Precision *B* Lifetimes and *B* Mixing in CDF

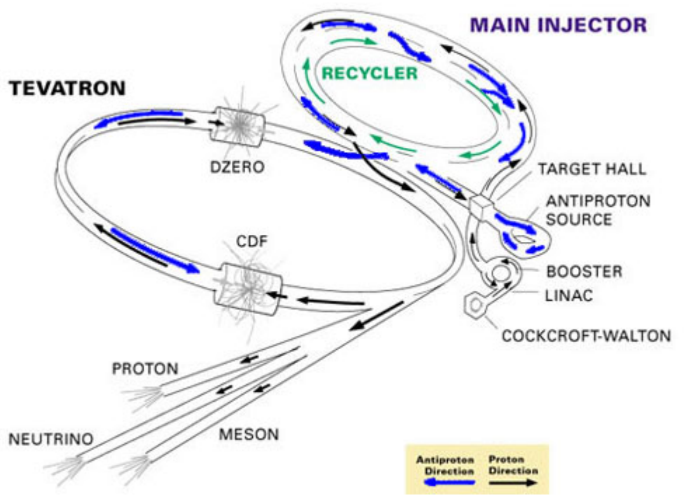
- Precision *B* Lifetimes
  - $B^+ \to J/\psi\ K^+$
  - $B_d \to J/\psi\ K^{*0}$
  - $B_s \to J/\psi\ \phi$
  - $\Lambda_B \to J/\psi\ \Lambda$
- Measurement of Polarization Amplitudes
  - $B_d \to J/\psi\ K^{*0}$
  - $B_s \to J/\psi\ \phi$
- *B* Mixing
  - *B* Flavor Tagging using Opposite Side *SMT* and *JQT*
  - Δm_d using *SST* in Fully Reconstructed *B* Decays
  - Δm_d using *SST* in Semileptonic *B* Decays
  - Δm_s Measurement Prospects

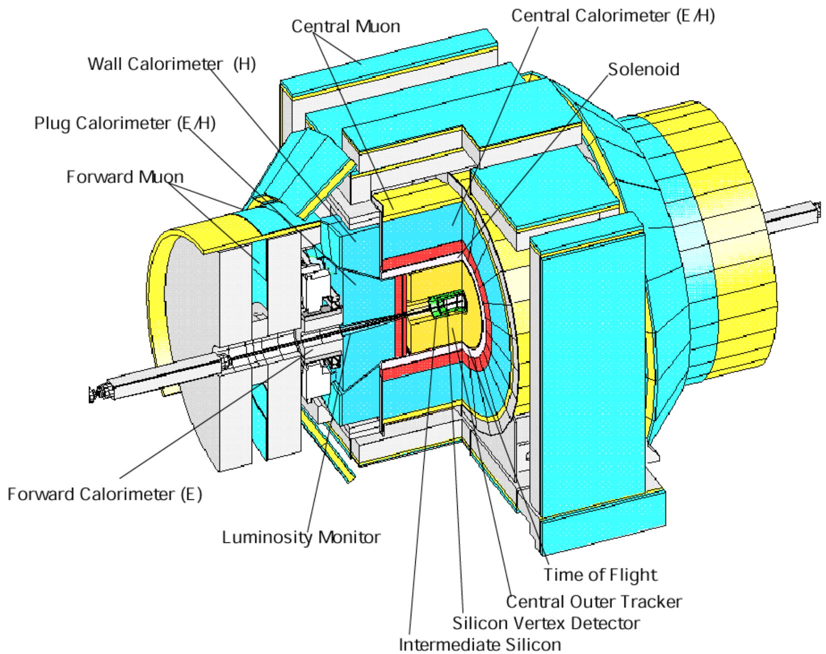
Jónatan Piedra, June 28 2004

6th International Conference on Hyperons, Charm and Beauty Hadrons

Tevatron & CDF

- 980 + 980 GeV $p\bar{p}$ collisions
- Record peak luminosity 9 x 10^{31} sec^{-1} cm^{-2}
- ~450 pb^{-1} on tape (Run I ≈ 100 pb^{-1})
- Interaction region
  - 30 cm z ⇒ need a long Si detector
  - 30 μm xy << cτ(B) ~ 450 μm



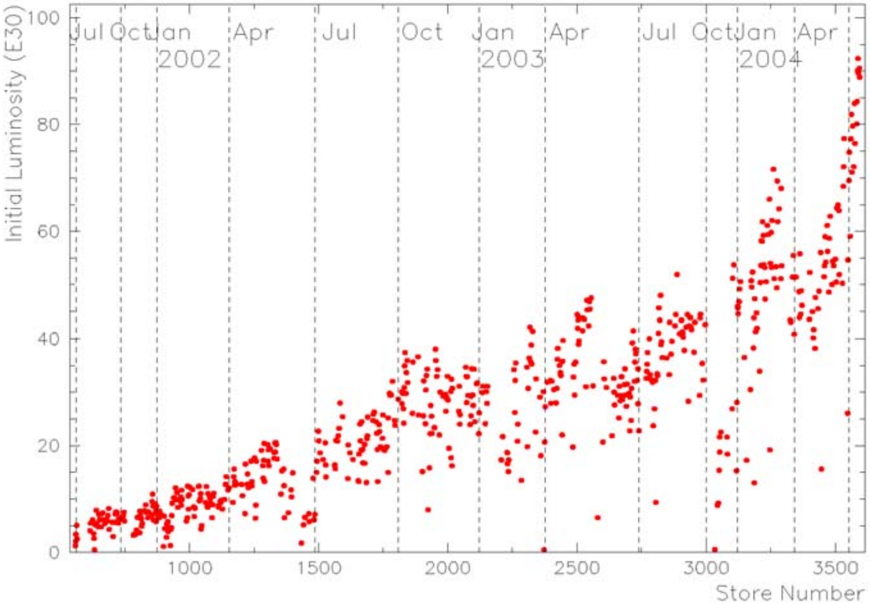


- Improved Silicon coverage
  - |η| < 2

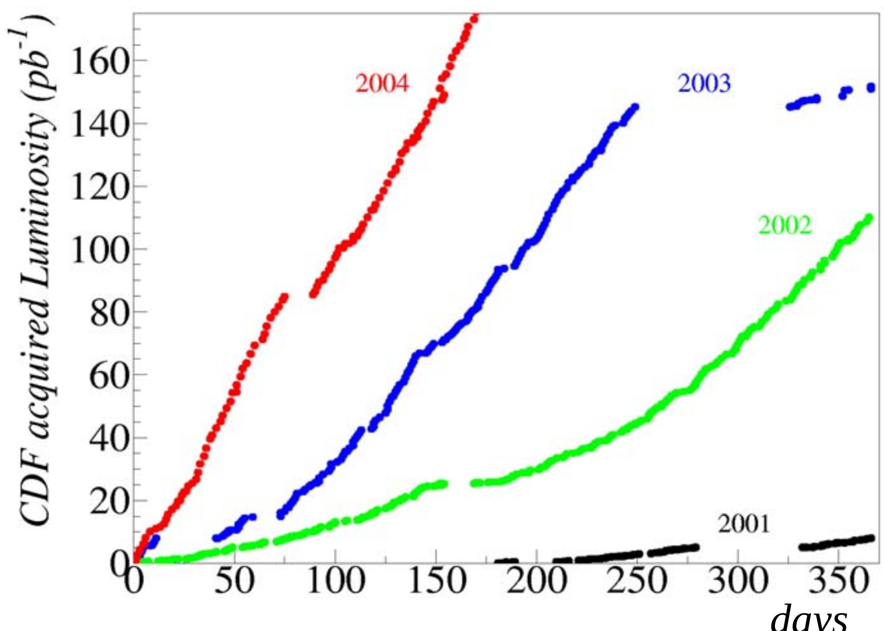
  EXCELLENT TRACKING
- Central Drift Chamber (COT)
  - 96 layers

  EXCELLENT TRACKING
- Time of Flight
- Expanded muon coverage
- Trigger on displaced tracks at L2

Tevatron & CDF Luminosity



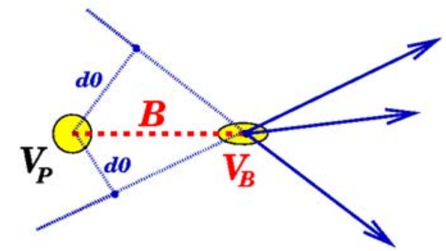
- Record peak luminosity
  $9.23 \times 10^{31}\ sec^{-1}\ cm^{-2}$
  June 22, 2004



- Acquired luminosity in 2004 already surpassed 2003 total
- But with high luminosity
  - Less trigger bandwidth for *B* Physics
  - Overlapping events degrade performance

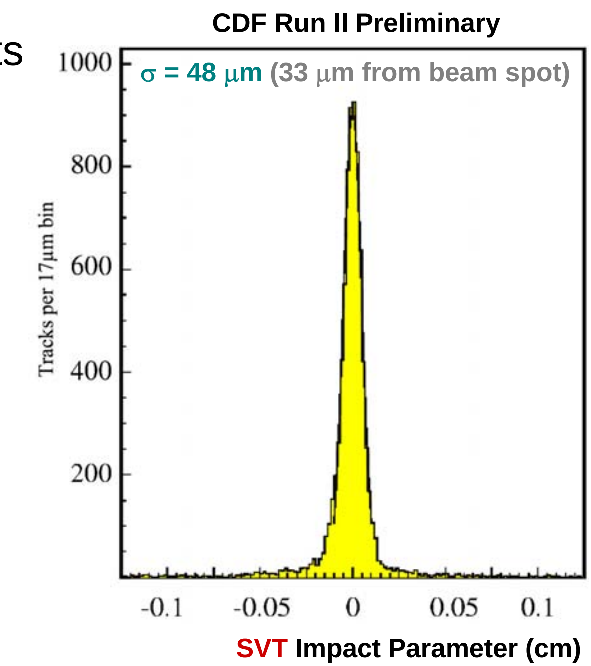
B Physics & *B* Triggers

- Huge production rates
  - $\sigma(p\bar{p} \rightarrow bX, |y| < 0.6) = 17.6 \pm 0.4$ (stat.) $\pm$ 2.5 (syst.) μb
- 3 orders of magnitude higher than at $e^+e^- \rightarrow \Upsilon(4S)$
- Heavy states produced
  - B^0, B^+, B_s, B_c, Λ_b, Ξ_b
- Backgrounds are also 3 orders of magnitude higher
  - Inelastic cross section ~100 mb
  - Challenge is to pick one *B* decay from ~10^3 QCD events



IT'S ALL ABOUT THE TRIGGER

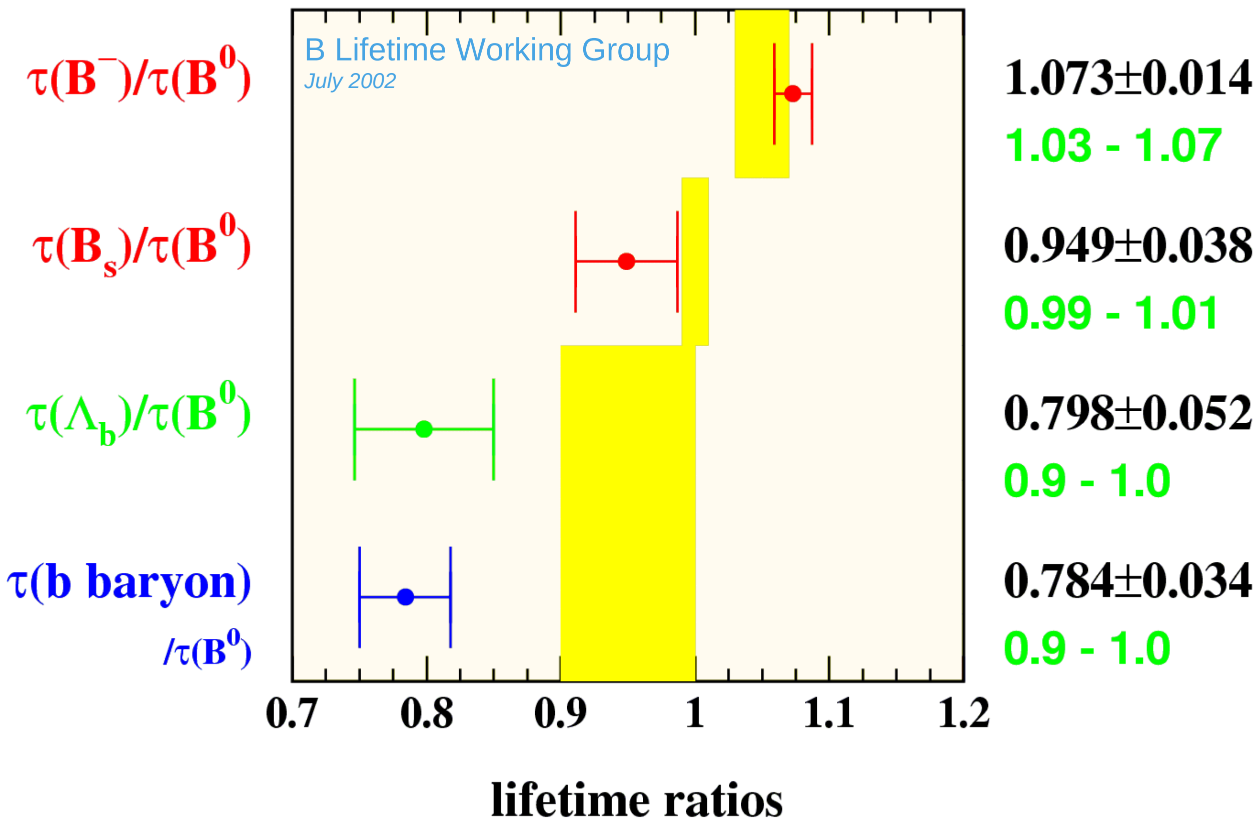
- Di-muon trigger
  - $p_T(\mu) > 1.5$ GeV/c
  - *B* yields 2x Run I (lowered p_T threshold, increased acceptance)
- Lepton + displaced-track trigger
  - $p_T(\mu,e) > 4$ GeV/c, $120\ \mu m < d_0 < 1$ mm, $p_T > 2$ GeV/c
  - *B* yields 3x Run I
- Two displaced-tracks trigger
  - $p_T > 2$ GeV/c, $120\ \mu m < d_0 < 1$ mm, $\Sigma\ p_T > 5.5$ GeV/c



HADRONIC MODE SENSITIVITY INCREASED ~4 ORDERS OF MAGNITUDE WRT RUN I

Precision *B* Lifetimes

Motivation



- Test HQET measuring $\frac{\tau_{B^+}}{\tau_{B^0}}, \frac{\tau_{B_s}}{\tau_{B^0}}$
- Extract $\frac{\Delta\Gamma_{B_s}}{\Gamma_{B_s}}$ with *Polarization Amplitudes* ⇒ indirect Δm_s measurement

$$\frac{\Delta\Gamma_s^{\rm SM}}{\Delta m_s^{\rm SM}} \simeq \frac{5\pi}{6}\frac{m_b^2}{M_W^2\,\eta_B b_B S(m_t^2/M_W^2)}|F_S(z)|\frac{B_{B_s}^{S\prime}}{B_{B_s}}\left[1+\mathcal{O}\left(\frac{\Lambda_{QCD}}{m_b}\right)\right] = \left(3.7^{+0.8}_{-1.5}\right)\times 10^{-3}$$

FERMILAB-Pub-01, 197

Selection and Fit Method

Decay	$p_T(B)$ GeV/c²	$p_T(K/\phi)$ GeV/c²	$Pr(\chi^2)$	K/ϕ mass MeV/c²	B mass MeV/c²
$B^+ \to J/\psi\, K^+$	> 5.5	> 1.6	> 10^{-3}	–	5170 – 5390
$B_d \to J/\psi\, K^{*0}$	> 6.0	> 2.6	> 10^{-4}	$M_{PDG}(K^{*0}) \pm 50.0$	5170 – 5390
$B_s \to J/\psi\, \phi$	> 5.0	> 1.5	> 10^{-5}	$M_{PDG}(\phi) \pm 6.5$	5220 – 5520

- Fraction of signal events in the sample *1 parameter*
- Mass *3 parameters*

$$\mathrm{Gaus}(m)+\mathrm{Pol}_1(m)$$

gaussian signal | linear background

- Proper decay length *8 parameters*

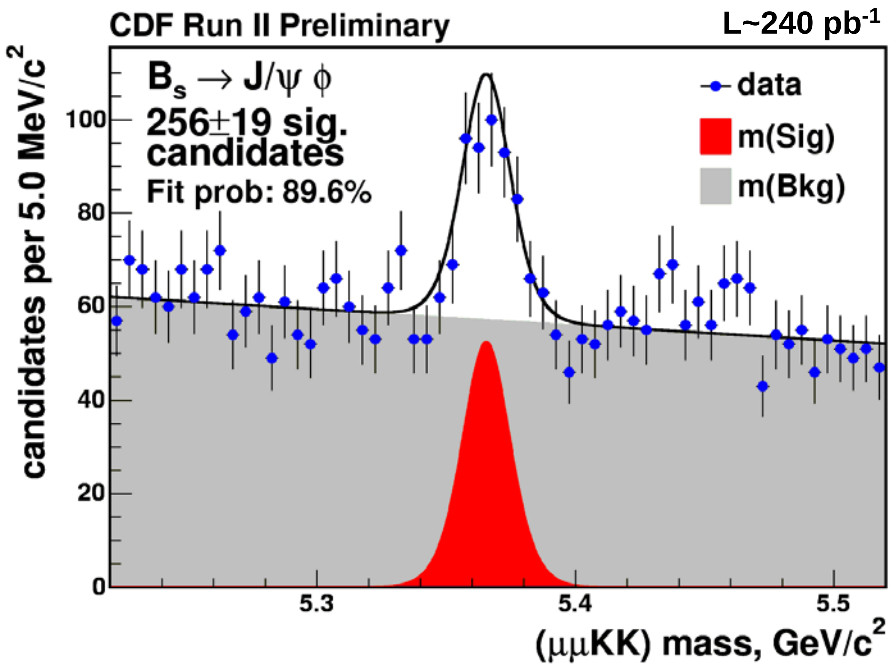
$$\delta\otimes\mathrm{Gaus}(ct)+\sum_n \mathrm{Exp}_n\otimes\mathrm{Gaus}(ct)$$

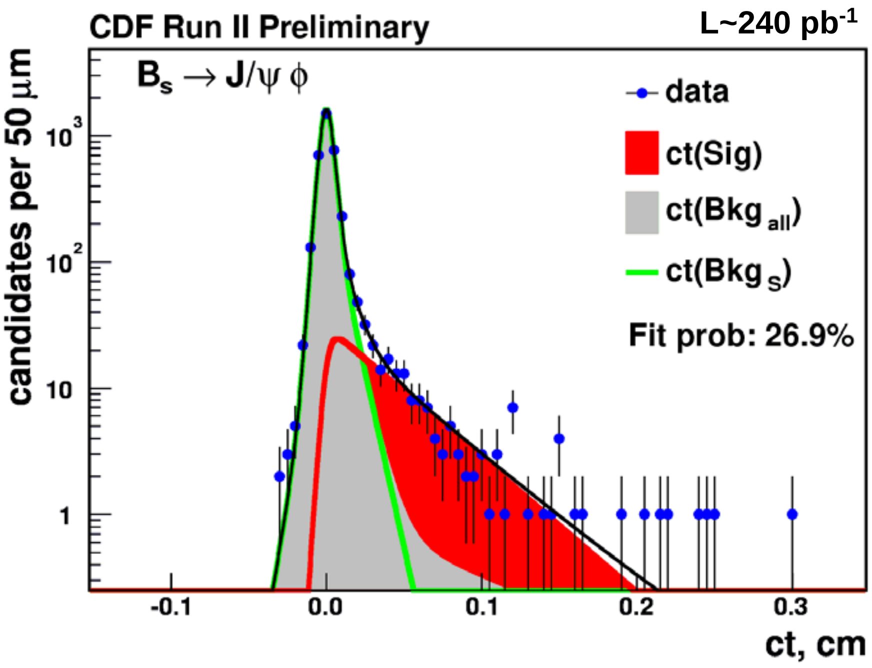
prompt J/ψ background | +lived signal | 3 background tails

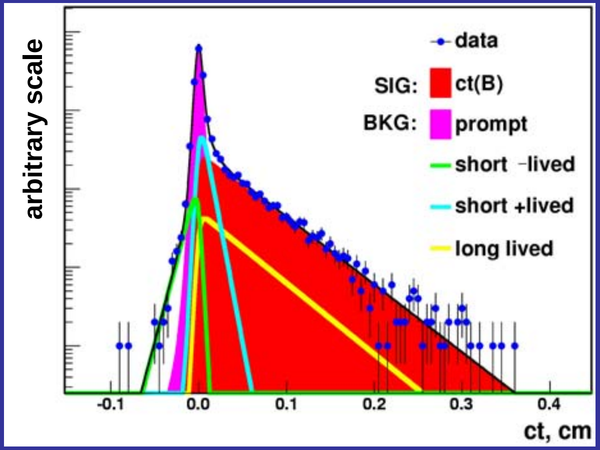
- Unbinned maximum likelihood *1+3+8 = 12 parameters*

$$\mathcal{L} = -2\log\prod_i f(m_i, \sigma_{m_i}, ct_i, \sigma_{ct_i} | \overrightarrow{\mathrm{parameters}})$$

Precision B Lifetimes B_s Projections







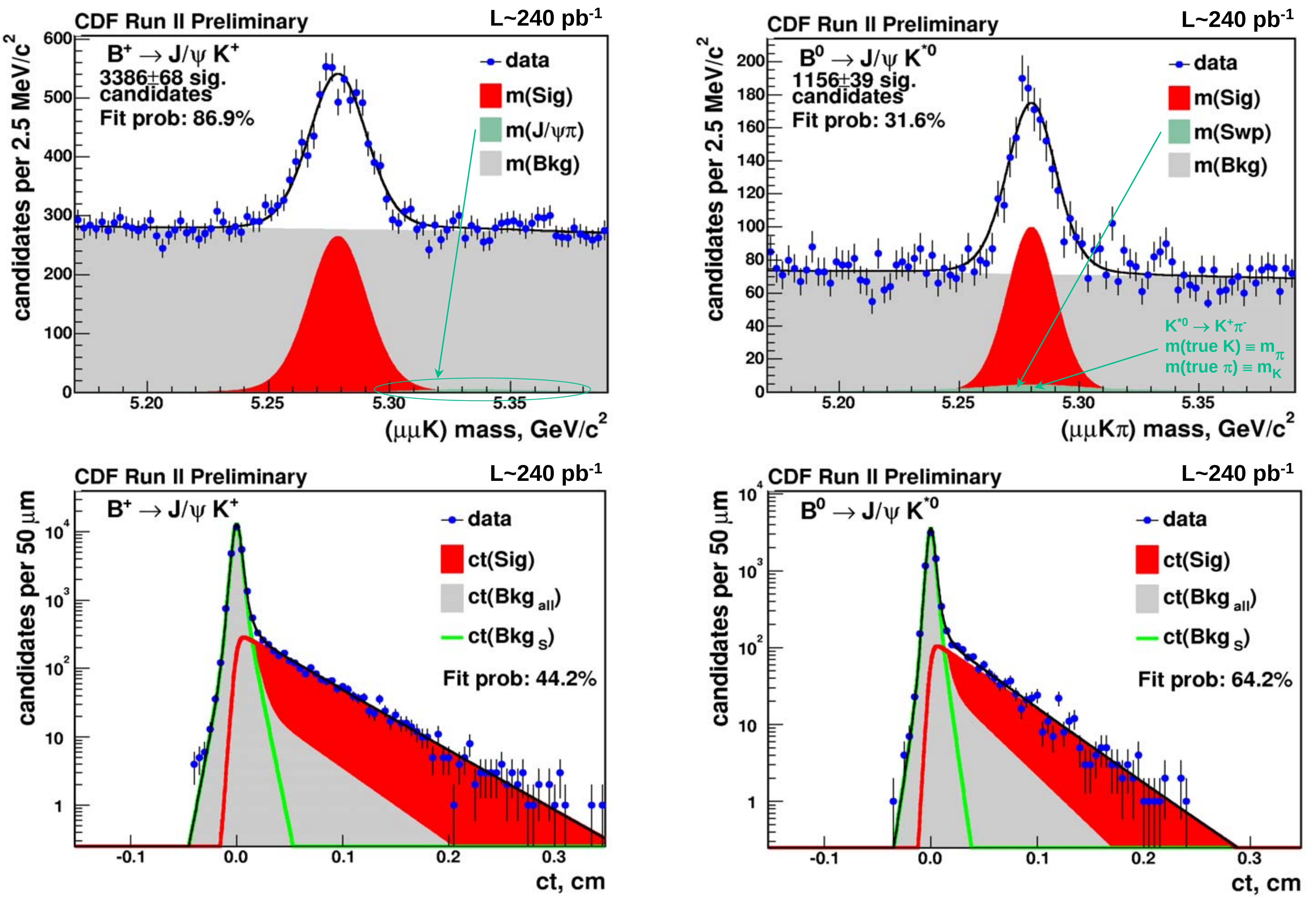
long lived

- Displaced J/ψ (~15%) paired with (random) track
- $b \to c \to s$
- Remaining reflections and partially reconstructed *B*

short lived

- Combinations with mis-measured tracks (± *lived*)
- Prompt J/ψ (~85%) paired with (slightly) displaced track (+ *lived*)

B^+ and B^0 Projections



Results

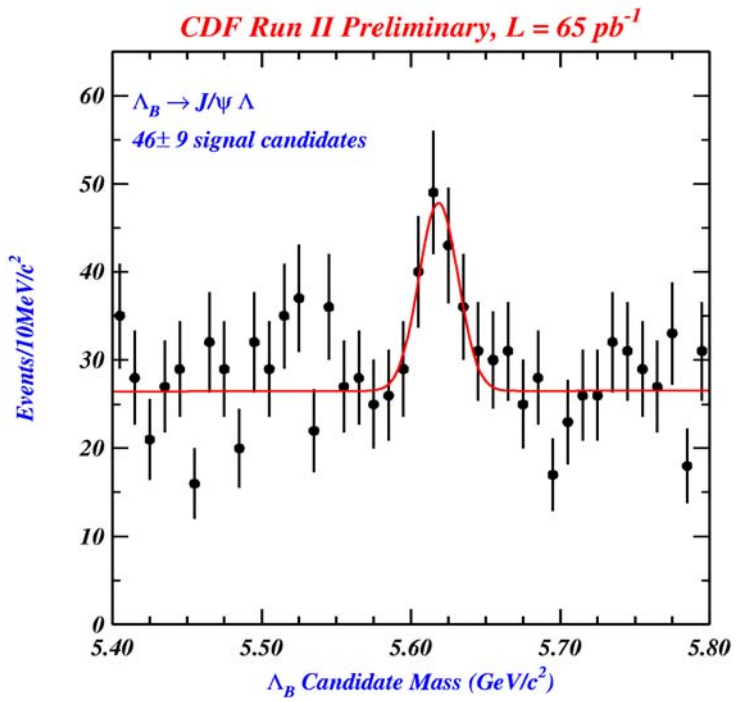
$$c\tau_{B^+} = 498.1 \pm 9.9\,(stat.) \pm 2.4(syst.)\ \mu m$$
$$c\tau_{B^0} = 461.3 \pm 15.4\,(stat.) \pm 2.4(syst.)\ \mu m$$
$$c\tau_{B_s} = 410.4 \pm 30.0\,(stat.)^{+2.4}_{-2.9}(syst.)\ \mu m$$

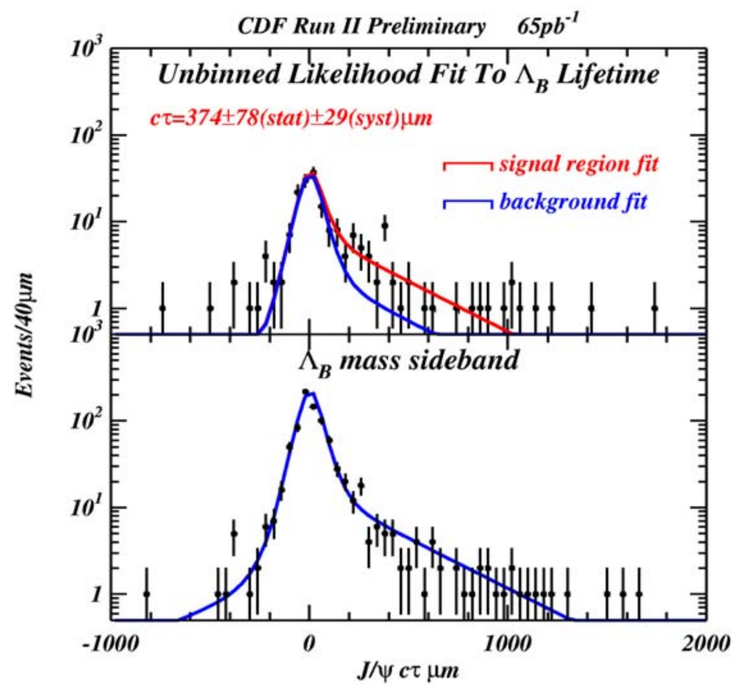
	This	PDG'03	Single best
B^+	$1.662 \pm 0.033 \pm 0.008$	1.671 ± 0.018	$1.695 \pm 0.026 \pm 0.015$
B^0	$1.539 \pm 0.051 \pm 0.008$	1.537 ± 0.015	$1.529 \pm 0.012 \pm 0.029$
B_s	$1.369 \pm 0.100^{+0.008}_{-0.010}$	1.461 ± 0.057	$1.36 \pm 0.09^{+0.06}_{-0.05}$

$$\tau_{B^+}/\tau_{B^0} = 1.080 \pm 0.042(tot.)$$
$$\tau_{B_s}/\tau_{B^0} = 0.890 \pm 0.072(tot.)$$

Precision B Lifetimes $\Lambda_B \to J/\psi\ \Lambda$ $J/\psi \to \mu^+ \mu^-$, $\Lambda \to p^+ \pi^-$

- First measurement of $\tau(\Lambda_B)$ in a fully reconstructed mode
  $\Lambda_B \to \Lambda_c l\nu$ ($\Lambda_c \to pK\pi$) $\tau = 1.33 \pm 0.15 \pm 0.07$ ps CDF Run I





- World average[2002] for $\tau(\Lambda_B)/\tau(B^0)$ is 0.798 ± 0.052
- Theory predicts 0.9 – 1.0
- Nowadays **only Tevatron produces Λ_B**

$c\tau(\Lambda_B) = 374 \pm 78$ (stat.) ± 29 (syst.) μm

$\tau(\Lambda_B) = 1.25 \pm 0.26$ (stat.) ± 0.10 (syst.) ps

$\tau(\Lambda_B$ PDG 2002) = 1.23 ± 0.08 ps

Polarization Amplitudes

Polarization Amplitudes Motivation

- $B_{d(s)} \rightarrow J/\psi\ K^{*0}(\phi)$ Pseudoscalar $\rightarrow$ Vector – Vector

- Decay amplitude decomposed into 3 linear polarization states
  - $|A_0|^2 + |A_{||}|^2 + |A_\perp|^2 = 1$
  - A_0 = S + D wave $\Rightarrow$ P even
  - $A_{||}$ = S + D wave $\Rightarrow$ P even
  - $A_\perp$ = P wave $\Rightarrow$ P odd

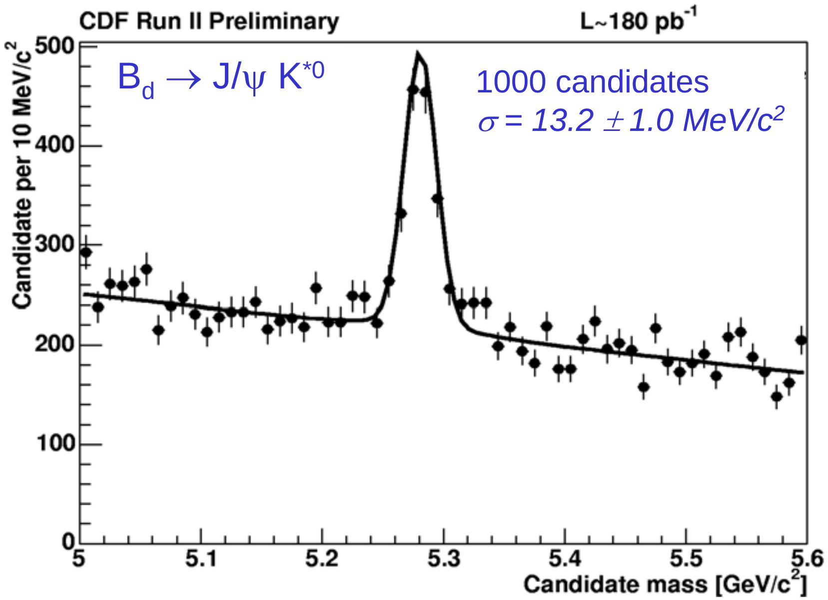
- The mass eigenstates $B_{s,H}$ and $B_{s,L}$ have $\frac{\Delta\Gamma_s}{\Gamma_s} = 0.07^{+0.09}_{-0.07}$ $(< 0.29\ \ 95\%\ \mathrm{CL})$

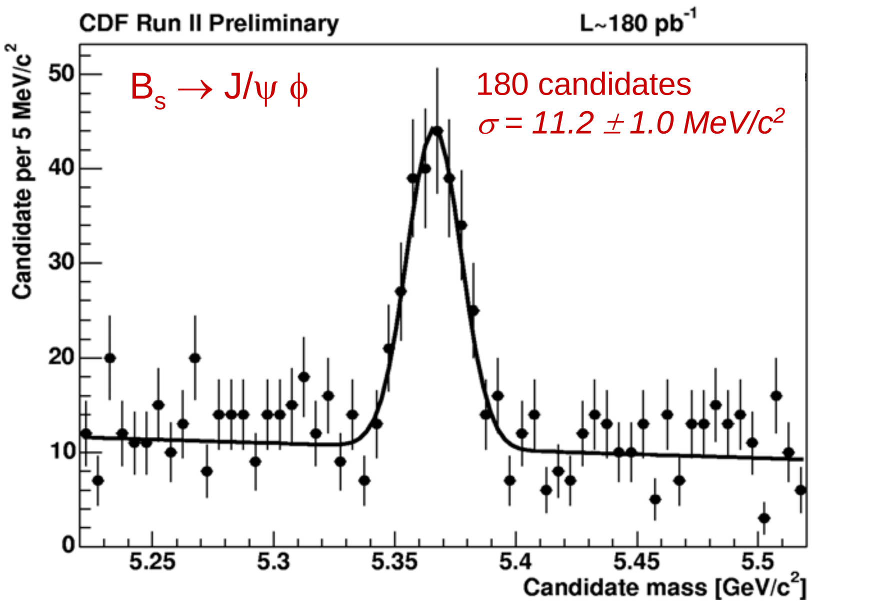
WORLD AVERAGE WITH $\tau(B_s) \equiv \tau(B_d)$ CONSTRAINT

- If CP violation neglected
  - $B_{s,Light} \approx$ CP even
  - $B_{s,Heavy} \approx$ CP odd
  - Angular distributions are different

- Together with lifetime measurement, angular analysis can separate both states and determine $\Delta\Gamma_s$

Event Reconstruction





- $|M_{J/\psi} - 3096.87_{(PDG)}| < 80$ MeV
- $|M_{\phi} - 1019.46_{(PDG)}| < 15$ MeV
- $|M_{K^{*0}} - 896_{(PDG)}| < 80$ MeV
- $c\tau(B) > 0$

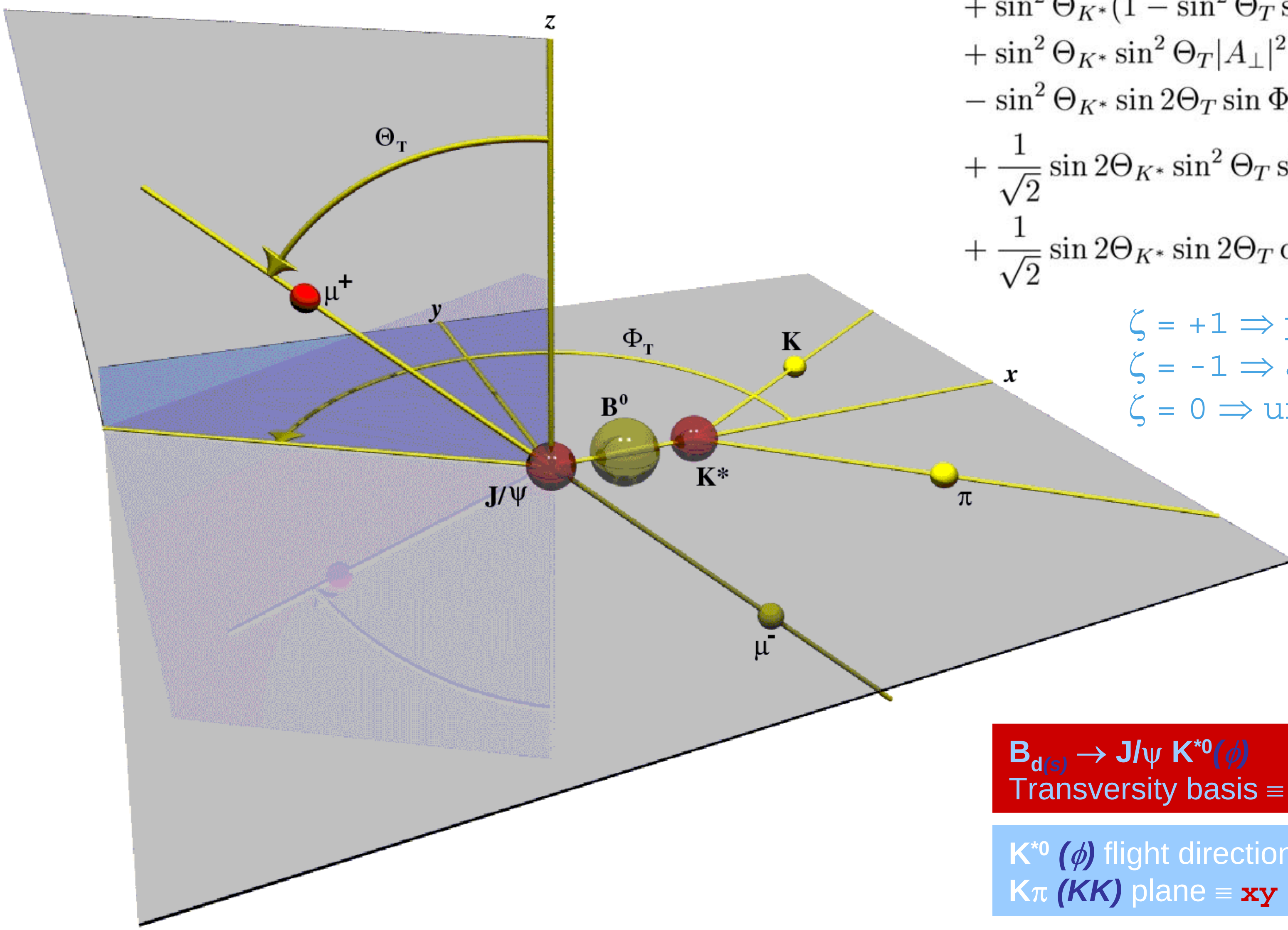
Transversity Basis

$$\mathcal{G} = \frac{9}{32\pi}\Big\{2\cos^2\Theta_{K^*}(1-\sin^2\Theta_T\cos^2\Phi_T)|A_0|^2 + \sin^2\Theta_{K^*}(1-\sin^2\Theta_T\sin^2\Phi_T)|A_{||}|^2 + \sin^2\Theta_{K^*}\sin^2\Theta_T|A_\perp|^2 - \sin^2\Theta_{K^*}\sin 2\Theta_T\sin\Phi_T Im(A_{||}^*A_\perp)\zeta + \frac{1}{\sqrt{2}}\sin 2\Theta_{K^*}\sin^2\Theta_T\sin 2\Phi_T Re(A_0^*A_{||}) + \frac{1}{\sqrt{2}}\sin 2\Theta_{K^*}\sin 2\Theta_T\cos\Phi_T Im(A_0^*A_\perp)\zeta\Big\}$$

ζ = +1 ⇒ particle

ζ = -1 ⇒ antiparticle

ζ = 0 ⇒ untagged B_s



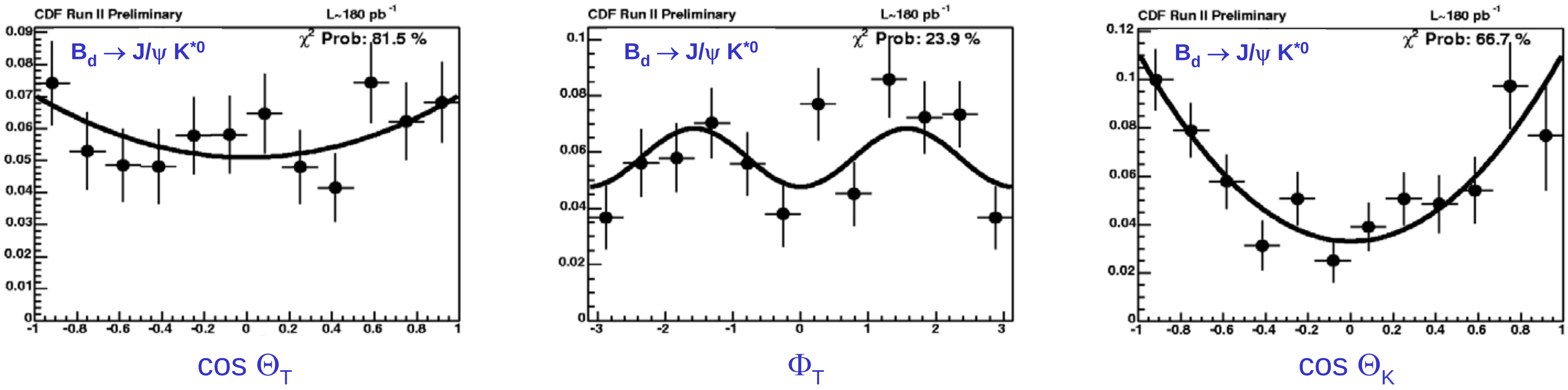
$B_{d(s)} \rightarrow J/\psi\ K^{*0}(\phi)$

Transversity basis ≡ J/ψ rest frame

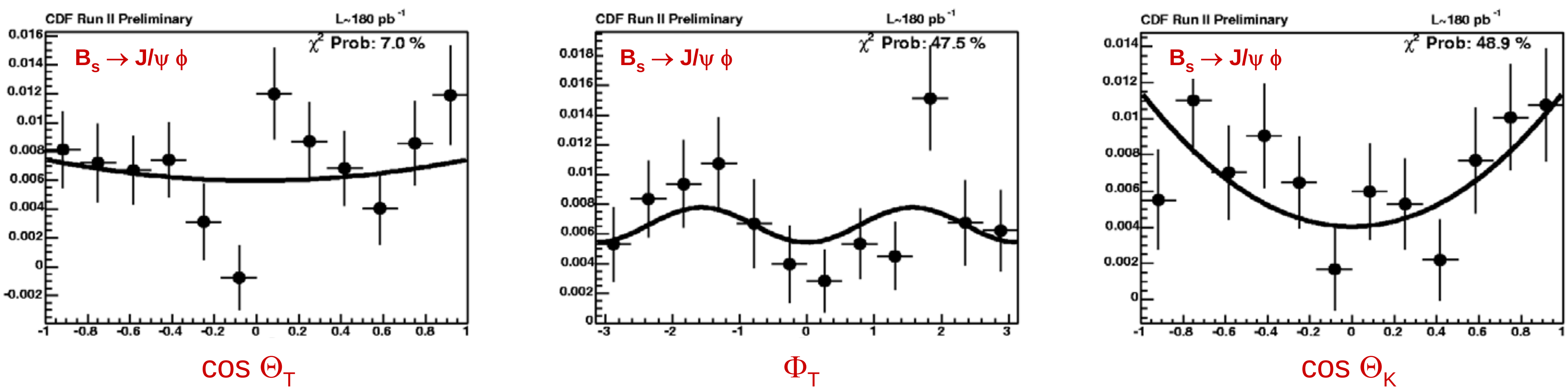
K^{*0} (ϕ) flight direction ≡ positive **x**

Kπ (KK) plane ≡ **xy** plane

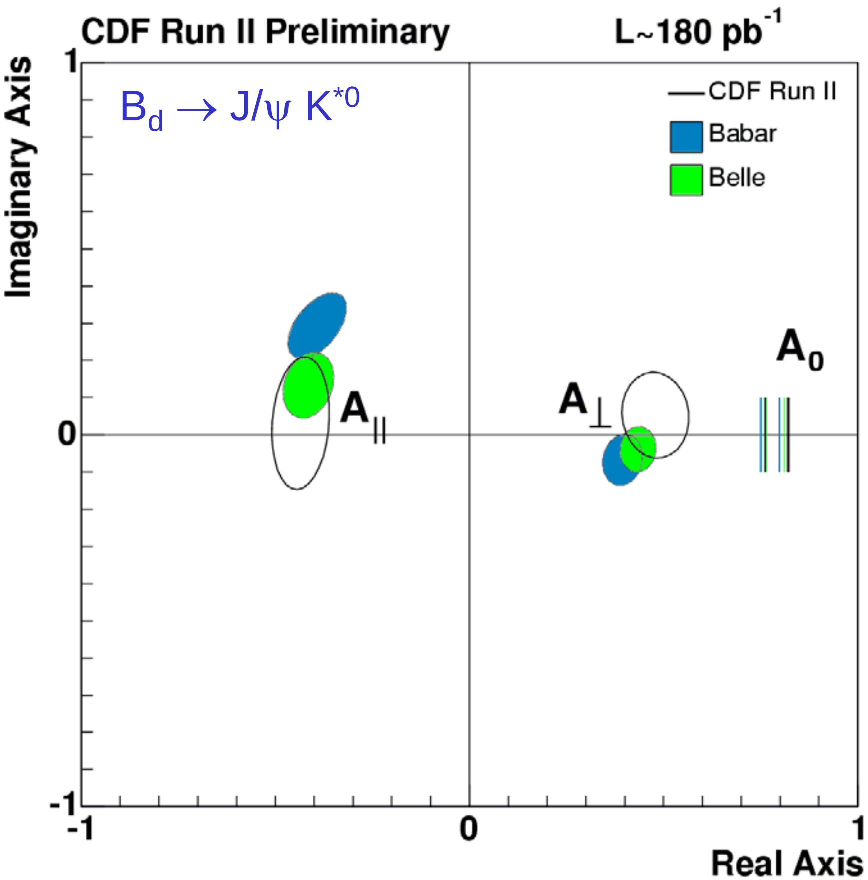
Polarization Amplitudes Angular Projections



sideband subtracted distributions



Polarization Amplitudes Results



$A_0 = 0.792 \pm 0.024 \pm 0.016$

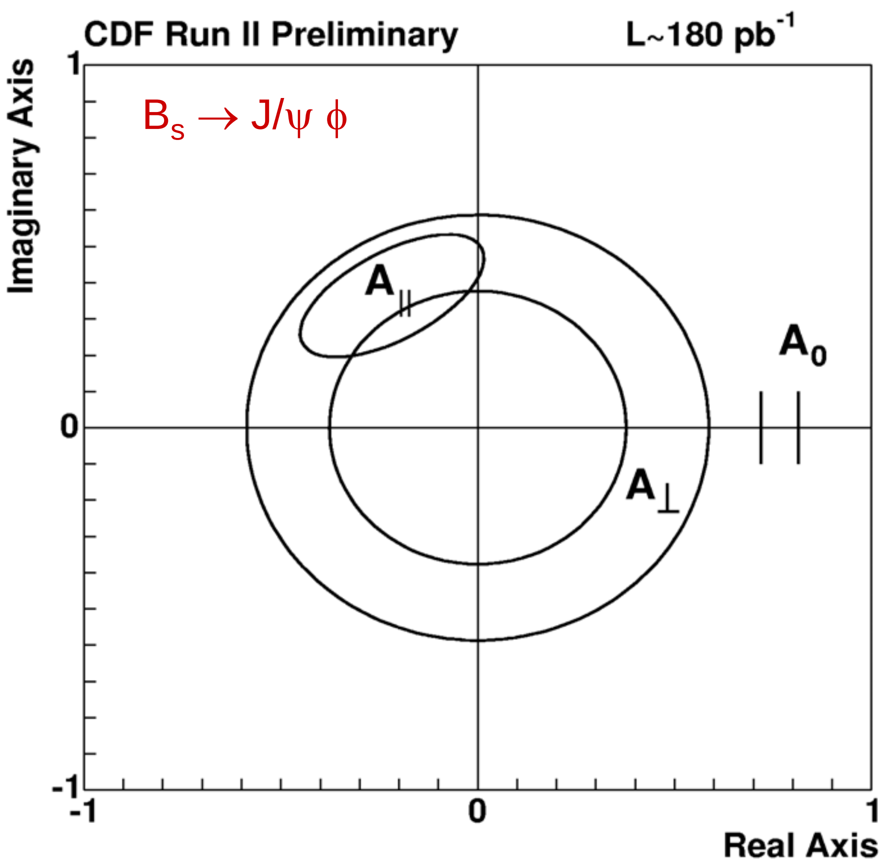
$A_{||} = (0.436 \pm 0.057 \pm 0.045)\, e^{(3.07 \pm 0.40 \pm 0.07)i}$

$A_{\perp} = (0.428 \pm 0.059 \pm 0.063)\, e^{(0.11 \pm 0.23 \pm 0.06)i}$

$A_0 = 0.767 \pm 0.045 \pm 0.017$

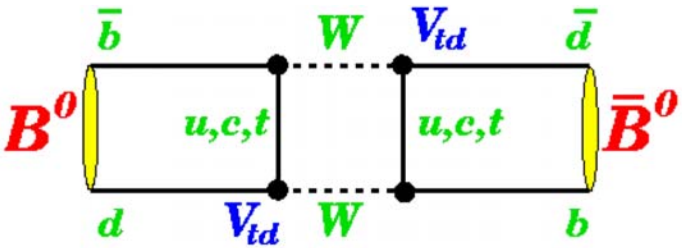
$A_{||} = (0.424 \pm 0.118 \pm 0.013)\, e^{(2.11 \pm 0.55 \pm 0.29)i}$

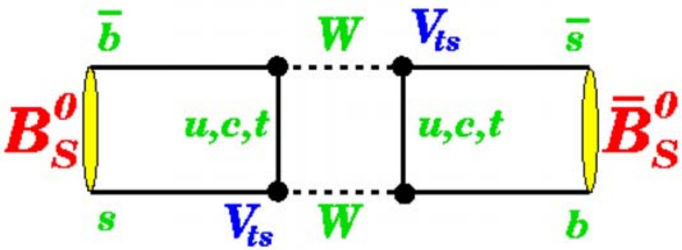
$|A_{\perp}| = 0.482 \pm 0.104 \pm 0.014$



B Mixing

B Mixing Motivation



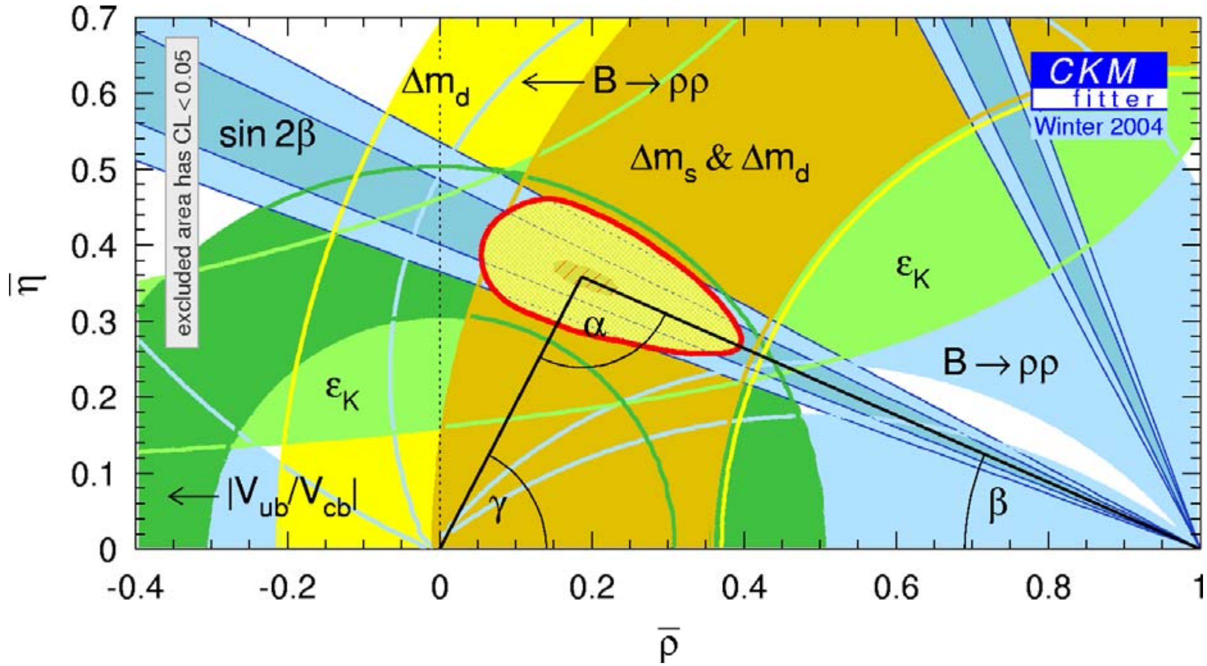


- B_d oscillations are sensitive to $|V_{td}|$
- Compromised by hadronic uncertainties
- Most cancel in B_d/B_s oscillation ratio

$$\frac{|V_{td}|}{|V_{ts}|} = 1.01\xi\sqrt{\frac{\Delta m_d}{\Delta m_s}}$$

from LATTICE

- New Physics may affect $\Delta m_s/\Delta m_d$
- Δm_s prerequisite for time-dependent B_s CP violation measurement



B_s Mixing Current Status

- Heavy Flavor Averaging Group

  LEP, SLD and CDF I combined

- Most analyses used partially reconstructed decays

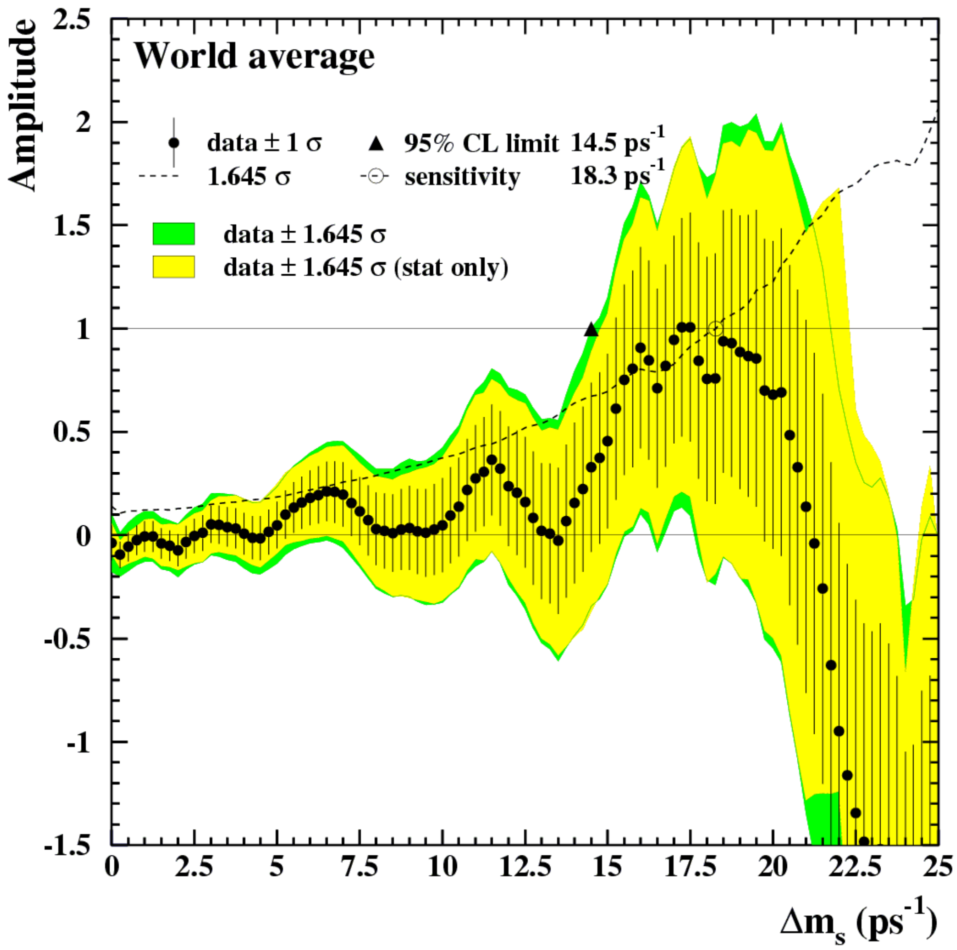
  Poor sensitivity at high Δm_s

$$\sigma(A) \propto e^{\frac{(\sigma_{ct}\Delta m_s)^2}{2}}$$

$$ct = \frac{L_{xy}}{\beta\gamma} = \frac{L_{xy} m^B}{p_T^B} \Rightarrow \sigma_{ct} = \frac{m^B}{p_T^B}\sigma_{L_{xy}} \oplus ct\left(\frac{\sigma_{p_T^B}}{p_T^B}\right)$$

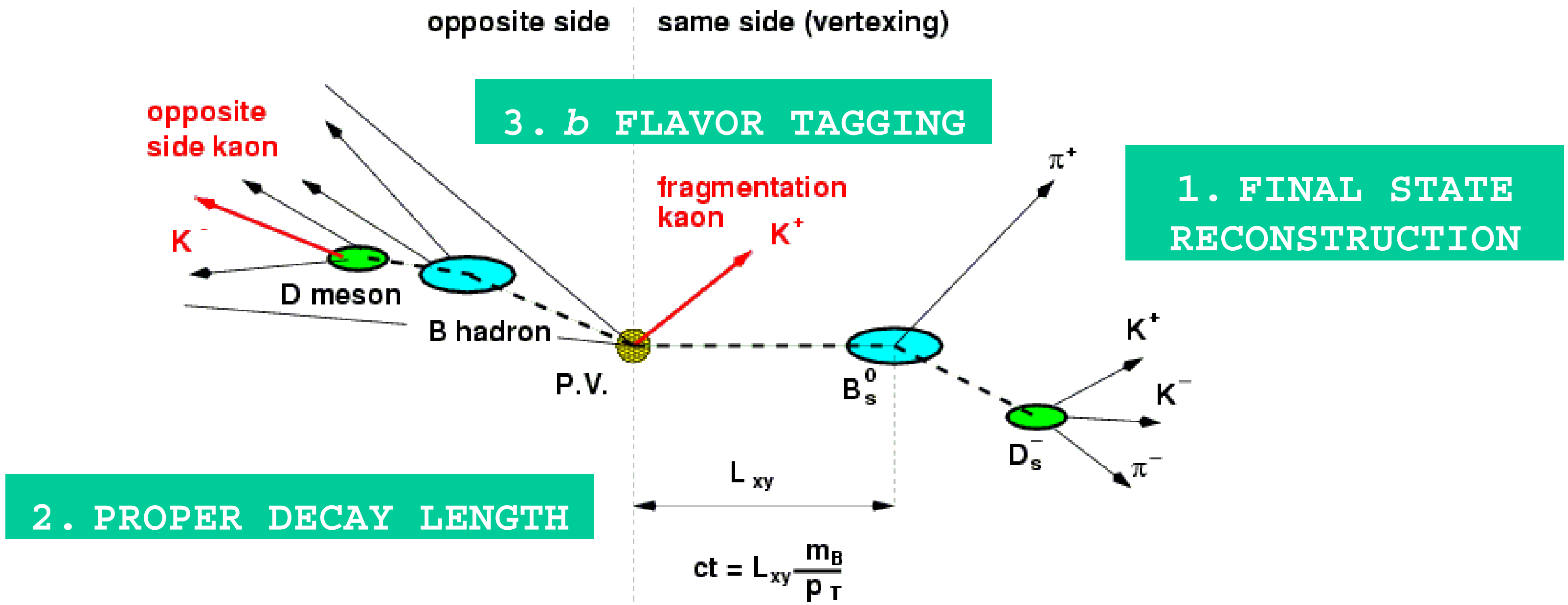
Semileptonic decays $\left(\frac{\sigma_{p_T^B}}{p_T^B}\right)_{CDF} \approx 15\%$

Hadronic decays $\left(\frac{\sigma_{p_T^B}}{p_T^B}\right)_{CDF} \approx 0.5\%$



$\Delta m_s > 14.5\ ps^{-1}$ 95% CL (more than 3 full oscillations per lifetime)
From CKM fit $\Delta m_s < 30\ ps^{-1}$ 95% CL

B Mixing Ingredients



- Efficiency $\varepsilon \equiv$ fraction of tagged events
- Dilution $D \equiv 2P - 1$ with P the correct answer probability
- Tagging effectiveness εD^2 shows statistical power of the tagger
- Flavor taggers can be topologically separated
  - Same-Side is sample dependent
  - Opposite-Side is based on properties of the non-reconstructed *b*

B Mixing Soft Muon & Jet Charge

- Find events with Opposite Side $B \to \mu X$
- Opposite Side μ charge gives Soft Muon Tagger **SMT** decision
- Qualities
  - High purity (OS μ almost always from $B \to \mu X$)
  - Low efficiency, BR($B \to \mu X$) ~ 10%
  - OS *B* mixing reduces performance
- Combined $\Sigma\varepsilon D^2$ for all subsamples

  based on muon subdetectors and p_T^{rel} bins

εD^2 = 0.660 ± 0.193 (stat.) %

- Find jet of the Opposite Side *b*
- Calculate weighted average Q of jet tracks
- Q_{jet} sign gives Jet Charge Tagger **JQT** decision
- Qualities
  - Moderate purity (Q_{jet} not 100% correlated with *b* flavor)
  - High efficiency (*b* in acceptance almost always gives a jet)
  - Non-*b* jets in the event complicate *b*-jet finding
- Combined $\Sigma\varepsilon D^2$ for all subsamples

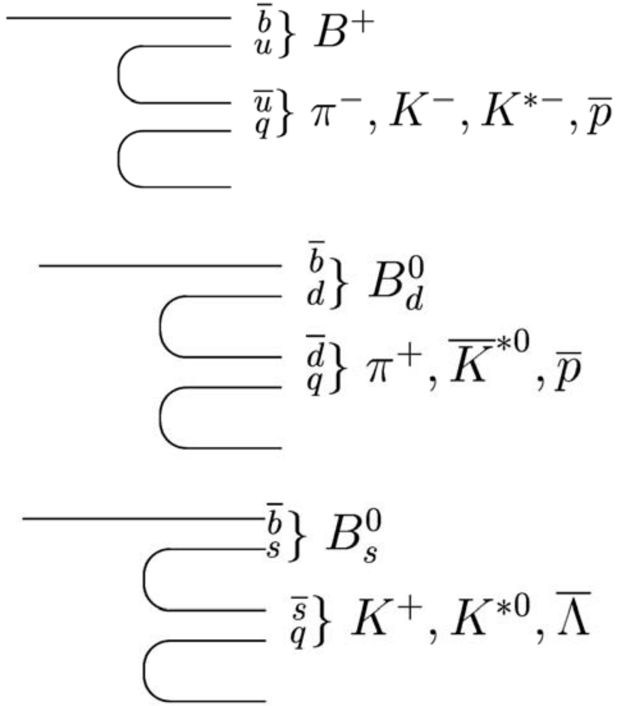
  with or without secondary vertex and Q_{jet} bins

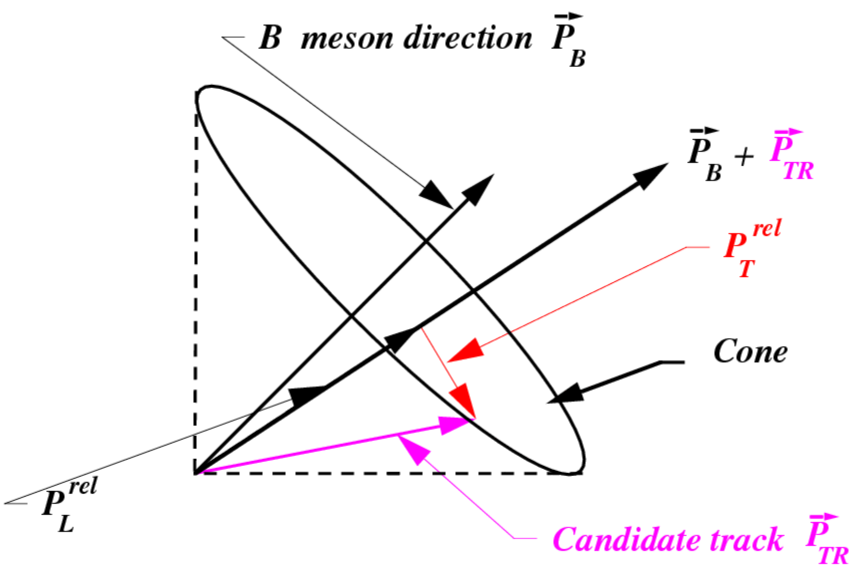
εD^2 = 0.415 ± 0.017 (stat.) %

✗ Run I JQT algorithm
✗ Not optimized

B Mixing Same Side Tagger Algorithm

- Look for the fragmentation track that is charge correlated with the produced *B*
- Divide data into 3 subsamples depending on tagger decision
  - Right-Sign events (unmixed), Wrong-Sign events (mixed) and Not-Tagged events





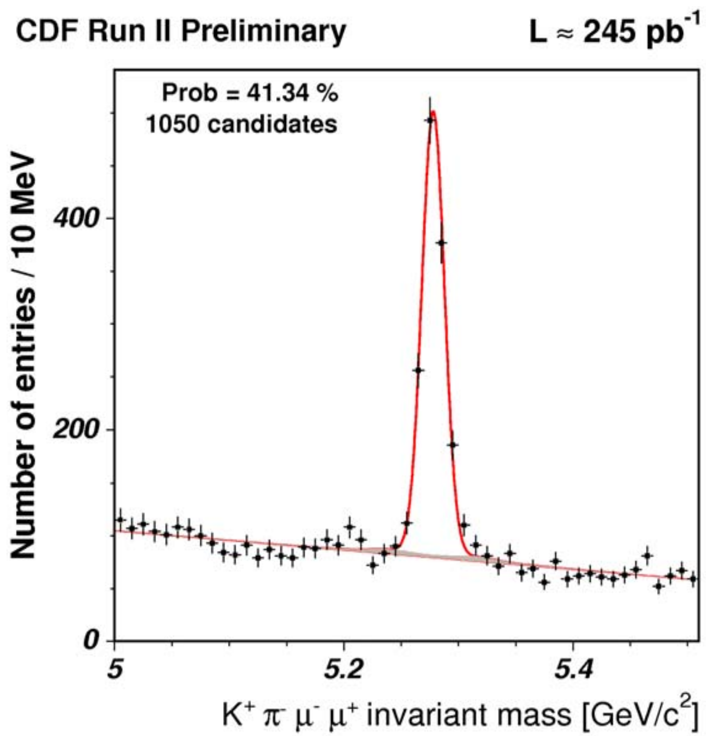
- Consider tracks close to the *B* meson

$$\Delta R(\text{track},B) = \sqrt{\Delta\eta^2 + \Delta\varphi^2} < 0.7$$

- Originating from primary vertex
- If multiple track candidates, select the one with minimum p_T^{rel}

Fully Reconstructed Decays

$B^0 \to J/\psi K^{*0},\ J/\psi \to \mu^+\mu^-,\ K^{*0} \to K^+\pi^-$



J/ψ

- $|M(J/\psi) - M_{PDG}| < 80$ MeV/c^2

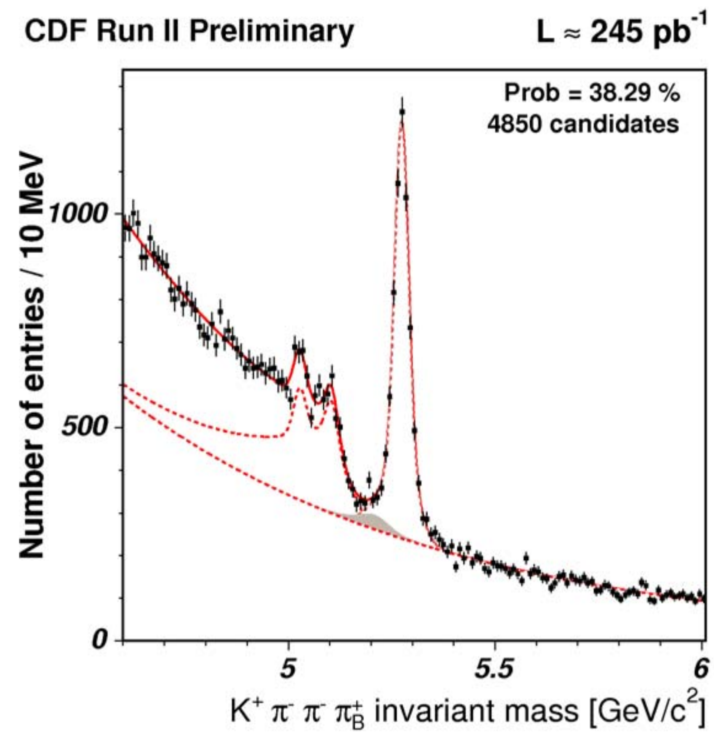
K^{*0}

- $|m(K^{*0}) – m_{PDG}| < 50$ MeV/c^2
- Reject events with >1 K^{*0} candidate

B

- Vertex probability > 0.1%
- $L_{xy} > 100$ μm

$B^0 \to D^-\pi_B^+,\ D^- \to K^+\pi^-\pi^-$



D

- $\chi^2_{\rho\phi} < 14$
- $\Delta R(D,\pi_B) < 1.5$

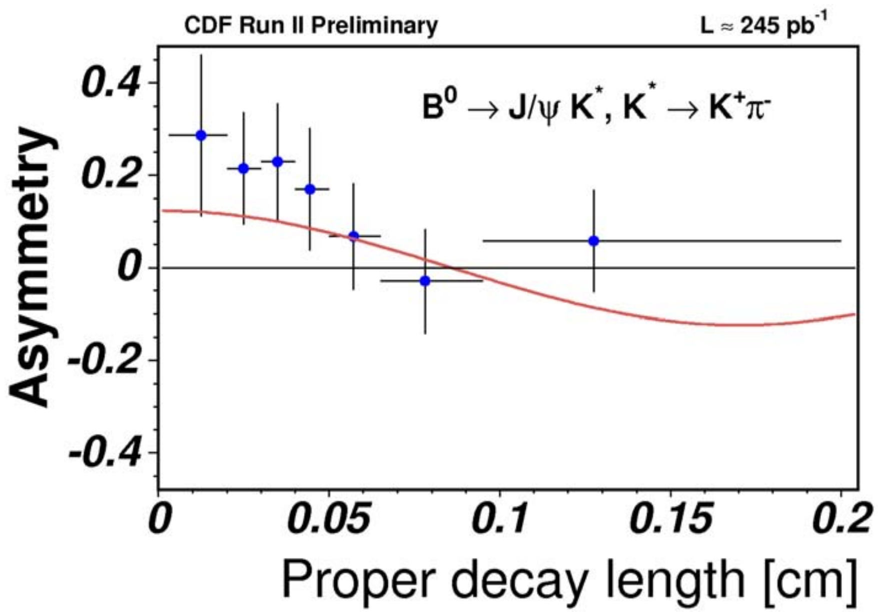
π_B

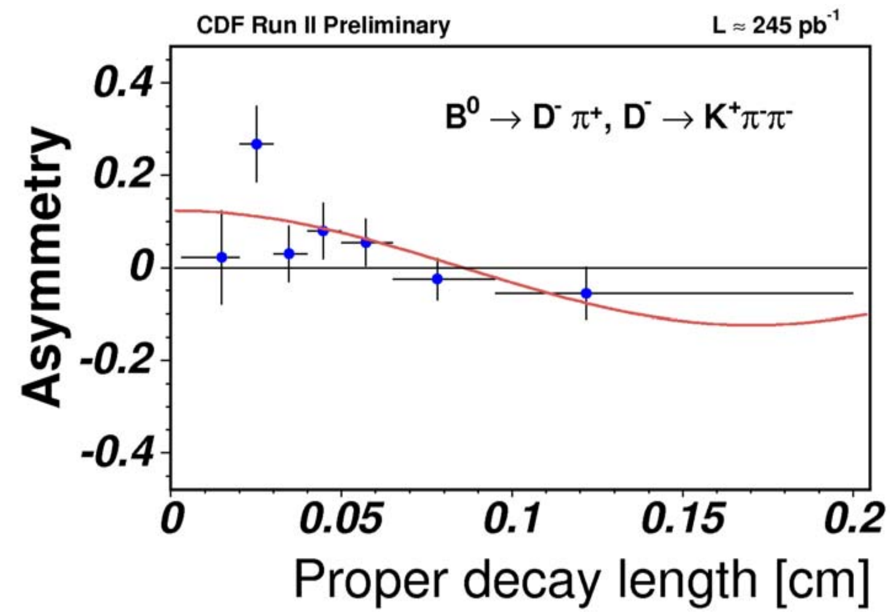
- $p_T > 1.6$ GeV/c

B

- $\chi^2_{r\phi} < 15$
- $L_{xy} > 300$ μm

Δm_d using SST in $B_d \to J/\psi K^{*0}$ ($D^-\pi^+$)





exact proper time

$$A^{meas}(t) = D\cos\Delta m_d t$$

⇒

detector finite resolution

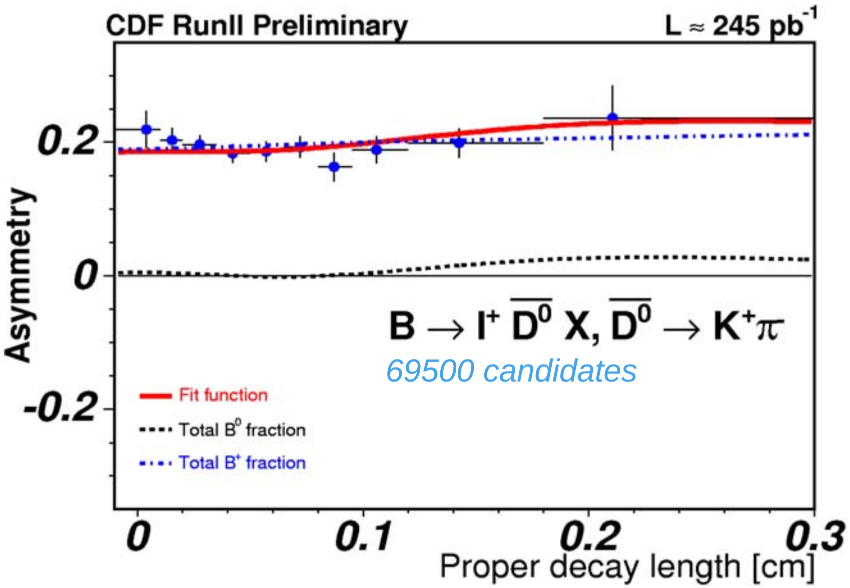
$$A^{meas}(t) = \frac{G(ct;ct',\sigma_{ct}) \otimes \left[e^{-t'/\tau} D\cos(\Delta m_d t)\right]}{G(ct;ct',\sigma_{ct}) \otimes e^{-t'/\tau}}$$

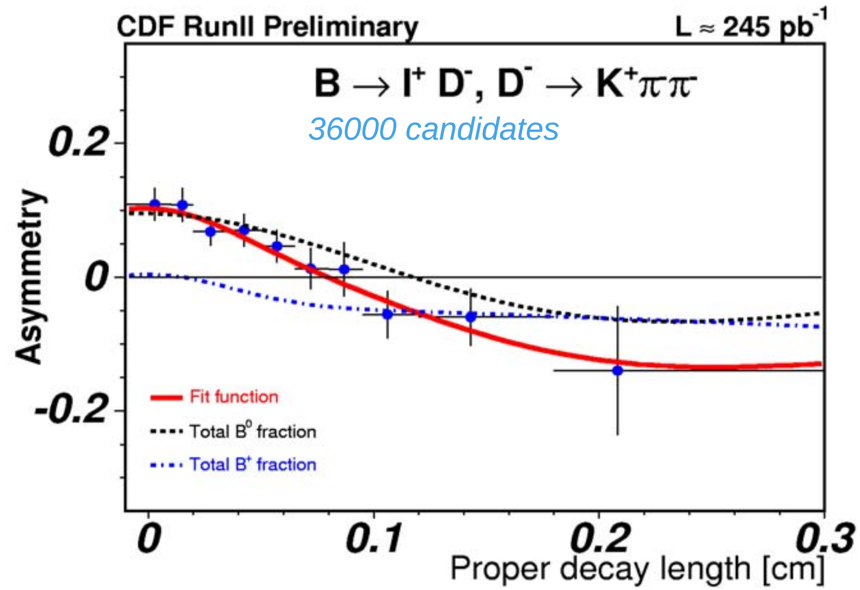
combined χ^2 fit

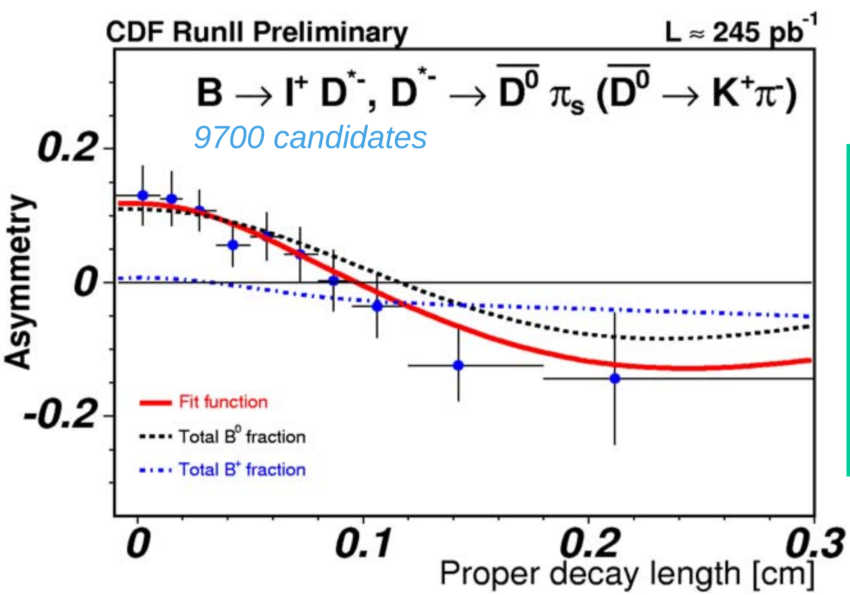
Δm_d = 0.55 ± 0.10 (stat.) ± 0.01 (syst.) ps^{-1}
D = 12.4 ± 3.3 (stat.) ± 1.2 (syst.) %
εD^2 = 1.0 ± 0.5 (stat.) ± 0.2 (syst.) %

- More decays soon
- Increased statistics
- SST not optimized

Δm_d using SST in $B_d \to lD^{(*)}$ Decays







Δm_d = 0.443 ± 0.052 (stat.) ± 0.030 (s.c.) ± 0.012 (syst.) ps^{-1}

D_0 = 12.8 ± 1.6 (stat.) ± 1.0 (s.c.) ± 0.6 (syst.) %

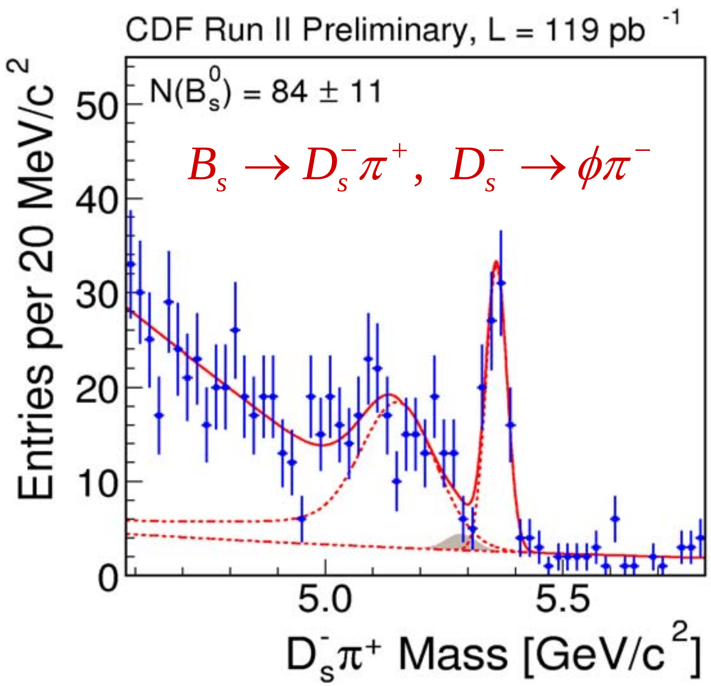
D_+ = 28.3 ± 1.3 (stat.) ± 1.1 (s.c.) ± 1.0 (syst.) %

$\varepsilon D^2(B^0)$ = 1.1 ± 0.3 (stat.) ± 0.2 (s.c.) ± 0.1 (syst.) %

Δm_s Measurement Prospects

- Requirements
  - Clean signals (S/B)
  - Vertexing resolution
  - Tagging effectiveness

- Modest improvements
  - Adding $D_s \to K^* K$, $D_s \to K_s K$ and $B_s \to D_s 3\pi$
  - L00 innermost silicon layer
    $\sigma_t = 67$ fs $\to \sigma_t = 50$ fs



- Short term 500 pb^{-1} *no improvement up to 2005*
  - 2σ (for $\Delta m_s = 15$ ps^{-1})
  - Reach the current limit
  - Cover the Standard Model favored range

- Beyond the SM favored range *conservative improvements up to 2008*
  - 5σ if $\Delta m_s = 18$ ps^{-1} with 1.8 fb^{-1}
  - 5σ if $\Delta m_s = 24$ ps^{-1} with 3.2 fb^{-1}

Conclusions

Precision B Lifetimes

- B^0, B^+, B_s competitive with PDG
- First time Λ_B lifetime is measured in a fully reconstructed decay

Polarization Amplitudes

- B_d amplitudes consistent with *B* factories
- Best B_s amplitude measurement
- $B_s \rightarrow J/\psi\ \phi$ mostly CP-even *$\Delta\Gamma_s$ measurement imminent*

B Mixing

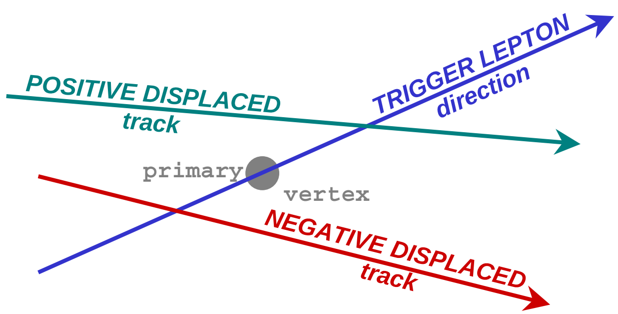
- First time Δm_d is measured based on the displaced-track trigger
- We are able to reproduce the B_d oscillation frequency
- B_s mixing
  - Reach current limit with 500 pb^{-1} *near future*


Calvin and HOBBES
WOW, IT REALLY SNOWED LAST NIGHT! ISN'T IT WONDERFUL?
EVERYTHING FAMILIAR HAS DISAPPEARED! THE WORLD LOOKS BRAND-NEW!
A NEW YEAR... A FRESH, CLEAN START!
IT'S LIKE HAVING A BIG WHITE SHEET OF PAPER TO DRAW ON!
A DAY FULL OF POSSIBILITIES!
IT'S A MAGICAL WORLD, HOBBES, OL' BUDDY...
...LET'S GO EXPLORING!

Back Up Slides

Semileptonic Sample

- Test arena for Soft Muon and Jet Charge
- Based on lepton + displaced-track trigger
  - High statistics ~1 million semileptonic *b* events
  - lepton charge ⇒ signal *B* flavor at decay



- Background suppression ⇒ pure *bb* sample
  - QCD background $pp \to uu, dd, ss$
    - Remove with signed impact parameter
  - Charm background $pp \to cc$
    - Remove by $2 < M_{\text{lepton-track}} < 4$ GeV/c^2