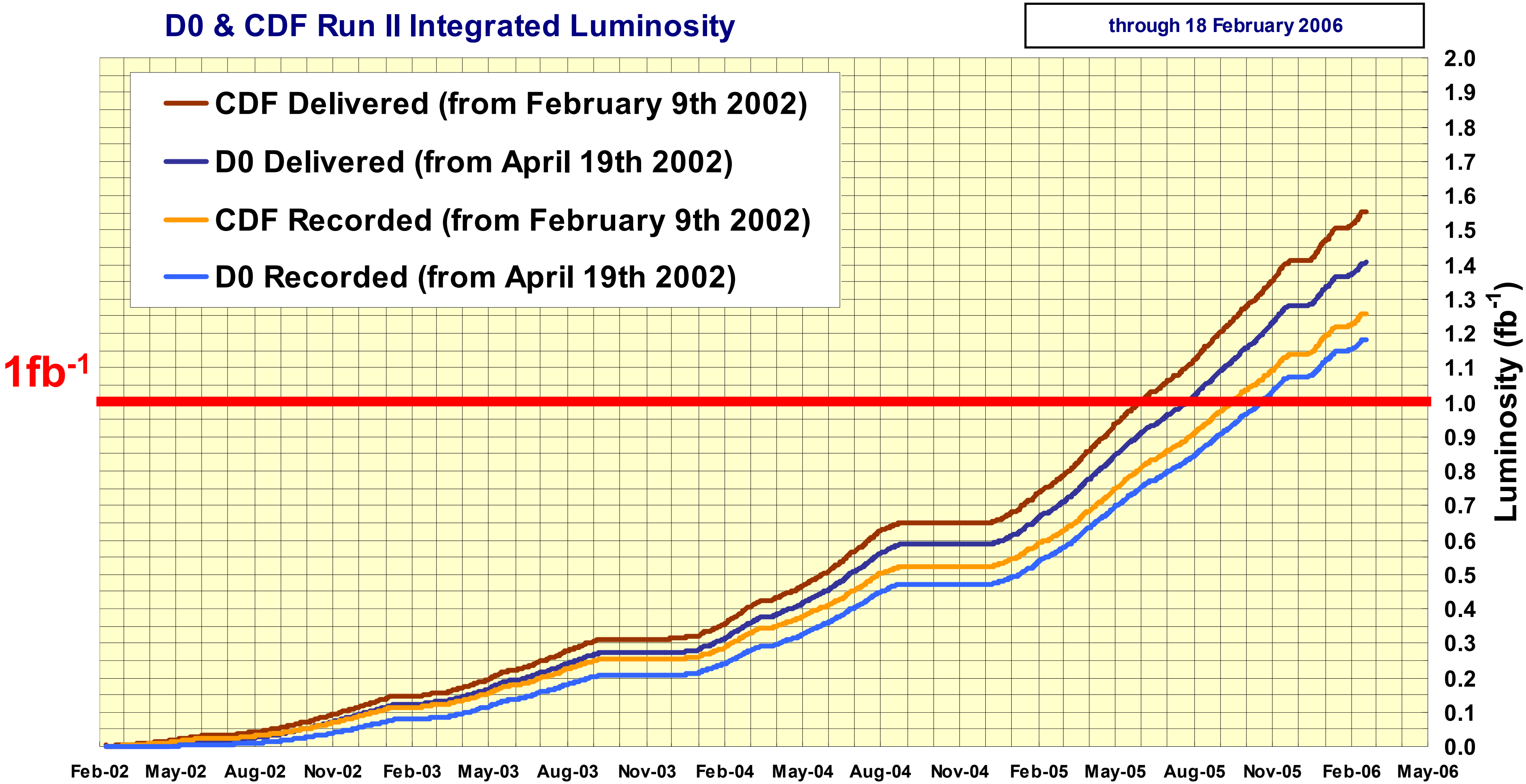
Bs Properties at Tevatron

Sergey Burdin (Fermilab) on behalf of the CDF & DØ Collaborations

- Overview of Tevatron B_s results
- B_s mixing analyses
- $\Delta\Gamma_s$ measurements
- CP violation prospects
- Conclusion

Excellent Tevatron and Detectors Performance



- Several Bs analyses used 1 fb^{-1} data samples

Recent B_s Results from Tevatron

	CDF	DØ
Δm_s, ps^{-1}	$17.33\,^{+0.42}_{-0.21} \pm 0.07$ (1fb^{-1})	17–21 @ 90% (1fb^{-1})
$\Delta\Gamma_s$, ps^{-1}	$0.47\,^{+0.19}_{-0.24} \pm 0.01$ (260)	$0.15 \pm 0.10\,^{+0.03}_{-0.04}$ (800)
$\Delta\Gamma_{CP}/\Gamma_{CP}(B_s \to KK)$	$-0.08 \pm 0.23 \pm 0.03$ (360)	–
$c\tau_s$, ps	$1.381 \pm 0.055\,^{+0.052}_{-0.046}$ (360)	$1.398 \pm 0.044\,^{+0.028}_{-0.025}$ (400)
$Br(B_s \to \mu\mu) \times 10^7$	<1 @ 95% (780)	<2.3@ 95%(exp)(1fb^{-1})
$Br(B_s \to \mu\mu\varphi)$	$<6.7\times10^{-5}$ @ 95% (Run I)	$<4.1\times10^{-6}$ @ 95% (450)
$Br(B_s \to D_s D_s)$	–	$0.071 \pm 0.032\,^{+0.029}_{-0.025}$ (1fb^{-1})
$\frac{Br(B_s \to D_s^+ D_s^-)}{Br(B_d \to D_s^+ D^-)}$	$1.67 \pm 0.41 \pm 0.47$ (355)	–
$Br(B_s \to \varphi\varphi) \times 10^3$	$7.6 \pm 1.3 \pm 0.6$ (180)	–
$Br(B_s \to D_s^{1-}\mu^+\nu X) \times 10^2$	–	$0.86 \pm 0.16 \pm 0.16$ (1fb^{-1})
$\frac{Br(B_s \to D_s(3)\pi)}{Br(B_d \to D^-(3)\pi)}$	1.14 — 1.19	–
$\frac{Br(B_s \to \psi(2S)\phi)}{Br(B_s \to J/\psi\phi)}$	$0.52 \pm 0.13 \pm 0.07$ (360)	$0.58 \pm 0.24 \pm 0.09$ (300)
B_{s2}^{0*}	–	135±31 ev. (1fb^{-1})

Under the Sign of the B_s Mixing

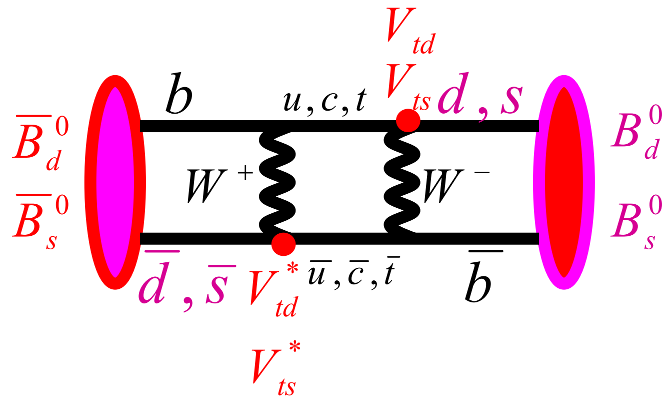
- **Long dominance of the LEP and SLD B_s mixing results**
- **Spring 2005: First results on B_s mixing from Tevatron Run II**
- **Spring 2006: First measurement of the B_s oscillation frequency**
  - ***March: two-sided limit from DØ:***
    - ✓ **$17 < \Delta m_s < 21\ ps^{-1}$ @ 90% C.L.**
    - ✓ **accepted for publication in PRL**
  - ***April: measurement from CDF***
    - ✓ **$\Delta m_s = 17.33\ ^{+0.42}_{-0.21}$ (stat.) ± 0.07 (syst.) ps^{-1}**
    - ✓ **$17.00 < \Delta m_s < 17.91\ ps^{-1}$ @ 90% C.L.**
  - ***~20 theoretical works already***
    - ✓ **New constraints on $\Delta\Gamma_s$, ~~CP_s~~ and $B_s \rightarrow \mu\mu$**
  - ***New Tevatron results on all these parameters are in line***

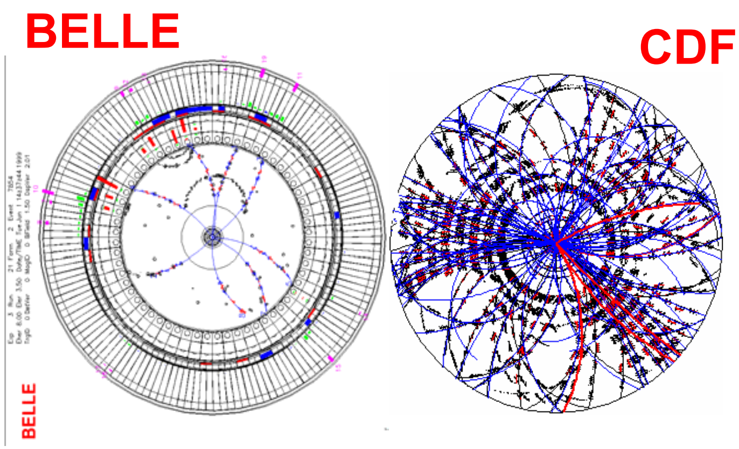
B Mixing Theory

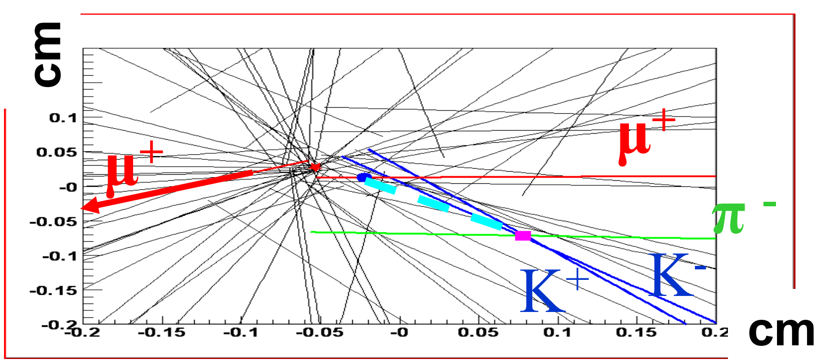
- **Decay of two-body system** $i\frac{d}{dt}\begin{pmatrix}|B(t)\rangle \\ |\bar{B}(t)\rangle\end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M_{12}^* - \frac{i\Gamma_{12}^*}{2} & M - \frac{i\Gamma}{2}\end{pmatrix}\begin{pmatrix}|B(t)\rangle \\ |\bar{B}(t)\rangle\end{pmatrix}$
- **B mixing depends on $|M_{12}|$, $|\Gamma_{12}|$ and $\varphi \approx \arg(-M_{12}/\Gamma_{12}) = O(|V_{us}|^2(m_c/m_b)^2) \sim 5 \cdot 10^{-3} = 0.3^o$ (SM)**
- **Two mass eigenstates**
  - ***Light*** $|B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$
  - ***Heavy*** $|B_H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$
  - ***Masses $M_{L,H}$ and widths $\Gamma_{L,H}$***
    - ✓ $\Delta m = M_H - M_L \approx 2|M_{12}|$ (SM: $\sim 20 ps^{-1}$)
    - ✓ $\Delta\Gamma = \Gamma_L - \Gamma_H \approx -\Delta m \, Re(\Gamma_{12}/M_{12}) = 2|\Gamma_{12}| \cos\varphi$ (SM: $\sim 0.1 ps^{-1}$)
    - ✓ $\Delta\Gamma/\Delta m \approx |\Gamma_{12}/M_{12}| = O((m_b/M_W)^2)$ (SM: $\sim 4 \cdot 10^{-3}$)
  - $a_{fs} = Im(\Gamma_{12}/M_{12}) = |\Gamma_{12}/M_{12}| \sin\varphi$ *(SM: $\sim 2 \cdot 10^{-5}$)*
    - ✓ CP asymmetry in flavor-specific B decays
    - ✓ measures CP violation in mixing

Search for New Physics in Boxes

- Small effect on Γ_{12}
  - *Γ_{12} stems from tree-level decays*
- M_{12} is very sensitive to virtual effects of new heavy particles → $\Delta m \approx 2|M_{12}|$ can change
- as well as $\varphi \approx \arg(-M_{12}/\Gamma_{12})$
  - $|\Delta\Gamma| = \Delta\Gamma_{SM}\,|\cos\varphi|$ *is depleted*
  - $|a_{fs}|$ *is enhanced*
    - ✓ up to $5 \cdot 10^{-3}$ (Nierste)
- Currently Tevatron is the best place for measurements of the B_s properties
  - *Large B cross-section*
  - *Production of all B species*
  - *Large boost of B mesons*
  - *But large background*

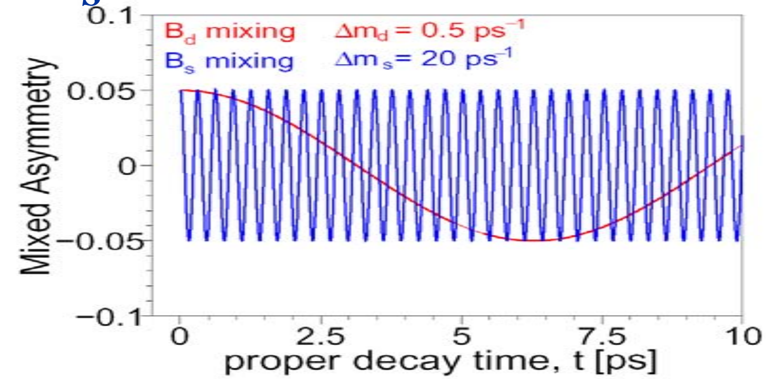






DØ

Principals of Δm_s Measurements



- **Challenge: very fast oscillations**
  - *~40 times faster than B_d oscillations*
  - *Period ~100 μm*
    - ✓ **Resolution should be ~25 μm**
- **Need B_s signal with high statistics and low background**

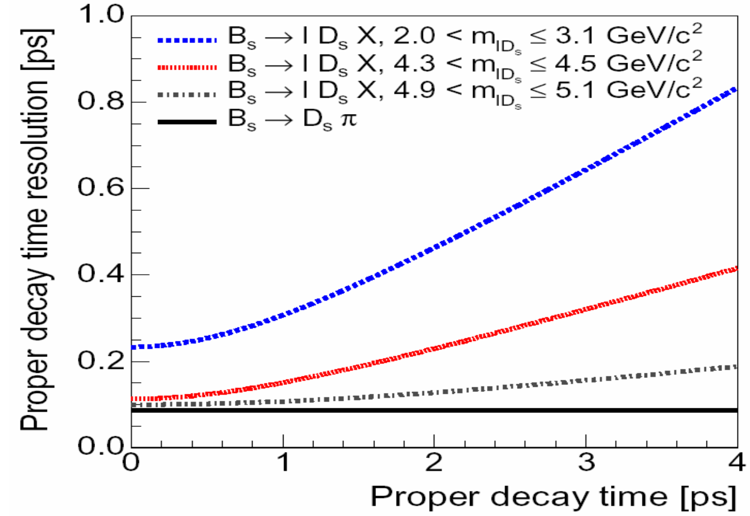
$$Signif \sim \sqrt{\frac{S\varepsilon\mathcal{D}^2}{2}} \cdot \exp\left(\frac{\Delta m_s^2}{2}\left(\sigma_t^2 + \left(t\frac{\sigma_p}{p}\right)^2\right)\right)\sqrt{\frac{S}{S+B}}$$

  - *Trigger*
    - ✓ **CDF: Displaced Track Trigger**
    - ✓ **DØ: Muon Triggers**
  - *Momentum Resolution*
    - ✓ **CDF: Central Outer Tracker**
    - ✓ **DØ: Central Fiber Tracker**
  - *Vertex Identification*
    - ✓ **CDF and DØ: Silicon Tracker**
  - *Lepton Identification*
    - ✓ **CDF: Muon Chambers and Calorimeter**
    - ✓ **DØ: Muon Chambers and Counters, Calorimeter and Pre-shower**

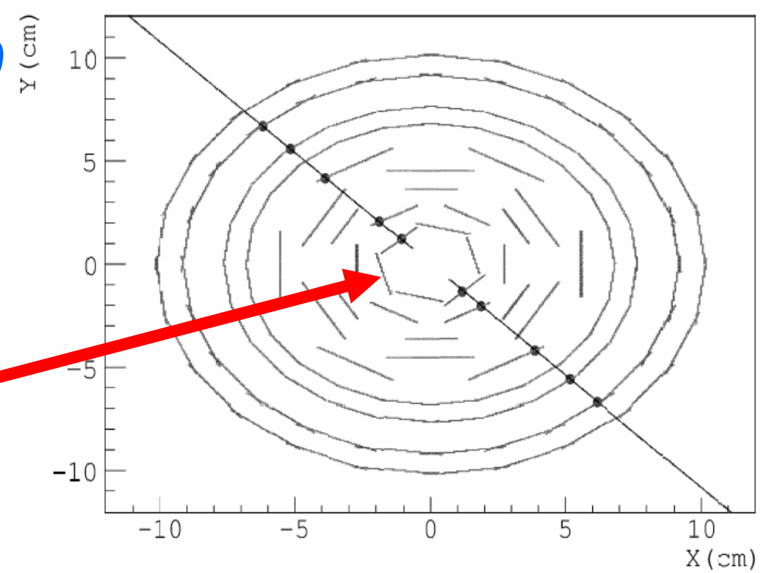
Proper Decay Length Resolution

$$Signif \sim \sqrt{\frac{S\varepsilon\mathcal{D}^2}{2}} \cdot \exp\left(\frac{\Delta m_s^2}{2}\left(\sigma_t^2 + \left(t\frac{\sigma_p}{p}\right)^2\right)\right)\sqrt{\frac{S}{S+B}}$$

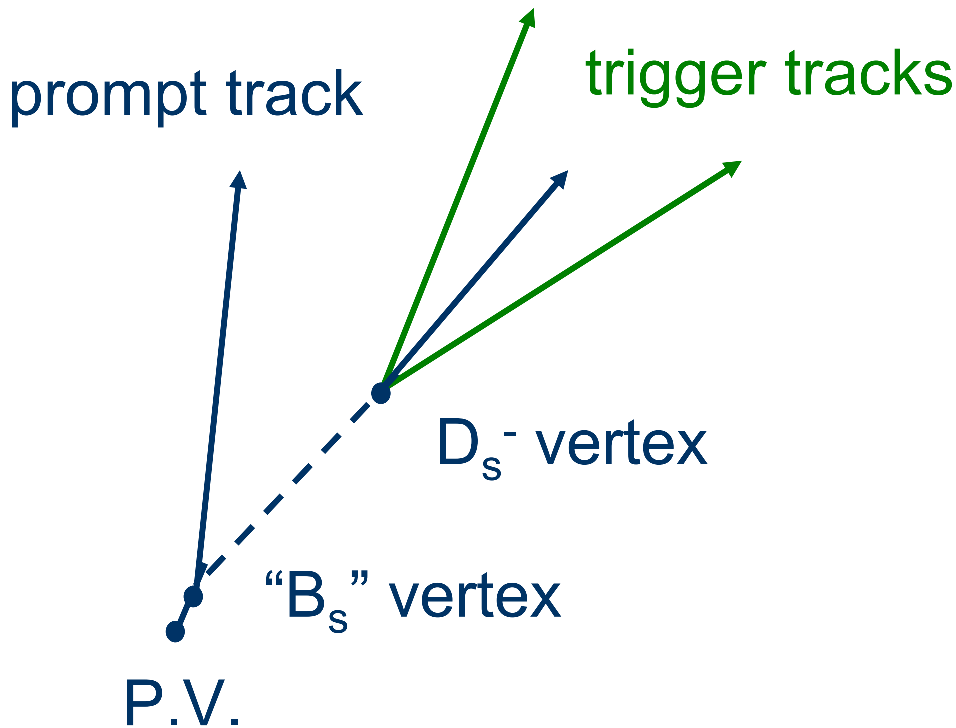
- **CDF:**
  - *the resolution does not degrade with PDL for hadronic modes*
    - ✓ **$\sigma_p/p \sim$ 3-20% for semileptonic modes**
  - *10-20% improvement from L00*
- **DØ:**
  - *work on hadronic modes in progress*
  - *L0 has been installed*

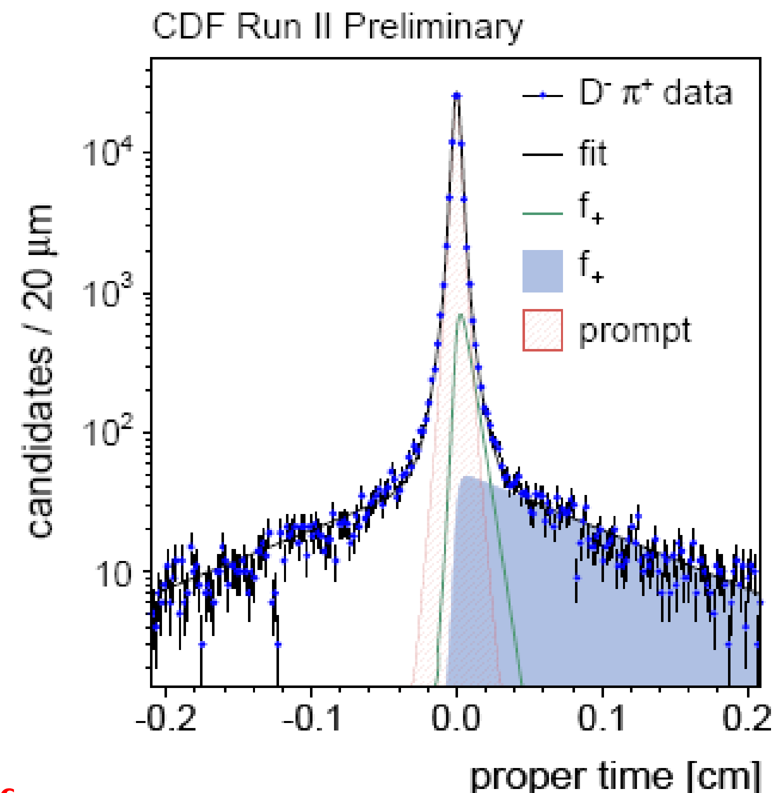


First cosmic tracks with L0



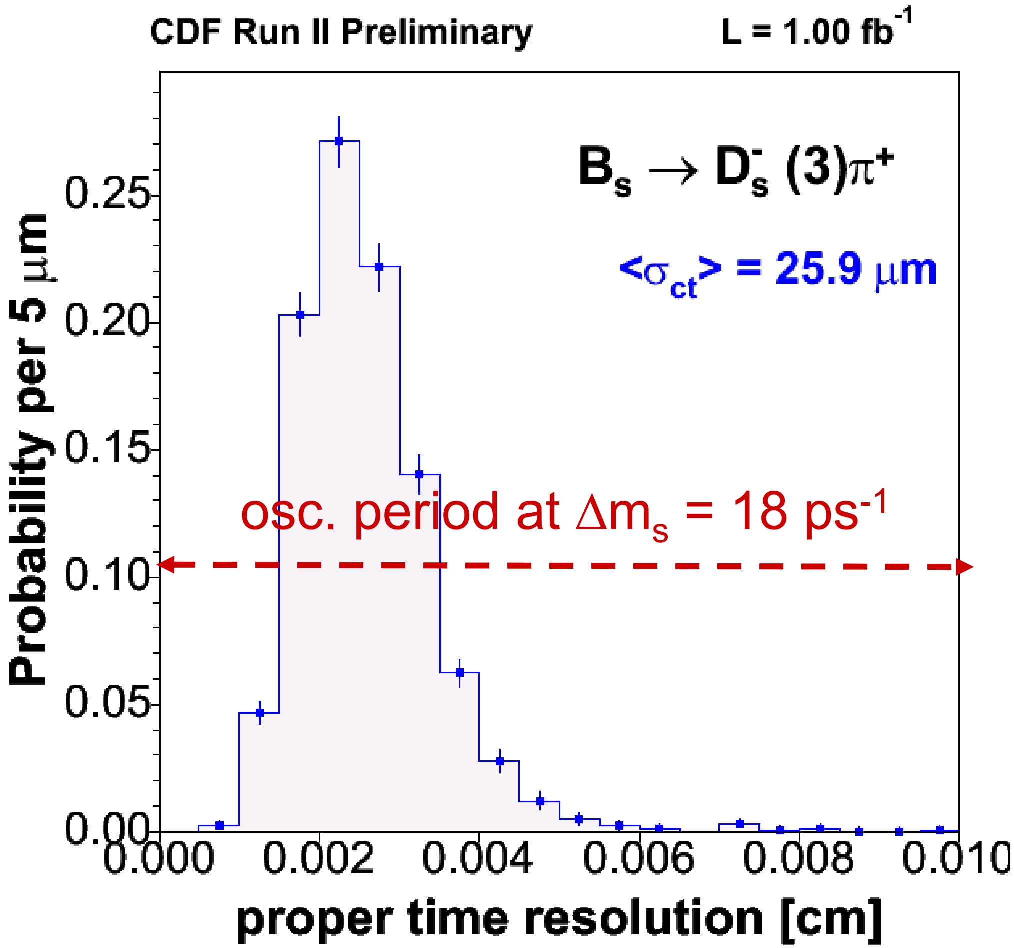
Calibrating the Proper Time Resolution @ CDF





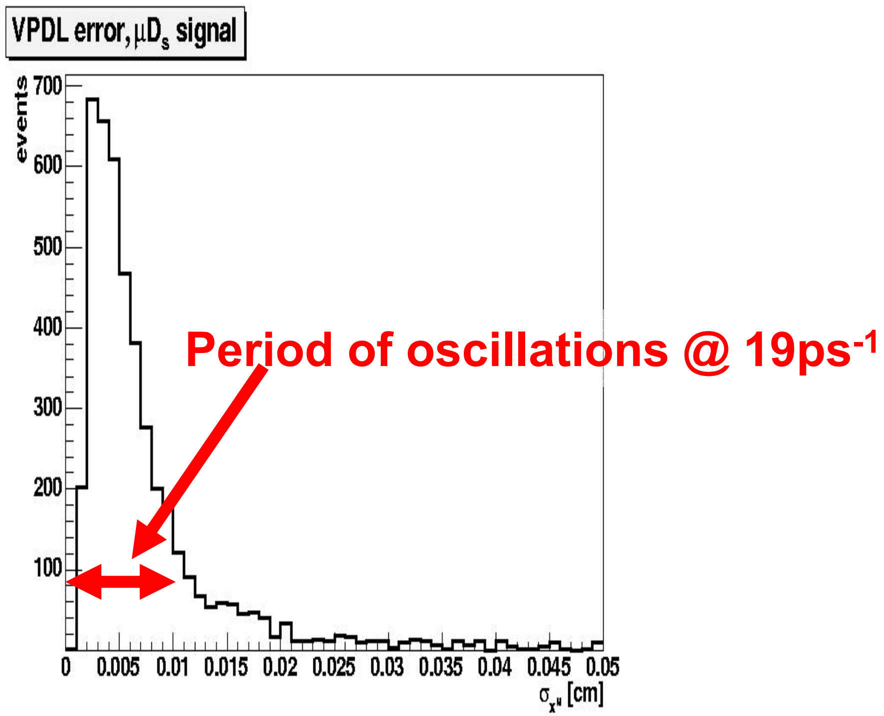
- utilize large prompt charm cross s
- construct "B^0-like" topologies of prompt D^- + prompt track
- calibrate ct resolution by fitting for "lifetime" of "B^0-like" objects

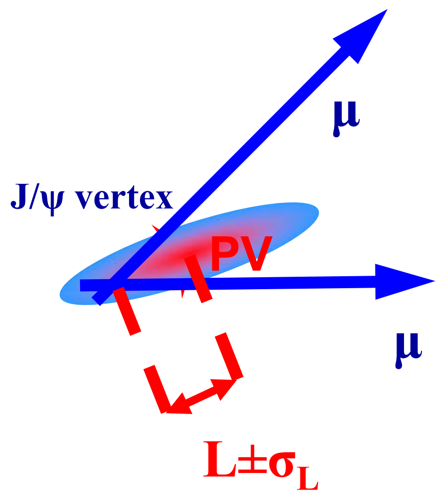
B_s Proper Time Resolution @ CDF



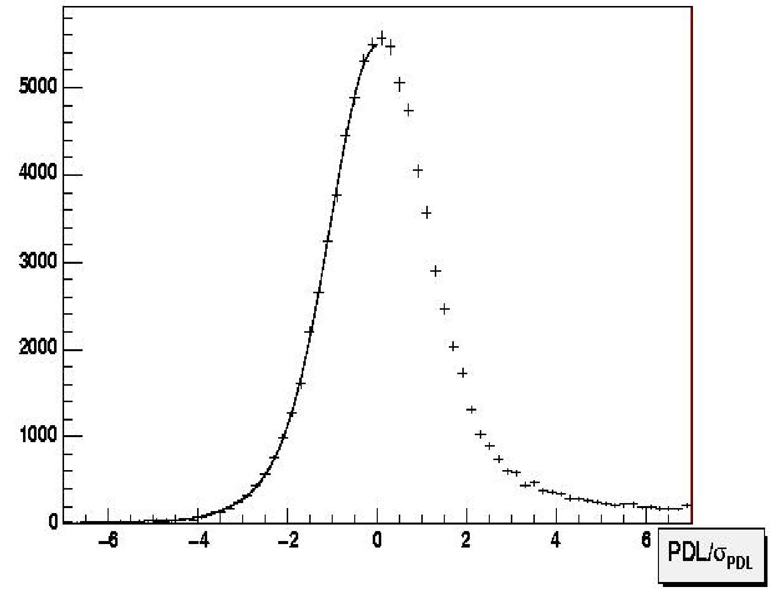
- average uncertainty ~ 26 μm
- this information is used per candidate in the likelihood fit

Vertex Resolution @ DØ

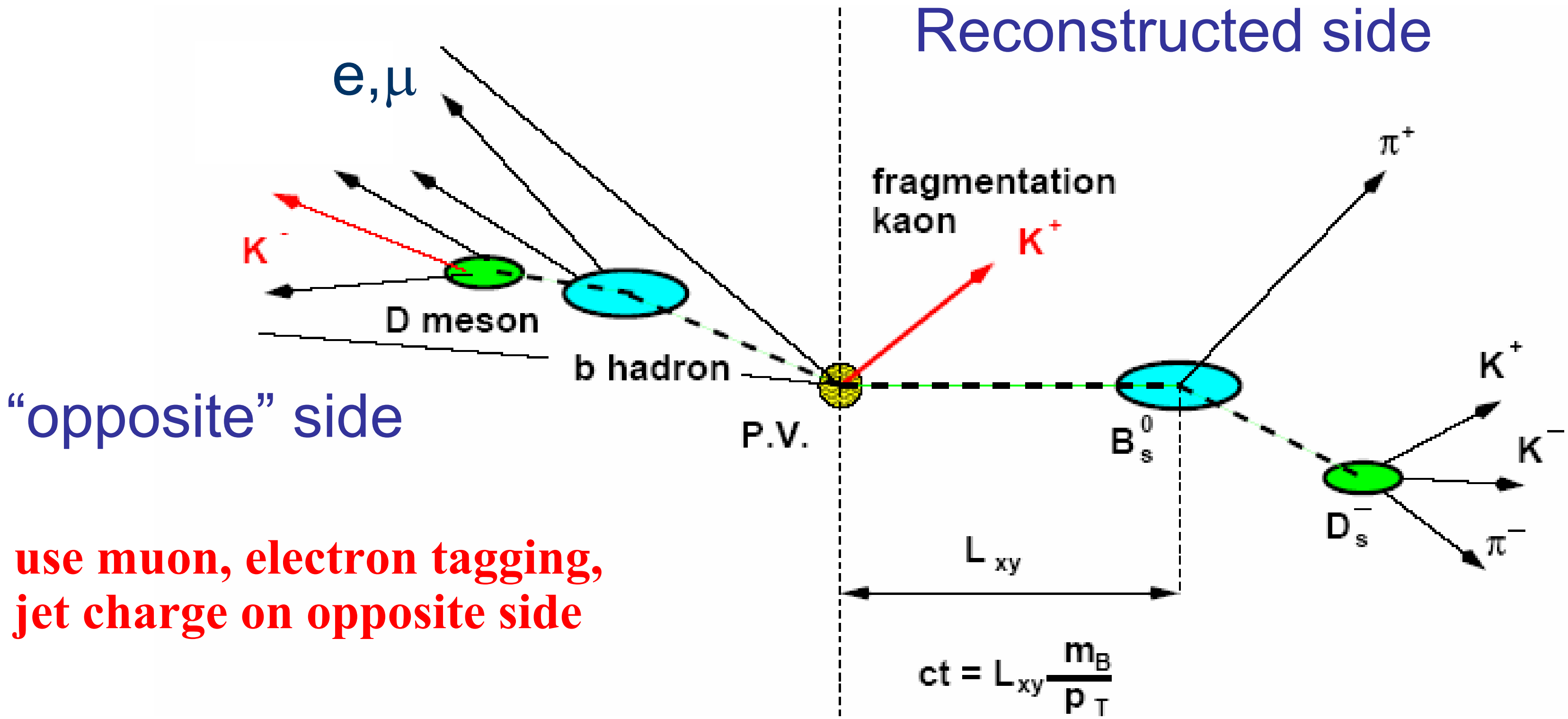




- Tune resolution using data
- Use $J/\psi \to \mu\mu$ events
  - *Clean sample → can study tails*
  - *Fit pull distribution for J/ψ Proper Decay Length with 2 Gaussians*
  - *Resolution Scale Factor is 1.0 for 72% of the events and 1.8 for the rest*
  - *Confirmed by Impact Parameter tuning procedure in MC*



Tagging the B Production Flavor



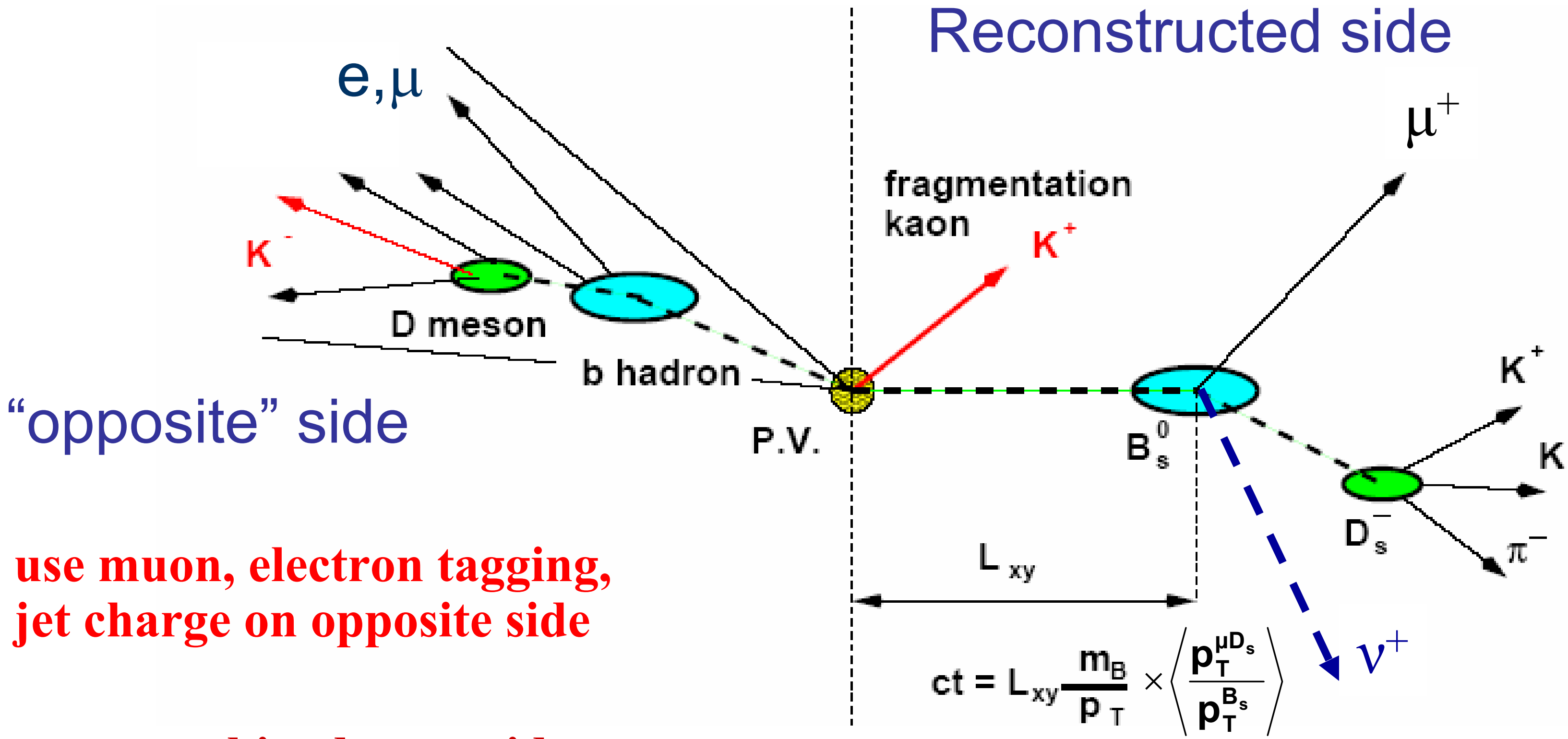
- use muon, electron tagging, jet charge on opposite side
- use a combined same side and opposite side tag (CDF)
- particle ID based kaon tag on same side (CDF)

- Significance of the measurement

$$Signif \sim \underbrace{\sqrt{\frac{S\varepsilon\mathcal{D}^2}{2}}} \cdot \exp\left(\frac{\Delta m_s^2}{2}\left(\sigma_t^2 + \left(t\frac{\sigma_p}{p}\right)^2\right)\right)\sqrt{\frac{S}{S+B}}$$

  - ε—efficiency of tagging
  - $\mathcal{D}=1-2w$ — tagging "dilution" (w — mistag rate)

Tagging the B Production Flavor



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Tagger Performance

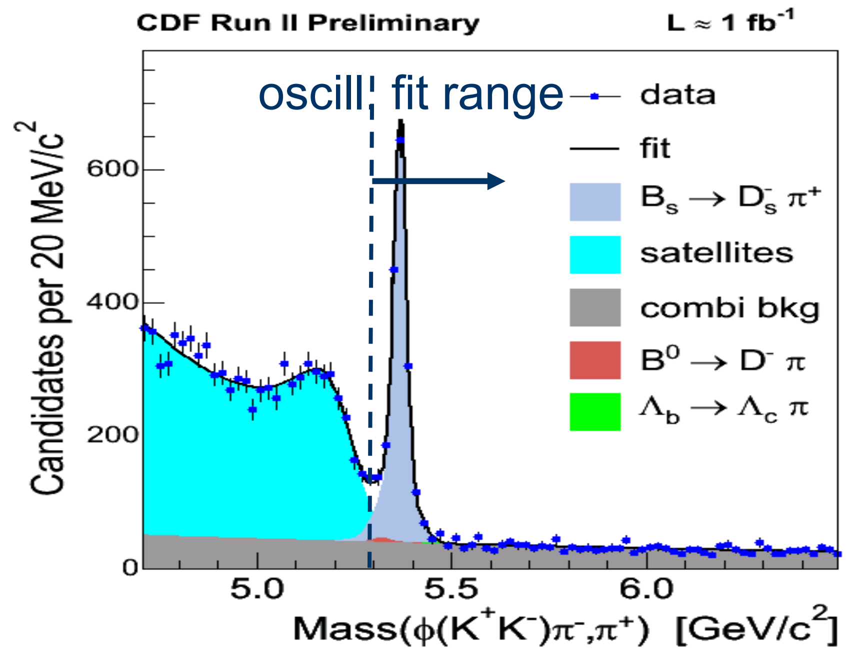
CDF	εD^2 Hadronic (%)	εD^2 Semileptonic (%)
Muon	0.48 ± 0.06 (stat)	0.62 ± 0.03 (stat)
Electron	0.09 ± 0.03 (stat)	0.10 ± 0.01 (stat)
JQ/Vertex	0.30 ± 0.04 (stat)	0.27 ± 0.02 (stat)
JQ/Prob.	0.46 ± 0.05 (stat)	0.34 ± 0.02 (stat)
JQ/High p_T	0.14 ± 0.03 (stat)	0.11 ± 0.01 (stat)
Total OST	1.47 ± 0.10 (stat)	1.44 ± 0.04 (stat)
SSKT	3.42 ± 0.98 (syst)	4.00 ± 1.02 (syst)
DØ		
Muon $\lvert d_{pr}\rvert>0.3$		1.48 ± 0.17 (stat)
Electron $\lvert d_{pr}\rvert>0.3$		0.21 ± 0.07 (stat)
SV charge $\lvert d_{pr}\rvert>0.3$		0.50 ± 0.11 (stat)
Combined $\lvert d_{pr}\rvert>0.3$		2.19 ± 0.22 (stat)
Total OST		2.48 ± 0.21 (stat)

- Calibrate OST using B_d sample
- Calibrate SST using tuned MC

CDF Signal Sample for Δm_s

Hadronic Modes

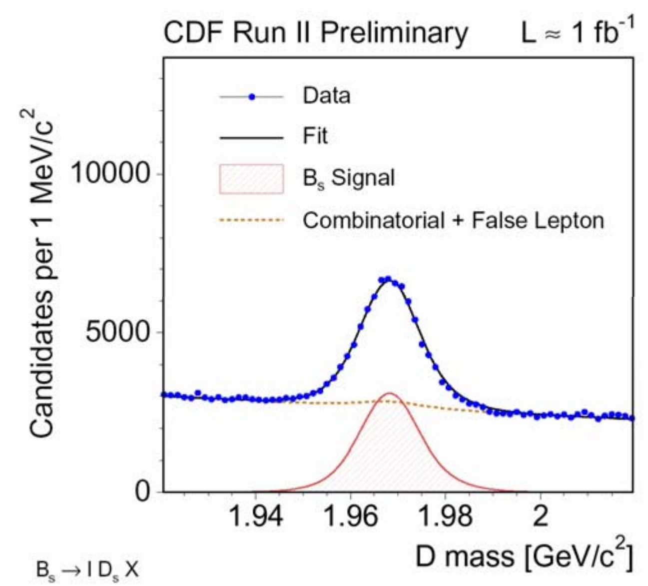
Hadronic Modes	Yield
$B_s \rightarrow D_s\pi$ ($\phi\pi$)	1600
$B_s \rightarrow D_s\pi$ (K^* K)	800
$B_s \rightarrow D_s\ \pi$ (3π)	600
$B_s \rightarrow D_s 3\pi$ ($\phi\ \pi$)	500
$B_s \rightarrow D_s 3\pi$ (K^*K)	200
Total	3700



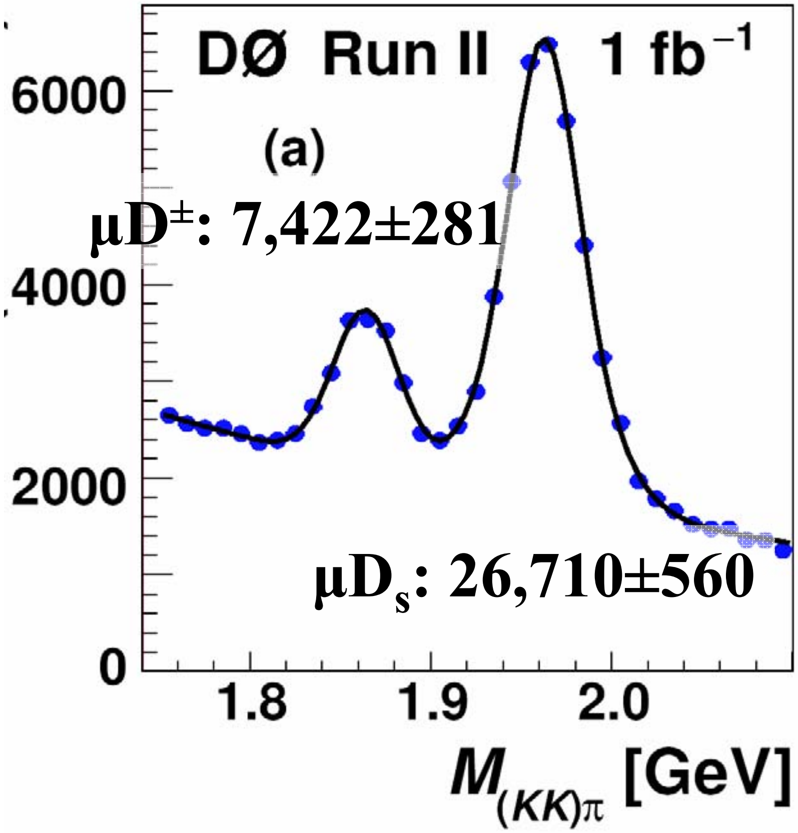
Semileptonic Modes

ℓD_s: $D_s \rightarrow \phi\pi$	32 K
ℓD_s: $D_s \rightarrow K^*K$	11 K
ℓD_s: $D_s \rightarrow \pi\pi\pi$	10 K

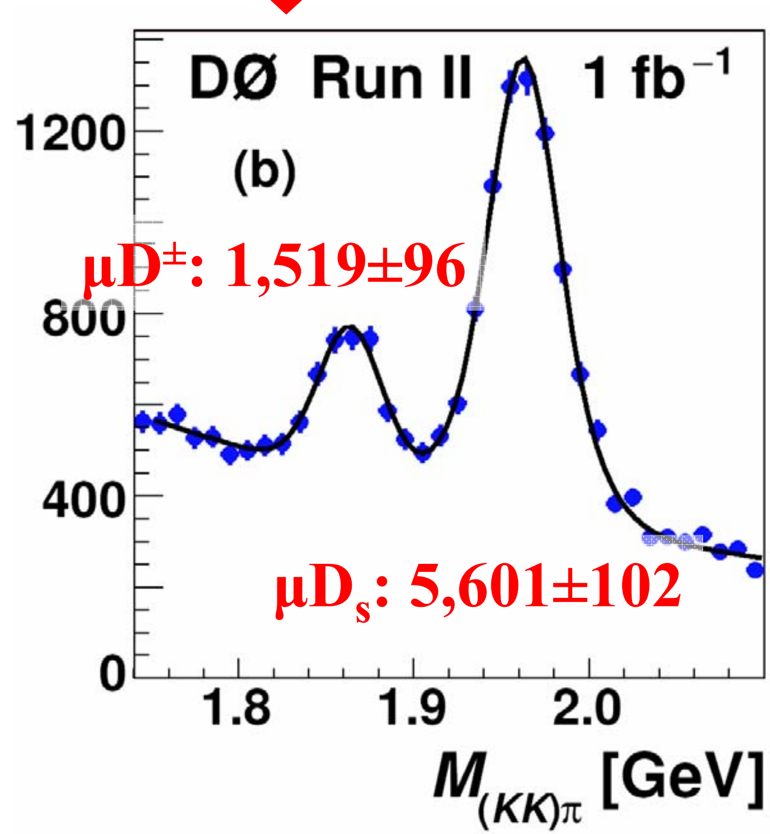
~53 K events



$\mu\phi\pi$ sample @ DØ (~1 fb^{-1})

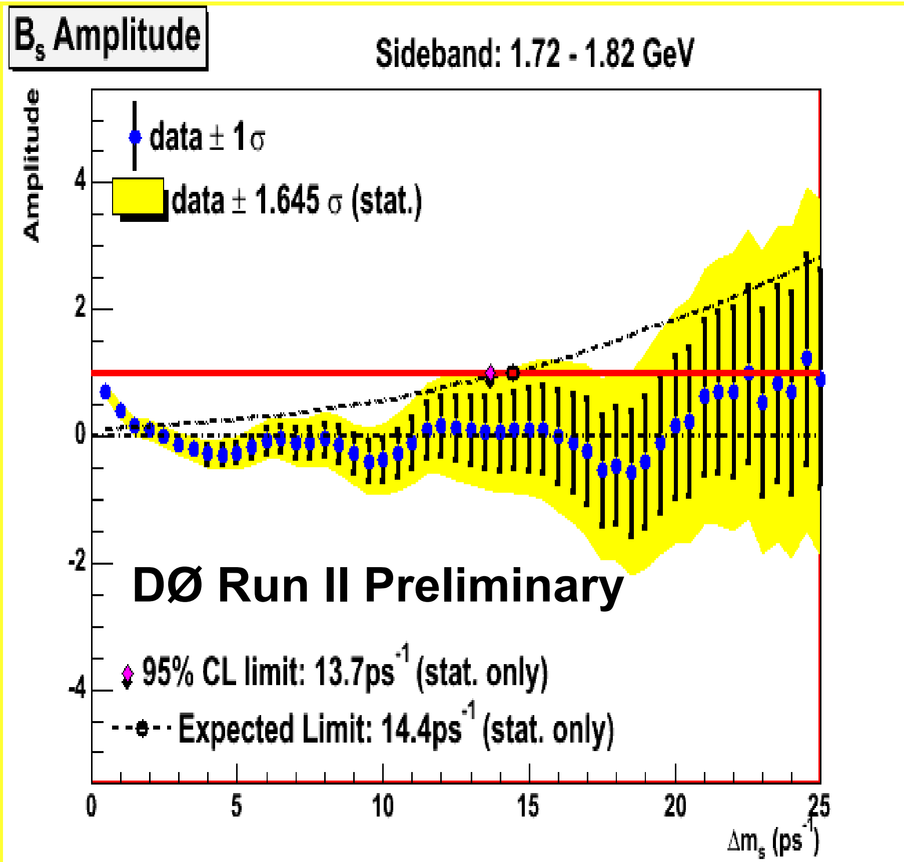


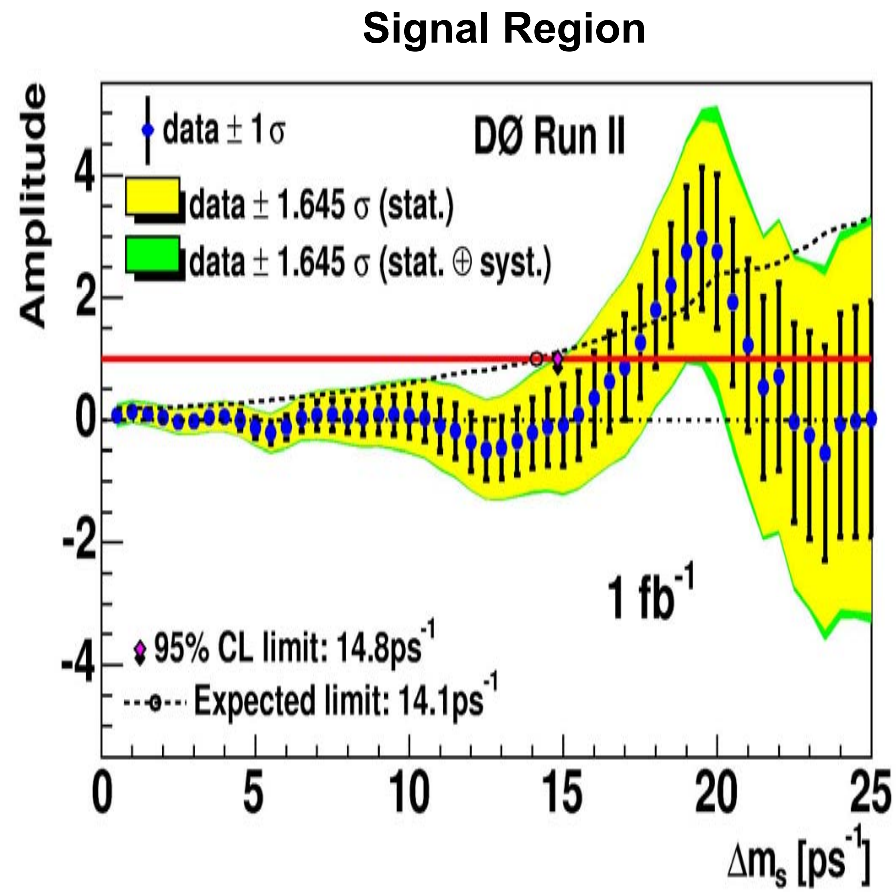
Opposite-side flavor tagging



Tagging efficiency ~20%

DØ Amplitude Scan

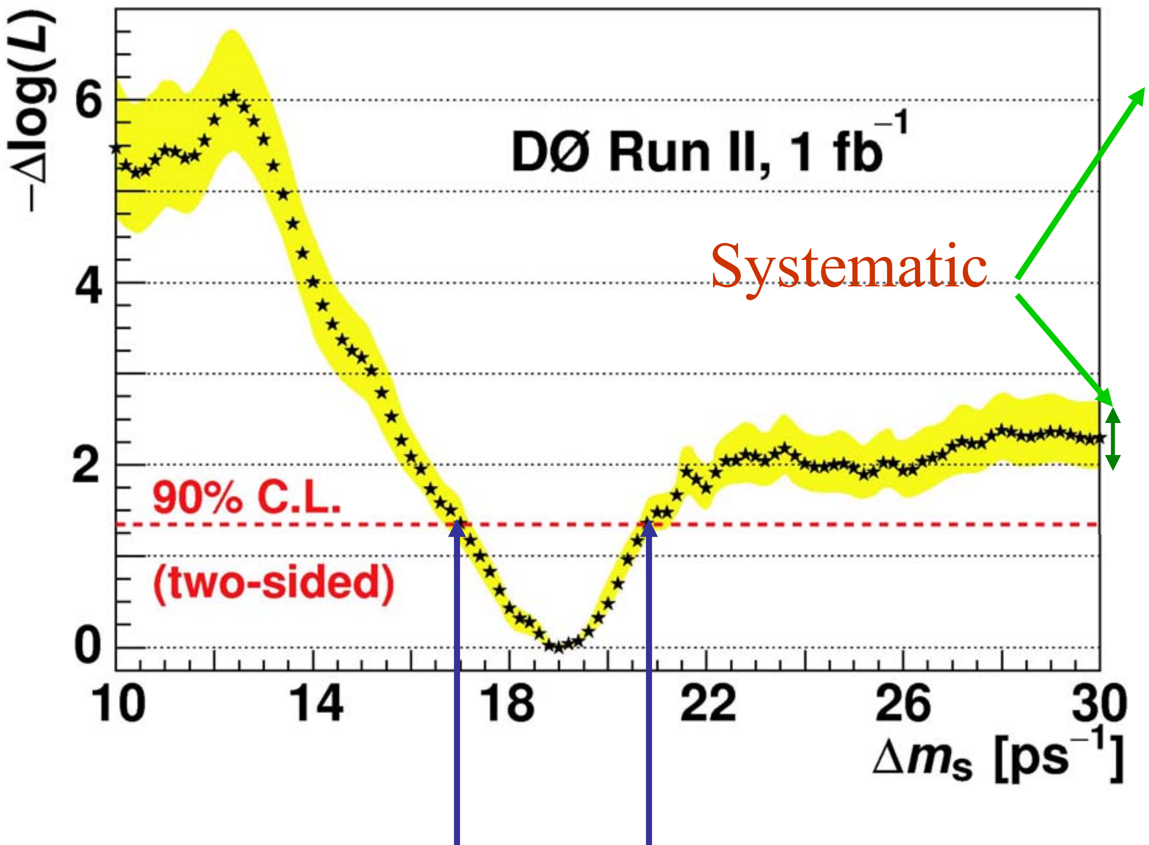




$$p_s^{nos/osc} = \frac{K}{c\tau_{B_s}} e^{-\frac{Kx}{c\tau_{B_s}}} \cdot 0.5 \cdot \left(1 \pm \mathcal{D}\cos\left(\Delta m_s \cdot Kx/c\right) \cdot \mathcal{A}\right)$$

- **Deviation of the amplitude at 19 ps-1**
  - *2.5σ from 0*
  - *1.6σ from 1*

DØ Log Likelihood Scan



- Resolution
- K-factor variation
- BR ($B_s \to \mu D_s X$)
- VPDL model
- BR ($B_s \to D_s D_s$)

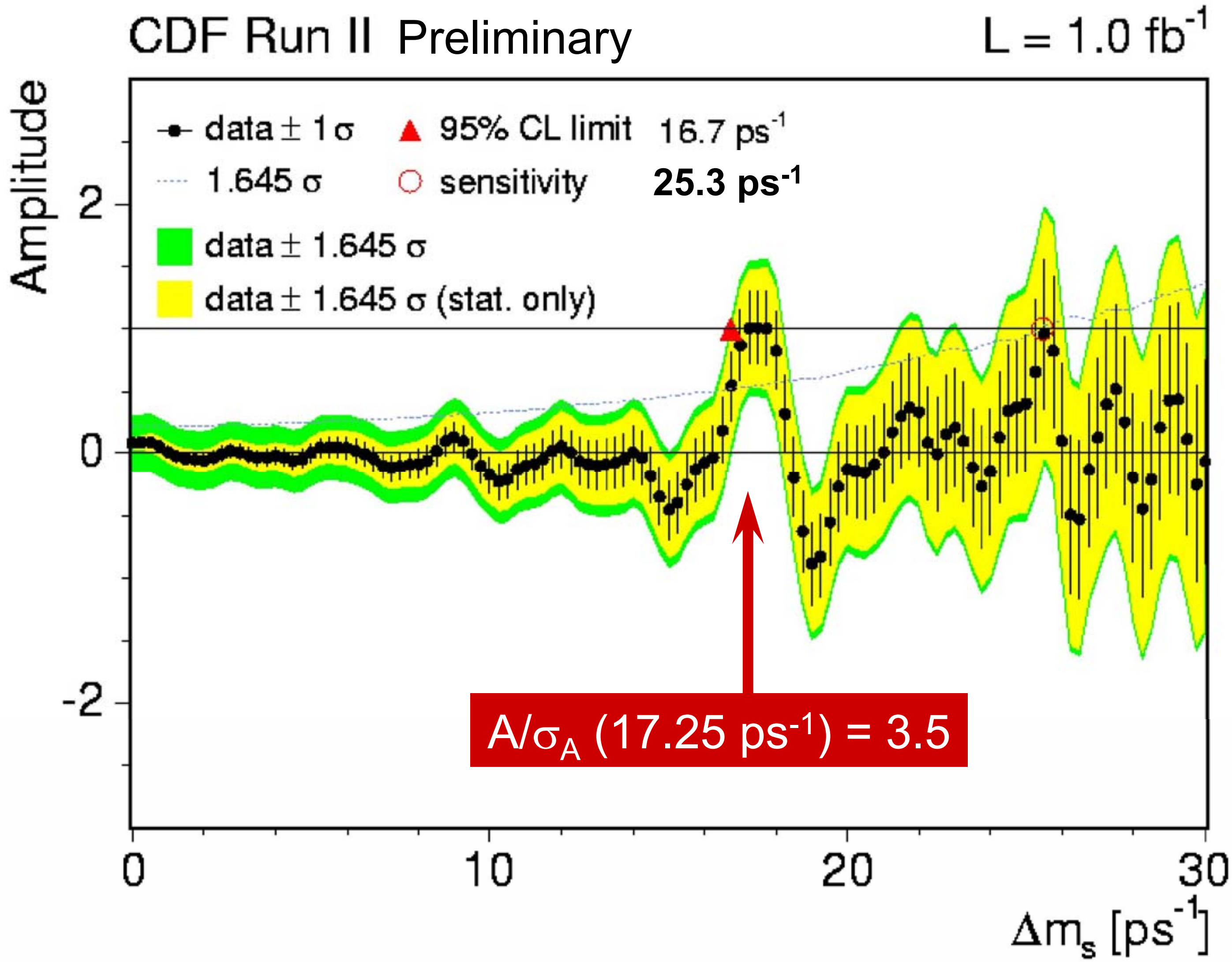
Have no sensitivity above 22 ps^{-1}

Probability of background fluctuation: 3.8% (5% with syst. uncertainties)

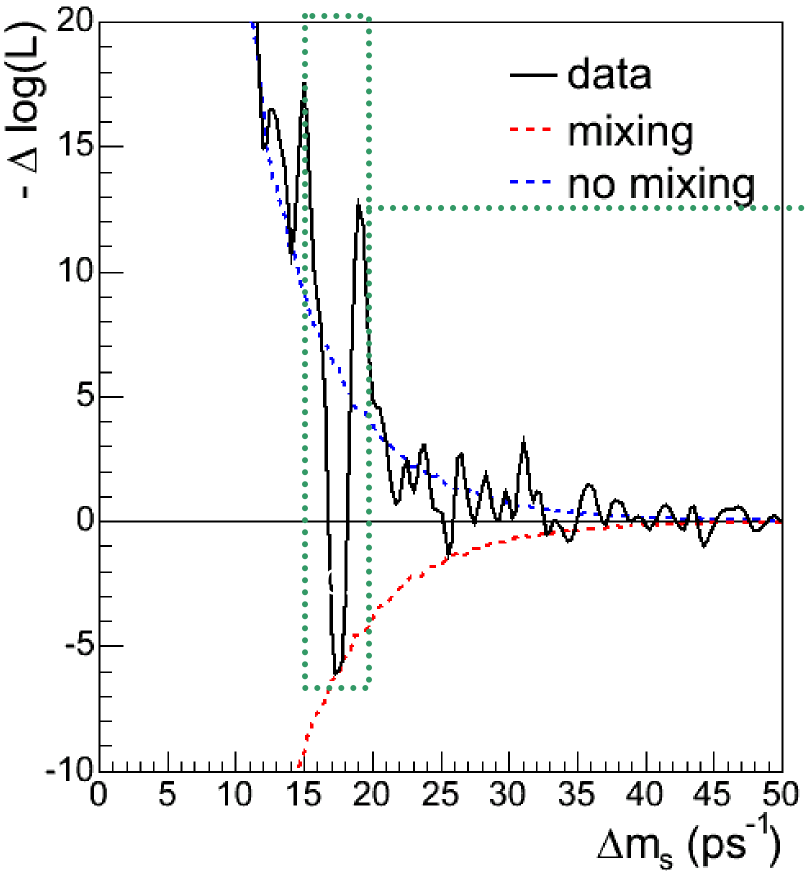
***17 < Δm_s < 21 ps^{-1}* @ 90% CL assuming Gaussian errors**

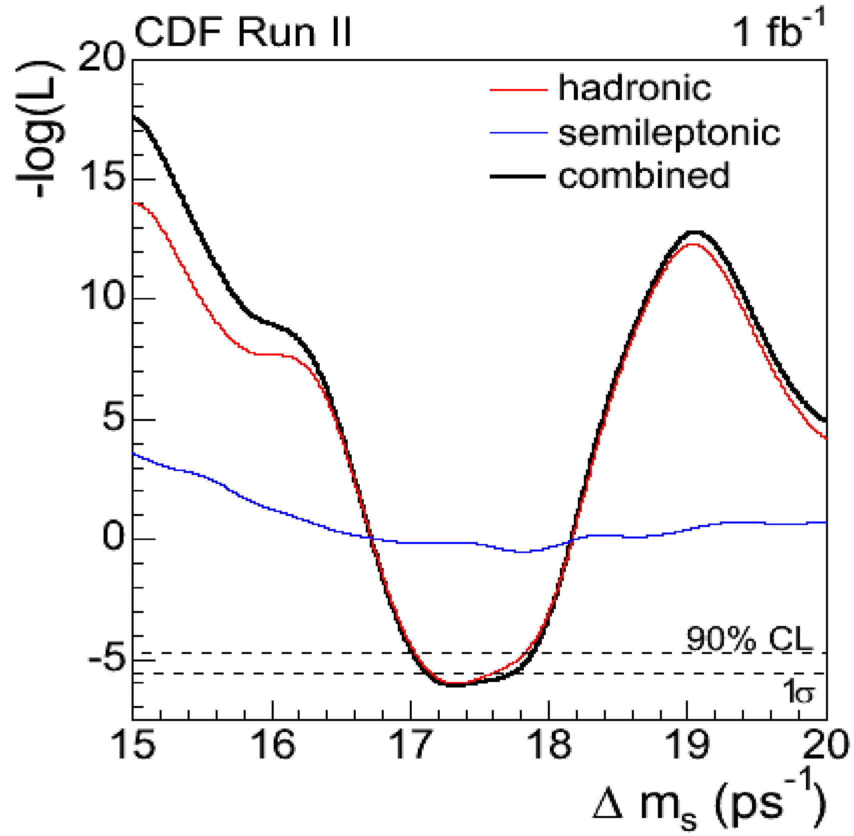
Most probable value of Δm_s = 19 ps^{-1}

CDF Combined Amplitude Scan



Measurement of Δm_s from CDF





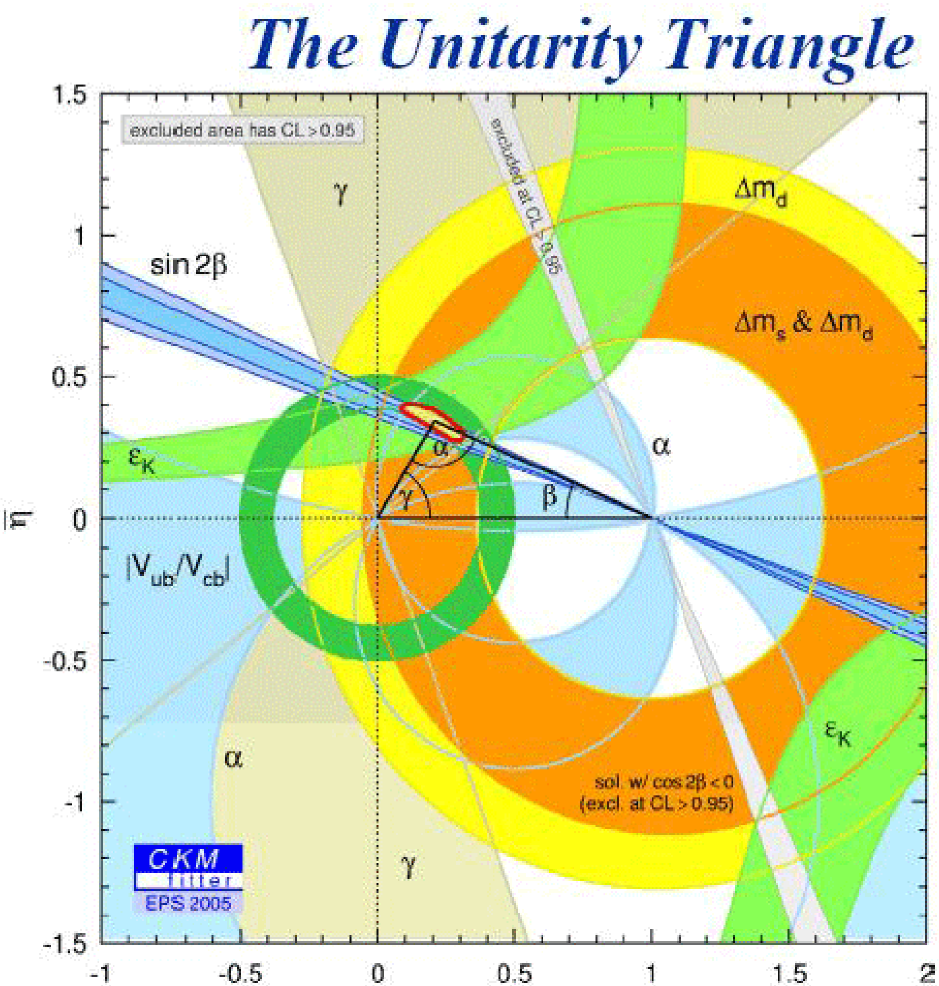
$$\Delta m_s = 17.33 ^{+0.42}_{-0.21} \text{(stat)} \pm 0.07 \text{(syst)} \ \ ps^{-1}$$

Δm_s in [17.00, 17.91] ps^{-1} at 90% CL

Δm_s in [16.94, 17.97] ps^{-1} at 95% CL

Probability of background fluctuation: 0.5%

Results on Δm_s

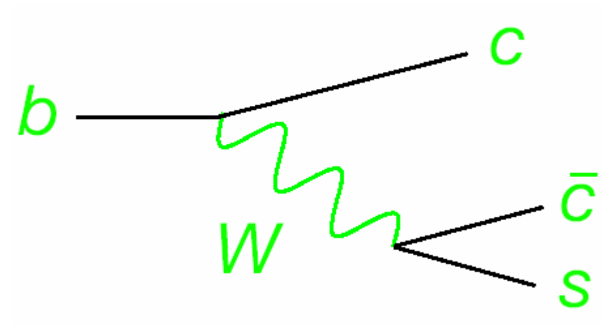


- **DØ:**
  - *17—21 ps^{-1} @ 90%C.L.*
- **CDF:**
  - **$17.33\ ^{+0.42}_{-0.21} \pm 0.07\ \text{ps}^{-1}$**
- **UT Fit:**
  - *21.5 ± 2.6 ps^{-1}*
- **CKM Fit:**
  - $21.7^{+5.9}_{-4.2}$ *ps^{-1}*

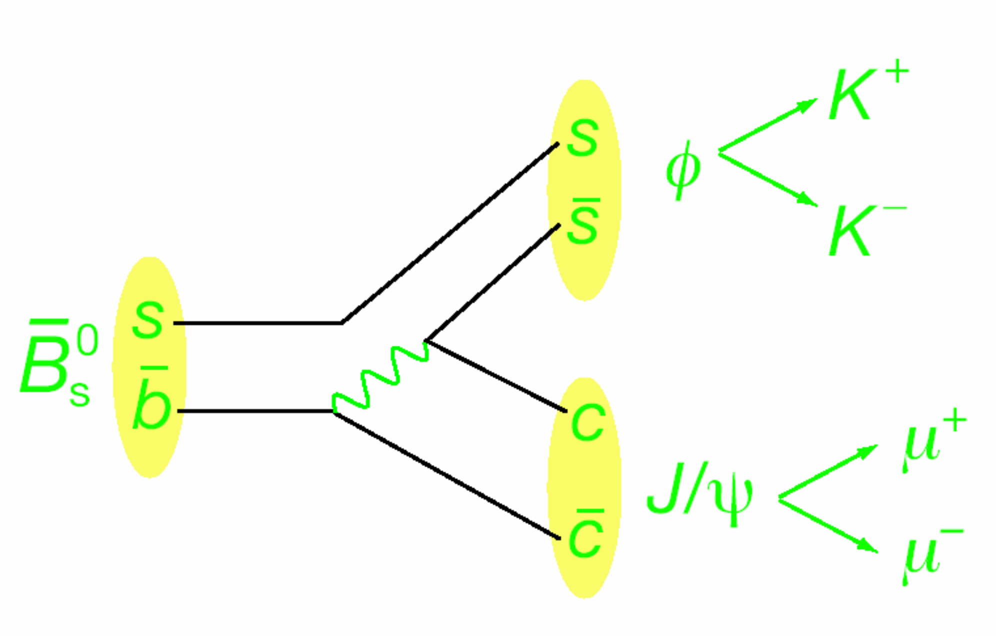
Animation: Courtesy of Gordon Watts
(http://gordonwatts.wordpress.com/tag/physics/)

Width Difference, $\Delta\Gamma_s$

- Γ_{12} dominated by decay $b \rightarrow c\bar{c}s$ from decays into final states common to both $B^0_s(\bar{b}s)$ and $\bar{B}^0_s(b\bar{s})$



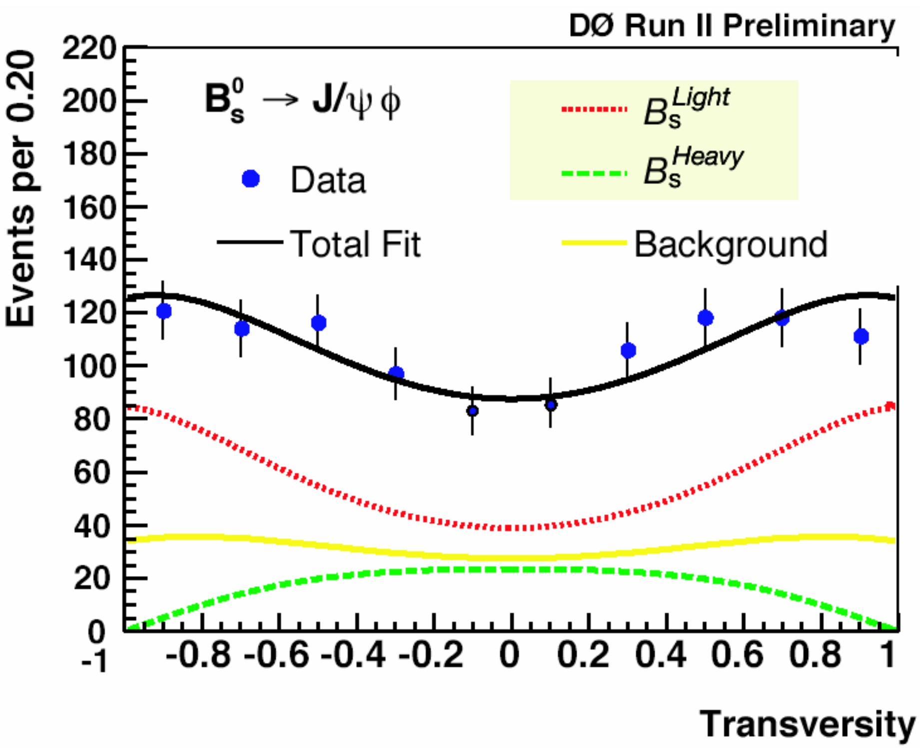
$B_s \rightarrow J/\psi\ \varphi$

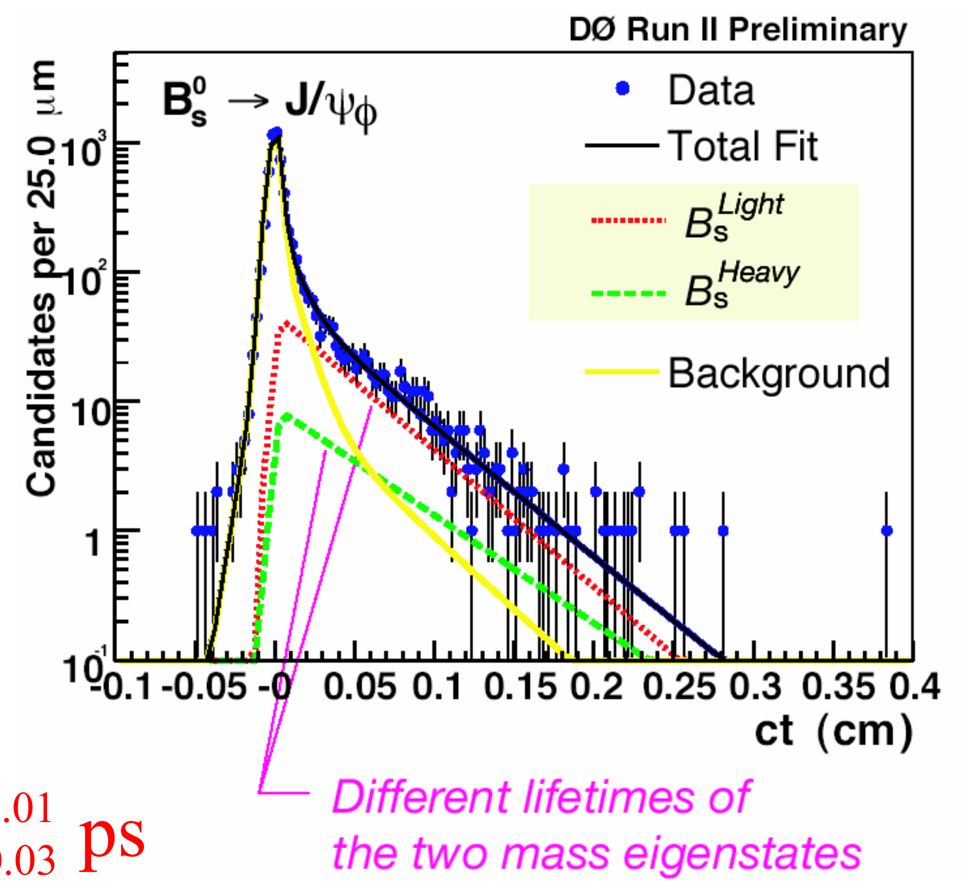


- A mix of CP-even and CP-odd states could be separated using angular distributions of J/ψ and φ decay products
- Simultaneous fit to lifetimes

Width Difference, $\Delta\Gamma_s$ @ DØ

- **Update of published analysis with 800 pb^{-1}**
  - **3-angle fit**



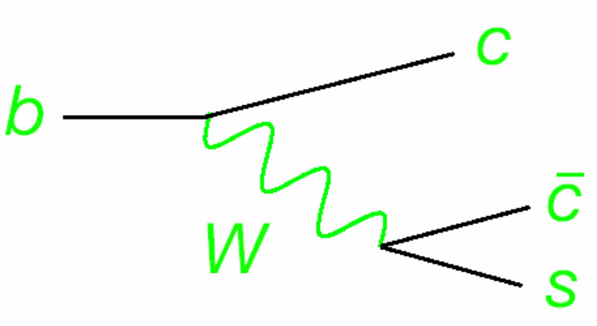


$$\bar{\tau}_{Bs} = 1.53 \pm 0.08^{+0.01}_{-0.03}\ \text{ps}$$

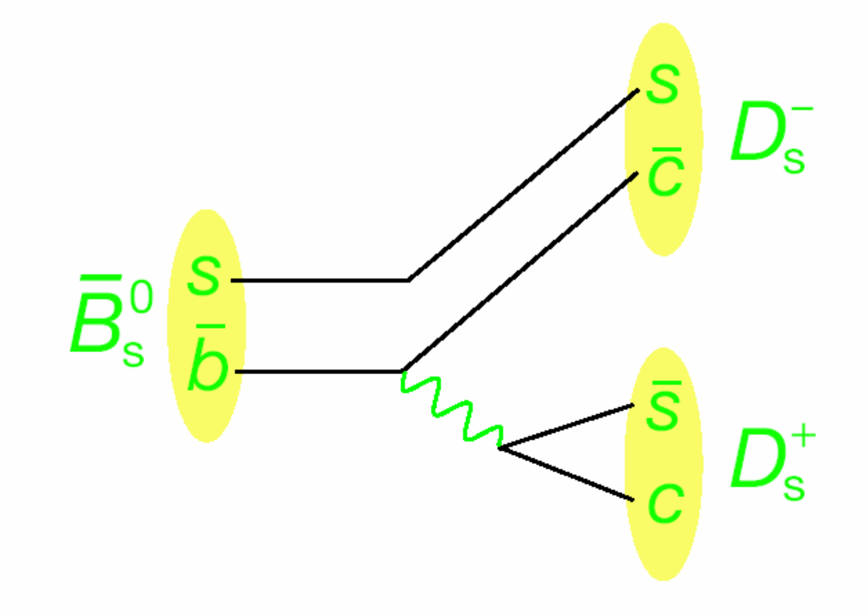
$$\Delta\Gamma_s = 0.15 \pm 0.10^{+0.03}_{-0.04}\ \text{ps}^{-1}$$

Width Difference, $\Delta\Gamma_s$

- Γ_{12} dominated by decay $b \to c\bar{c}s$ from decays into final states common to both $B^0_s(\bar{b}s)$ and $\bar{B}^0_s(b\bar{s})$
- $\Delta\Gamma_{CP} = 2|\Gamma_{12}| = \Gamma(B_s^{even}) - \Gamma(B_s^{odd})$



- $B_s \to D^+_s D^-_s$ is pure CP even
- $B_s \to D^{(*)+}_s D^{(*)-}_s$ inclusive is also CP even with 5% (?) theoretical uncertainty



$$\frac{\Delta\Gamma_{CP}}{\Gamma} \sim \frac{2Br\left(B_s^0 \to D_s^{(*)+} D_s^{(*)-}\right)}{1 - Br\left(B_s^0 \to D_s^{(*)+} D_s^{(*)-}\right)/2}$$

- $\varphi = 0 \to \Delta\Gamma_S = \Delta\Gamma_{CP}$

New results from CDF and DØ

BELLE is in game as well!

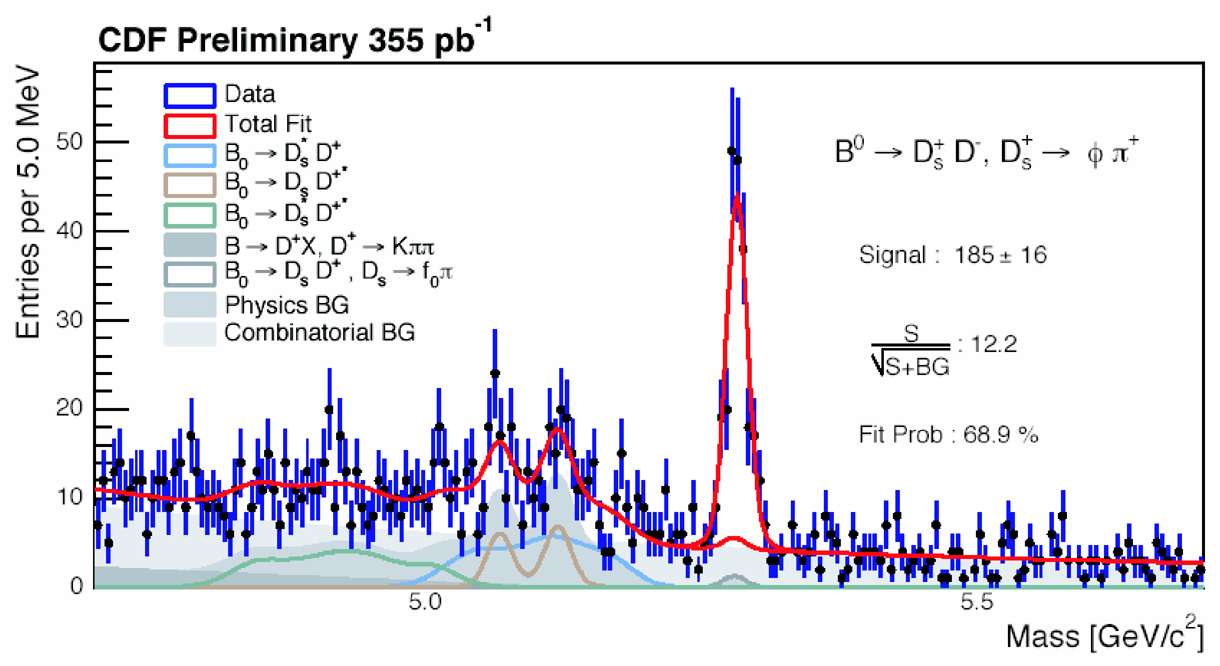
CDF $Br(B^0_s \to D^+_s D^-_s)$

- **Hadronic decay modes**

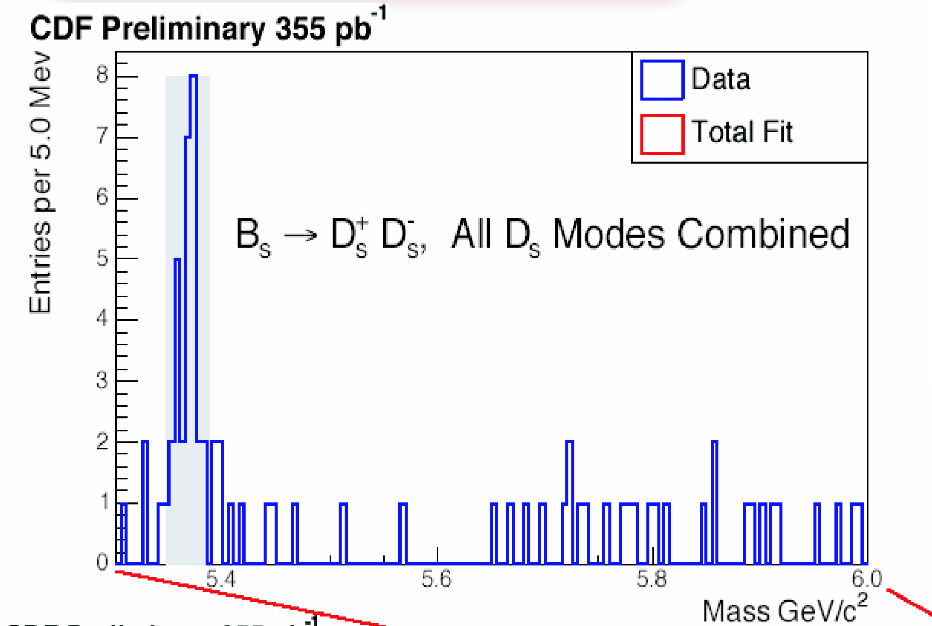
$$B_s^0 \to D_s^+\left(\phi\pi^+, 3\pi, K^*K\right) D_s^-\left(\phi\pi^-, 3\pi, K^*K\right)$$

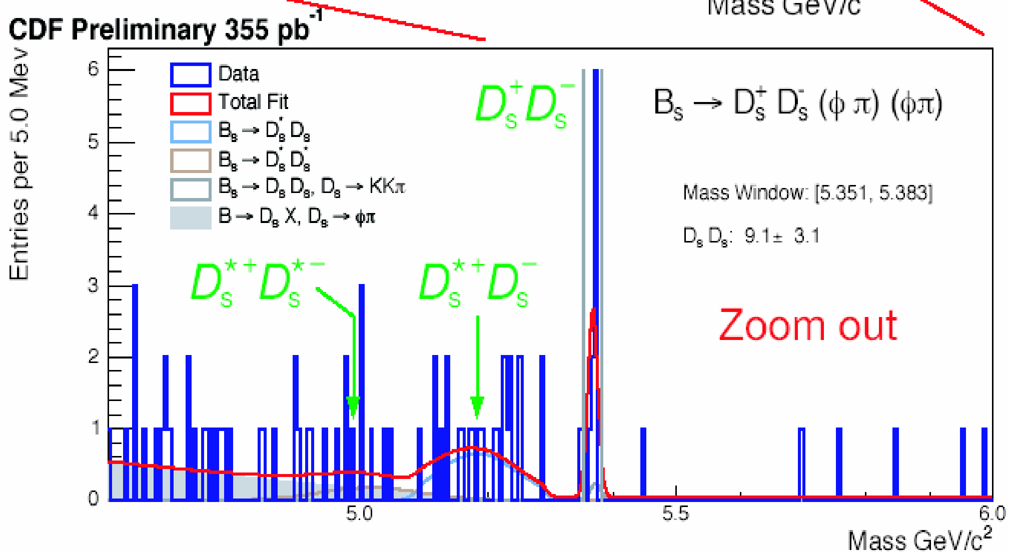
- **Normalized to**

$$B_d^0 \to D_s^+\left(\phi\pi^+, 3\pi, K^*K\right) D^-\left(K\pi\pi\right)$$



CDF $Br(B^0_s \rightarrow D^+_s D^-_s)$





- **23.5 ± 5.5 signal candidates**
- $$\frac{Br(B^0_s \rightarrow D^+_s D^-_s)}{Br(B^0_s \rightarrow D^+_s D^-)} =$$
  $$= 1.67 \pm 0.41\,(\text{stat.}) \pm 0.12\,(\text{syst.}) \pm 0.24\,(f_s/f_d) \pm 0.39\,(Br_{\phi\pi})$$
- **Work on $\Delta\Gamma_{CP}$ is in progress**

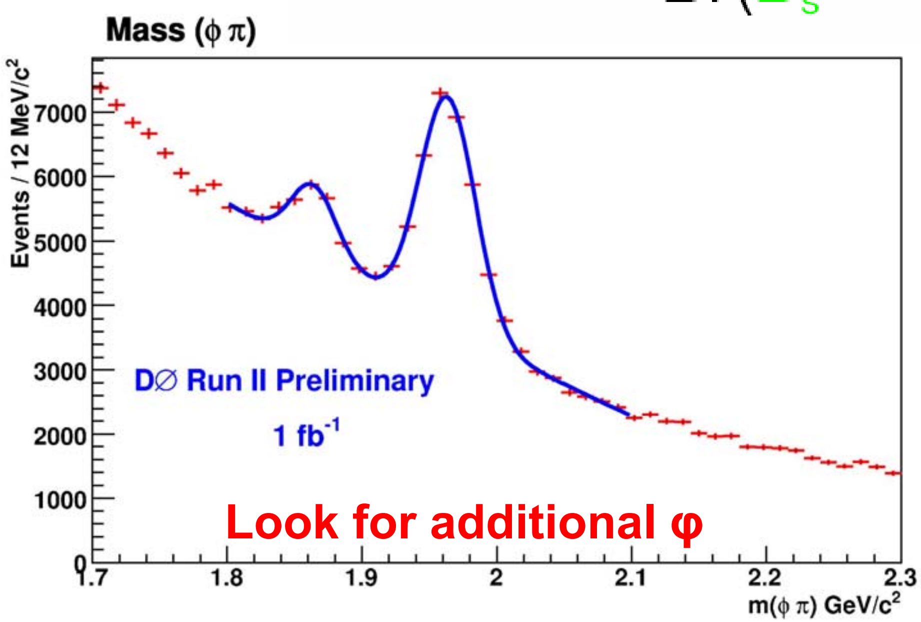
DØ $Br(B^0_s \rightarrow D^{(*)+}_s D^{(*)-}_s)$

- **Semileptonic D_s decays (need trigger)**

$$B_s^0 \rightarrow D_s^{(*)+}(\phi\mu^+\nu)D_s^{(*)-}(\phi\pi^-)$$

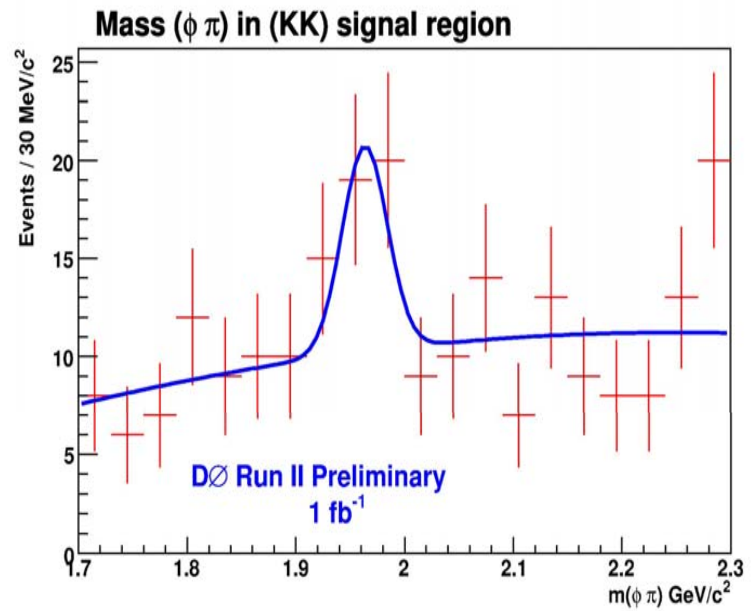
- **Normalize to** $B_s^0 \rightarrow D_s^{(*)+}(\phi\pi^+)\mu^-\nu$

- **Measure ratio** $R = \dfrac{Br(B_s^0 \rightarrow D_s^{(*)+}D_s^{(*)-}) \cdot Br(D_s \rightarrow \phi\mu\nu)}{Br(B_s^0 \rightarrow \mu\nu D_s^{(*)-})}$

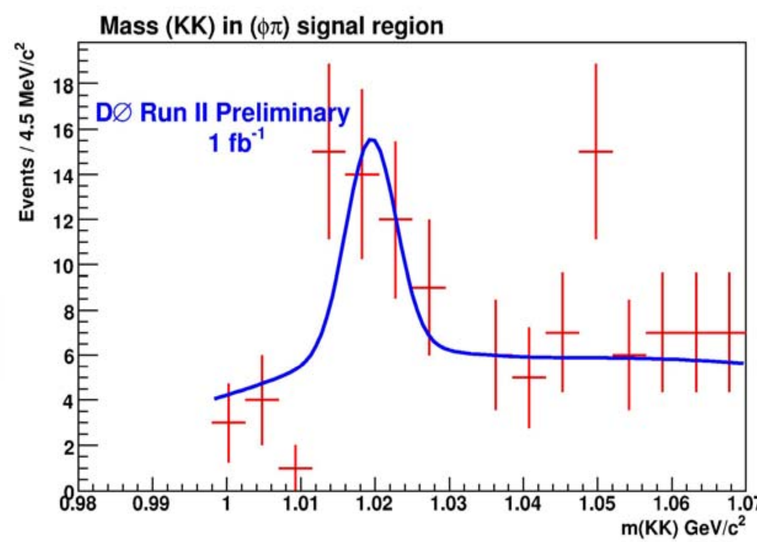


DØ $Br(B^0_s \rightarrow D^{(*)+}_s D^{(*)-}_s)$

- **19.3 ± 7.8 signal candidates**
- **Backgrounds**



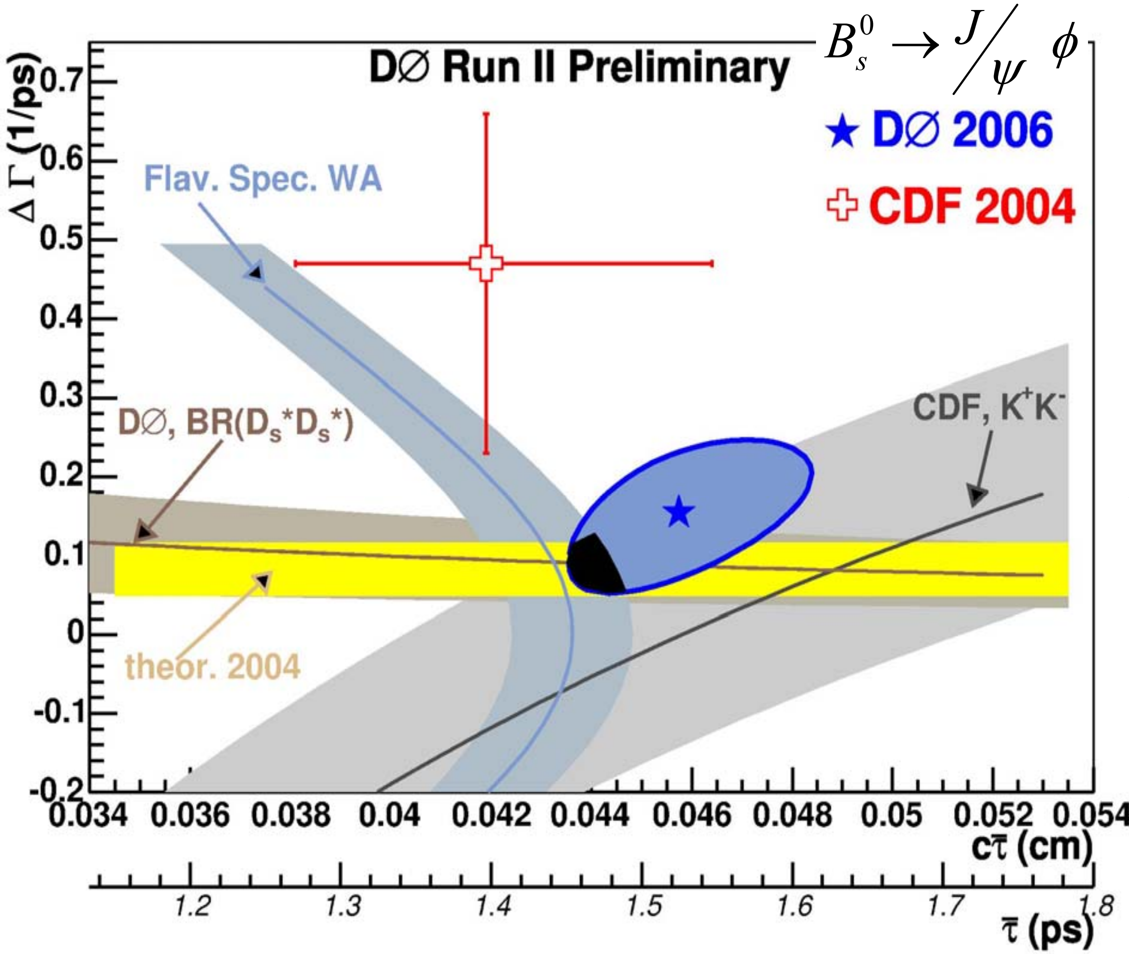
- $B \rightarrow D_s^{(*)+} D_s^{(*)-} K X$ 0.44 ± 0.30
- $B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-} X$ suppressed
- $B_s^0 \rightarrow \mu \nu D_s^{(*)} \phi X$ 1.27 ± 1.14
- $c\bar{c} \rightarrow \mu \phi D_s^{(*)}$ lifetime cuts



- $Br(B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-}) =$
$= 0.071 \pm 0.032\,(\text{stat})\,^{+0.029}_{-0.025}\,(\text{syst})$

$$\Delta\Gamma_{CP}/\Gamma(B^0_s) = 0.142 \pm 0.064(\text{stat})^{+0.058}_{-0.050}(\text{syst})$$

Combined $\Delta\Gamma_s$ Results



- **Theoretical prediction (Nierste)**

$$\Delta\Gamma_s = 0.10 \pm 0.03\ \mathrm{ps}^{-1} \left(\frac{f_{B_s}}{250\ \mathrm{MeV}} \right)^2$$

- ***Unofficial world average***

$$\Delta\Gamma_s = 0.097^{+0.041}_{-0.042}\ \mathrm{ps}^{-1}$$

$$\bar{\tau}_s = \frac{1}{\Gamma_s} = 1.461 \pm 0.030\ \mathrm{ps}$$

See the poster: "Measurement of the Lifetime Difference in the Bs System"

CP Violation in Mixing

- **Sensitive to new physics**
  - *Very small in SM for B_s system ~$2 \cdot 10^{-5}$*
  - *Could be enhanced up to $5 \cdot 10^{-3}$*
- **Develop and tune technique using B_d**

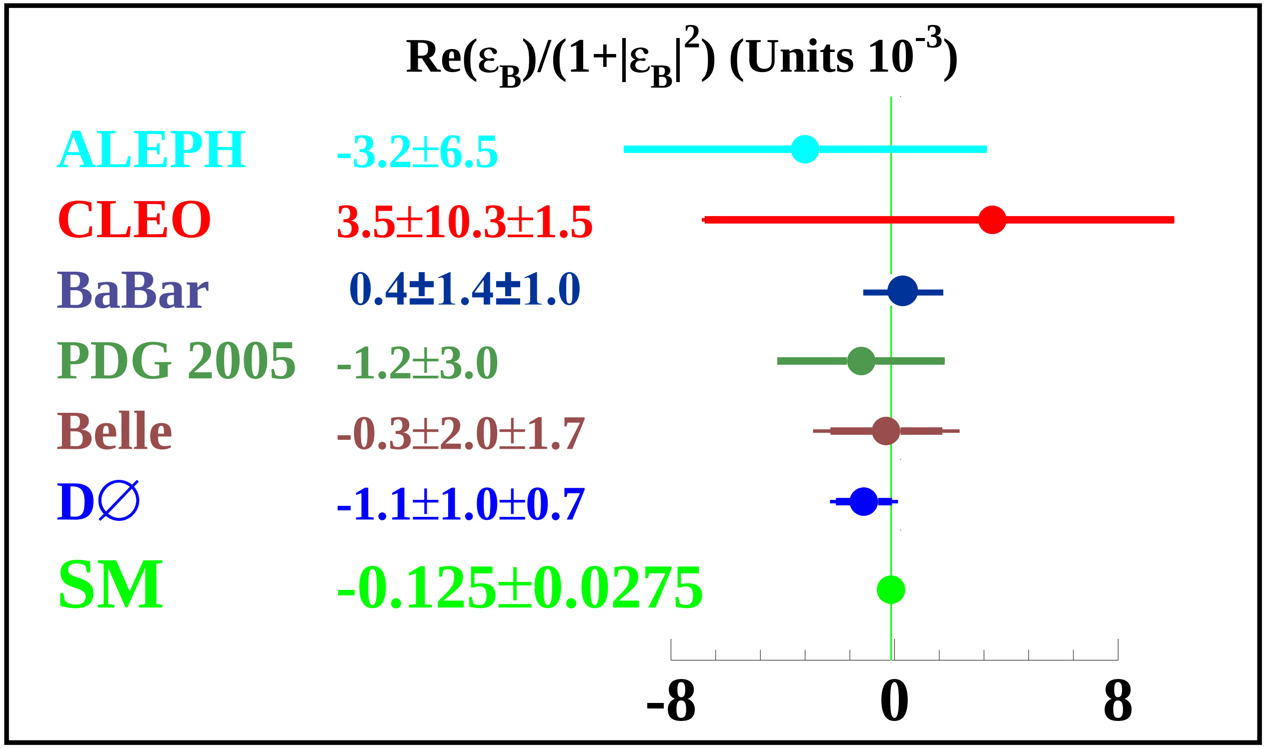
$$\frac{4\,\mathrm{Re}(\varepsilon_b)}{1+|\varepsilon_b|^2} \cong \frac{1-|q/p|^4}{1+|q/p|^4} = A_{SL} = (-5.0 \pm 1.1)\cdot 10^{-4}$$

- **CPV in Mixing can be obtained by measuring the asymmetry of the same sign lepton pairs coming from direct B decays:**

$$A_{SL} = \frac{N(b\bar{b} \to l^+l^+X) - N(b\bar{b} \to l^-l^-X)}{N(b\bar{b} \to l^+l^+X) + N(b\bar{b} \to l^-l^-X)}$$

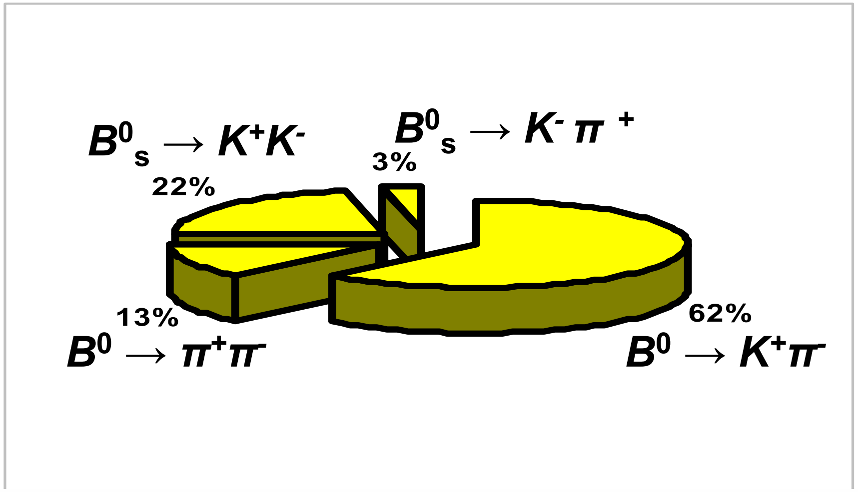
- **Difficulty of this measurement is in separating the asymmetry from detector effects**
- **Changing Magnet polarities is an important feature of DØ detector, which reduces significantly systematics in CP violation measurements**

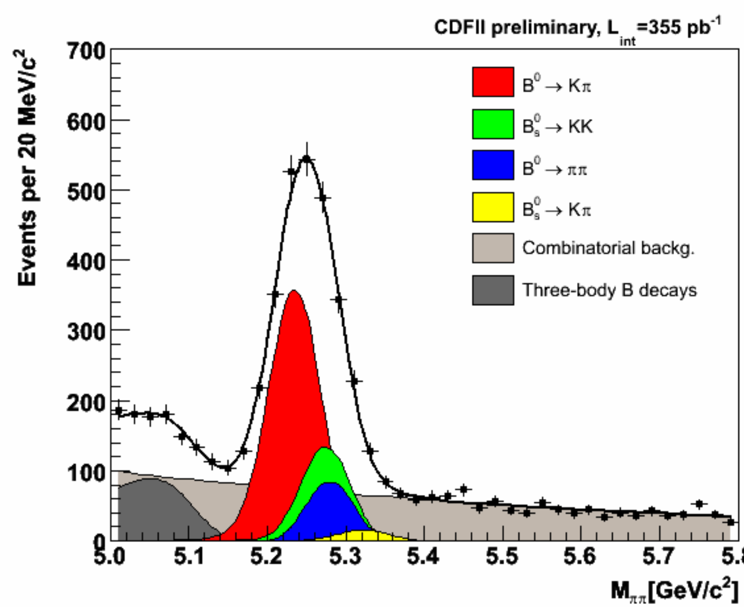
Results on ε_B



- The DØ result is the most precise measurement of ε_B
- Consistent with SM and other measurements
- Important step to the a_{fs} measurement

Measurements of Direct CP Violation @ CDF (360 pb^{-1})





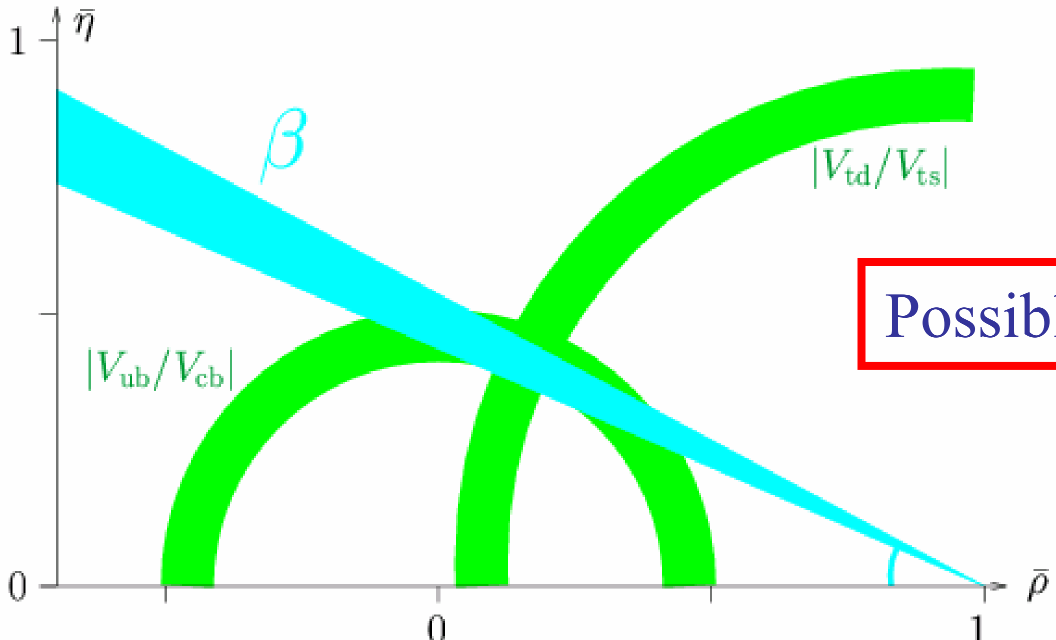
$$A_{CP}^{CDF}(B^0 \to K^+\pi^-) = -0.058 \pm 0.039\ (stat.) \pm 0.007\ (syst.)$$

$$A_{CP}^{Belle}(B^0 \to K^+\pi^-) = -0.113 \pm 0.022\ (stat.) \pm 0.008\ (syst.)$$

$$A_{CP}^{Babar}(B^0 \to K^+\pi^-) = -0.133 \pm 0.030\ (stat.) \pm 0.009\ (syst.)$$

- **Result is ~1.5σ different from 0, and compatible with *B*-factories**
- **Systematic uncertainties from CDF and *B*-factories are comparable**
- **Expect with data already available on disk**
  - ***2.5% statistical uncertainty***
  - ***first observation of $B^0_s \to K^-\pi^+$ decay***
    - ✓ **BR and CP asymmetry**
    - ✓ ***Model-independent NP-probe*** *(Lipkin, Phys.Lett.B621:126, 2005)*

Hopes 4 years ago



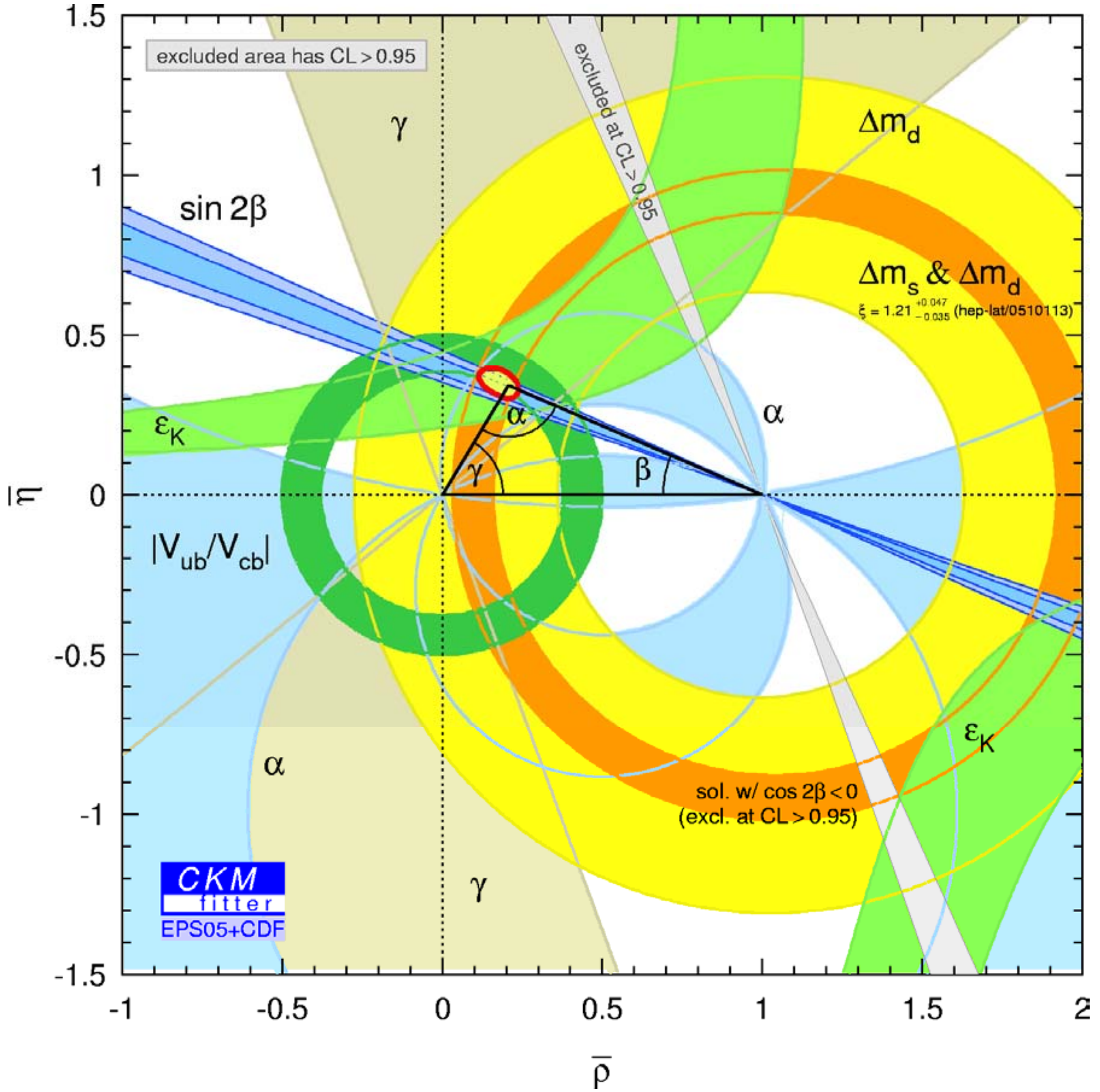
Possible situation in 2005

- $\sigma(\sin 2\beta) \approx 0.03$ by BABAR, Belle, ...
- $|V_{td}/V_{ts}|$ from Δm_s by CDF, DØ
- $|V_{ub}/V_{cb}|$ from $b \to u$ by BABAR, Belle

} Dominated by theoretical errors

© P. Soler

Unitarity Triangle Now



Conclusion

- **Exciting progress in measurements of key parameters of the B_s system at Tevatron**
  - **$\Delta\Gamma_s$ and Δm_s**
- **Good prospects for CP violation measurements**
  - **Results competitive with the B-factories**
  - **Extension to B_s sector**
- **Bunch of other B_s results from Tevatron**
- **These measurements indicate good understanding of the Detectors**
- **New results are coming**
- **Stay Tuned**