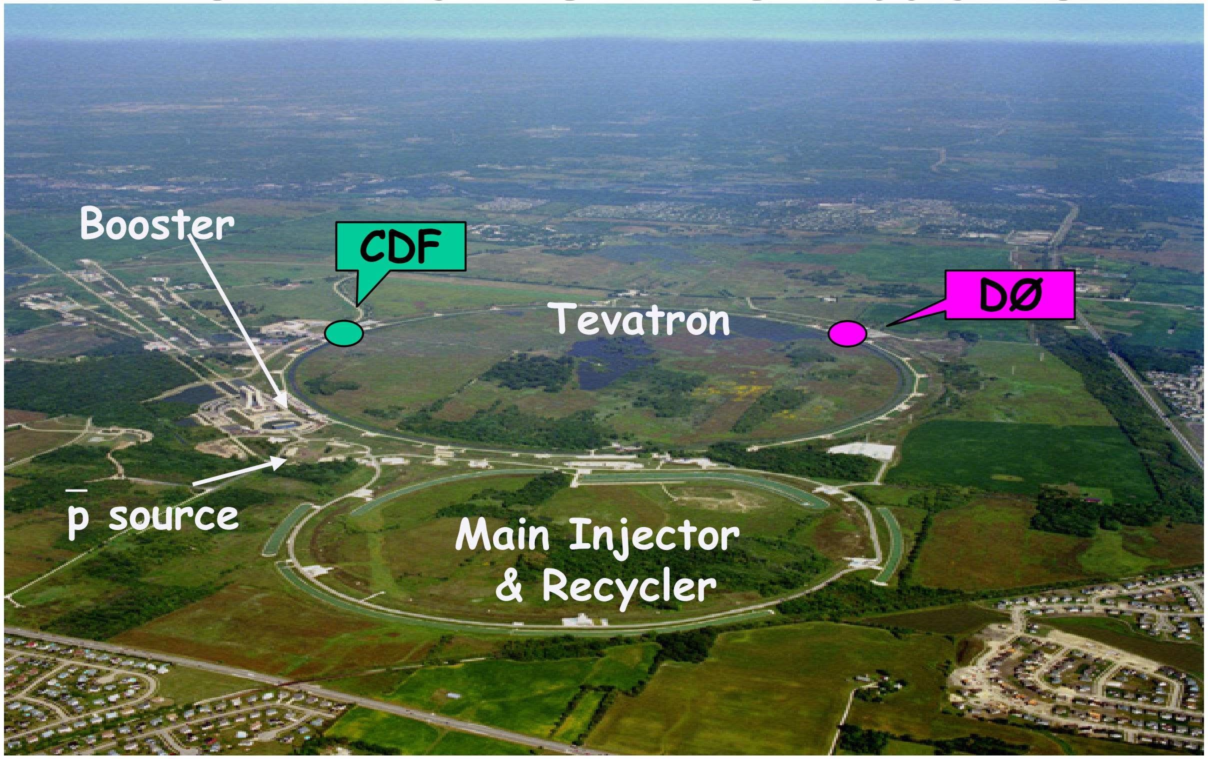
Recent *B* Physics Results from the Tevatron



KEK TC6
February 7, 2007

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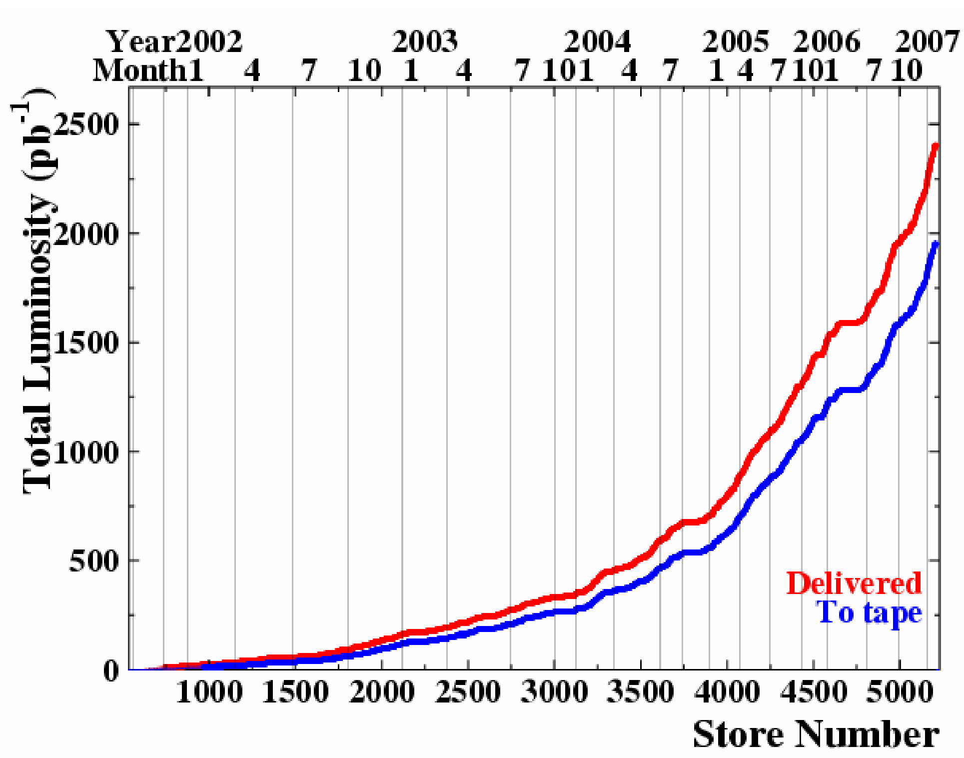
University of Illinois

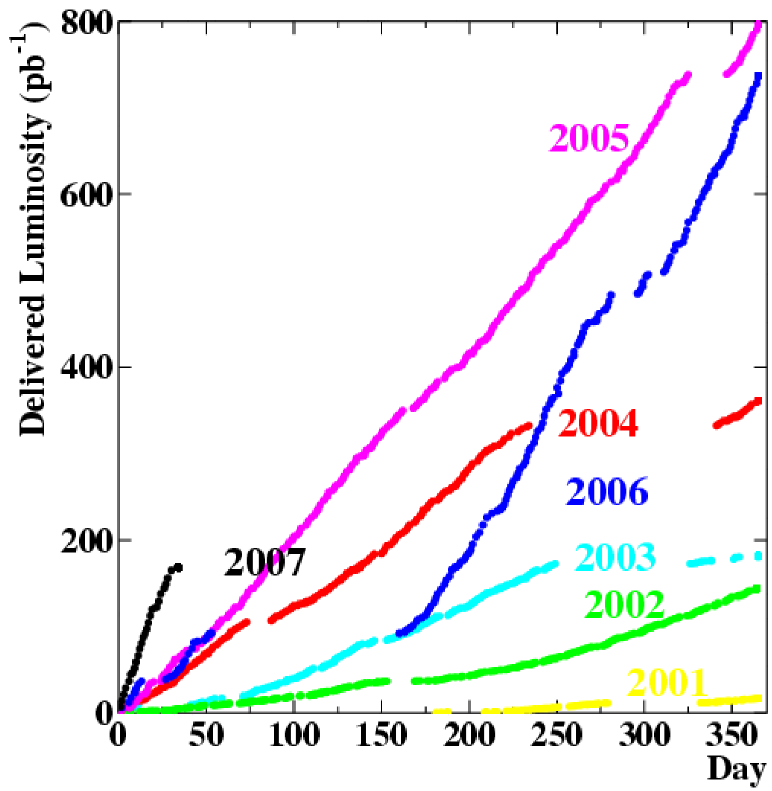
Outline

- Introduction
  - Tevatron, CDF and DØ detectors
  - Experimental challenges
  - Triggering
- Recent Results
  - B_s Mixing
  - $B \to hh'$
  - Λ_b Lifetime, Σ_b observation
- Things not covered
- Prospects
- Conclusions

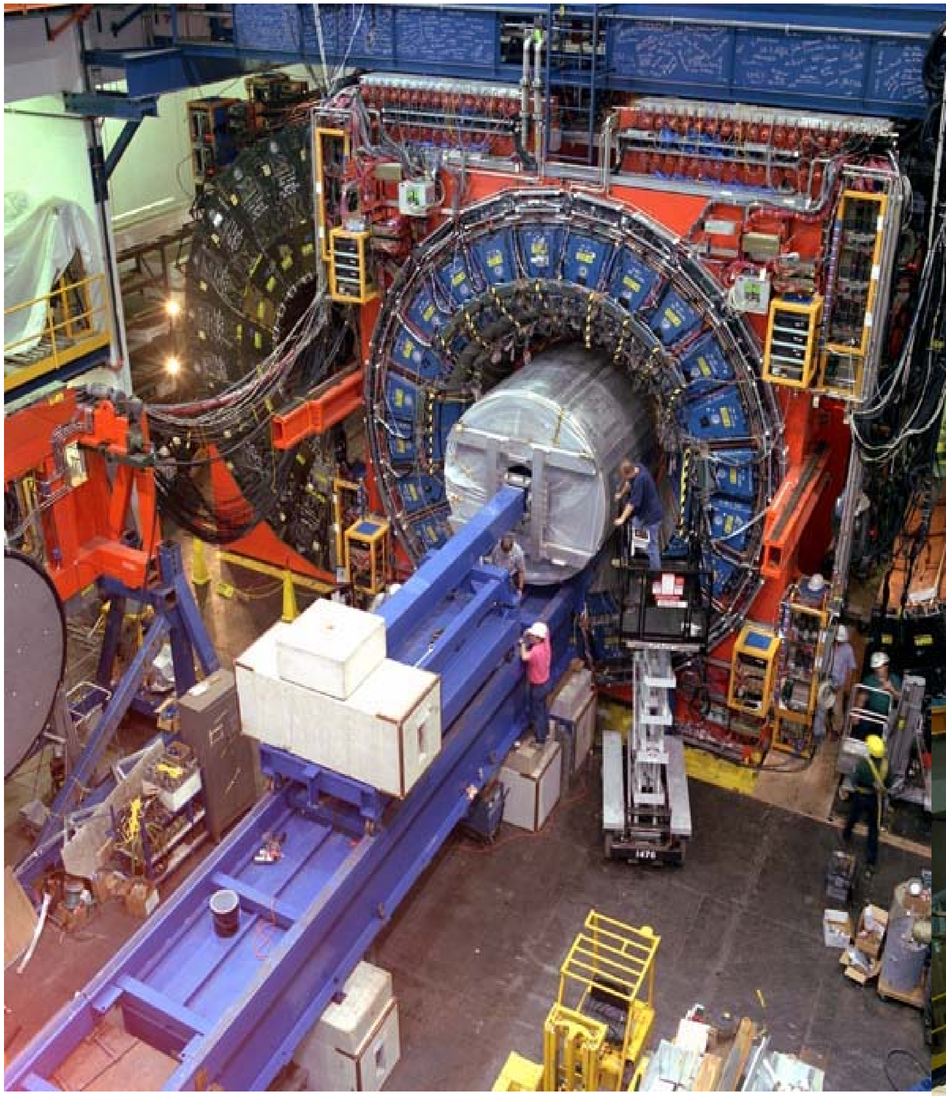
Fermilab Tevatron

- $p\bar{p}$ collisions at 1.96 TeV
- 1.7 fb^{-1} "good" data on tape (results today 1fb^{-1})
- 1.7MHz collision rate (396 ns bunch spacing)
- Peak luminosity $2.6 \times 10^{32} cm^{-2} s^{-1}$
  - Average ~5-6 $p\bar{p}$ interactions per bunch crossing
- Anticipate luminosity as high as $3 \times 10^{32} cm^{-2} s^{-1}$
  - Challenging for the detector, trigger and event reconstruction

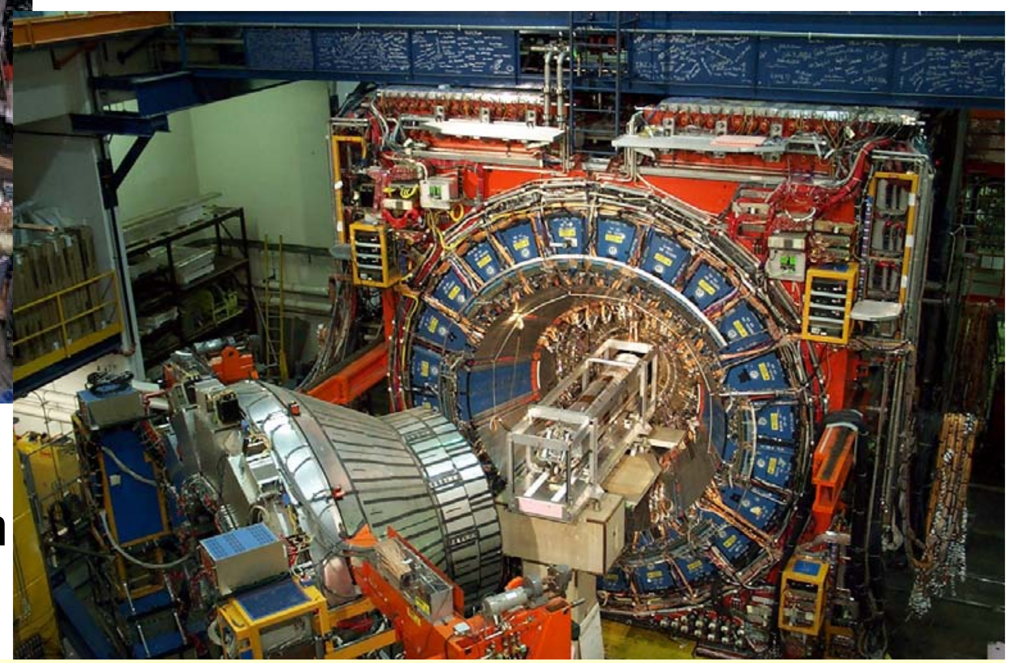




CDF Detector



- Strong central tracking
- Silicon vertex detector
- Good lepton identification
- Particle ID (TOF and dE/dx)
- Excellent mass resolution

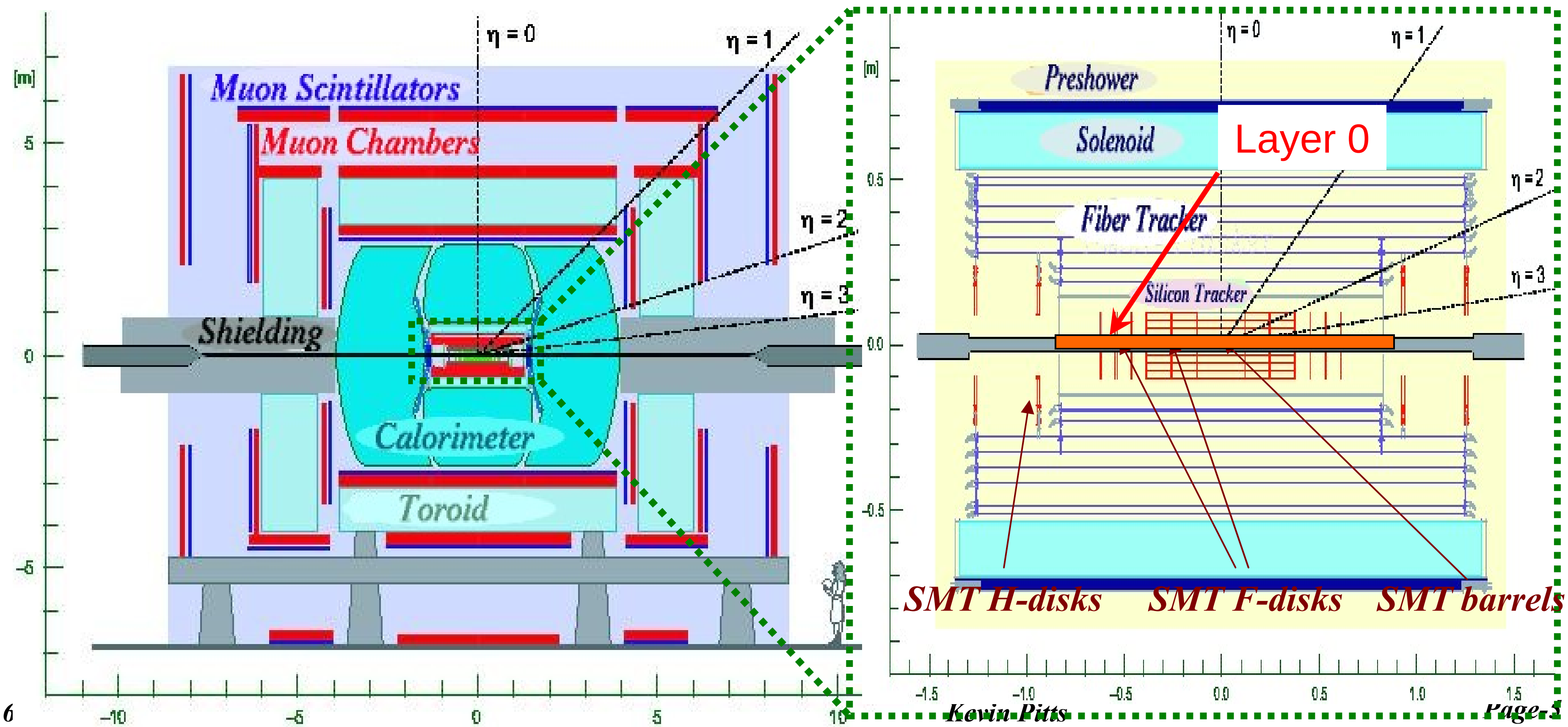


CDF silicon detector installation

- High rate trigger/DAQ system
- Silicon vertex trigger

DØ Detector

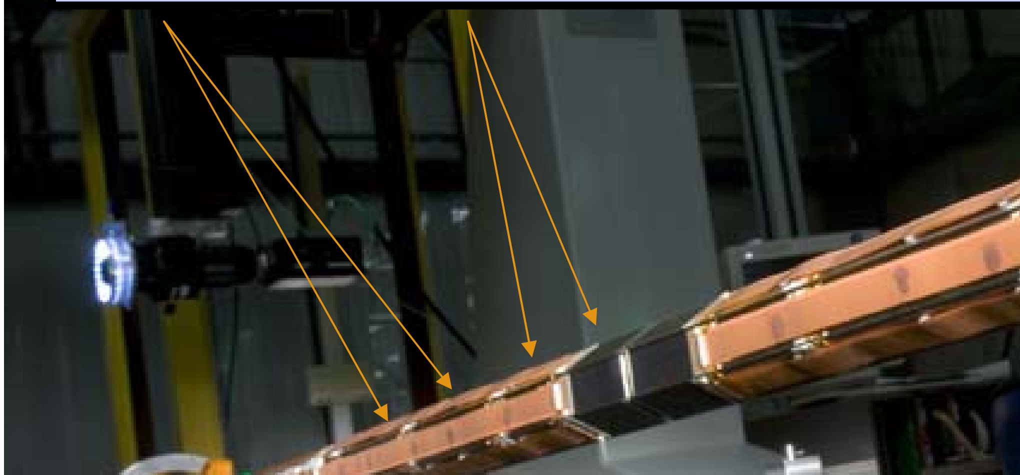
- Excellent coverage of Tracking and Muon Systems
- Excellent calorimetry and electon ID
- 2 T Solenoid, polarity reversed weekly
- High efficiency muon trigger with muon p_T measurement at Level1 by toroids

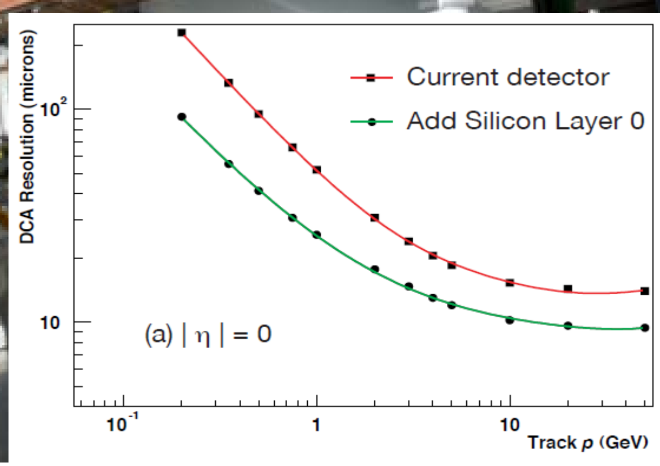


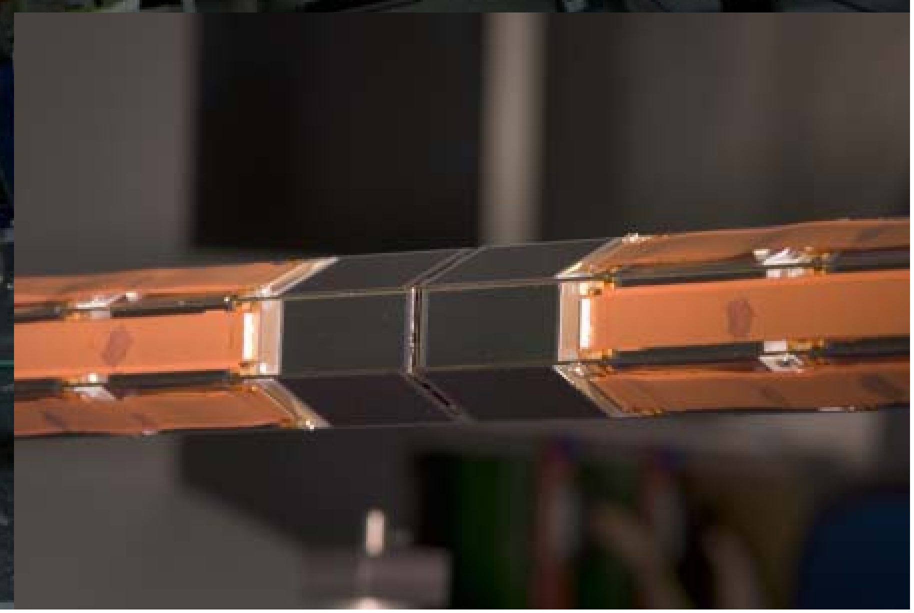
April 2006 Layer 0 Installation

The detector consists of:

- 48 modules mounted on carbon fiber support structure at 1.7 cm radius
  - 6 f-segments, 8 z-segments
- Four sensor types provide 98.4% of acceptance
  - Sensors 12 and 7 cm lengths

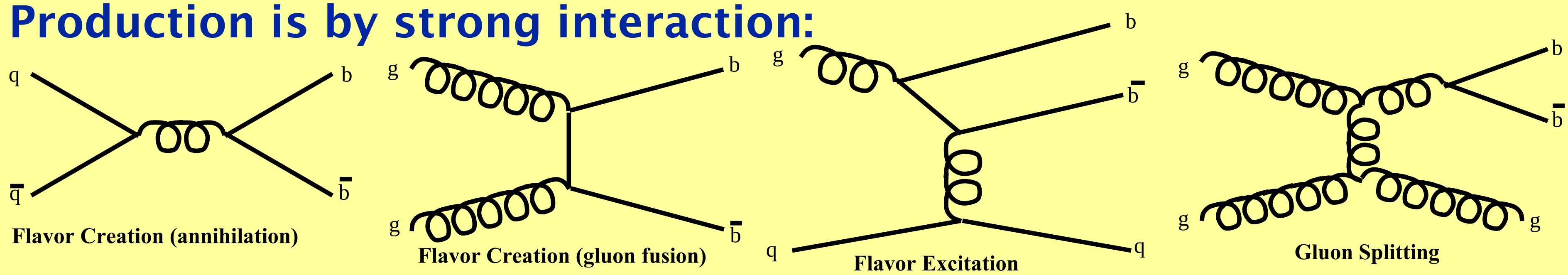






B Physics at the Tevatron

Production is by strong interaction:



Pros

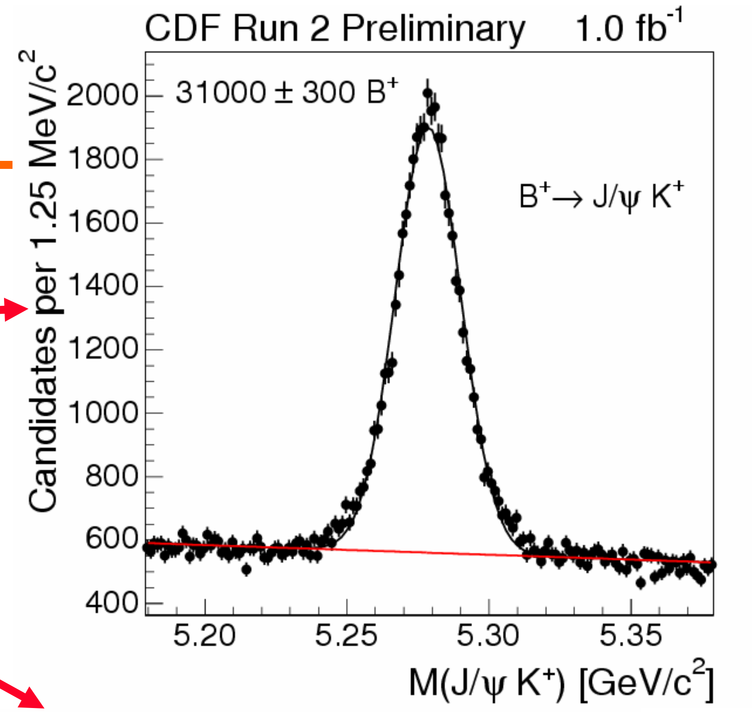
- **Enormous cross-section**
  - ~50 μbarn total
  - ~3-5 μbarn "reconstructable"
  - At $1 \times 10^{32} cm^{-2} s^{-1} \Rightarrow$ ~400Hz of reconstructable $B\bar{B}$!!
- **All *B* species produced**
  - $B_u, B_d, B_s, B_c, \Lambda_b, \Sigma_b$...
- **Production is incoherent**

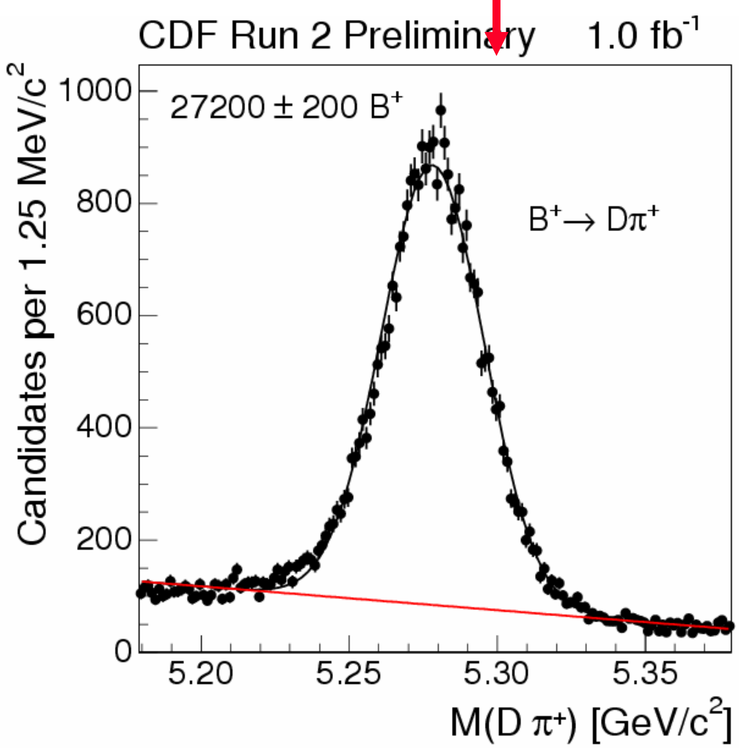
Cons

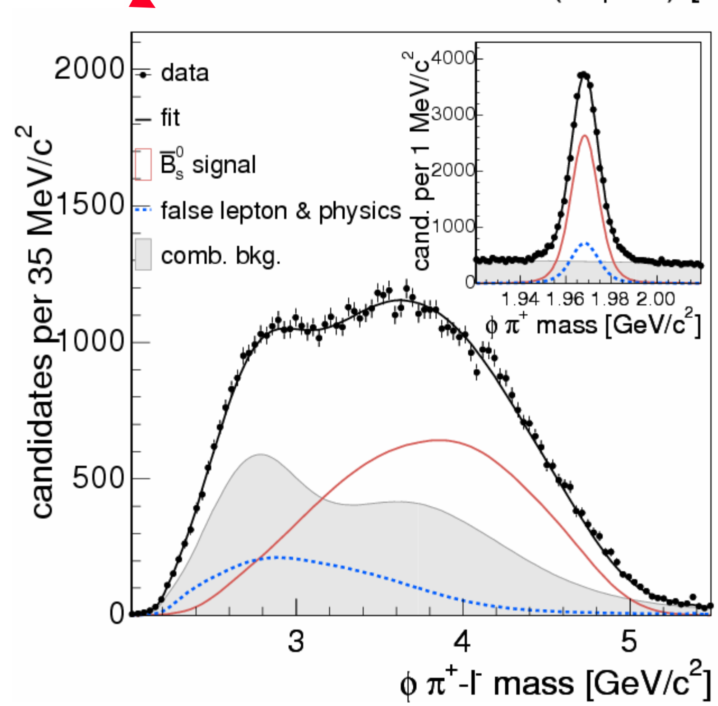
- **Large inelastic background**
  - Triggering & reconstruction are challenging
  - Modes with π^0's are tough
- **Reconstruct a *B* hadron, ~25% chance 2nd *B* is within detector acceptance**
- **p_T spectrum relatively soft**
  - Typical $p_T(B)$~10-15 GeV for trigger+reconstructed *B*'s

Trigger Strategies

- **Dimuons (dielectrons)**
  - **Clean signatures, less background**
  - **Get lots of $B \to J/\psi$ modes**
  - **Also rare decays ($B \to \mu\mu$, $\mu\mu$ X)**
- **Single electrons/muons**
  - **Semileptonic decays**
- **Track only**
  - **Hadronic modes**







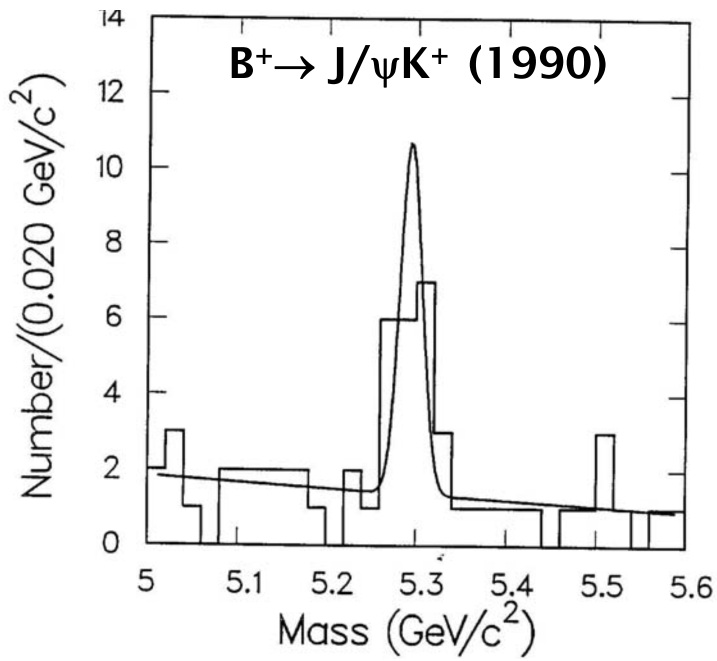
We've come a long way…

- Success of the Tevatron *B* program has benefited from:
  - More luminosity
  - Better detectors, triggers, DAQ systems
  - Better understanding of production
  - Better understanding of analysis techniques

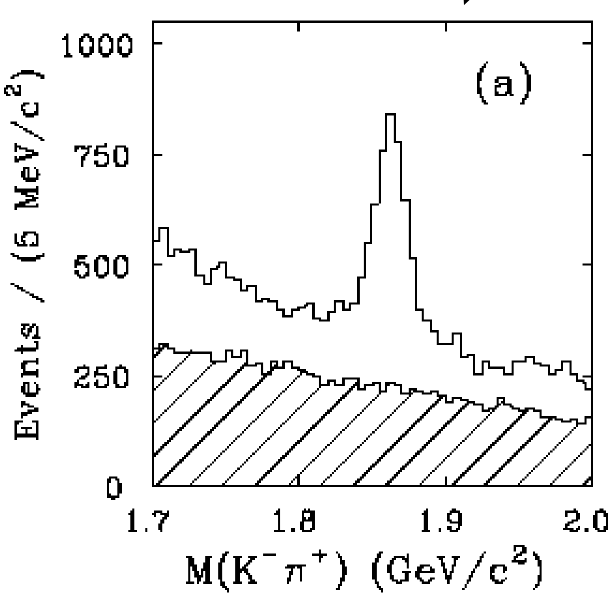
- On two occassions, there has been a major transition in our capabilities:
  1. silicon microvertex detector (~1991)
  2. utilizing silicon in the trigger (~2002)

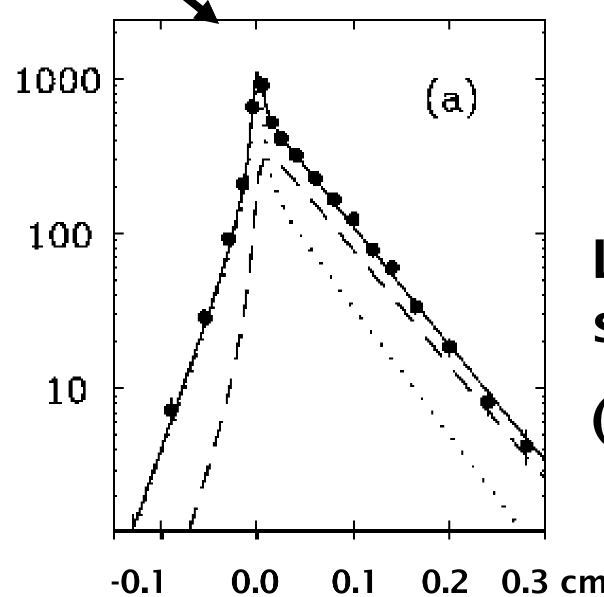
The early days…

- **Before silicon**



- **After silicon**



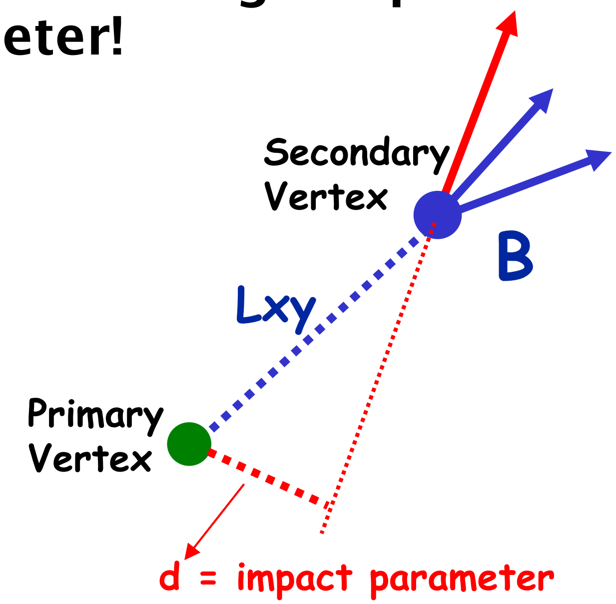


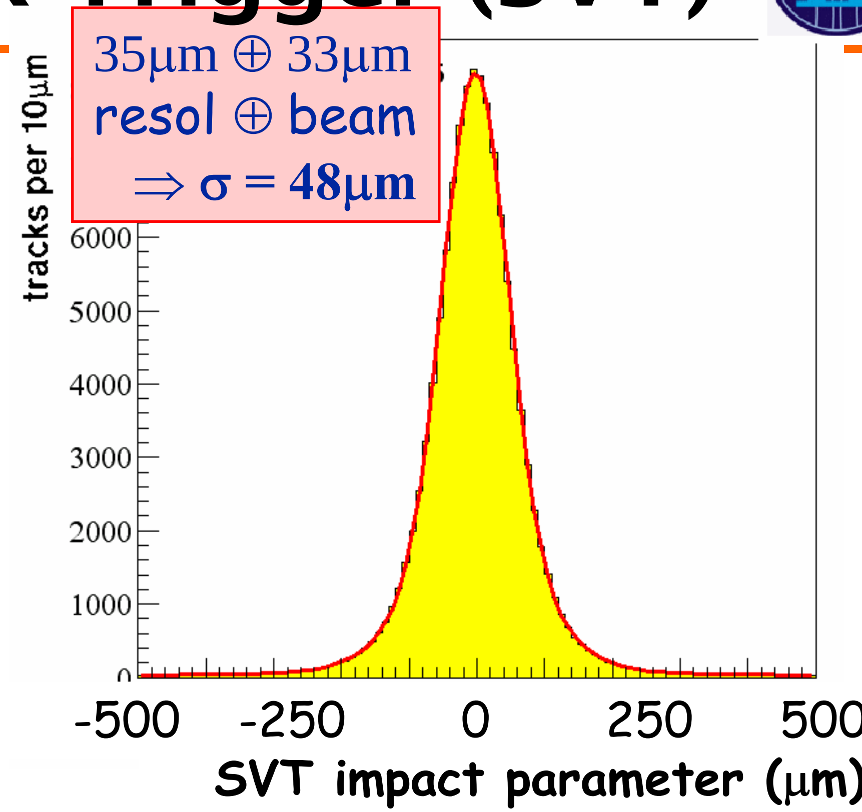
Lifetimes in semileptonic decays

(F. Ukegawa et al.)

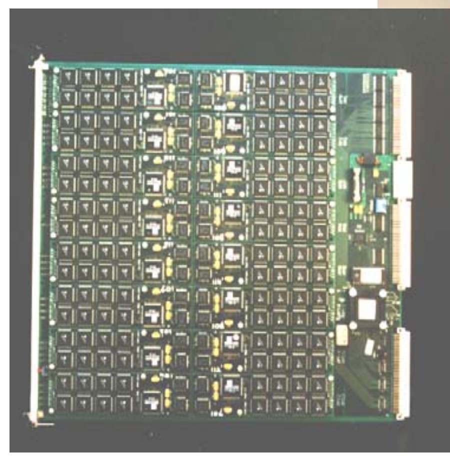
Silicon Vertex Trigger (SVT)

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

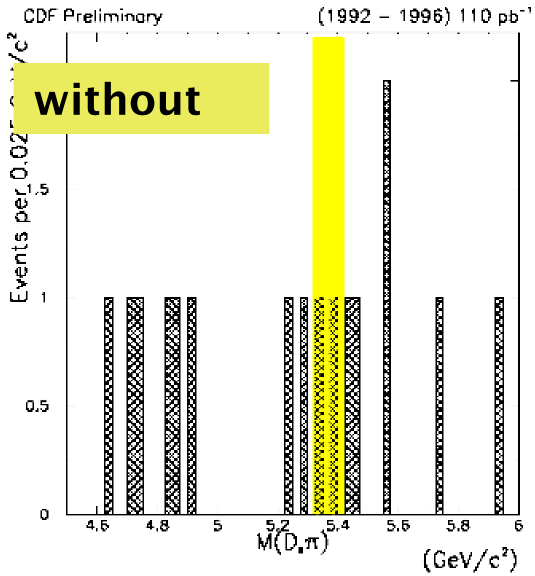




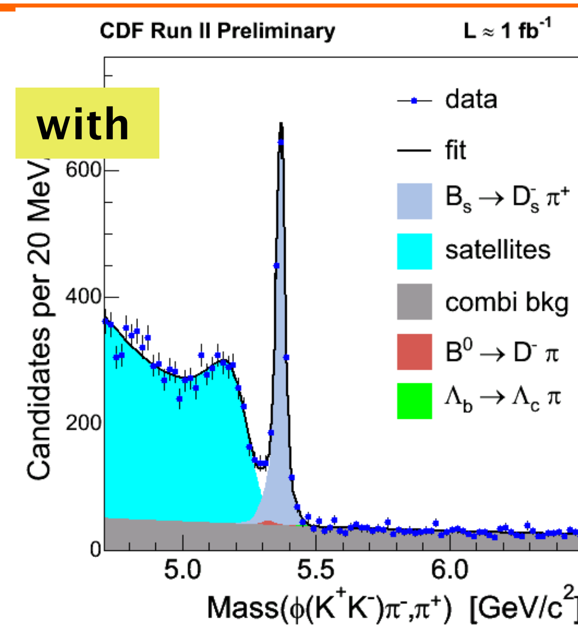
- **Uses fitted beamline**
- **impact parameter per track**
- **System is "deadtimeless":**
  - **~25μsec/event for readout + clustering + track fitting**

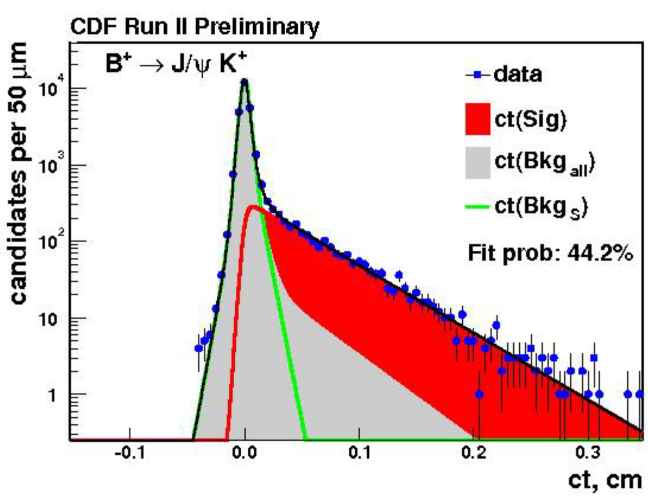


What do we get with the SVT?



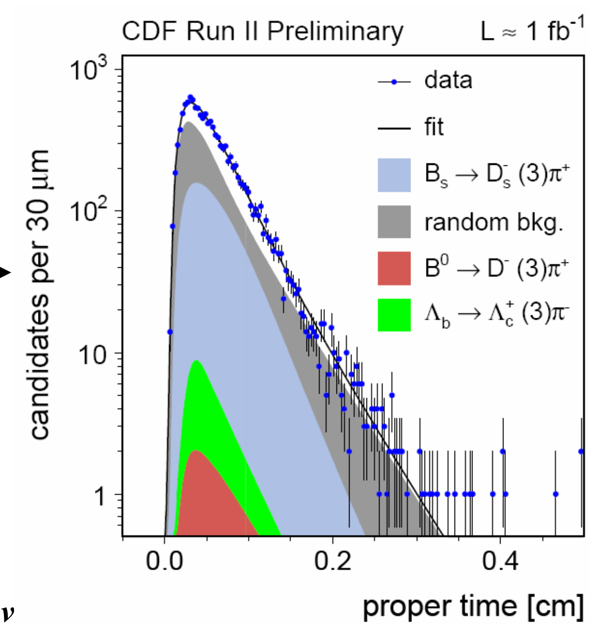
Access to many new modes





inefficiency for events with low decay time

[can be accounted for *e.g.* Bs mixing]



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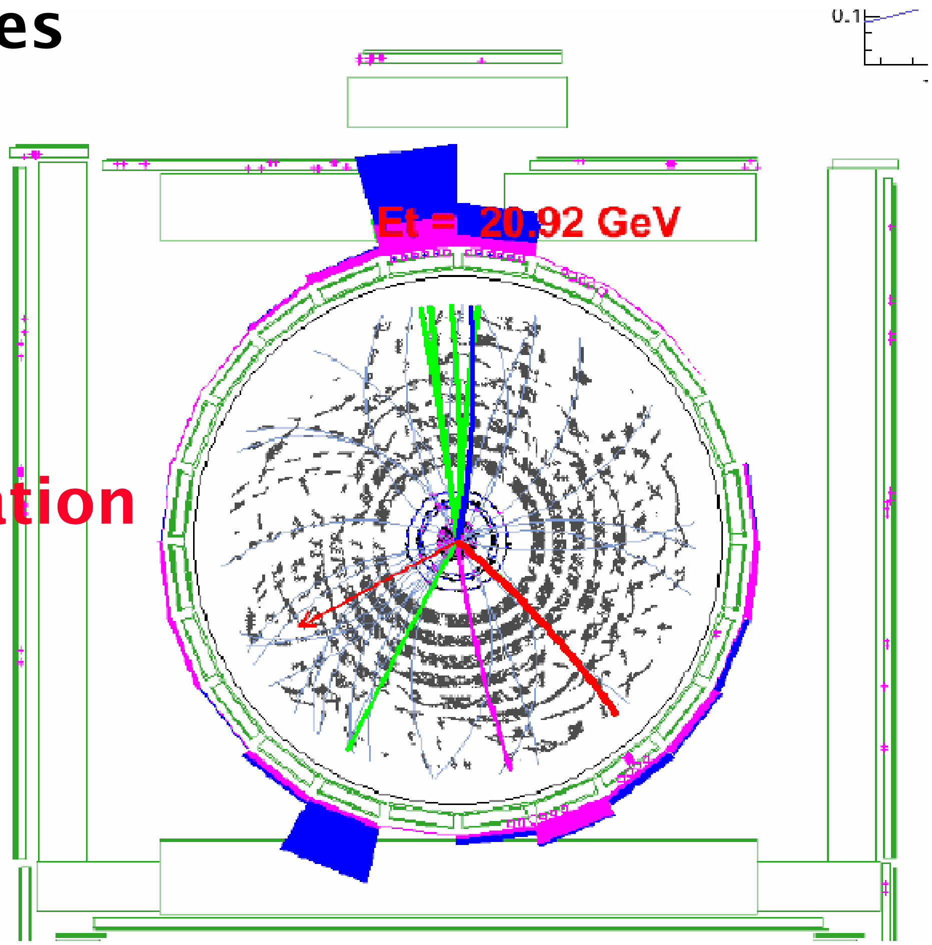
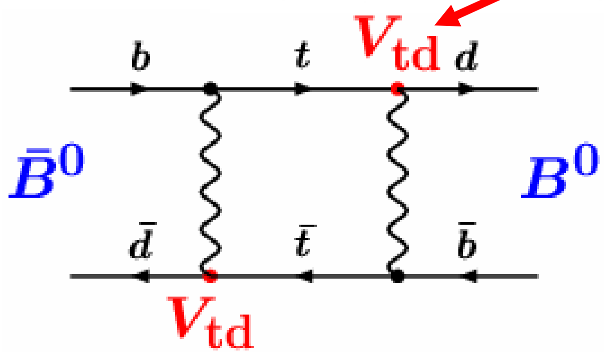
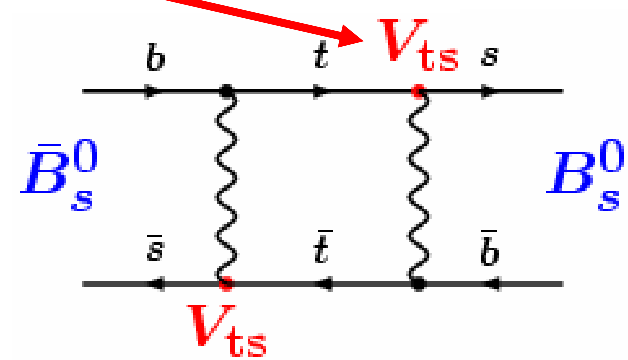


Neutral *B* Meson Oscillations

Cabibbo-Kobayashi-Maskawa Matrix **fundamental parameters that must be measured**

$$\text{weak} \quad \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad \text{mass}$$





Oscillation frequencies (Δm_d, Δm_s) determine poorly known V_{td}, V_{ts}

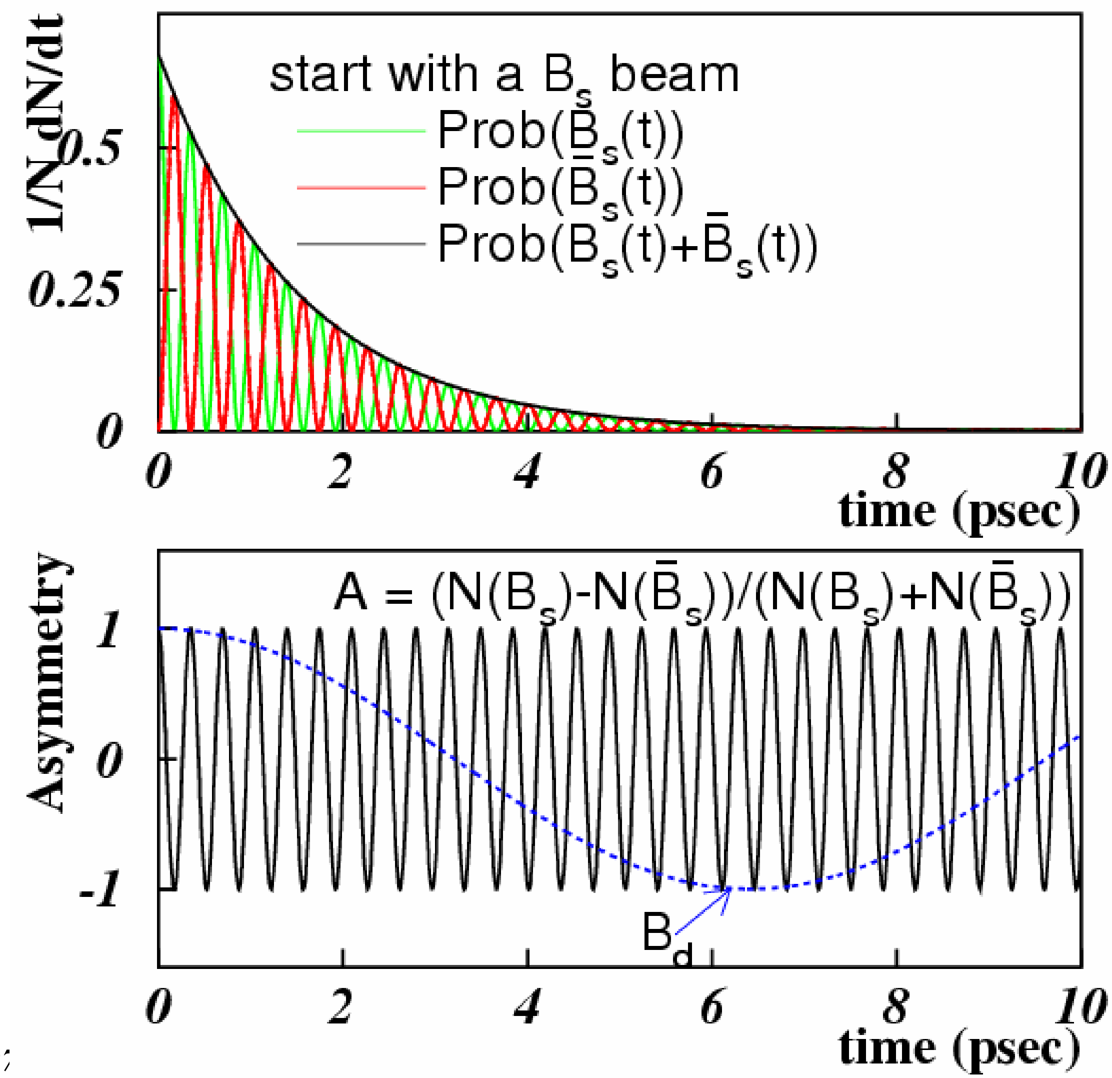
Theoretical uncertainties <u>reduced</u> in ratio:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \left| \frac{V_{ts}}{V_{td}} \right|^2 \qquad \xi = \frac{B_{B_s}\sqrt{f_{B_s}}}{B_{B_d}\sqrt{f_{B_d}}} = 1.210^{+0.047}_{-0.035}$$

~4%

Experimental Asymmetry

$$\mathcal{A}(t) = \frac{dN(t)_{\text{unmixed}}/dt - dN(t)_{\text{mixed}}/dt}{dN(t)_{\text{unmixed}}/dt + dN(t)_{\text{mixed}}/dt}$$



- ***B^0* oscillations**
  - **Δm_d = 0.507±0.005 ps^{-1}**
  - **mixing period is 8.4τ**
- ***B_s* oscillations**
  - **Δm_s > 14.4 ps^{-1}@ 95% CL (2005 world average)**
  - **mixing period < τ/3.**

Example: Fully Reconstructed Signal

Cleanest decay sequence

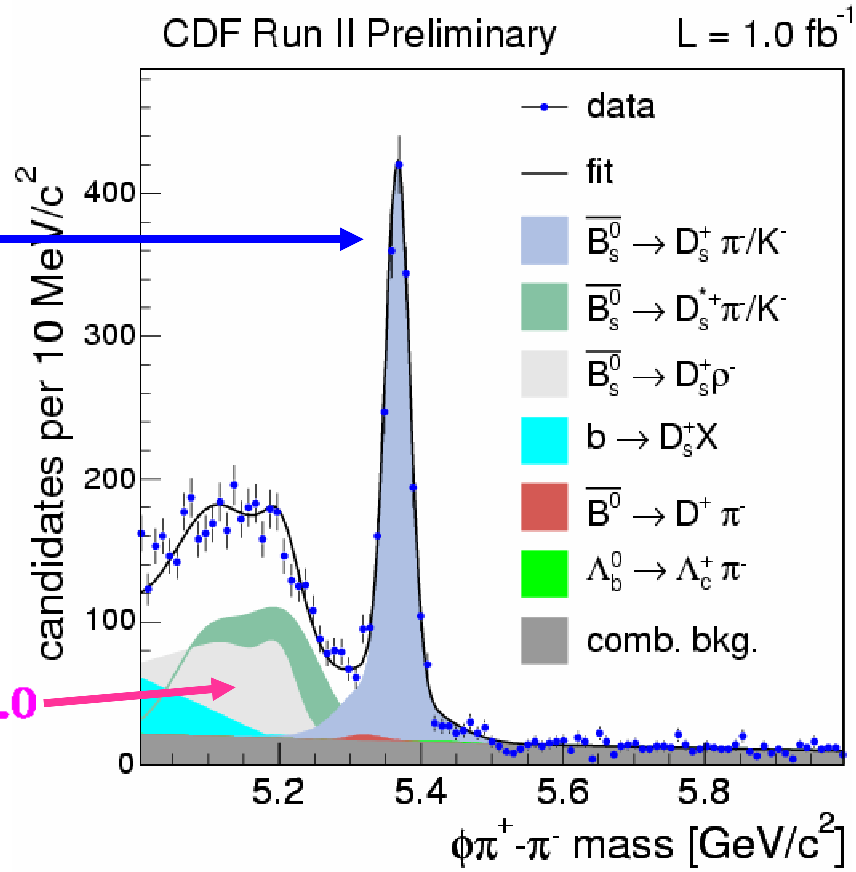
$\bar{B}^0_s \rightarrow D^+_s \pi^-$

$D^+_s \rightarrow \phi\pi^+$

$(D^+_s \rightarrow K^{*0}K^+, \pi^+\pi^-\pi^+)$

Include partially reconstructed decays:

$D^{*+}_s \pi^-$ $D^+_s \rho^-$ missing γ or π^0

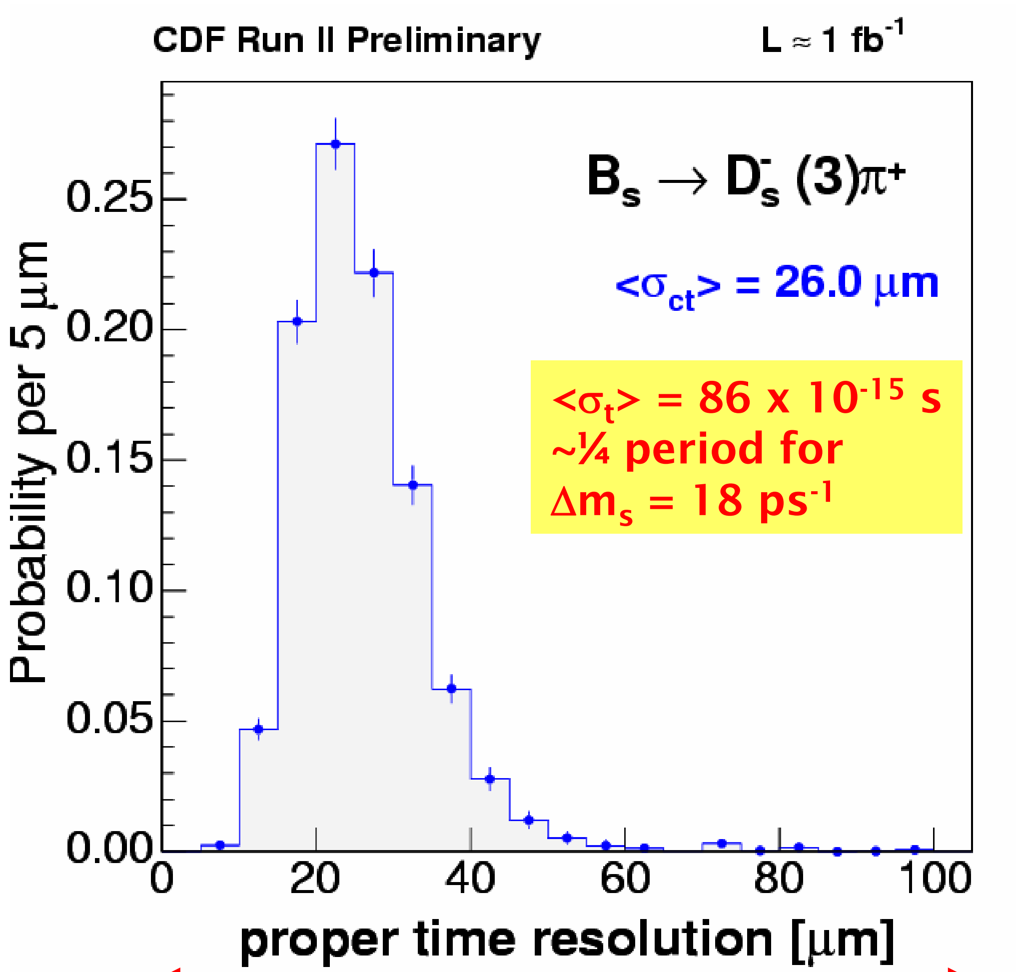


Also use 6 body modes:

$$\bar{B}^0_s \rightarrow D^+_s \pi^-\pi^+\pi^-,\ D^+_s \rightarrow \phi\pi^+, K^{*0}K^+, \pi^+\pi^-\pi^+$$

Total hadronic signal: 8700 events

Decay Time Resolution

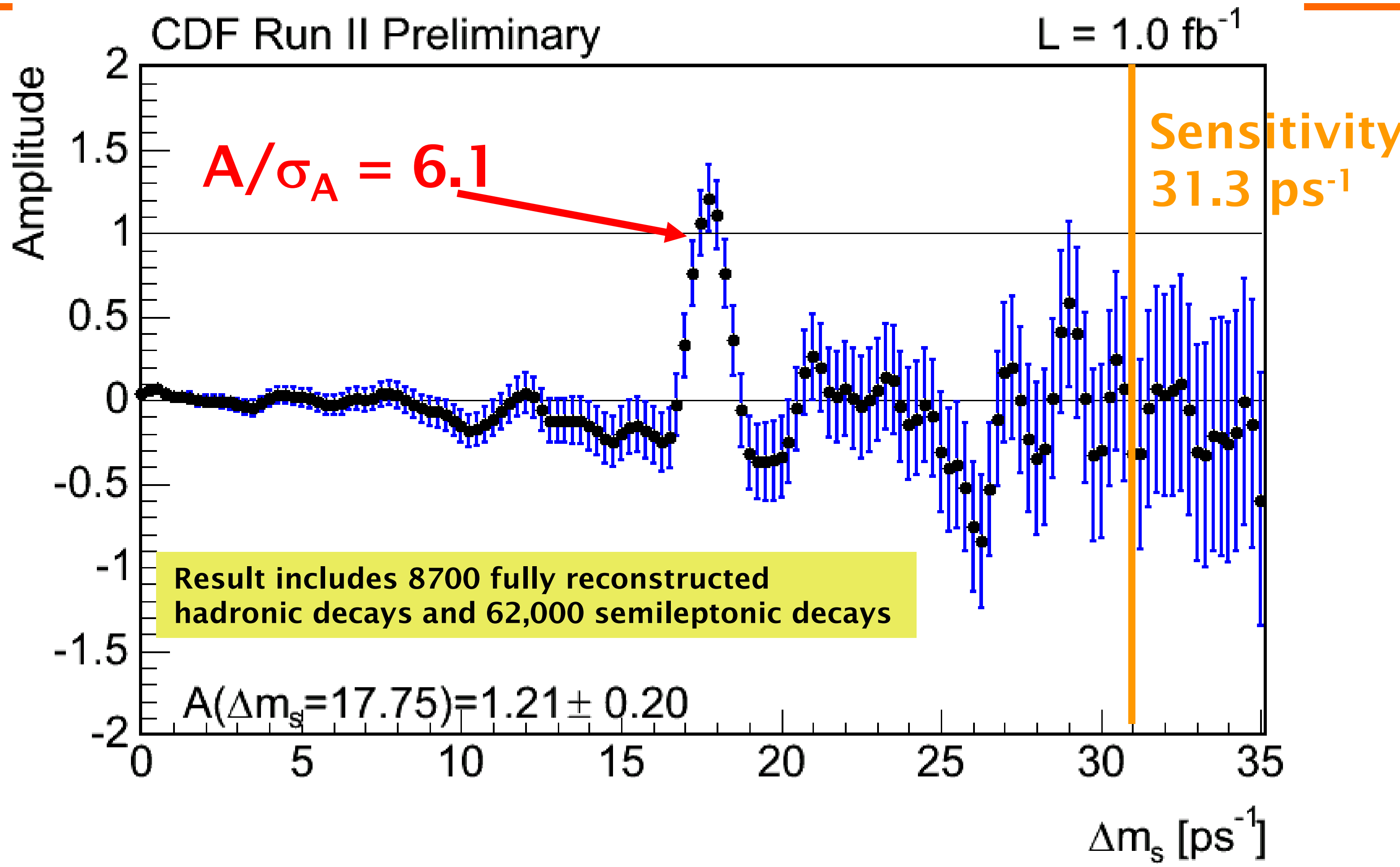


Oscillation period for $\Delta m_s = 18\ ps^{-1}$

Maximize sensitivity: use candidate specific decay time resolution

Superior decay time resolution gives CDF sensitivity at much larger values of Δm_s than previous experiments

Results: Amplitude Scan

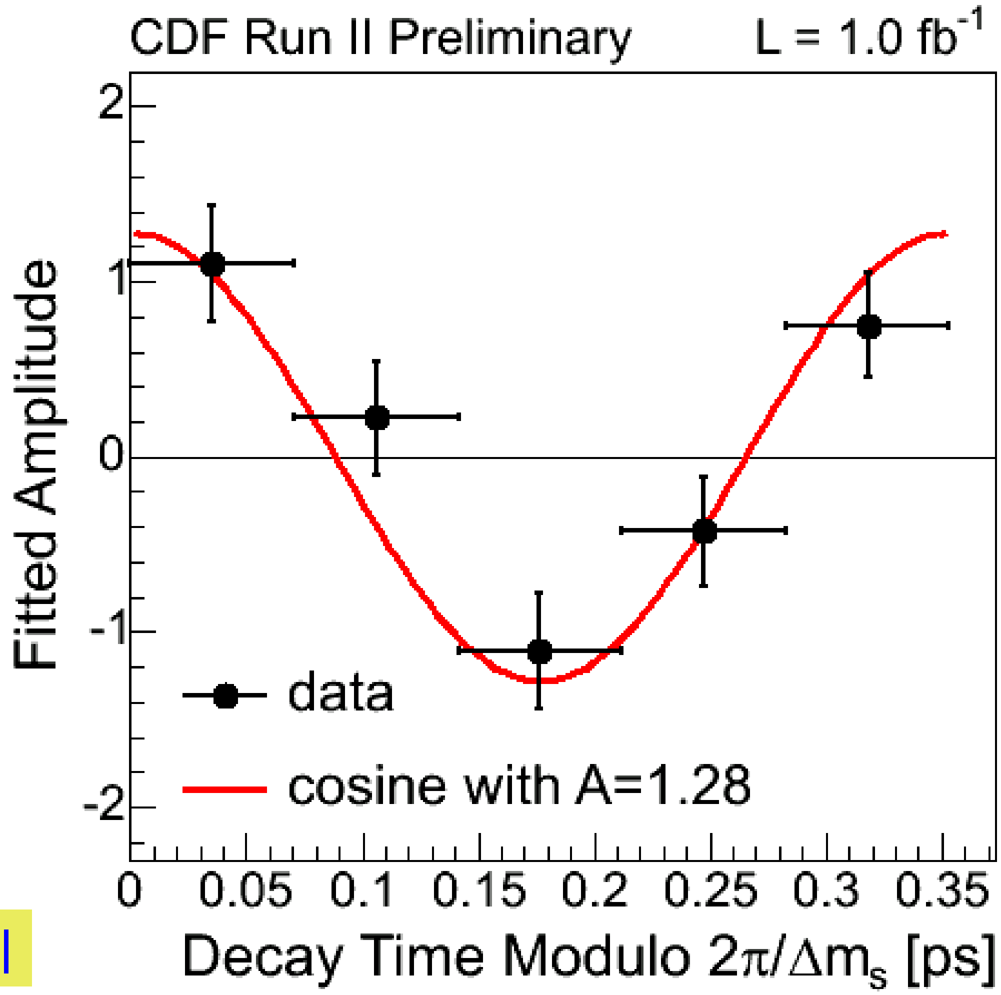


$$\Delta m_s = 17.77 \pm 0.10\,(\text{stat.}) \pm 0.07\,(\text{syst.})\ \text{ps}^{-1}$$

(2.83 THz, 0.012 eV)

Probability random fluctuation mimics signal: $8\times10^{-8} \Rightarrow 5.4\sigma$

Asymmetry in Time Domain

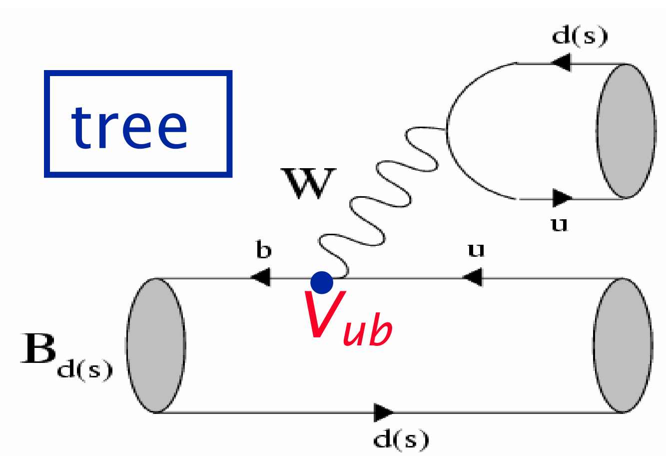


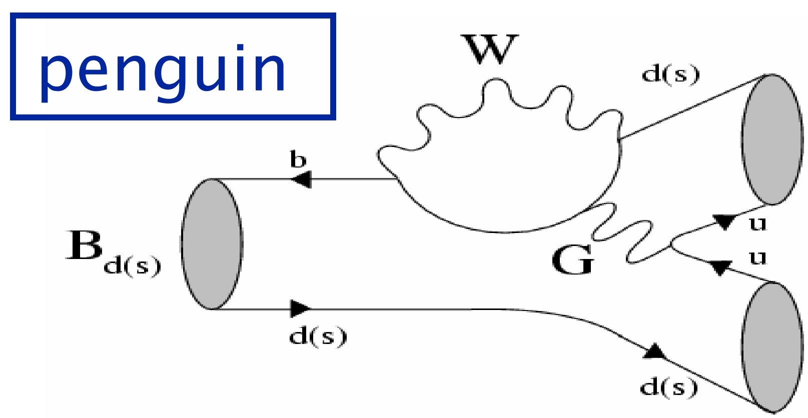
extract $|V_{td}/V_{ts}|$

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2060 \pm 0.0007\,(\text{exp.})^{+0.0081}_{-0.0060}\,(\text{theo.})$$

Charmless Two-Body Modes

- Previous studies of B^0 modes have provided a wealth of information
- The Tevatron simultaneous access to B_s & B^0 (plus baryons) allows an original physics program complementary to the e^+e^- B-factories
  - Belle Υ(5s) running can access B_s

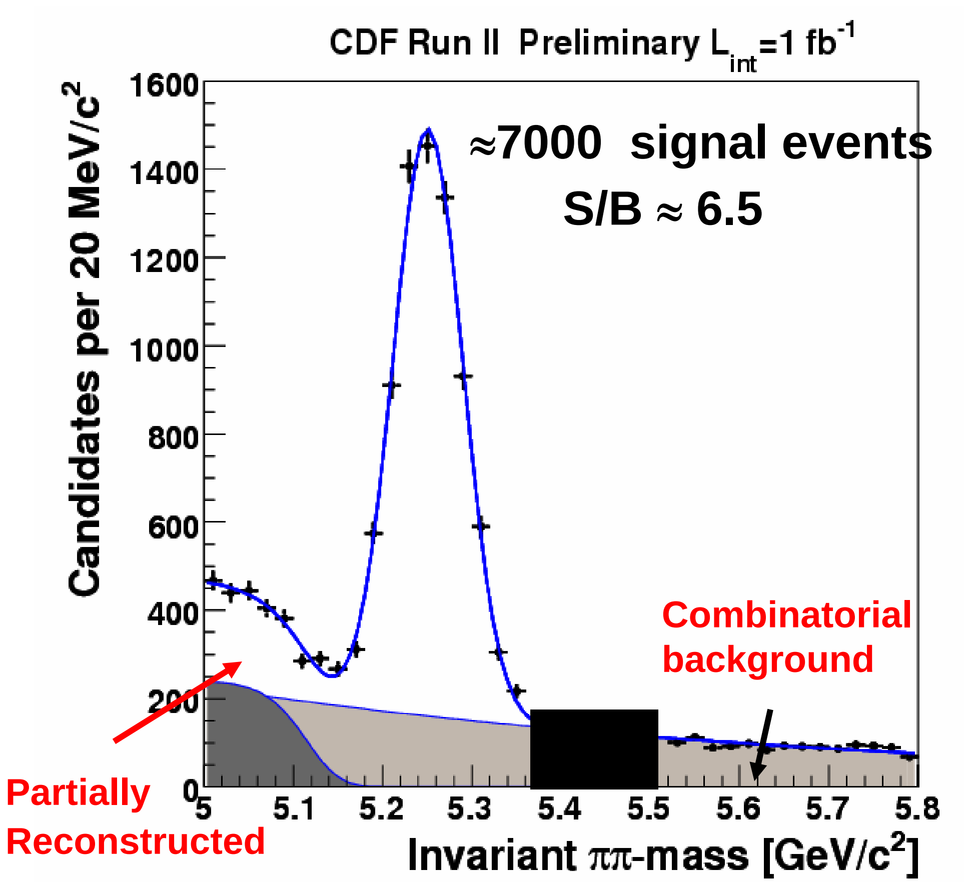


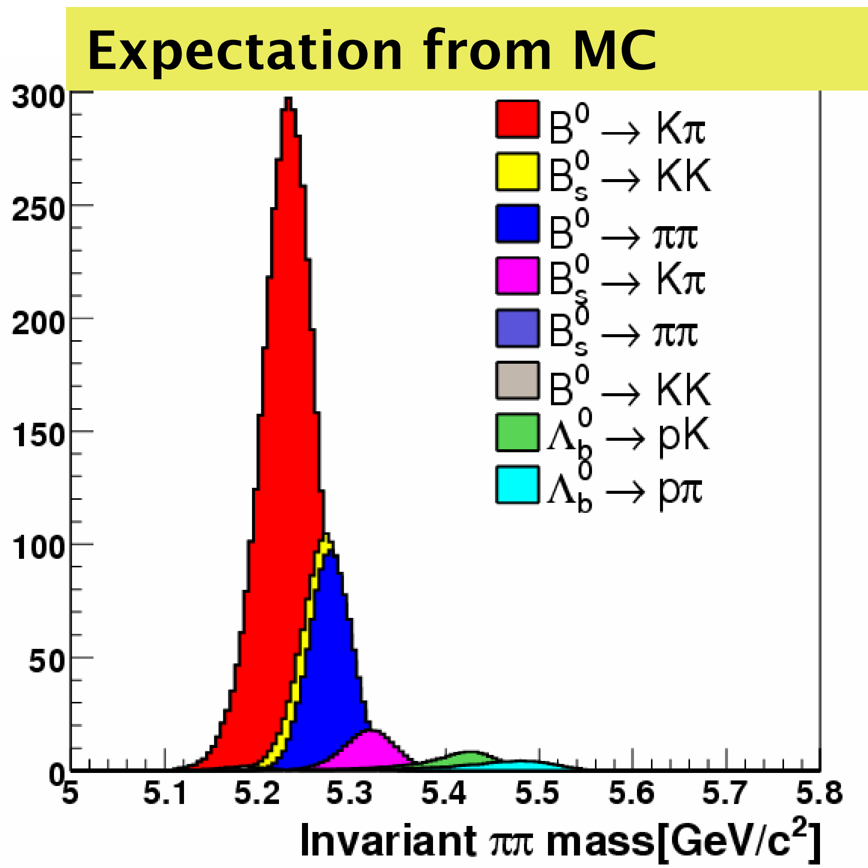


- Very rich physics: BR, *CP* asymmetries
  - B_s and baryons help complete the picture
  - Current and future (tagged) results help extract *CP* angle γ

Two-body invariant mass

•For h^+h^- each pair passing cuts, plot mass under $\pi\pi$ hypothesis.
➢good mass resolution (≈22 MeV/c^2), several modes overlap in one peak.

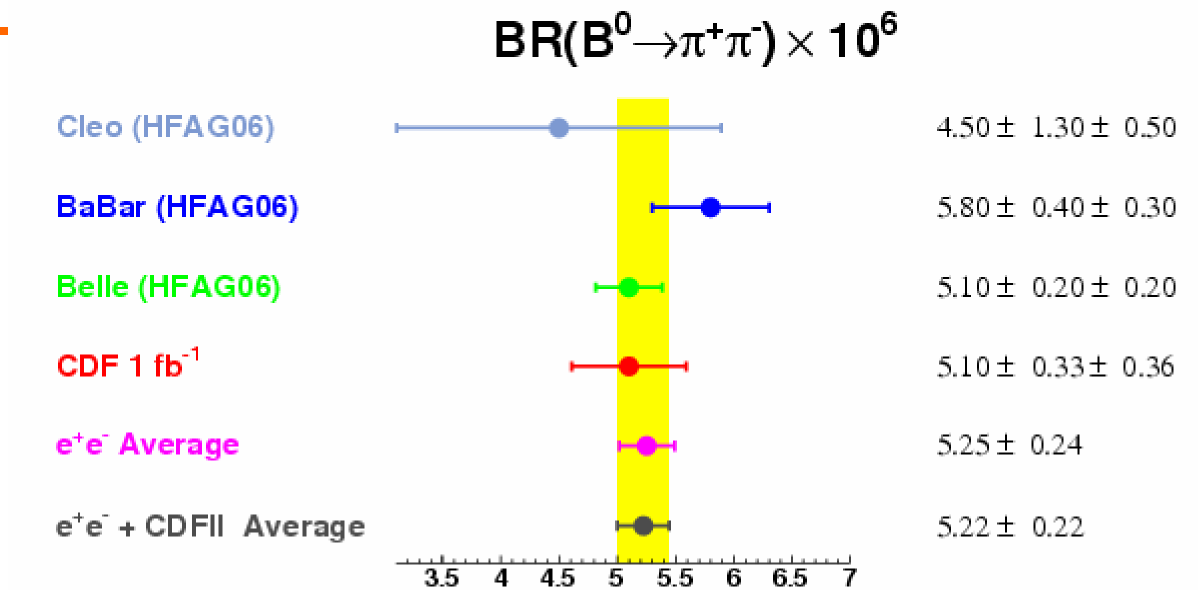




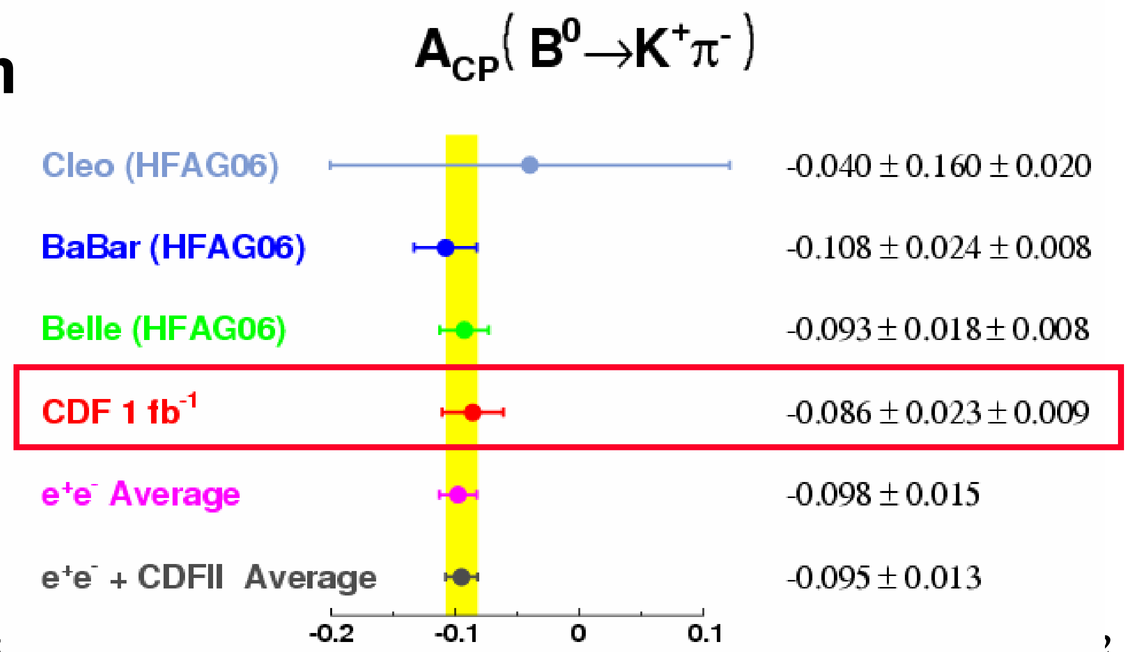
•Determine signal composition with a Likelihood fit, combining information from kinematics (mass and momenta) and particle ID (*dE*/*dx*).

B^0 results

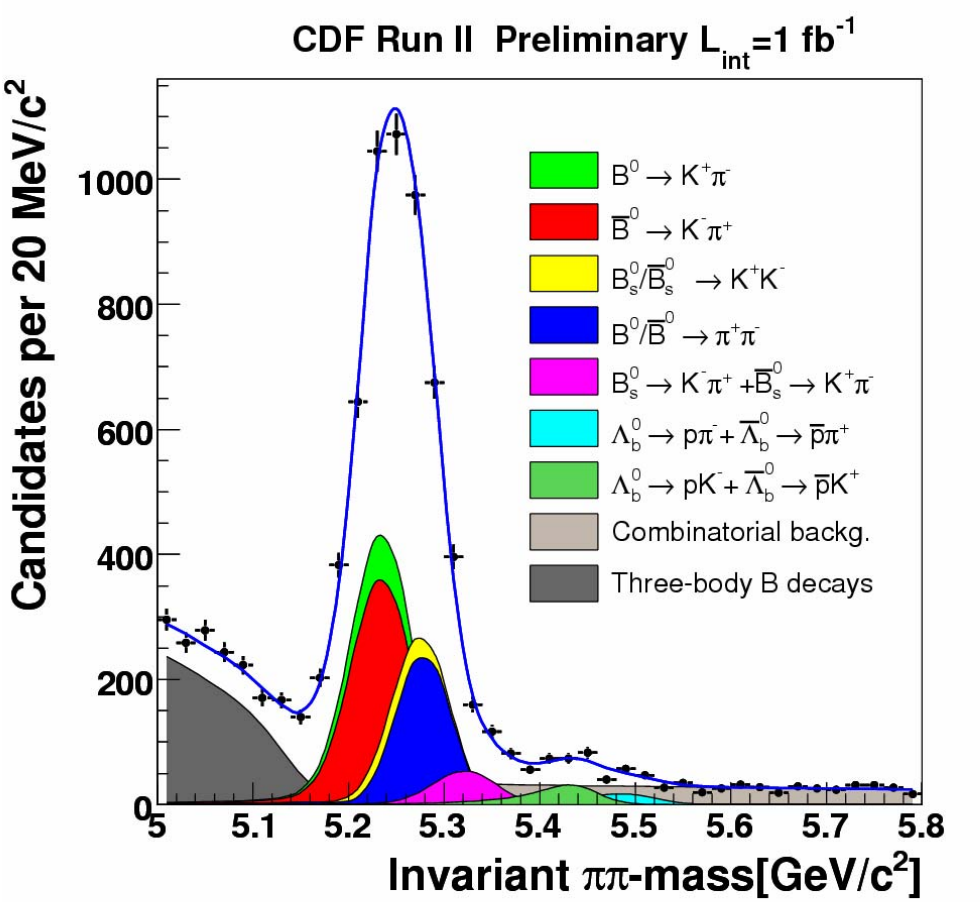
- Br($B^0 \to \pi^+\pi^-$)



- Direct CP violation in Br($B^0 \to K^+\pi^-$)

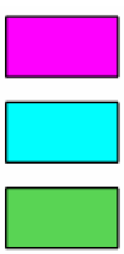


Rare modes search



- **BR Cuts optimized to measure yield best discovery/limit for $B_s \to K^-\pi^+$ (physics/0308063)**
- **Signal is a combination of six modes (three newly observed)**
  - **$B^0 \to \pi^+\pi^-/K^+\pi^-$ & $B_s \to K^+K^-$ already established.**
- **Also set limits on annihilation modes $B_s \to \pi^+\pi^-$ and $B^0 \to K^+K^-$**

3 new rare modes observed



$$N_{raw}(B_s^0 \to K^-\pi^+) = 230 \pm 34\ (stat.) \pm 16\ (syst.)$$ **(8σ)**

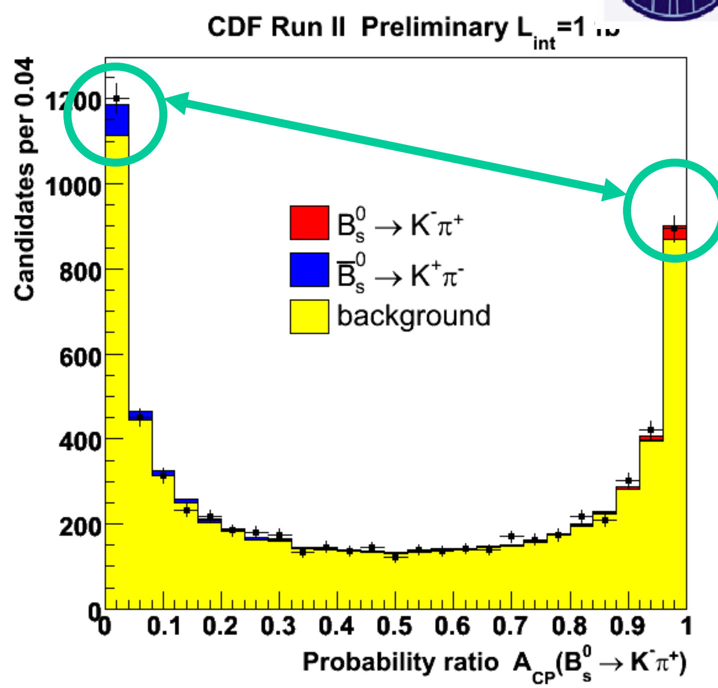
$$N_{raw}(\Lambda_b^0 \to p\pi^-) = 110 \pm 18\ (stat.) \pm 16\ (syst.)$$ **(6σ)**

$$N_{raw}(\Lambda_b^0 \to pK^-) = 156 \pm 20\ (stat.) \pm 11\ (syst.)$$ **(11σ)**

Direct CPV in $B_s \to K^- \pi^+$

"Is observed direct CP violation in $B^0 \to K^+\pi^-$ due to new physics? Check standard Model prediction of equal violation in $B_s \to K^-\pi^+$"
[Lipkin, Phys. Lett. B621:126, 2005],
[Gronau&Rosner Phys.Rev. D71 (2005) 074019].

Expect large $A_{cp} \approx 0.37$ in this mode, sign opposite to $A_{cp}(B^0 \to K^+\pi^-)$

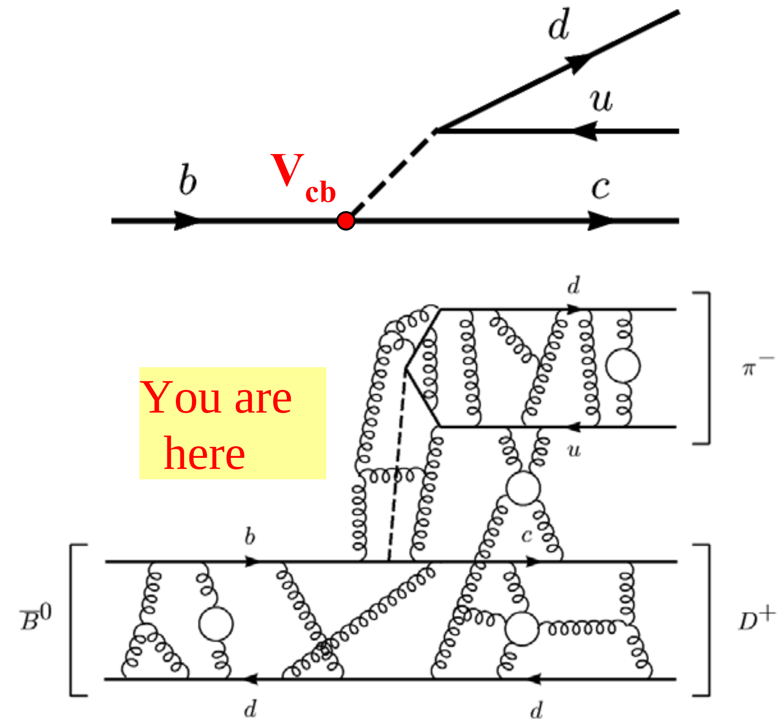


$$A_{CP} = \frac{N(\overline{B}_s^0 \to K^+\pi^-) - N(B_s^0 \to K^-\pi^+)}{N(\overline{B}_s^0 \to K^+\pi^-) + N(B_s^0 \to K^-\pi^+)} = 0.39 \pm 0.15\ (stat.) \pm 0.08\ (syst.)$$

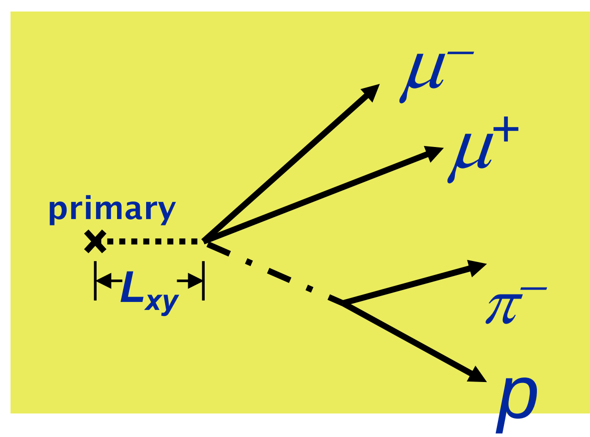
- First measurement of CP asymmetry in the B_s system
- Very interesting to pursue with more data!
- Direct CP asymmetry measurements for Λ_b modes in progress.

Λ_b Lifetime in $J/\psi\Lambda$

- **Going back to first measurements at LEP, $\tau(\Lambda_b)$ has been low compared to HQE expectations.**
  - **For $\tau(\Lambda_b)/\tau(B^0)$, early theory predictions (~0.94) and experiment differed by more than $2\sigma \Rightarrow$ "Λ_b lifetime puzzle"**
  - **Current NLO QCD + $1/m_b^4$ calculation:**
    $\tau(\Lambda_b)/\tau(B^0) = 0.86 \pm 0.05$
    consistent w/HFAG 2005 world avg:
    $\tau(\Lambda_b)/\tau(B^0) = 0.803 \pm 0.047$
  - **Experimental sensitivity dominated by semileptonic Λ_b measurements**

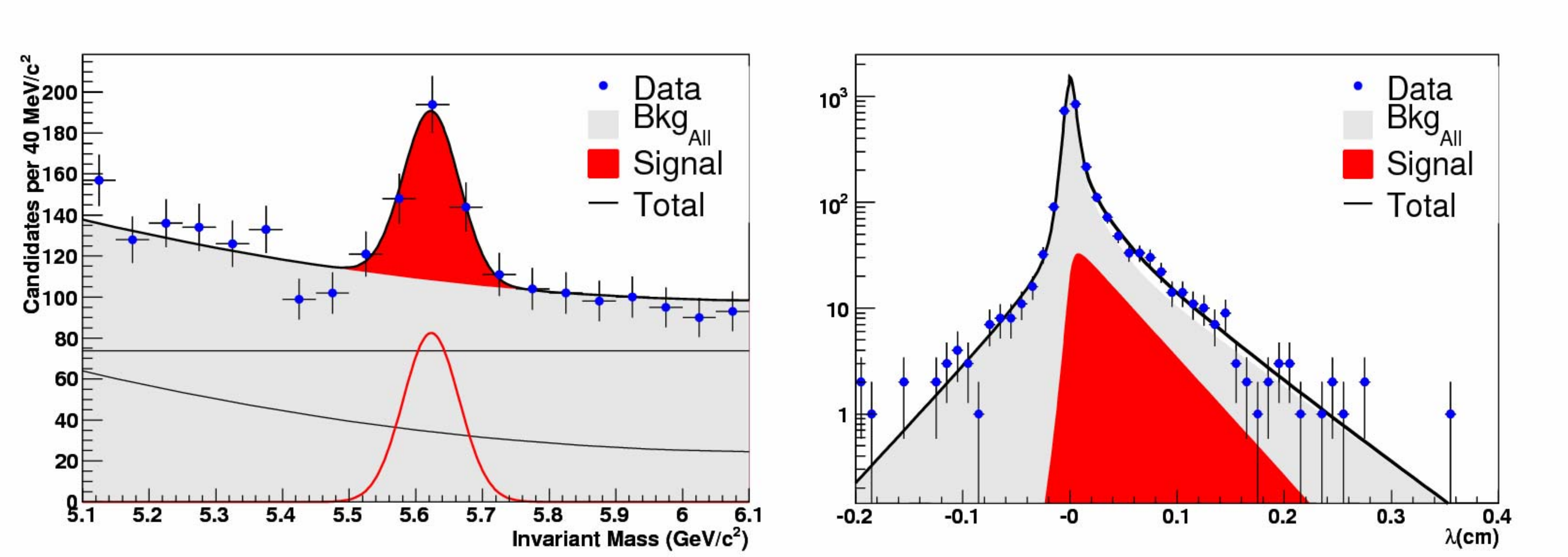


- **D0 and CDF now have sufficient statistics to weigh in with fully reconstructed $\Lambda_b \to J/\psi\,\Lambda$**
  - **Trigger on $J/\psi\to\mu\mu$, reconstruct $\Lambda\to p\pi$.**



Λ_b Lifetime in $J/\psi\Lambda$

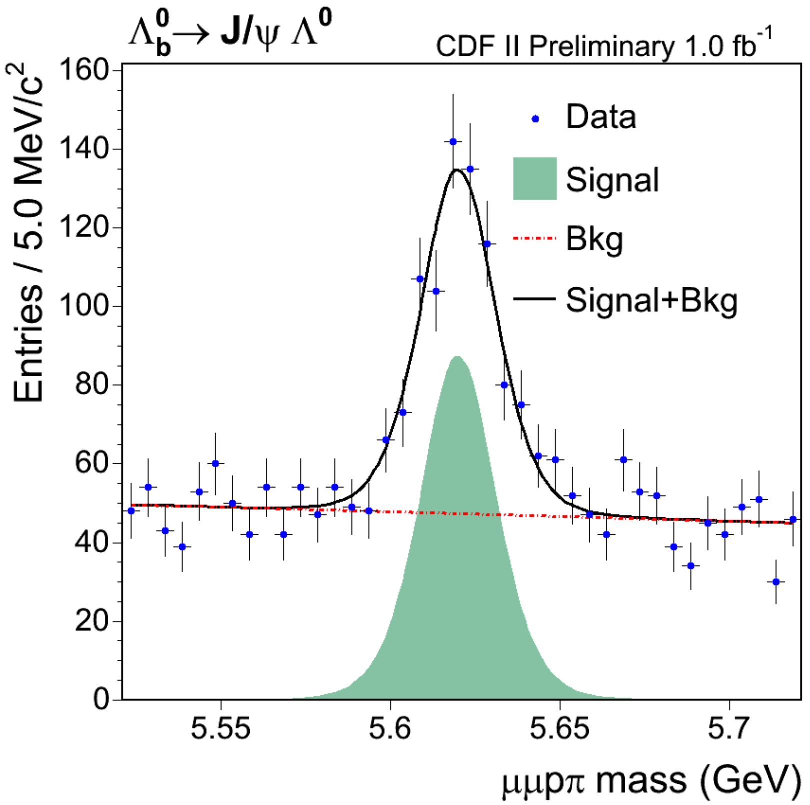
- 174±21 signal events
- Use Λ_b vertex to measure decay length
- Dominant systematic uncertainty comes from $B^0 \to J/\psi K_S$ contamination

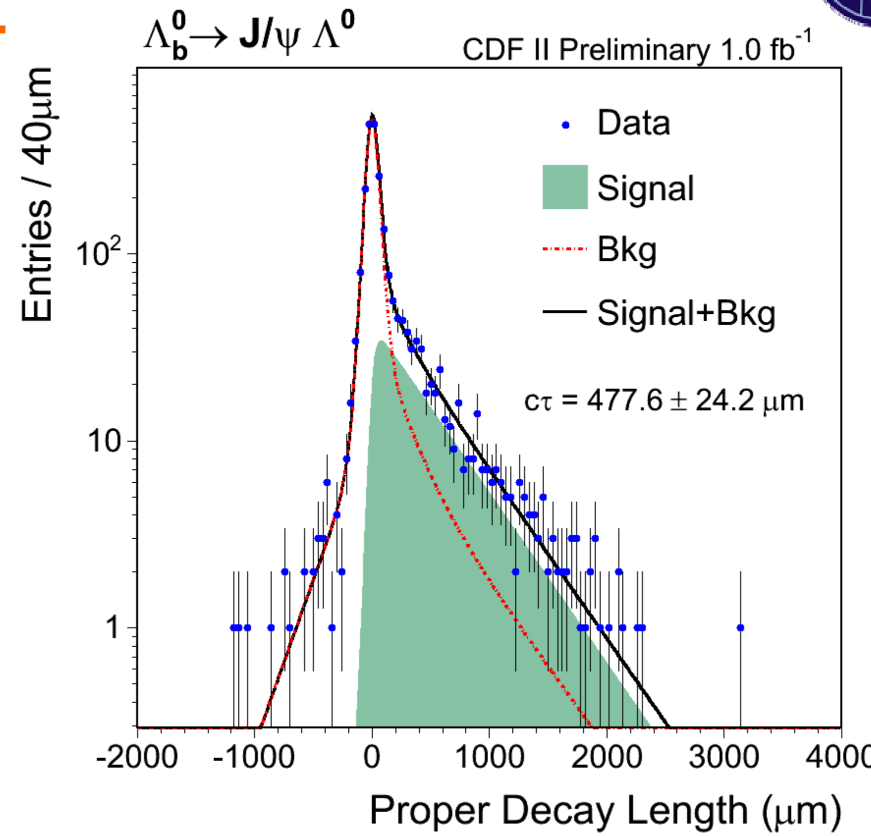


$\tau(\Lambda_b)$ = 1.298 ±0.137(stat)±0.050(syst) ps

Λ_b Lifetime in $J/\psi\Lambda$

- **Signal: 538 ± 38 Λ_b events**





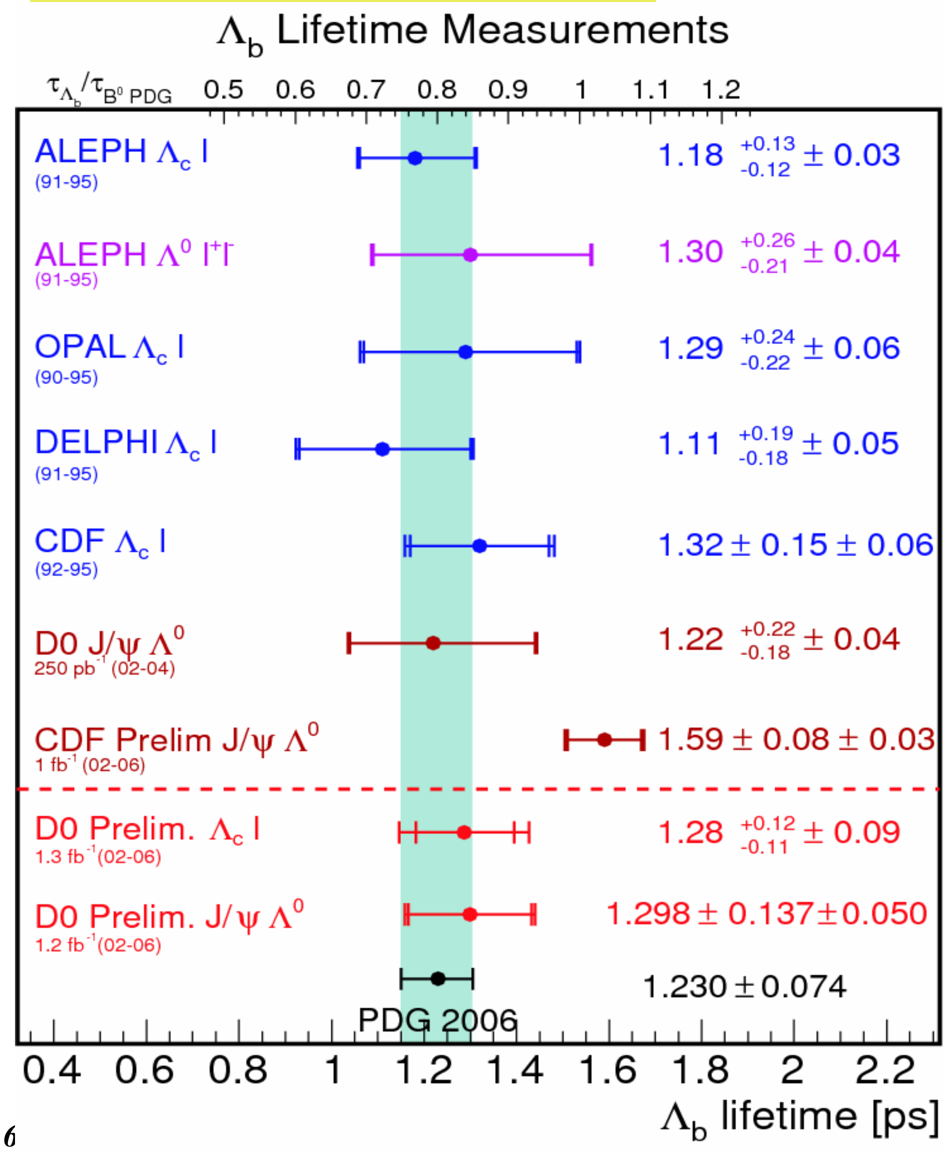
- **Use J/ψ vertex to measure Λ_b decay length**
- **Major sources of systematics are due to modeling of ct resolution and V^0 pointing**

- **Result**

$$\tau(\Lambda_b) = 1.593^{+0.083}_{-0.078}\,(\text{stat}) \pm 0.033(\text{syst})\text{ps}$$

Λ_b lifetime summary

The jury's still out…



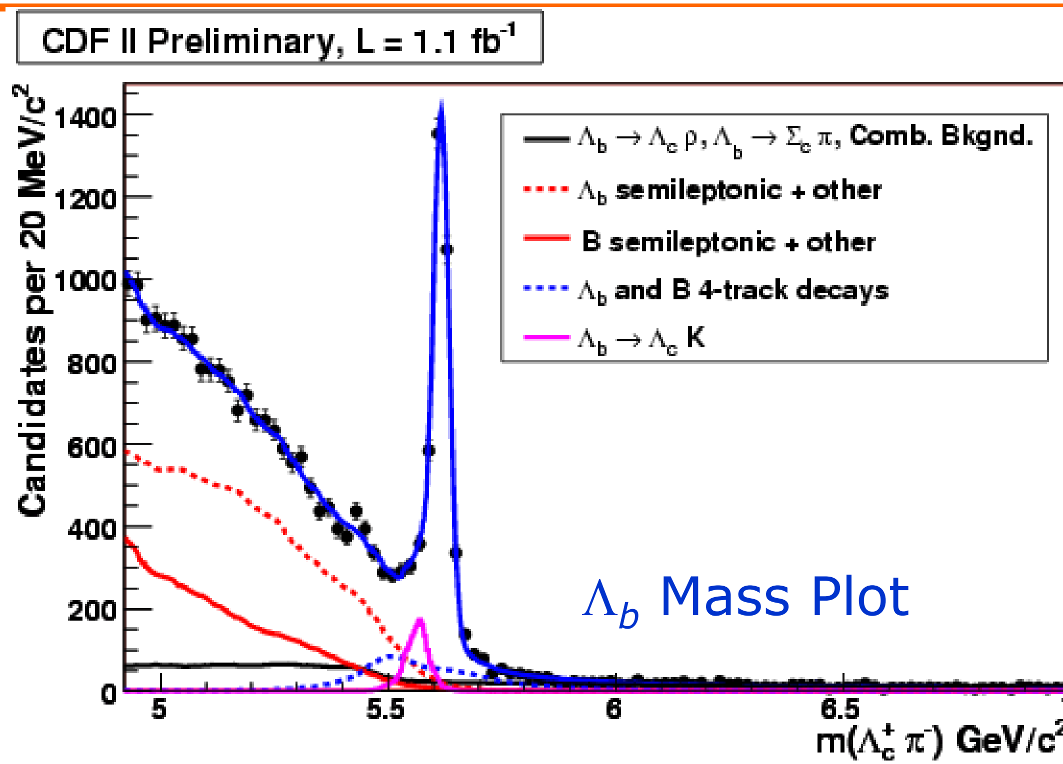
- **Prior world average $\tau(\Lambda_b)/\tau(B^0)$ was lower than the NLO prediction.**
- **New CDF result sits about 3σ above world average!**
- **New D0 results consistent with world average & CDF.**
  - **New D0 semileptonic result ($\Lambda_b \rightarrow \Lambda_c \mu\nu$ with $\Lambda_c \rightarrow pK_S$) also shown**
- **Need more experimental inputs to conclude the issue.**
- **Looking forward to $\tau(\Lambda_b)$ in fully hadronic decay modes, e.g. $\Lambda_b \rightarrow \Lambda_c\ \pi$.**
  - **Larger sample (~3000 signal)**

Reconstructing $\Lambda_b \to \Lambda_c \pi$

- **Use silicon vertex trigger sample to reconstruct:**

$$\Lambda_b^0 \to \Lambda_c^+ \pi^-$$
$$\Lambda_c^+ \to pK^- \pi^+$$

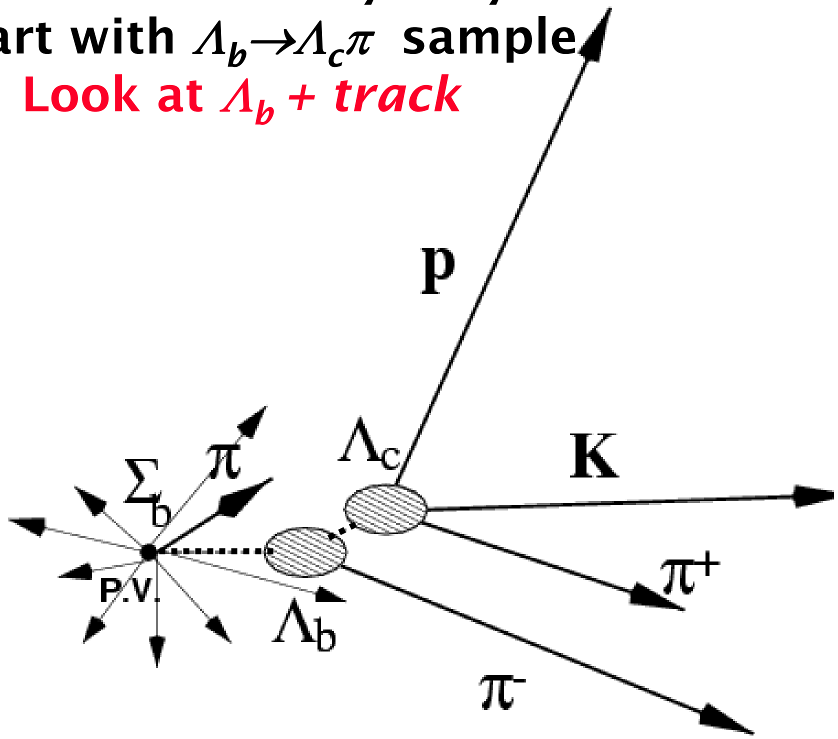
- **3000 Λ_b signal events**
  - **Much larger than $J/\psi\Lambda$**
  - **Lifetime measurement in progress**

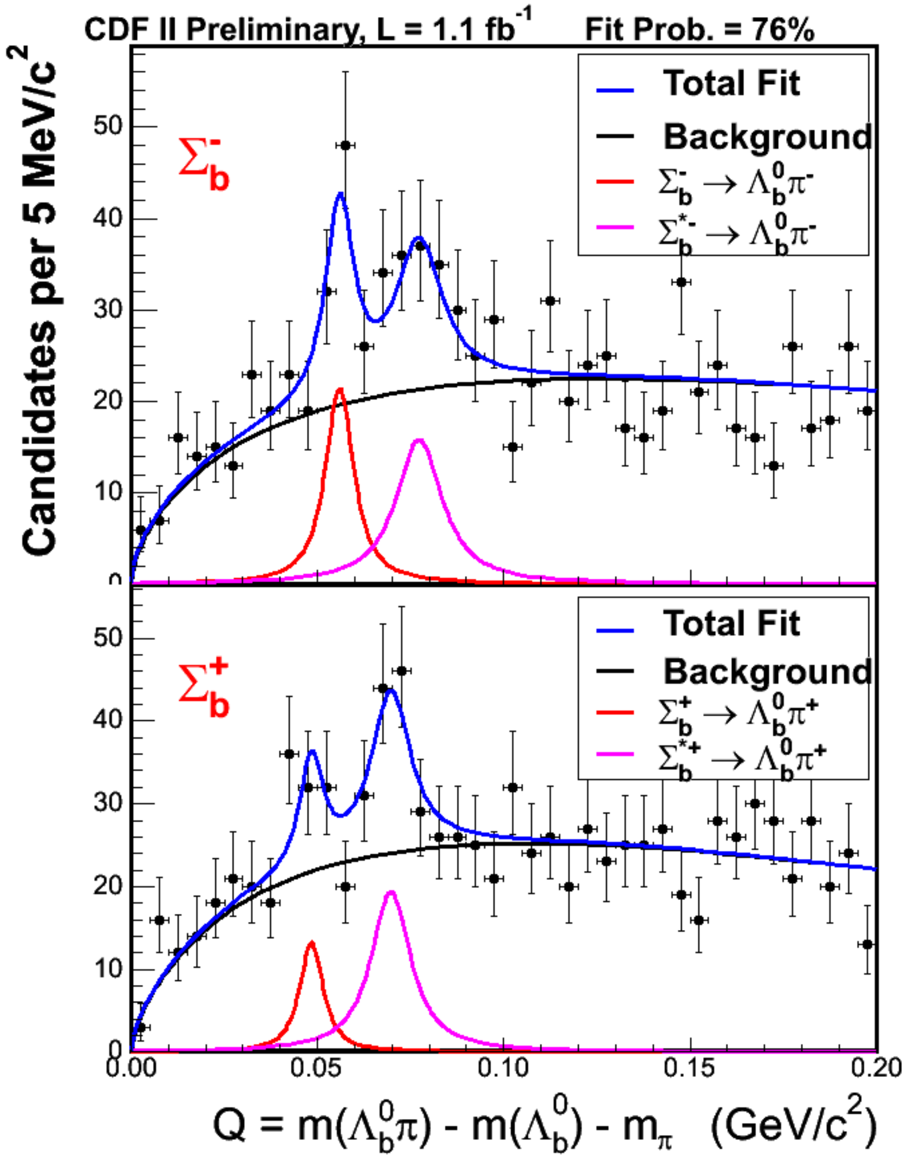


Λ_b^0 Signal Region Composition $\Lambda_b^0 \in [5.565, 5.670]$ GeV/c^2	
$N(\Lambda_b^0)$	86%
$N(B)$	9%
Comb. Bkg.	5%

Σ_b Observation

- Λ_b (udb) only established *b* baryon
- Sufficient statistics at Tevatron to probe other heavy baryons
- Start with $\Lambda_b \rightarrow \Lambda_c \pi$ sample
  - Look at Λ_b + *track*





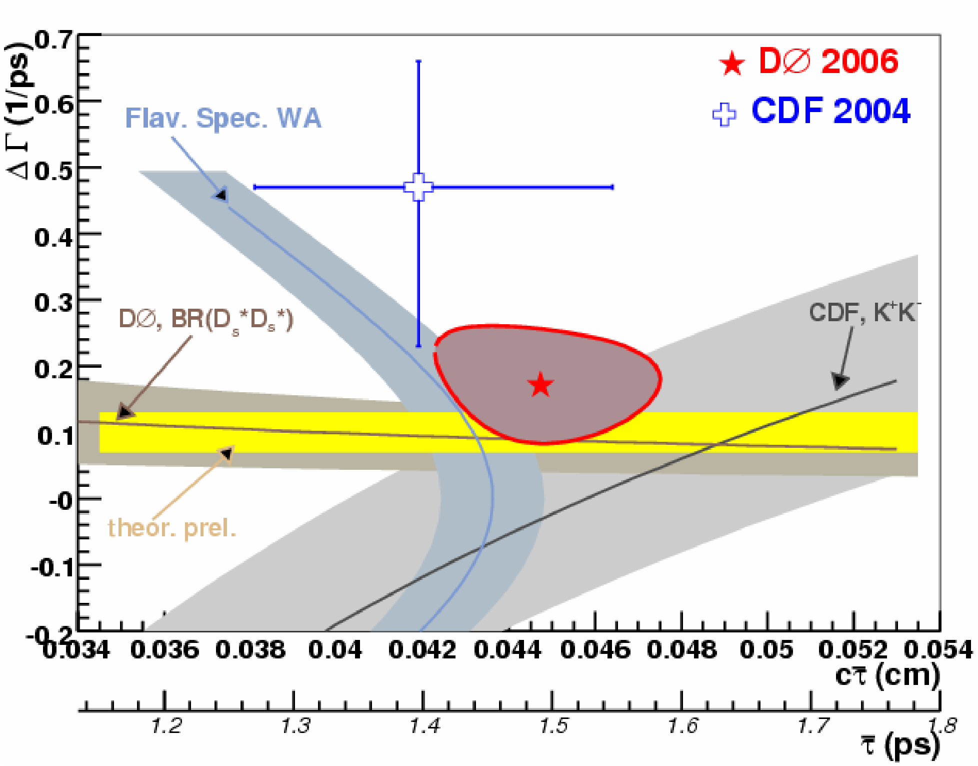
- Next accessible baryons are uub and ddb states with $J^P = 1/2 (\Sigma_b)$ and $3/2 (\Sigma_b^*)$
- Observe signals consistent with lowest lying charged Σ_b states

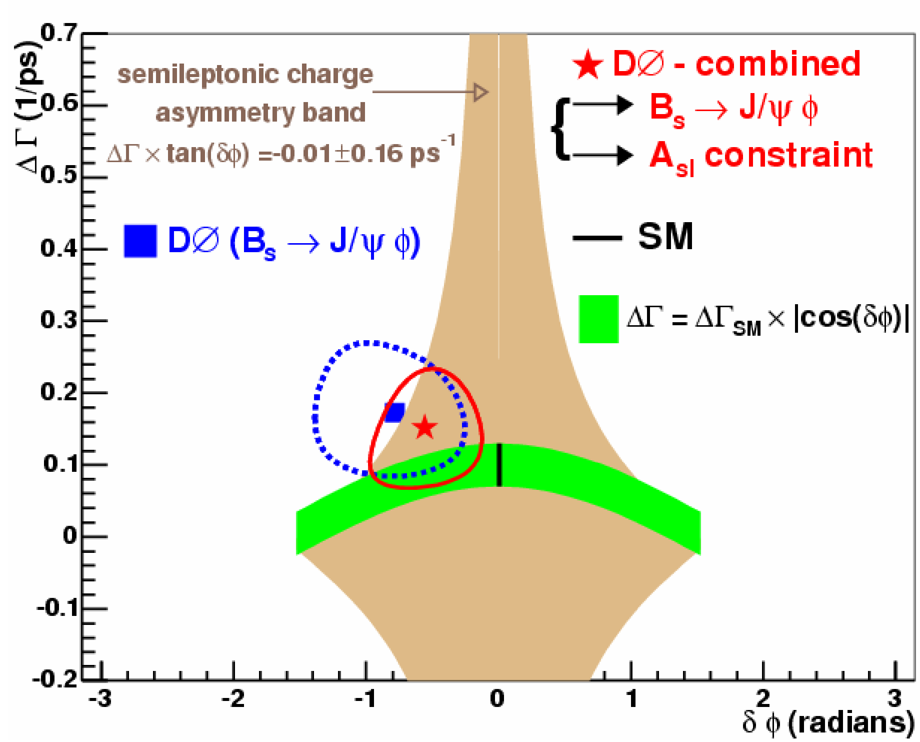
Topics Not Covered

- Recent Tevatron results in the following areas
  - B_s lifetime difference ($\Delta\Gamma_s$)
  - B_s mixing phase (ϕ_s)
  - Excited states (B_s^{**})
  - *CP* asymmetries in semileptonic decays
  - X(3872)
  - Charmonium
    - χ_c states, J/ψ, ψ' polarization
  - Rare $B^0 \to \mu\mu$, $B_s \to \mu\mu$
  - Rare $B \to \mu\mu X$ decays
  - *B* cross section measurements
  - B_c measurements
  - *B* lifetimes
  - *B* branching ratios
  - Charm physics(rare decays, BR, DCS)

Prospects

- Expect several fb^{-1} of data by 2009
  - many measurements will continue to be updated
  - Many new modes & measurements are possible
- We see no new physics in the B_s oscillation frequency, but work towards constraining the B_s lifetime difference $\Delta\Gamma_s$ and mixing phase is ongoing.





Conclusion

- The *B* program at the Tevatron has been an incredibly fruitful endeavor.
- The program is complementary to and competitive with e^+e^- *B* factories
- With higher Tevatron luminosity, we are accumulating data at a tremendous rate.
  - We expecting ~several fb^{-1} by the end of the run.
- There is lots more to come!

Backup Slides

Extracting $|V_{td}|$, $|V_{ts}|$ & $|V_{td}/V_{ts}|$

$$\Delta m_q = \frac{G_f^2}{6\pi^2} m_{B_q} M_W^2 f\left(\frac{m_t^2}{M_W^2}\right)\eta_{\rm QCD} B_{B_q} f_{B_q}^2 |V_{tb}^* V_{tq}|^2 \quad q = d, s$$

All factors well known *except* $\sqrt{B_{B_d}} f_{B_d} = 244 \pm 26$ MeV

from Lattice QCD calculations - see Okamoto, hep-lat/0510113

Limits precision on V_{td}, V_{ts} to ~ 10%

Theoretical uncertainties reduced in ratio:

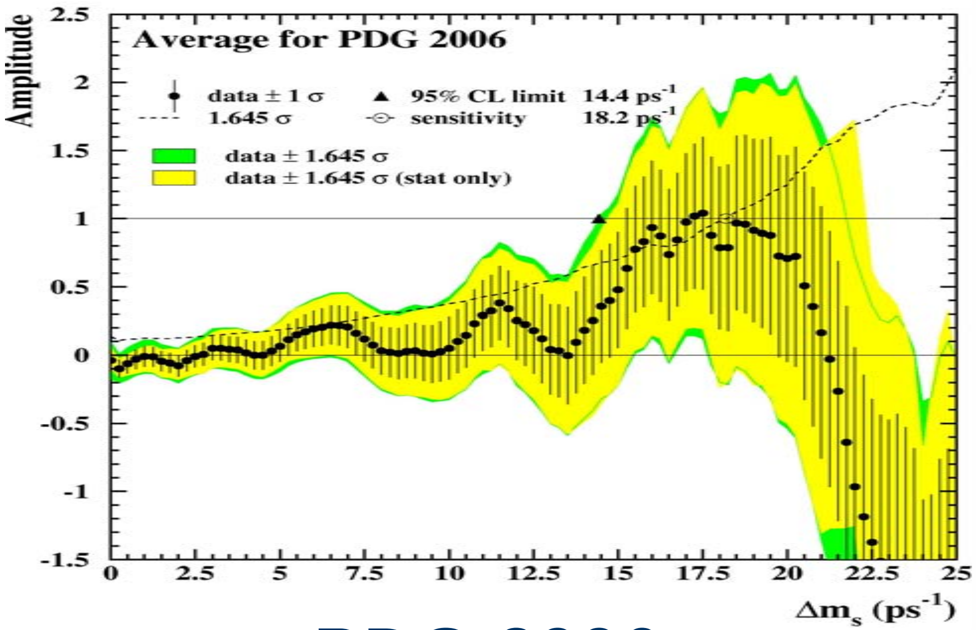
$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \left|\frac{V_{ts}}{V_{td}}\right|^2 \qquad \xi = \frac{B_{B_s}\sqrt{f_{B_s}}}{B_{B_d}\sqrt{f_{B_d}}} = 1.210^{+0.047}_{-0.035}$$

~ 4%

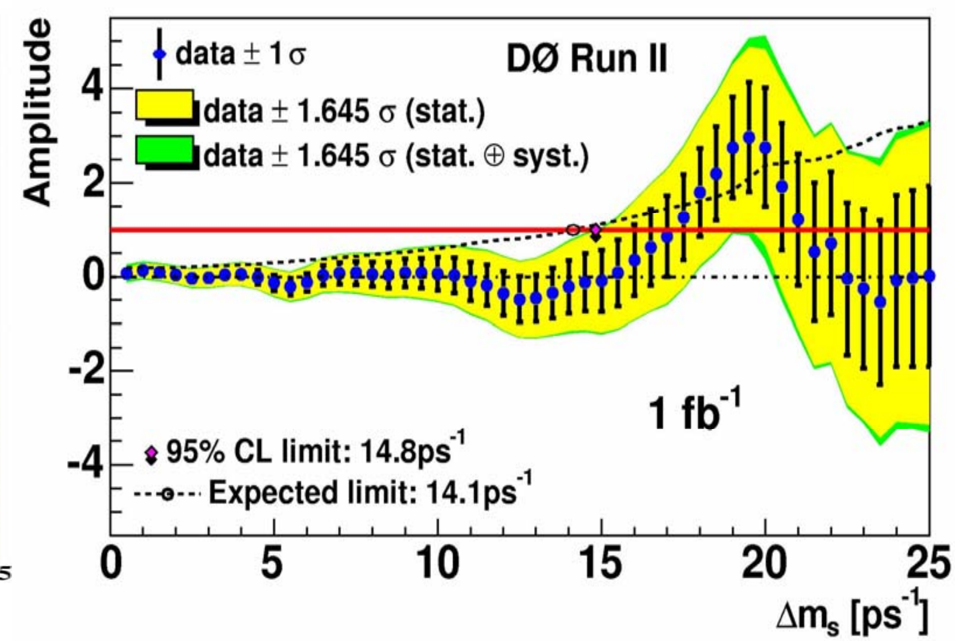
PDG 2006 $\Delta m_d = 0.507 \pm 0.005$ ps^{-1}

Precision measurement Δm_s yields $\frac{V_{td}}{V_{ts}}$ to 4%

World Knowledge on Δm_s



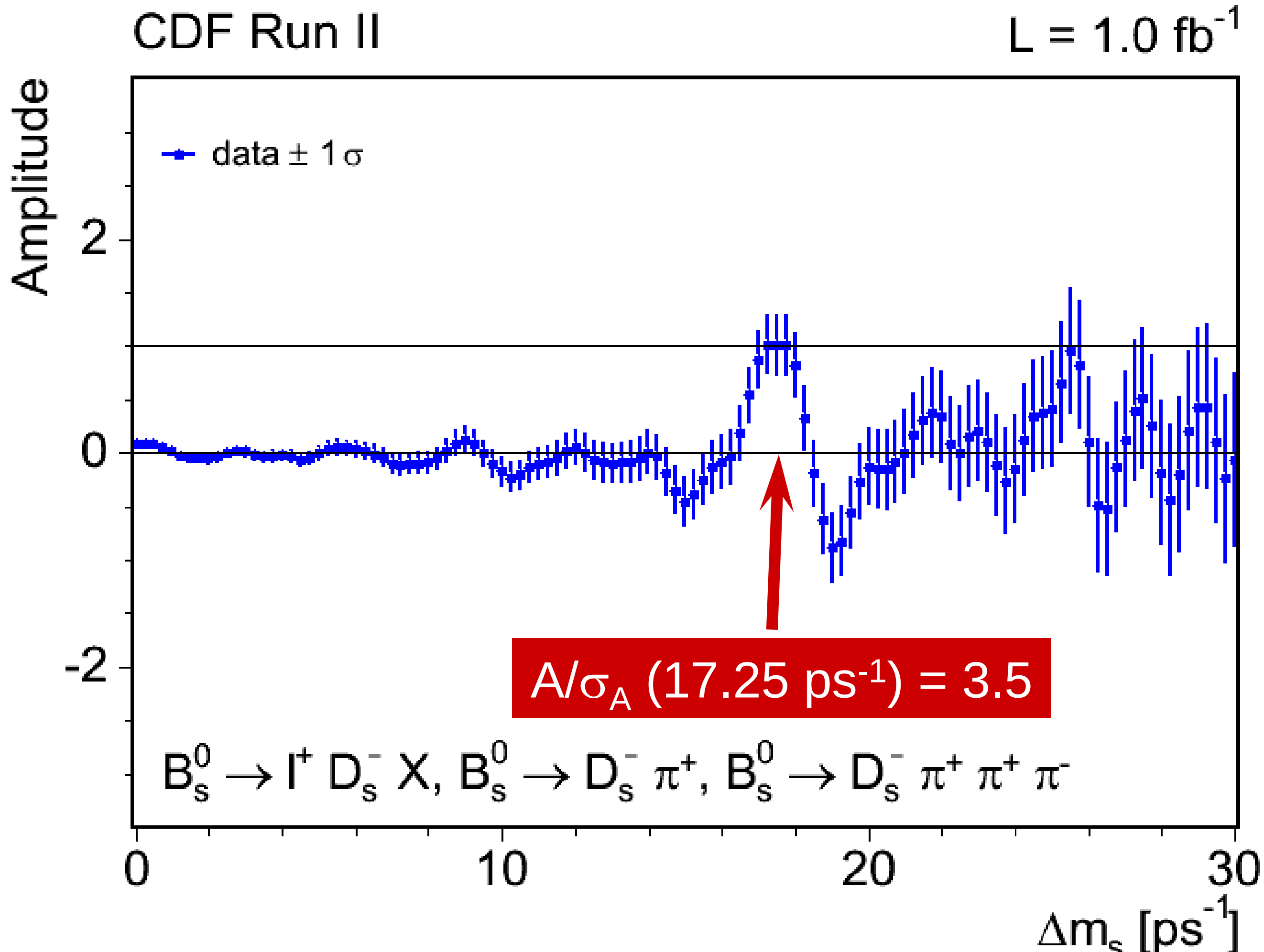
PDG 2006



Spring 2006 D0 Result

- D0 sensitivity = 14.1 ps^{-1}
- Observe large positive amplitude value around 19 ps^{-1}
  - Probability it's consistent with no oscillation = 5%
  - Probability it's consistent with A=1 (oscillation) = 15%
- "Two sided limit" requires assumption that the peak is associated with real signal…
  - $17 < \Delta m_s < 21$ ps^{-1} at 90% CL

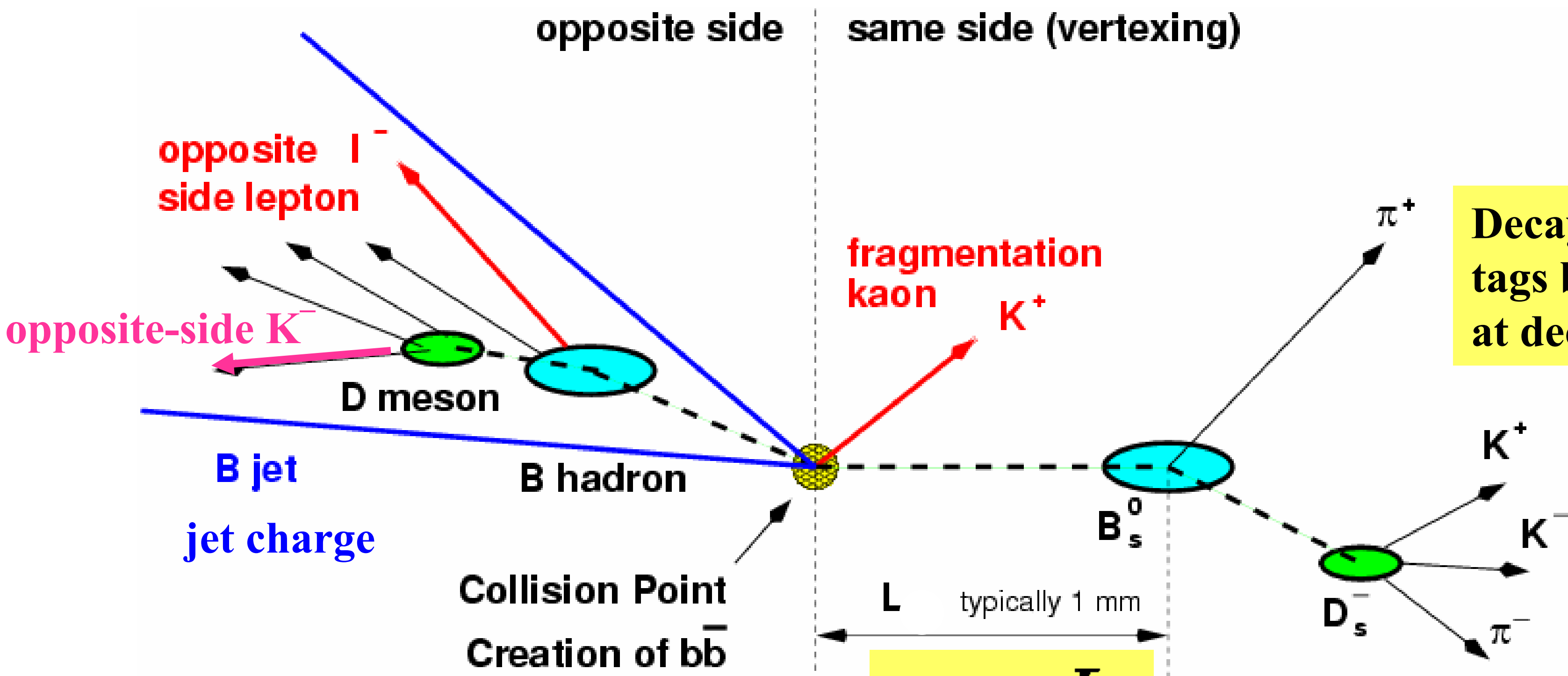
CDF April 2006



- **Probability that background could fluctuate to mimic a signal of this significance: 0.2% ≈ 3σ**

Δm_s = 17.33 +0.42 (stat) ± 0.07 (syst) ps^{-1}

Ingredients in Measuring Oscillations



Decay mode tags b flavor at decay

$$t = m\frac{L}{p}$$

2nd B tags production flavor

Dilution $D = 1 - 2w$

w = mistag probability

Proper decay time from displacement (L) and momentum (p)

$$(\delta t)^2 = \left(\frac{m}{p}\delta L\right)^2 \oplus \left(t\frac{\delta p}{p}\right)^2$$

$B_s \to \pi^+\pi^-$ and $B^0 \to K^+K^-$

$$\frac{f_s \cdot BR(B_s^0 \to \pi^+\pi^-)}{f_d \cdot BR(B^0 \to K^+\pi^-)} = 0.007 \pm 0.004\ (stat.) \pm 0.005\ (syst.)$$

$$\frac{BR(B^0 \to K^+K^-)}{BR(B^0 \to K^+\pi^-)} = 0.020 \pm 0.008\ (stat.) \pm 0.006\ (syst.)$$

using HFAG:

$$BR(B^0 \to K^+K^-) = (0.39 \pm 0.16\ (stat.) \pm 0.12\ (syst.)) \times 10^{-6}$$ **(< 0.7 x 10^{-6} @ 90% C.L.)**

Expect [0.01 - 0.2] x10^{-6} [Beneke&Neubert Nucl.Phys. B675, 333(2003)]

WA (0.7± 0.12)x10^{-6} → New WA : (0.15 ± 0.10)x10^{-6}

CDF result for $B^0 \to K^+K^-$ has similar precision as *B*-factories!

$$BR(B_s^0 \to \pi^+\pi^-) = (0.53 \pm 0.31\ (stat.) \pm 0.40\ (syst.)) \times 10^{-6}$$ **(<1.36 x 10^{-6} @ 90% C.L.)**

Expected: [0.007 - 0.08]x10^{-6} [Beneke&Neuber t Nucl.Phys. B675, 333(2003)]
Expected: 0.42 ± 0.06x10^{-6} [Ying Li et al. Phys.Rev. D70:034009 (2004)]

World best limit by far.