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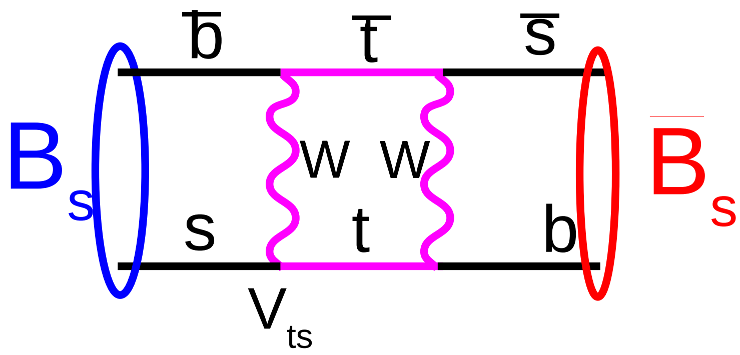
mixing at CDF

Overview

- Introduction
  - Motivation
  - CDF Detector / Trigger
- Analysis
  - Signal Reconstruction
  - Lifetime Measurement
  - Flavor Tagging and Calibration
- Results

Flavor Oscillations



B and B mesons can transform into each other. They form a single QM system:

$$\psi(t) = a(t)|B_s\rangle + b(t)|\bar{B}_s\rangle \equiv \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

The Schrodinger equation:

$$i\frac{\partial}{\partial t}\psi = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & 0 \\ 0 & \Gamma \end{pmatrix}\psi$$

H not diagonal => B and $\bar{\text{B}}$ are not mass eigenstates
the mass eigenstates are:

$$|B_H\rangle = \frac{1}{\sqrt{2}}\left(|B\rangle + |\overline{B}\rangle\right) \qquad \mathrm{M_L = M_{11} - M_{12}}$$

$$|B_L\rangle = \frac{1}{\sqrt{2}}\left(|B\rangle - |\overline{B}\rangle\right) \qquad \mathrm{M_H = M_{11} + M_{12}}$$

$$\Delta \mathrm{M} = 2\mathrm{M}_{12}$$

Oscillation probability as function of time

Solving the time dependent SE

$$|B(t)> \;=\; e^{-iMt}e^{-\frac{\Gamma}{2}t}\left(\cos\frac{\Delta m}{2}t|B> + \sin\frac{\Delta m}{2}t|\overline{B}>\right)$$

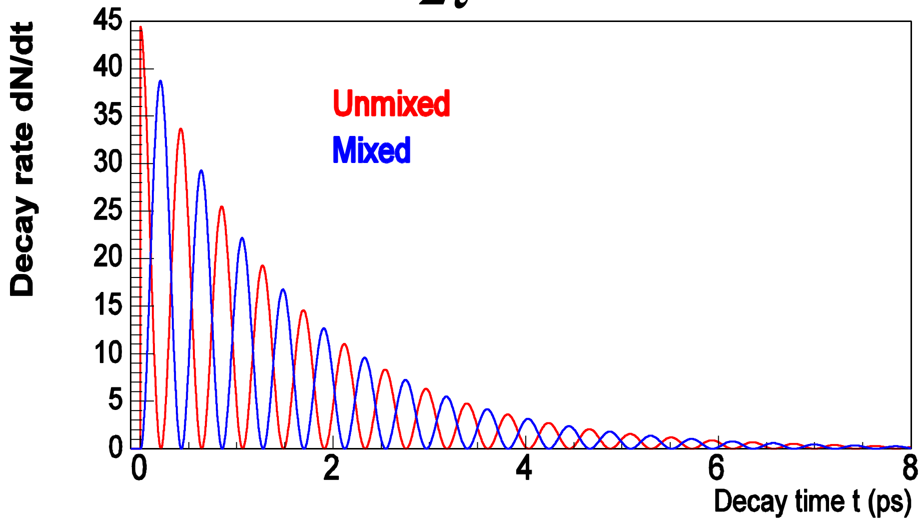
$$|\overline{B}(t)> \;=\; e^{-iMt}e^{-\frac{\Gamma}{2}t}\left(\cos\frac{\Delta m}{2}t|\overline{B}> + \sin\frac{\Delta m}{2}t|B>\right)$$

decay time

oscillation frequency.
1 ps^{-1} ~ 7 x 10^{-4} eV (~$1.5 \times 10^{-13} m_b$)

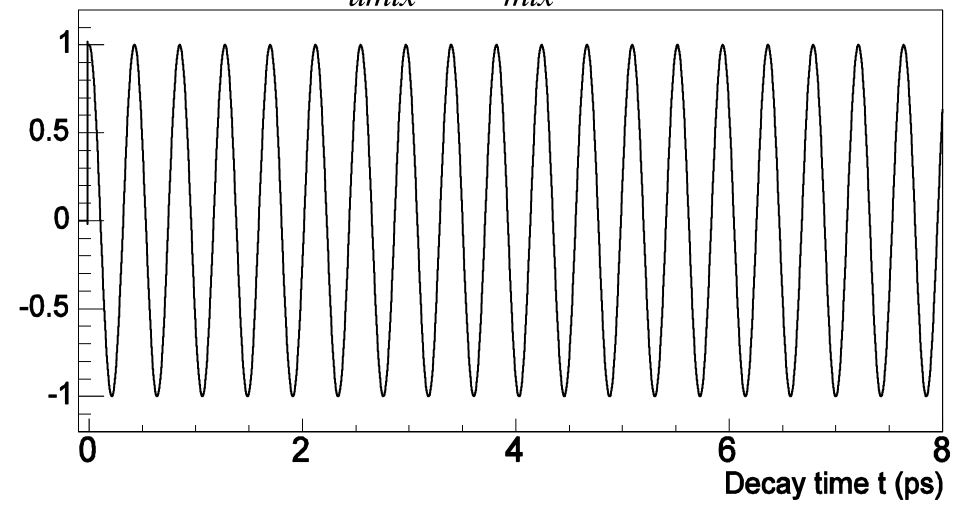
$$P(B \to B) = \frac{e^{-t/\tau}}{2\tau}(1+\cos\Delta mt) = P_{umix}$$

$$P(B \to \overline{B}) = \frac{e^{-t/\tau}}{2\tau}(1-\cos\Delta mt) = P_{mix}$$



asymetry

$$A = \frac{P_{umix} - P_{mix}}{P_{umix} + P_{mix}} = \cos\Delta mt$$

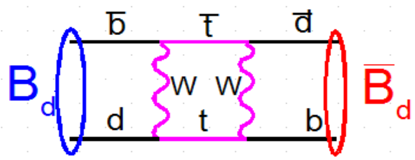


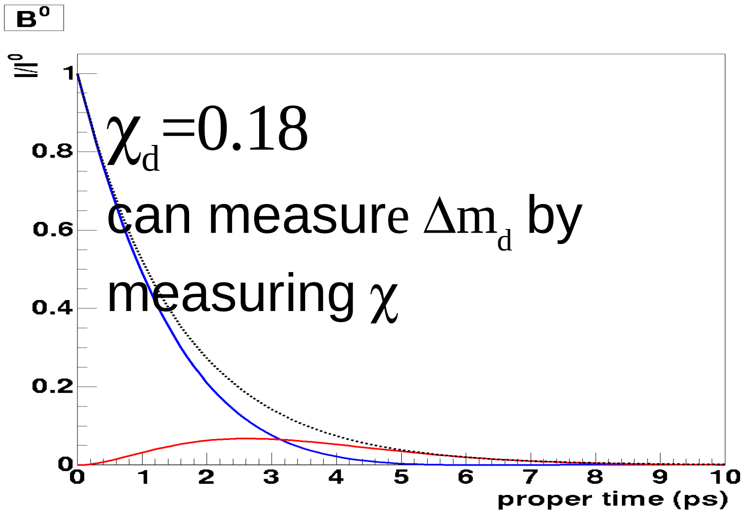
B_s vs B_d

B_d

τ=1.54 ps

Δm_d=0.5 ps^{-1}





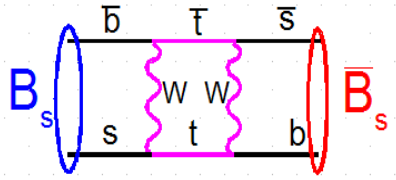
χ_d=0.18

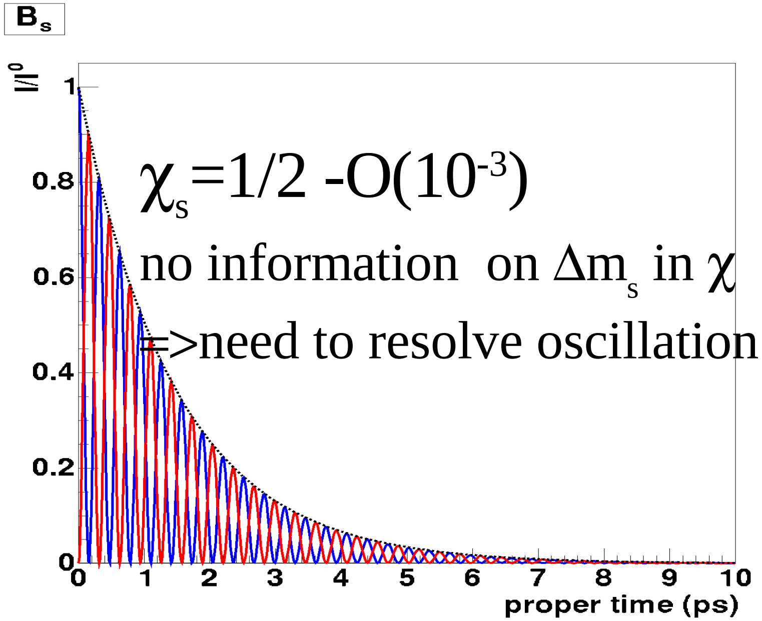
can measure Δm_d by measuring χ

B_s

τ=1.41 ps

Δm_s=~20 ps^{-1}





χ_s=1/2 -O(10^{-3})

no information on Δm_s in χ

=>need to resolve oscillation

fraction of mixed events

$$\chi = \int_0^\infty P_m(t)$$

$$\chi = \frac{1}{2} \frac{1}{1+(\tau\,\Delta m)^{-2}}$$

Bs oscillations more difficult to measure: Need to resolve very rapid oscillation.

Motivation

New physics is constrained by testing prediction of SM...
in particular: test unitarity of the CKM matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

pretty well known

not wel known and interesting

To get at Vtd: measure Δm_d (Bd oscillations)

$$\Delta m_q = \frac{G_F^2}{6\pi^2} m_{B_q} m_t^2 F(m_t^2/m_W^2) f_{B_q}^2 B_{B_q} \eta_{QCD} |V_{tb}^* V_{tq}|^2$$

q=s or d

hard to calculate (lattice QCD). uncertainty: 11%

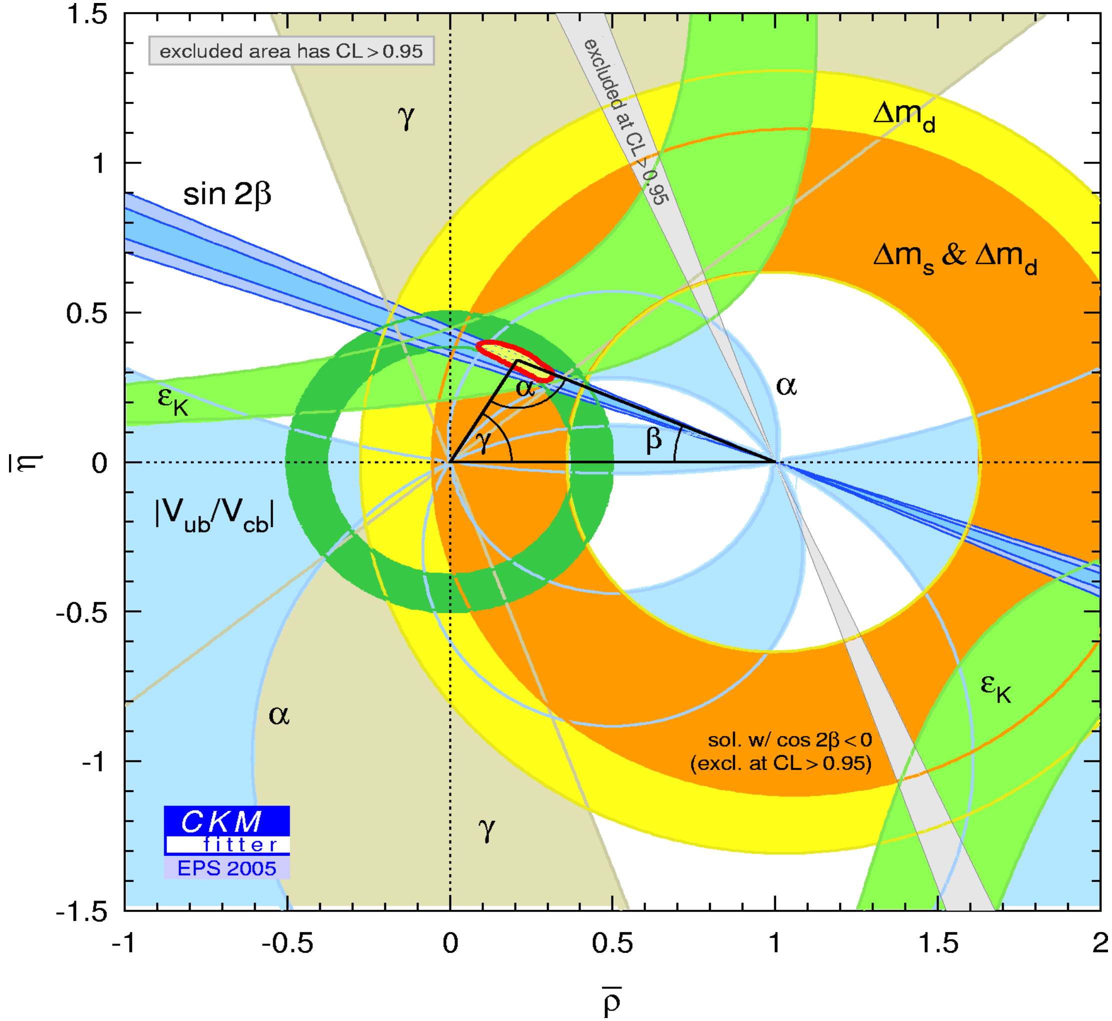
If we measure Δm_s, we can form the ratio which allows for much more accurate measurement of V_{ts}/V_{td}

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s} f_{B_s}^2 B_{B_s}}{m_{B_d} f_{B_d}^2 B_{B_d}} \left|\frac{V_{ts}}{V_{td}}\right|^2 = 1.21 \pm 0.05 \left|\frac{V_{ts}}{V_{td}}\right|^2$$

(hep-lat/0510113)

Motivation

$V_{td} = A\lambda^3(1-\rho-i\eta)$



Plot Combines many different measurements to constrain ρ and η.

2005 Limit on Δm_s was already helping to measure CKM matrix...

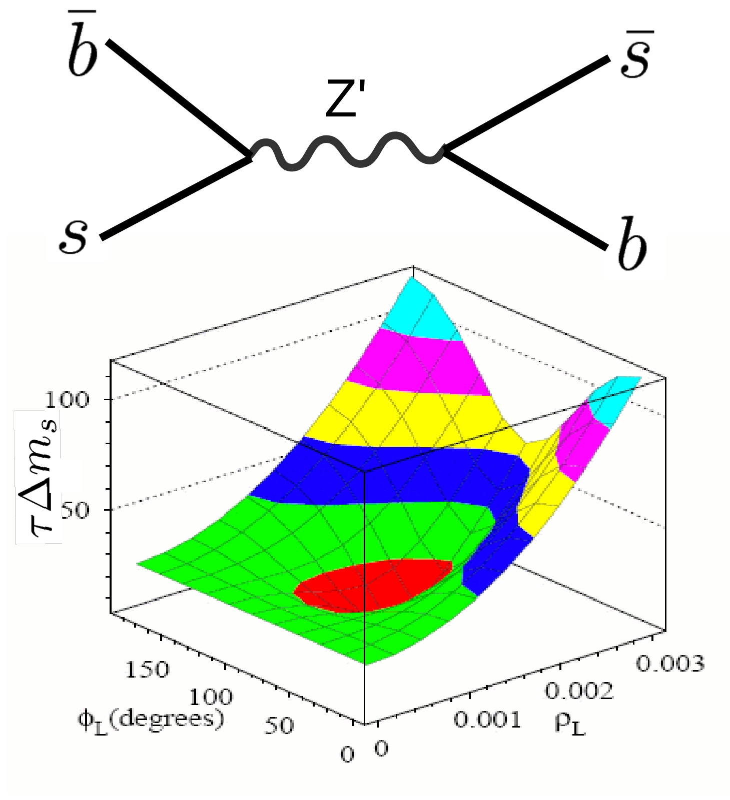
Check that all measurements are consistent: i.e. that CKM matrix is unitary.

Turn the argument around: standard model prediction:

Δm_s: $18.3^{+6.5}_{-1.5}$ (1σ) : $^{+11.4}_{-2.7}$ (2σ) ps^{-1}

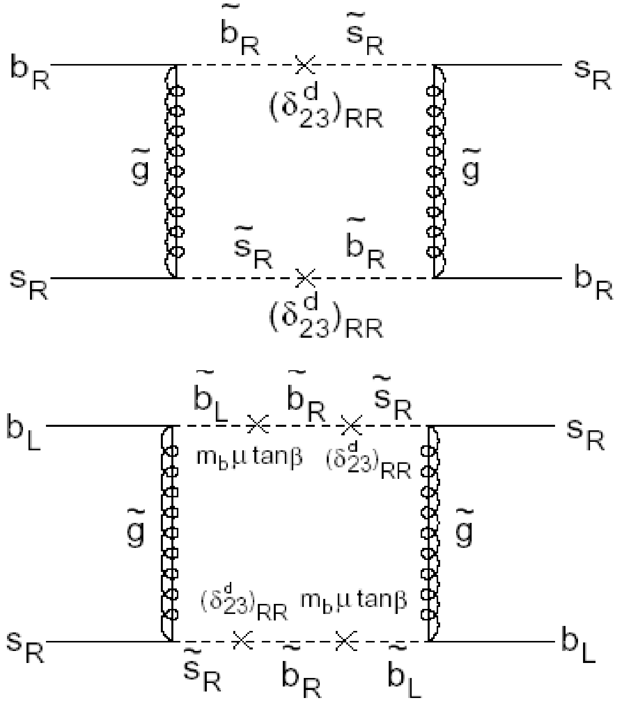
Motivation: new physics

New particles that can show up in the box diagram will influence the mixing frequency.



Phys.Lett.B596:229-239,2004

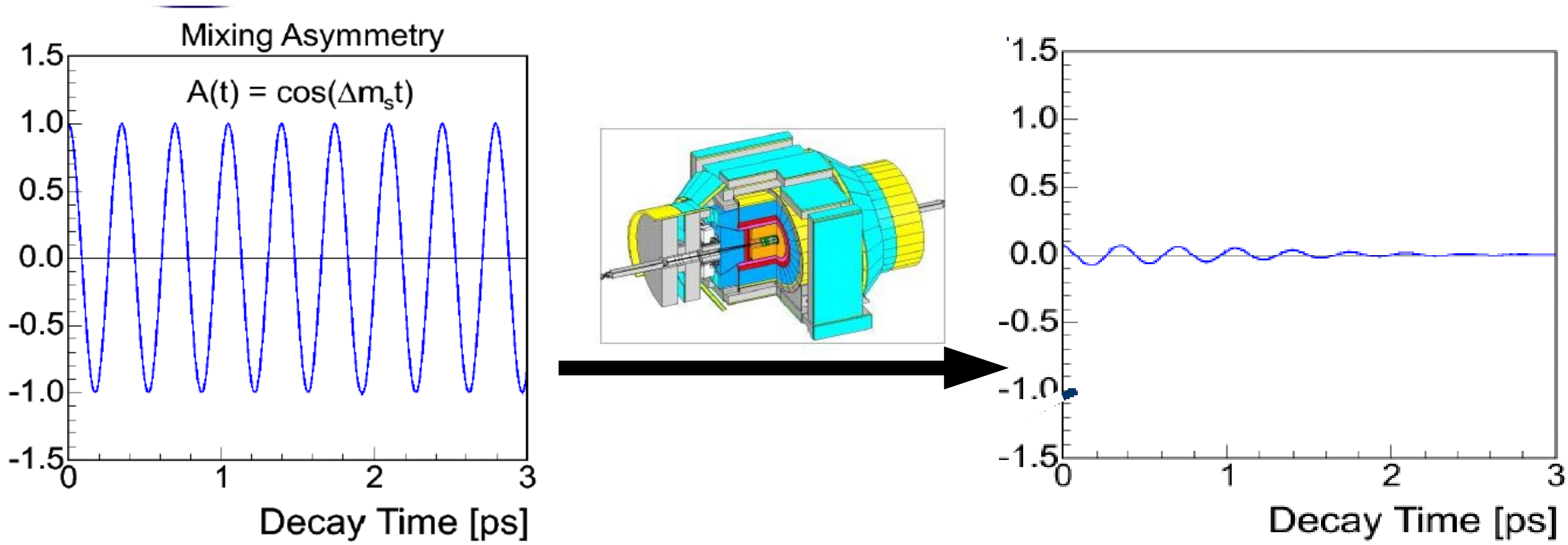
supersymmetry with large mixing between squarks



harnik et al. hep-ph/0212180

Δm_s is sensitive to new physics

Amplitude scan



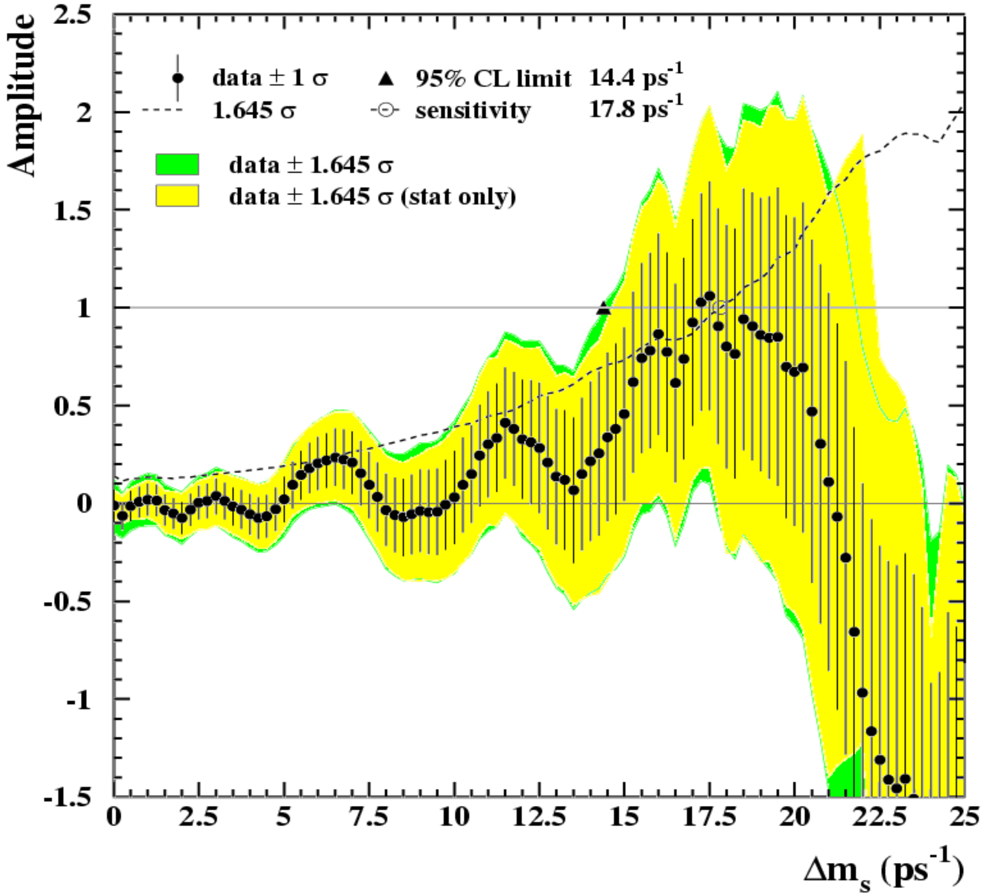
Experimental effects dampen the asymmetry

$$\mathcal{L}(t) = 1 \pm D \times A \times \cos(\Delta m_s t) \otimes R(t)$$

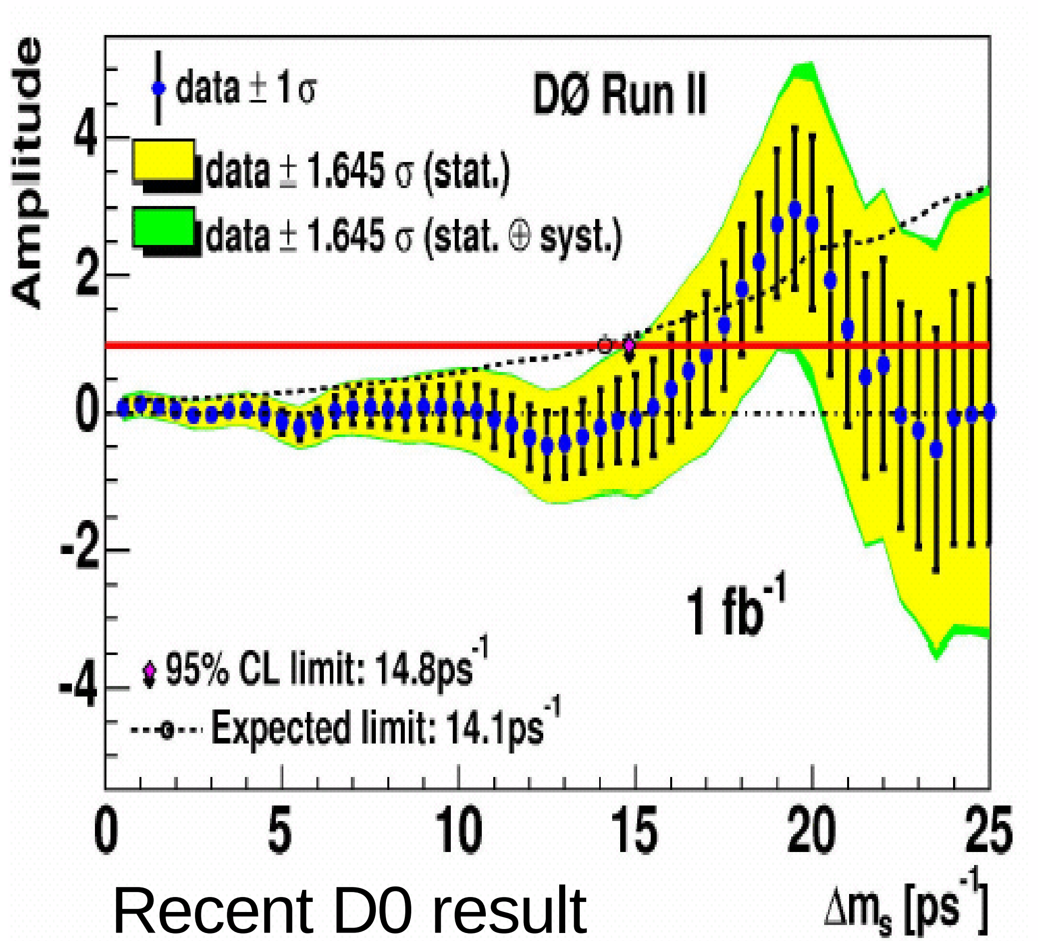
- A is know as the Amplitude: the size of the asymmetry, corrected for detector effects.
  - A=1 means mixing
  - A=0 means data is compatible with no mixing
- knowledge about detector is punt into likelihood, to 'correct' for damping of the asymmetry

What we know already

Amplitude scan: fix Δm_s and measure the amplitude of the corresponding frequency component (Fourier)



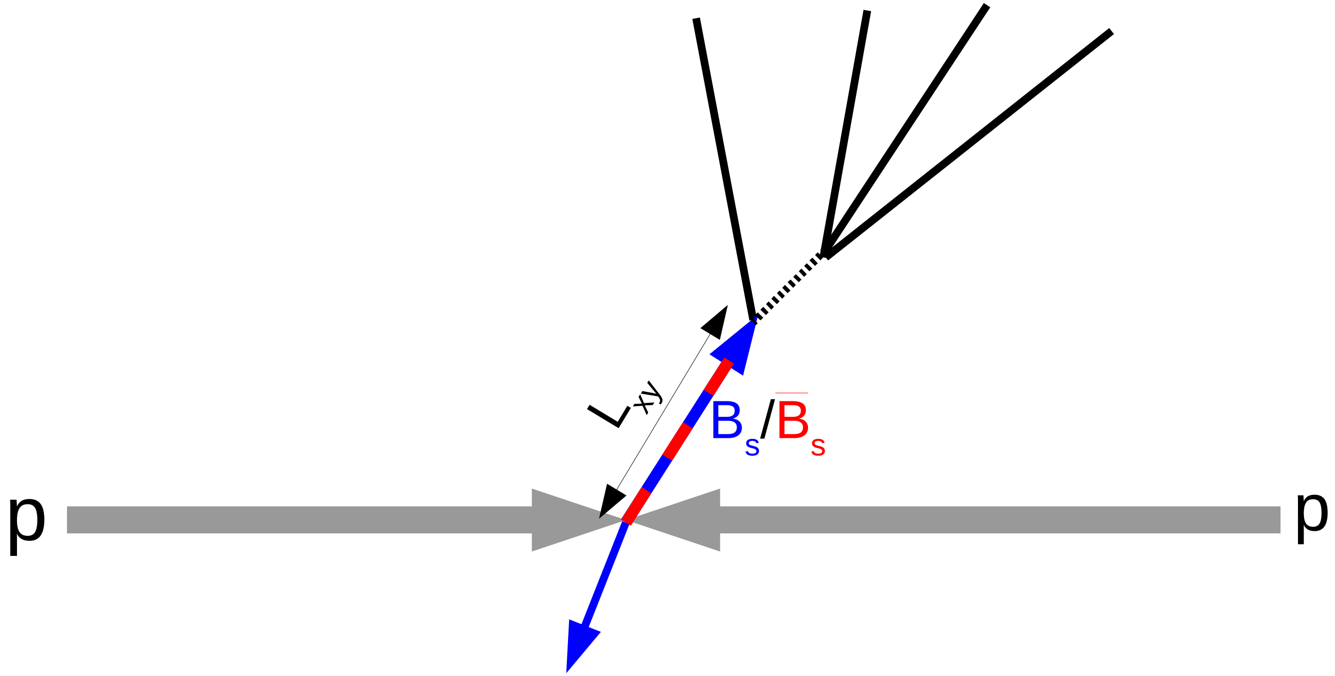
World average before Tevatron run II



Recent D0 result

- $17 < \Delta ms < 21$ ps-1 at 90% CL
- p-value = 5%

Outline of the measurement



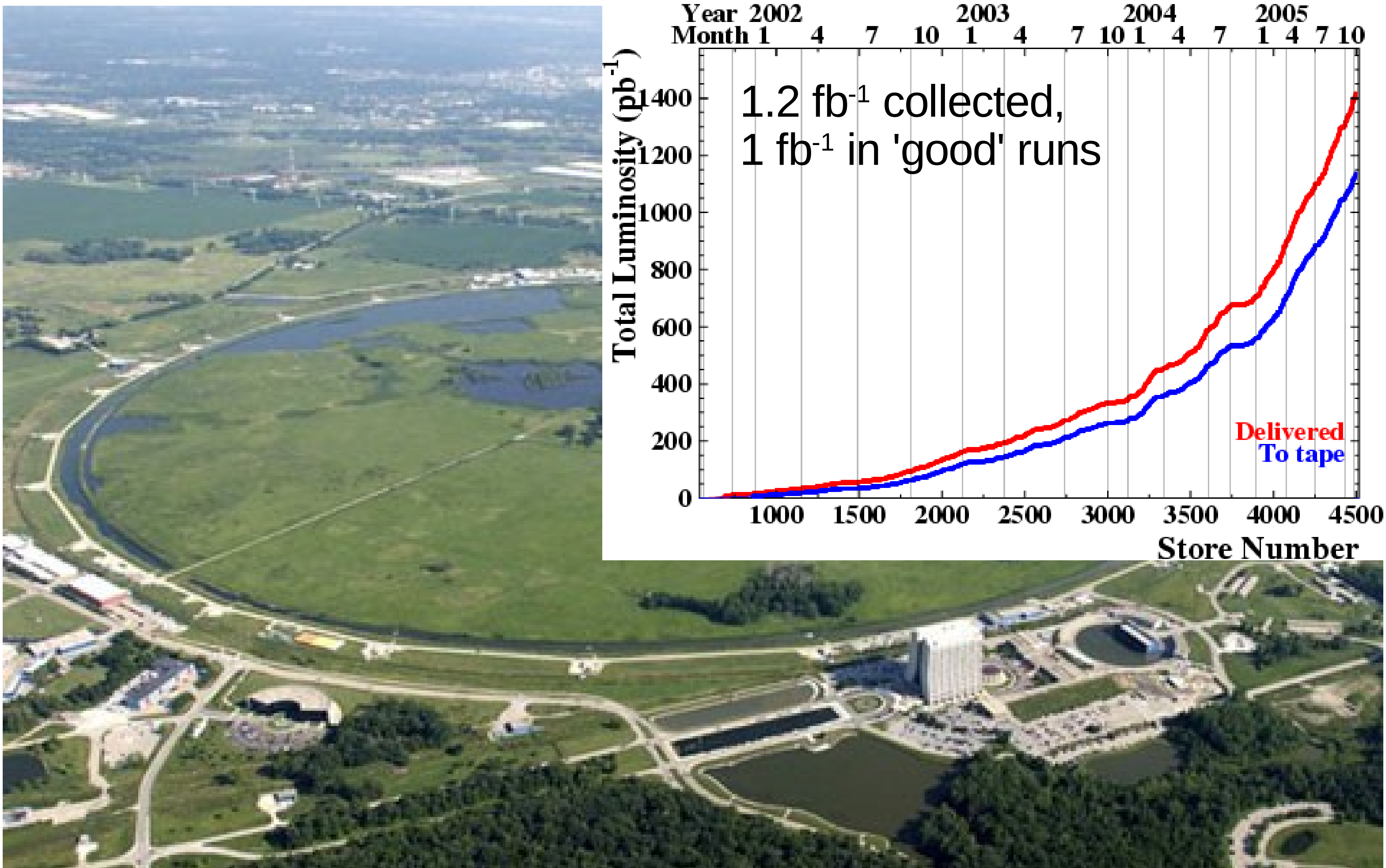
$$\sigma_A = \sqrt{\frac{2}{\epsilon D^2 S}} \sqrt{\frac{S+B}{S}}\, e^{(\sigma_t \Delta m_s)^2/2}$$

Need to:

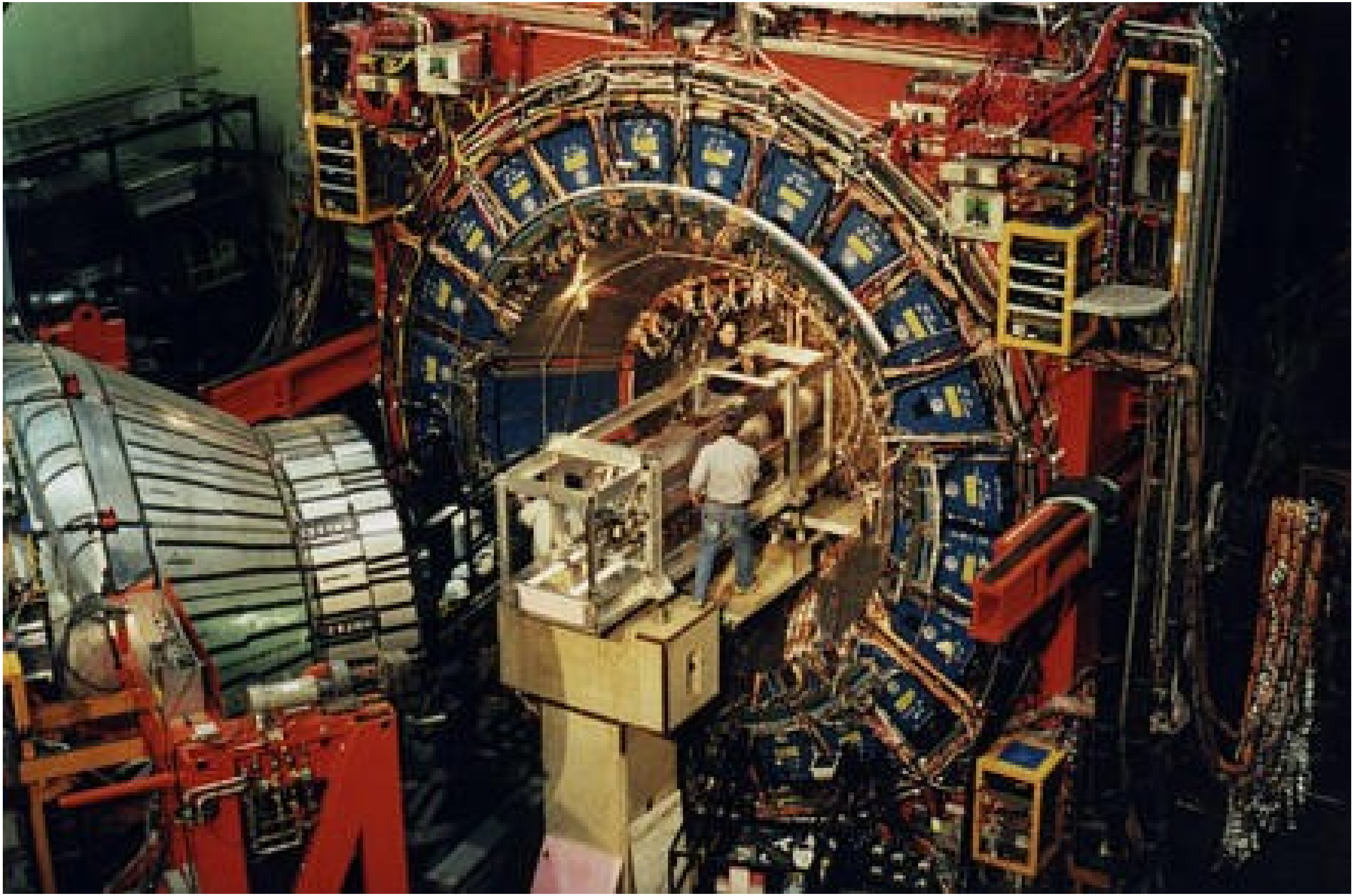
1) collect a lot of Bs decays — Trigger/reconstruction
2) determine the flavor of Bs at production — 'flavor tagging'
3) measure the proper decay time of Bs — measure L_{xy}

Getting the B_s signals

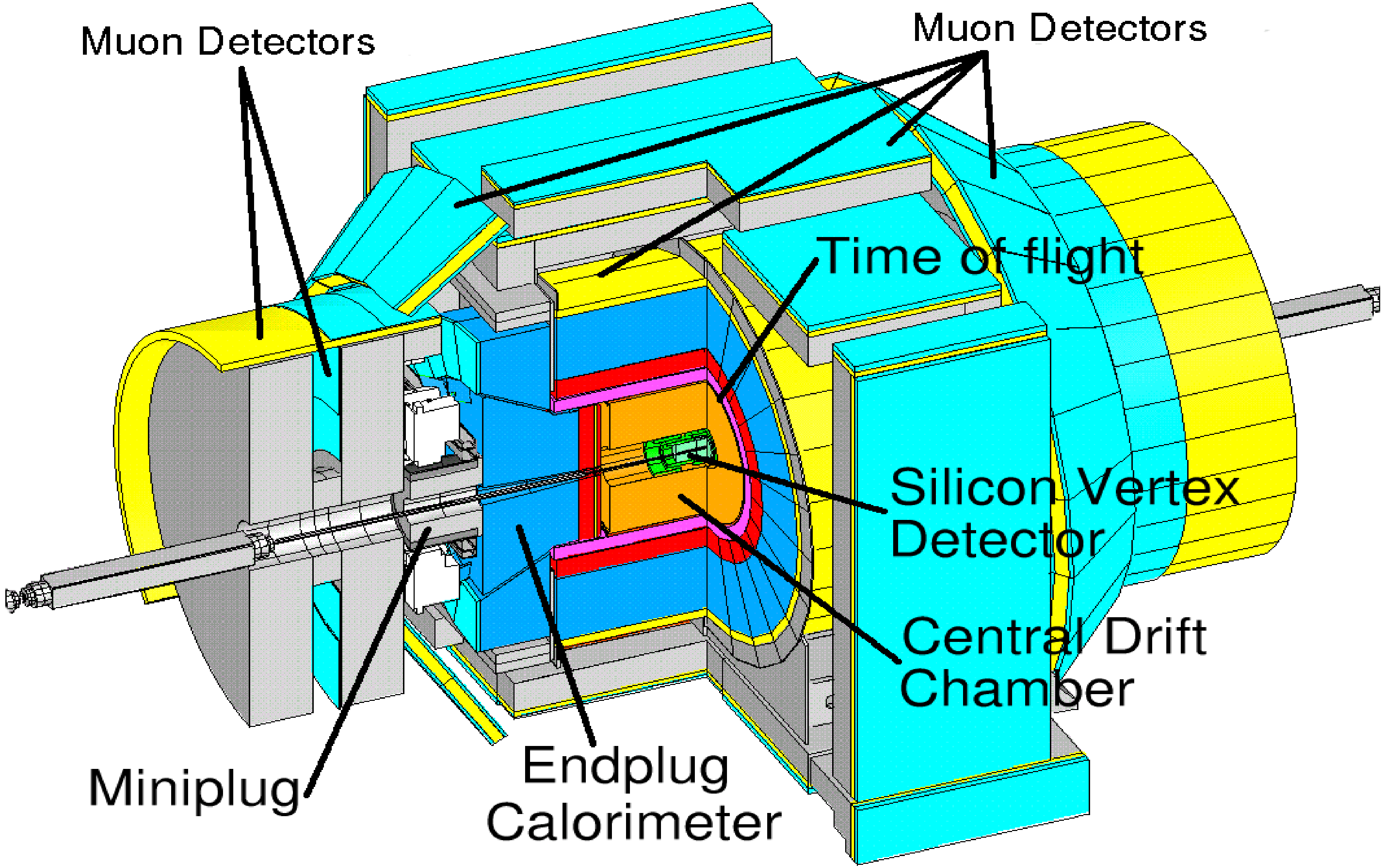
The Tevatron



The CDF detector

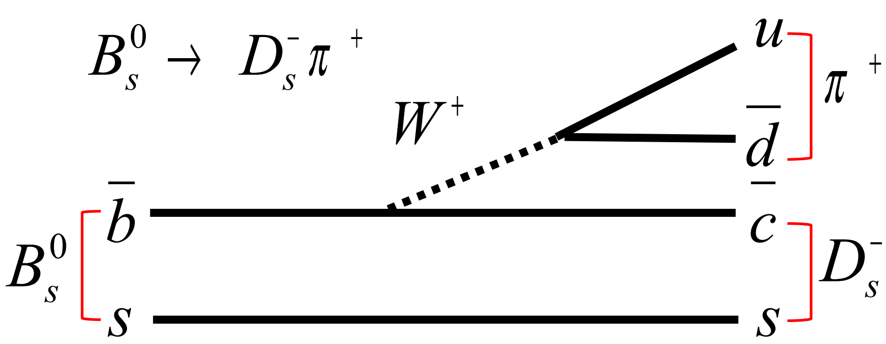


The CDF detector



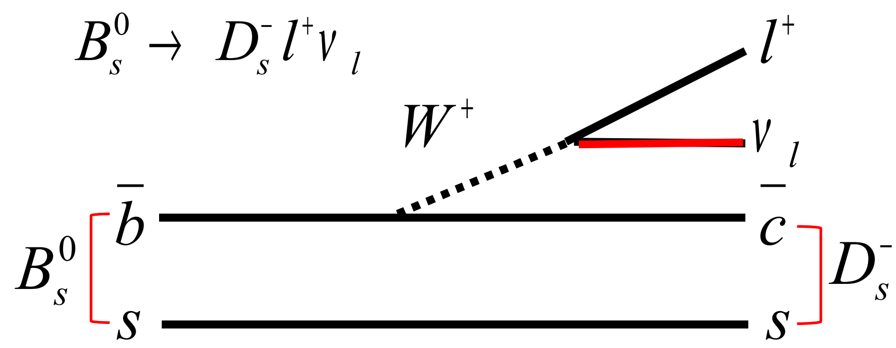
The signals we are looking for

Hadronic



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

Semileptonic

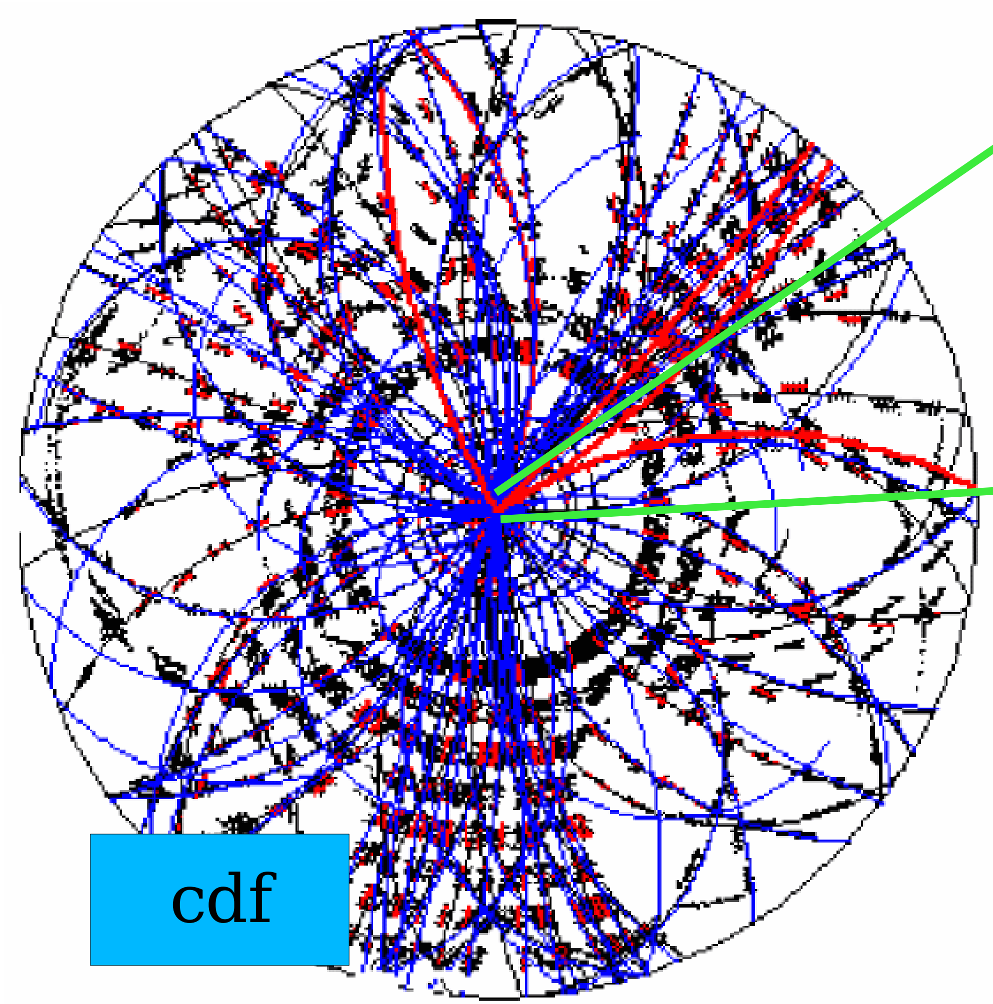


- Missing momentum (ν)
- Need to rely on D_s mass
- Large branching ratio: high yield

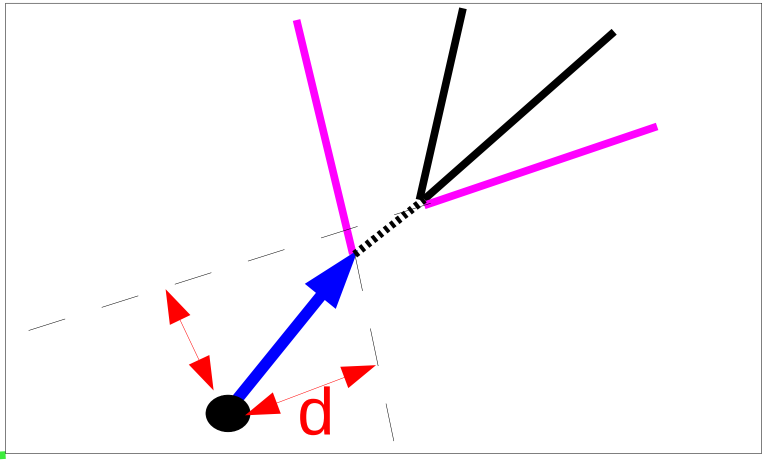
$$D_s^- \to \phi\pi^-, \quad \phi \to K^+K^-;$$
$$D_s^- \to K^{*0}K^-, \quad K^{*0} \to K^+\pi^-;$$
$$D_s^- \to \pi^+\pi^-\pi^-.$$

Displaced track trigger

A typical B event at a hadron collider

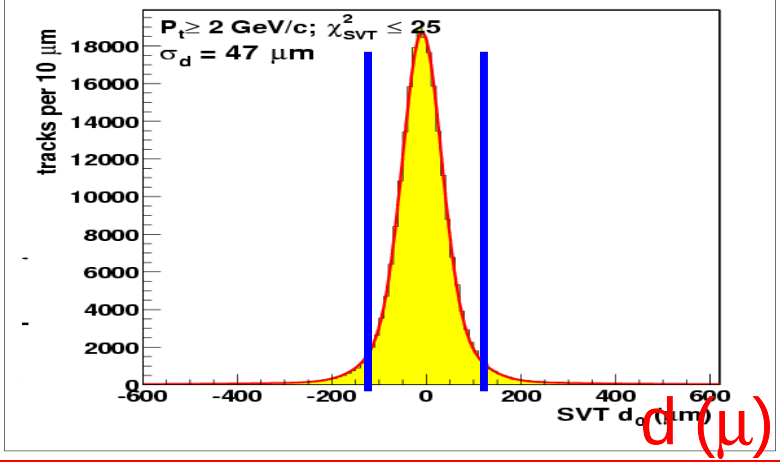


Trigger on events with two displaced (d>120 μm) tracks



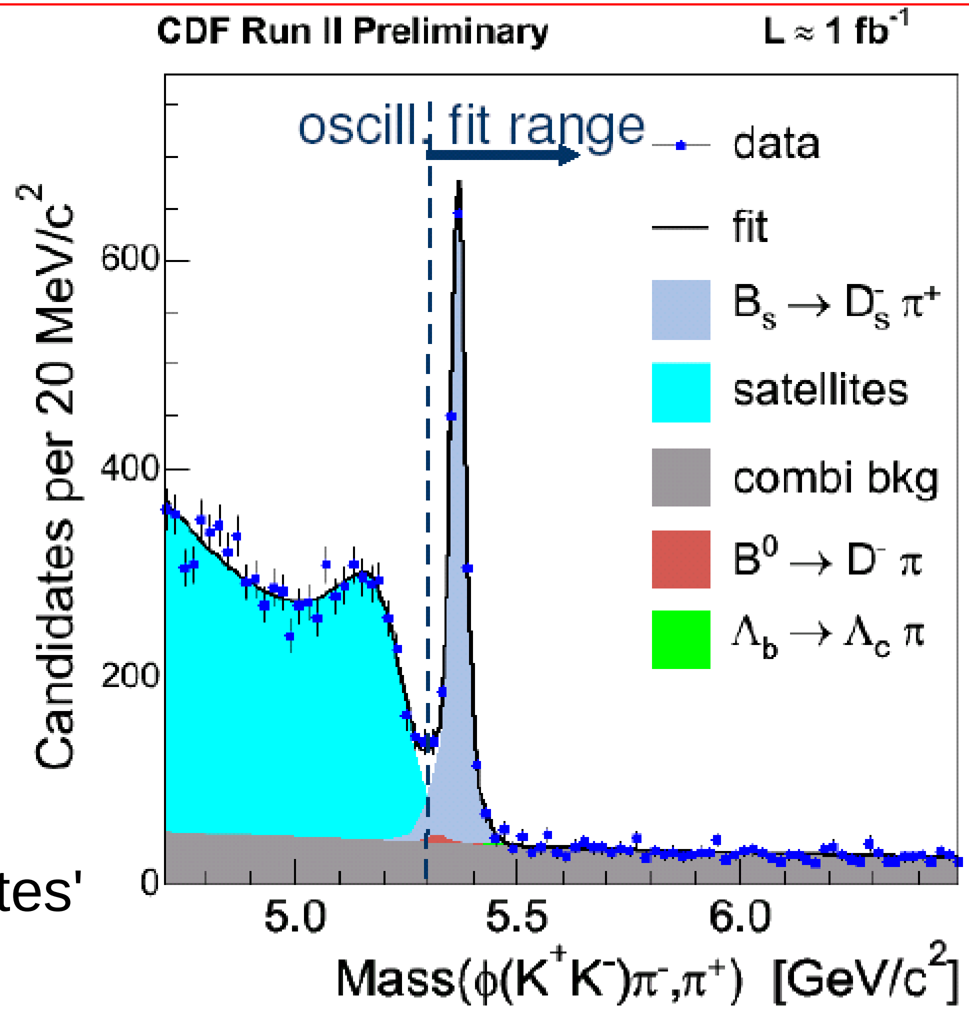
=> look for displaced tracks

very fast (20μs) reconstruction @L2 by dedicated hardware: SVT



Hadronic signals

Decay	Candidates
$B_s \to D_s\pi, D_s \to \phi\pi$	1600
$B_s \to D_s\pi, D_s \to K^*K$	800
$B_s \to D_s\pi, D_s \to \pi\pi\pi$	600
$B_s \to D_s3\pi, D_s \to \phi\pi$	500
$B_s \to D_s3\pi, D_s \to K^*K$	200
Total	3700

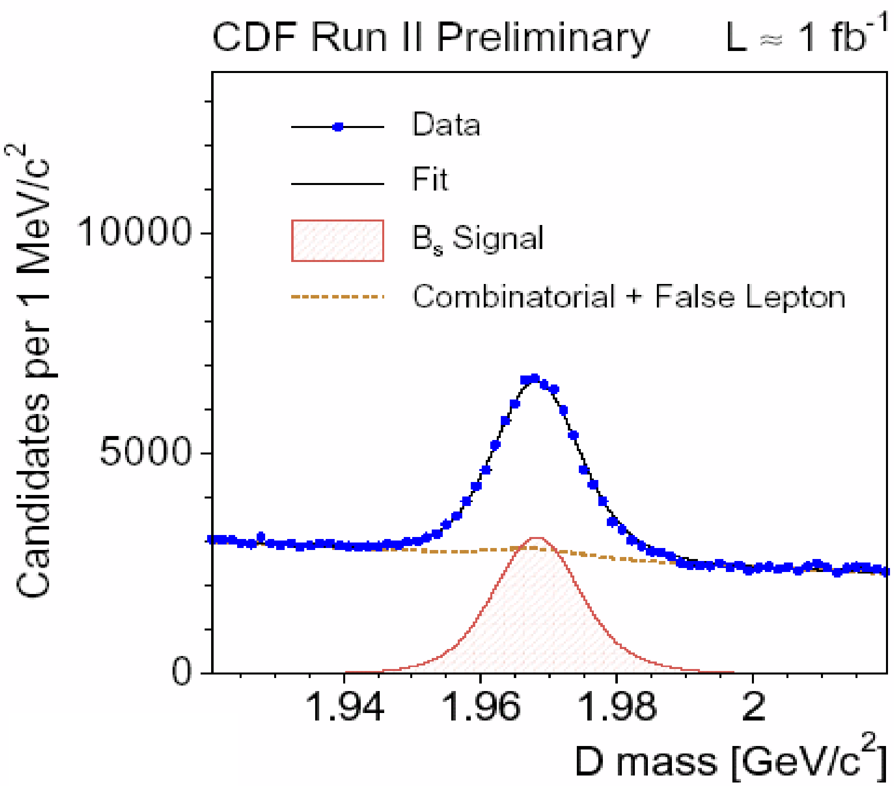


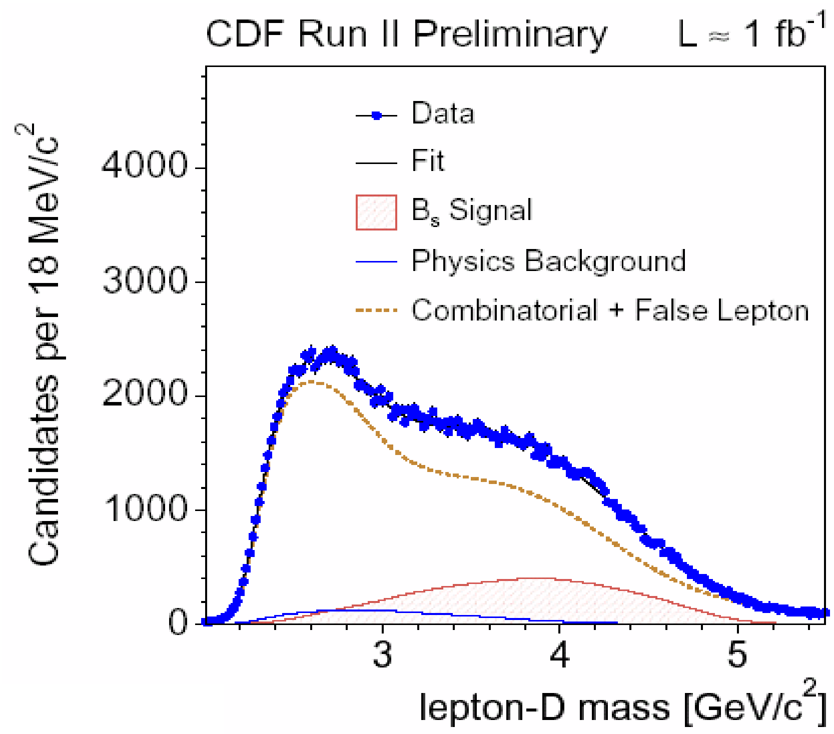
- low background under the B_s peak
- $P_T(B_s)$ 'perfectly' measured
- mixing fit in range > 5.3 GeV to remove partially reconstructed 'satellites'

high statistics 'light B' samples:

- $B^+ \to D^0 \pi$ (26 k events)
- $B^0 \to D\text{-} \pi$ (22 k events)

Semileptonic signals





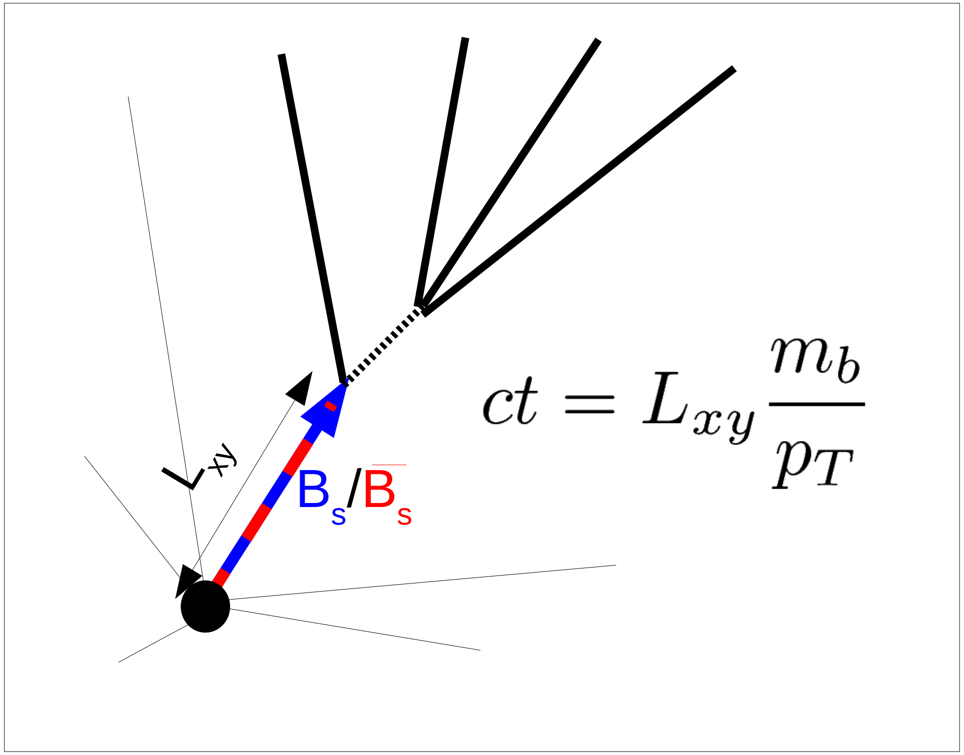
ℓD_s: $D_s \rightarrow \phi\pi$	32 K
ℓD_s: $D_s \rightarrow K^*K$	11 K
ℓD_s: $D_s \rightarrow \pi\pi\pi$	10 K

missing particles (ν):
no B-mass peak, but mass of lepton+D_s gives discriminating power.

~50.000 l D_s candidates (and ~1M in B^0/B^+)

Proper decay time and proper decay time resolution

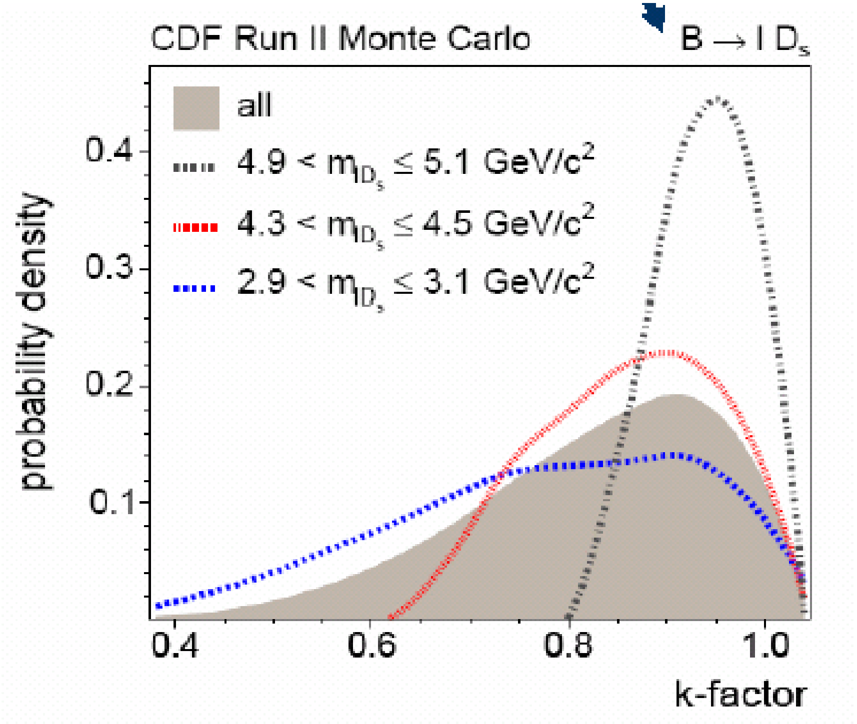
Proper time reconstruction



- can not measure p_T for semileptonic
- correct for missing p_T on average

$$ct = L_{xy}\frac{m_b}{p_T(lD_s)} \times k$$

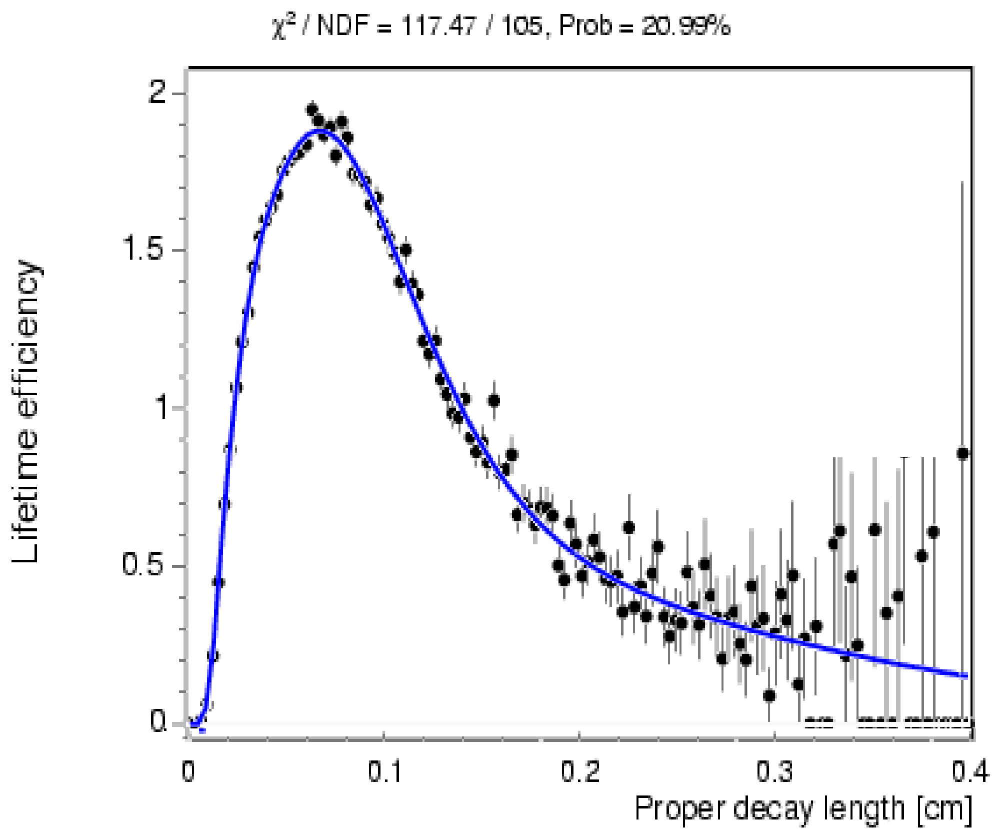
$$k = p_T(lD_s)/p_T(B_s)$$



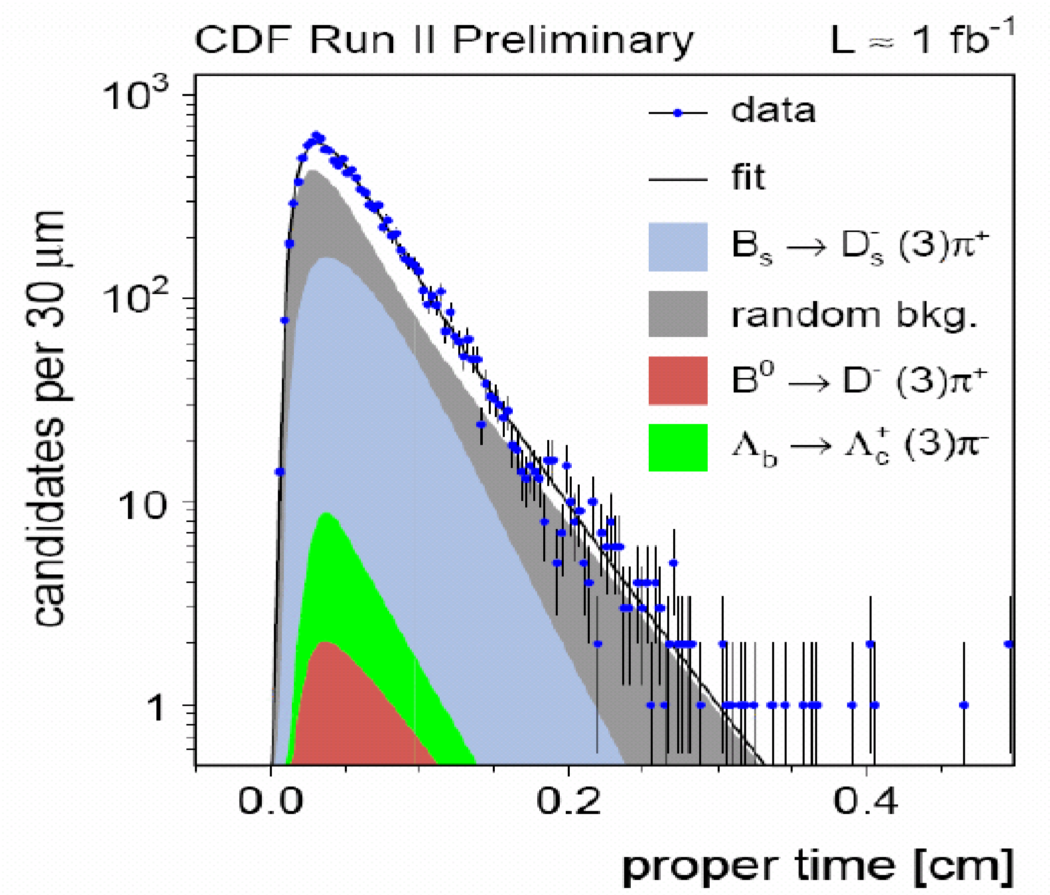
- k-factor obtained from Monte Carlo
- Take advantage of variation in k-factor distribution with l D_s mass. (high m_{lDs} means small missing p_T)

Proper time reconstruction

- Displaced track trigger sculpts proper decay length distribution
- Modeled by efficiency function ε(t)
- Derived from MC
- Not crucial for mixing measurement, but important for lifetimes



Lifetime measurement (hadronic)



Mode	Lifetime [ps] (stat. only)
$B^0 \to D^- \pi^+$	1.508 ± 0.017
$B^- \to D^0 \pi^-$	1.638 ± 0.017
$B_s \to D_s \pi(\pi\pi)$	1.538 ± 0.040

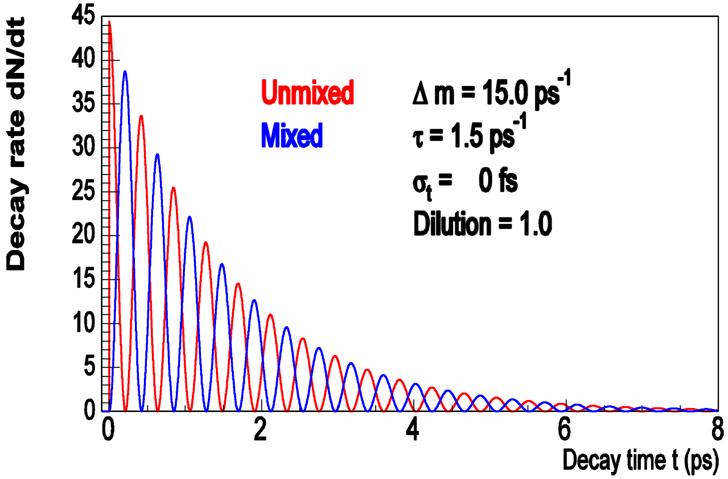
- World Average:

$B^0 \to 1.534 \pm 0.013$ ps
$B^+ \to 1.653 \pm 0.014$ ps
$B_s \to 1.469 \pm 0.059$ ps

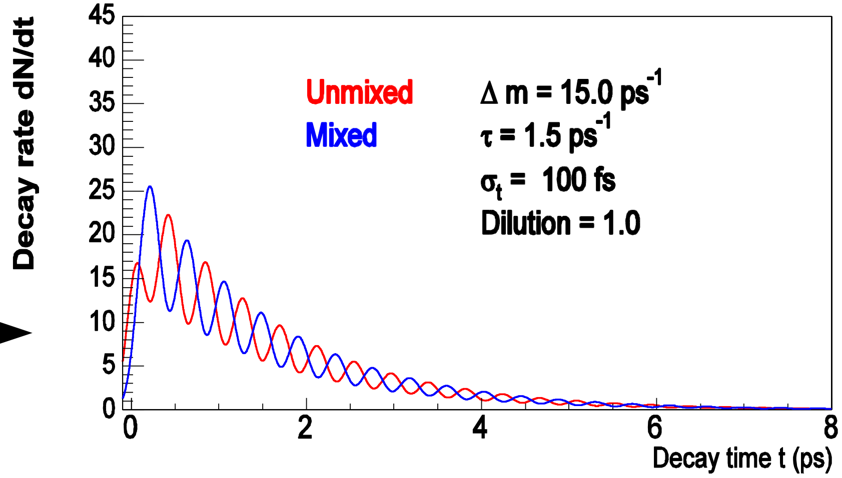
Excellent agreement!

Proper time resolution

Effect of non-zero ct error asymmetry: attenuation of the oscillation



$$D_{\sigma_t} = e^{-\frac{(\Delta m \cdot \sigma_t)^2}{2}}$$

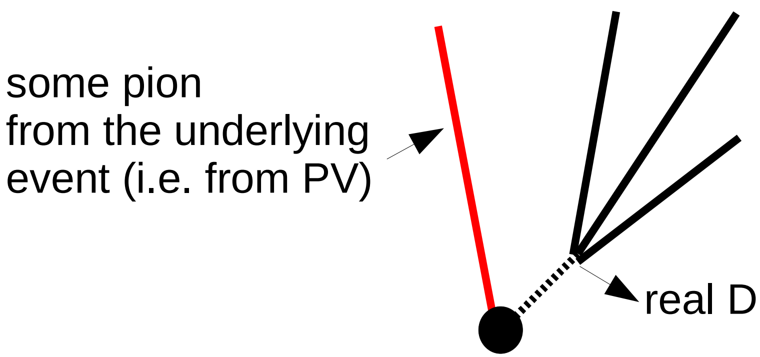


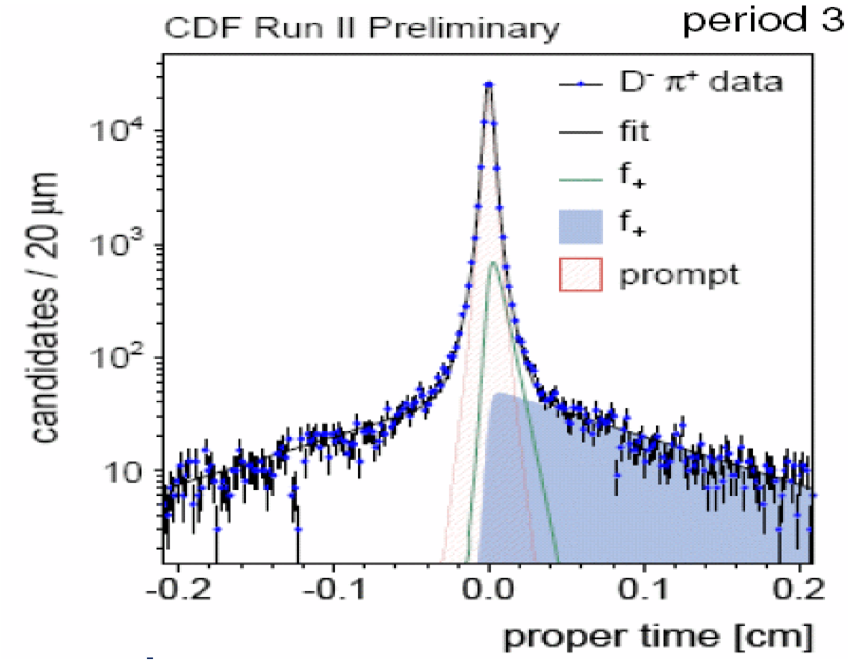
- Smearing of decay time causes attenuation of asymmetry signal:
- Have to know σ_{ct} to measure the mixing amplitude
- How to measure σ_{ct}?

Measuring the proper time resolution

Cannot measure the ct resolution directly on data (no prompt peak in the B_s signal due to trigger)

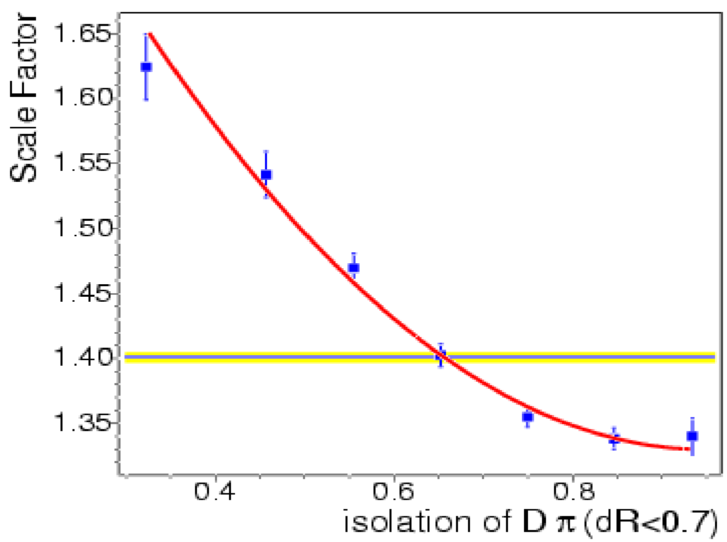
Solution: construct events that look like a B but are *known* to come from the PV..



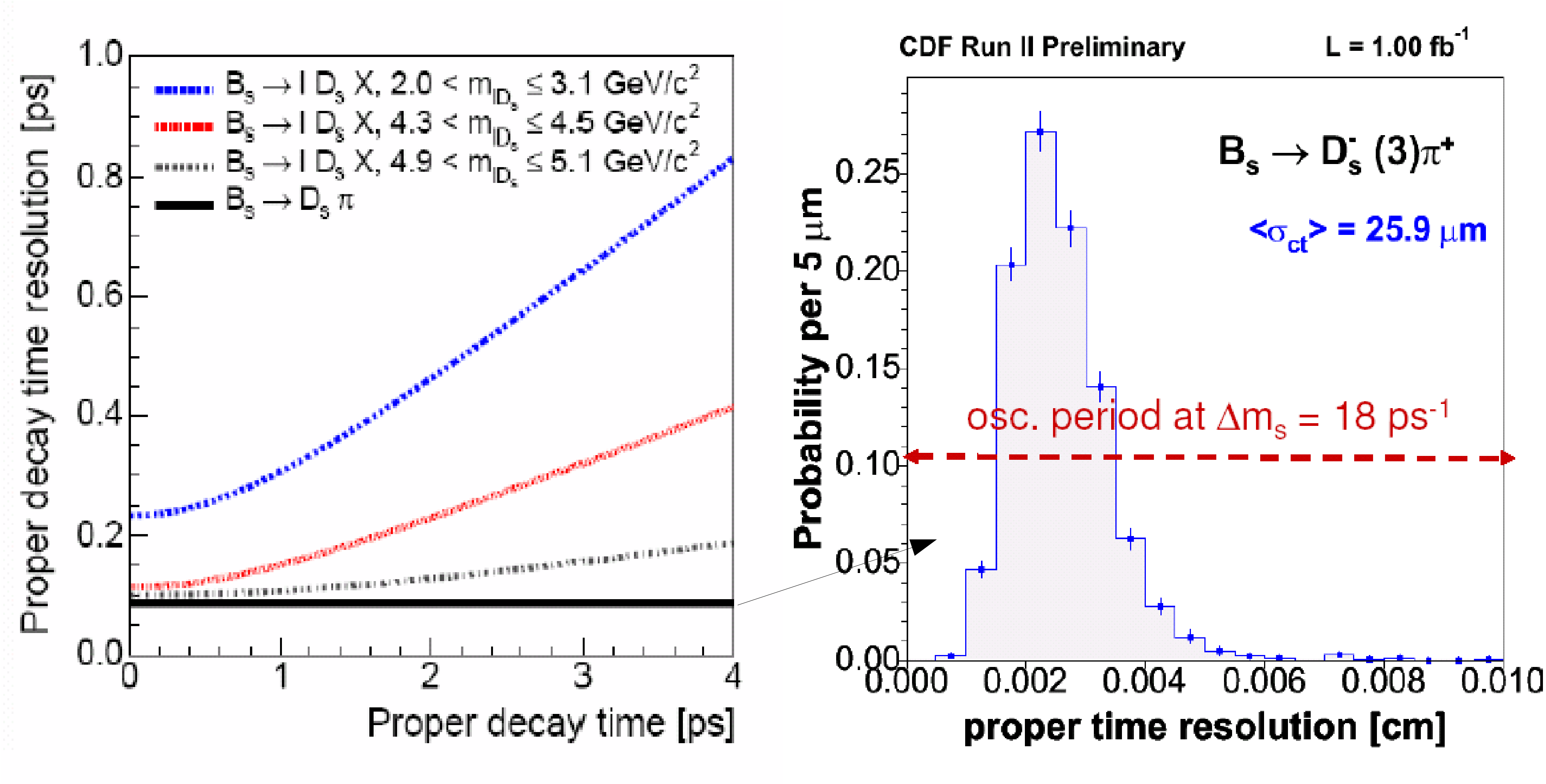


True <ct> must be zero; compare error with predicted error from the vertex fit.

And study dependence on kinematic variables, isolation, χ^2 of fit etc..

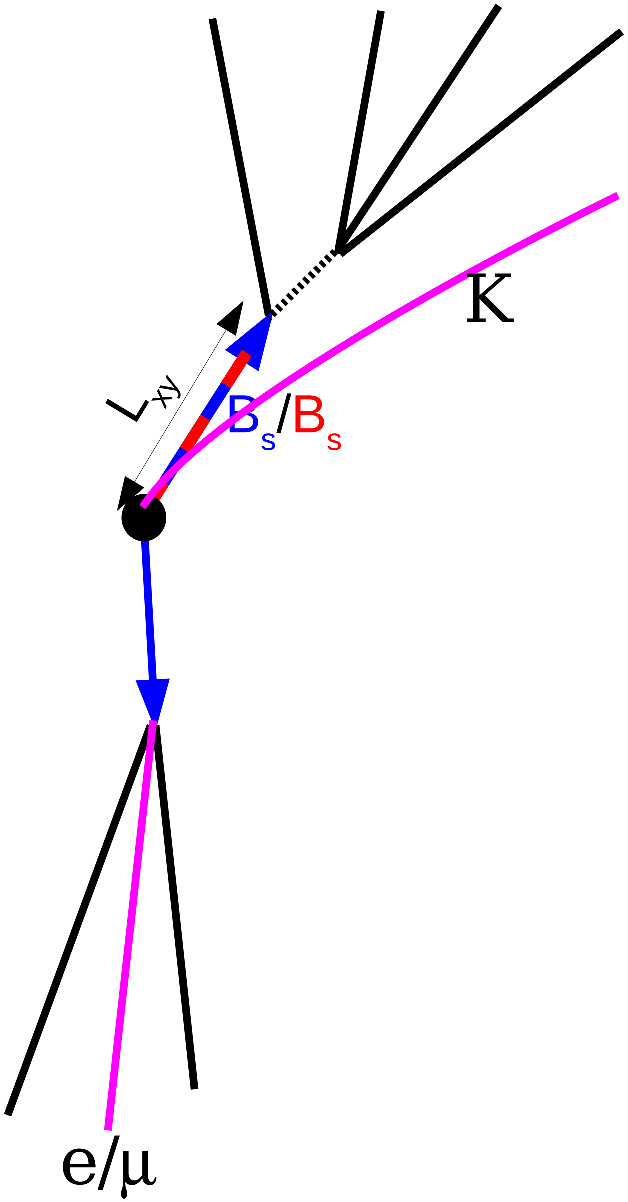


proper time resolution



3) Flavor tagging

Flavour tagging



We need to know the flavor of the B_s at production.

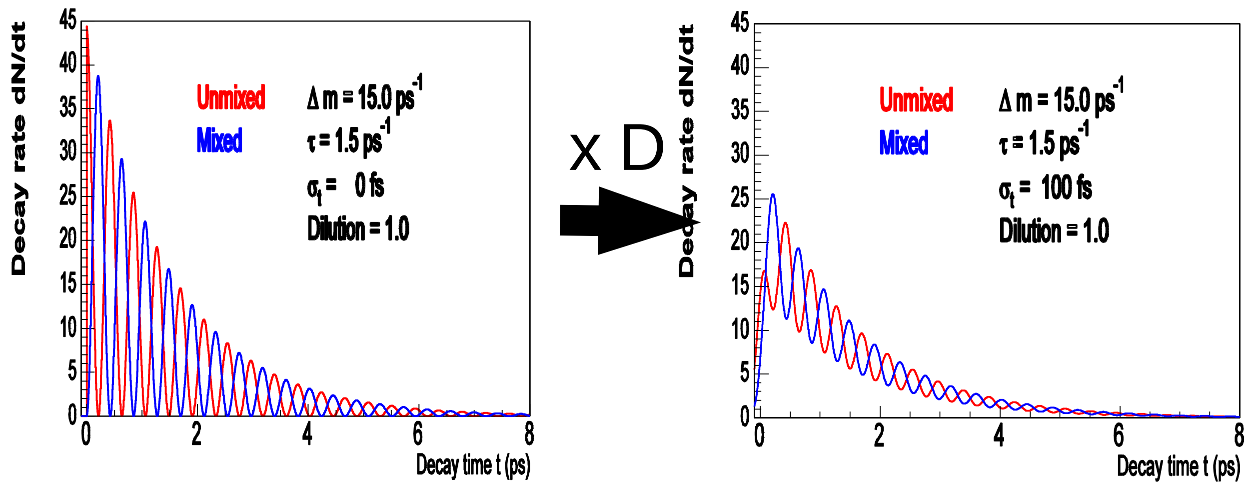
- Opposite side tag:
  - look at the decay products of the other b quark in the event:
    - Leptons
    - charge of the b-'jet'
  - the two b quarks fragment *independently*: can calibrate opposite side taggers with B_d & B_u
  - other B often outside acceptance
- Same side tag: look at particles produced in B meson formation (K in case of Bs)
  - Very powerful (high acceptance)
  - but cannot calibrate on B_d & B_u
    - Need to rely on MC
  - need to identify Kaons

Flavor tagging II

A tagger is characterized by

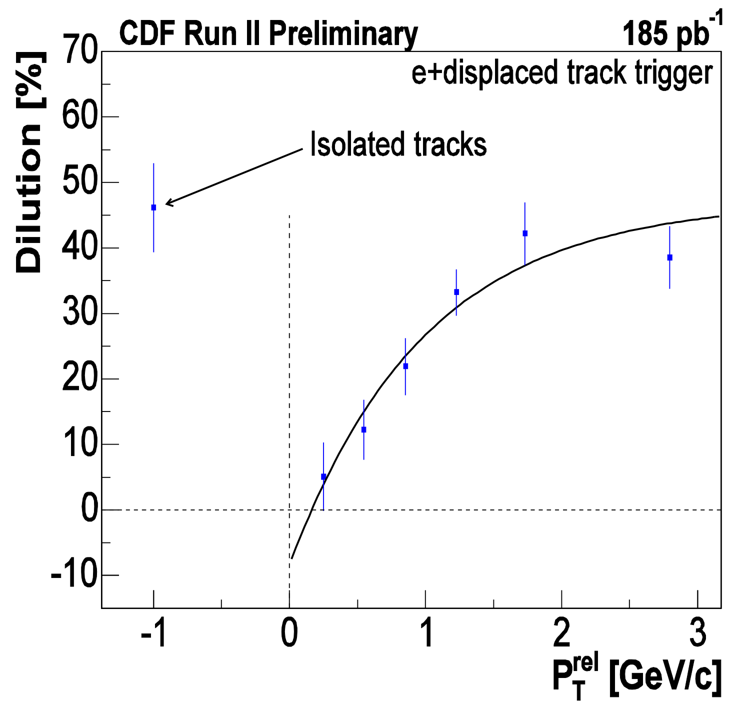
- ε: efficiency
- D: dilution = 1-2 x mistag rate (large dilution is good)
  - Dampens asymmetry: $A \rightarrow D \times A$
- Figure of merit: ε D^2

D<1 dampens the oscillation signal



We must know what D is to measure A

Opposite side taggers



Dilution predicted on event-by-event basis (based on P_T^{rel}, lepton-id etc).

how to check/calibrate the prediction is correct?

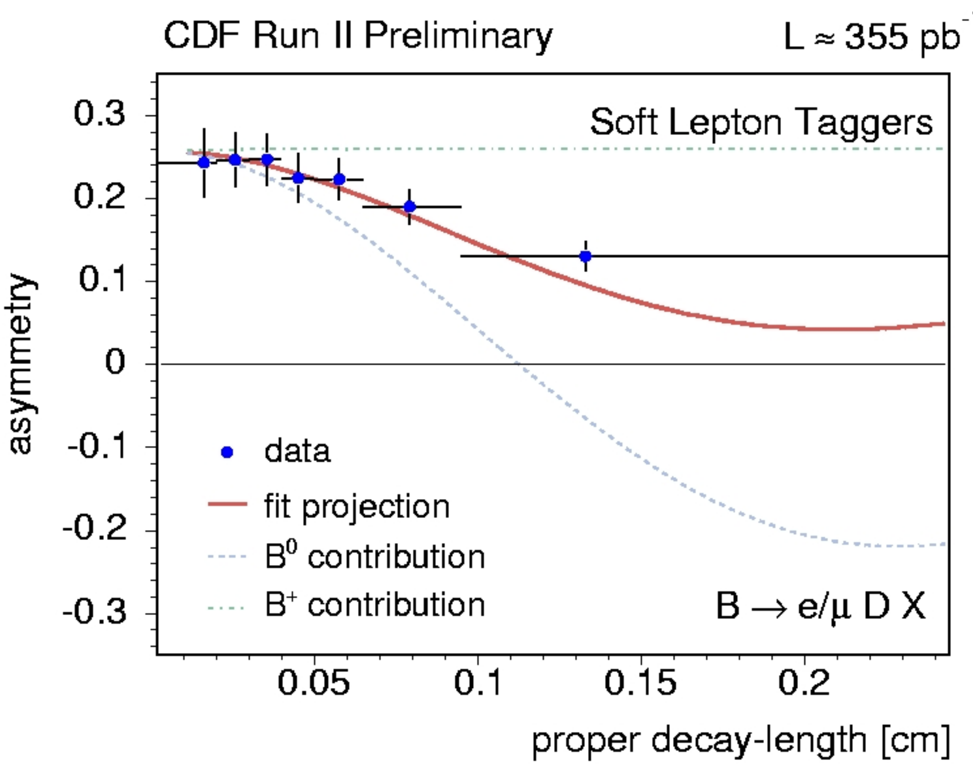
- Measure opposite side tagger dilutions
- Simultaneous fit to lD^+, lD^0 and lD^* modes

$$B^0 : e^{-t/\tau}\left(1 \pm S \cdot D \cdot \cos(\Delta m_d t)\right)$$

$$B^+ : e^{-t/\tau}\left(1 \pm S \cdot D\right)$$

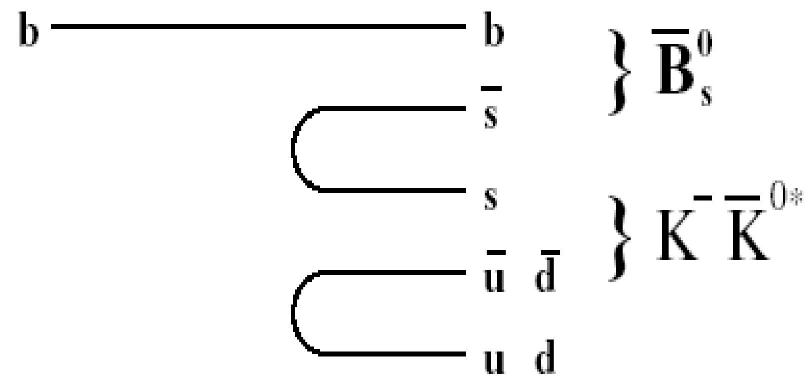
predicted dilution (D)

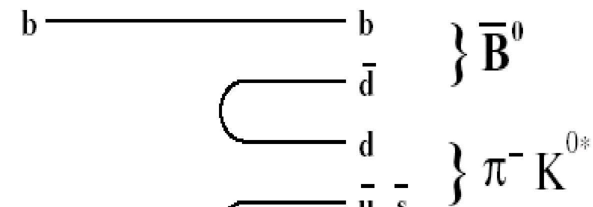
dilution scale factor (S)

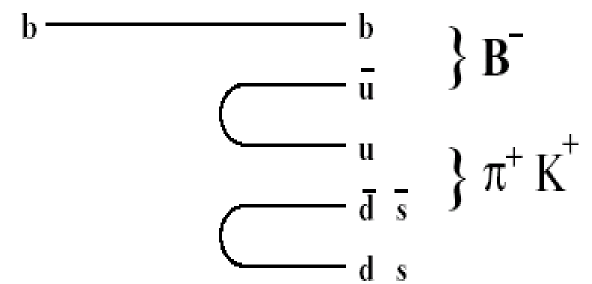


Same side kaon tagging

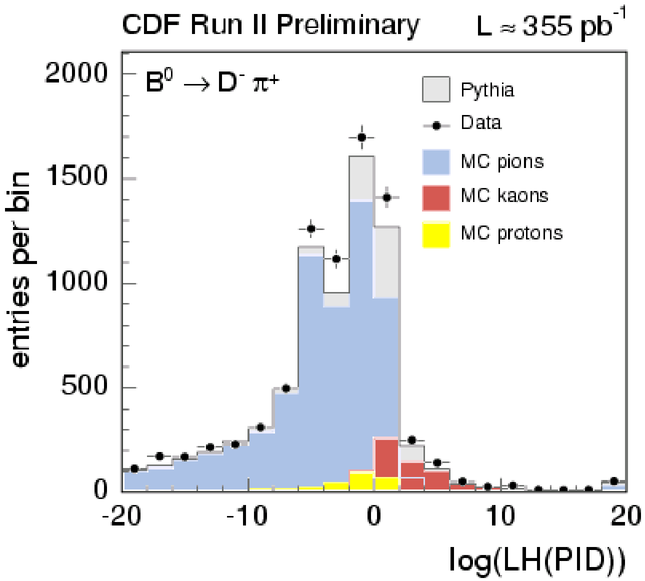
- Fragmentation into B_s tends to produce an additional kaon.
- B^0 and B^+ mostly accompanied by pions
- Use combined likelihood from time-of-flig detector and dE/dx in COT identify Kaon
- Charge of K identifies B_s flavor at production



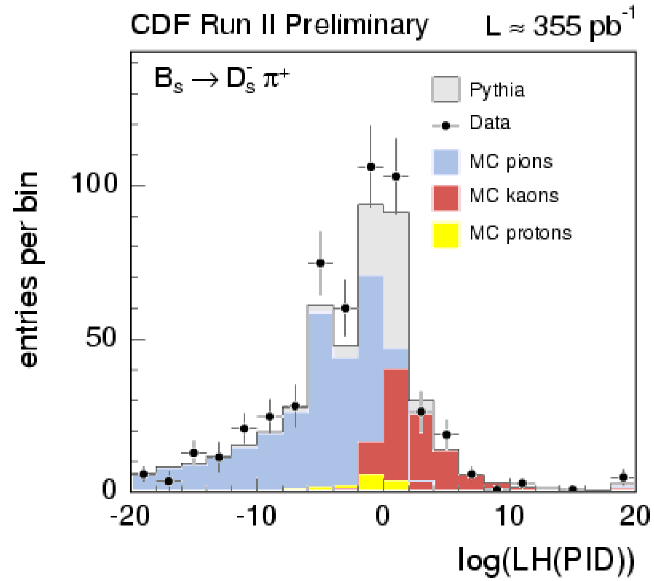




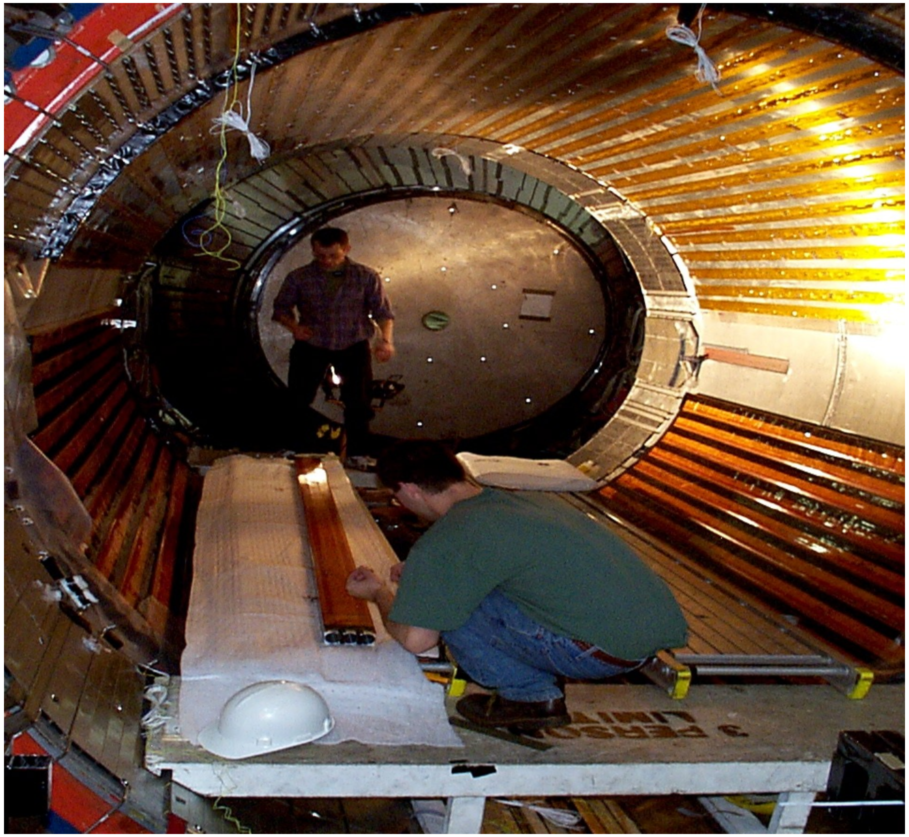
$B^0 \to D^- \pi^+$

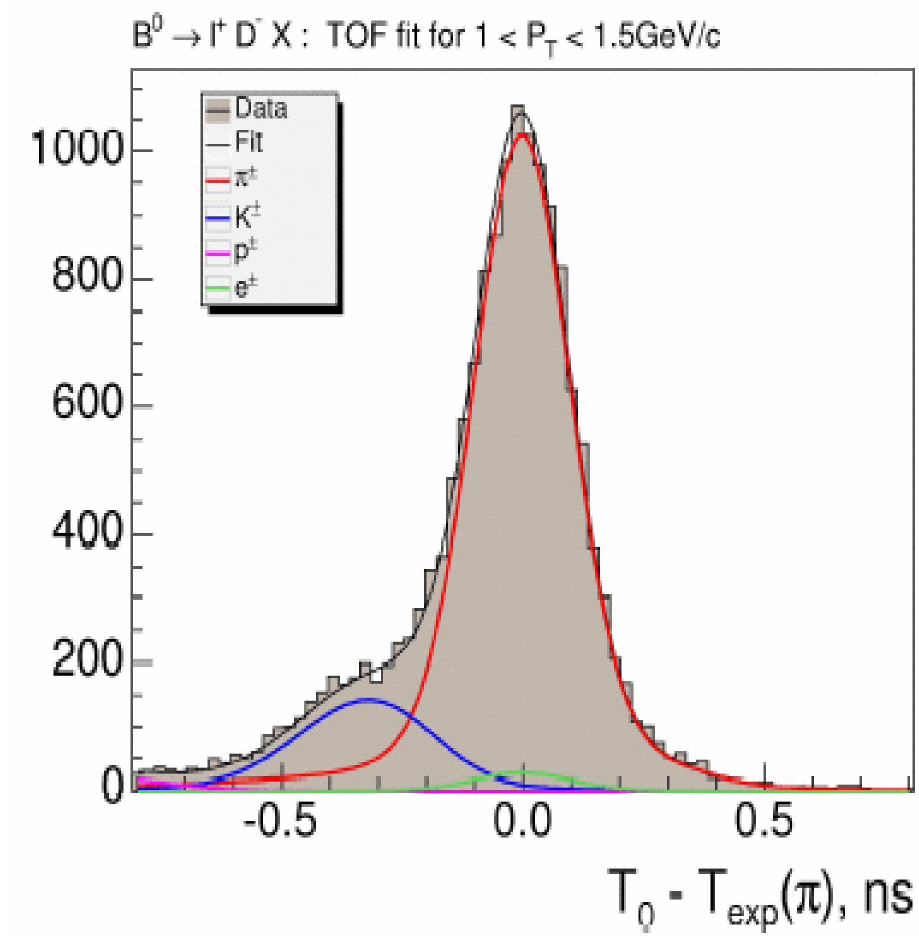


$B^0_s \to D^-_s(\phi\pi)\pi^+$



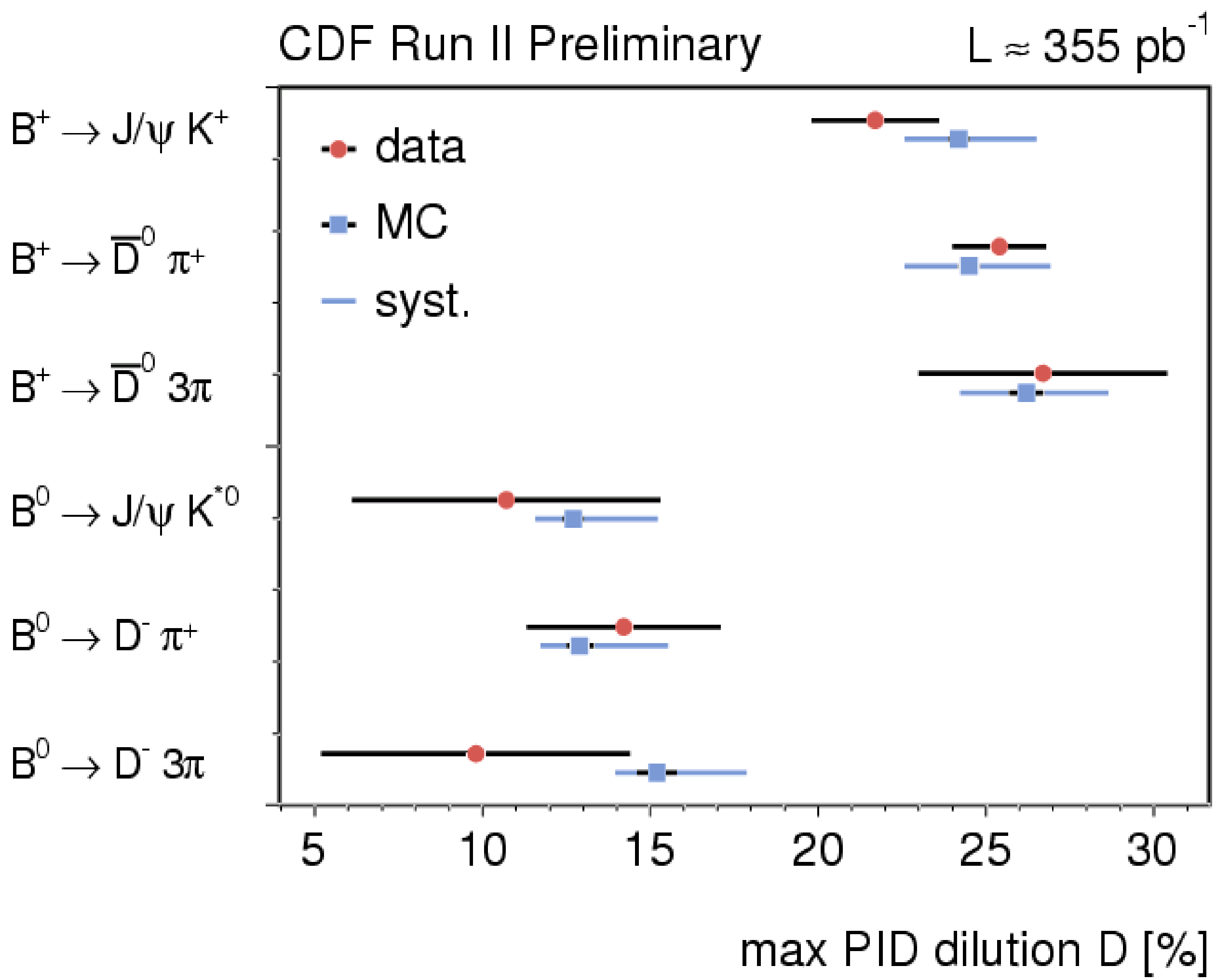
Time of flight detector





- resoluton ~ 100 ps
- seperates kaons from pions up to 1.5 GeV
- crucial for SSKT

Same side kaon tagging



tagger not optimized for these modes, but valuable check that MC predicts the right dilution

Flavor tagging: results

	Hadronic	Semileptonic
$\varepsilon\mathcal{D}^2$(SMT) (%)	0.48 ± 0.06	0.62 ± 0.03
$\varepsilon\mathcal{D}^2$(SET) (%)	0.09 ± 0.03	0.09 ± 0.01
$\varepsilon\mathcal{D}^2$(JVX) (%)	0.30 ± 0.04	0.28 ± 0.02
$\varepsilon\mathcal{D}^2$(JJP) (%)	0.46 ± 0.05	0.34 ± 0.02
$\varepsilon\mathcal{D}^2$(JPT) (%)	0.14 ± 0.03	0.11 ± 0.01
$\varepsilon\mathcal{D}^2$(OST) (%)	1.47 ± 0.10	1.44 ± 0.04
$\varepsilon\mathcal{D}^2$(SSKT) (%)	3.42 ± 0.96	4.00 ± 1.12

- Exclusive combination of opposite side taggers
- Same side combined with opposite side assuming independence
- Recently added kaon tagger increases effective statistics by a factor 3.5!

Combining it all

	Hadronic	Semileptonic
$\varepsilon\mathcal{D}^2$(SMT) (%)	0.48 ± 0.06	0.62 ± 0.03
$\varepsilon\mathcal{D}^2$(SET) (%)	0.09 ± 0.03	0.09 ± 0.01
$\varepsilon\mathcal{D}^2$(JVX) (%)	0.30 ± 0.04	0.28 ± 0.02
$\varepsilon\mathcal{D}^2$(JJP) (%)	0.46 ± 0.05	0.34 ± 0.02
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$\varepsilon\mathcal{D}^2$(OST) (%)	1.47 ± 0.10	1.44 ± 0.04
$\varepsilon\mathcal{D}^2$(SSKT) (%)	3.42 ± 0.96	4.00 ± 1.12

unbinned maximum likelihood fit

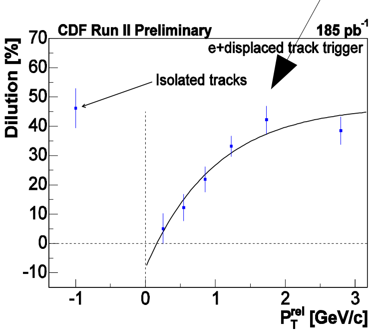
for each event:

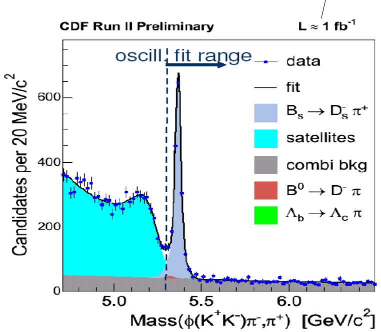
$$\mathcal{L}_k = \mathcal{L}_k^{Mass} \cdot \mathcal{L}_k^{ct} \cdot \mathcal{L}_k^{\sigma_{ct}} \cdot \mathcal{L}_k^{D}$$

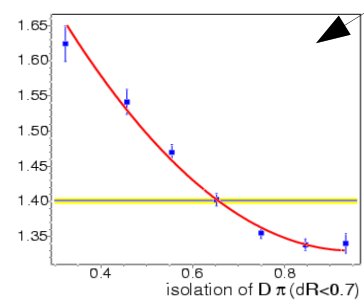
k=sig,bg

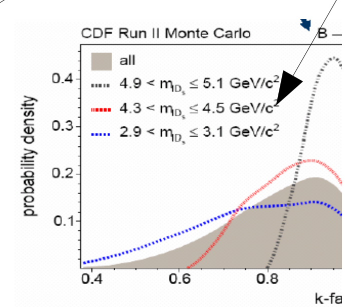
$$\mathcal{L}_{sig}^{ct} = \epsilon_i \cdot \left(\frac{1 \pm A \cdot S_{D_i} \cdot D_i \cdot cos(\Delta m_s \cdot k \cdot ct')}{2} \cdot \frac{1}{N} e^{-\frac{k \cdot ct'}{c\tau}} \right) \otimes G(ct - ct'; S_{\sigma_t}\sigma_t) \otimes F(k) \cdot \epsilon(ct)$$

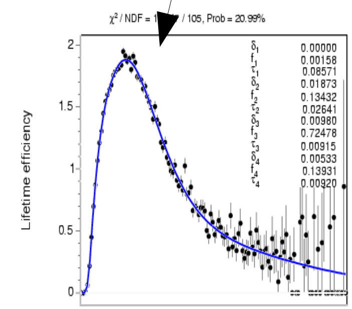
pdg







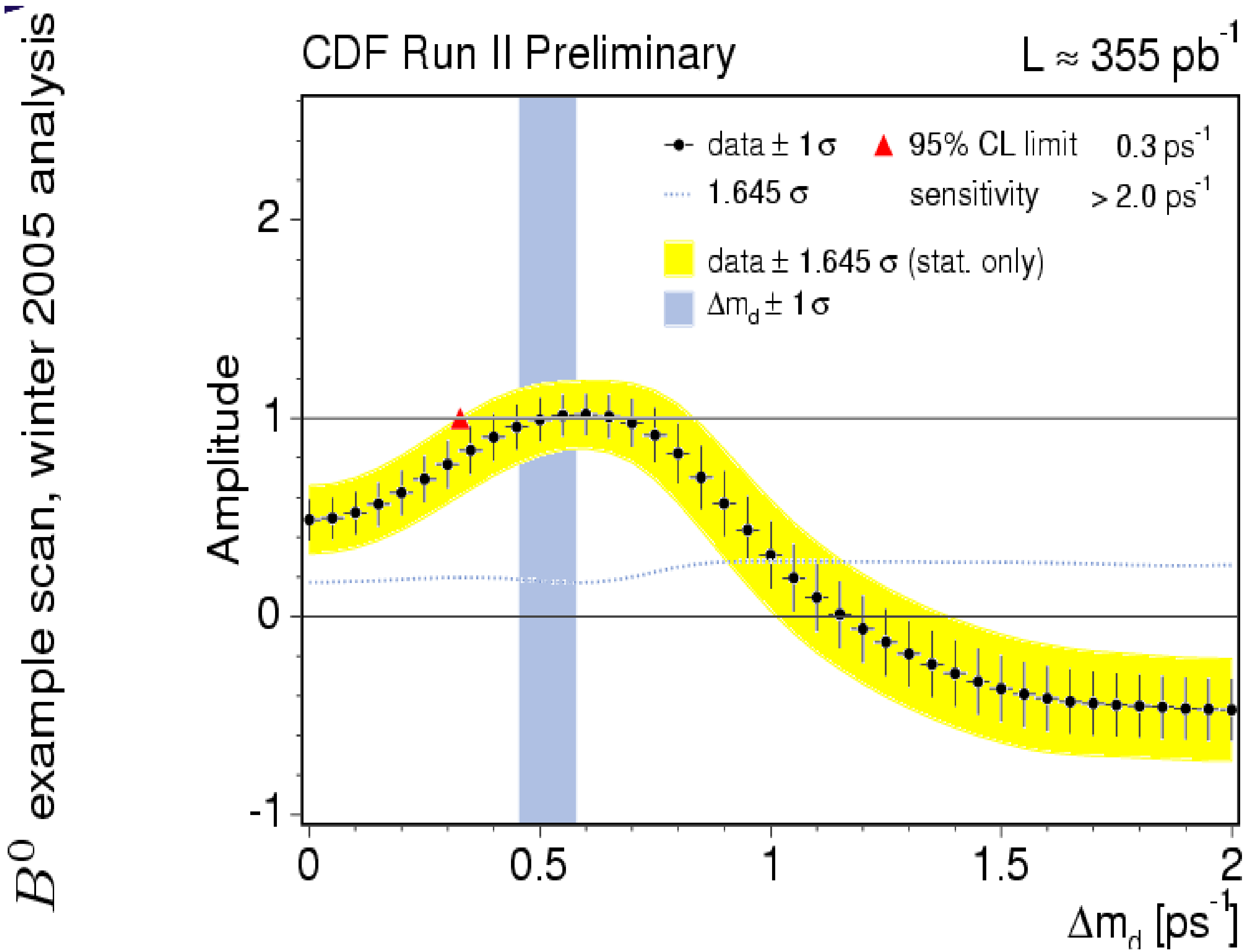




- fix Δm_s
- integrate over true decay length ct and true k-factor
- get $A(\Delta m_s)$

Before fitting for Δm_s: test whole procedure by on B_d mixing

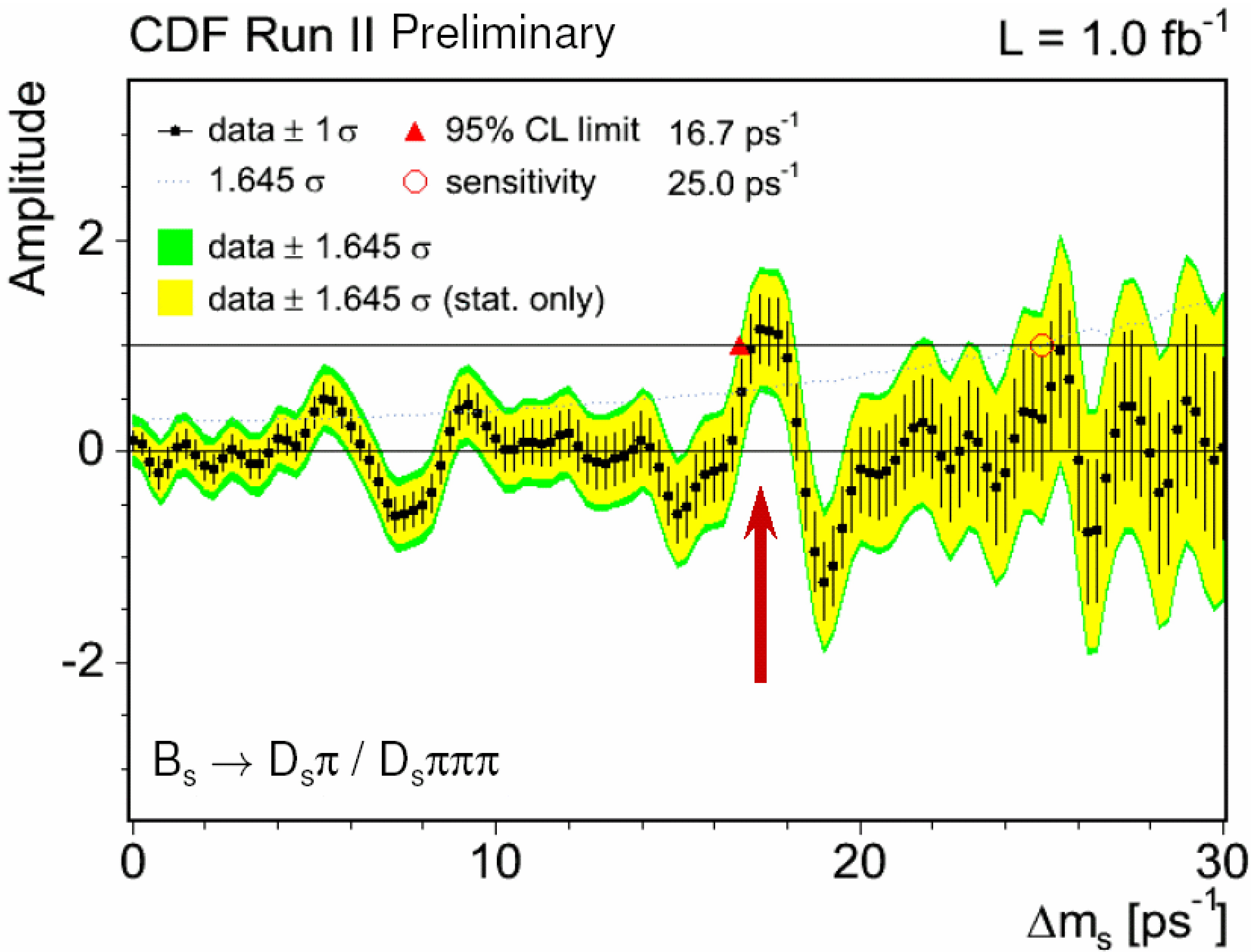
Amplitde scan: B_d



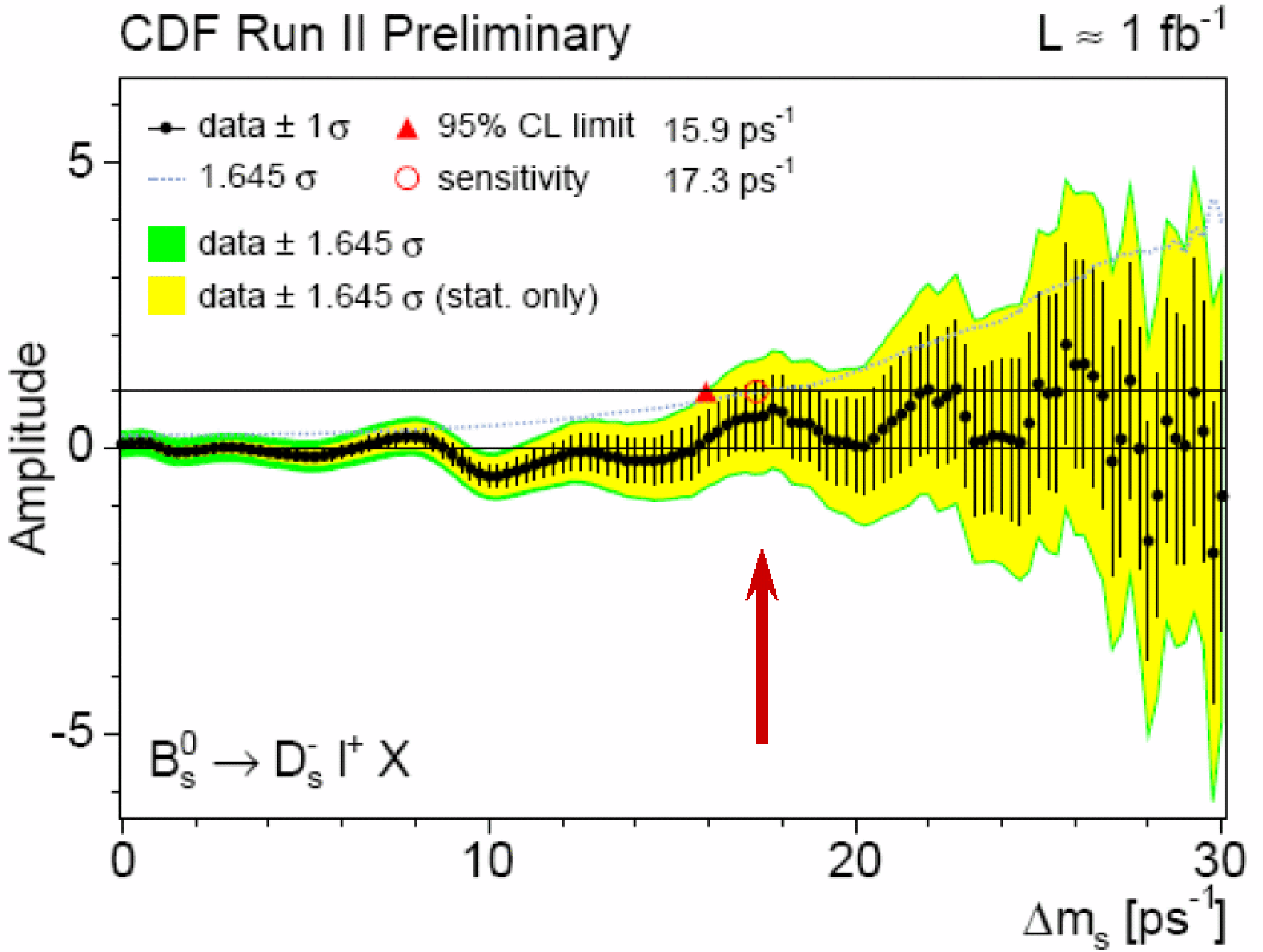
Verify validity of procedure fitted value of Δm_d agrees with world average.

Results

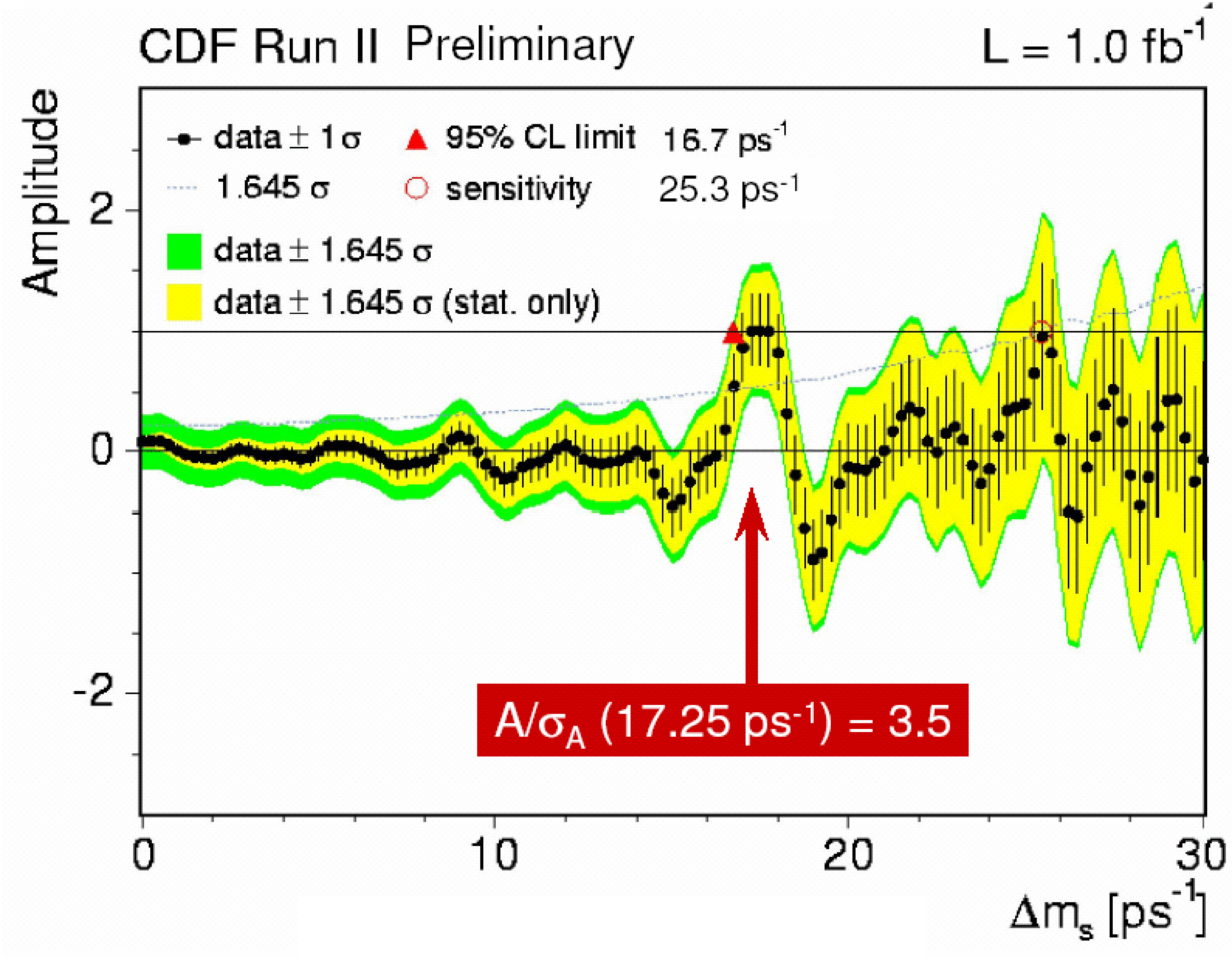
Amplitude scan: hadronic



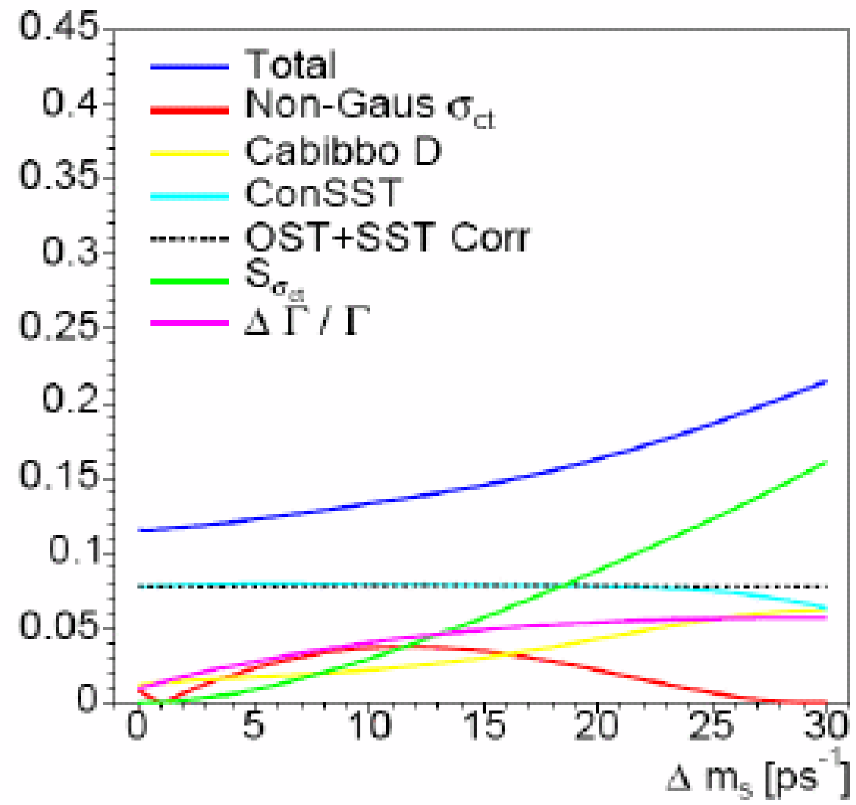
Amplitude scan: semileptonic

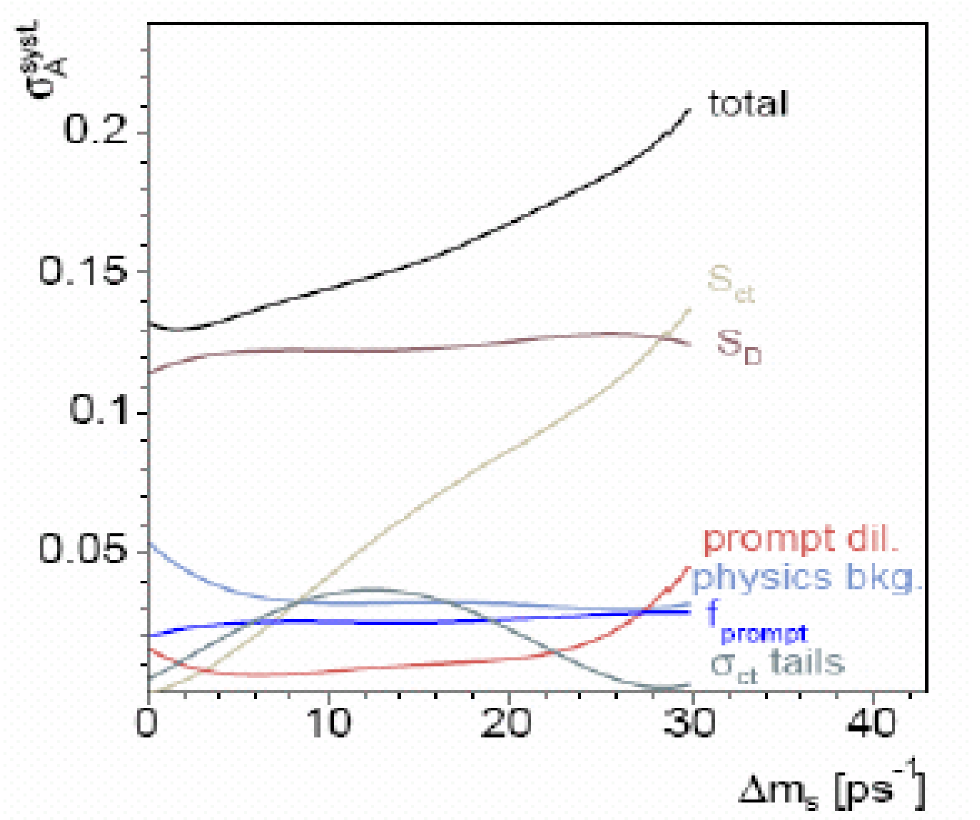


Amplitude scan: combined



Systematics on the amplitude

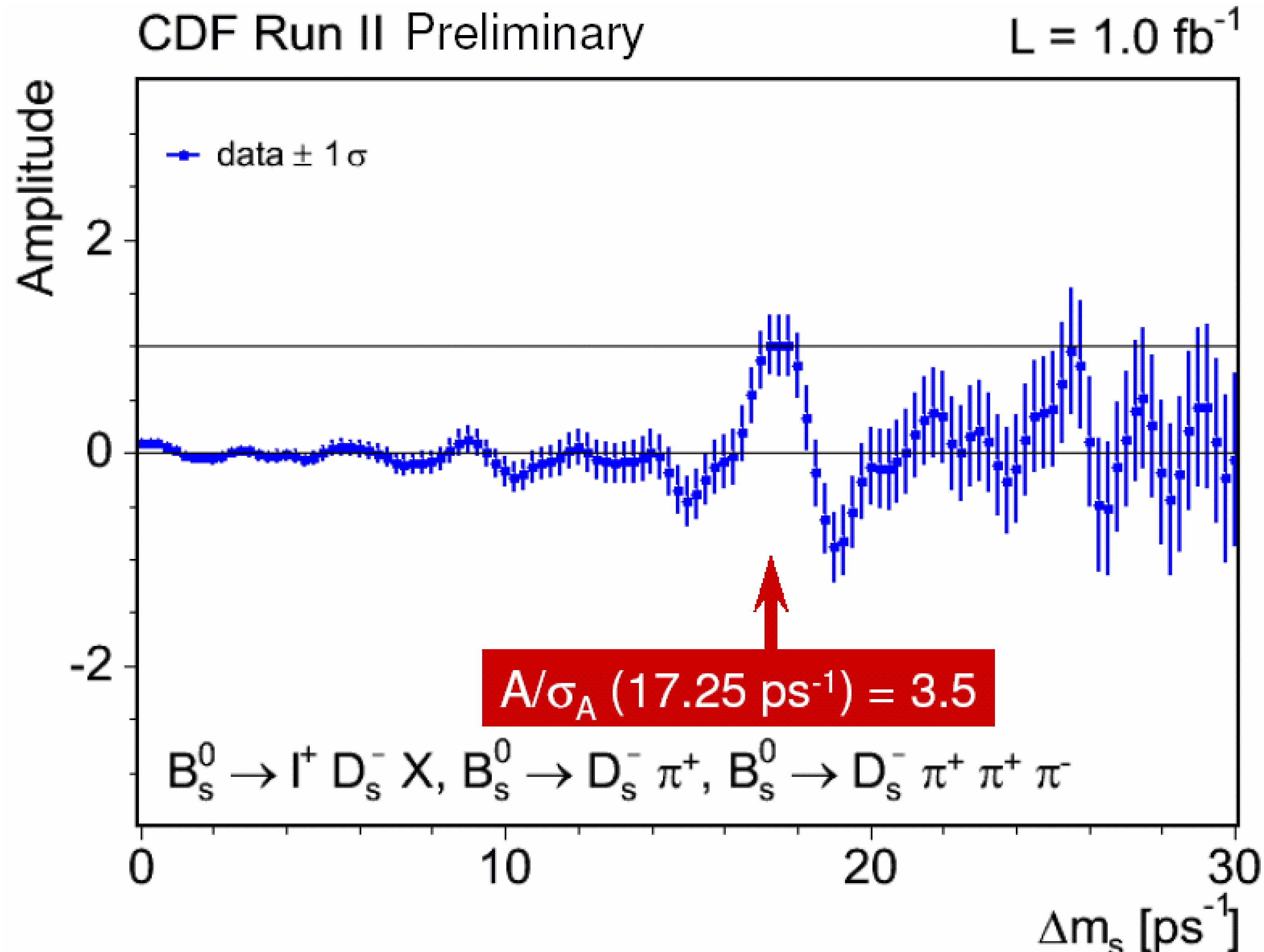




systematics on amplitude scale: both A and σ_A

Amplitude scan

without the yellow and green stuff



How significant is this result?

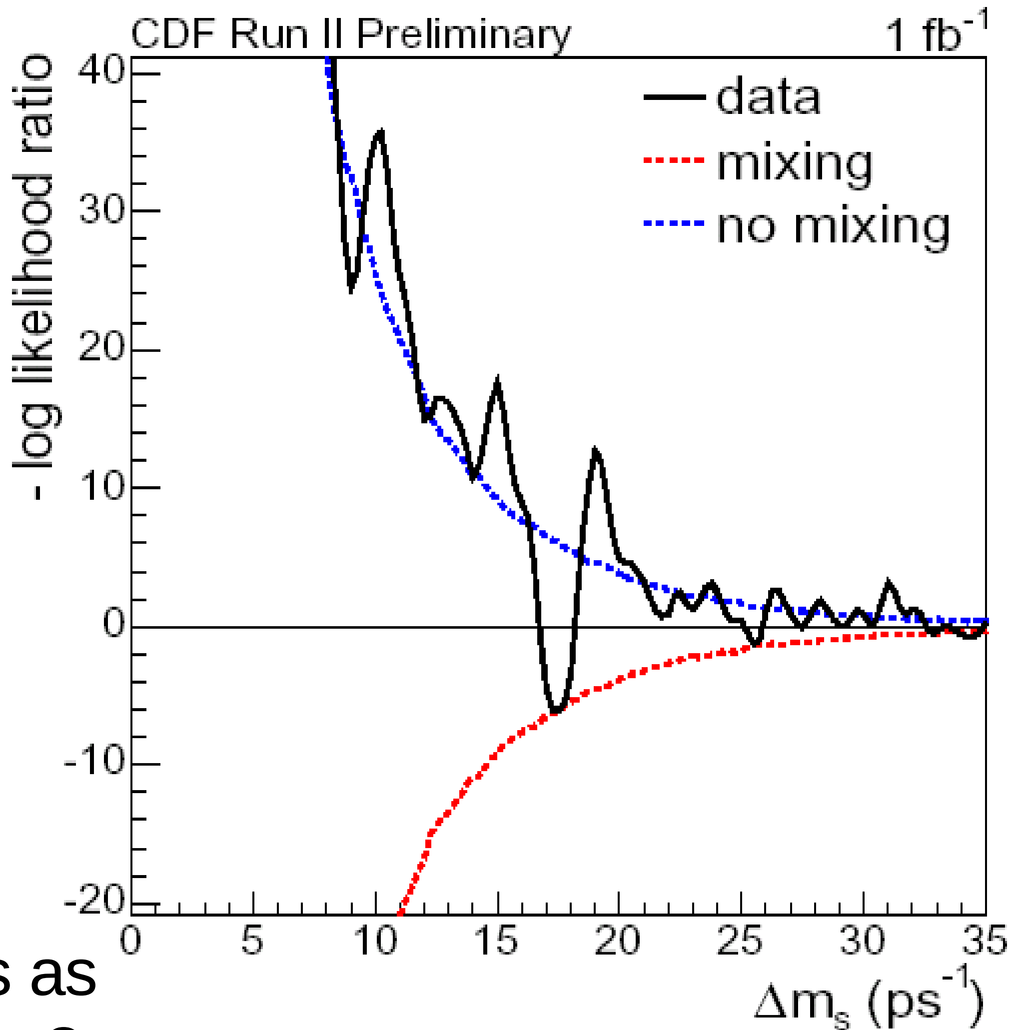
Significance of the result

- Amplitude scan not used for significance evaluation, instead:
- Look at

$-\Delta\log(L) = -\log(L^{mixing}/L^{no\ mixing})$

$= -\log(L^{A=1}/L^{A=0})$

- gives better discriminating power than $A/\sigma(A)$
- no search window needed



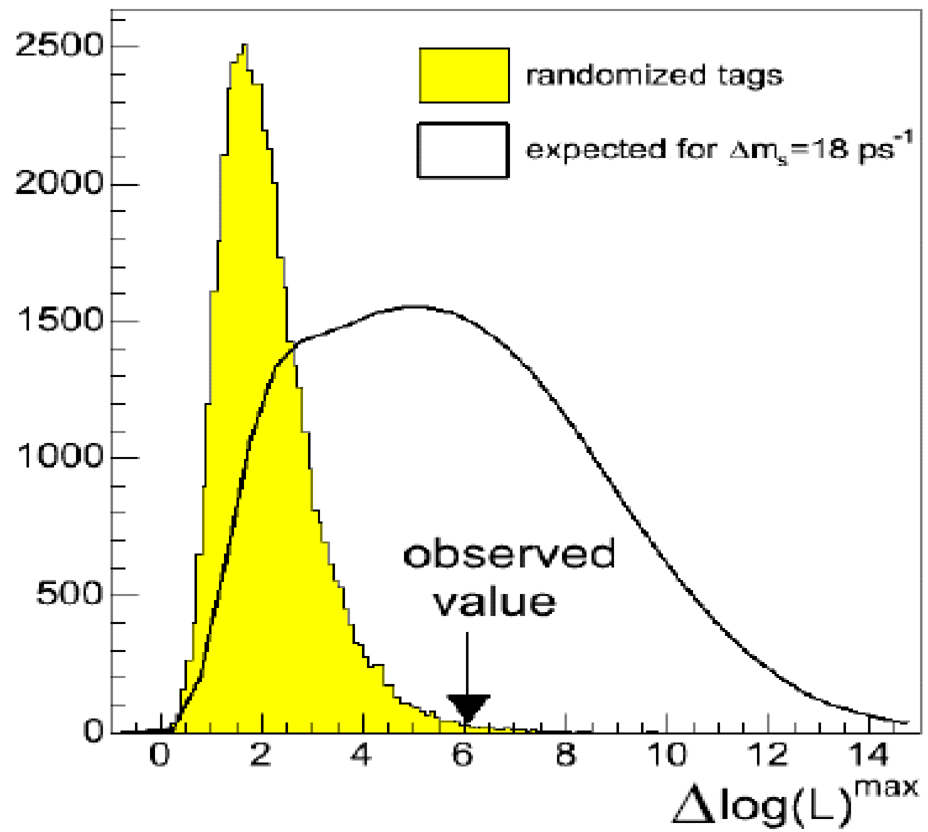
Minimal value observed

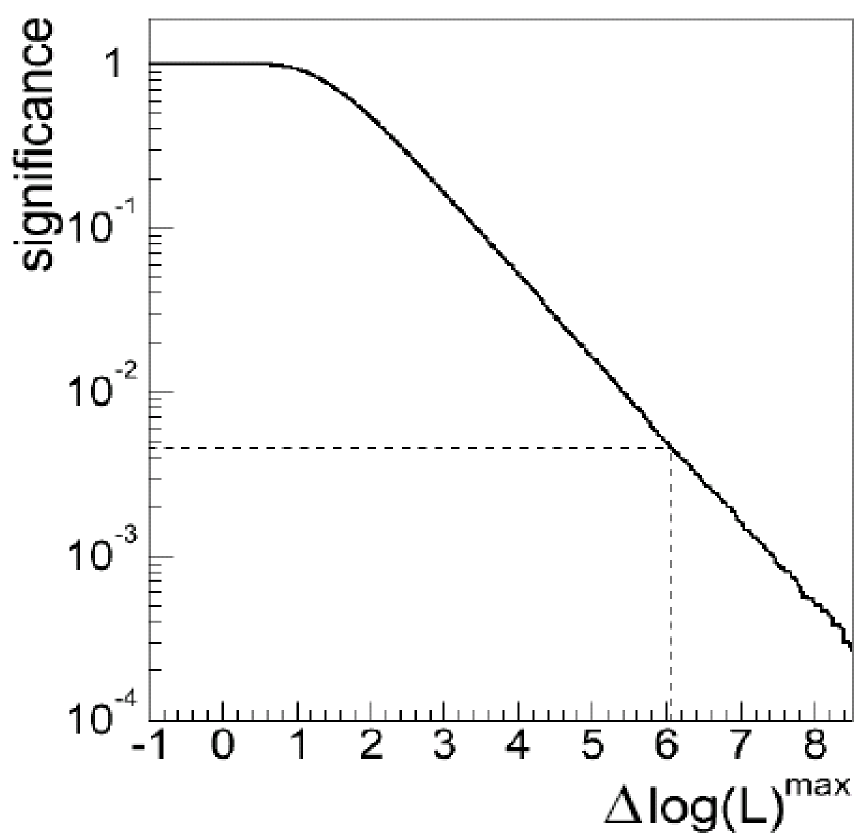
$-\Delta\log(L)=-6.06$

What is the probability that happens as result of fluctuation if Δm_s=very large?

Significance of the result

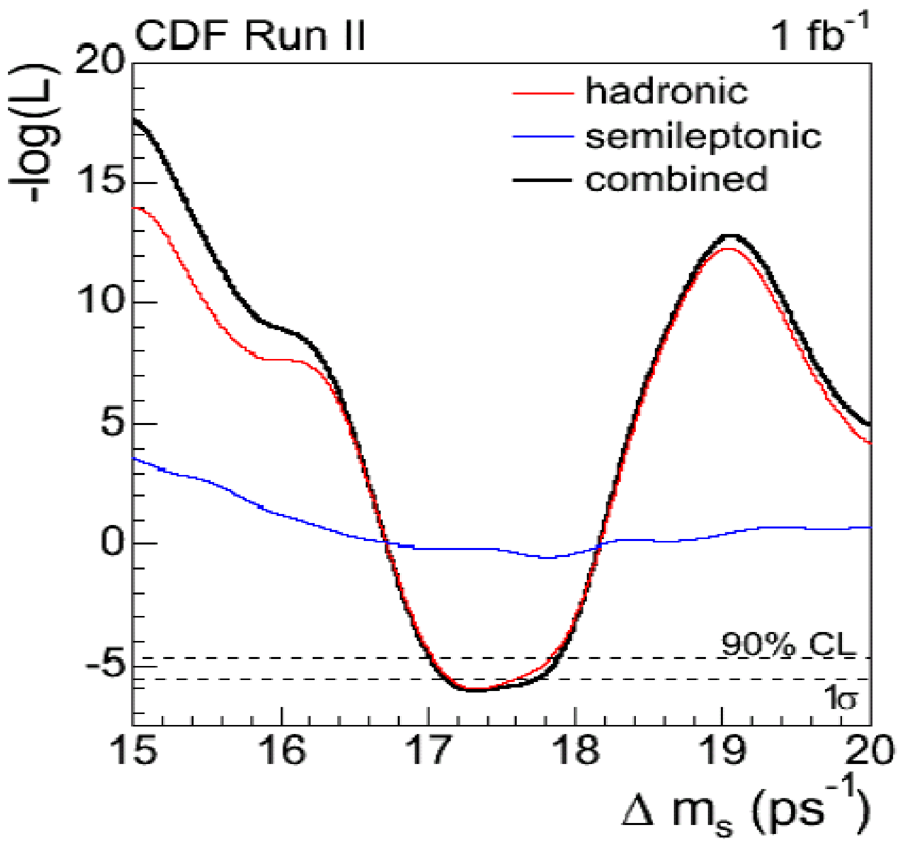
Repeat likelihood scan many times while randomizing the tagger decisions





probability to see such a large value of $\Delta\log(L)$ as result of a statistical fluctuation (aka p-value) = 0.5 %

Measurement of Δm_s



- Decided (a-priory) to extract Δm_s if the p-value < 1%
- it's 0.5%, so here we go...

- systematics on A are unimportant for Δm_s. only lifetime scale matters.
- effect considered: Si alignment, bias from ct-curvature correlations, primary vertex

$$\Delta m_s = 17.33^{+0.42}_{-0.21}(stat.) \pm 0.07(syst.)\mathrm{ps}^{-1}$$

Δm_s in [17.00, 17.91] ps^{-1} at 90% C.L.

Δm_s in [16.94, 17.97] ps^{-1} at 95% C.L.

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

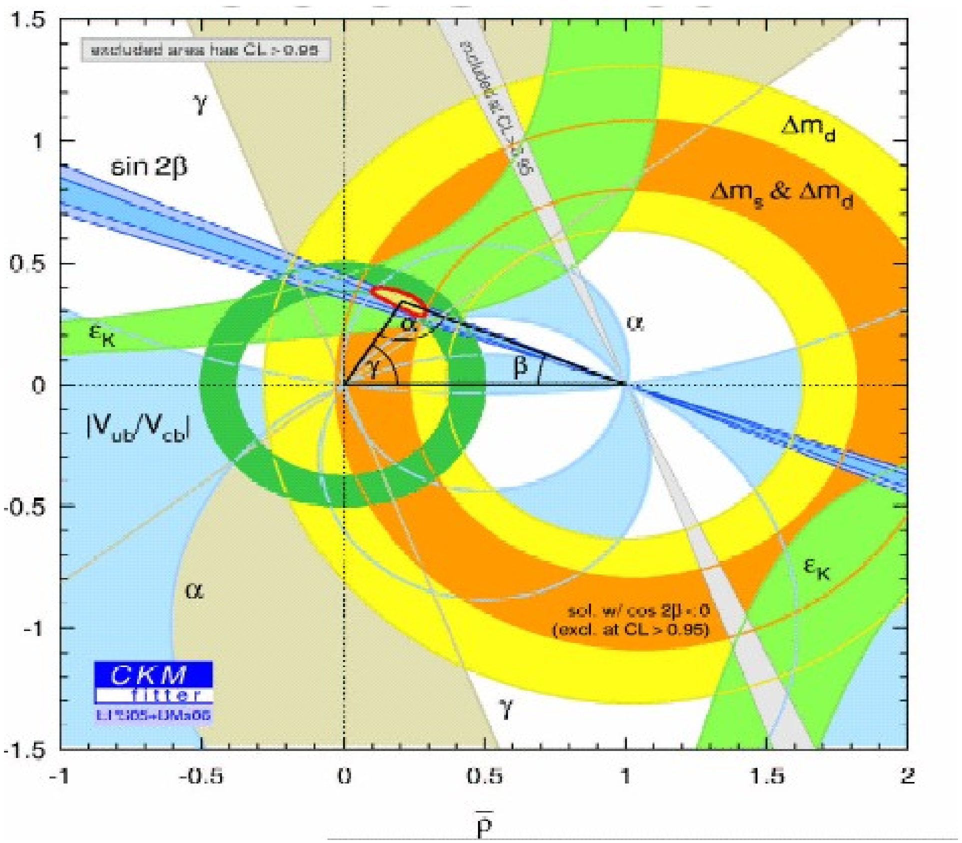
Input	Value	Source
$m(B_d)/m(B_s)$	0.98320	PDG
ξ^2	$1.21\,^{+0.047}_{-0.035}$	Okamoto, Lattice 2005
Δm_d	0.505 ± 0.005	PDG
Δm_s	$17.330\,^{+0.426}_{-0.221}$	This analysis

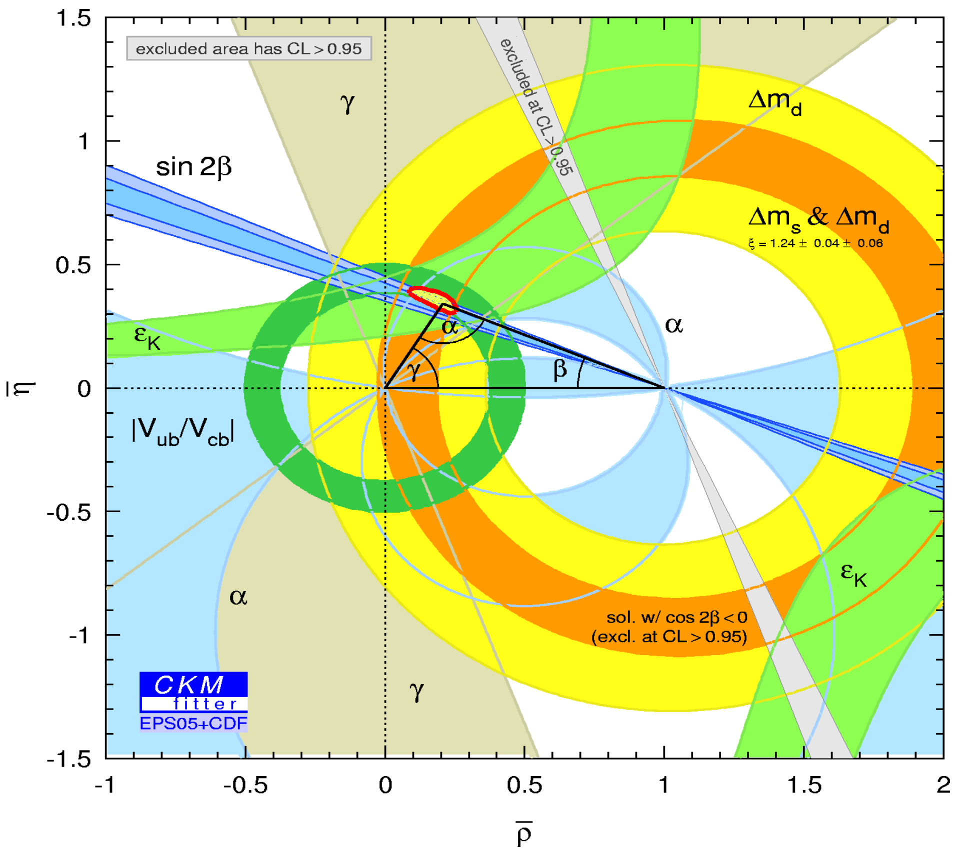
$$|V_{td}|/|V_{ts}| = 0.208\,^{+0.008}_{-0.007}$$

Belle measurement $b \to d\gamma$: $|V_{td}|/|V_{ts}| = 0.200\,^{+0.026}_{-0.025}(exp.)\,^{+0.038}_{-0.029}(theo.)$

now again limited by theory error

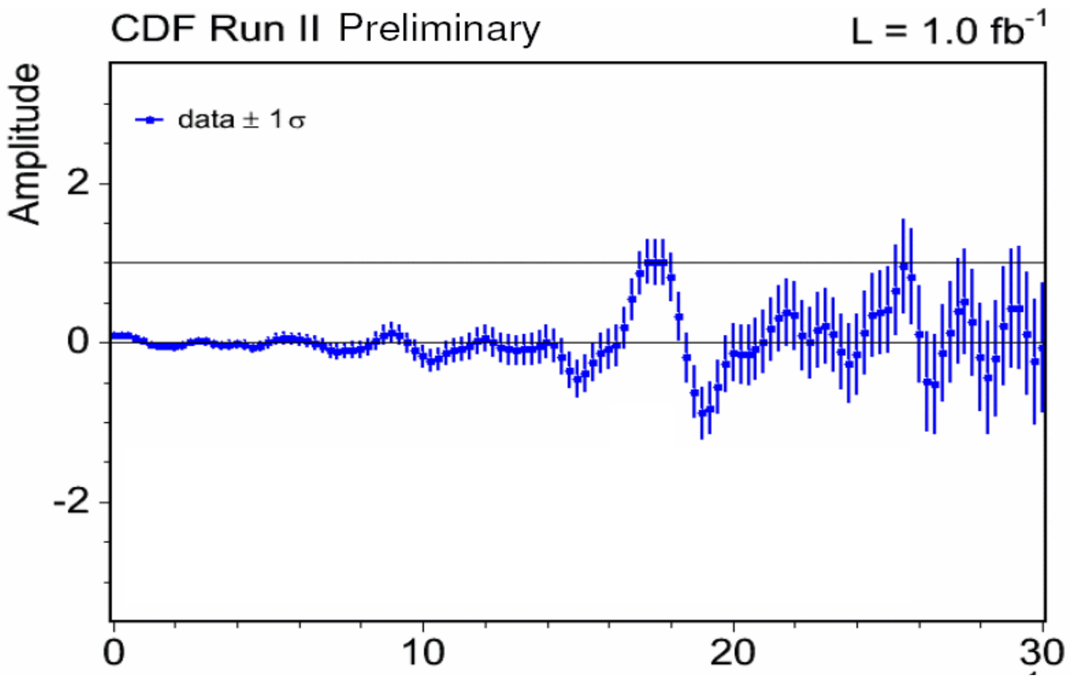
Effect on unitarity triangle





Conclusions

- Experimentally challenging... made possible by
  - Tevatron: ~only place where B_s is made
  - B-physics trigger: CDF has displaced track trigger
  - Good lifetime resolution to resolve fast oscillations: SVX (L00)
  - Flavor tagging (time-of-flight detector for SSKT)



$$\Delta m_s = 17.33^{+0.42}_{-0.21}(stat.) \pm 0.07(syst.)\mathrm{ps}^{-1}$$