# B Physics at CDF

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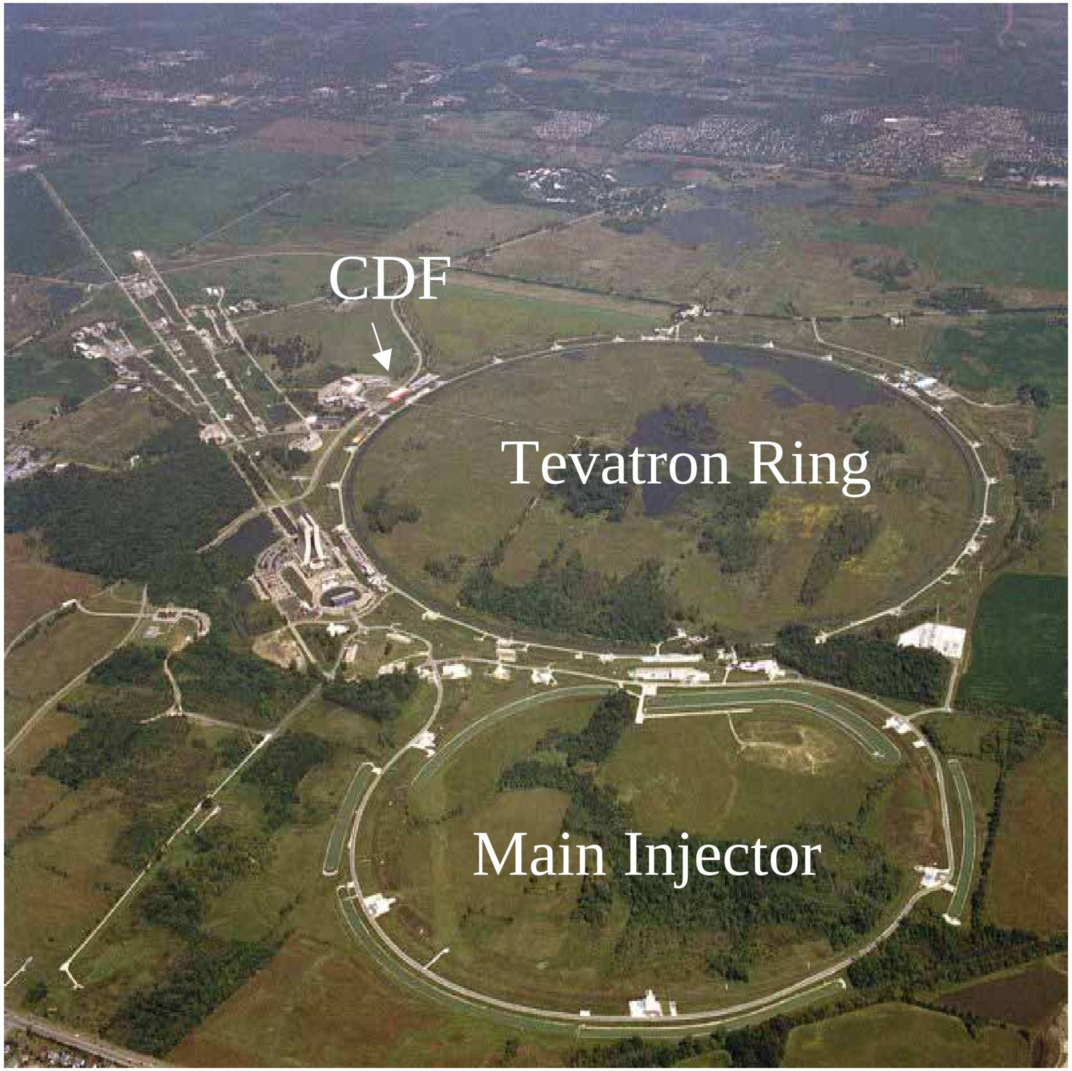
ICFP2003 at KIAS, Seoul

# Tevatron $\bar{p}p$ Collider at Fermilab




RunI (1992〜1996)
$\sqrt{s}$ = 1.8 TeV

RunII (2001〜)
$\sqrt{s}$ = 1.96 TeV
+ Main Injector

# Tevatron Status

## Run I（1992～1996）：

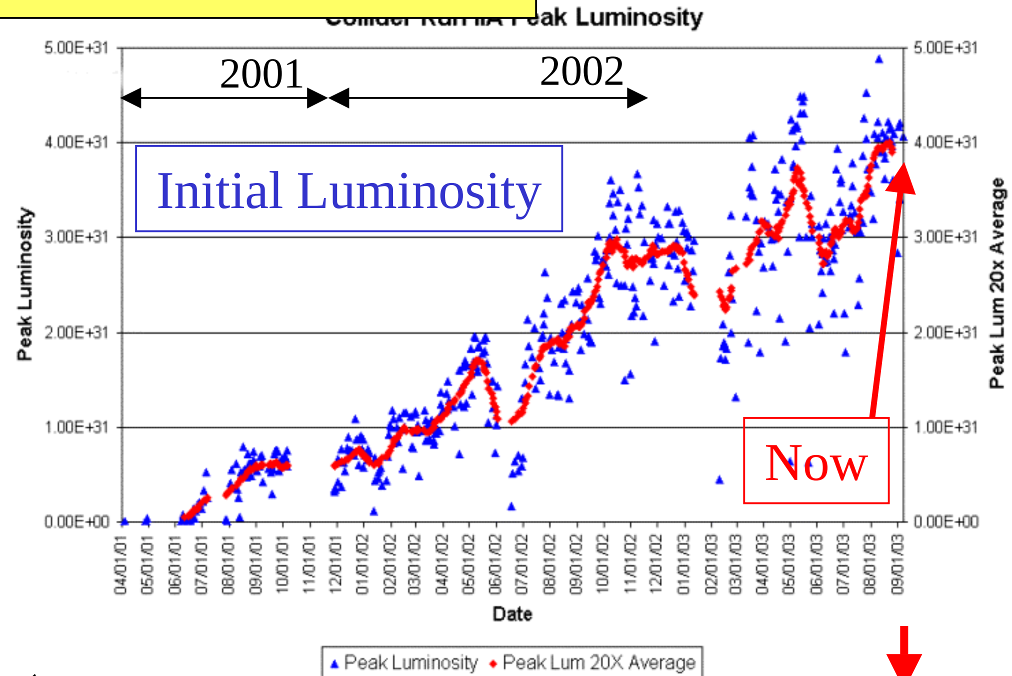
- Record Luminosity
  $2\times10^{31}$ $cm^{-2}sec^{-1}$
- Integrated Luminosity
  110 $pb^{-1}$ on Tape

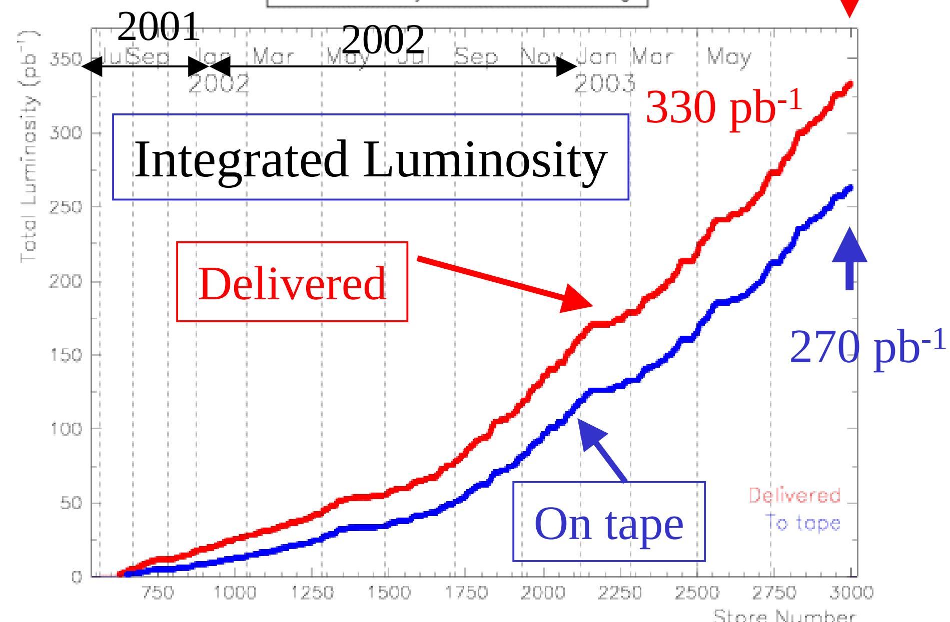
## Run II（2001～）：

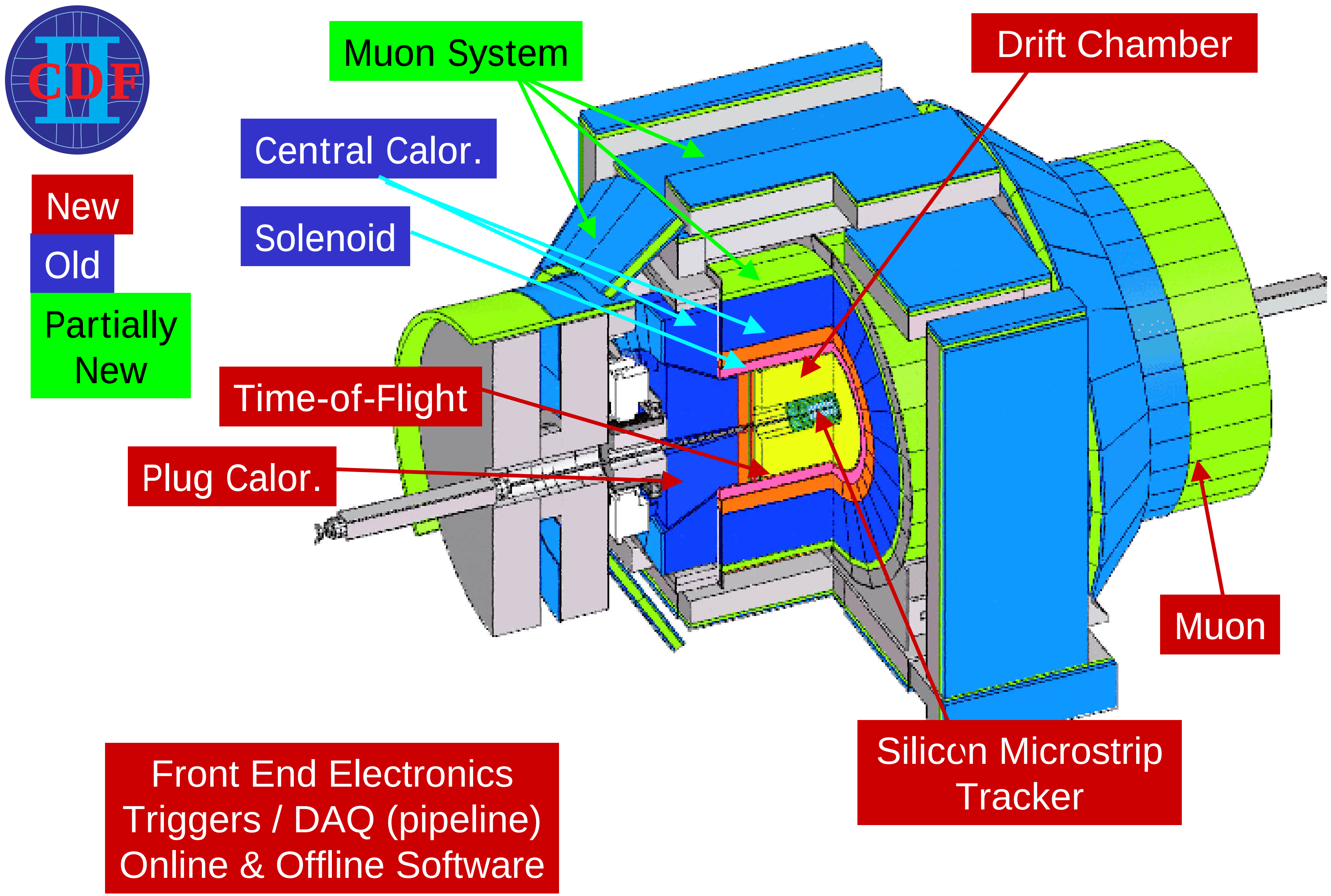
- 5 $\times10^{31}$ $cm^{-2}sec^{-1}$（August 2003）
- Integrated Luminosity 330 $pb^{-1}$
  - 270 $pb^{-1}$ on Tape
  - 120 $pb^{-1}$ analyzed

## Schedule:

- 2 $fb^{-1}$ (by the end of 2005)
- 9 $fb^{-1}$ (by the end of 2009)

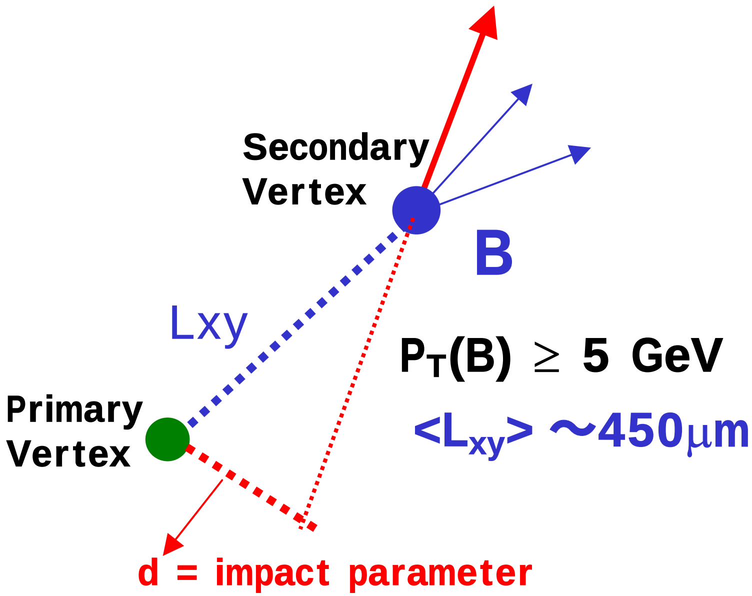


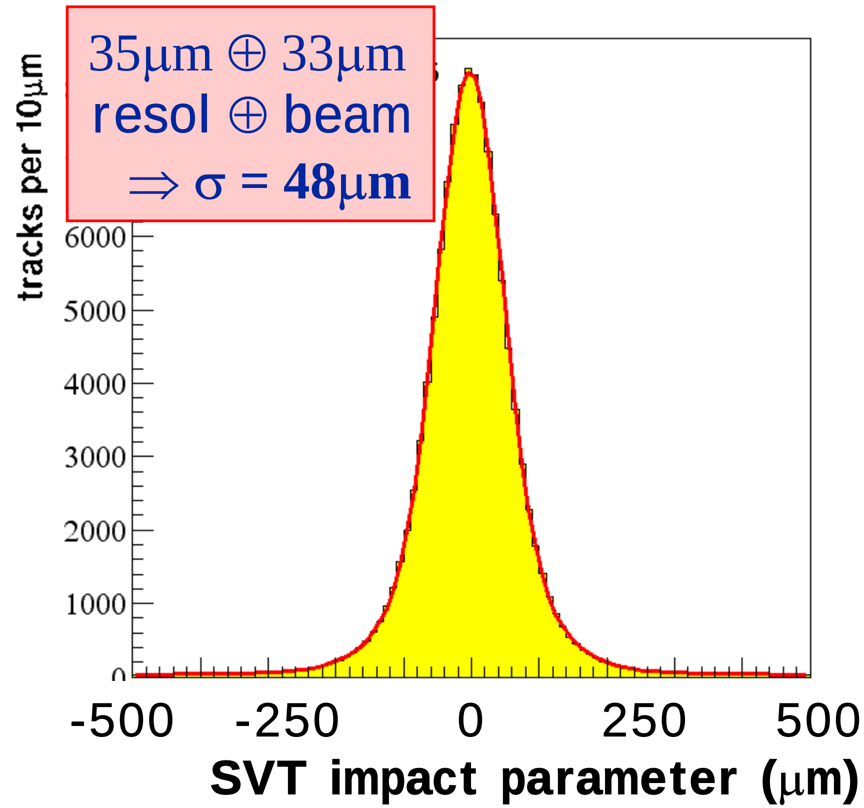




CDF II
New
Old
Partially New
Muon System
Central Calor.
Solenoid
Time-of-Flight
Plug Calor.
Drift Chamber
Muon
Silicon Microstrip Tracker
Front End Electronics
Triggers / DAQ (pipeline)
Online & Offline Software

# 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:
  - ~ 25 µsec/event for readout + clustering + track fitting

# *B* Physics at Hadron Colliders

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

Advantage

- Enormous cross-section
  - ~100 μb total
  - ~ 4 μb "reconstructable"
  - **At 4x10$^{31}$cm$^{-2}$s$^{-1}$ ⇒ ~150Hz of reconstructable *BB*!!**
- All *B* hadrons produced
  - $B_u, B_d, \mathbf{B_s}, \mathbf{B_c}, \Lambda_b, \ldots$

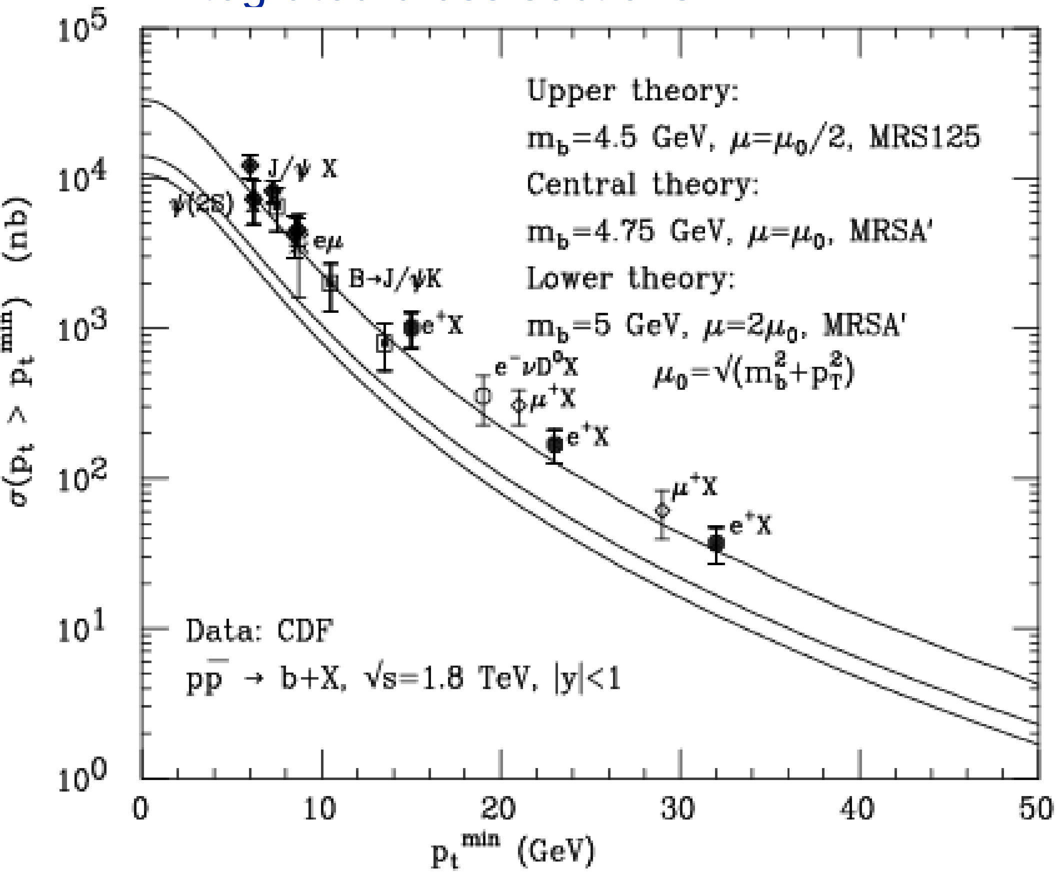
Disadvantage

- Large inelastic background
  - Triggering and reconstruction are challenging

# Heavy Flavor Cross Sections (RunI)

- Tevatron *B* cross sections measured at $\sqrt{s}$ =1.8TeV (Run I: 1992-1996) consistently higher than NLO calculation

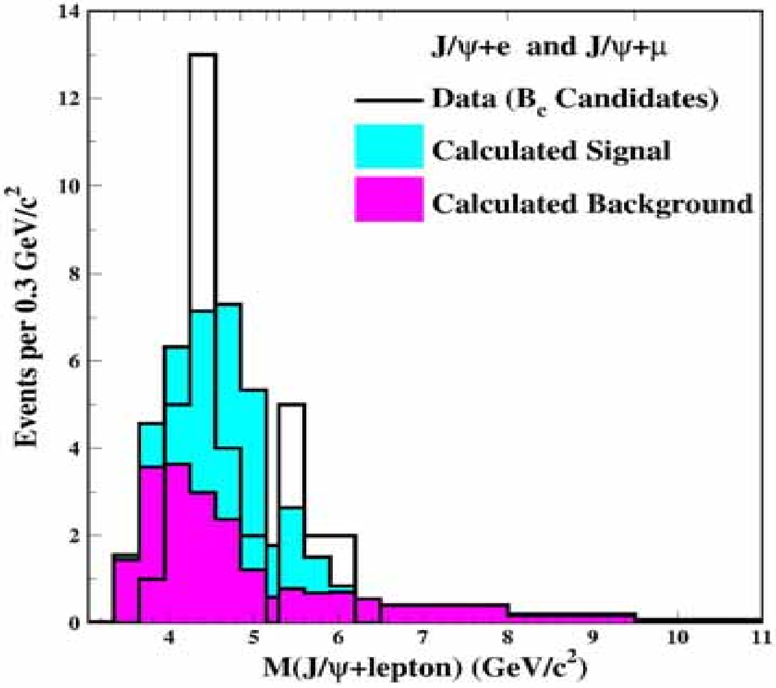
Integrated cross sections



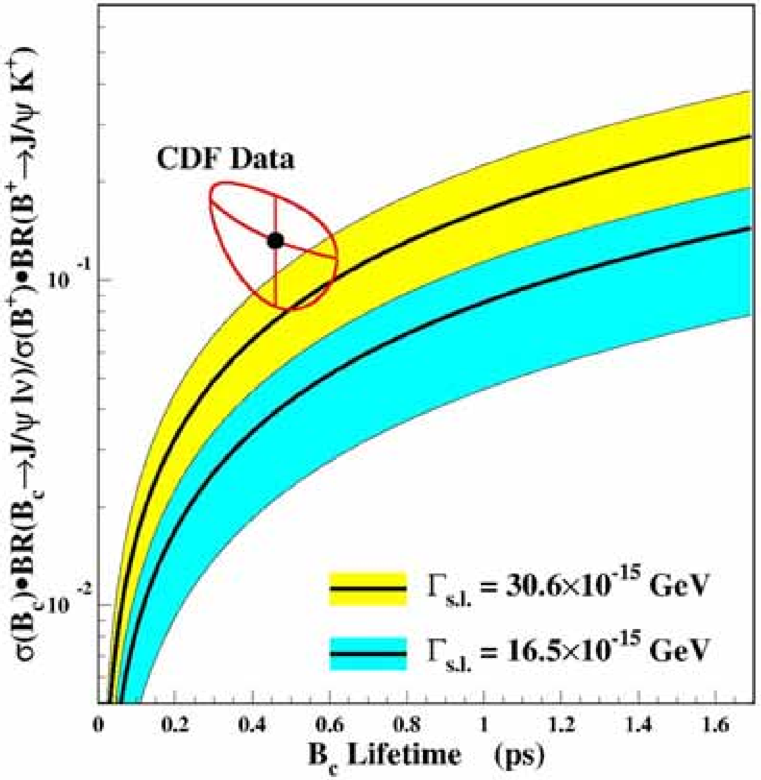

- Theoretical work is ongoing
  - Fragmentation effects
  - Small *x*, threshold effects
  - Proposed beyond SM effects
- What can experiments do?
  - Measure more cross sections
    - $\sqrt{s}$ =1.96 TeV
    - go to lower $p_T(B)$
  - Look at $b\bar{b}$ correlations
  - Measure the charm cross section

# Observation of $B_c$ meson (RunI)

**Invariant mass of $J/\psi + l$ in $B_c \to J/\psi l \nu$ decay mode**




**Cross section times Branching ratio vs Lifetime**




$$\mathrm{N}\left(B_c\right) = 20.4^{+6.2}_{-5.6}$$

$$\tau(B_c) = 0.46 \pm 0.18\,\mathrm{ps}$$

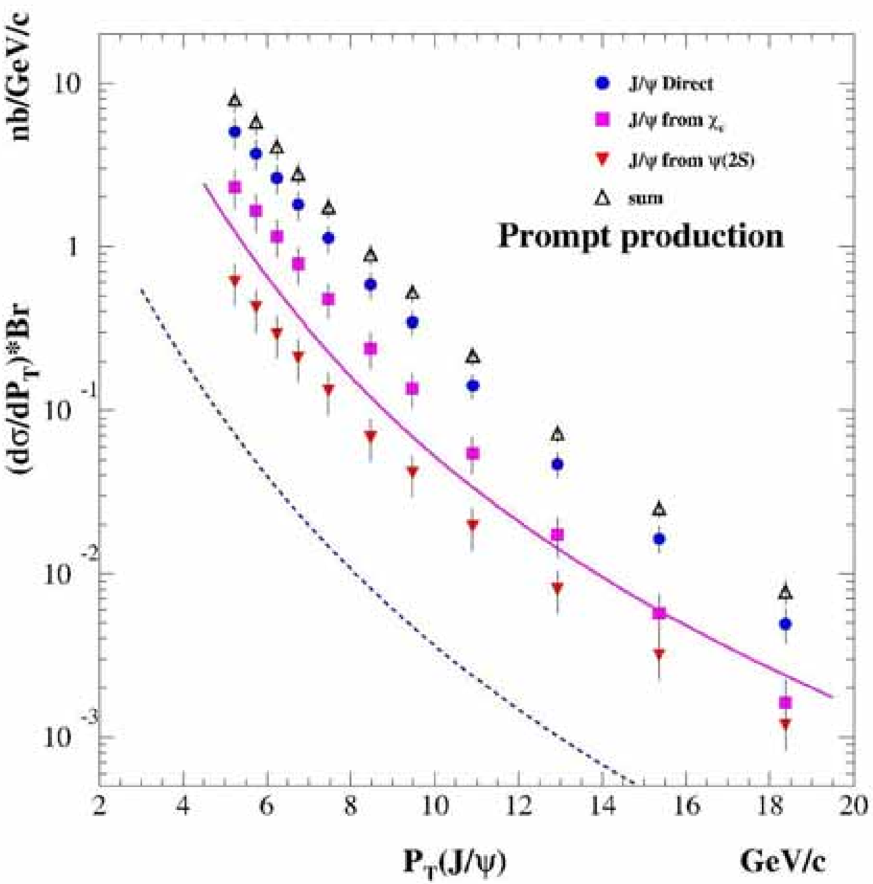
$$\frac{\sigma(p\bar{p} \to B_c \mathrm{X})\mathrm{BR}(B_c \to J/\psi \ell \nu)}{\sigma(p\bar{p} \to B_u \mathrm{X})\mathrm{BR}(B_u \to J/\psi K)} = 0.132^{+0.061}_{-0.052}$$

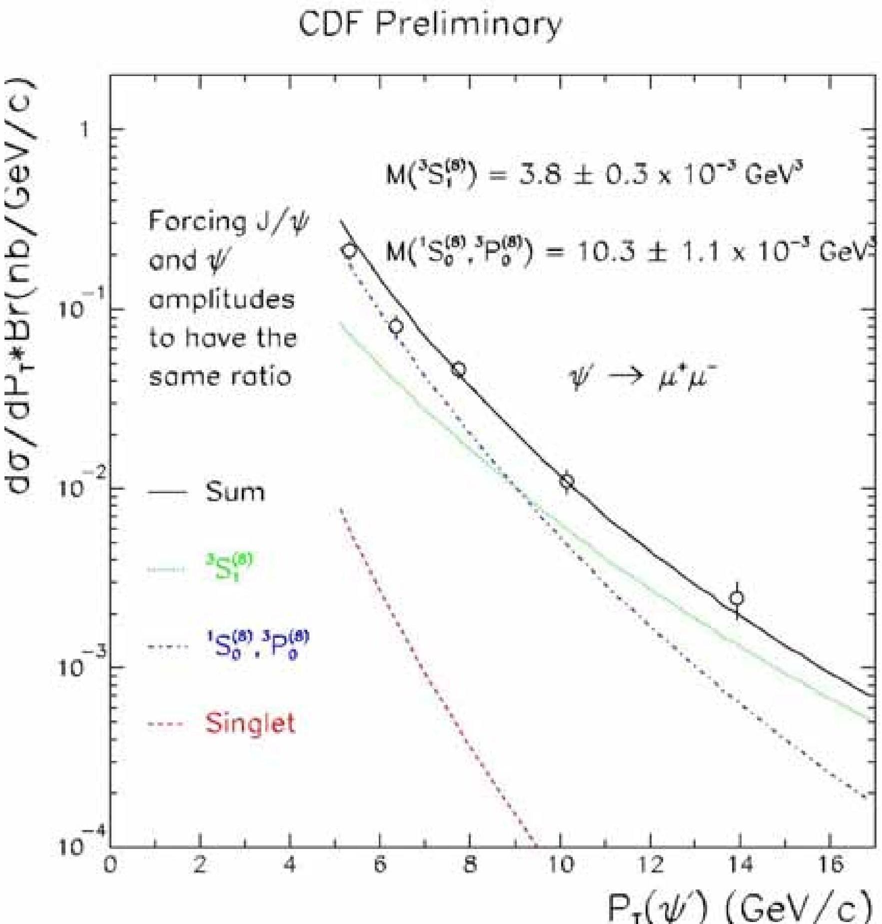
# Anomalous J/ψ Direct Production (RunI)

- Cross section of $J/\psi$ and $\psi$(2s) direct production is larger than QCD theoretical prediction by a factor of 50.

  *PRL 79 (1997) 572, PRL 79 (1997) 578*

- Polarization of $J/\psi$ and $\psi$(2s) disfavors the color octet model.



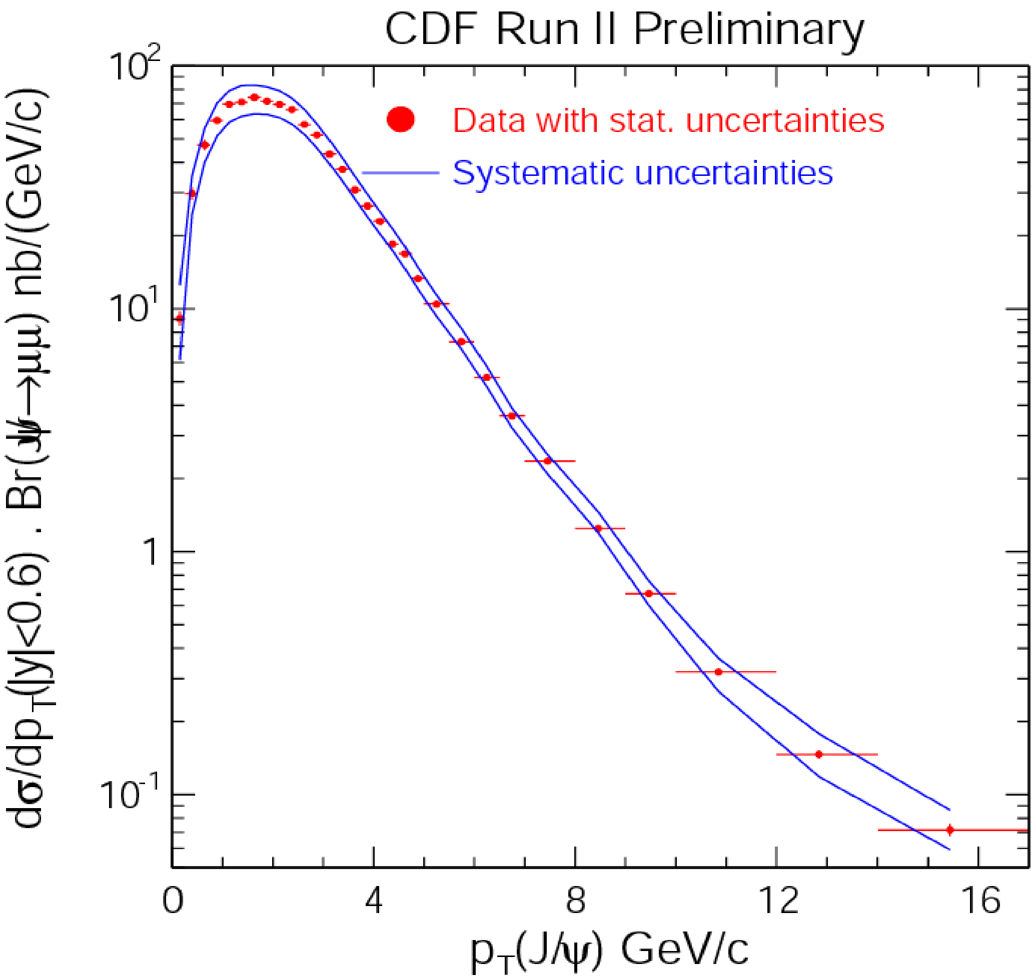



# $J/\psi$ production cross section ( Run II )

**CDF measured the $J/\psi$ cross section from $P_T$ > 0GeV/c by lowering the trigger threshold.**

**Consistent with Run I Measurement in $P_T$ > 5GeV/c region.**

**Need a comparison between this result and theoretical prediction in the $P_T$ < 5GeV/c region.**



# $B$ Hadron Lifetimes

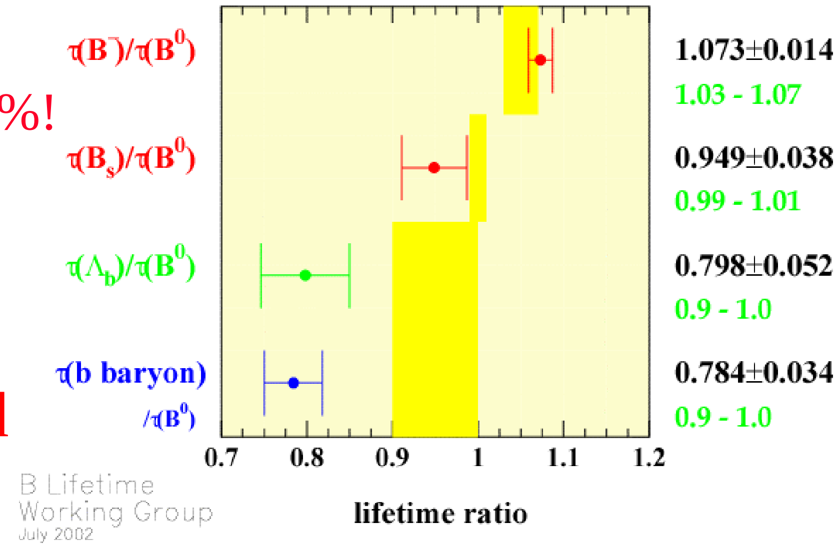
- All lifetimes equal in spectator model.
  - Differences from interference & other nonspectator effects
- <u>H</u>eavy <u>Q</u>uark <u>E</u>xpansion predicts the lifetimes for different B hadron species

$$\tau(B^+) \geq \tau(B^0) \approx \tau(B_s) > \tau(\Lambda_b) \gg \tau(B_c)$$

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

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

- Measurements:
  - $B^0$,$B^+$ lifetimes measured to better than 1%!
  - $B_s$ known to about 4%
  - LEP/CDF (Run I) $\Lambda_b$ lifetime lower than HQE prediction
- Tevatron can contribute to $B_s$, $B_c$ and $\Lambda_b$ (and other *b*-baryon) lifetimes.

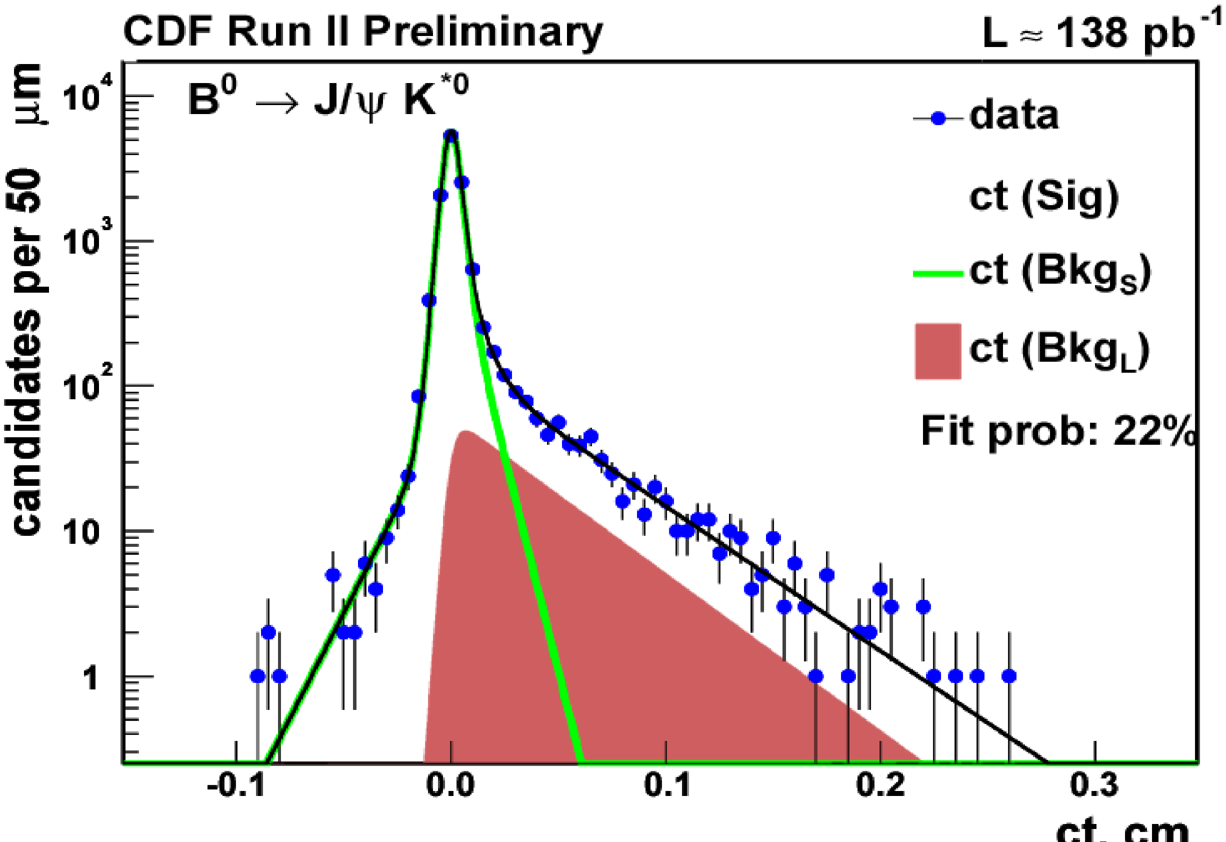


# $B^+$, $B^0$ Lifetimes in $J/\psi$ Modes

$\tau(B^0)$ **1.63 ± 0.05(*stat.*) ± 0.04 (*syst.*) ps**

$\tau(B^+)$ **1.51 ± 0.06(*stat.*) ± 0.02 (*syst.*) ps**

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




Proper decay length:

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

# $B_s$ Lifetime

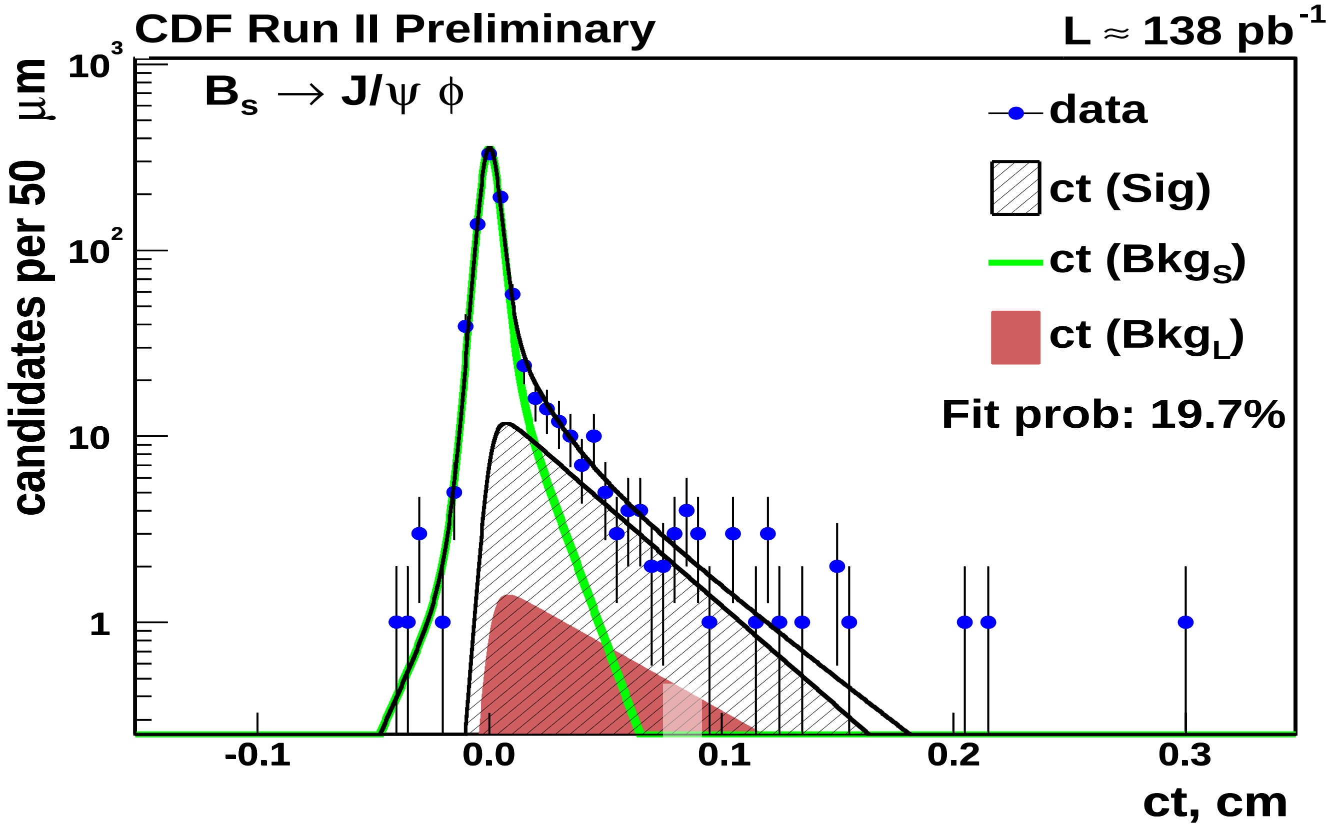
$B_s \to J/\psi\ \Phi$ with $J/\psi \to \mu^+ \mu^-$ and $\Phi \to K^+K^-$

$B^+ \to J/\Psi K^+$, $B^0 \to J/\Psi K^{*0}$ check technique, systematics

$$ct = L_{xy} \frac{m_B}{p_T^B}$$

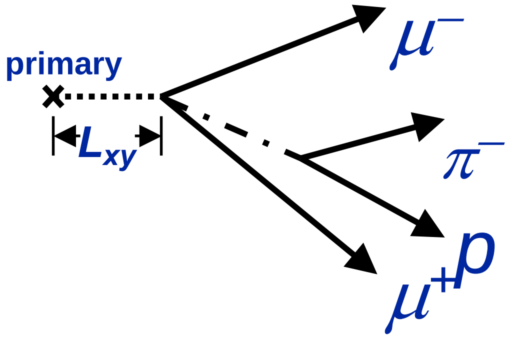
$B_s$ lifetime - PDG 1.461 ± 0.057 ps

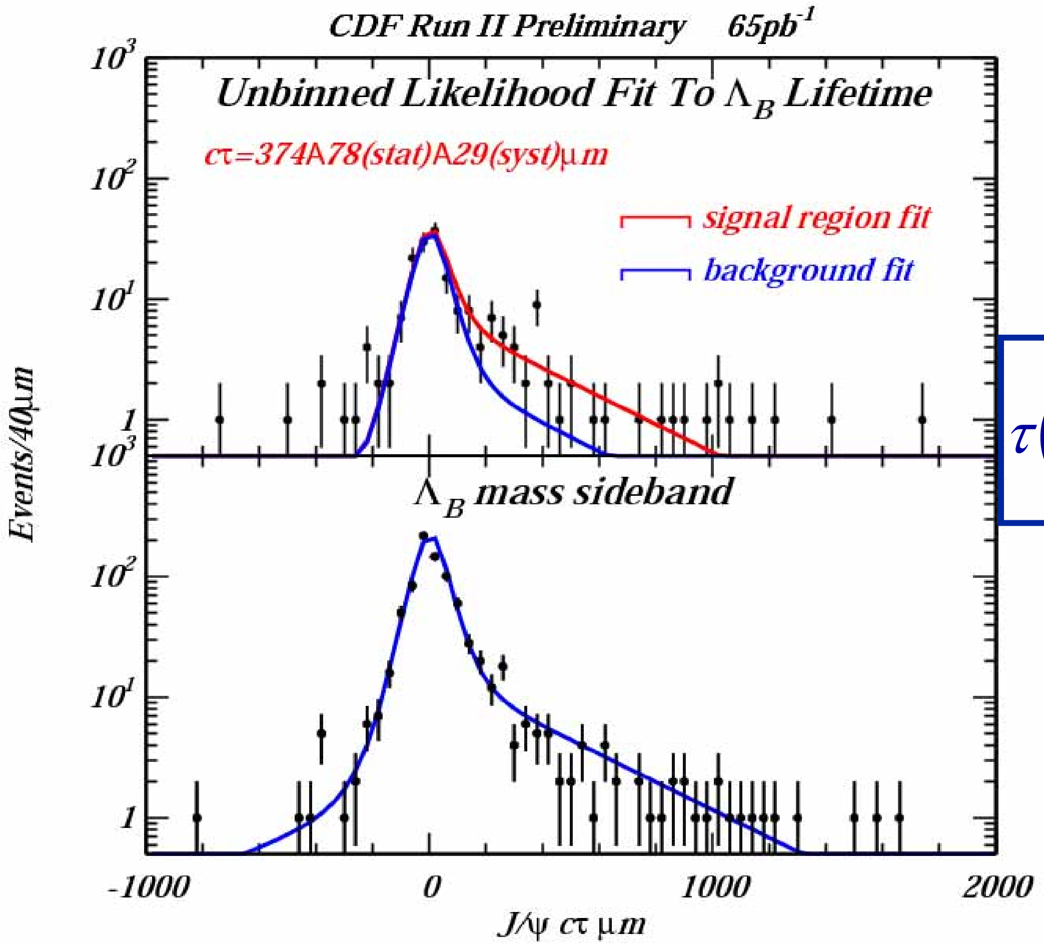
$1.33 \pm 0.14_{(stat)} \pm 0.02_{(sys)}$ ps



# $\Lambda_b$ 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




46±9 signal

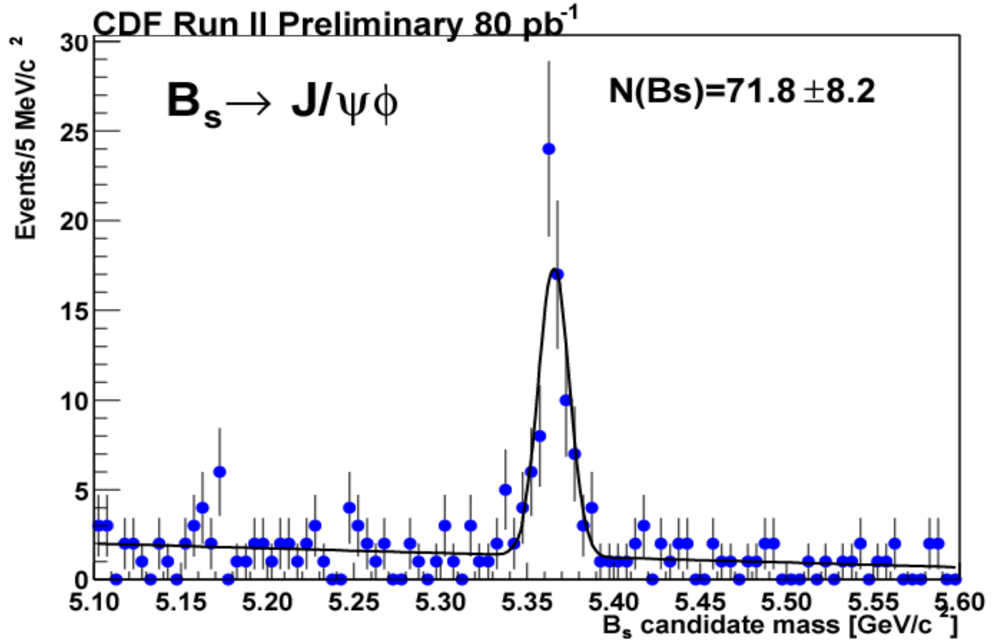
$$\tau(\Lambda_b) = 1.25 \pm 0.26(stat.) \pm 0.10(syst.)\,\mathrm{ps}$$

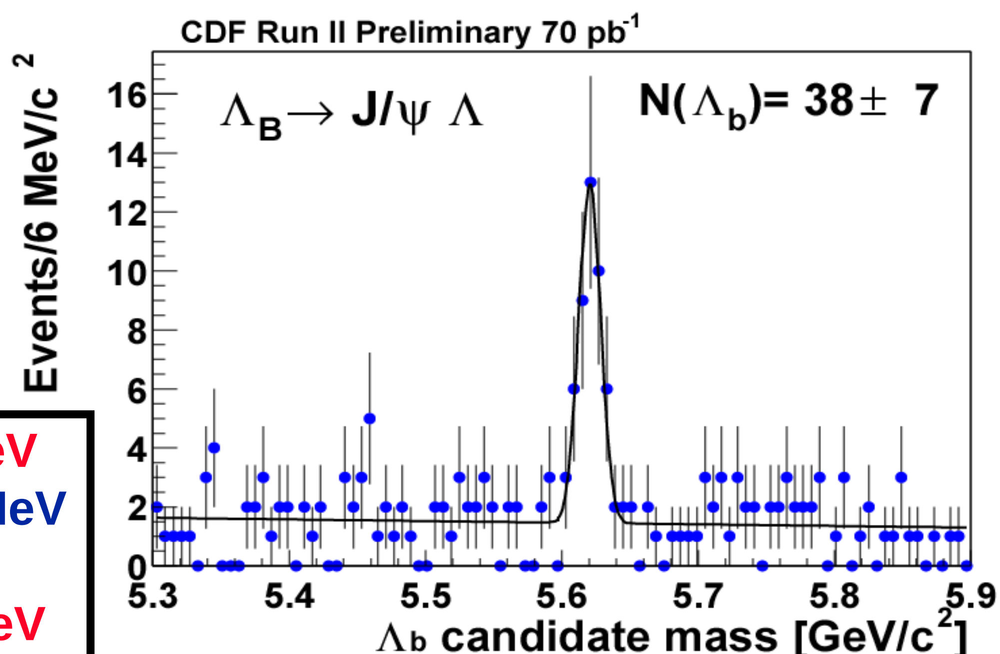
**First lifetime from fully reconstructed $\Lambda_b$ decay!**

# $B$ 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 $\Lambda_b$ measurements are world's best.**

| | | | |
|---|---|---|---|
| CDF result: | $M(B_s)$=5365.5 | $\pm$1.6 | MeV |
| World average: | $M(B_s)$=5369.6 | $\pm$2.4 | MeV |
| CDF result: | $M(\Lambda_b)$=5620.4 | $\pm$2.0 | MeV |
| World average: | $M(\Lambda_b)$=5624 | $\pm$9 | MeV |

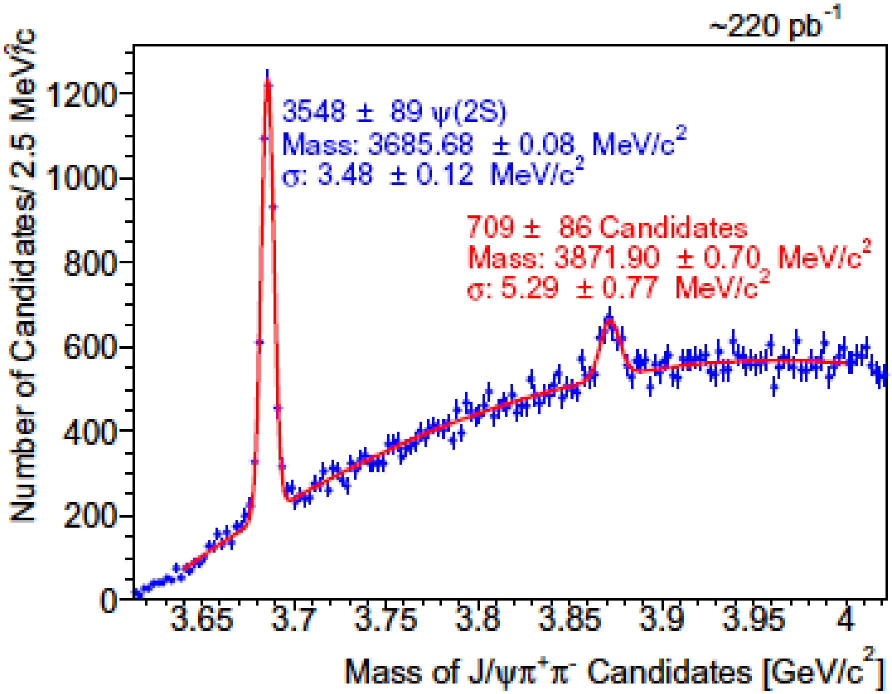


# New Particle decaying to $J/\psi\, \pi^+ \pi^-$

Belle observes narror state final state $J/\psi\, \pi^+ \pi^-$

- exclusive: $B^+ \rightarrow J/\psi\, \pi^+ \pi^- K^+$
- 35.7 ±6.8 events
- possibly charmonium
- mass is unexpected
- shown August 12, 2003




CDF confirms this September 20

- final state $J/\psi\, \pi^+ \pi^-$
- mostly prompt prodction
- 709±86 events

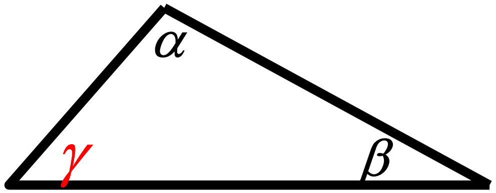
Mass measured by CDF:

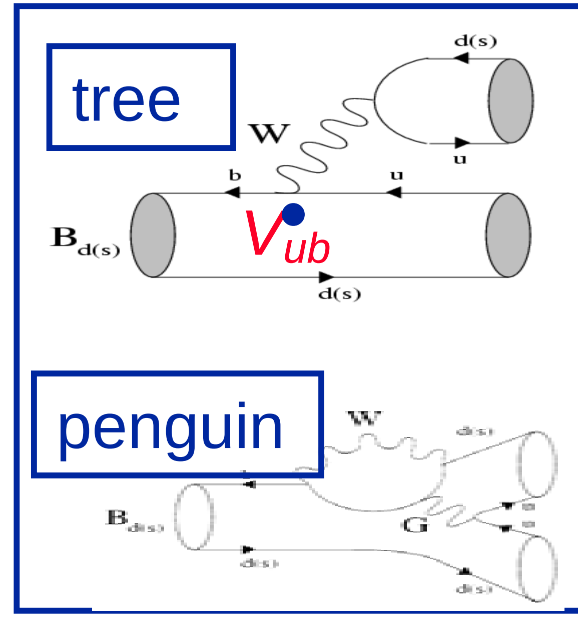
$3871.4 \pm 0.7 \pm 0.4$ MeV/$c^2$

Compares well with Belle:

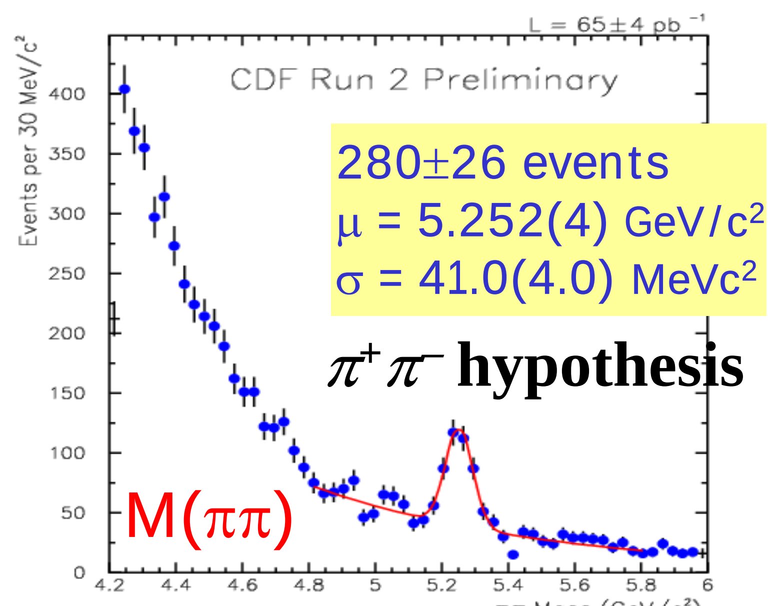
$3872.0 \pm 0.6 \pm 0.5$ MeV/$c^2$

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

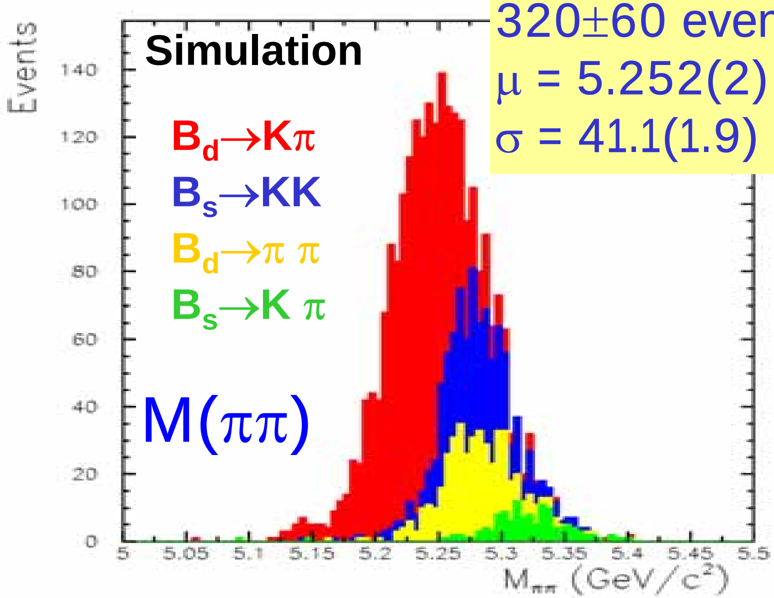



- charmless two-body decays
  - longer term $B_s$ modes help extract unitarity angle $\gamma$
- Signal is a combination of:
  - $B^0 \to \pi^+\pi^-$ $BR{\sim}5x10^{-6}$
  - $B^0 \to K^+\pi^-$ $BR{\sim}2x10^{-5}$ } $\Upsilon$(4s),Tevatron
  - $B_s \to K^+K^-$ $BR{\sim}5x10^{-5}$
  - $B_s \to \pi^+K^-$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



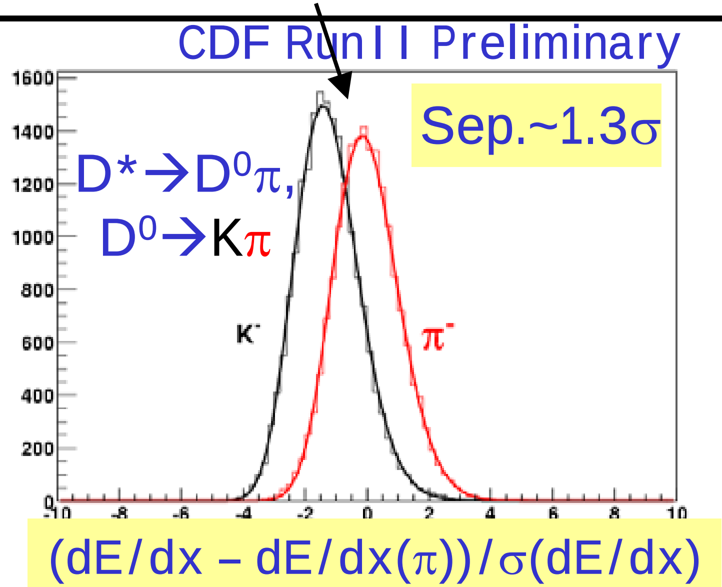
# $BR(B_s \to K^+K^-)$




## *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) |

**kinematics & *dE/dx* to separate contributions**



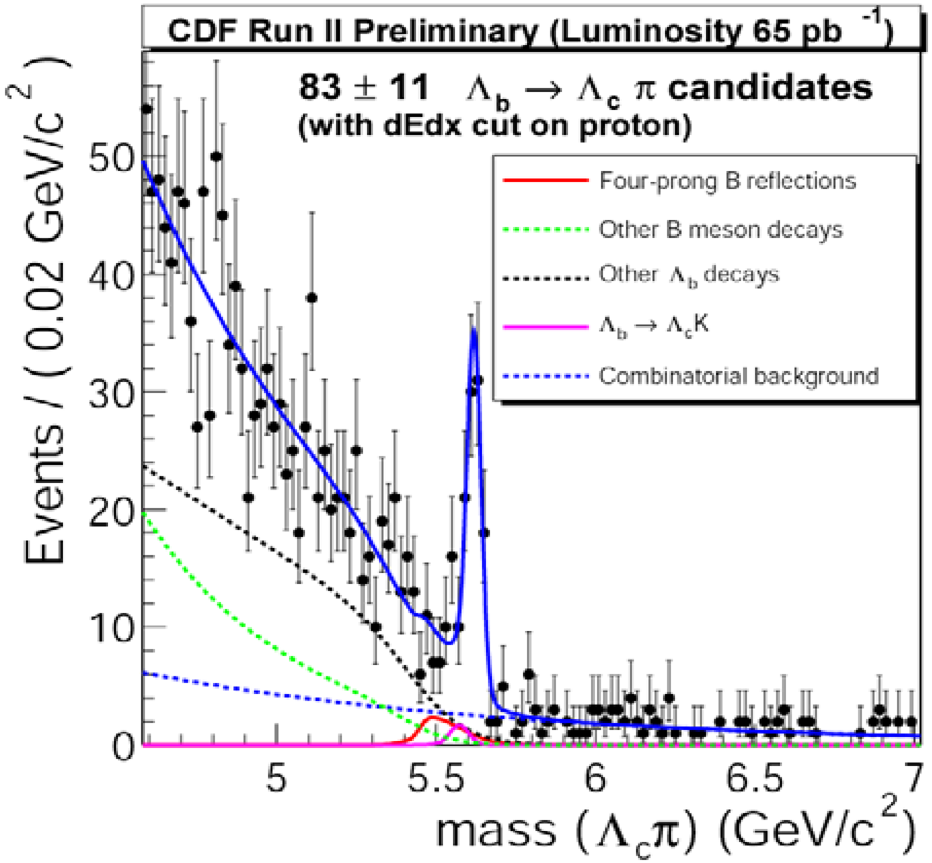

**First observation of $B_s \to K^+K^-$ !!**

**Result:** $$\frac{f_s BR(B_s \to KK)}{f_d BR(B^0 \to K\pi)} = 0.74 \pm 0.20 \pm 0.22$$

**Measure $A_{CP}$**

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

# $\Lambda_b \rightarrow \Lambda_c \pi$ with $\Lambda_c \rightarrow pK\pi$




Backgrounds: real $B$ decays

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

- 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:

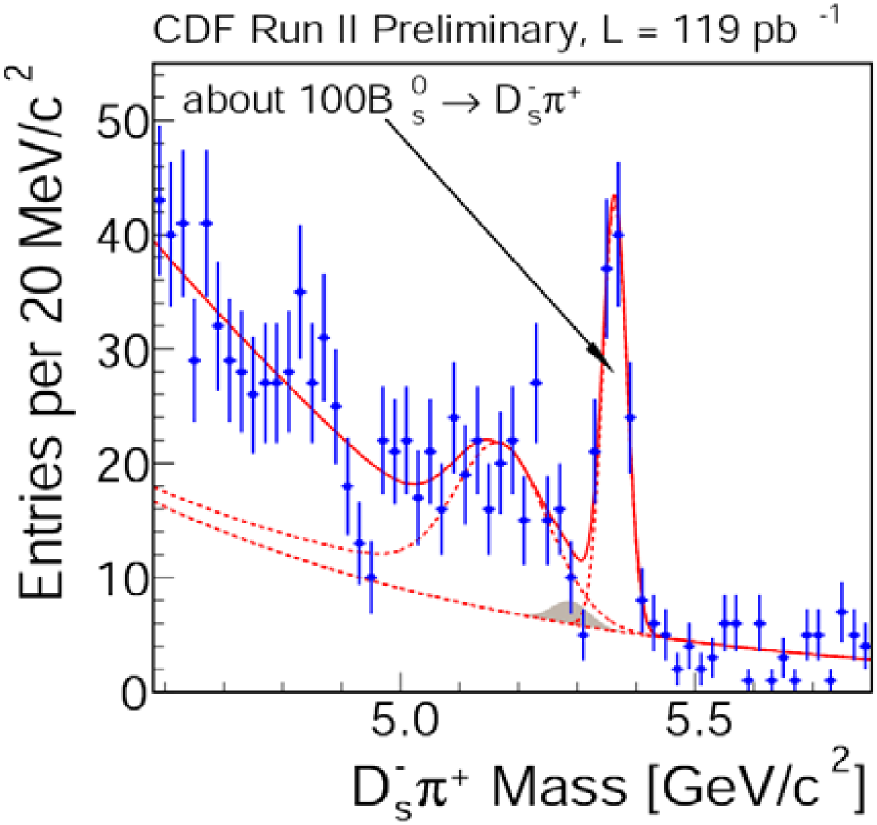
$$N_{\Lambda_b} = 96 \pm 13(stat.)^{+6}_{-7}(syst.)$$

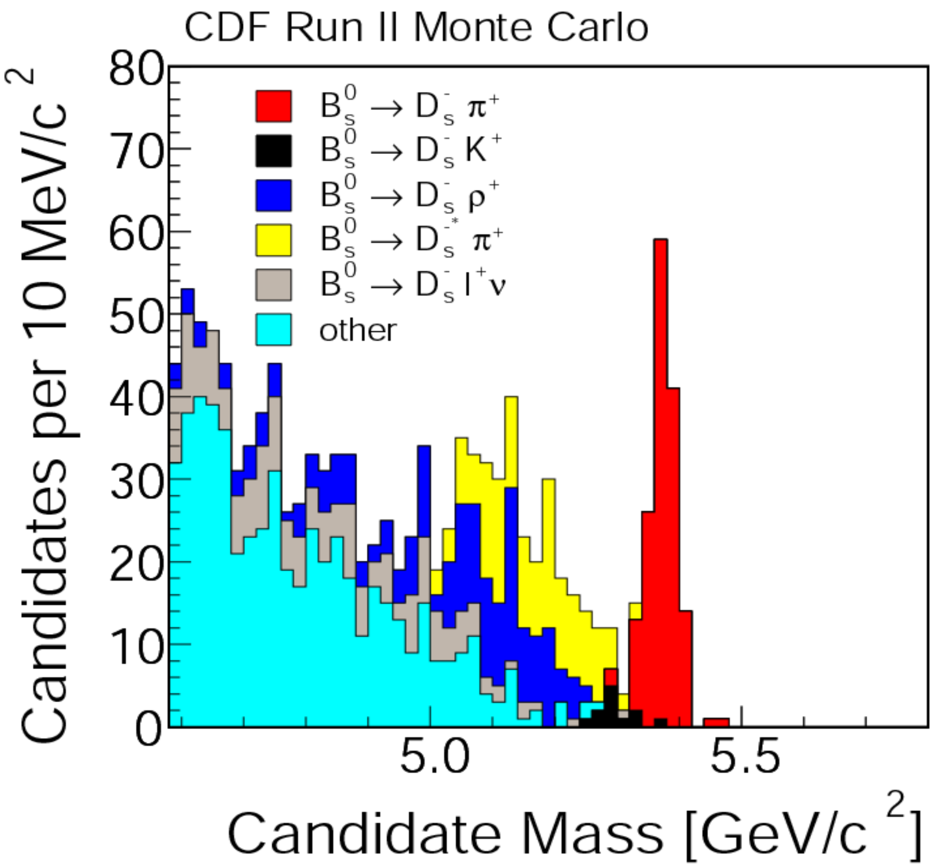
Measure: $\dfrac{\sigma_b \times f_{baryon} \times BR(\Lambda_b \rightarrow \Lambda^+_c \pi^-)}{\sigma_b \times f_d \times BR(B^0 \rightarrow D^- \pi^+)}$

***New Result !***

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

# $B_s$ 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.*

# Measuring $B_s$ Oscillation

- **$B_s$ reconstruction**
  - e.g. $B_s \to D_s^- \pi^+$

- **Flavor tagging ( $B_s$ or $\overline{B}_s$ at the time of production?)**
  - Tagging "dilution": D=1-2w
  - Tagging power proportional to: $\varepsilon D^2$

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

- **Proper decay time**

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

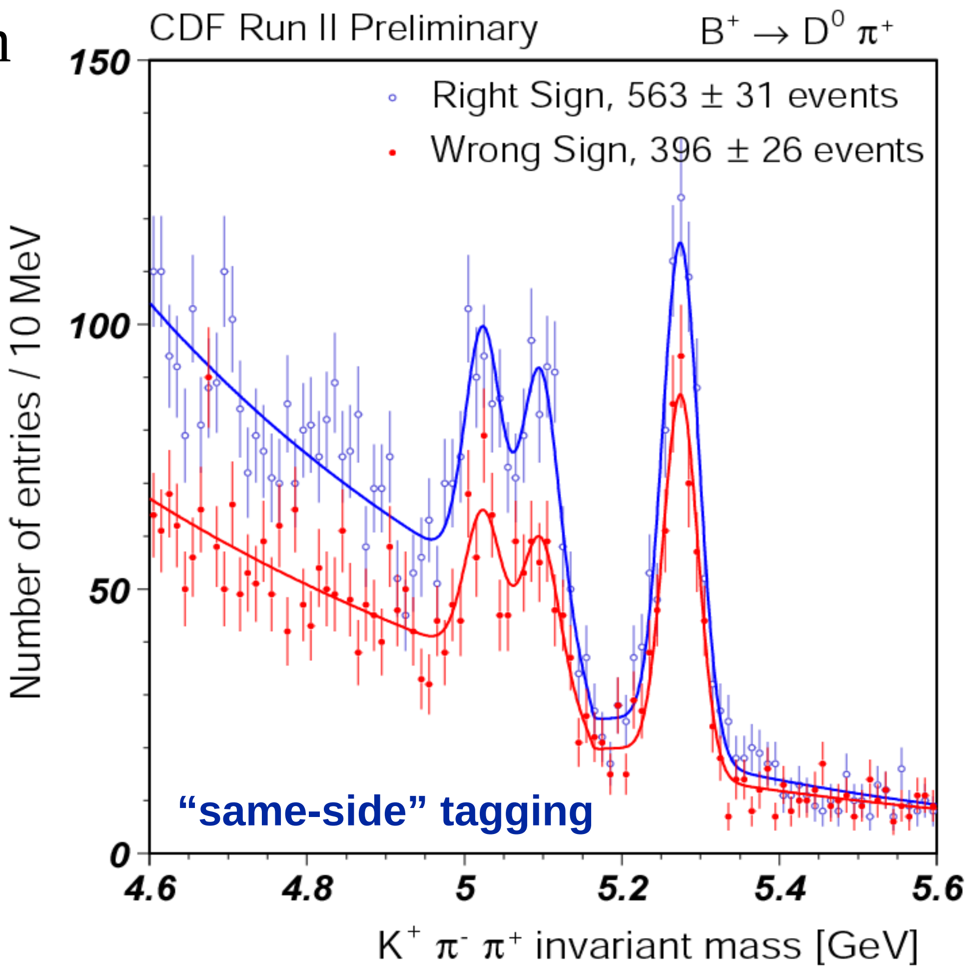
*uncertainty*

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

  - 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.




Results:

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

# *CDF* $B_s$ Sensitivity Estimate

**hadronic mode only**

- Current performance:
  - 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 $\Delta m_s$ =15ps$^{-1}$ with ~0.5fb$^{-1}$ of data

surpass the current world average

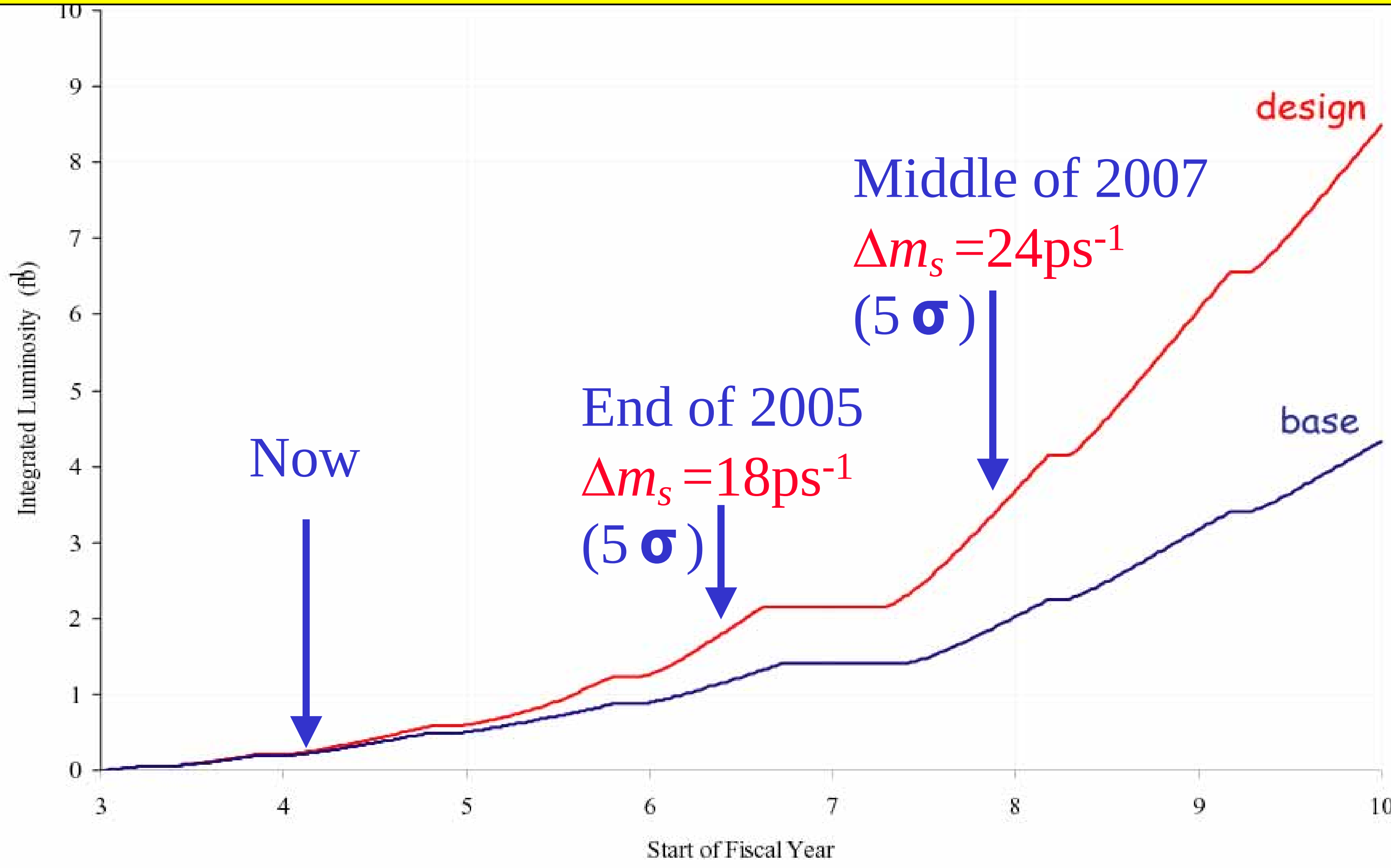
- With "modest" improvements
  - S=2000 fb (improve trigger, reconstruct more modes)
  - S/B = 2/1 (unchanged)
  - $\varepsilon D^2$ = 5% (kaon tagging)
  - $\sigma_t$ = 50fs (event-by-event vertex + L00)

5σ sensitivity for $\Delta m_s$ =18ps$^{-1}$ with ~1.7fb$^{-1}$ of data
5σ sensitivity for $\Delta m_s$ =24ps$^{-1}$ with ~3.2fb$^{-1}$ of data

$\Delta m_s$=24ps$^{-1}$ "covers" the expected region based upon indirect fits.

- *This is a difficult measurement.*
- *There are ways to further improve this sensitivity…*

# RunII Projected Integrated Luminosity



# Conclusion

- **New results of masses, lifetimes and branching ratio on *B* physics produced at CDF, especially on heavier *B*-hadrons.**

- **New measurements on heavier *B*-hadrons, such as $B_s$ oscillation, $B_c$ mass and $\Lambda_b$ branching ratio will come in the near future.**

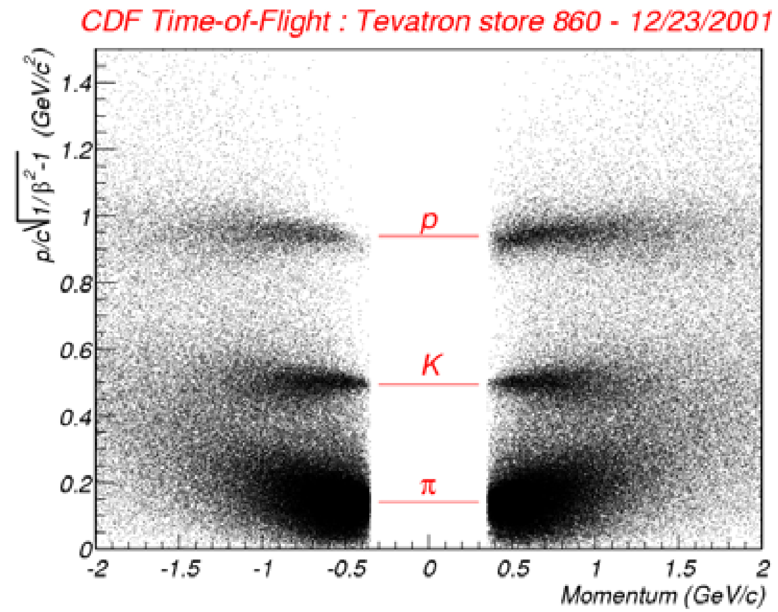
# BACKUP SLIDES

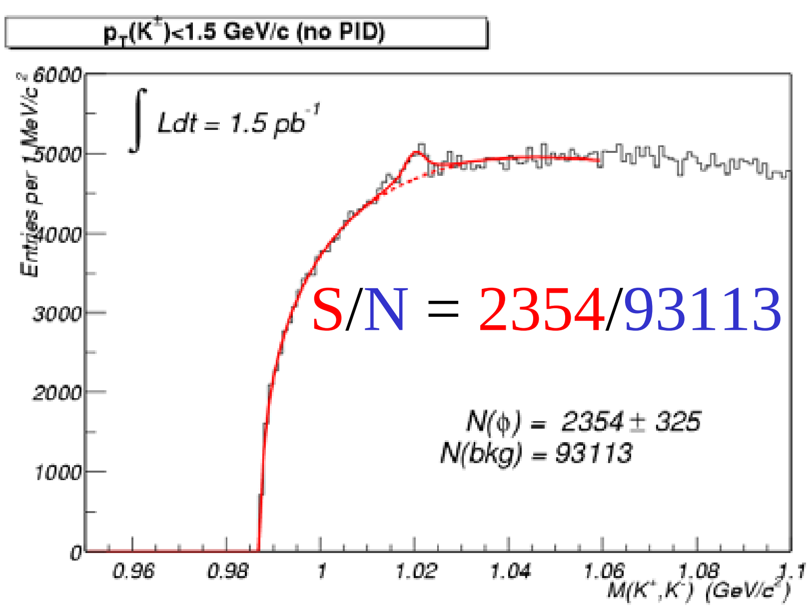
# TOF counter

- TOF time resolution

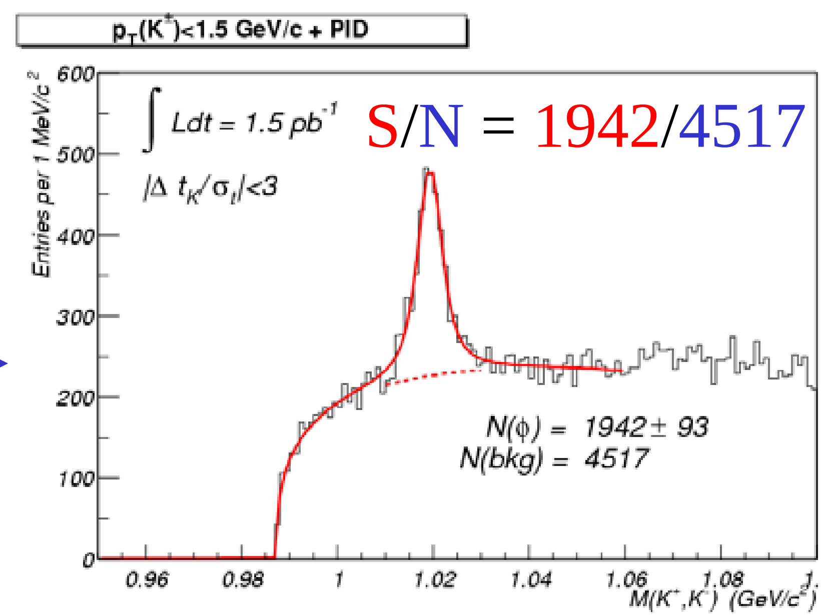
  ～100ps(design value)
- ***Φ*** meson → ***K⁺ K⁻***

  **S/N: 0.025 → 0.45**



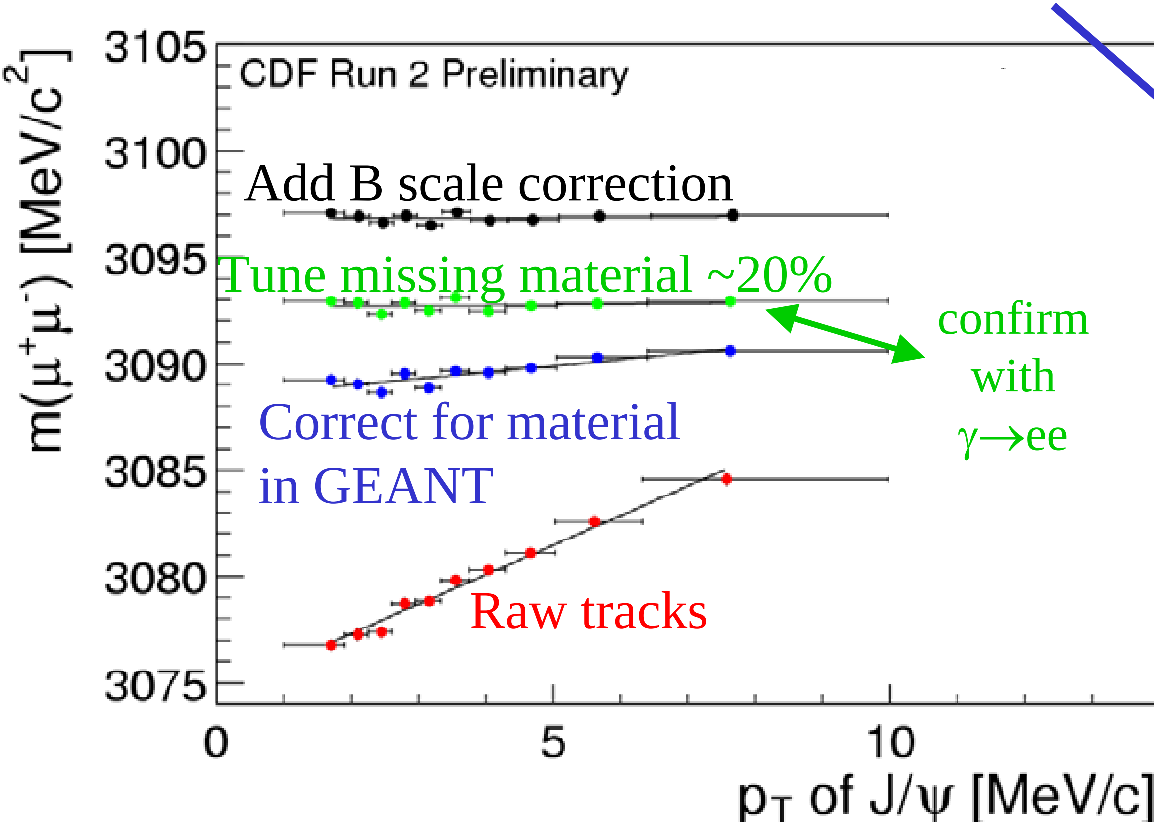



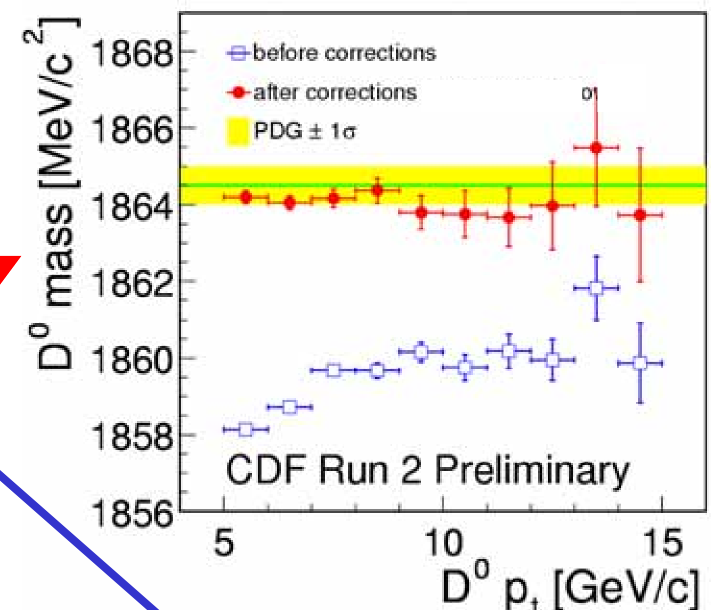

**TOF**

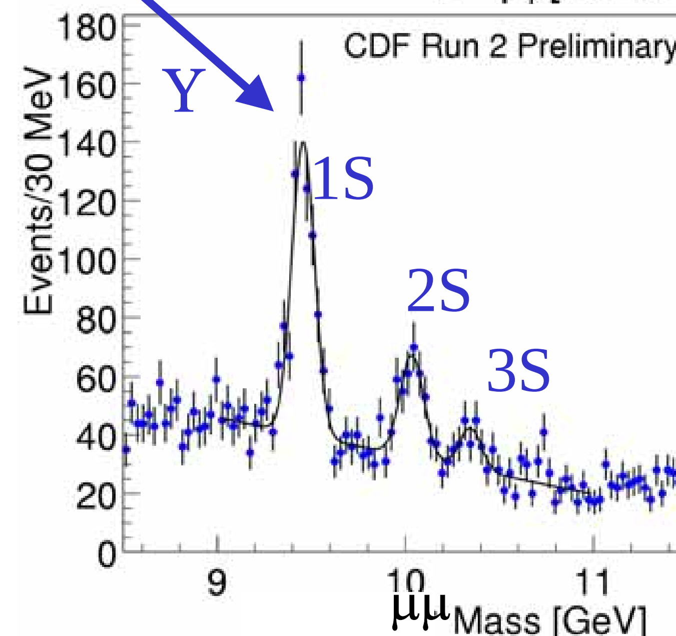


# Material & Momentum Calibration

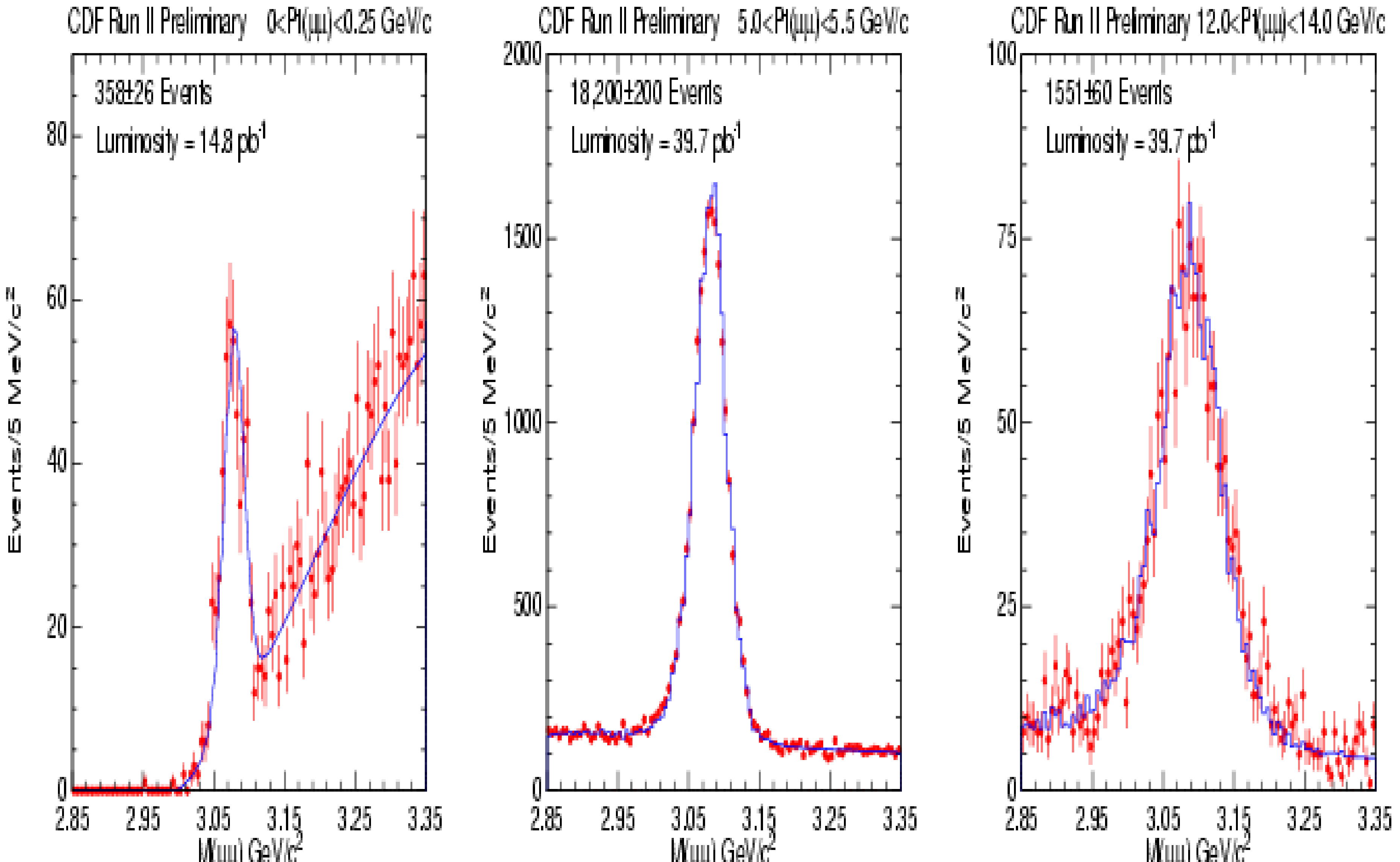
- Use J/ψ's to understand E-loss and B-field corrections
  - σ(scale)/scale ~ 0.02% !
- Check with other known signals



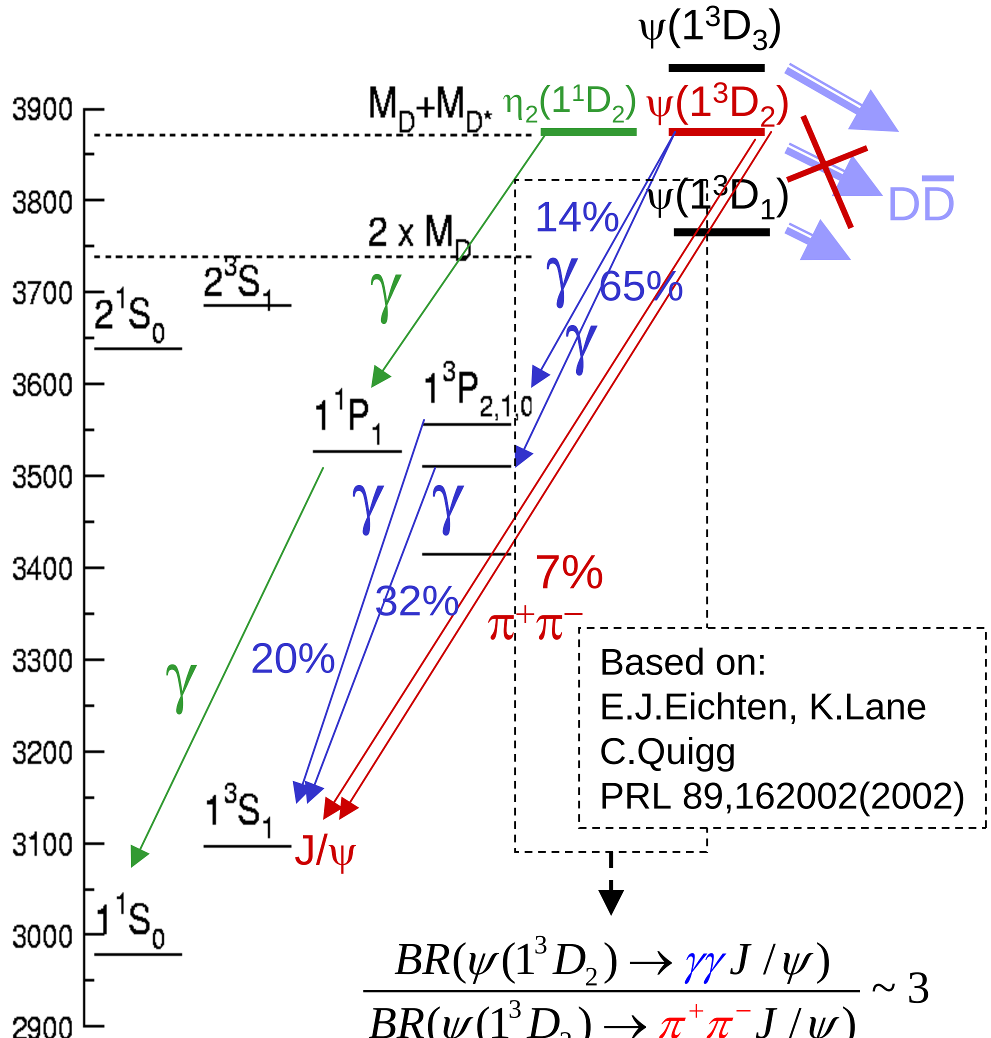



# J/ψ production in Run IIa



# Possible interpretations

- A $\psi(1^3D_2)$ state:
  - Because D-states have negative parity, spin-2 states cannot decay to $D\bar{D}$
  - They are narrow as long as below the DD* threshold
  - $\eta_2(1^1D_2)$ preferentially decays to $h_c(1^1P_1)$. Decays to $\pi^+\pi^- J/\psi$ would be of magnetic type and are suppressed.
  - Some models predict large widths for $\psi(1^3D_2) \rightarrow \pi^+\pi^- J/\psi$
  - All models predict even larger widths for $\psi(1^3D_2) \rightarrow \gamma\, \chi_c (1^3P_{2,1})$ Should easily see $\psi(1^3D_2) \rightarrow \gamma\gamma\, J/\psi$.
    - Discovery of the signal is very recent. Belle is working on this channel but is not ready to present any results.

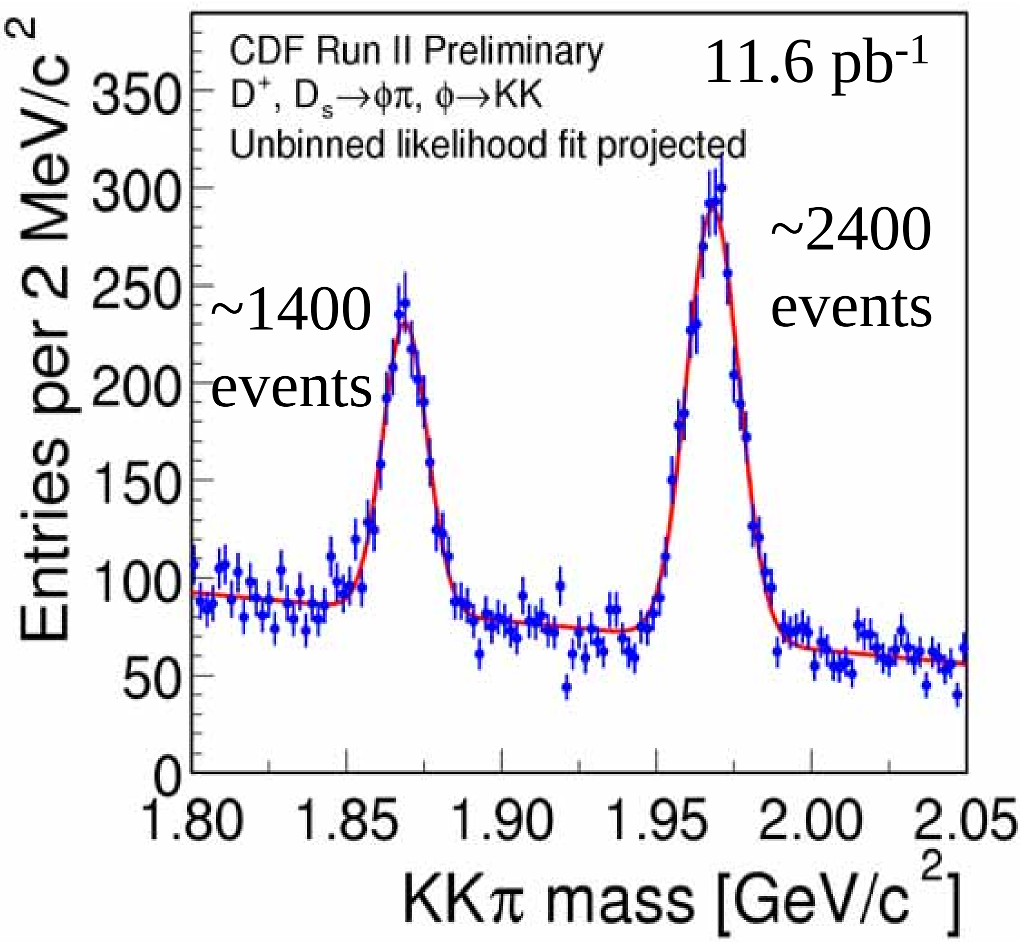



$$\frac{BR(\psi(1^3D_2) \rightarrow \gamma\gamma J/\psi)}{BR(\psi(1^3D_2) \rightarrow \pi^+\pi^- J/\psi)} \sim 3$$

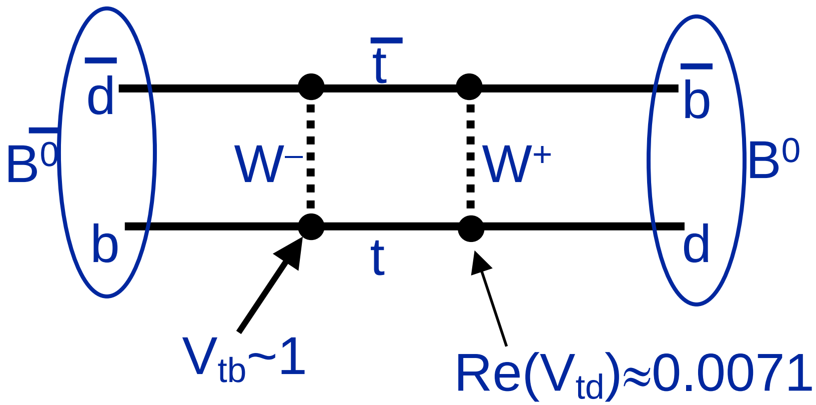
# $D_s$, $D^+$ mass difference

- $D_s^{\pm}$ - $D^{\pm}$ mass difference
  - Both D → $\phi\pi$  ($\phi$→KK)
  - □ $\Delta m = 99.28 \pm 0.43 \pm 0.27$ MeV
    - PDG: $99.2 \pm 0.5$ MeV (CLEO2, E691)
  - Systematics dominated by background modeling

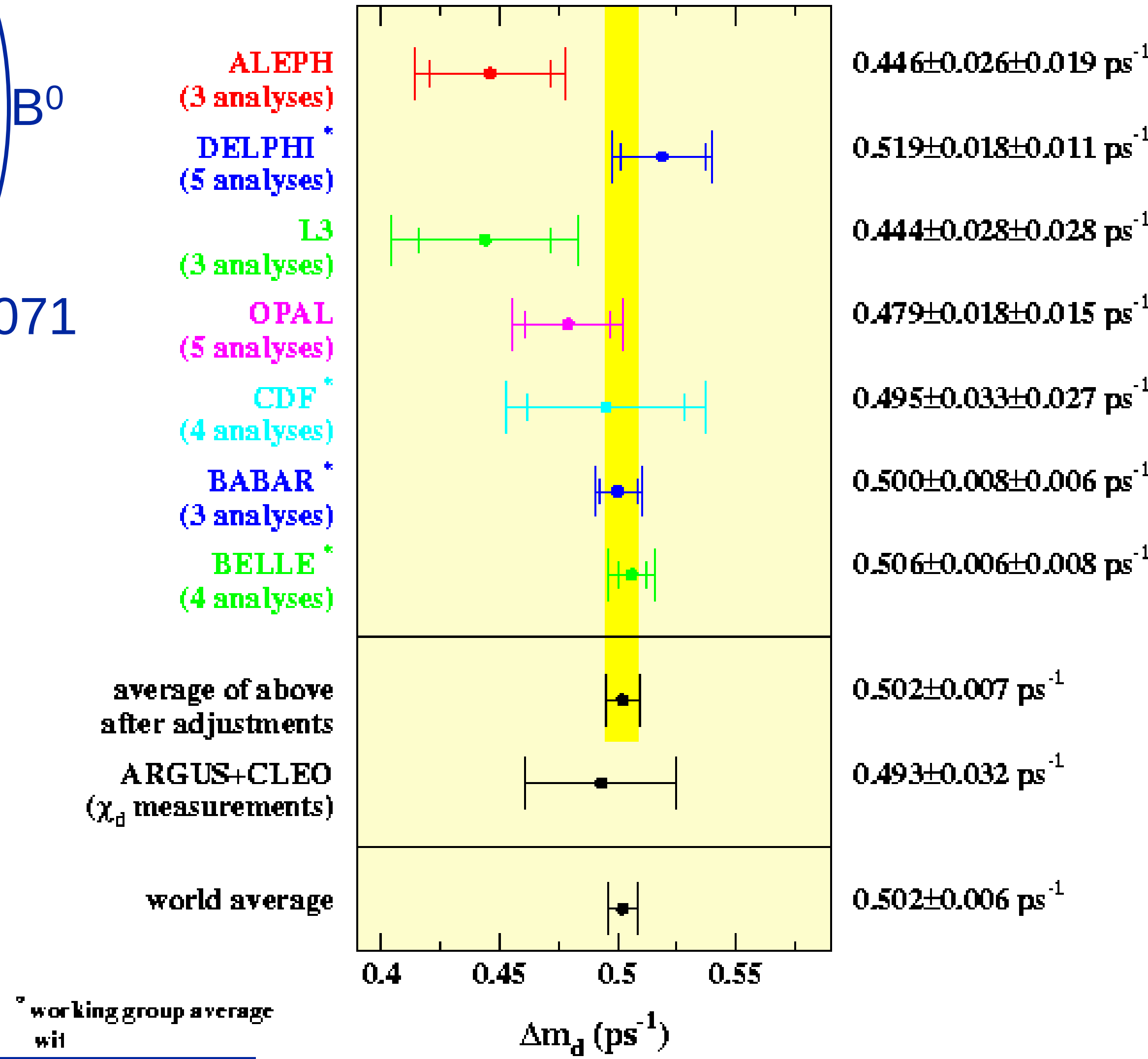
Brand new CDF capability



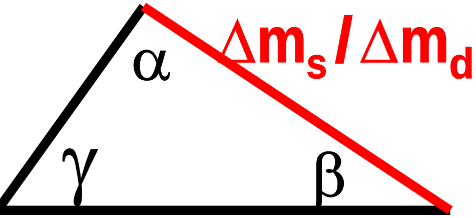
# $B_d$ Mixing




- $B_d$ mixing measured with great precision
  - World average now dominated by Babar and Belle



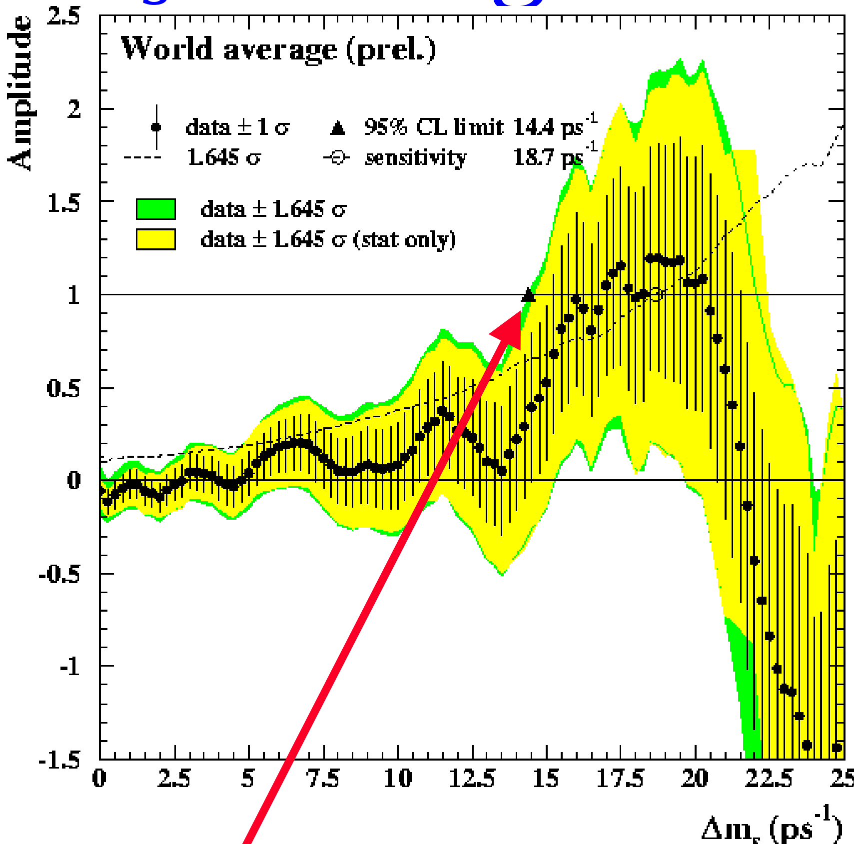

**$B_d$ fully mixes in about 4.1 lifetimes**

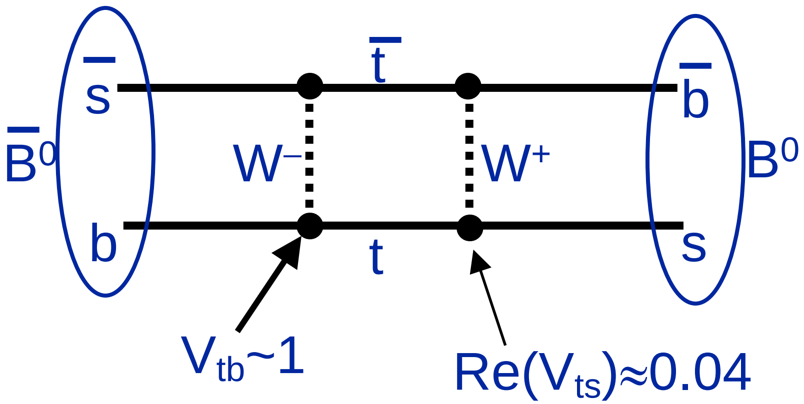



# Towards $B_s$ Mixing

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

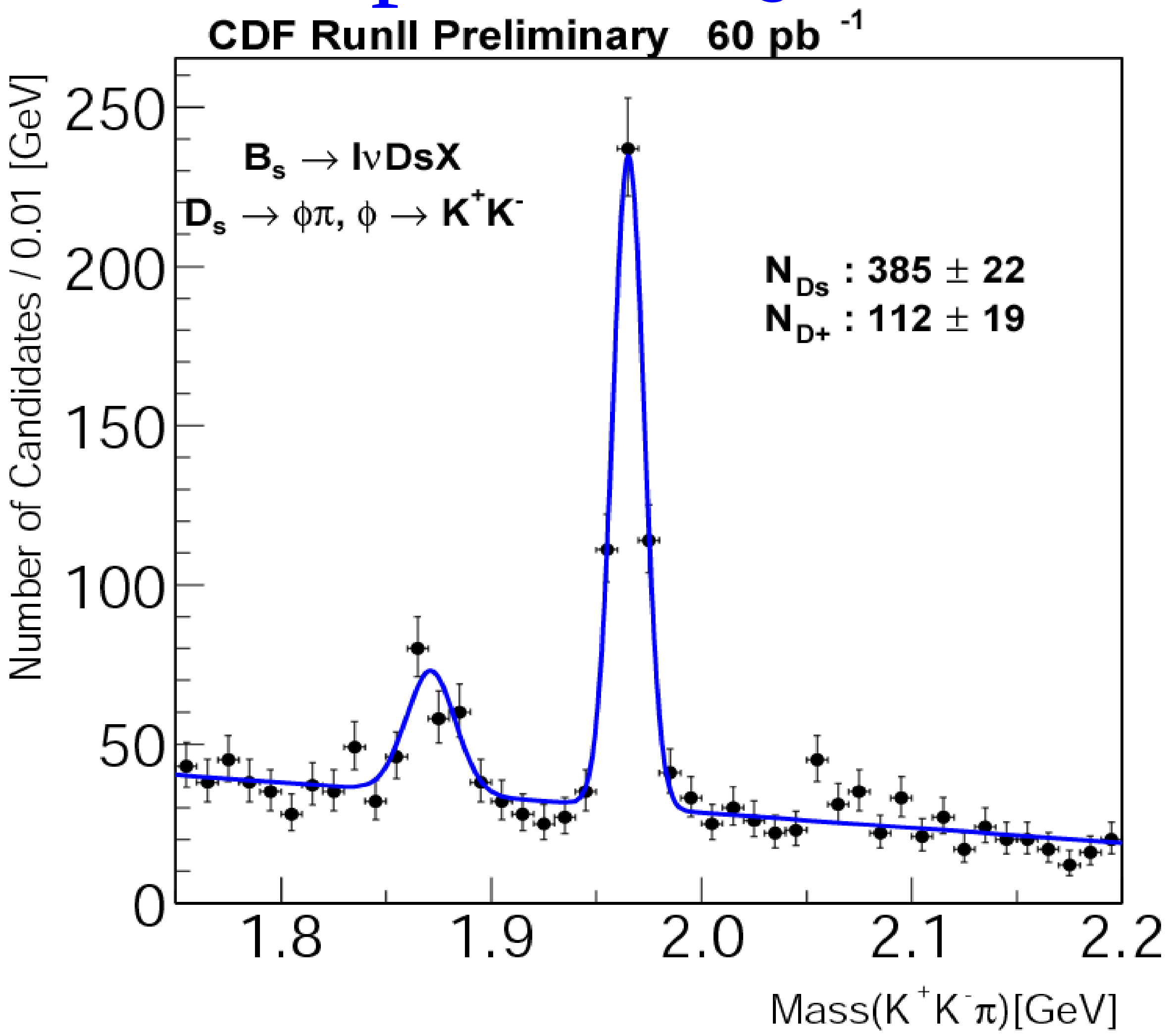
$Re(V_{ts}) \approx 0.040 > Re(V_{td}) \approx 0.007$




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

# 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 $D_s \to K_s K^+$)***

# RunII Luminosity

## Projections

### Design Projection

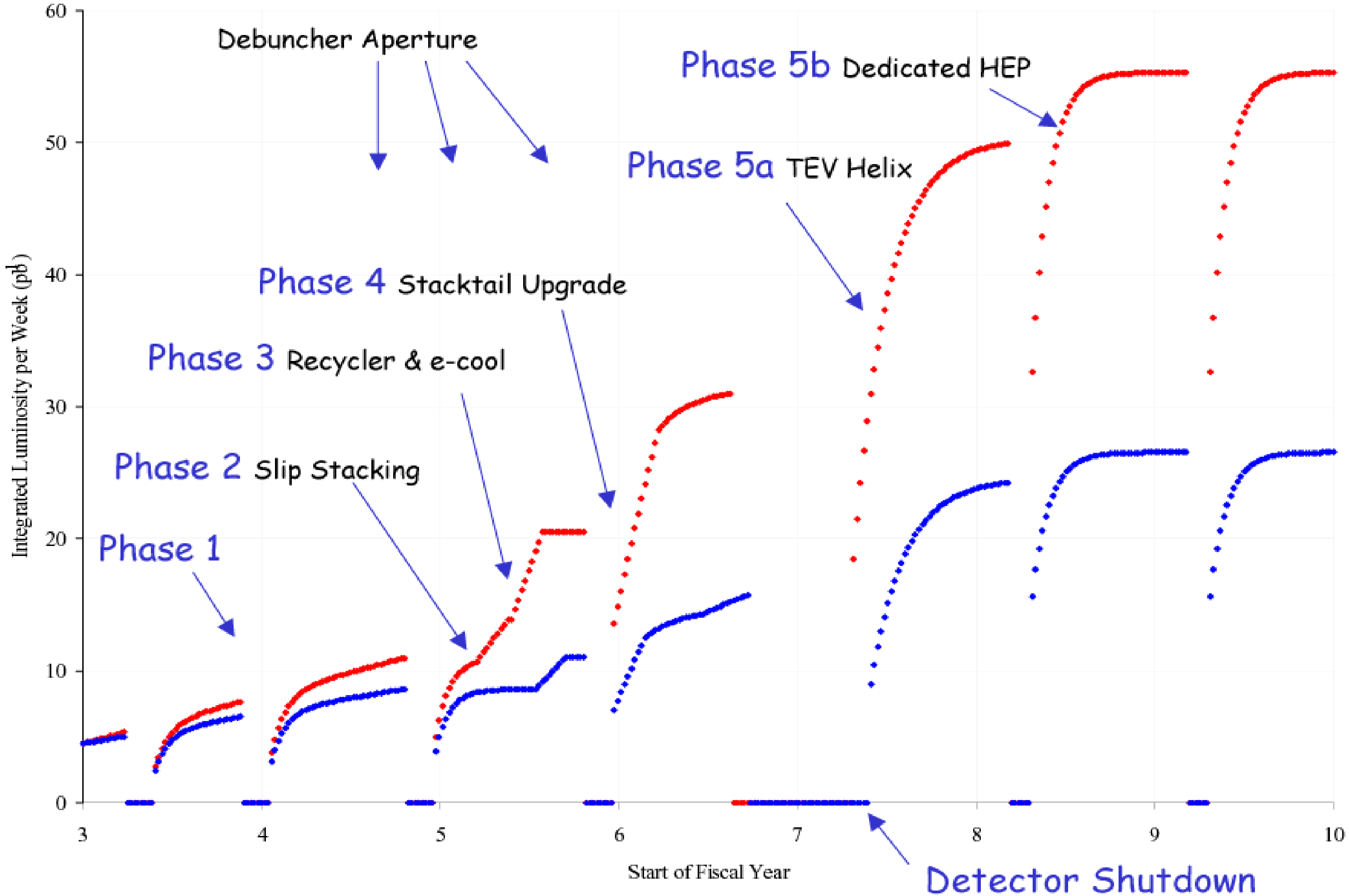
- uses the design performance parameters for the upgrade projects (additional margin is included in subproject specs)
- assumes improvement in the HEP store hours only in the last phase of the upgrades
- does not include schedule contingency

### Base Projection

- uses conservative performance parameters that the subprojects are likely to exceed
- does not assume improvements in HEP store hours per week
- includes 6 months schedule slip for bringing upgrades online

# RunII Weekly Luminosity

## Weekly Luminosity and Phases



# Run II Physics Program

## Run II Physics Program

**15 $fb^{-1}$**

- $5\sigma$ Higgs signal @ $m_H$ = 115 GeV
- $3\sigma$ Higgs signal @ $m_H$ = 115-135, 150-175 GeV
- Reach ultimate precision for top, W, B physics

**10 $fb^{-1}$**

- $3\sigma$ Higgs signal @ $m_H$ = 115-125, 155-170 GeV
- Exclude Higgs over whole range of 115-180 GeV
- Possible discovery of supersymmetry in a larger fraction of parameter space

**5 $fb^{-1}$**

- $3\sigma$ Higgs signal @ $m_H$ = 115 GeV
- Exclude SM Higgs 115-130, 155-170 GeV
- Exclude much of SUSY Higgs parameter space
- Possible discovery of supersymmetry in a significant fraction of minimal SUSY parameter space (the source of cosmic dark matter?)

**2 $fb^{-1}$**

- Measure top mass ± 3 GeV and W mass ± 25 MeV
- Directly exclude $m_H$ = 115 GeV
- Significant SUSY and SUSY Higgs searches
- Probe extra dimensions at the 2 TeV ($10^{-19}$ m) scale
- B physics: constrain the CKM matrix

**300 $pb^{-1}$**

- Improved top mass measurement
- High $p_T$ jets constrain proton structure
- Start to explore $B_s$ mixing and B physics
- SUSY Higgs search @ large tan $\beta$
- Searches beyond Run I sensitivity

*Each gain in luminosity yields a significant increase in reach and lays the foundation for the next steps*