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mixing at CDF

Overview

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

- Public documentation is available at:
  - http://www-cdf.fnal.gov/physics/new/bottom/bottom.html

CDF/DOC/BOTTOM/CDFR/7861
October 11, 2005 Version 2.6

Updated Study of B_s Oscillations in $B_s \to D_s(3)\pi$

76 people from 24 institutions

B_s Mixing group

Farrukh Azfar [19], Gary Barker [7], Gerry Bauer [13], Franco Bedeschi [10], Satyajit Behari [15], Stefano Belforte [11], Alberto Belloni [13], Eli Ben-Haim [12], Juerg Beringer [5], Arkadiy Bolshov [13], Joe Boudreau [22], Massimo Casarsa [11], Pierluigi Catastini [10], Alessandro Cerri [5], Agnese Ciocci [10], David Clark [2], Saverio D'Auria [6], Saverio Da Ronco [20], Sandro De Cecco [9], Amanda Deisher [5], Francesco Delli Paoli [20], Gianpiero Di Giovanni [12], Simone Donati [10], Mauro Donega [16], Sinead Farrington [18], Michael Feindt [7], Armando Fella [10], Ivan Furić [4], Stefano Giagu [9], Karen Gibson [3], Kim Giolo [14], Gavril Giurgiu [3], Guillelmo Gomez-Ceballos [8], Robert Harr [25], Aart Heijboer [21], Matt Herndon [24], Todd Huffman [19], Boris Iyutin [13], Matthew Jones [14], Ulrich Kerzel [7], Ilya Kravchenko [13], Joe Kroll [21], Tom LeCompte [1], Claudia Lecci [7], Nuno Leonardo [13], Donatella Lucchesi [20], Johannes Mülmenstädt [5], Petar Maksimović [15], Stephanie Menzemer [13], Jeffrey Miles [13], Michael Morello [10], Reid Mumford [15], Steve Nahn [26], Rolf Oldeman [18], Manfred Paulini [3], Christoph Paus [13], Jonatan Piedra [12], Kevin Pitts [17], Giovanni Punzi [10], Jonas Rademacker [19], Azizur Rahaman [22], Marco Rescigno [9], Alberto Ruiz [8], Giuseppe Salamanna [9], Aurore Savoy-Navarro [12], Fabrizio Scuri [10], Marjorie Shapiro [5], Paola Squillacioti [10], Masa Tanaka [1], Vivek Tiwari [3], Fumi Ukegawa [23], Satoru Uozumi [23], Denys Usynin [21], Ivan Vila [8], Barry Wicklund [1], Chun Yang [26]

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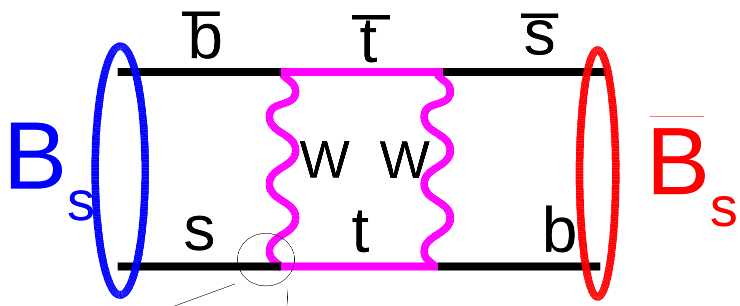
Flavor Oscillations



W couples to quarks from different families

off-diagonal element is a measure for coupling between B and B.

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

$$\Psi(t) = a(t)\left|B^0\right\rangle + b(t)\left|\bar{B}^0\right\rangle \equiv \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

The Schrodinger equation:

$$i\frac{\partial}{\partial t}\Psi = H\Psi$$

$$H = \underbrace{\begin{pmatrix} M & M_{12} \\ M_{12}^{*} & M \end{pmatrix}}_{\text{hermitian}} - \frac{i}{2}\underbrace{\begin{pmatrix} \Gamma & 0 \\ 0 & \Gamma \end{pmatrix}}_{\text{hermitian}}$$

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

the mass eigenstates are:

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

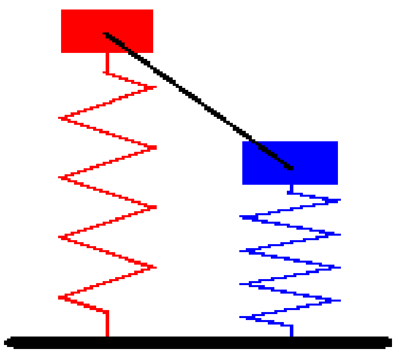
$$\left|B_L\right\rangle = \frac{1}{\sqrt{2}}\left(\left|B\right\rangle - \left|\bar{B}\right\rangle\right) \qquad M_H = M_{11} + M_{12}$$

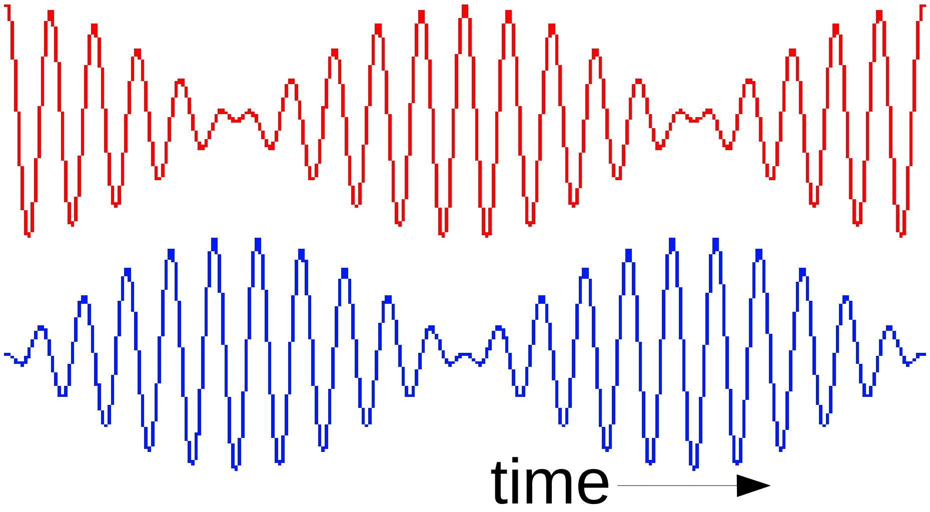
$$\Delta M = 2M_{12}$$

introducing a coupling introduces splitting in the energy levels; we've seen that before.....

Coupled oscillators

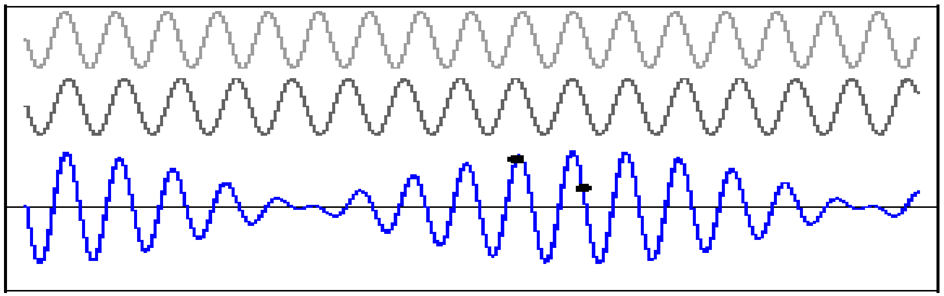
coupling induces splitting in energy levels (not only in QM)





- the red and blue oscillator eigen-frequencies are no longe eigen-frequency of the system
- two different eigenfrequencies, split by small value
- size of splitting proportional to the amount of coupling between red and blue
- oscillation (envelope) between pure blue and pure red

oscillation pattern is made up of two fundamental frequencies:



Oscillation probability as function of time

Solving the time dependent SE

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

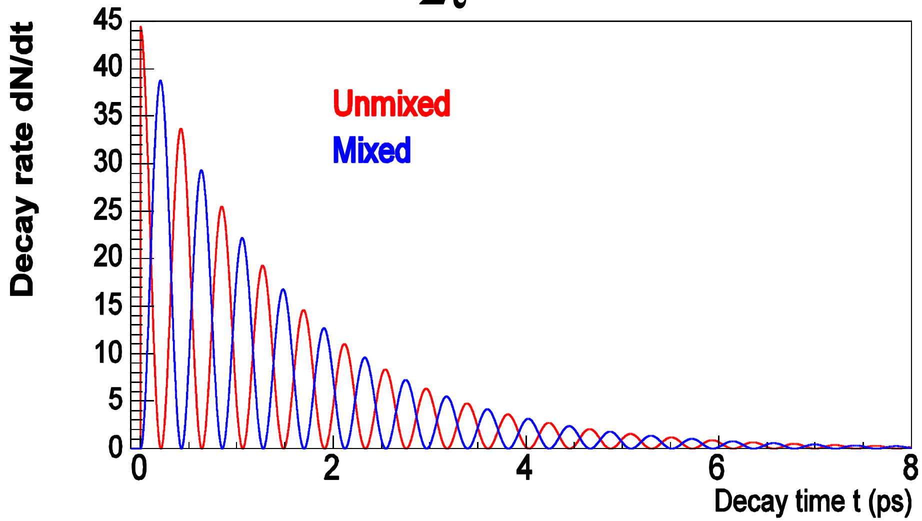
$$|\overline{B}(t)> \;=\; e^{-iMt}e^{-\frac{\Gamma}{2}t}\left(\cos\frac{\Delta m}{2}t|\overline{B}> + \sin\frac{\Delta m}{2}t|B>\right)$$

decay time

oscillation frequency.
1 ps^{-1} ~ 7 x 10^{-4} eV (~1.5x10^{-13}m$_b$)

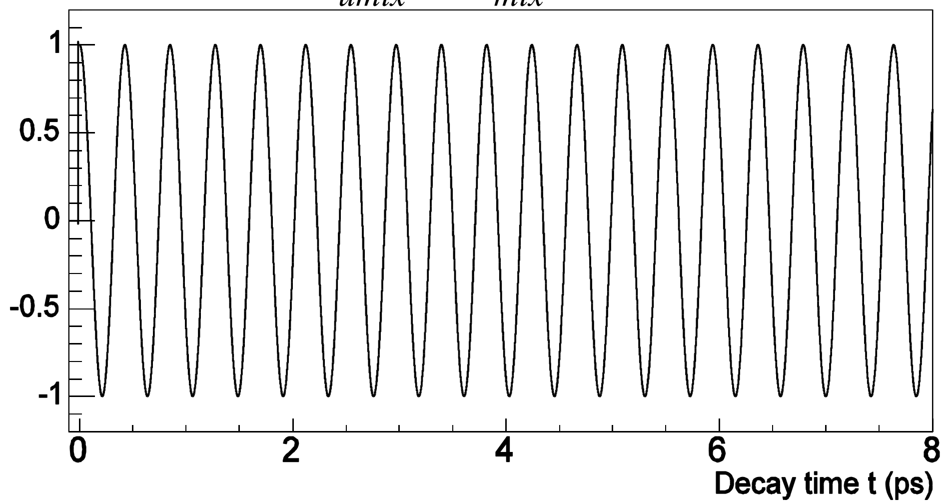
$$P(B\rightarrow B) = \frac{e^{-t/\tau}}{2\tau}(1+\cos\Delta mt) = P_{umix}$$

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



assymetry

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



B_s vs B_d

fraction of mixed events

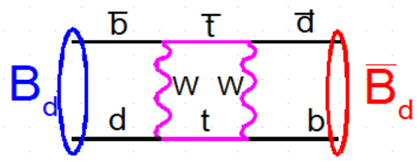
$$\chi = \int_0^\infty P_m(t)$$

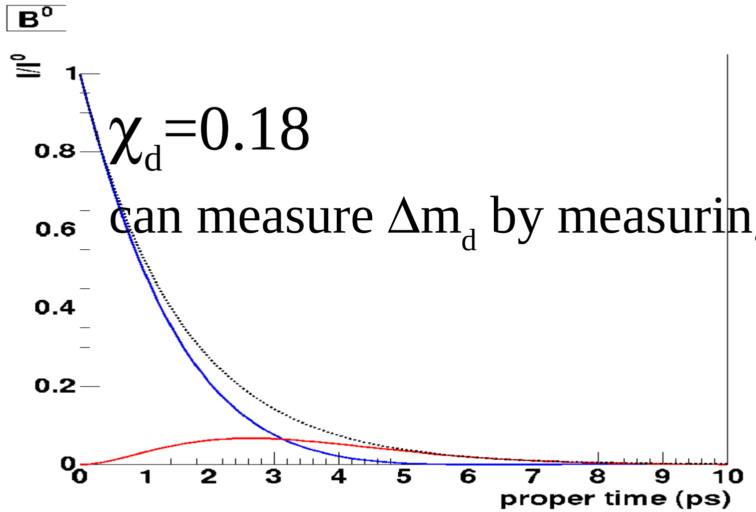
$$\chi = \frac{1}{2} \frac{1}{1 + (\tau \Delta m)^{-2}}$$

B_d

τ=1.54 ps

Δm_d=0.5 ps^{-1}





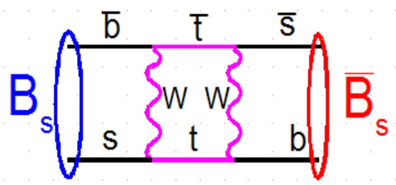
χ_d=0.18

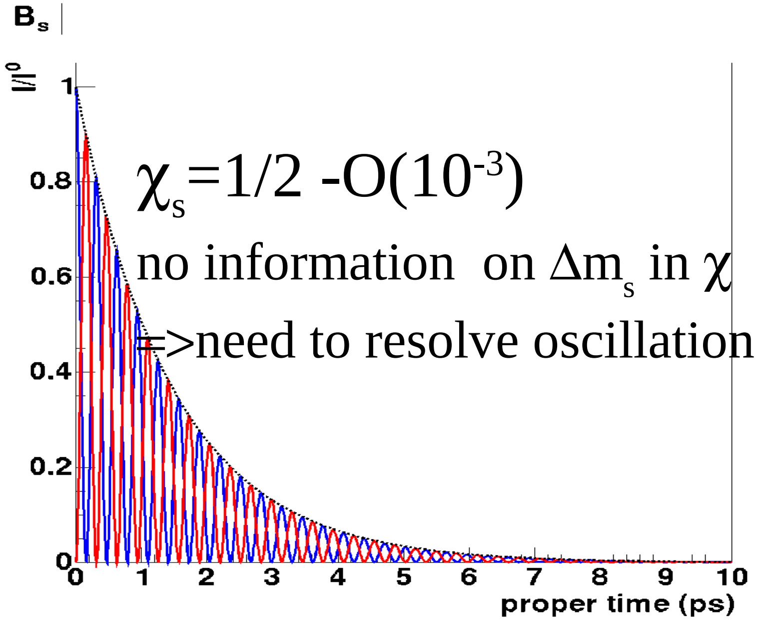
can measure Δm_d by measuring χ

B_s

τ=1.41 ps

Δm_s=~20 ps^{-1}



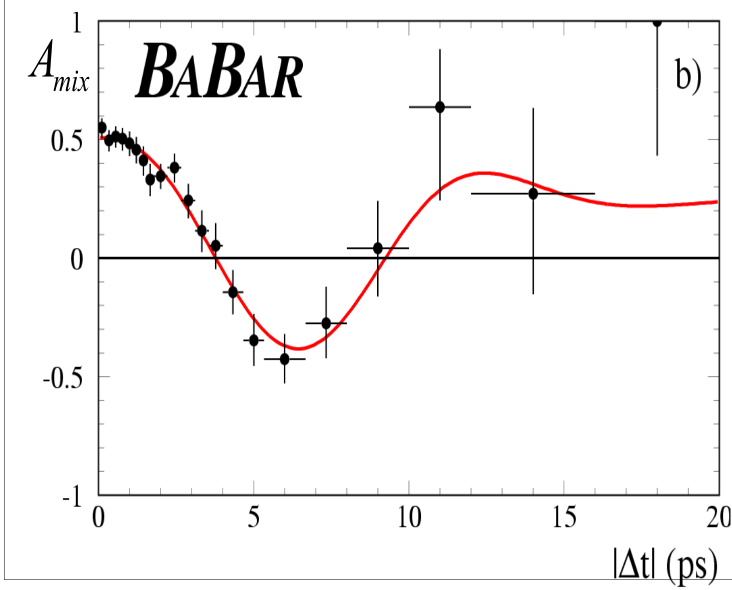


χ_s=1/2 -O(10^{-3})

no information on Δm_s in χ

=>need to resolve oscillation

Bd mixing first observed by measuring χ_d (UA1, ARGUS 1987)



nb: neutral meson mixing first predicted in Kaons (1955 Gell-Man & Pais) observed Brookhaven 1956

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)

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

q=s or d

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

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

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s} f_{B_s}^2 B_{B_s}}{m_{B_d} f_{B_d}^2 B_{B_d}} \left| \frac{V_{ts}}{V_{td}} \right|^2 = 1.21 \pm 0.02 \quad \left| \frac{V_{ts}}{V_{td}} \right|^2$$

Motivation

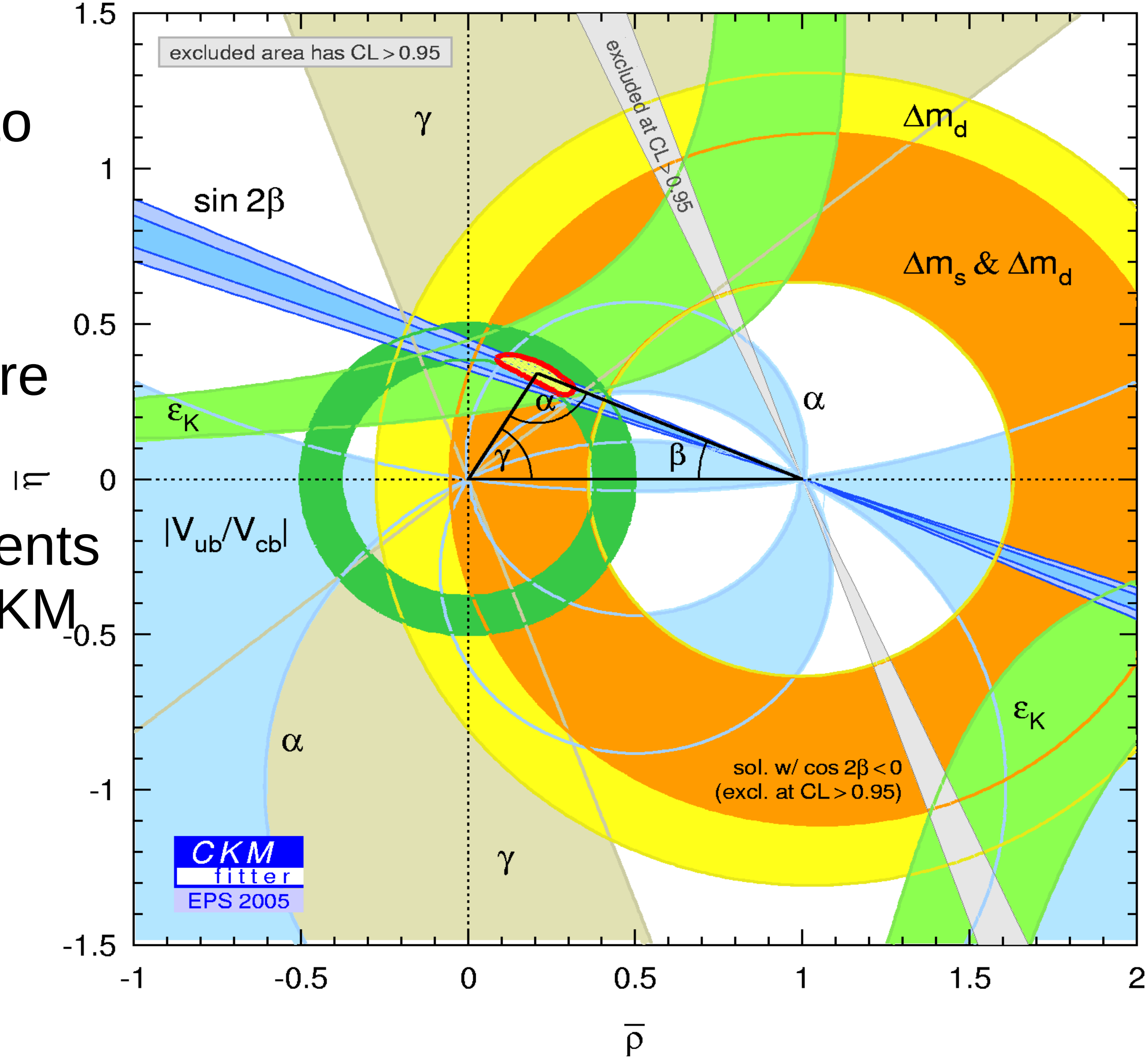
Plot Combines many different measurements to constrain ρ and η.

Current limit on Δm_s is already helping to measure CKM matrix...

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

if not...

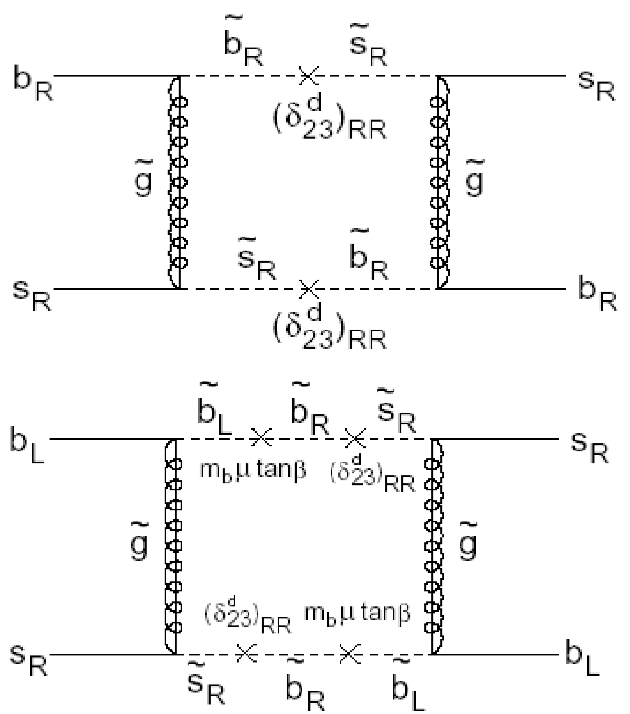
$V_{td} = A\lambda^3(1-\rho-i\eta)$



Motivation: new physics

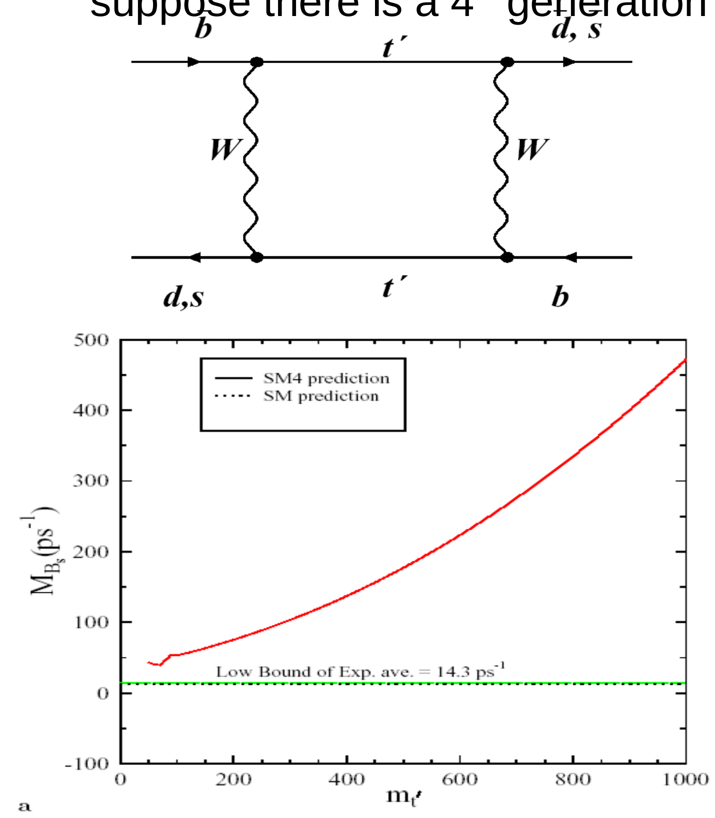
New particles that can show up in the box diagram
will influence the mixing frequency.

supersymmetry with large
mixing between squarks



harnik et al. hep-ph/0212180

suppose there is a 4th generation

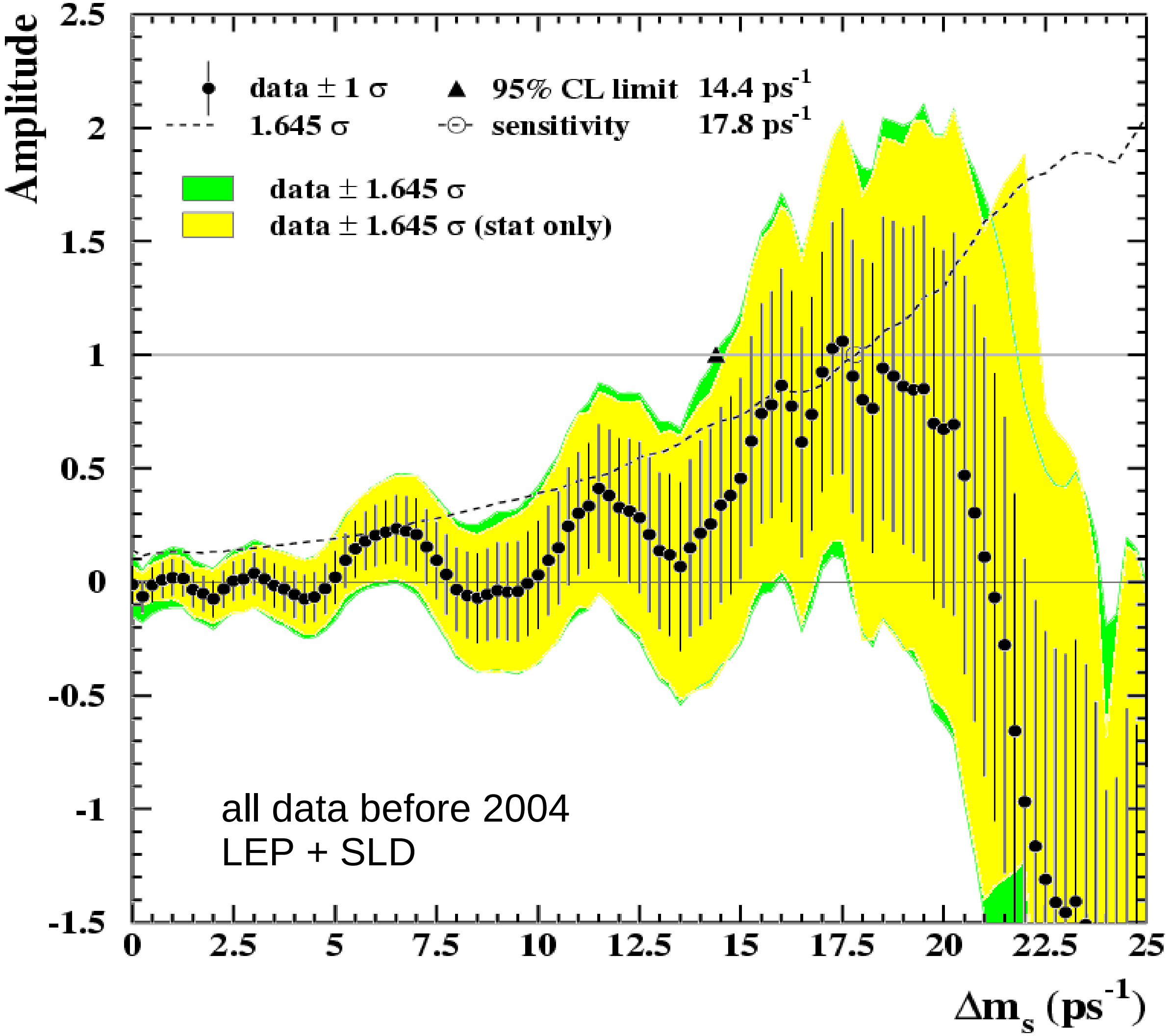


Eur. Phys. J. C 24, 275-280 (2002)

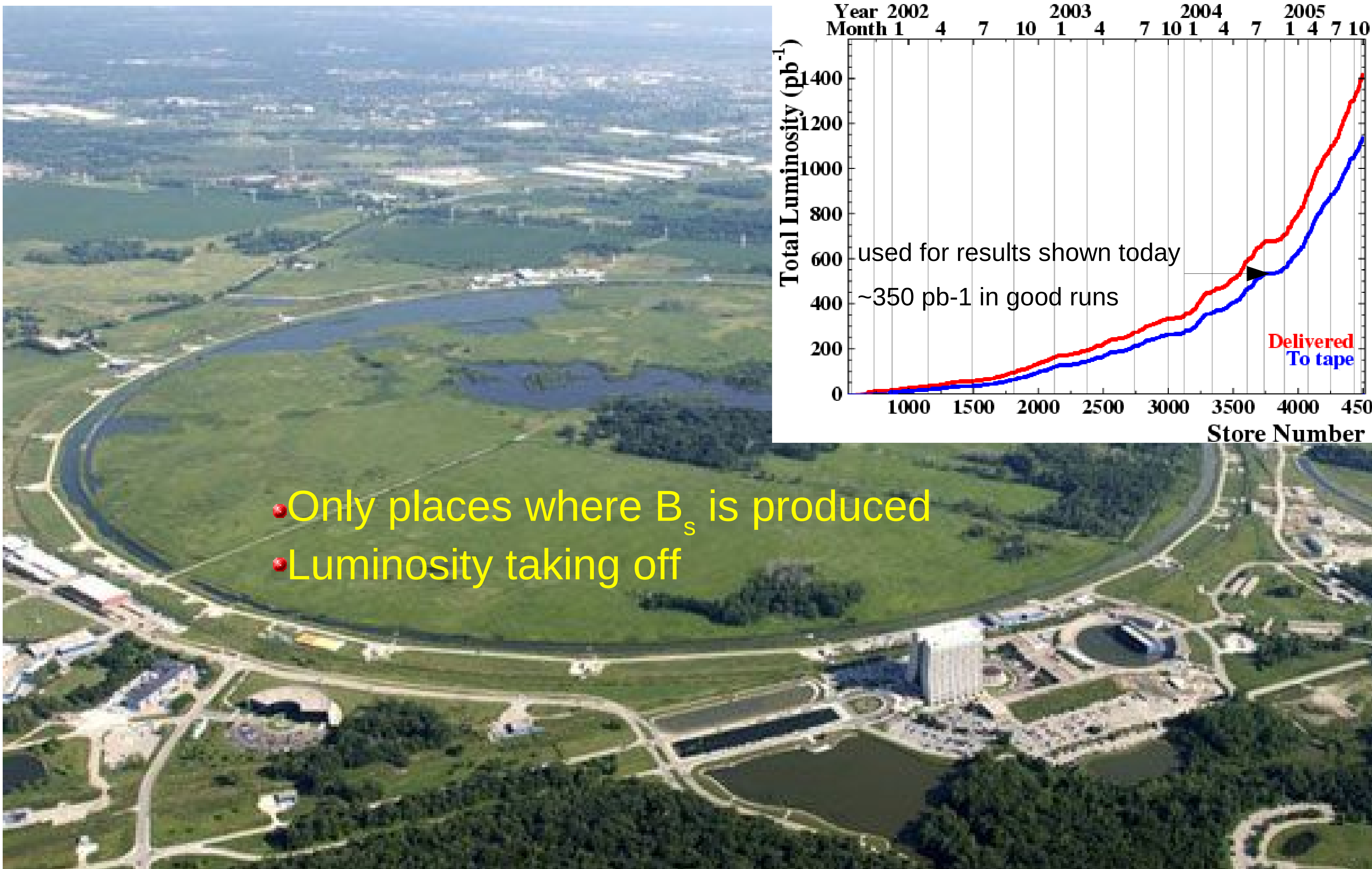
Δm_s is sensitive to new physics

What we know already

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

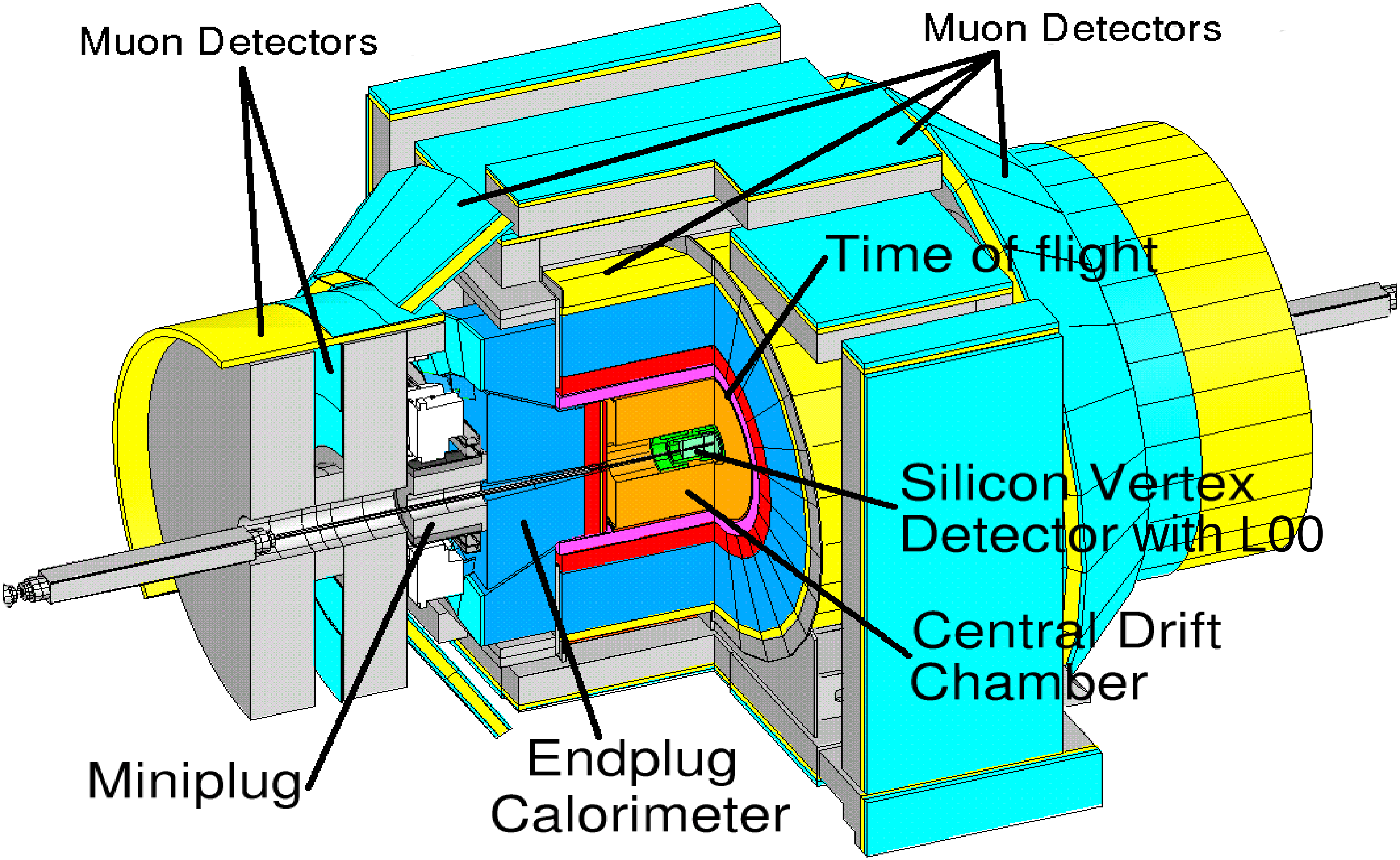


The Tevatron

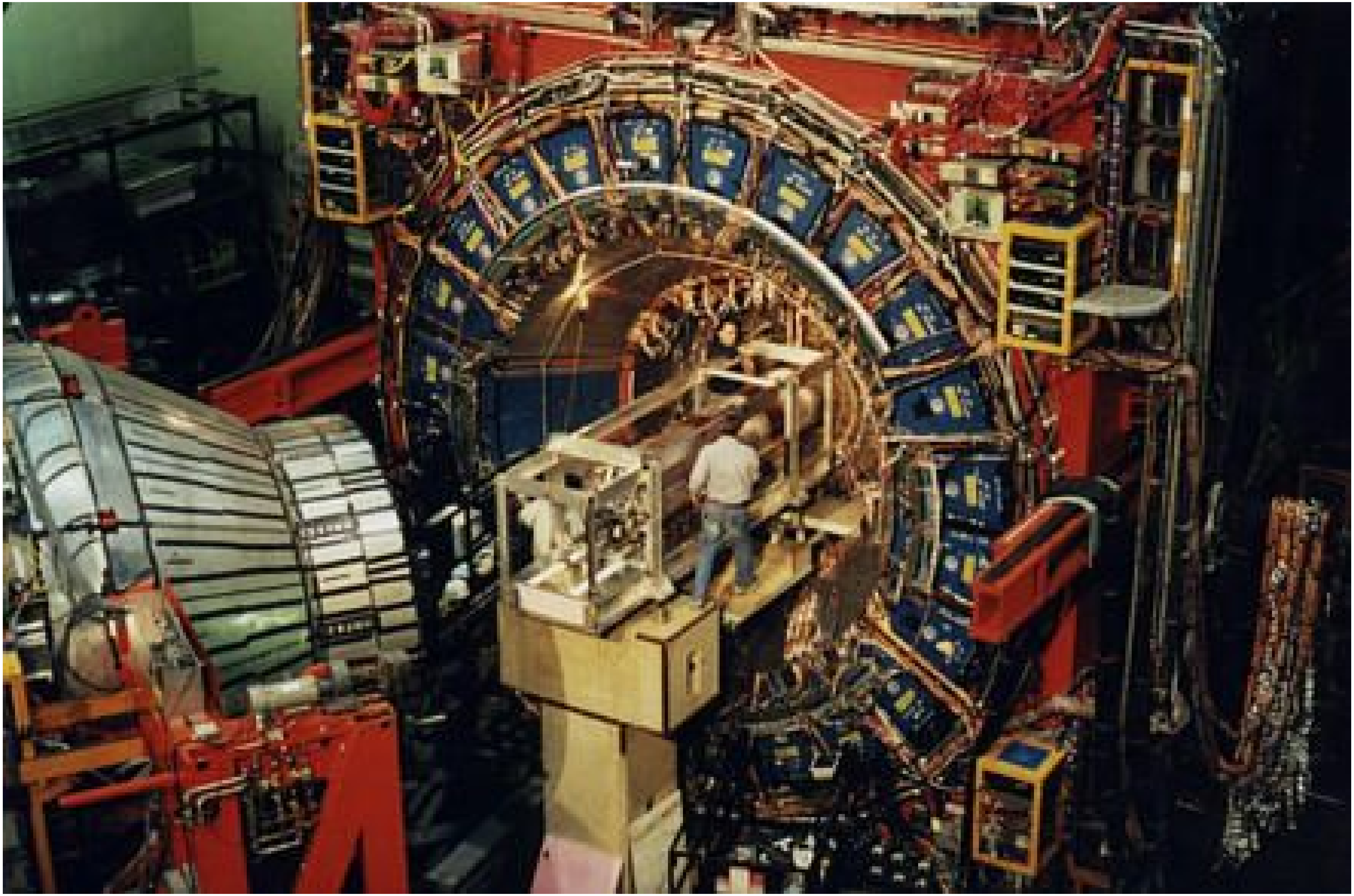


- Only places where B_s is produced
- Luminosity taking off

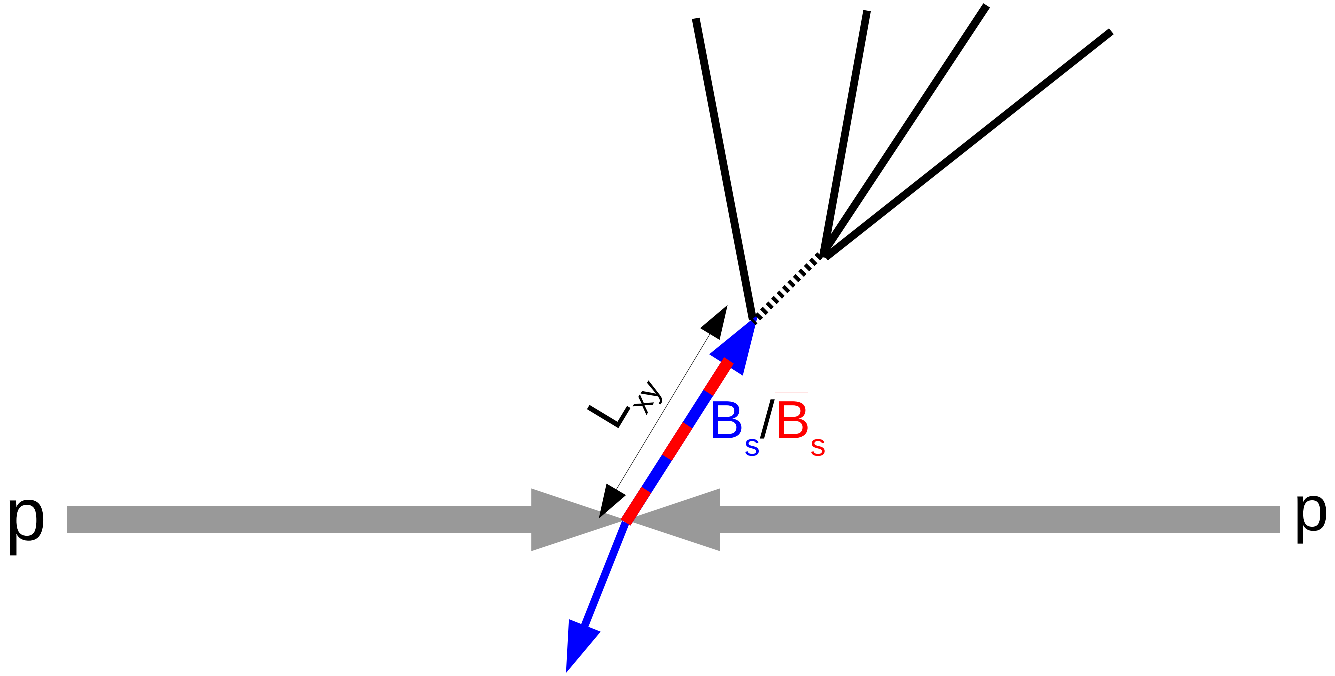
The CDF detector



The CDF detector



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:

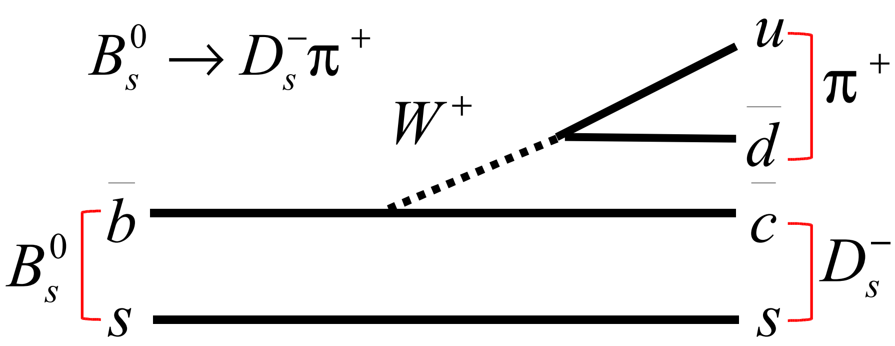
1) Collect a lot of Bs decays — Trigger/reconstruction
2) measure the flavor of Bs at production — 'flavor tagging'
3) measure the proper decay time of Bs — measure L_{xy}

1) Getting the signals

The signals we are looking for

"Hadronic"

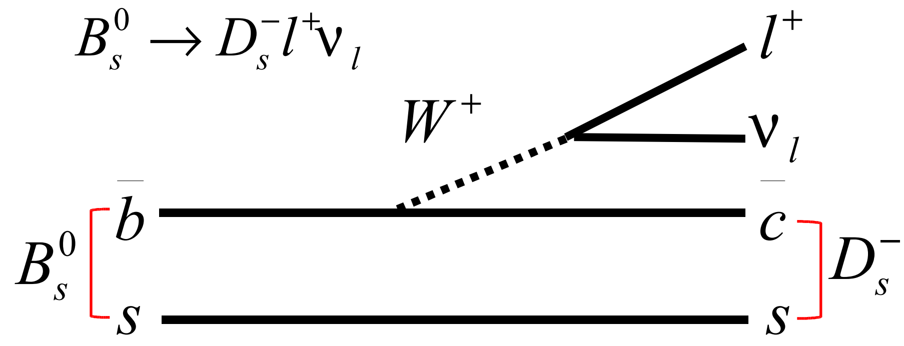
$B_s^0 \to D_s^- \pi^+$



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

"Semileptonic"

$B_s^0 \to D_s^- l^+ \nu_l$

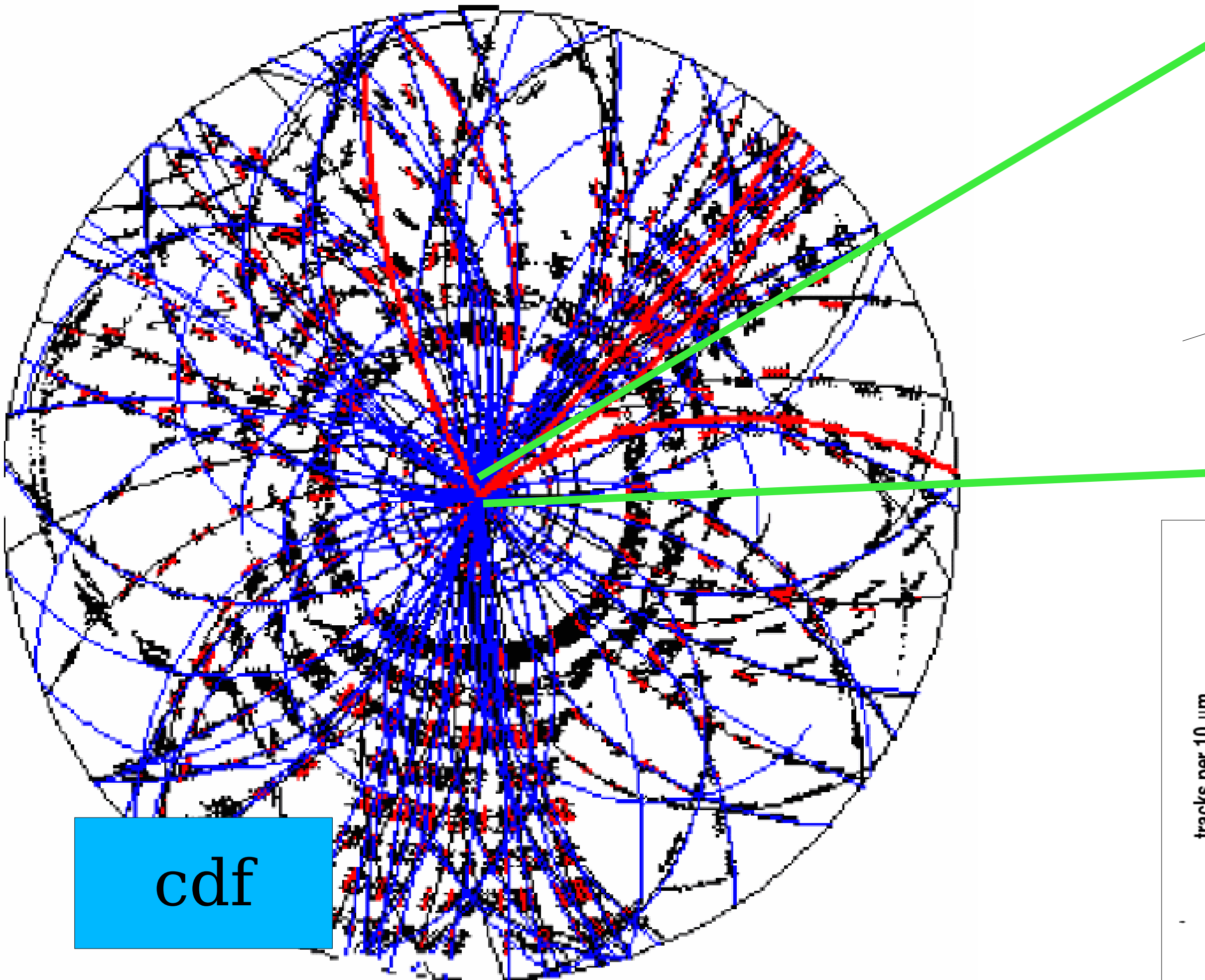


Missing momentum (ν)
Need to rely on Ds mass
Large branching ratio: low yield

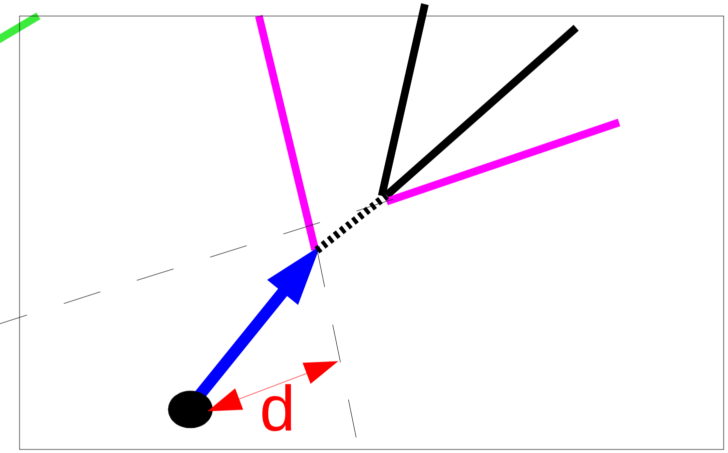
$$D_s^- \to \phi\pi^-, \quad \phi \to K^+K^-;$$
$$D_s^- \to K^{*0}K^-, \quad K^{*0} \to K^+\pi^-;$$
$$D_s^- \to \pi^+\pi^-\pi^-.$$

A typical B event at a hadron collider

...looks just like any other event

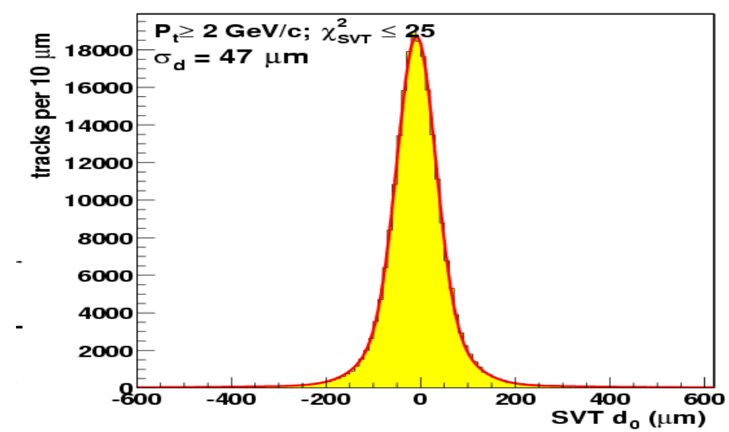


Trigger on events with displaced (d>120 μm) tracks

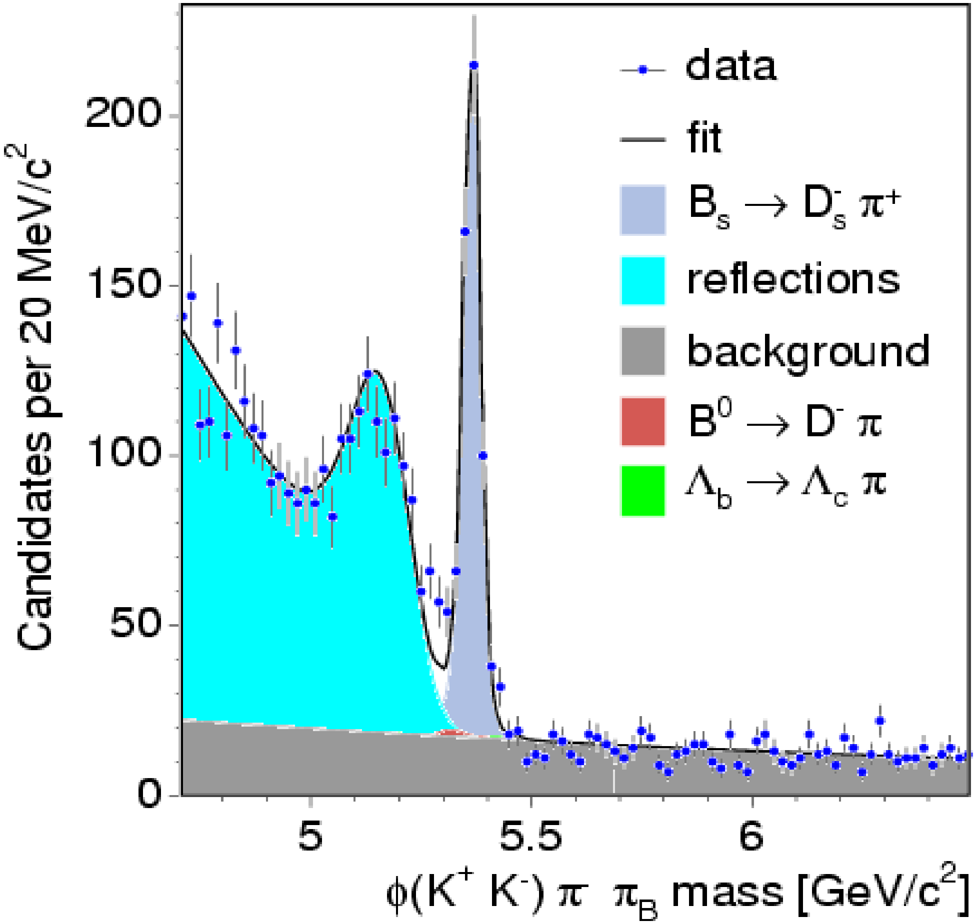


=> use the silicon detector to zoom in

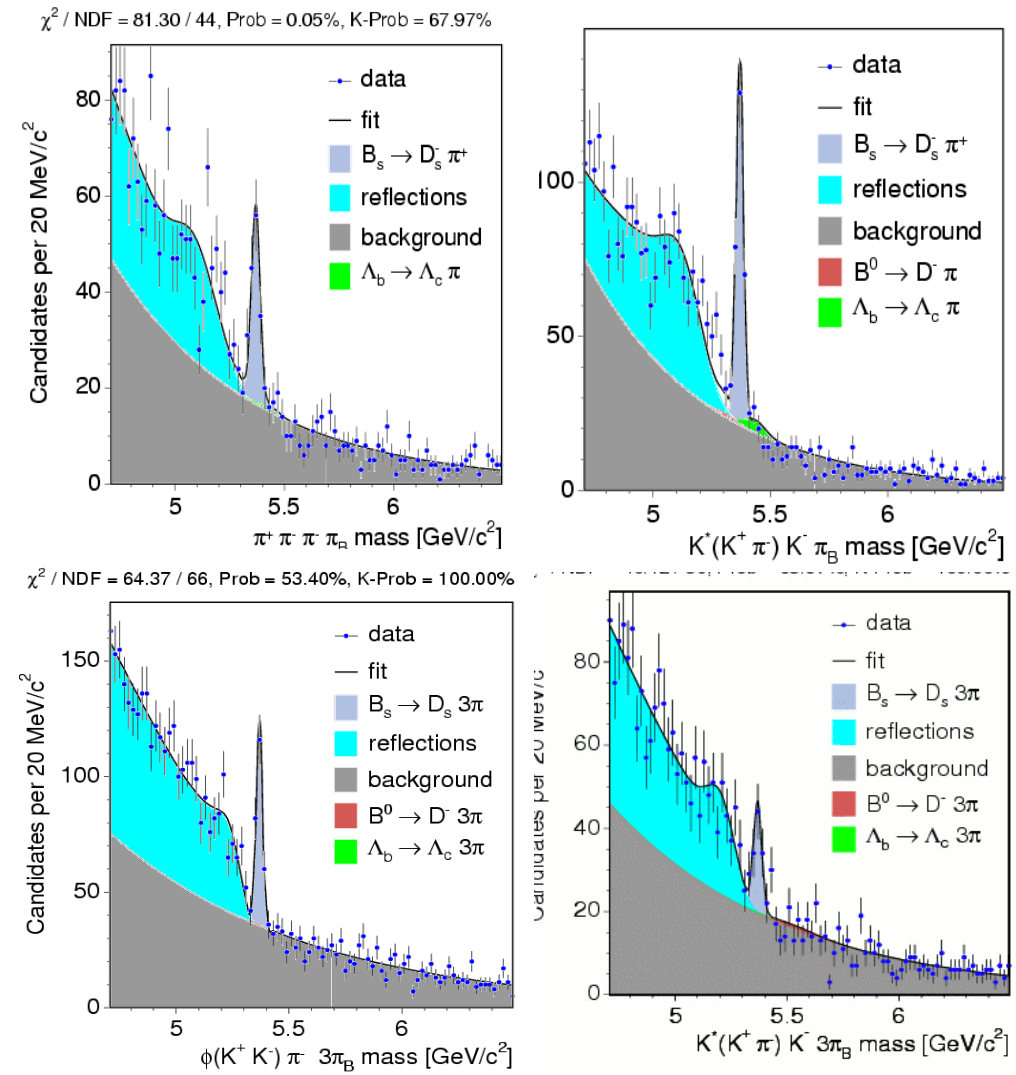
very fast reconstruction by dedicated hardware: SVT



Hadronic signals



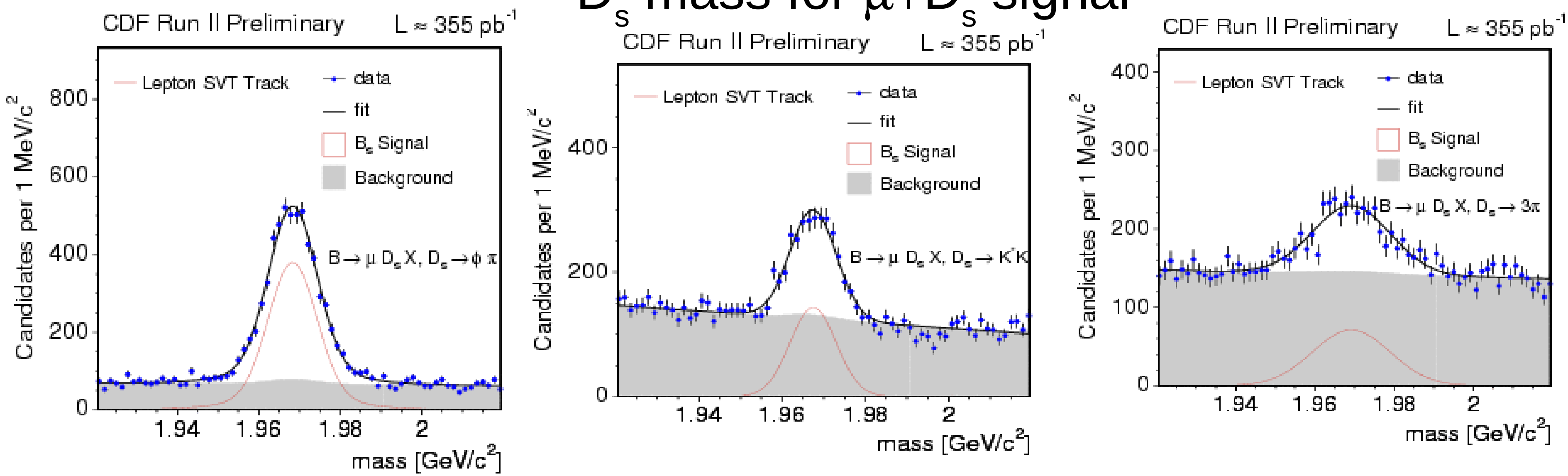
$$B_s \to D_s^- \pi^+,\ D_s \to \phi\pi$$
$$B_s \to D_s^- \pi^+,\ D_s \to K^* K$$
$$B_s \to D_s^- \pi^+,\ D_s \to 3\pi$$
$$B_s \to D_s^- (3\pi)^+,\ D_s \to \phi\pi$$
$$B_s \to D_s^- (3\pi)^+,\ D_s \to K^* K$$



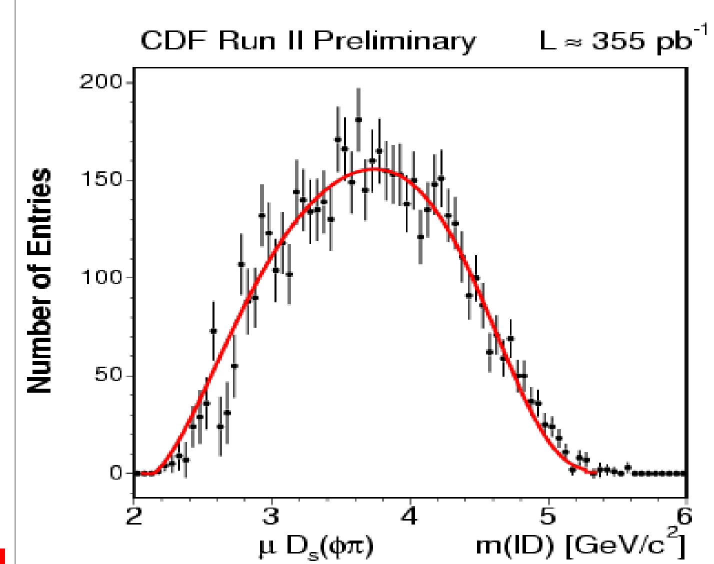
1118
fully reconstructed events

Semi-leptonic signals

D_s mass for $\mu+D_s$ signal



'B-mass'

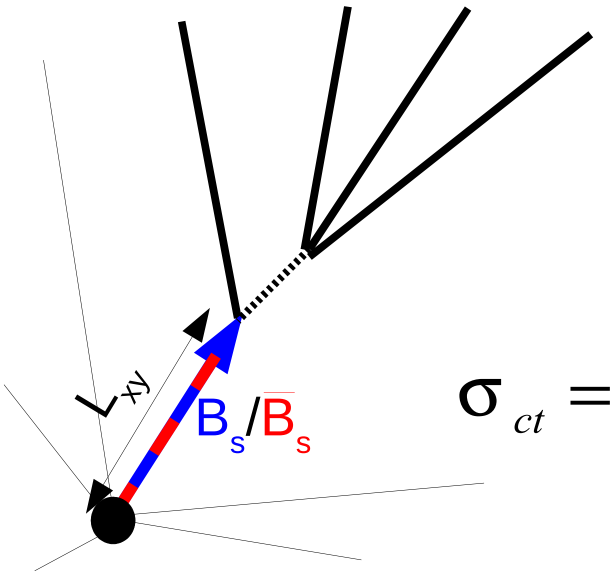


$$B_s^0 \rightarrow D_s^- \ell^+ X,\quad D_s^- \rightarrow \phi\pi^-,\quad \phi \rightarrow K^+K^-;$$
$$B_s^0 \rightarrow D_s^- \ell^+ X,\quad D_s^- \rightarrow K^{*0}K^-,\quad K^{*0} \rightarrow K^+\pi^-;$$
$$B_s^0 \rightarrow D_s^- \ell^+ X,\quad D_s^- \rightarrow \pi^+\pi^-\pi^-.$$

total of 16893 partially recontructed events

2) Proper time reconstruction

Proper time reconstruction

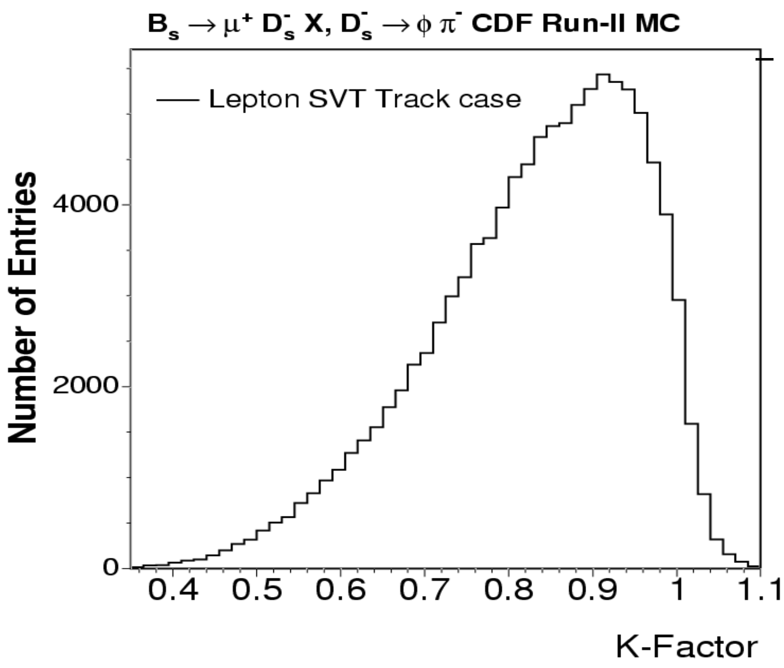


$$ct = L_{xy}\frac{m_B}{p_T}$$

$$\sigma_{ct} = \sqrt{\left(\sigma^0_{ct}\right)^2 + \left(ct \times \frac{\sigma_p}{p}\right)^2}$$

Two sources of uncertainty:

- L_{xy}
  - Lxy is biased because of the SVT trigger
  - contributions from primary and secondary vertex
    - improved recently by using EBE primary
- P_T
  - Uncertainty on P_T only an issue for semi-leptonic
  - Determine $K \equiv P_T(l+D)/P_T(B)$ from MC

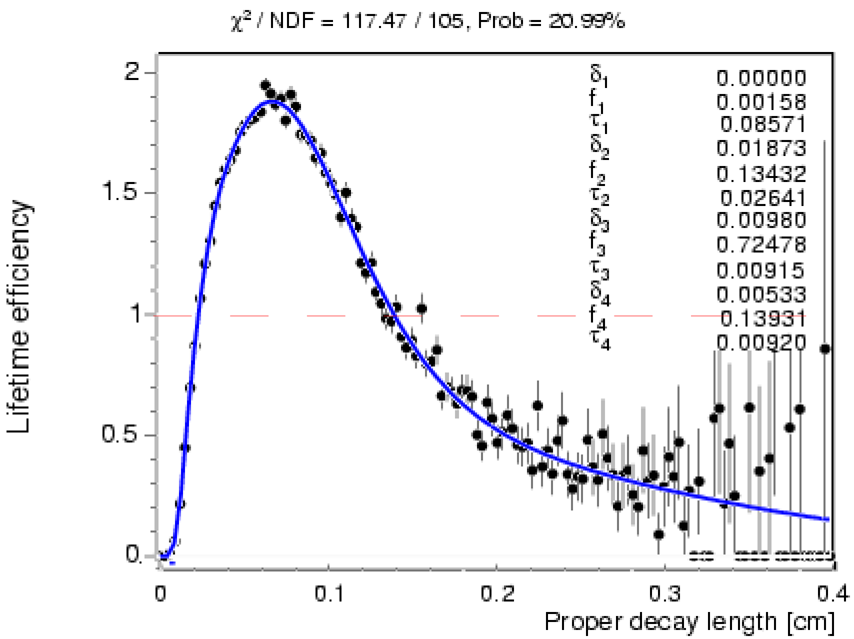


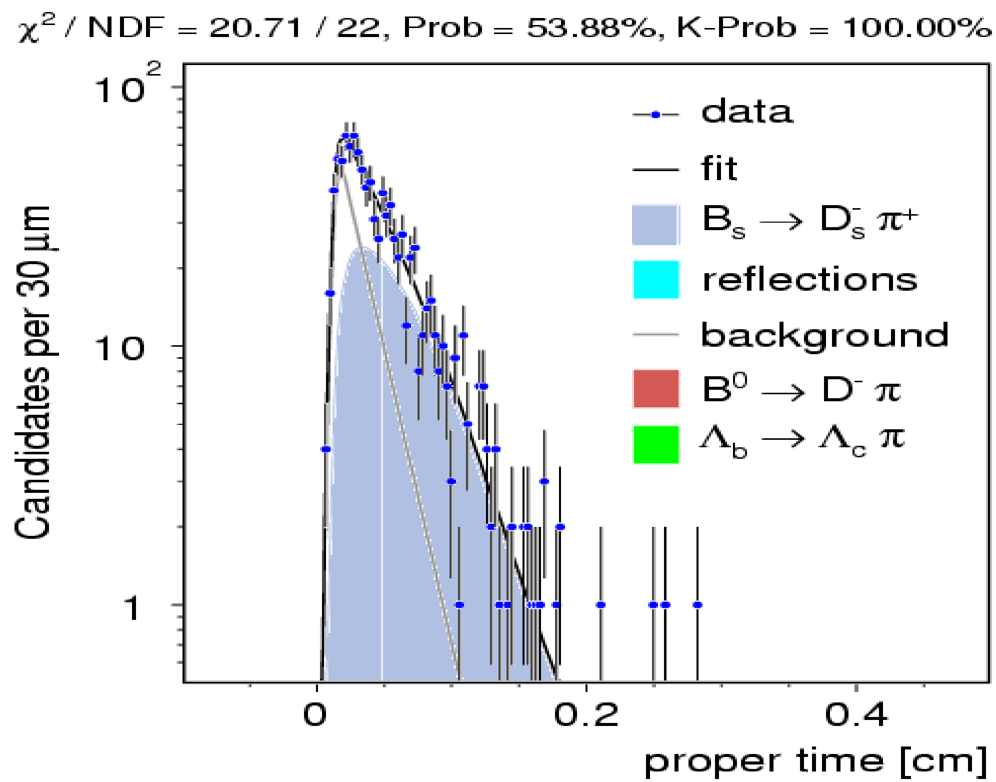
Proper time reconstruction

Tigger (and selection cuts) bias the proper decay time distribution

To test: measure Bs lifetime, including efficiency in the fit

Efficiency from MC

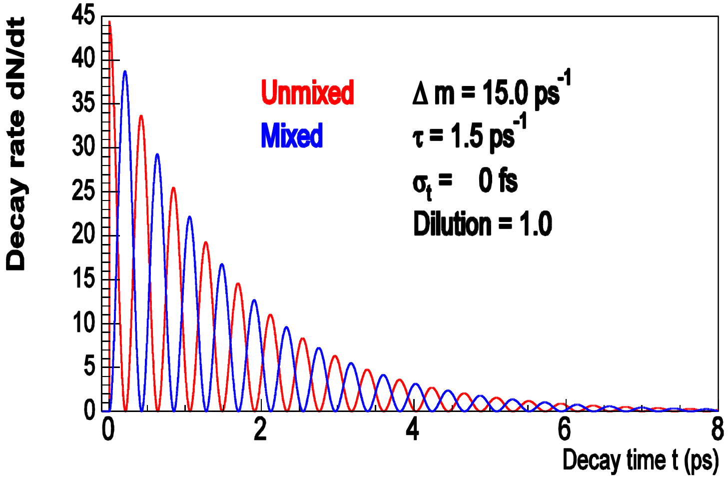




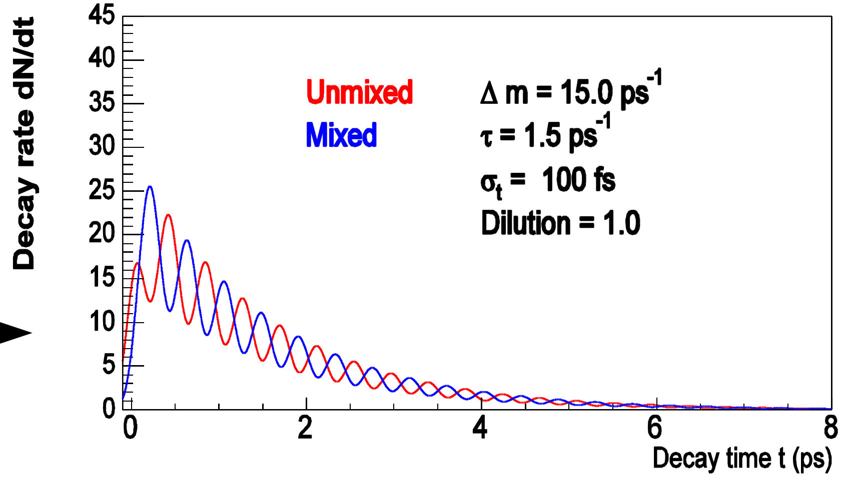
combined hadronic lifetime agrees with world average

Measuring the proper time resolution

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



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

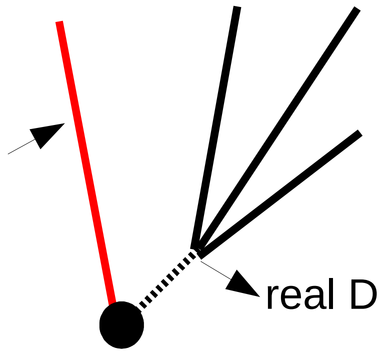


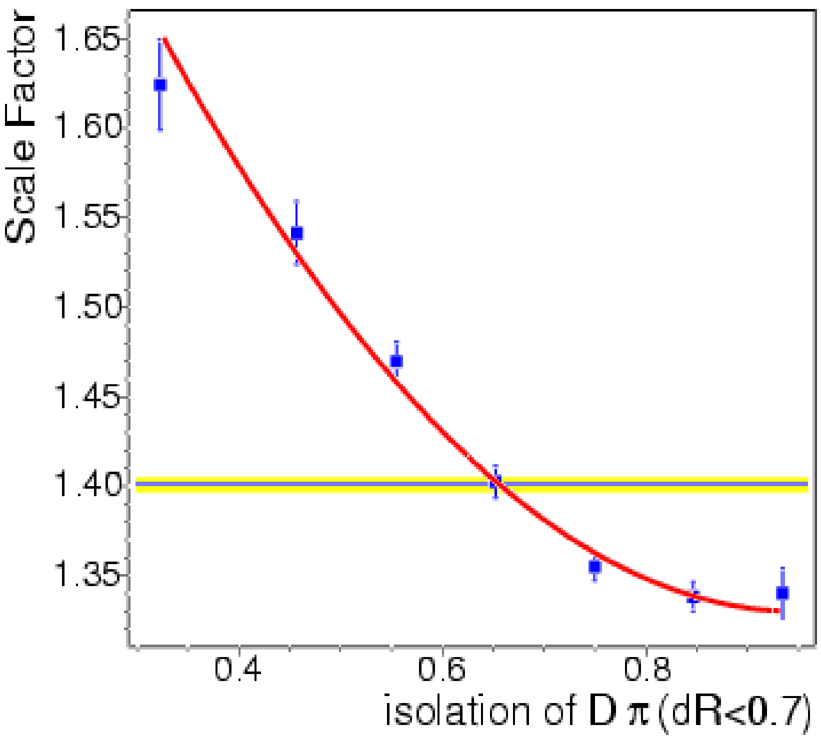
- No problem if we observe mixing:
  - we know the true Asymmetry=1
- But if we do not see mixing: *must* know σ_{ct}
  - need to correct for effect of σ_{ct} to set limit on A

How to measure σ_{ct}?

Measuring the proper time resolution

Cannot measure the ct resolution directly on data. Solution: reconstruct events that look like a B but are known to come from the PV..





<ct> must be zero; compare error with expected error from the fit....

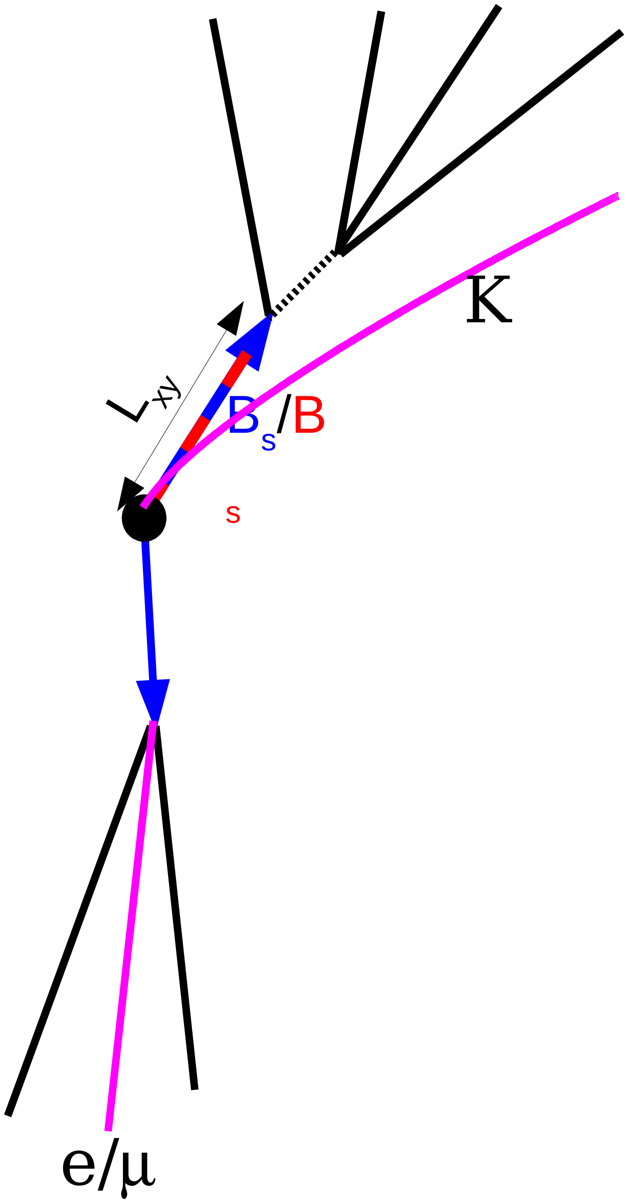
And study dependence on kinematic variables, isolation, χ^2 of fit etc..

Mode	$< \sigma(ct) >$ [μm]
$B_s \to D_s(3)\pi$	30
$B_s \to \ell D_s X$	50*

* not include <k-factor> = 0.85

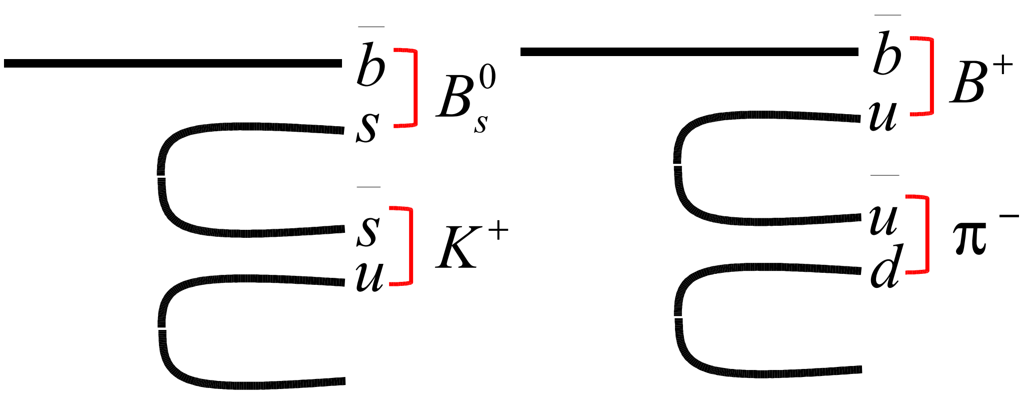
3) Flavor tagging

Flavour tagging



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

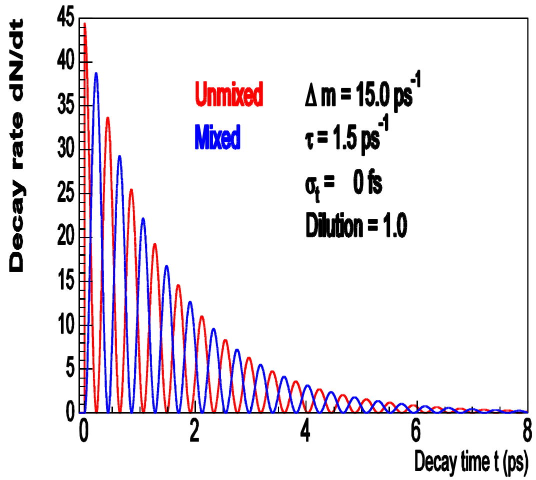
- Opposite side tag:
  - look at the decay products of the other b quark in the event:
    - Leptons
    - charge of the b-'jet' → combination of NNs
  - the two b quarks fragment *independently*: can calibrate opposite side taggers with B_d
- Same side tag: look at particles produced in B meson formation (K in case of Bs)
  - need to rely on MC to calibrate this tagger
  - potentially very powerful, but not yet used



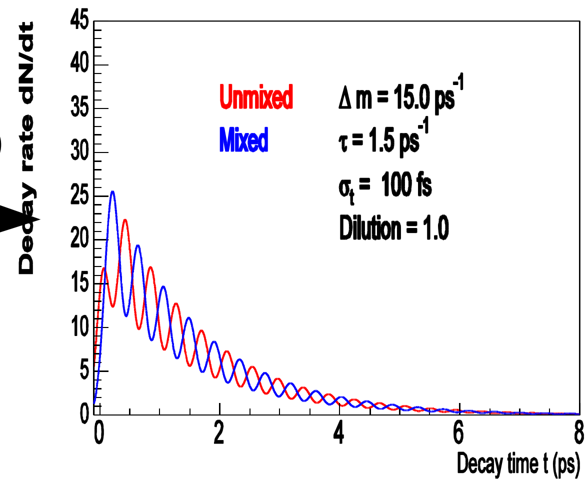
Flavour tagging: dilution

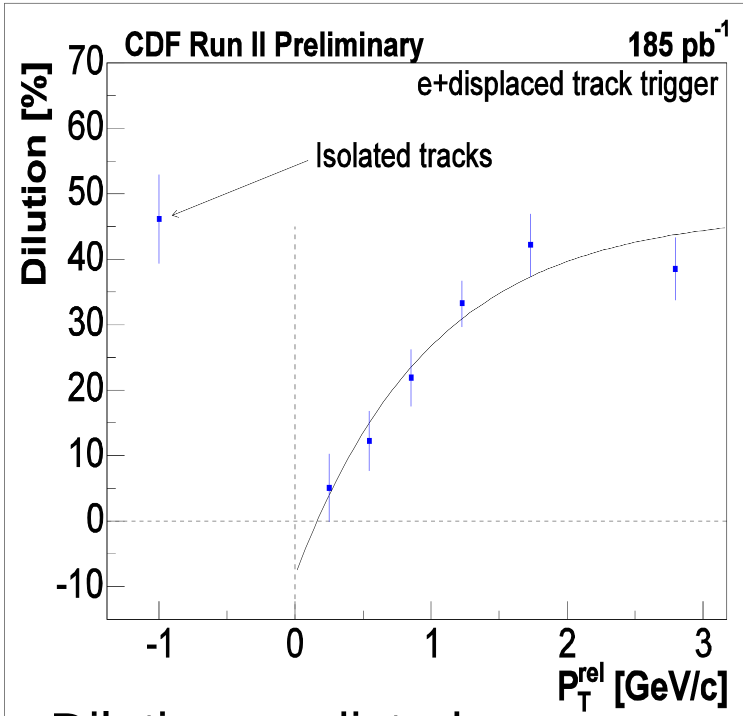
A tagger is characterized by

- ε: efficiency
- D: dilution = 1-2 x mistag rate (large dilution is good)
- Figure of merit: εD^2



x D





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

for setting limit, we *must* know what D is

how to check/calibrate the prediction is correct?

Tagger calibration: B_d mixing

For setting limit, we *must know* the dilution

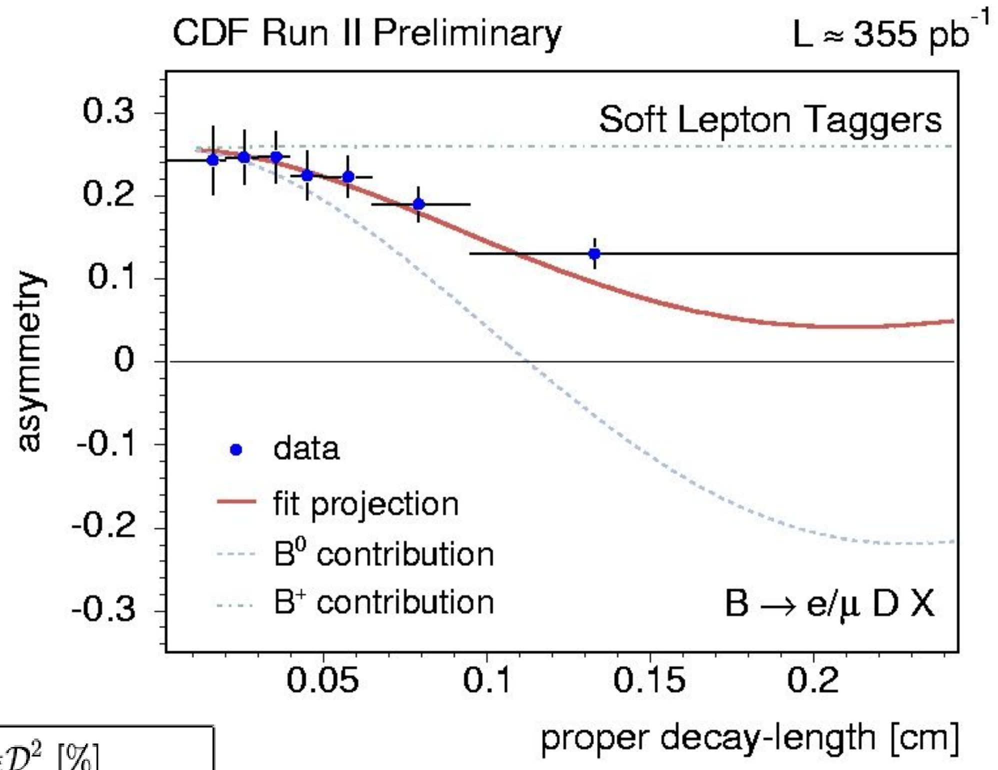
- Calibrate taggers (we know A=1)
- Simultaneous likelihood lD+ lD0 and lD*

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

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

dilution scale factor

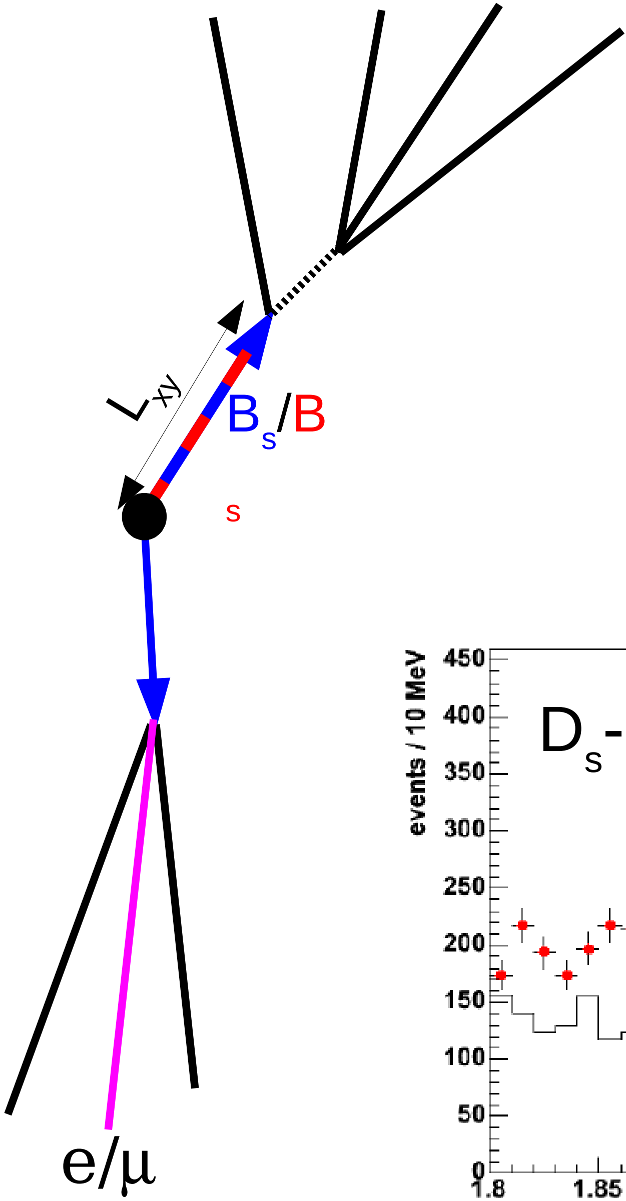
predicted dilution



Tagger	$\sqrt{<\mathcal{D}^2_{pred}>}$[%]	ϵ[%]	Scale factor [%]	$\epsilon\mathcal{D}^2$ [%]
SMT	36.18	4.81 ± 0.04	93.58 ± 3.77 ± 1.30	0.551 ± 0.048 ± 0.020
SET	30.10	2.96 ± 0.04	107.21 ± 4.54 ± 1.69	0.308 ± 0.030 ± 0.008
JVX	18.93	8.21 ± 0.06	91.72 ± 5.84 ± 1.31	0.247 ± 0.033 ± 0.010
JJP	11.50	27.58 ± 0.09	100.11 ± 6.03 ± 2.79	0.366 ± 0.045 ± 0.021
JPT	4.57	51.63 ± 0.10	83.77 ± 10.63 ± 4.29	0.076 ± 0.019 ± 0.009
Total	–	95.19 ± 0.16	97.26 ± 2.47	1.550 ± 0.083 ± 0.029

SSKT may give εD^2=2-3% !

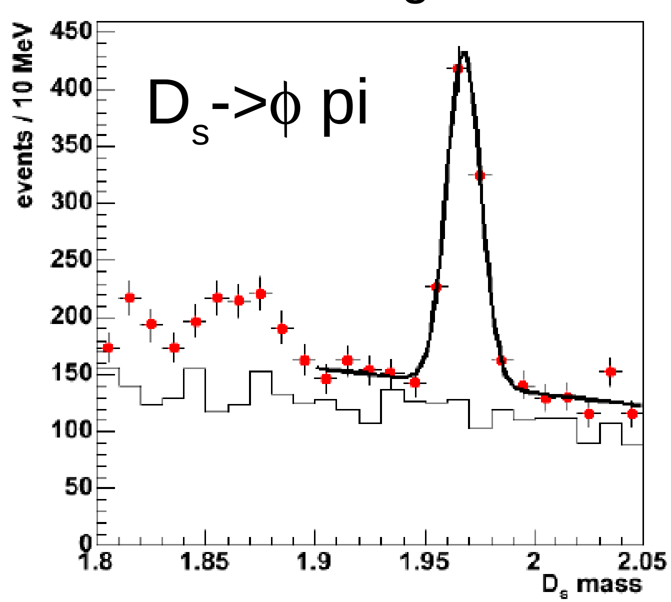
Datasets with high tagging efficiency



Default: trigger or decay products of the reconstructed B and hope for a tag
'New' idea: trigger on tagged events

- muon (tag) + two displaced tracks (B-decay)

Di-lepton trigger
- one lepton from semi-leptonic decay one for OST
- trigger already existed (used for SUSY searches)
  - modest yield, but very high εD^2:
- Adding this data in next round of analysis.

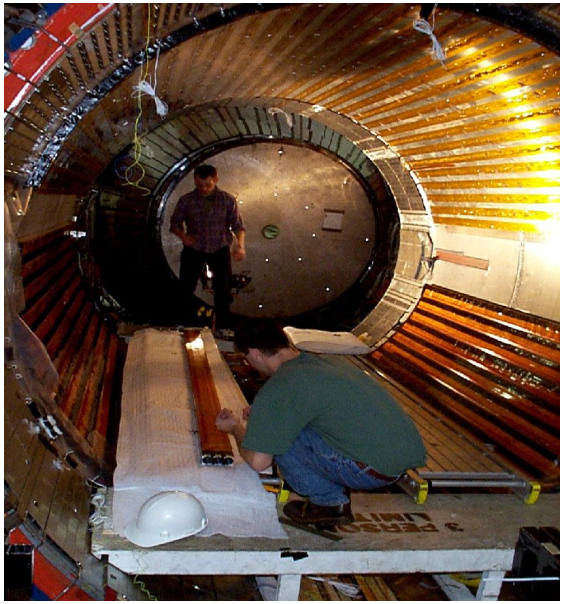


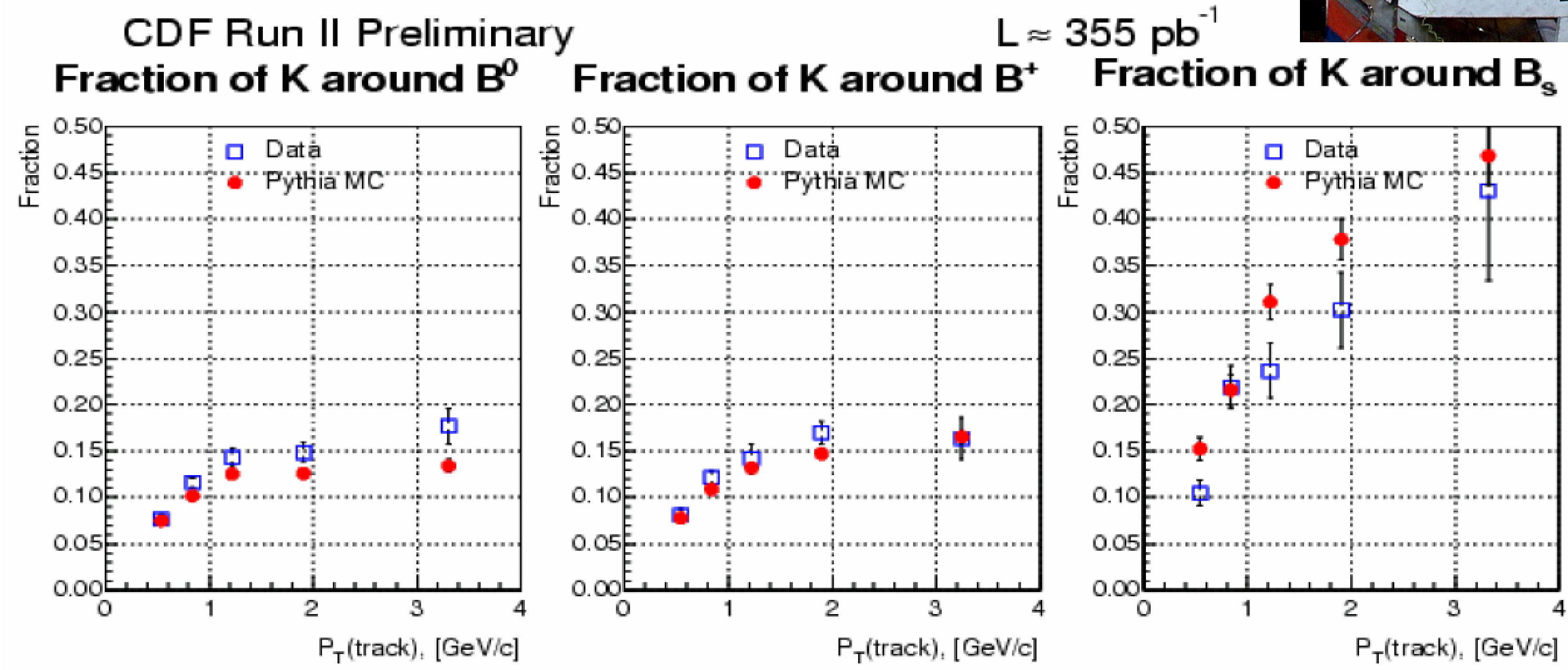
εD^2 from lepton taggers measured on B^0 and B^+ in this sample: 4.5% !

(compare with 1.5 for other samples)

Towards same side kaon tagging

- Use de/dx in COT and *time of flight detector* to identify which particles (π,p.k,e) are produced around B mesons...
- Extra K's around B_s mesons!
- Gives handle for MC tuning





See Denys Usynin's thesis!

Combining it all

Tagger	$\sqrt{<\mathcal{D}^2_{pred}>}$ [%]	ϵ[%]	Scale factor [%]	$\epsilon\mathcal{D}^2$ [%]
SMT	36.18	4.81 ± 0.04	$93.58 \pm 3.77 \pm 1.30$	$0.551 \pm 0.048 \pm 0.020$
SET	30.10	2.96 ± 0.04	$107.21 \pm 4.54 \pm 1.69$	$0.308 \pm 0.030 \pm 0.008$
JVX	18.93	8.21 ± 0.06	$91.72 \pm 5.84 \pm 1.31$	$0.247 \pm 0.033 \pm 0.010$
JJP	11.50	27.58 ± 0.09	$100.11 \pm 6.03 \pm 2.79$	$0.366 \pm 0.045 \pm 0.021$
JPT	4.57	51.63 ± 0.10	$83.77 \pm 10.63 \pm 4.29$	$0.076 \pm 0.019 \pm 0.009$
Total	-	95.19 ± 0.16	97.26 ± 2.47	$1.550 \pm 0.083 \pm 0.029$

unbinned maximum likelihood fit

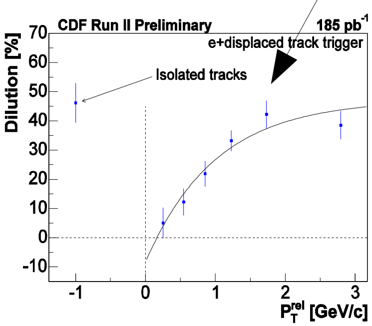
for each event:

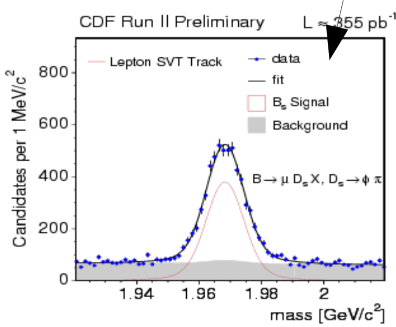
$$\mathcal{L}_k = \mathcal{L}_k^{Mass} \cdot \mathcal{L}_k^{ct} \cdot \mathcal{L}_k^{\sigma_{ct}} \cdot \mathcal{L}_k^{D}$$

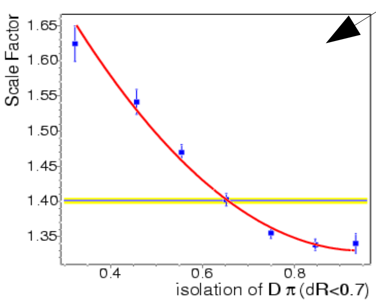
k=sig,bg

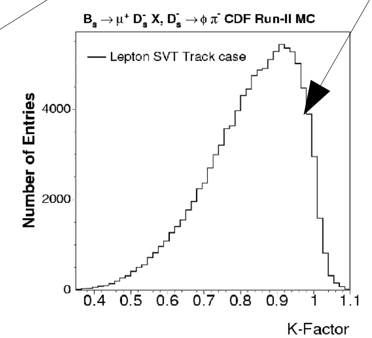
$$\mathcal{L}_{sig}^{ct} = \epsilon_i \cdot \left(\frac{1 \pm A \cdot S_{D_i} \cdot D_i \cdot cos(\Delta m_s \cdot k \cdot ct')}{2} \cdot \frac{1}{N} e^{-\frac{k \cdot ct'}{c\tau}} \right) \otimes G(ct - ct'; S_{\sigma_t} \sigma_t) \otimes F(k) \cdot \epsilon(ct)$$

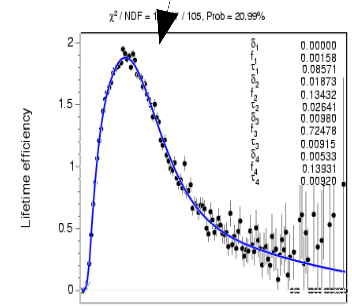
pdg









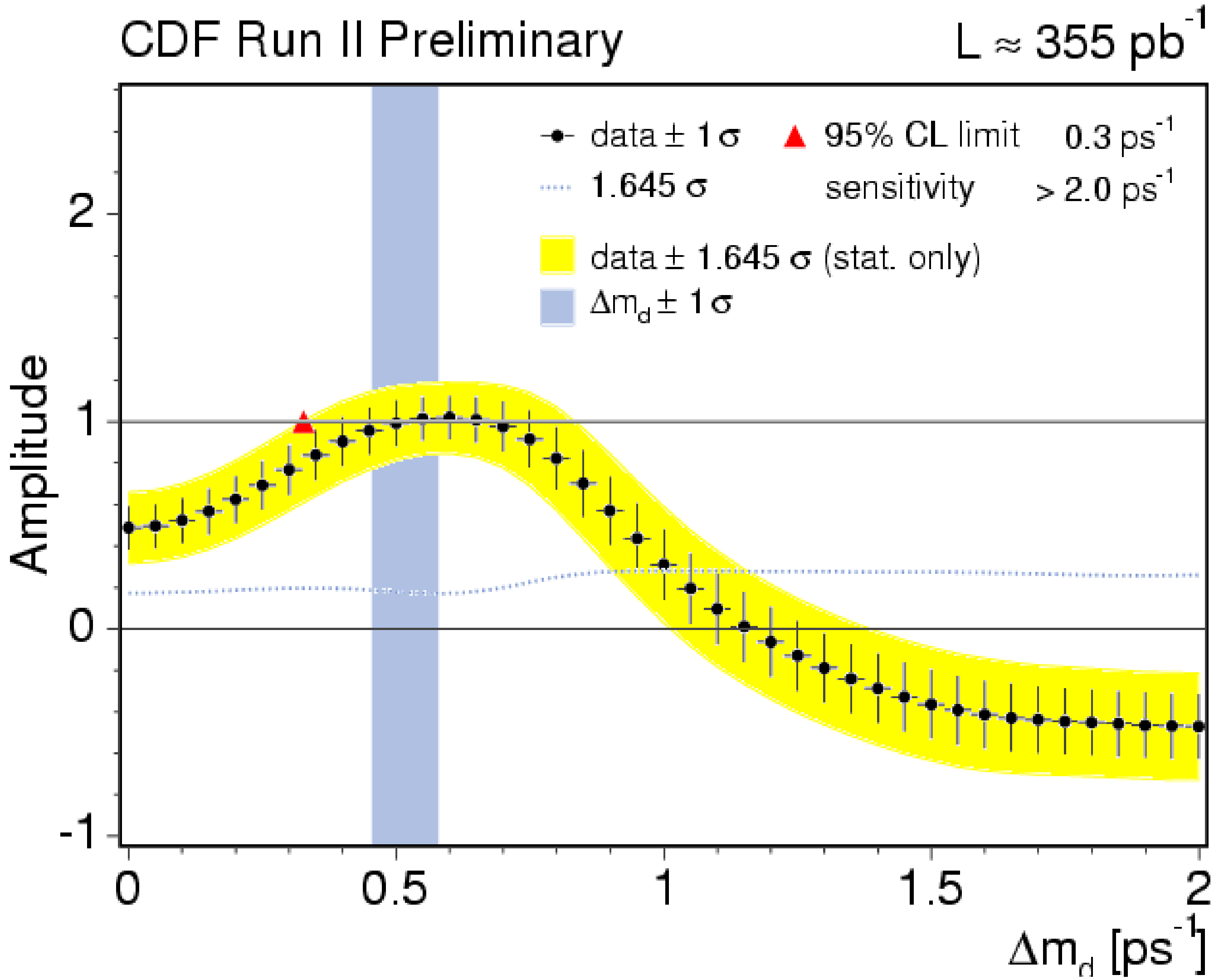


- fix Δm_s
- integrate over true decay length ct and true k-factor
- get $A(\Delta m_s)$

Before fitting doing Dm_s: test whole procedure by on B_d mixing

Amplitde scan: B_d

B^0 example scan, winter 2005 analysis

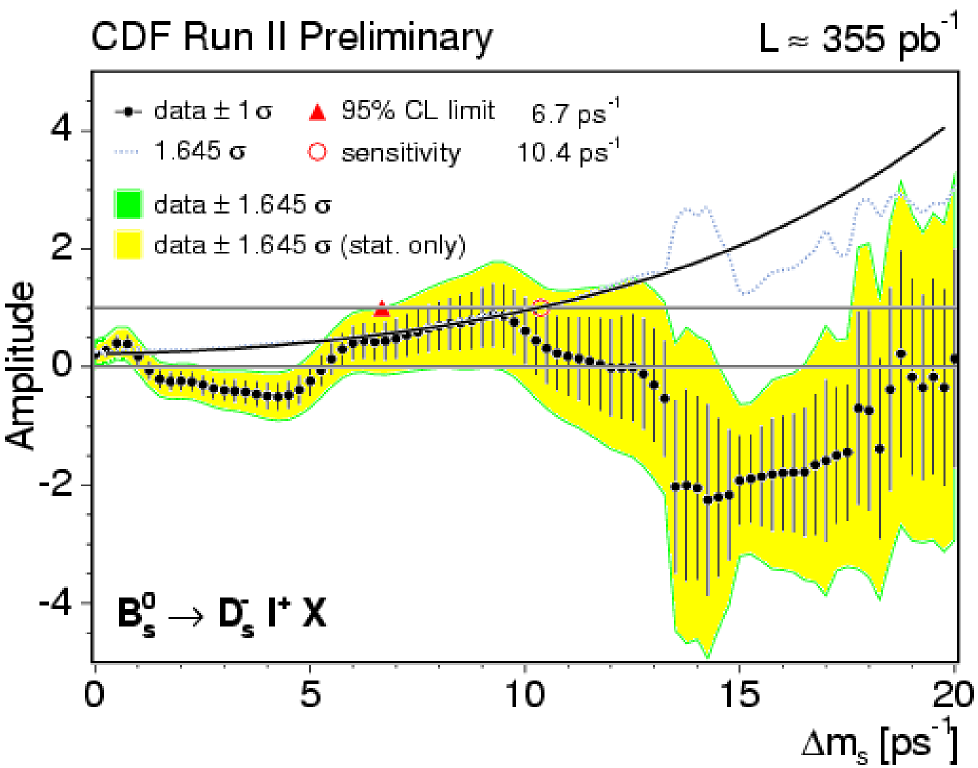


Current Result

Semileptonic modes

Sensitivity: 10.4 ps^{-1}

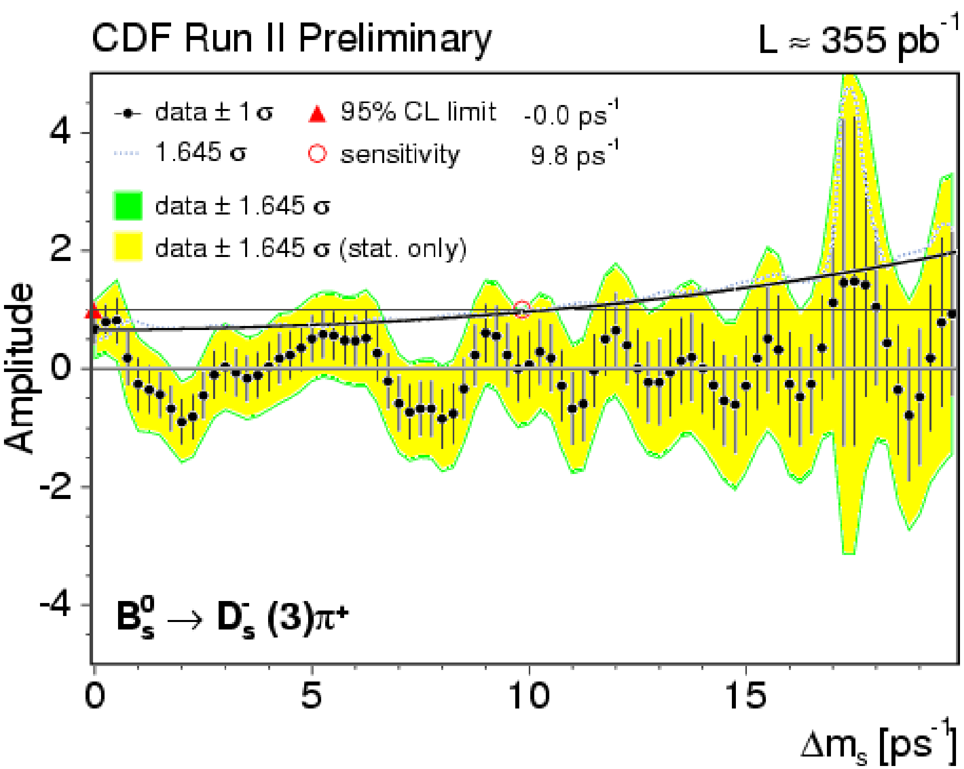
95% CL Limit: 6.7 ps^{-1}



Hadronic modes

Sensitivity: 9.8 ps^{-1}

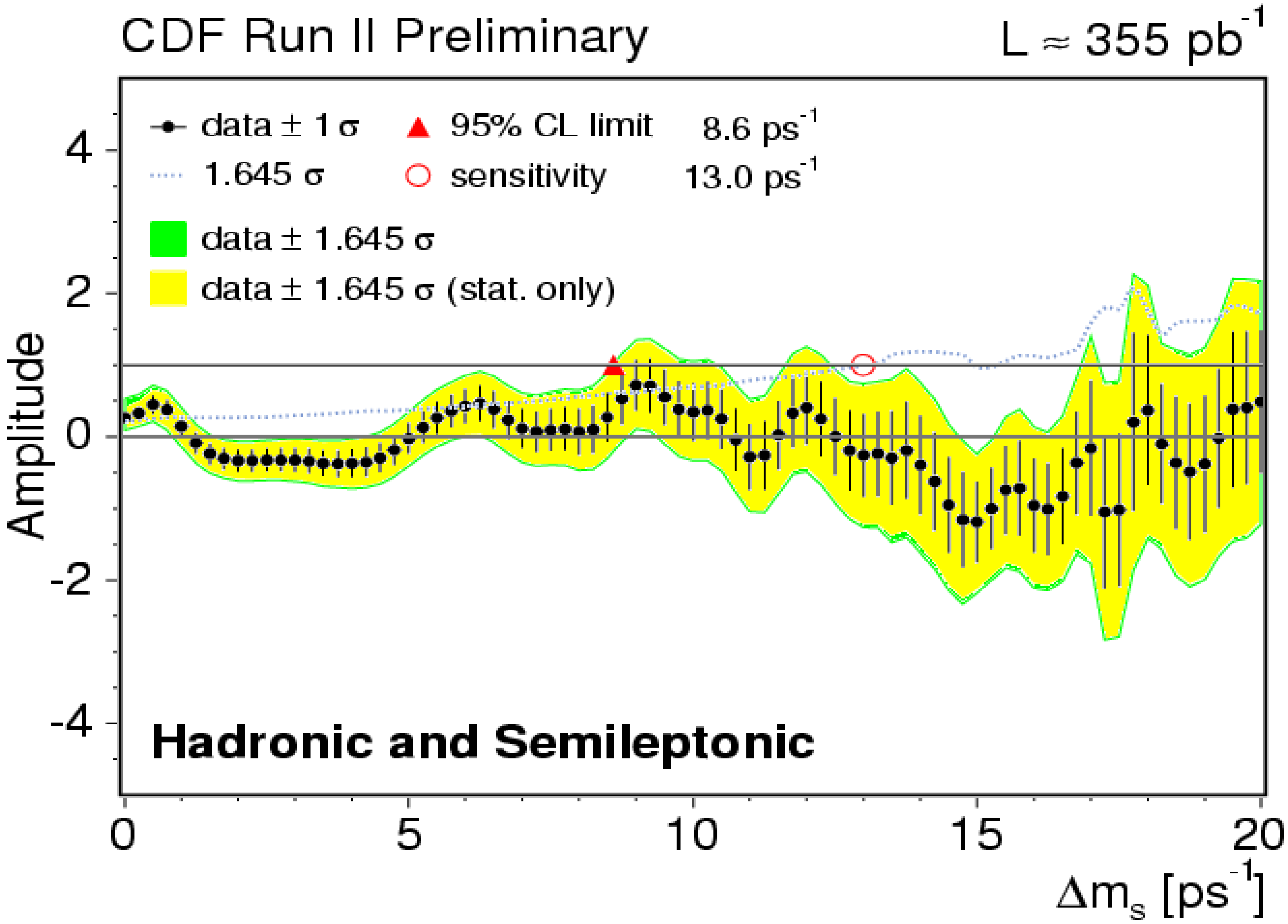
95% CL Limit: 0.0 ps^{-1}



Current Result: combined

Sensitivity: 13.0 ps^{-1}

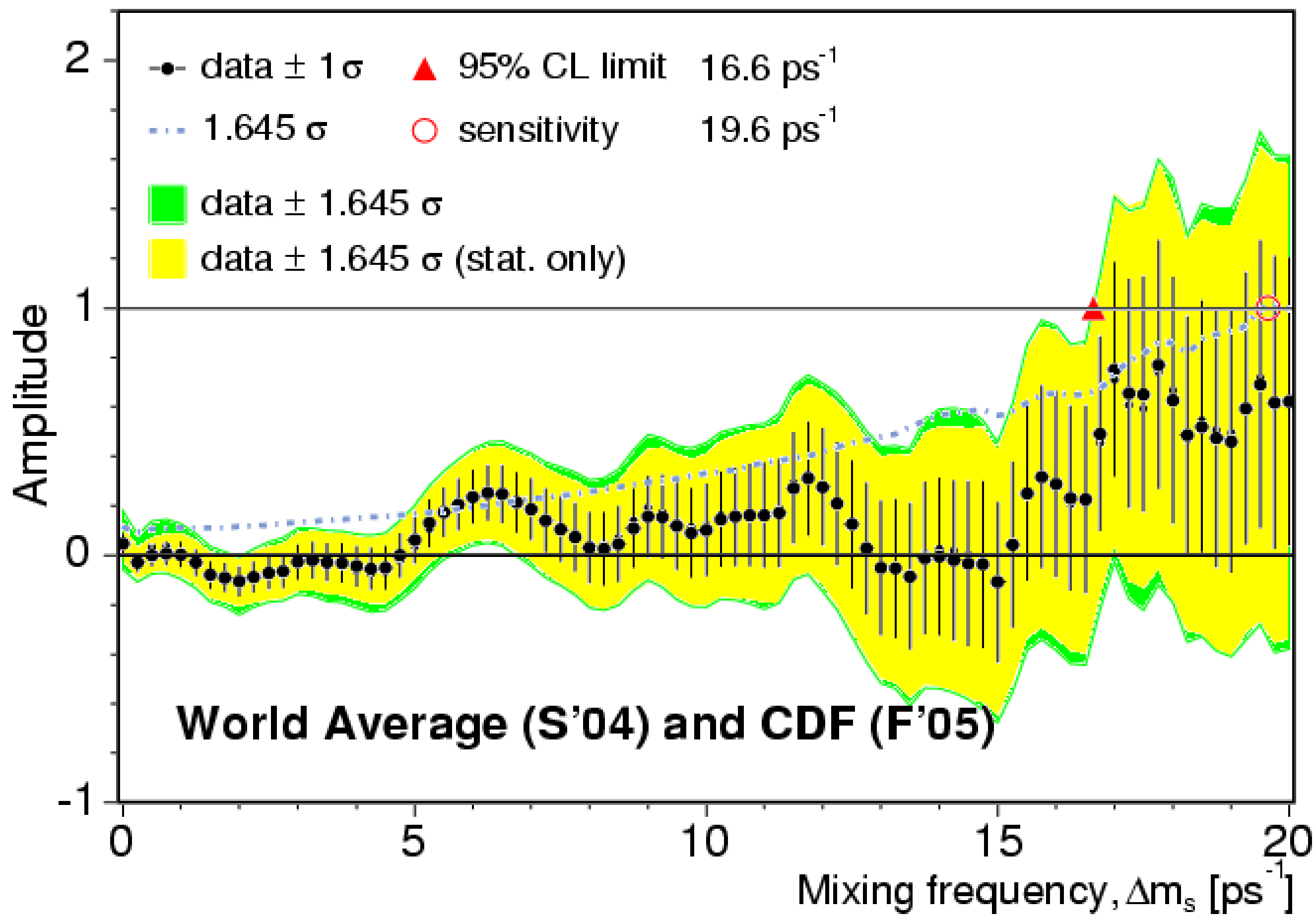
95% CL Limit: 8.6 ps^{-1}



impact on world average

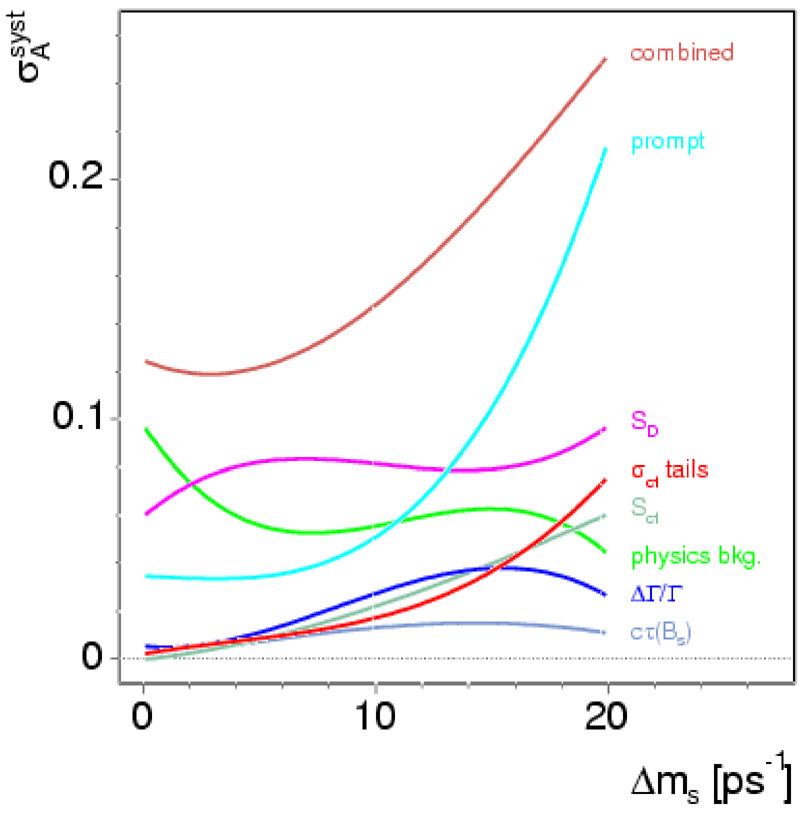
Sensitivity: 19.6 ps^{-1}

95% CL Limit: 16.6 ps^{-1}

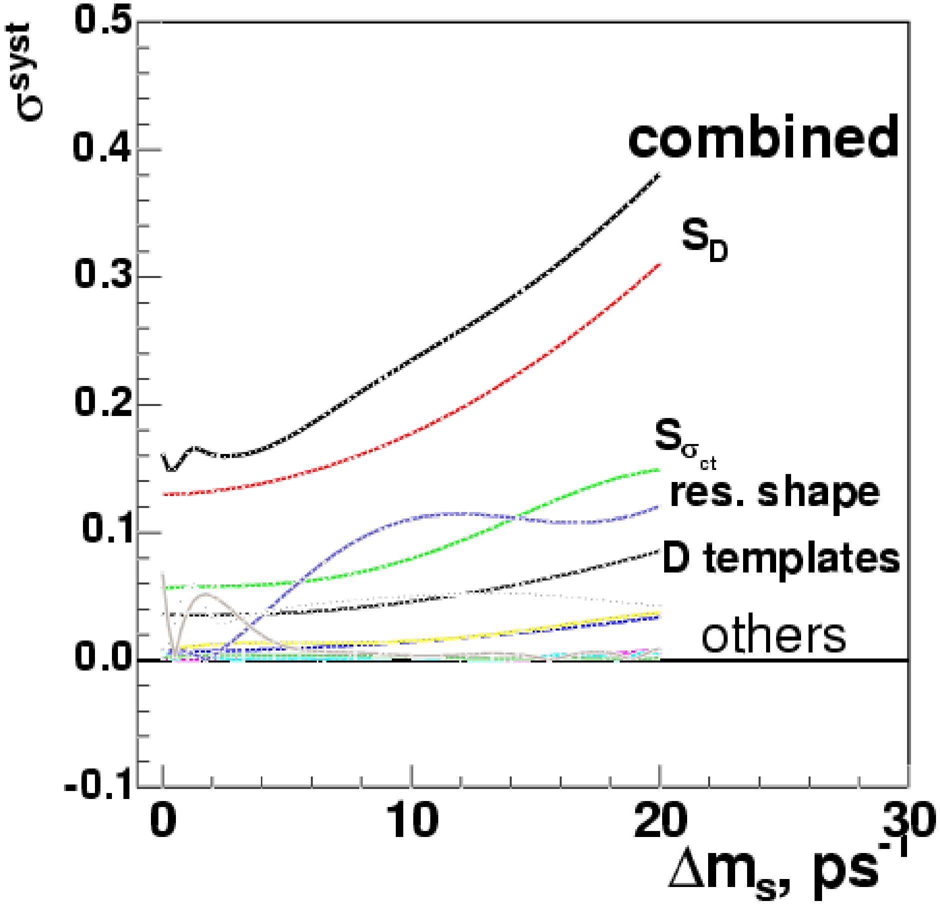


Current Result: systematics

Semileptonic Modes

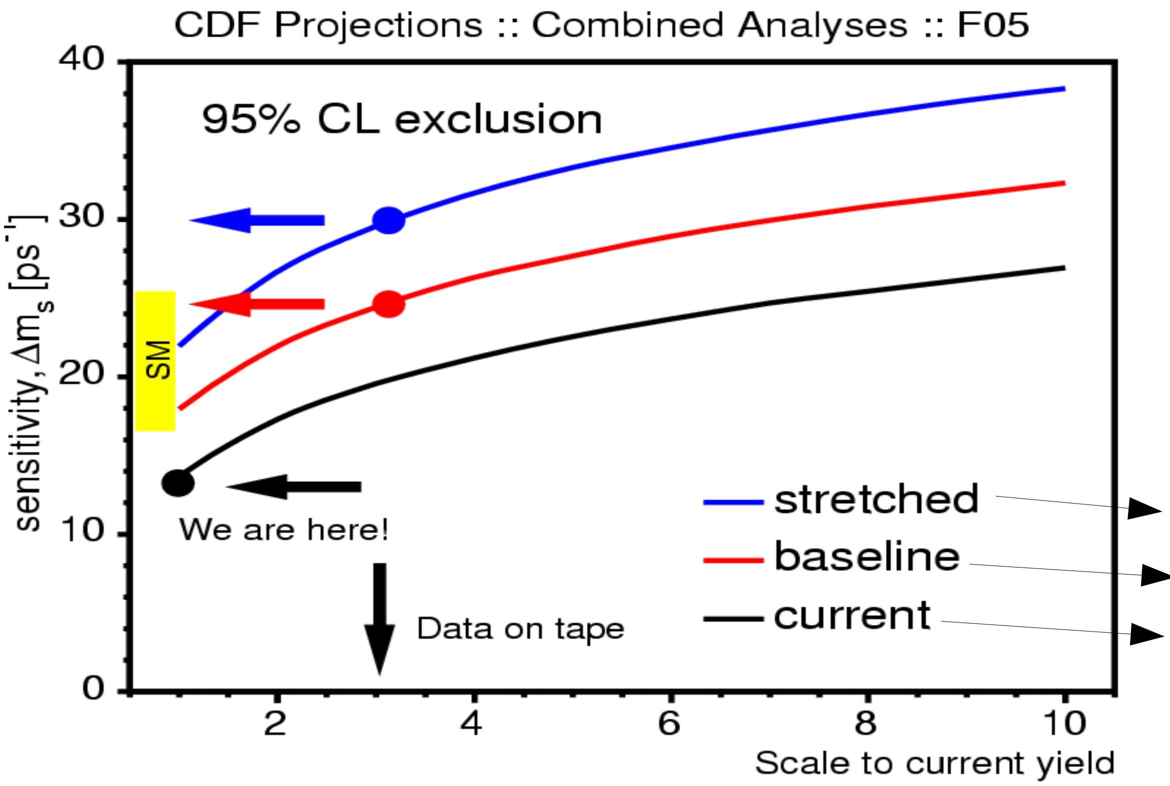


Hadronic Modes



Systematic errors are small compared to statistical errors and will also decrease as more data comes in.

The Future



Many improvements on the way:

- more data
  - factor 2-3 more already collected
  - Tevatron Luminosity going up
- Same Side Kaon tagging
- Additional trigger paths
- Use satellites in hadronic modes
- Improve ct resolution
- Reoptimize event selection (NN)

εD^2 = 5% & improve σ(ct) by 10%

εD^2 = 3.5%

εD^2 = 1.55%

Summary

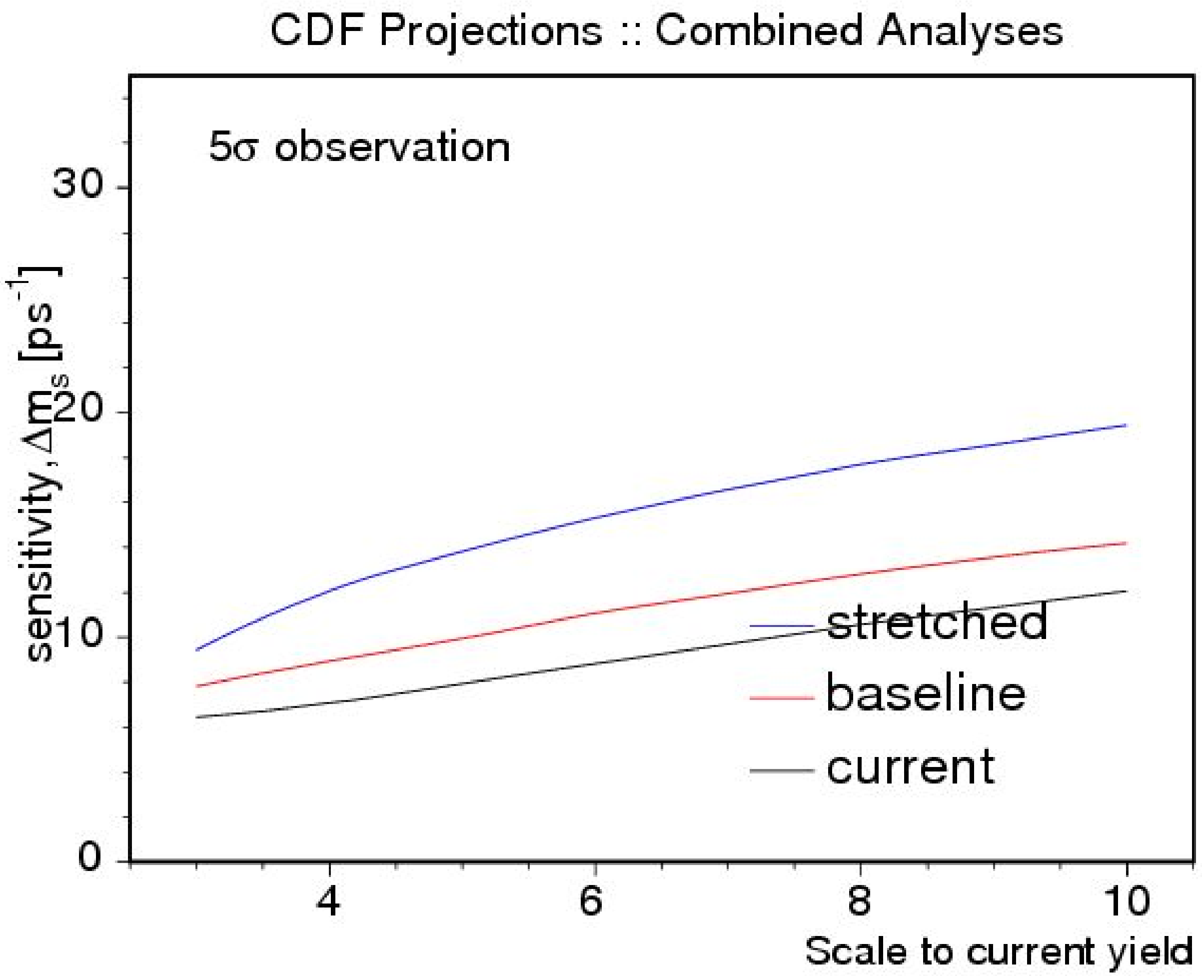
- B_s oscillations are know to occur: frequency=Δm_s unknown
- Will measure $|V_{ts}|^2/|V_{td}|^2$ (when combined Δm_d)
- Sensitive to new physics (heavy particles in box)

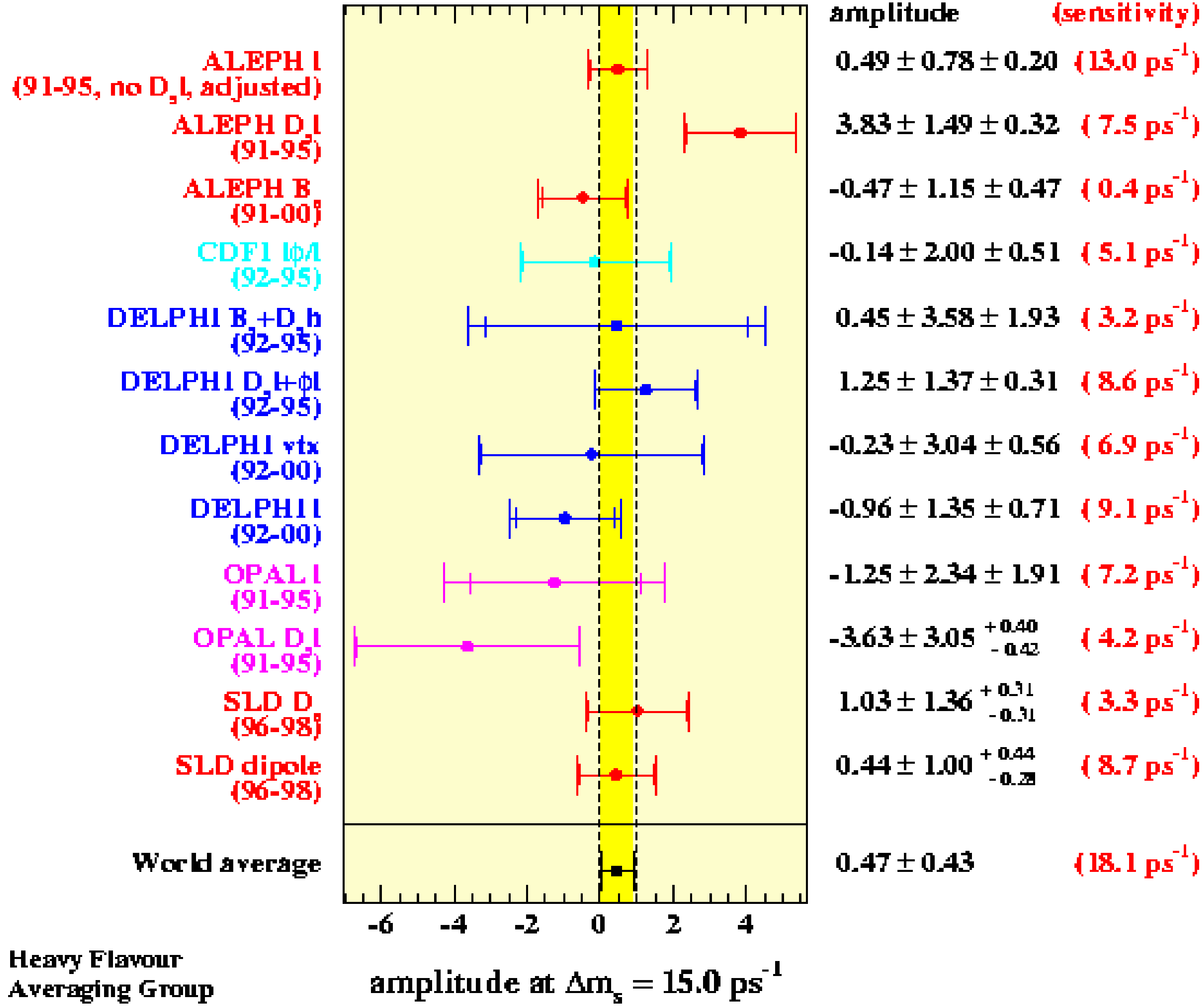
- Experimentally challenging... need
  - Bs mesons: Tevatron is the only place
  - B-physics trigger: CDF has displaced track trigger
  - Good lifetime resolution to resolve fast oscillations: SVX (L00)
  - Flavor tagging (will exploit time-of-flight detector for SSKT)

- Current CDF result: $\Delta m_s > 8.6\ ps^{-1}$ (95% CL), sensitivity 13 ps^{-1}
- Already significant impact on world average
- Much more to come! some of it very soon...
  - will dominate world average soon
  - possibility to measure Δm_s within a few years

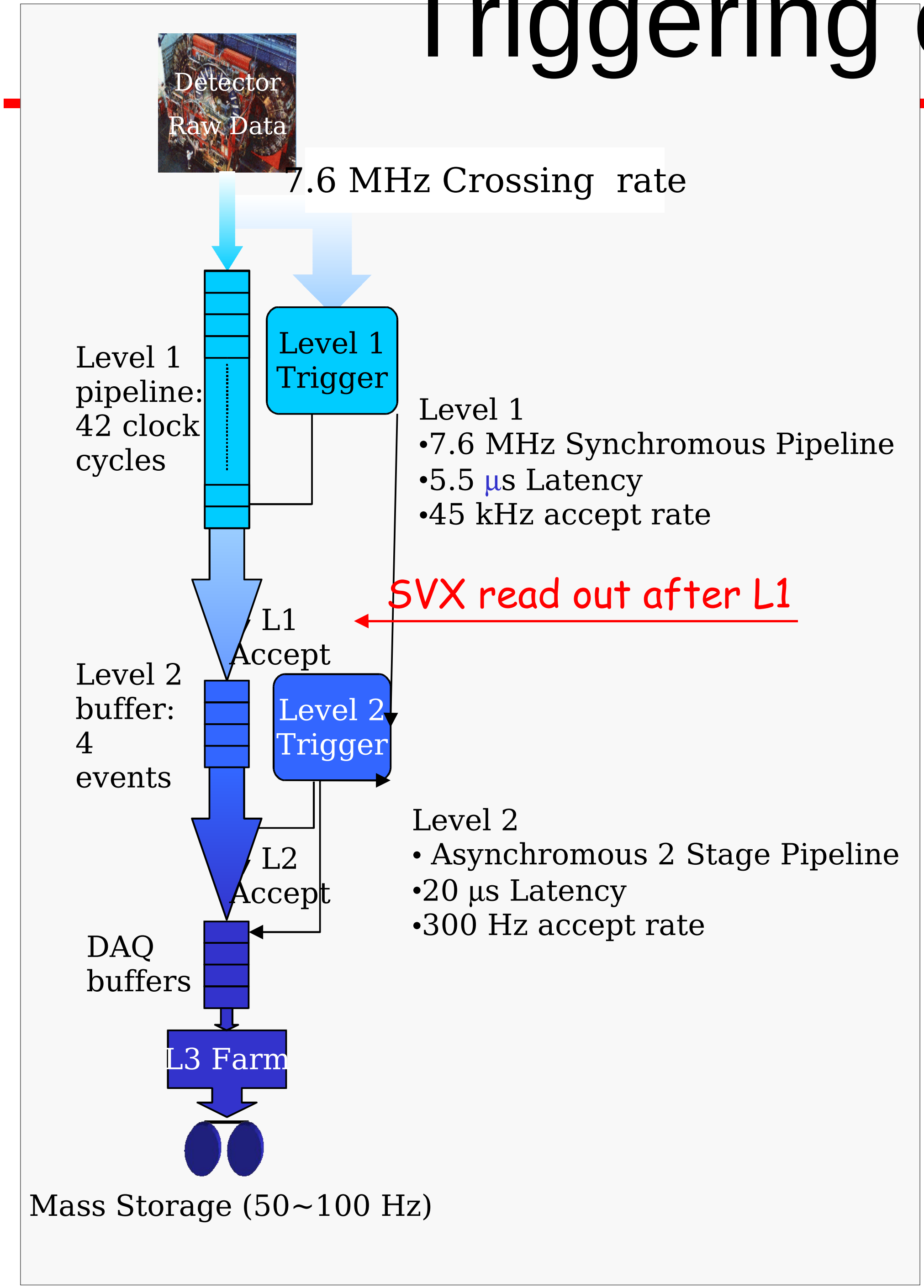
Sensitivity Projections

Combined 5σ observation




amplitude
(sensitivity)
ALEPH l
(91-95, no D_sl, adjusted)
0.49 ± 0.78 ± 0.20
(13.0 ps^{-1})
ALEPH D_sl
(91-95)
3.83 ± 1.49 ± 0.32
(7.5 ps^{-1})
ALEPH B_s
(91-00)
-0.47 ± 1.15 ± 0.47
(0.4 ps^{-1})
CDF1 lφ/l
(92-95)
-0.14 ± 2.00 ± 0.51
(5.1 ps^{-1})
DELPHI B_s+D_sh
(92-95)
0.45 ± 3.58 ± 1.93
(3.2 ps^{-1})
DELPHI D_sl+φl
(92-95)
1.25 ± 1.37 ± 0.31
(8.6 ps^{-1})
DELPHI vtx
(92-00)
-0.23 ± 3.04 ± 0.56
(6.9 ps^{-1})
DELPHI l
(92-00)
-0.96 ± 1.35 ± 0.71
(9.1 ps^{-1})
OPAL l
(91-95)
-1.25 ± 2.34 ± 1.91
(7.2 ps^{-1})
OPAL D_sl
(91-95)
$-3.63 \pm 3.05 ^{+0.40}_{-0.42}$
(4.2 ps^{-1})
SLD D_s
(96-98)
$1.03 \pm 1.36 ^{+0.31}_{-0.31}$
(3.3 ps^{-1})
SLD dipole
(96-98)
$0.44 \pm 1.00 ^{+0.44}_{-0.28}$
(8.7 ps^{-1})
World average
0.47 ± 0.43
(18.1 ps^{-1})
-6
-4
-2
0
2
4
Heavy Flavour
Averaging Group
amplitude at Δm_s = 15.0 ps^{-1}

Triggering on B decays

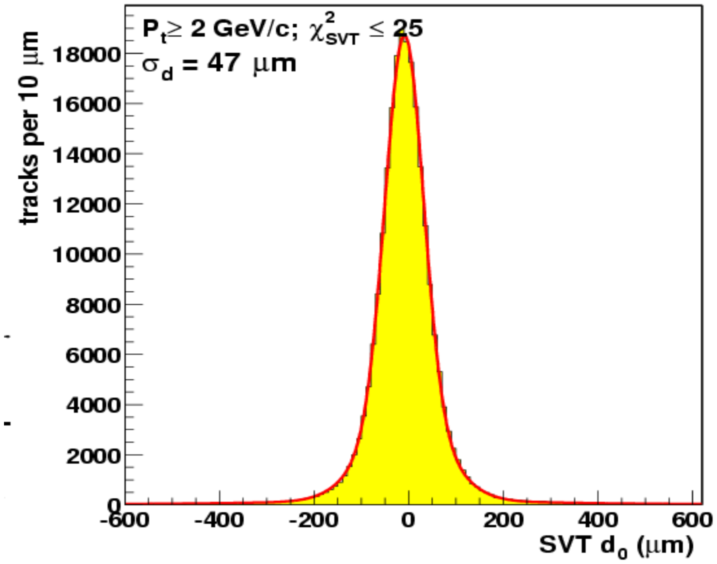


Level 1: (396 ns)

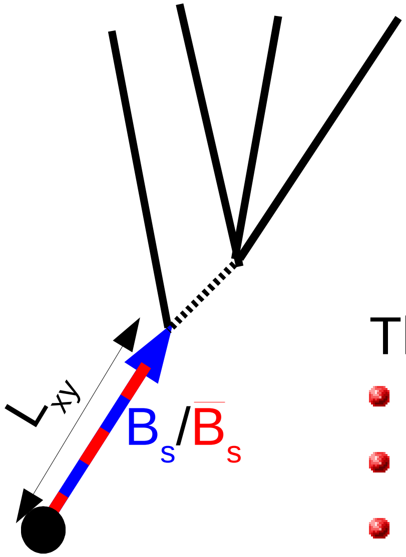
- Reconstruct COT tracks (!) on dedicated hardware: XFT
- require pair of tracks

Level 2 (20 µs):

- Add Silicon information to XFT tracks.. look for:
- two displaced tracks
- or lepton+displaced track



Proper time reconstruction

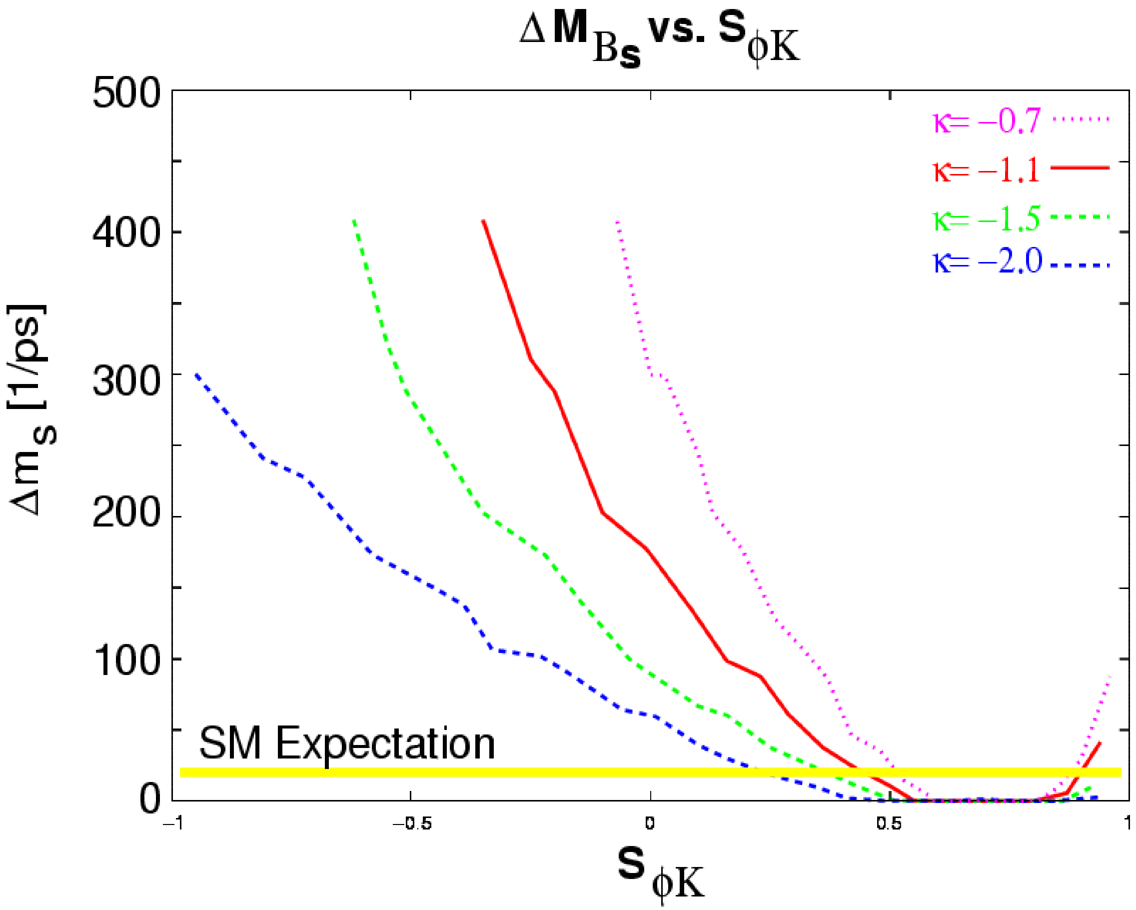


In principle, measing the proper time at decay is easy

$$ct = L_{xy} \frac{m_B}{p_T}$$

Three problems...

- Lxy distribution is biased by the trigger
- P_T is not measured accurately in semi-leptonic modes
- How do we measure our ct resolution?


ΔM_Bs vs. S_φK
Δm_s [1/ps]
500
400
300
200
100
0
–1
–0.5
0
0.5
1
S_φK
κ= –0.7
κ= –1.1
κ= –1.5
κ= –2.0
SM Expectation