Observation of B_s mixing

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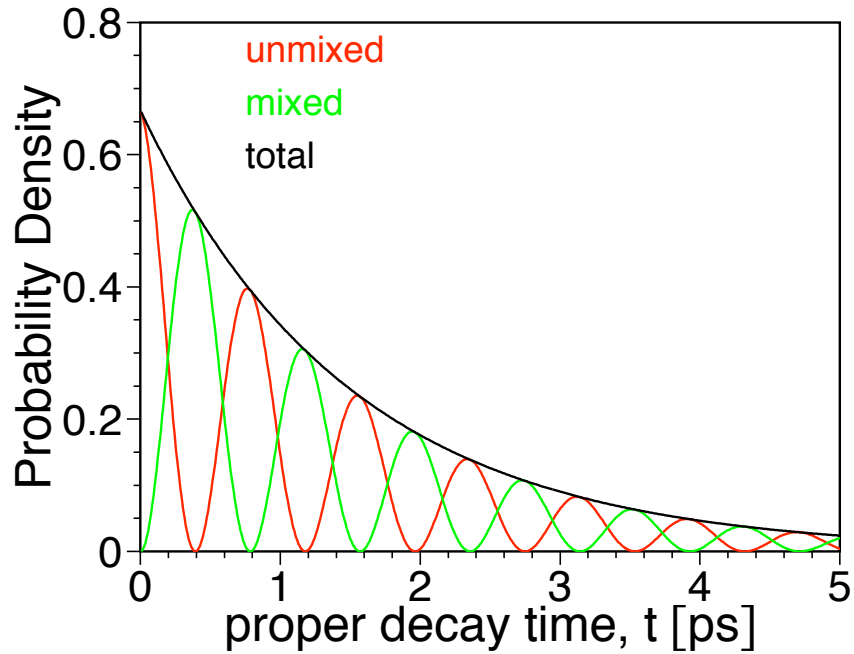
Flavor Oscillations

- described by basic quantum mechanics
- two-state system: { B, $\underline{B}$ }
- $H = H_0 + H_{\Delta B}$
  - diagonalize Hamiltonian
- mass eigenstates: { B_H, B_L }
  - separately evolve in time
- mass difference

  $\Delta m = m_H - m_L$

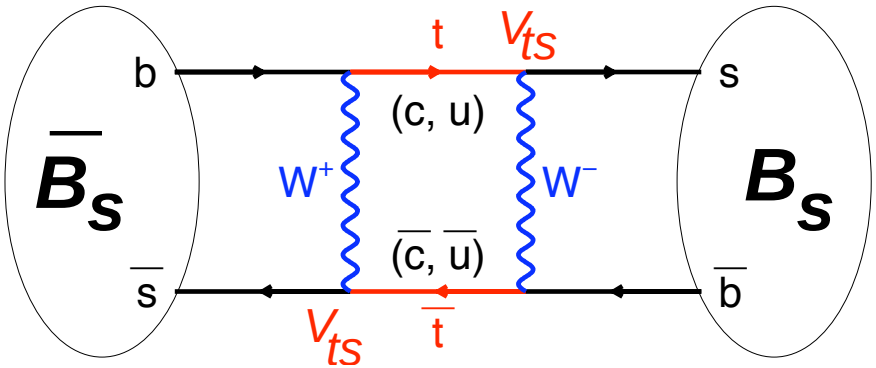


$$\mathcal{P}(B \to \bar{B}) \sim \frac{e^{-t/\tau}}{2\tau}(1 - \cos \Delta m\, t)$$

determines oscillation frequency of the system

In the Standard Model

- Mixing occurs via 2nd order flavor changing weak transitions



$$\Delta m_q \propto |V_{tq}|^2$$

- Ratio of B_s^0 and B_d^0 oscillation frequencies

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B^0}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

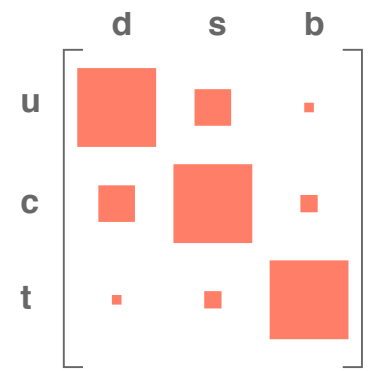
allows precise determination of CKM elements

- Δm_d measured to high precision
- Δm_s had not been measured

Flavor Parameters CKM matrix

Cabibbo-Kobayashi-Maskawa matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



Wolfenstein parameterization

- CKM matrix unitarity condition

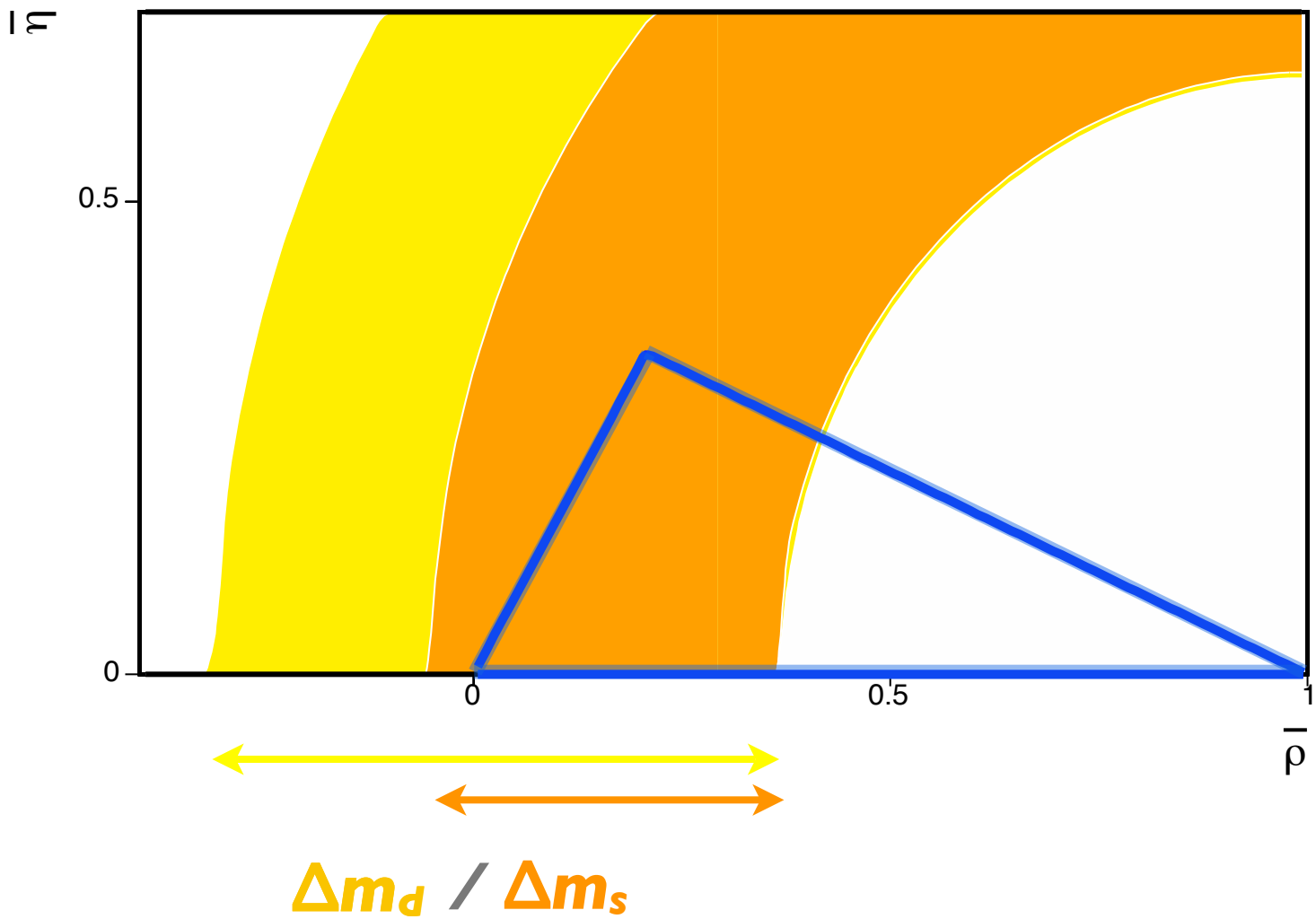
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

may be represented as a triangle in complex plane

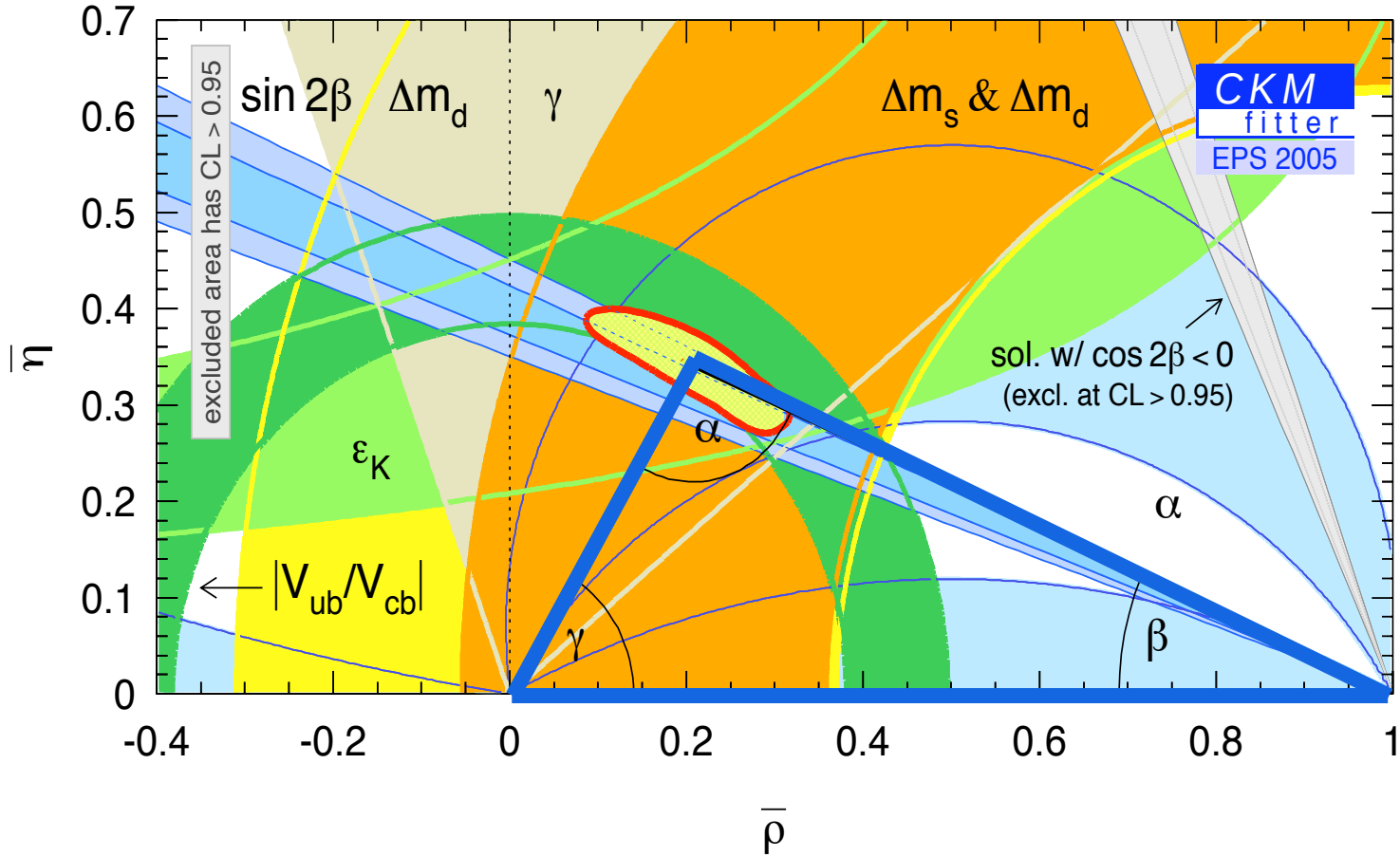
- in terms of re-scaled ρ and η parameters

$$\bar{\rho} = (1-\lambda^2/2)\,\rho \qquad \bar{\eta} = (1-\lambda^2/2)\,\eta$$

The Beauty Unitarity Triangle



Full UT/CKM Fit



Before Δm_s measurement

History *a 20 year quest*

1987

first evidence of B^0 mixing by UA1 — PLB 186, 247 (1987)

followed by observation of B^0 mixing by Argus — PLB 192, 245 (1987)

1989

CLEO confirms Argus results — PRL 62, 2233 (1989)

1990s

inclusive B mixing measurements from LEP establish B_s mixing

1993

first time dependent measurements of Δm_d by ALEPH — PLB 313, 498 (1993)

first lower limit on Δm_s by ALEPH — PLB 322, 441 (1994)

1999

CDF Run I result on Δm_s: $\Delta m_s > 5.8\ ps^{-1}$ — PRL 82, 3576 (1999)

2005

DØ first result Δm_s: $\Delta m_s > 5.0\ ps^{-1}$

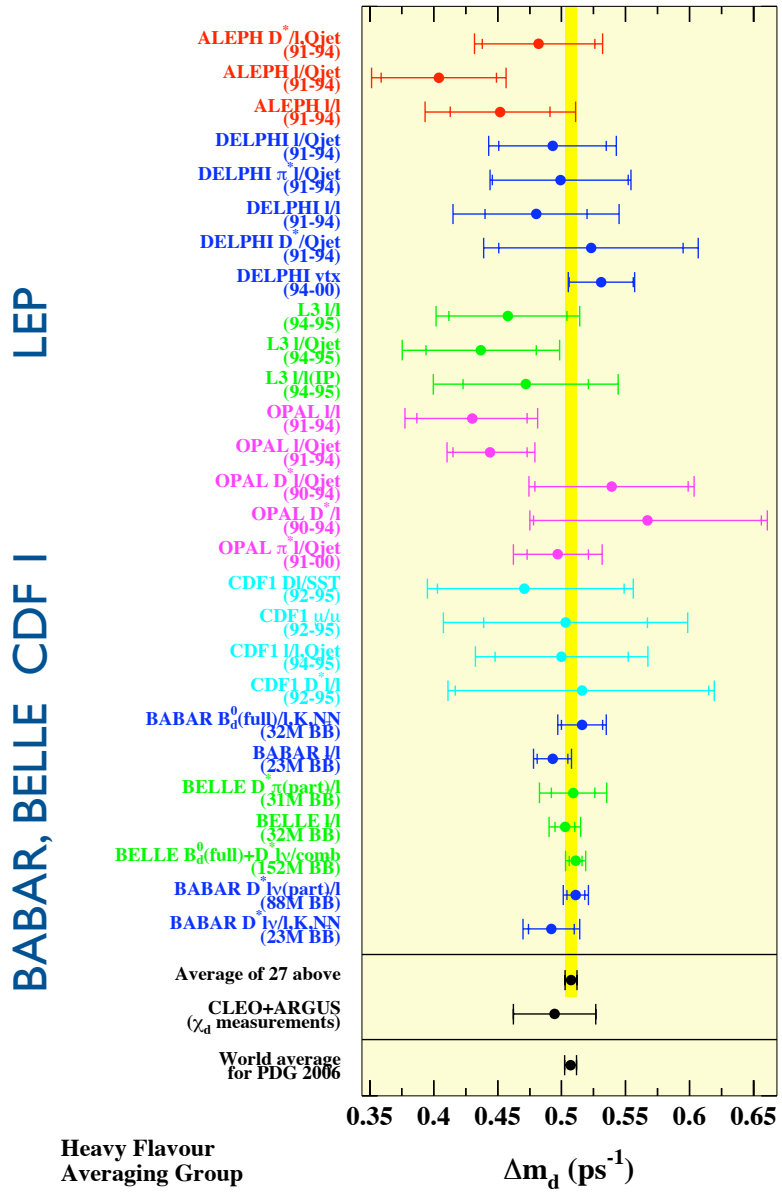
CDF Run II first results Δm_s: $\Delta m_s > 7.9\ ps^{-1}$

2006

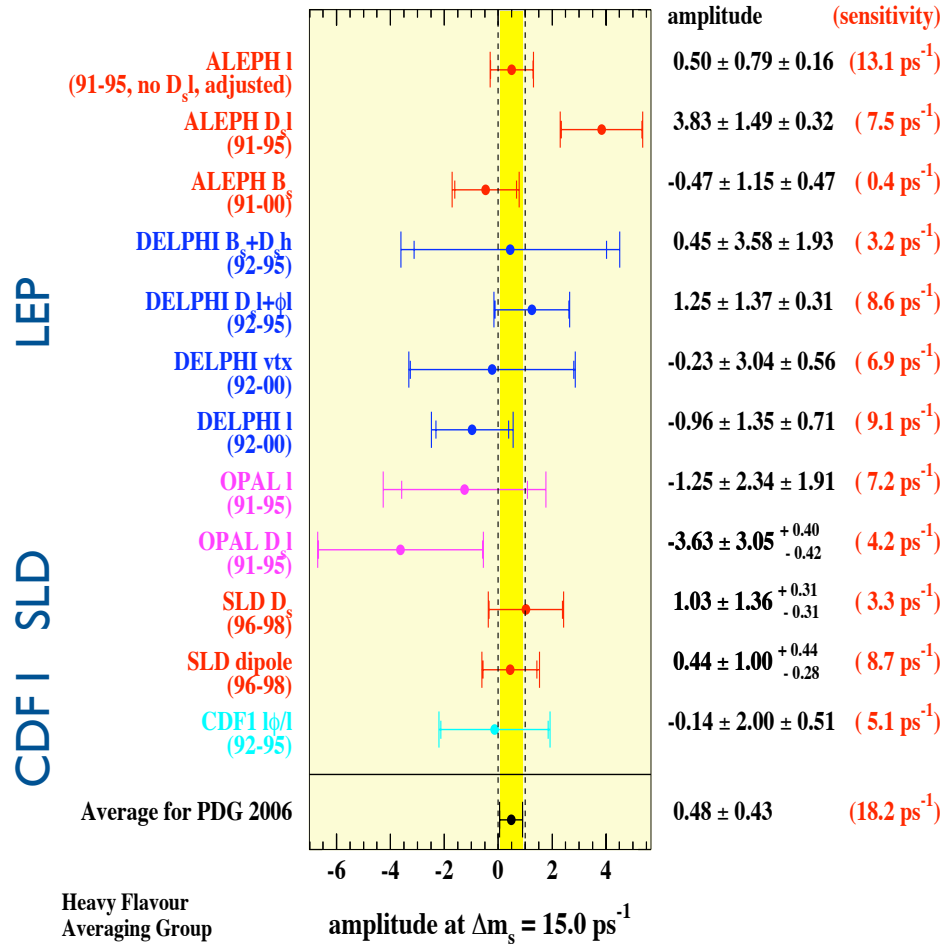
DØ reports interval: $\Delta m_s \in [17,21]\ ps^{-1}$ at 90% CL — PRL 97, 021802 (2006)

CDF Run II first measurement $\Delta m_s = 17.31^{+0.33}_{-0.18} \pm 0.07\ ps^{-1}$ — PRL 97, 062003 (2006)

B mixing status



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

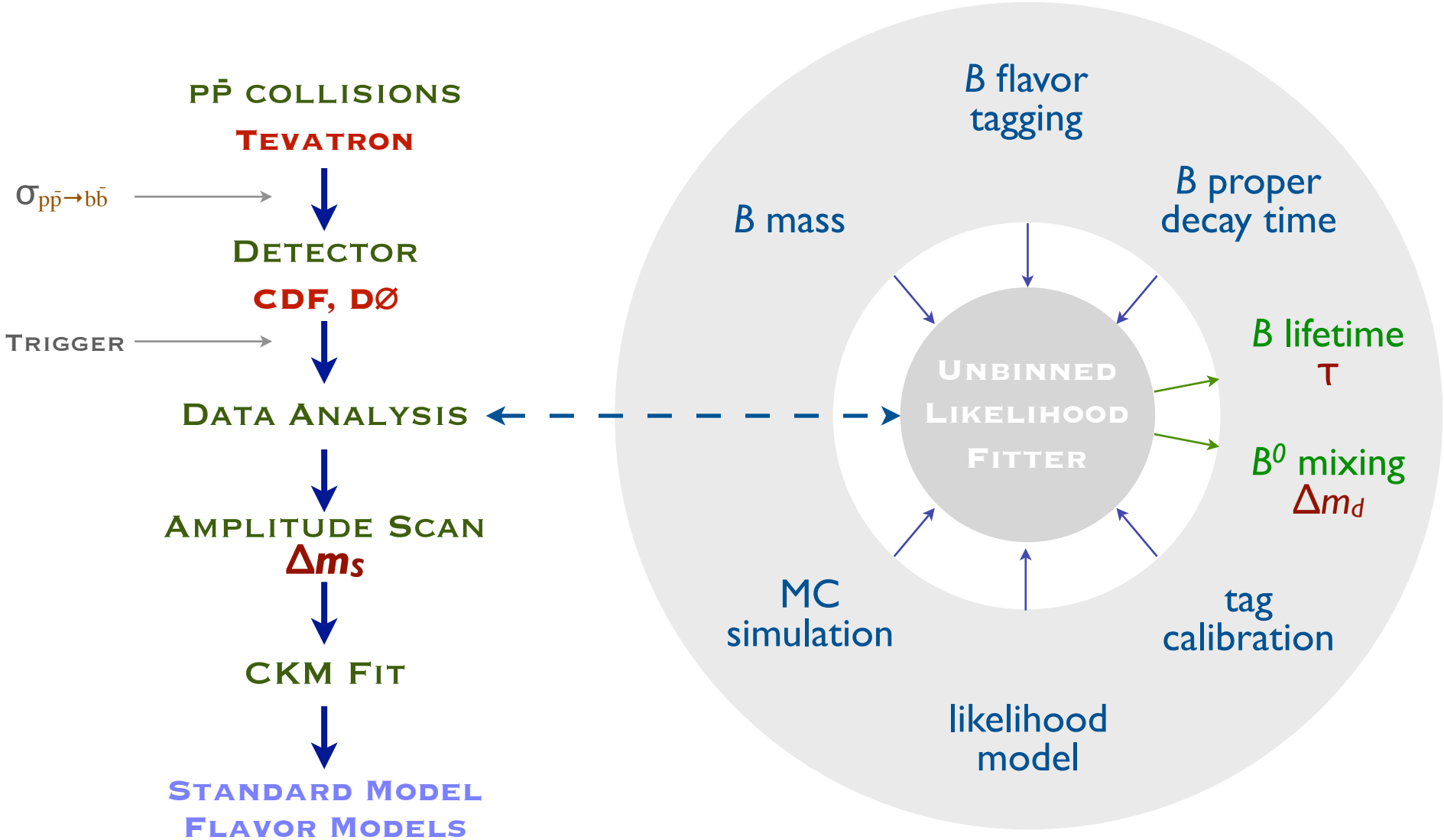


$\Delta m_s > 14.4\ ps^{-1}$ at 95%CL

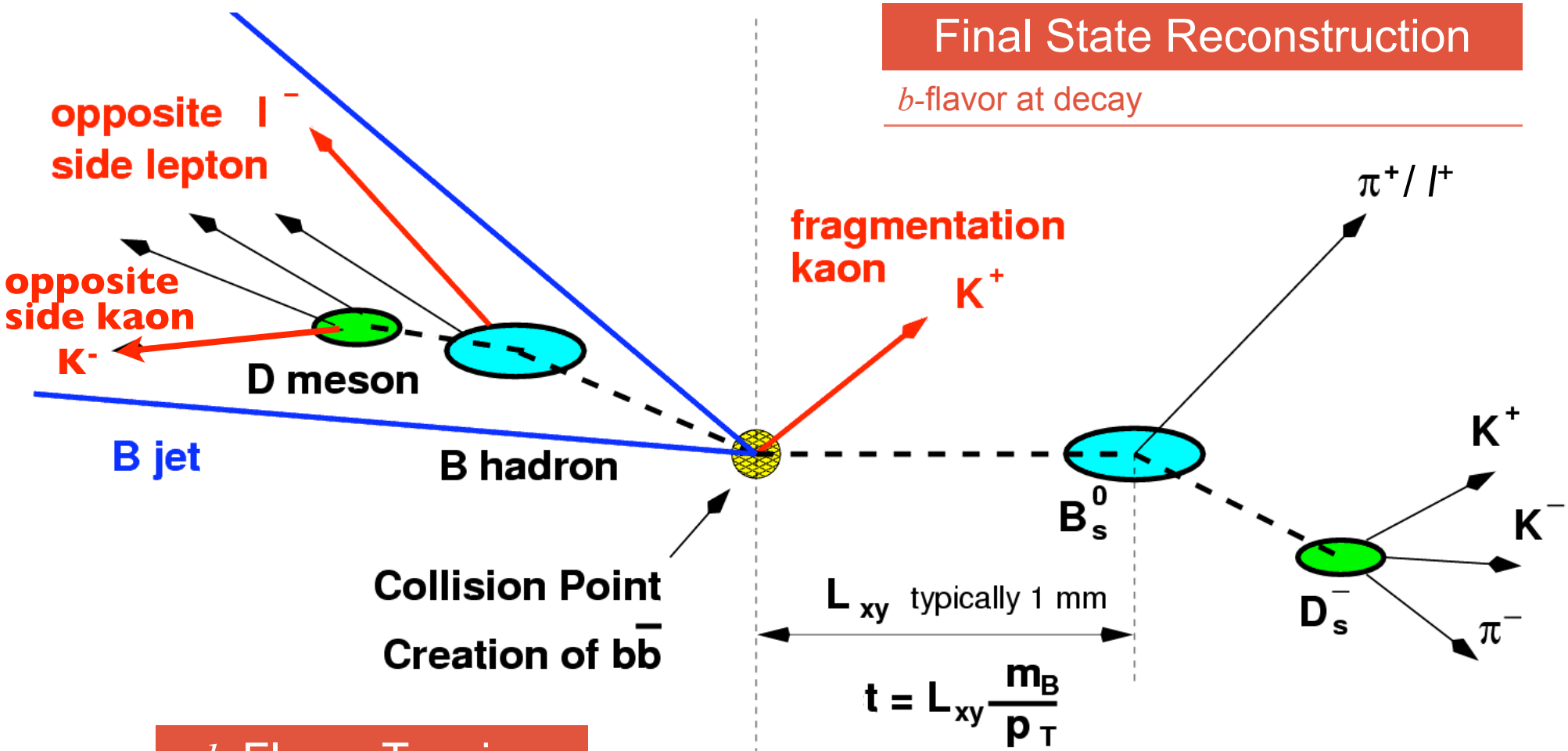
sensitivity $18.2\ ps^{-1}$

[prior to Tevatron Run II results]

Scope & Overview



Analysis Ingredients



Final State Reconstruction

b-flavor at decay

***b*-Flavor Tagging**

b-flavor at production

Proper Decay Time

In *B* rest frame

Opposite Side

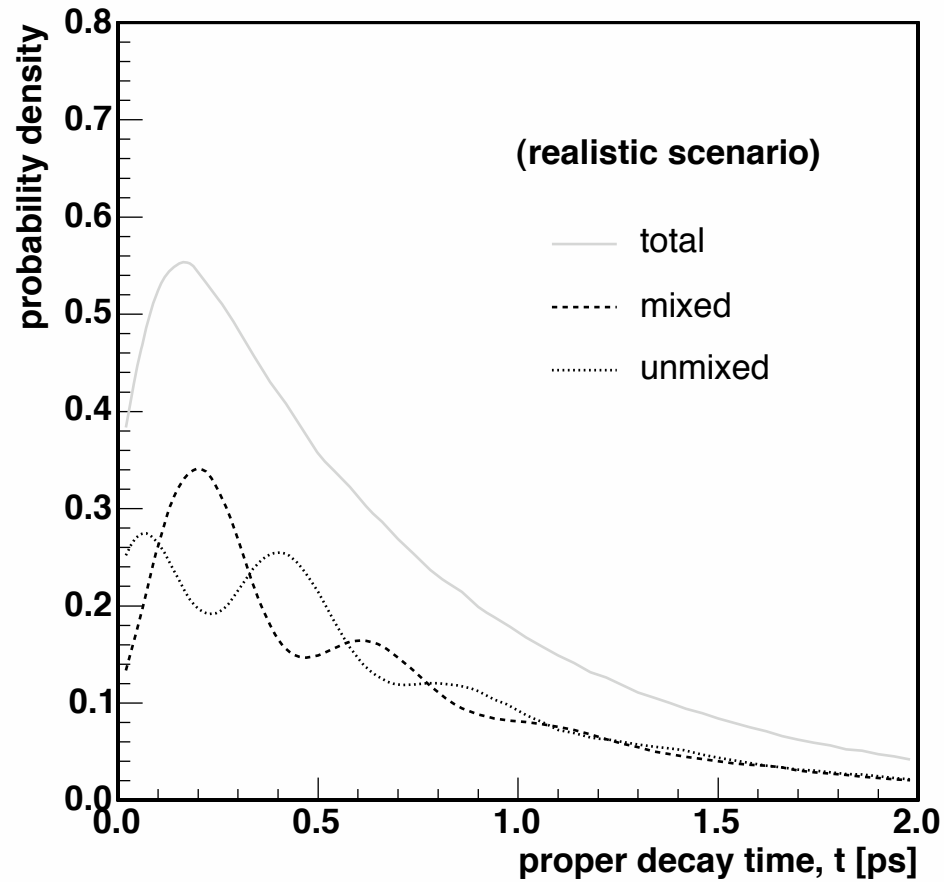
Trigger Side

Realistic Effects oscillation dampening

$$\sigma_A = \sqrt{\frac{2}{\epsilon D^2}} \frac{\sqrt{B+S}}{S} \, e^{(\Delta m \, \sigma_t)^2/2}$$

resolution of mixing signal

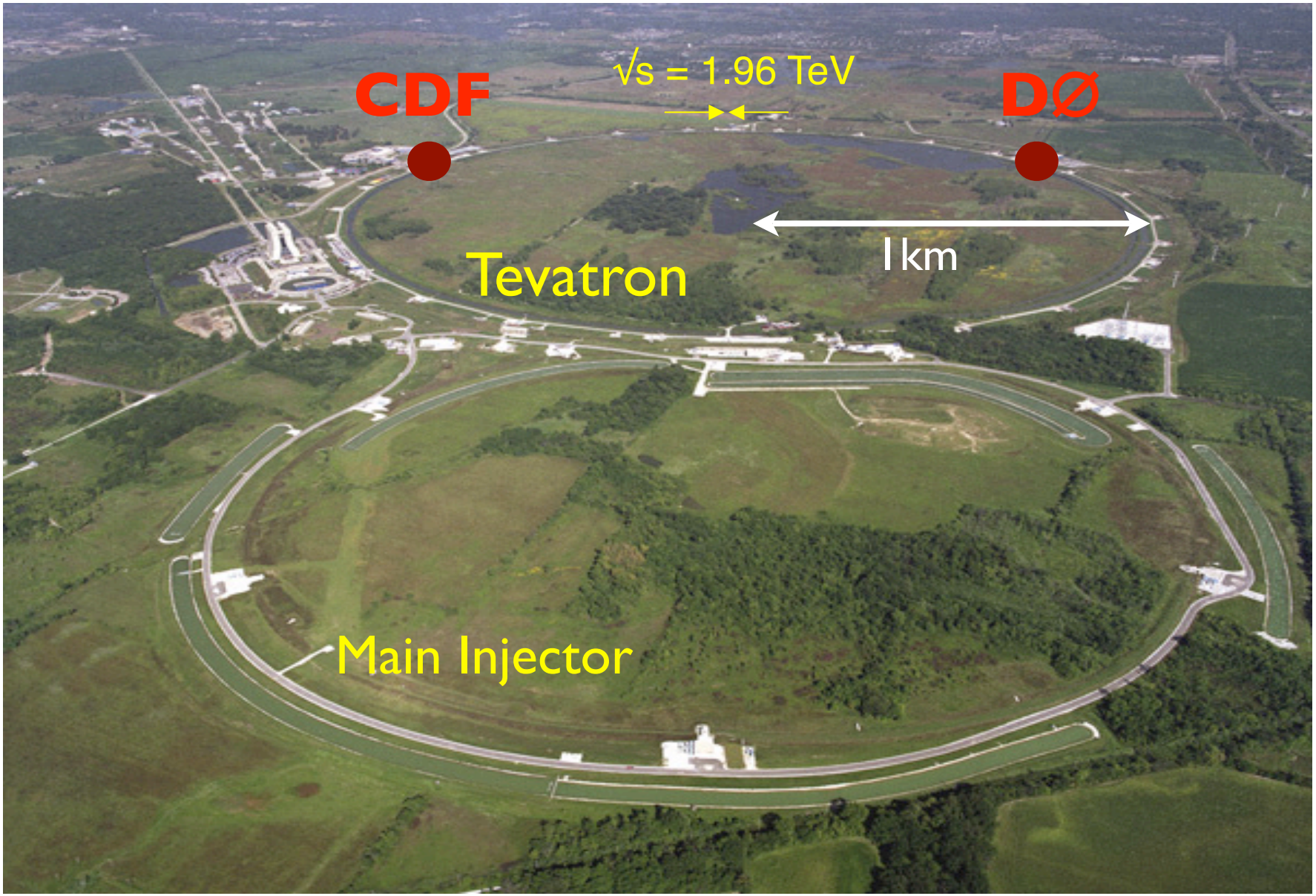
- signal yield, S
- purity, S/B
- flavor tagging power, ϵD^2
- proper time uncertainty, σ_t
  - decay-length resolution
  - effective momentum resolution



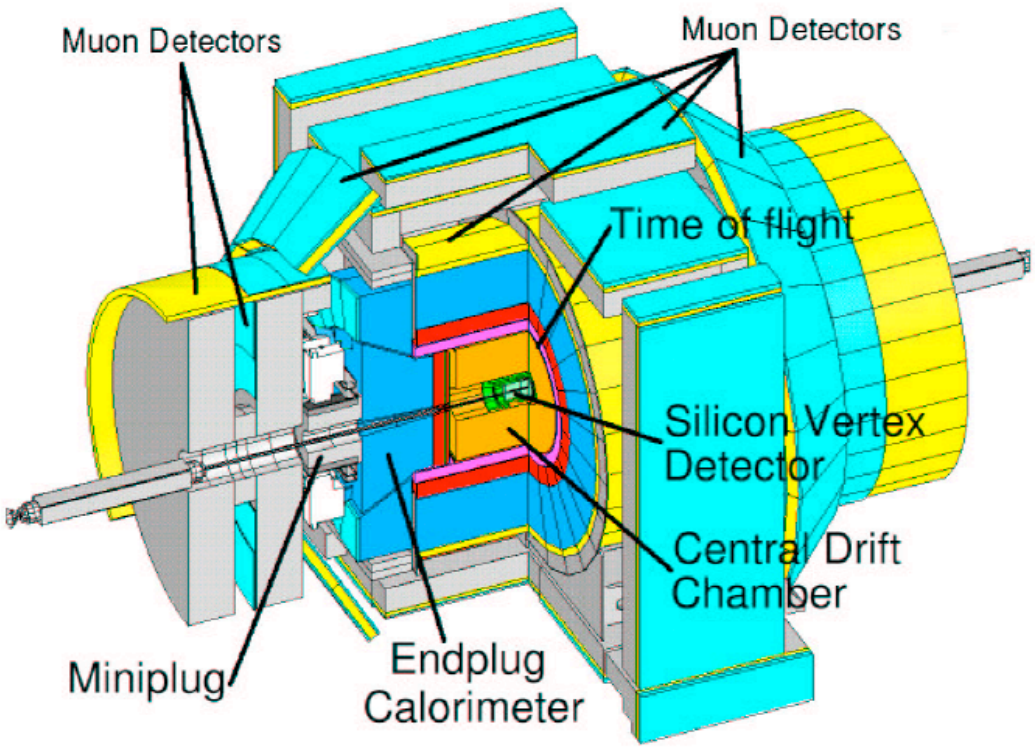
Getting the Data

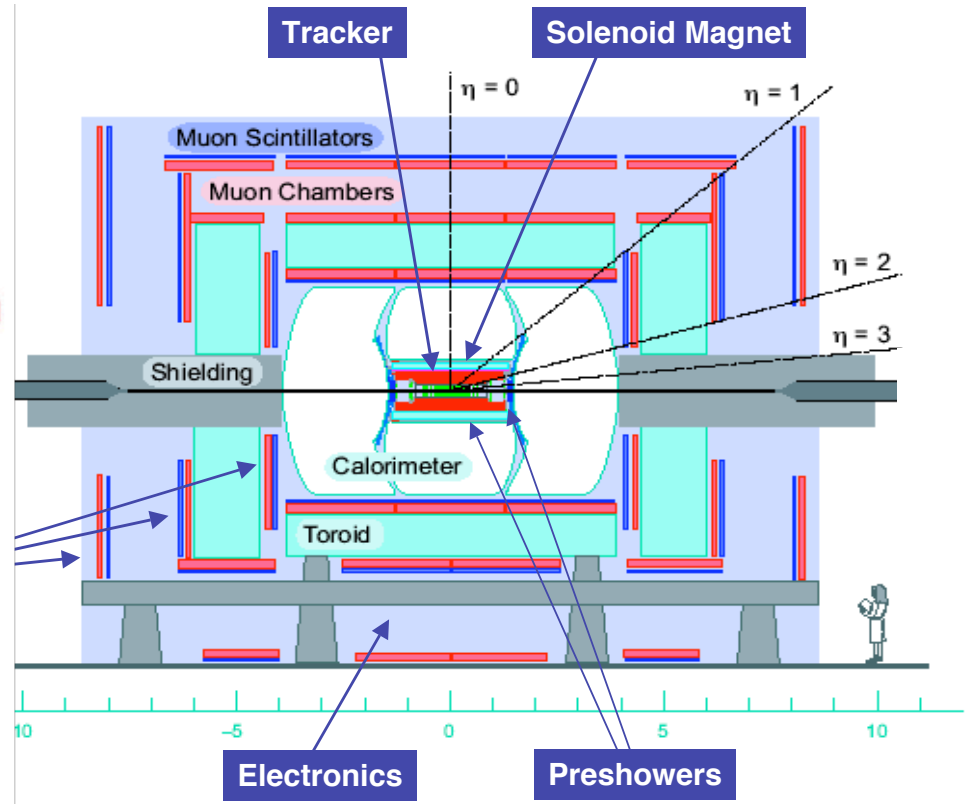
Tevatron Collider

@Fermilab



CDF and DØ Detectors



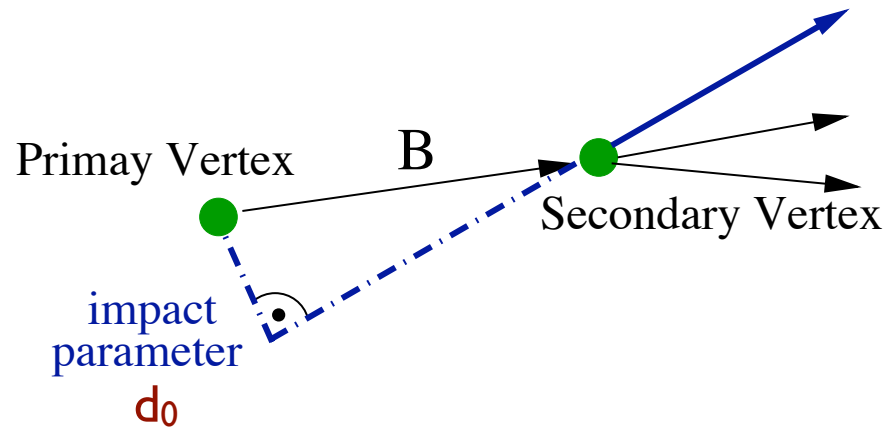


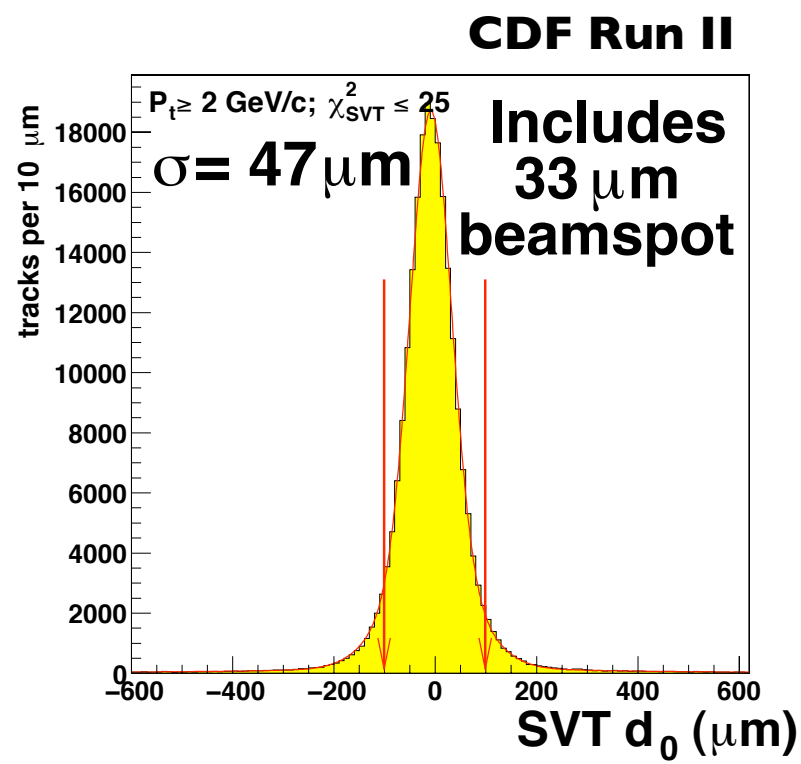
Key features for Δm_s

momentum and vertexing resolution
particle identification
'deadtimeless' trigger system

Triggering on Displaced Tracks

- heavy flavor decays displaced from the primary vertex
  - daughter tracks tend to have large impact parameter
- trigger on displaced tracks
  - p_T>2GeV/c, 120μm<|d_0|<1mm
- requires precision tracking in silicon detector (SVT)





B meson samples

- collect large data samples of B mesons:

$$B^+, \quad B^0, \quad B_s$$

- fully reconstructed decays
  - all B decay products are reconstructed
  - complete event information ⇒ superior resolutions
  - smaller yields
- partially reconstructed decays
  - some decay products are missed: eg neutrinos
  - partial event information ⇒ poorer resolution
  - large yields

Signal and Control Samples

- Signal samples
  - hadronic: $B_s \to D_s^- \pi^+ (\pi^+ \pi^-)$ 8.7k (CDF)
  - semileptonic: $B_s \to D_s^- l^+ X$ 50k(DØ), 61.5k (CDF)

  with $\mathrm{D_s^-} \to \phi\pi^-, \mathrm{K^{*0}K^-}, \pi^+\pi^-\pi^-$

- Calibration and validation samples

  $B^+ \to J/\psi K^+, \bar{D}^0 \pi^+ (\pi^+ \pi^-)$ 50k (CDF)

  $B^0 \to J/\psi K^{*0}, D^- \pi^+ (\pi^+ \pi^-), D^{*-} \pi^+ (\pi^+ \pi^-)$ 60k (CDF)

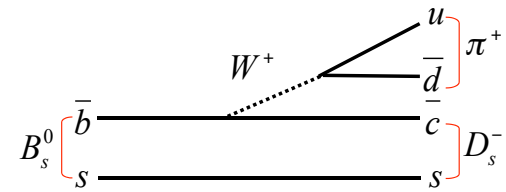
  $B^{+,0} \to \bar{D}^0 l^+ X, D^- l^+ X, D^{*-} l^+ X$ 300k(DØ),900k (CDF)

  $B_s \to J/\psi \phi$

  with $\mathrm{D^{*-}} \to \mathrm{D^0}\pi^-, \mathrm{D^0} \to \mathrm{K^-}\pi^+(\pi^+\pi^-), \mathrm{D^-} \to \mathrm{K^+}\pi^-\pi^-$

- Sample to tune flavor taggers (largest)
  - inclusive lepton + displaced track sample

Hadronic samples



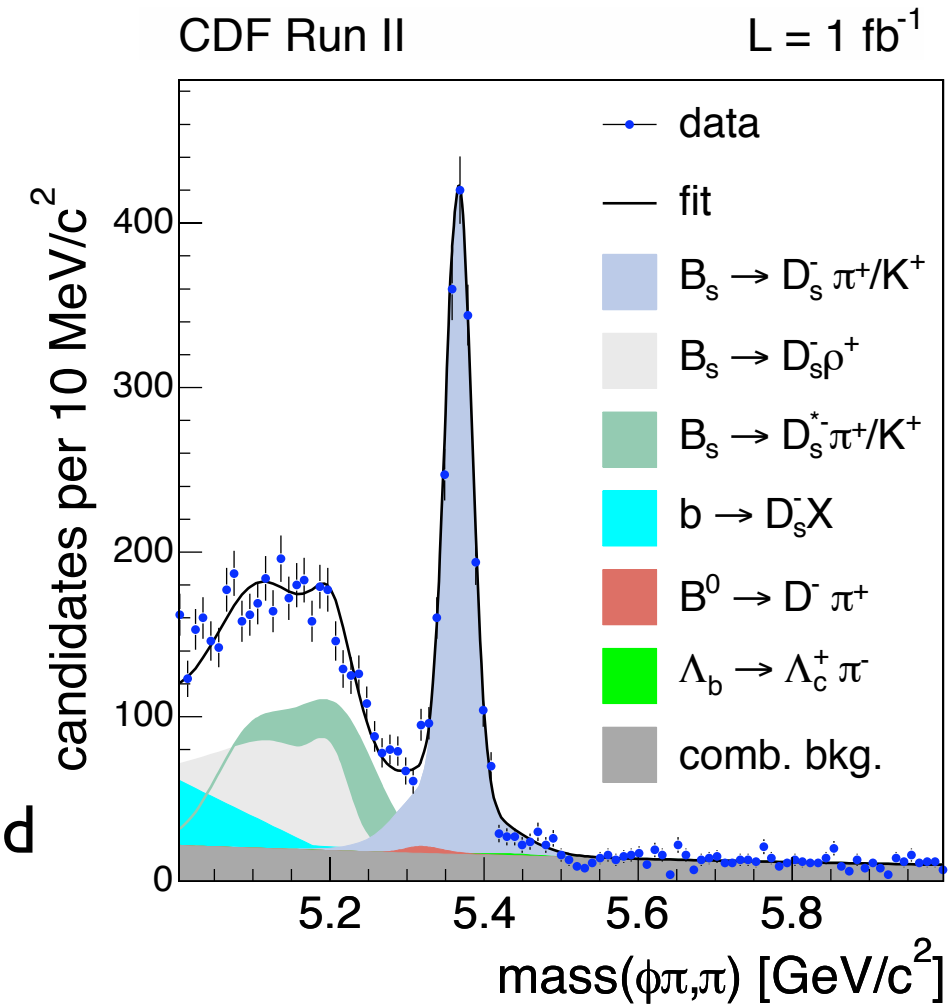
- fully reconstructed peak

$$B_s \to D_s^- \pi^+, D_s^- \to \phi\pi^-$$

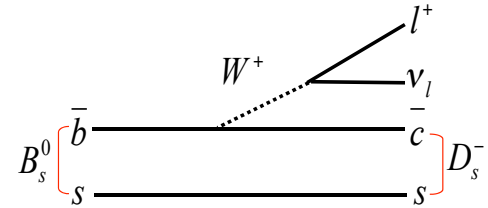
  - 'golden mode'
    (narrow Φ, low comb. bkg)

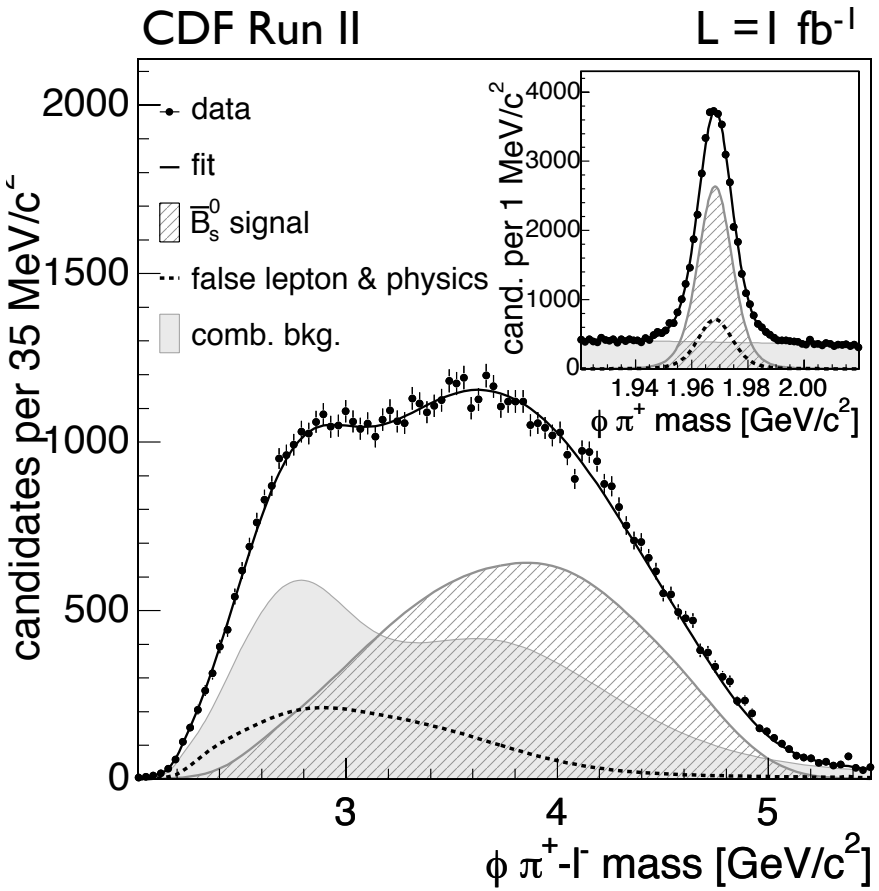
- partially reconstructed
  - double signal yield
  - soft ϒ and π^0 lost
  - but *nearly* fully reconstructed

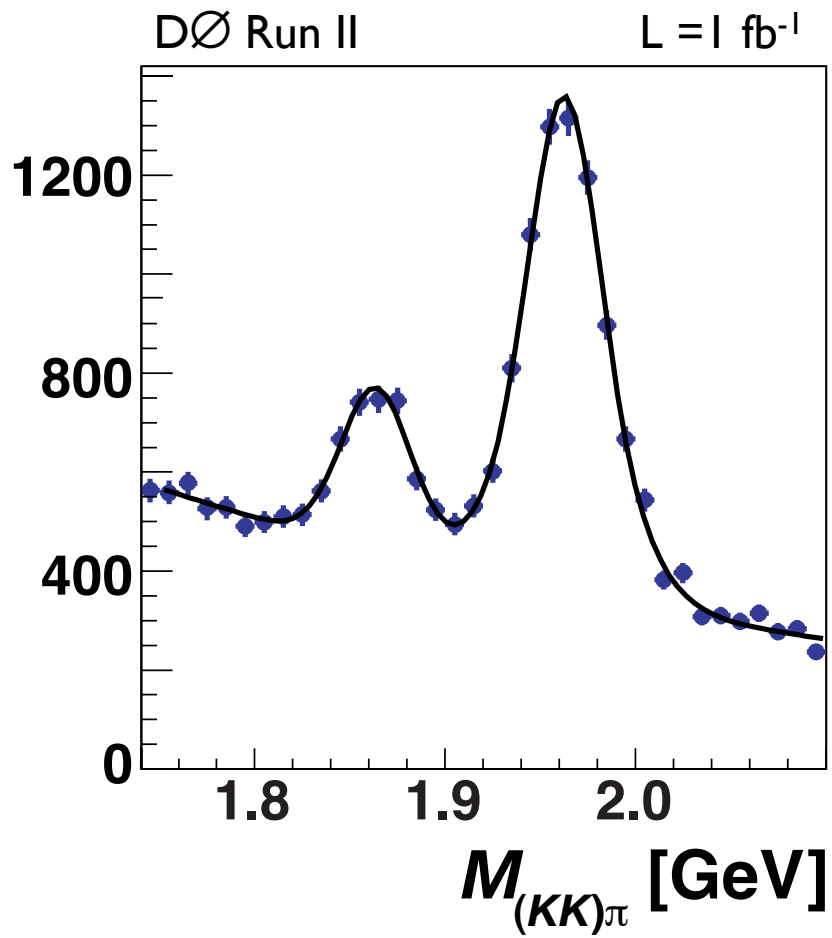
(fraction of rec'd p_T ~96%)



Semileptonic samples







partial reconstruction, limited resolution, large yields

Proper Decay Time

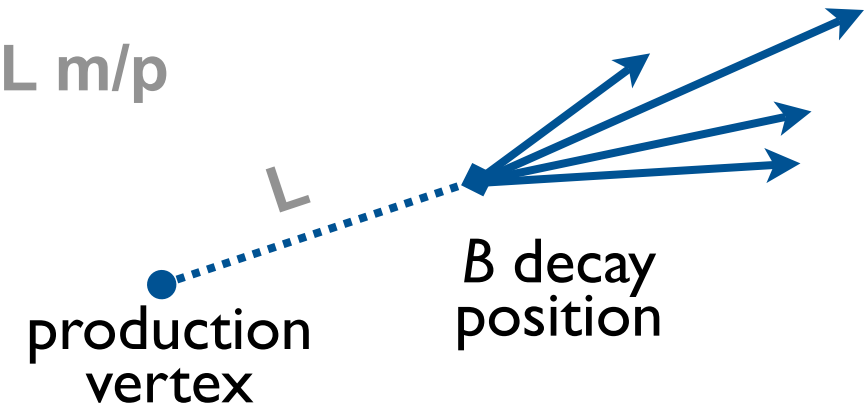
B Lifetime measurement

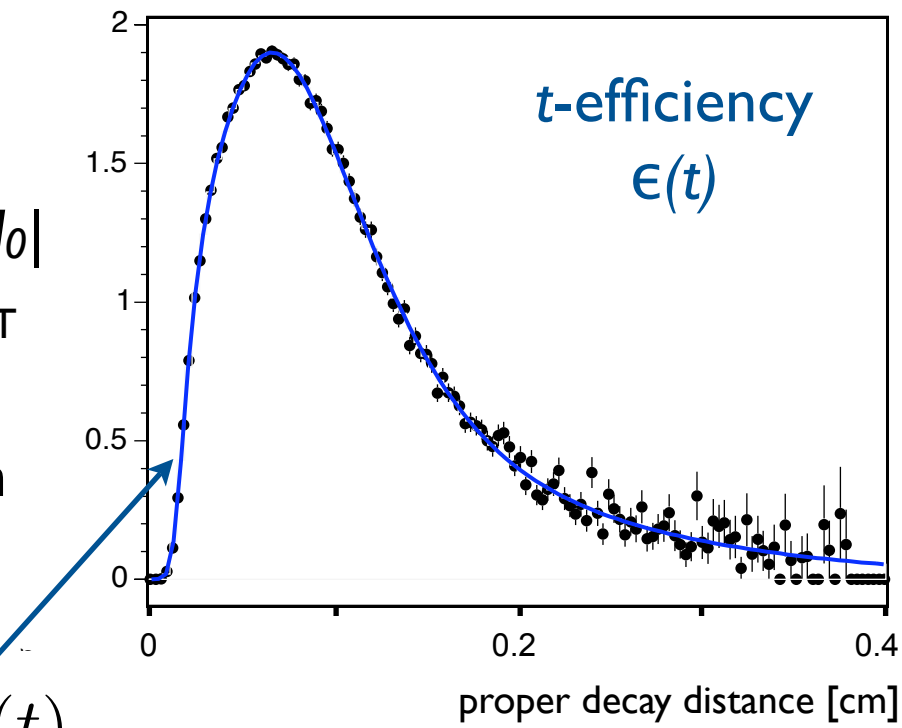
Proper Decay Time

Decay time in *B* rest frame: t = L m/p

t-distribution determined by

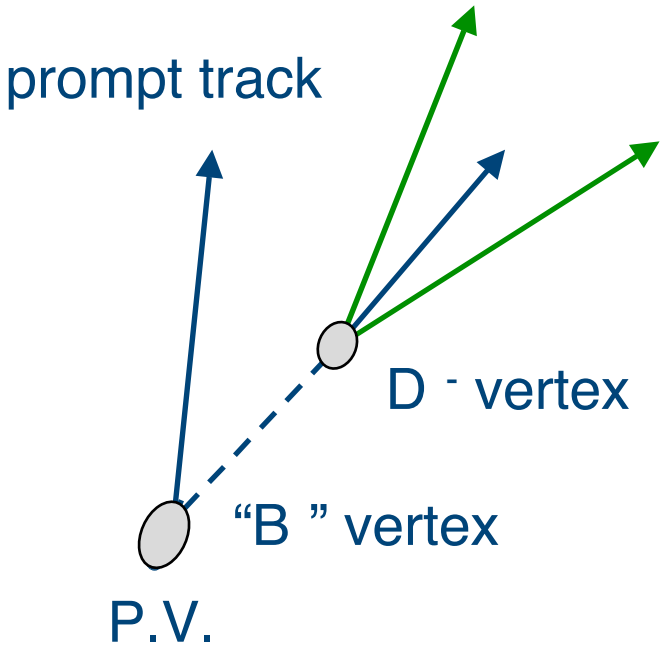
- *B* meson lifetime
- decay distance resolution
- trigger/selection sculpting
  - trigger (SVT) requirements on $|d_0|$ and event selection criteria on L_T modify PDF shape
  - described by *t*-efficiency function from Monte Carlo, $\epsilon_t(t)$

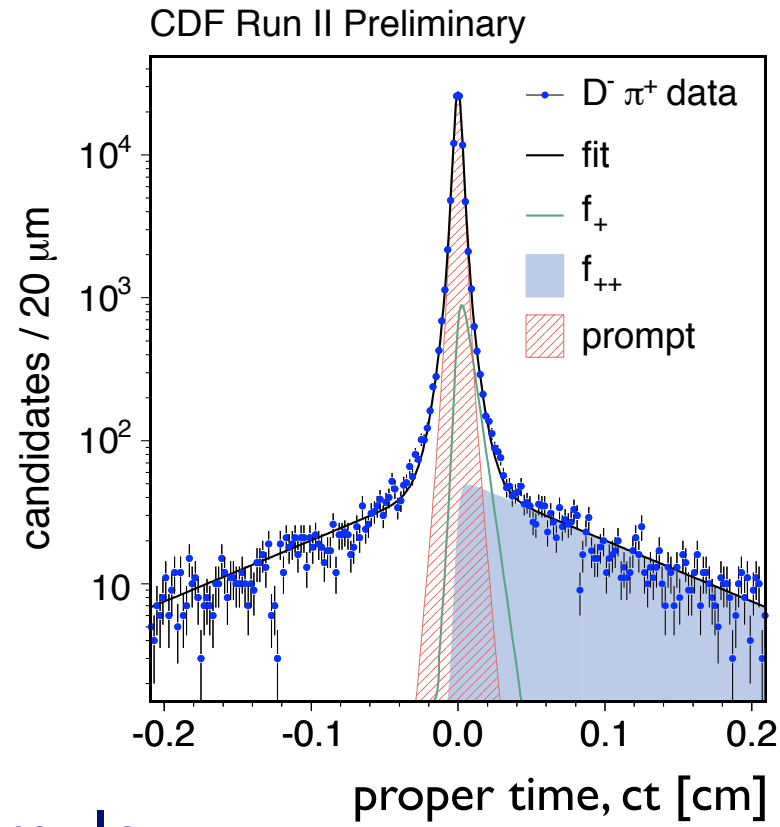




$$\mathcal{P}(t) \propto e^{-t'/\tau} \otimes R(t-t';\sigma_t) \cdot \mathcal{E}(t)$$

Calibrating Resolution on Data





- use large prompt *D* meson sample to construct *B*-like topologies of prompt *D*+track
- compare reconstructed decay point to interaction point
- calibrate *t*-resolution by fitting prompt *t*-distribution

Proper time resolution

$$\sigma_t = \sigma_l \oplus t \cdot \frac{\sigma_p}{p}$$

- fully rec'd $B_s \to D_s(3)\pi$:

  $\sigma_l \sim 26$ μm (87 fs)

  $\sigma_p/p < 1\%$

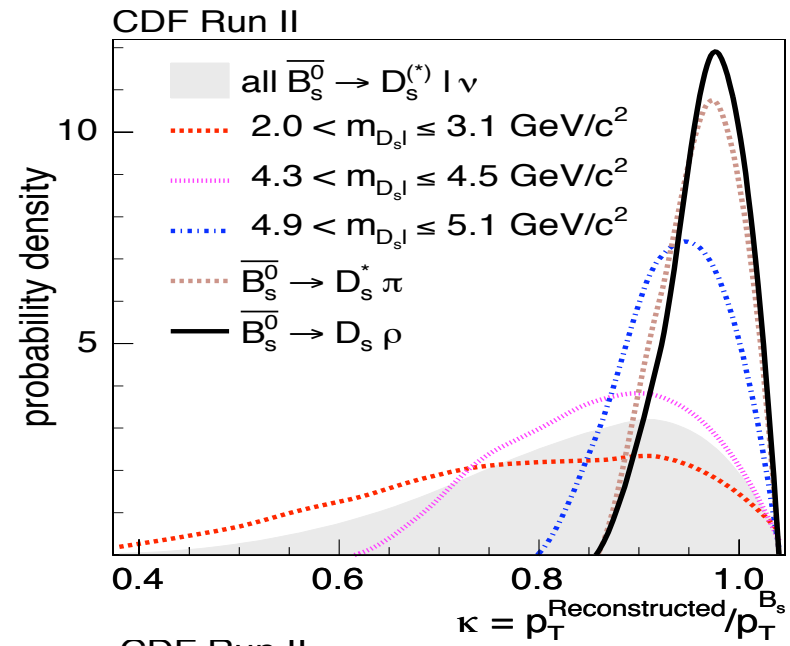
- partially rec'd $B_s \to D_s^*\pi, D_s\rho$:

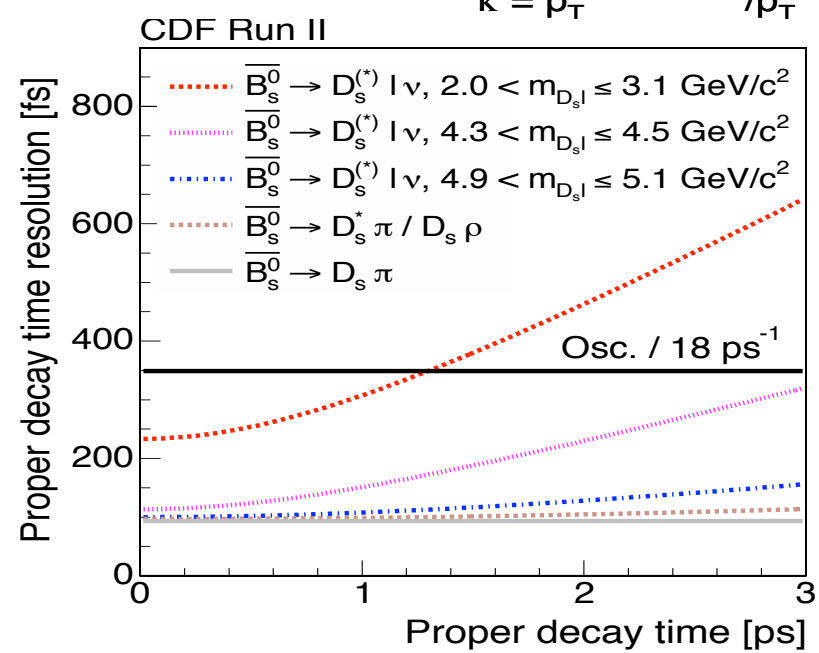
  $\sigma_l \sim 29$ μm (97 fs)

  $\sigma_p/p \sim 2\%$

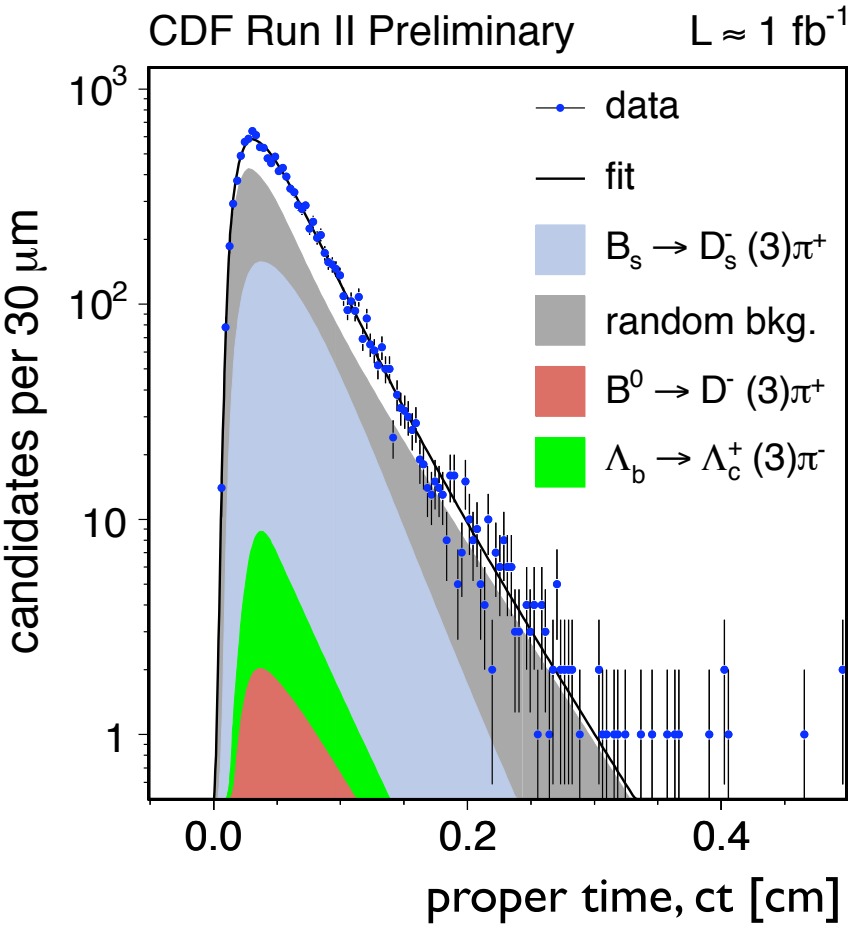
- semileptonic $B_s \to D_s l X$:
- $\sigma_l \sim 30\text{-}70$ μm (100-230 fs)
- $\sigma_p/p \sim 3\text{-}20\%$

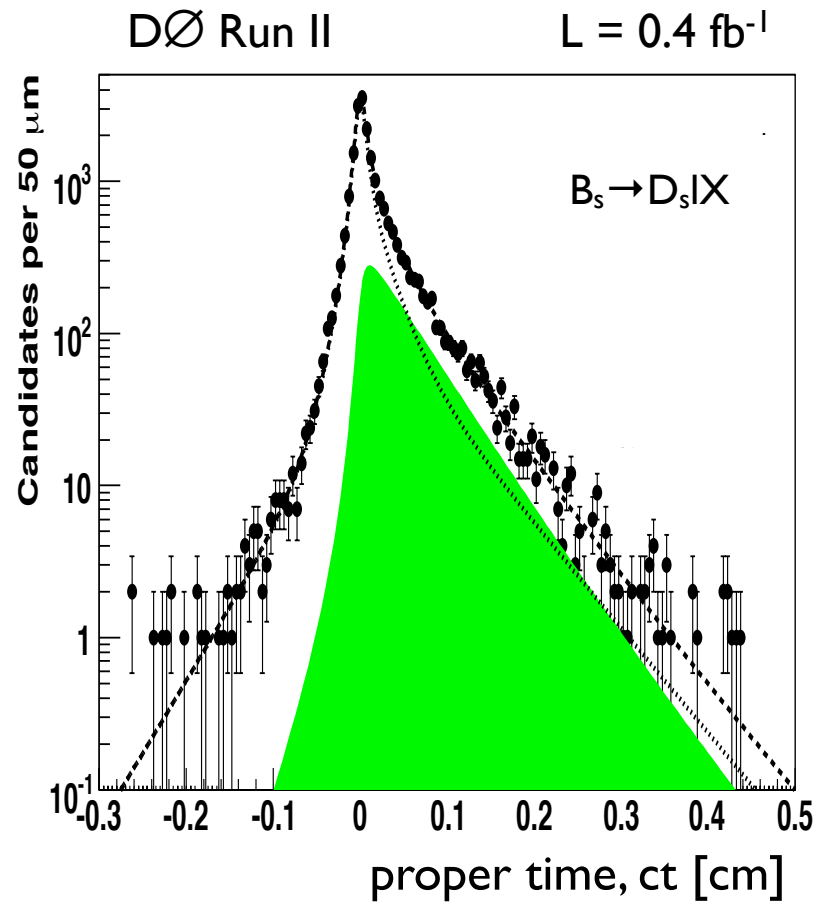
$$\mathcal{P}(t) \mapsto \mathcal{P}(\kappa t) \otimes_\kappa \mathcal{F}(\kappa)$$





Lifetime Fits





$\tau(B_s)$ = 1.54± 0.04 (sta.) ps

$\tau(B_s)$ = 1.398 ± 0.052 ps

Consistent with World Average: $\tau(B_s)$ = 1.461 ± 0.057 ps

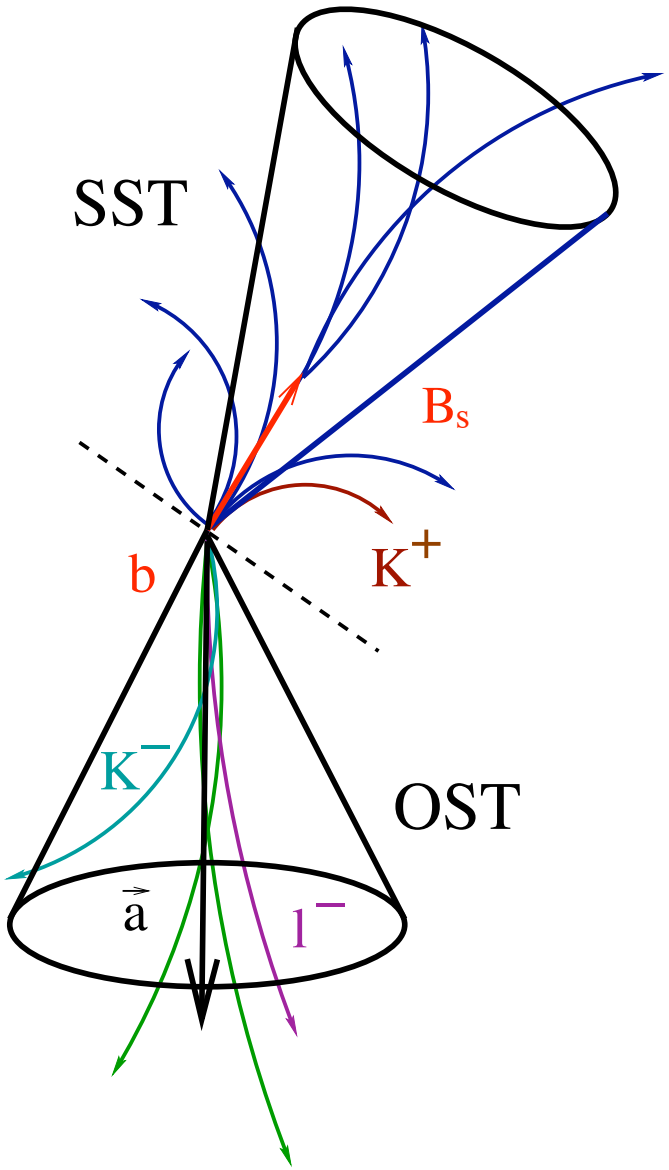
b Flavor Tagging

Δm_d measurement

Tagging *B* Production Flavor

- produced $B(\bar{b})$ or $\bar{B}(b)$?
- use combined flavor taggers
  - Opposite side (OST)
  - Same side (SST)
- quantify performance with
  - *efficiency*, $\epsilon \equiv$ fraction of tagged events
  - *dilution*, $D \equiv 1 - 2 \times$ mistag probability
  - effective statistics for mixing becomes

$$N \Rightarrow N\,\epsilon D^2$$



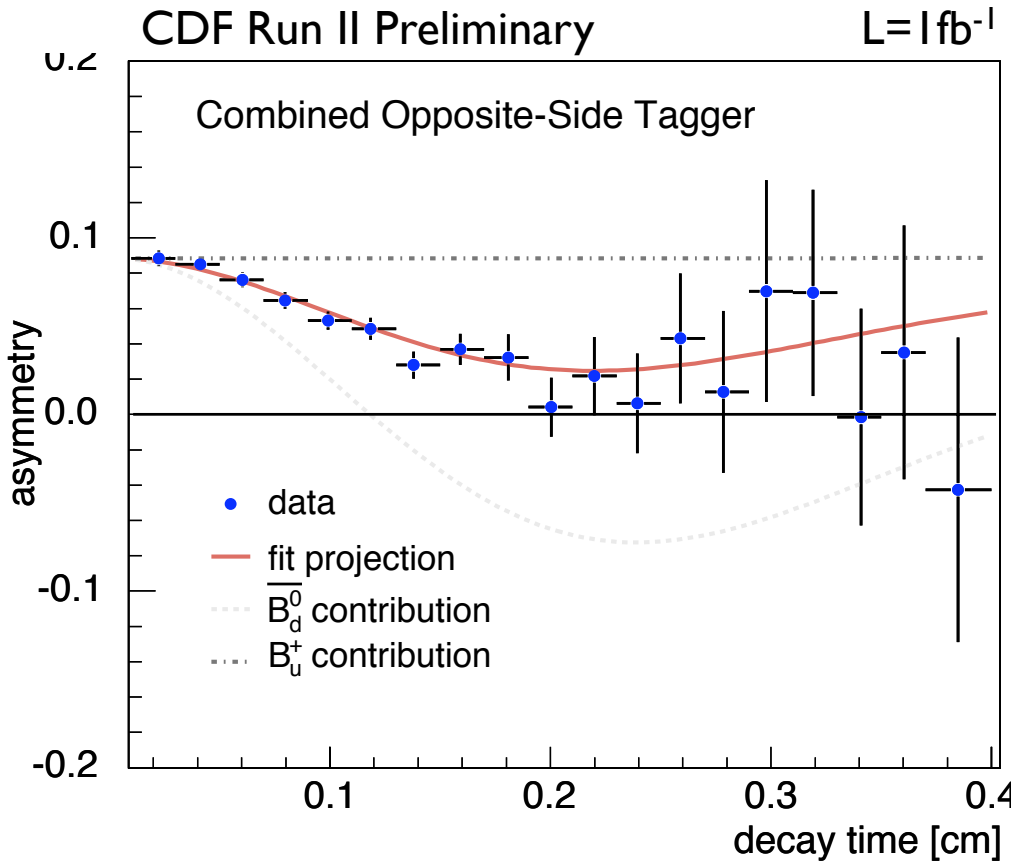
Opposite Side Tagging

- lepton (e,μ)
  from semileptonic decay of opposite *b*
- kaon
  from $b \to c \to s$ decay of opposite *b*
- jet
  momentum-weighted charge average of tracks in opposite side *b* jet

- taggers combined with Neural Network
- performance independent of *B* species
  calibrated in high statistics B^+/B^0 data

ϵD^2(OST) : 1.8% (CDF), 2.2% (DØ)

B^0 Mixing Fit Δm_d



tagging calibration factor

$$\mathcal{P} \sim \frac{e^{-t/\tau}}{2\tau}(1 - S_D \cdot D \cdot \cos \Delta m_d t)$$

B^0 oscillation frequency

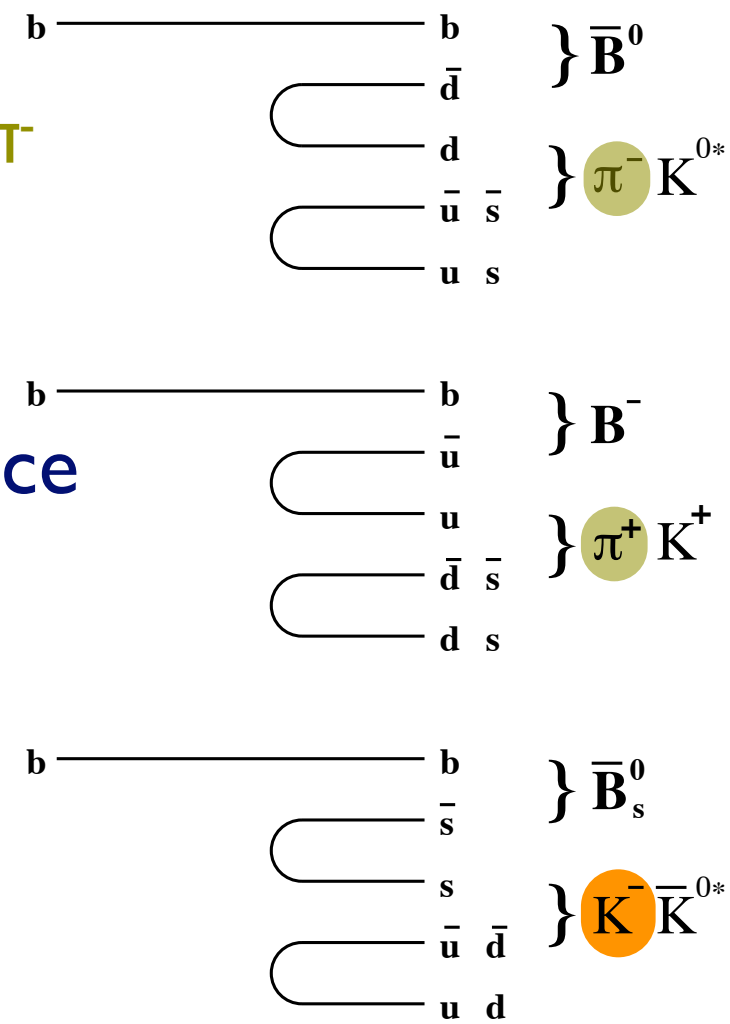
CDF: $\Delta m_d = 0.509 \pm 0.010$ (stat) ± 0.016 (syst) ps^{-1}

DØ: $\Delta m_d = 0.506 \pm 0.020$ (stat) ± 0.016 (syst) ps^{-1}

World average: $\Delta m_d = 0.507 \pm 0.005$ ps^{-1}

Same-Side Tagging *(I)*

- exploit *b* quark fragmentation
  - B^0 / B^+ likely accompanied by π^+ / π^-
  - B_s likely accompanied by K^+
  - ➥ identify charge of leading track
- particle ID improves performance
  - separate kaons from pions
  - time-of-flight (TOF) & dE/dx
- dependent on *B* species
  - results in B^0/B^+ *not applicable* to B_s
- need to rely on Monte Carlo
  - data and MC thoroughly compared

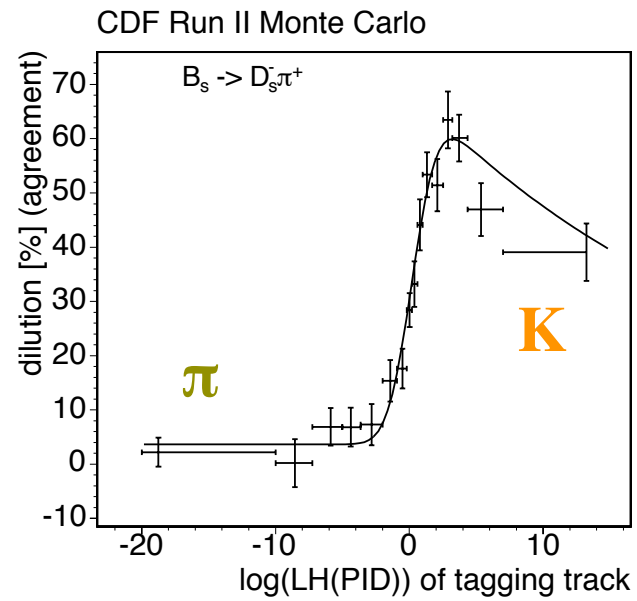


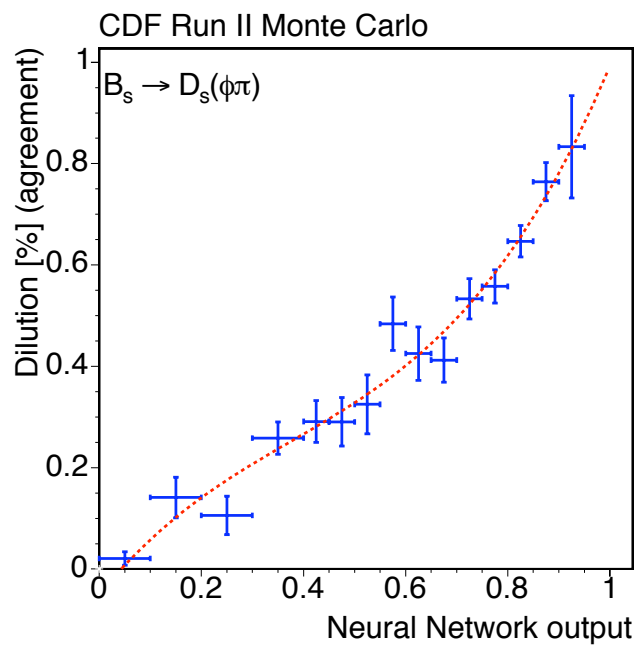
Same-Side Tagging *(II)*

most powerful tagger available

- select quality tracks around *B*
- study algorithms based on
  - PID, p_L^{rel}, p_T^{rel}, p_T, ΔR
- decision: track charge of hightest NN tag candidate
- dilution: event-by-event, function of NN output
- power:

  $\epsilon D^2(SST)$ = 3.5%(had), 4.8% (sem)



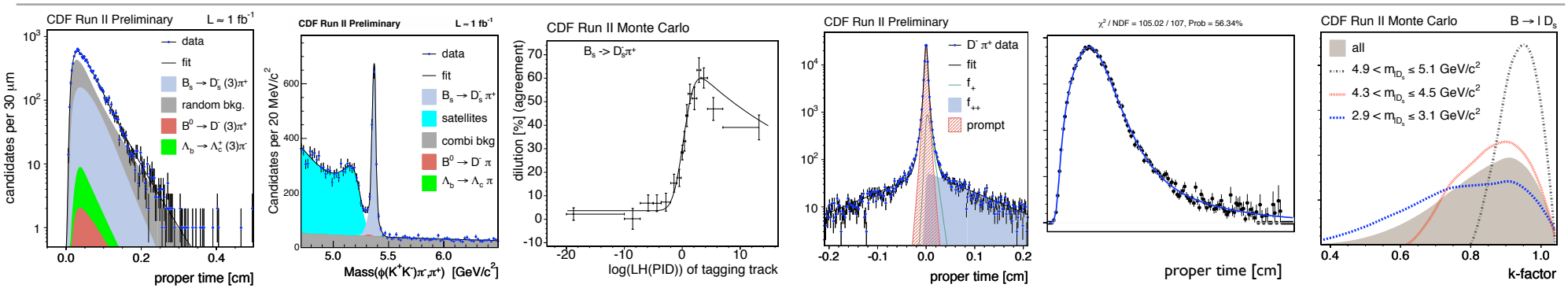


Fitting

Likelihood putting it all together

$$\mathcal{L} = \mathcal{L}_{mass} \cdot \mathcal{L}_t \cdot \mathcal{L}_{\sigma_t} \cdot \mathcal{L}_D$$

[for each sample component & event]



$$\mathcal{L}_t = \frac{1}{N}\,\kappa\,\frac{e^{-\frac{\kappa\, t'}{\tau}}}{\tau}\;\frac{1 \pm A\; S_D\, D\, \cos(\Delta m_s\, \kappa\, t')}{2} \otimes R(t-t'; S_{\sigma_t}\sigma_t)\cdot \mathcal{E}(t) \otimes F(\kappa)$$

analytical computation

Frequency Δm_s

or

Amplitude (A, σ_A) for fixed Δm_s

Fourier analysis

Time domain

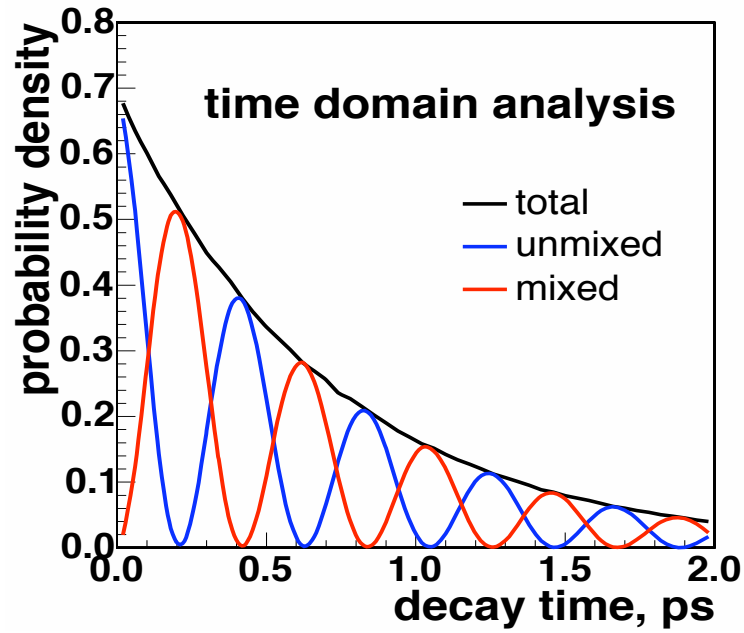
$P(t) \sim 1 \pm D \cos \Delta m_s t$

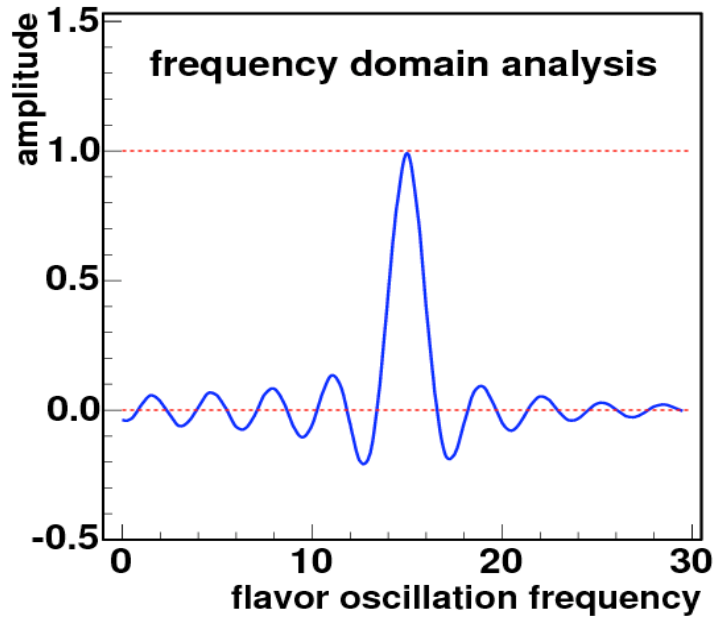
Frequency domain

$P(t) \sim 1 \pm A\, D \cos \Delta m_s t$

- fit amplitude A for different Δm_s probe values
  - true $\Delta m_s \Rightarrow A=1$, else $A=0$
- 95% CL exclusion condition

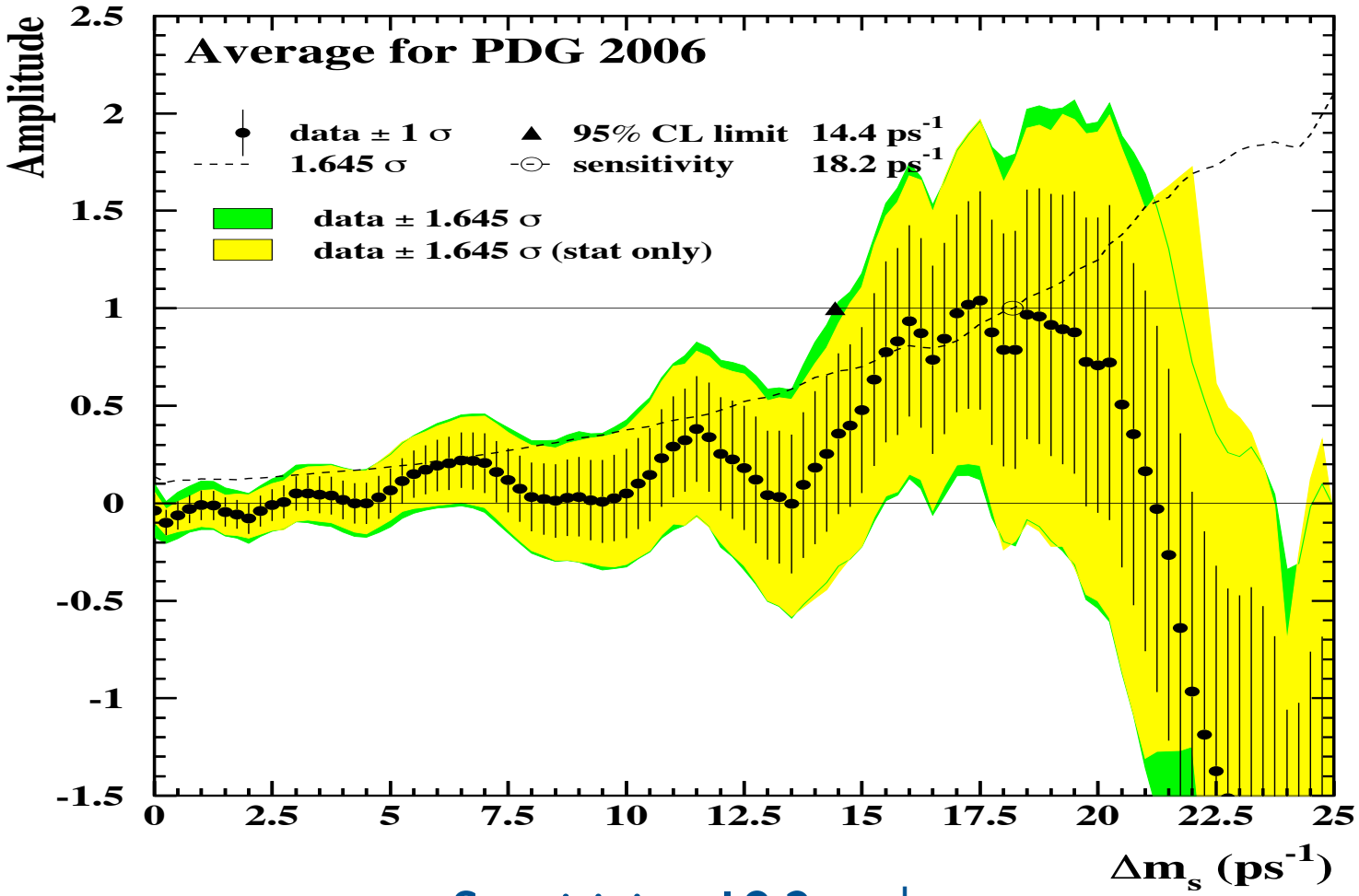
  $A + 1.645\, \sigma_A < 1$





Oscillation Results

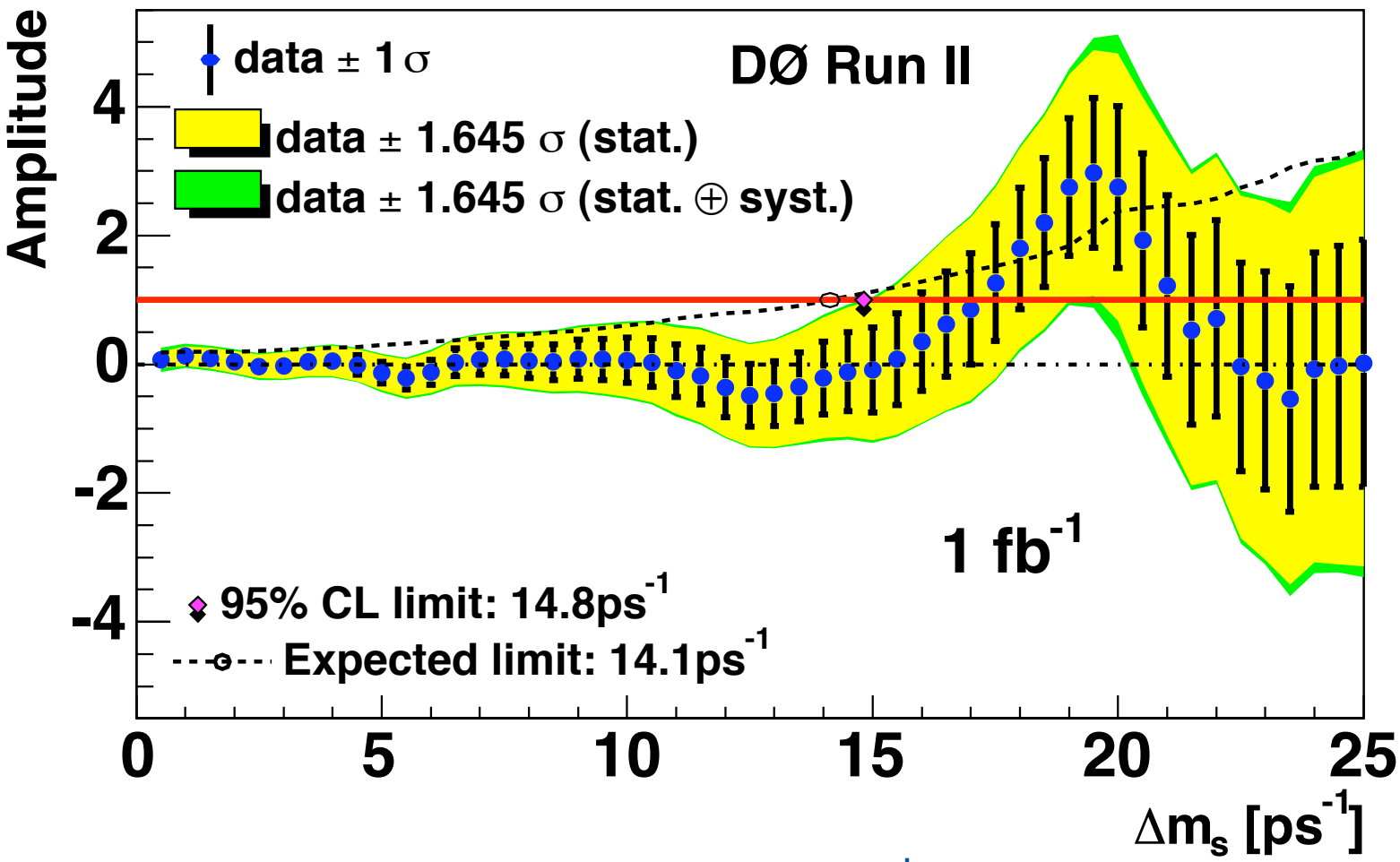
World Average Before Tevatron Run II



Sensitivity: 18.2 ps^{-1}

Δm_s>14.4 ps^{-1} @95%CL

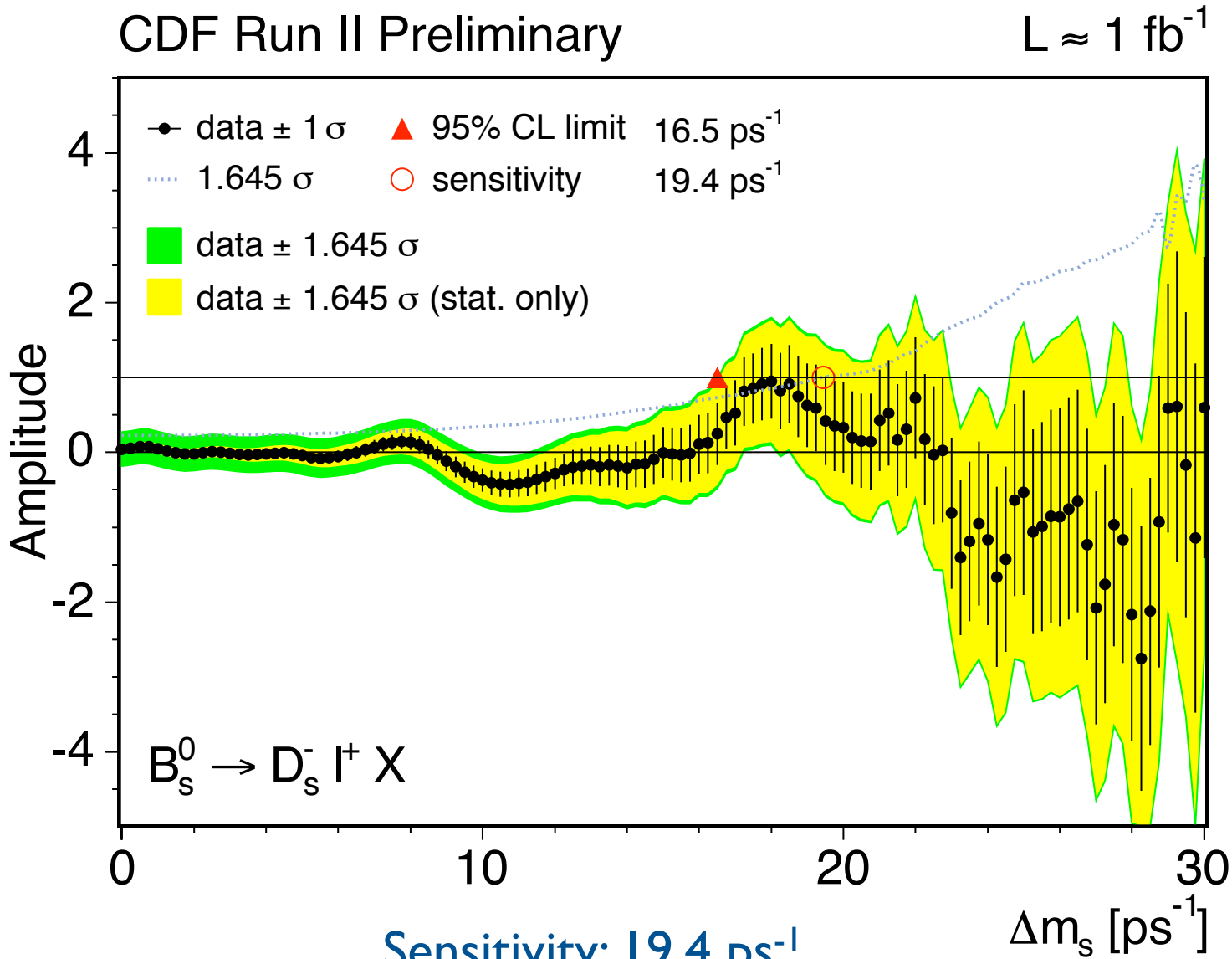
DØ Result



Sensitivity: 14.8 ps^{-1}

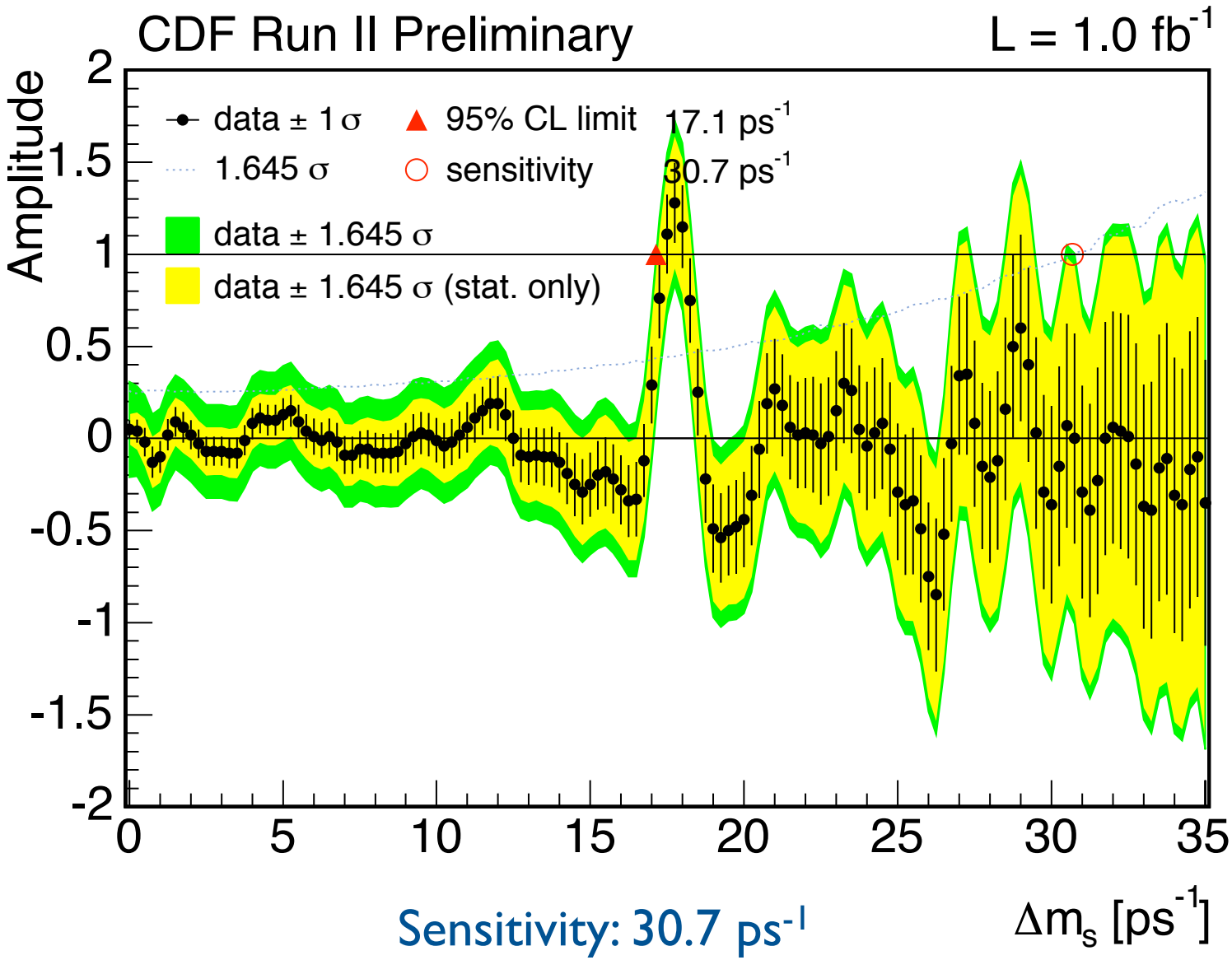
$\Delta m_s \in [17,21]$ ps^{-1} @90%CL

Semileptonic Scan



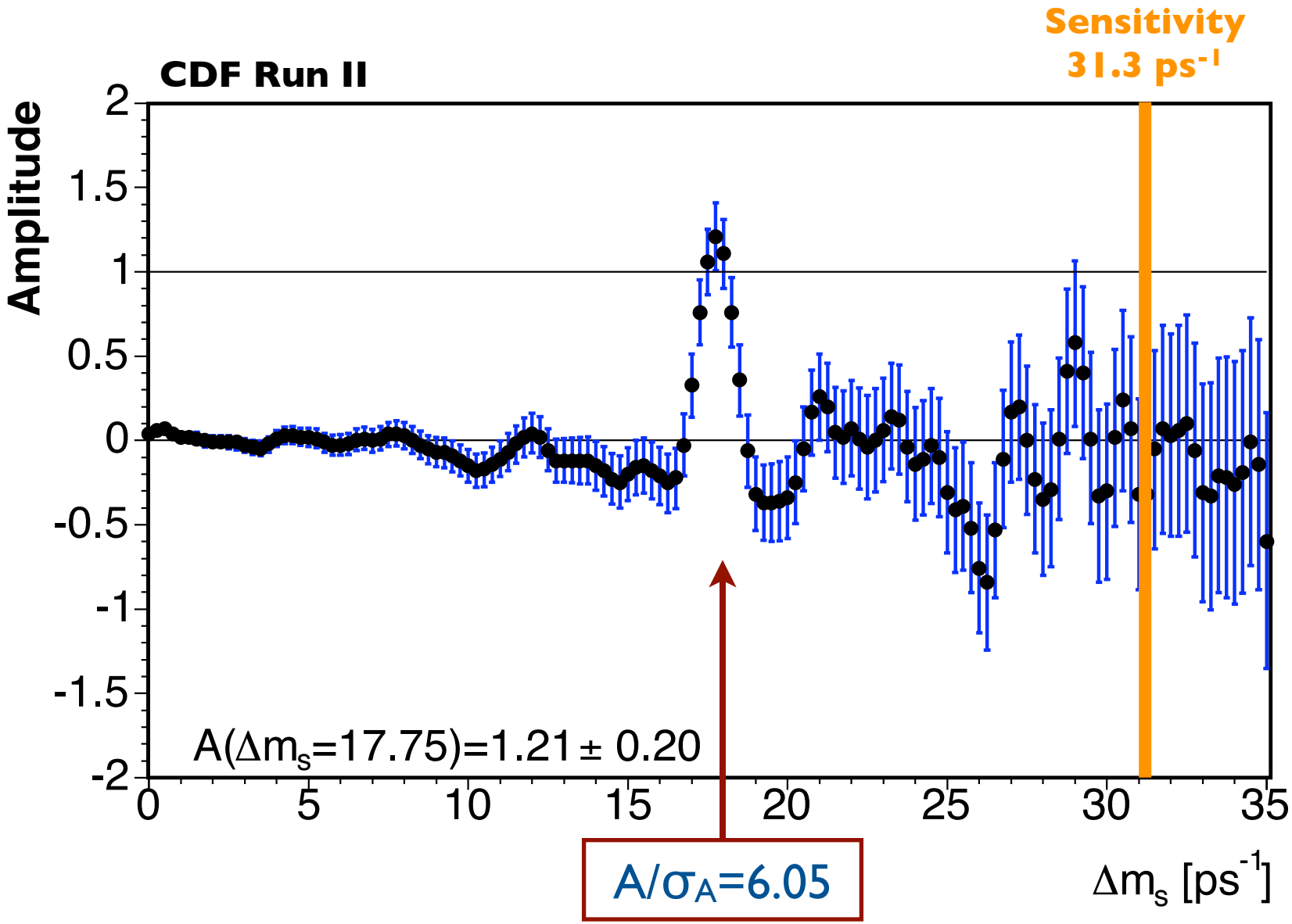
Sensitivity: 19.4 ps^{-1}

Hadronic Scan

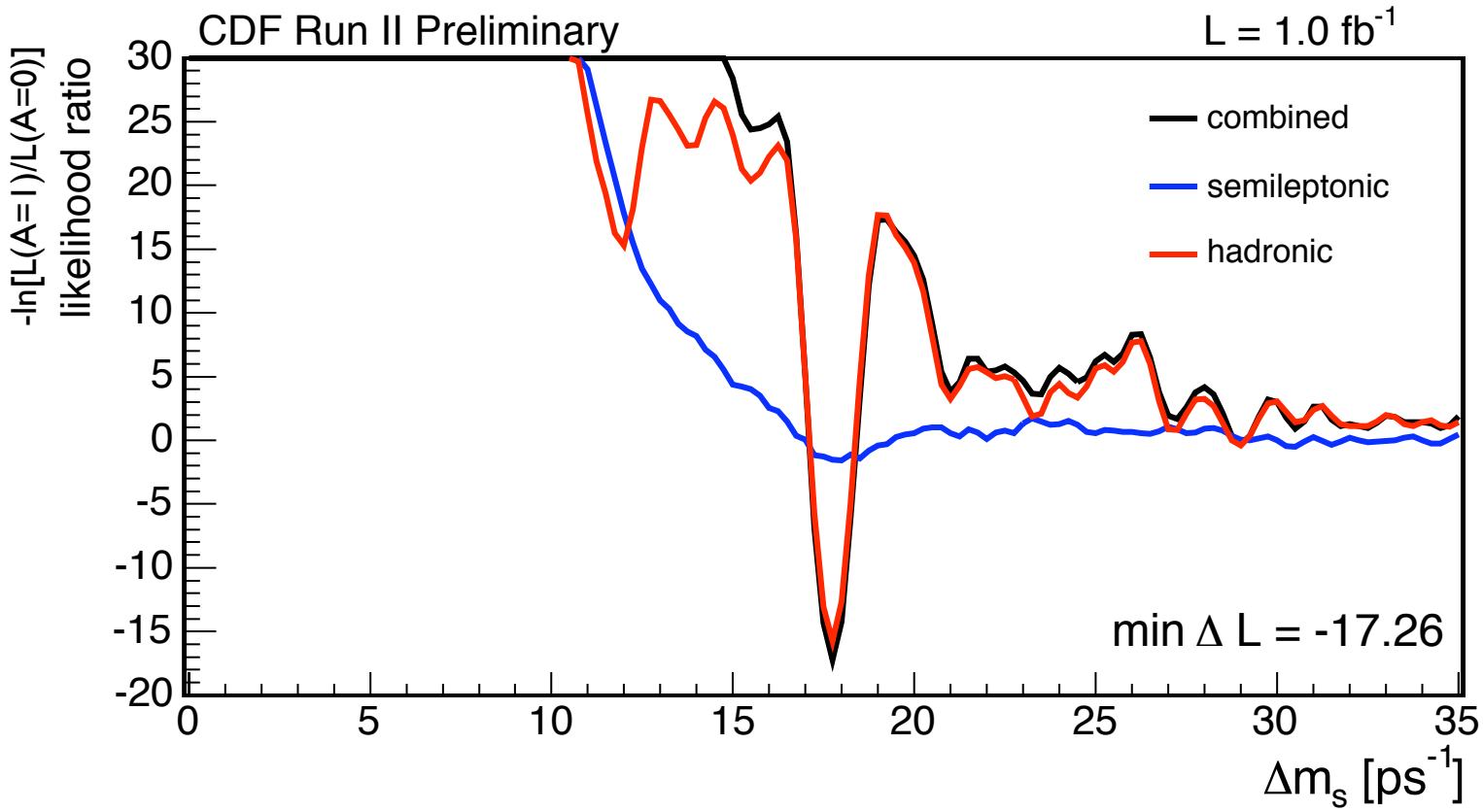


Sensitivity: 30.7 ps^{-1}

Combined Amplitude Scan

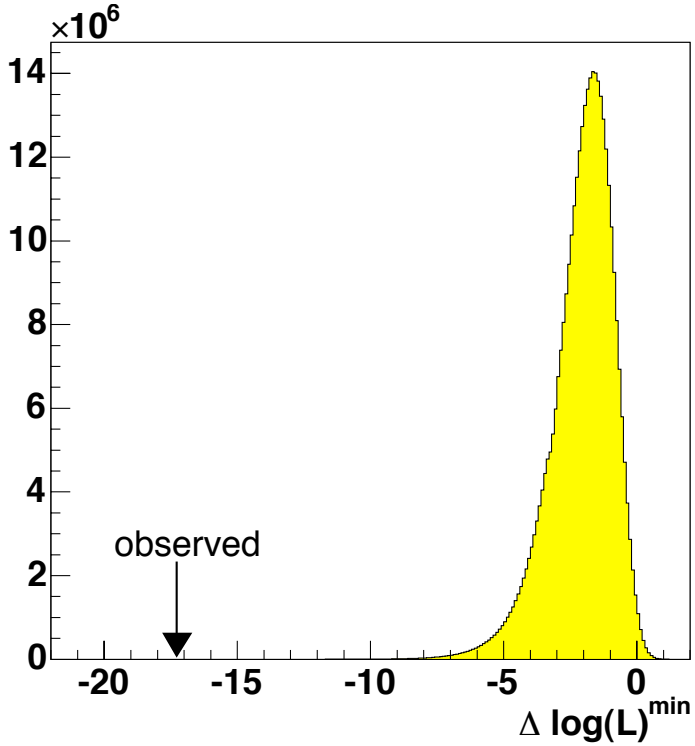


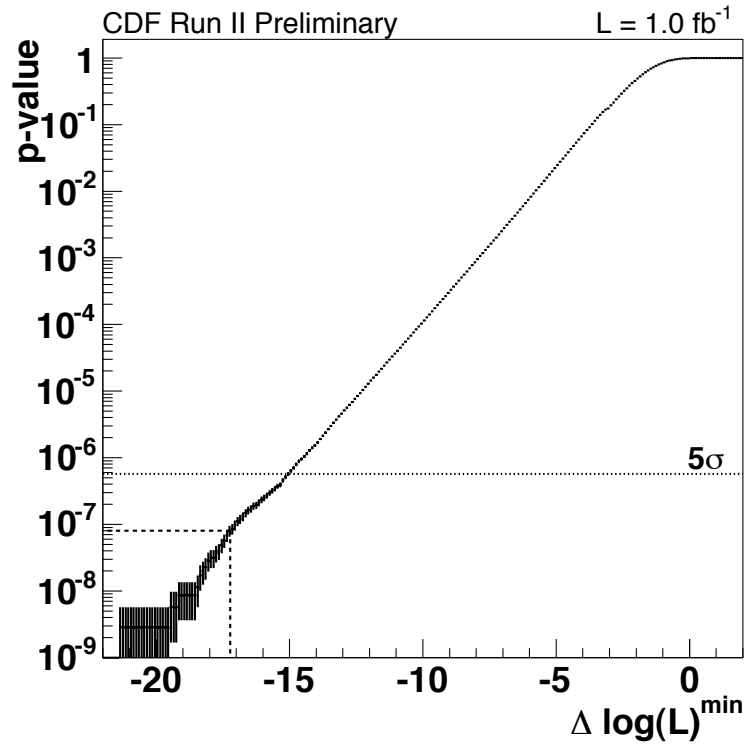
Likelihood Profile



How often can random tags produce a minimum at least as deep?

Likelihood Significance



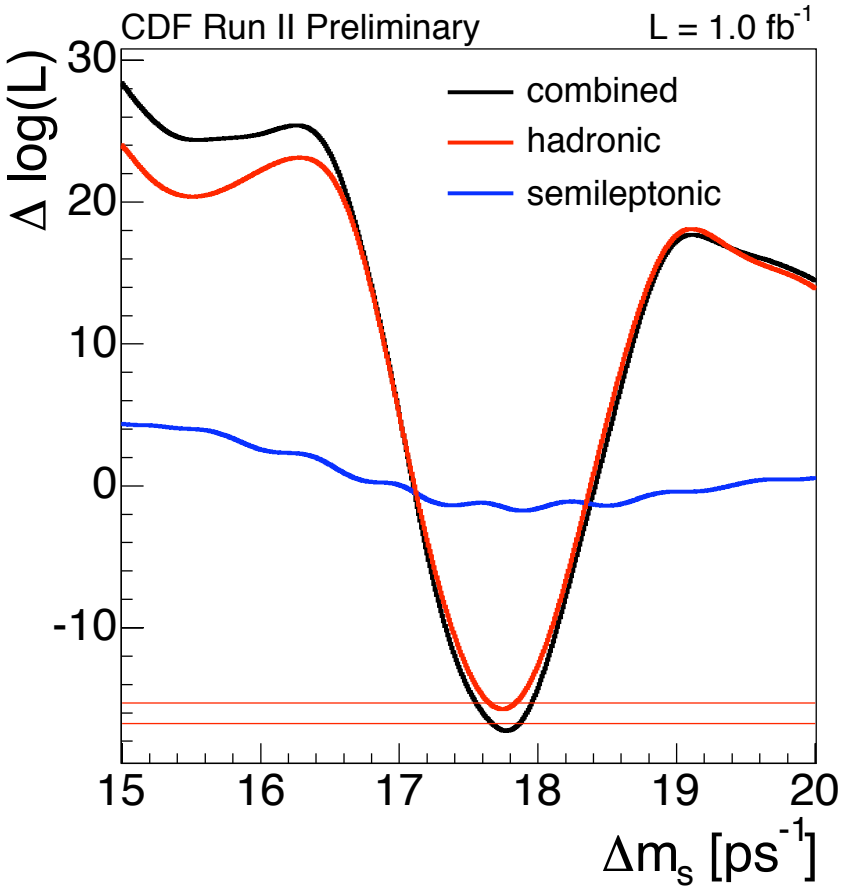


28 trials out of 350 million

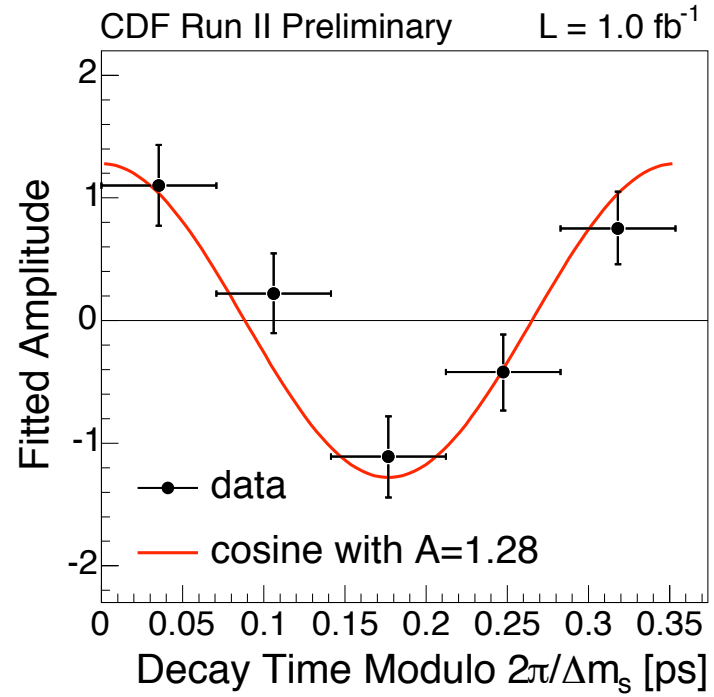
p-value = 8×10^{-8} corresponding to 5.4σ

➠passed observation criteria

Δm_s Measurement



Visualizing the Result



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

Impact on CKM

matrix elements determination

Determination of $|V_{td}/V_{ts}|$

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B^0}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2} \Rightarrow \left|\frac{V_{td}}{V_{ts}}\right| = 0.2060 \pm 0.0007(\text{exp}) \pm^{0.0081}_{0.0060} (\text{th})$$

no longer limited by experimental measurements

other inputs:

$$\xi^2 = 1.21^{+0.047}_{-0.035}$$

[M.Okamoto, hep-lat/0510113]

$$m_{B^0}/m_{B_s} = 0.98390$$

[PRL 96, 202001 (2006)]

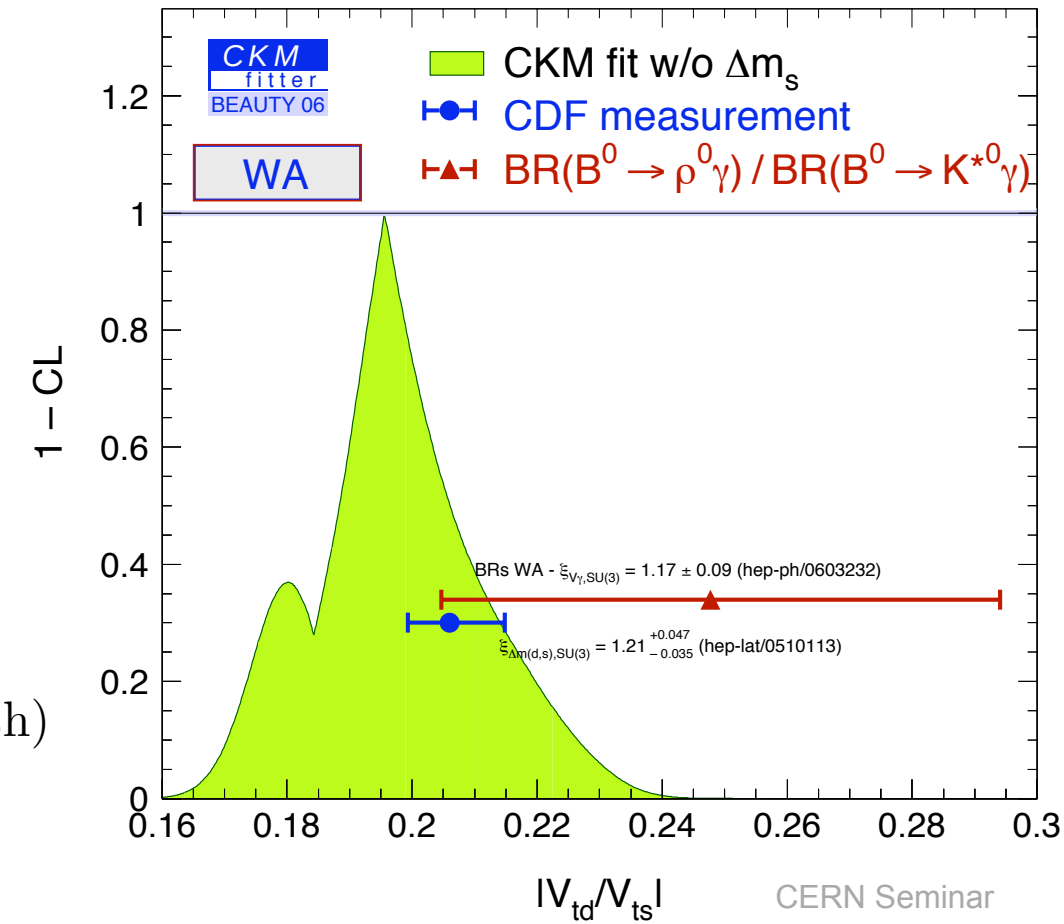
$$\Delta m_d = 0.505 \pm 0.005 \text{ ps}^{-1}$$

[PDG 2006]

compare to Belle b→dϒ:

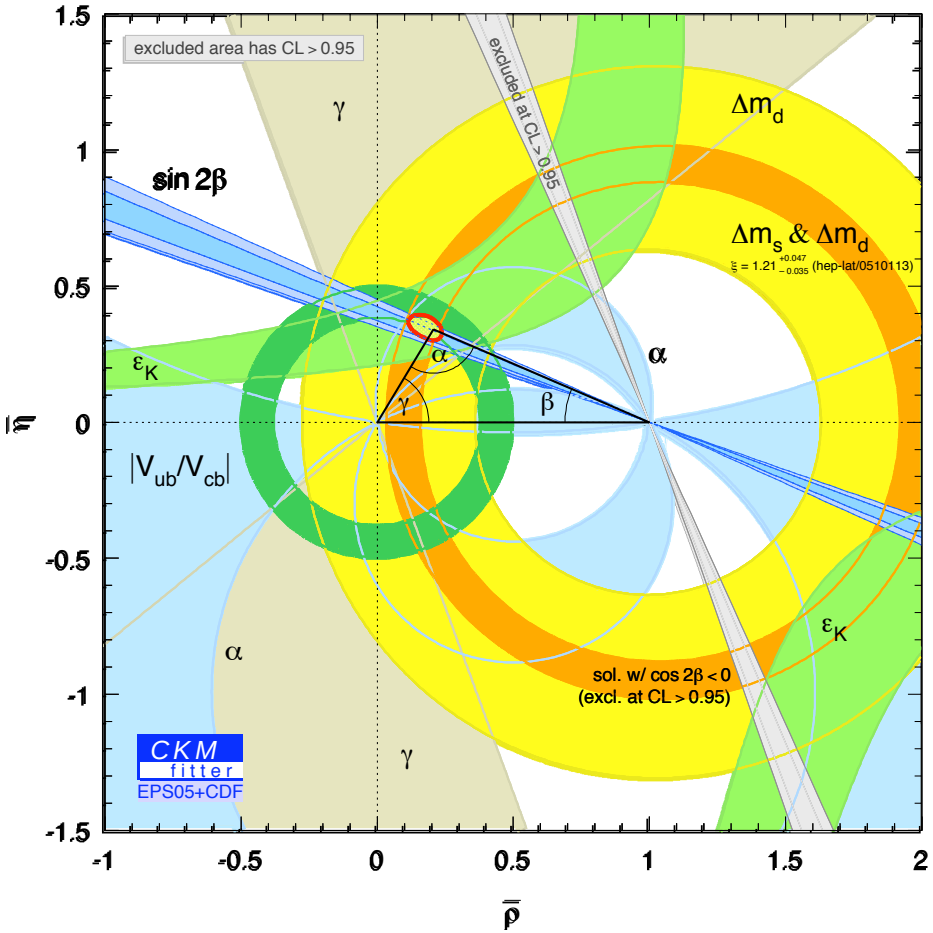
$$|V_{td}/V_{ts}| = 0.199^{+0.026}_{-0.025}(\text{exp})^{+0.018}_{-0.015}(\text{th})$$

[PRL 96, 221601 (2006)]

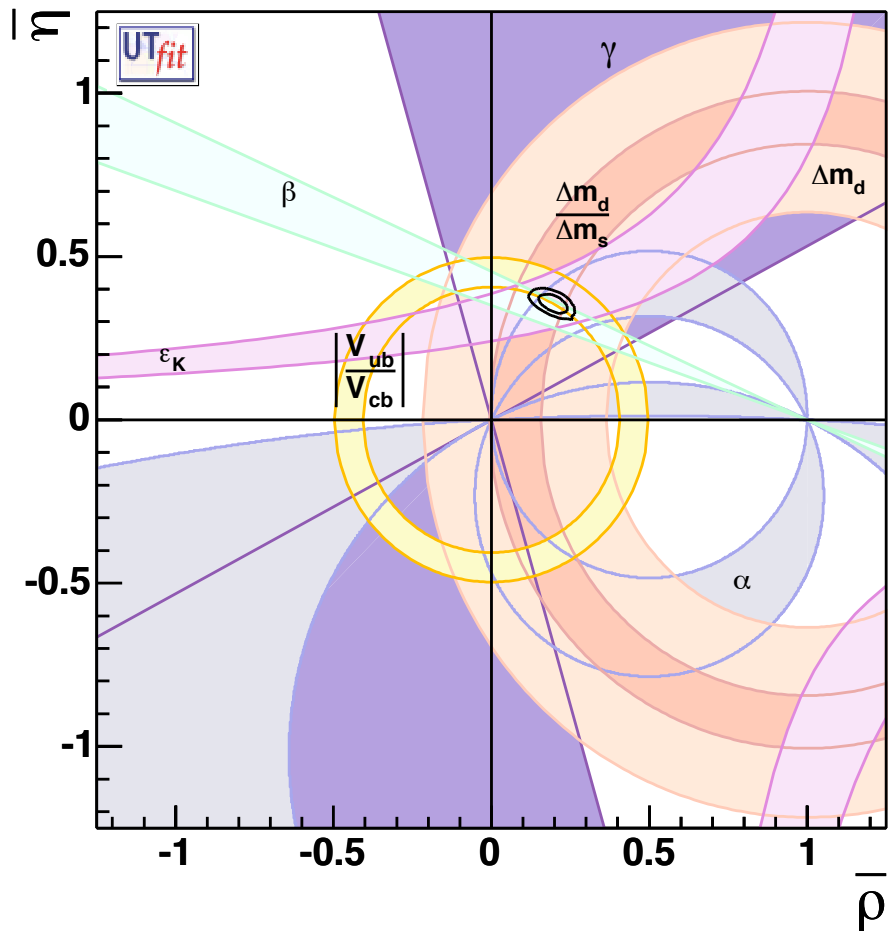


Impact on Unitarity Triangle Fit

after



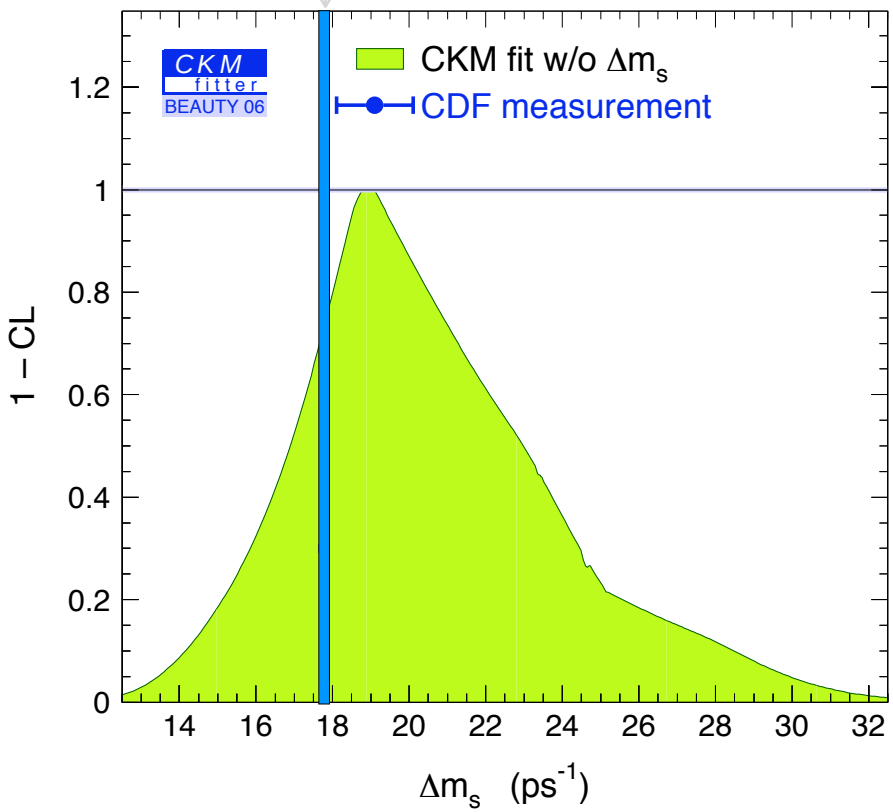
CKM Fit, with CDF measurement

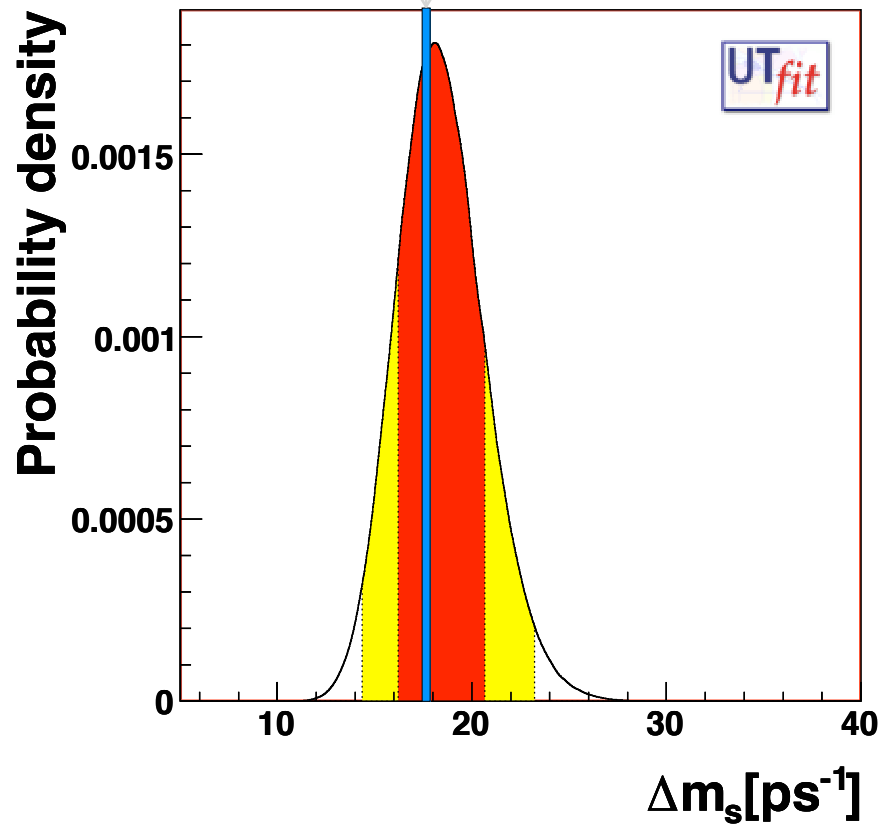


UT Fit, with CDF measurement

Measurement vs Expectation

CDF Δm_s Measurement





Combined measurement of mixing frequency and mixing phase provides model independent limits on New Physics

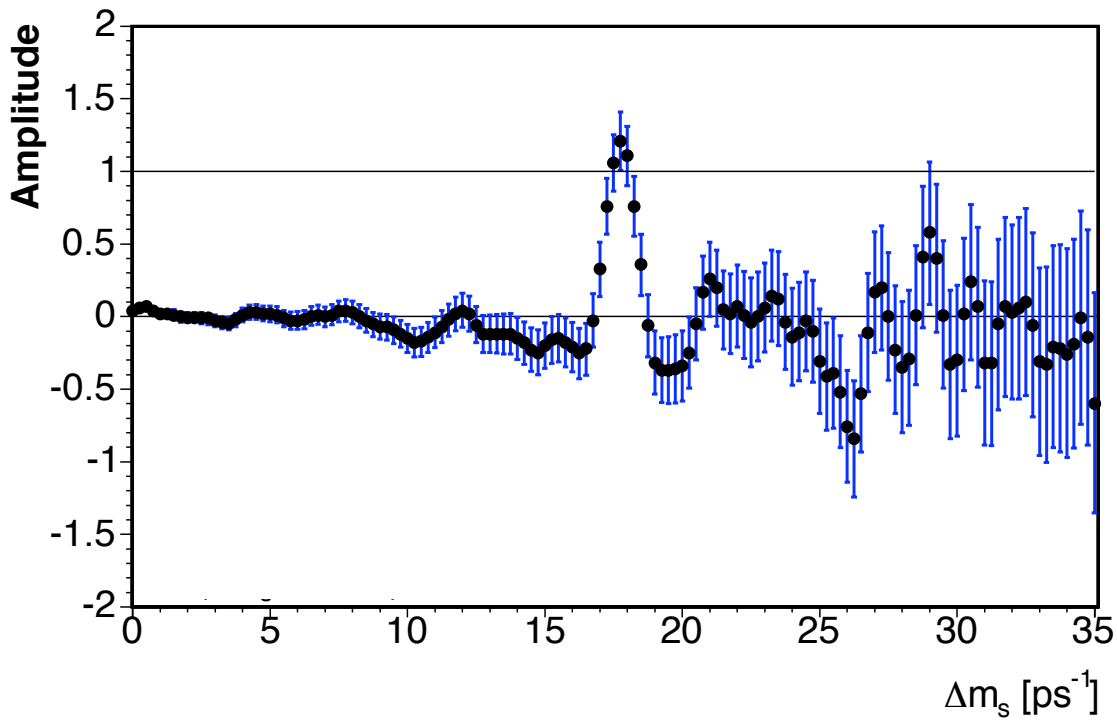
Conclusion

Long journey ended

Observation of B_s-$\bar{B}_s$ oscillations

- probability of random tag fluctuation ~ 8.10^{-8}: $>5\sigma$
- most precise measurement of oscillation frequency

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



PRL 97, 242003 2006