あるいは
第3世代クォークのフレイバー物理

- B_s^0-$\bar{B}_s^0$ oscillations
- $B \to PP \quad (P \equiv \pi^{\pm},\ K^{\pm})$
- その他

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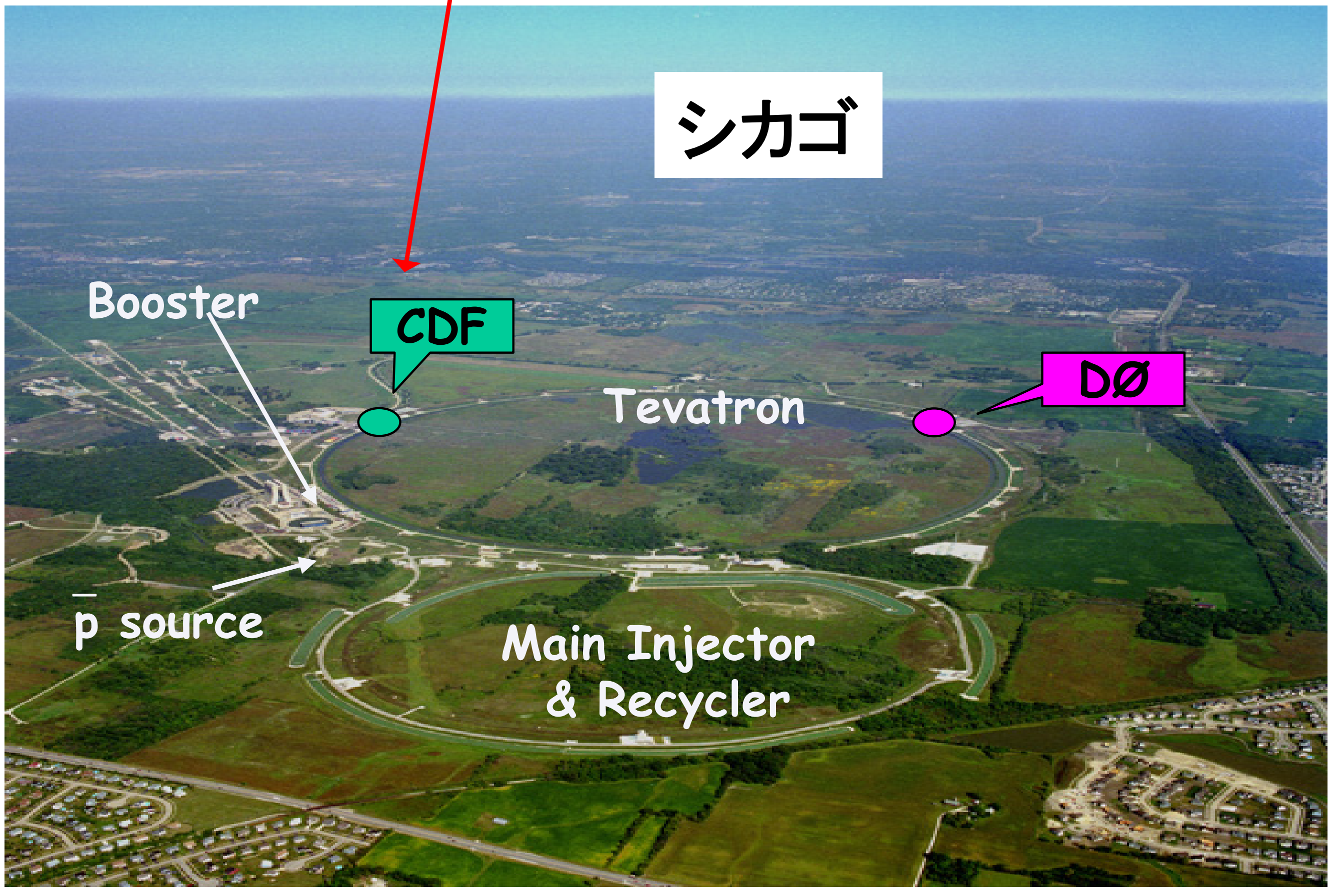
March 16 - 17, 2007

Fermilab Tevatron

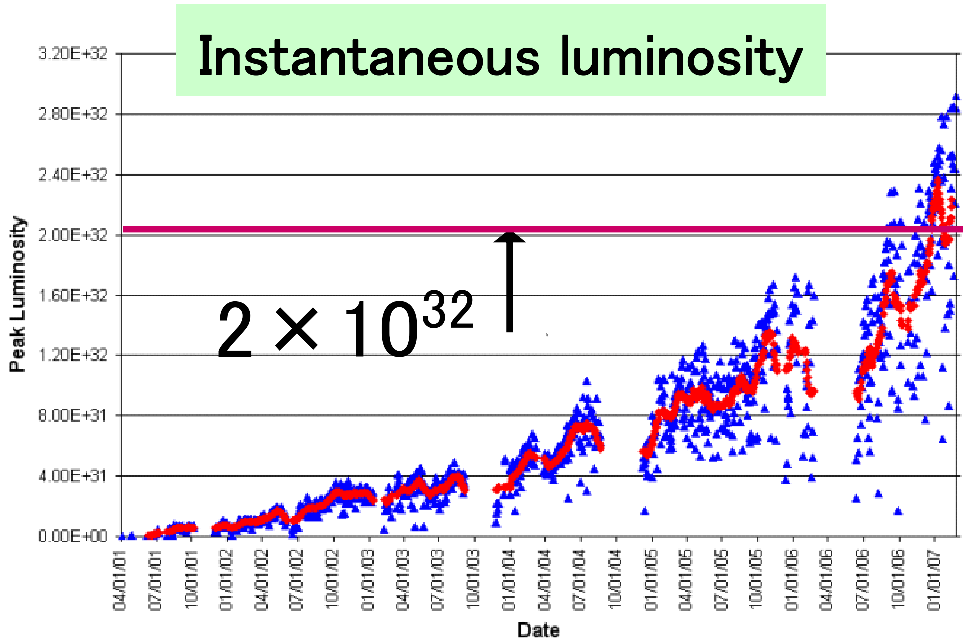
- New 120/150 GeV Main Injector replaced Main Ring
  - Higher intensity of protons and antiprotons.
- Tevatron operates with 36 x 36 bunches (had been 6 x 6)
- Increased CM energy 1.8 TeV to 1.96 TeV

at B0 interaction point

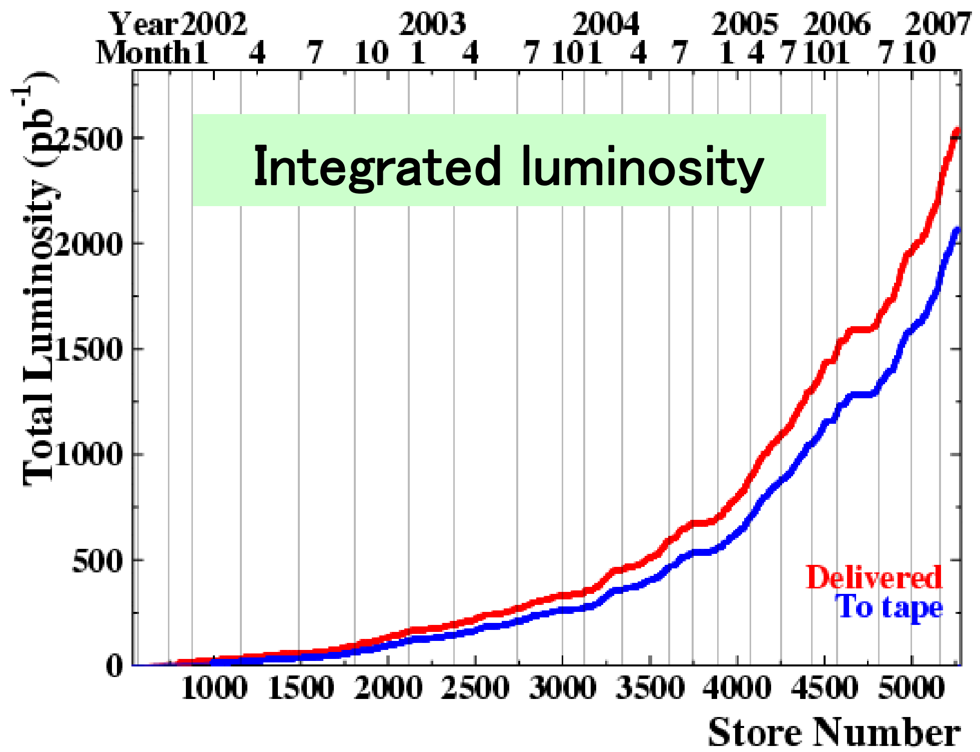


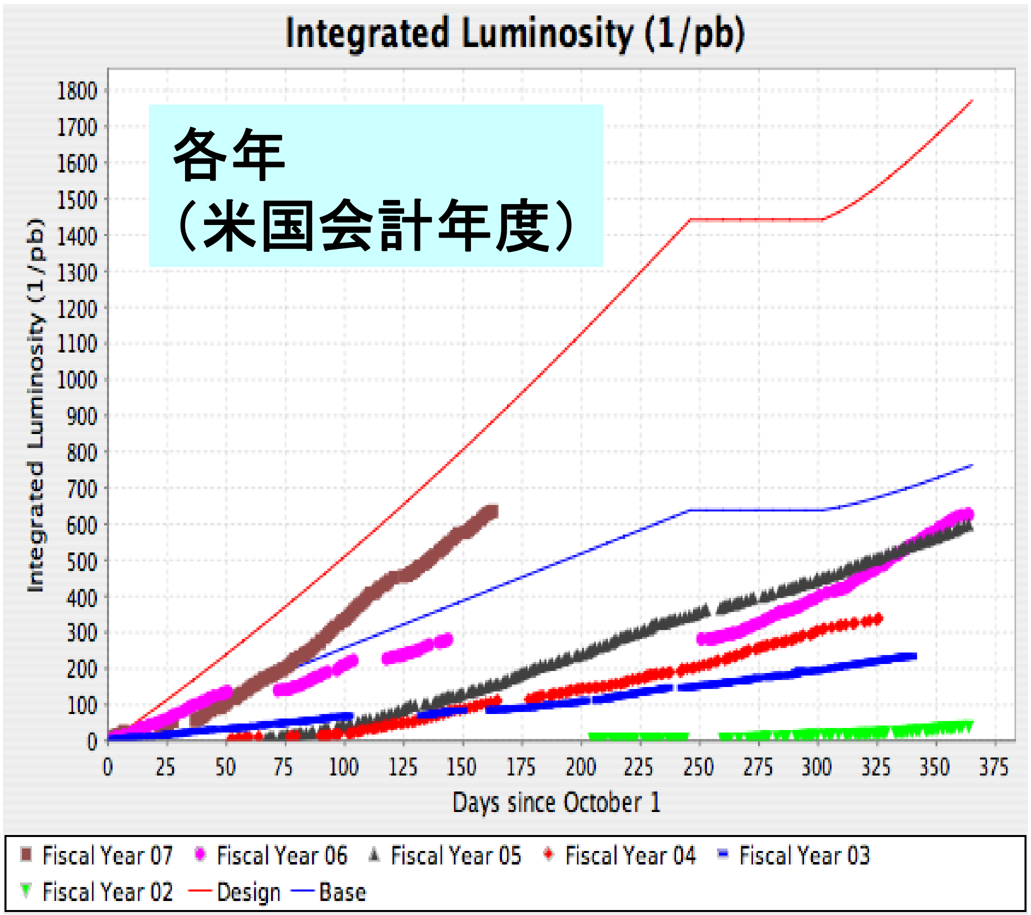
Run II started in March 2001

Tevatron performance : Run-II

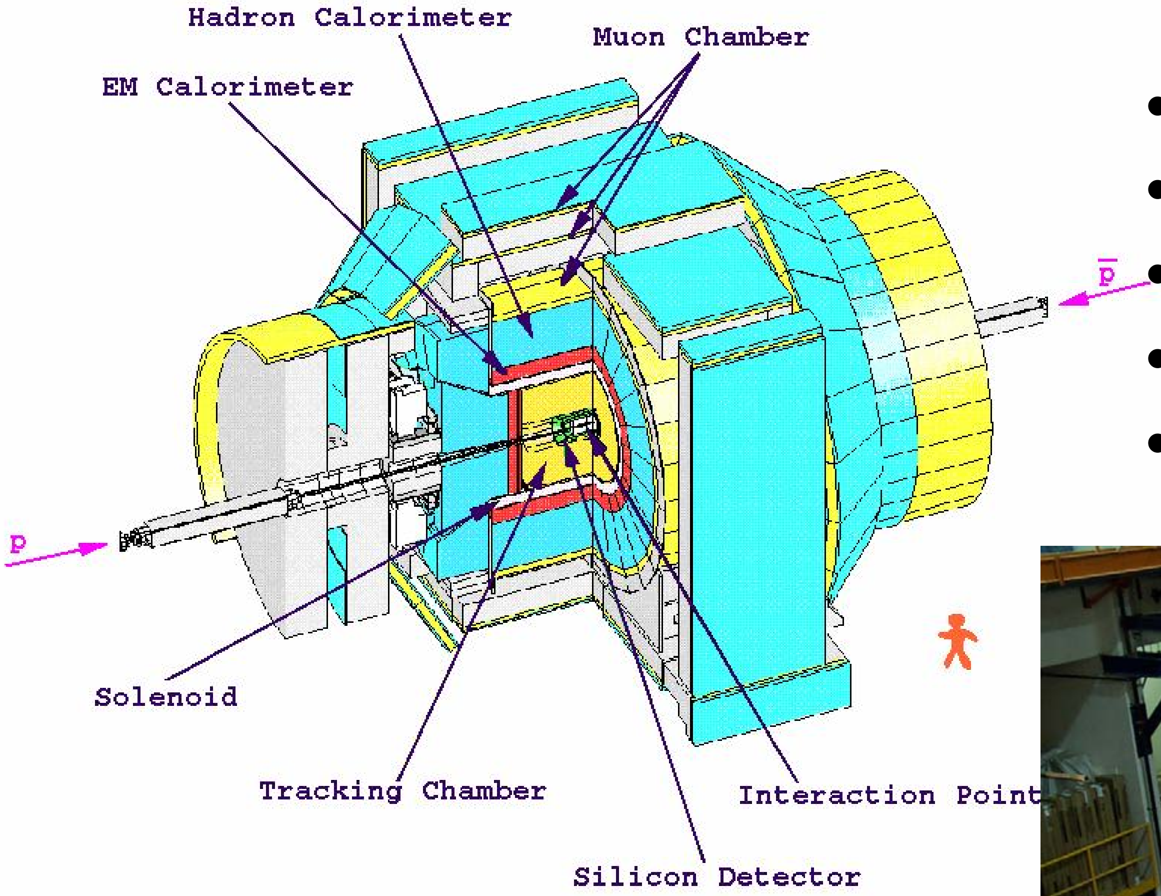


- Highest peak luminosity
  $2.92 \times 10^{32}\ cm^{-2}\ s^{-1}$
  (Feb 27, 2007)
- Delivered luminosity
  $\sim 2.5\ fb^{-1}$
- Recorded luminosity
  $\sim 2.1\ fb^{-1}$

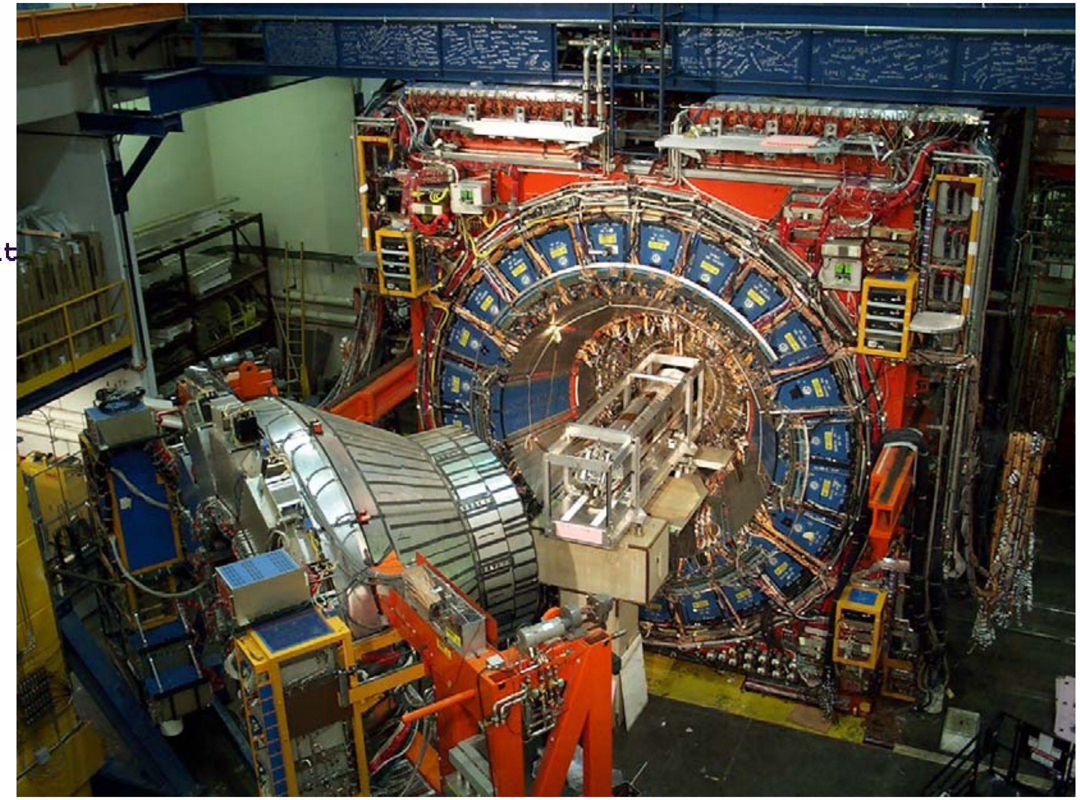




Run-II CDF Detector



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

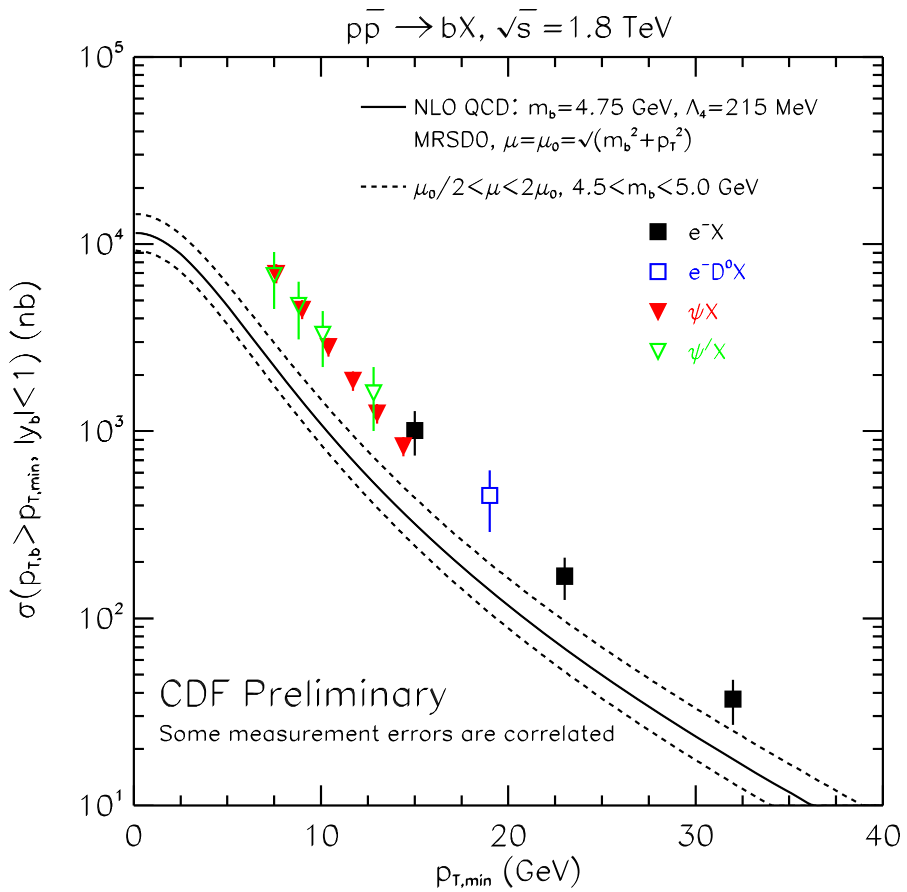


Good lepton ID capabilities
Excellent tracking (large solenoid)
High-rate DAQ w/ Si trigger

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.



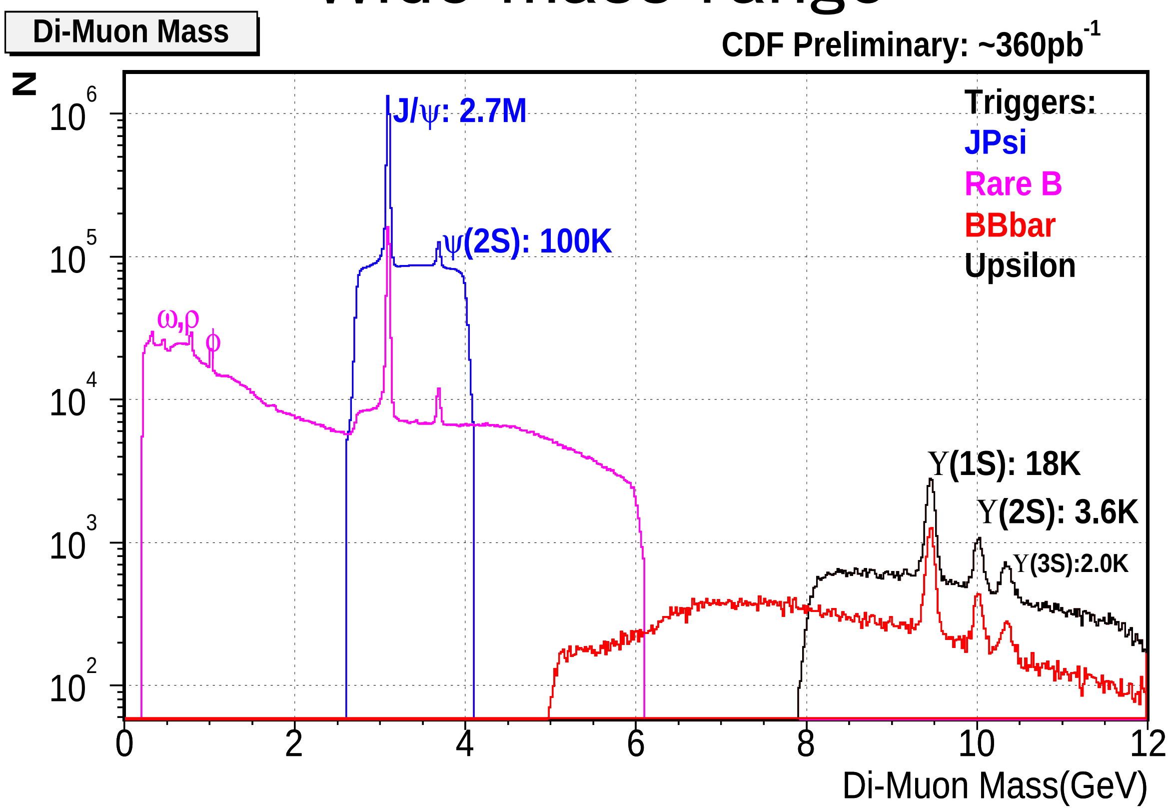
To utilize these fatures, need to trigger them efficiently :

- 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)

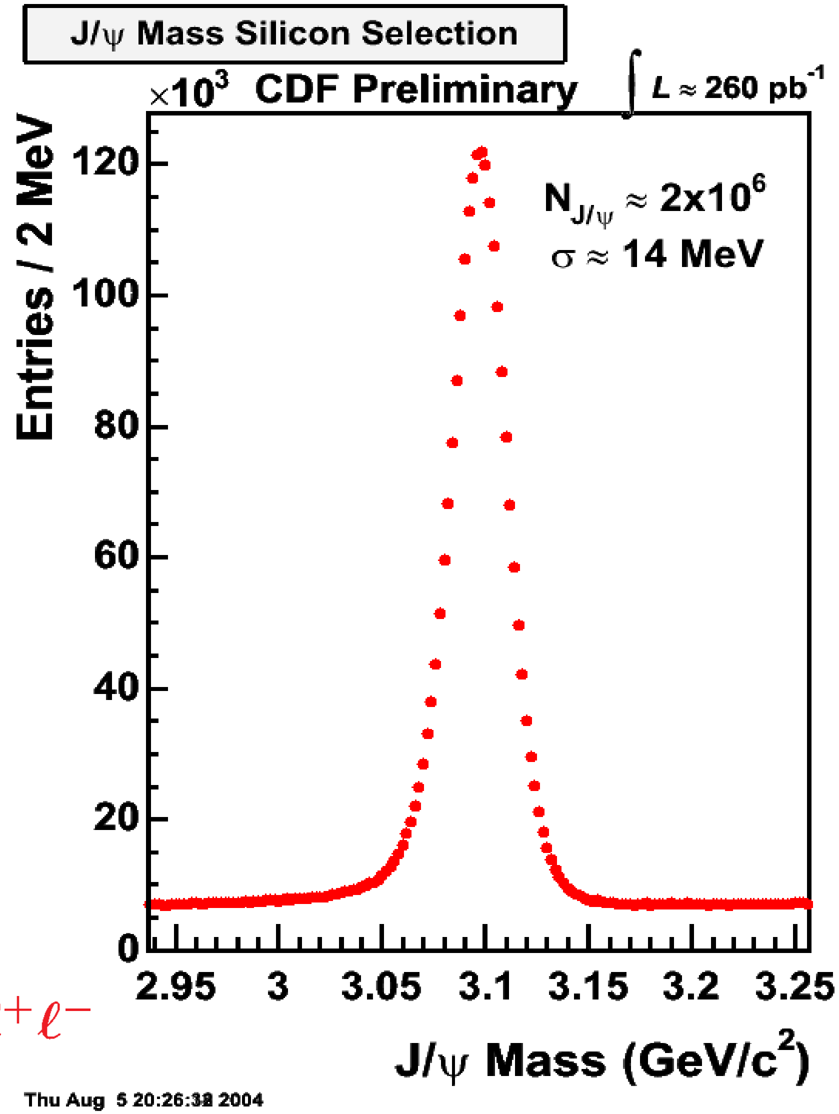
  $\Rightarrow$ can collect all-hadronic final states

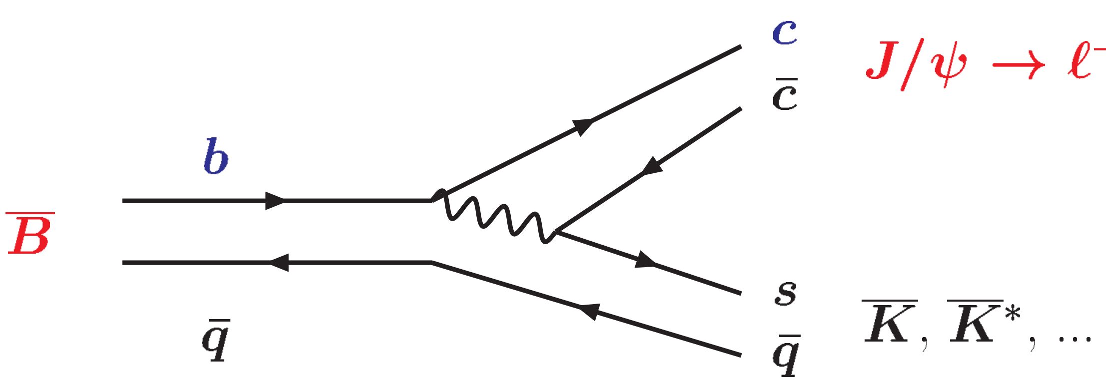
CDF di–muon triggers

Wide mass range



Near J/ψ

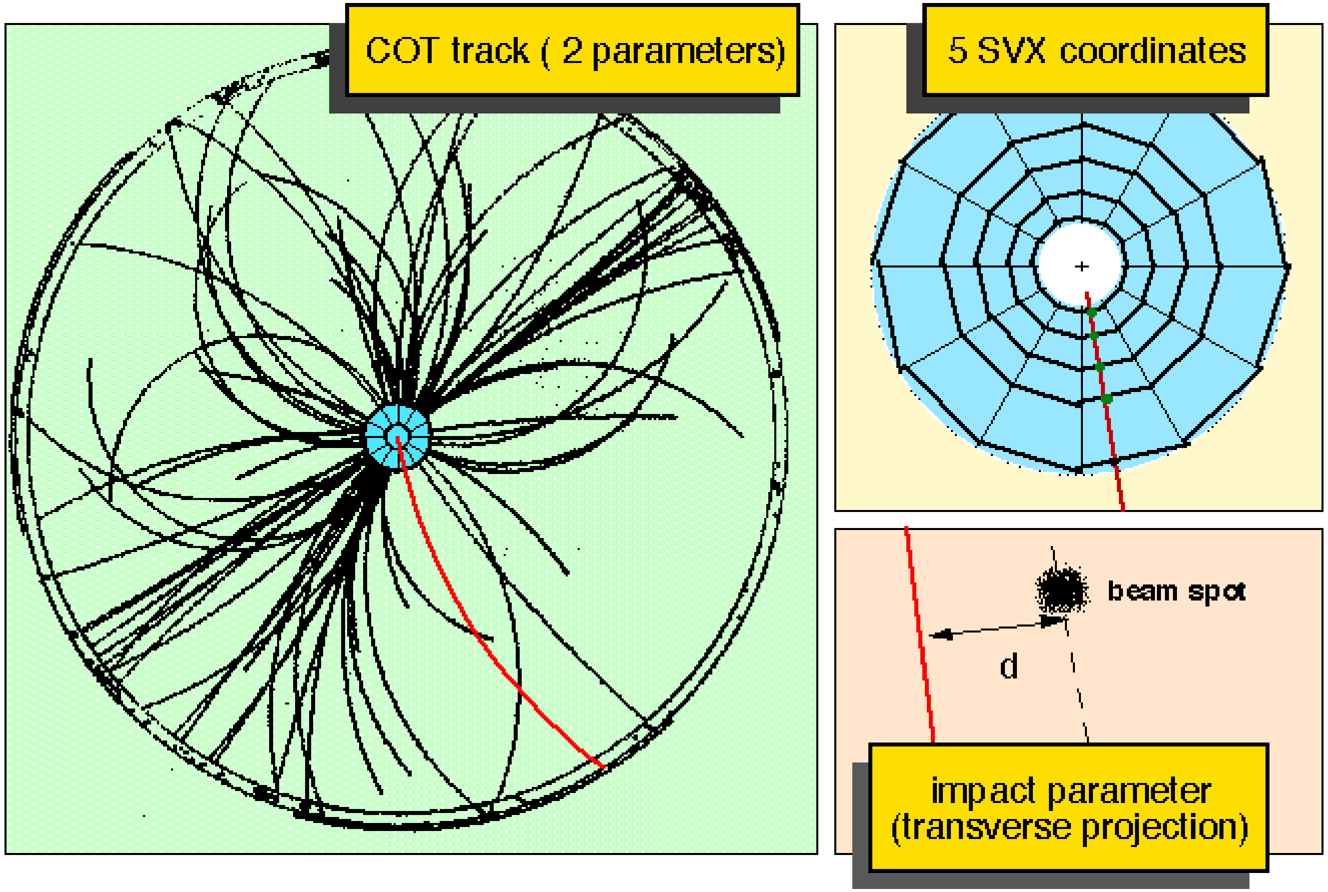




~15% from *B* decays

Run-II Silicon Vertex Trigger : SVT

Use silicon information at the 2nd level of trigger

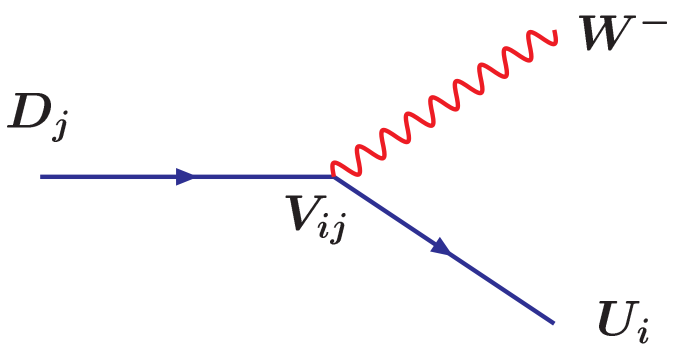


- Find a track in the main tracker COT.
- Extrapolate toward the SVX.
- Find SVX hits along the road.
- Calculate impact parameter wrt the primary vertex (beam spot).
- Resolution ~50 μm for > 2 GeV/c.

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

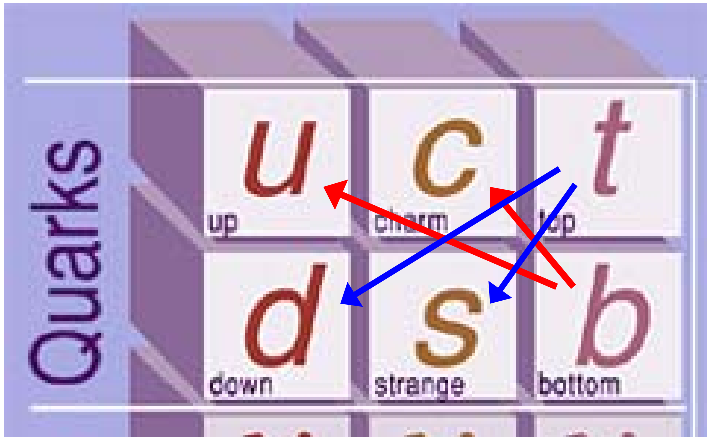
B Physics

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

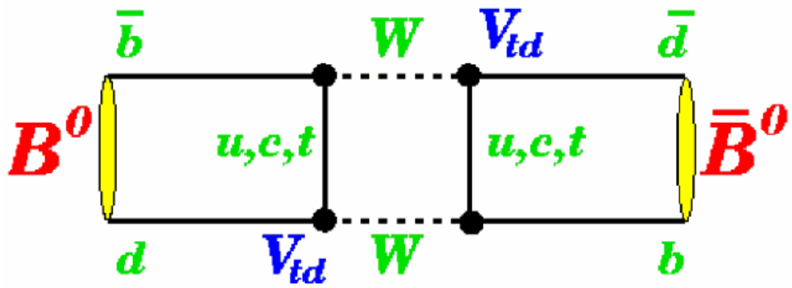


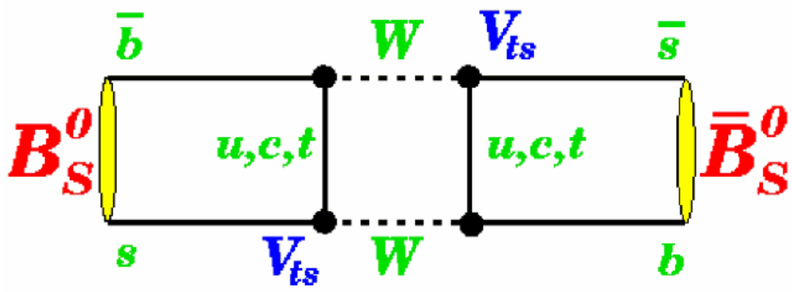
$$D' \equiv \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$\Rightarrow$ Quark flavors are not always conserved, e.g. $b \to c$ and $t \to s$ transitions occur at the first order ($|\Delta B| = |\Delta T| = 1$).

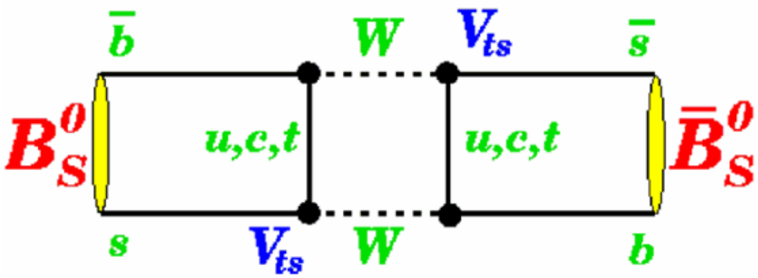


- At the second order, $\Delta B = 2$ transitions can happen.
- B_d^0-$\bar{B}_d^0$ and B_s^0-$\bar{B}_s^0$ oscillations ! Top quark dominant in the loop.
- B physics is sometimes top flavor physics.





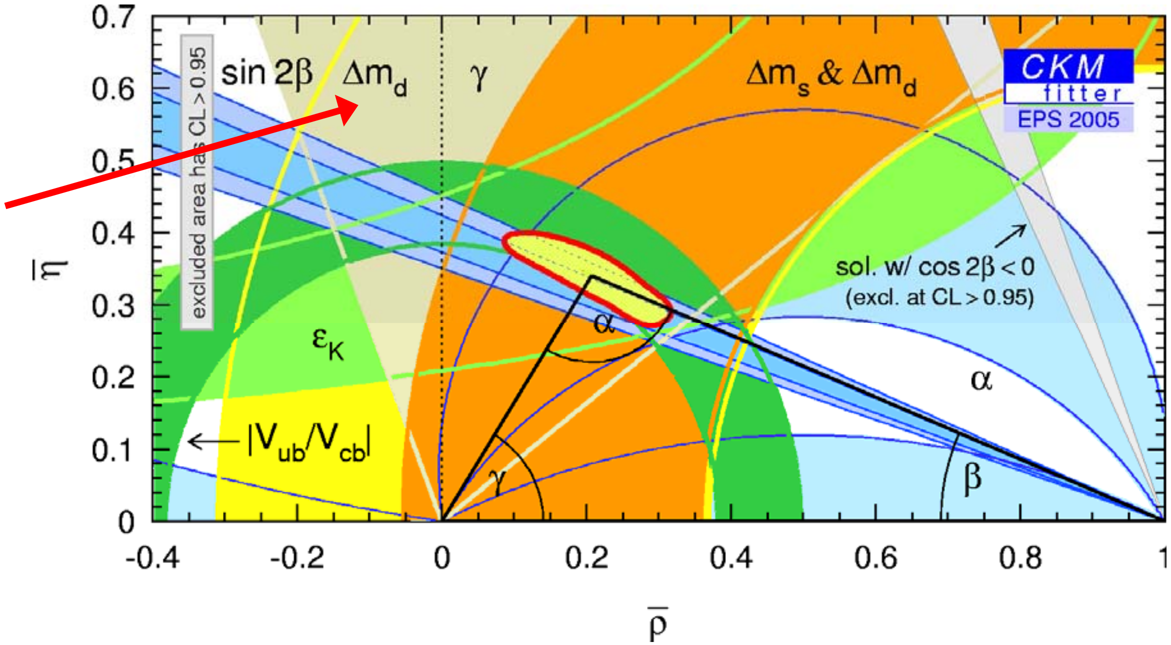
B_q^0-$\bar{B}_q^0$ oscillations $(q \equiv d,\ s)$



$$\Delta m_q = \frac{G_F^2}{6\pi^2} |V_{tb}V_{tq}^*|^2\, m_W^2\, m_B\, f_B^2\, B_B\, \eta_B\, S\left(\frac{m_t}{m_W}\right)$$

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

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.

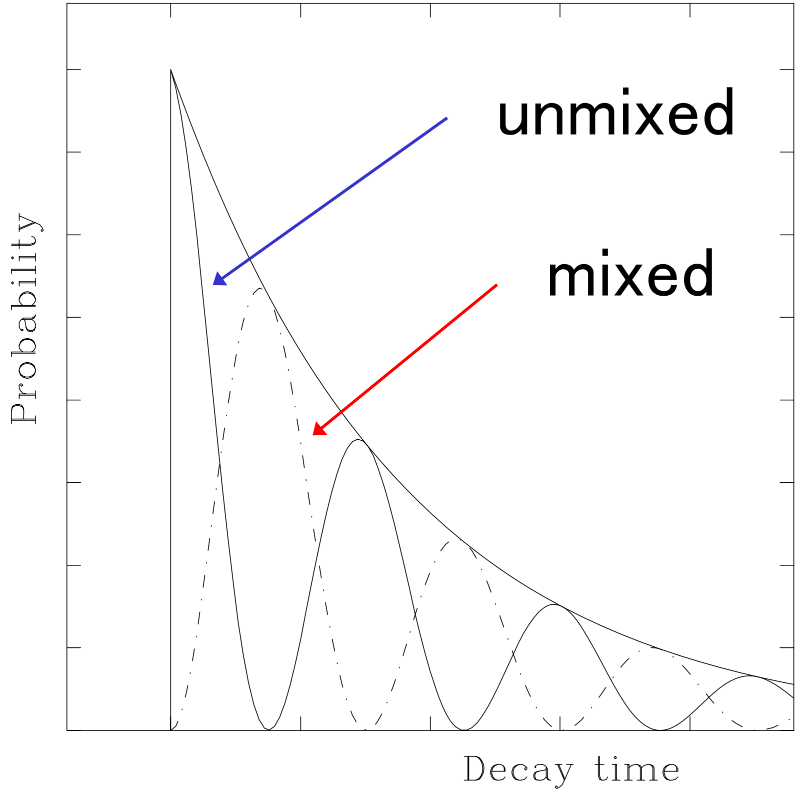
$$\xi \equiv \frac{\sqrt{B_{B_s}}\, f_{B_s}}{\sqrt{B_{B_d}}\, f_{B_d}} = 1.210\,^{+0.047}_{-0.035} \quad \texttt{(Okamoto, hep-lat/0510113)}$$

4%

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

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

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



Analysis steps

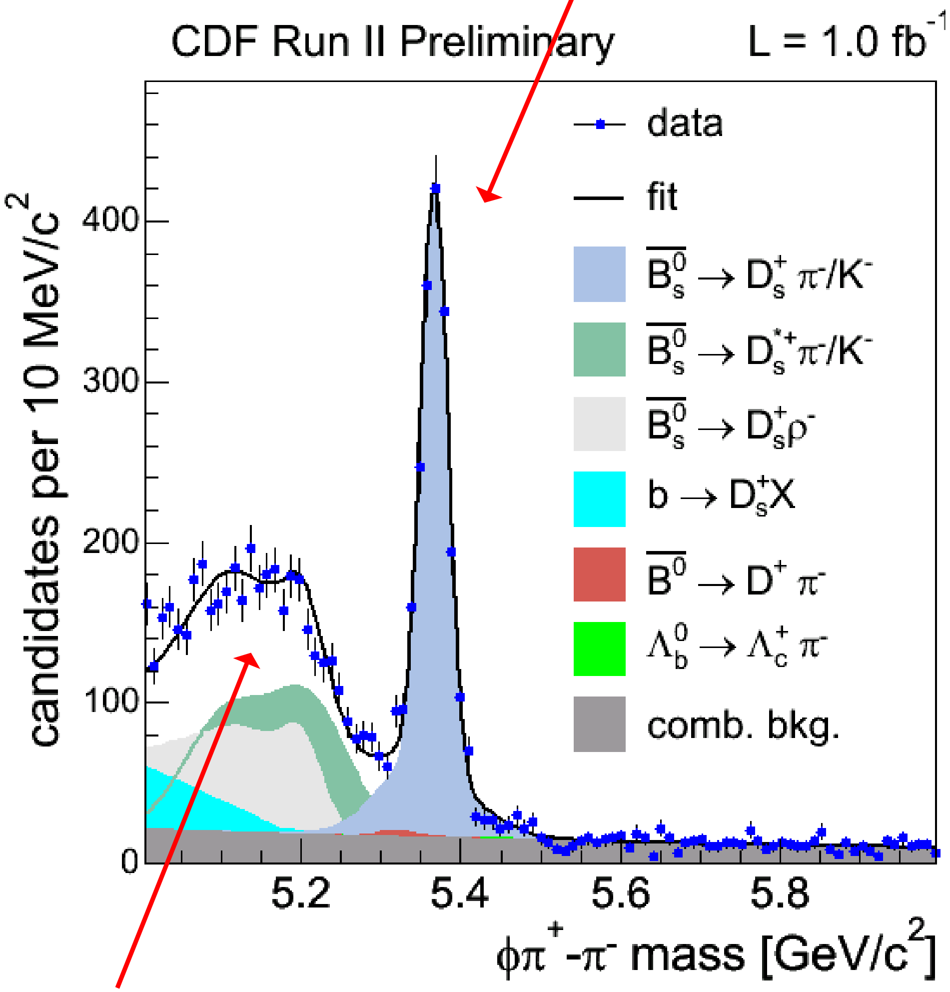
- Reconstruct B meson decay with flavor-specific final state, such as $\bar{B}_d^0 \to D^+(n\pi)^-$ and $\bar{B}_d^0 \to \ell^- \bar{\nu} D^{*+}$.
- Measure decay length L and momentum p
- Extract proper decay time $t = \frac{L/c}{\beta\gamma} = L\frac{m}{p}$
- Determine the initial flavor, B_q^0 or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

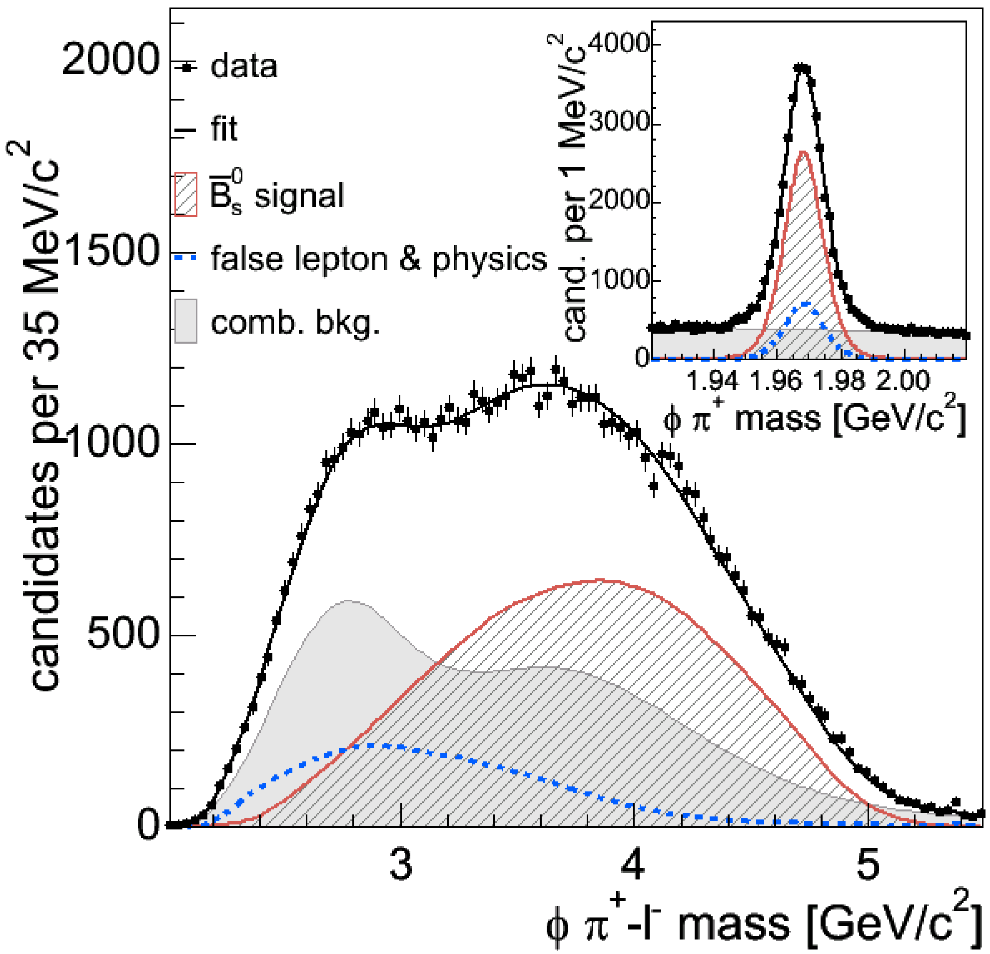
$\bar{B}_s^0$ signals, 1 fb^{-1}

Silicon trigger crucial

Hadronic : $\bar{B}_s^0 \to D_s^+ \pi^-$

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





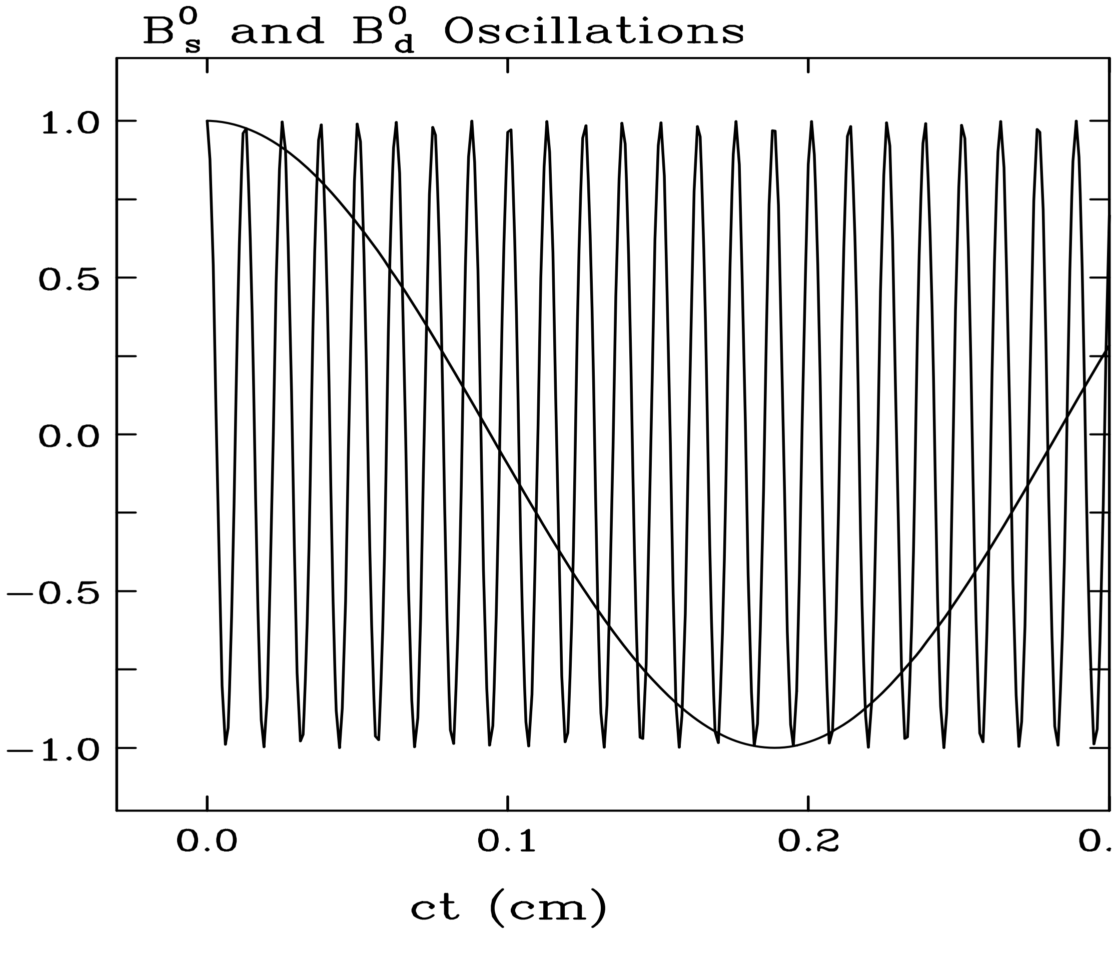
Partially reconstructed :

$\bar{B}_s^0 \to D_s^{*+} \pi^-$, $\bar{B}_s^0 \to D_s^+ \rho^-$ (γ/π^0 missing)

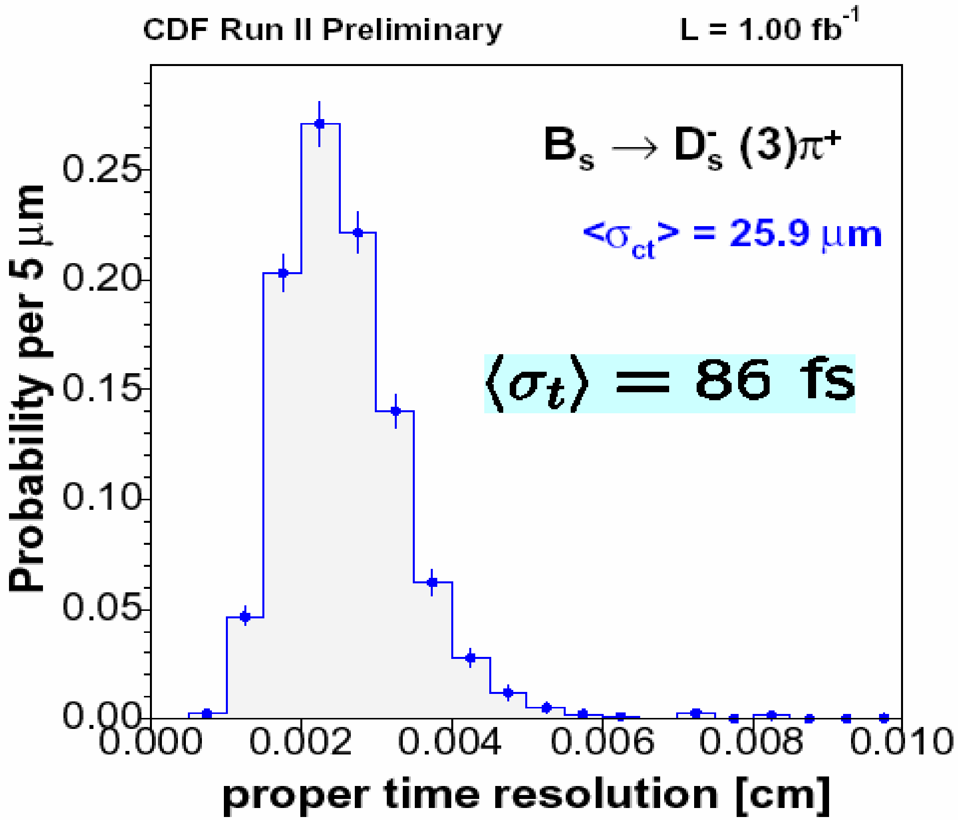
One of the challenges : resolving very quick oscillations

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

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



Proper time resolution
Real data, hadromic mode

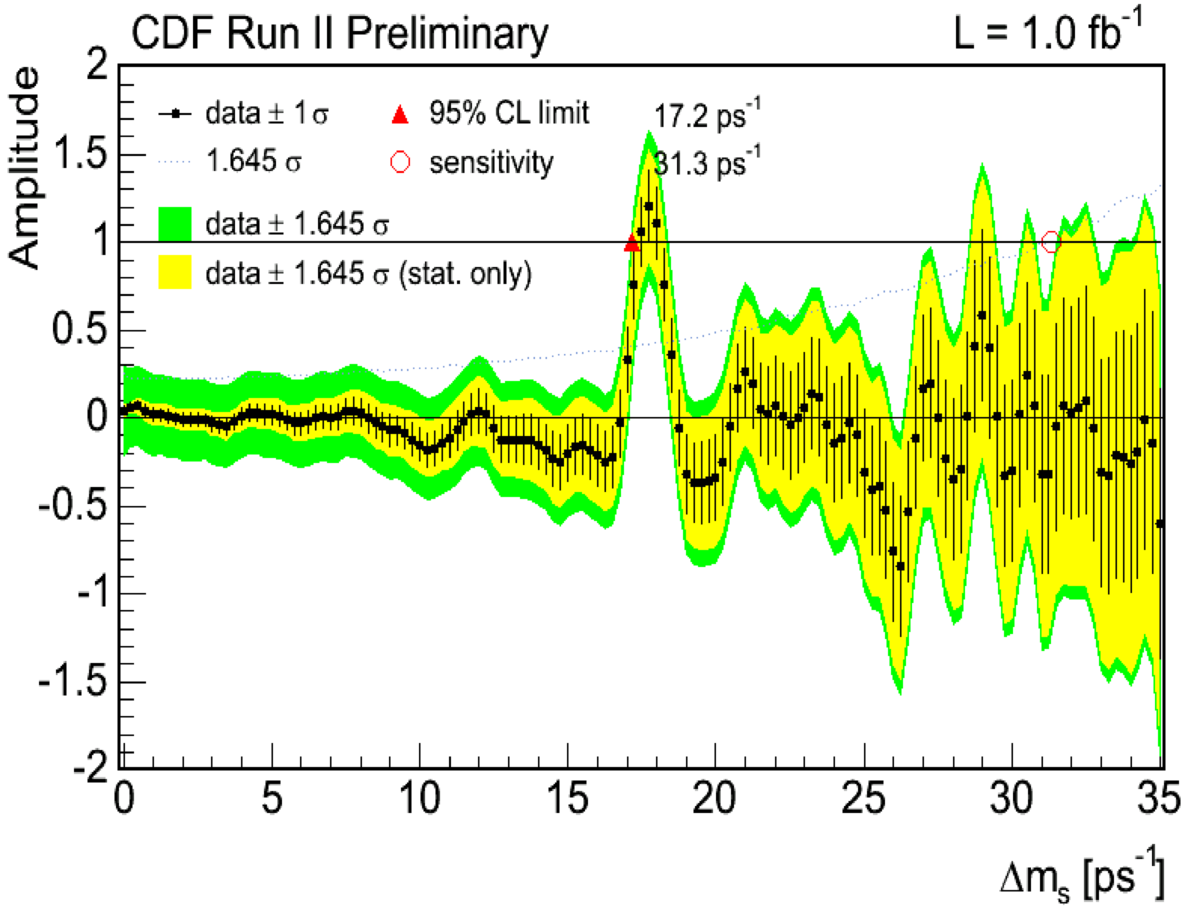


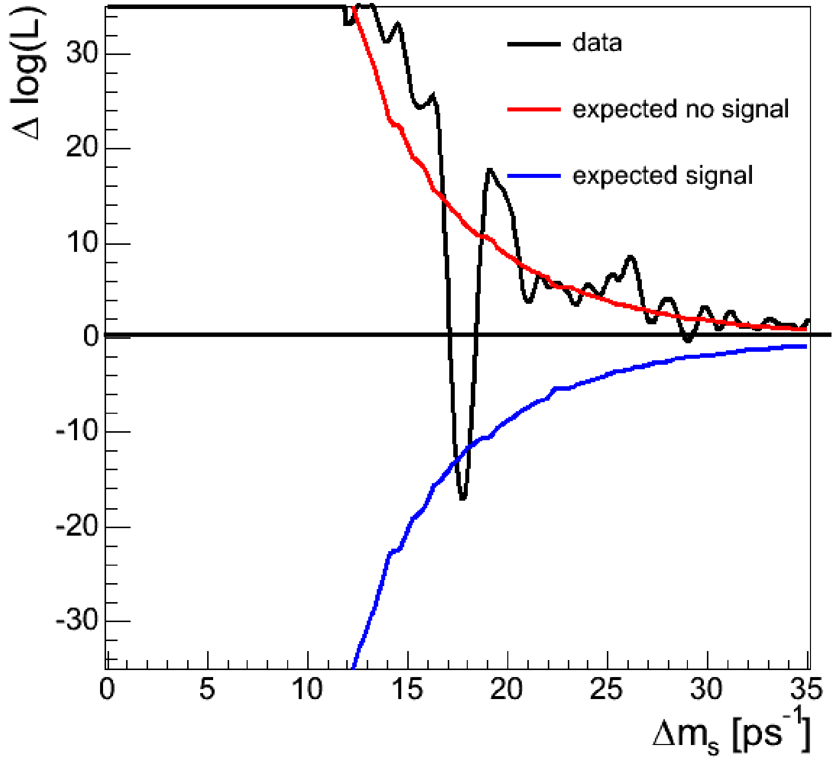
Roughly 20 times better than Belle/BaBar

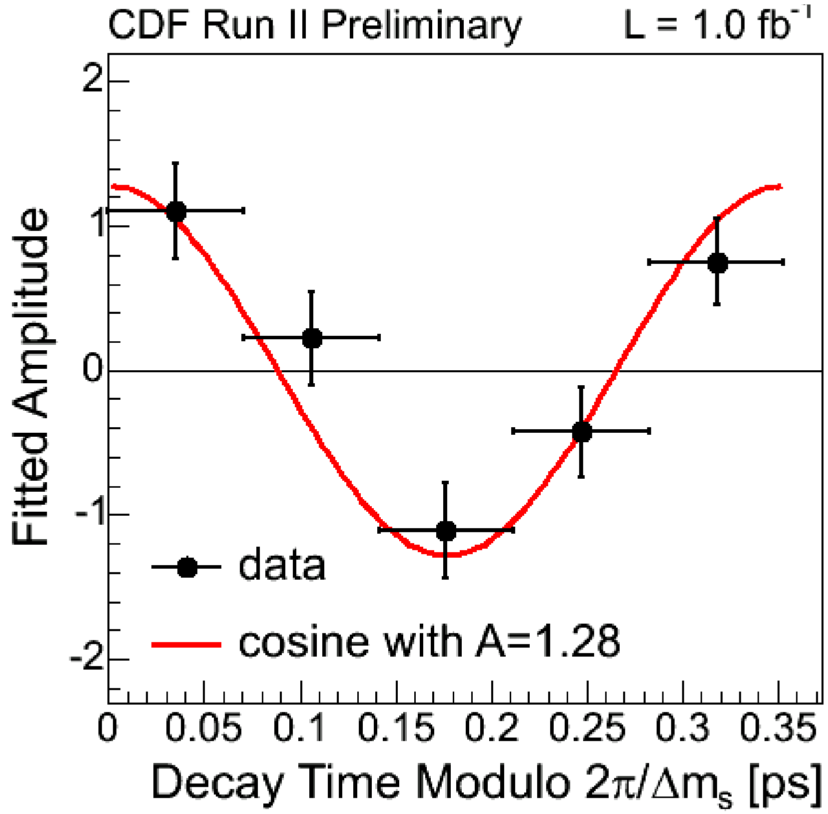
$\bar{B}_s^0$-$\bar{B}_s^0$ oscillations : analysis

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

$\mathcal{A} = 1$ if oscillating, $\mathcal{A} = 0$ if not.



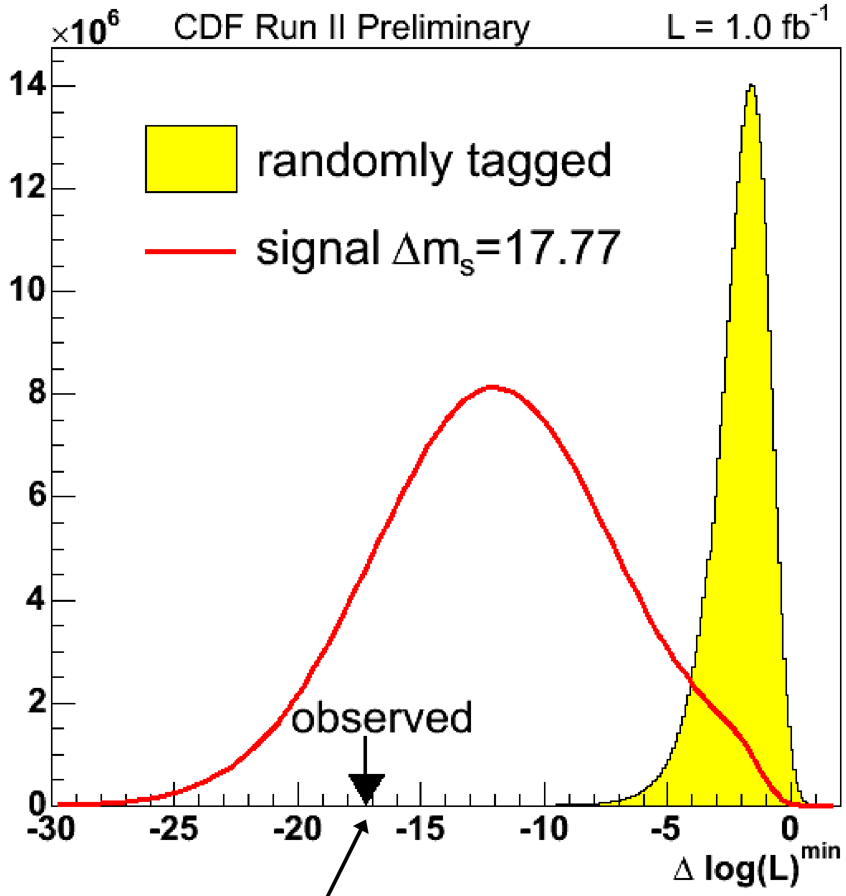




Could have excluded up to 31 ps^{-1}, if it were not there.

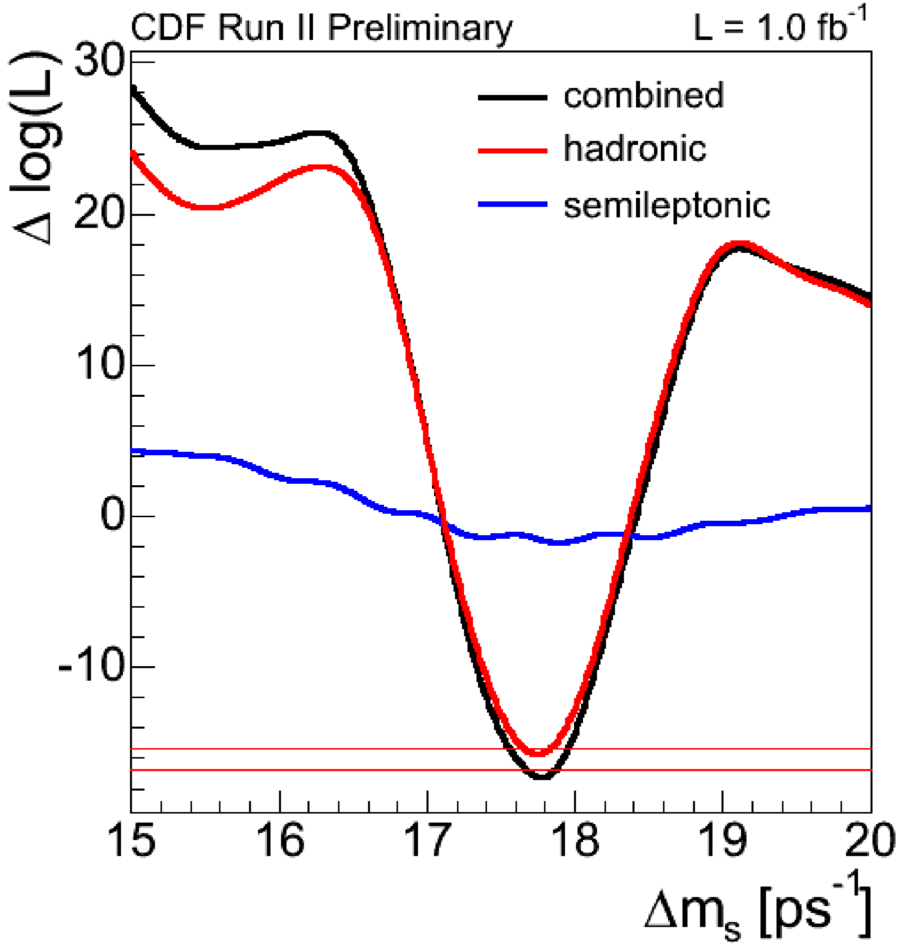
$\bar{B}_s^0$-$\bar{B}_s^0$ oscillations : analysis (cont'd)

Δ ln(L) の深さ



確率 8×10^{-8}, $> 5\sigma$

Likelihood dist.（拡大図）



$$\Delta m_s = 17.77 \pm 0.10 \pm 0.07 \ \mathrm{ps}^{-1}$$

Impact on the unitarity triangle

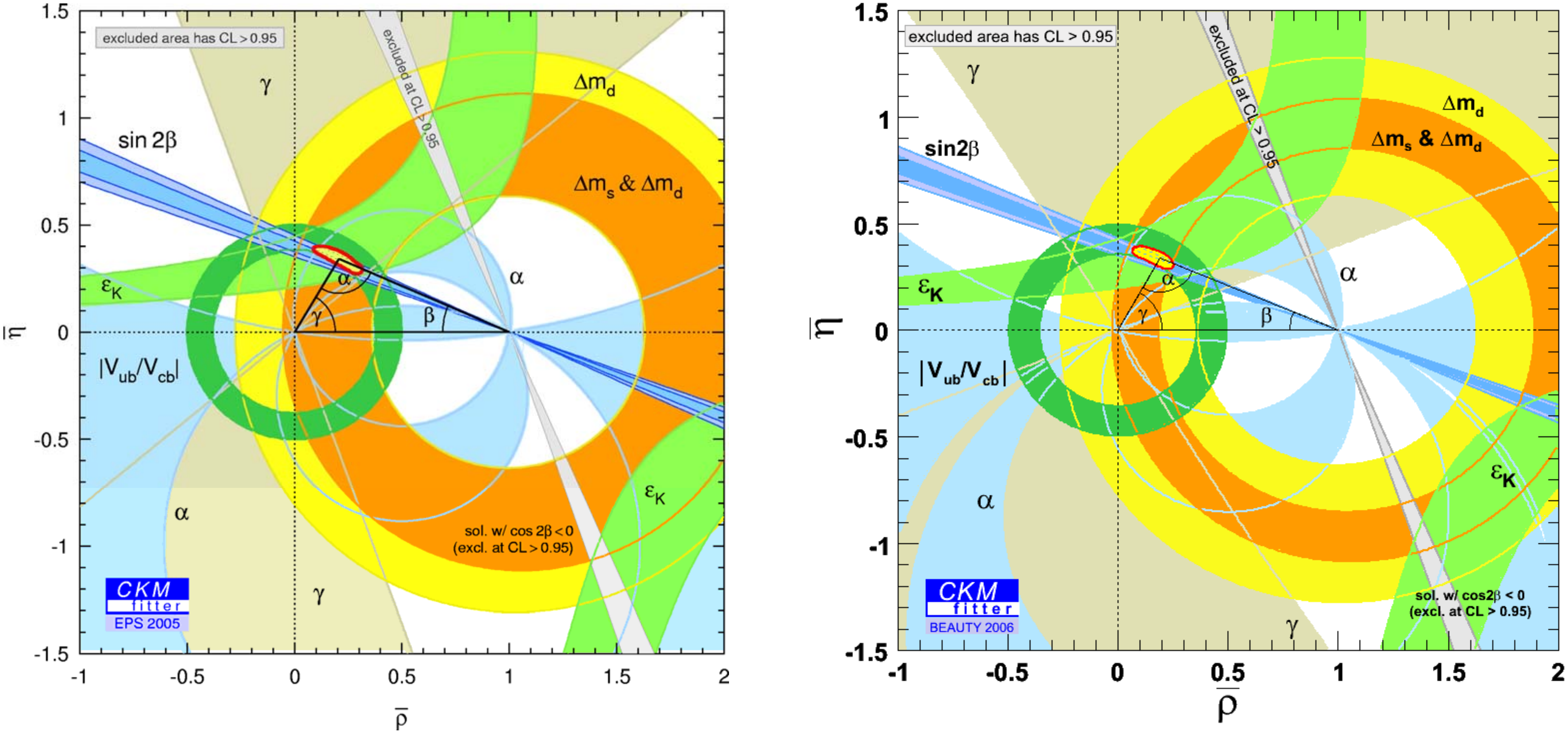
CDF

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

ξ, Δm_d

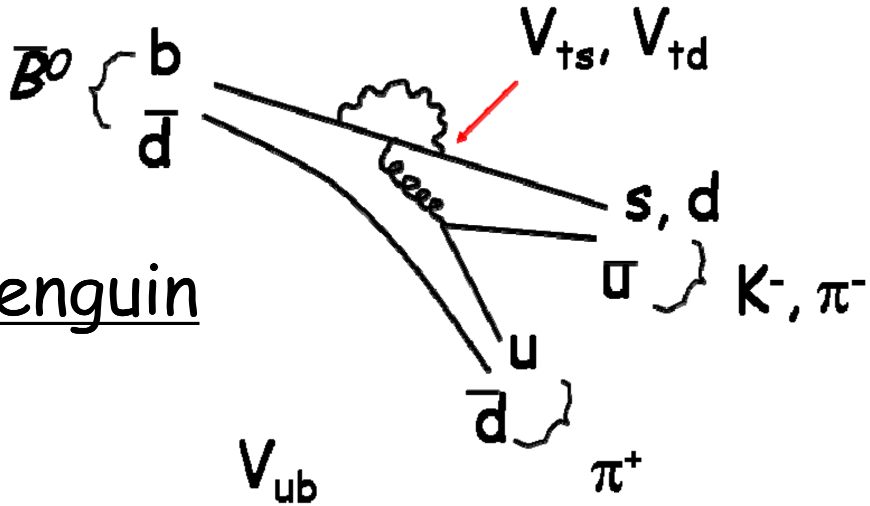
$$\Rightarrow \quad |V_{td} / V_{ts}| = 0.2060 \pm 0.0007 {}^{+0.0081}_{-0.0060}$$

Summer 2005 → Fall 2006

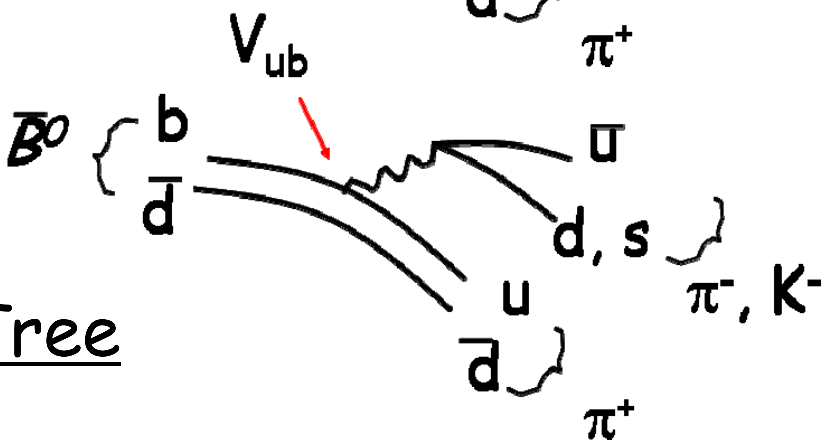


$B^0_{d,s} \to h^+ h^{(\prime)-}$ $h^\pm = \pi^\pm,\ K^\pm$

Penguin



Tree



$\bar{B}^0_d \to K^-\pi^+ \quad P > T$

$\bar{B}^0_d \to \pi^+\pi^- \quad T > P$

spectator

$\bar{d} \leftrightarrow \bar{s}$

$\bar{B}^0_s \to K^+K^- \quad P > T$

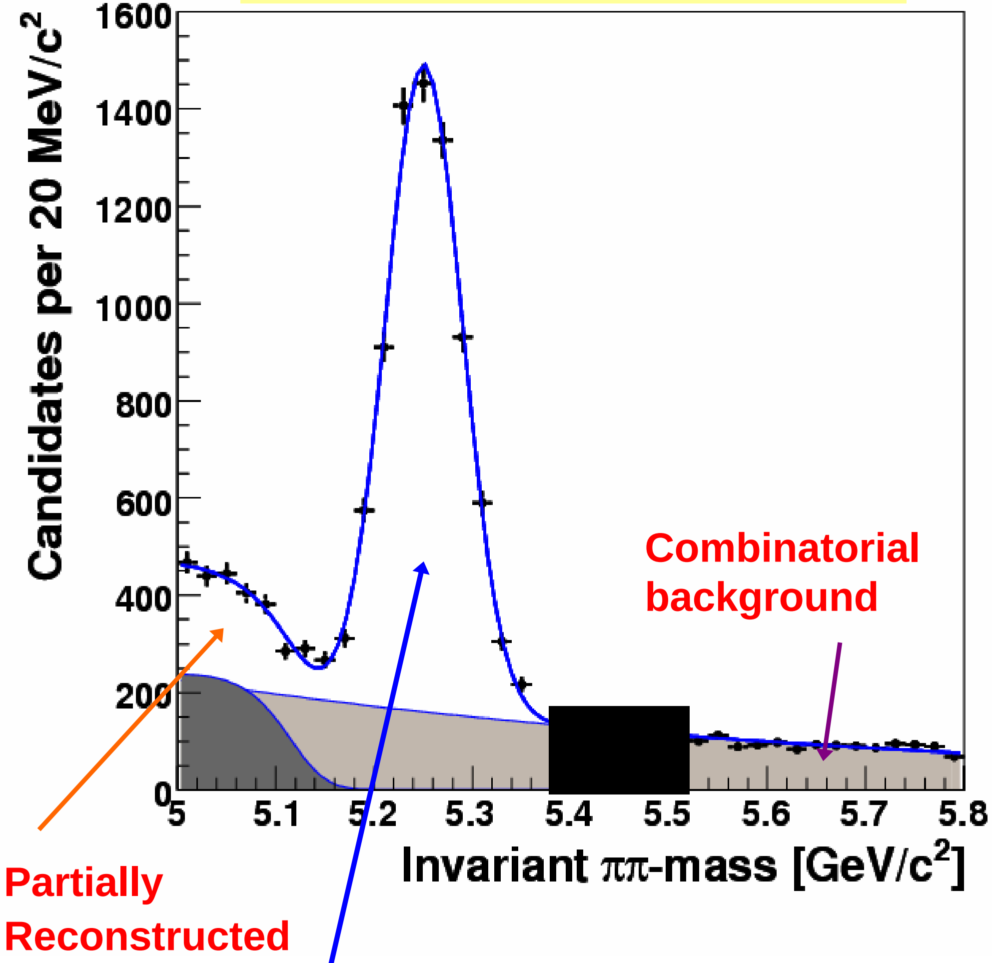
$\bar{B}^0_s \to K^+\pi^- \quad T < P$

- $\bar{B}^0_d$ modes observed at B factories and CP asymmetries measured. Also seen at CDF.
- $\bar{B}^0_s \to K^+K^-$ observed at CDF.
- Proposed to use $\bar{B}^0_d \to \pi^+\pi^-$ and $\bar{B}^0_s \to K^+K^-$ simultaneously to extract angle γ (phase of V_{ub}).

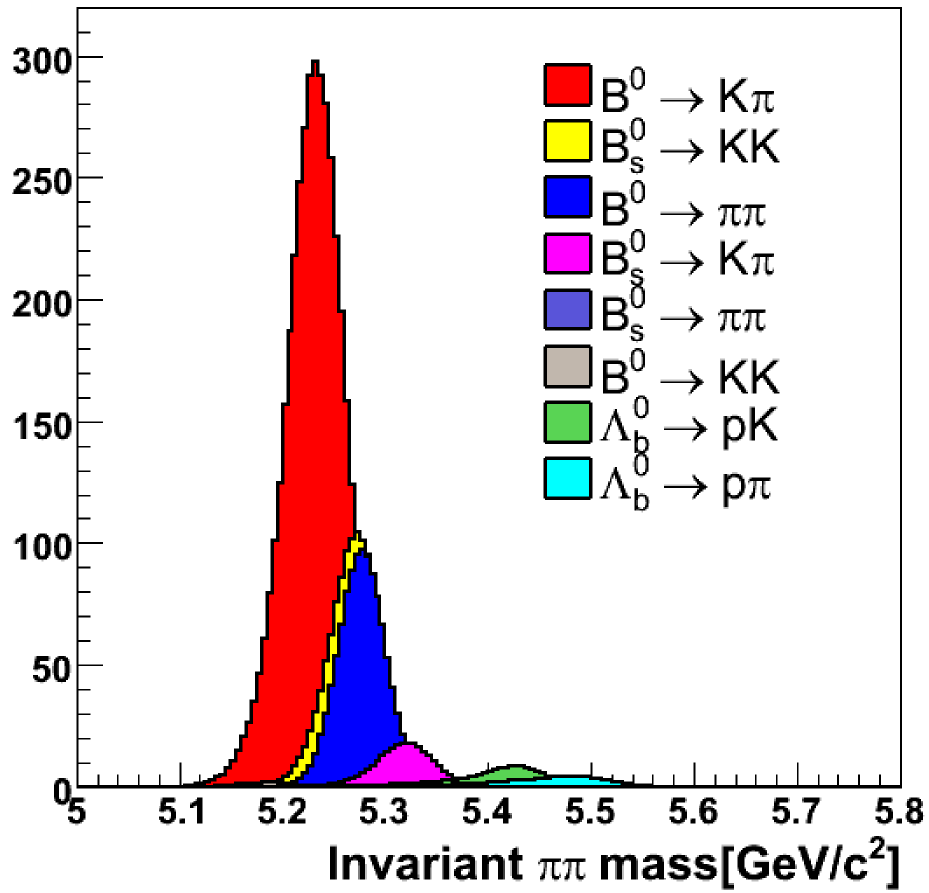
$B^0_{d,s} \to h^+h^{(\prime)-}$ signal

assigning the pion mass

Real Data, 1 fb^{-1}



Expectation from MC



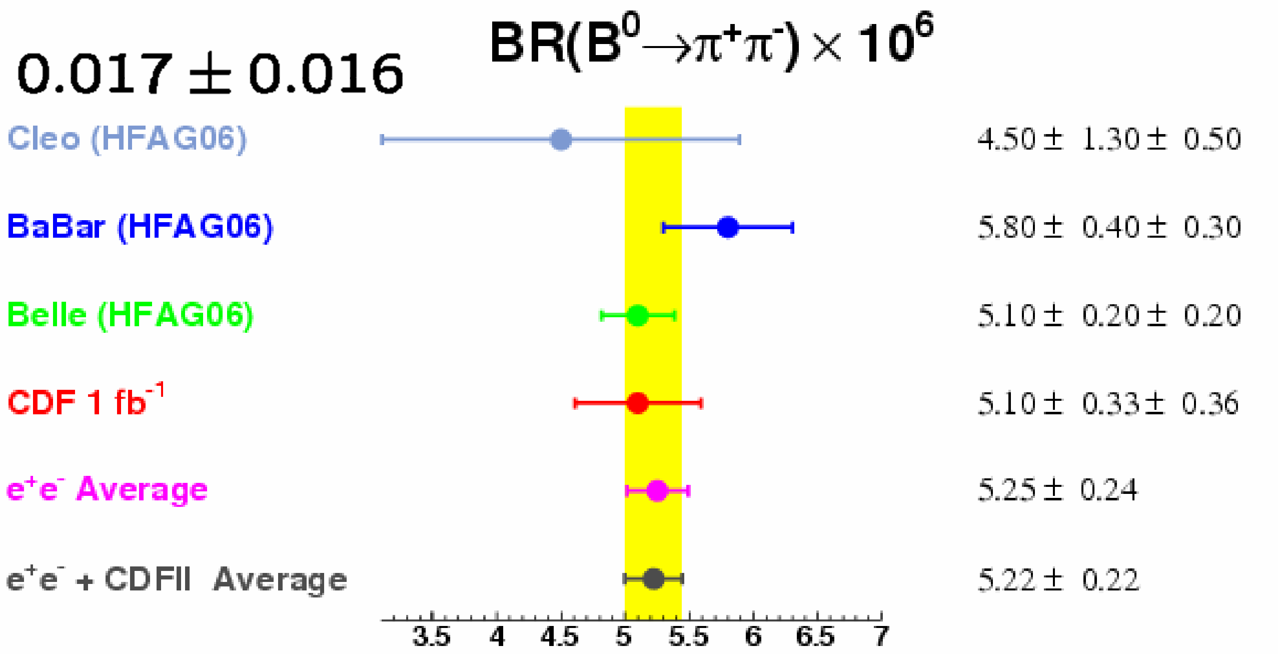
Main contribution from
$\bar{B}^0_d \to K^-\pi^+$, $\bar{B}^0_d \to \pi^+\pi^-$, $\bar{B}^0_d \to K^+K^-$

Statistical separation using mass, kinematics, dE/dX

$\bar{B}_d^0$ results

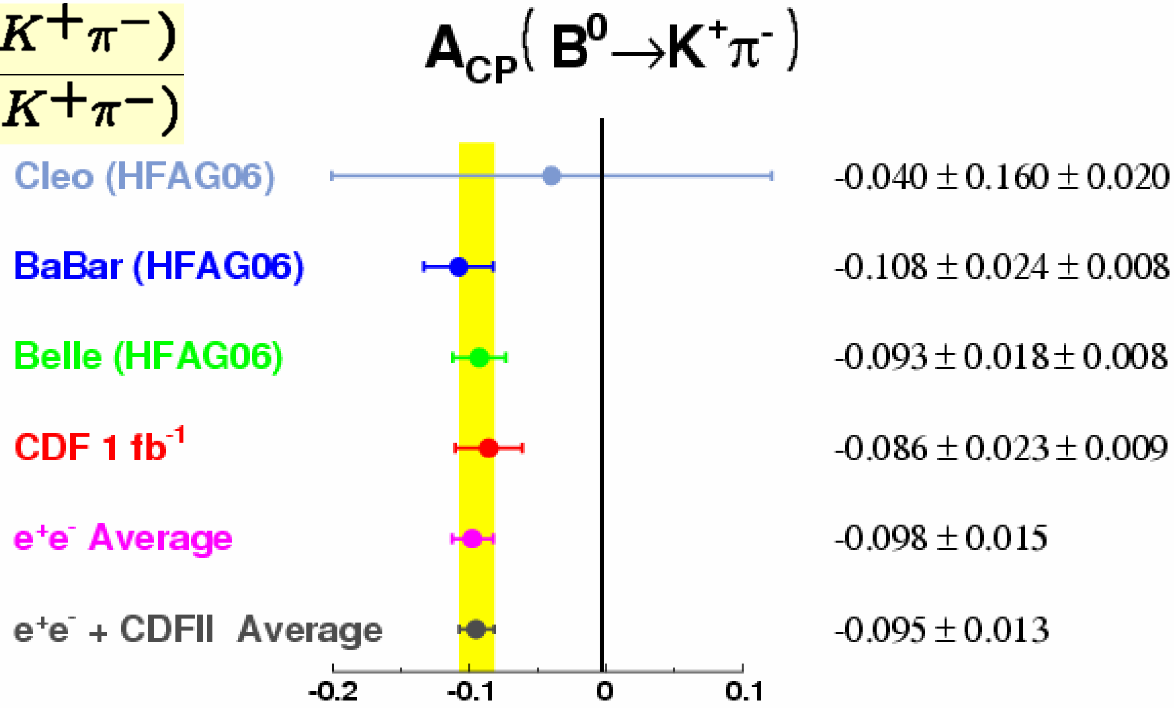
$$\frac{\mathcal{B}(\bar{B}_d^0 \to \pi^+\pi^-)}{\mathcal{B}(\bar{B}_d^0 \to K^-\pi^+)} = 0.259 \pm 0.017 \pm 0.016$$

$$\mathcal{B}(\bar{B}_d^0 \to \pi^+\pi^-) = (5.10 \pm 0.33 \pm 0.36) \times 10^{-6}$$



$$\mathcal{A}_{CP} \equiv \frac{\Gamma(\bar{B}_d^0 \to K^-\pi^+) - \Gamma(B_d^0 \to K^+\pi^-)}{\Gamma(\bar{B}_d^0 \to K^-\pi^+) + \Gamma(B_d^0 \to K^+\pi^-)}$$

$$= -0.086 \pm 0.023 \pm 0.009$$



$\bar{B}_s^0$ results

$$= (5.10 \pm 0.33 \pm 0.36) \times 10^{-6}$$

$$\frac{f(b \to \bar{B}_s^0) \cdot \mathcal{B}(\bar{B}_s^0 \to K^+K^-)}{f(b \to \bar{B}_d^0) \cdot \mathcal{B}(\bar{B}_d^0 \to K^-\pi^+)} = 0.324 \pm 0.019 \pm 0.041$$

Or: $\mathcal{B}(\bar{B}_s^0 \to K^+K^-) = (24.4 \pm 1.4 \pm 4.4) \times 10^{-6}$

spectator $\bar{d} \leftrightarrow \bar{s}$

$\mathcal{B}(\bar{B}_d^0 \to K^-\pi^+) = (18.2 \pm 0.8) \times 10^{-6}$ (PDG 2006)

Future :

Measure CP asymmetries

$\mathcal{A}_{CP}^{mix} \sin(\Delta m\, t) + \mathcal{A}_{CP}^{dir} \cos(\Delta m\, t)$

in $B_d^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$,

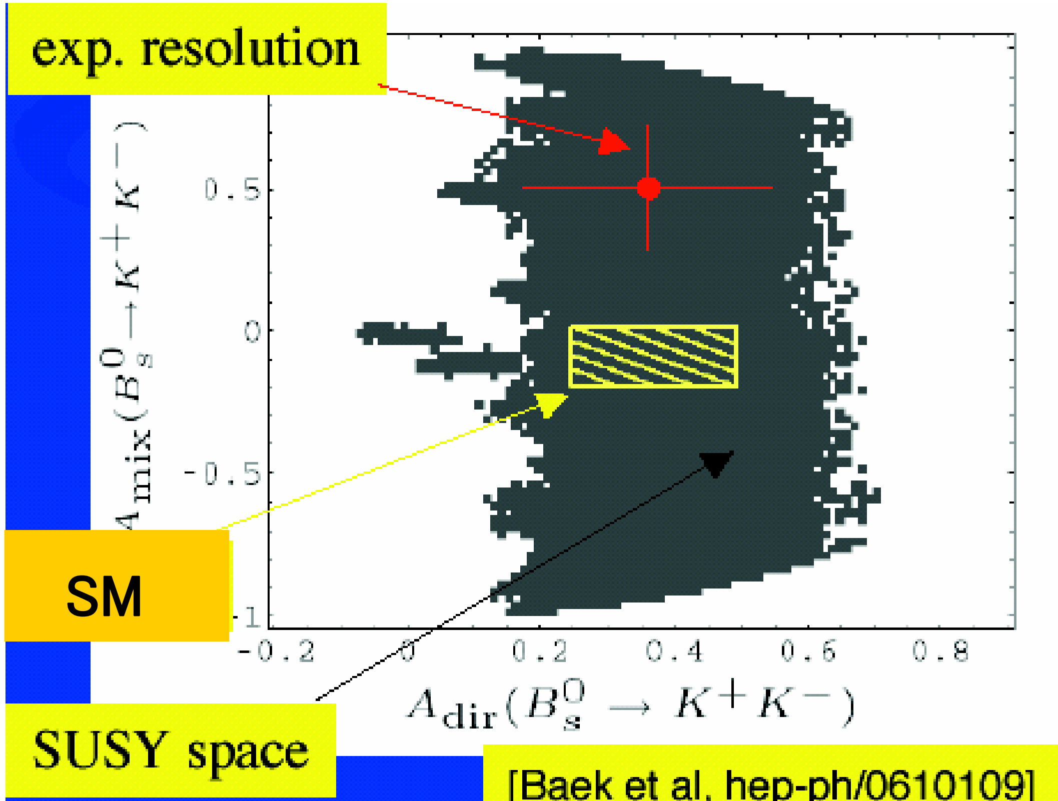
and extract angle γ (V_{ub} phase)

R. Fleischer

Expect

$\sigma(\mathcal{A}_{CP}) \sim 0.15 - 0.20$

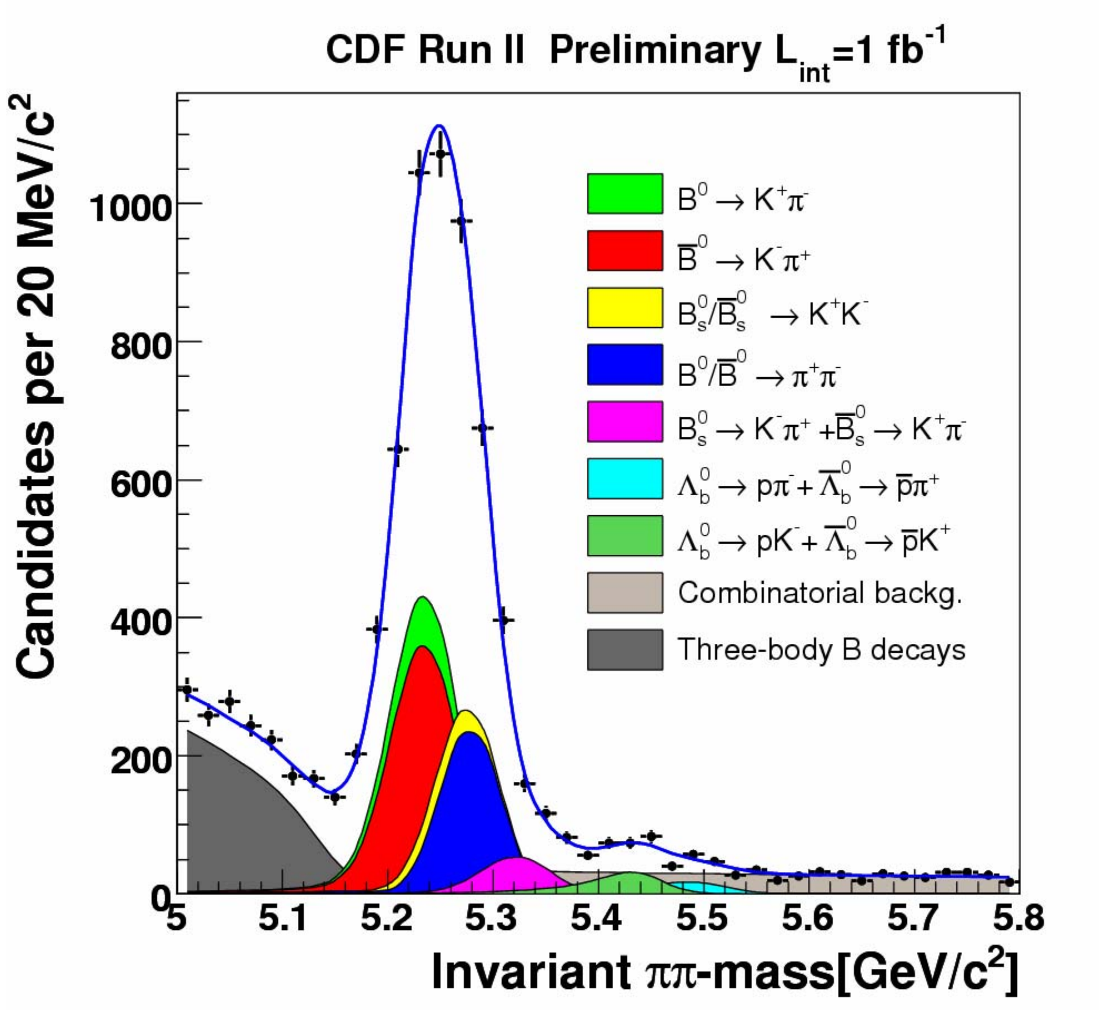
Angle γ to $\sim 10°$

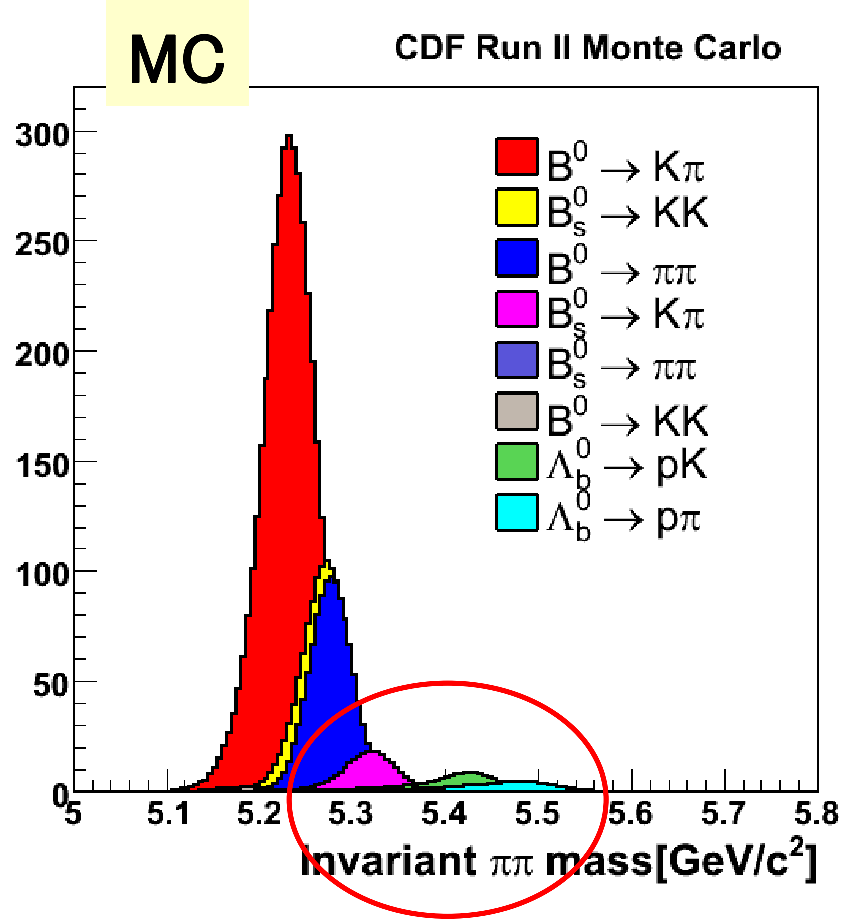


[Baek et al, hep-ph/0610109]

Rarer modes

Tighter cuts optimized for $\bar{B}_s^0 \to K^+\pi^-$





Three new modes observed

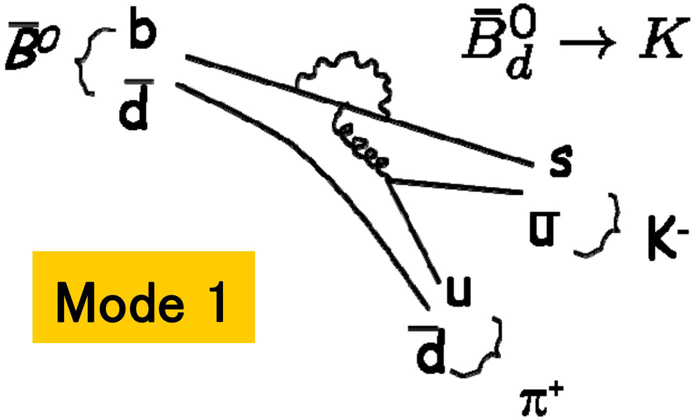
$$N(\bar{B}_s^0 \to K^+\pi^-) = 230 \pm 34 \pm 16 \longrightarrow \mathcal{B}(\bar{B}_s^0 \to K^+\pi^-) = (5.0 \pm 0.75 \pm 1.0) \times 10^{-6}$$

$$N(\Lambda_b^0 \to p\pi^-) = 110 \pm 18 \pm 16$$

$$N(\Lambda_b^0 \to pK^-) = 156 \pm 20 \pm 11$$

CP violation in $\bar{B}_s^0 \to K^+\pi^-$

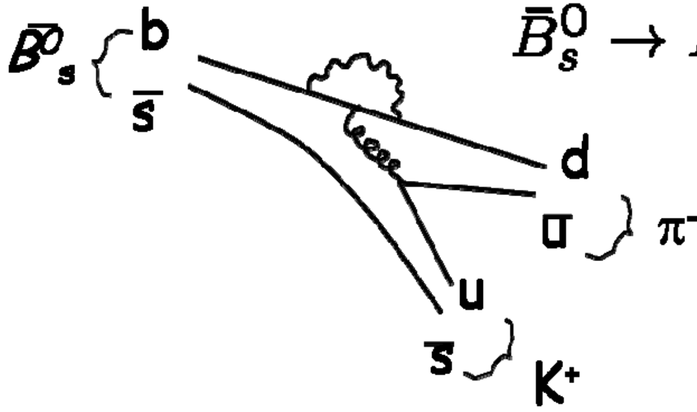
$\bar{B}_d^0 \to K^-\pi^+$



Mode 1

U-spin
$d \leftrightarrow s$
$\bar{d} \leftrightarrow \bar{s}$

$\bar{B}_s^0 \to K^+\pi^-$



Mode 2

Under U-spin, CP asymmetries are related :

$$-\frac{\mathcal{A}_{CP}^{dir}(\text{mode 1})}{\mathcal{A}_{CP}^{dir}(\text{mode 2})} = \frac{\mathcal{B}(\text{mode 2})}{\mathcal{B}(\text{mode 1})}$$

Gronau, PL B 492, 297 (2000)

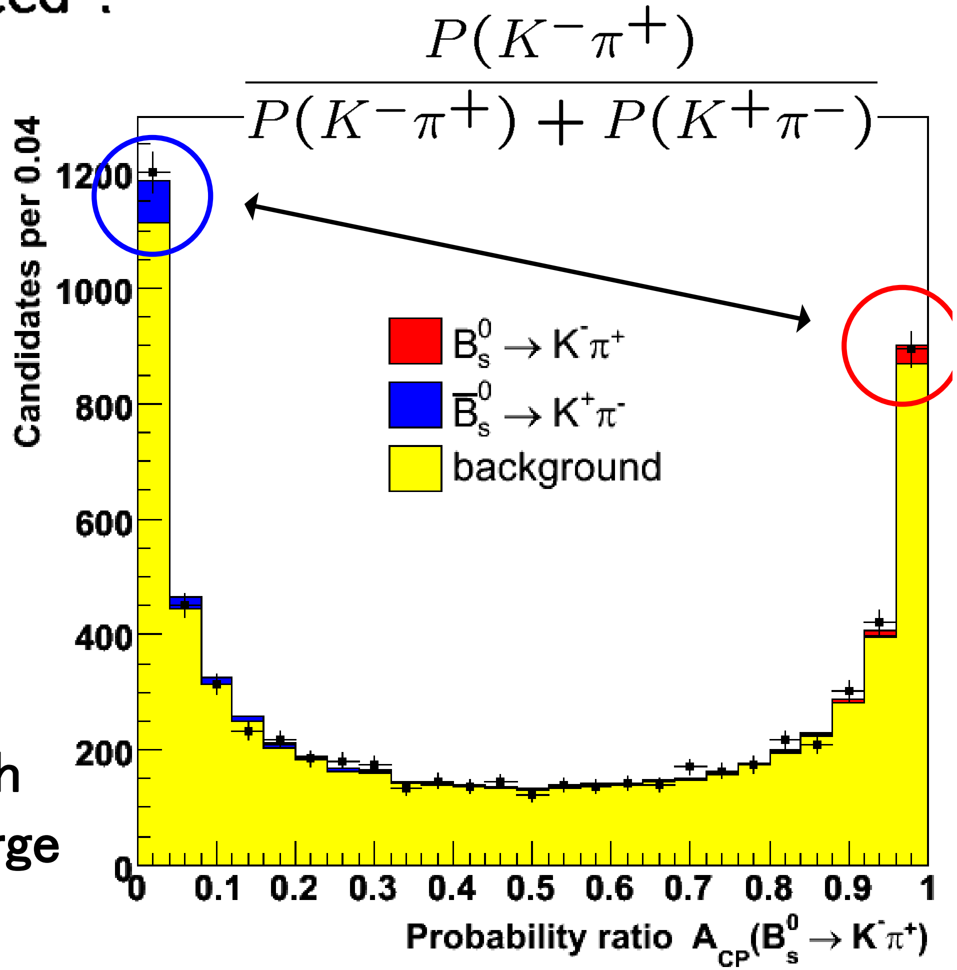
CDF sees :

$$\mathcal{A}_{CP} \equiv \frac{\Gamma(\bar{B}_s^0 \to K^+\pi^-) - \Gamma(B_s^0 \to K^-\pi^+)}{\Gamma(\bar{B}_s^0 \to K^+\pi^-) + \Gamma(B_s^0 \to K^-\pi^+)}$$
$$= +0.39 \pm 0.15 \pm 0.08$$

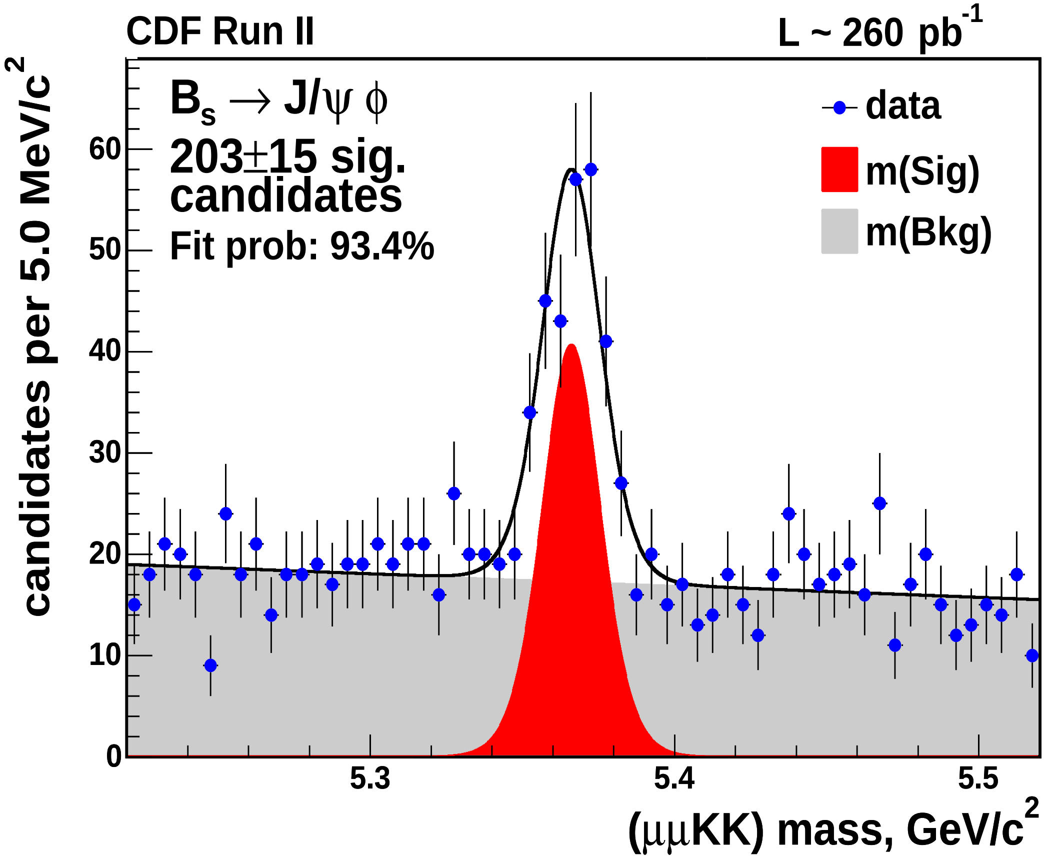
$$-\frac{\mathcal{A}_{CP}(B_s^0)}{\mathcal{A}_{CP}(B_d^0)} = 4.2 \pm 2.0$$

$$\frac{\mathcal{B}(B_d^0 \to K^-\pi^+)}{\mathcal{B}(B_s^0 \to K^+\pi^-)} = 3.9 \pm 1.0$$

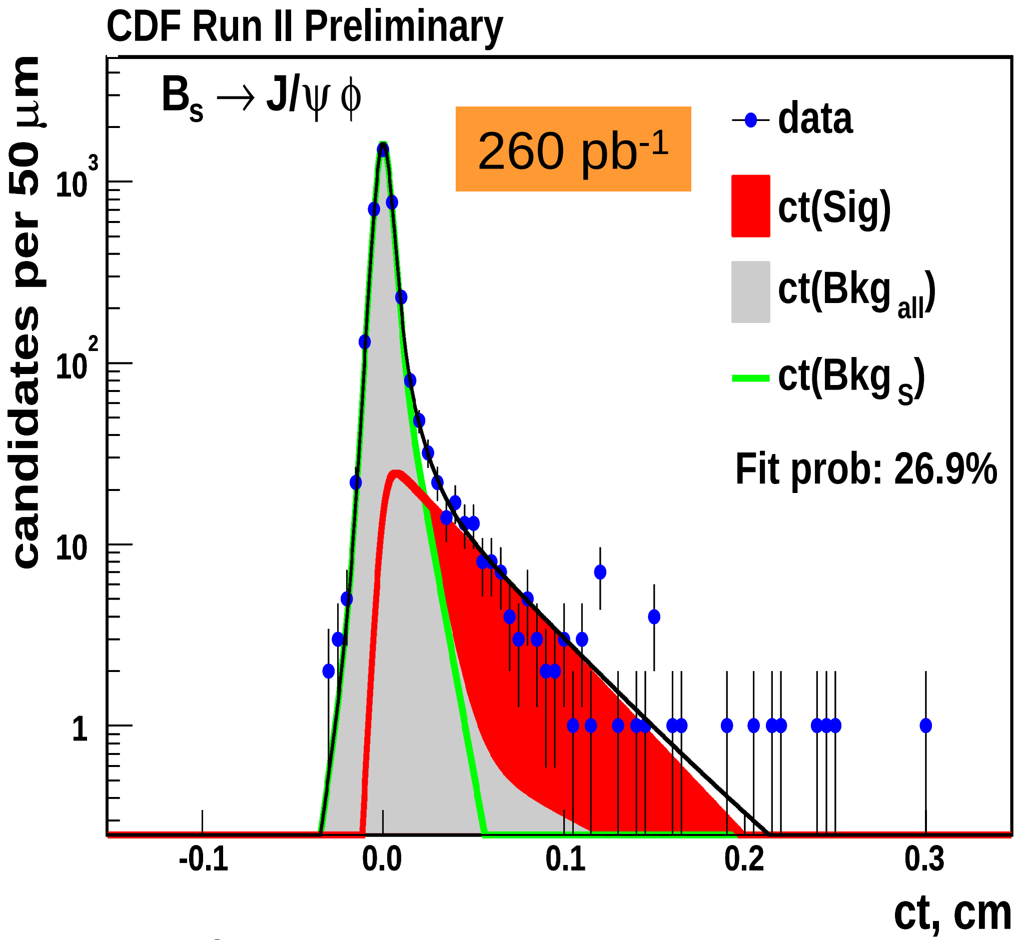
Agree, though errors are large



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



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



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

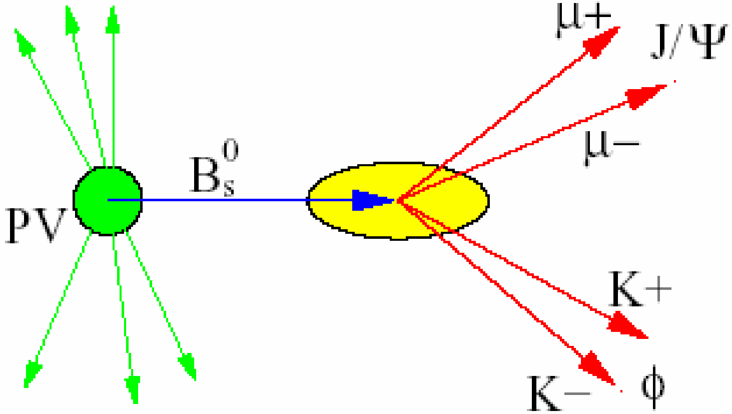
Predict $\tau(B_s^0)/\tau(B^0) = 1.0 \pm \mathcal{O}(1\%)$
But expect $\Delta\Gamma_s/\Gamma_s \sim 0.1$.
Mode dominated by CP even
($\Gamma_\perp/\Gamma = 0.232 \pm 0.100 \pm 0.013$, CDF).

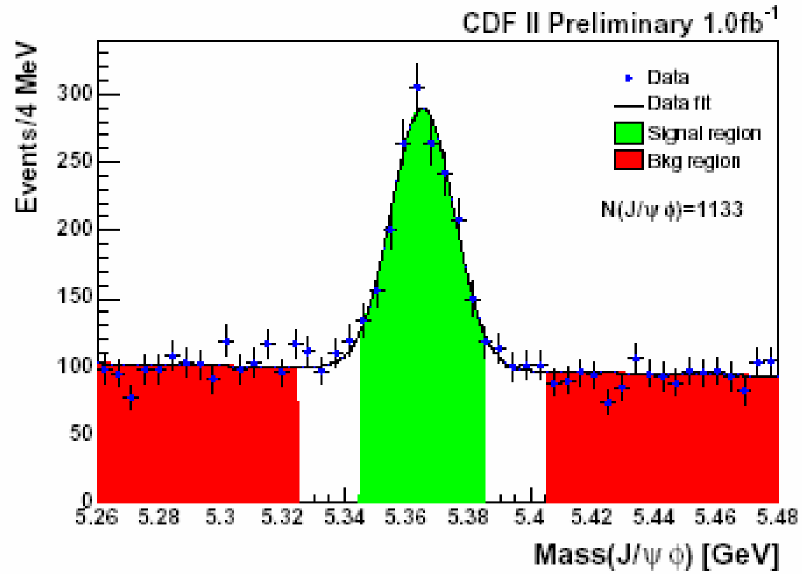
Can exhibit a different τ than in flavor eigenstates.

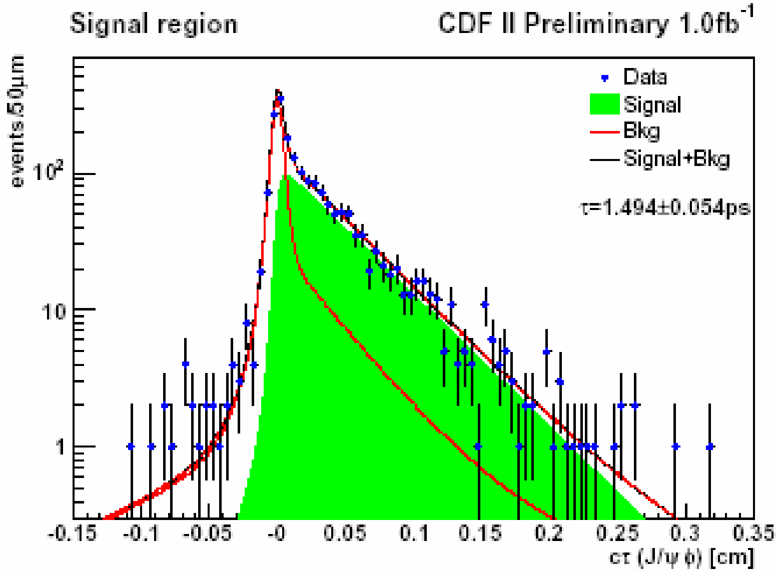
Future : look for CP-violation, ~0 expected in SM, arg(V_{ts}).

$B_s^0 \to J/\psi\phi$ Lifetime

1 fb^{-1}







- Topology similar to $B^0 \to J/\psi K^{*0}$

$$N(J/\psi\Lambda) = 1133$$

$$c\tau(B_s^0) = 447.9 \pm 16.2(stat) \pm 2.8(syst)\mu m$$
$$\tau(B_s^0) = 1.494 \pm 0.054(stat) \pm 0.009(syst)ps$$

Guess: $\sigma(\sin 2\phi_s) \sim 0.2 - 0.3$ with 8 fb^{-1}

Summary

CDF has a rich B-physics program, complementary to $\Upsilon(4S)$.

Recent results include :

- Δm_s, finally.
- $B \to hh$, some previously unobserved modes.

(Near) future :

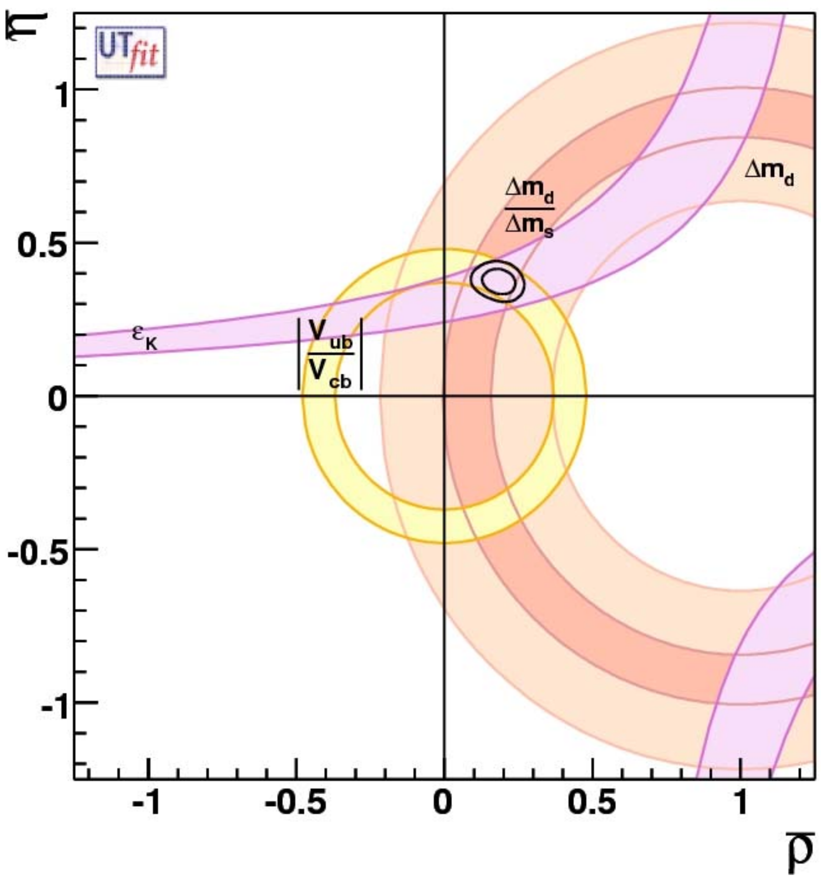
- CP asymmetry in $B_s^0 \to K^+K^-$ (and $B_d^0 \to \pi^+\pi^-$)
- CP asymmetry in $B_s^0 \to J/\psi\,\phi$,
  phase of B_s^0-$\bar{B}_s^0$ mixing m_{12}, $\simeq 0$ expected in SM.
- Continue search for $B_s^0 \to \mu^+\mu^-$.
- Lifetime difference $\Delta\Gamma_s$, non-zero? Phase in Γ_{12}??
- $\bar{B}_s^0 \to D_s^+ K^-$ and angle γ?

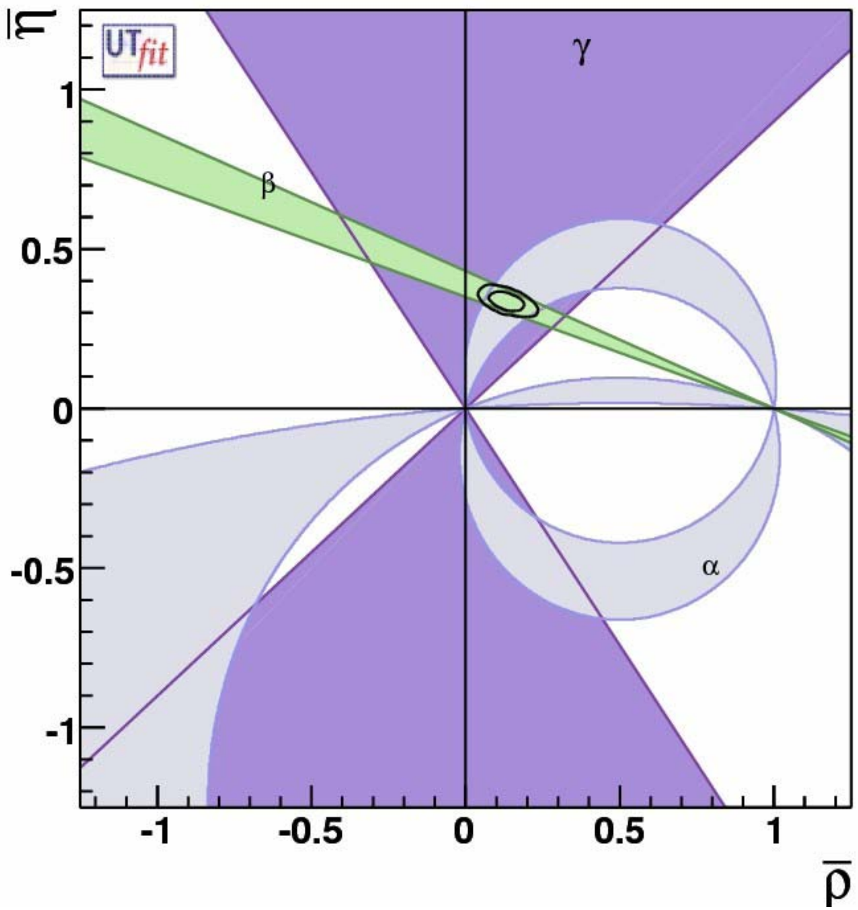
Many studies of FCNC *b* → *s* transitions

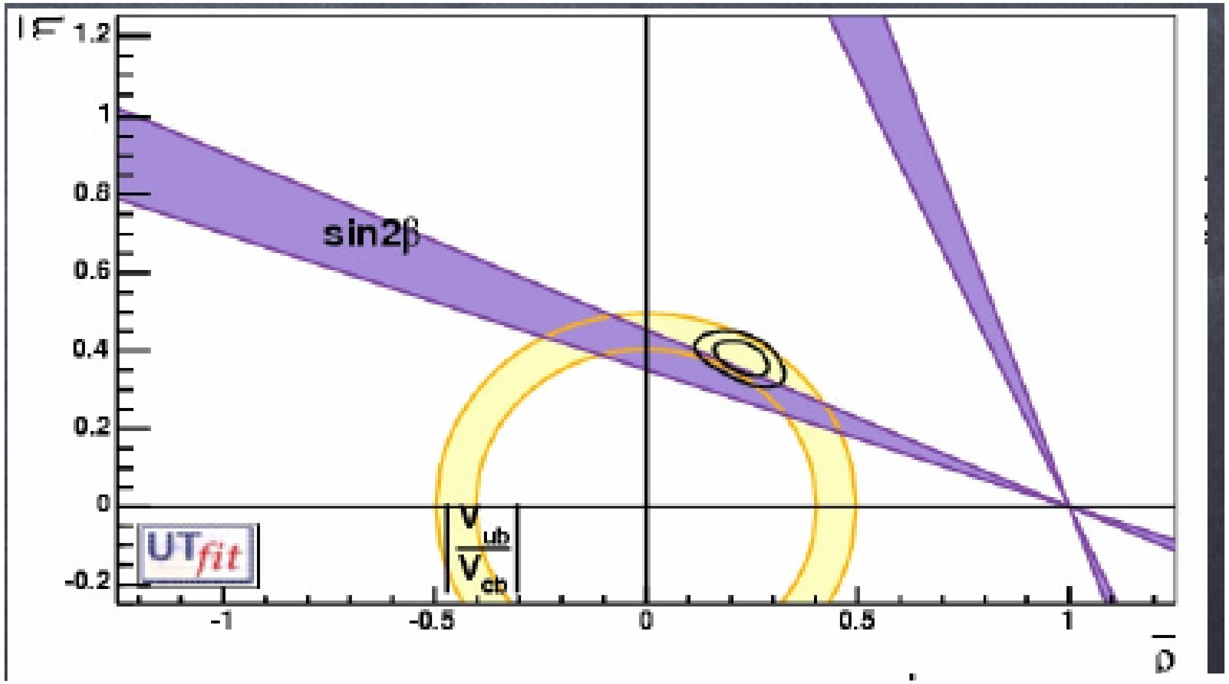
Backup slides

長さ(角度以外)のみ

角度のみ



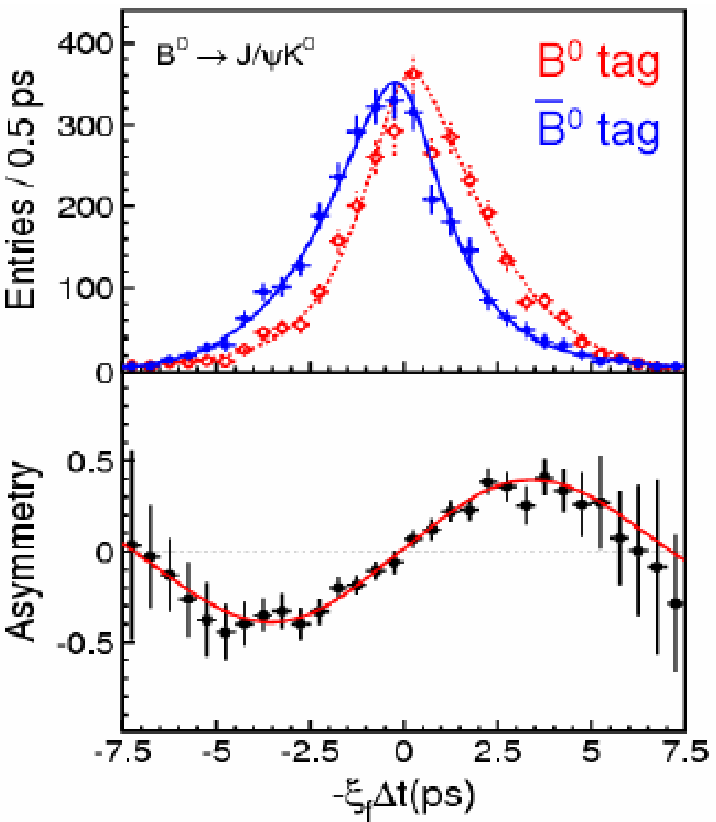


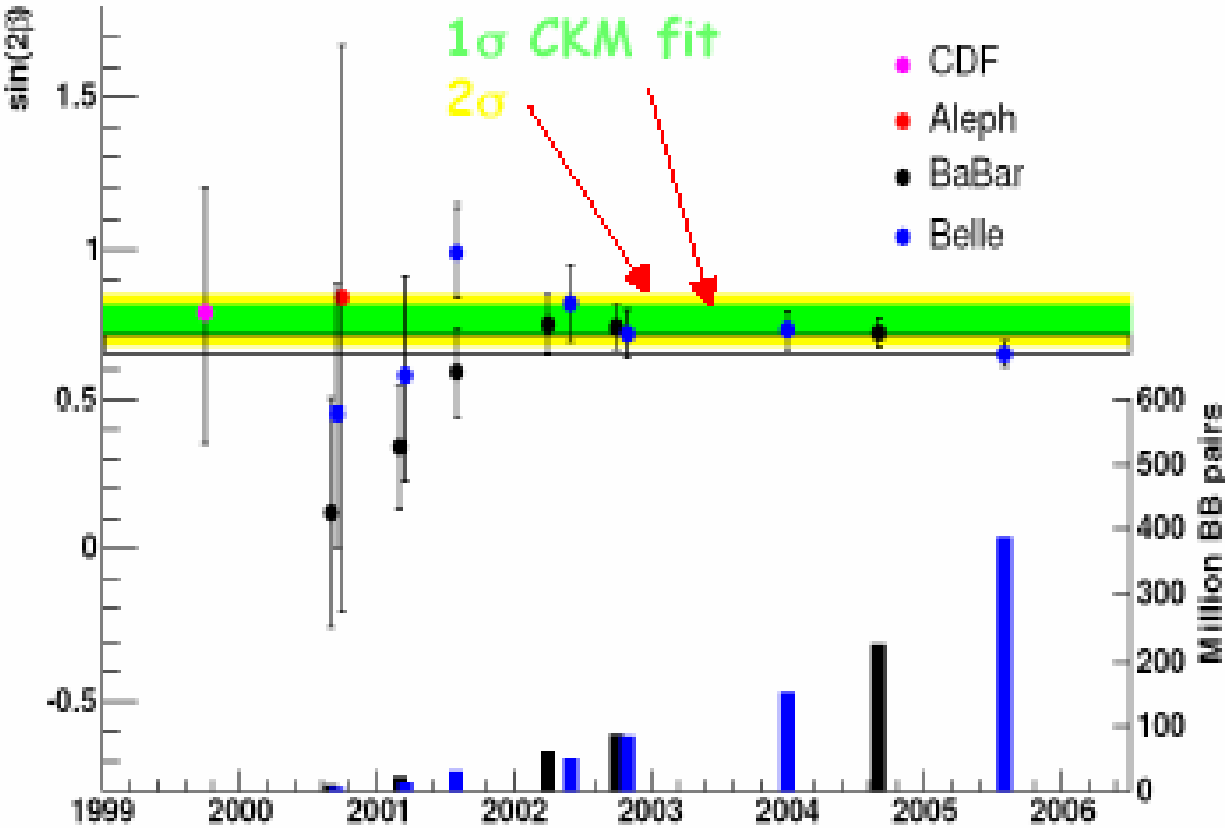


V_{ub} and $\sin 2\beta$

Tension ??

$\sin 2\beta$ vs. year



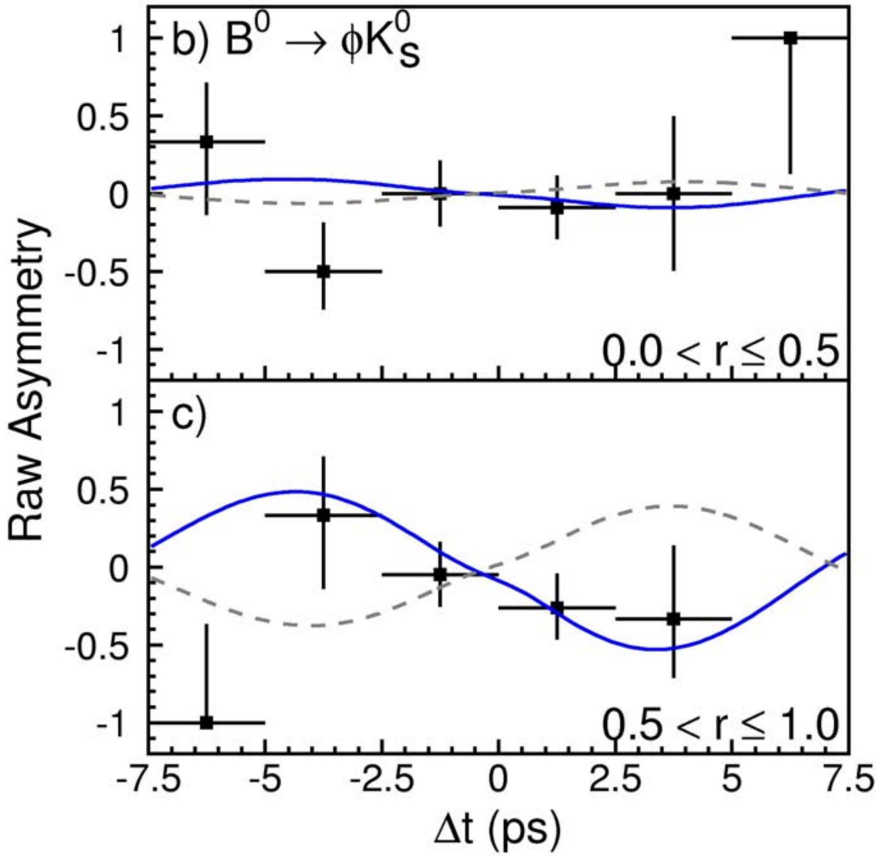


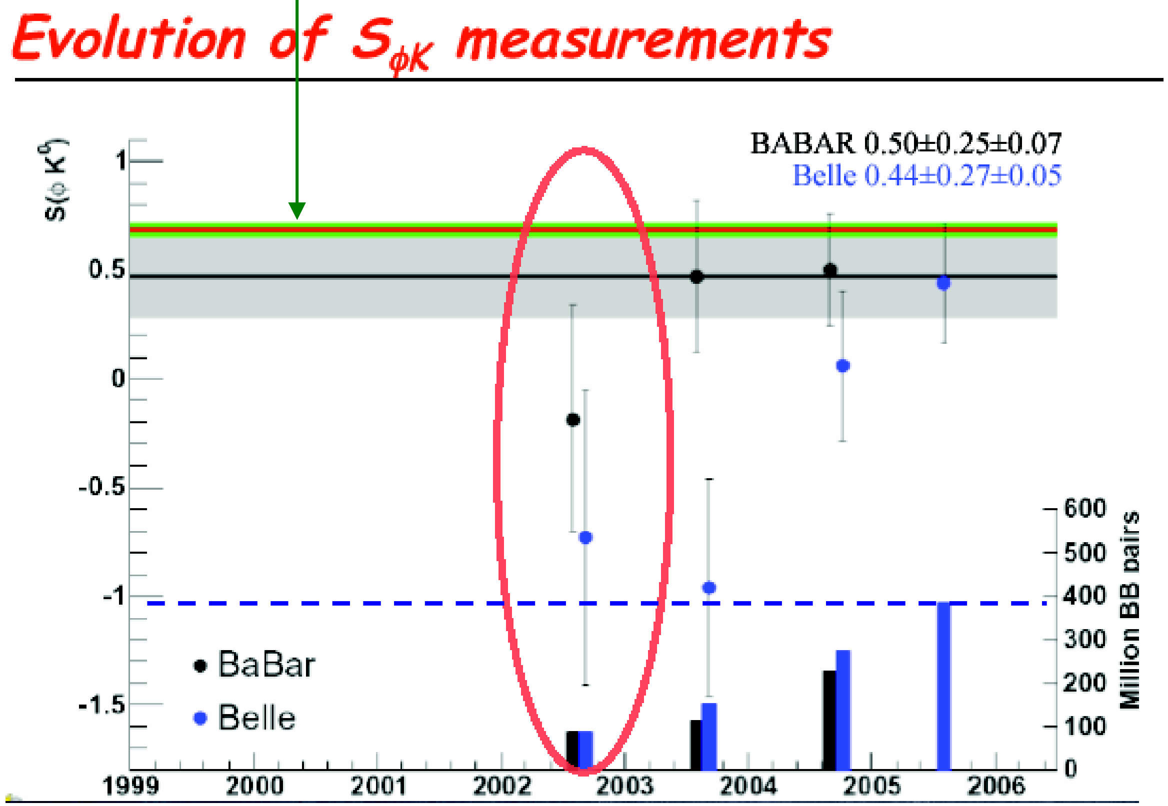
New physics in $b \to s$ transition ?

Belle : PRL 91, 261602 (2003)

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

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





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

Was 3.5 σ away, but now ...

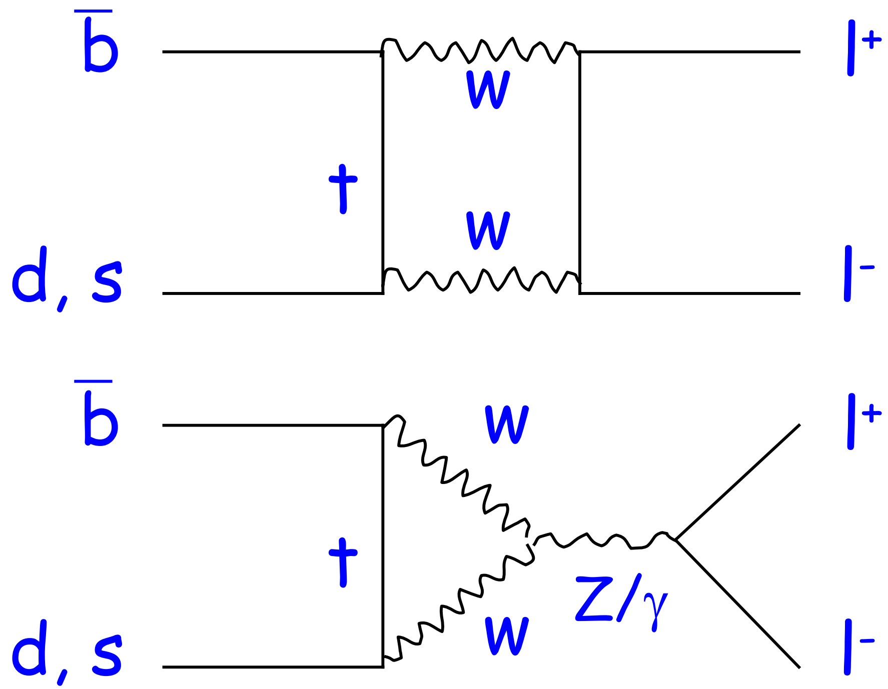
CDF can provide tests of $b \to s$ (new phys?)

- ~~$B_s^0 \bar{B}_s^0$ oscillations.~~
  ~~If $\Delta m_s \gg 18\ \mathrm{ps}^{-1}$, 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 $B_d^0/B_s^0 \to \mu^+\mu^-$

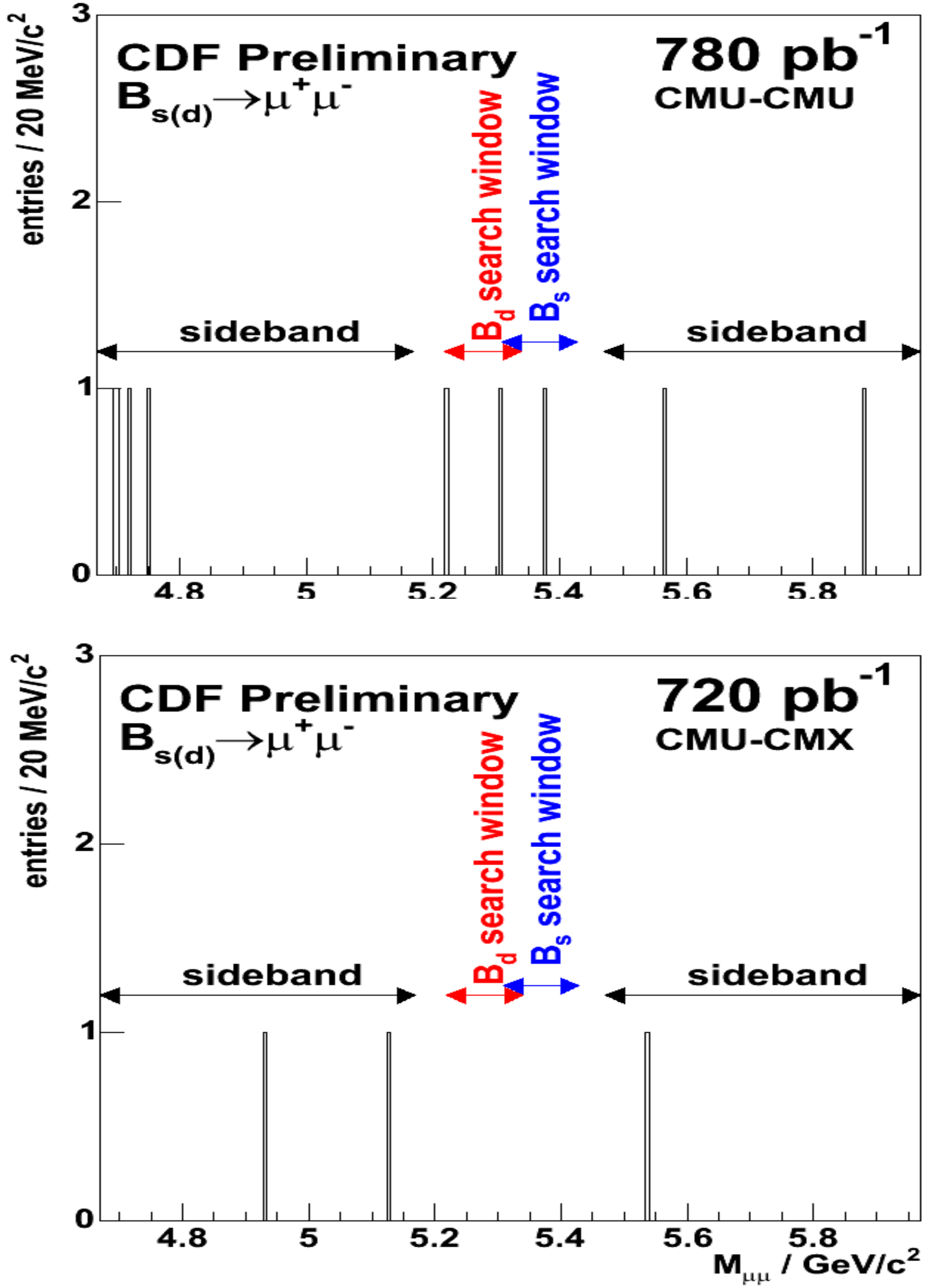
- FCNC
- V_{td} for B^0_d, V_{ts} for B^0_s
- Helicity suppressed.
- B.F. very small.



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

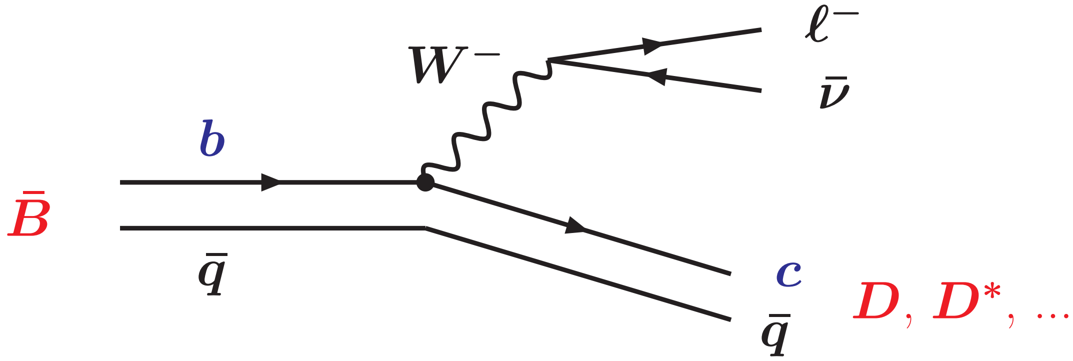
B.R. < 2.6 x 10^{-6} for B^0_s

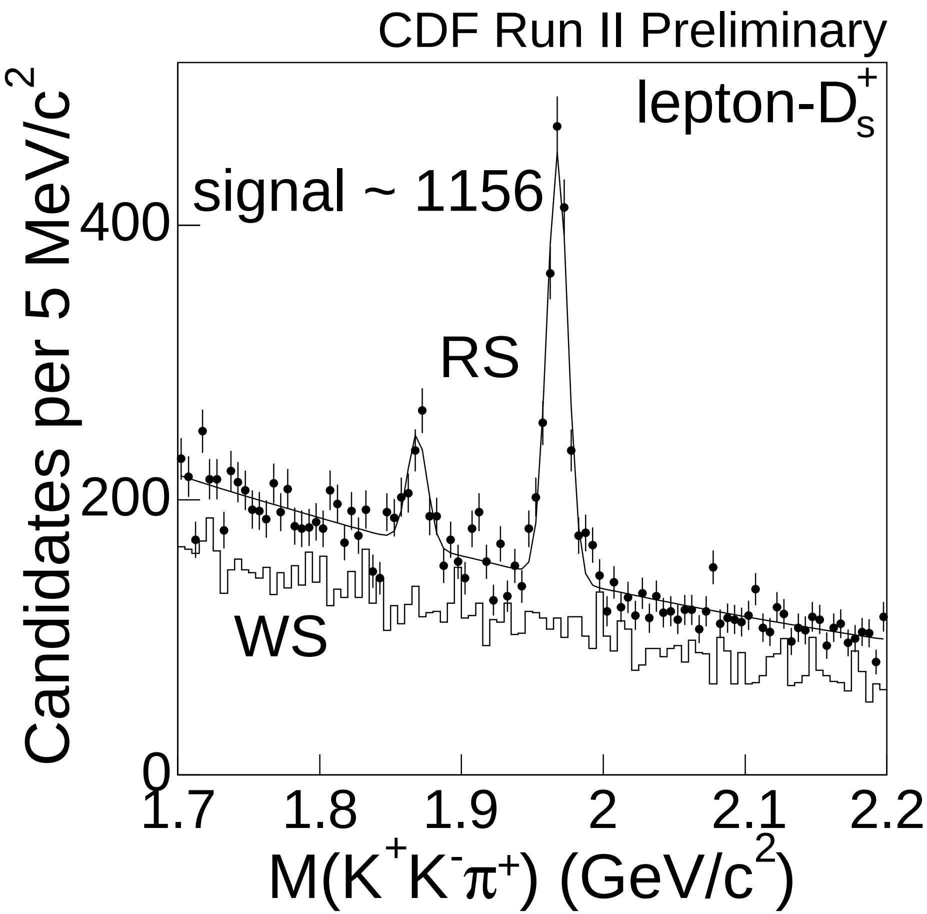
PRD 57, 3811 (1998)

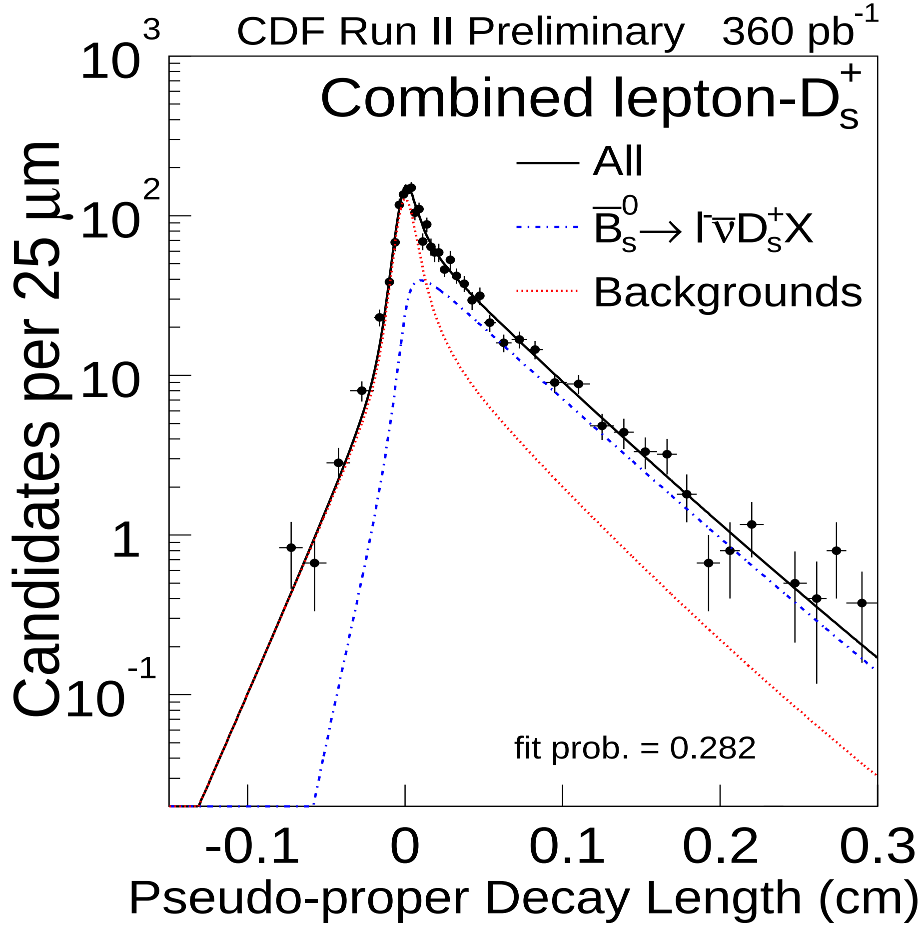
B_s^0 meson

Use semileptonic decay

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





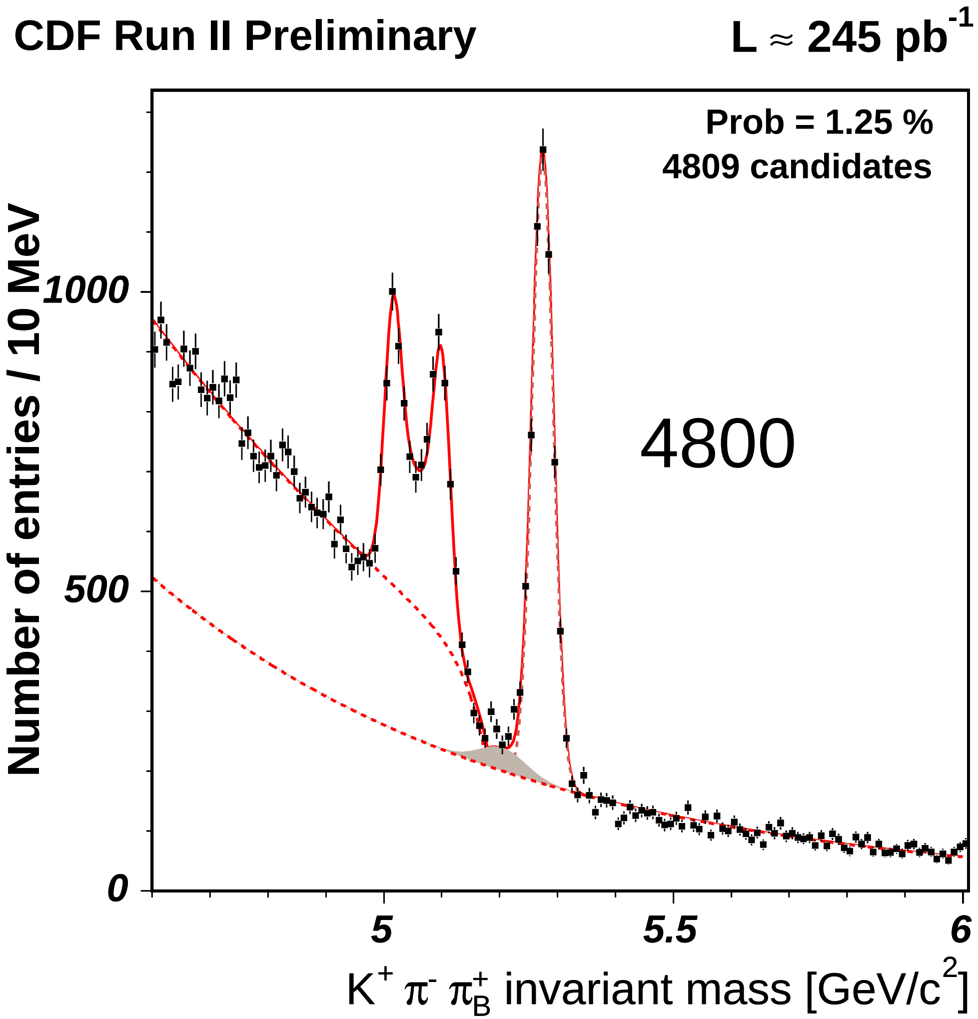


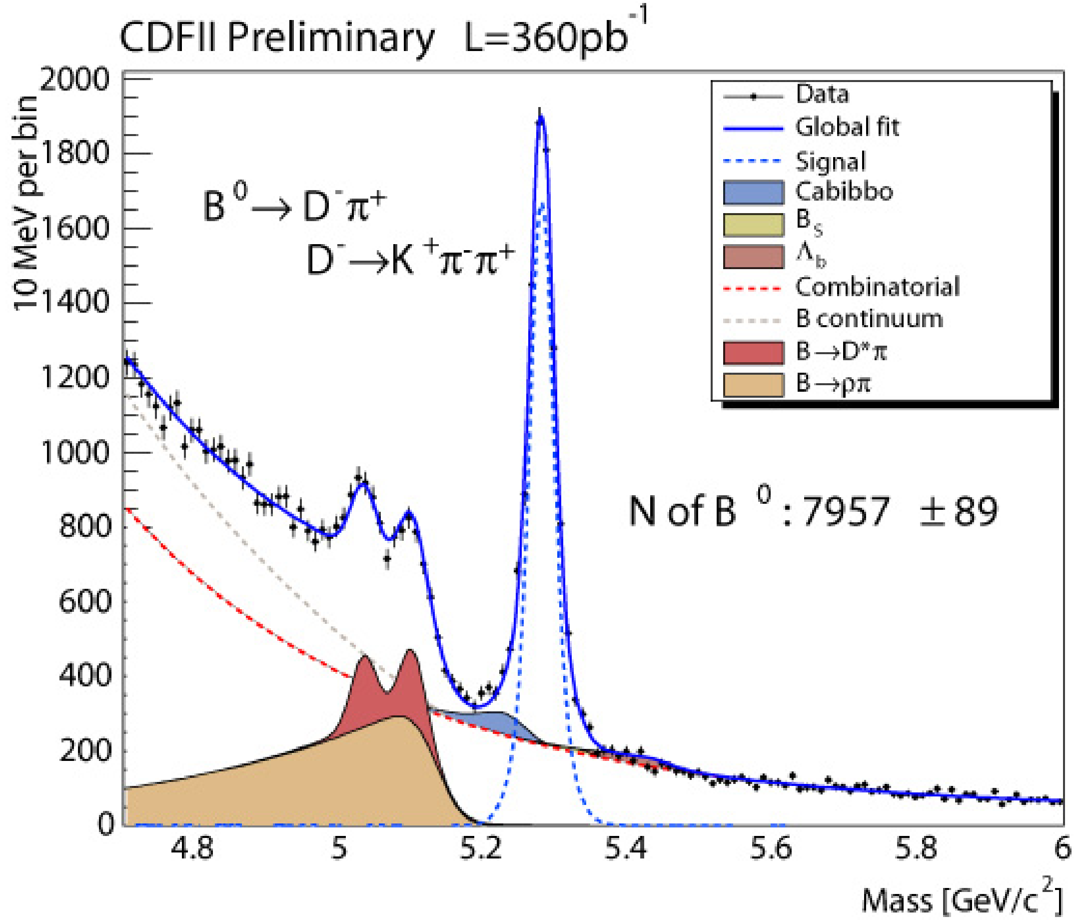
$$\tau(B_s^0) = 1.381 \pm 0.055\,^{+0.052}_{-0.046}\ \text{ps}$$

Satoru Uozumi, Ph.D. thesis, 2005

B signals from CDF SVT triggers : full reconstruction

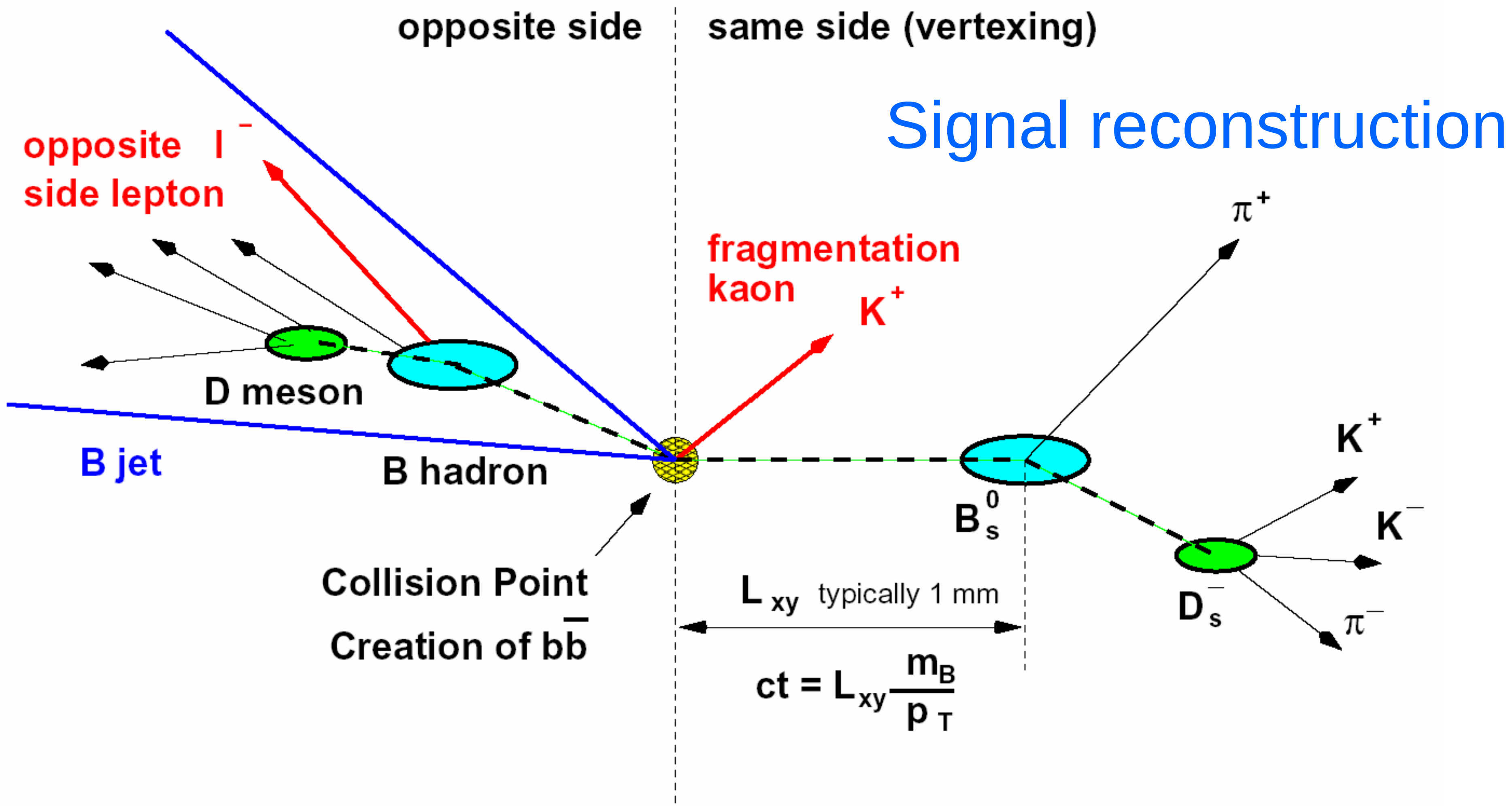
$B^- \to D^0\pi^- \to (K^-\pi^+)\,\pi^-$ $\bar{B}^0 \to D^+\pi^- \to (K^-\pi^+\pi^+)\,\pi^-$





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

Understand proper time resolution and flavor tagging



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.

Flavor tagging 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)

Big improvement came from same-side kaon tagging using TOF information.