Latest results on B_s-meson particle-antiparticle oscillations at

Contents
- Introduction
- Result on Δm_s
- How we got it
- Future

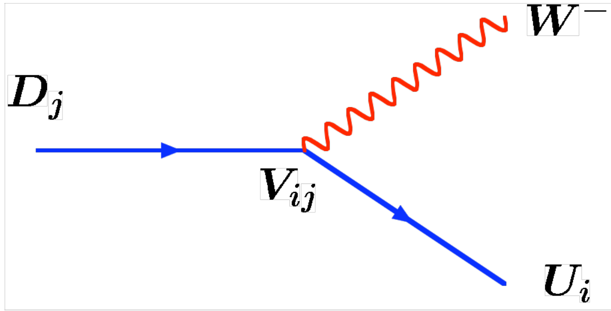
Fumihiko UKEGAWA
CDF Collaboration
University of Tsukuba

KEK Physics Seminar
April 25, 2006
IPNS, KEK

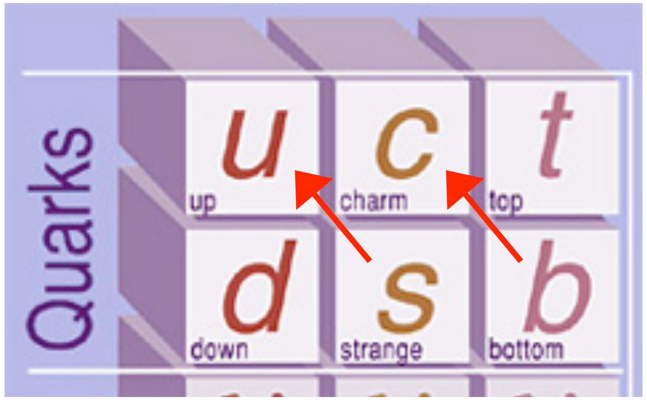
Introduction

Weak interactions (charged currents) :
$\mathcal{L} \propto \bar{U} W^{\mu} \gamma_{\mu} (1 - \gamma_5) D'$,

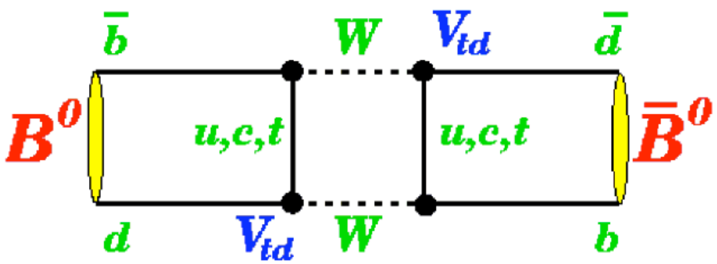
$$D' \equiv \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\rm CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



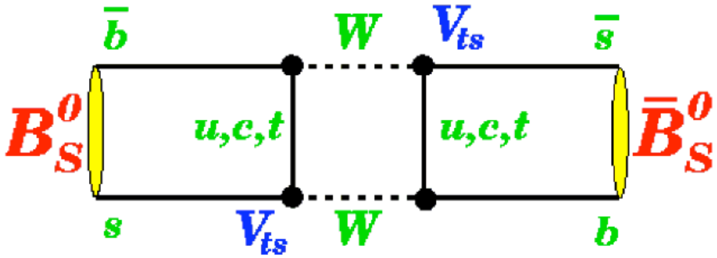
$\Rightarrow$ Quark flavors are not always conserved, e.g. $b \to c$ and $s \to u$ transitions occur at the first order.



- At the second order, ΔS $(\Delta B) = 2$ transitions can happen.
- Physical neutral mesons can turn into their antiparticles !
- Phenomena established for K^0-$\bar{K}^0$ and B^0_d-$\bar{B}^0_d$ meson systems



B^0_s-$\bar{B}^0_s$ system : today



Quantum mechanics

$B_q^0 = \bar{b}q$ or $\bar{B}_q^0 = b\bar{q} \quad (q \equiv d$ or $s)$,
state at $t = 0$ (production via $\bar{p}p \to b\bar{b}X$)

For $t > 0$, $\psi(t) = e^{-i\mathcal{H}t/\hbar}\,\psi(0)$

Two-state system $|B^0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad |\bar{B}^0\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$,

with a Hamiltonian $\mathcal{H} = \begin{pmatrix} m_{11} & m_{12} \\ m_{12}^* & m_{11} \end{pmatrix}$

Eigenvalues

$$\lambda = m_{11} \pm |m_{12}| = m_{H,L}$$

$$\Delta m \equiv m_H - m_L = 2\,|m_{12}| > 0$$

Eigentates

$$|B_L^0\rangle,\ |B_H^0\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle$$

$$\Rightarrow \quad |B^0\rangle = \tfrac{1}{2p}(|B_L^0\rangle + |B_H^0\rangle), \quad |\bar{B}^0\rangle = \tfrac{1}{2q}(|B_L^0\rangle - |B_H^0\rangle)$$

Time development of a state

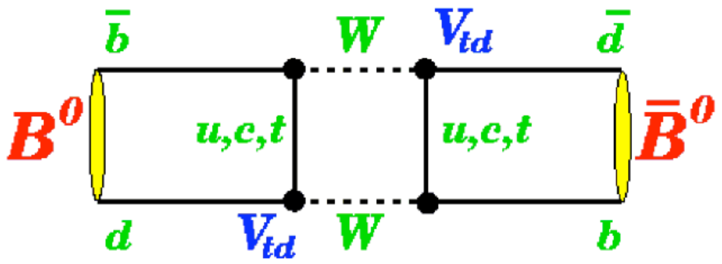
$$|\bar{B}^0(t)\rangle = \frac{e^{-i m_L t}|B^0_L\rangle - e^{-i m_H t}|B^0_H\rangle}{2q}$$
$$= f_+(t)\,|\bar{B}^0\rangle + f_-(t)\,|B^0\rangle$$

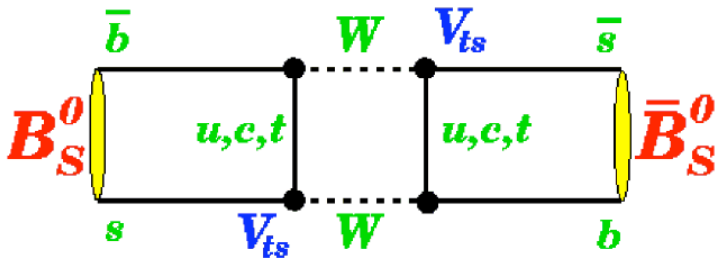
with $f_-(t) = i\,e^{-imt}\sin(\Delta m t/2)$

$\Rightarrow$ for $t > 0$, the B^0 component appears for $\bar{B}^0$ at $t = 0$.

m_{12} ?

$$m_{12} = \frac{G_F^2}{12\pi^2}(V_{tb}V_{tq})^2\, m_W^2\, m_B\, f_B^2\, B_B\, \eta_B\, S\left(\frac{m_t}{m_W}\right)$$





f_B : decay constant

B_B : bag pamrameter

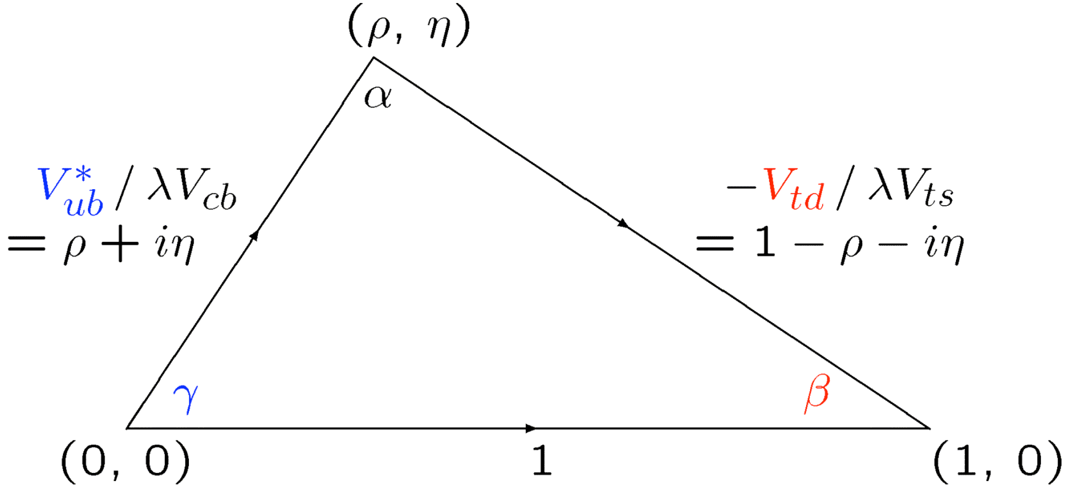
$S(x)$: Inami-Lim function

Is it relevant ?

$$\Delta m_q = \frac{G_F^2}{12\pi^2} |V_{tb}V_{tq}|^2 \, m_W^2 \, m_B \, f_B^2 \, B_B \, \eta_B \, S\left(\frac{m_t}{m_W}\right)$$

$\Rightarrow$ measure Δm_q, extract $|V_{tq}|$

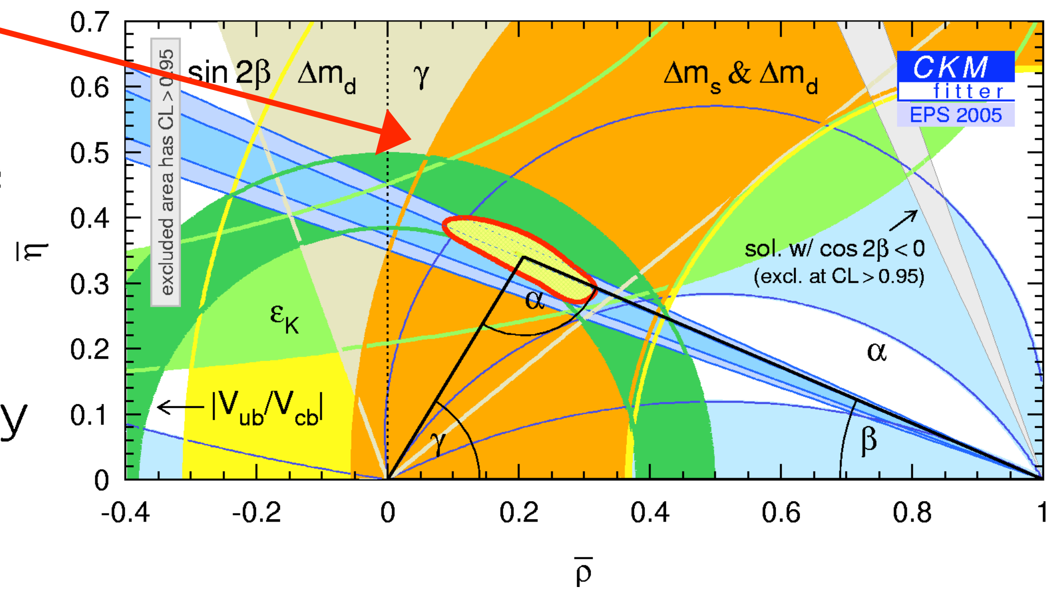
Crucial information on the unitarity triangle of the CKM matrix,
length of one of the sides



Δm_d known to 1%,
but $|V_{td}|$ is determined only to $\sim 20\%$.

Why? $B_B f_B^2$ has to come from theory.

But much smaller uncertainty in the ratio for B_s^0 and B_d^0.



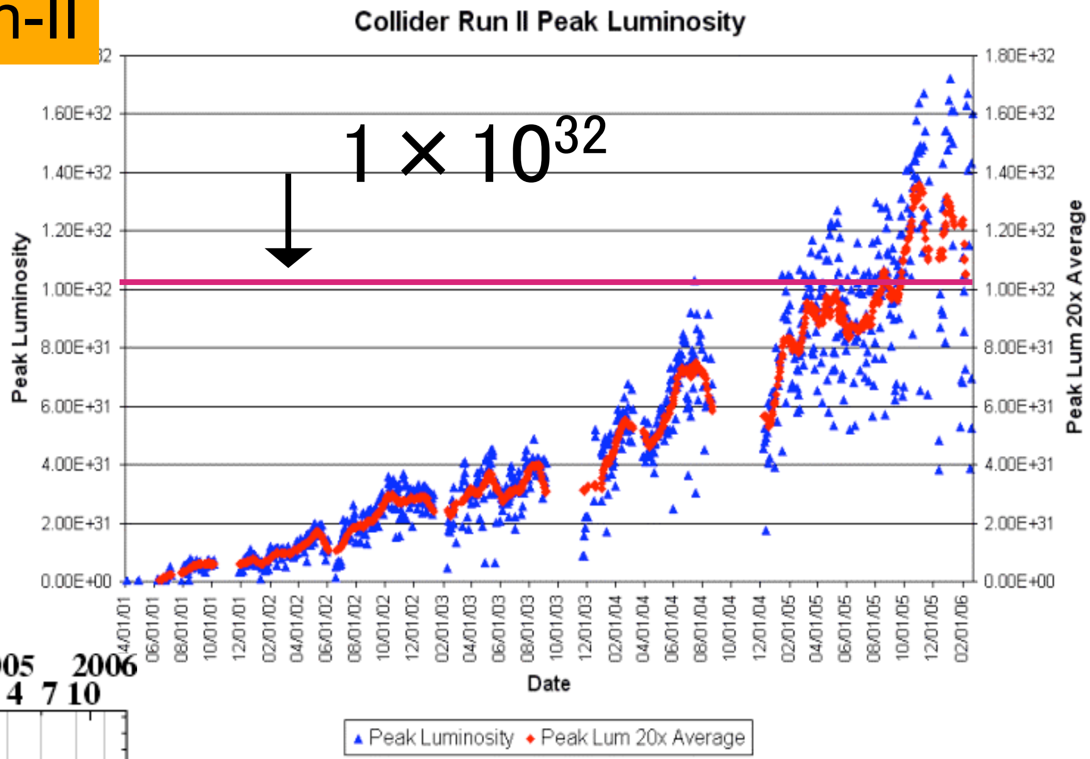
Tevatron accelerator complex

- New 120/150 GeV Main Injector replaced Main Ring
  - Higher intensity of protons and antiprotons.
- Tevatron operates with 36 x 36 bunches (had been 6 x 6)
- Increased CM energy 1.8 TeV to 1.96 TeV

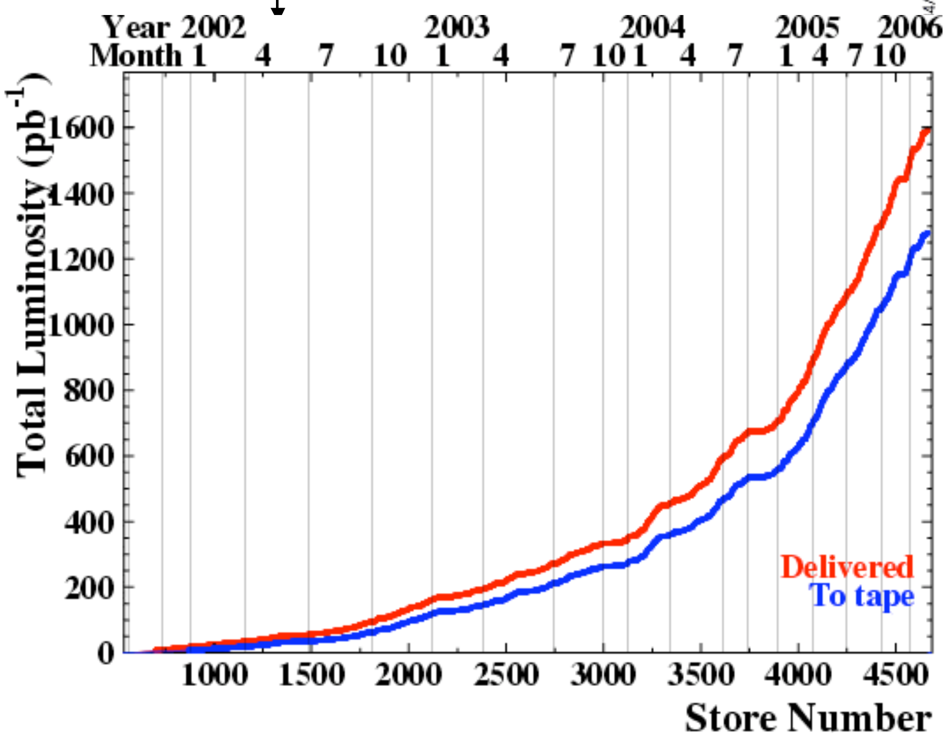
Run II started in March 2001

Tevatron Luminosity : Run-II

Instantaneous luminosity

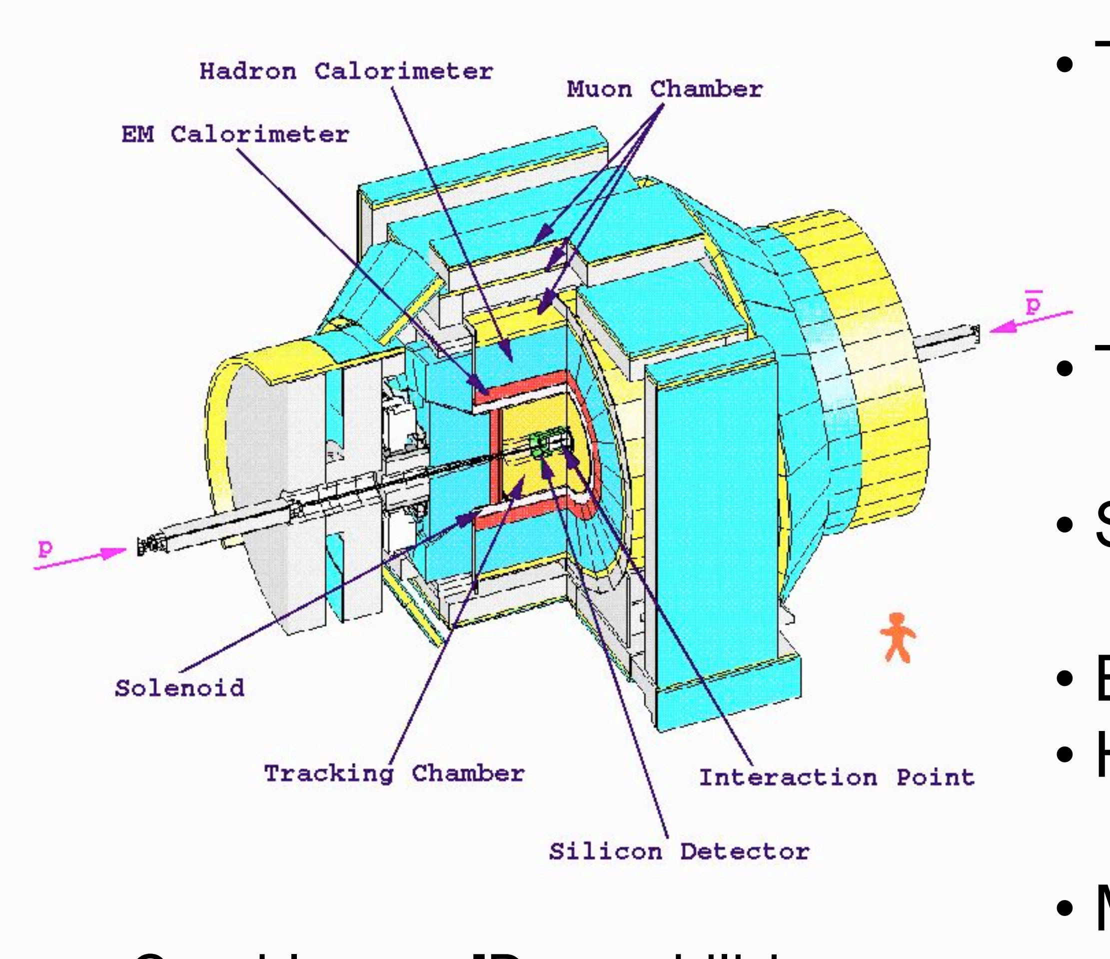


Integrated lum.



- Peak luminosity
  $1.82 \times 10^{32}\ cm^{-2}\ s^{-1}$
  (Feb 12, 2006)
- Delivered luminosity
  $\sim 1.6\ fb^{-1}$
- Recorded luminosity
  $\sim 1.3\ fb^{-1}$

Run-II CDF Detector



From inside outward

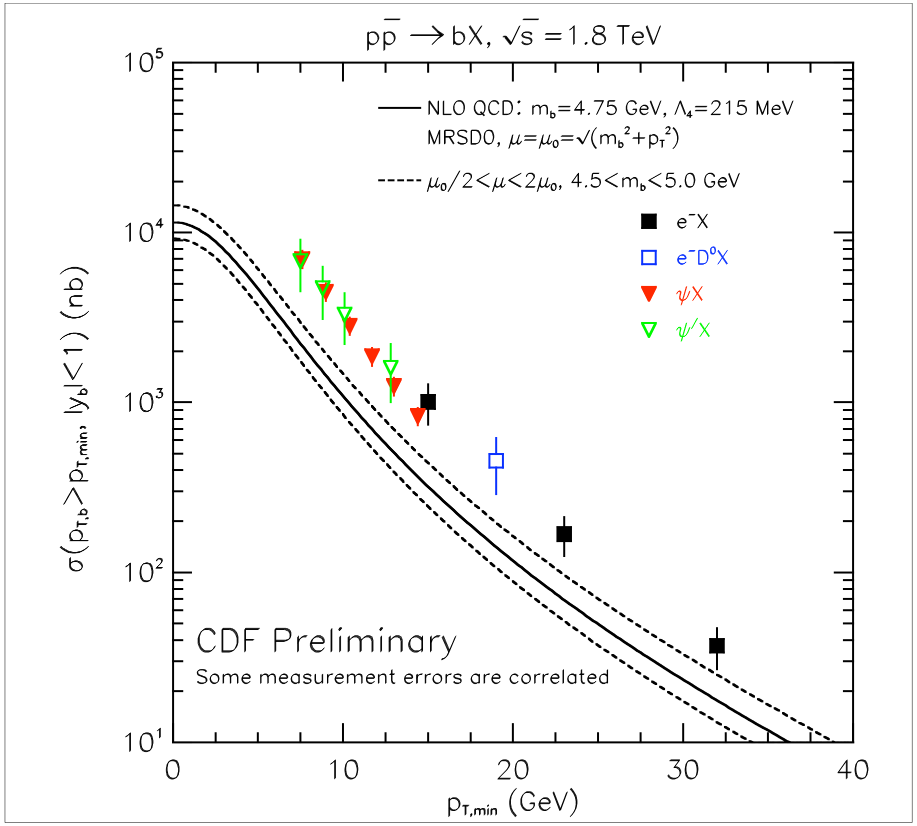
- Tracking system
  - Silicon detectors : vertex
  - Main drift chamber : *p*
- TOF system : K/π sep.
- Solenoid ： 1.5 Tesla
- EM calorimeters
- Hadron calorimeters
- Muon chambers

Good lepton ID capabilities
Excellent tracking (large solenoid)
Not just high-p_T physics, but also *B* physics.

Tevatron : it is an inexpensive *B*-factory

Compared to e^+e^- experiments on $\Upsilon(4S)$:

- Larger production rates, $\sim 10\,\mu$b vs. 1.1 nb
- Not just $B^-/\bar{B}^0$, also $\bar{B}^0_s$, B^-_c, Λ^0_b.
- Sizable Lorentz boost, $\beta\gamma \simeq 2-4 \Rightarrow$ good ct resolution.

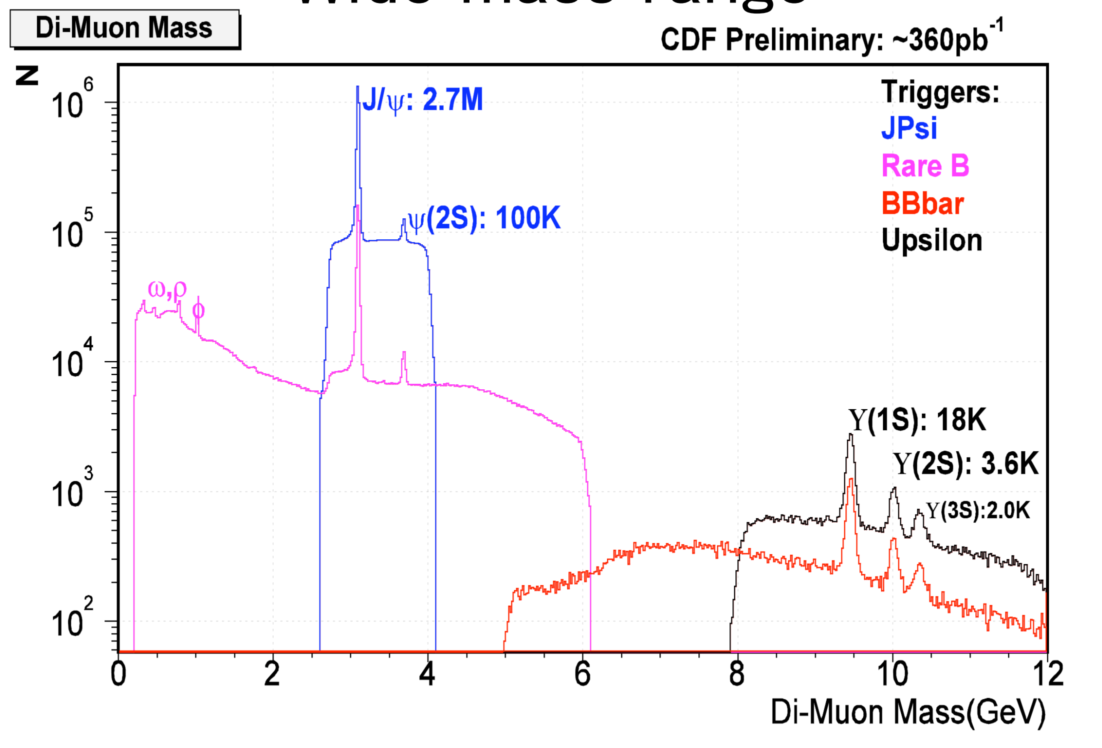


To utilize these fatures, need to trigger them efficiently :

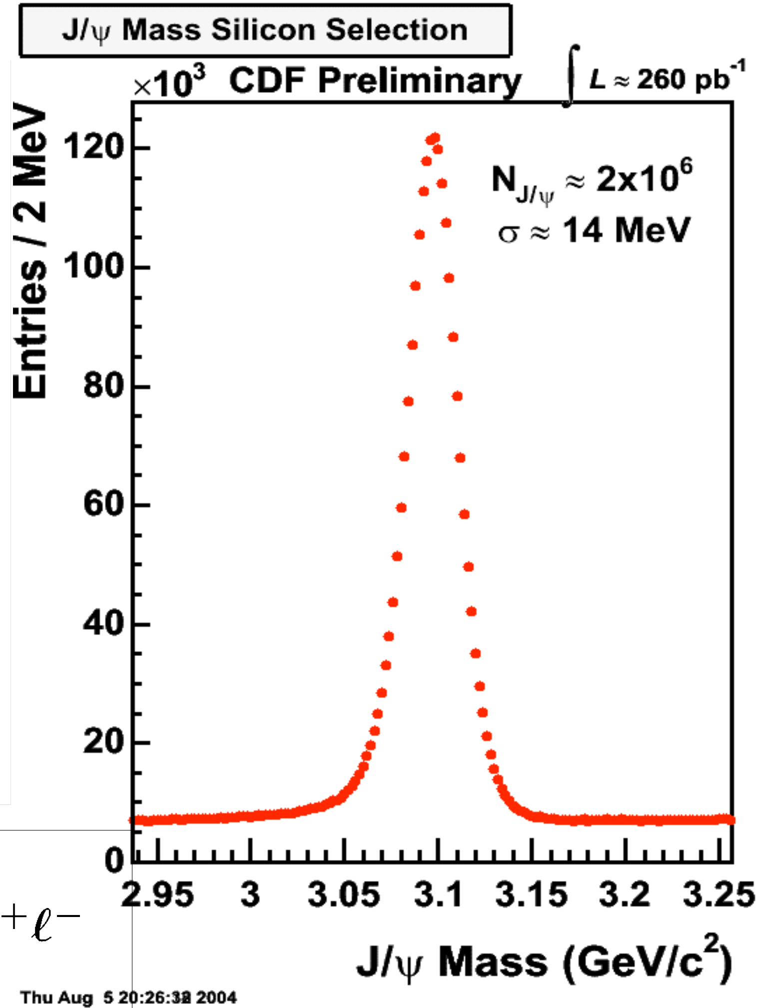
- Historically relied on leptons
  - $b \to \ell^- \bar{\nu} c$
  - $B \to J/\psi X \to \ell^+\ell^- X$.
- Run-II employs displaced-track trigger (SVT)
  $\Rightarrow$ can collect all-hadronic final states

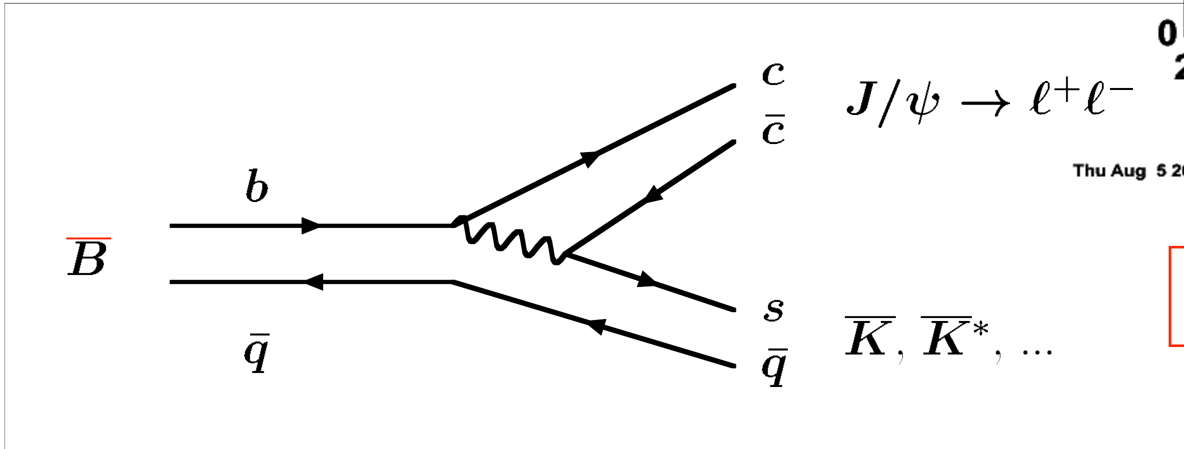
CDF di-muon triggers

Wide mass range



Near J/ψ



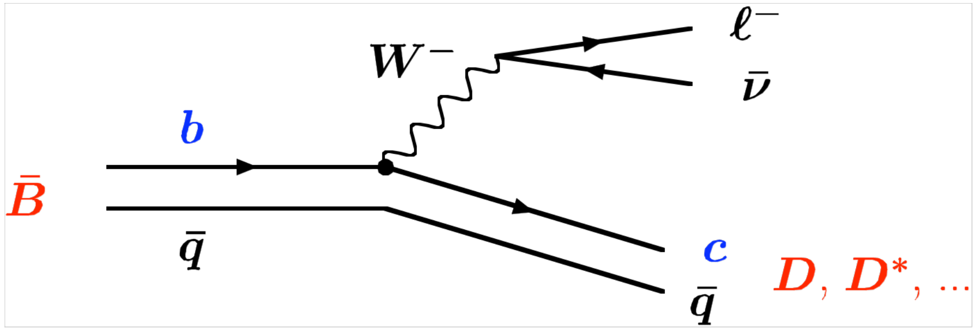


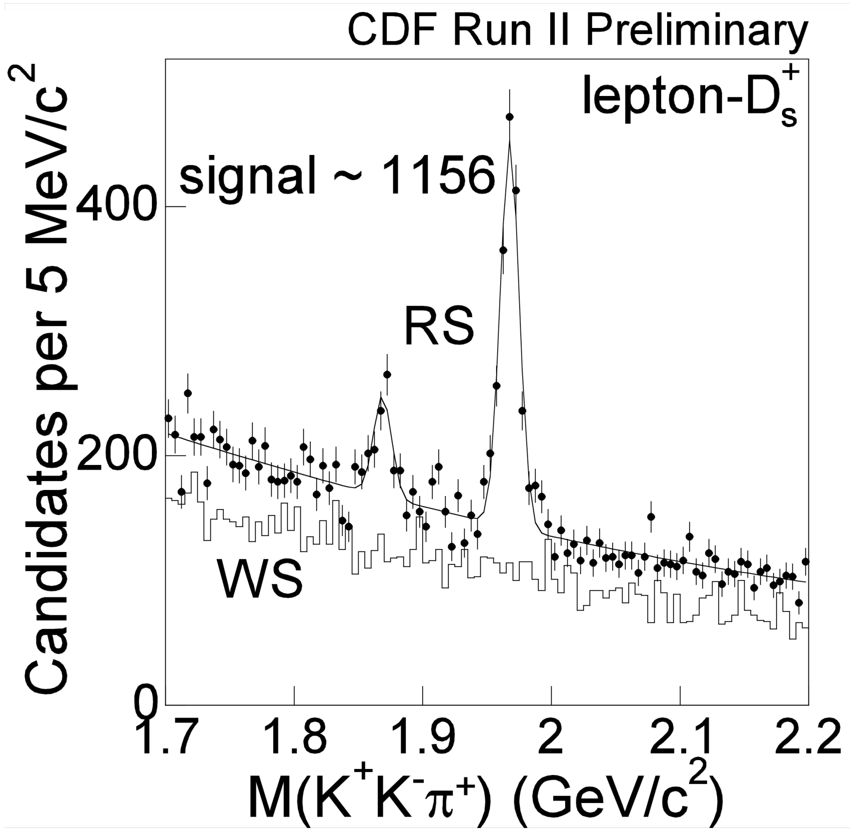
~15% from B decays

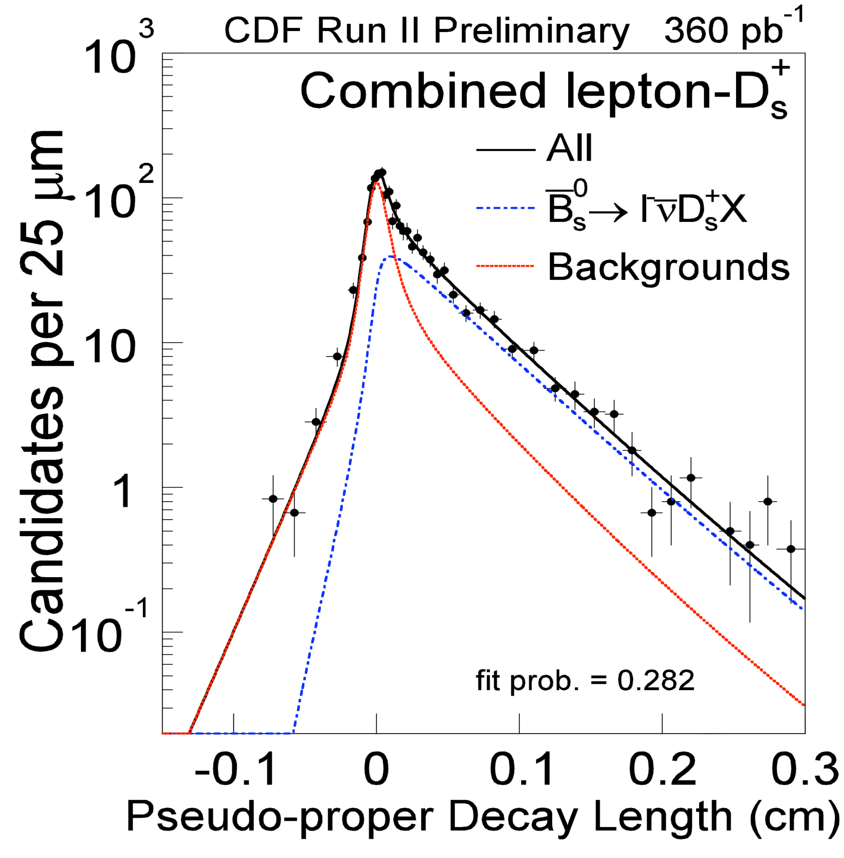
B_s^0 meson

Use semileptonic decay

$\bar{B}_s^0 \to \ell^- \bar{\nu} D_s^+ X,\ D_s^+ \to \phi\pi^+$





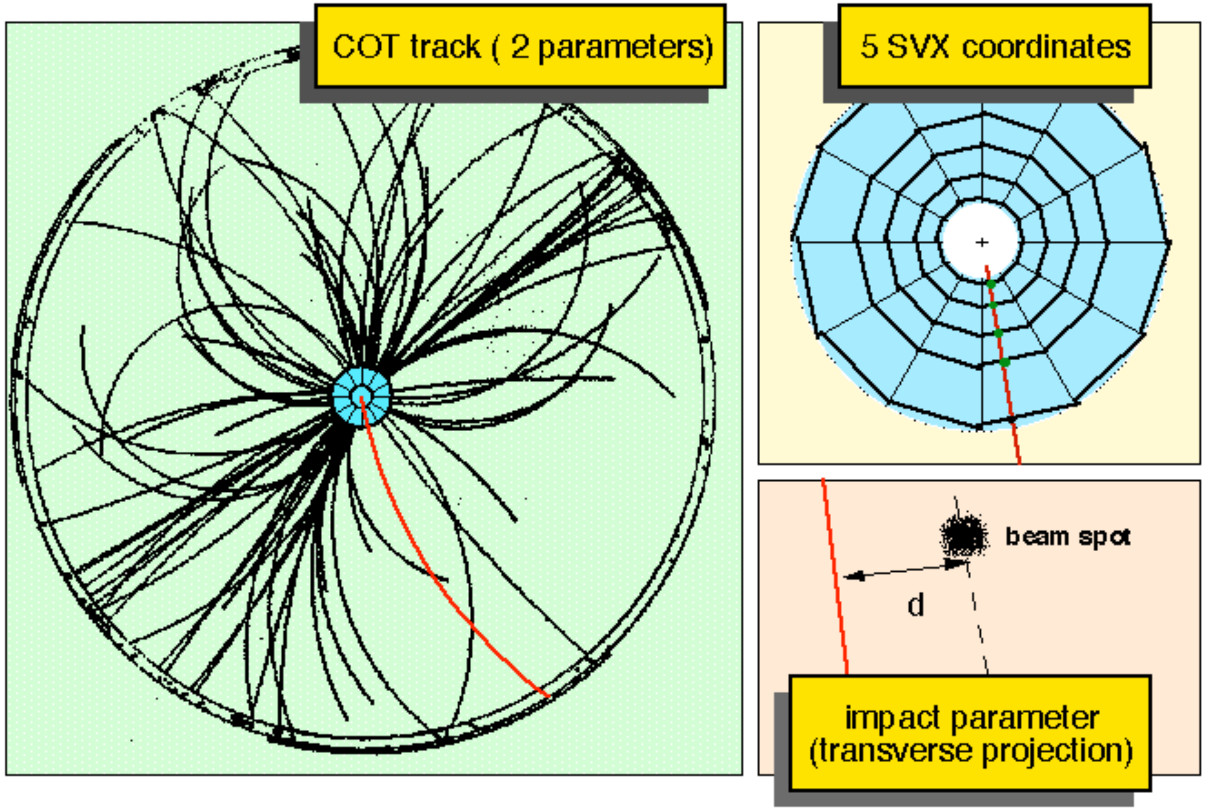


$$\tau(B_s^0) = 1.381 \pm 0.055\,^{+0.052}_{-0.046}\ \text{ps}$$

Satoru Uozumi, Ph.D. thesis, 2005

Run-II Silicon Vertex Trigger : SVT

Use silicon information at the 2nd level of trigger

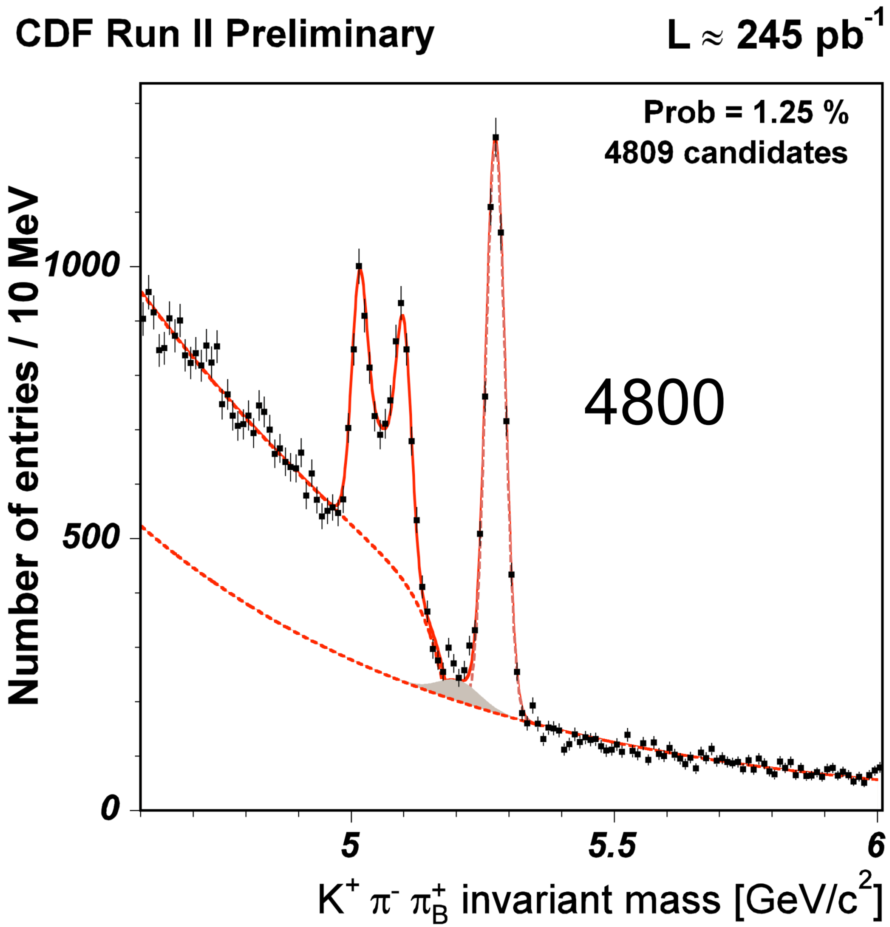


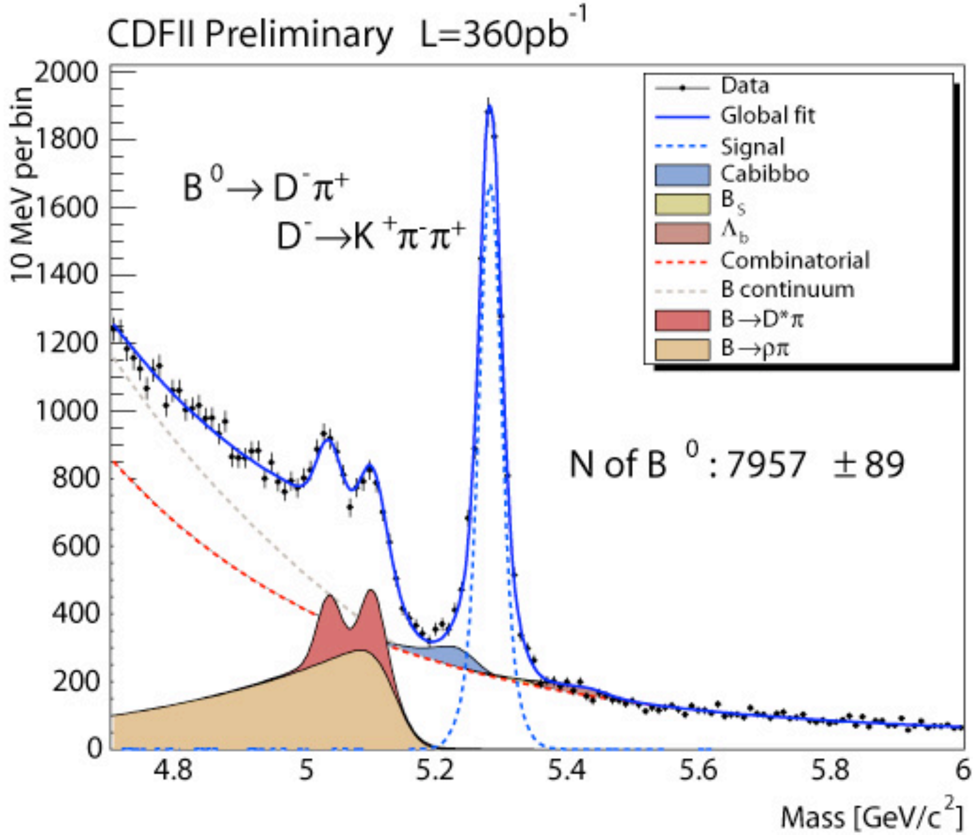
- Find a track in the main tracker COT.
- Extrapolate toward the SVX.
- Find SVX hits along the road.
- Calculate impact parameter wrt the primary vertex (beam spot).
- Resolution ~50 μm for > 2 GeV/c.

Typical trigger requirement :
two tracks above 2 GeV/c,
$|d| > 120\ \mu$m,
$L_{xy} > 500\ \mu$m.

B signals from CDF SVT triggers : full reconstruction

$B^- \to D^0\pi^- \to (K^-\pi^+)\,\pi^-$ $\qquad$ $\bar{B}^0 \to D^+\pi^- \to (K^-\pi^+\pi^+)\,\pi^-$

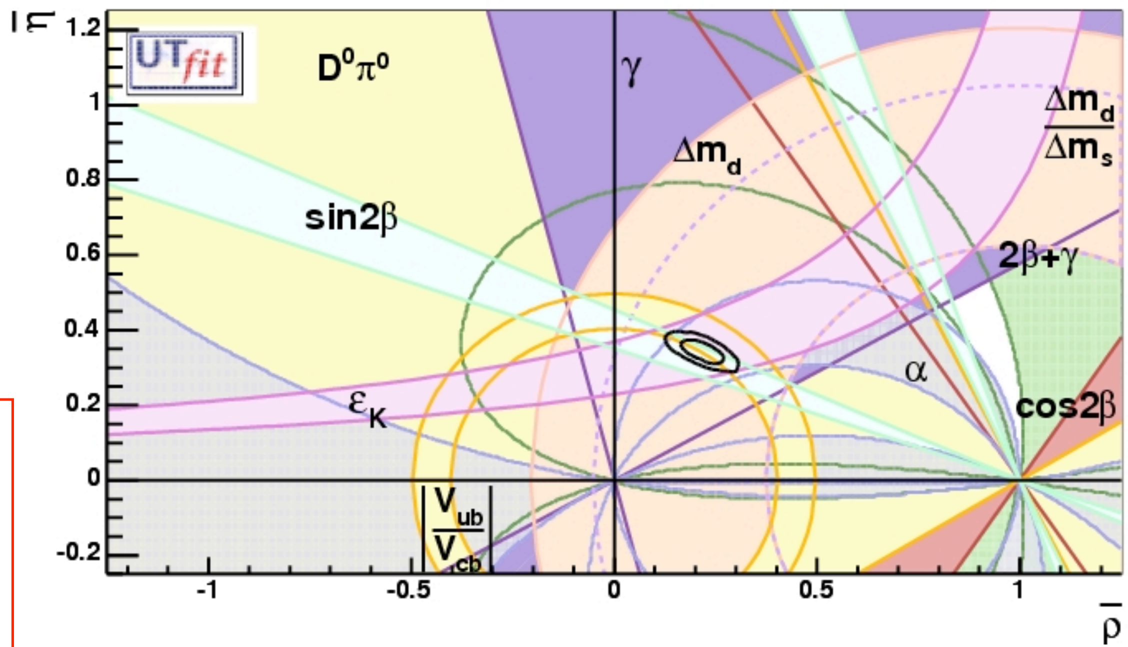




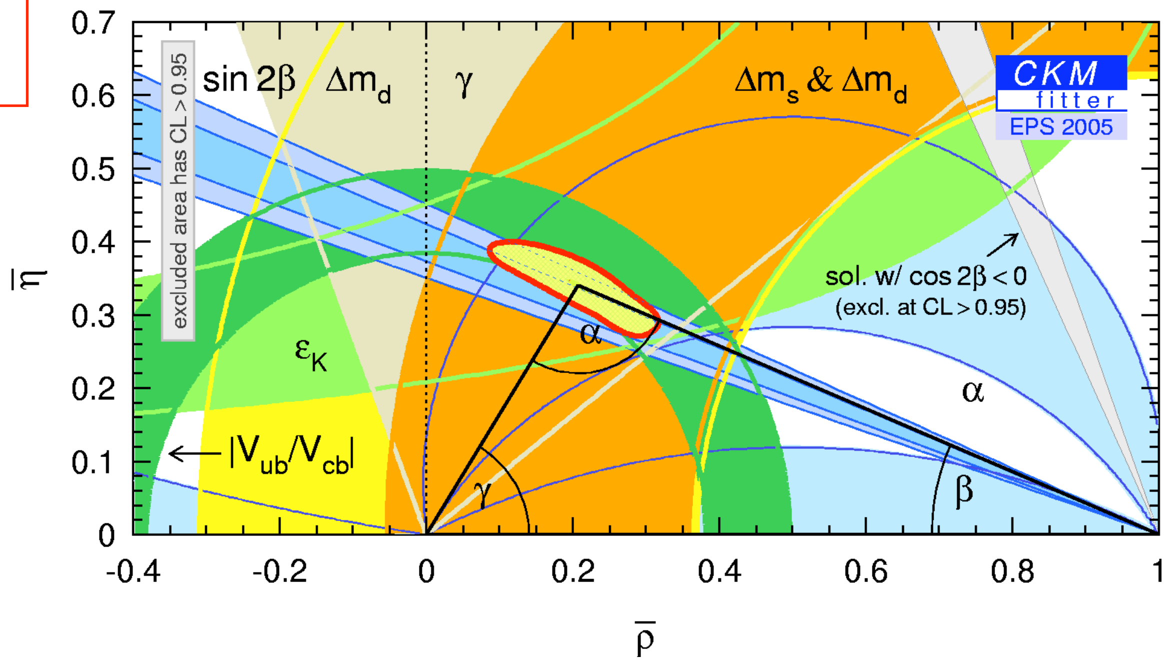
Calibration modes for B_s^0-$\bar{B}_s^0$ oscillations.

Understand proper time resolution and flavor tagging

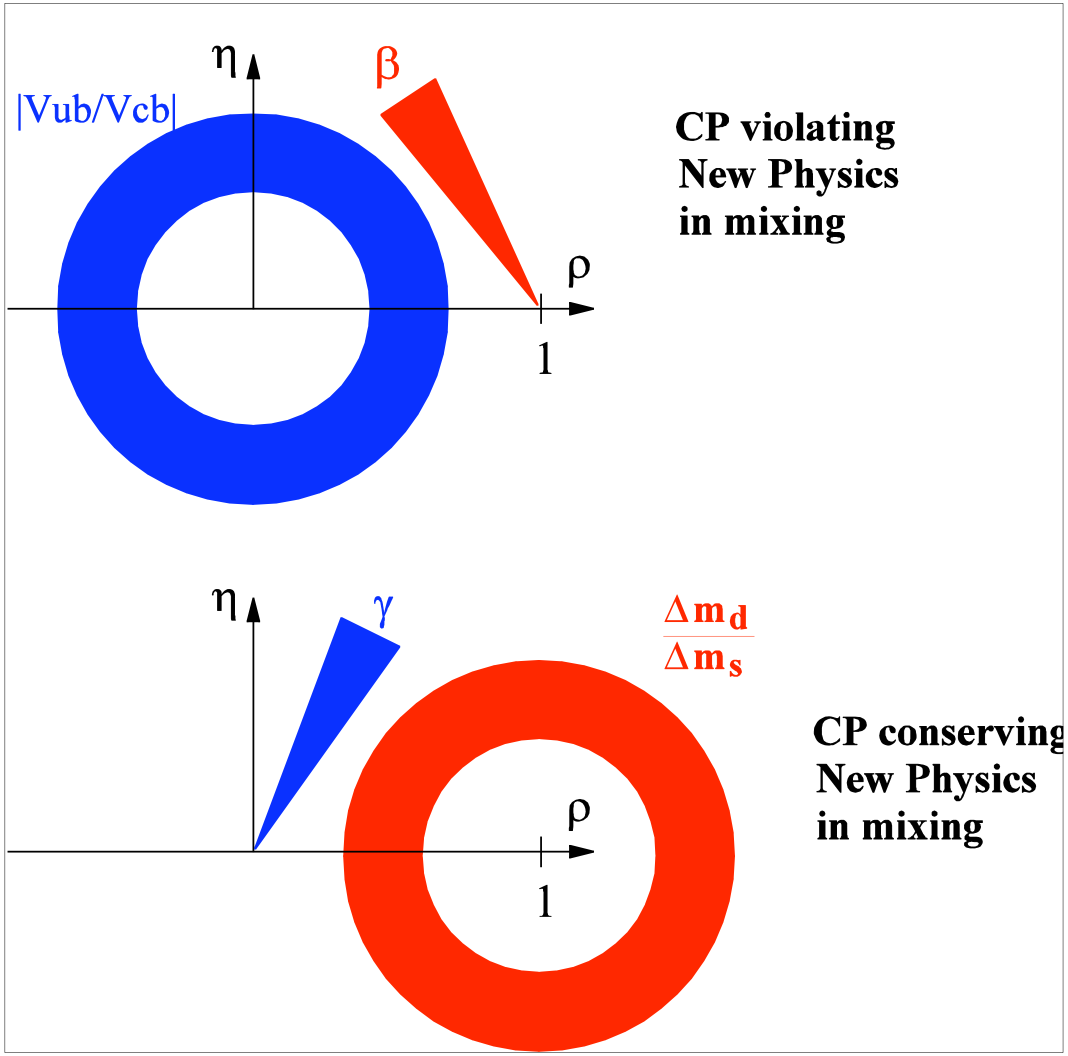
2005



Kobayashi-Maskawa picture holds good, but we are looking for possible discrepancies!



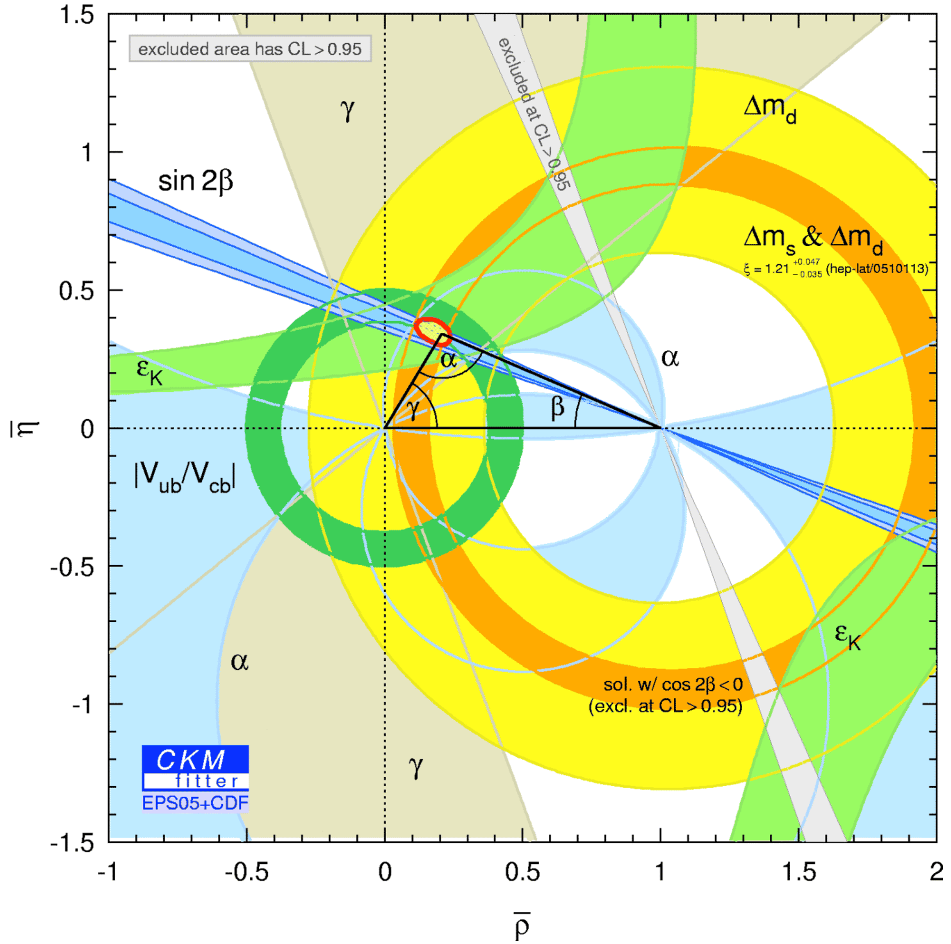
New physics effects on the unitarity triangle ?

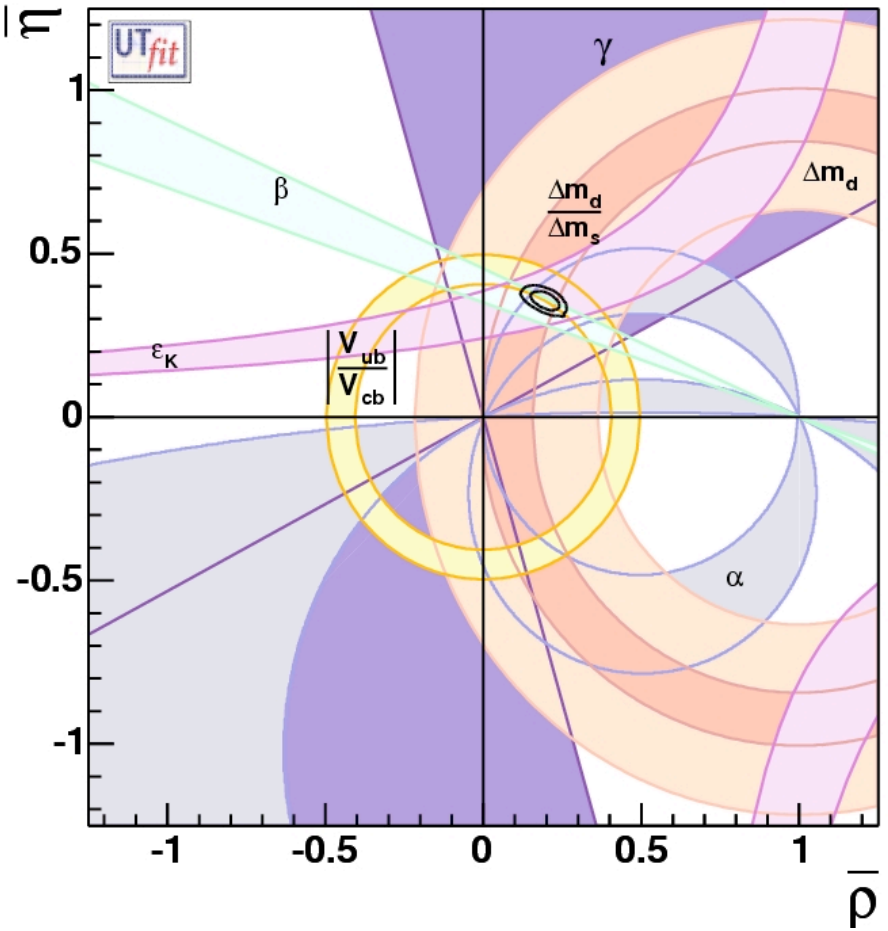


Now seems unlikely, or looking for a very small discrepancy. Need more precision, but systematic unc. becoming dominant?

Still largely untested. B_s oscillations crucial. Precise angle γ ?

Now we have :





Thanks to, or because of :

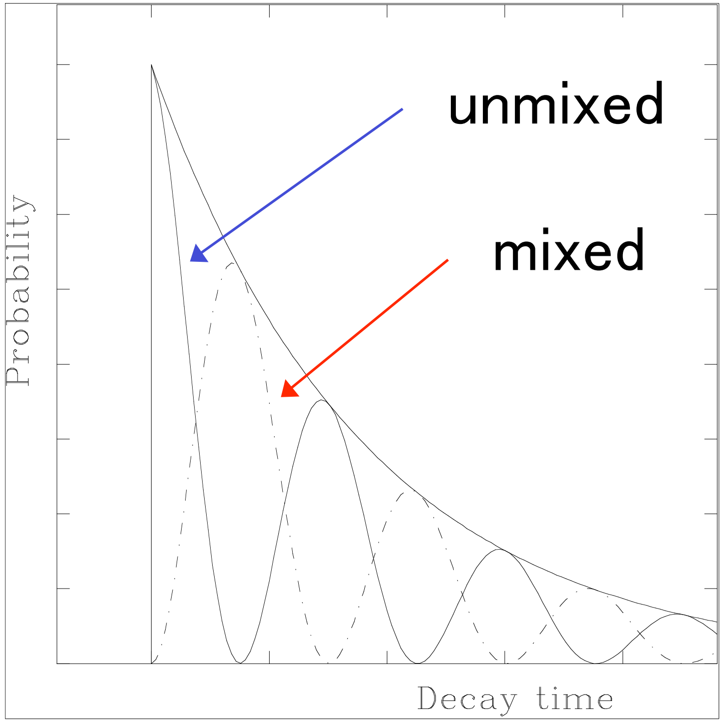
$$\Delta m_s = 17.33\,^{+0.042}_{-0.021} \pm 0.07\ \text{ps}^{-1}$$

$$\Rightarrow \quad |V_{td}/V_{ts}| = 0.208\,^{+0.008}_{-0.007}$$

$B_q^0 \bar{B}_q^0$ oscillations $\quad (q \equiv d, s)$

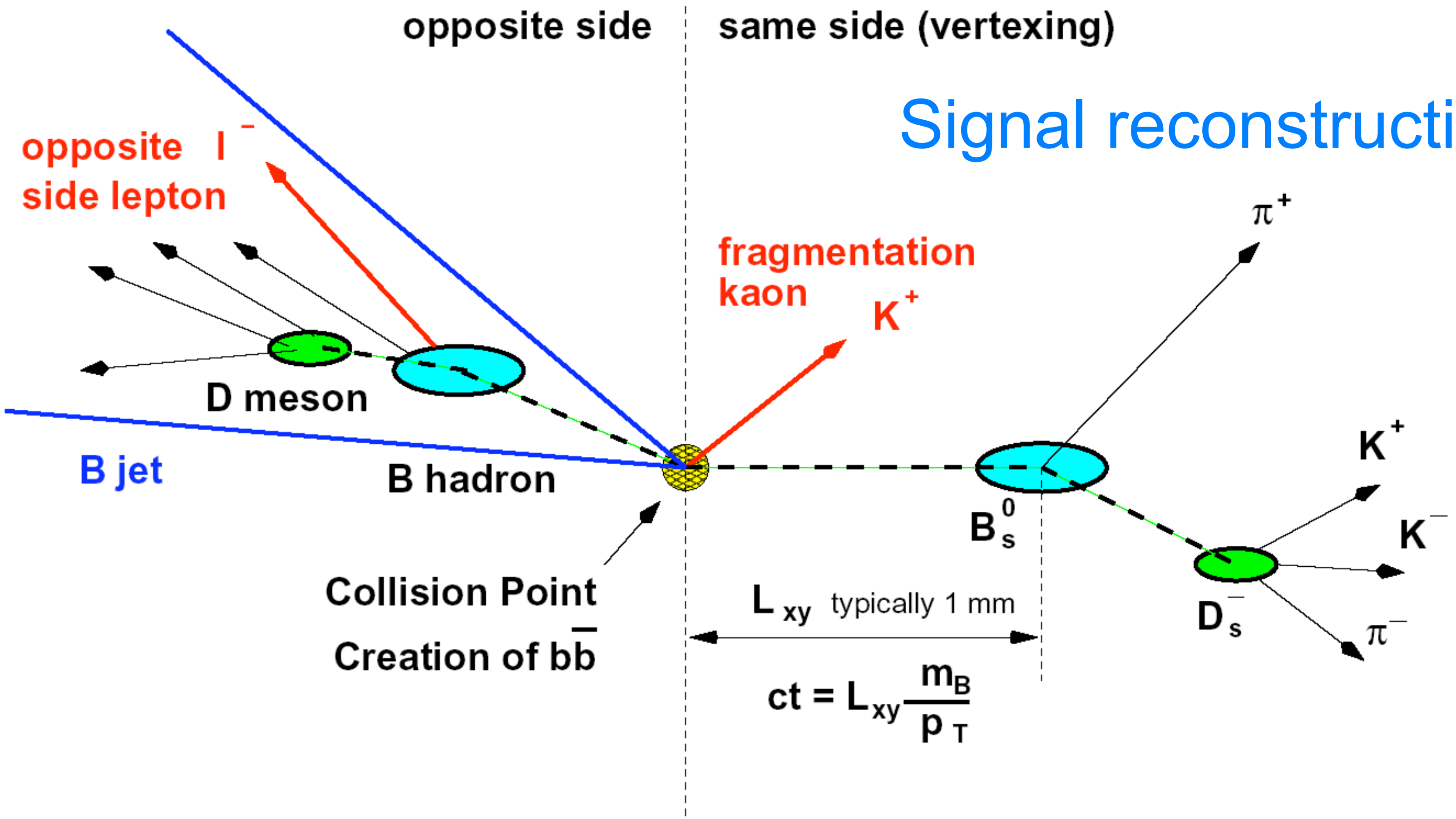
$$\mathcal{P}_{\text{unmix}}(t) \equiv \mathcal{P}(B^0(0) \to B^0(t)) = \frac{1}{2\tau} e^{-t/\tau} (1 + \cos \Delta m\, t)$$

$$\mathcal{P}_{\text{mix}}(t) \equiv \mathcal{P}(B^0(0) \to \bar{B}^0(t)) = \frac{1}{2\tau} e^{-t/\tau} (1 - \cos \Delta m\, t)$$



Procedure

- Reconstruct B meson decay with flavor-specific final state, such as $\bar{B}^0 \to D^+(n\pi)^-$ and $\bar{B}^0 \to \ell^- \bar{\nu} D^{*+}$.
- Measure decay length L and momentum p
- Extract proper decay time $t = \frac{L/c}{\beta\gamma} = L\frac{m}{p}$
- Determine the initial flavor, B^0 or $\bar{B}^0$
- Fit for Δm



Flavor tagging : B^0 or $\bar{B}^0$ at $t = 0$?

$\bar{p}p \to b\bar{b}X$, pair-produced.

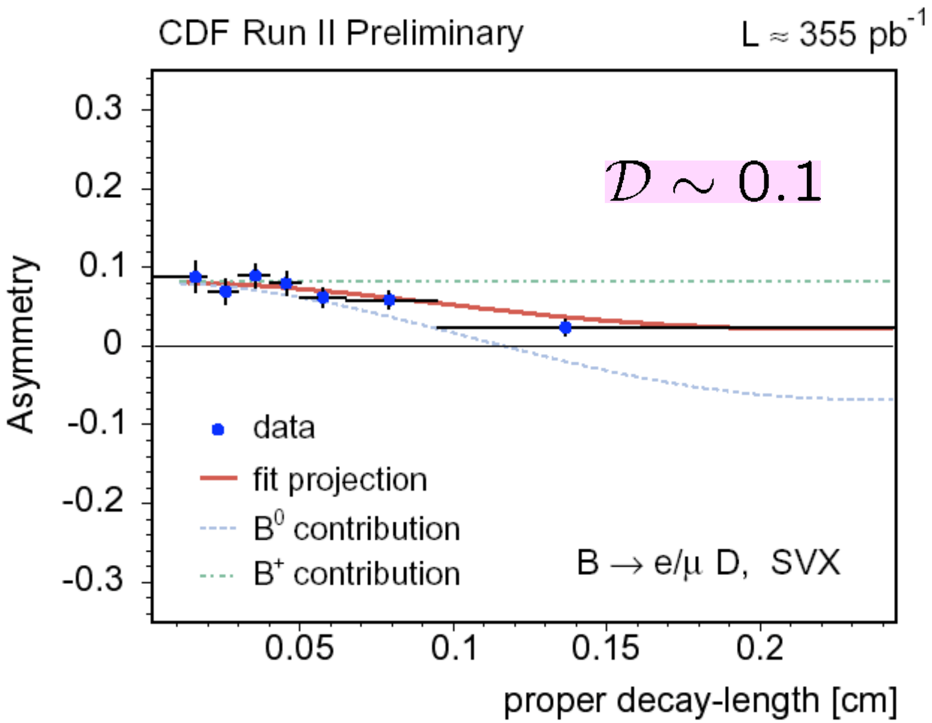
The other B hadron in the event and its daughters (e.g. lepton) gives the information.

Measure flavor tagging using B^+ and B^0 decays

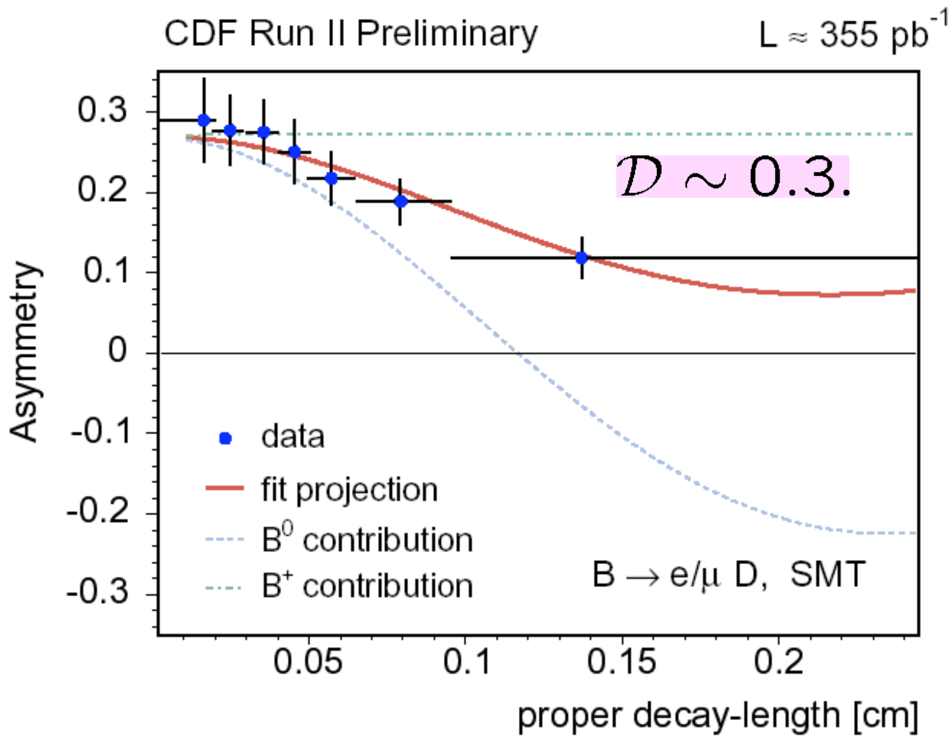
$$\mathcal{A}_{\text{mix}}(t) = \frac{N(t)_{\text{unmix}} - N(t)_{\text{mixed}}}{N(t)_{\text{unmix}} + N(t)_{\text{mixed}}} = \cos(\Delta m\, t)$$

Incompleteness in flavor tagging : wrong tag probability $\mathcal{W}$
$\cos(\Delta m\, t) \Rightarrow (1 - 2\mathcal{W}) \cos(\Delta m\, t)$, dilution $\mathcal{D} \equiv 1 - 2\mathcal{W}$

Jet charge



Leptons

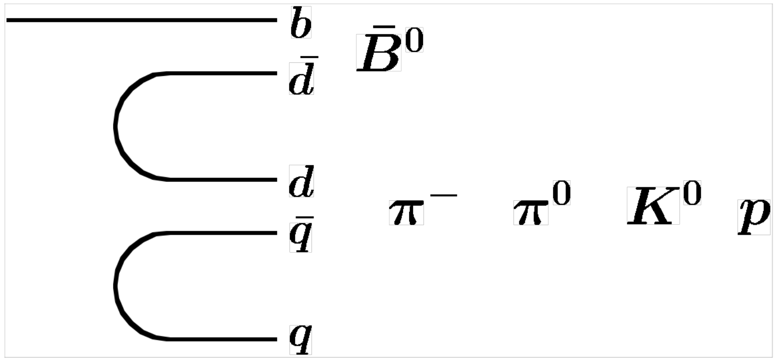


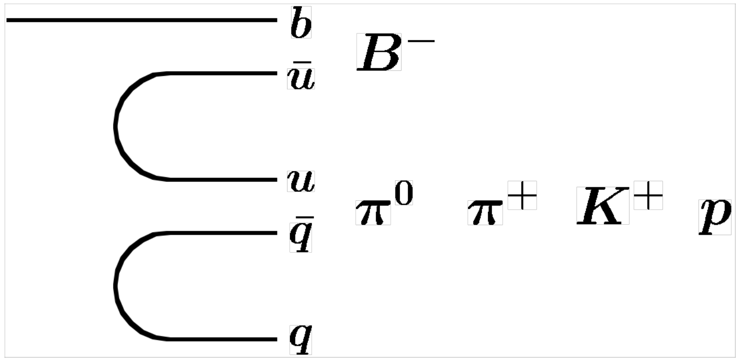
Same-side flavor tagging

Gronau, Nippe, Rosner

Suppose you are looking for $D^0\bar{D}^0$ mixing :
$c \to D^0\,(t=0) \to \bar{D}^0 \to K^+\pi^-\,(t>0)$.
Use the decay $D^{*+} \to D^0\pi^+$, and charge of π^+ tells it was D^0.

$\bar{B}^* \to \bar{B}\pi$ not allowed, so $\bar{B}^{**} \to \bar{B}\pi$, or fragmentation pions.

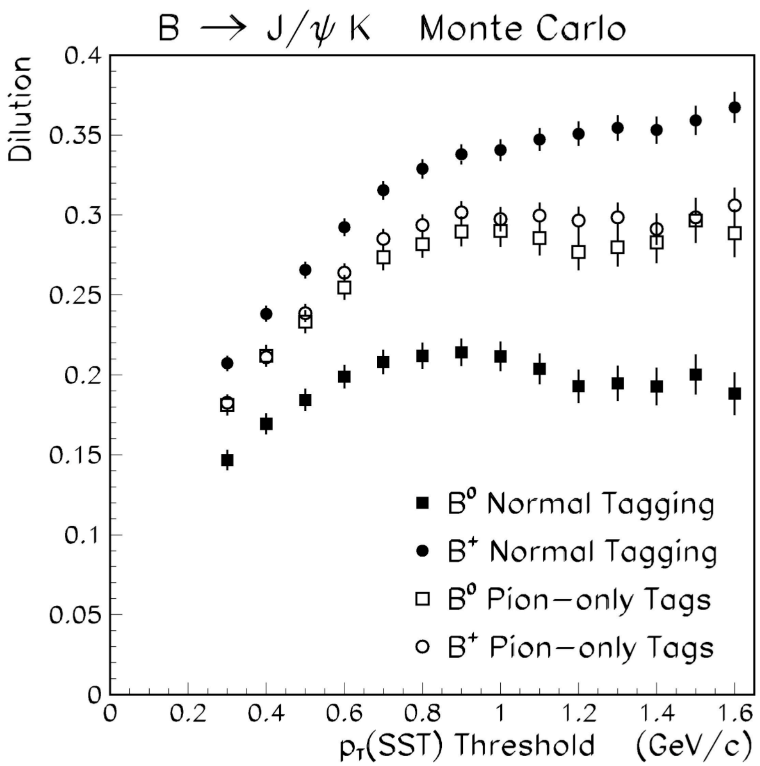


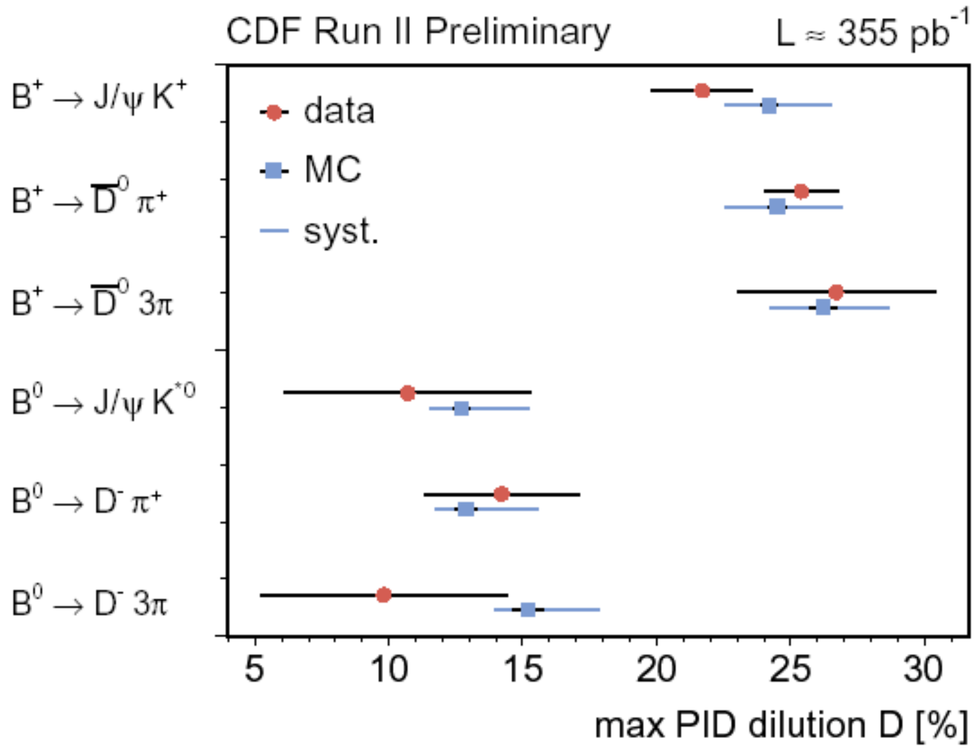


Note :

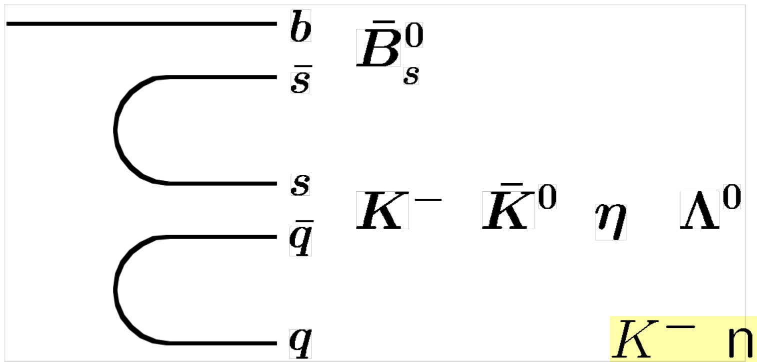
- Charge correlations opposite for $\bar{B}^0$ and B^-.
- $\bar{s}$-quark and diquarks do bad for $\bar{B}^0$, good for B^-.

Same−side flavor tagging





b-quark fragmentation into $\bar{B}_s^0$:



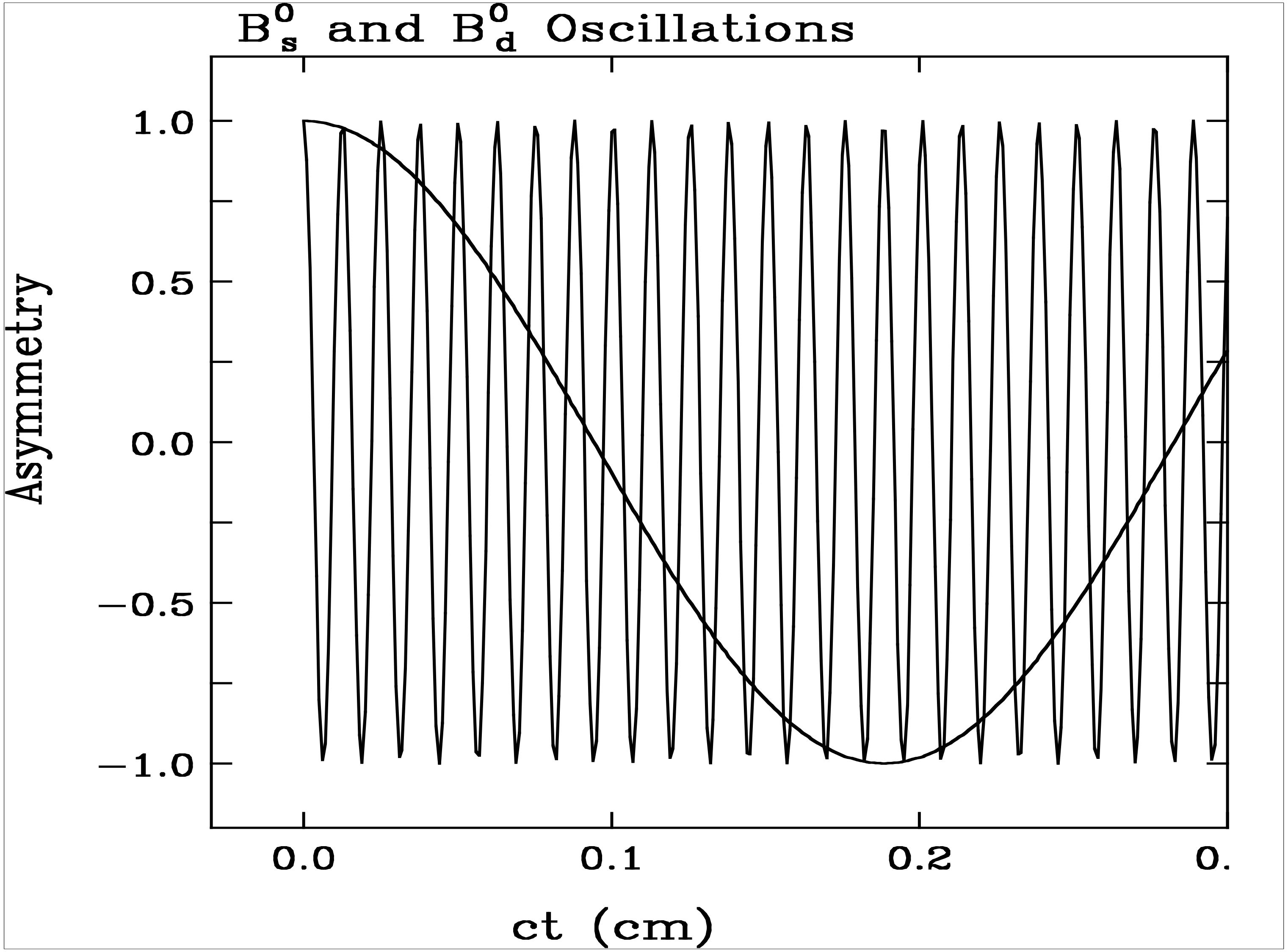
K^- nearby $\Rightarrow$ TOF and dE/dx PID.

Flavor tag summary

	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)

- use exclusive combination of tags on opposite side
- same side – opposite side combination assumes independent tagging information

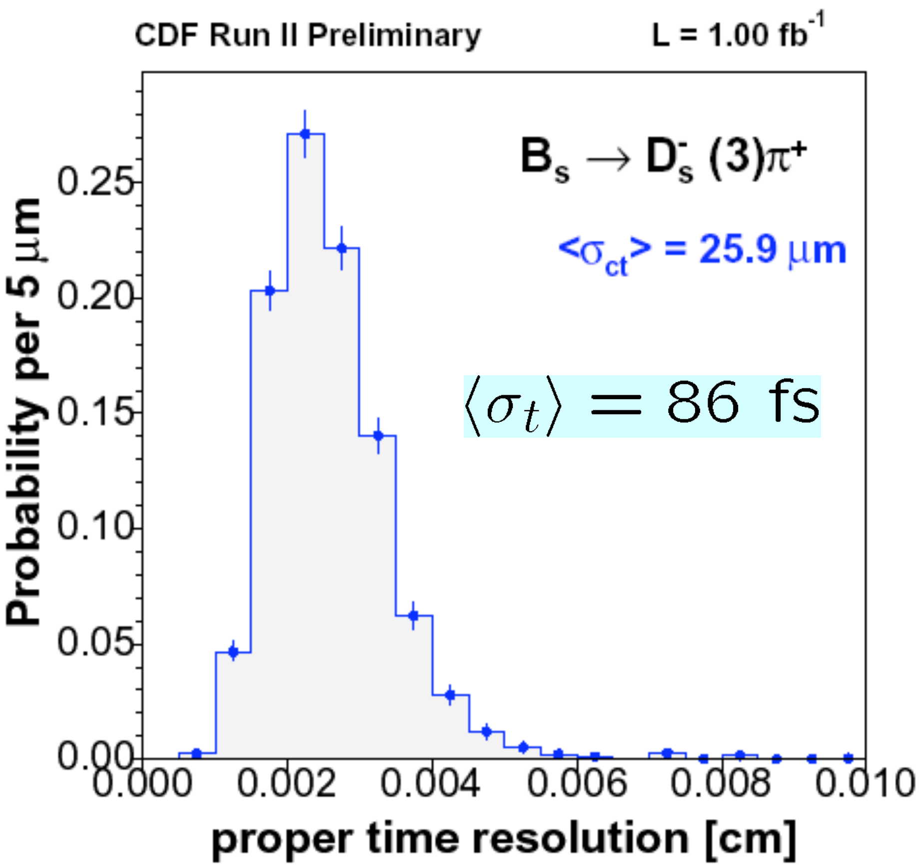
Oscillations with $\Delta m = 0.5\ \text{ps}^{-1}$ and $15\ \text{ps}^{-1}$



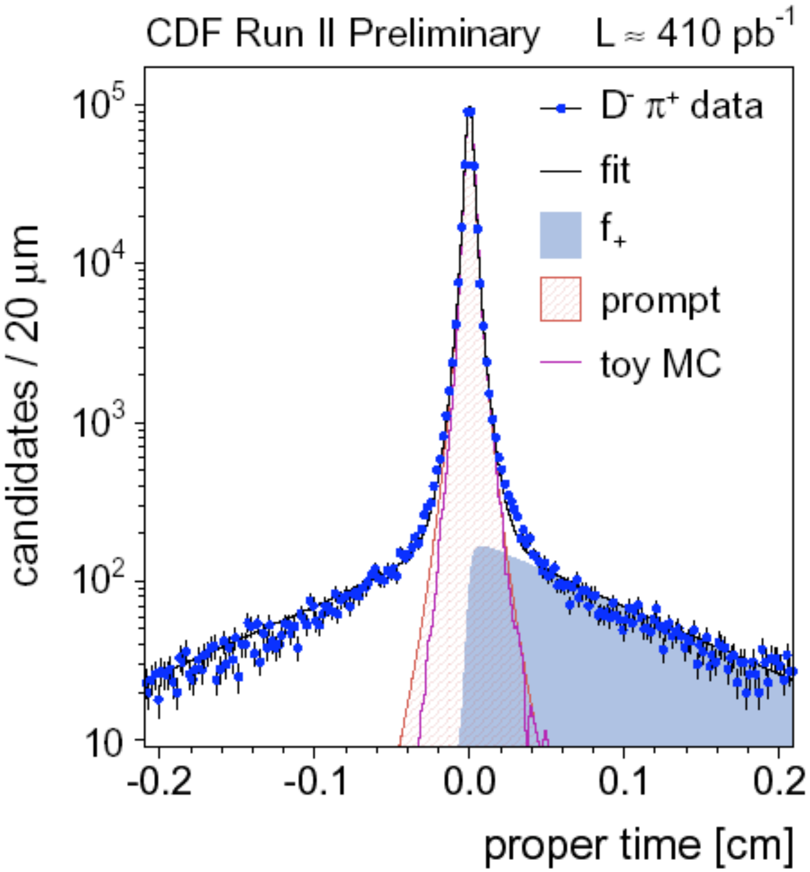
$\Delta m_s = 15\ \text{ps}^{-1} \Leftrightarrow$ Period $T = 0.4$ ps, need $\sigma_t < 100$ fs

Proper time resolution : vetexing

Real data, hadromic mode



Check with prompt charm



Looking for oscillations : Amplitude analysis

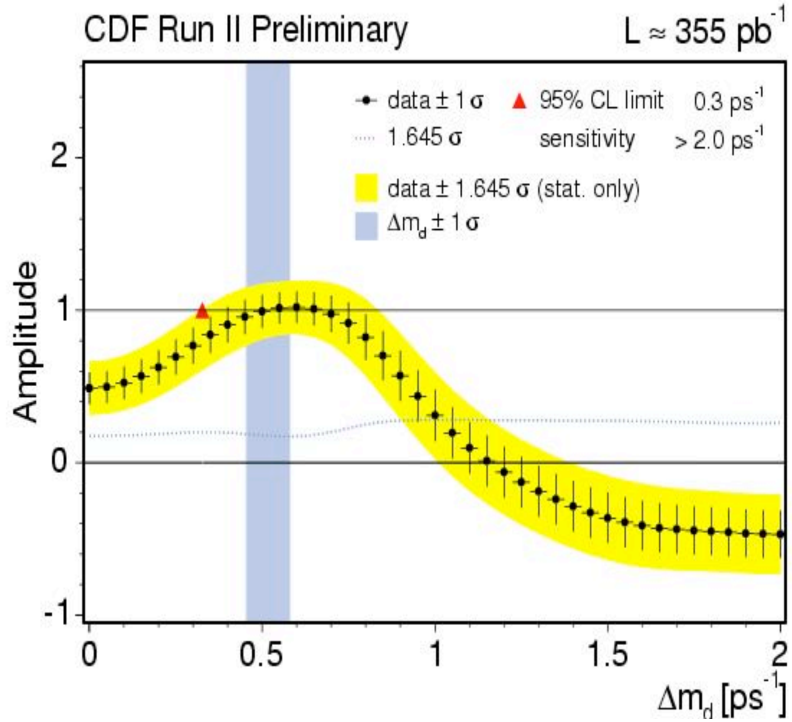
$1 \pm \cos(\Delta m\, t) \;\rightarrow 1 \pm \mathcal{A} \cos(\Delta m\, t)$, then fit for $\mathcal{A}$

Fourier analysis :
Interpret the time development in terms of many cosine waves with different frequencies.

$\mathcal{A} = 1$ (and away from 0) :
$\Leftrightarrow$ oscillating

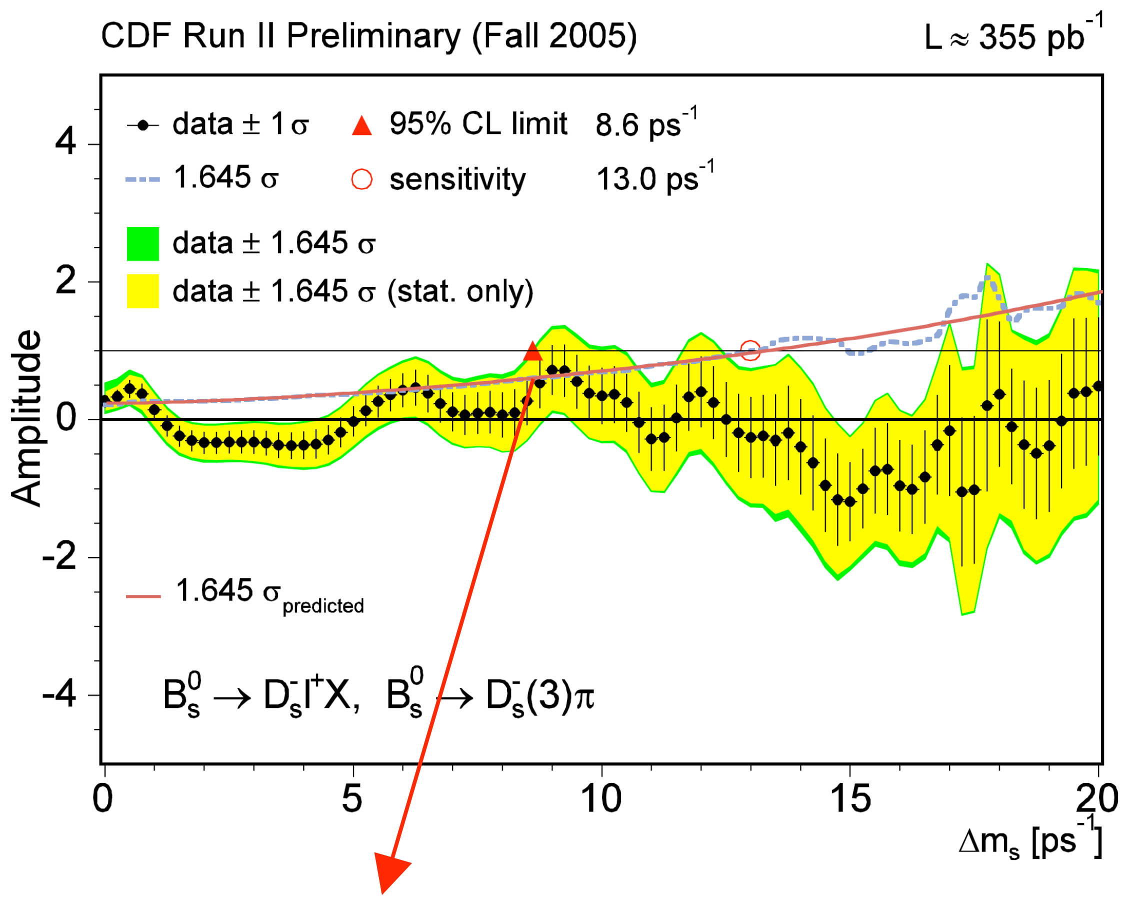
$\mathcal{A} = 0$:
$\Leftrightarrow$ no wave of that frequency, not oscillating.

$B_d^0 \bar{B}_d^0$ at ~ 0.5 ps^{-1}



Amplitude scan : $\bar{B}_s^0$ sample, previous result

Sensitivity $\sim$ 13 ps^{-1}



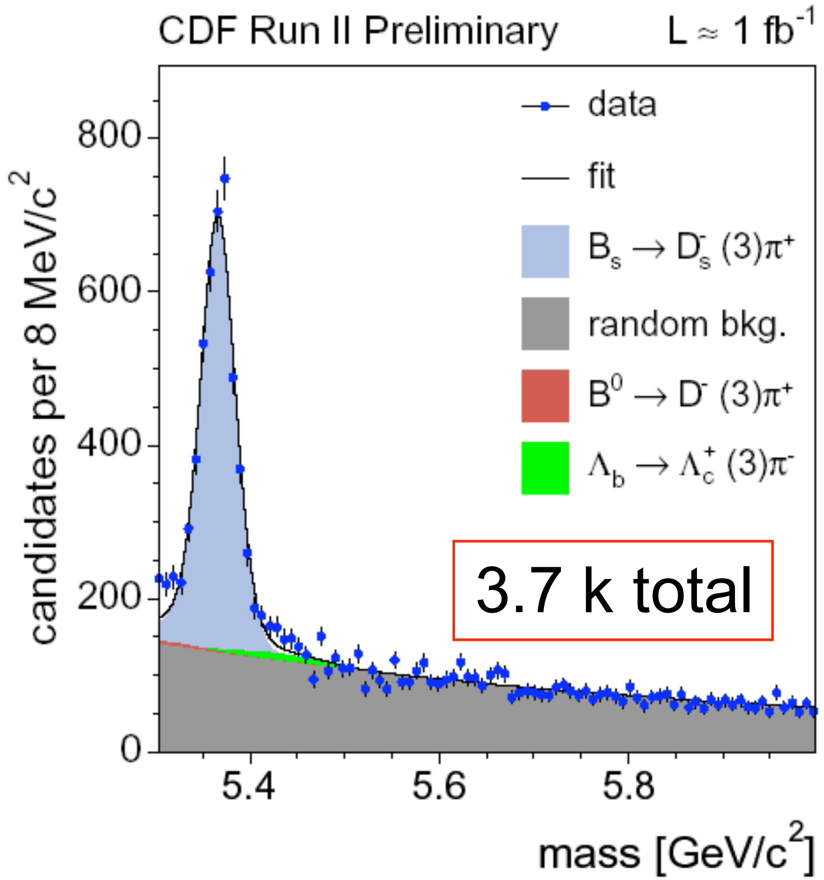
$\Delta m_s < 8.6$ ps^{-1} excluded (sensitivity $\sim$ 13 ps^{-1}).

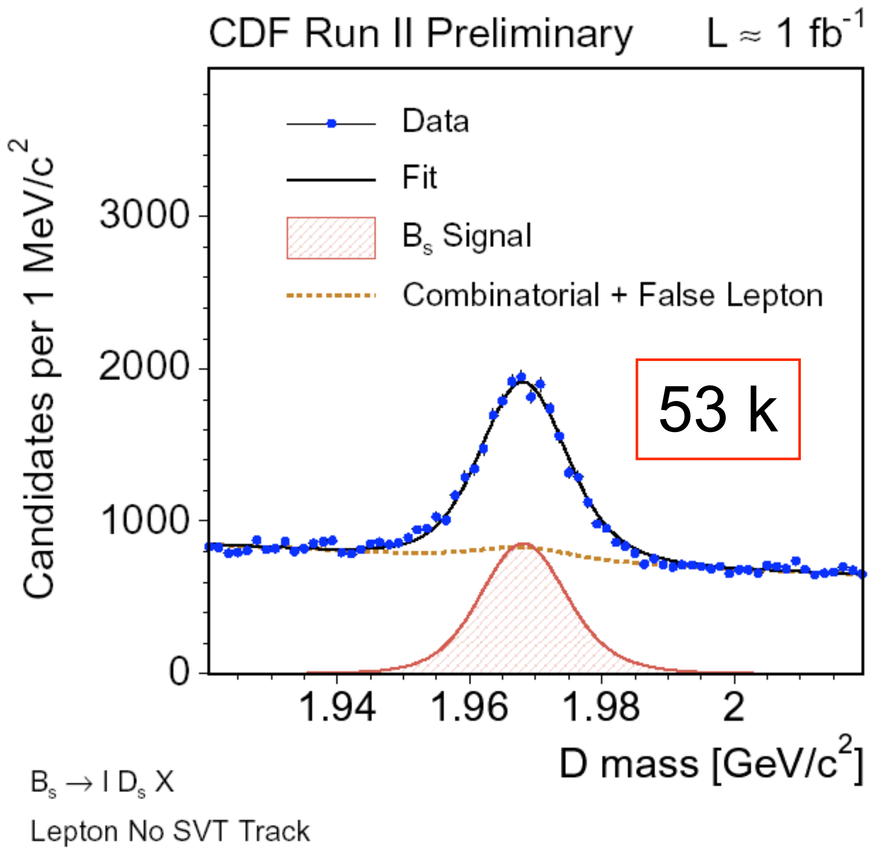
Note : uncertainties are mostly statistical (yellow〜green)

B_s^0 signals : 1 fb^{-1}

Hadronic :
$\bar{B}_s^0 \to D_s^+ (n\pi)^- \ (n = 1, 3)$
$\hookrightarrow \phi\pi^+, \ \bar{K}^{*0}K^+, \ \pi^+\pi^+\pi^-$

Semileptonic :
$\bar{B}_s^0 \to \ell^- \bar{\nu} D_s^+ X$





Amplitude scan : $\bar{B}_s^0$ sample, 1 fb^{-1}

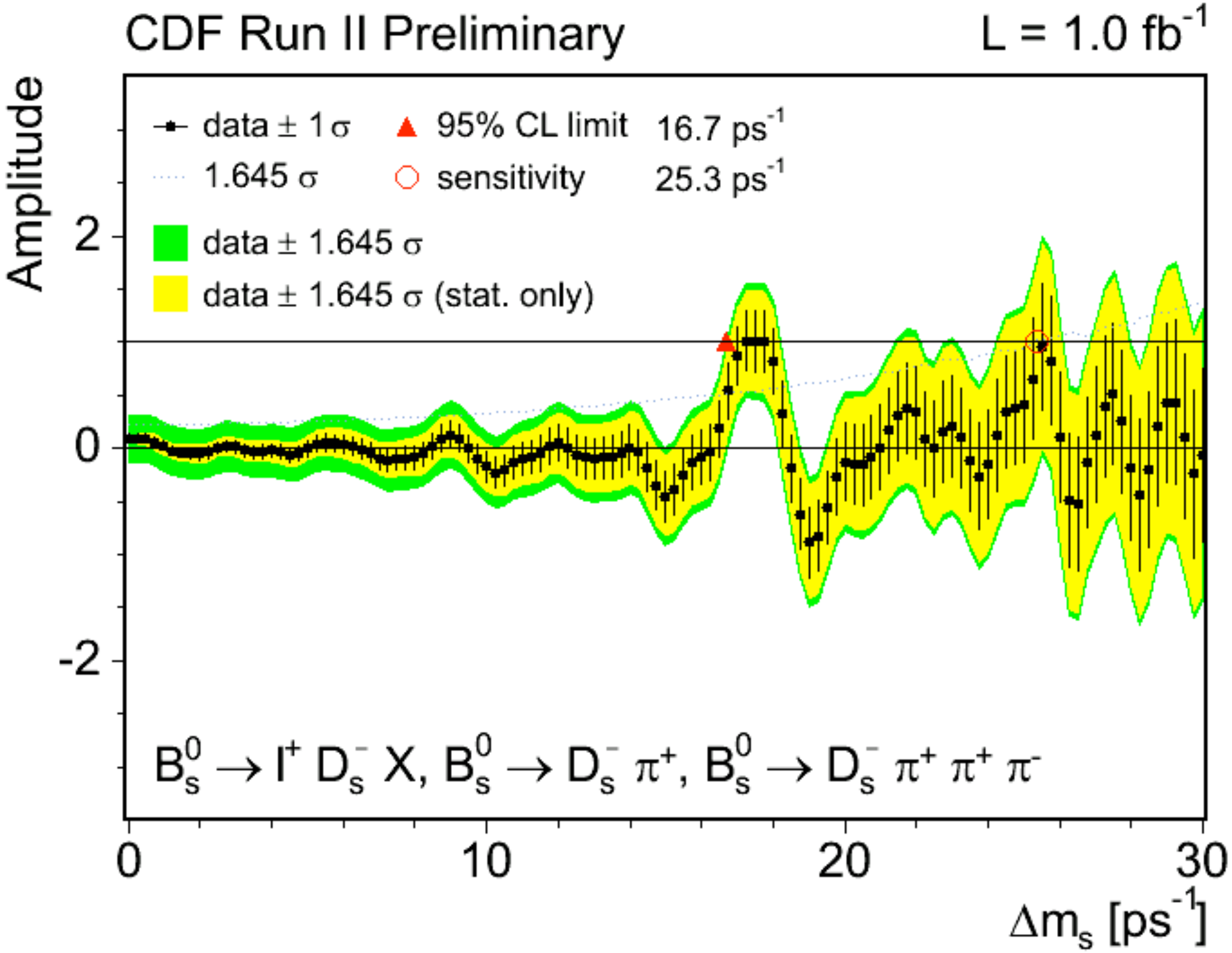
Now the sensitivity is $\sim 25\ \text{ps}^{-1}$,

World ave. :

$18.2\ \text{ps}^{-1}$.

D0 :

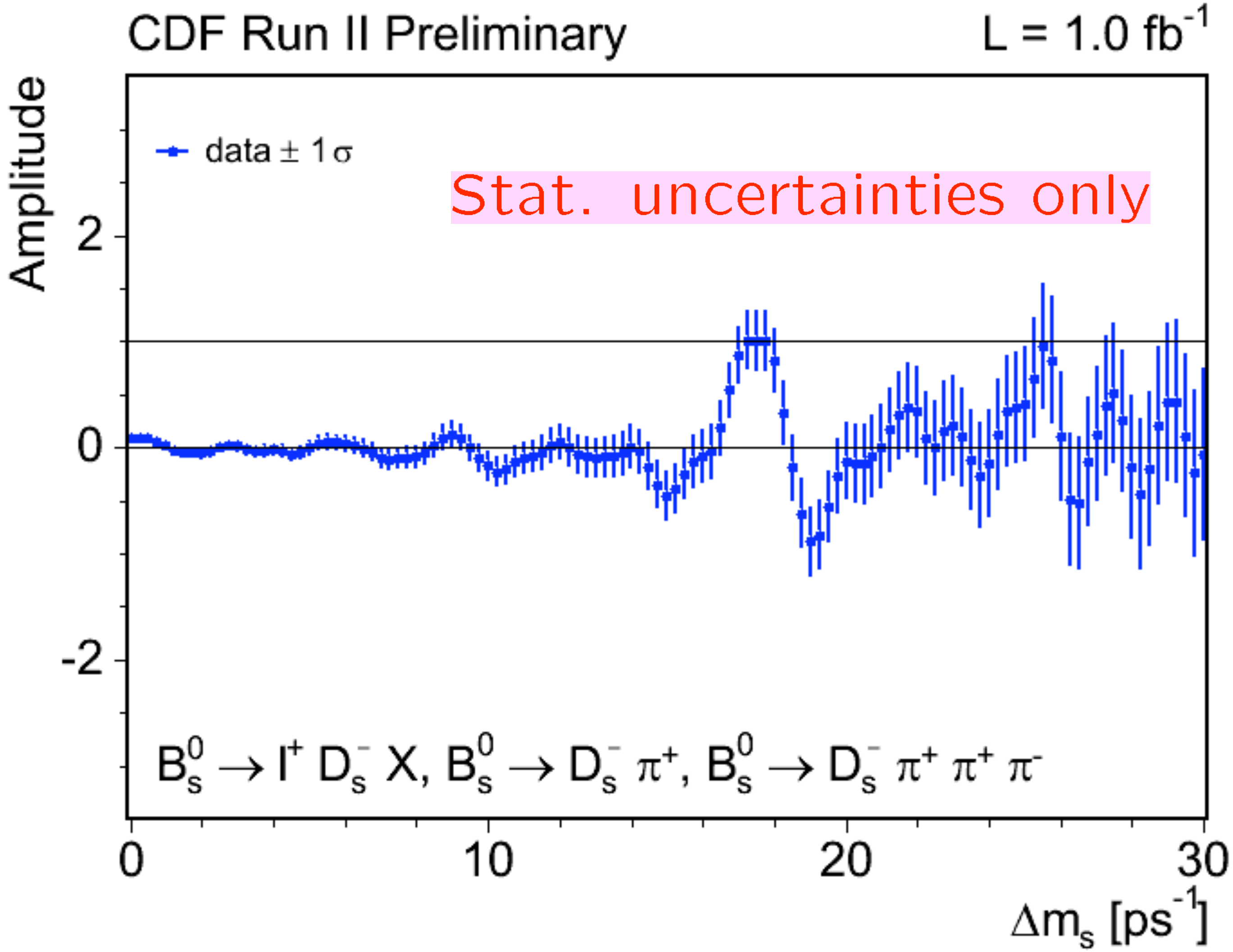
$14.1\ \text{ps}^{-1}$.



Data points touch the $\mathcal{A} = 1$ line at $\Delta m_s \sim 16\ \text{ps}^{-1}$.

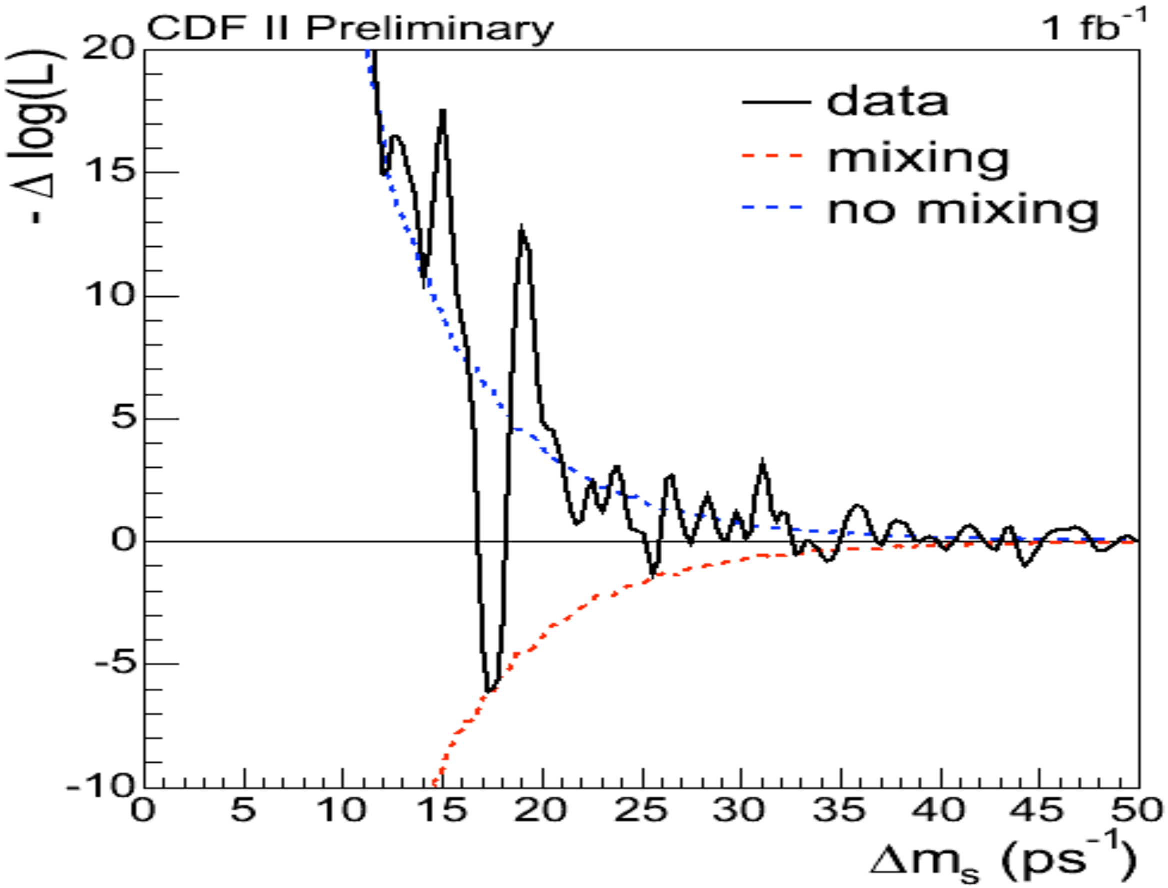
And an interesting structure around $17\ \text{ps}^{-1}$.

Amplitude scan : $\bar{B}_s^0$ sample, 1 fb^{-1}



Amplitude $\mathcal{A} = 1.009\,^{+0.283}_{-0.287}$ at $\Delta m_s \sim 17$ ps^{-1}, or a 3.5-σ effect (naive interpretation).

Likelihood distribution : "fitting" for Δm_s



Max. likelihood at $\Delta m_s \sim 17$ ps^{-1},
and a "depth" of 6.6 in $-\ln \mathcal{L}$.

Is it real?

Significance

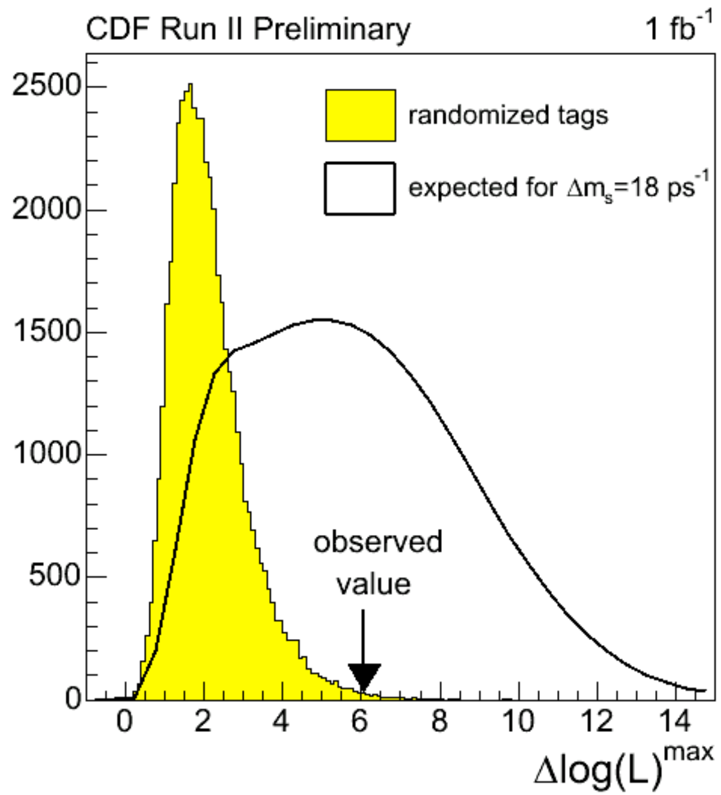
Null hypothesis :

What is the probability of obtaining a phenomenon of this significance when there is no oscillations at all?

Evaluate this prob. by :

- Toy Monte Carlo experiments
- Randomize tags in real data

Two methods give same results ;



Probability for obtaining "depth" > 6 at any value of Δm is 0.5% (yellow histogram).

It's there at 99.5% C.L.

Conversely, if true $\Delta m_s = 18$ ps^{-1}, what depth would you expect? (solid curve, pretty reasonable)

Let us assume it is real.

A closer look at the likelihood distribution.

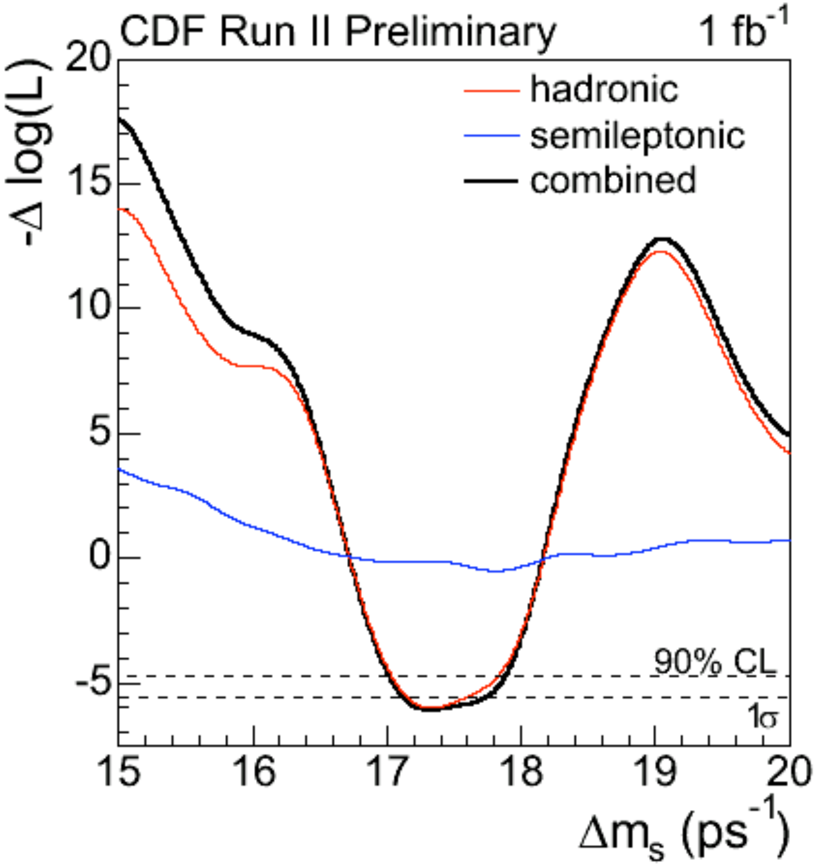
– ln $\mathcal{L}$ is minimal at $\Delta m_s = 17.33$ ps^{-1},
0.5 increment gives :

$$\Delta m_s = 17.33\,^{+0.42}_{-0.21} \pm 0.07 \text{ ps}^{-1}$$

Also:

$17.00 < \Delta m_s < 17.91$ ps^{-1} (90% CL)

$16.94 < \Delta m_s < 17.99$ ps^{-1} (95% CL)



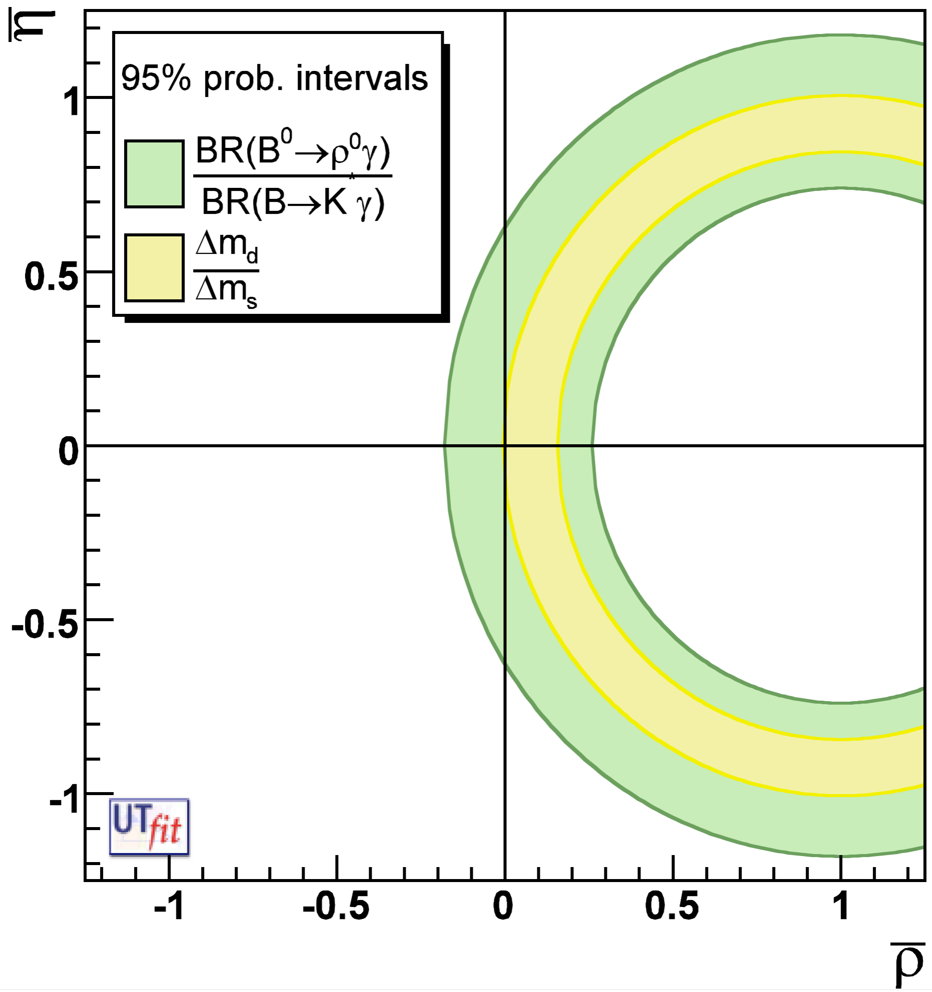
$$\frac{\Delta m_s}{\Delta m_d} = \left|\frac{V_{ts}}{V_{td}}\right|^2 \frac{m_{B_s}}{m_{B_d}}\,\xi^2$$

$$\xi \equiv \frac{\sqrt{B_{B_s}}\,f_{B_s}}{\sqrt{B_{B_d}}\,f_{B_d}} = 1.210\,^{+0.047}_{-0.035}$$ (Okamoto, hep-lat/0510113)

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.208\,^{+0.008}_{-0.007}$$

(4% precision)

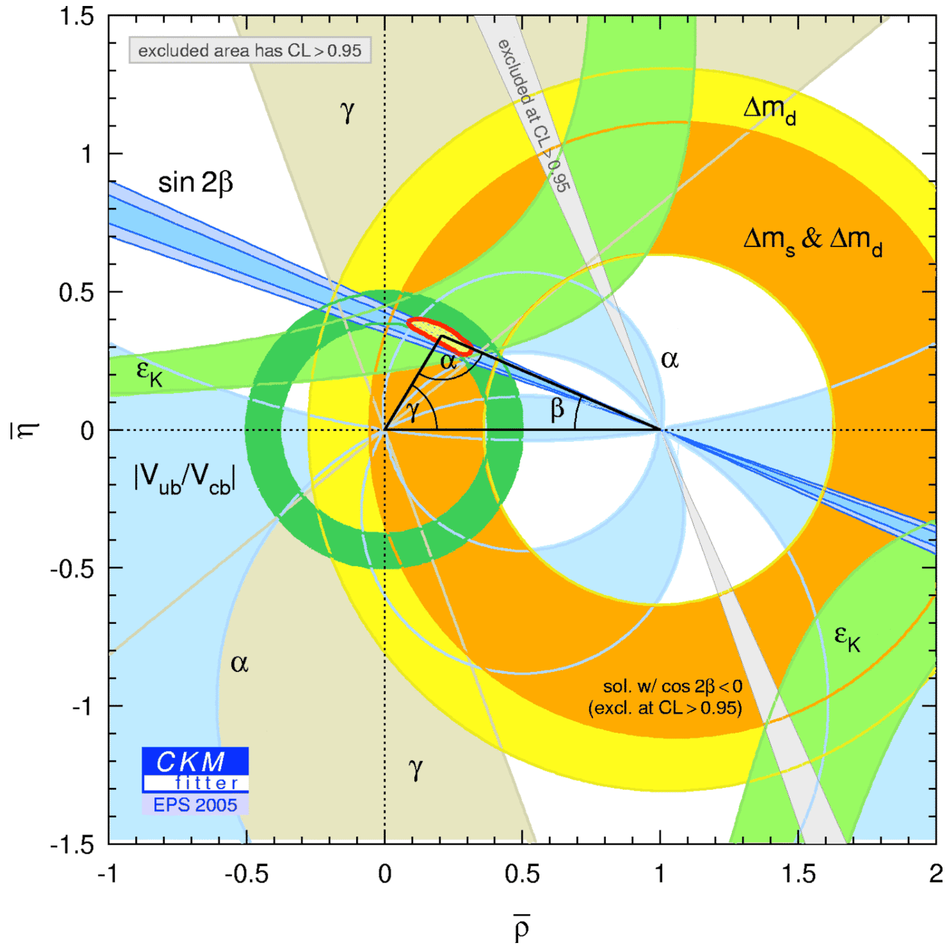
cf : $\left|\frac{V_{td}}{V_{ts}}\right| = 0.199\,^{+0.026}_{-0.025}\,^{+0.018}_{-0.015}$ Belle, from $\frac{\Gamma(b\to d\gamma)}{\Gamma(b\to s\gamma)}$

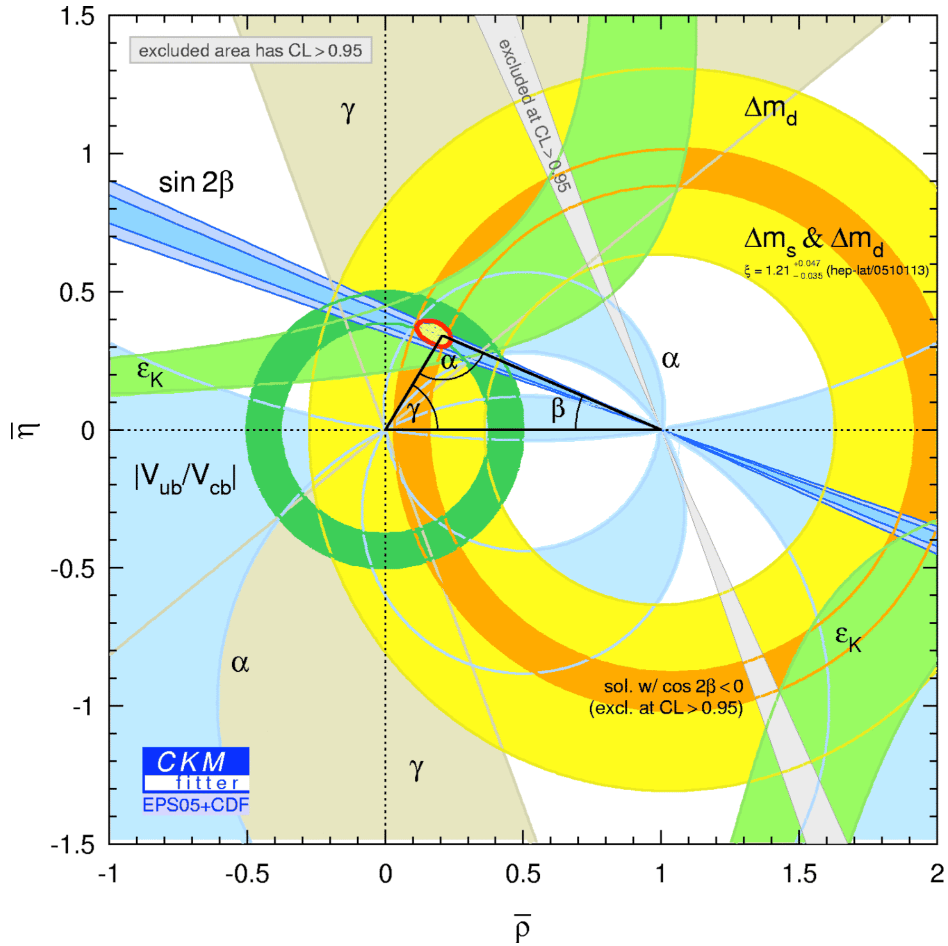


$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.208\,^{+0.008}_{-0.007}$$

Plot courtesy of
Tom Browder

Summer 2005 → Now





End of the oscillation analysis part :

Questions?

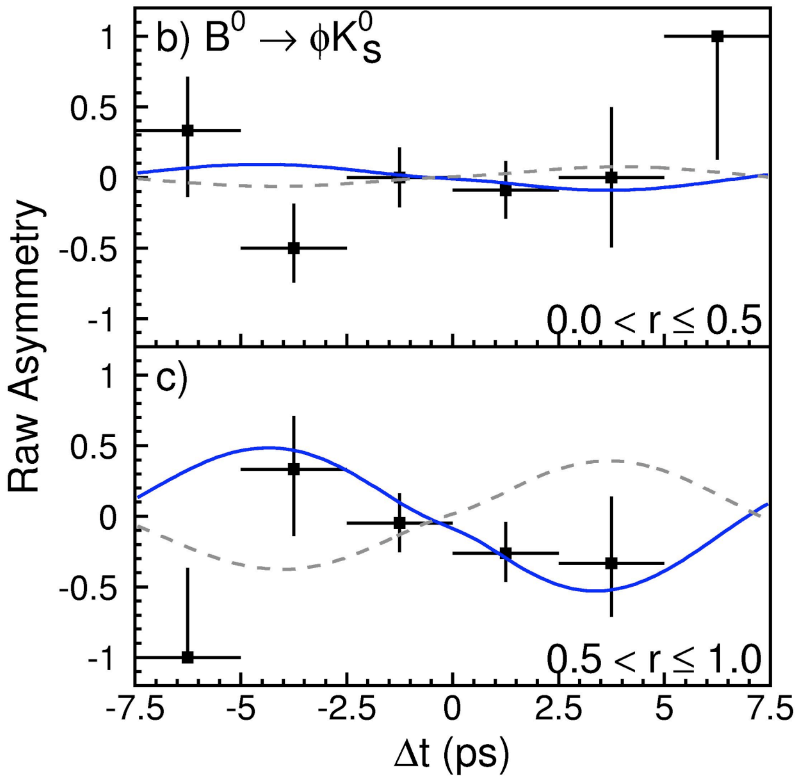
If not, want to show some prospects,
because this is not the end of the story,
rather it is just a beginning.

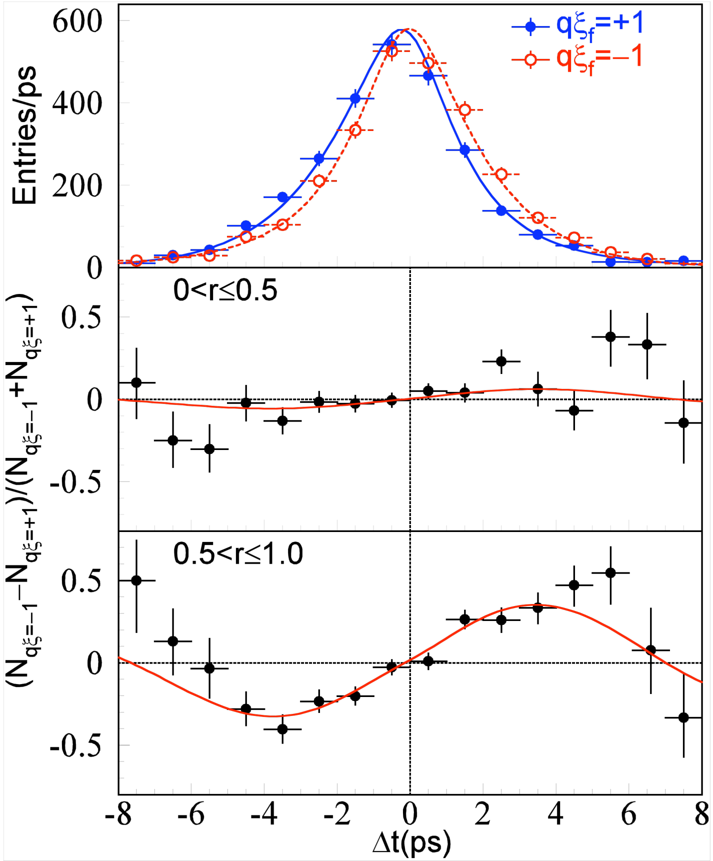
New physics in $b \to s$ transition ?

Belle : PRL 91, 261602 (2003)

$B^0/\bar{B}^0 \to \phi\, K_S^0\ (b \to s\bar{s}s)$

$B^0/\bar{B}^0 \to J/\psi\, K_S^0\ (b \to c\bar{c}s)$





$\sin 2\beta = -0.99 \pm 0.50, \quad \text{vs.} \ +0.731 \pm 0.056.$

Was 3.5 σ away, but now ...

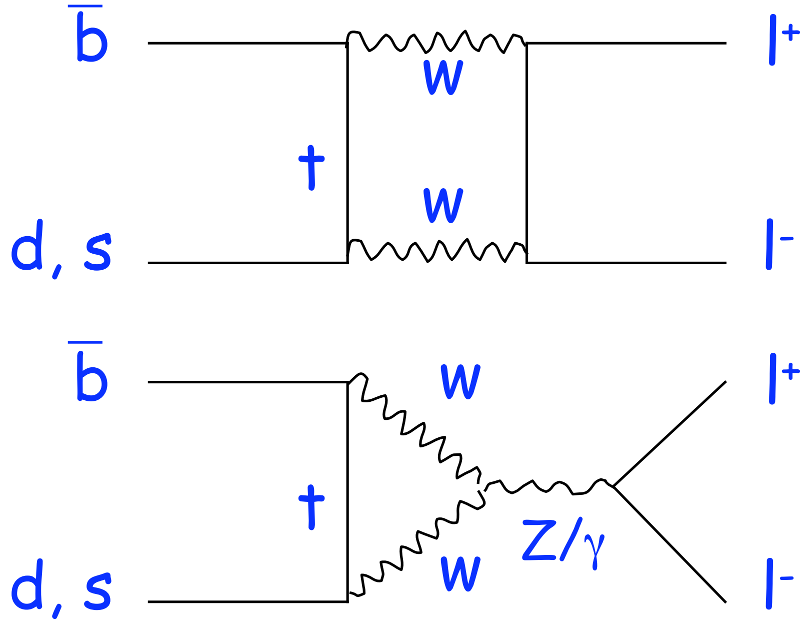
CDF can provide unique tests of $b \to s$ (SUSY?)

- $B_s^0 \bar{B}_s^0$ oscillations.
  If $\Delta m_s \gg 18$ ps^{-1}, a new particle in the loop.
- Look for CP violation in $B_s^0 \to J/\psi\,\phi$.
  This is phase of V_{ts} in SM, so expect ~ 0.
- CP asymmetries in $B_d^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$.
  Latter dominated by $b \to s$ penguin.
- Look for rare decays $B_s^0 \to \mu^+\mu^-$.
  Extremely suppressed in SM, $\mathcal{B} \sim 10^{-9}$ predicted.

The s-quark in the B_s^0 meson isn't just a spectator.

Rare decays $B_d^0/B_s^0 \to \mu^+\mu^-$

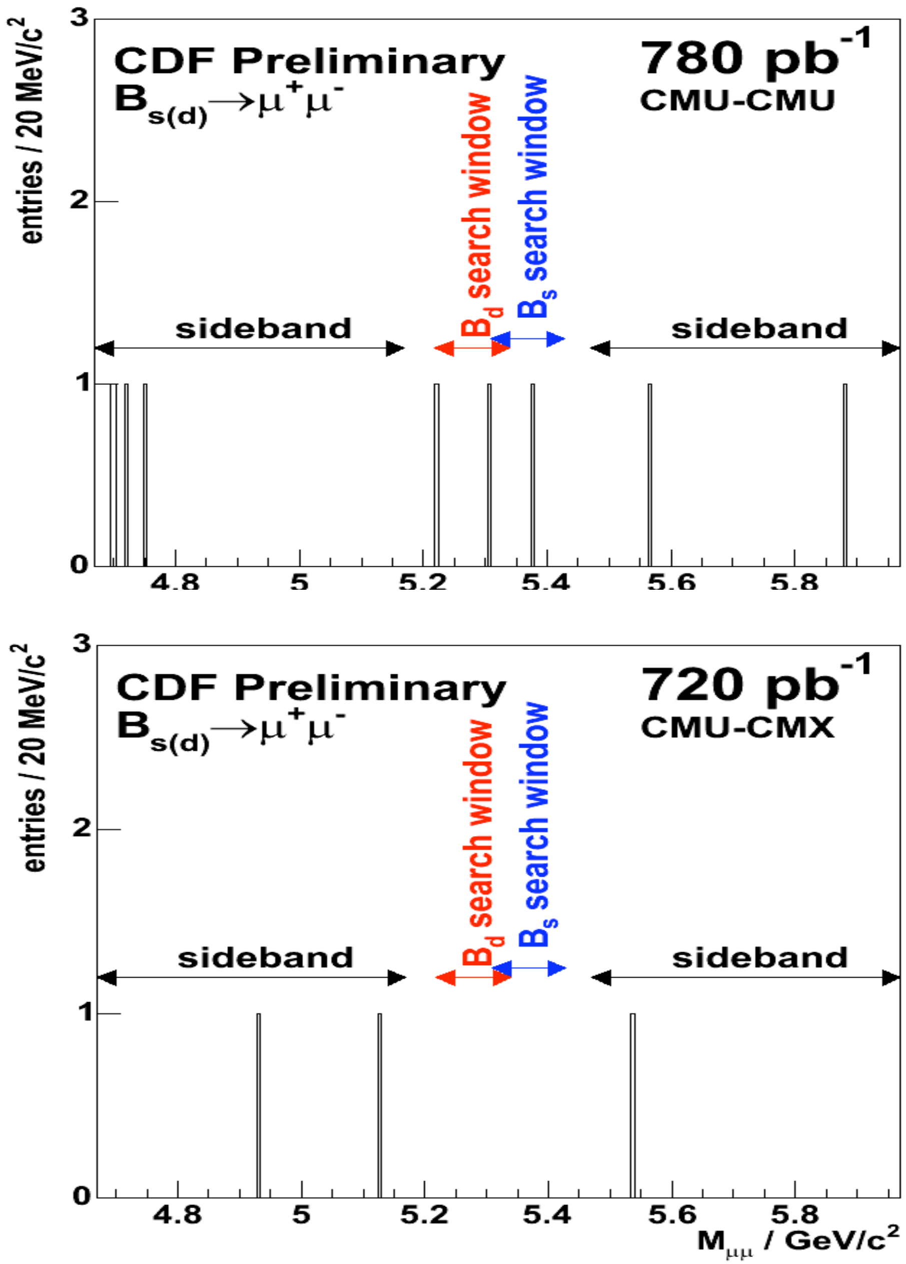
- FCNC
- V_{td} for $B^0{}_d$, V_{ts} for $B^0{}_s$
- Helicity suppressed.
- B.F. very small.



SM predictions for B.F.

- $B_d^0 \to \mu^+\mu^-$ $(1.00 \pm 0.14) \times 10^{-10}$
- $B_s^0 \to \mu^+\mu^-$ $(3.4 \pm 0.5) \times 10^{-9}$
- Five orders smaller for e^+e^- modes.

Search for $B_d^0/B_s^0 \to \mu^+\mu^-$



Two and one candidates in the B^0_d and B^0_s mass windows.

B.R. < 3.0 x 10^{-8} for B^0_d

B.R. < 1.0 x 10^{-7} for B^0_s

@ 95% C.L.

Preliminary.

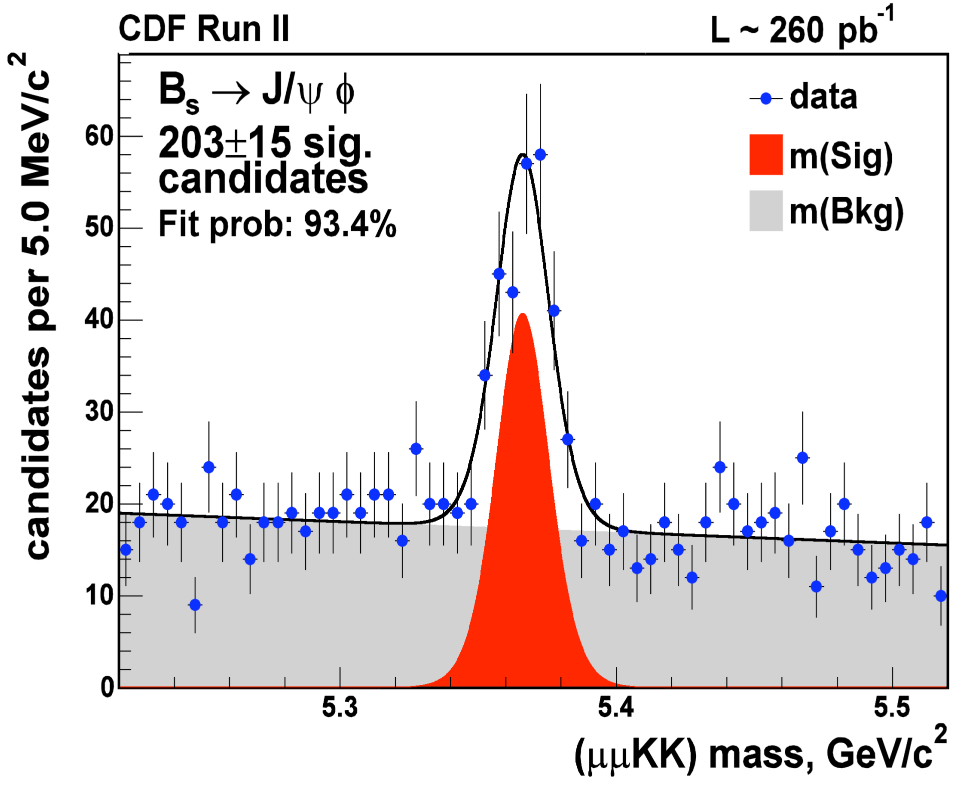
CDF Run-I limits :

B.R. < 8.6 x 10^{-7} for B^0_d

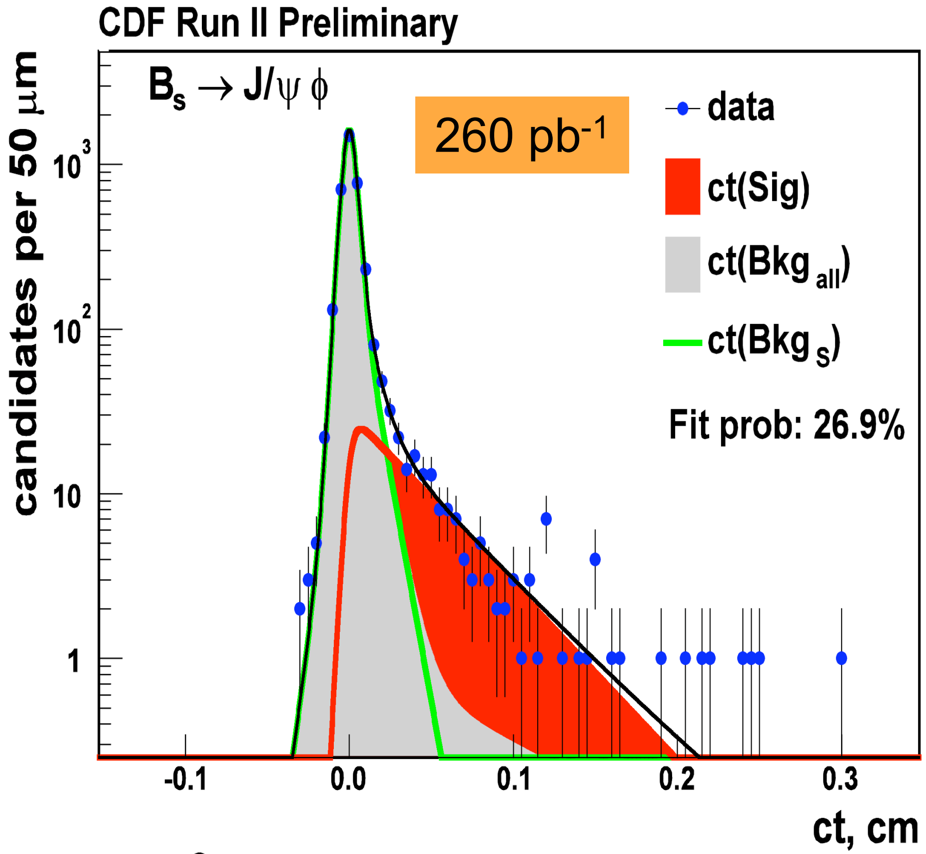
B.R. < 2.6 x 10^{-6} for B^0_s

PRD 57, 3811 (1998)

$B_s^0 \to J/\psi\,\phi \to \mu^+\mu^- K^+ K^-$



$m(B_s^0) = 5366.01 \pm 0.73 \pm 0.33$ MeV/c^2



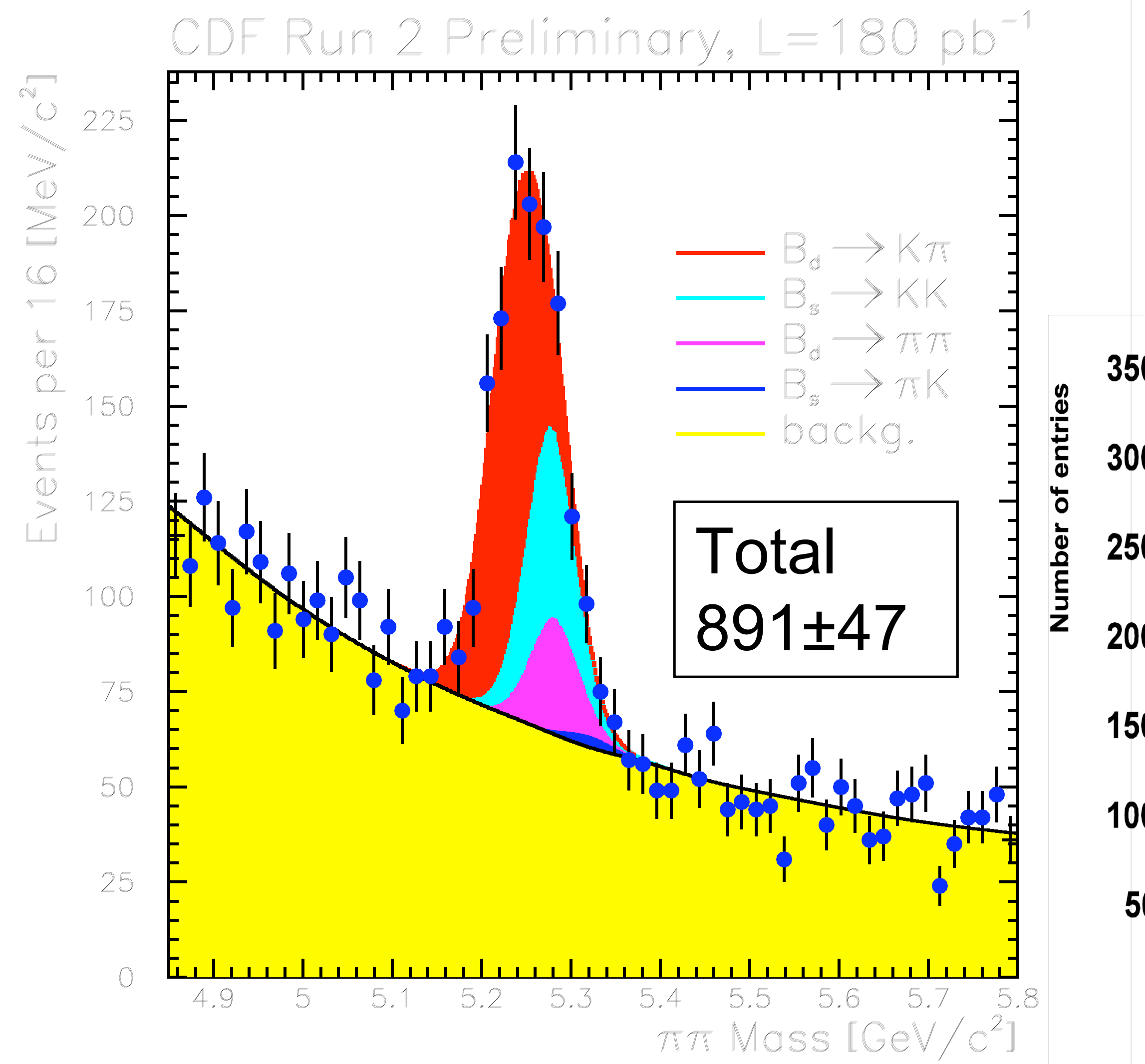
$\tau(B_s^0) = 1.369 \pm 0.100 \pm 0.010$ ps

Predict $\tau(B_s^0)/\tau(B^0) = 1.0 \pm \mathcal{O}(1\%)$
But expect $\Delta\Gamma_s/\Gamma_s \sim 0.1$.
Mode dominated by CP even
($\Gamma_\perp/\Gamma = 0.232 \pm 0.100 \pm 0.013$, CDF).

Can exhibit a different τ than in flavor eigenstates.

Future : look for CP-violation, ~0 expected in SM, arg(V_{ts}).

$B_d^0/B_s^0 \rightarrow h^+h'^-$

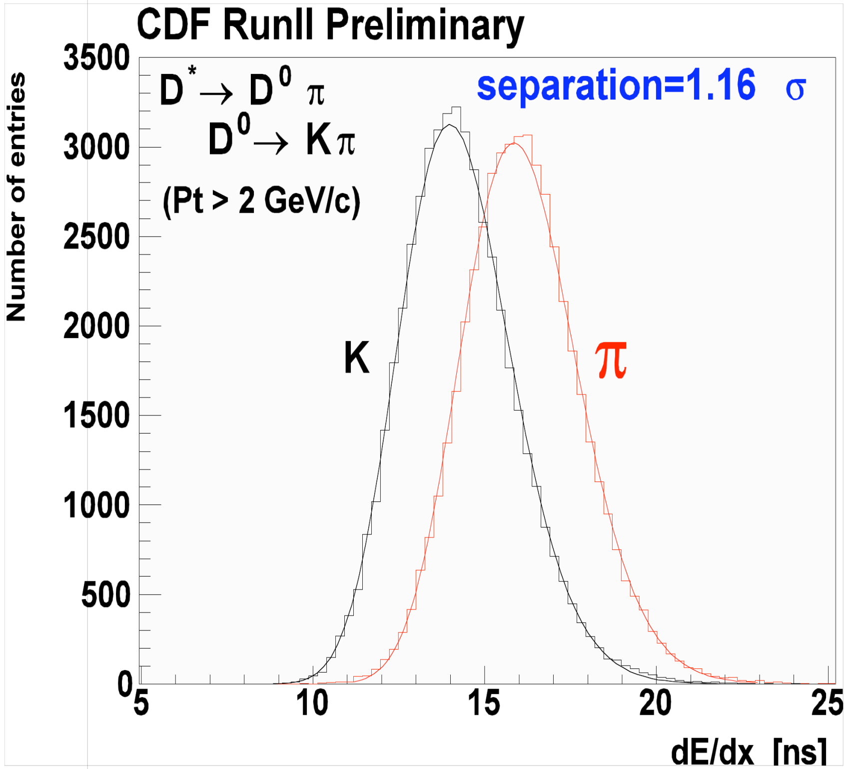


Pion mass assigned to $h^+ h^-$

Peak is sum of

$B^0 \rightarrow K^+\pi^-,\ \pi^+\pi^-$

$B_s^0 \rightarrow K^+K^-,\ K^-\pi^+$



Use dE/dx and mass distributions to determine composition

$B_d^0/B_s^0 \to h^+h'^-$ measurements

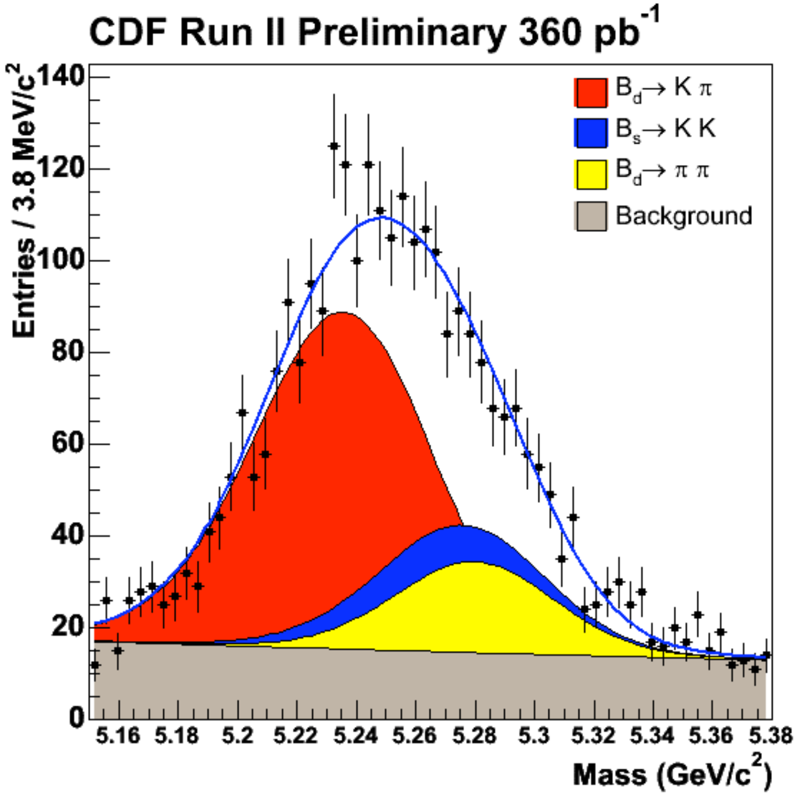
First observation of $B_s^0 \to K^+K^-$

$$\frac{f(\bar{b} \to B_s^0) \cdot \mathcal{B}(B_s^0 \to K^+K^-)}{f(\bar{b} \to B_d^0) \cdot \mathcal{B}(B_d^0 \to K^+\pi^-)} = 0.50 \pm 0.08 \pm 0.07$$

$$\mathcal{B}(B_d^0 \to \pi^+\pi^-)/\mathcal{B}(B_d^0 \to K^+\pi^-) = 0.24 \pm 0.06 \pm 0.05$$

$$\mathcal{A}_{CP}(B^0 \to K^+\pi^-) = -0.058 \pm 0.039 \pm 0.007 \ (360 \text{ pb}^{-1})$$

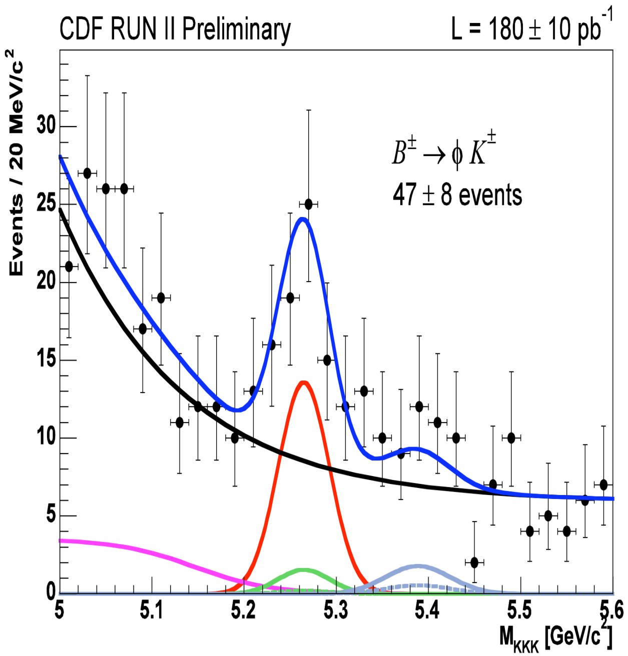
$B_s^0 \to K^+K^-$ (360 pb^{-1}) :
$\tau(B_s^0) = 1.53 \pm 0.18 \pm 0.02$ ps
(CP eigenstate)
$\Rightarrow$ width difference
$|\Delta\Gamma_s|/\bar{\Gamma}_s = -0.08 \pm 0.23 \pm 0.02$
using world ave τ_s from flavor-specific final states.



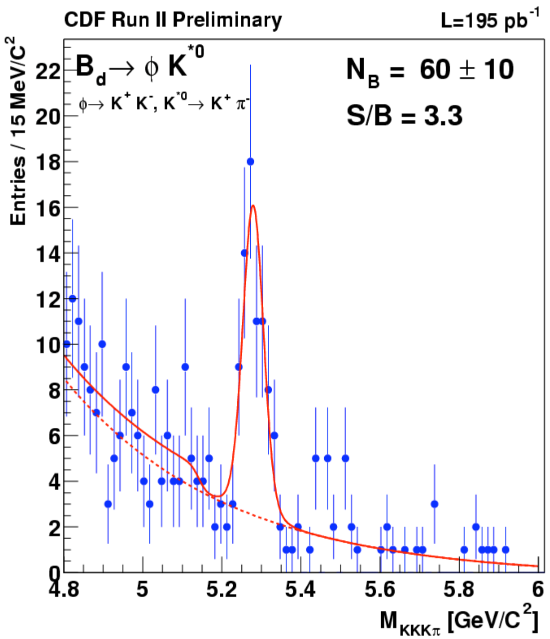
Angle γ in a longer term (given Δm_s)

Direct look at some $b \to s\bar{s}s$ modes

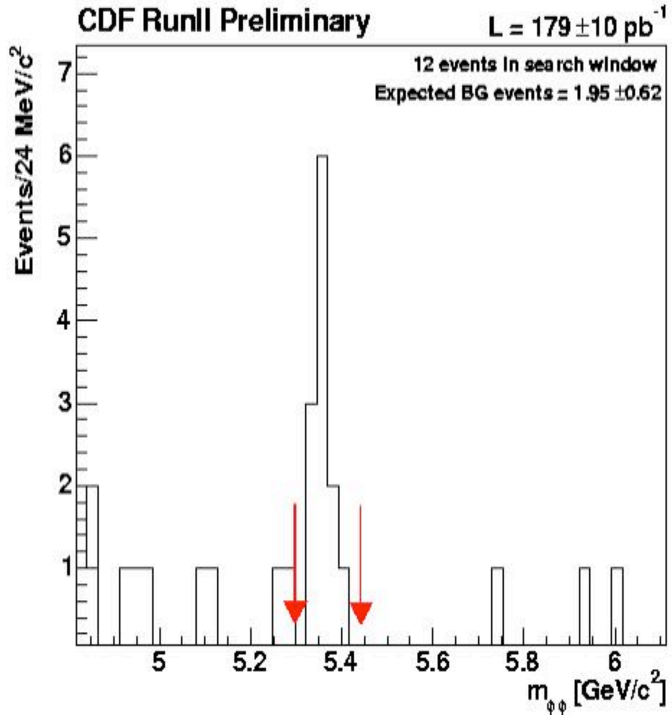
$B^+ \to \phi K^+$



$B^0 \to \phi K^{*0}$



$B_s^0 \to \phi\phi$



$\mathcal{B}(B^+ \to \phi K^+)$
$= (7.6 \pm 1.3 \pm 0.6) \times 10^{-6}$

$\mathcal{A}_{CP} = -0.07 \pm 0.17 {}^{+0.06}_{-0.05}$

$\mathcal{B}(B_s^0 \to \phi\phi)$
$= (1.4 \pm 0.6 \pm 0.6) \times 10^{-5}$

Theory : $(1.8 - 3.7) \times 10^{-5}$,
hep-ph/0309136

Near future : polarizations

Summary

A phenomenon consistent with $B_s^0 \bar{B}_s^0$ oscillations has been observed at 99.5% CL :

- Δm_s already very precise, $|V_{td}/V_{ts}|$ to a few %.
- $\Delta m_s \sim 17$ ps$^{-1} \approx$ SM, no new particle in the loop?

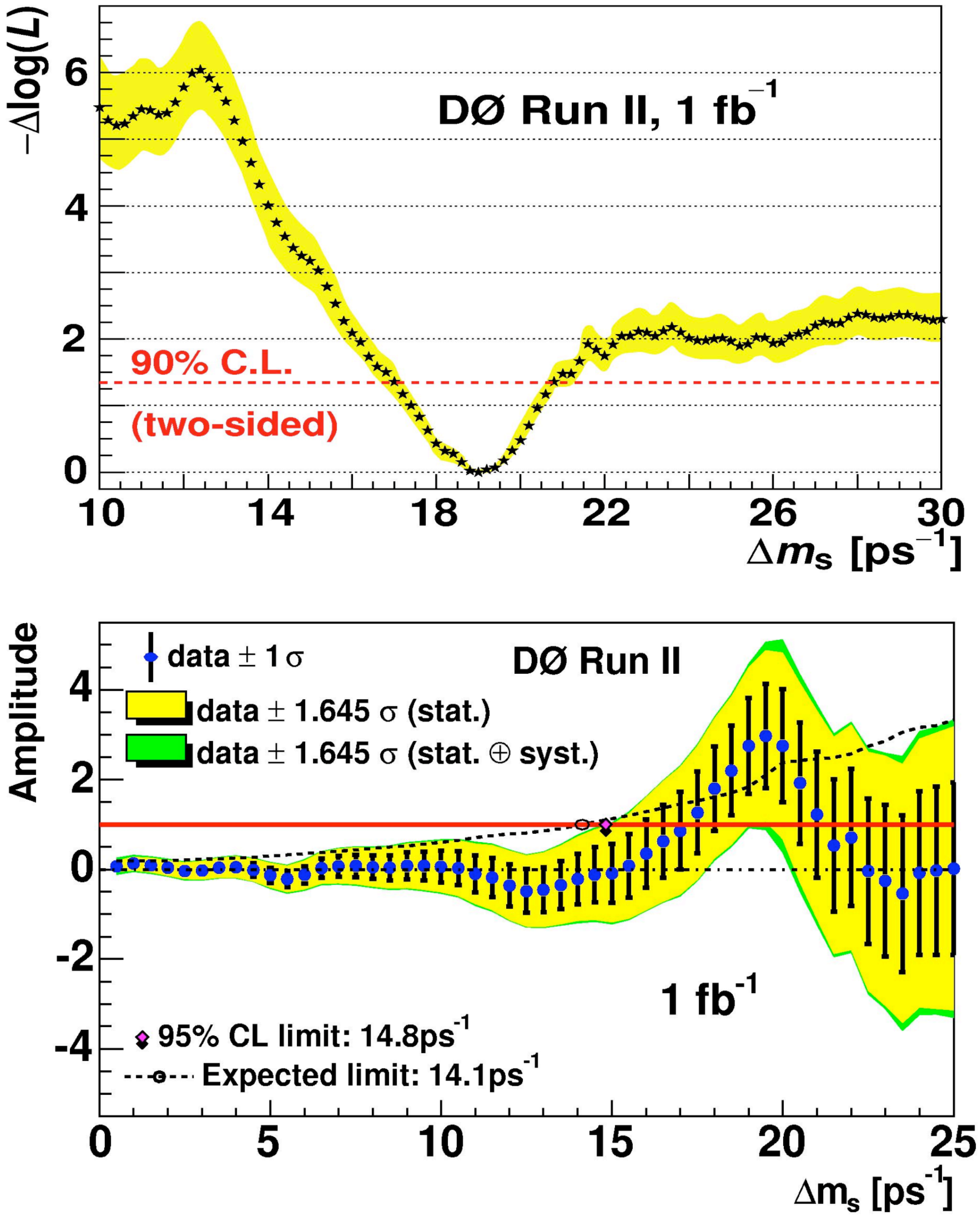
It is not the end of CDF B-physics.
Rather, possibilities for new measurements modulated by $B_s^0 \bar{B}_s^0$ mixing:

- Look for CP violation in $B_s^0 \to J/\psi\, \phi$.
  This is phase of V_{ts} in SM, so expect ~ 0.
- CP asymmetries in $B_d^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$.
  Should allow a determination of γ.

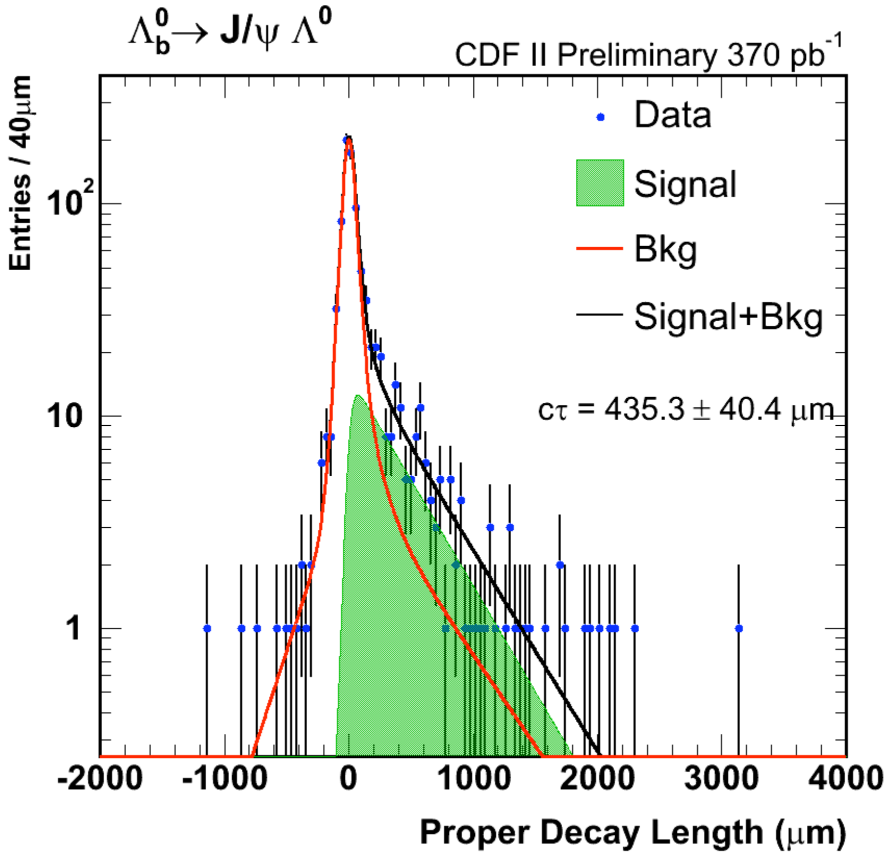
Backup slides

D0 experiment

hep-ex/0603029



$$\Lambda_b^0 \to J/\psi\,\Lambda^0 \to \mu^+\mu^-\,p\pi^-$$

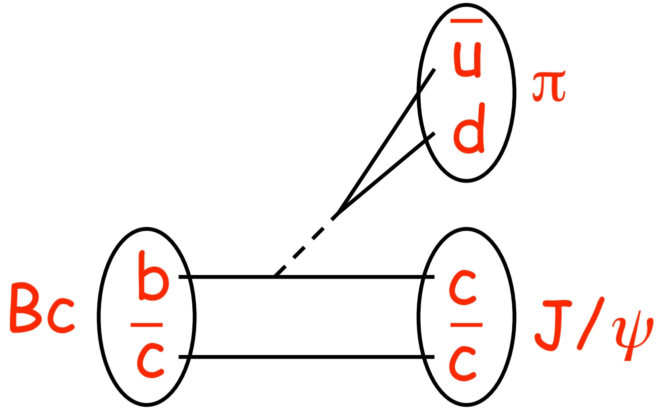


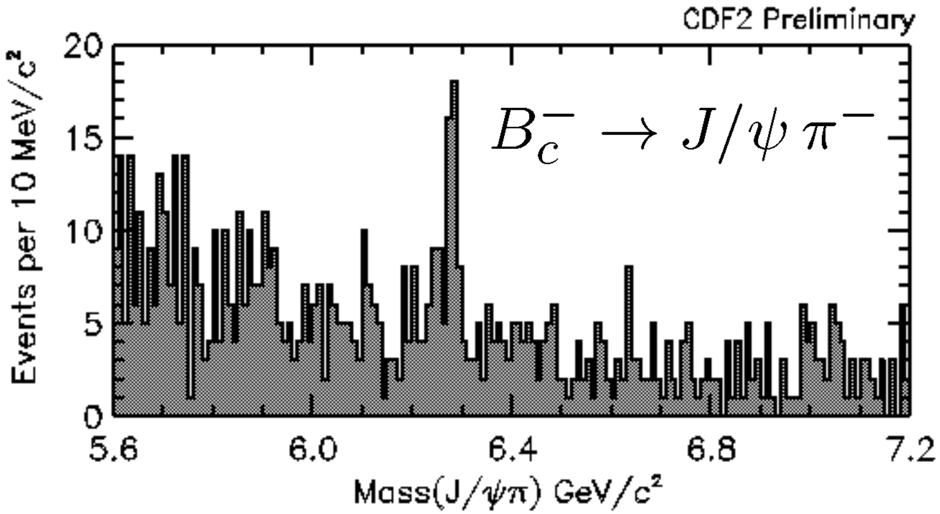
$$\tau(\Lambda_b^0) = 1.45\,^{+0.14}_{-0.13} \pm 0.02 \text{ ps}$$

$$\tau(\Lambda_b^0)/\tau(B^0) = 0.944 \pm 0.089$$

Theory, Gabbiani *et al.*
PRD 70, 094031 (2004)
$= 0.86 \pm 0.05$

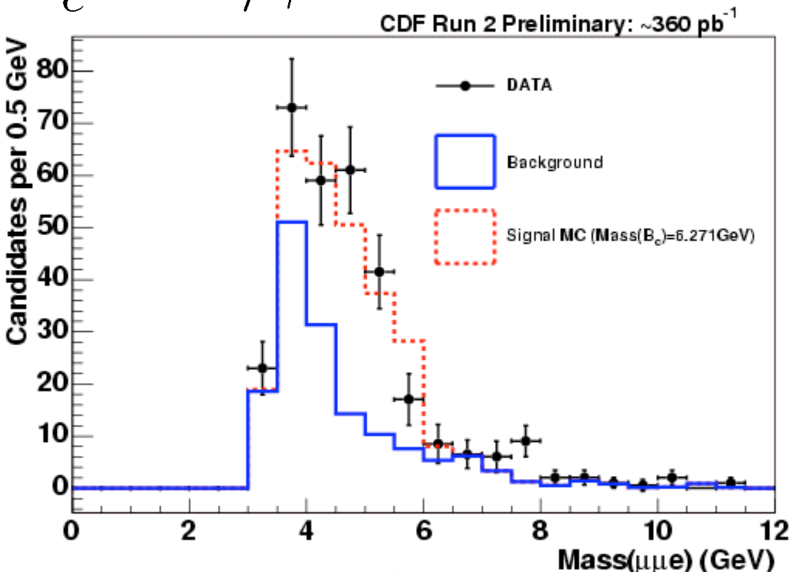
$B_c^- \text{ meson} \equiv b\bar{c}$ Bound state of two different heavy quarks

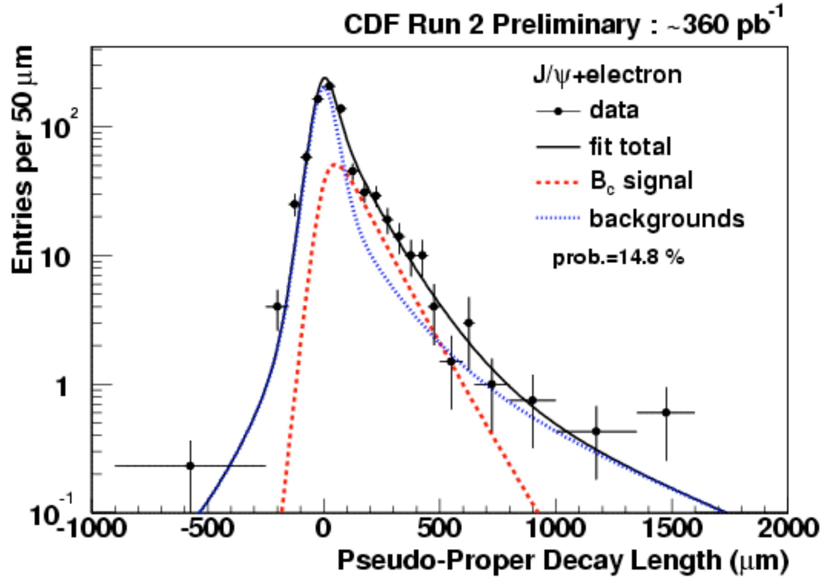




$$m(B_c^-) = 6275.2 \pm 4.3 \pm 2.3 \text{ MeV}/c^2$$

$B_c^- \to J/\psi\, e^- \bar{\nu} X$

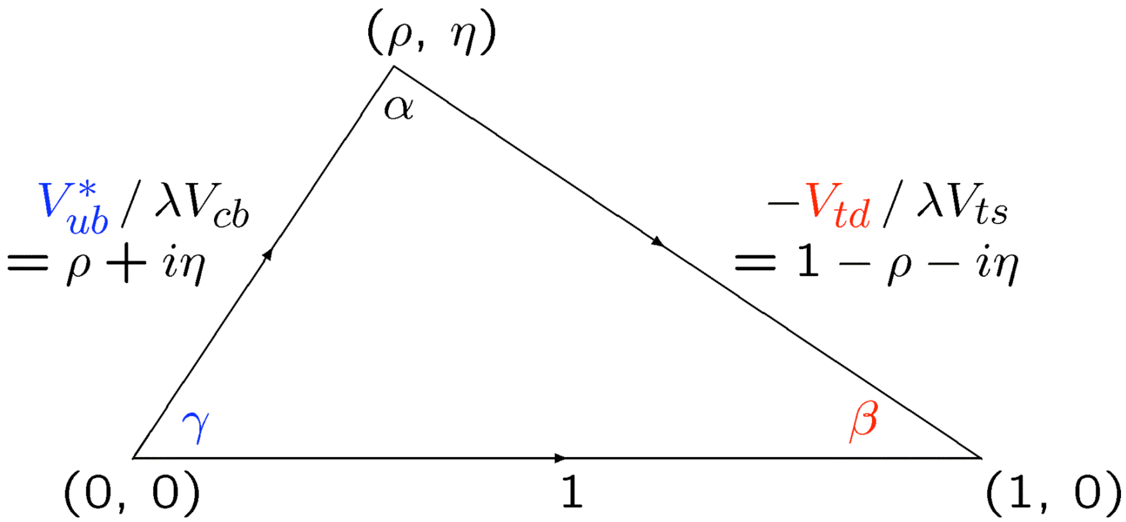


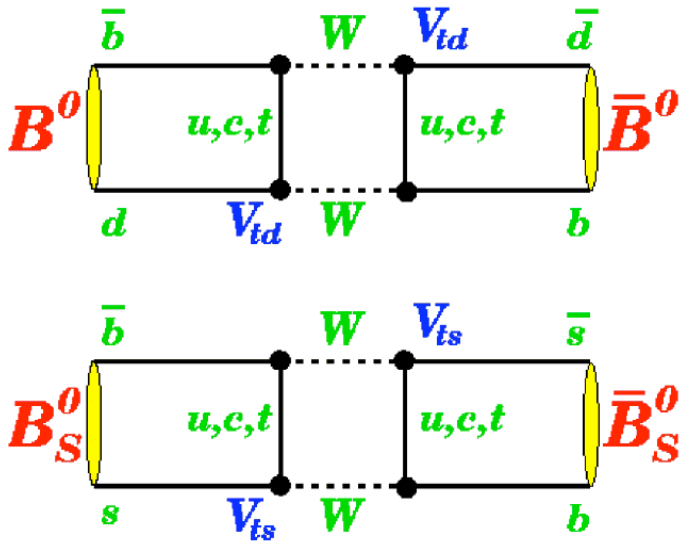


Masato Aoki,
Ph.D. thesis, 2006

$$\tau(B_c^-) = 0.474\,^{+0.073}_{-0.066} \pm 0.033 \text{ ps}$$

B physics : does the unitarity triangle close?





- $|V_{cb}|$ from $b \to c\ell\nu$, $|V_{ub}|$ from $b \to u\ell\nu$.
- $|V_{td}|$ from Δm_d, better if we use ratio

$$\frac{\Delta m_s}{\Delta m_d} = \left|\frac{V_{ts}}{V_{td}}\right|^2 \frac{m_{B_s}}{m_{B_d}} \xi^2 \quad (\xi = 1.210\,^{+0.047}_{-0.035})$$

- $\sin 2\beta$ from $B^0/\bar{B}^0 \to J/\psi K_S^0$. Now precisely known.
- α from $B^0/\bar{B}^0 \to \pi^+\pi^-$, etc.
- γ from $B \to DK$, etc.

PDG 2000

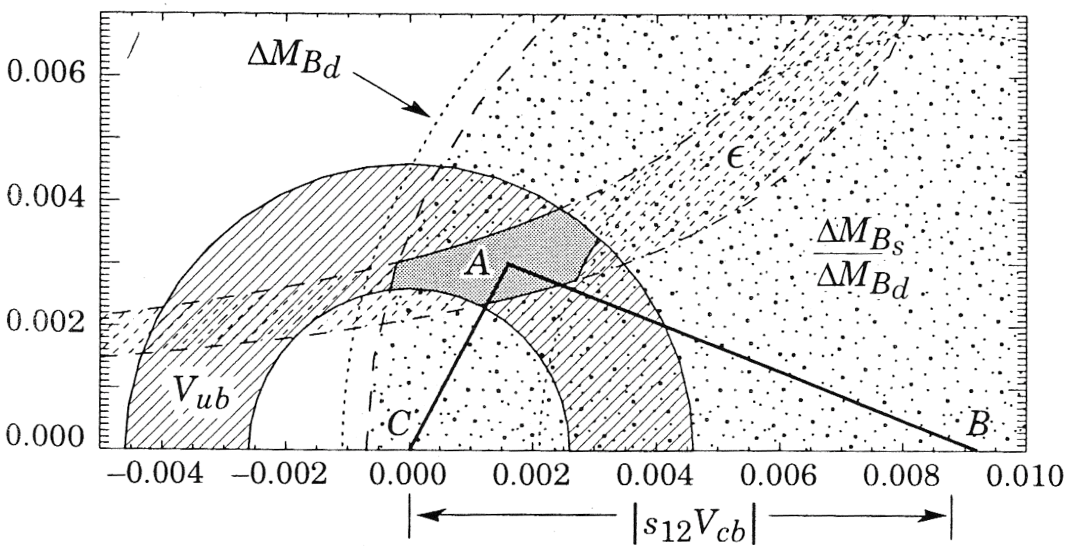
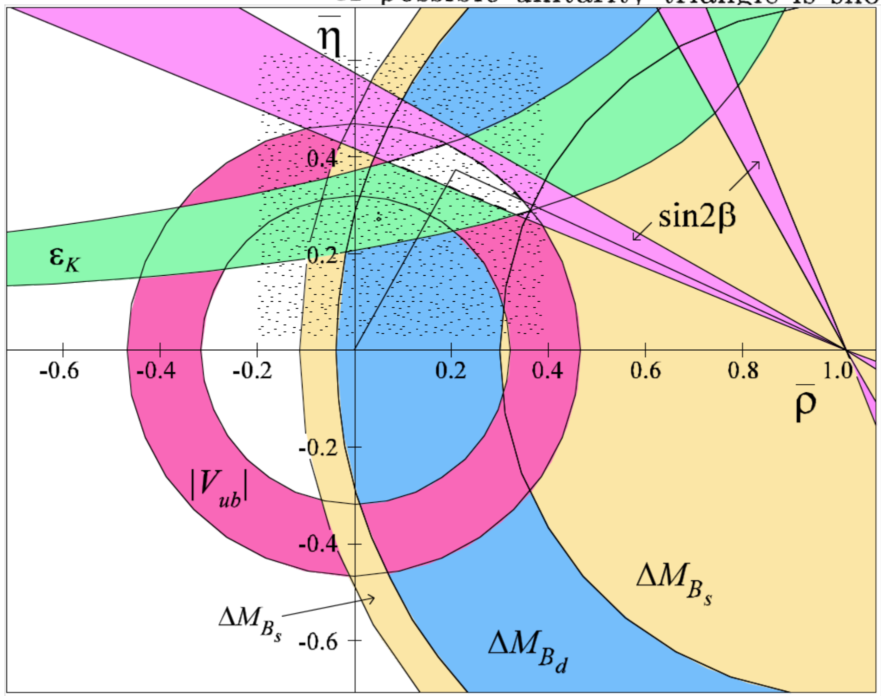
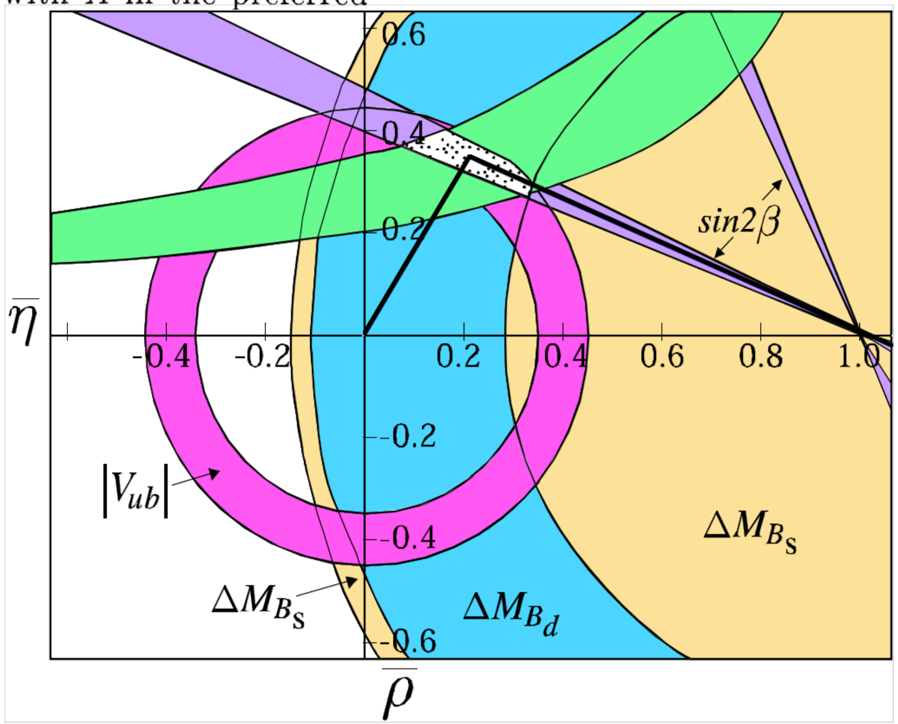


Figure 11.2: Constraints on the position of the vertex, A, of the unitarity triangle following from $|V_{ub}|$, B mixing, and ϵ. A possible unitarity triangle is shown with A in the preferred

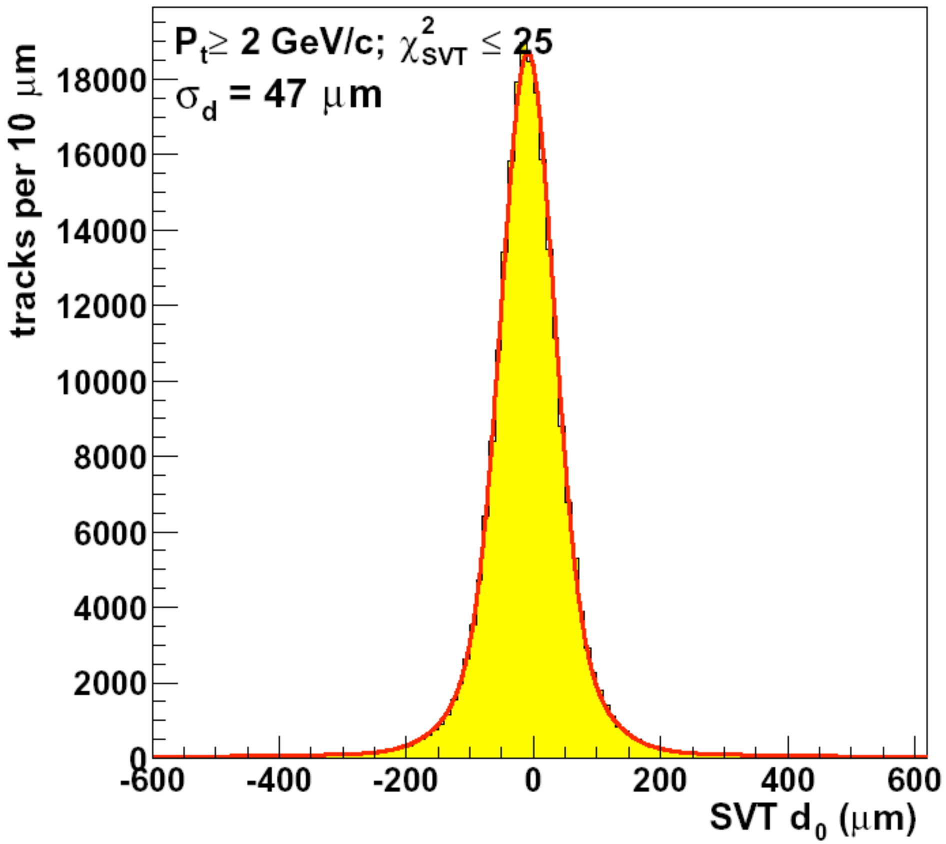
2002



2004



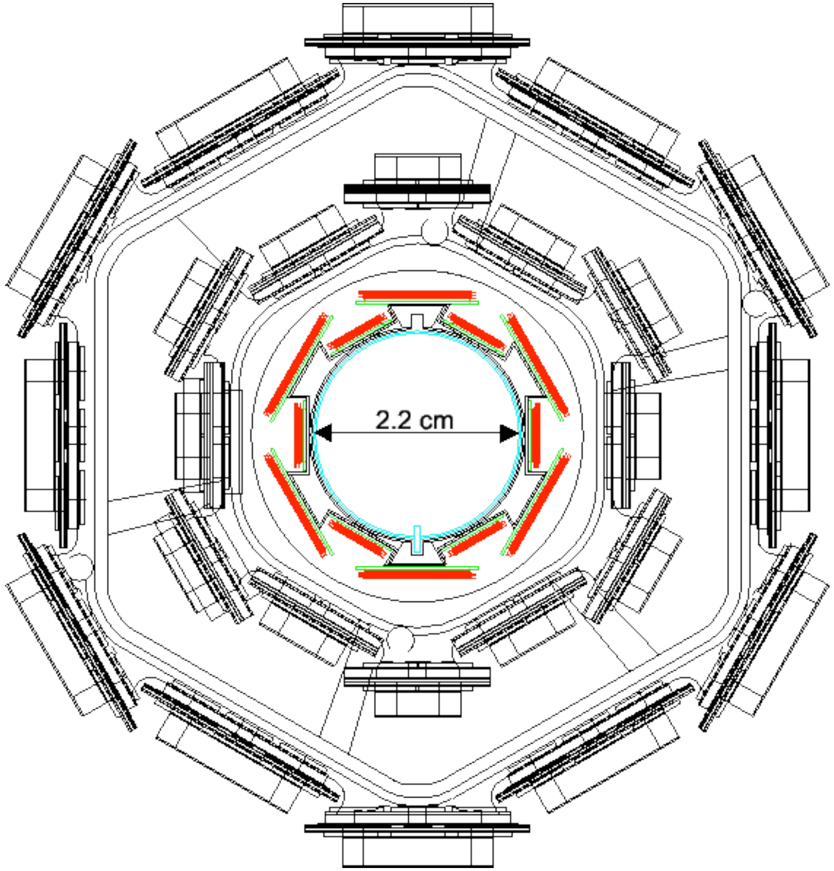
SVT impact parameter resolution

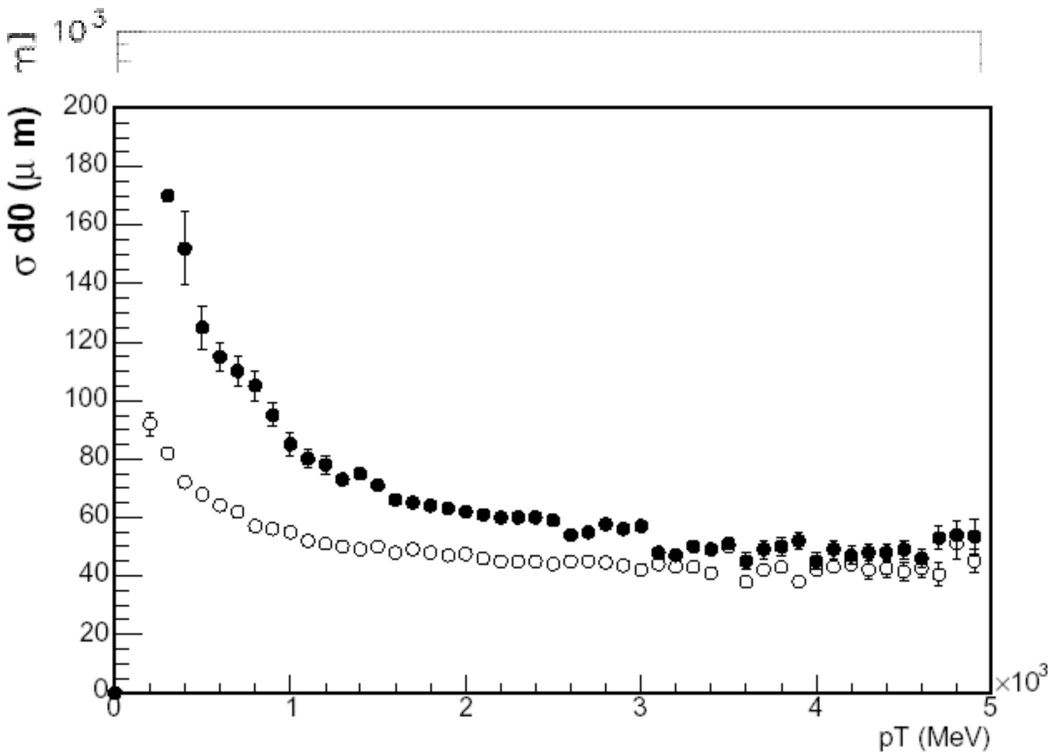


Layer 00

Detector

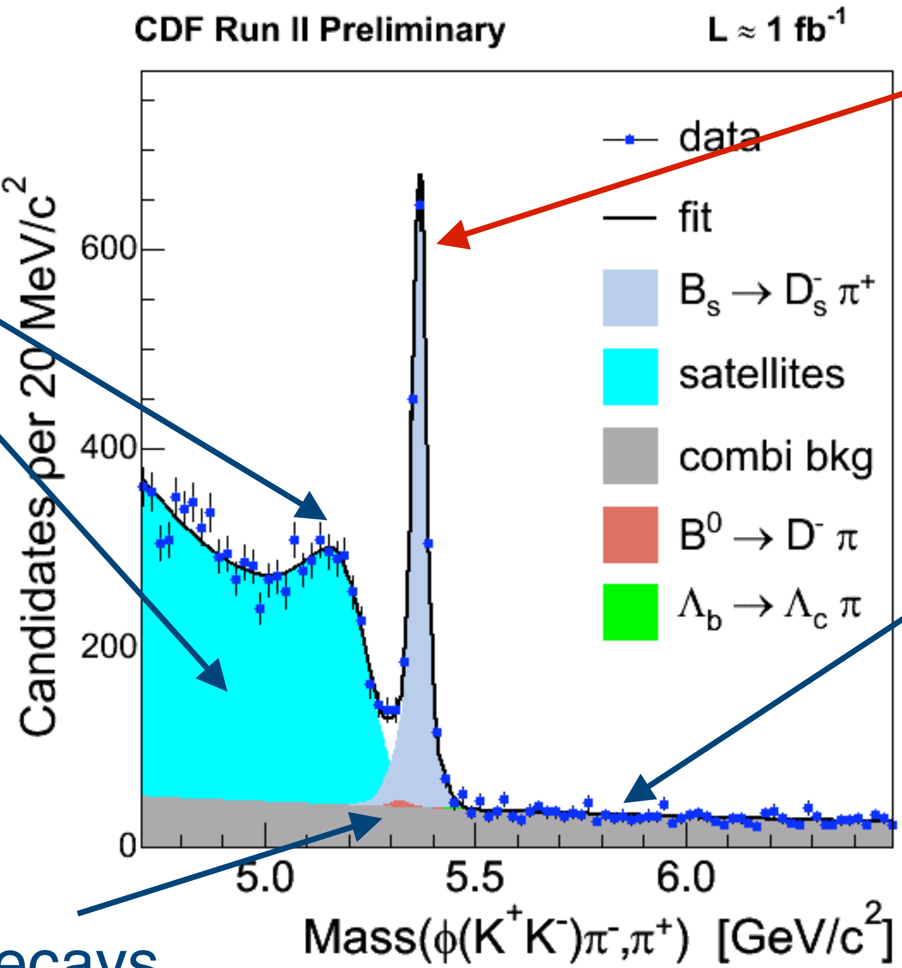
- Single-sided
- At radius ~ 1.6 cm, minimize effect of multiple scattering.
- Can operate up to ~ 5 fb^{-1}





Example Mass Spectrum

partially reconstructed B mesons (satellites)



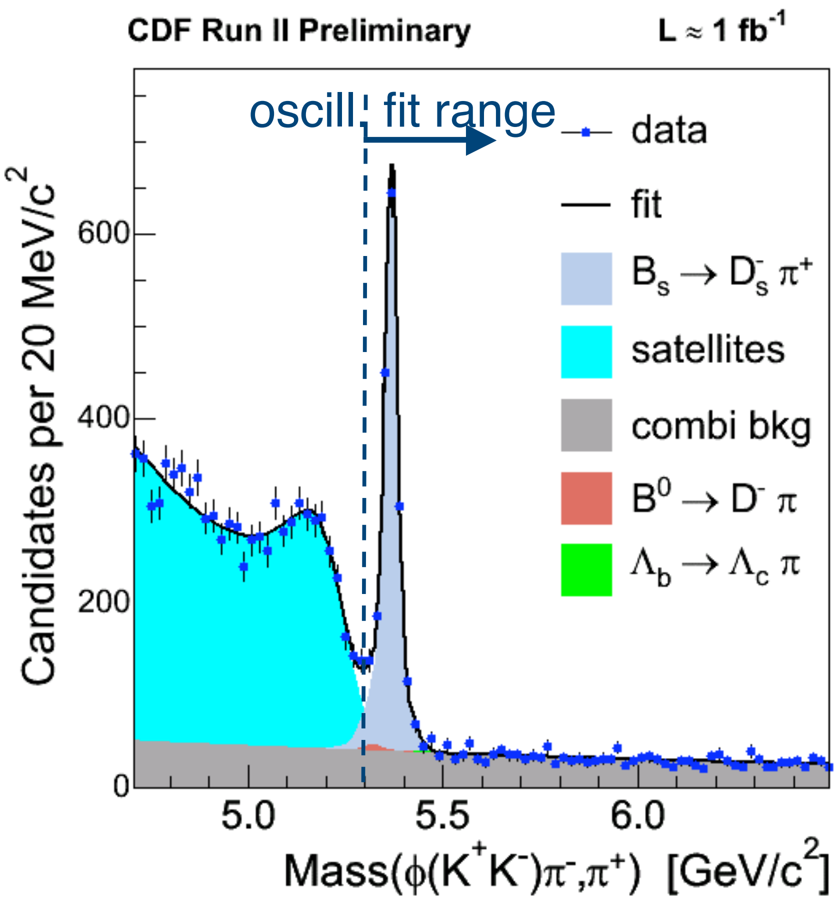
signal
B_s! $D_s\pi$,
D_s ! $\phi\pi$,
ϕ ! K^+K^-

combinatorial background

B^0! $D^-\pi$ decays

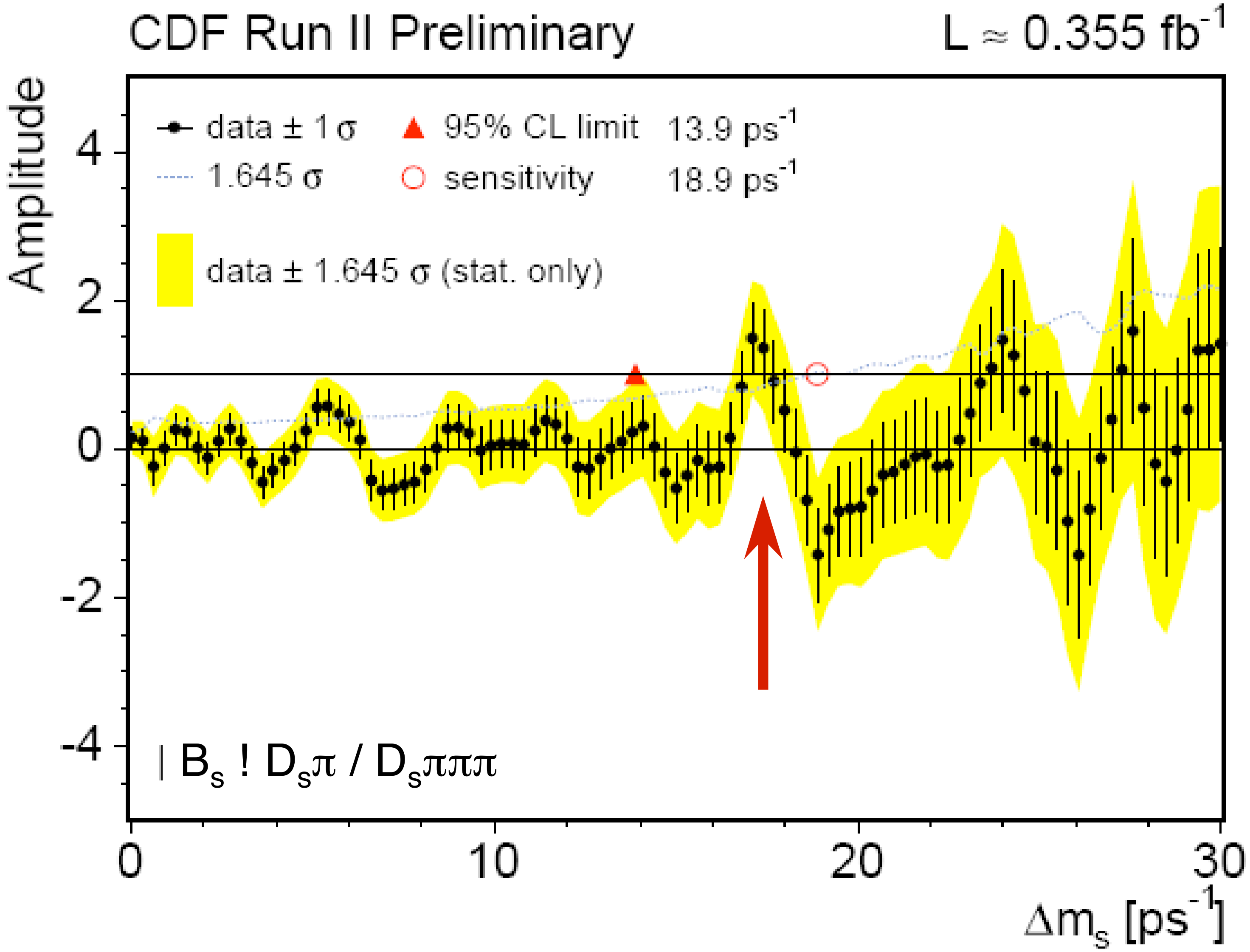
Signal Yield Summary: Hadronic

	Yield
B_s! $D_s\pi$ ($\phi\pi$)	1600
B_s! $D_s\pi$ (K^* K)	800
B_s! D_s π (3π)	600
B_s! $D_s3\pi$ (ϕ π)	500
B_s! $D_s3\pi$ (K^*K)	200
Total	3700

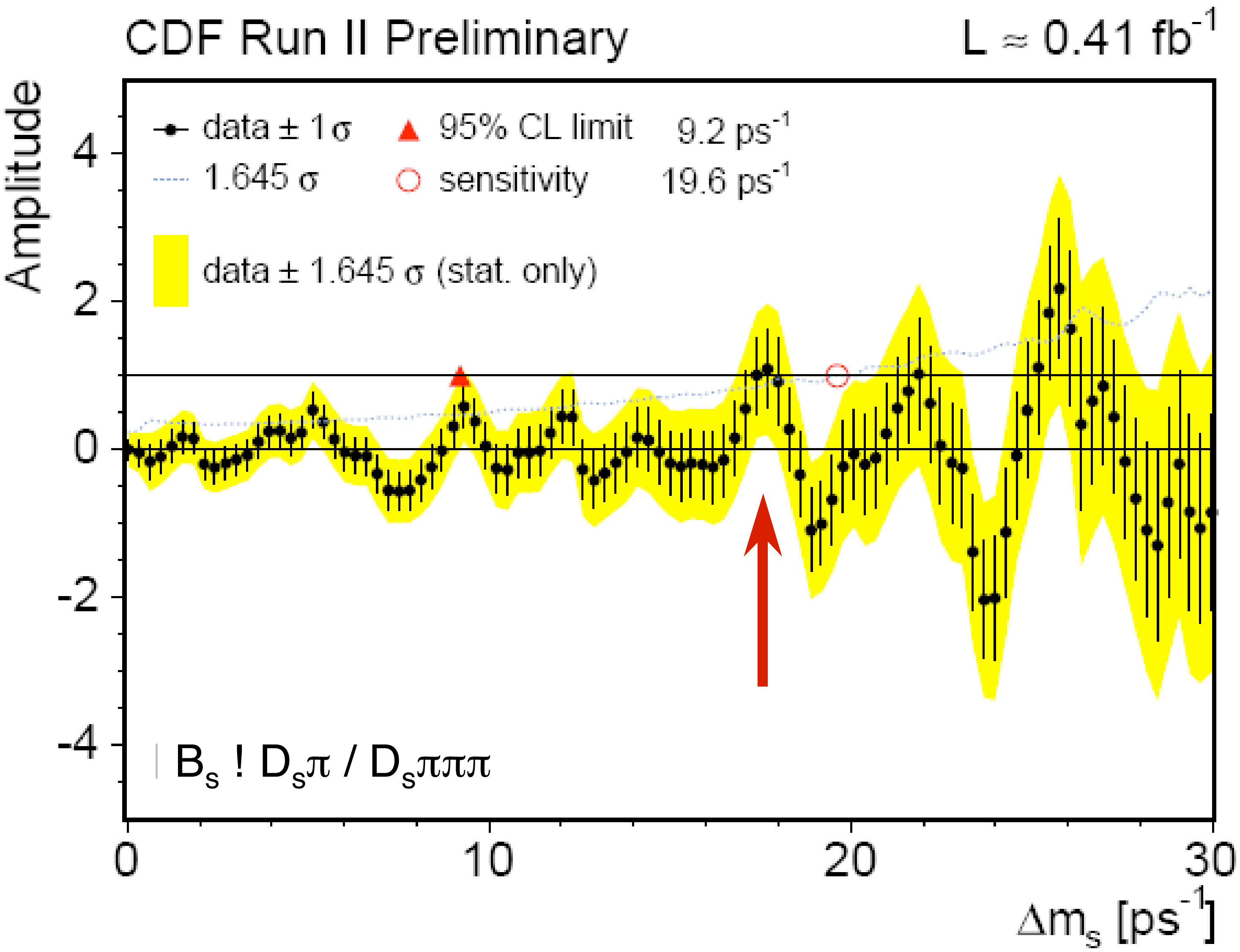


- high statistics light B meson samples:
  B^+ ($D^0\pi$): 26k events
  B^0 ($D^-\pi$): 22k events

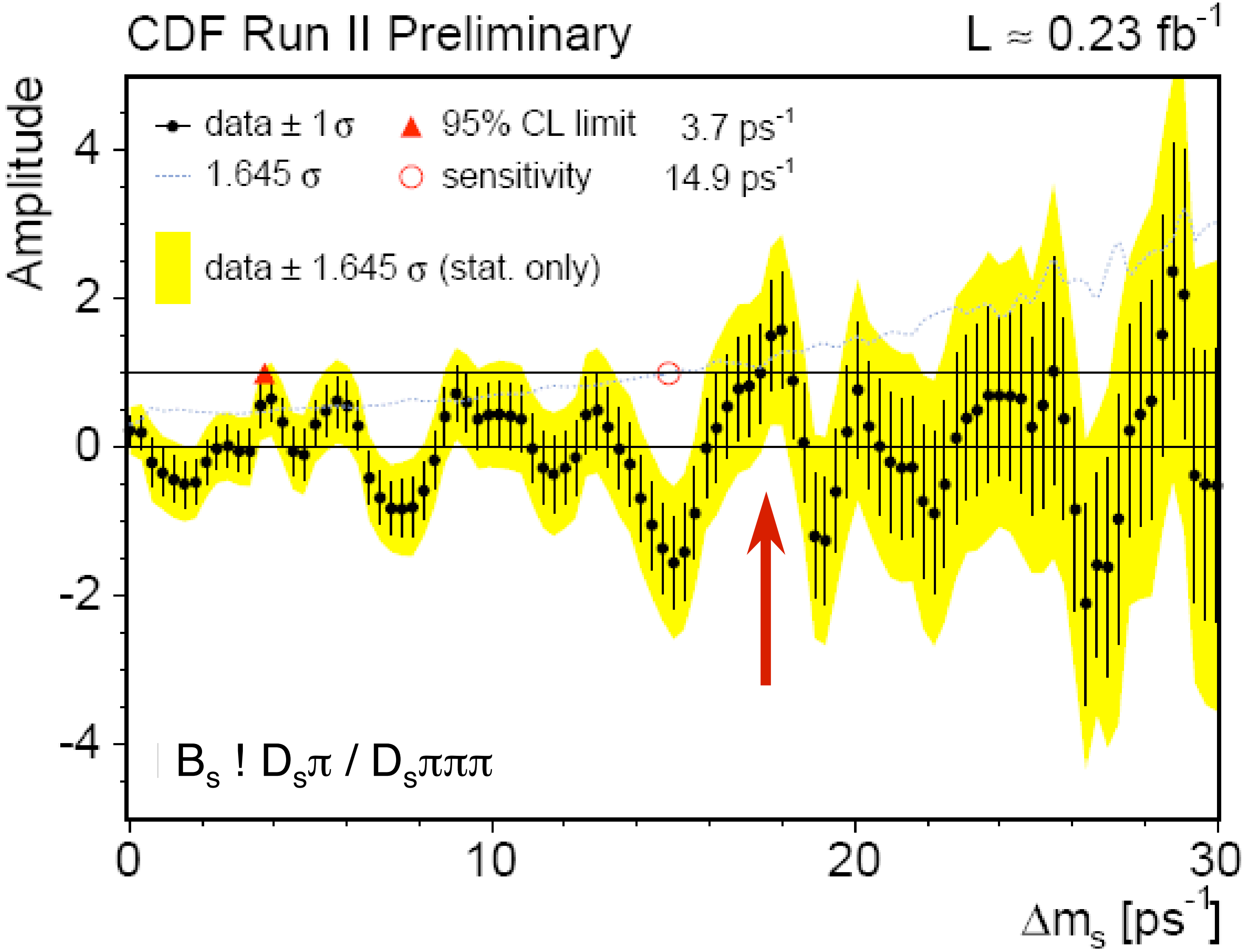
Amplitude Scan: Hadronic Period 1



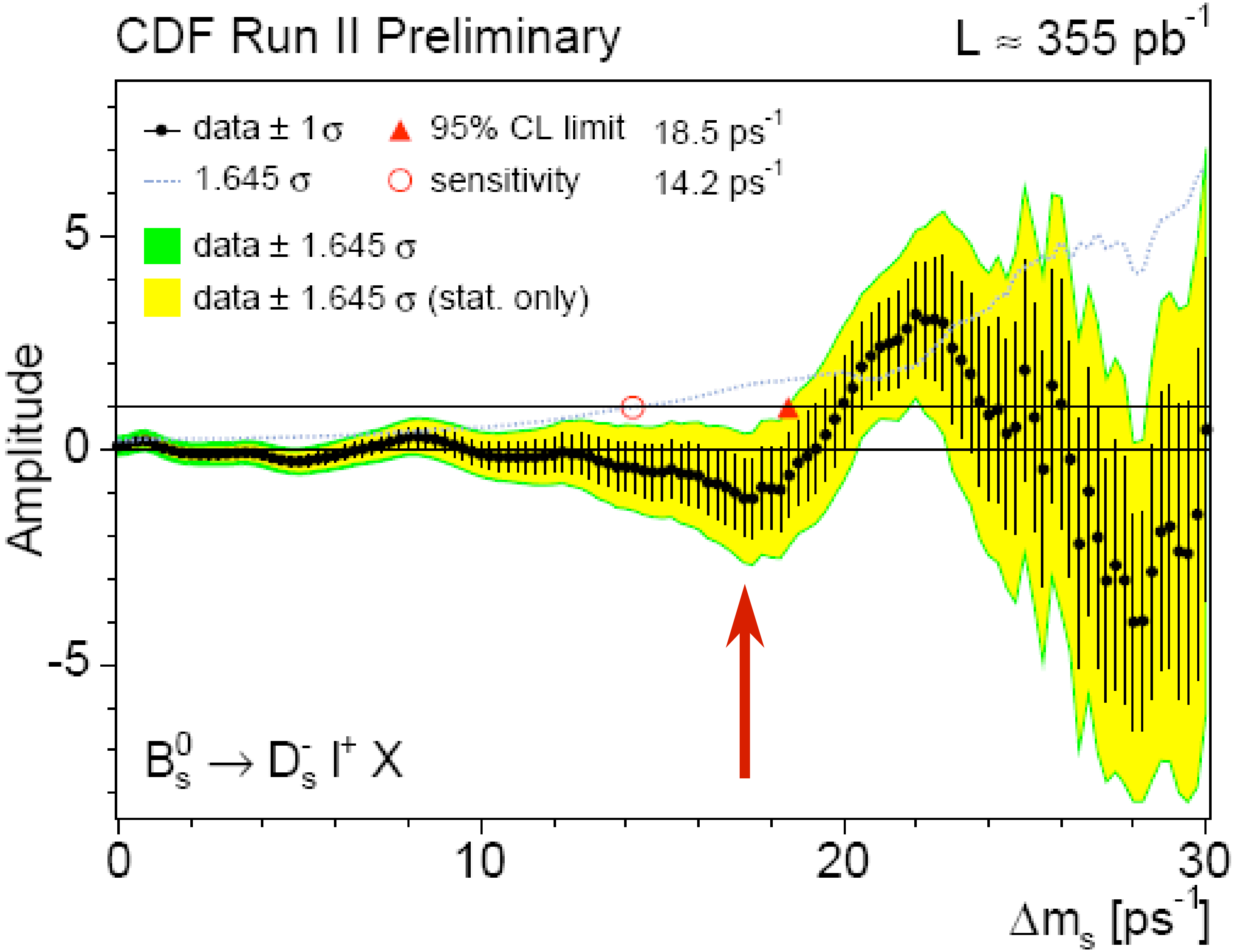
Amplitude Scan: Hadronic Period 2



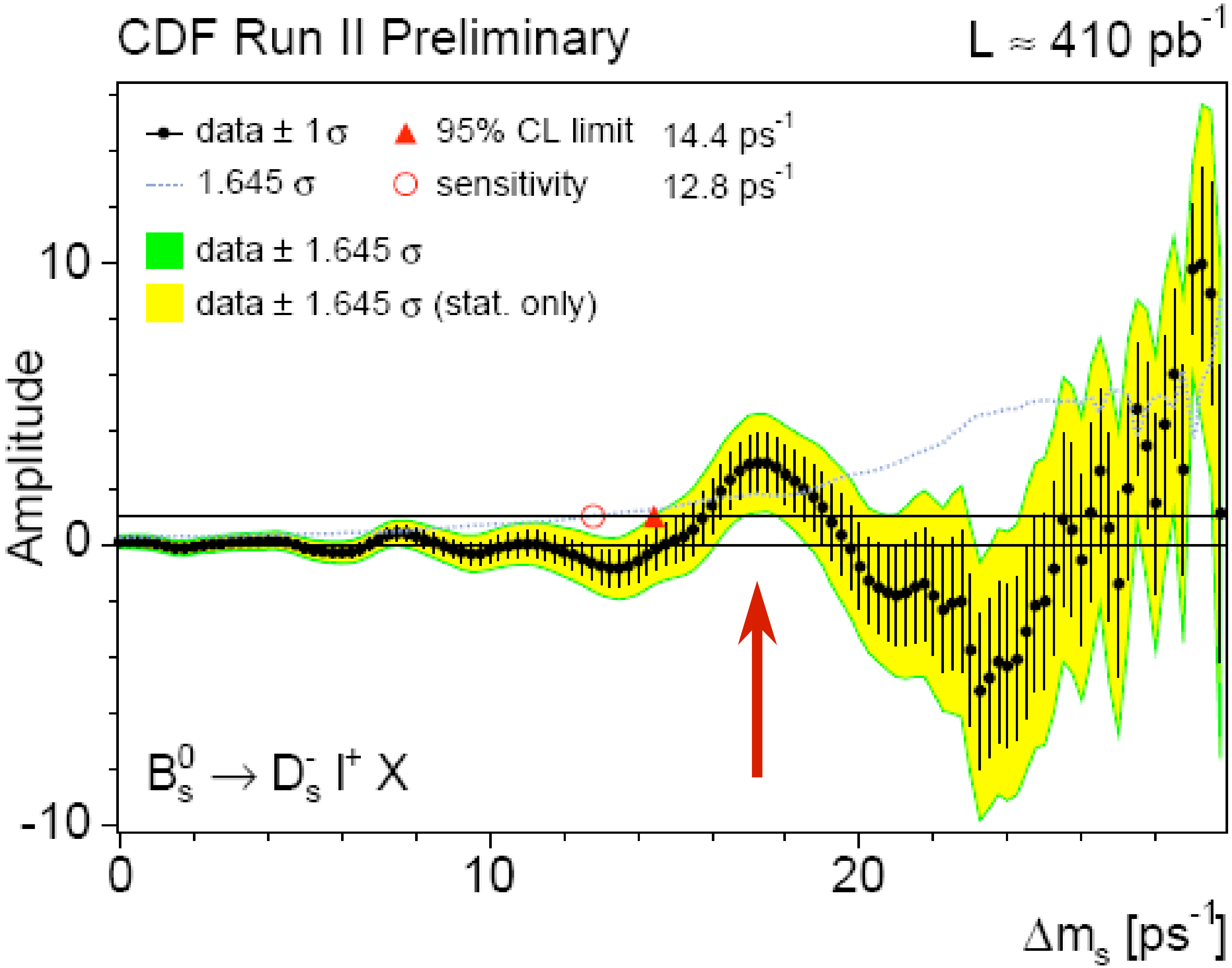
Amplitude Scan: Hadronic Period 3



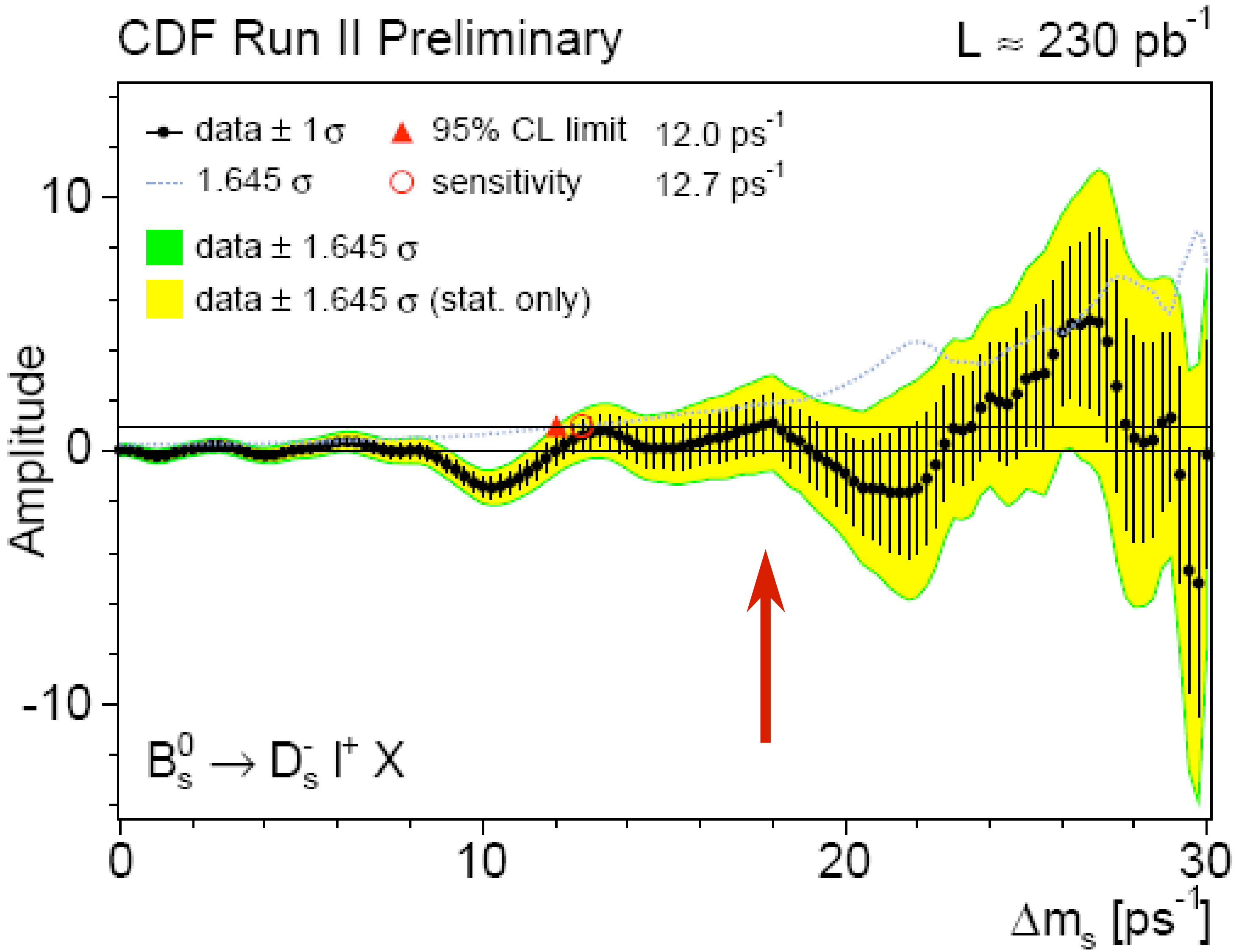
Semileptonic Scan: Period 1



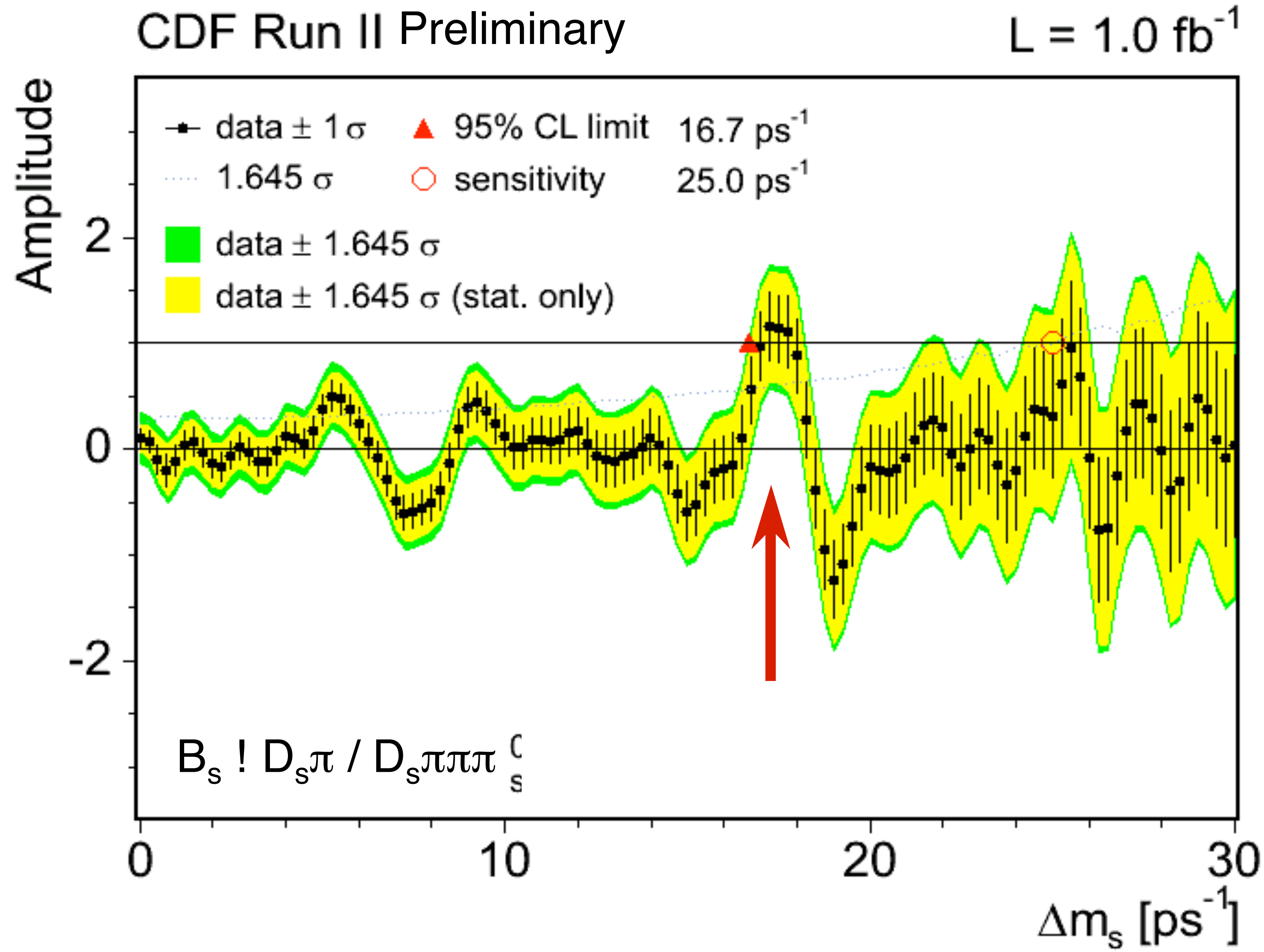
Semileptonic Scan: Period 2



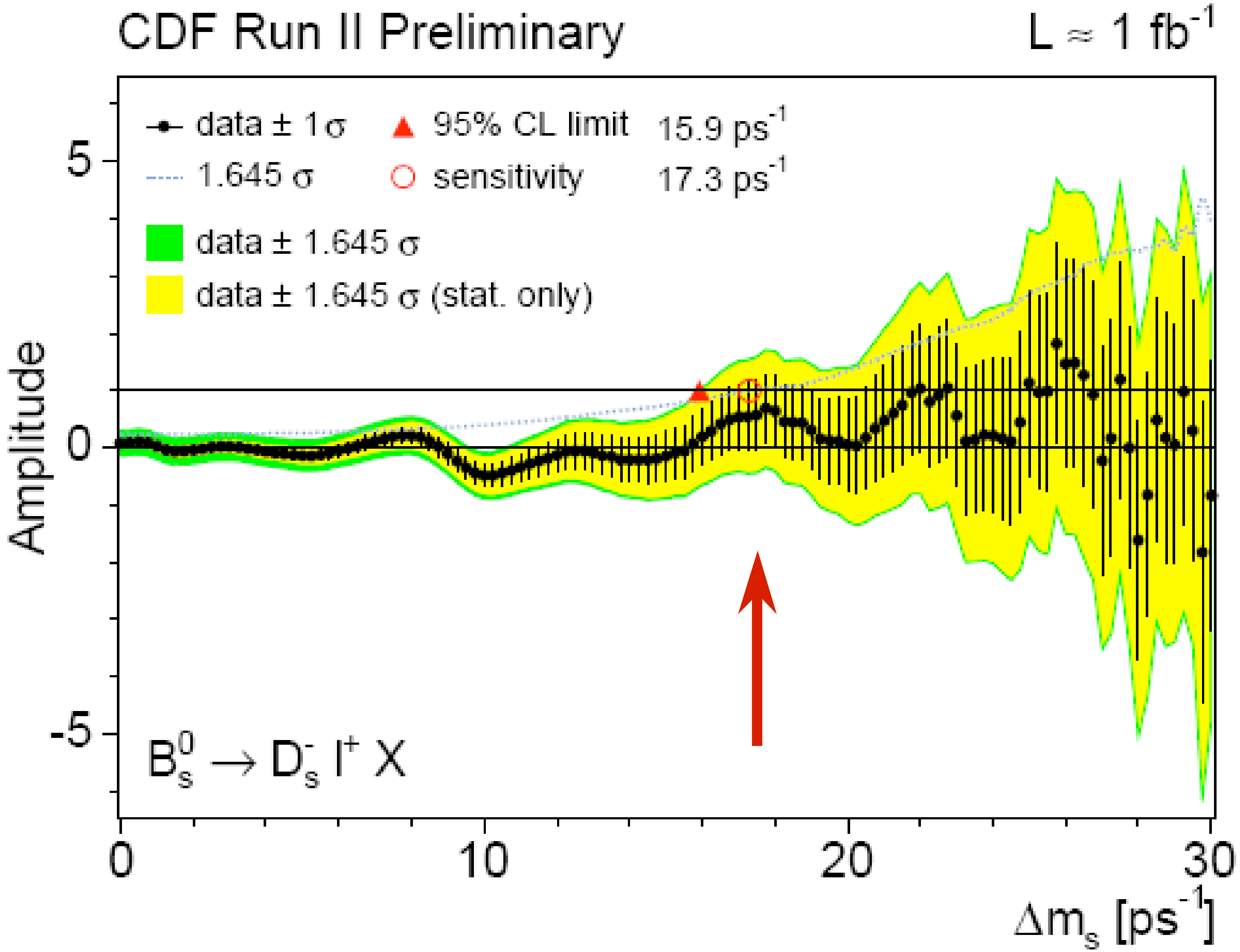
Semileptonic Scan: Period 3



Hadronic Scan: Combined



Semileptonic Scan: Combined

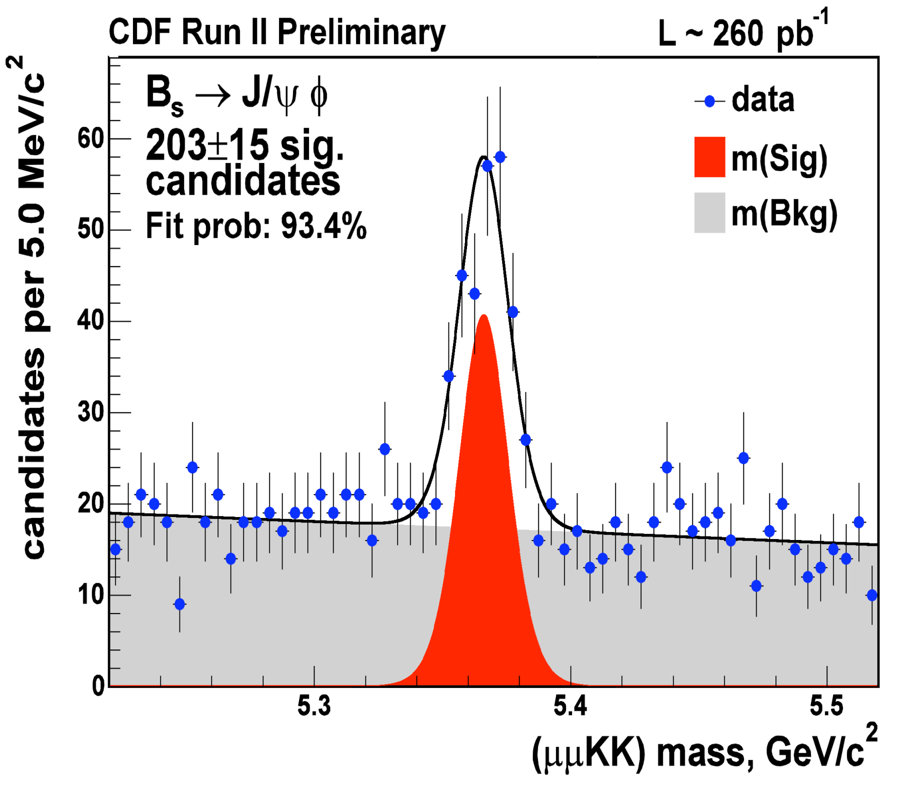


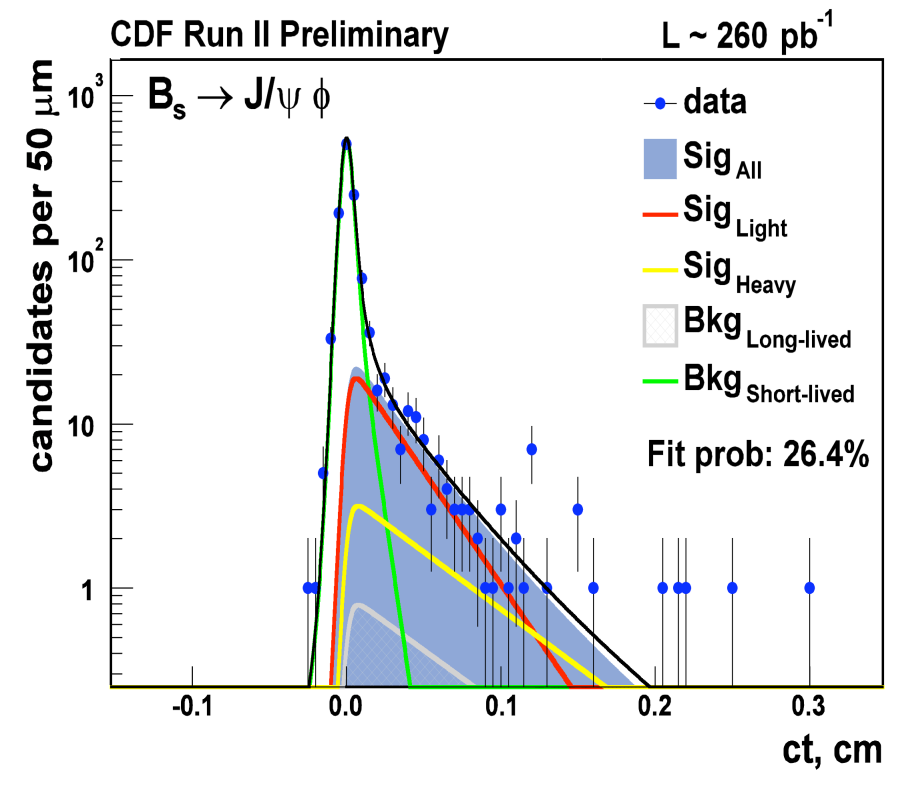
測定法２

厳密には2成分必要

$$確率分布\ P(t) = \frac{f_L}{\tau_L} e^{-t/\tau_L} + \frac{1-f_L}{\tau_S} e^{-t/\tau_S}$$

$$f_L = |A_\perp|^2 = 0.125 \pm 0.019$$



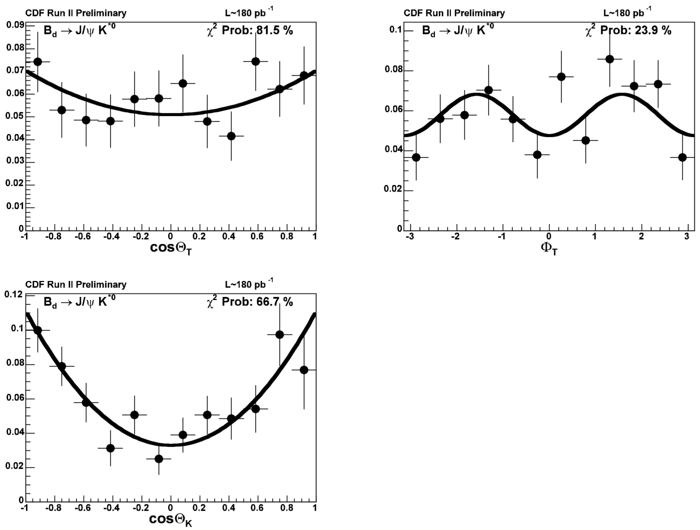


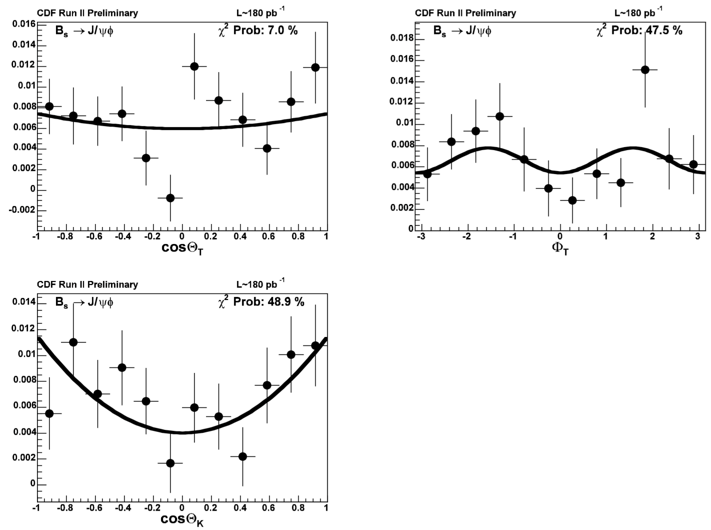
$$\tau_S = 1.05 \pm 0.15\ \text{ps},\ \tau_L = 2.07 \pm 0.52\ \text{ps}.$$

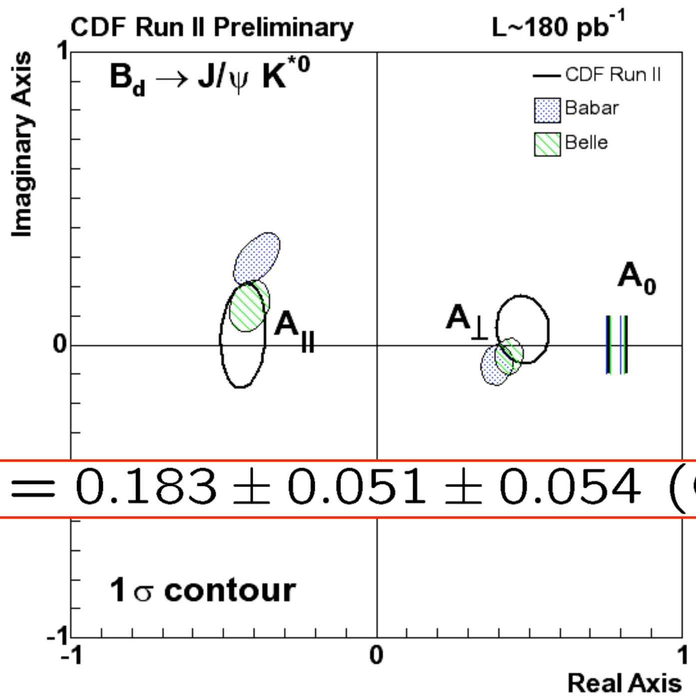
$$\Leftrightarrow\ \tau = 1.40 \pm 0.14\ \text{ps},\ (\Delta\Gamma/\Gamma)_s = 0.65^{+0.25}_{-0.33}.$$

$B^0 \to J/\psi\, K^{*0}$ and $B_s^0 \to J/\psi\, \phi$ polarizations

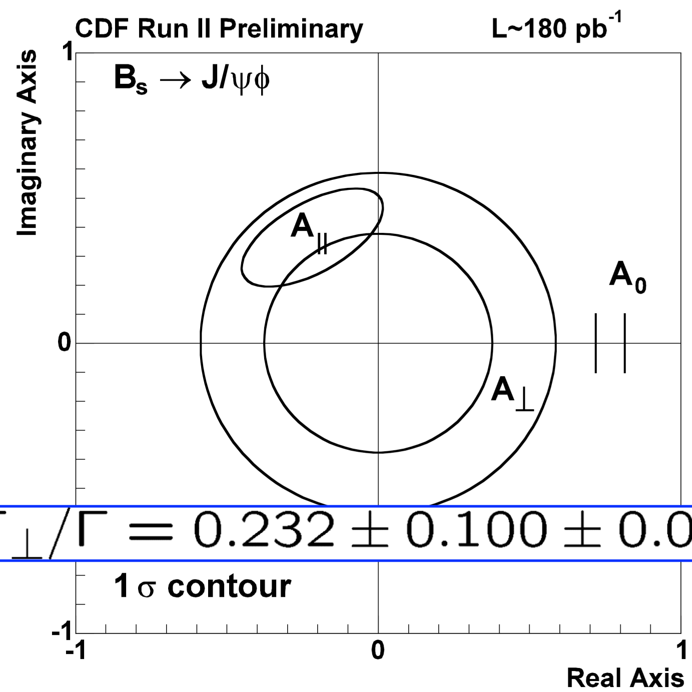
CDF







$$\Gamma_\perp/\Gamma = 0.183 \pm 0.051 \pm 0.054 \ \text{(CDF)}$$



$$\Gamma_\perp/\Gamma = 0.232 \pm 0.100 \pm 0.013$$

Probing angle γ (phase of V_{ub})

- $B^0 \rightarrow \pi^+ \pi^-$ once thought to be the mode for $\sin 2(\pi-\gamma-\beta)$.

  (assuming $b \rightarrow u$ tree dominance over penguin)
- CLEO finds much larger $K^- \pi^+$ and tiny $\pi^+ \pi^-$.
- Not just small rates, but also means penguin pollution.

  $\rightarrow$ Relation to $\sin(2\alpha)$ less clear.
- Strategies proposed, but are challenging experimentally...

New approach : R. Fleischer, Phys. Lett. B 459, 306 (1999).
Throw in $B^0_s \rightarrow K^+ K^-$, measure asymmetries in both B^0 and B^0_s.

In general, for a decay $B^0 \rightarrow f$ (f = CP eigenstate) :

$$A_{CP}(t) = A^{dir} \cos(\Delta m t) + A^{mix} \sin(\Delta m t).$$

A^{dir} : "direct" CP violation, A^{mix} : CP violation thru mixing.
Experimentally, measure 4 A's from $B^0 \rightarrow \pi^+ \pi^-$ and $B^0_s \rightarrow K^+ K^-$.
Then extract β, γ and penguin and tree decay amplitudes.

Angle γ (phase of V_{ub}) continued

Four CP asymmetries to measure. ($\lambda = \sin\theta_c$)

- $A^{dir}(B^0 \to \pi^+\pi^-) = -2d\sin\theta\sin\gamma \,/\, (1 - 2d\cos\theta\cos\gamma + d^2)$
- $A^{mix}(B^0 \to \pi^+\pi^-) = [\,\sin 2(\beta+\gamma) - 2d\cos\theta\sin(2\beta+\gamma) + d^2\sin 2\beta\,]$
  $/\,[1 - 2d\cos\theta\cos\gamma + d^2\,]$
- $A^{dir}(B^0_s \to K^+K^-) \sim 2(\lambda^2/d)\sin\theta\sin\gamma$
- $A^{mix}(B^0_s \to K^+K^-) \sim 2(\lambda^2/d)\cos\theta\sin\gamma$

If no penguin,
$A^{dir} = 0$ (B^0, B^0_s)
$A^{mix} = \sin 2(\beta+\gamma)$ (B^0)
$A^{mix} = \sin(2\gamma)$ (B^0_s)

Four unknowns to extract :

- β, γ = angles of the unitarity triangle.
- d = ratio of penguin *(P)* to tree *(T)* decay amplitudes,
  θ = phase of "*P/T*"
  $d\,e^{i\theta} \equiv \lambda|V_{cb}/V_{ub}| \,/\, (1-\lambda^2/2)\,[\,P/(T+P)\,]$

Expect ~5 k $B^0 \to \pi^+\pi^-$, ~10 k $B^0_s \to K^+K^-$
$\to$ angle γ to ~10°.

Tree | Penguin