Measurement of the $B_s^0 - \overline{B}_s^0$ Oscillation Frequency

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Tollestrup Award Talk

Not Alone...

Of course, we could not perform this analysis among ourselves alone!

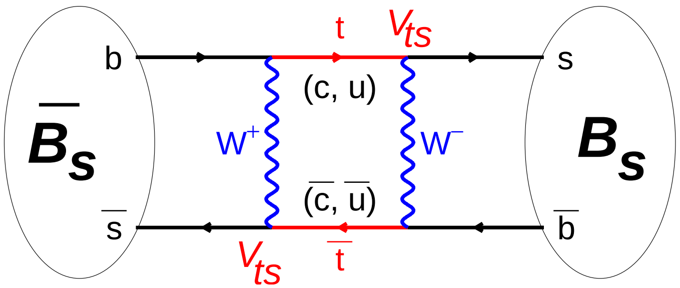
Not easy to define a line to separate work of people in many aspects

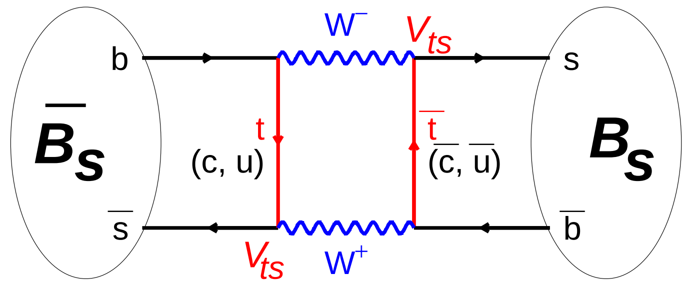
CDF Detector: several pieces of the detector are critical for this analysis, thanks to everyone

B_s Mixing Analysis:

- "Core" of the Group: $\sim$ 15 people
- Many other people involved helping in several parts

Neutral B Meson Mixing





Two-state mixing system

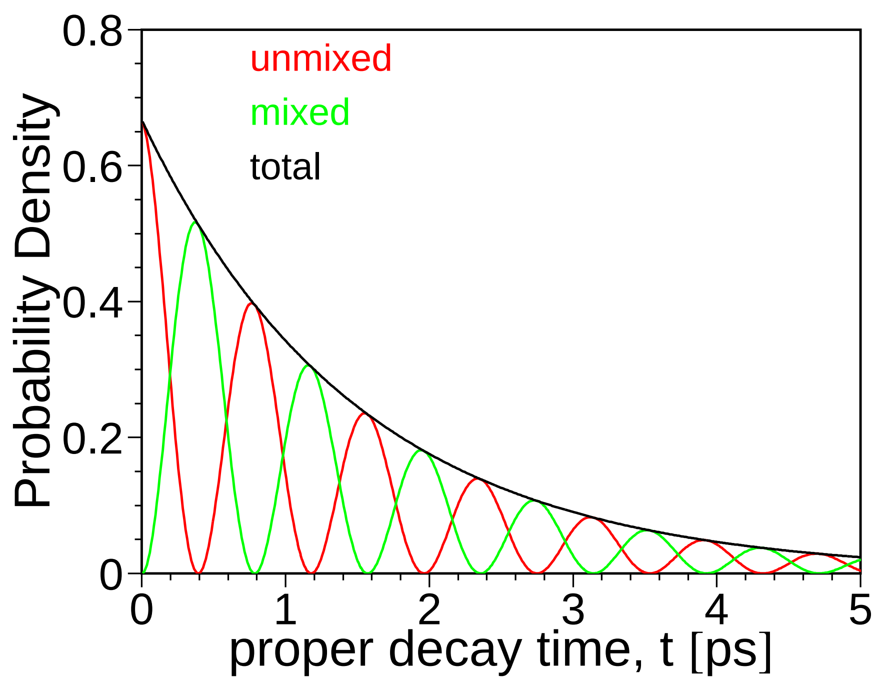
- "heavy" and "light" weak eigenstates
- B and $\overline{B}$ mass eigenstates

$$|B_s\rangle = \frac{1}{\sqrt{2}}(|B_{s,H}\rangle + |B_{s,L}\rangle)$$
$$|\overline{B}_s\rangle = \frac{1}{\sqrt{2}}(|B_{s,H}\rangle - |B_{s,L}\rangle)$$

Solution in proper time

$$P(t)_{B^0\to B^0} = \frac{1}{2\tau}e^{-t/\tau}(1+\cos\Delta m t)$$
$$P(t)_{B^0\to \overline{B^0}} = \frac{1}{2\tau}e^{-t/\tau}(1-\cos\Delta m t)$$

- mixing par. $\Delta m = m_H - m_L$

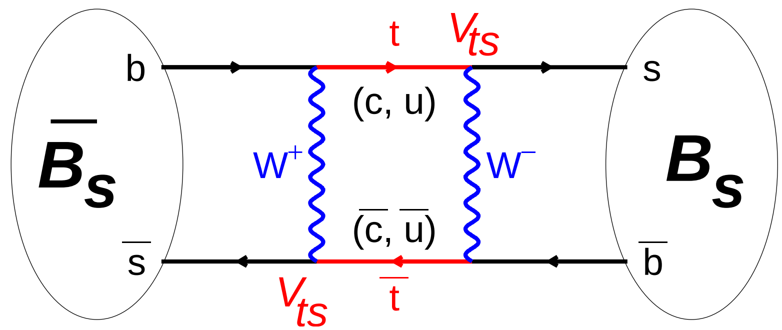


Theoretical Predictions for Δm

B^0/B_s^0 mix through box diagram:

$$\Delta m_q \propto m_{B_q} \hat{B}_{B_q} f_{B_q}^2 \left| V_{tb} V_{tq}^* \right|^2$$

$$q = s, d$$

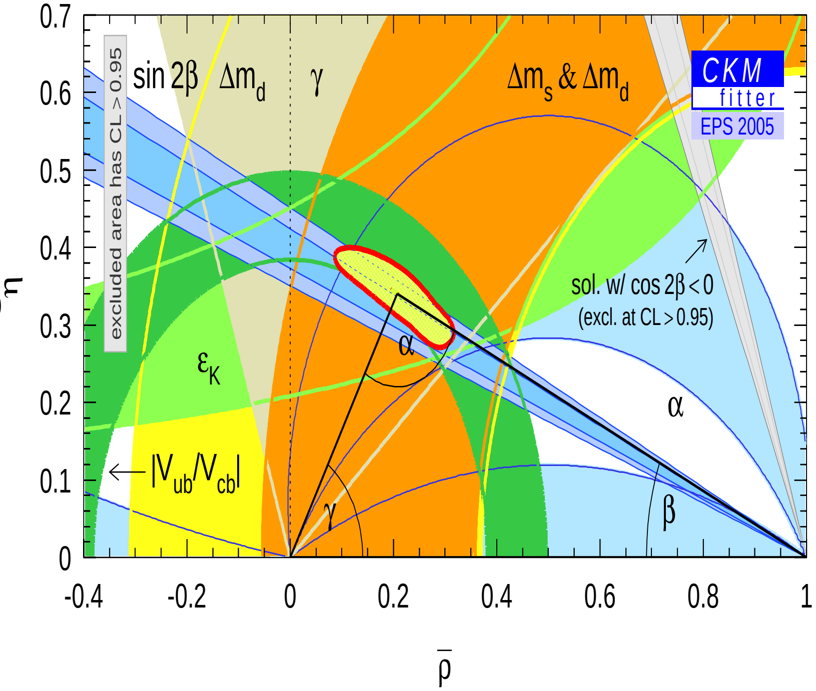


Uncertainties cancel in ratio:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

with $\xi = 1.21 \, ^{+0.047}_{-0.035}$

(Okamoto, Lattice 2005)

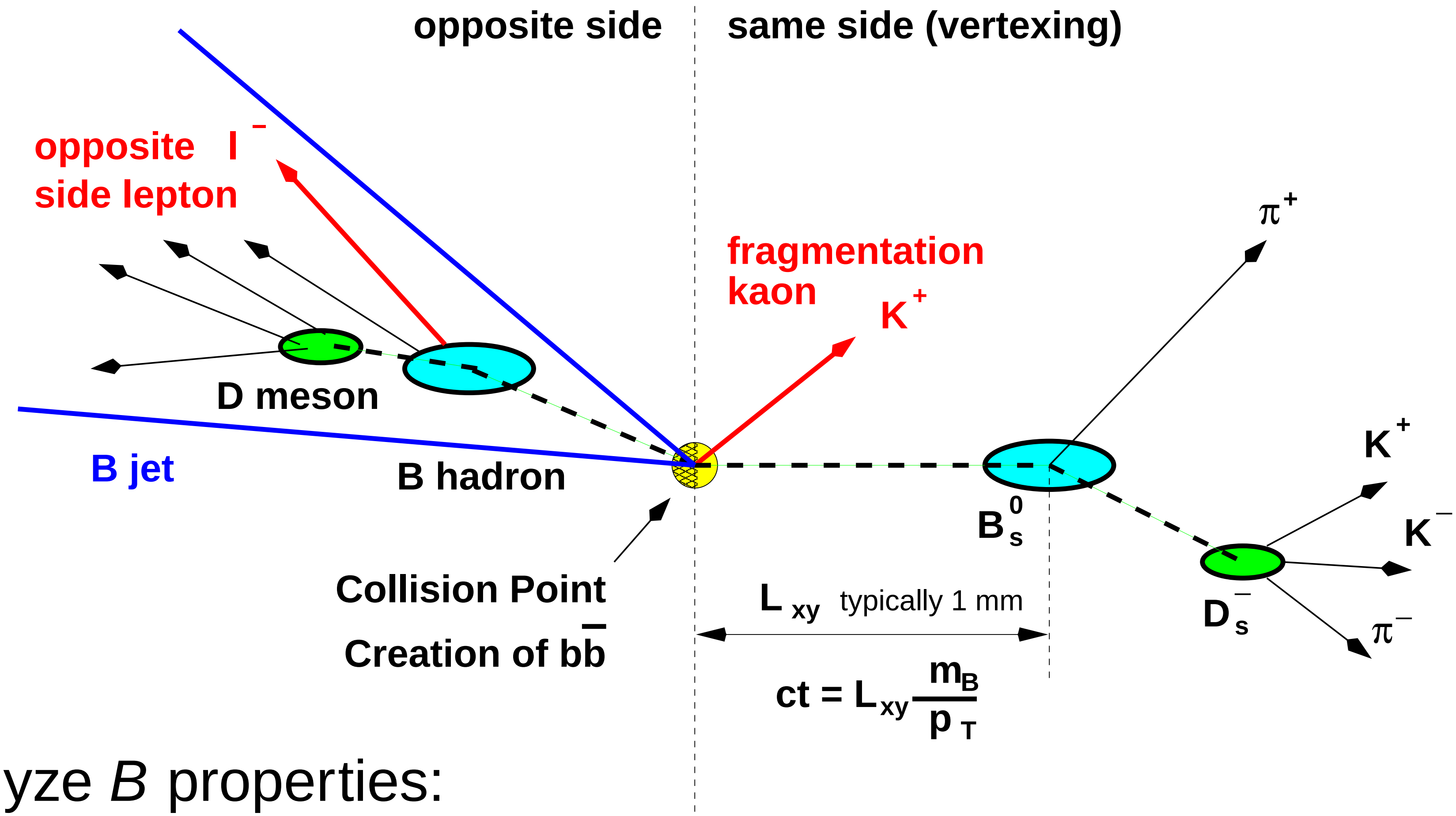


- \+ measure $\frac{\Delta m_s}{\Delta m_d} \Rightarrow$ find $\frac{|V_{ts}|^2}{|V_{td}|^2}$ to 2.5%
- \+ Δm_d measured to high precision
- \+ Δm_s not measured yet
- \+ Standard Model CKM fit:

$$\Delta m_s = 18.3 \, ^{+6.5}_{-1.5} \text{ ps}^{-1}$$

- \+ potential new physics discovery

Understanding Single B_s^0 Meson Candidate



Analyze *B* properties:

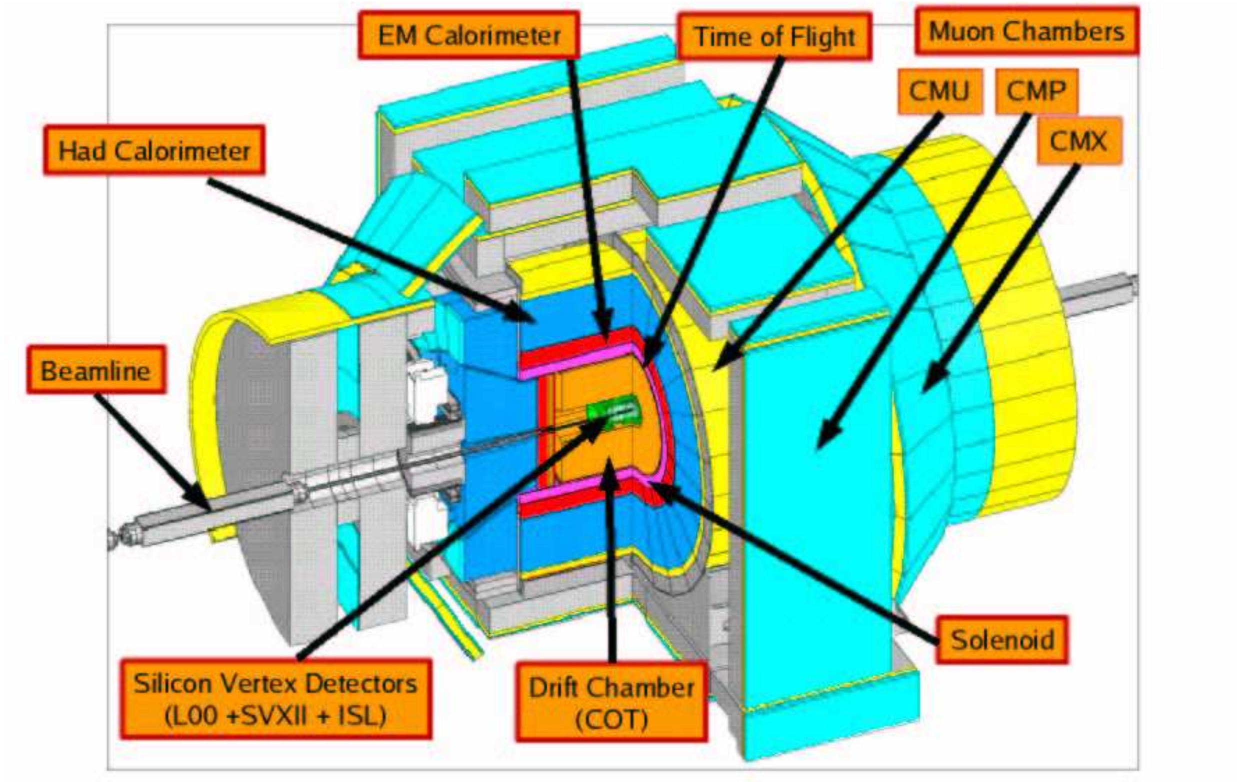
+ flavor at decay: from final state
+ proper decay length ct: in *B* rest frame
+ flavor at production: from flavor tagging

CDF Detector: Critical Components for Δm_s

- Yields:
  SVT based Triggers

- Proper decay time resolution:
  SVX-II, ISL, L00

- Tagging power:
  TOF, dE/dx in COT



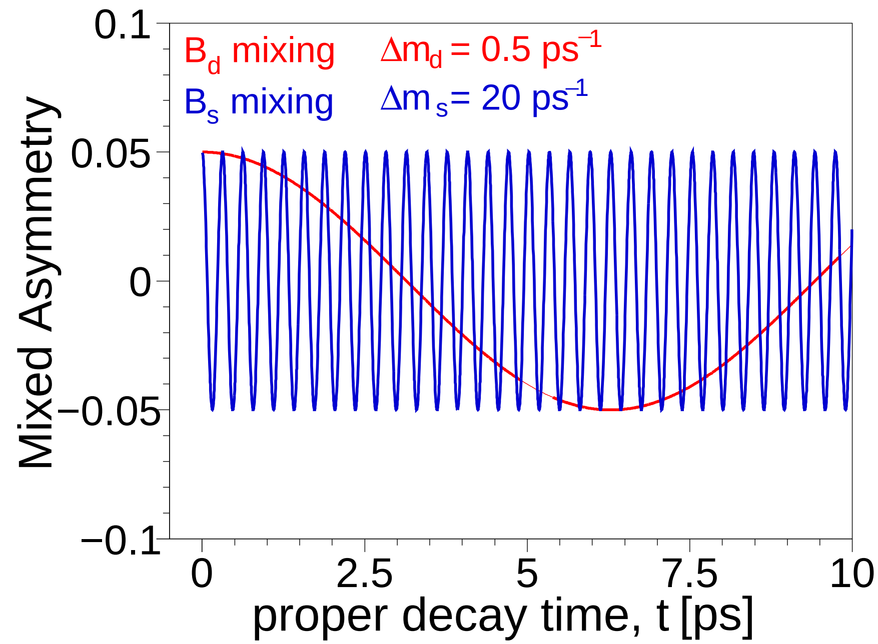
Δm_s Measurement

Why is this measurement so difficult?:

B_s mesons oscillate really really fast!

In order to measure:

$$\mathcal{A}_{mix}(t) = \frac{N_{unmix}(t) - N_{mix}(t)}{N_{unmix}(t) + N_{mix}(t)} = \mathcal{D} * \cos(\Delta m_s t)$$



Key elements of the analysis:

$$1/\sigma = \sqrt{\frac{S}{S+B}} e^{-\Delta m_s^2 \sigma_t^2/2} \sqrt{S \varepsilon \mathcal{D}^2/2}$$

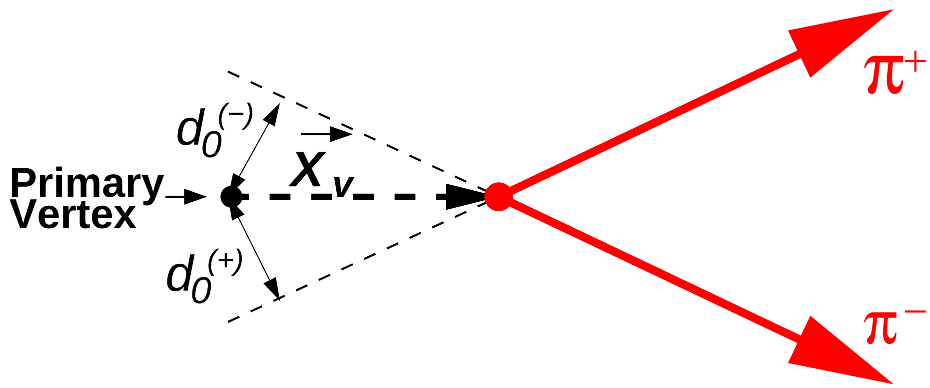
- + Statistics:
  - + hadronic modes
  - + semileptonic modes
- + Proper decay time resolution: fully reconstructed modes provide better accuracy
- + Production flavor: effective statistics, $S\varepsilon\mathcal{D}^2$

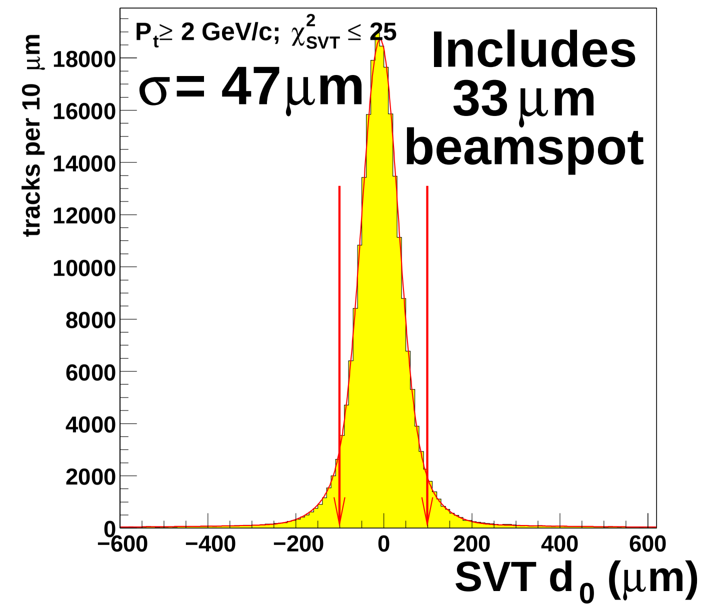
Efficiency: $\varepsilon = \frac{N_{wrong}+N_{right}}{N}$; Dilution: $\mathcal{D} = 1 - 2\frac{N_{wrong}}{N_{wrong}+N_{right}}$

Reconstructing B_s Mesons

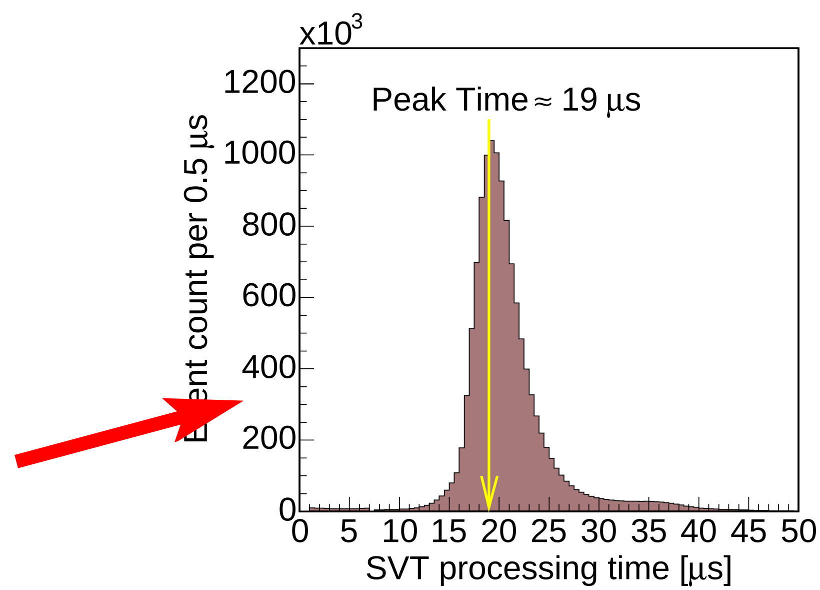
Triggering on Displaced Tracks

- trigger $B \rightarrow \pi\pi$, $B_s \rightarrow D_s\pi, \ell D_s X$
- challenge: read out SVX and track at 20+ kHz $\rightarrow$ SVT



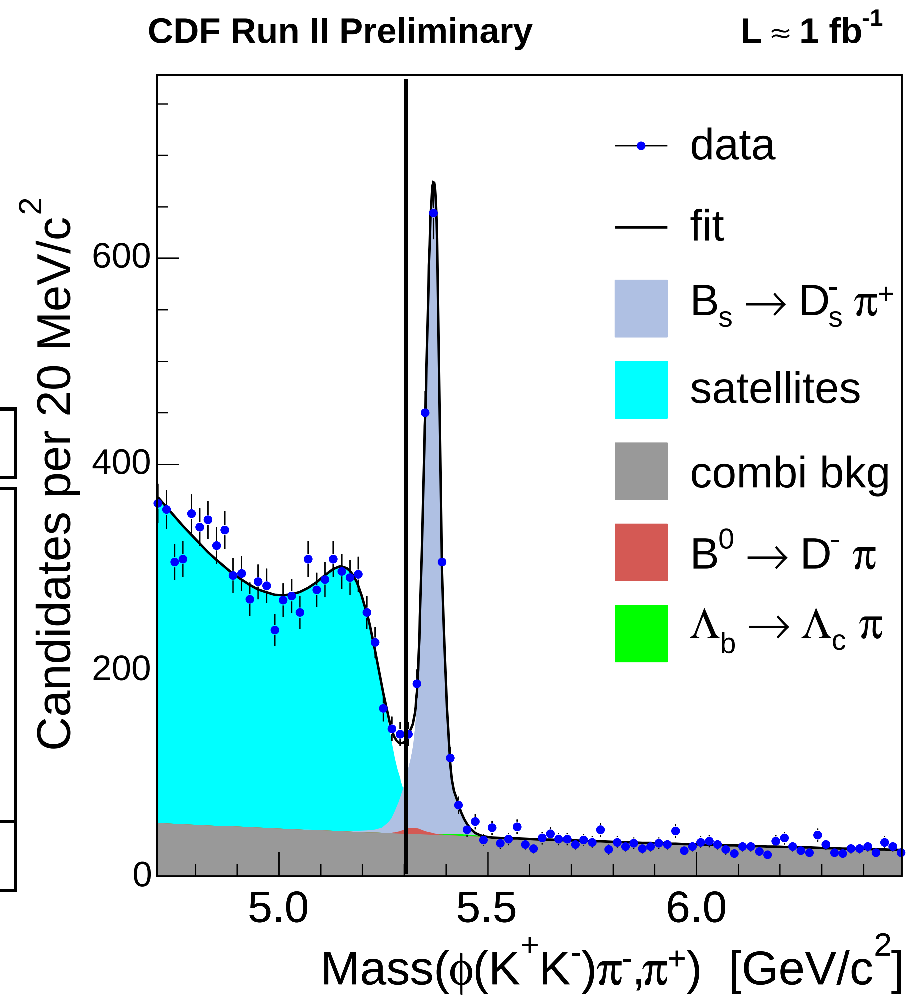


- trigger on 2 displaced tracks
  ($p_T > 2$ GeV/c, 120 $\mu m < |d_0| < 1$ mm)
- ~90%efficient in this p_T range
- mean processing time ~20 μs
- SVT $\rightarrow$ all B_s mixing samples



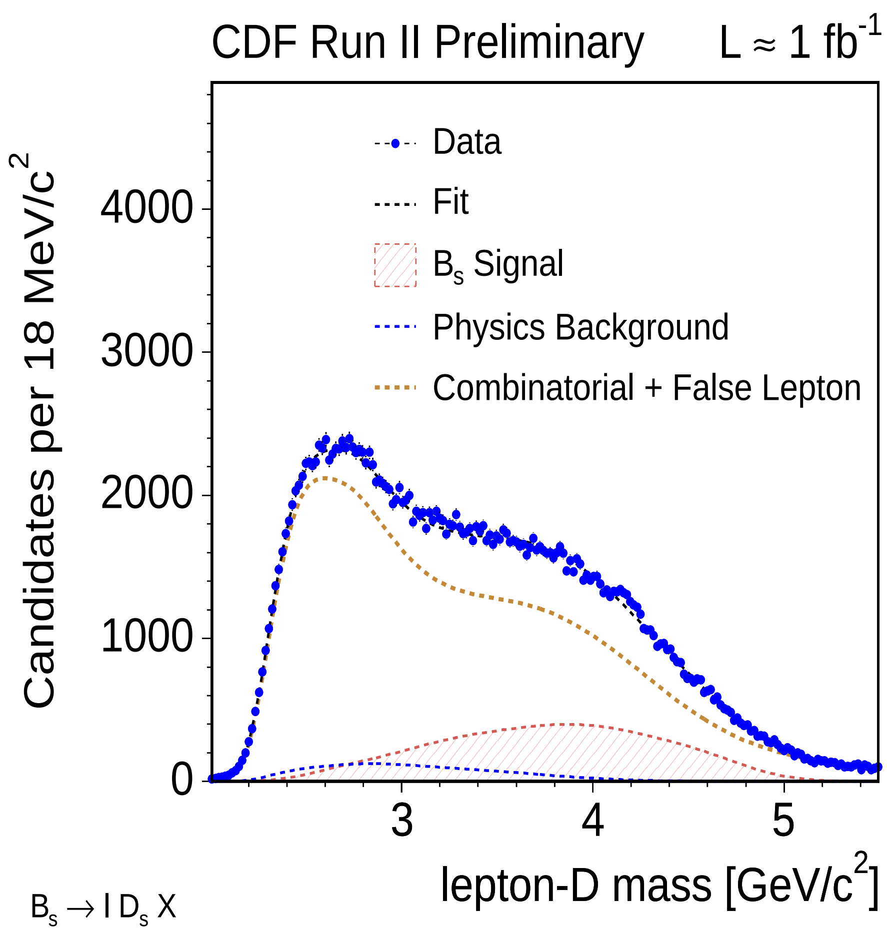
Fully Reconstructed Decays

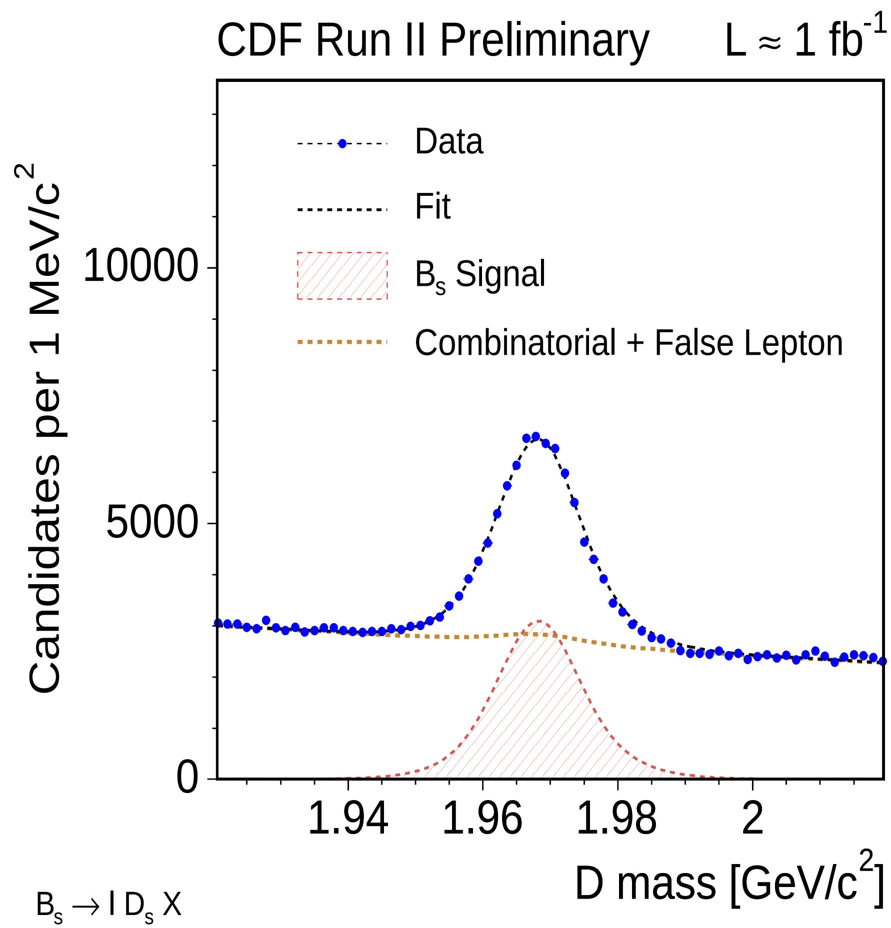
Decay	Candidates
$B_s \to D_s\pi, D_s \to \phi\pi$	1600
$B_s \to D_s\pi, D_s \to K^*K$	800
$B_s \to D_s\pi, D_s \to \pi\pi\pi$	600
$B_s \to D_s 3\pi, D_s \to \phi\pi$	400
$B_s \to D_s 3\pi, D_s \to K^*K$	200
Total	3600



Low background under B_s mass peak

Semileptonic Decays





$m(\ell D_s)$
New powerful variable used in the unbinned likelihood fit

$B_s \rightarrow D_s \ell X$
~48K Candidates
(75% B_s signal)

Proper Decay Time

&

Proper Decay Time Resolution

Proper Decay Time Reconstruction

+ Fully reconstructed decays:

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

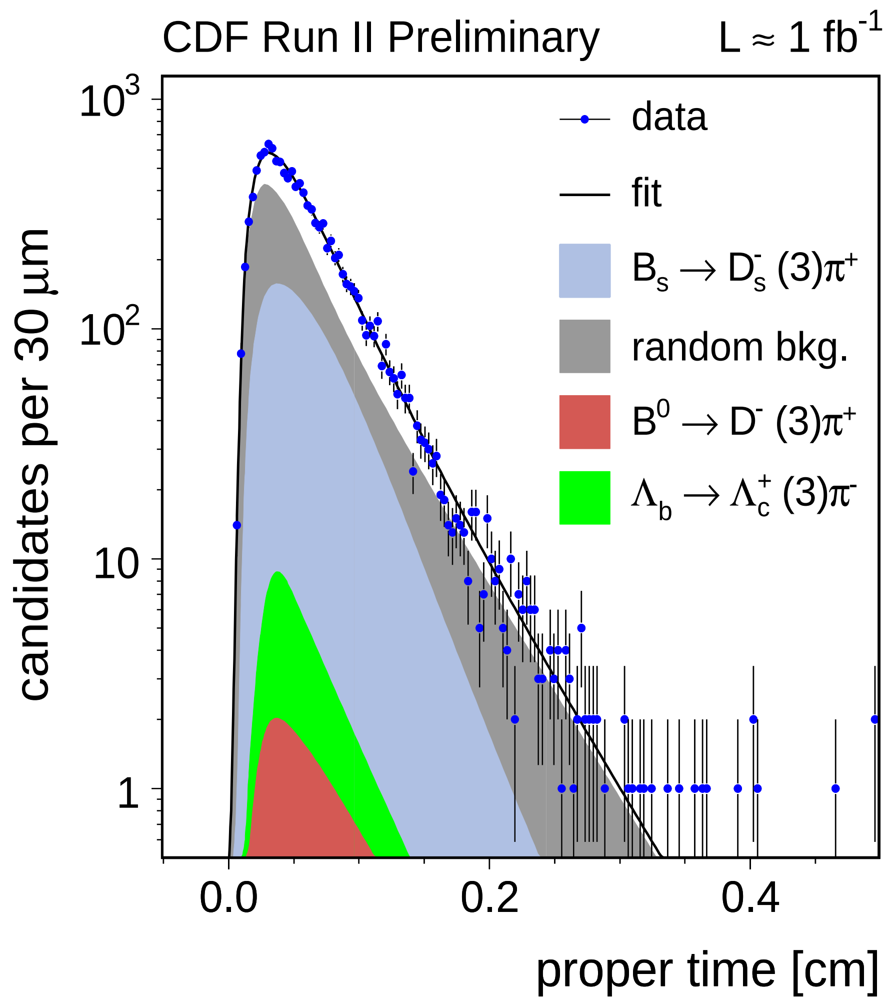
+ Semileptonic decays:

$$ct = L_{xy}^{\ell D} \frac{m_B}{p_T^{\ell D}} \cdot k$$

$$k = \left\langle \frac{p_T^{\ell D}}{p_T^B} \frac{L_{xy}^B}{L_{xy}^{\ell D}} \right\rangle \text{ from MC}$$

Model from well studied $B^{+/0}$ semileptonic decays

Lifetime measurements consistent with PDG



Proper Decay Time Resolution

$$\sigma_{ct} = \sqrt{(\sigma_{ct}^0)^2 + \left(ct \cdot \frac{\sigma_p}{p}\right)^2}$$

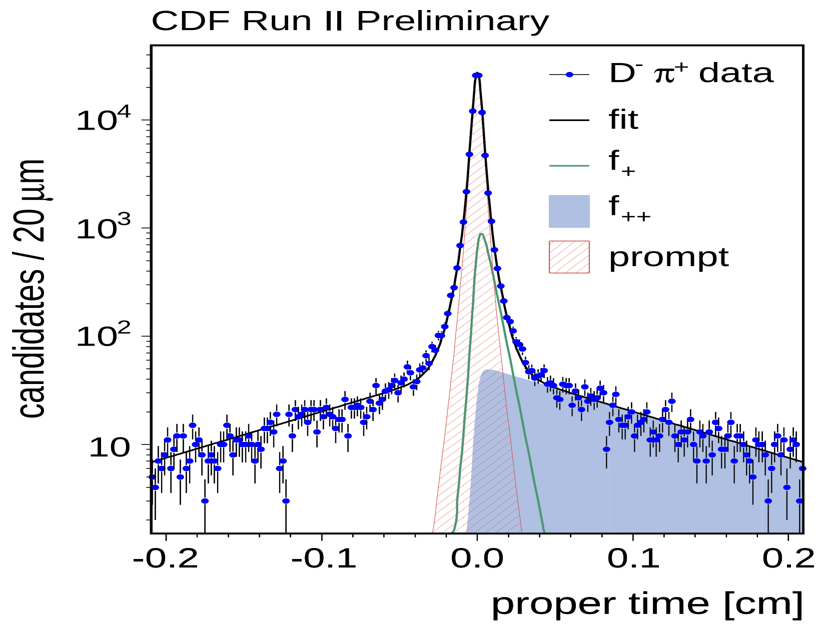
Hadronic $B_s \to D_s(3)\pi$:

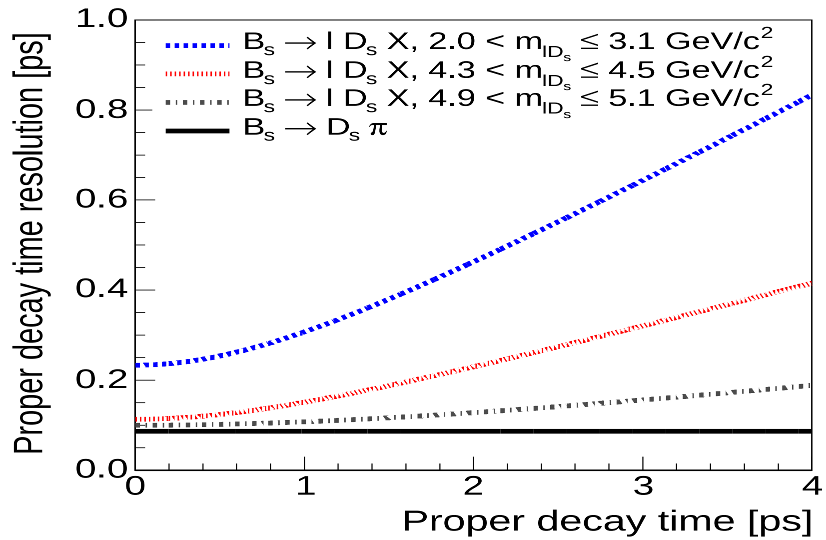
- $\sigma_{ct}^0 \sim 26\ \mu m\ (87\ fs)$
- $\sigma_p/p < 1\%$

Semileptonic $B_s \to D_s \ell X$:

- $\sigma_{ct}^0 \sim$ 30-70 μm (100-230 fs)
- $\sigma_p/p \sim$ 3-20%

Variation of k-factor with $m(\ell D)$ significantly improves decay time resolution in semileptonic





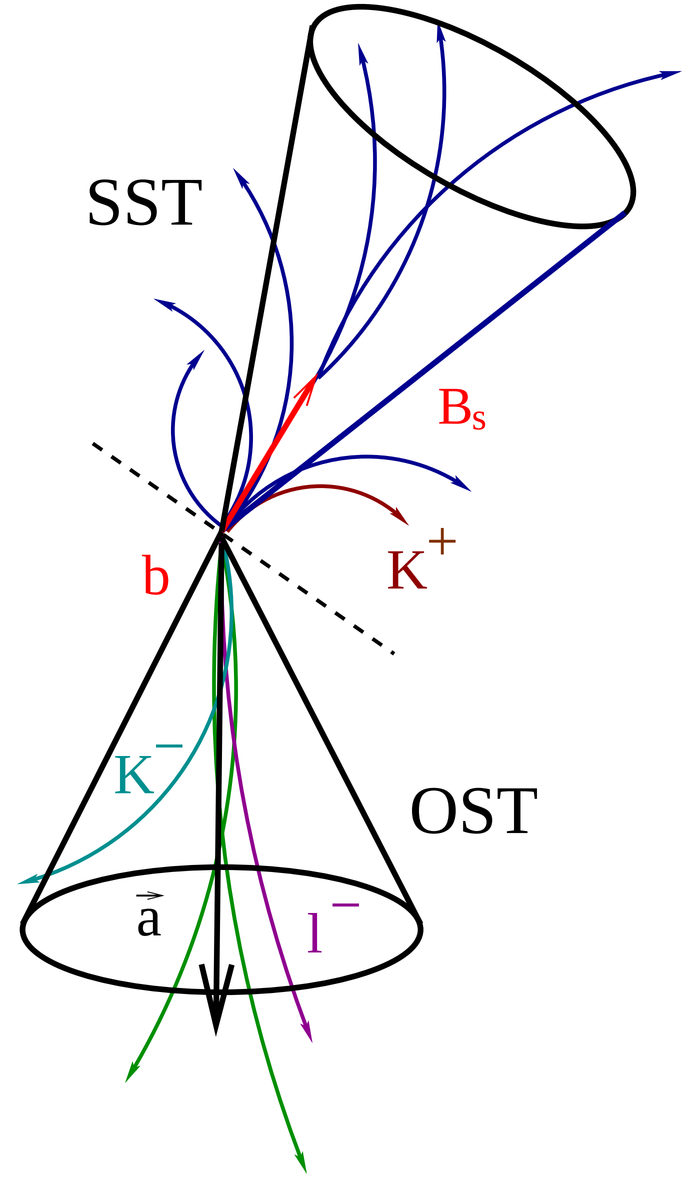
b Flavor Tagging

Opposite-Side Tagging

B mesons are produced in pairs → production flavors are correlated

- Jet-Charge-Tagging (high efficiency, low purity)
  Weighted sum of fragmentation and decay tracks of the opposite-side *B*
- Lepton-Tagging (high purity, low efficiency)
  Semileptonic decay of opposite *B* (≈ 20% *B*'s mix before the decay)

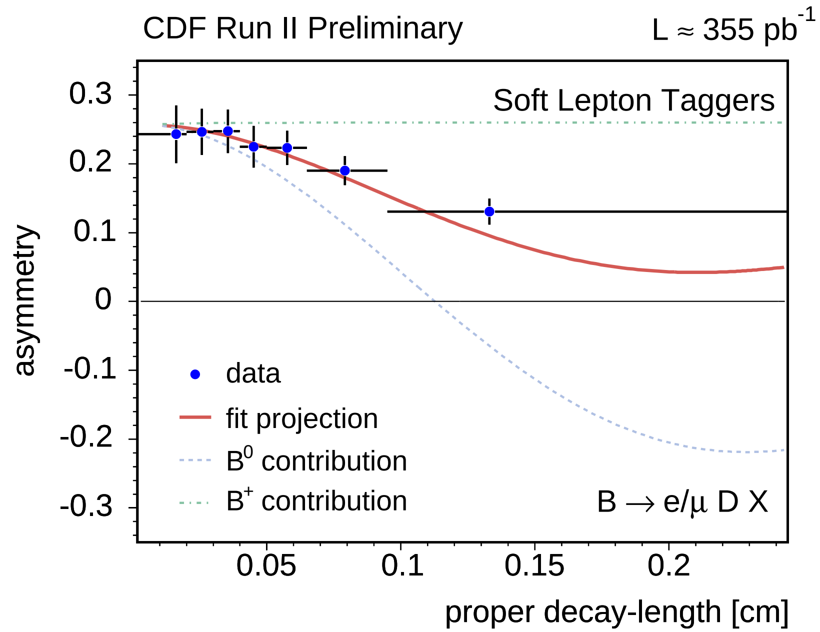
  - Often opposite-side *B* not in detector acceptance
  - Additional gain in tagging performance:
    - + Classification of events (dilution parametrization)
    - + Combination of all opposite-side tagging information



OST in B^+ & B^0

- Important test of the fitter (complex unbinned Likelihood Fit)
- Calibration of opposite-side taggers

(opposite-side *B* independent of signal side)

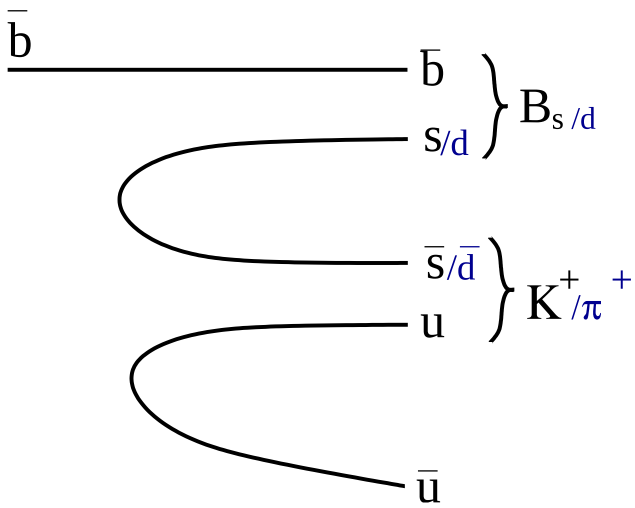


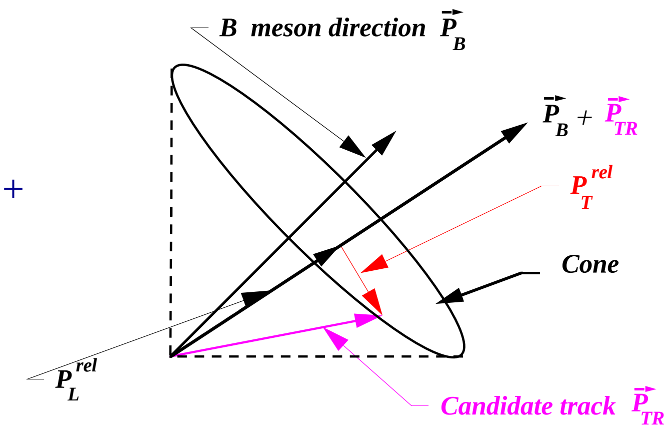
εD^2 (semil.) = 1.54 ± 0.05% εD^2(hadr.) = 1.47± 0.10%

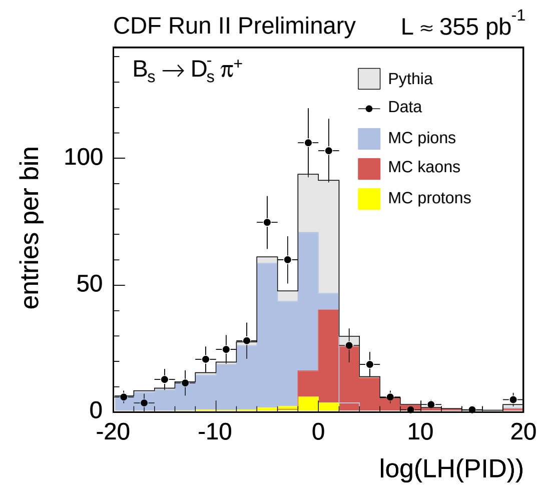
Δm_d (semil.) = 0.509 ± 0.019 ps^{-1} Δm_d (hadr.) = 0.536± 0.029 ps^{-1}

(Consistent with PDG - less precise than *B* factories, but most precise semileptonic Δm_d measurement at the TeVatron)

Same-Side (Kaon) Tagger (I)





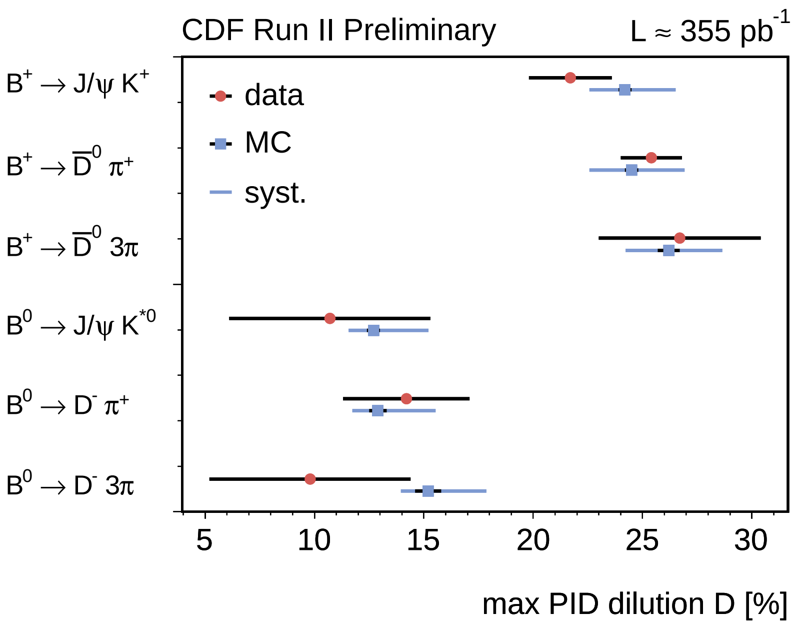


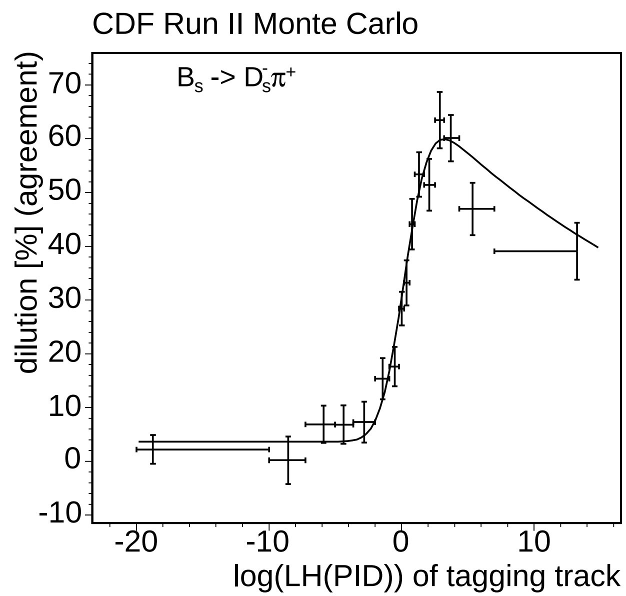
- Charge of closest fragmentation track correlated to *B* production flavor
- Particle ID helps to select tagging kaons (TOF & dE/dx)
- SSKT performance can NOT be determined on data before B_s mixing is observed
  Understanding of Monte Carlo crucial!

Same-Side Kaon Tagger (II)

Different tagging algorithms test different event properties (select tagging track by momentum, by kaon probability, ...)

Very good data MC agreement in all algorithms and decay modes!





Tagging dilution as a function of kaon probability

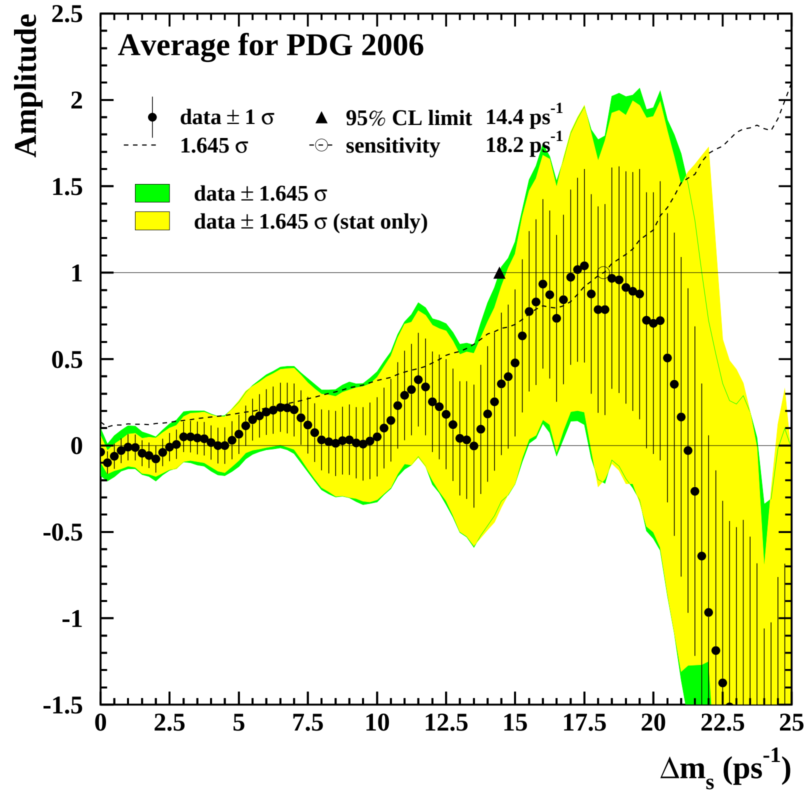
$\varepsilon D^2(\textit{semil.}) = 4.0 \pm 1.12\%$, $\varepsilon D^2(\textit{hadr.}) = 3.42 \pm 0.96\%$

Overall Tagging performance enlarged by $\times$ 3-4!

B_s Oscillation Analysis

Amplitude Scan Notations

- $\mathcal{P} \propto (1 \pm A\, D \cos(\Delta m\, t))$
- $A = 1$ for oscillation signal
- Scan Δm; do fit; record A, σ_A
  - Sensitivity: $1.645 \cdot \sigma_A = 1$
  - Limit: $A + 1.645 \cdot \sigma_A = 1$

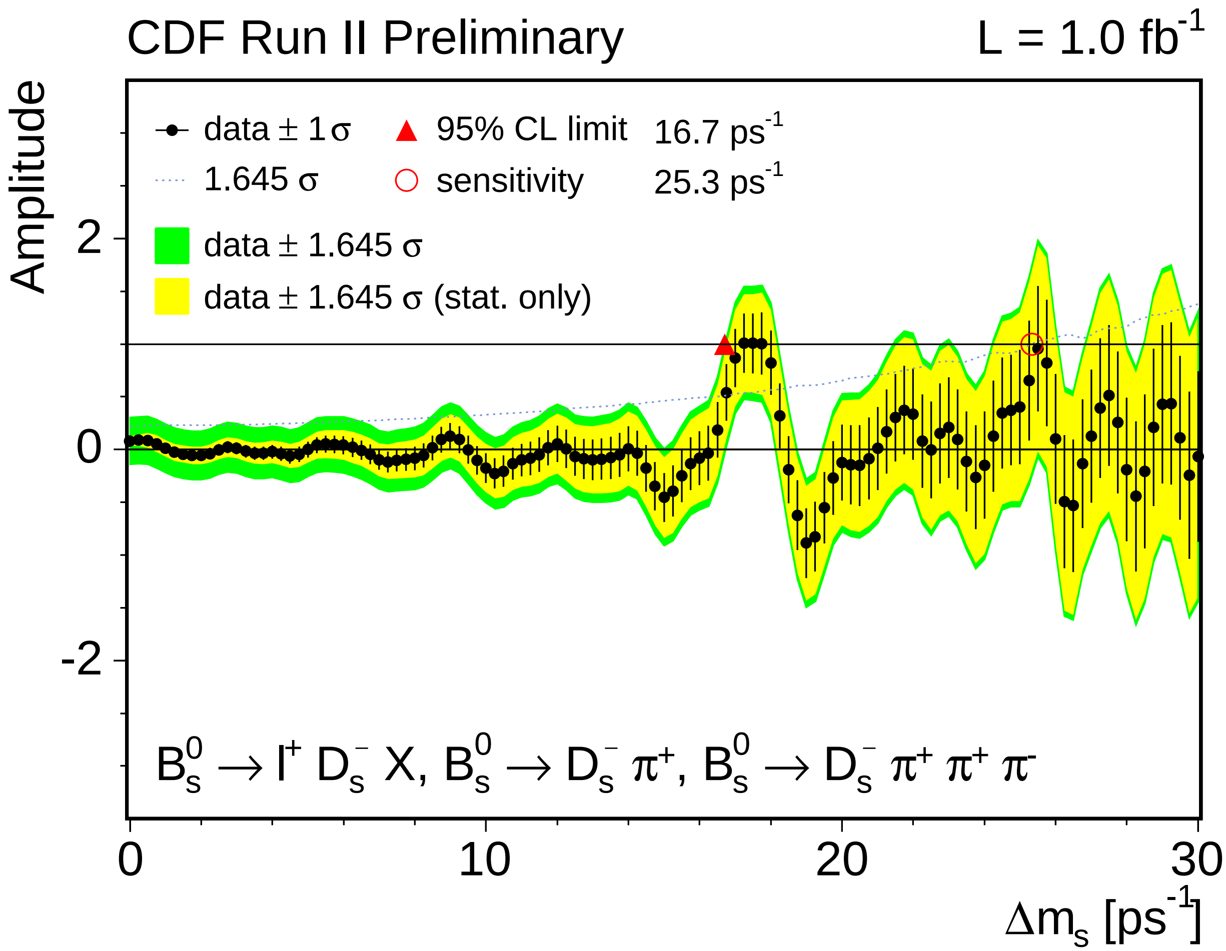


Powerful method: allows combination of different analyses

Expect to observe mixing, if it is within sensitivity

The Data

Combined Amplitude Scan



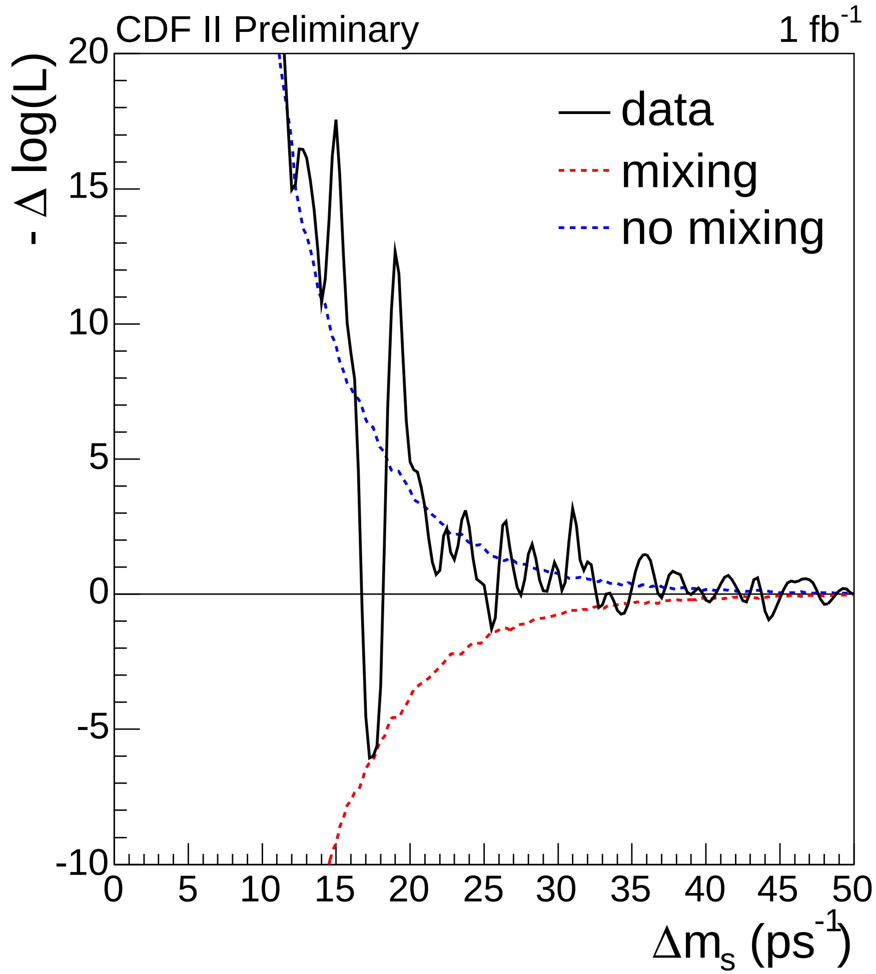
$\mathcal{A}$ compatible with 1 for $\Delta m_s \sim 17.25$ ps^{-1}!

$\mathcal{A}/\sigma_{\mathcal{A}}(\Delta m_s = 17.25 \text{ ps}^{-1}) \sim 3.5$

Probability of being background fluctuation: 0.5%

→→→ Measure Δm_s

Δm_s Measurement



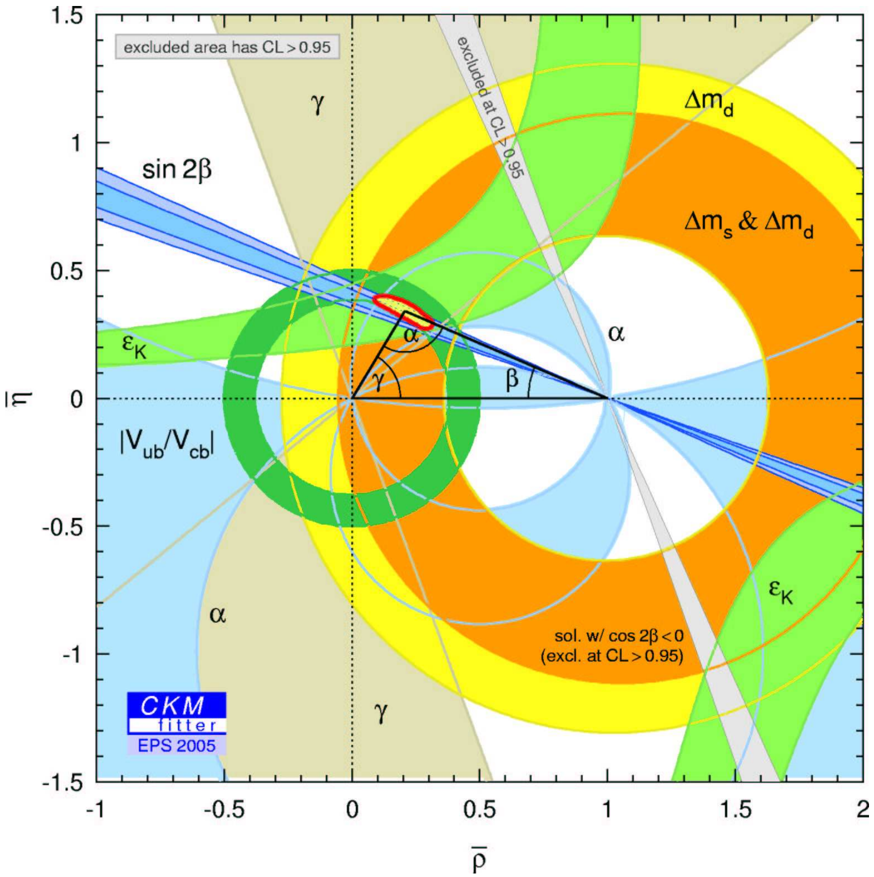
Δm_s in [17.00, 17.91] ps^{-1} at 90% C.L.

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

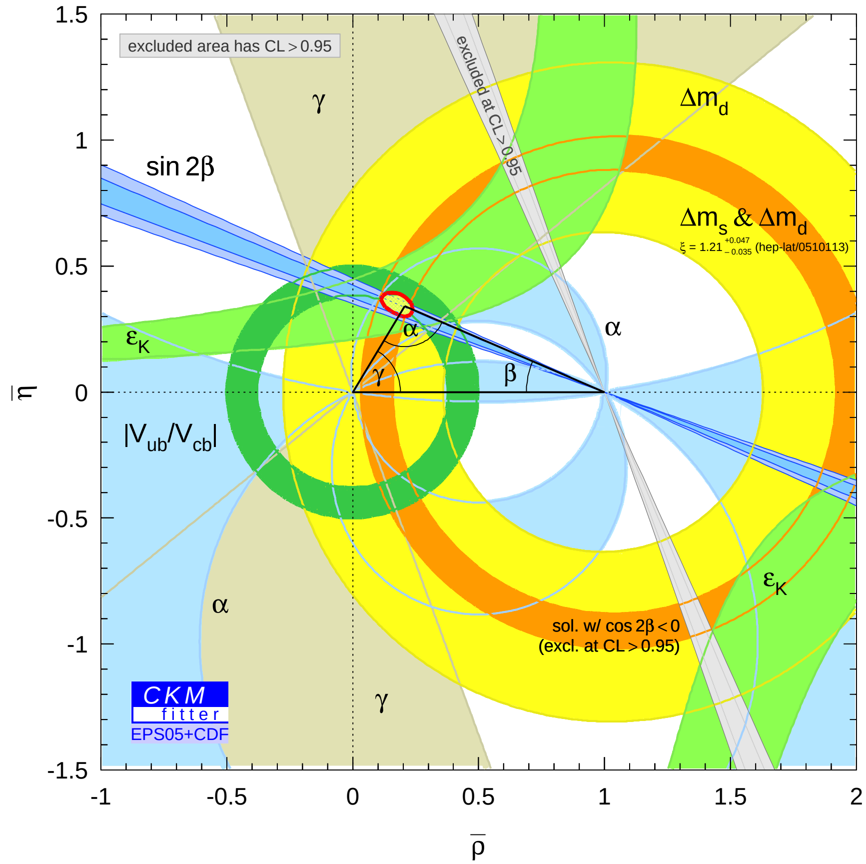
$$\Delta m_s = 17.33^{+0.42}_{-0.21}(stat.) \pm 0.07(syst.)\mathrm{ps}^{-1}$$

Systematic dominated by the *ct* scale, any other effect very small

Summary



EPS 2005



EPS 2005 + CDF 2006

Use $\Delta m_d/\Delta m_s$ ratio to infer: $|V_{td}|/|V_{ts}| = 0.208\,^{+0.008}_{-0.007}$

Compare to Belle $b \to d\gamma$: $|V_{td}|/|V_{ts}| = 0.199\,^{+0.026}_{-0.025}(exp.)\,^{+0.018}_{-0.015}(th.)$