Results from the Tevatron on

B_s oscillations, $\Delta\Gamma_s$,ϕ_s and discovery of $\Sigma_b^{(*)}$

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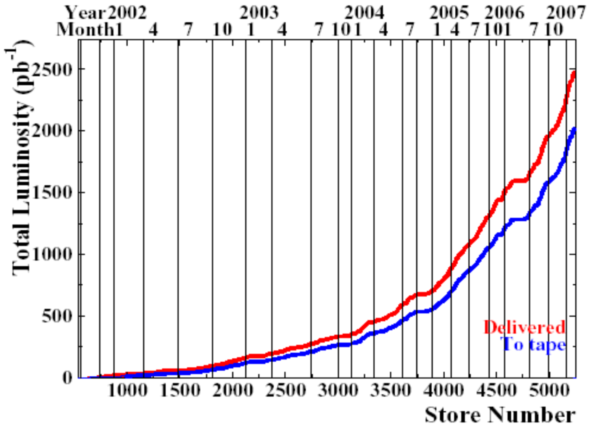
42nd Recontres de Moriond

Experiments at the Tevatron

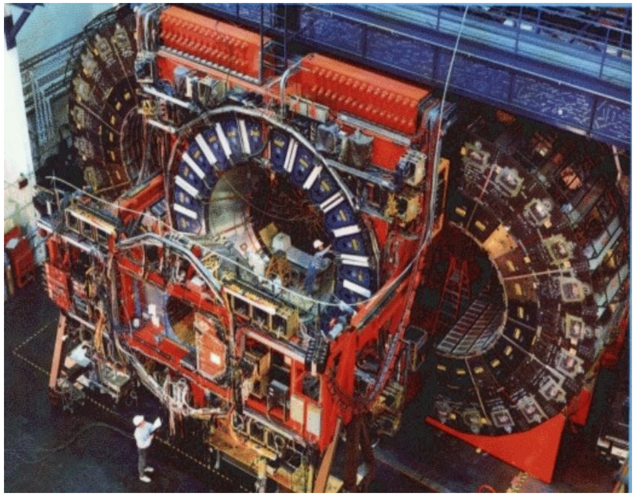
Tevatron is a unique place to study
B_s and b-baryons



now 2fb^{-1} on tape, results today based on ~1 fb^{-1}

Luminosity still increasing

- good forward tracking
- excellent muon coverage
  - $\Delta\Gamma_s$ in $B_s \rightarrow J/\psi(\mu\mu)\,\phi$
  - B_s oscillaitons & charge asymmetry in muonic B decays

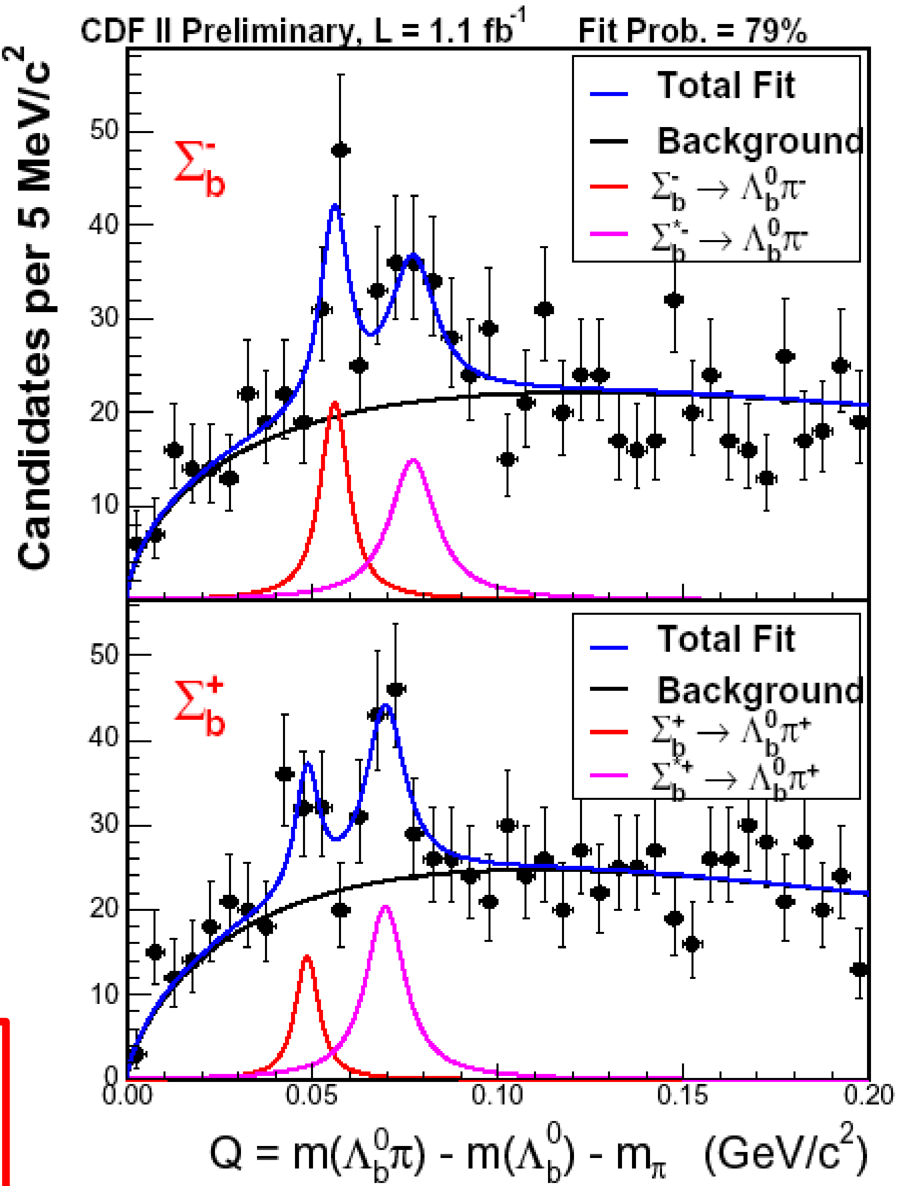


- momentum resolution
  - spectroscopy (Σ_b)
- displaced track trigger
  - gives unique access to hadronic decays e.g:
    - CP violation in $Bs \rightarrow hh$
    - B_s oscillations in hadronic decays

Discovery of new bottom Baryons

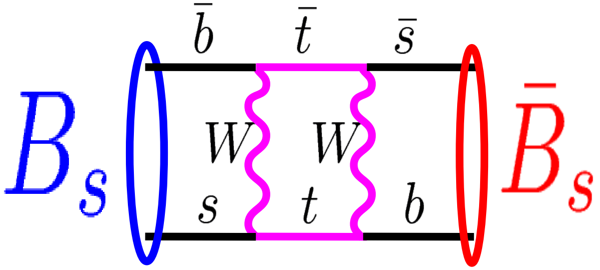
$$\Sigma_b^{(*)\pm} \rightarrow \Lambda_b^0\pi^\pm, \Lambda_b^0 \rightarrow \Lambda_c^+\pi^-, \Lambda_c^+ \rightarrow pK^-\pi^+$$

State	Quarks	J^P	(I, I_3)
Λ_b^0	$b[ud]$	$(1/2)^+$	$(0,0)$
Σ_b^+	buu	$(1/2)^+$	$(1,+1)$
Σ_b^0	$b\{ud\}$	$(1/2)^+$	$(1,0)$
Σ_b^-	bdd	$(1/2)^+$	$(1,-1)$
Σ_b^{*+}	buu	$(3/2)^+$	$(1,+1)$
Σ_b^{*0}	$b\{ud\}$	$(3/2)^+$	$(1,0)$
Σ_b^{*-}	bdd	$(3/2)^+$	$(1,-1)$
Λ_b^{*0}	$b[ud]$	$(1/2)^-$	$(0,0)$
Λ_b^{*0}	$b[ud]$	$(3/2)^-$	$(0,0)$



See Jen Pursley's talks in the young scientist forum on Tuesday!

The B$_s$ system



$\mathrm{B_s}$ transforms into $\bar{\mathrm{B}}_\mathrm{s}$

$$i\frac{\partial}{\partial t}\left| \begin{array}{c} B_s \\ \bar{B}_s \end{array} \right\rangle = \left(\begin{array}{cc} m_{11} - \frac{i}{2}\Gamma_{11} & m_{12}e^{-i\phi} - \frac{i}{2}\Gamma_{12} \\ m_{21}e^{-i\phi} - \frac{i}{2}\Gamma_{21} & m_{11} - \frac{i}{2}\Gamma_{11} \end{array} \right) \left| \begin{array}{c} B_s \\ \bar{B}_s \end{array} \right\rangle$$

mass eigenstates are linear combinations.

e.g if no cp violation:

$$|B_H\rangle = \frac{1}{\sqrt{2}}(|B\rangle - |\bar{B}\rangle \qquad |B_L\rangle = \frac{1}{\sqrt{2}}(|B\rangle + |\bar{B}\rangle$$

$$\mathrm{SM}: \quad \phi \approx 0$$

Two questions for the rest of this talk:

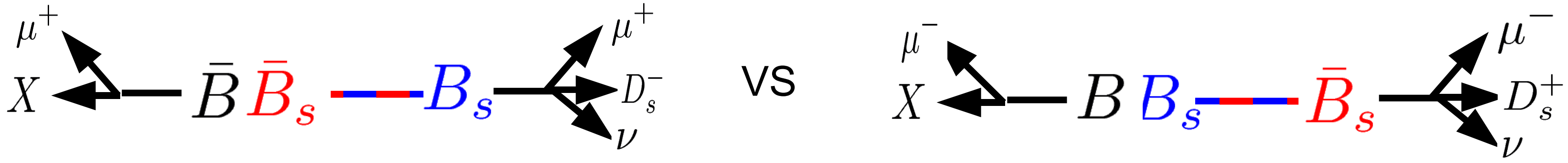
- Does this process violate CP conservation: what is the value of ϕ?
  - two handles:
    - charge asymmetry in a sample of semileptonic B$_s$ decays $A_{SL}^{B_s} = \tan(\phi_s)\frac{\Delta\Gamma_s}{\Delta m_s}$
      - look for net production of B$_s$ or $\bar{\mathrm{B}}_\mathrm{s}$
    - lifetime difference between B_H and B_L

$$\Delta\Gamma = \Gamma_L - \Gamma_H \approx \Delta\Gamma_{CP,SM}\cos(\phi)$$

- Is the oscillation frequency consistent with the SM prediction

$$\Delta m = m_H - m_L = 2|m_{12}|$$

Charge asymmetry measurements



- Two measurements:
  - Inclusive, tagged measurement for B mesons measured with 310k dimuon pairs

$$A_{SL}^{\mu\mu} = \frac{N(b\bar{b} \to \mu^+\mu^+X) - N(b\bar{b} \to \mu^-\mu^-X)}{N(b\bar{b} \to \mu^+\mu^+X) + N(b\bar{b} \to \mu^-\mu^-X)}. = -0.0092 \pm 0.0044 \pm 0.0032$$

    - contributions for B_d and B_s: combine with B-factory results to extract:

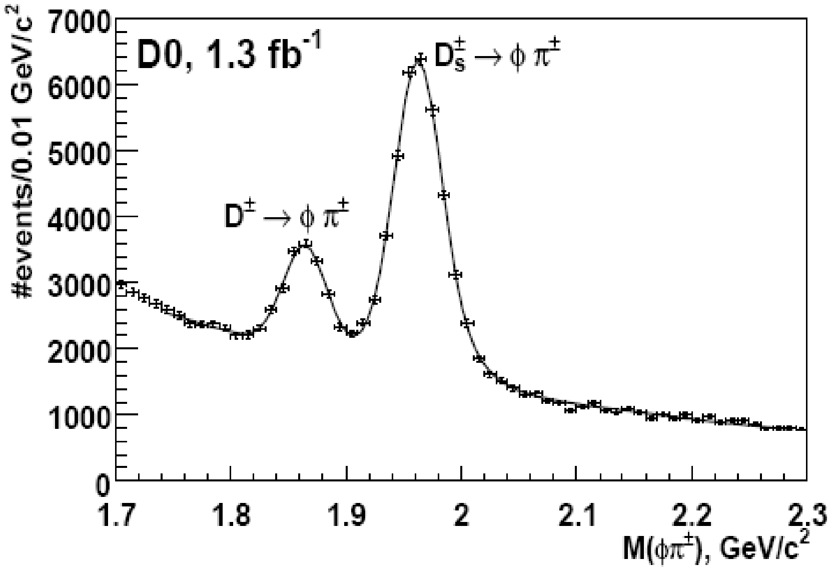
$$A_{SL}^{B_s} = -0.0064 \pm 0.0101$$

  - Untagged asymmetry in sample of $B_s \to \mu D_s$

$$A_{SL}^{B_s} = \frac{N(D_s\mu^+) - N(D_s\mu^-)}{N(D_s\mu^+) + N(D_s\mu^-)} = 0.0245 \pm 0.0193 \pm 0.0035$$

$$\text{combined}: \quad A_{SL}^{B_s} = 0.0001 \pm 0.0090$$

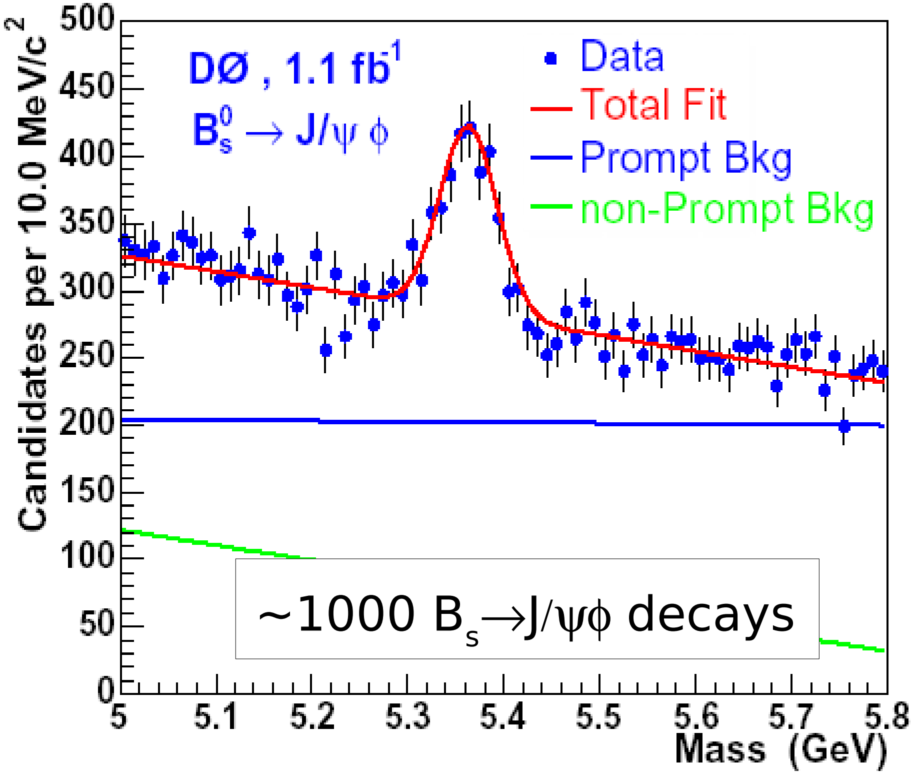
consistent with 0: no evidence for CP violation



Systematics greatly reduced by regular flipping of D0's B-fields

PRD 74, 092001 (2006)
hep-ex/0701007

$\Delta\Gamma_s$ angular analysis on $B_s \to J/\psi\phi$

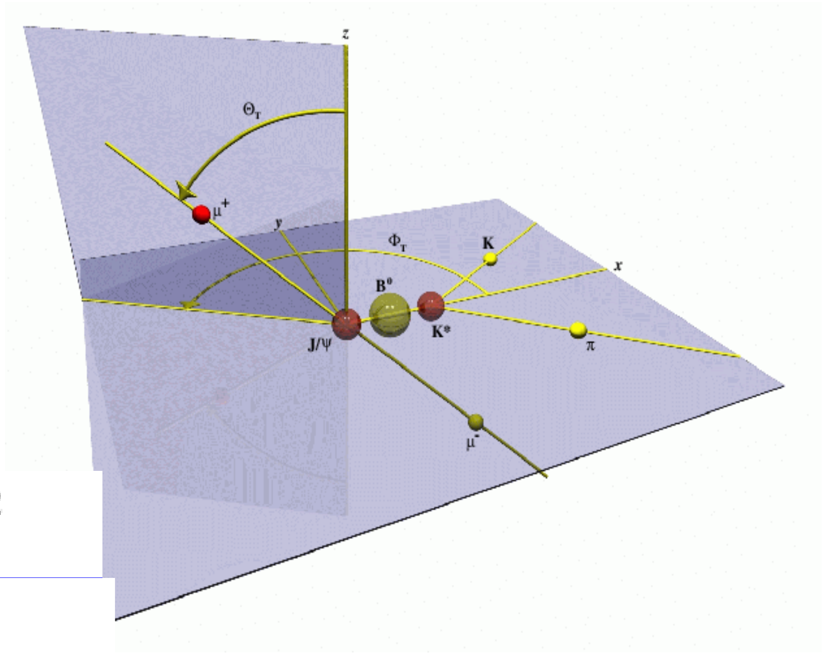


~1000 $B_s \to J/\psi\phi$ decays

Angular analysis::

- Three angles θ, ψ, φ to resolve CP even/odd components as function of time
- untagged analysis, can still extract:

$$\bar{\Gamma}, \Delta\Gamma_s, \phi_s, A_0, A_{||}, A_{\perp}, \delta_1, \delta_2$$



schematically

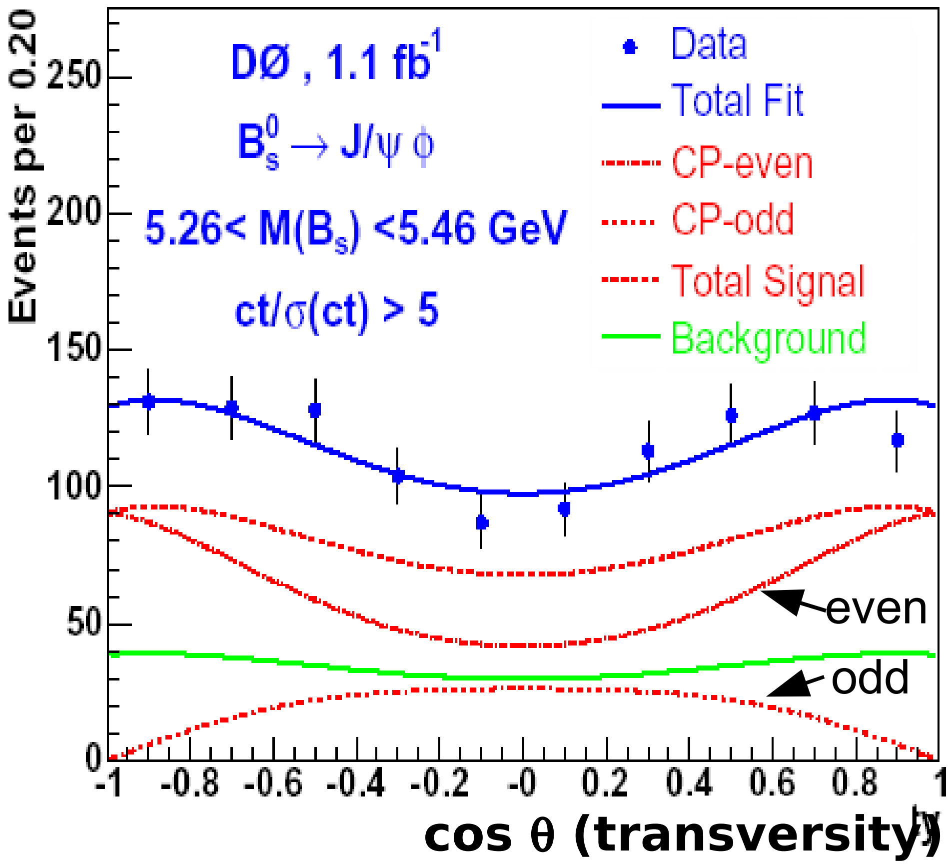
$$\Gamma(t) \approx \left|A_{even}(\theta,\psi,\varphi,t)\right|^2 + \left|A_{odd}(\theta,\psi,\varphi,t)\right|^2$$

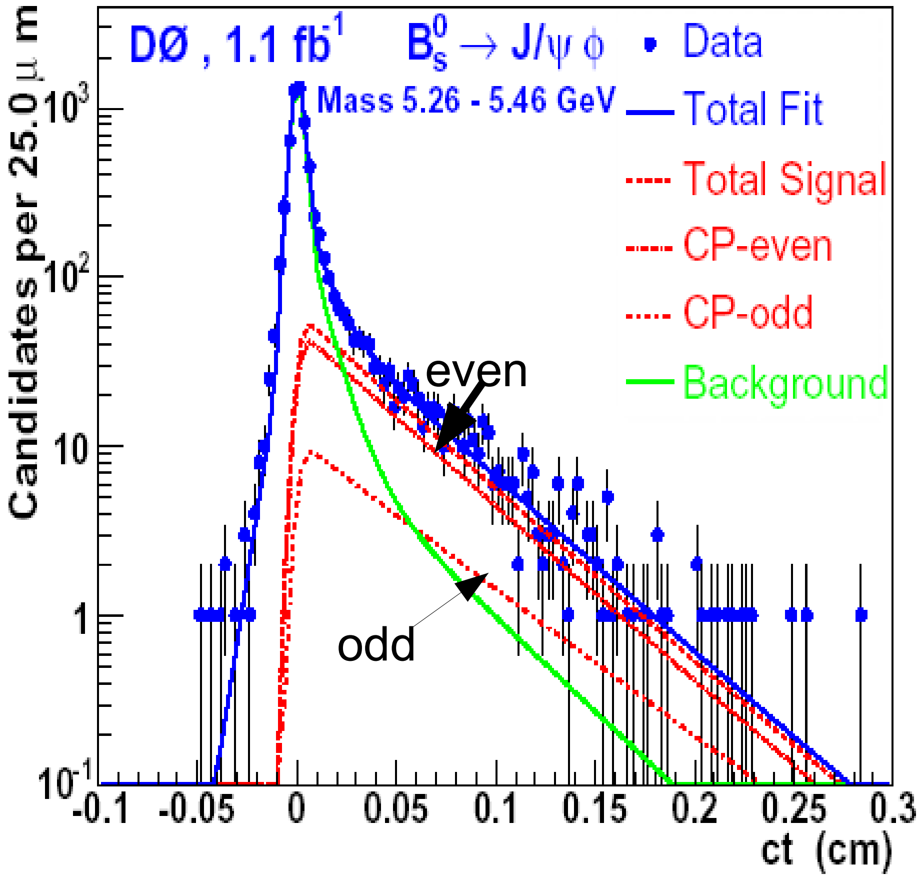
$+A^* A(CPC)$ ◄— cp conserving interference

$+A^* A(CPV)(e^{-\Gamma_L t} - e^{-\Gamma_H t})\sin\phi_s$ ◄— cp violating interference

$\Delta\Gamma_s$ Assuming no CP violation

Assume no CP violation (ϕ=0), then $\Delta\Gamma = \Delta\Gamma^{CP}$
 -> separate CP-odd and CP-even states.





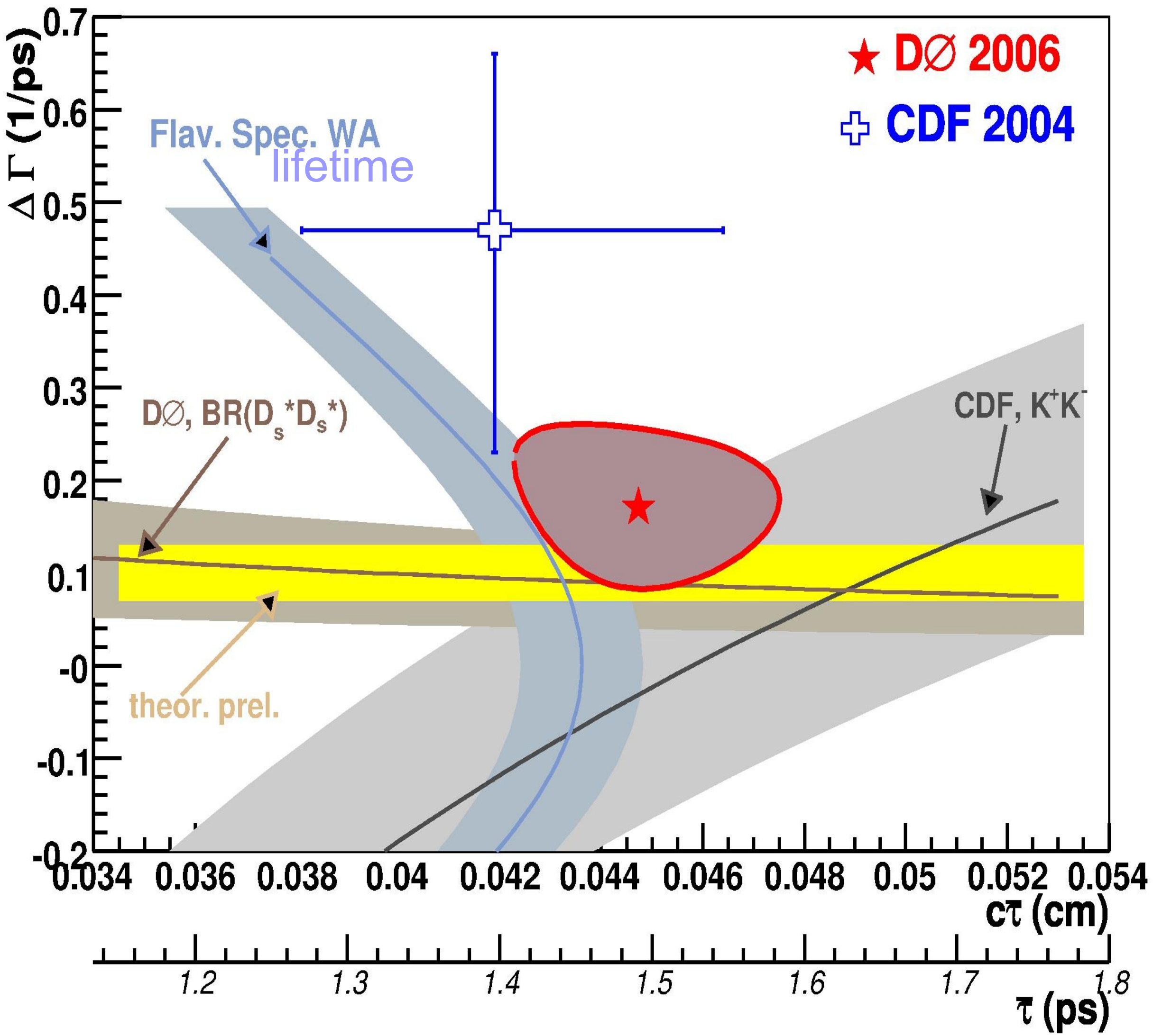
$$\Delta\Gamma_s = 0.12^{+0.08}_{-0.10} \pm 0.03\ \mathrm{ps}^{-1}$$

hep-ex/0702049

$\Delta\Gamma_s$ Allowing for CP violation

$$\Delta\Gamma_s = 0.17 \pm 0.08 \pm 0.02 \text{ ps}^{-1}$$
$$|\phi_s| = 0.79 \pm 0.56$$
$$\bar{\tau} = 1.49 \pm 0.08 \text{ ps}$$

Different measurements & SM prediction give consistent picture



BR(Ds(*)Ds(*)) : hep-ex/0702049
theor pred: hep-ph/0406300
CDF: Phys.Rev.Lett. 94 (2005) 101803

$\Delta\Gamma_s$ and ϕ_s combined

combine with measurement of
time integrated charge asymmetry

$$A^s_{\mathrm{SL}} = 0.0001 \pm 0.0090 = \tan(\phi_s)\frac{\Delta\Gamma_s}{\Delta m_s}$$

And world-average flavour specific lifetime

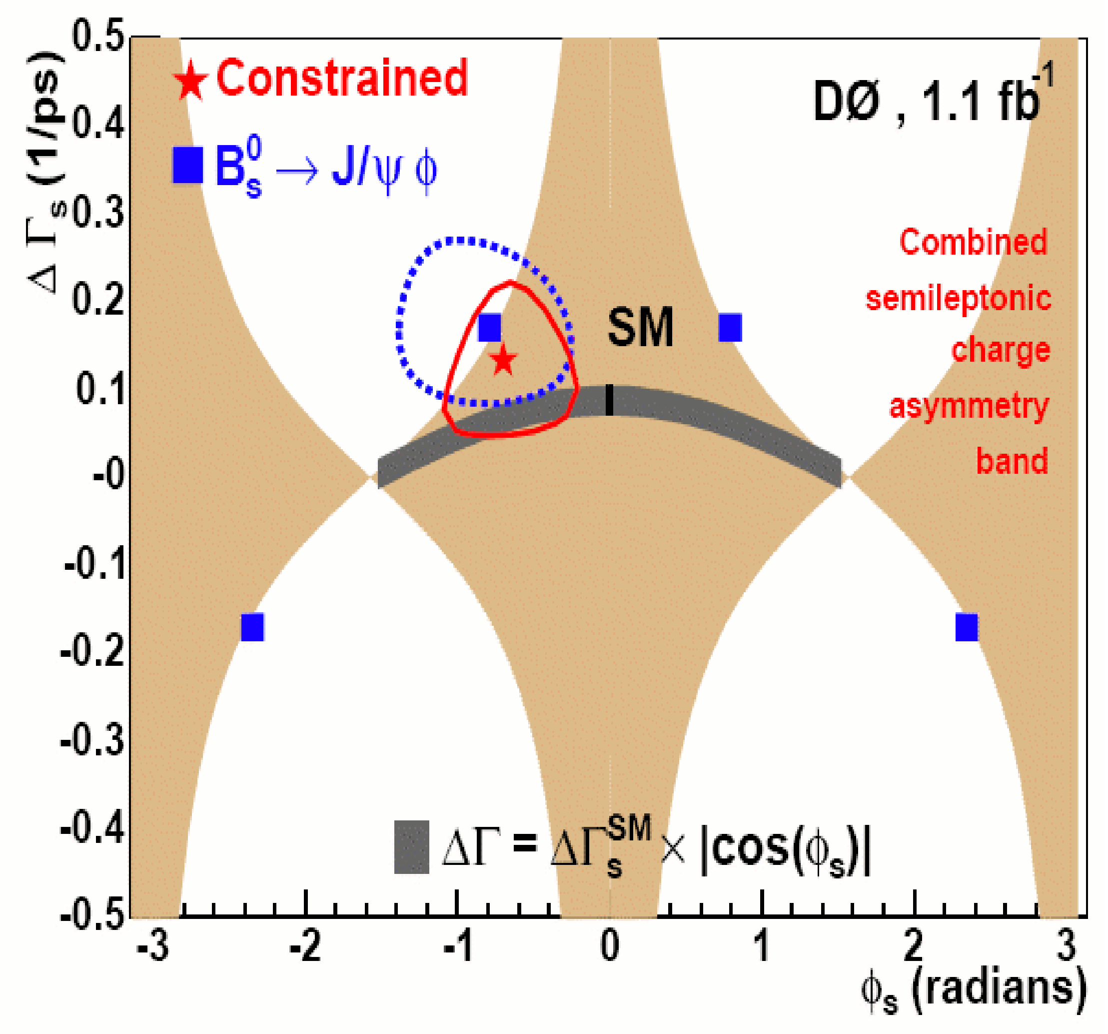
$$\Delta\Gamma_s = 0.13 \pm 0.9 \text{ ps}^{-1}$$

$$\phi_s = -0.70^{+0.47}_{-0.39}$$

SM prediction (hep-ph/0406300)

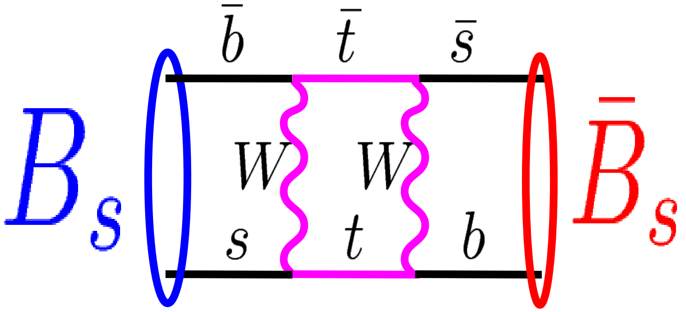
$$\Delta\Gamma_s = 0.10 \pm 0.03 \text{ ps}^{-1}$$

$$\phi_s = -0.03 \pm 0.005$$



$\Delta\Gamma$ non-zero & consistent with SM!

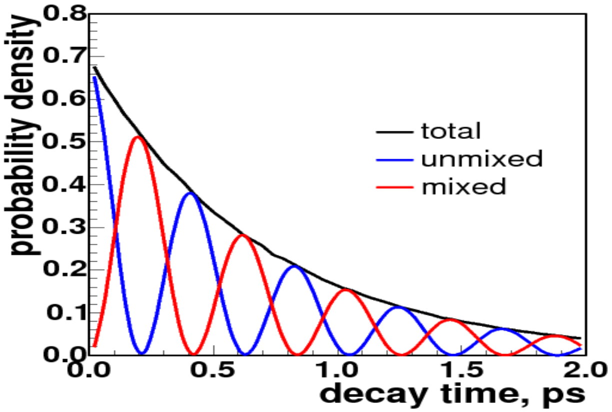
B_s oscillations



Oscillation frequency is given by the mass difference between the two mass eigenstates.

in the SM:

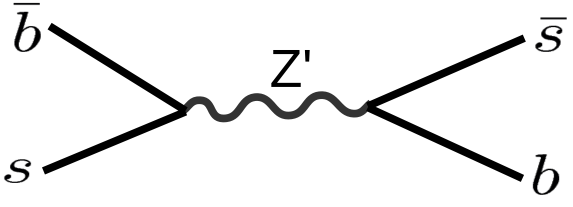
$$\Delta m_s = \frac{G_F^2 M_W^2 \eta S(m_t^2/m_W^2)}{6\pi^2} m_{B_s} f_{B_{B_s}}^2 |V_{ts}^* V_{tb}|^2$$



hadronic uncertainties reduced in ratio:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2} \qquad \xi = 1.21^{+0.047}_{-0.035}$$

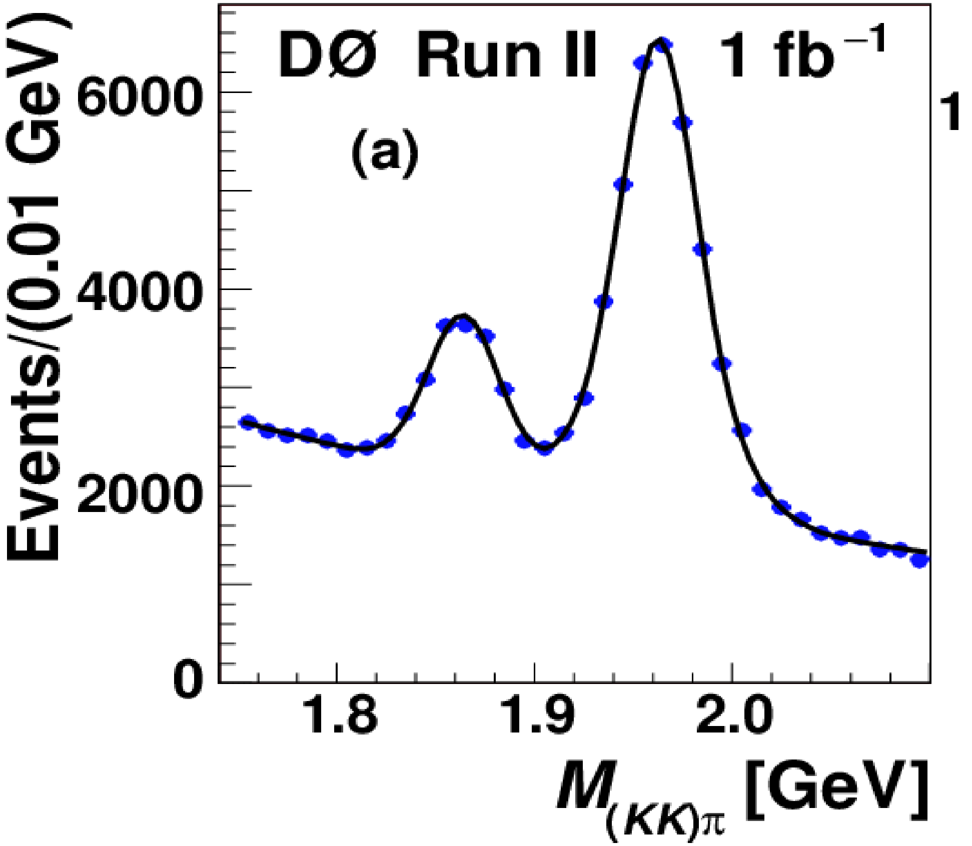
Δm_s gives powerful check of CKM unitarity

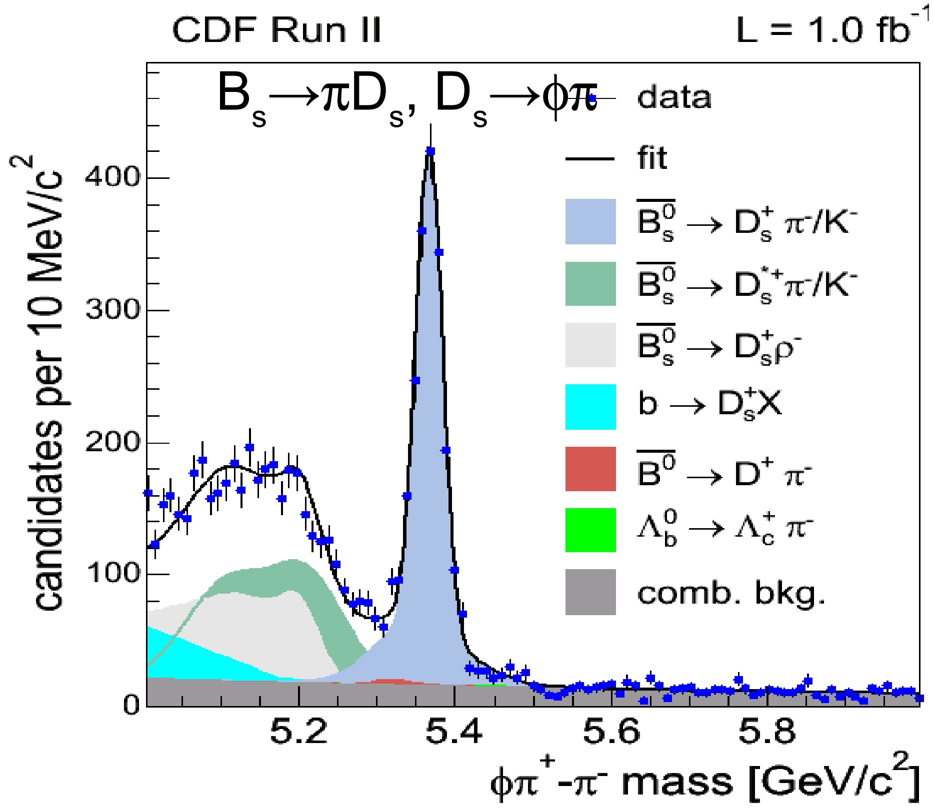


new physics can result in non-SM value of Δm_s

observing Bs oscillations was a major objective of the Tevatron physics program

B_s oscillations : signals





$\sim 27.000\ B_s \to \mu D_s(\phi\pi)X$

$\sim 12.600\ B_s \to \mu D_s(K^*K)X$

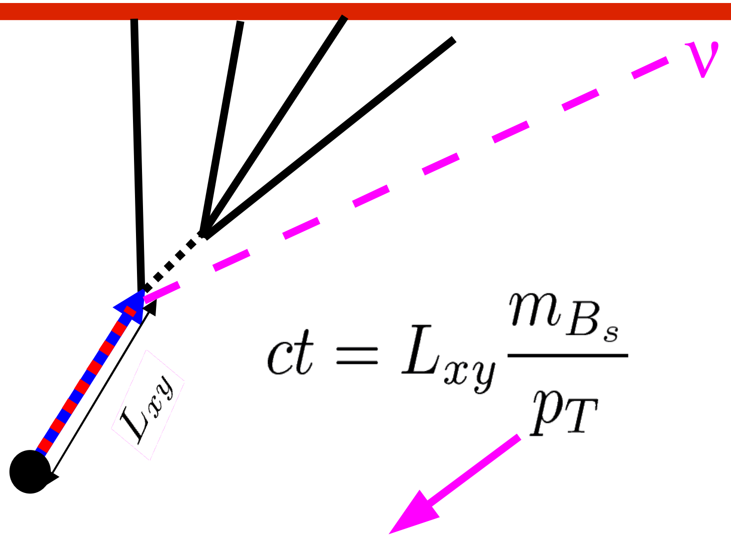
$\sim 2000\ B_s \to e D_s(\phi\pi)X$

$\sim 600\ B_s \to \mu D_s(K_s K)X$

42k partially reconstructed events

~5600 fully rec. hadronic (6 modes)
~3100 partially rec. hadronic (2 modes)
~61.500 semileptonic (eD_sX & μD_sX)
(6 modes)

Bs oscillations : decay time

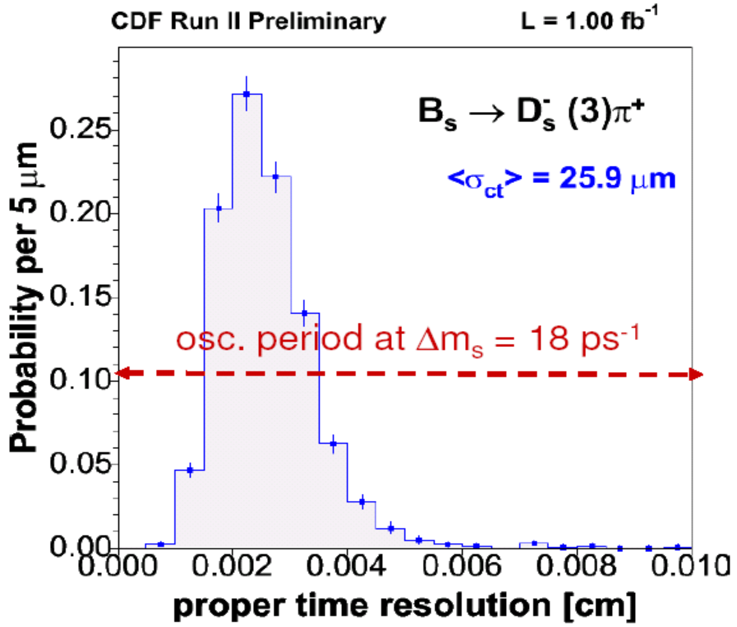


$$ct = L_{xy}\frac{m_{B_s}}{p_T}$$

Can not accurately measure p_T for partially reconstructed events

- degraded decay time resolution
- (fully rec.) hadronic modes by CDF most powerful.

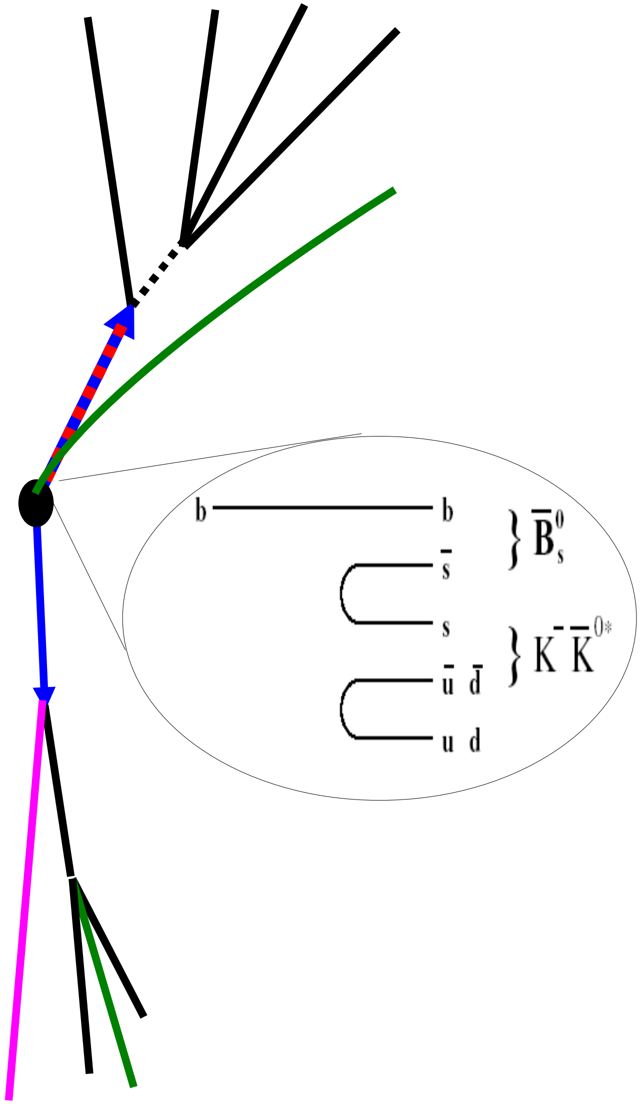
- σ_{ct} is measured on auxiliary data samples
- The best events have: $\sigma_{ct} \approx$ ¼ osc. period



Mode	$<\sigma(ct)>$ [μm]
$B_s \to D_s(3)\pi$ (CDF)	26
$B_s \to \ell D_s X$ (CDF)	45
$B_s \to \mu D_s X$ (D0)	50-60

(Δm_s = 18 ps^{-1} $\approx$ 100μm)

Bs oscillations : initial flavor tagging



Opposite side tagging (OST):

- Look at the decay products of the other b quark in the event to determine B_s production flavor
    - Lepton
    - Kaon
    - Charge of the b-jet
    - The two b quarks fragment *independently*: can calibrate opposite side taggers with B_d & B_u
    - Opposite side often outside acceptance
    - CDF: combined OST quality $\varepsilon D^2 = 1.8\%$
    - D0: $\varepsilon D^2 = 2.5\%$

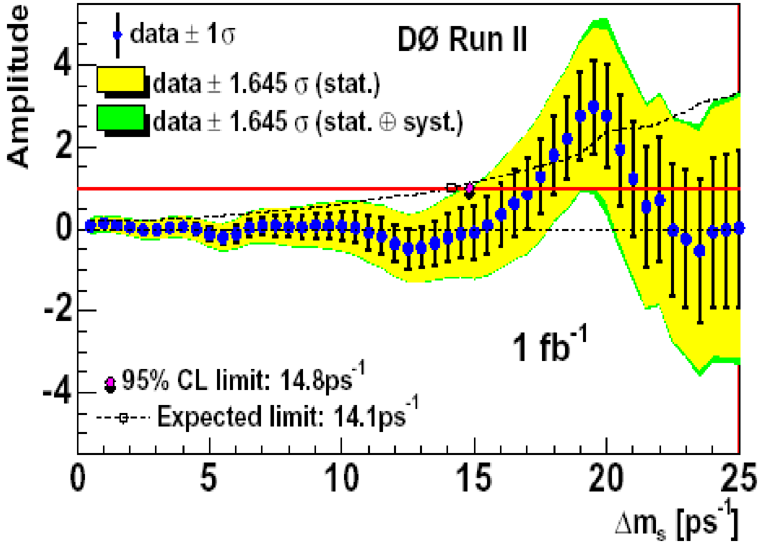
Same side kaon tagging (CDF only):

- Fragmentation into B_s tends to produce Kaon
    - Charge of K identifies B_s flavor at production
    - Find these kaons using Time-of-flight, dE/dx and kinematical variables in NN.
- Need to understand MC to predict power: extensive checks
- High efficiency, since K is close to the B_s
- >2 times as powerful as OST: $\varepsilon D^2 = 3.5\%$ (had) / 4.8% (SL

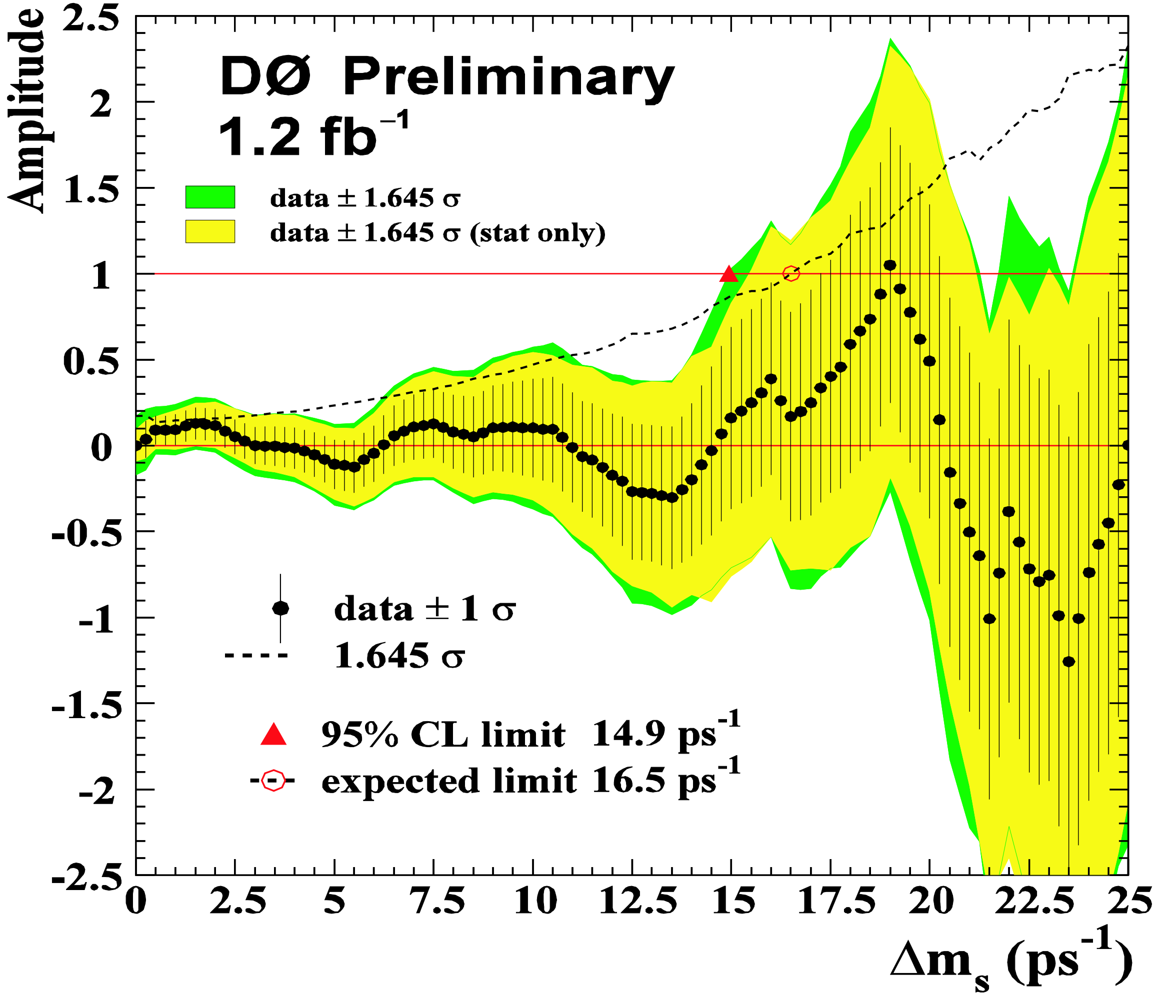
In future, taggers will be used to resolve oscillations in $B_s \rightarrow J/\psi\phi$ analysis

B_s oscillations : D0 results

march 2005 result:
Phys Rev. Lett. 97, (2006) 061802



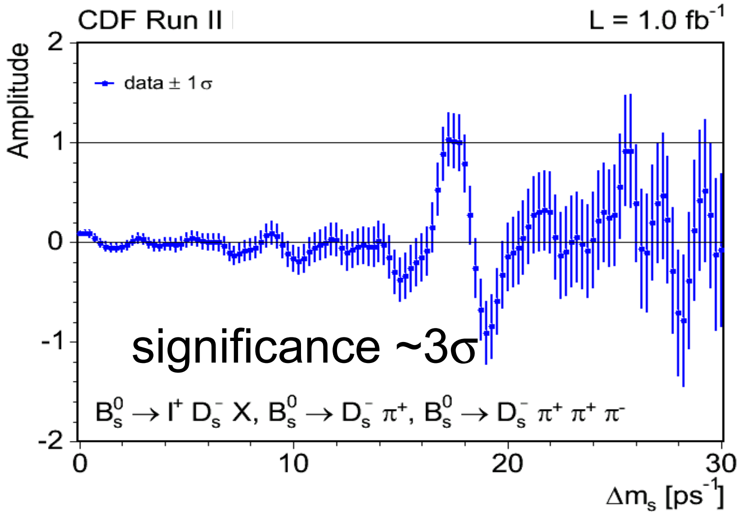
since then:
Additional signal: Bs→e Ds +X
and Bs→μ Ds with Ds→K*K
and Bs→μ Ds with Ds→K_sK



amplitude consistent with 1 around $\Delta m_s = 18$ ps^{-1}
double sided 90% CL limit $17 < \Delta m_s < 21$ ps^{-1}
p-value (false probability) = 8%

Bs oscillations: CDF results

April 2005, Phys Rev Lett. 97 (2006) 062003

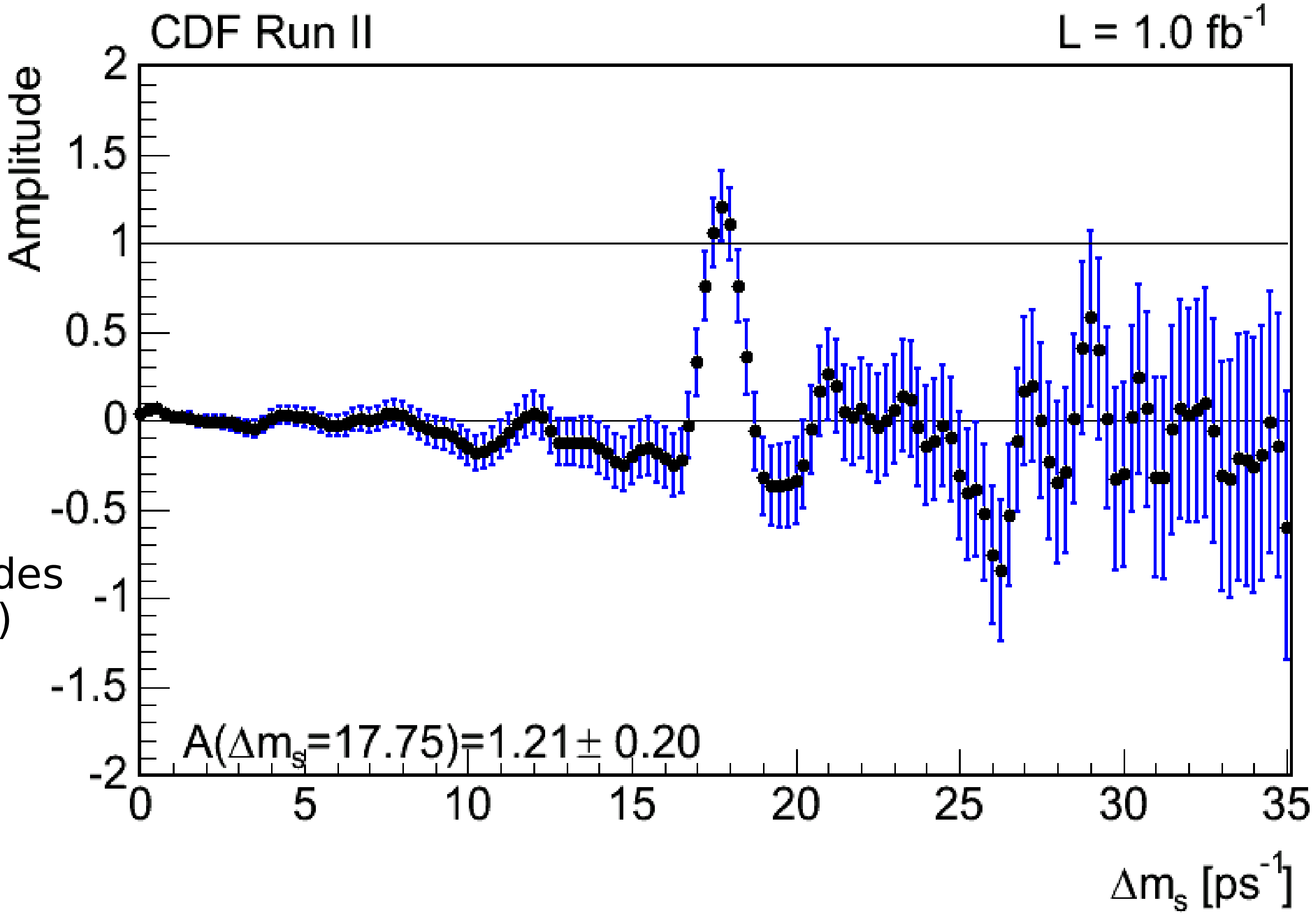


significance ~3σ

since then:

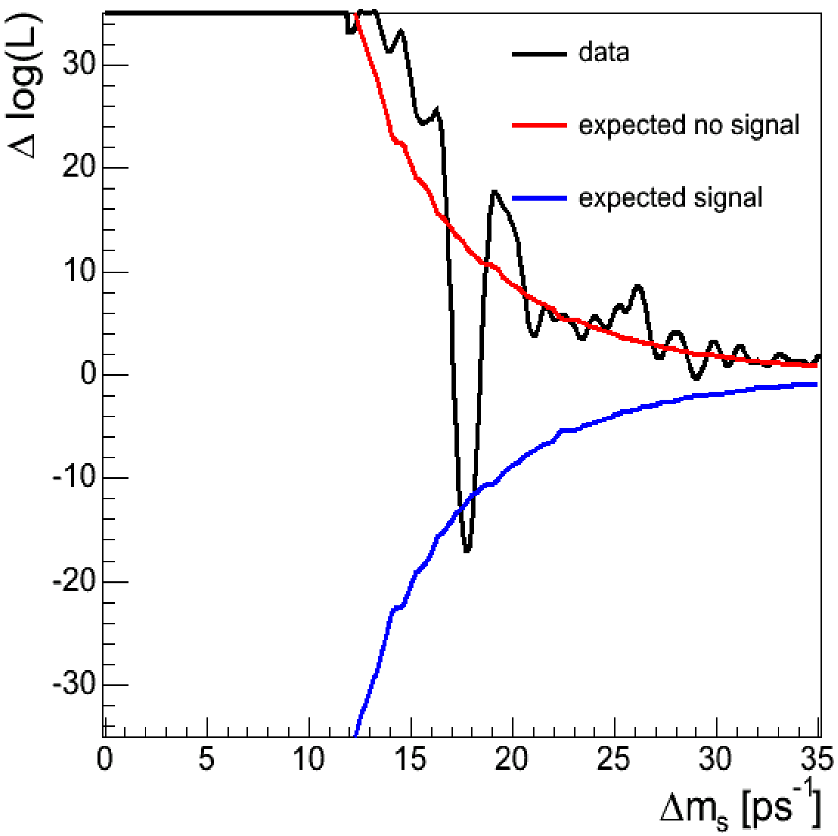
- added partially rec. hadronic modes
- NN and particle ID (TOF & dE/dX) for signal selection
- smarter tagger combination

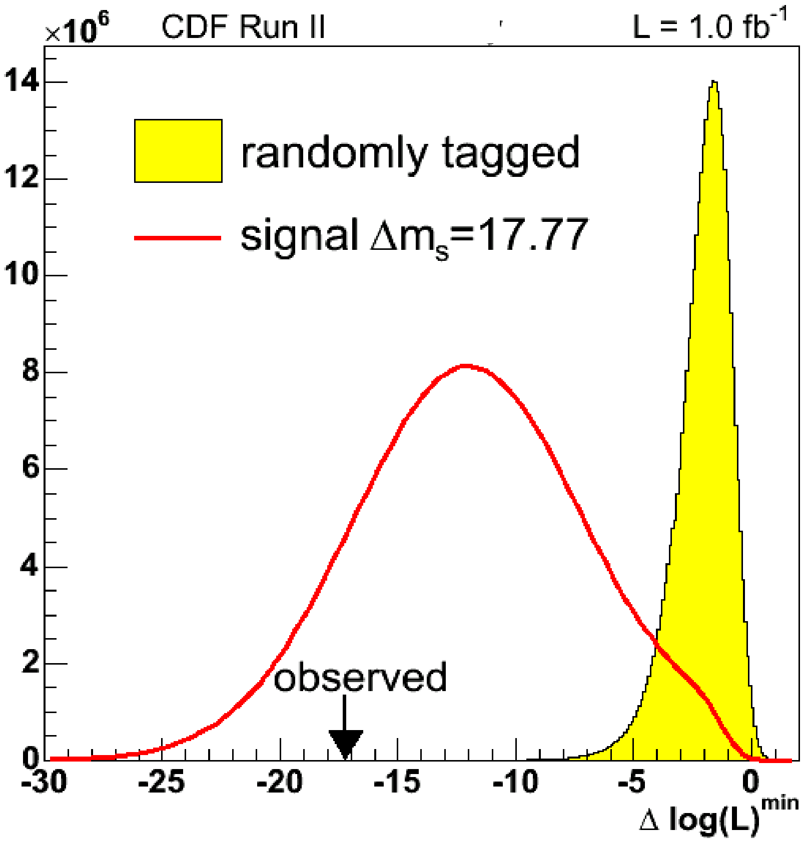
Current result Phys. Rev. Lett. 97, 242003 (2006)



$A(\Delta m_s=17.75)=1.21 \pm 0.20$

B_s oscillations : CDF results





$$p - \text{value} = 8 \times 10^{-8} \quad \text{significance} : 5.4\sigma$$

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

$$\frac{|V_{td}|}{|V_{ts}|} = 0.2060 \ \pm 0.0007(\text{exp})\ ^{+0.0081}_{-0.0060}(\text{theo})$$

Conclusions

- Tevatron is combing the B_s system for new physics
  - precision measurements on $\Delta\Gamma_s$ and CP violating phase ϕ_s

    $$\Delta\Gamma_s = 0.13 \pm 0.9 \text{ ps}^{-1} \quad \phi_s = -0.70^{+0.47}_{-0.39}$$

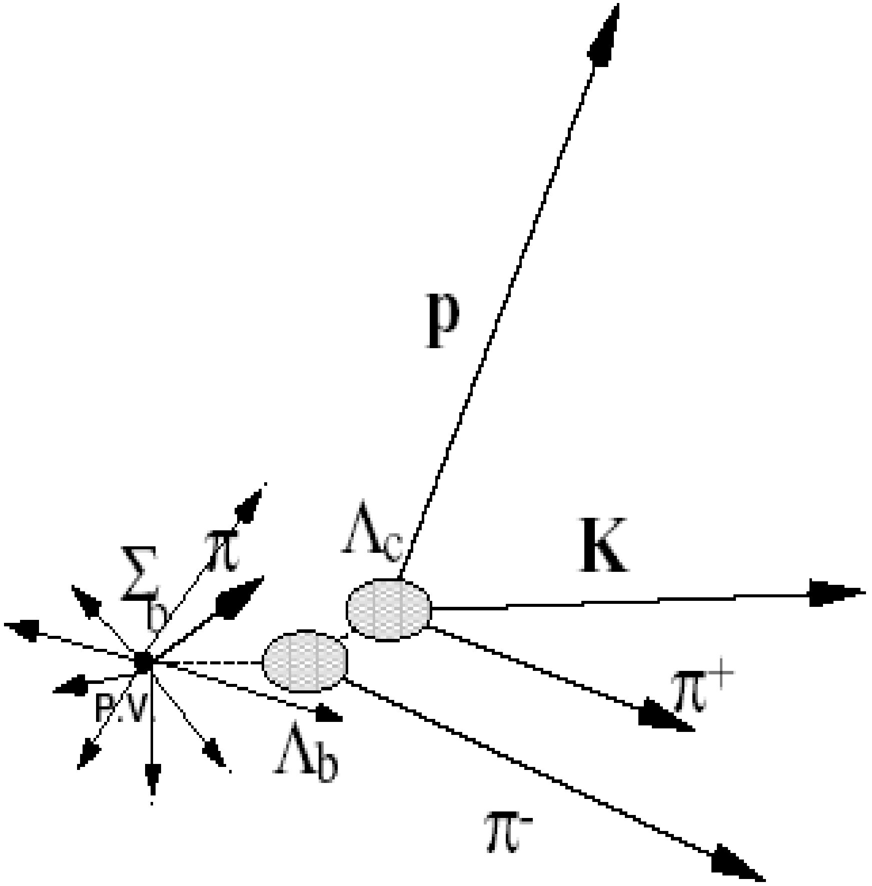
  - B_s oscillations seen by both experiments:
    signal >5σ significant and Δm_s measured with <1% accuracy

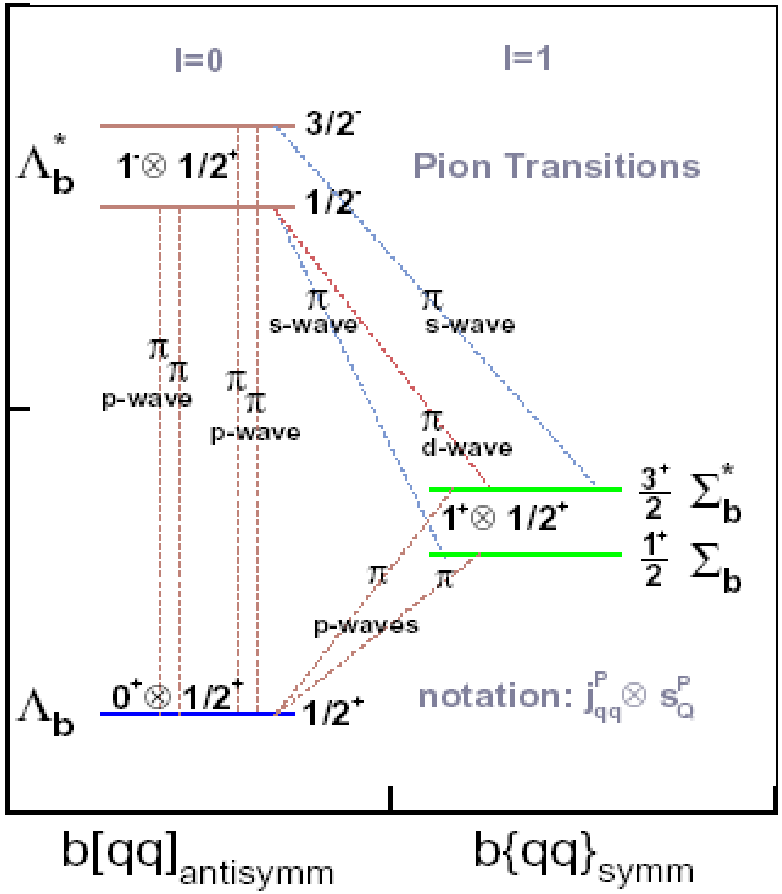
    $$\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})$$

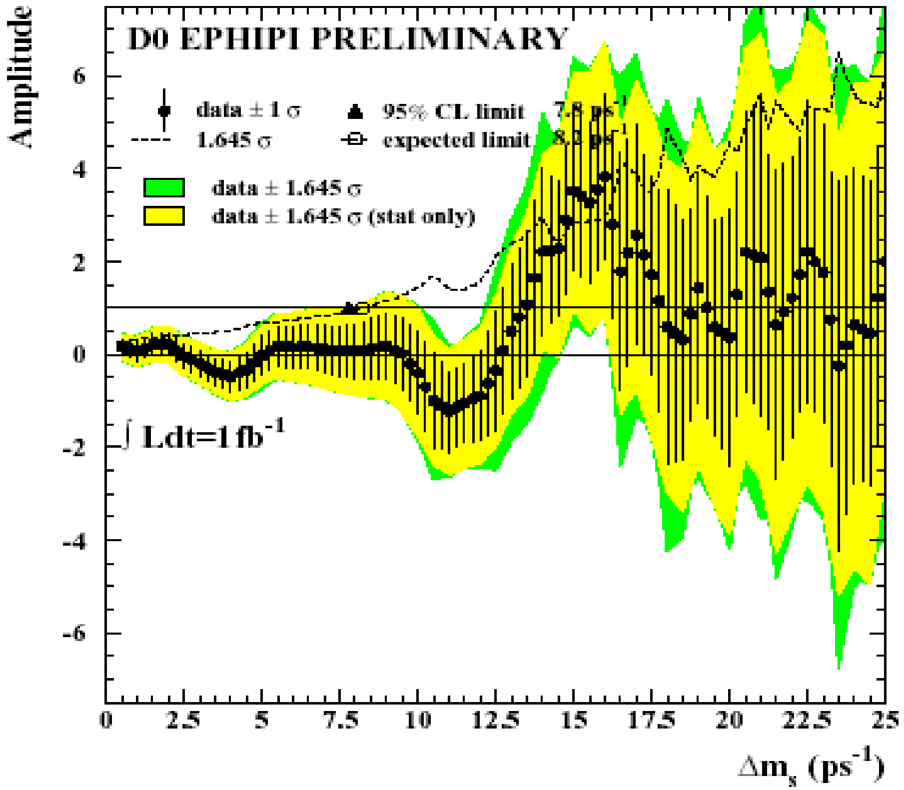
    consistent with SM prediction

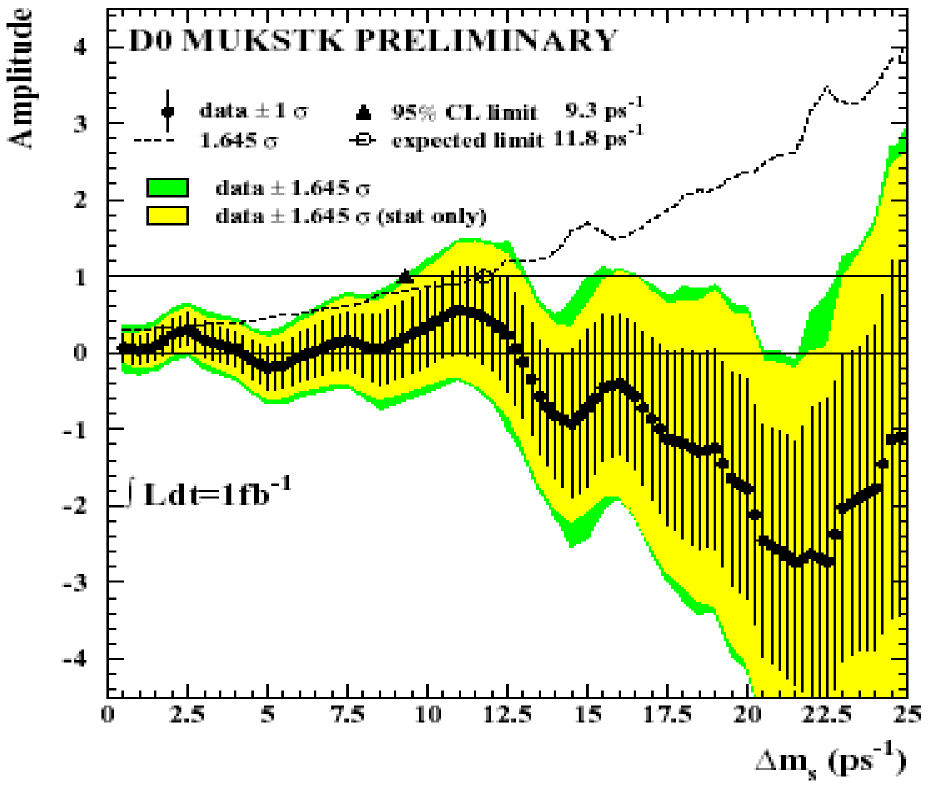
- Much more B-physics ongoing...
  - Discovery of new b-baryons Σ_b and Σ_b^*
- ...and still to come:
  - ~twice the luminosity already on tape

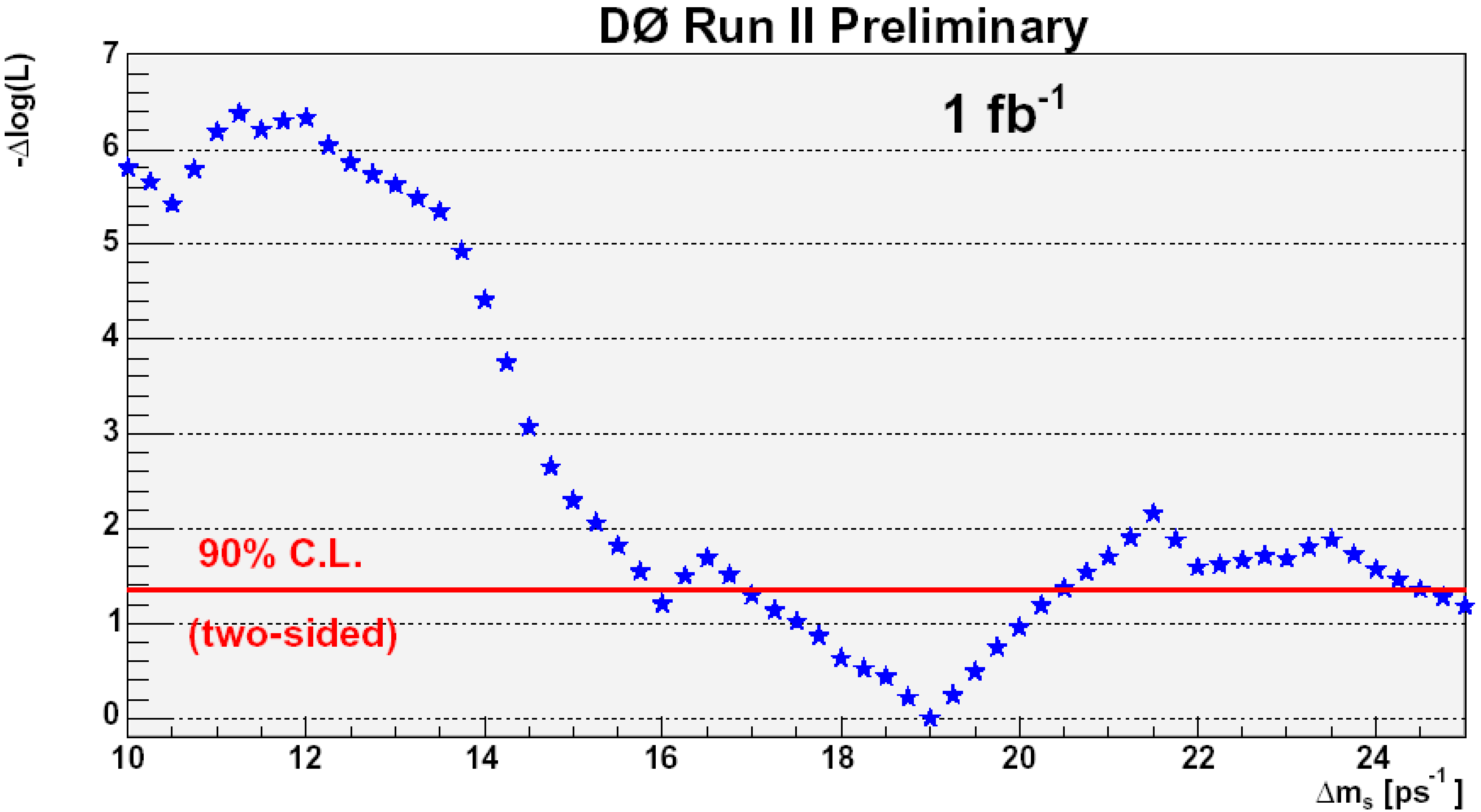
BACKUP


p
K
Λc
Σb
π
π+
π-
P.V.
Λb


I=0
I=1
3/2-
Λb*
1-⊗ 1/2+
1/2-
Pion Transitions
π s-wave
π s-wave
π π p-wave
π π p-wave
π d-wave
3+/2 Σb*
1+⊗ 1/2+
1+/2 Σb
π π p-waves
0+⊗ 1/2+
1/2+
Λb
notation: jqqP ⊗ sQP
b[qq]antisymm
b{qq}symm

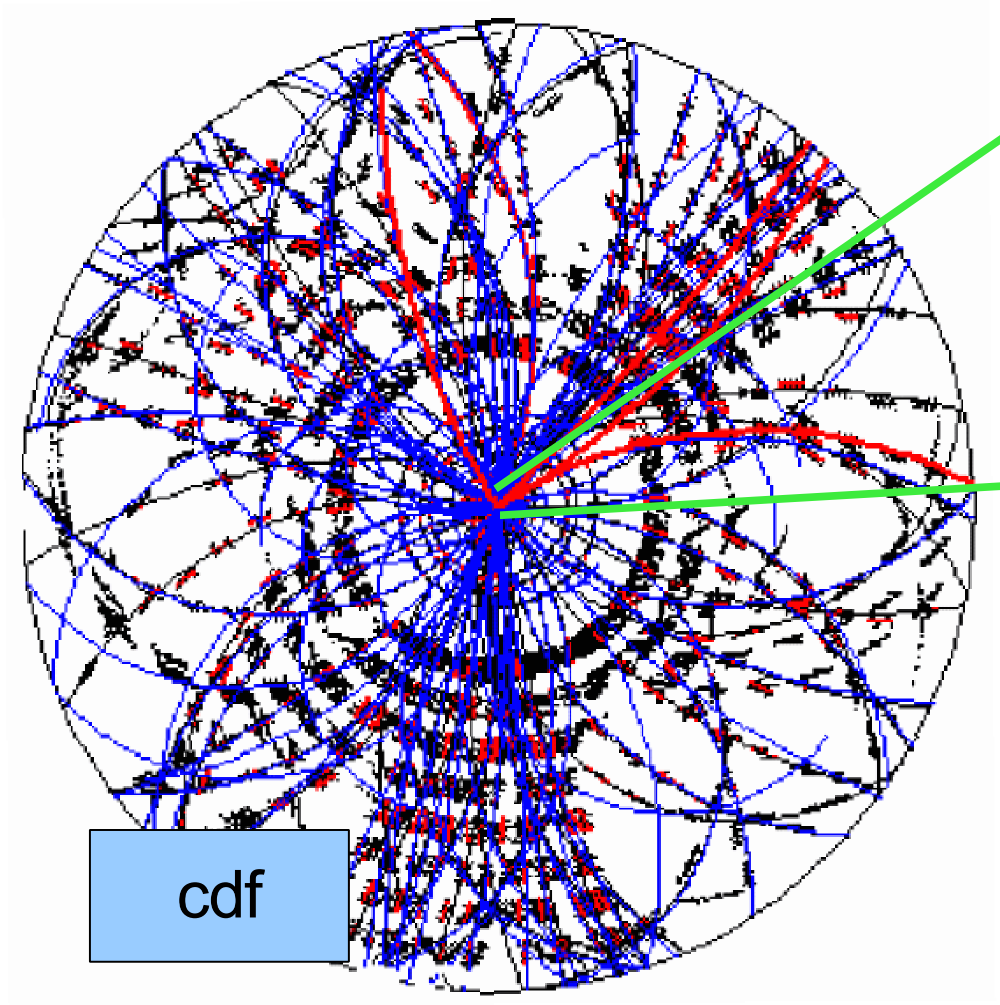

D0 EPHIPI PRELIMINARY
data ± 1 σ
1.645 σ
95% CL limit 7.8 ps^{-1}
expected limit 8.3 ps^{-1}
data ± 1.645 σ
data ± 1.645 σ (stat only)
∫ Ldt=1 fb^{-1}
Amplitude
Δm_s (ps^{-1})
6
4
2
0
-2
-4
-6
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25


D0 MUKSTK PRELIMINARY
data ± 1 σ
1.645 σ
95% CL limit 9.3 ps^{-1}
expected limit 11.8 ps^{-1}
data ± 1.645 σ
data ± 1.645 σ (stat only)
∫ Ldt=1fb^{-1}
Amplitude
Δm_s (ps^{-1})
4
3
2
1
0
-1
-2
-3
-4
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25


DØ Run II Preliminary
1 fb^{-1}
-Δlog(L)
90% C.L.
(two-sided)
0
1
2
3
4
5
6
7
10
12
14
16
18
20
22
24
Δm$_s$ [ps^{-1}]

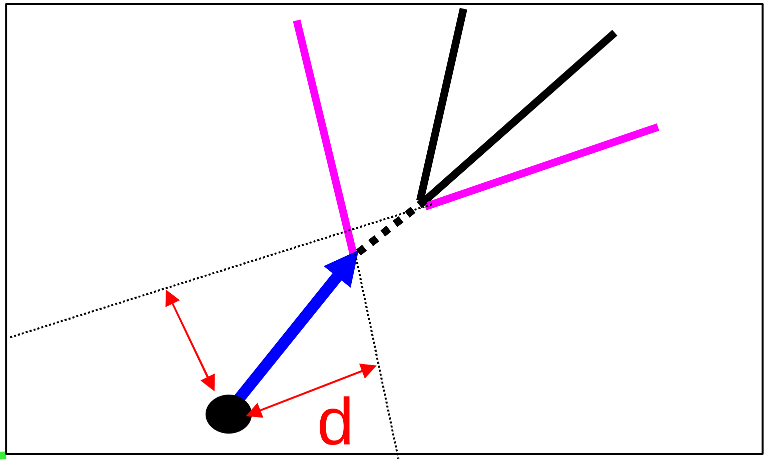
Displaced track trigger

A typical B event at a hadron collider

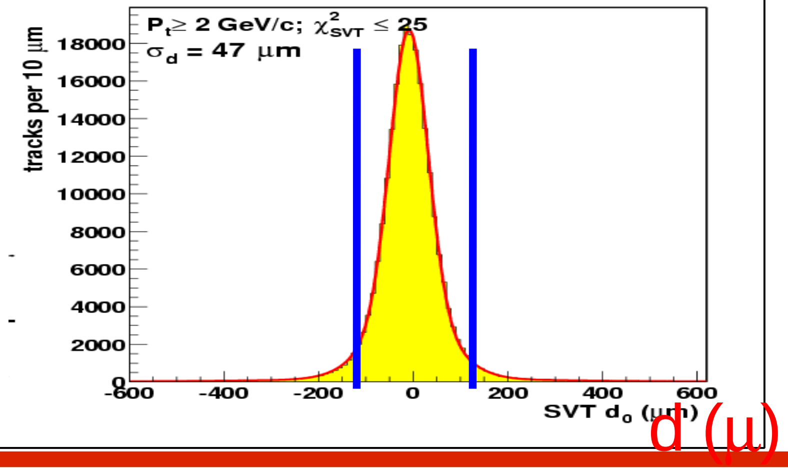


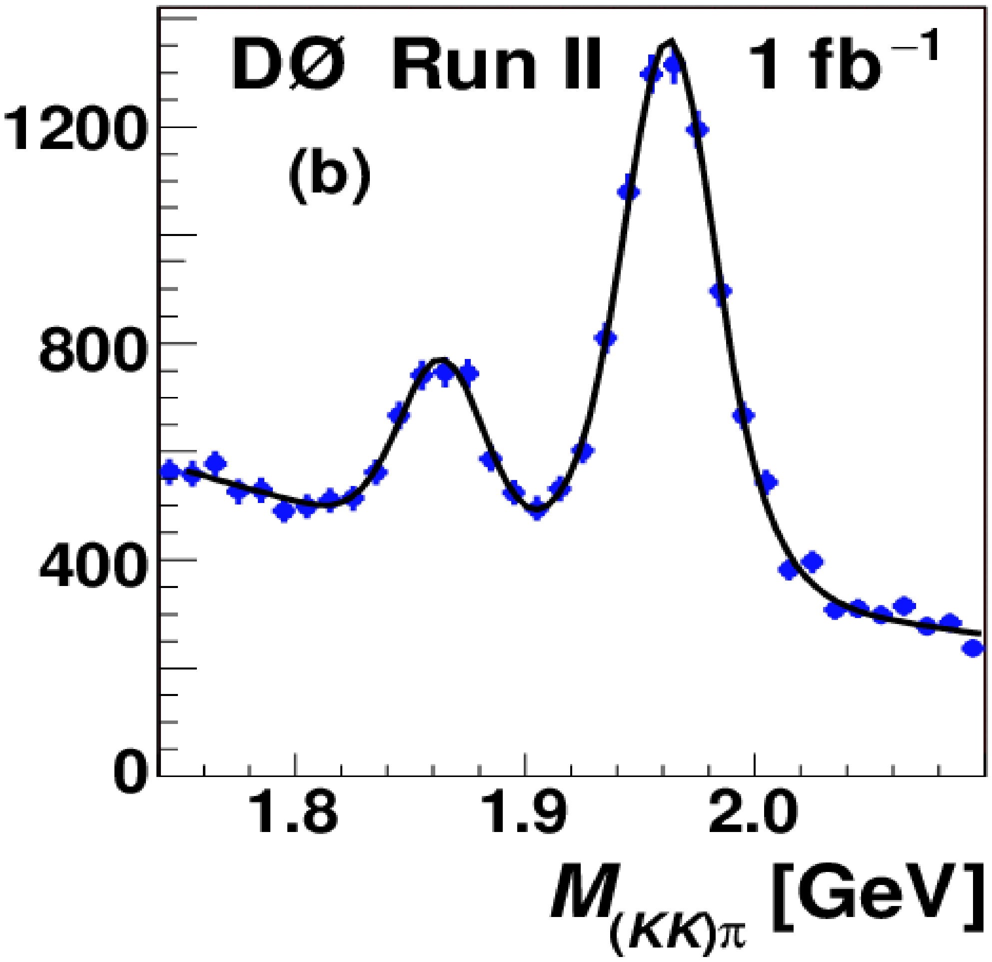
=> look for displaced tracks

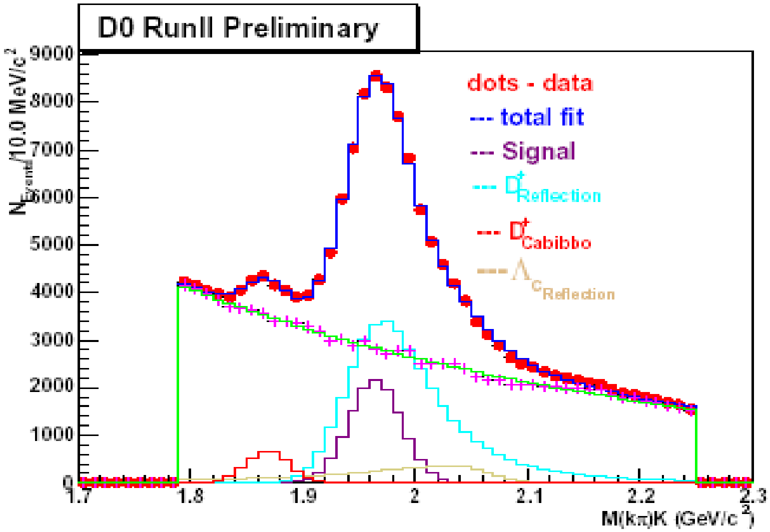
Trigger on events with two displaced (d>120 μm) tracks

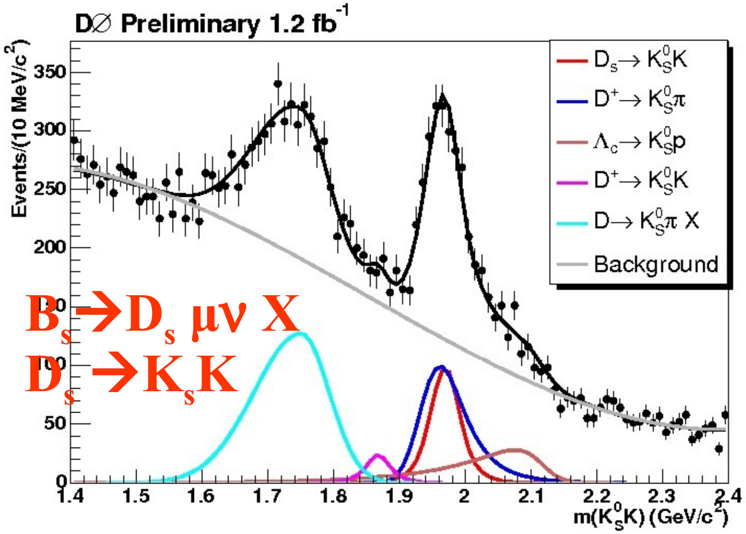


very fast reconstruction of silicon data at L2 (20μs latency) by dedicated hardware: SVT





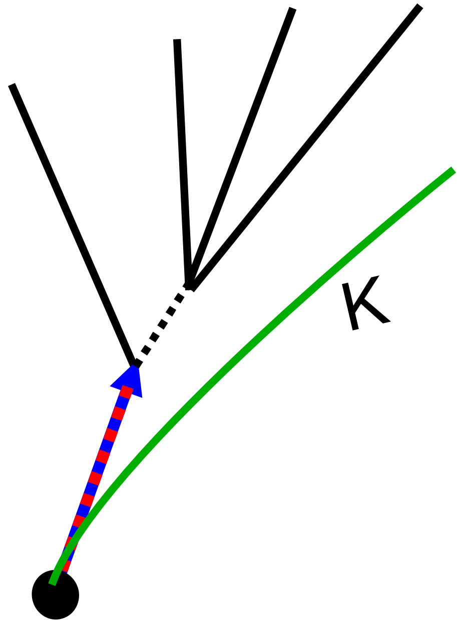


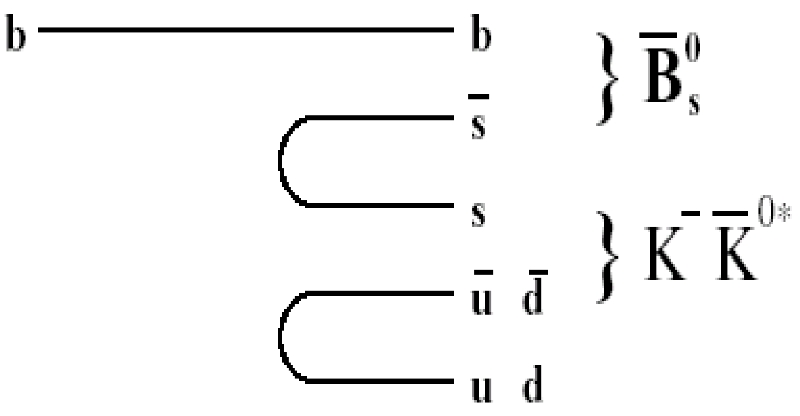


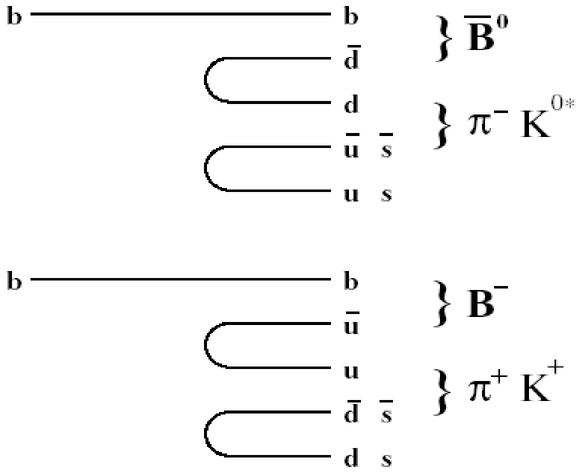
$B_s \to D_s\ \mu\nu\ X$

$D_s \to K_s K$

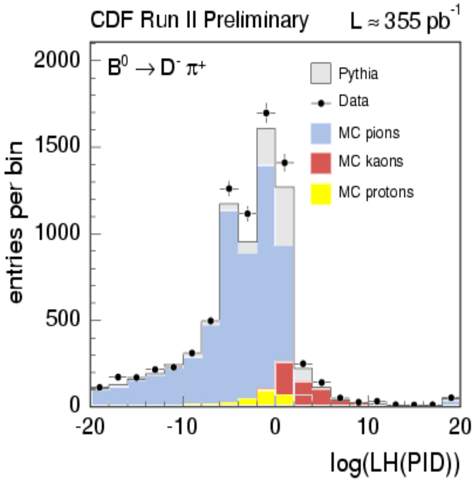
Same side kaon tagging



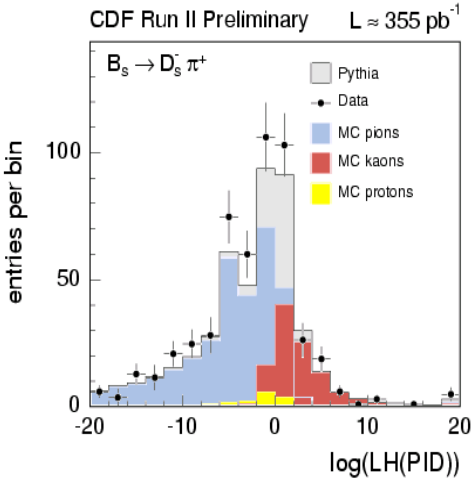


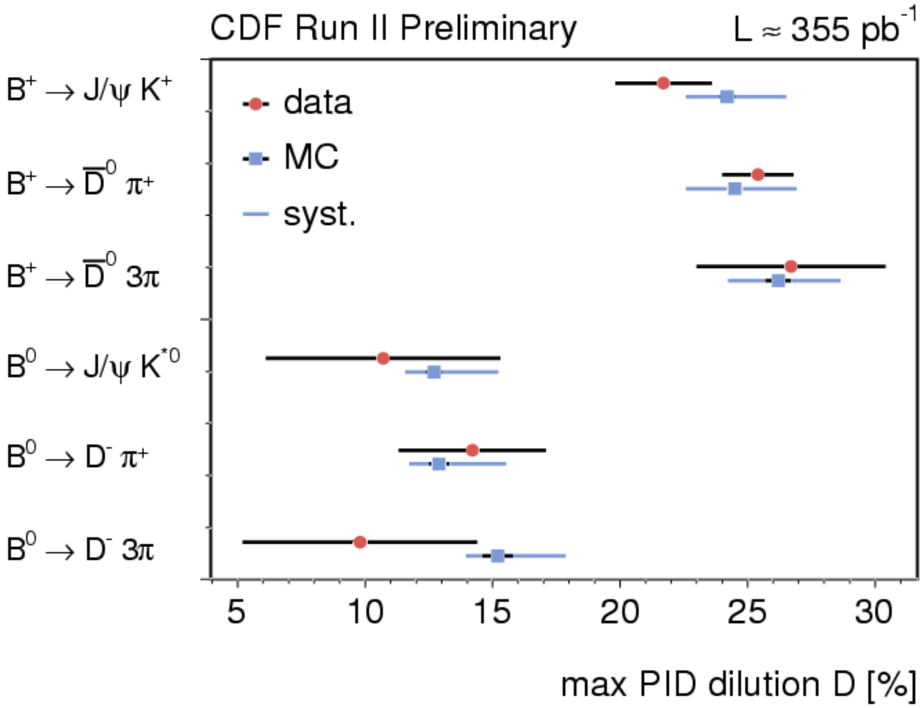


$B^0 \to D^- \pi^+$



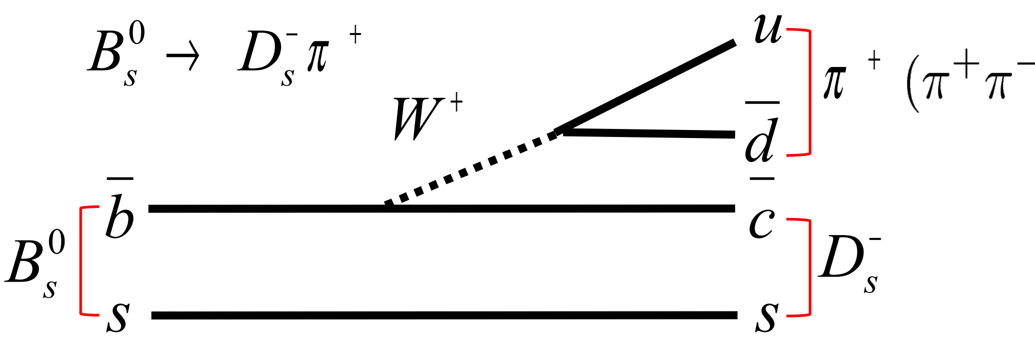
$B^0_s \to D^-_s(\phi\pi)\pi^+$





The signals

Hadronic

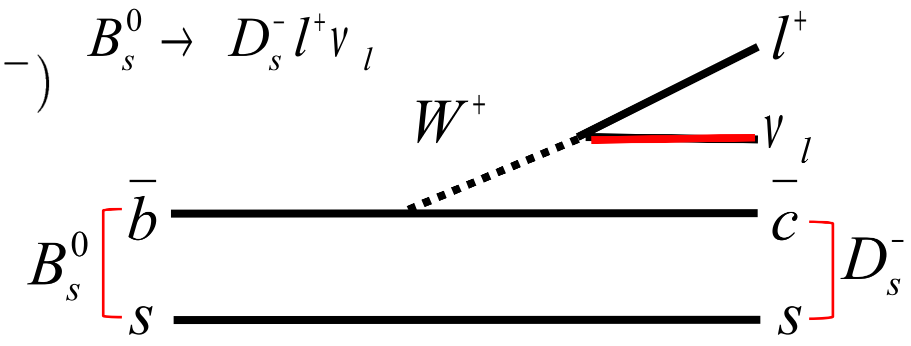


$\pi^+ \; (\pi^+\pi^-)$

- B_s Momentum is measured
- B_s mass used for good S/N
- Small branching ratio: low yield

$$D_s^- \to \phi\pi^-, \quad \phi \to K^+K^-;$$
$$D_s^- \to K^{*0}K^-, \quad K^{*0} \to K^+\pi^-;$$
$$D_s^- \to \pi^+\pi^-\pi^-.$$

Semileptonic



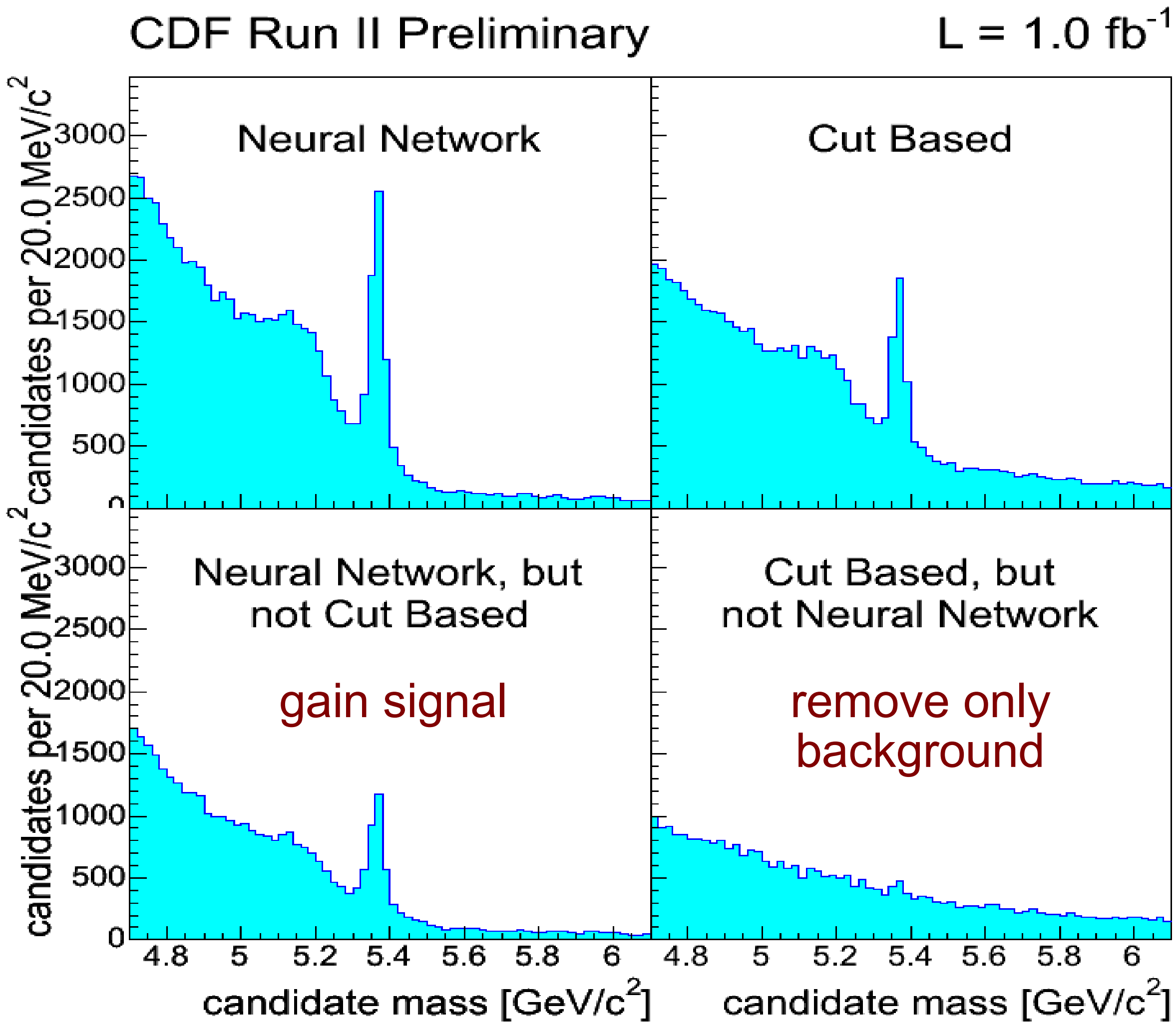
- Missing momentum (ν)
- Need to rely on D_s and D_s mass
- Large branching ratio: high yield

data collected using:

- Hadronic: Two Track Trigger
- semileptonic: TTT & lepton+SVT

SVT rules!

neural network selection

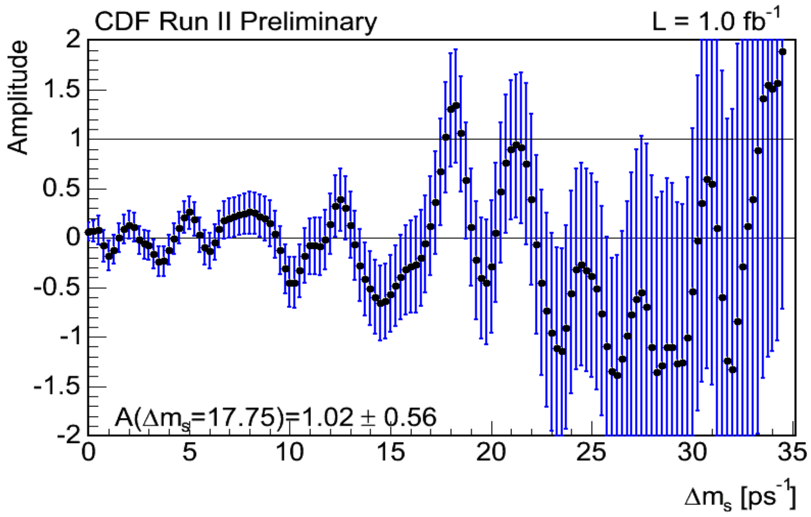


- select signal using NN inputs: O(30) variables including vertex displacement, fit quality, P_T of tracks, D_s's ϕ's, K*, **PID**

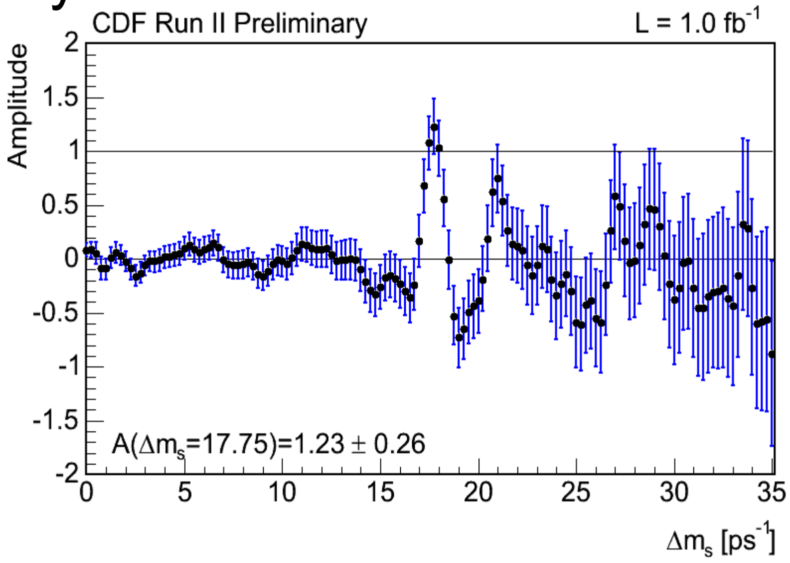
- careful to make sure NN is not trained to select mass. (e.g. ΔR not used as input variable)

comparing datasets

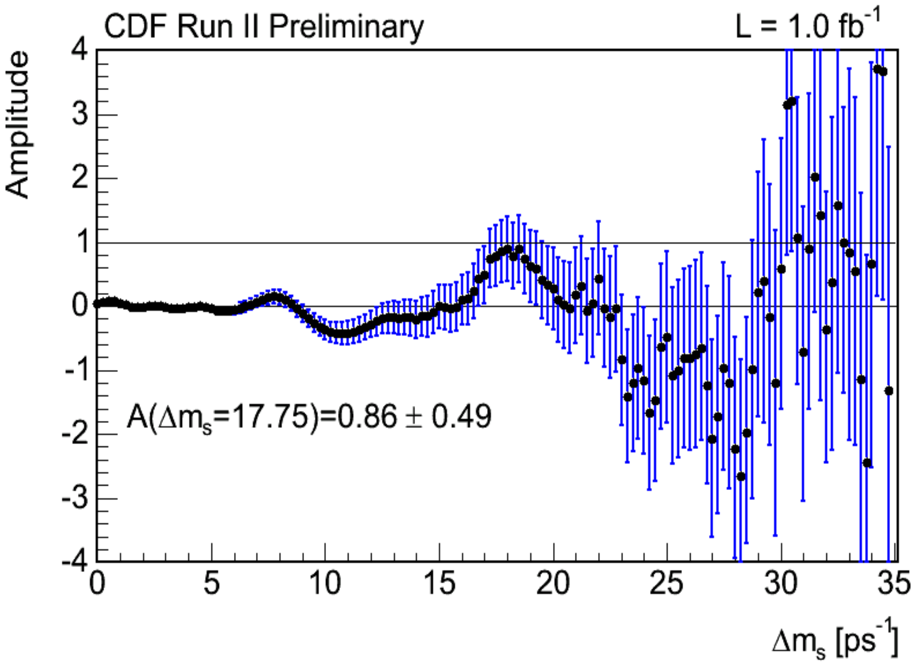
partially reconstructed hadronic modes



fully reconstructed hadronic modes

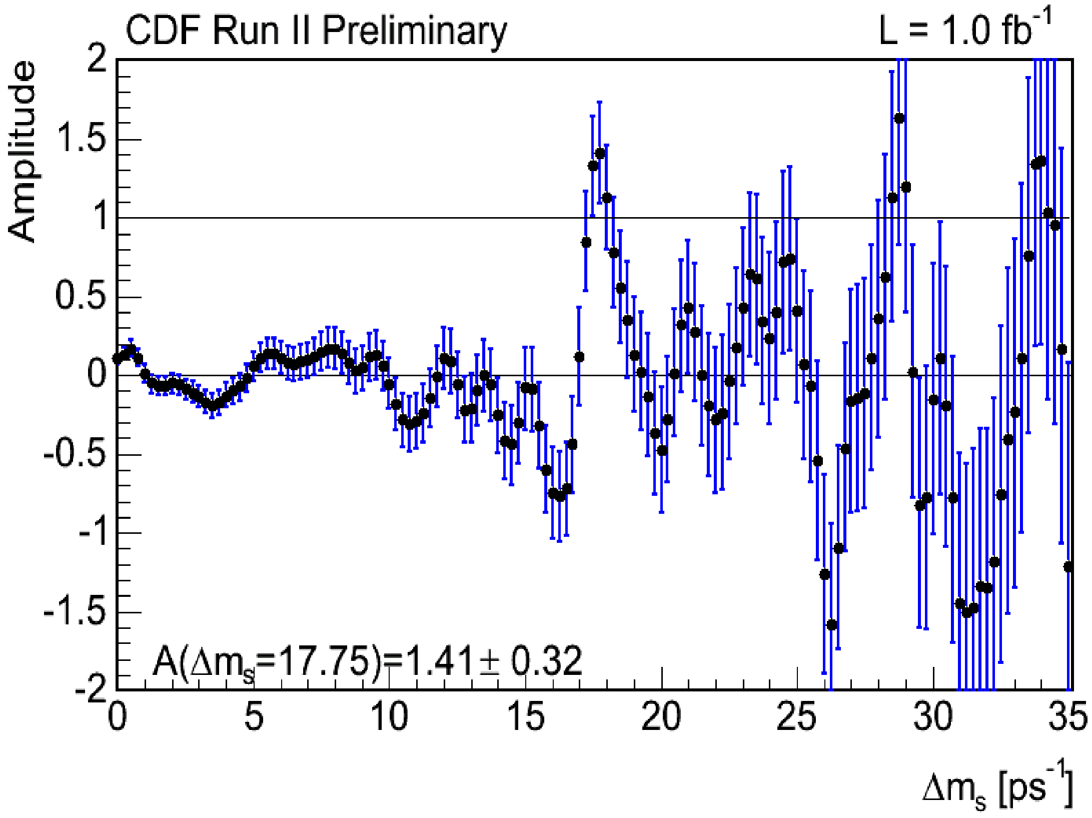


semileptonic modes

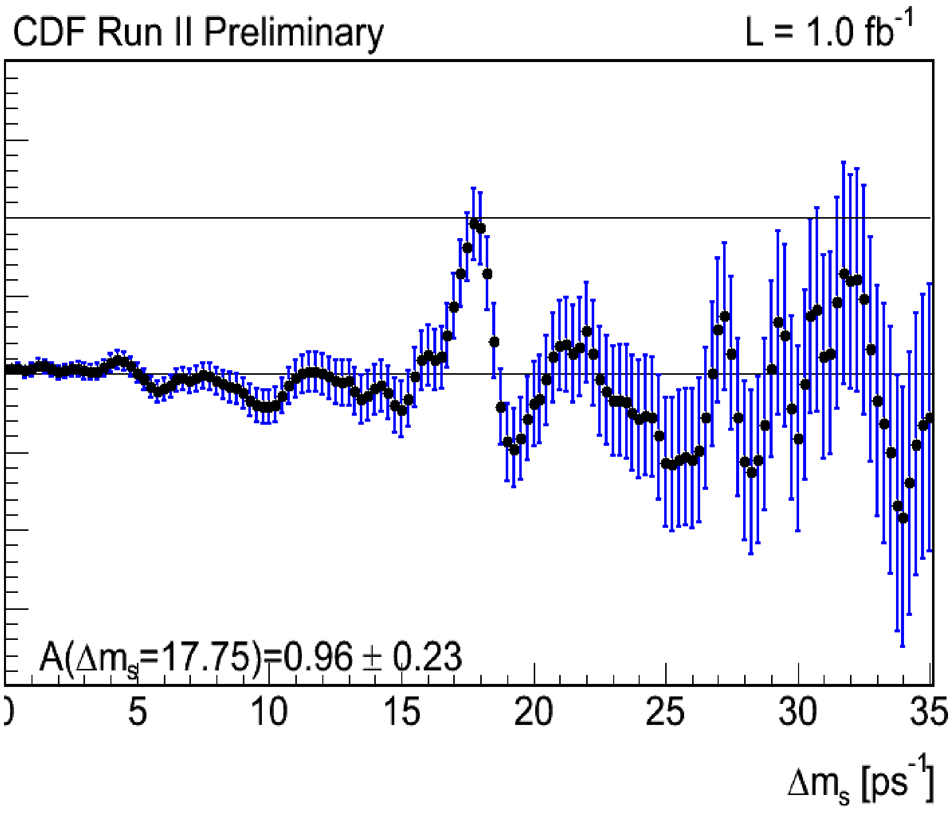


all see the signal!

comparing taggers



Opposite side tagger

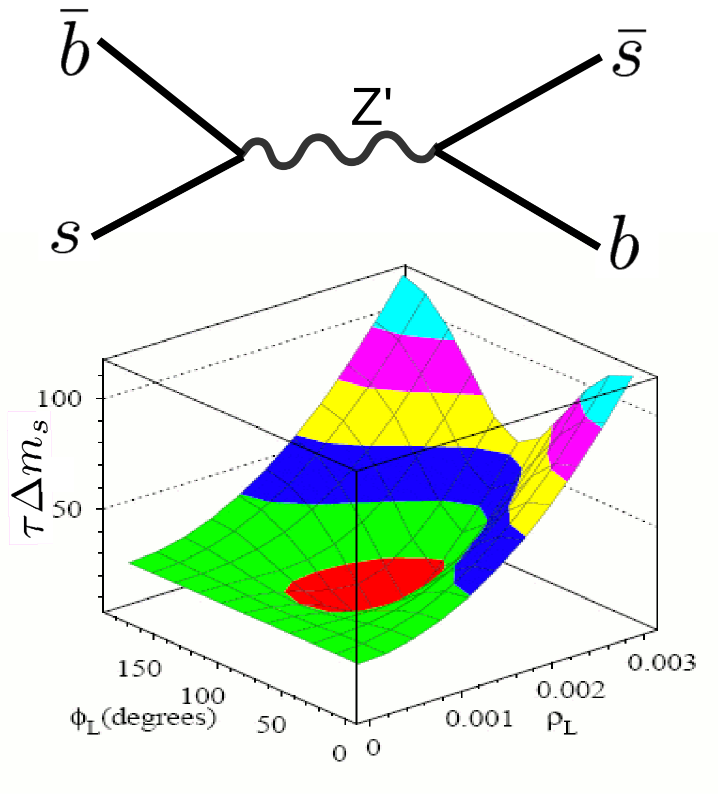


Same side kaon tagger

Both taggers see the oscillations

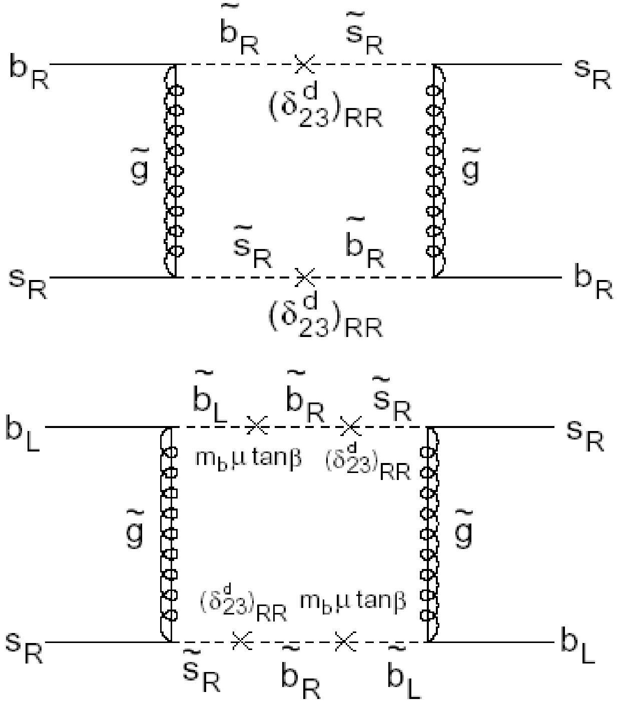
new physics

New particles can enhance the $B_s \bar{B}_s$ transition



Phys.Lett.B596:229-239,2004

supersymmetry with large mixing between squarks



harnik et al. hep-ph/0212180

Δm_s is sensitive to new physics

A nice event

Run 204720, Event 109026