CDF *B* Physics

Run-I Results and Run-II Prospects

KEK Workshop

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- Introduction
- Selected Run-I Results
  mixing, sin(2β), rare decays
- Run-II Prospects (x 20 more data)
- Conclusion

Introduction

Why *B* Physics at a Hadron Machine?

Because the production rates are high.

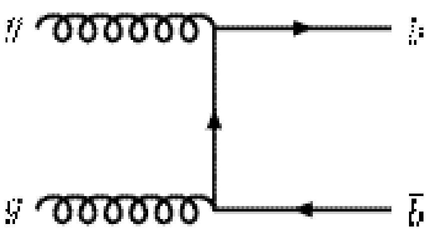
$\sigma(b\bar{b}) \sim 1$ nb at $\Upsilon(4S$

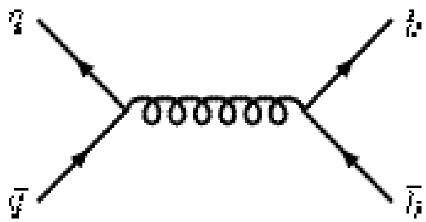
6 nb at Z^0

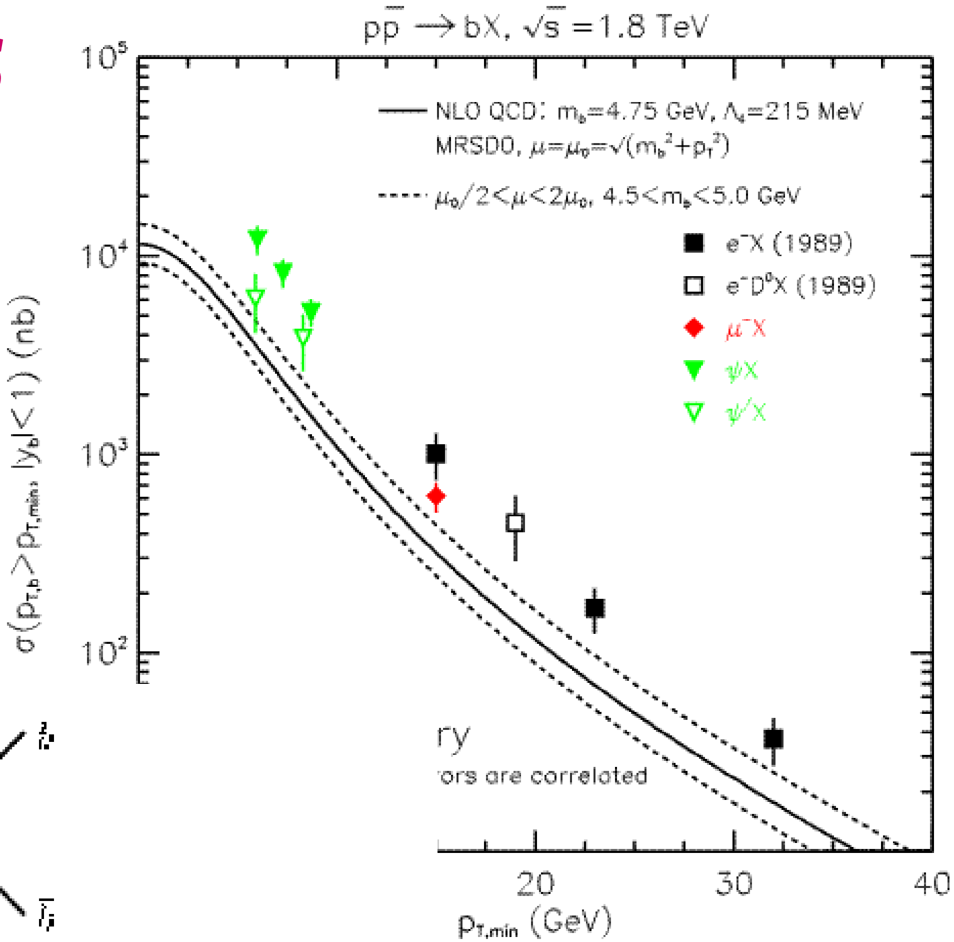
$p\bar{p} \rightarrow b\bar{b}$ x via

strong interaction

$\sigma \sim 10\ \mu$b at 1.8 TeV







Need to trigger on *B* decays, though.

So far relied on leptons:

- Single leptons (e, μ)
  - $B \rightarrow l^+ \nu X$

$p_T > 8$ GeV/c

$\langle p_T(B) \rangle \sim 20$ GeV/c

purity ~ 40%

- Di-leptons (μμ, eμ)
  - $B \rightarrow J/\psi X,\ J/\psi \rightarrow \mu^+\mu^-$
  - $b \rightarrow e \nu X,\ \bar{b} \rightarrow \mu \nu X'$

$p_T > 2$ GeV/c

$\langle p_T(B) \rangle \sim 10$ GeV/c

purity ~ 20% (J/ψ)

Run II will employ impact parameter trigger.

→ can collect all-hadronic final states such as $B^0 \rightarrow \pi^+\pi^-$, $B^0_s \rightarrow D_s^-\pi^+$.

CDF Detector (Run I)

- Silicon micro-strip detector

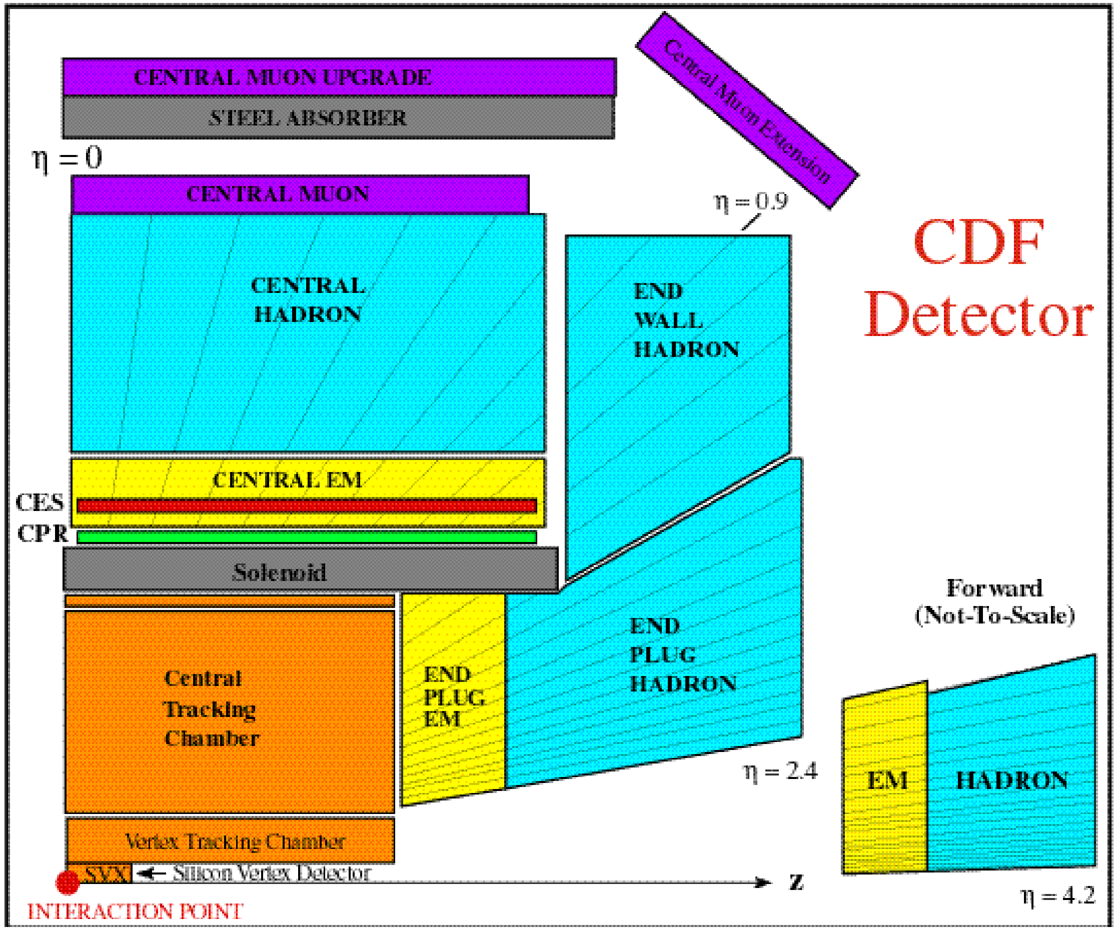
  Impact parameter

  $\sigma = (13 + 40/p_T)\ \mu m$

- Central tracking chamber

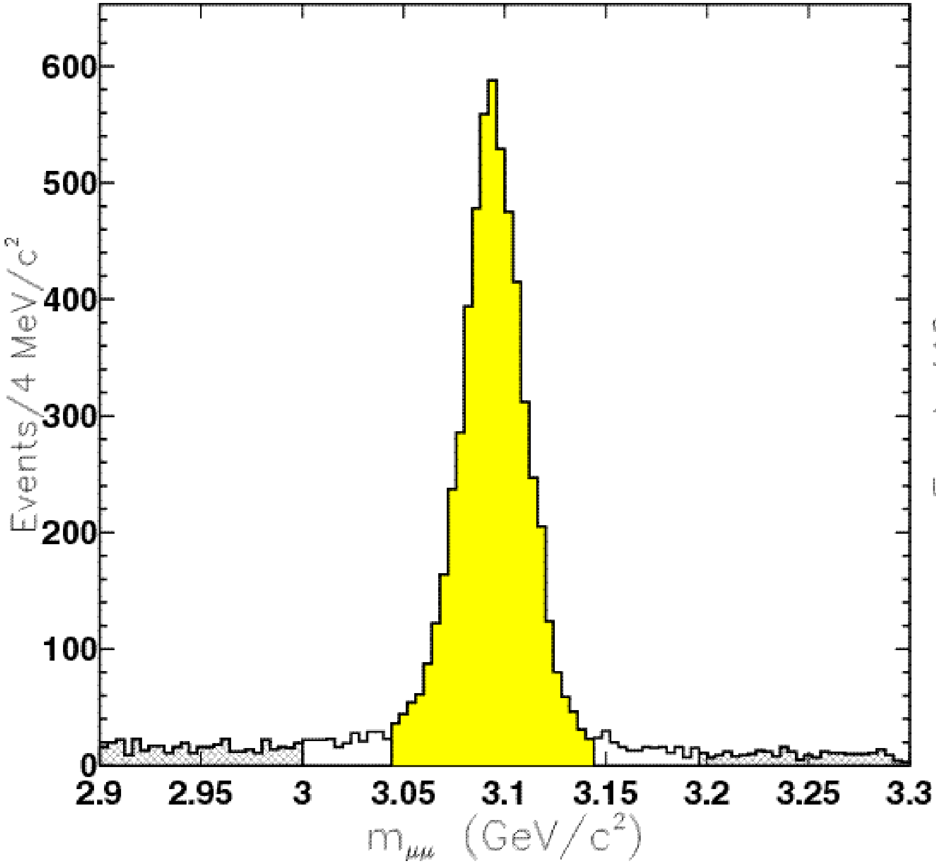
  $\sigma(p_T)/p_T \sim 0.001\ p_T$

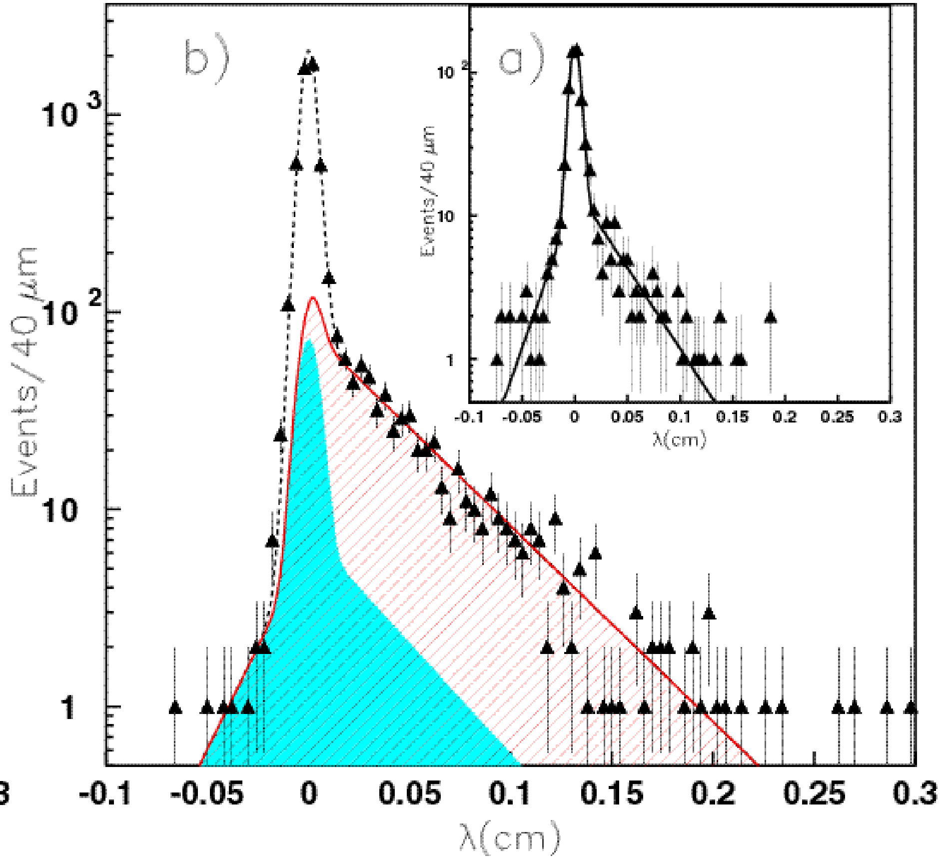
- Lepton detection



Collected ~ 110 pb^{-1} in 1992 - 96.

Signal $J/\psi \rightarrow \mu^+\mu^-$ Decay length dist.





- ~ 250 k $J/\psi \rightarrow \mu^+\mu^-$.
- Mass resolution ~ 15 MeV/c^2.
- ~ 20% from *B* decays, others direct / $\chi_c \rightarrow J/\psi\ \gamma$.

Run-I CDF *B* physics results

B hadron properties

- Mass measurements of B^0_s and Λ_b.
- Lifetime measurements of B^+, B^0, B^0_s, Λ_b.
- B^0-$\bar{B}^0$ oscillations and flavor tagging.
- $\sin(2\beta)$ from $B^0/\bar{B}^0 \rightarrow J/\psi\ K^0_S$.
- B_c meson.
- Rare decay searches (FCNC decays)
  - $B \rightarrow K^{(*)} l^+ l^-$, B^0, $B^0_s \rightarrow l^+ l^-$.

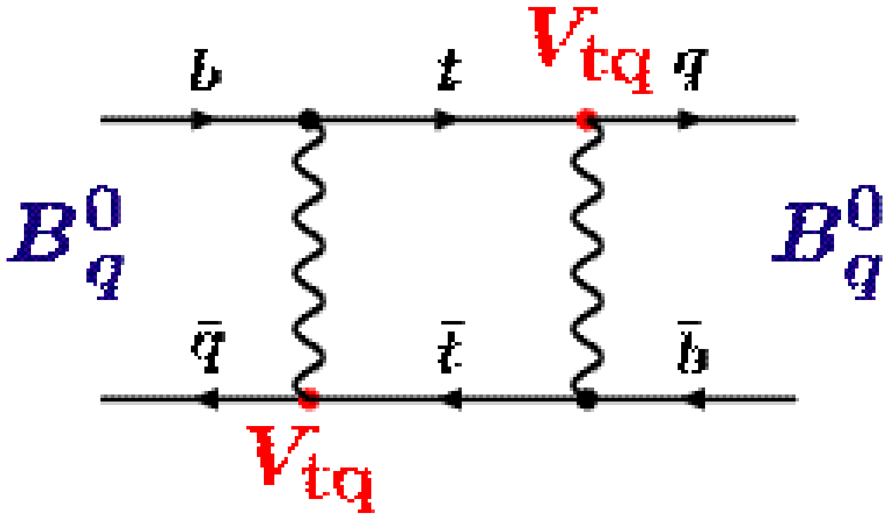
Run-I results (continued)

QCD studies

- Inclusive b and B production.
- $b\bar{b}$ production correlations.
- b-quark fragmentation fractions, f_u, f_d, f_s ...
- Onium production (J/ψ, Υ)
  - Prompt and non-prompt (from B, χ_c) production
  - Production polarization

I cannot cover all results today. Please visit
http://www-cdf.fnal.gov/physics/physics.html

B^0-$\bar{B}^0$ Oscillation



- 2nd order weak interaction.
- Decay probability:

$$P_{B^0 \to B^0}(t) = \frac{1}{2\tau} e^{-t/\tau}(1 + \cos \Delta m t) \quad \text{Unmixed}$$

$$P_{B^0 \to \bar{B}^0}(t) = \frac{1}{2\tau} e^{-t/\tau}(1 - \cos \Delta m t) \quad \text{Mixed}$$

- Oscillation frequency = $\Delta m = m_H - m_L$:

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

- $\Delta m_s / \Delta m_d \rightarrow |V_{ts}| / |V_{td}|$ with less theory uncertainty

Ingredients for B^0-$\bar{B}^0$ Oscillation Measurements

- Proper decay time
- Decay flavor ($B^0 \rightarrow l^+ \nu X$ vs $\bar{B}^0 \rightarrow l^- \nu X$)
- Production flavor, b or $\bar{b}$? Flavor tagging

Flavor tagging is the hardest part.

Conventional approach:

identify the flavor of the other B

semileptonic decay leptons,

kaons, jet charge

infer the flavor of the signal B

Flavor Tagging (cont'd)

Exploit charge-flavor correlation with a nearby pion (Gronau, Nippe, Rosner).

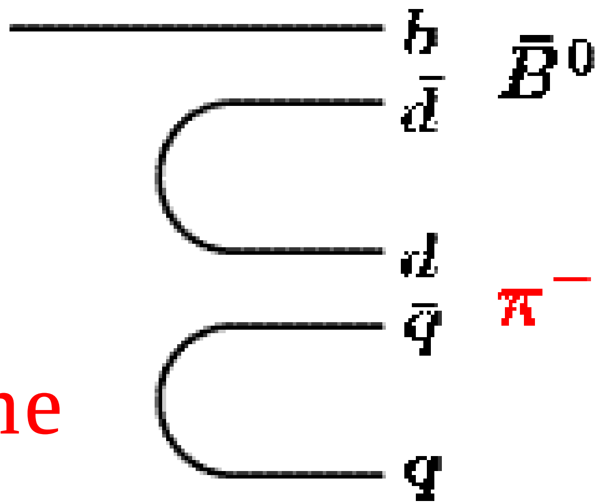
Example: $D^{*+} \rightarrow D^0 \pi^+$.

Since $B^* \not\rightarrow B\,\pi$, use pions from

$B^{**} \rightarrow B\,\pi$ (resonant) or

Fragmentation $b \rightarrow B\,\pi$

(non-resonant).



The correlations are the same if it is resonant or not.

Tagging Dilution

No tag is perfect. e.g. for lepton tag:

- Leptons from $b \rightarrow c \rightarrow l^+ \nu\ s$
- B^0, B^0_s mixes.
- Fakes.

Probability of misidentification W

Dilution $D = 1 - 2W$.

Oscillation amplitude reduced by a factor D.

(unmixed - mixed) / total = $\cos(\Delta m\ t)$

$\rightarrow D \cos(\Delta m\ t)$

Tag effectiveness = εD^2,

ε is the efficiency of the tag.

Proper decay time and decay flavor: signal side

- l^- with inclusive charm vertex

  (Secondary vertices)

  High stat, lower B^0 content

  B^-, B^0, B^0_s, Λ_b, … , charm, fakes

- l^- with exclusive D reconstruction

  Low stat, high B^0 content

  e.g. $B^0 \rightarrow l^- \bar{\nu} D^{*+} X$, $D^{*+} \rightarrow D^0 \pi^+$.

Charge of the lepton identifies the decay flavor :

$$b \to l^- \bar{\nu} \bar{c}, \bar{b} \to l^+ \nu \bar{c}.$$

CDF Mixing Measurements

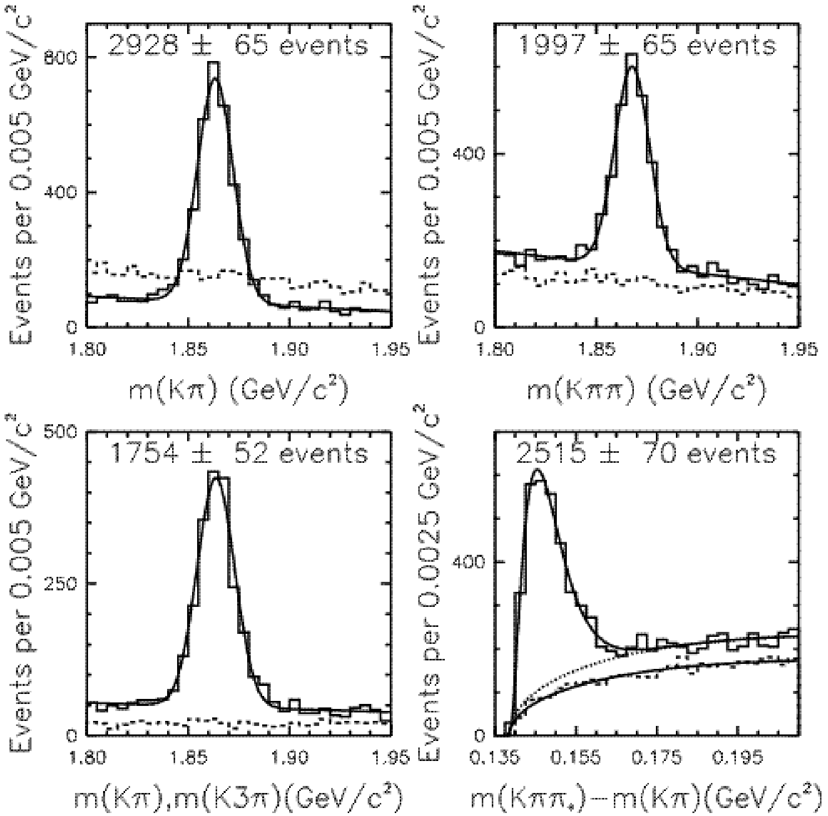
- Combination of signal and tags.
- Six measurements so far.

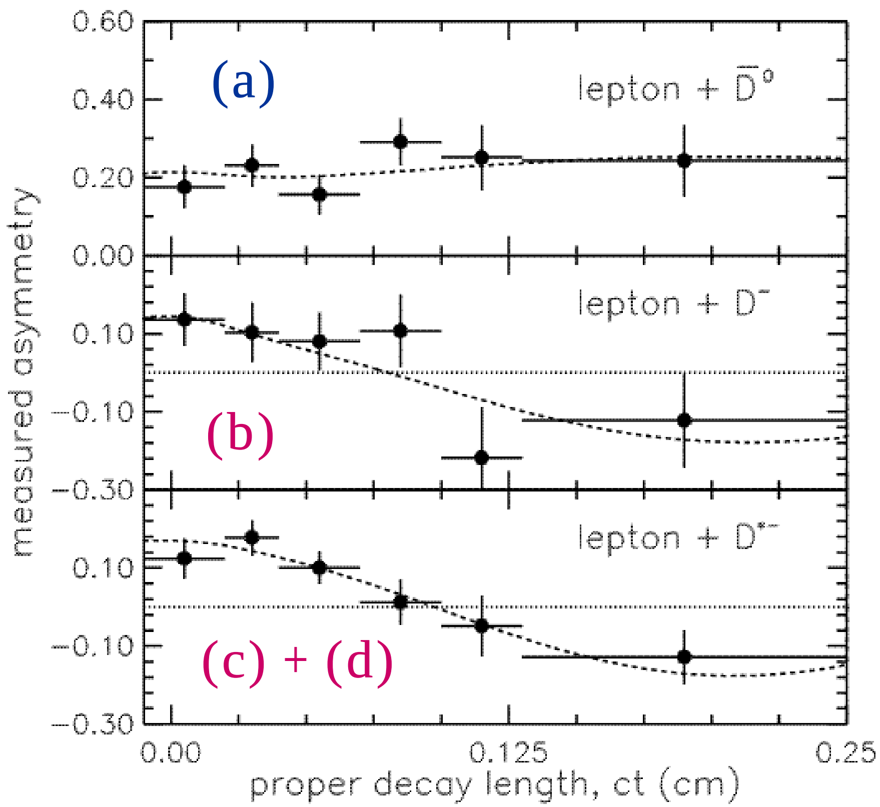
Trigger	Signal	Tag
• single lep	• l + incl. charm	• jet Q + lepton
• single lep	• $l + D$	• same-side pion
• single lep	• D X	• lepton
• dilepton	• l + incl. charm	• lepton ($e\mu$, $\mu\mu$)
• dilepton	• $l + D$	• lepton

Tag lepton can be part of trigger

Mixing from l^- $D^{(*)}$ and same-side pion tag

Charm signal near l^-





(a) $D^0 \rightarrow K^- \pi^+$. (b) $D^+ \rightarrow K^- \pi^+ \pi^+$.

(c) $D^{*+} \rightarrow D^0 \pi^+$,

$D^0 \rightarrow K^- \pi^+$, $K^- \pi^+ \pi^+ \pi$.

(d) $D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow K^- \pi^+ \pi^0$.

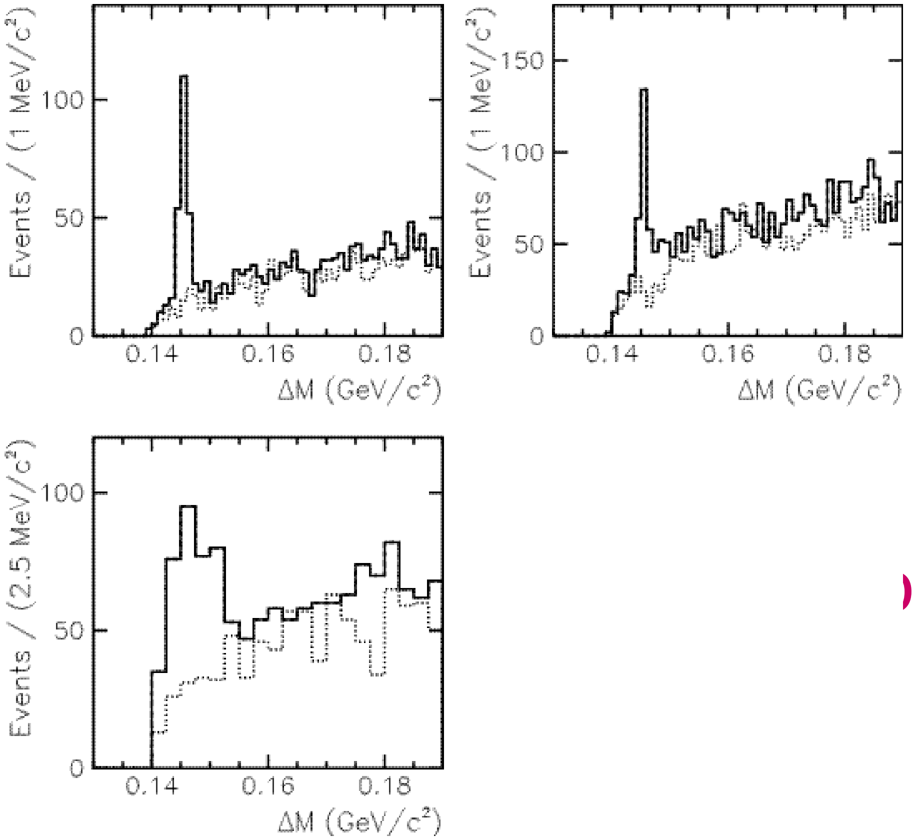
$$\Delta m = 0.471^{+0.078}_{-0.068} \pm 0.034\, ps^{-1}$$

$D(B^+) = 0.27 \pm 0.03 \pm 0.02$

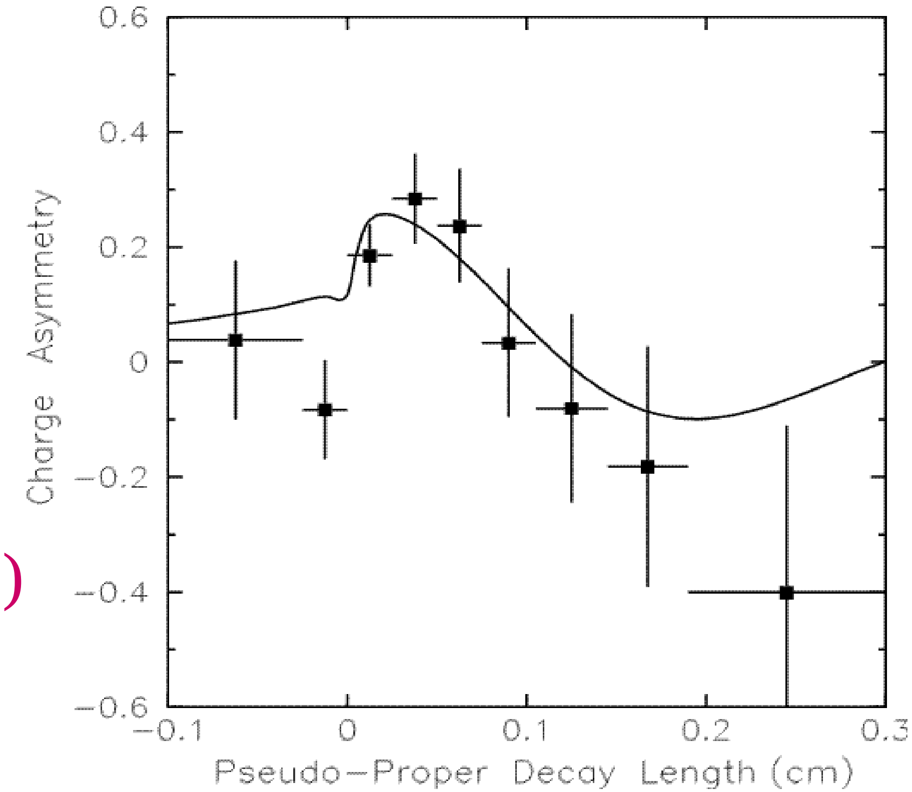
$D(B^0) = 0.18 \pm 0.03 \pm 0.02$

Mixing from l^{-} D^{*+} and lepton tag

Charm signal near l^{-}



Asymmetry = (RS-WS) / Total



$D^{*+} \rightarrow D^0 \pi^+$, followed by

(a) $D^0 \rightarrow K^- \pi^+$,

(b) $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$.

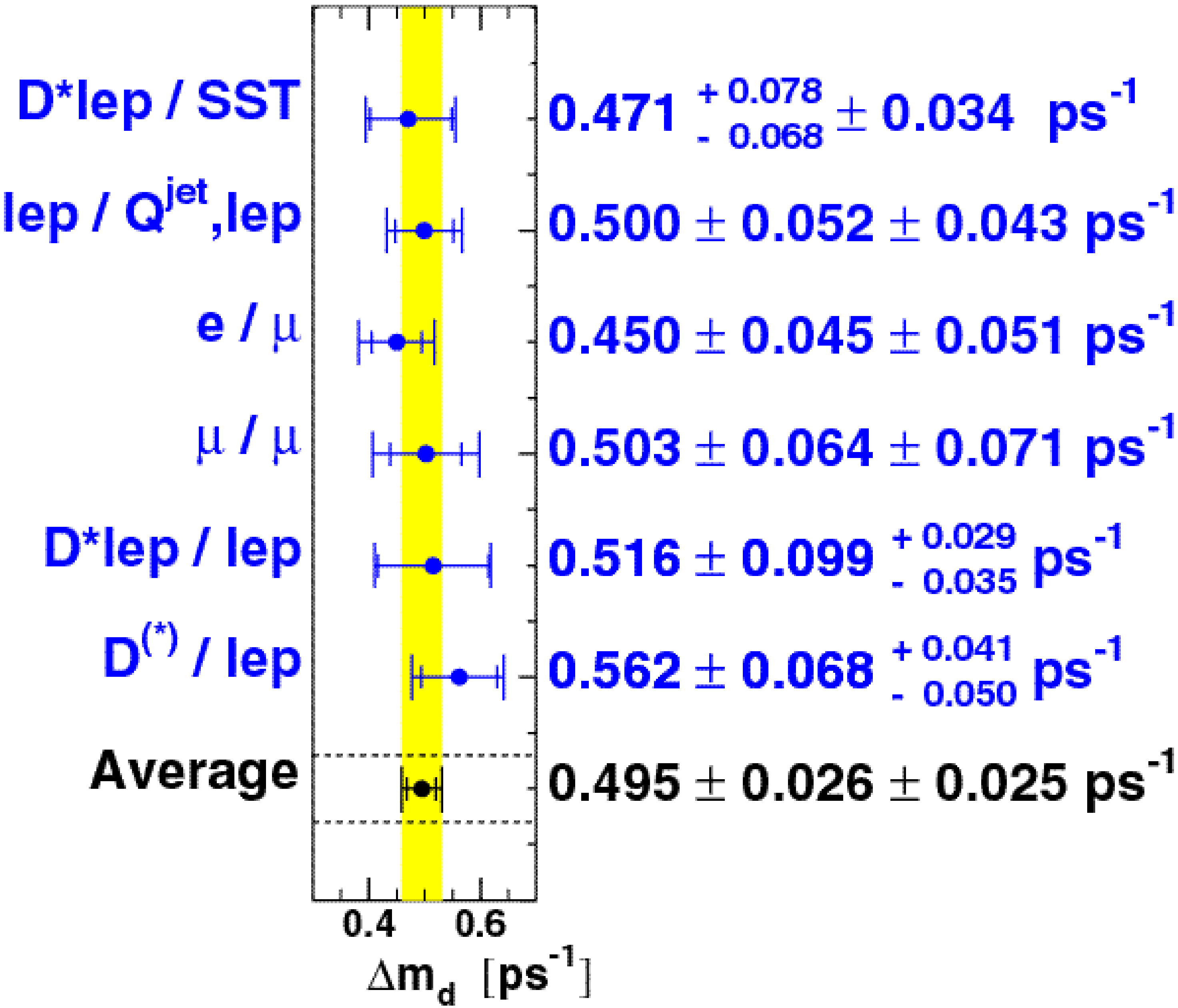
(c) $D^0 \rightarrow K^- \pi^+ \pi^0$.

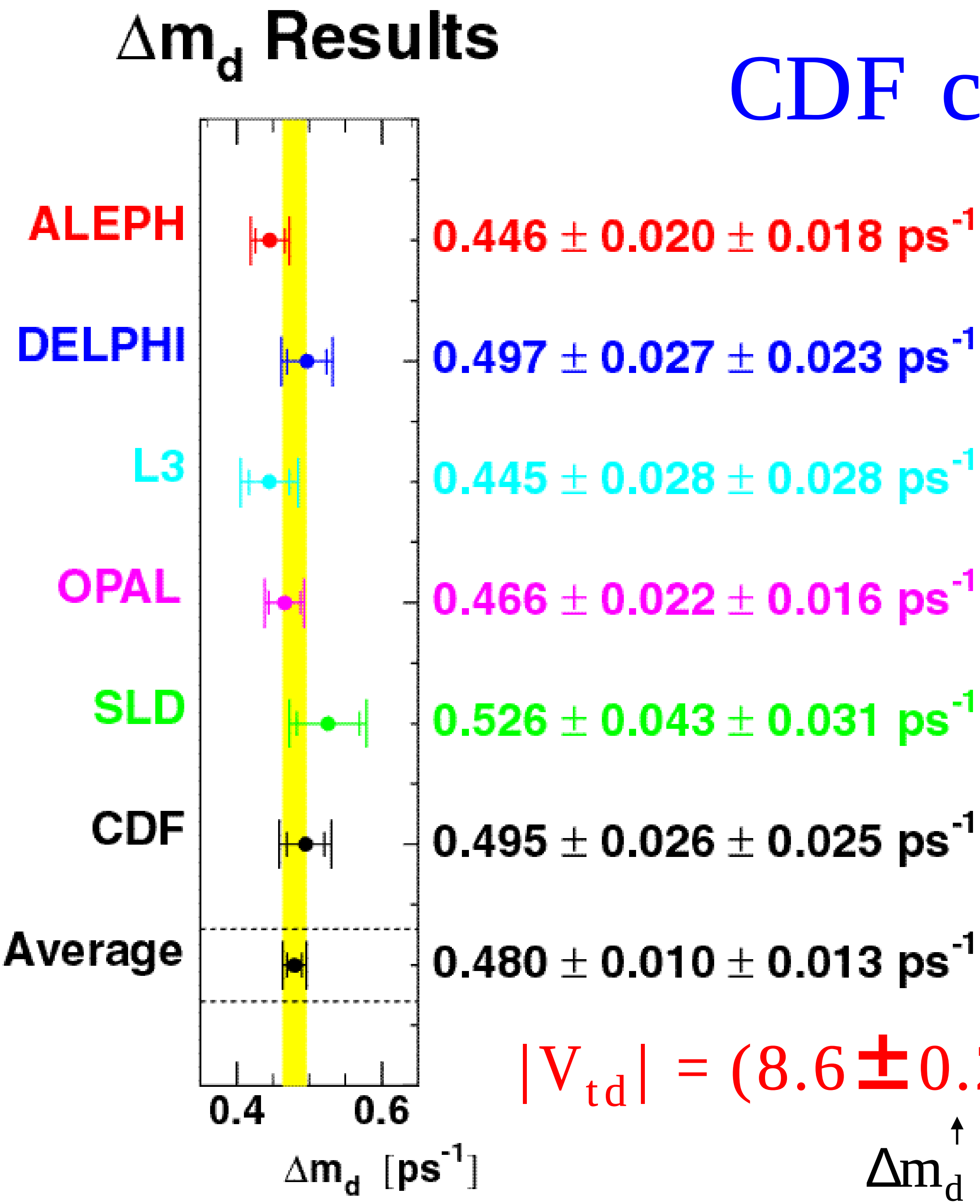
$$\Delta m = 0.516 \pm 0.099^{+0.029}_{-0.035}\, ps^{-1}$$

$W = 0.325 \pm 0.033 \pm 0.012$

$\rightarrow D = 0.350 \pm 0.070.$

CDF Δm_d Results





CDF competitive with e^+e^-

$$|V_{td}| = (8.6 \pm 0.2 \pm 0.2 \pm 1.7) \times 10^{-3}$$

Δm_d ↑ m_{top} ↑ theory ↑

CP Violation in $B^0/\bar{B}^0 \to J/\psi\, K^0_S$

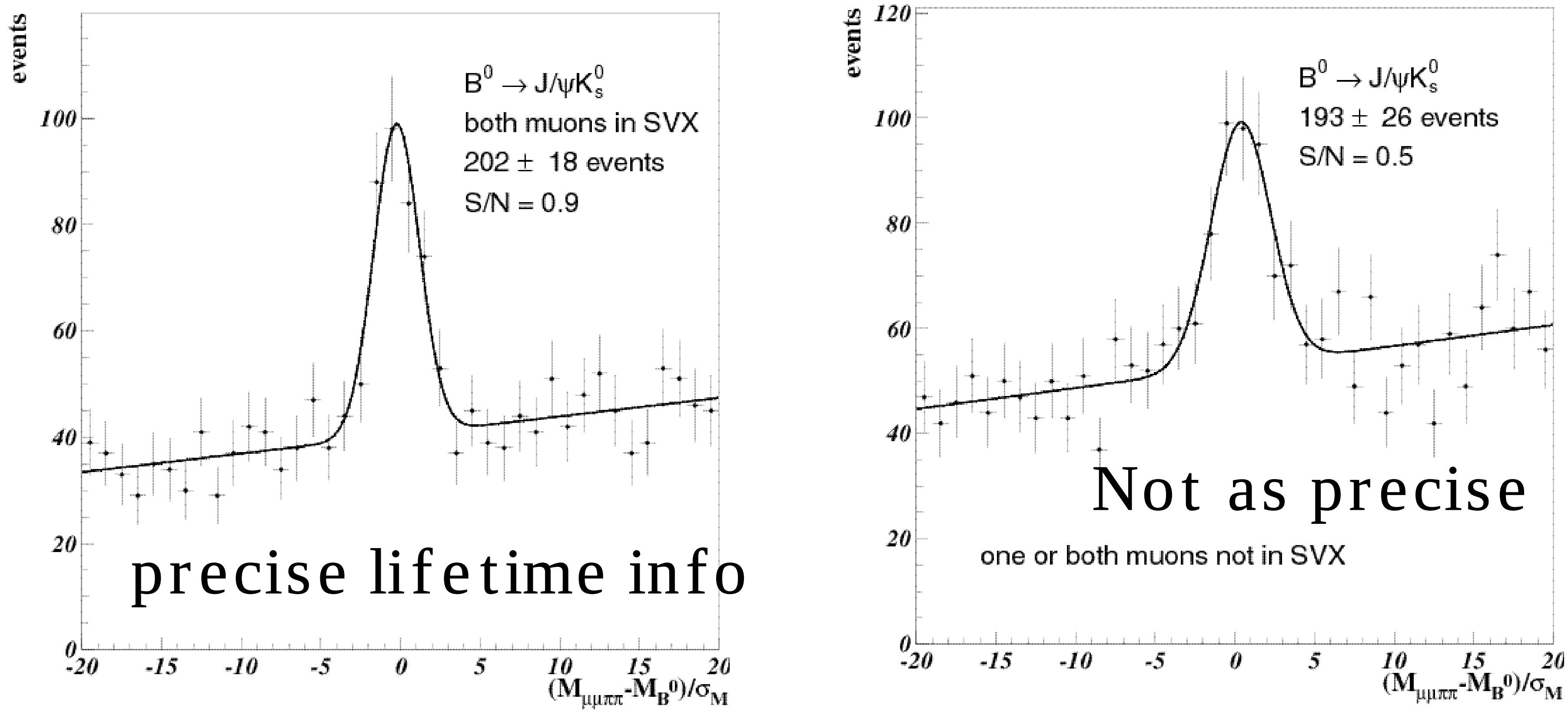
CP viol. $\Leftrightarrow \Gamma(\, i \to f\,) \neq \Gamma(\, \bar{i} \to \bar{f}\,)$

$$A(t) \equiv \frac{\Gamma(B^0 \to J/\psi K^0{}_S) - \Gamma(\bar{B}^0 \to J/\psi K^0{}_S)}{\Gamma(B^0 \to J/\psi K^0{}_S) + \Gamma(\bar{B}^0 \to J/\psi K^0{}_S)}$$

$$= -\sin(2\beta)\sin(\Delta m t)$$

- Now the amplitude is the quantity of interest.
- Final State = $J/\psi\, K^0{}_S \to \mu^+\mu^-\pi^+\pi^-$ "Trivial"
- Initial State, B^0 or $\bar{B}^0$? Flavor Tagging
- Decay Time: Not necessary at CDF, but helps.

$B^0/\bar{B}^0 \rightarrow J/\psi\, K^0{}_S$ ~ 400 signal ev. / 110 pb^{-1}

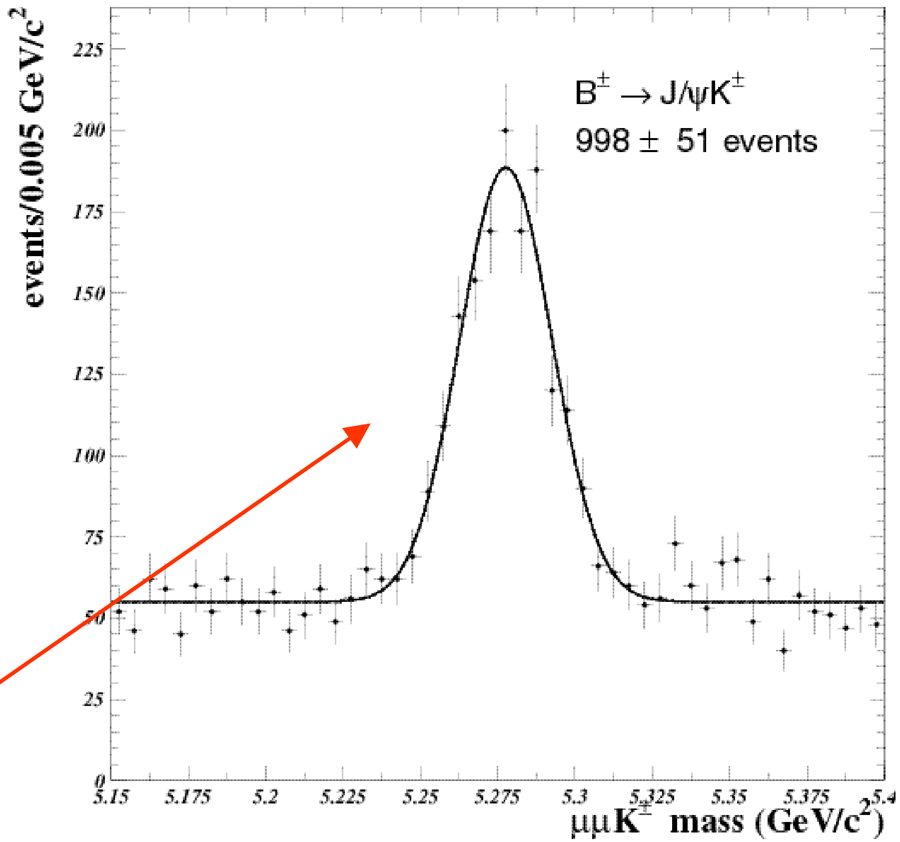


[Mass($J/\psi\, K^0{}_S$) - M(B^0)] / σ

Apply flavor tags, count B^0 vs $\bar{B}^0$.
Extract raw asymmetry = D sin(2β)
Divide it by dilution.

Apply 3 Flavor Tagging Methods

- Same-side "pions"
- Leptons
- Jet charge



Measure tag dilution from ~ 1000 $B^+ \to J/\psi\ K^+$ decays.

(For SST, extrapolation of *lepton-D* meas.)

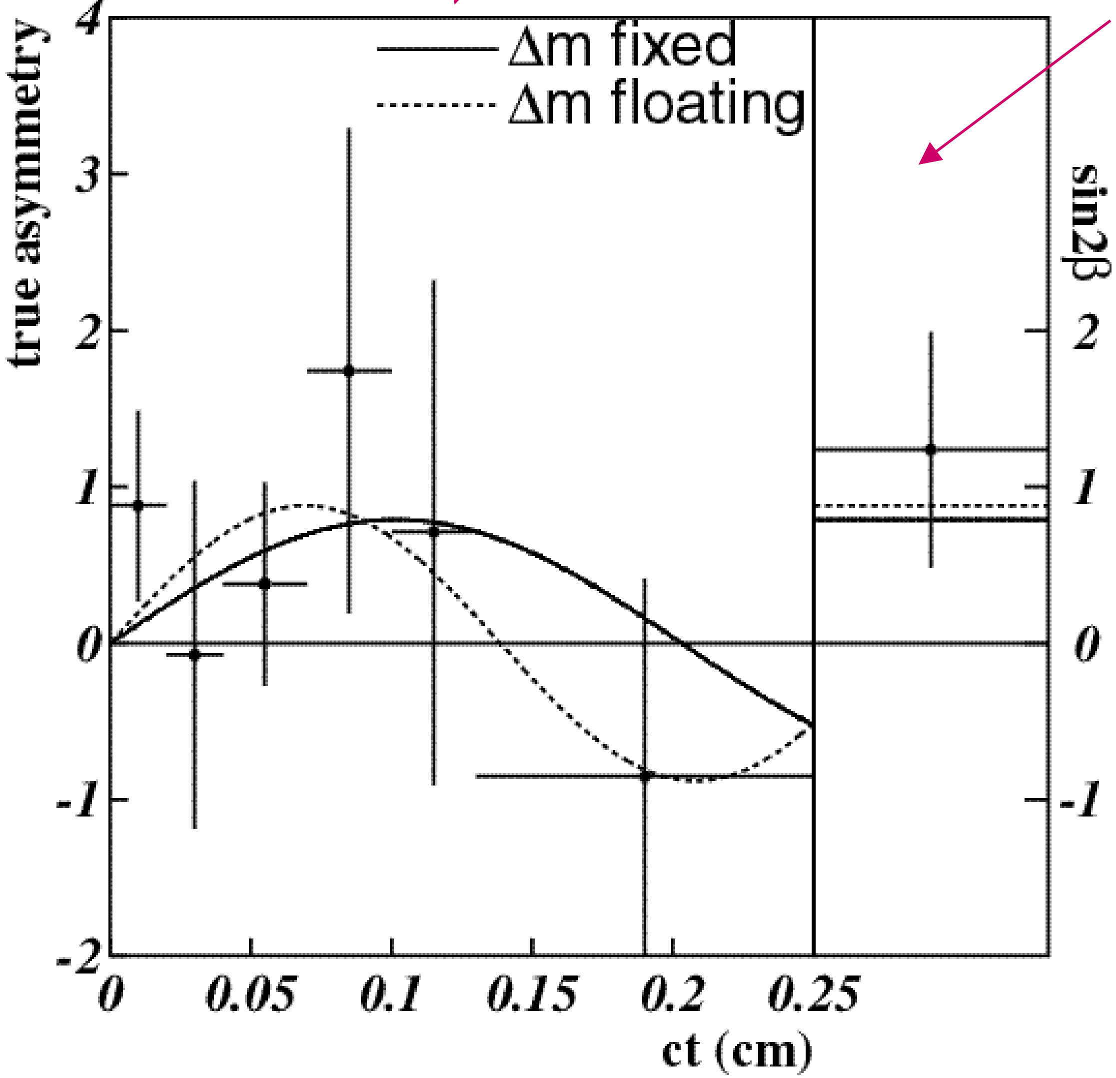
Tag	ε(%)	D(%)	εD^2(%)
SST	70	17±3	2.1±0.5
Lepton	6.5	63±15	2.2±1.0
Jet Q	45	22±7	2.2±1.3
Total			6.3±1.7

Asymmetry

Precise lifetime sample:

Asymmetry vs. time.

$\text{Asymmetry} = [\,N(\bar{B}^0) - N(B^0)\,] / \text{tot}$



Less precise lifetime sample:

Time-integrated

$\text{Asym} \times (1+x_d^2) / x_d$

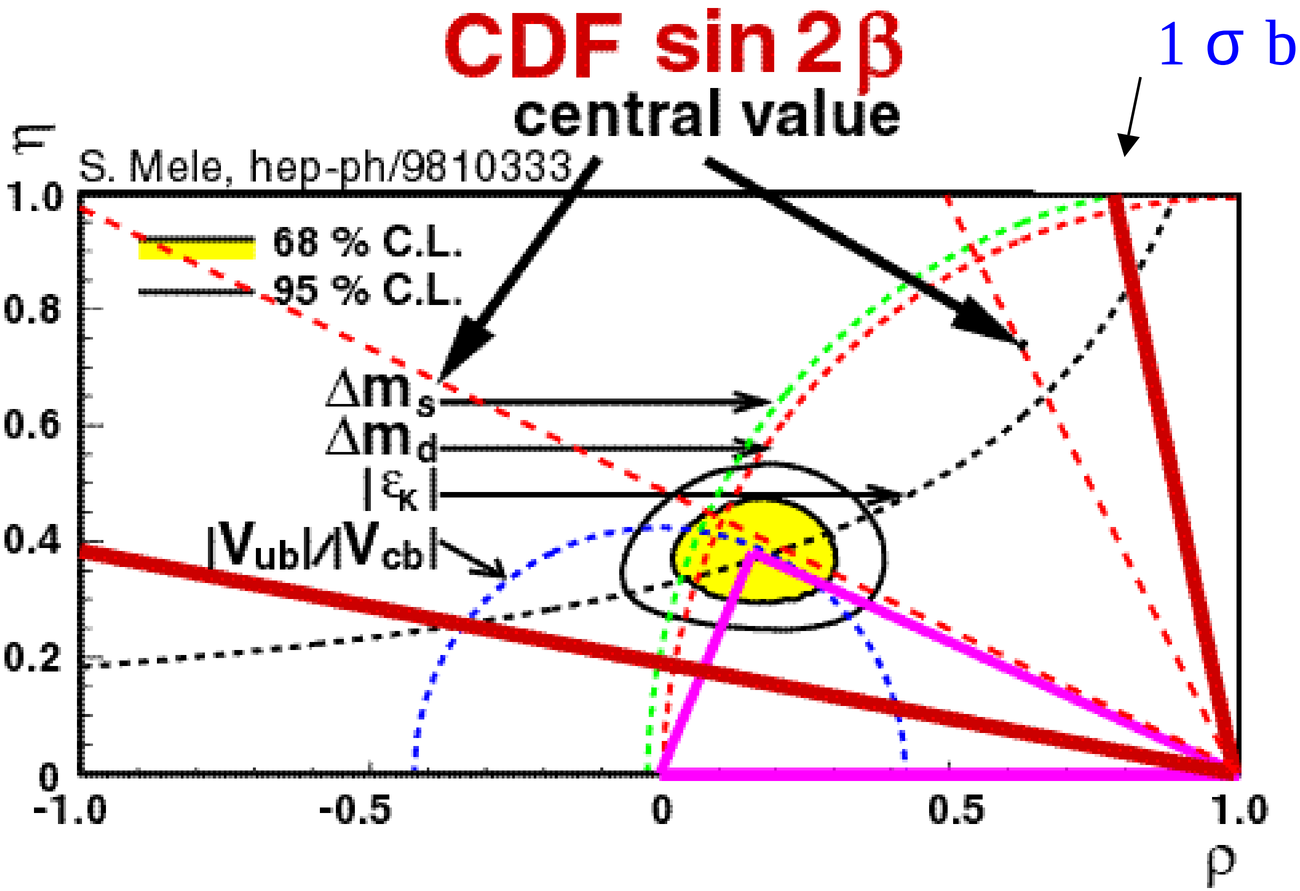
$= \sin(2\beta)$

$\sin(2\beta) = 0.79^{+0.41}_{-0.44}$

(stat + syst).

Constraints on the unitarity triangle

sin(2β) → β: four solutions, β_1, β_2, $\beta_1+\pi$, $\beta_2+\pi$ ($\beta_2=\pi/2-\beta_1$).



1 σ bound

1 σ bour

Not much constraint now, but should be interesting in Run-II, where we expect ±0.08 in sin(2β).

Rare Decays

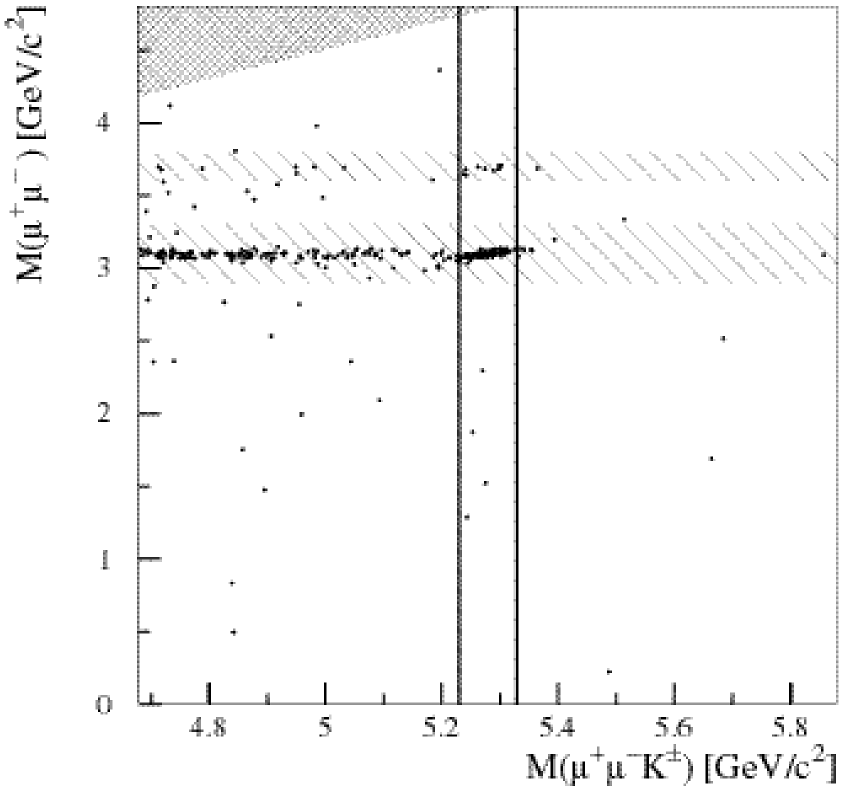
- $B \rightarrow K^{(*)} l^+ l^-$
  - $b \rightarrow s$ FCNC transition
  - $|V_{ts}|$
  - SM predicts B.R. ~ 10^{-7} to 10^{-6}.
  - New physics could enhance it.
  - Has yet to be observed.

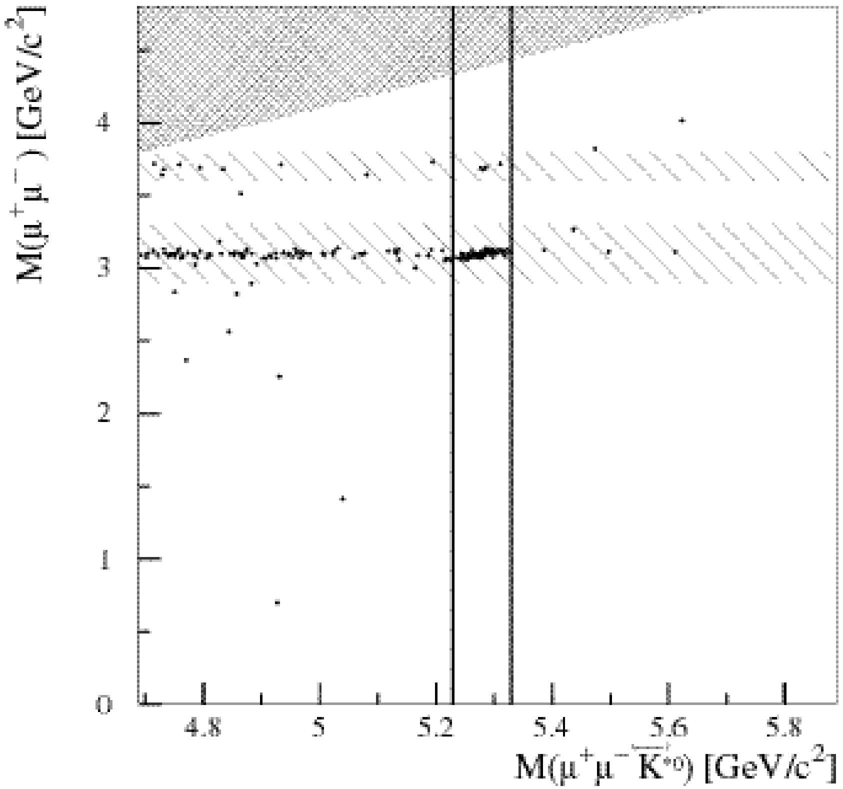
$l^+ l^-$ can be resonant, e.g. J/ψ, $\psi(2S)$.

$\rightarrow$ Indistinguishable from $b \rightarrow c\bar{c}s$

Look at non-resonant mass region.

$B^+ \rightarrow K^+ \mu^+ \mu^-$ | $B^0 \rightarrow K^{*0} \mu^+ \mu^-$





- 4 candidates
- BR < 5.2 X 10^{-6} @90% CL
- SM: few X 10^{-7}

- 0 candidate
- BR < 4.0 X 10^{-6} @90% CI
- SM: ~ 10^{-6}

Expected signal ~ 0.5 event each.
Should see a few signal events in Run II.

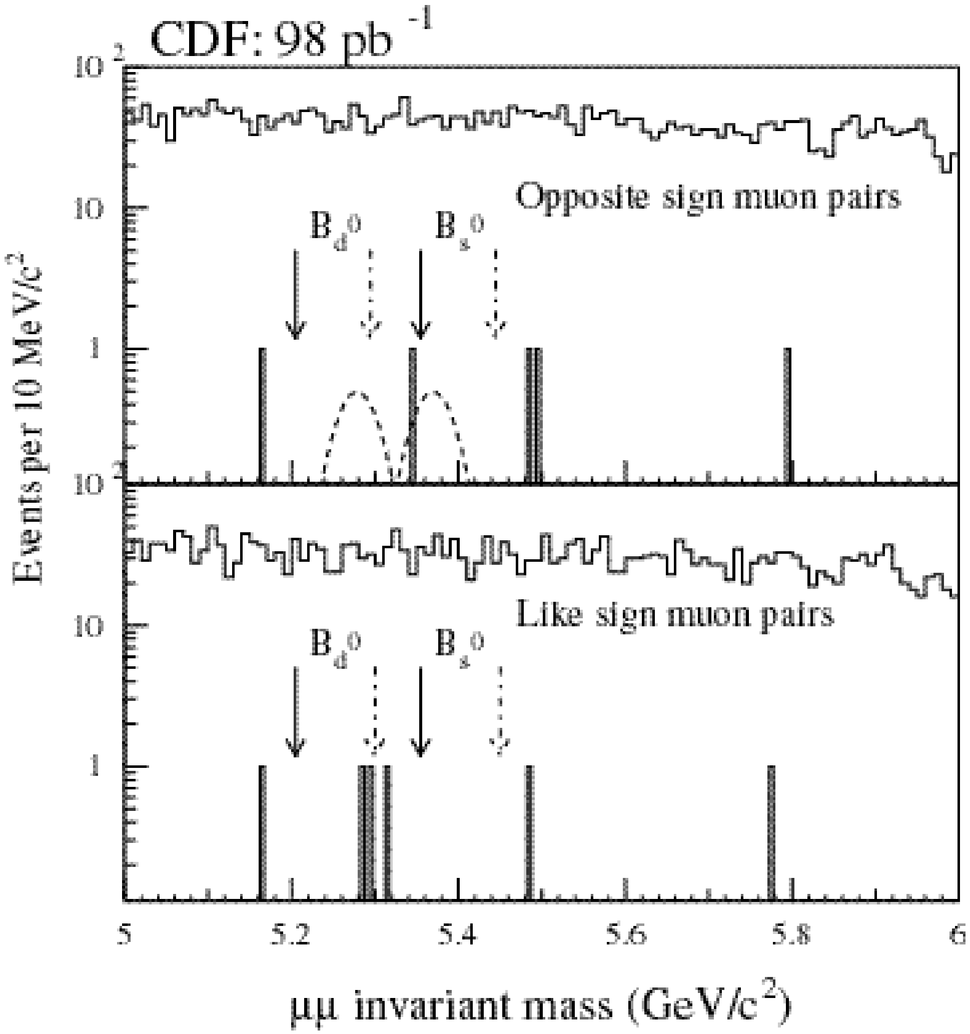
More Rare Decays: $B^0, B^0_s \rightarrow l^+l^-$

- V_{td} for B^0, V_{ts} for B^0_s
- Helicity suppressed
- B.R. highly suppressed:

SM predictions:

- $B^0 \rightarrow \mu^+\mu^-$ $(1.5 \pm 1.4) \times 10^{-10}$
- $B^0_s \rightarrow \mu^+\mu^-$ $(3.5 \pm 1.0) \times 10^{-9}$
- $B^0 \rightarrow e^+e^-$ $(3.4 \pm 3.1) \times 10^{-15}$
- $B^0_s \rightarrow e^+e^-$ $(8.0 \pm 3.5) \times 10^{-14}$

Rare Decays $B^0, B^0_s \to \mu^+\mu^-$



One candidate in the overlap region of B^0 and B^0_s mass windows.

B.R. < 8.6×10^{-7} for B^0

B.R. < 2.6×10^{-6} for B^0_s

both @ 95% C.L.

Also looked for decays to $e^+\mu^-$, $e^-\mu^+$

B.R. < 4.5×10^{-6} for B^0

B.R. < 8.2×10^{-6} for B^0_s

Still long way to go...

B Physics in CDF Run II

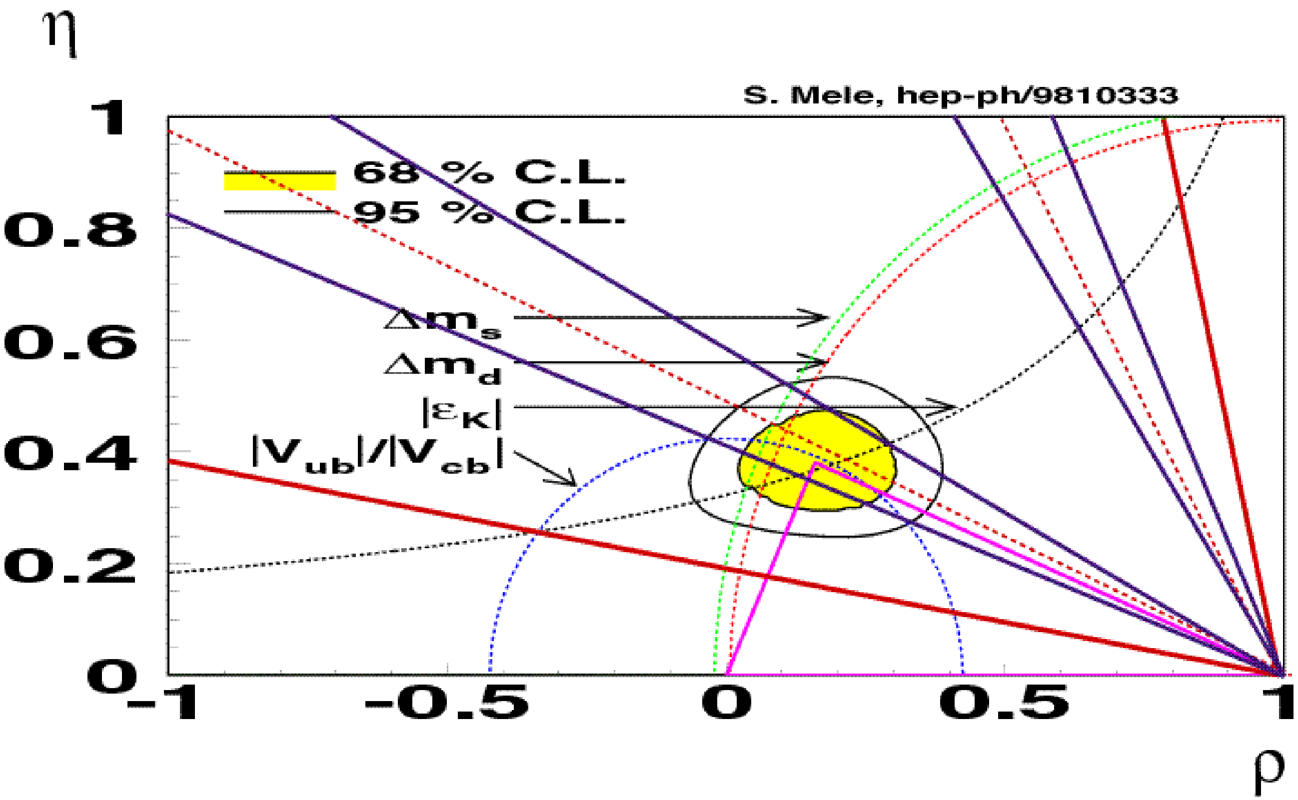
Two Major Goals:

I. Precisison sin(2β) from $B^0/\bar{B}^0 \rightarrow J/\psi\, K^0_S$

II. B^0_s - $\bar{B}^0_s$ Oscillation $\rightarrow$ Δm_s / Δm_d

$\downarrow$

$|V_{td}|$ / λ $|V_{ts}|$



Can be the first meaningful test of the unitarity triangle.

Summary

- CDF does B physics pretty well.
- Run I results cover virtually all aspects of B physics.
- Run II should produce more interesting results, in particular
  - $\sin(2\beta)$ precision of ± 0.08.
  - Δm_s up to 40 ps^{-1}.