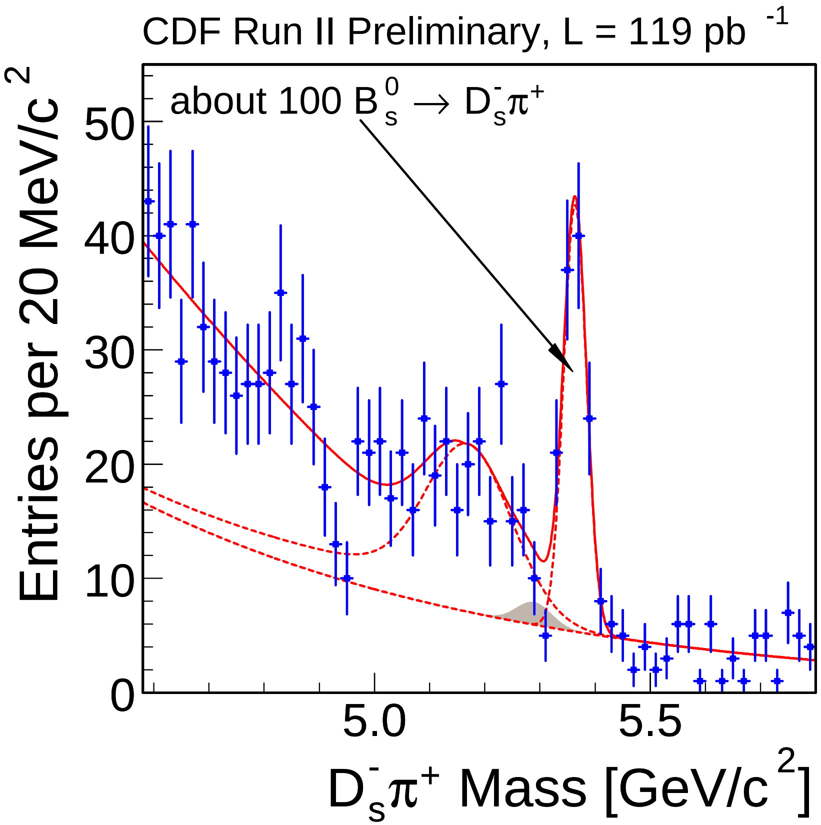
- Jet charge εD^2=(3.3±1.1)%
- Muon tagging εD^2=(1.6±0.6)%

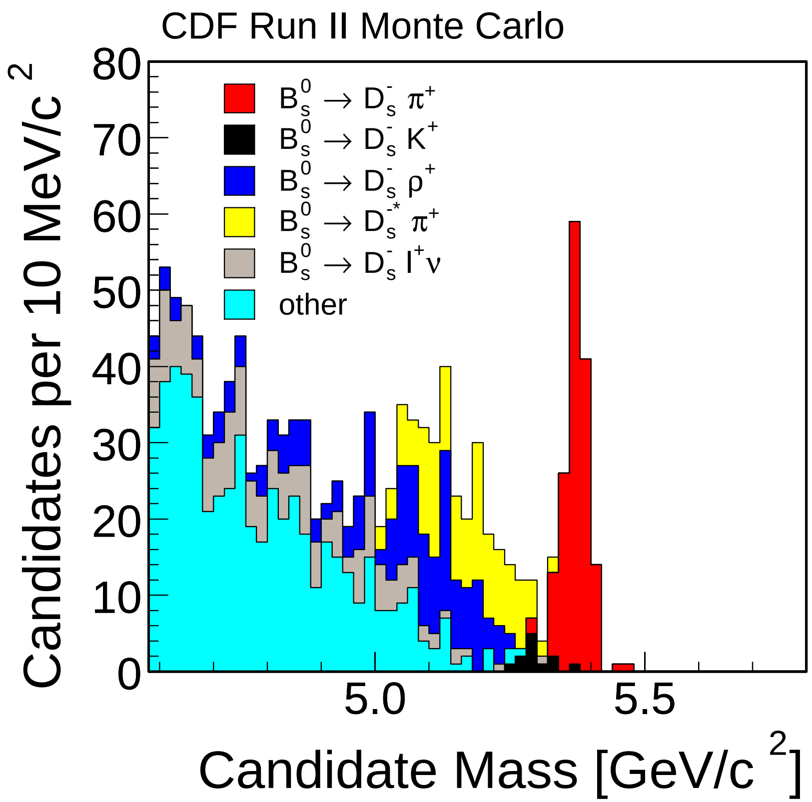


CDF Results:

- Same-side (B^+) εD^2=(2.1±0.7)%
  (B^+/ B^0/ B_s correlations different)
- Muon tagging εD^2=(0.7±0.1)%

B_s Yields: CDF $B_s \to D_s \pi^+$





$B_s \to D_s \pi^-$ with $D_s \to \phi \pi^+$ and $\phi \to K^- K^+$

$$BR(B_s \to D_s \pi^\pm) = (4.8 \pm 1.2 \pm 1.8 \pm 0.8 \pm 0.6) \times 10^{-3}$$

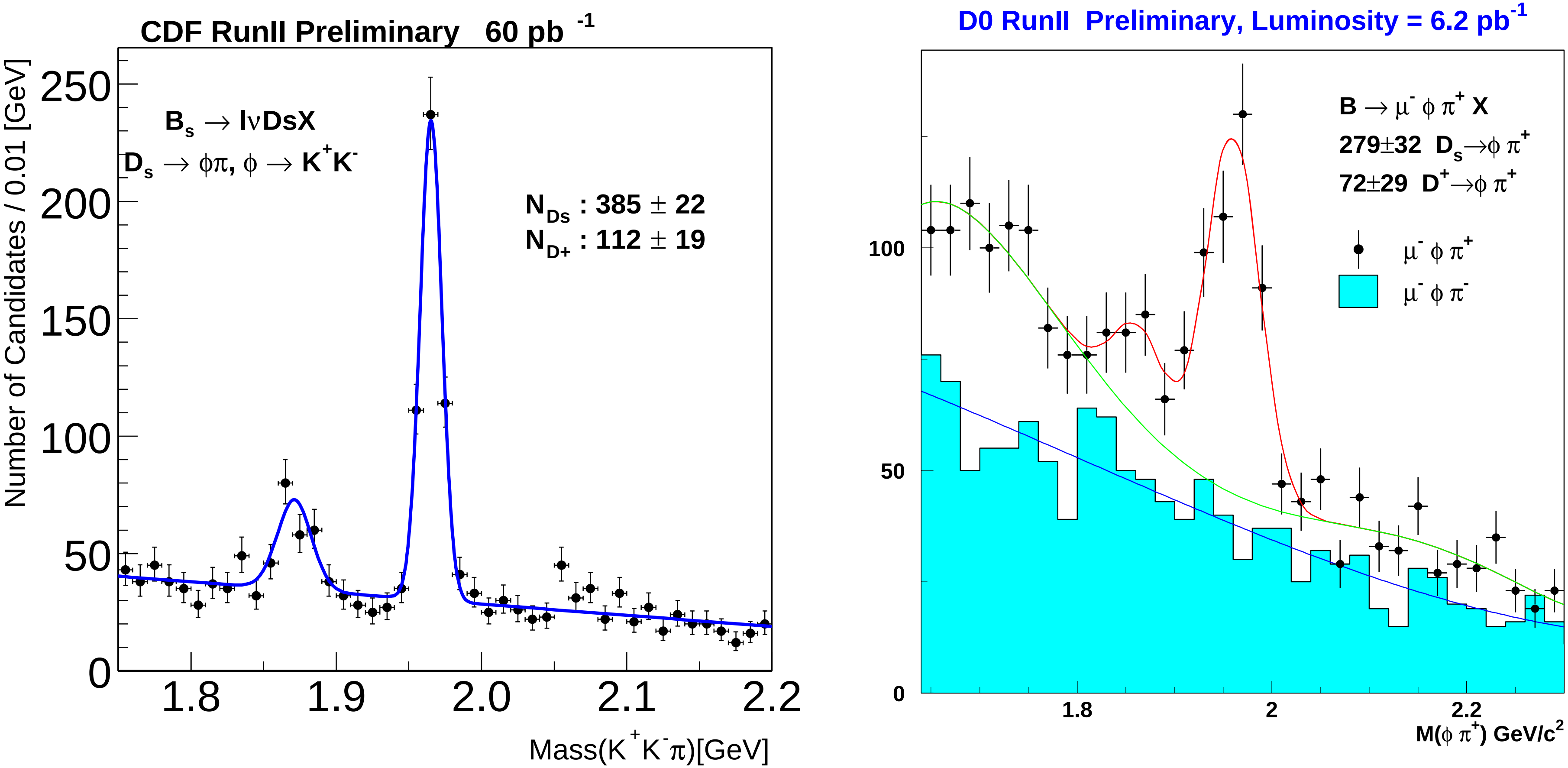
(Stat) (BR) (sys) (f_s/f_d)

New measurement !

Previous limit set by OPAL: BR ($B_s \to D_s \pi^\pm$) < 13%

BR result uses less data than shown in plot.

Semileptonic B_s Yields



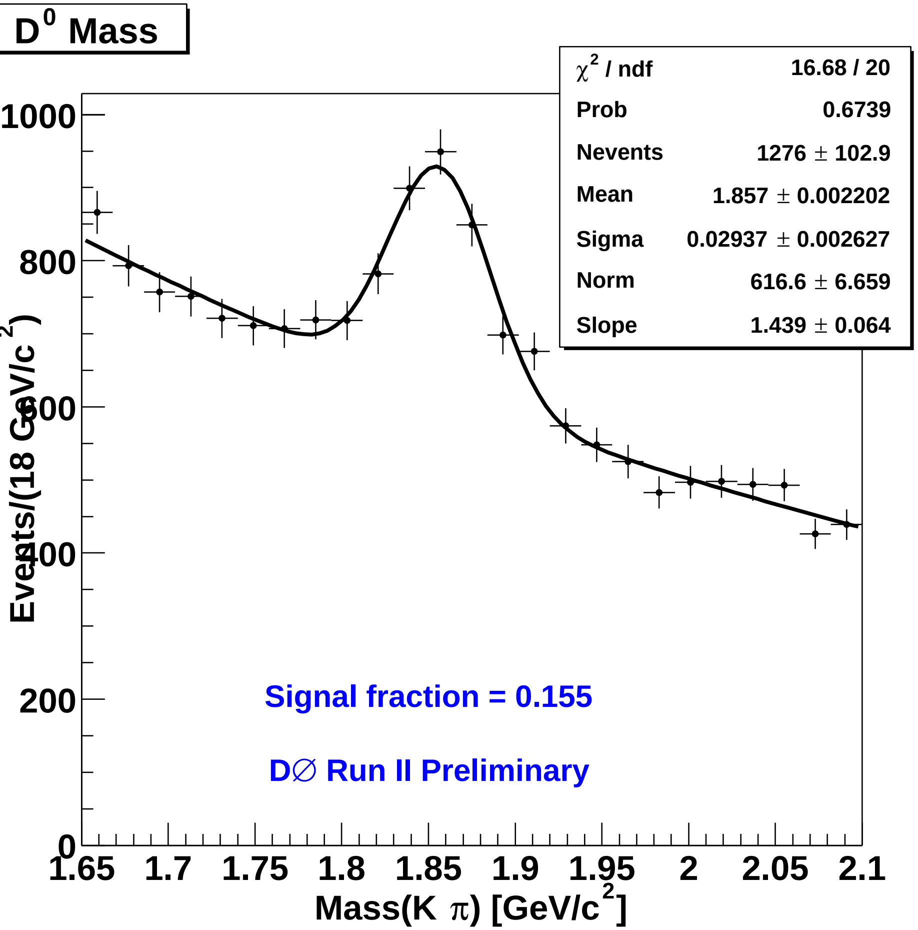
Plots show: $B_s \to D_s l^- \nu$ with $D_s \to \phi\pi^+$ and $\phi \to K^- K^+$

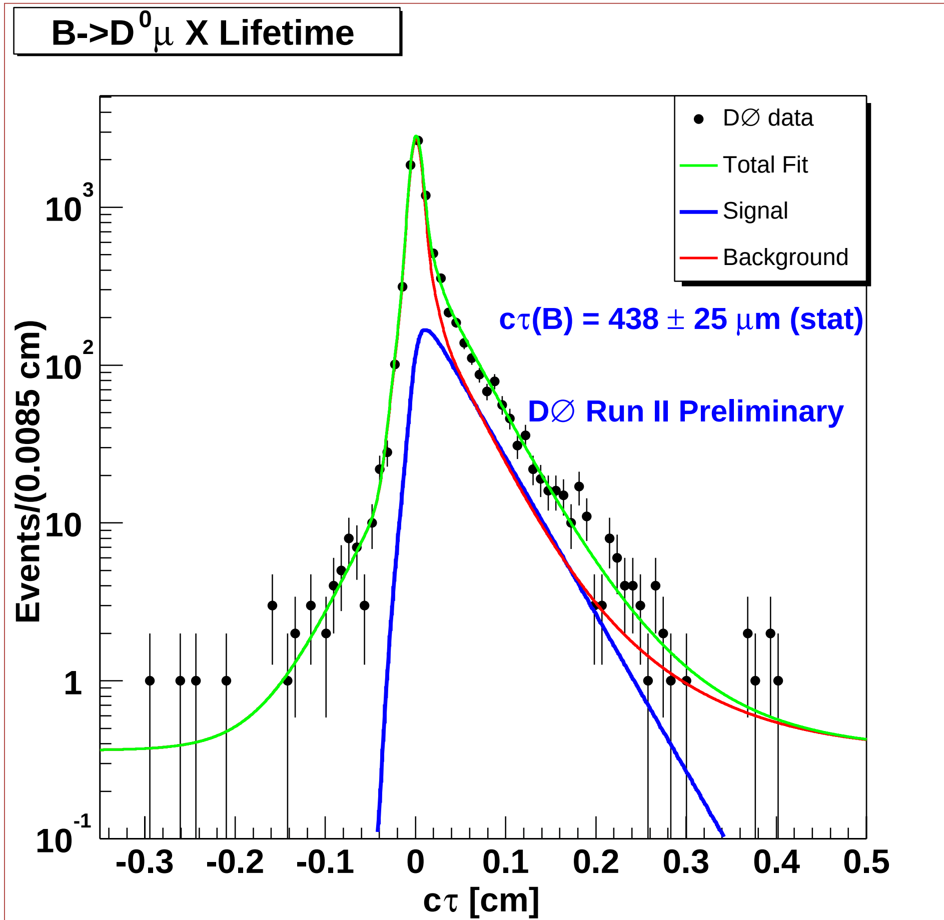
(will also reconstruct $D_s \to K^{*0} K^+$ and $D_s \to K_s K^+$)

DØ *B* Semileptonic Lifetime

$B \to \mu^- \nu_\mu D^0 X$ with $D^0 \to K^- \pi^+$

12pb^{-1} of data taken with single muon trigger.





Time dilation factor ($\beta\gamma$) must be corrected for missing ν

$$\tau(B) = 1.46 \pm 0.08(stat.)\ \text{ps}$$

B_s Sensitivity

- From data, now have some knowledge of the pieces that go into measuring Δm_s
  - ➔ *Yields* — *S = # signal events*
  - ➔ *Flavor tagging* — *tagging power = εD^2*
  - ➔ *Signal-to-noise* — *S/B = signal/background*
  - ➔ *Proper time resolution* — *σ_t = proper time resolution*

- *The sensitivity formula:*

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

- Significance (in number of standard deviations) is "average signficance"

CDF B_s Sensitivity Estimate

- Current performance: **hadronic mode only**
  - $S=1600$ events/fb^{-1} (*i.e.* $\sigma_{effective}$ for produce+trigger+recon)
  - $S/B = 2/1$
  - $\varepsilon D^2 = 4\%$
  - $\sigma_t = 67fs$

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

- surpass the current world average

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  - ➔ S=1600 events/fb^{-1} (*i.e.* $\sigma_{effective}$ for produce+trigger+recon)
  - ➔ S/B = 2/1
  - ➔ εD^2 = 4%
  - ➔ σ_t = 67fs

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

    - surpass the current world average
- With "modest" improvements
  - ➔ S=2000 fb (improve trigger, reconstruct more modes)
  - ➔ S/B = 2/1 (unchanged)
  - ➔ εD^2 = 5% (kaon tagging)
  - ➔ σ_t = 50fs (event-by-event vertex + L00)

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

    5σ sensitivity for Δm_s=24ps^{-1} with ~3.2fb^{-1} of data

    ✓ Δm_s=24ps^{-1} "covers" the expected region based upon indirect fits.
- *This is a difficult measurement.*
- *There are ways to further improve this sensitivity…*

Work In Progress

Estimates based current performance plus modest improvements. Further gain is possible on all of these pieces:

- σ_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

Matters most for going to Δm_s > 20 ps^{-1}

Trigger improvements matter most for yields

It's doable! It will take time, luminosity and hard work!

Tevatron B_s Sensitivity

- We know B_s mixing is a difficult measurement.

- Estimate shown is based solely CDF sensitivity for the hadronic modes.
  - DØ will have sensitivity in hadronic mode(opposite muon)
  - Semileptonic modes important, especially at lower Δm_s
  - DØ and CDF will both contribute to $B_s \rightarrow$lepton+D_s

- "This is a marathon, not a sprint."

- SM expectation: $\Delta\Gamma_s \propto \Delta m_s$
  - Experiments will also attempt to measure $\Delta\Gamma_s$
    - in untagged samples
    - by extracting *CP* even/odd components in $B_s \rightarrow J/\psi\phi$

Conclusion

- New cross sections, lifetime and branching ratio measurements from the Tevatron
  - ➔ Beginning to exploit high yields and upgraded detectors
    - **DØ has a new spectrometer**
    - **CDF has a new impact parameter trigger**
- Babar and Belle continue to provide an amazing breadth of B^+ and B^0 results
- Tevatron will contribute knowledge of heavier *B* hadrons
  - ➔ Many technical challenges have been overcome
  - ➔ Lots of work to do
- Stay tuned!

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