B_s Mixing at Tevatron

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On behalf of the CDF&D0 Collaborations

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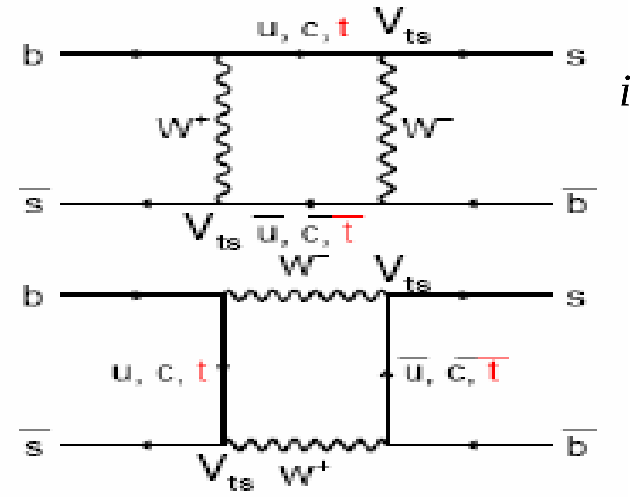
B_s Mixing in The Standard Model



$$i\frac{d}{dt}\begin{pmatrix}|B(t)\rangle\\|\bar{B}(t)\rangle\end{pmatrix}=\left(M-\frac{i}{2}\Gamma\right)\begin{pmatrix}|B(t)\rangle\\|\bar{B}(t)\rangle\end{pmatrix}\qquad H=\begin{pmatrix}M & M_{12}\\M_{12}^* & M\end{pmatrix}-\frac{i}{2}\begin{pmatrix}\Gamma & \Gamma_{12}\\\Gamma_{12}^* & \Gamma\end{pmatrix}$$

$$M_{H,L}=M\pm\overbrace{\mathrm{Re}(M_{12}-\tfrac{i}{2}\Gamma_{12})}^{\Delta m/2}$$

$$\Gamma_{H,L}=\Gamma\pm\underbrace{2\,\mathrm{Im}(M_{12}-\tfrac{i}{2}\Gamma_{12})}_{\Delta\Gamma/2}$$

$$\Gamma=\tfrac{1}{2}(\Gamma_L+\Gamma_H)\equiv\frac{1}{\tau}$$

$$\Delta\Gamma=\Gamma_L-\Gamma_H$$

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

Big uncertainties

In the ratio uncertainties cancels:

$$\frac{\Delta m_s}{\Delta m_d}=\frac{m_{Bs}}{m_{Bd}}\frac{f_{Bs}^2B_{Bs}}{f_{Bd}^2B_{Bd}}\frac{|V_{ts}|^2}{|V_{td}|^2}=\frac{m_{Bs}}{m_{Bd}}\xi^2\frac{|V_{ts}|^2}{|V_{td}|^2}$$

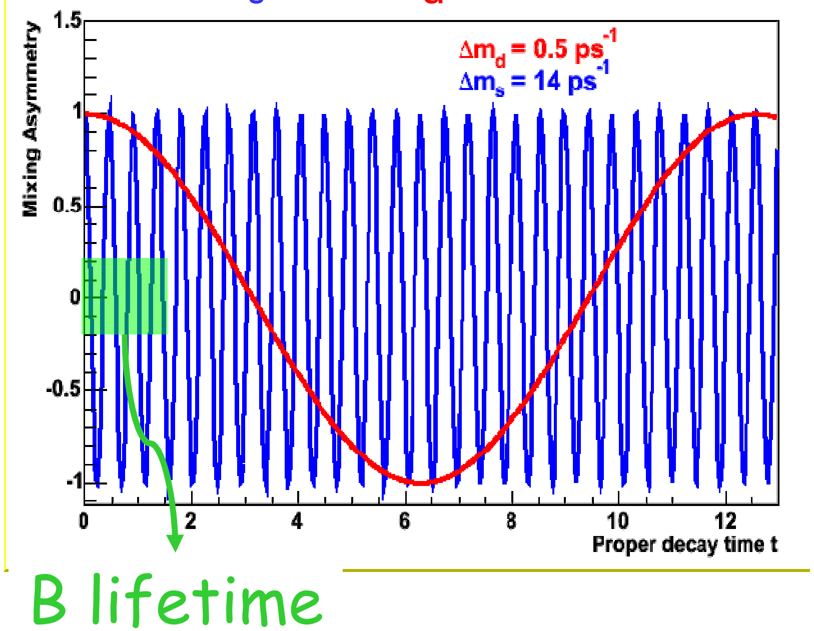
$\xi^2 = 1.21 \pm 0.02^{+0.035}_{-0.014}$

(M. Okamoto, hep-lat/0510113)

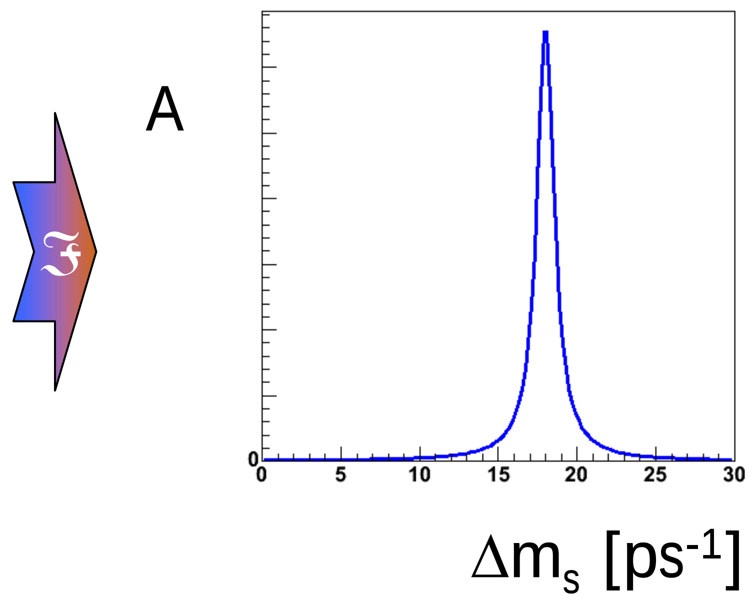
Measurement Principle in a Perfect World

$$P(t)_{B_q^0 \to \overset{(-)}{B}{}_q^0} = \frac{1}{2\tau} e^{-\frac{t}{\tau}} (1 \pm \cos(\Delta m_q t)) \qquad A = \frac{N^{nomix} - N^{mix}}{N^{nomix} + N^{mix}} = \cos(\Delta m_s t)$$

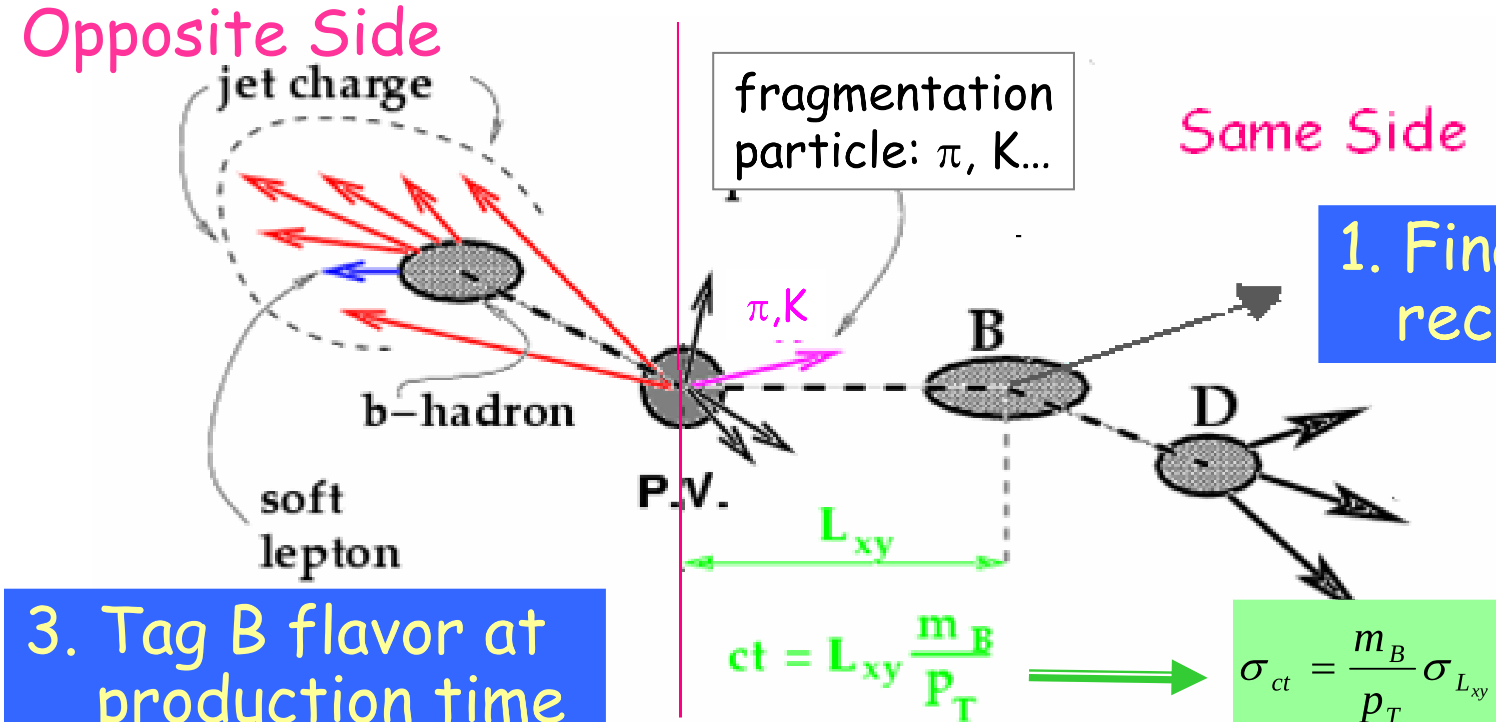
B_s vs. B_d oscillation



Rather than fit for frequency perform a 'Fourier transform'



Road Map to Δm_s Measurement



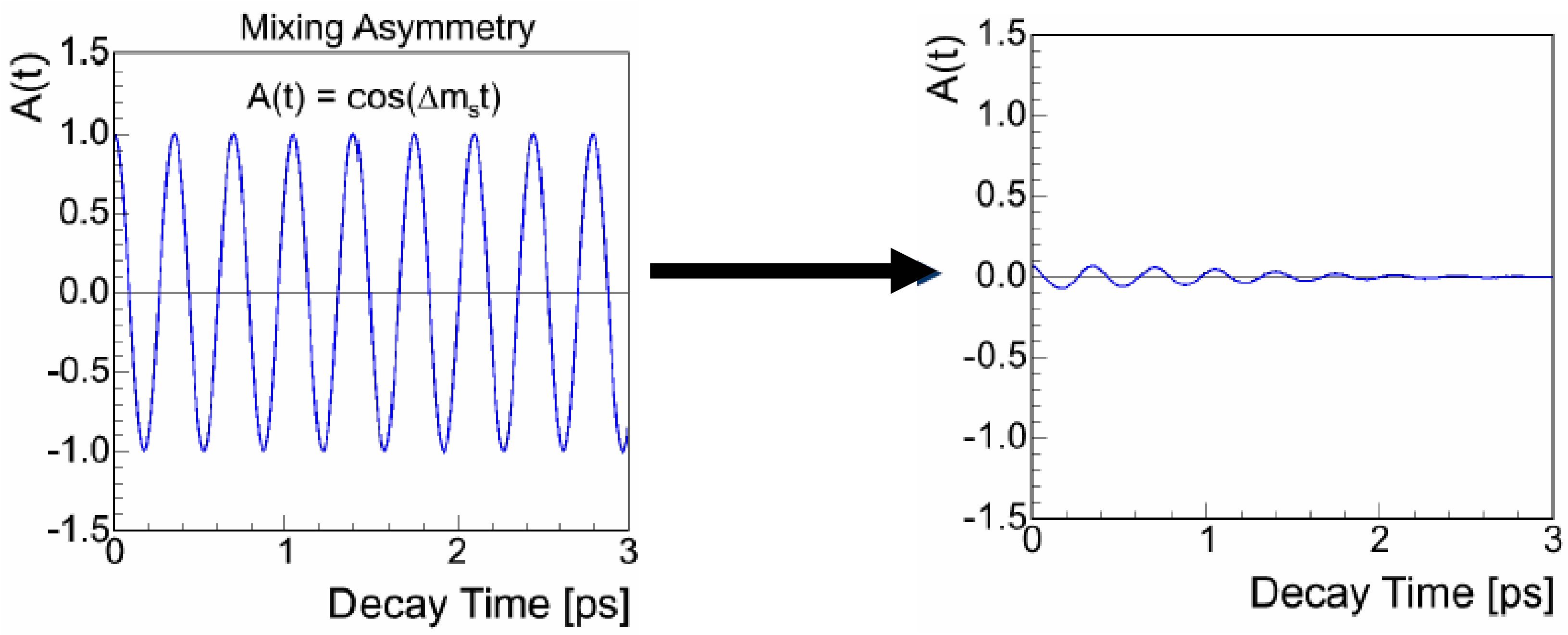
1. Final state reconstruction

$$\sigma_{ct} = \frac{m_B}{p_T}\sigma_{L_{xy}} \oplus ct\left(\frac{\sigma_{p_T}}{p_T}\right)$$

2. High resolution on proper decay length

3. Tag B flavor at production time

Adding all the realistic effects



Flavor tagging power

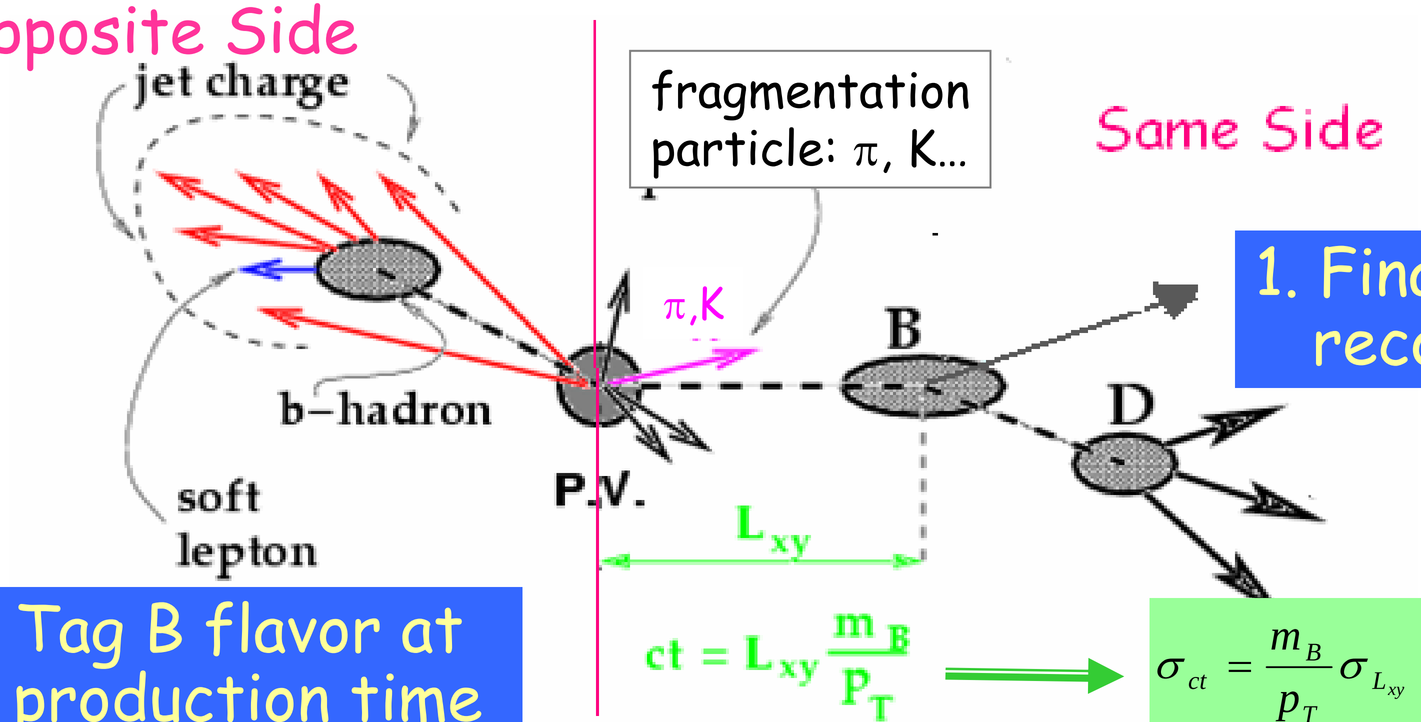
Proper time resolution

$$\frac{1}{\sigma} = \sqrt{\frac{S\epsilon D^2}{2}}\, e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

$$\sigma_{ct} = \frac{m_B}{p_T}\sigma_{L_{xy}} \oplus ct\left(\frac{\sigma_{p_T}}{p_T}\right)$$

Road Map to Δm_s Measurement

Opposite Side



1. Final state reconstruction

$$\sigma_{ct} = \frac{m_B}{p_T}\sigma_{L_{xy}} \oplus ct\left(\frac{\sigma_{p_T}}{p_T}\right)$$

2. High resolution on proper decay length

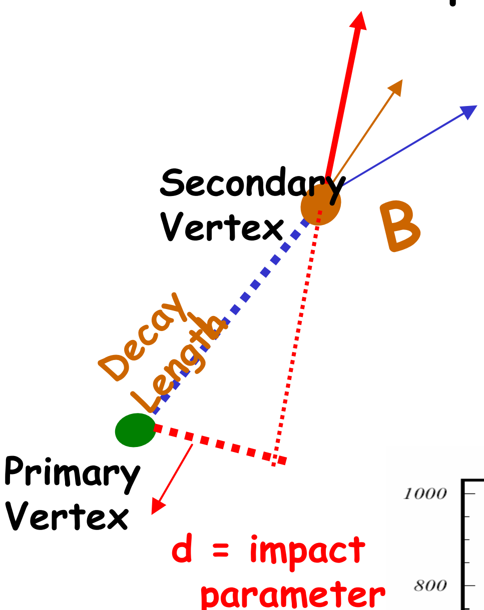
3. Tag B flavor at production time

measure efficiency ε and dilution D: εD^2 gives the "effective" number of events

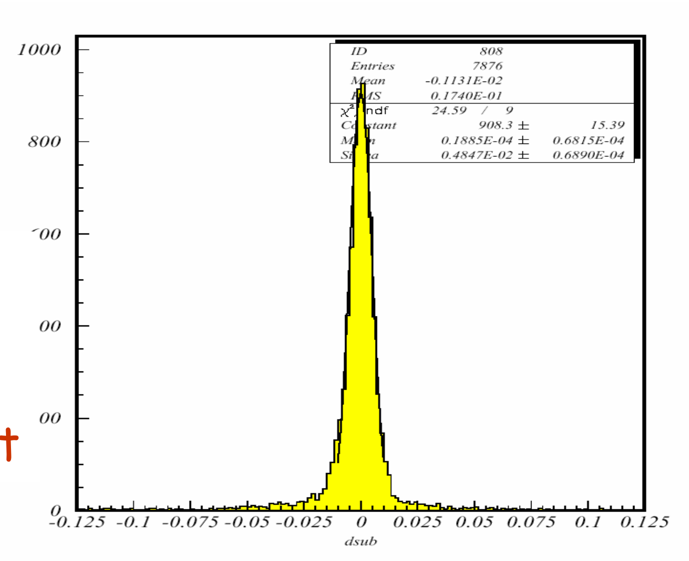
Triggers Used

CDF:

Two tracks displaced from PV



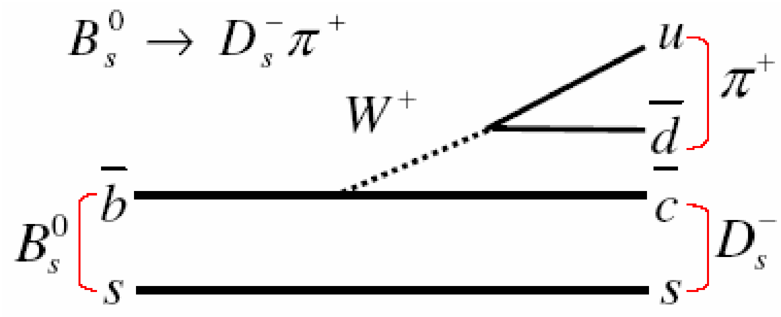
σ~ 48 μm includes 33 μm of beam spot



D0:

- Single inclusive muons
  - Pt>3,4,5 GeV
- Dimuons:
  - Other muon for flavor tagging

B_s Data sample



$B_s \rightarrow D_s \pi$

$D_s \rightarrow \phi\pi$ $\phi \rightarrow KK$

$D_s \rightarrow K^{*0}K$ $K^{*0} \rightarrow K\pi$

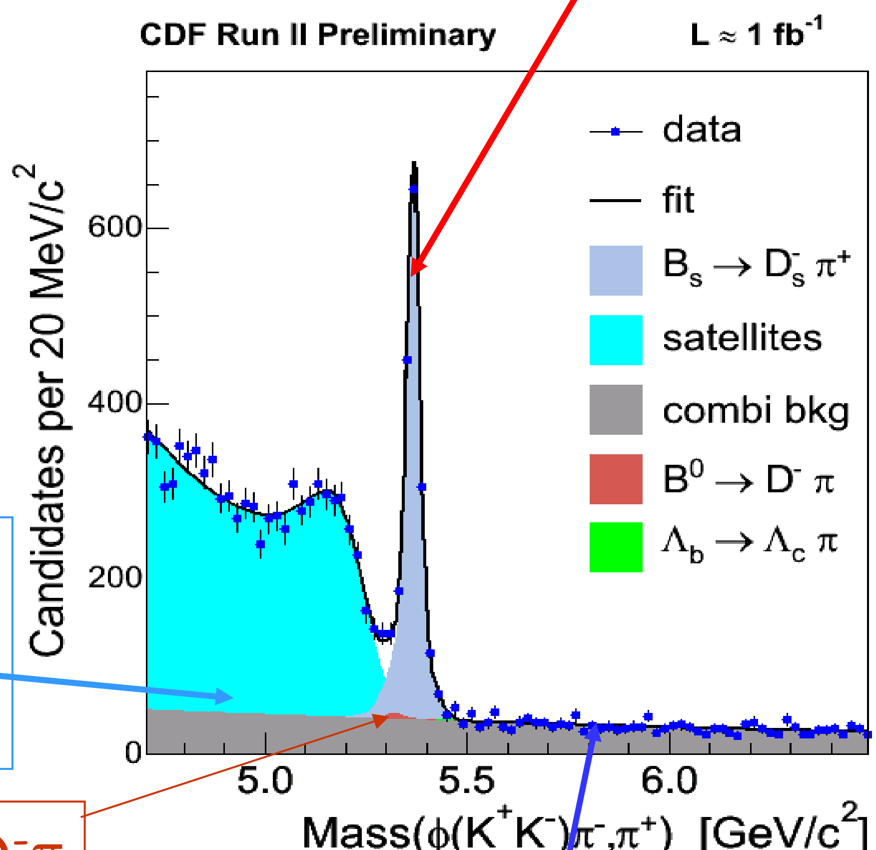
$D_s \rightarrow 3\pi$

$B_s \rightarrow D_s 3\pi$

$D_s \rightarrow \phi\pi$

$D_s \rightarrow K^{*0}K$

Signal $B_s \rightarrow D_s\pi$ $D_s \rightarrow \phi\pi$



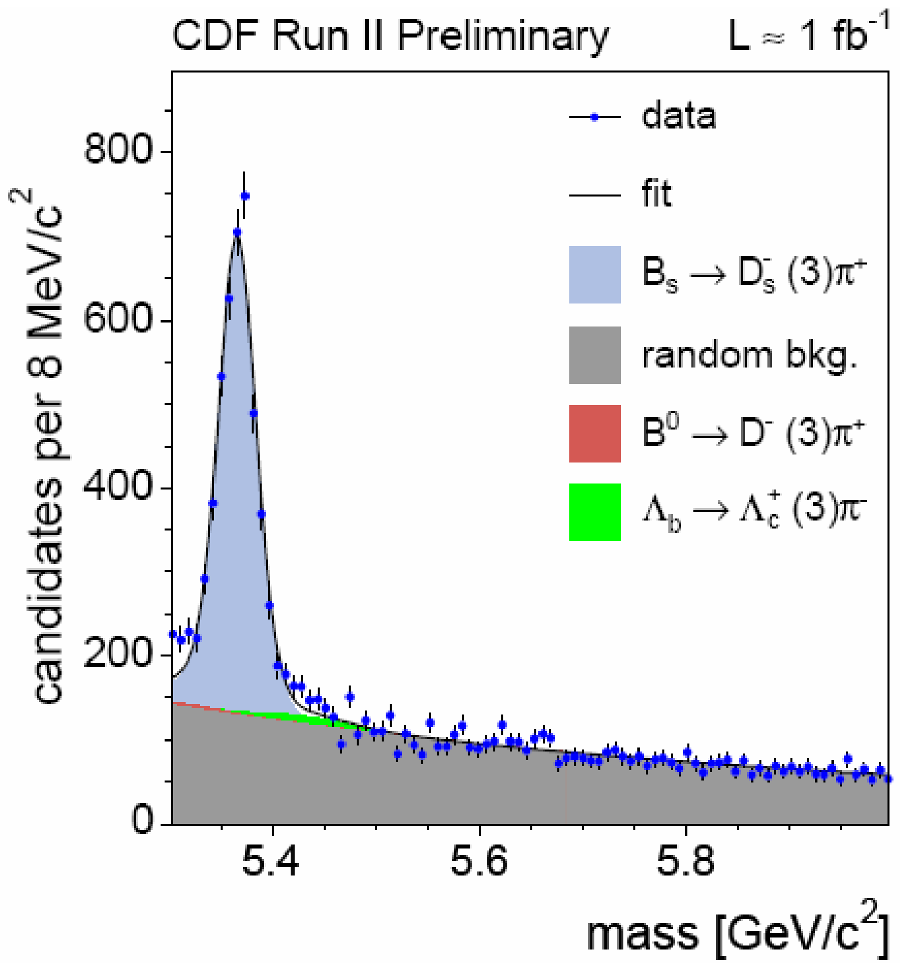
Partially reconstructed B mesons

$B^0 \rightarrow D^-\pi$

Combinatorial background

CDF Hadronic B_s yields summary

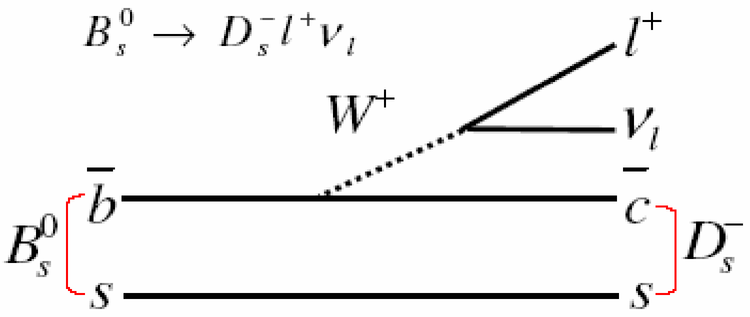
Decay channel	Yield
$B_s \to D_s \pi$ $D_s \to \phi\pi$	1570±43
$B_s \to D_s \pi$ $D_s \to K^{*0}K$	857±32
$B_s \to D_s \pi$ $D_s \to 3\pi$	612±37
$B_s \to D_s 3\pi$ $D_s \to \phi\pi$	493±37
$B_s \to D_s 3\pi$ $D_s \to K^{*0}K$	204±26
Total	3736±79



$B^+ \to D^0\pi \sim 26{,}000$

$B^0 \to D^-\pi \sim 22{,}000$

CDF Semileptonic samples



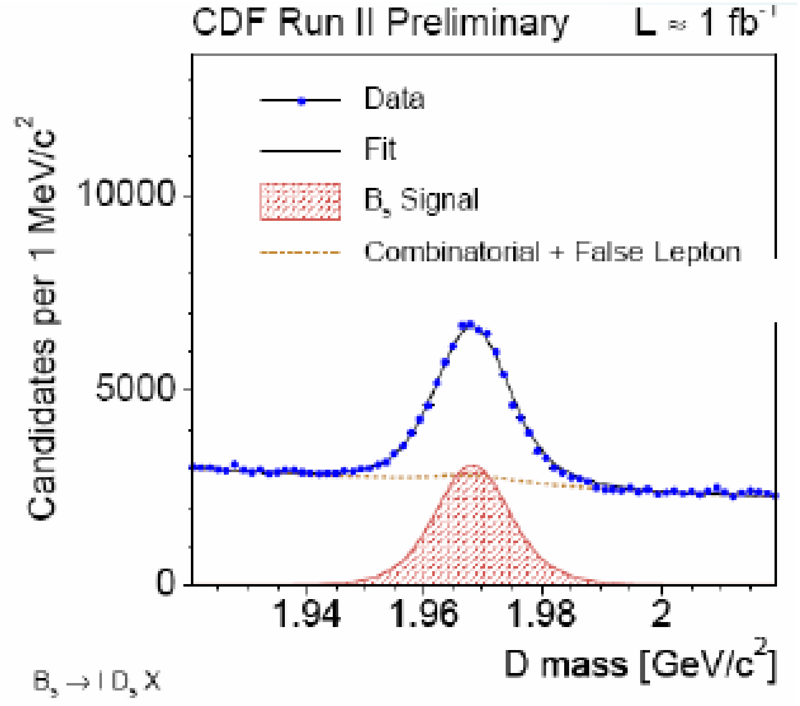
Decay	S/B	S
$\mu D0$	3.8	$409{,}600 \pm 970$
μD^+	1.3	$218{,}500 \pm 940$
μD^*	≥ 50	$53{,}900 \pm 230$
$\mu D_s(\phi\pi^-)$	2.1	$24{,}100 \pm 240$
$\mu D_s(K^{*0}K^-)$	0.4	$8{,}000 \pm 160$
$\mu D_s(\pi^+\pi^-\pi^-)$	0.2	$7{,}500 \pm 210$
$eD0$	3.7	$142{,}300 \pm 540$
eD^+	1.3	$79{,}500 \pm 630$
eD^*	≥ 50	$21{,}000 \pm 150$
$eD_s(\phi\pi^-)$	2.1	$8{,}200 \pm 130$
$eD_s(K^{*0}K^-)$	0.4	$2{,}900 \pm 90$
$eD_s(\pi^+\pi^-\pi^-)$	0.2	$2{,}600 \pm 130$

$B_s \to D_s l X$

$D_s \to \phi\pi$ $\phi \to KK$

$D_s \to K^{*0}K$ $K^{*0} \to K\pi$

$D_s \to 3\pi$

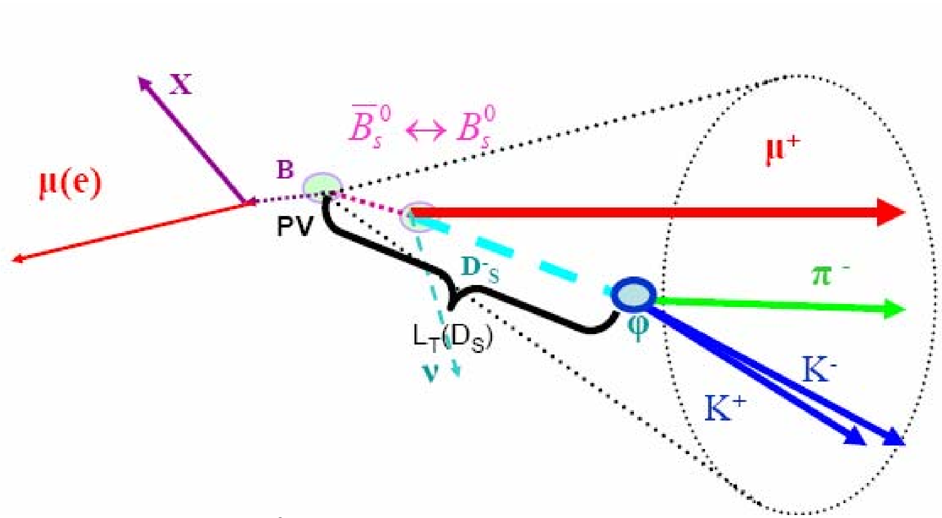


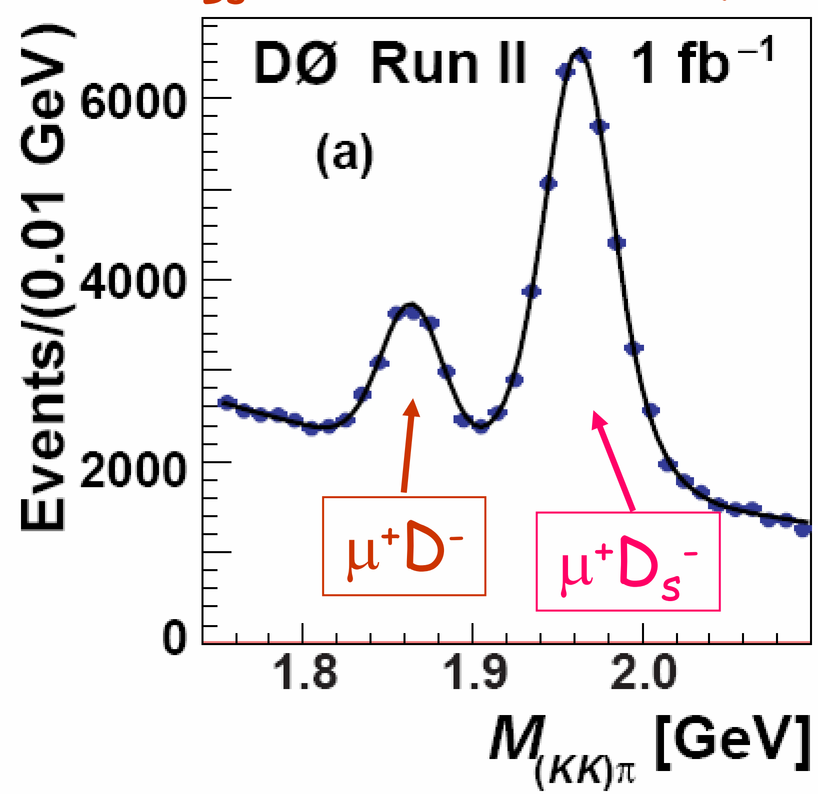
$D_s l \sim 53{,}000$

D0 Semileptonic samples

Decay channel:
$B_s \rightarrow \mu^+ D_s^- X$
$D_s^- \rightarrow \phi\pi^-$ and $\phi \rightarrow K^+K^-$

N_{Bs} = 26,710 ± 556(stat)



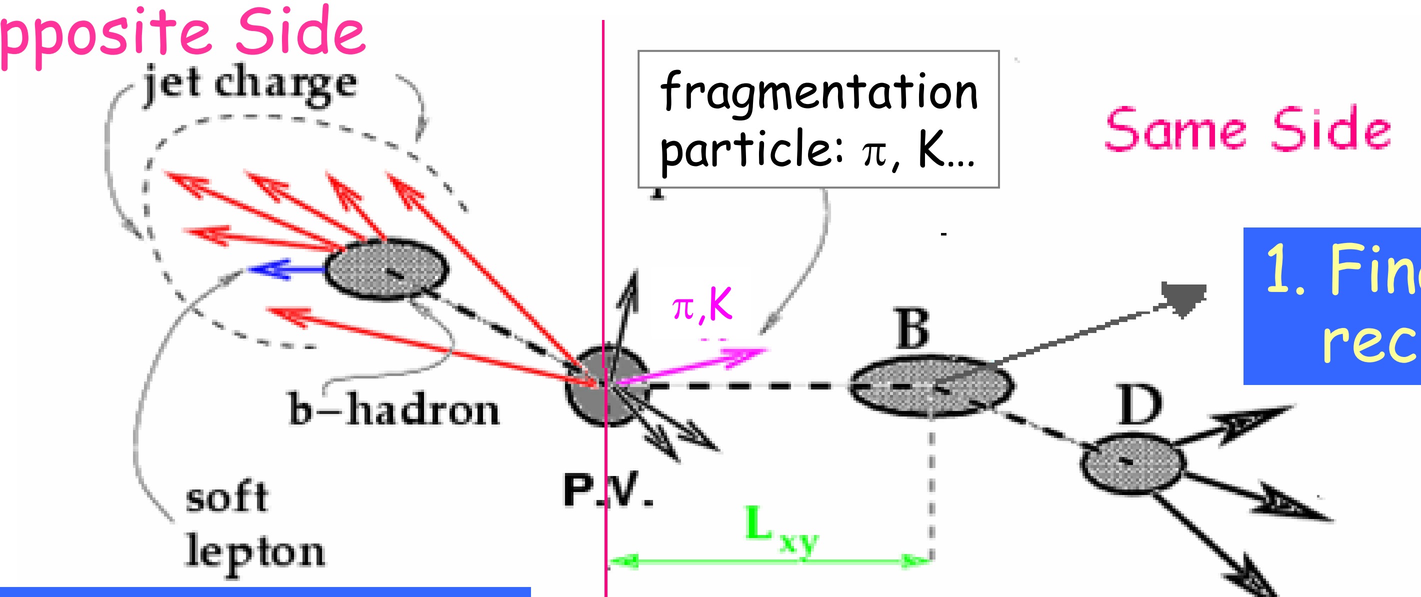


Cuts selected maximize

$$S/\sqrt{S+B}$$

Road Map to Δm_s Measurement

Opposite Side



1. Final state reconstruction

3. Tag B flavor at production time

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

$$\sigma_{ct} = \frac{m_B}{p_T}\sigma_{L_{xy}} \oplus ct\left(\frac{\sigma_{p_T}}{p_T}\right)$$

2. High resolution on proper decay length

Proper decay time reconstruction

- Fully reconstructed events $ct = L_{xy}^{B} M^{B} / P_{t}^{B}$
- Semileptonic decay $ct = L_{xy}^{lD} M^{B} / P_{t}^{lD} \cdot K$

CDF

$K = \langle P_{t}^{lD} / P_{t}^{B} \cdot L_{xy}^{B} / L_{xy}^{lD} \rangle$

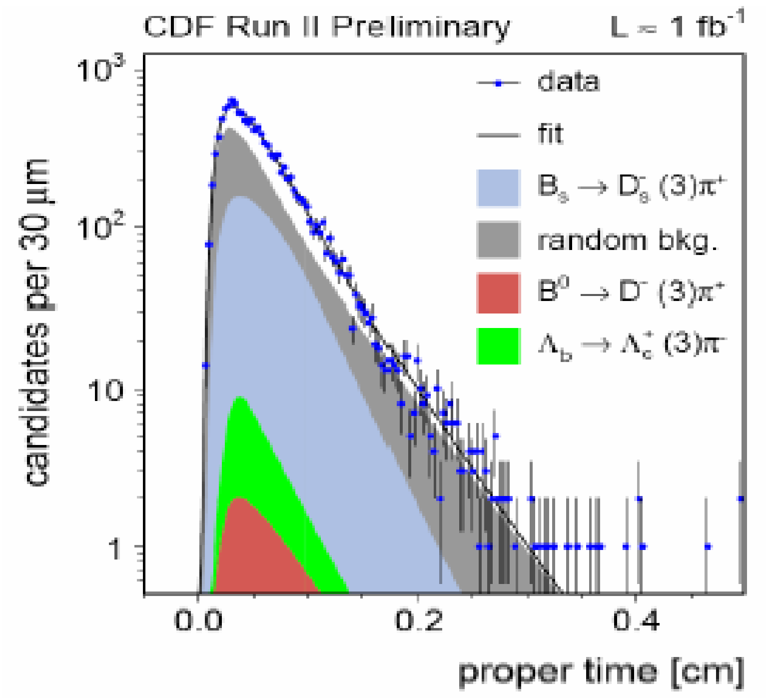
D0

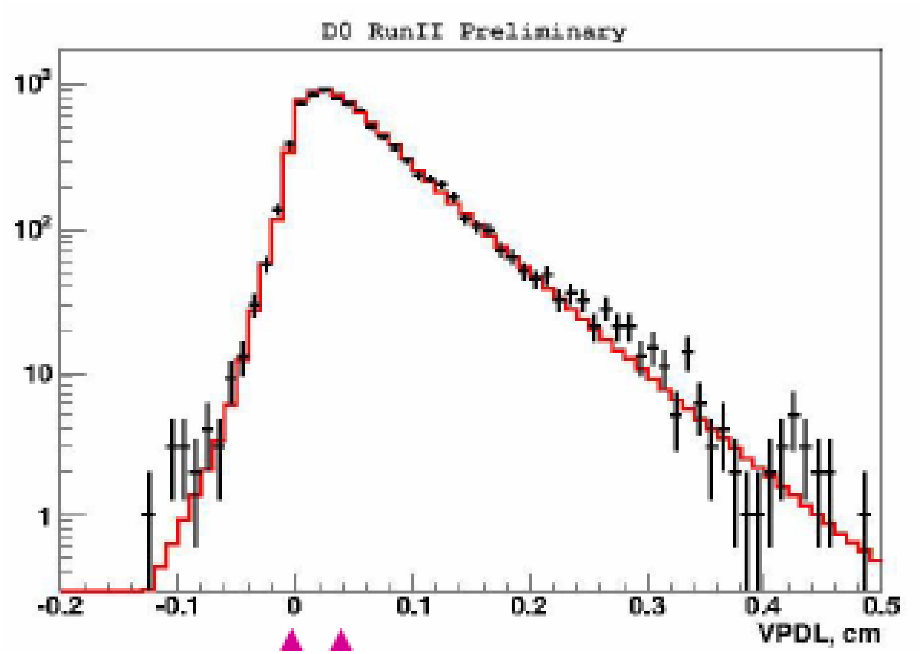
$K = \langle P_{t}^{lD} / P_{t}^{B} \rangle$

It is needed to:

- Measure the lifetime to establish the time scale
- Determine the time resolution

B Lifetime measurement





$c\tau(B_s)$=1.538±0.040(stat) ps

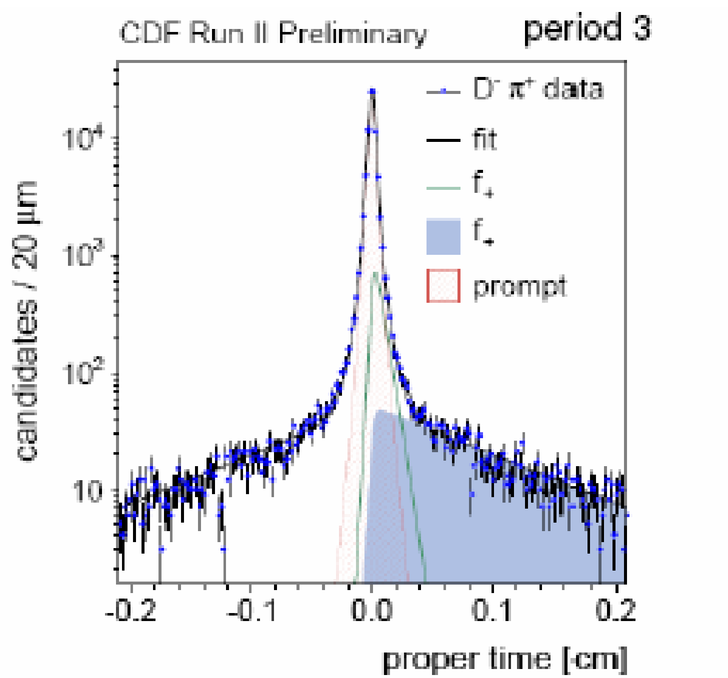
Central value $c\tau(B_s)$=404-416 μm

Statistical error ~10 μm

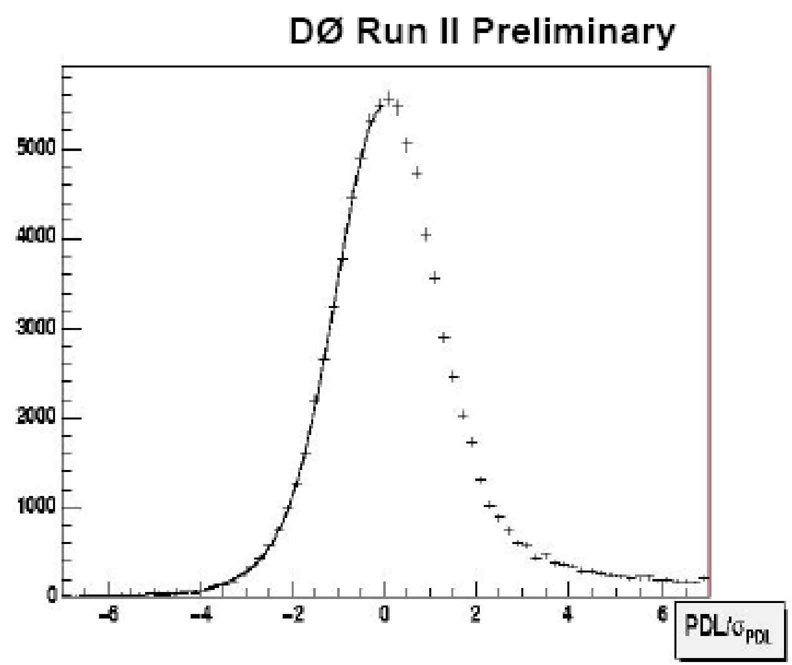
Proper time resolution, σ_t

- Lifetime measurement not very sensitive
- In the Δm_s fit each event weighted by its resolution
- Dedicated calibration needed

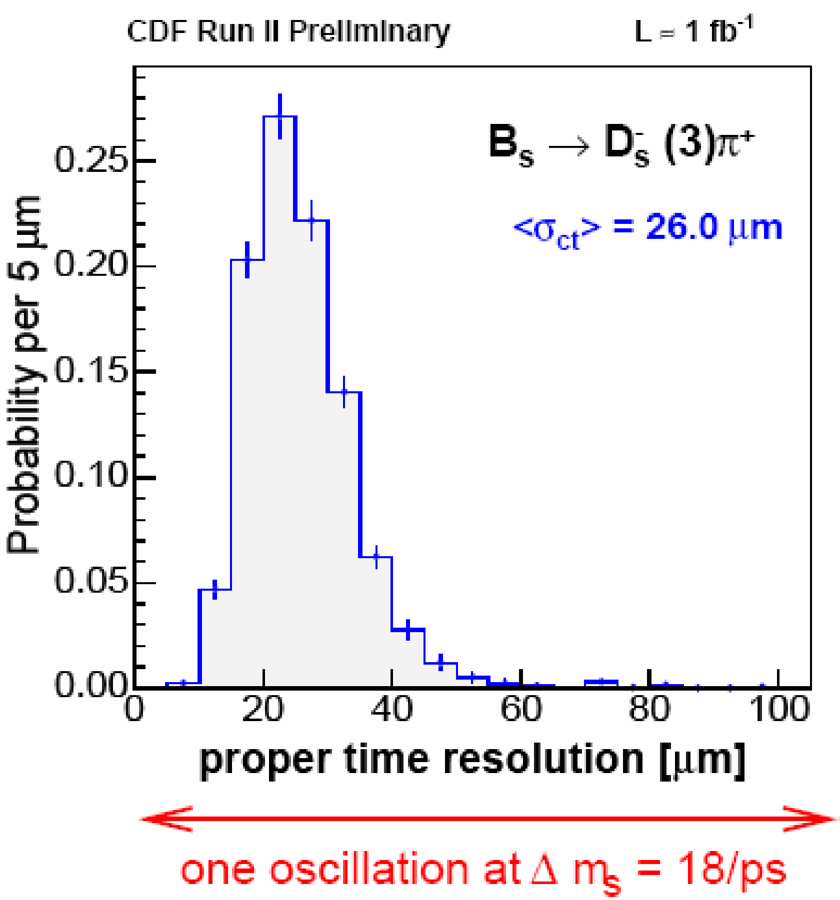
Prompt Charm + track sample

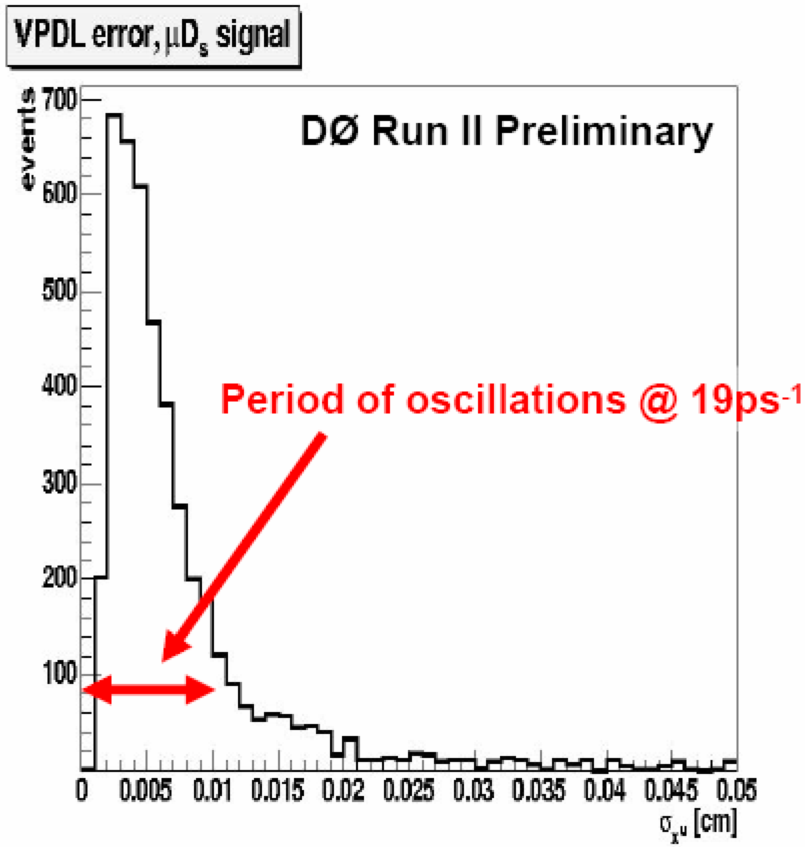


$J/\psi \to \mu^+\mu^-$ sample

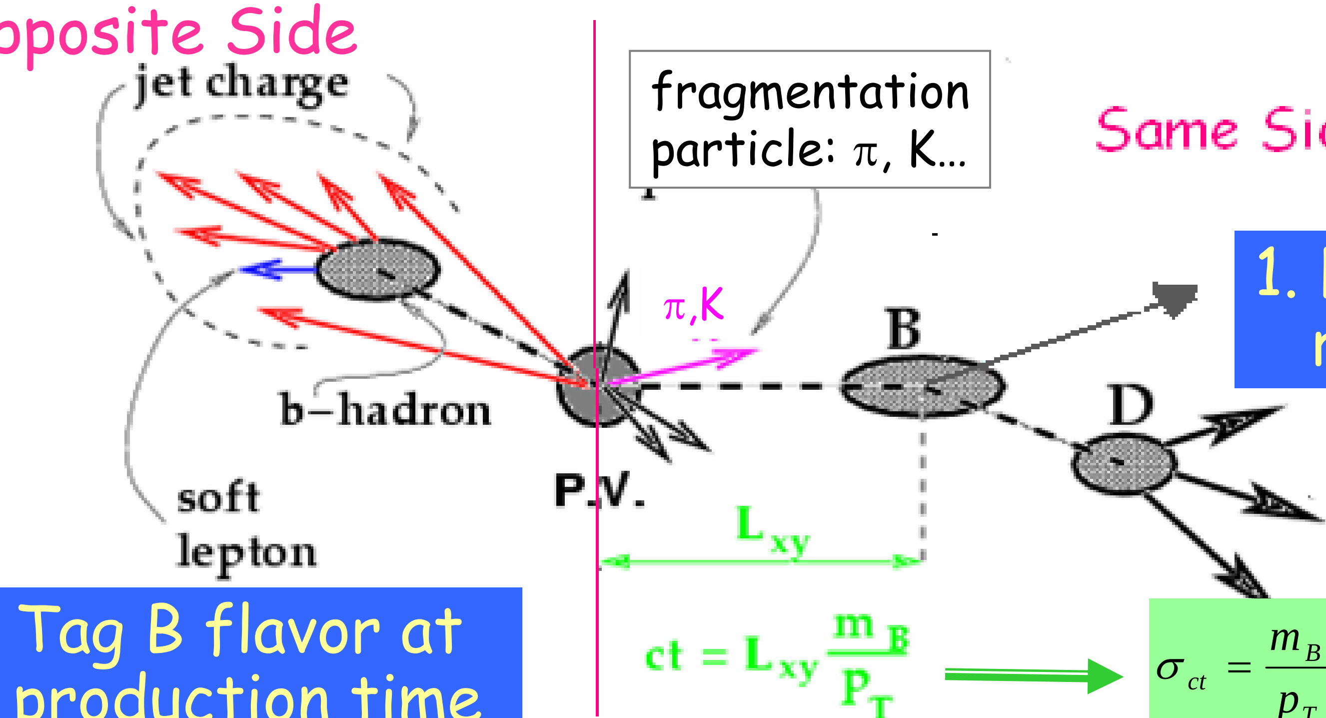


Proper time resolution, σ_t





Road Map to Δm_s Measurement



1. Final state reconstruction

$$\sigma_{ct} = \frac{m_B}{p_T}\sigma_{L_{xy}} \oplus ct\left(\frac{\sigma_{p_T}}{p_T}\right)$$

2. High resolution on proper decay length

3. Tag B flavor at production time

measure efficiency ε, dilution D

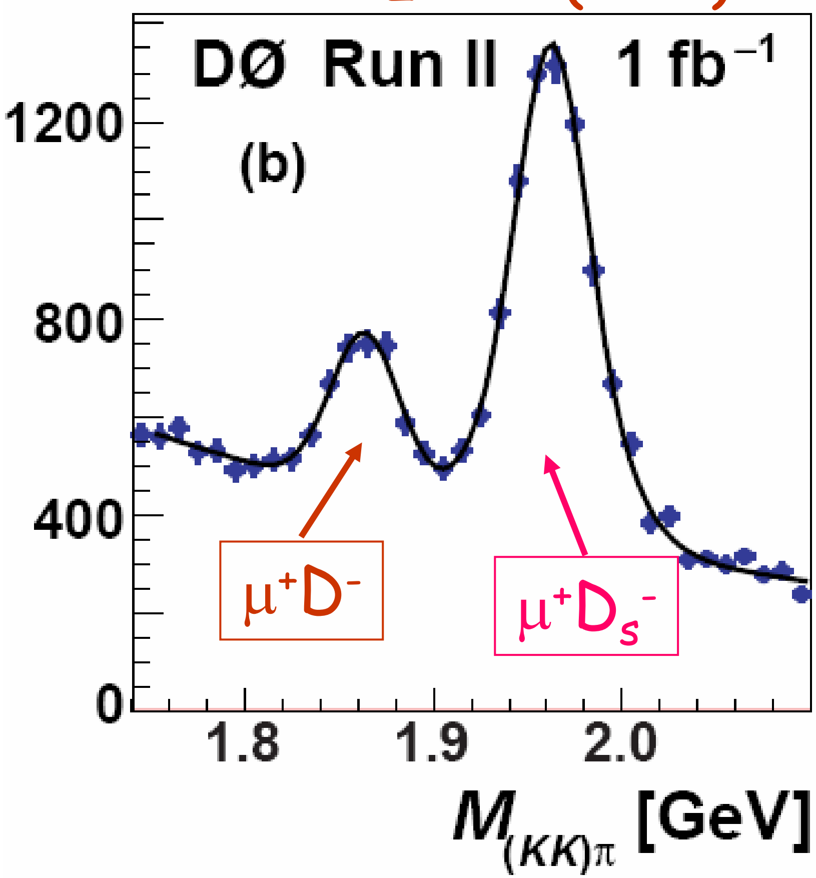
$$D = \frac{N_{right} - N_{wrong}}{N_{right} + N_{wrong}} = 2P_{right} - 1$$

εD^2 gives the "effective" number of events

Opposite Side Taggers

- Use data to calibrate the taggers and to evaluate D
- Fit semileptonic and hadronic B_d sample to measure: D, Δm_d

N = 5601 ± 102 (stat)



-lepton (electron or muon)

$$Q_J^\ell = \sum_i q^i p_T^i / \sum_i p_T^i$$

- Secondary Vertex

$$Q_{SV} = \sum_i (q^i p_L^i)^{0.6} / \sum_i (p_L^i)^{0.6}$$

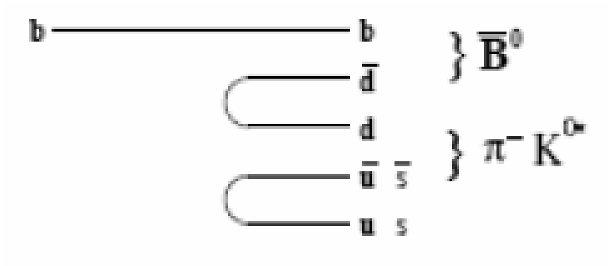
- Event Charge

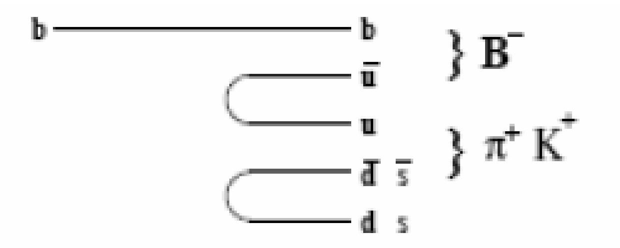
$$Q_{EV} = \sum_i q^i p_T^i / \sum_i p_T^i$$

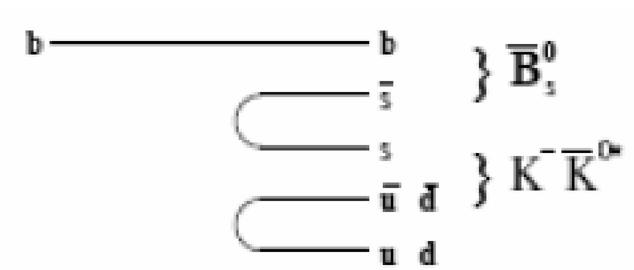
Tags combined

$\varepsilon D^2 = 2.48 \pm 0.21(\text{stat.})^{+0.08}_{-0.06}(\text{syst.})\%$

Same Side Tagger





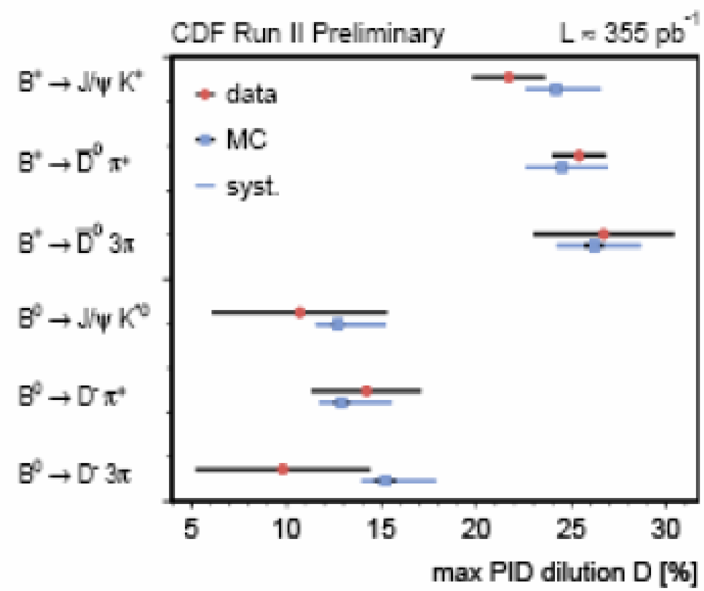


$B^0/B^{\pm}$ likely to have π nearby

B^0_s likely to have K

Use PID to separate pion from kaon

Tune Monte Carlo to reproduce B^0,B^- distributions then apply to B_s



Flavor Taggers performances

	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 ± 0.49 (syst)	4.00 ± 0.56 (syst)

- Exclusive combination of tags in OST
- SSTK-OST combination assumes independent tagging information

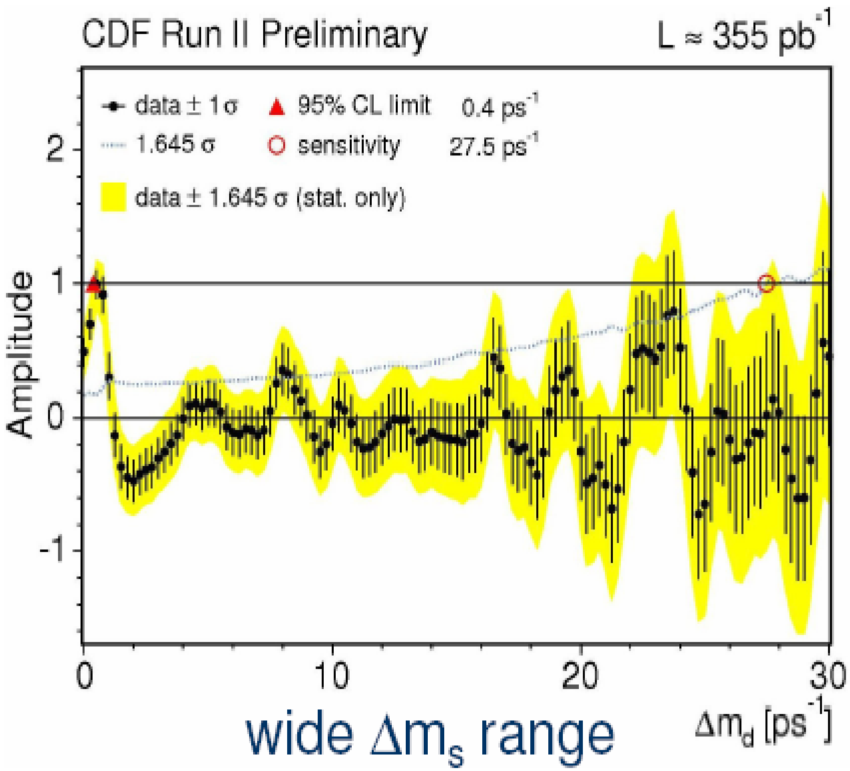
Amplitude Scan notation

- A is introduced: $P(t)_{B_q^0 \to \overset{(-)}{B}{}_q^0} = \frac{1}{2\tau} e^{-\frac{t}{\tau}} (1 \pm A\cos(\Delta m_q t))$
- A=1 when $\Delta m_s^{measured} = \Delta m_s^{true}$

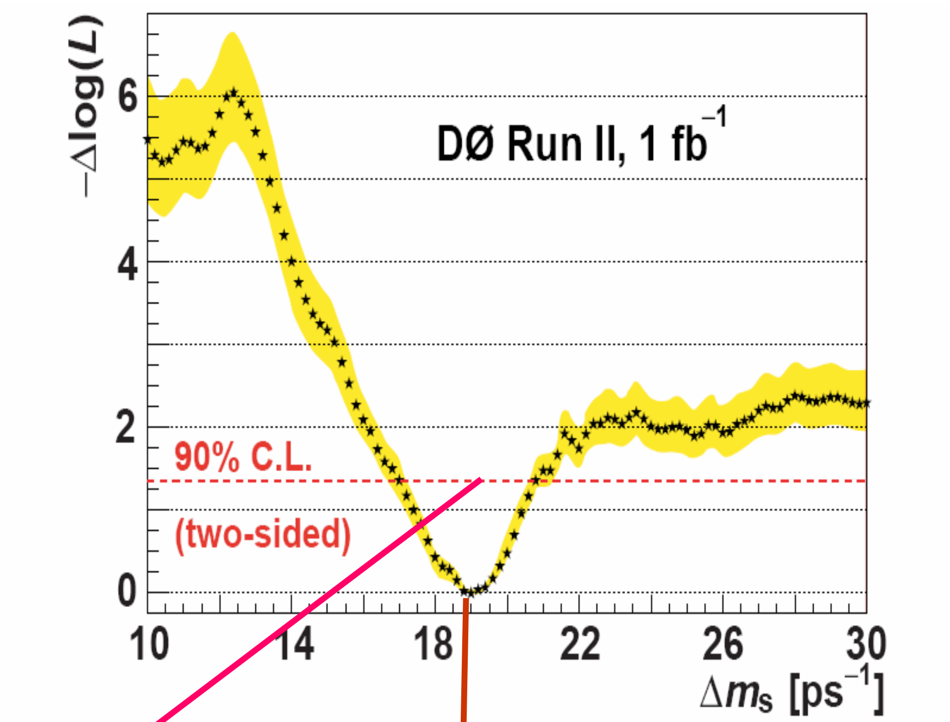
In the figure:

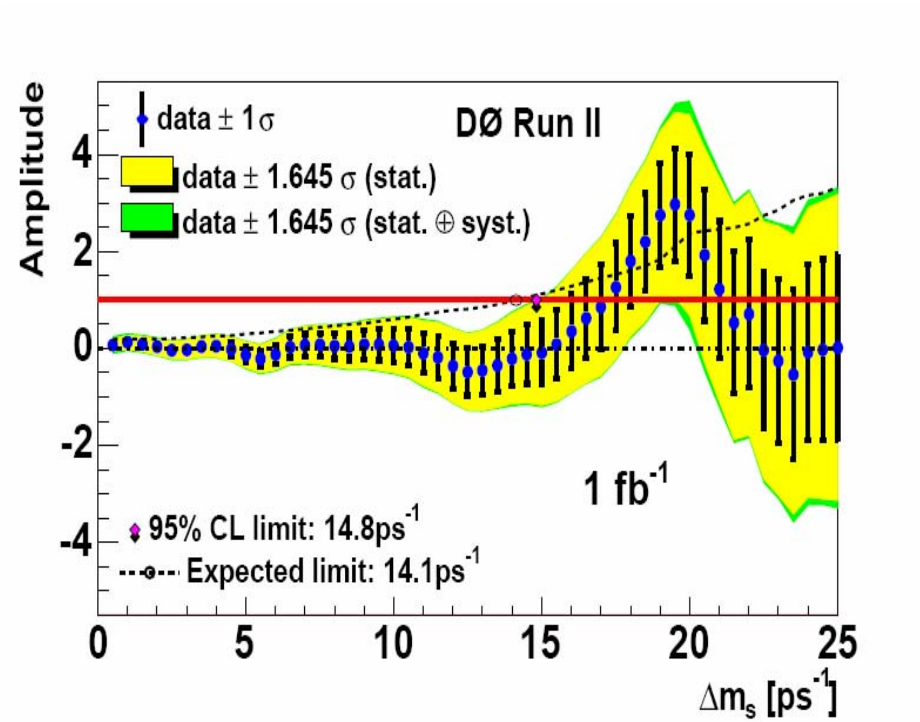
- Points: $A \pm \sigma(A)$ from Likelihood fit for different Δm
- Yellow band: $A \pm 1.645\sigma(A)$
- Dashed line: $1.645\sigma(A)$ vs. Δm
- Δm excluded at 95% C.L. if $A \pm 1.645\sigma(A) < 1$
- Measured sensitivity: $1.645\sigma(A) = 1$

B^0 mixing in hadronic decay



D0 Results





"favored value" = 19 ps^{-1}

$17<\Delta m_s<21$ ps^{-1} at the 90% C.L.

$\Delta m \approx 19$ ps^{-1} :

$A/\sigma A=2.5$ and $A-1/\sigma A=1.6$

Sensitivity = 14.1ps^{-1}

$\Delta m_s>14.8$ at the 95% C.L.

Choice of Procedure

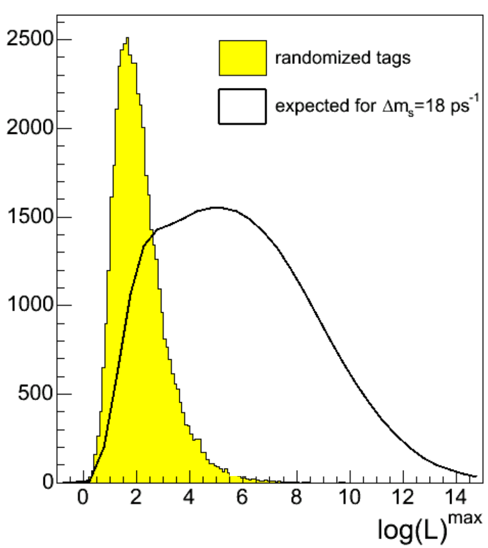
Before un-blinding: p-value probability that observed effect is due background fluctuation. No search window.

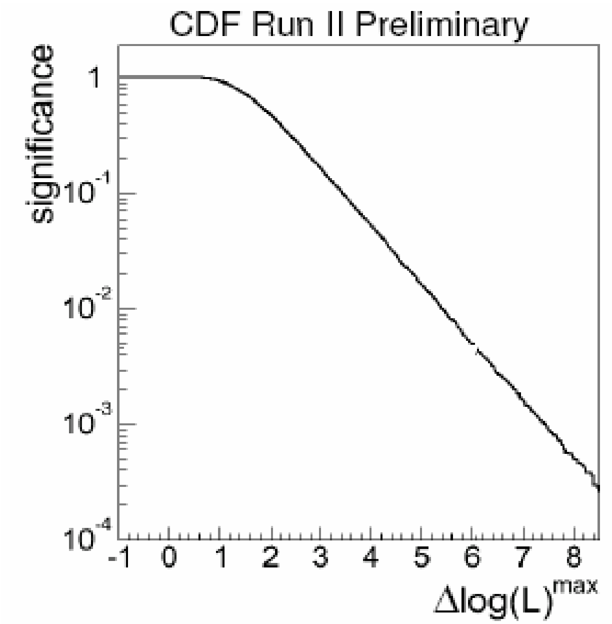
p-value<1%?

yes → make double sided confidence interval from $\Delta(\ln(L))$, measure Δm_s

no → set 95% C.L. based on Amplitude Scan

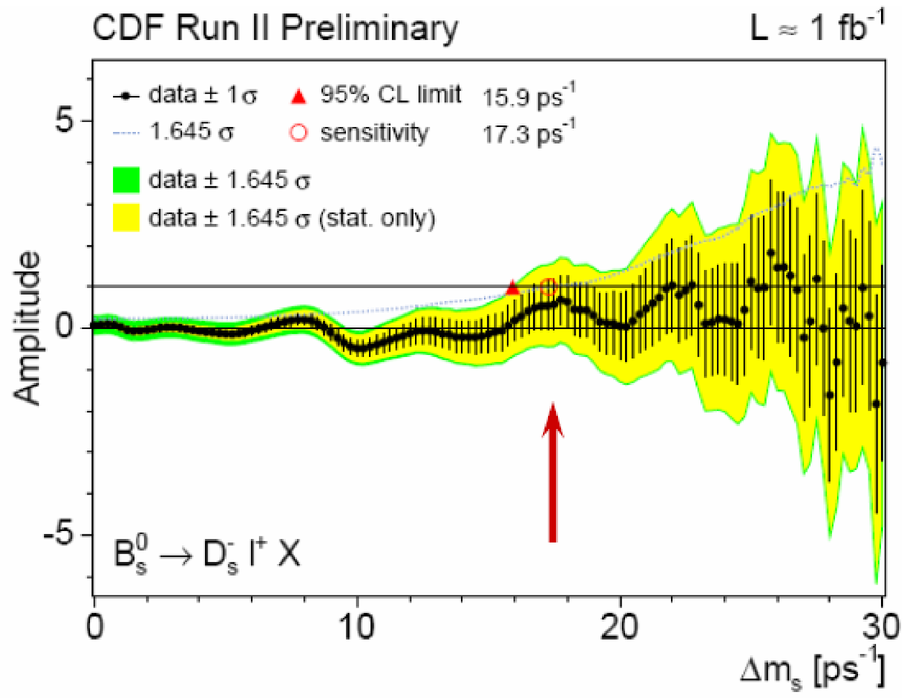
ln[L(A=1)/lnL(A=0)]

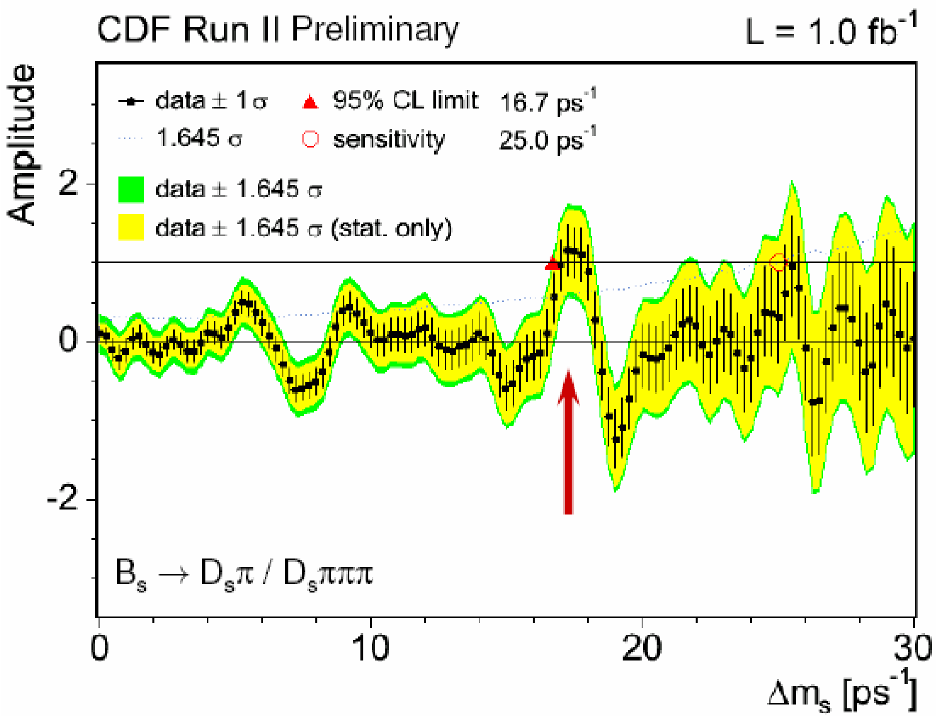




Probability of random tag fluctuation estimated on data (randomized tags) and checked with toy Monte Carlo

CDF Amplitude Scans





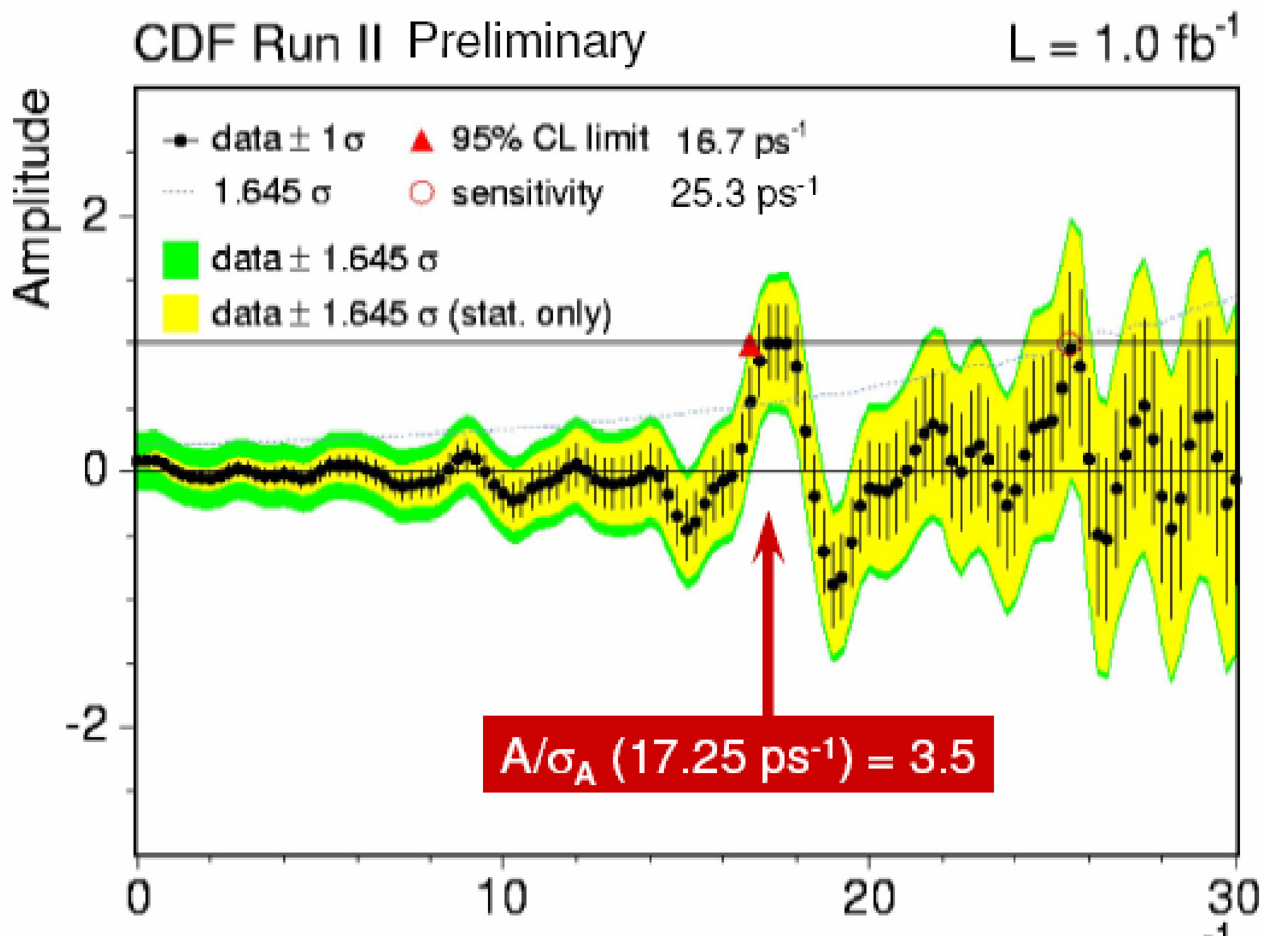
Sensitivity: 17.3 ps^{-1}
Δm_s> 15.9 ps^{-1} @ 95% CL

Sensitivity: 25 ps^{-1}
Δm_s> 16.7 ps^{-1} @ 95% CL

CDF Combined Amplitude Scan

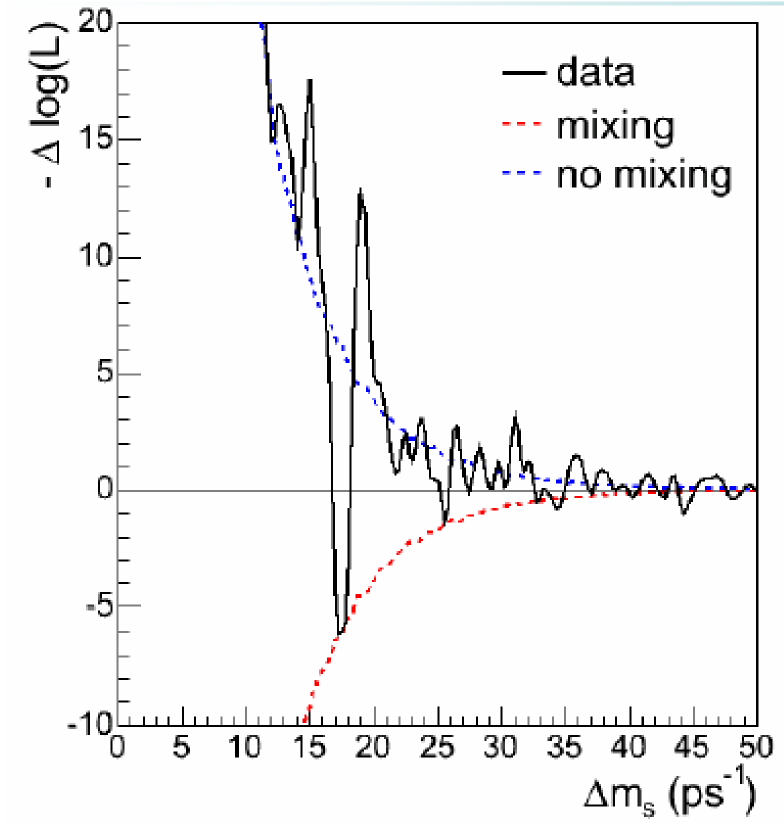
Sensitivity better than the W.A. 20.1 ps^{-1}

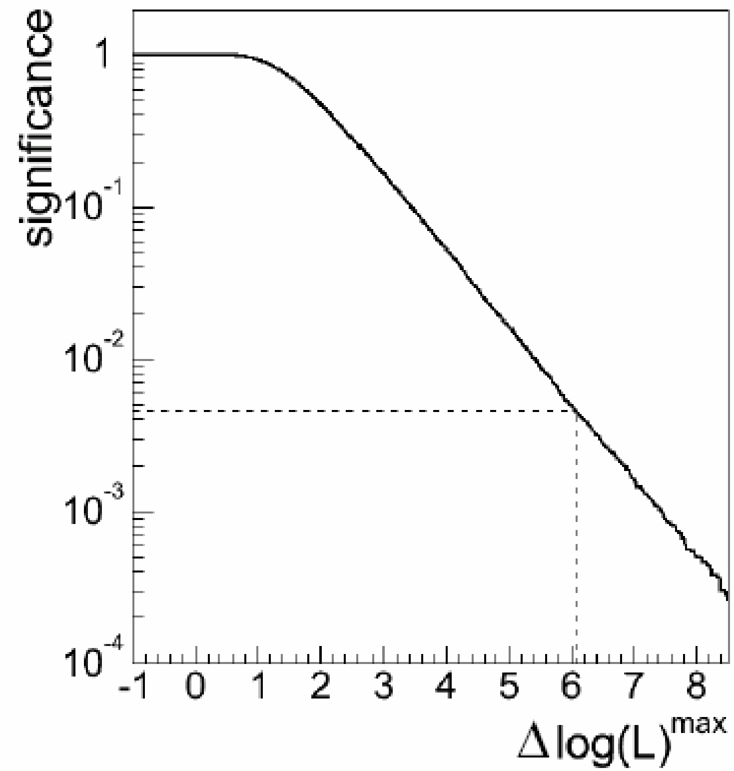
Rare case!!



How significant is this result?

Likelihood Profile & significance



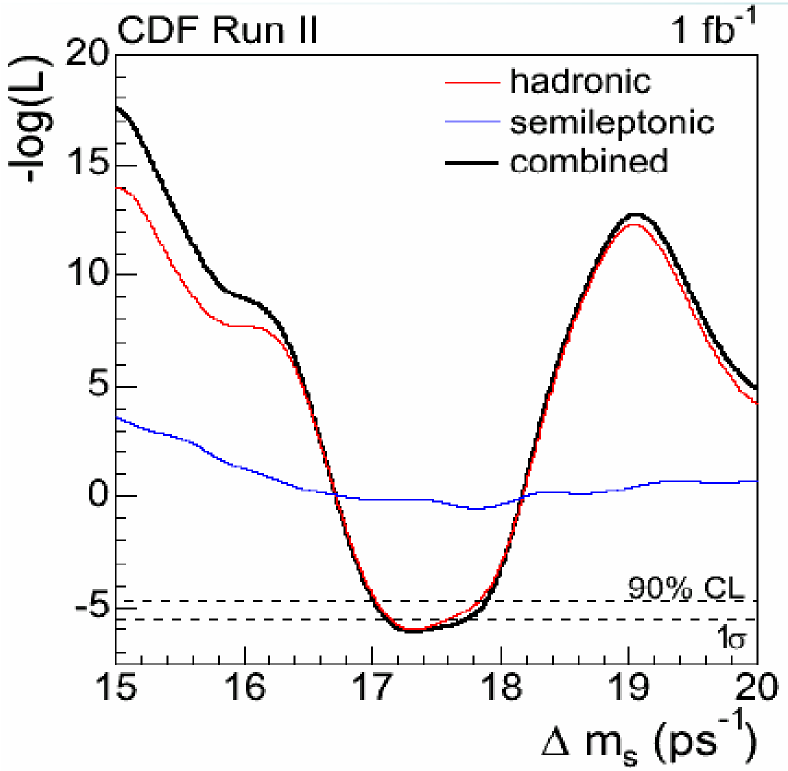


How often random tags produce a likelihood deep this dip?

Probability of fake: p-value=0.5%

Measure Δm_s !!!

Measurement of Δm_s



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

$17.00 < \Delta m_s < 17.91$ ps^{-1} at 90% C.L. $16.94 < \Delta m_s < 17.97$ ps^{-1} at 95% C.L.

$|V_{td}|/|V_{ts}|$ Determination

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{Bs}}{m_{Bd}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

Used as inputs:

- $m_{Bs}/m_{Bd} = 0.9830$ PDG 2006
- $\xi^2 = 1.210^{+0.47}_{-0.35}$ (M. Okamoto, hep-lat/0510113)
- $\Delta m_d = 0.507 \pm 0.005$ PDG 2006

$$|V_{td}|/|V_{ts}| = 0.208\ ^{+0.008}_{-0.007}\ \text{(stat.+syst.)}$$

Latest Belle result $b \rightarrow s\gamma$ (hep-ex/050679):

$$|V_{td}|/|V_{ts}| = 0.199\ ^{+0.026}_{-0.025}\ \text{(stat)}\ ^{+0.018}_{-0.015}\ \text{(syst)}$$

Conclusions

- 1 fb^{-1} of data used for Bs oscillation study
- D0:
  - 2.5σ deviation from 0 in the Amplitude Scan at Δm_s=19 ps^{-1}
  - 90% C.L. interval for Δm_s: 17-21 ps^{-1}
  - For the summer:
    - Include $D_s \rightarrow K^*K$, $D_s \rightarrow K_s K$ $D_s \rightarrow 3\pi$ and $e+D_s$
    - Include hadronic decays
    - Include Same Side Tagging

Conclusions cont'd

- CDF:
  - experimental signature for B_s-B_s oscillations
  - Probability of random fluctuation is 0.5%
  - First direct measurement of:

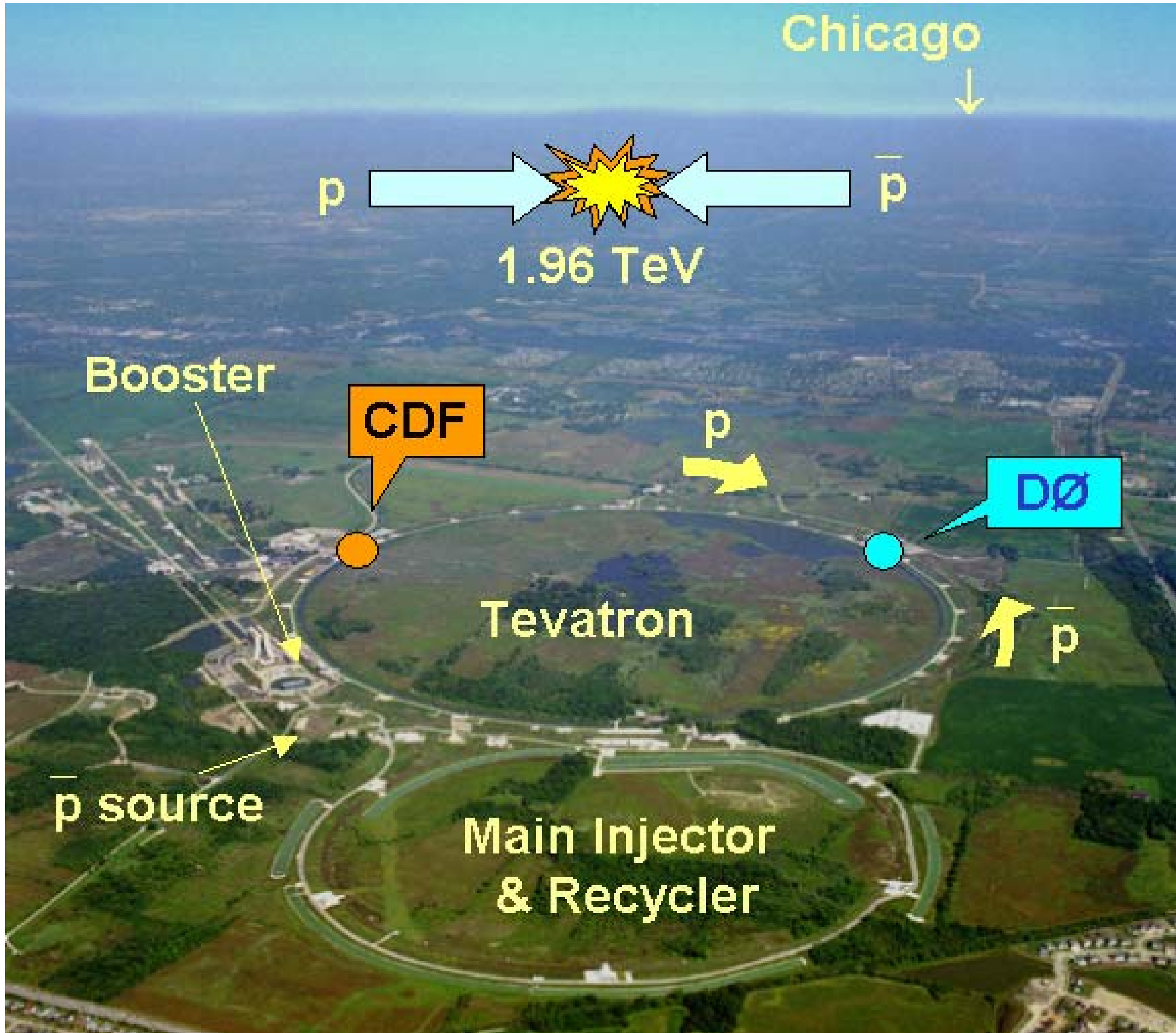
$$\Delta m_s = 17.33^{+0.42}_{-0.21} \pm 0.07\ \mathrm{ps}^{-1}$$

$$|V_{td}|/|V_{ts}| = 0.208^{+0.008}_{-0.007}\ \text{(stat.+syst.)}$$

- Future:
  - Include other decays (Partially recon. $D_s^* \rightarrow D_s\gamma/\rho$)
  - Combine efficiently flavor tags
  - Improve ct resolution

BACKUP

The Accelerator

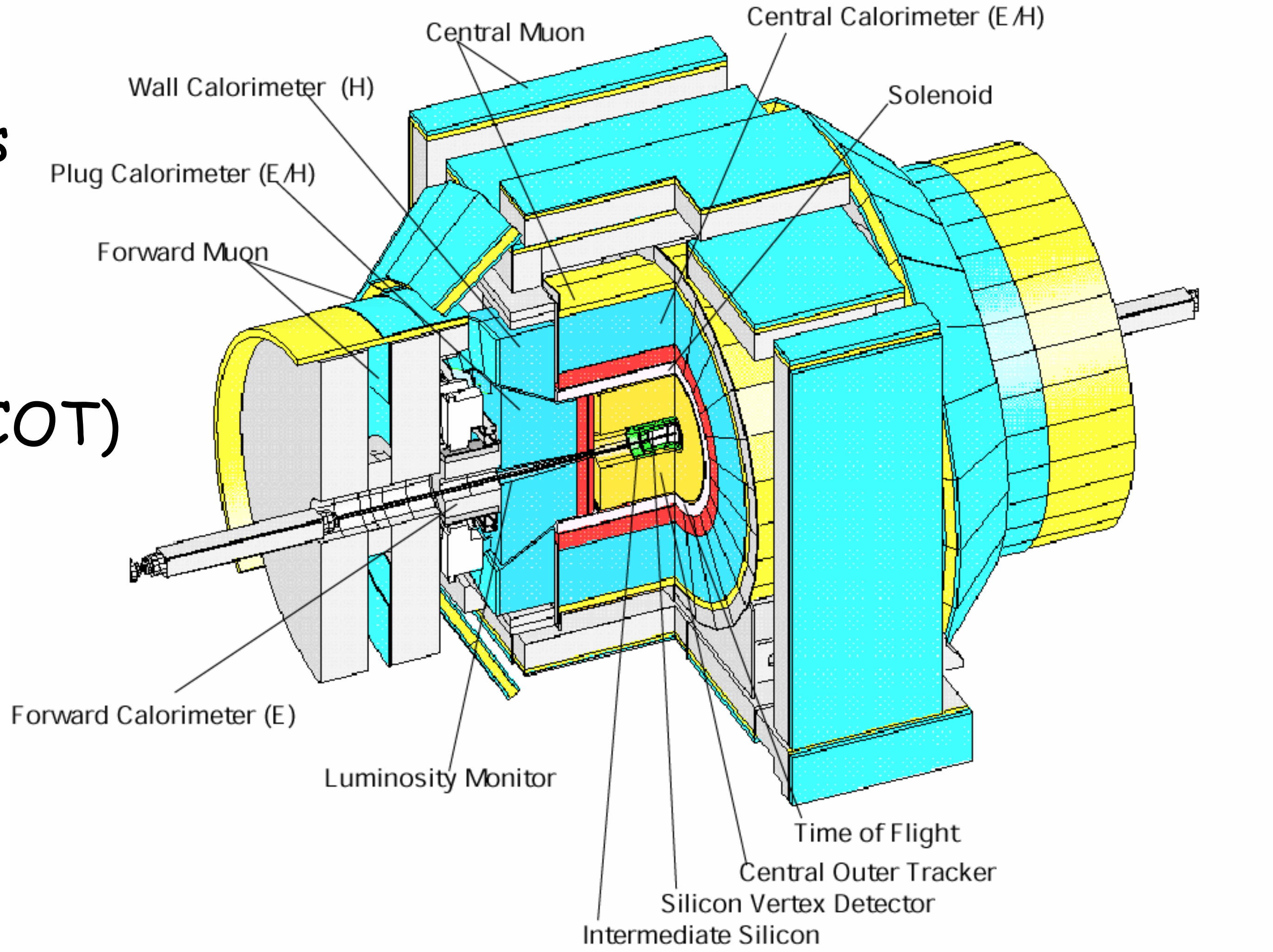


Detector for the measurement: CDF

Trigger:
displaced tracks (SVT)

Tagging Power:
TOF & dE/dX (COT)

Proper time Resolution:
SVX and L00

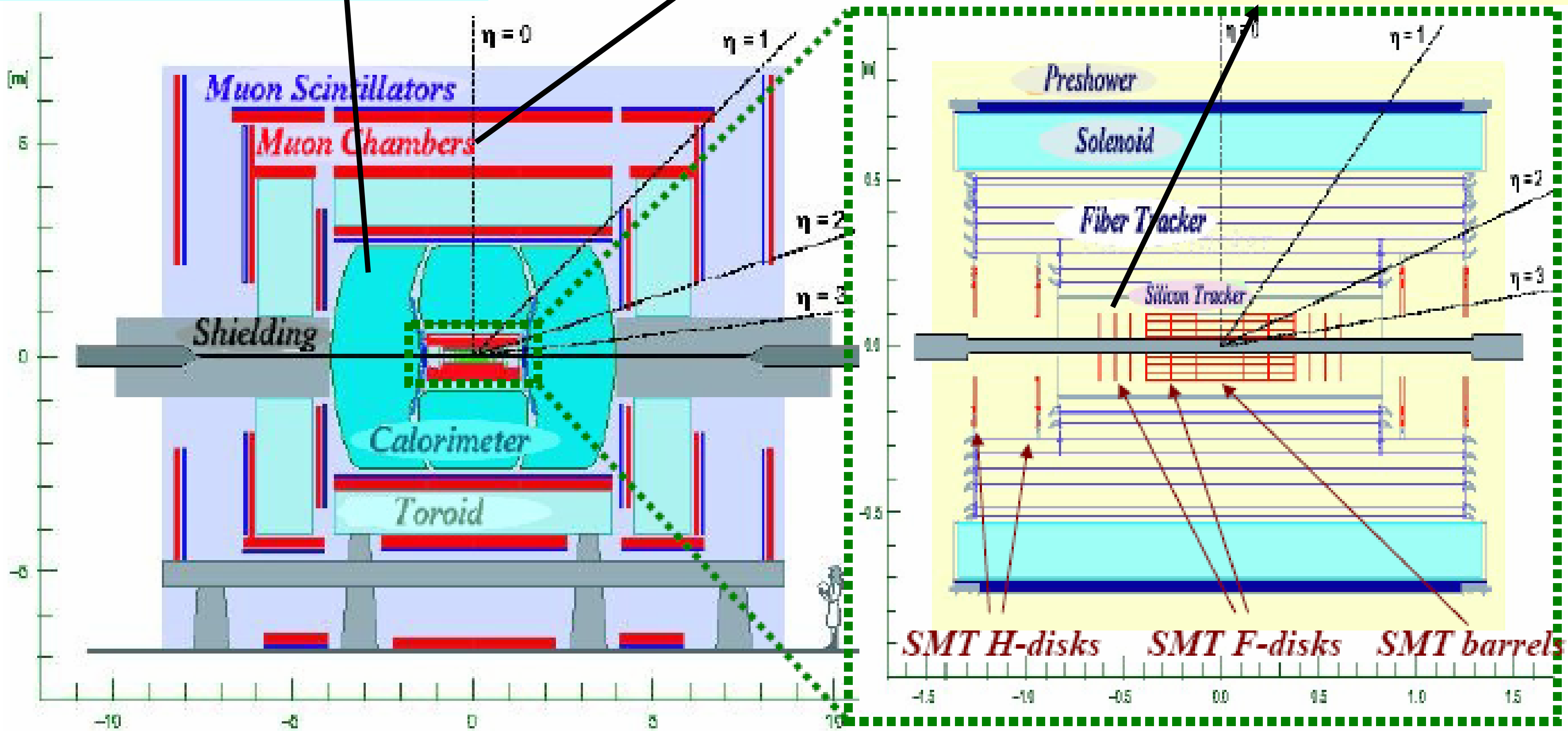


Detector for the measurement: D0

Fine segmentation Liquid Ar Calorimeter & Preshower

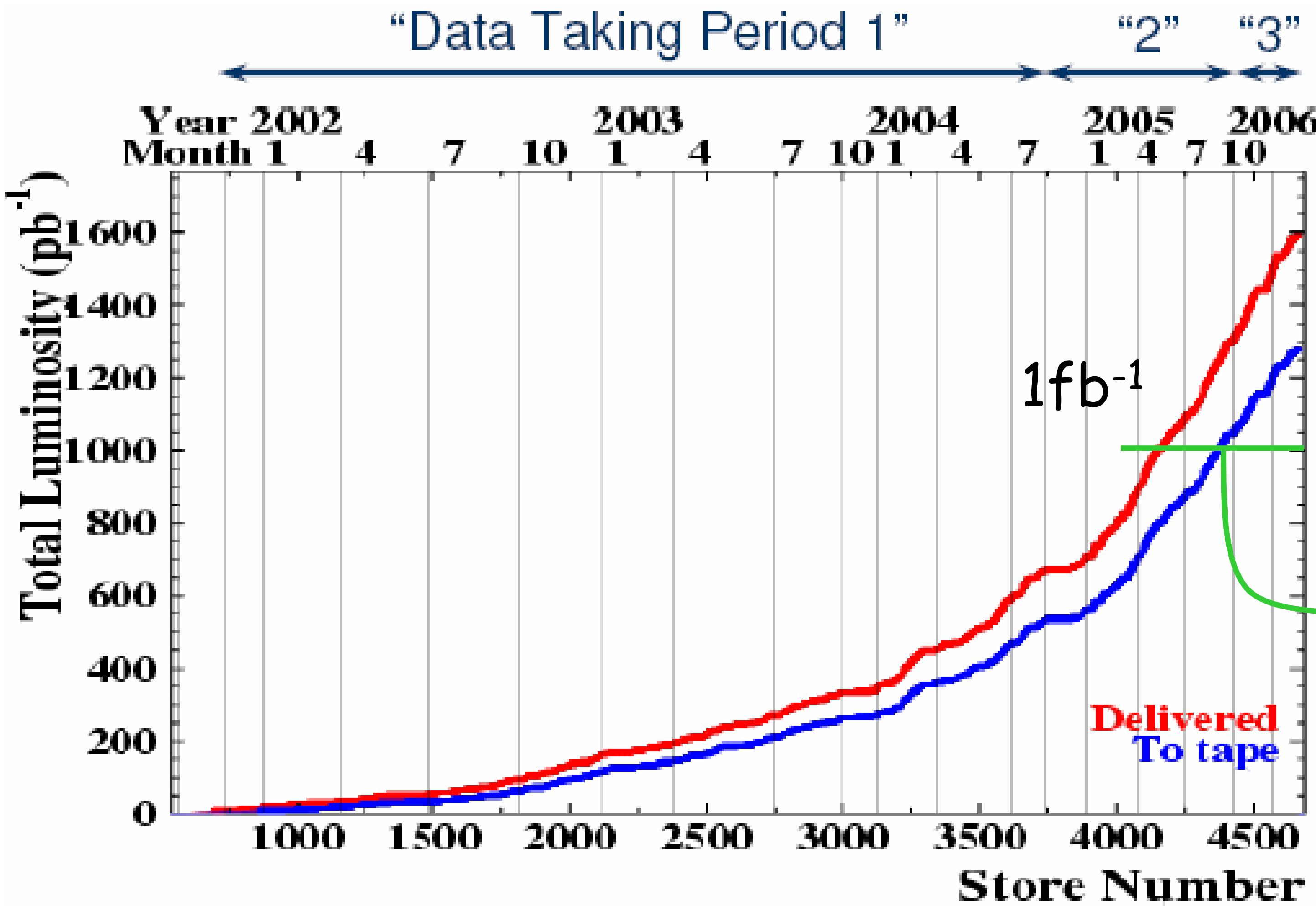
Three layers system & absorber

Fiber and Silicon trackers in 2T Solenoid field



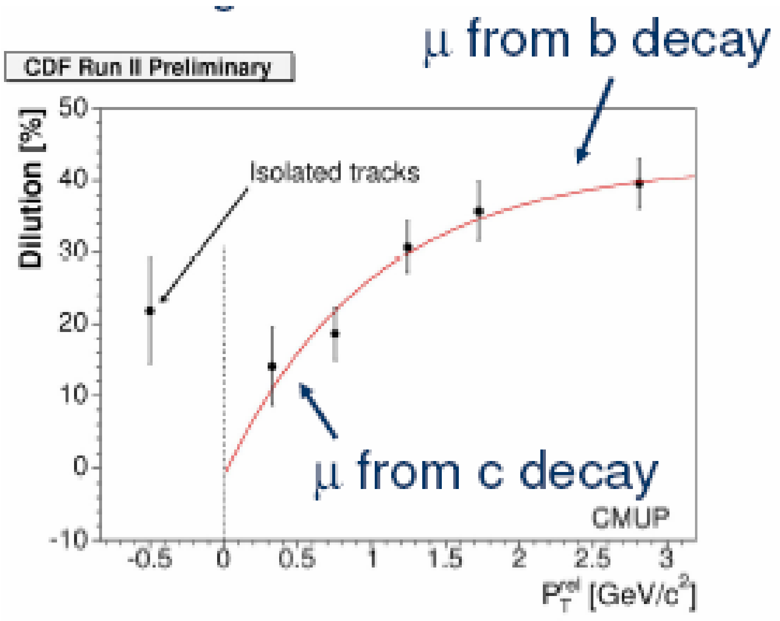
Hermetic detector

Tevatron Luminosity



Used in the analysis

Parametrizing tag decision



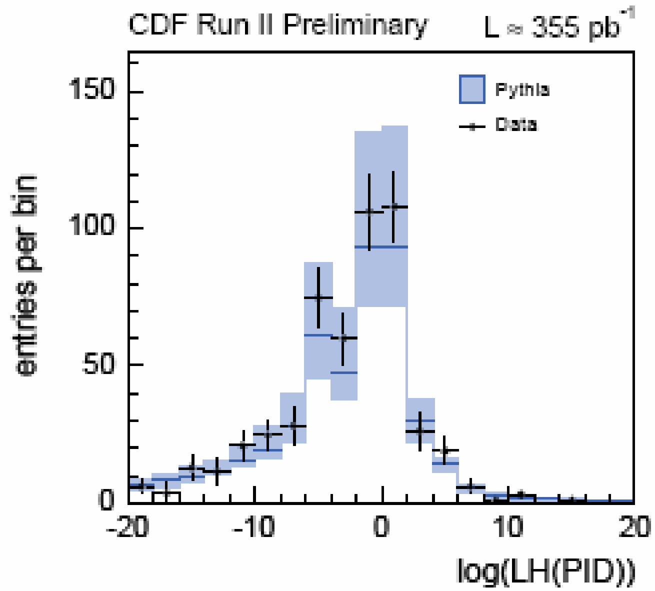
Opposite Side Taggers calibrated in our very high statistics $\ell + SVT$ samples
Dependence on several variables used to increase the tagging power

Overall scale factor measured on $B^{0/+}$ candidates to take care a possible overall (small) shift

Similar performace of semileptonic hadronic modes

Calibrating SSTK

Small discrepancies covered by systematics



Systematic studies cover:

- Fragmentation Model
- *bb* Production Mechanisms
- B^{**} content
- Detector/PID resolution
- Multiple interactions
- PID content around *B*
- Data/MC agreement

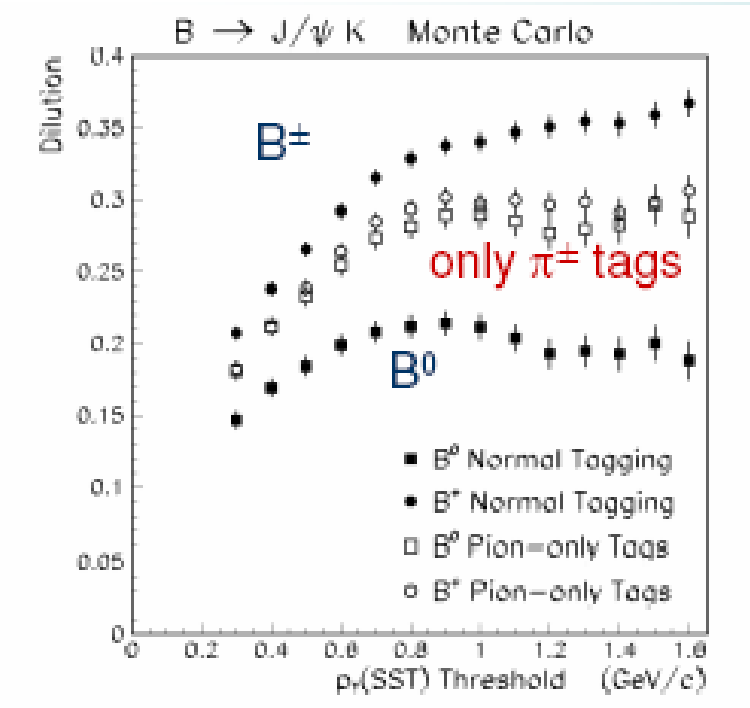
Select the most likely kaon track (PID *) as tagging track

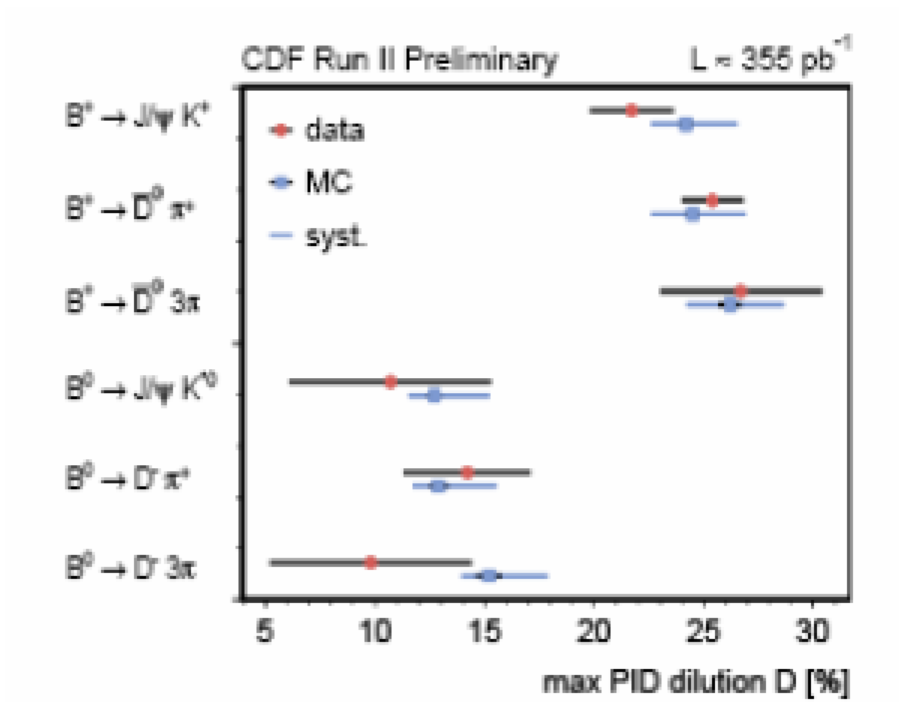
SS(K)T performance estimated from MC:

$\varepsilon D^2(B_s \to D_s(\phi\pi)\pi) = 4.0^{+0.8}_{-1.2}\%$ (1rst period of the data)

*) TOF & dE/dx are used for particle identification

Calibrating SSTK





Tune MC to reproduce $B^{0/\pm}$ dilution and then measure it for SSTK

D0 Procedure

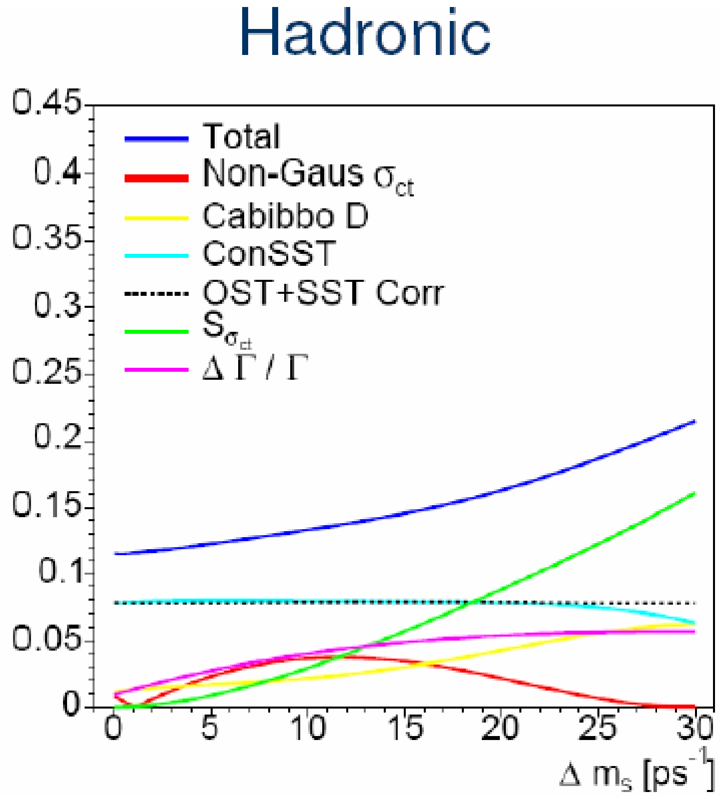
$$p_s^{\mathrm{nos/osc}}(l, K, d_{\mathrm{tag}}) = \frac{K}{c\tau_{B_s^0}} \exp\left(-\frac{Kl}{c\tau_{B_s^0}}\right)[1 \pm \mathcal{D}(d_{\mathrm{tag}}) \cos(\Delta m_s \cdot Kl/c)]/2.$$

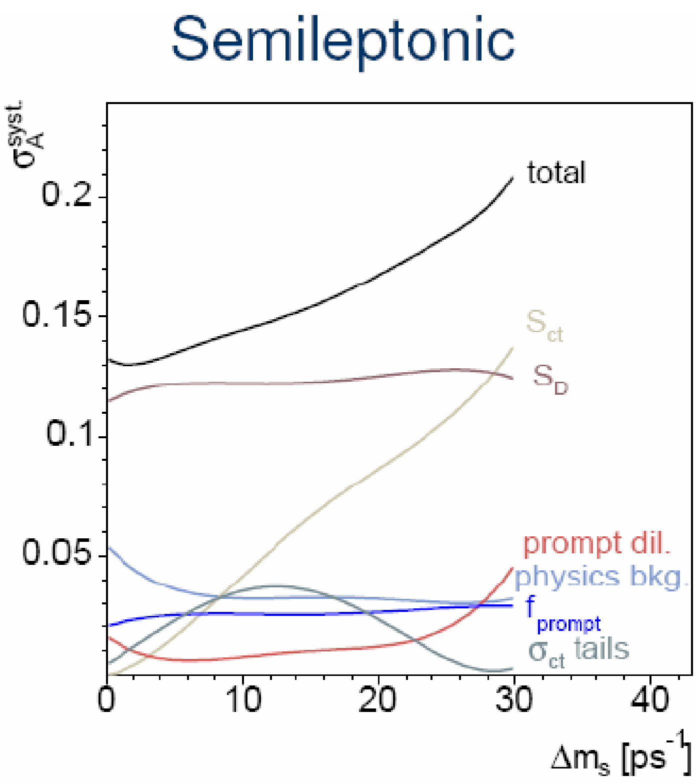
Correction factor due to missing neutrino

Several effects taken into account:

- Resolution scale factor for detector mismodeling
- Reconstruction efficiency as function of decay length
- Physical and combinatorial background contributions

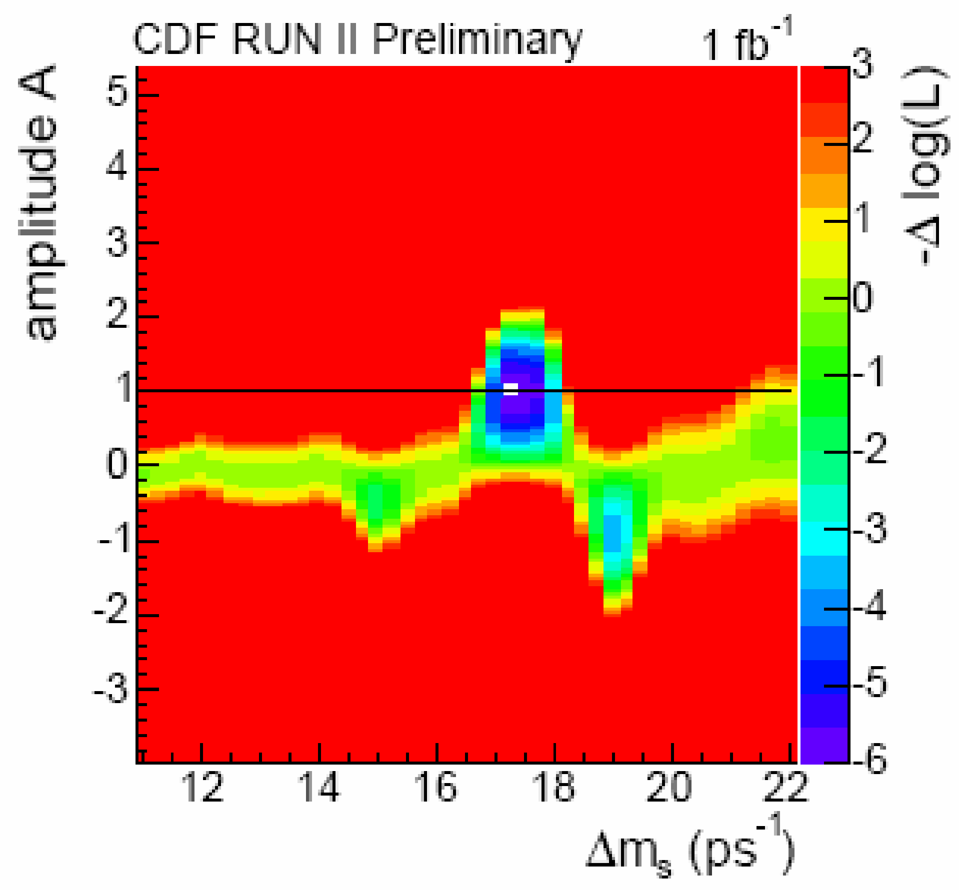
Systematic Uncertainties Amplitude Scan





Related to absolute value of *A* important when setting a limit
Cancel out in A/σ_A
Very small compared to statistical error

Combined Amplitude Scan: an other view



Systematic Uncertainties on Δm_s

	Syst. Unc
SVX Alignment	0.04 ps^{-1}
Track Fit Bias	0.05 ps^{-1}
PV bias from tagging	0.02 ps^{-1}
All Other Sys	< 0.01ps^{-1}
Total	0.07 ps^{-1}

Fit Model: negligible

Relevant only lifetime scale