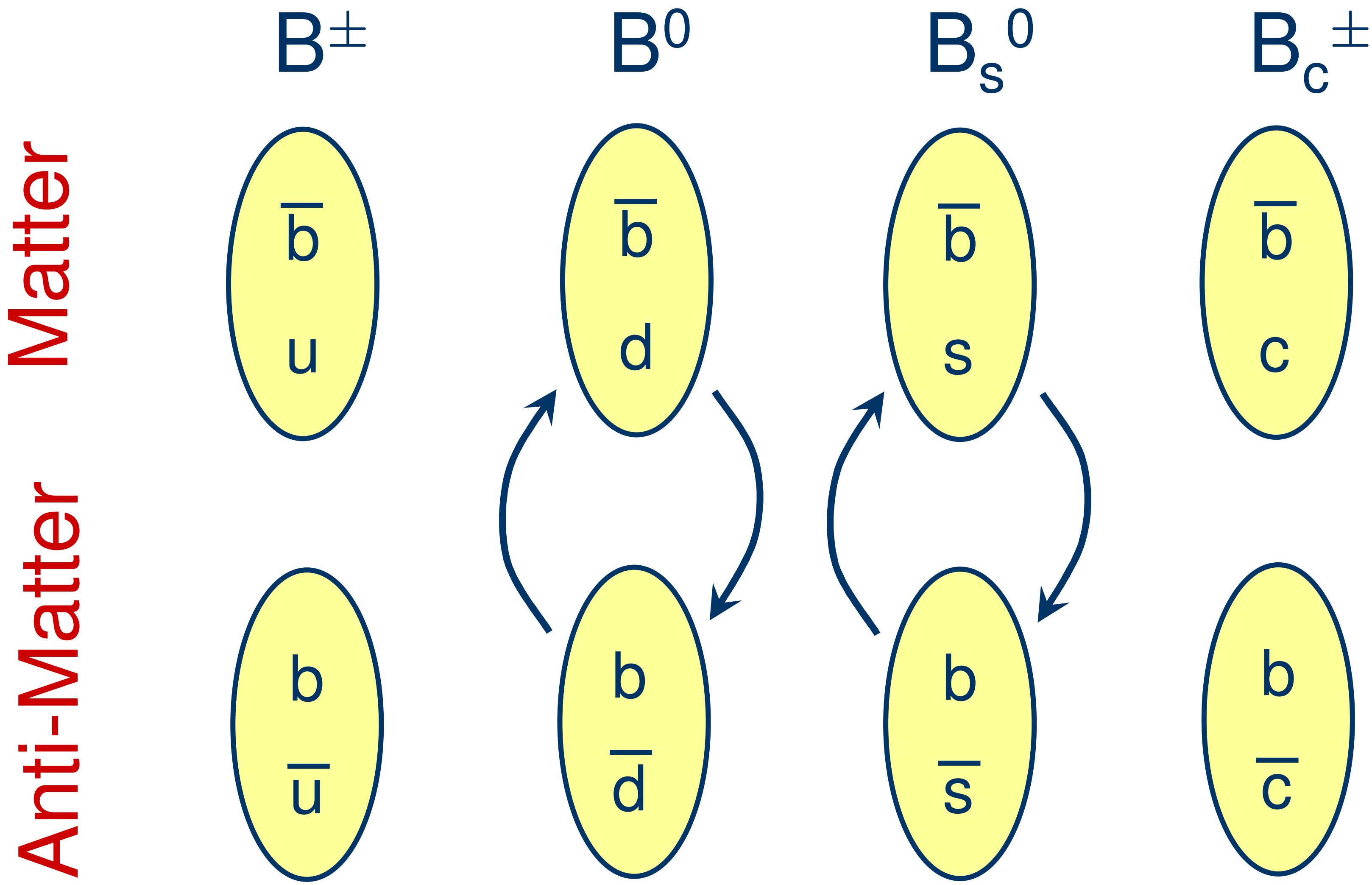
Measurement of the $B_s^0 - \overline{B_s}^0$ Oscillation Frequency and the Ratio $|V_{td}/V_{ts}|$ at CDF

Ivan K. Furić
EFI, University of Chicago

for the CDF Collaboration

B Mesons


$B^{\pm}$
B^0
B_s^0
$B_c^{\pm}$
Matter
Anti-Matter
$\bar{b}$ u
$\bar{b}$ d
$\bar{b}$ s
$\bar{b}$ c
b $\bar{u}$
b $\bar{d}$
b $\bar{s}$
b $\bar{c}$

B Mixing

- Neutral B Meson system

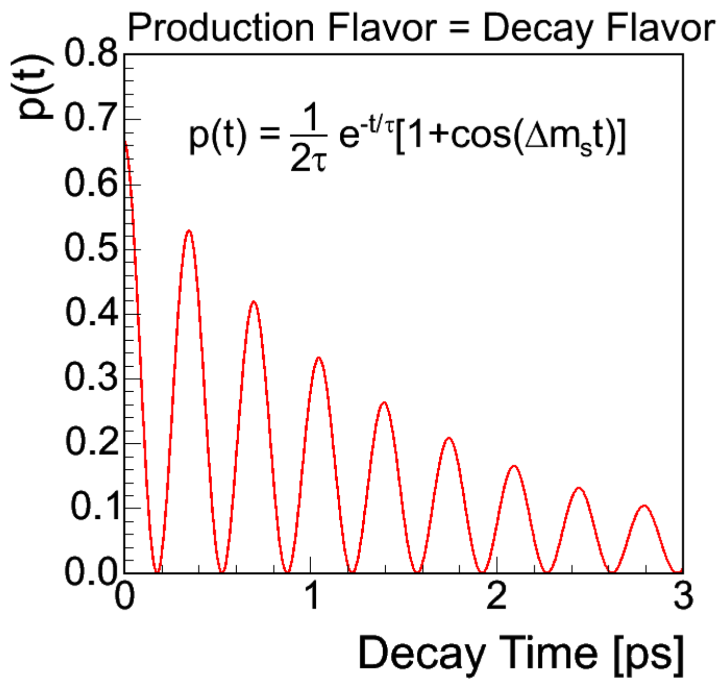
$$|B>=(\bar{b}s);\ |\overline{B}>=(b\bar{s})$$

mixture of two mass eigenstates (No CP violation case):

$$|B_H\rangle = \frac{1}{\sqrt{2}}\left(|B\rangle + |\overline{B}\rangle\right)$$

$$|B_L\rangle = \frac{1}{\sqrt{2}}\left(|B\rangle - |\overline{B}\rangle\right)$$

- B_H and B_L may have different mass and decay width
  - $\Delta m = M_H - M_L$ (>0 by definition)
  - $\Delta\Gamma = \Gamma_H - \Gamma_L$



- The case of $\Delta\Gamma = 0$

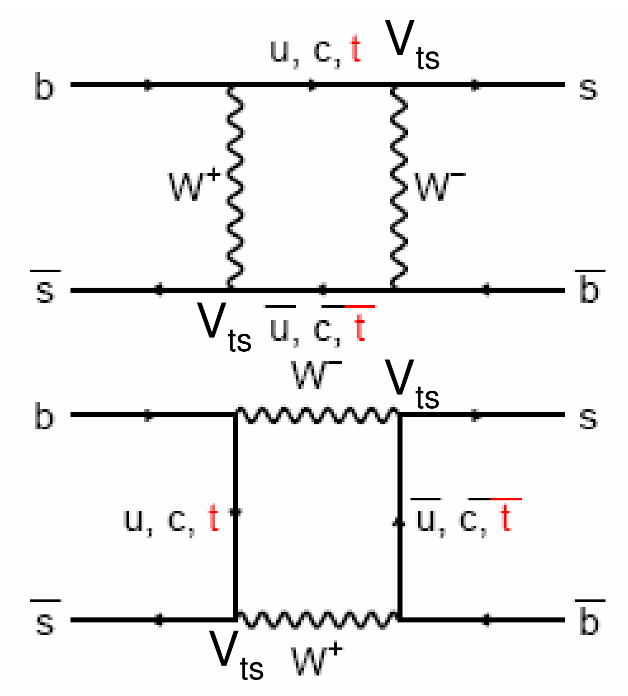
$$p(B\to B) = \frac{e^{-t/\tau}}{2\tau}(1+\cos\Delta m t)$$

$$p(B\to \overline{B}) = \frac{e^{-t/\tau}}{2\tau}(1-\cos\Delta m t)$$

Standard Model Prediction

CKM Matrix Wolfenstein parameterization

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



Ratio of frequencies for B^0 and B_s

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

$\xi = 1.210^{+0.047}_{-0.035}$ from lattice QCD

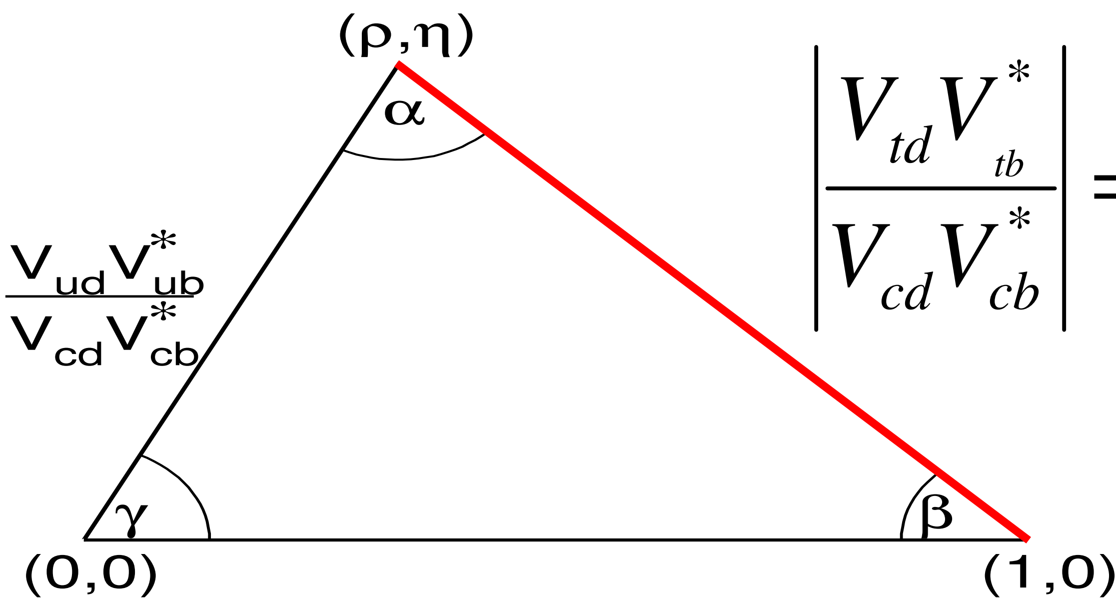
(hep/lat-0510113)

$V_{ts} \sim \lambda^2$, $V_{td} \sim \lambda^3$, $\lambda = 0.224 \pm 0.012$

Unitarity Triangle

CKM Matrix Unitarity Condition

$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

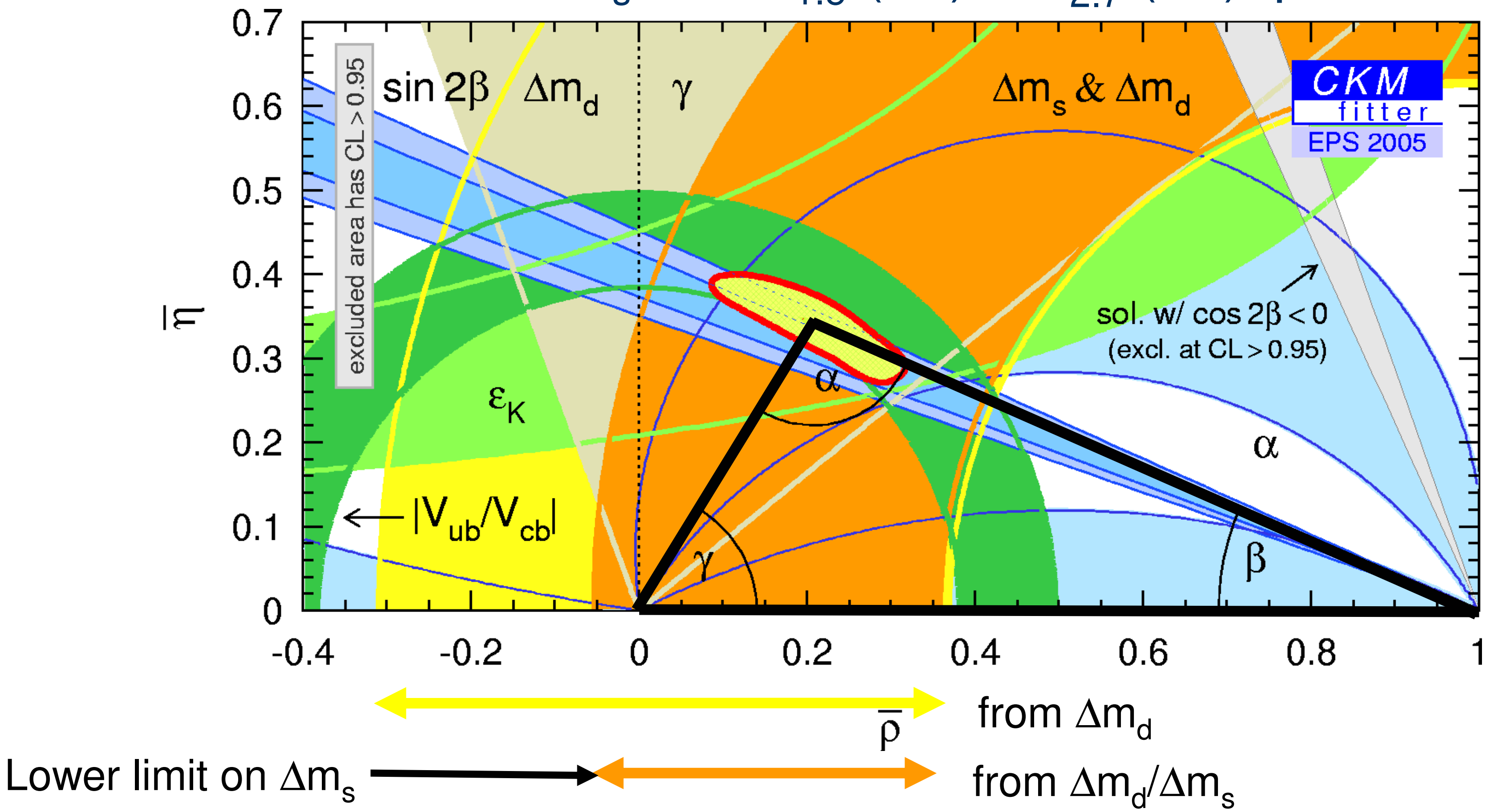


$$\left|\frac{V_{td}V_{tb}^{*}}{V_{cd}V_{cb}^{*}}\right| = \frac{|V_{td}|}{|V_{ts}|} \times \frac{1}{|V_{cd}|}$$

$$\sim \frac{\Delta m_d}{\Delta m_s}$$

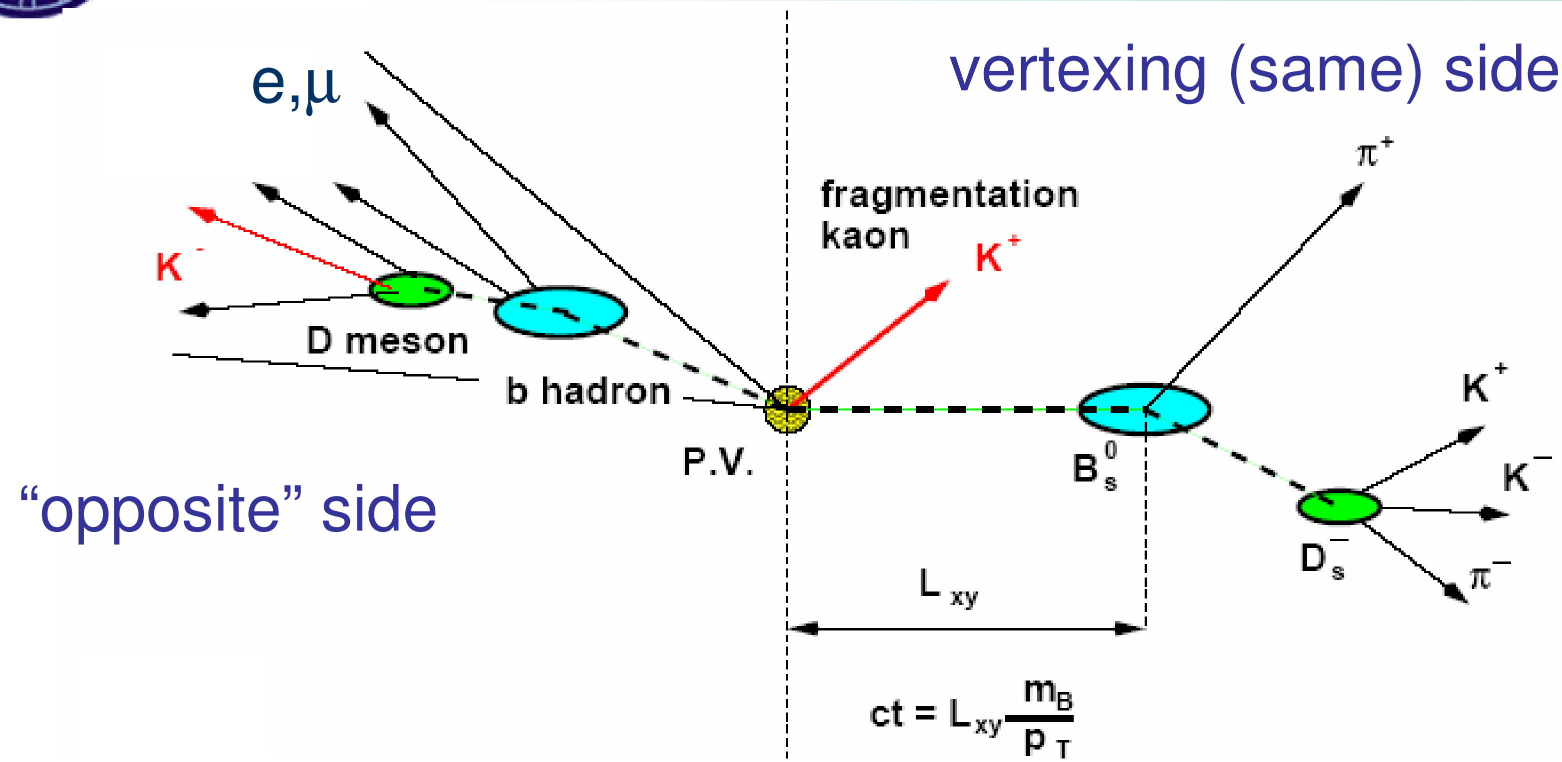
Unitarity Triangle Fit

- just for illustration, other fits exist
- CKM Fit result: Δm_s: $18.3^{+6.5}_{-1.5}$ (1σ) : $^{+11.4}_{-2.7}$ (2σ) ps^{-1}



Measurement Principle

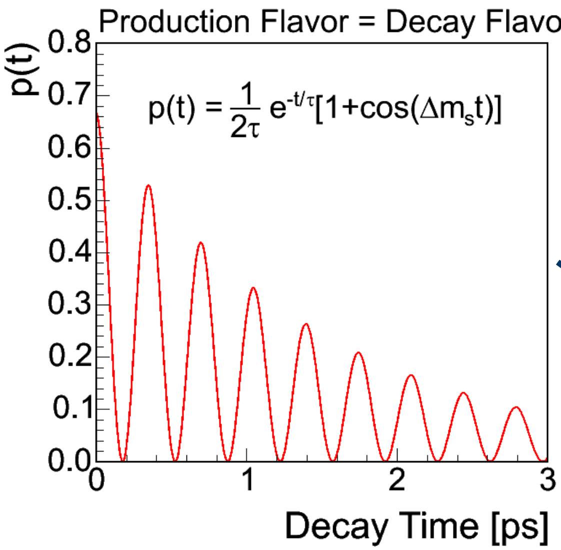
The "Big" Picture



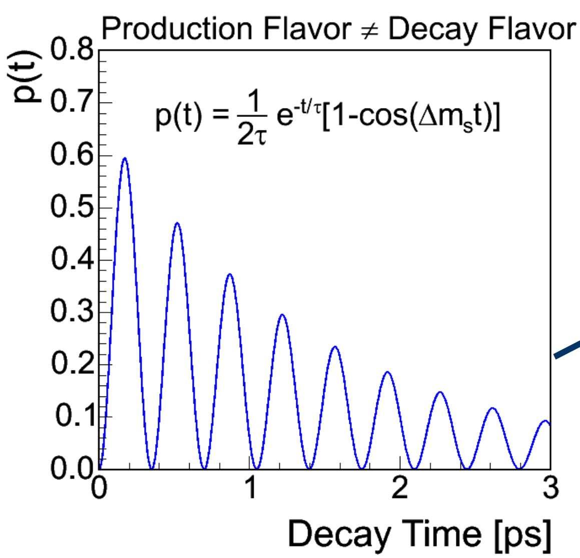
- reconstruct B_s decays $\rightarrow$ decay flavor from decay products
- measure proper time of the decay (very precisely)
- infer B_s production flavor (production flavor tagging)

Measurement .. In a Perfect World

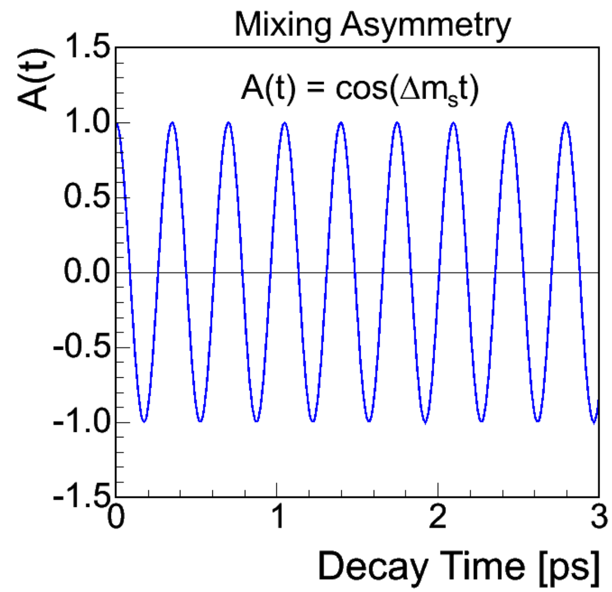
"Right Sign"



"Wrong Sign"



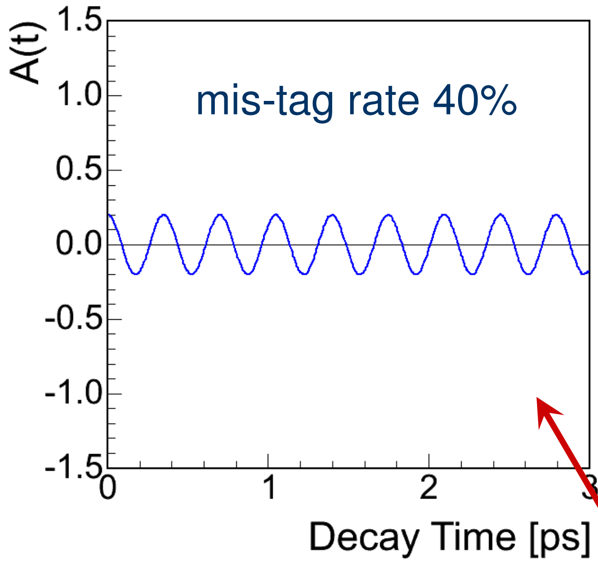
$$A(t) = \frac{N_{RS} - N_{WS}}{N_{RS} + N_{WS}}$$



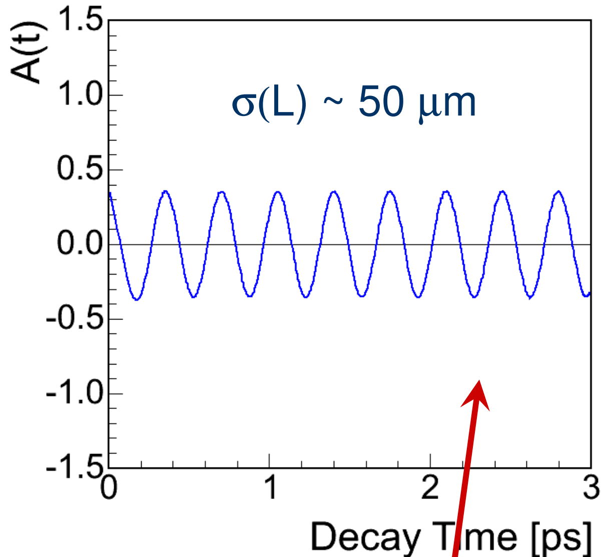
what about detector effects?

Realistic Effects

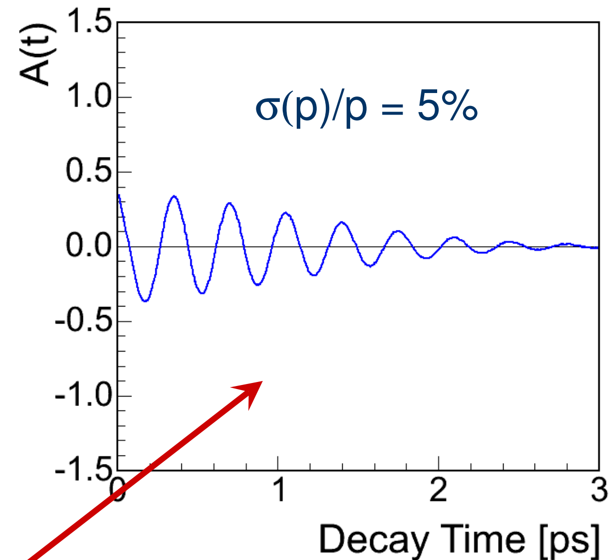
flavor tagging power, background



displacement resolution

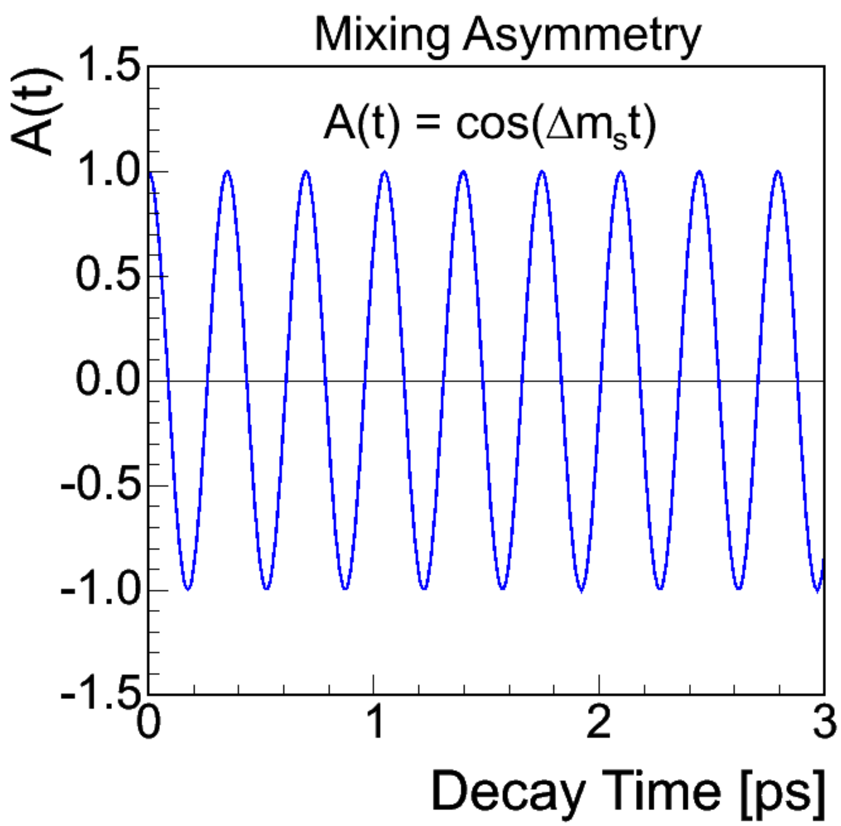


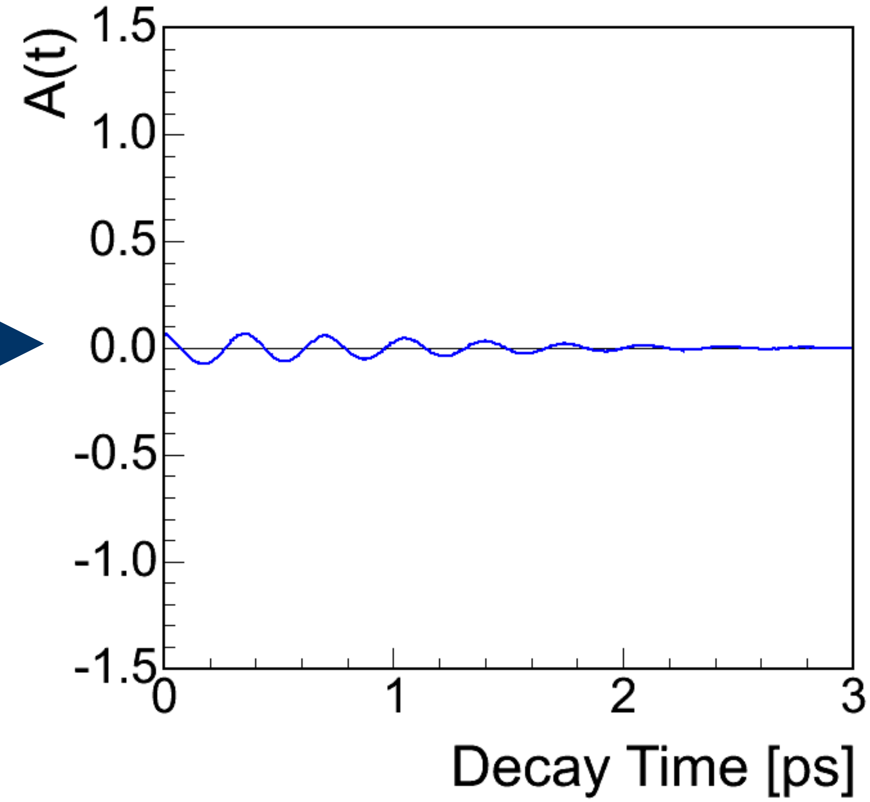
momentum resolution



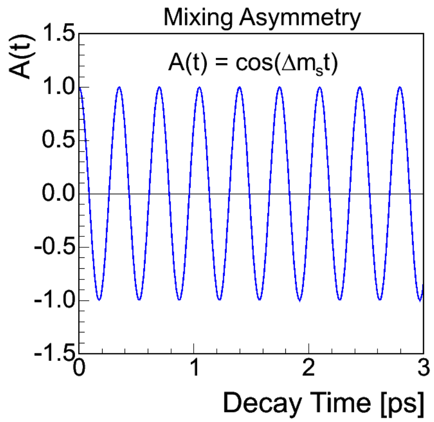
$$\frac{1}{\sigma} = \sqrt{\frac{S\epsilon D^2}{2}}\, e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

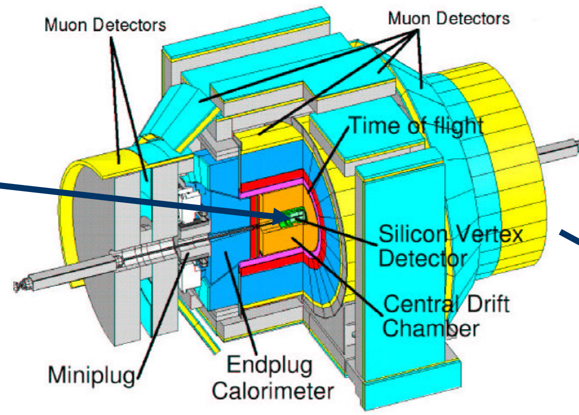
All Effects Together



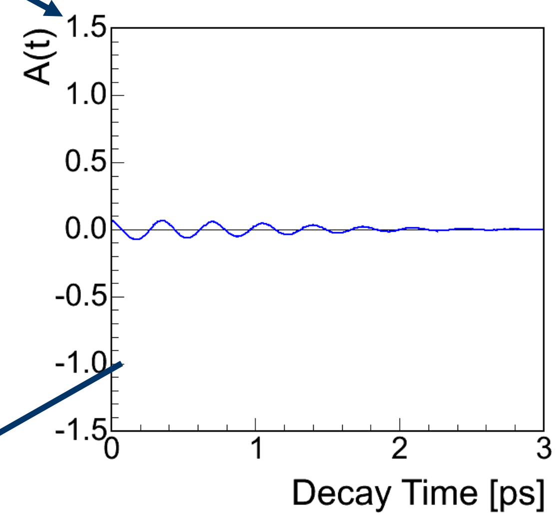


Real Measurement Layout





Data



momentum resolution
displacement resolution
flavor tagging power

scan for signal:

$A(\Delta m_s = 15\ ps^{-1}) = ?$

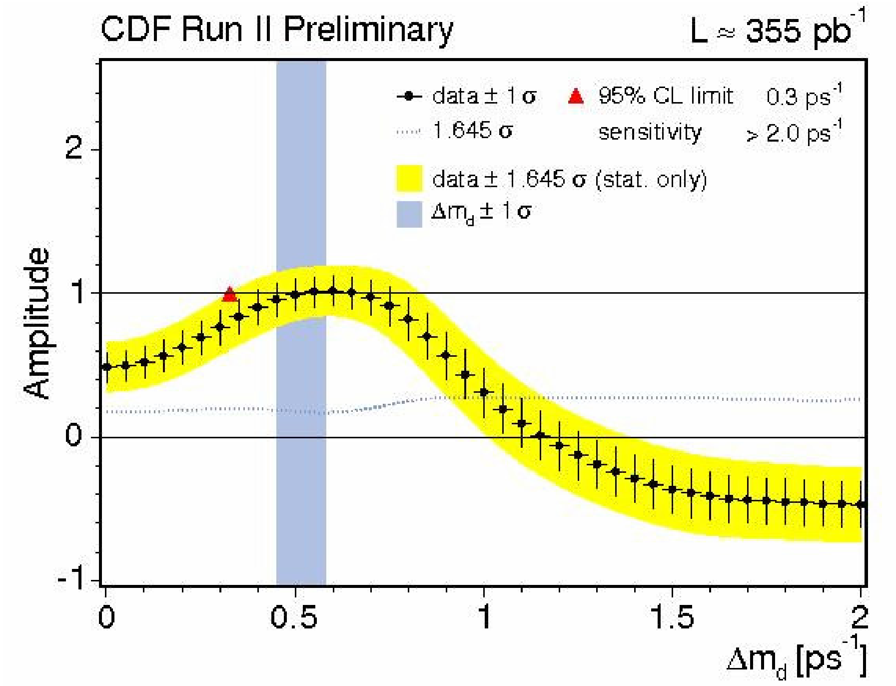
Unbinned Likelihood Fitter

$p \sim e^{-t/\tau}[1 \pm AD\cos\Delta mt] \otimes R(t)$

measure frequency:

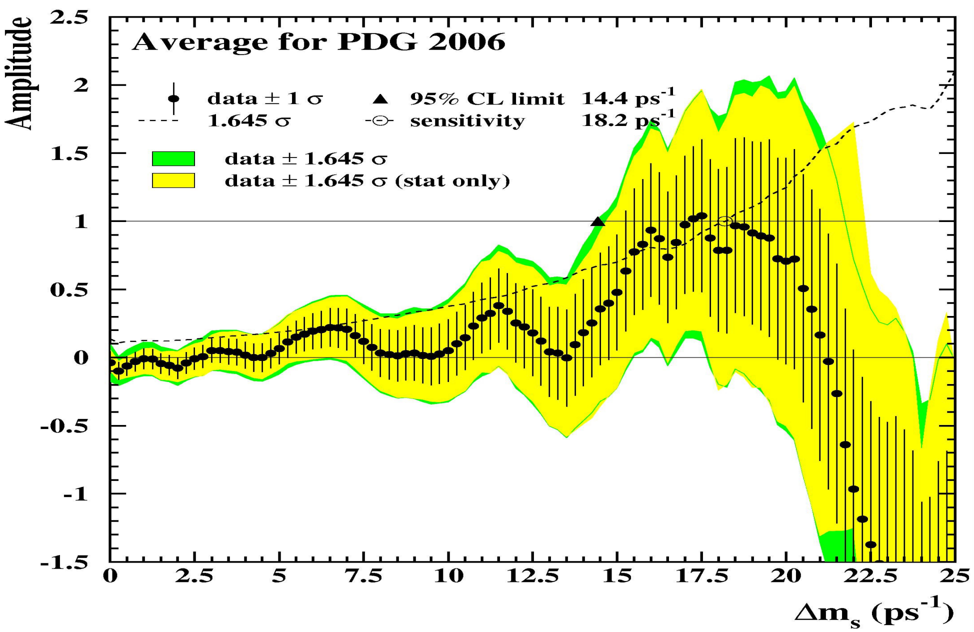
$\Delta m_s = ?$

Scanning for Signals

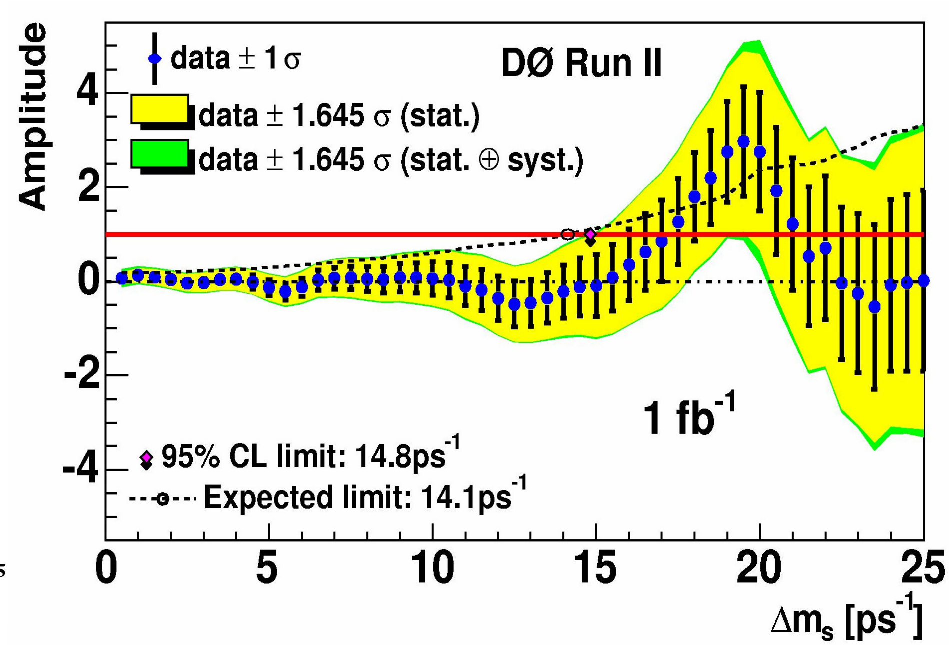


- fixed value of Δm_s, fit for Amplitude
- repeat for different values of Δm_s
- Signal: A ~ 1, Background: A ~ 0
- if a signal is found, fit for mixing frequency!

World Knowledge on Δm_s



PDG 2006

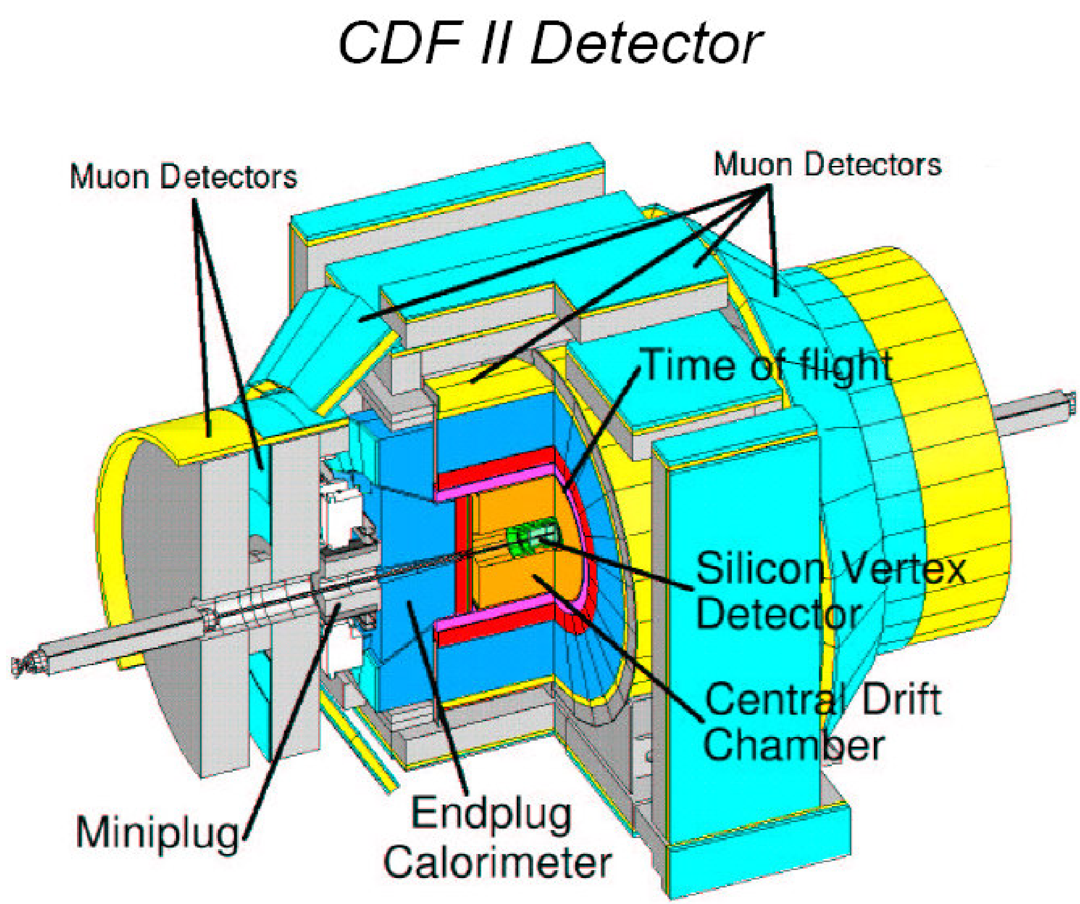


Recent D0 Result

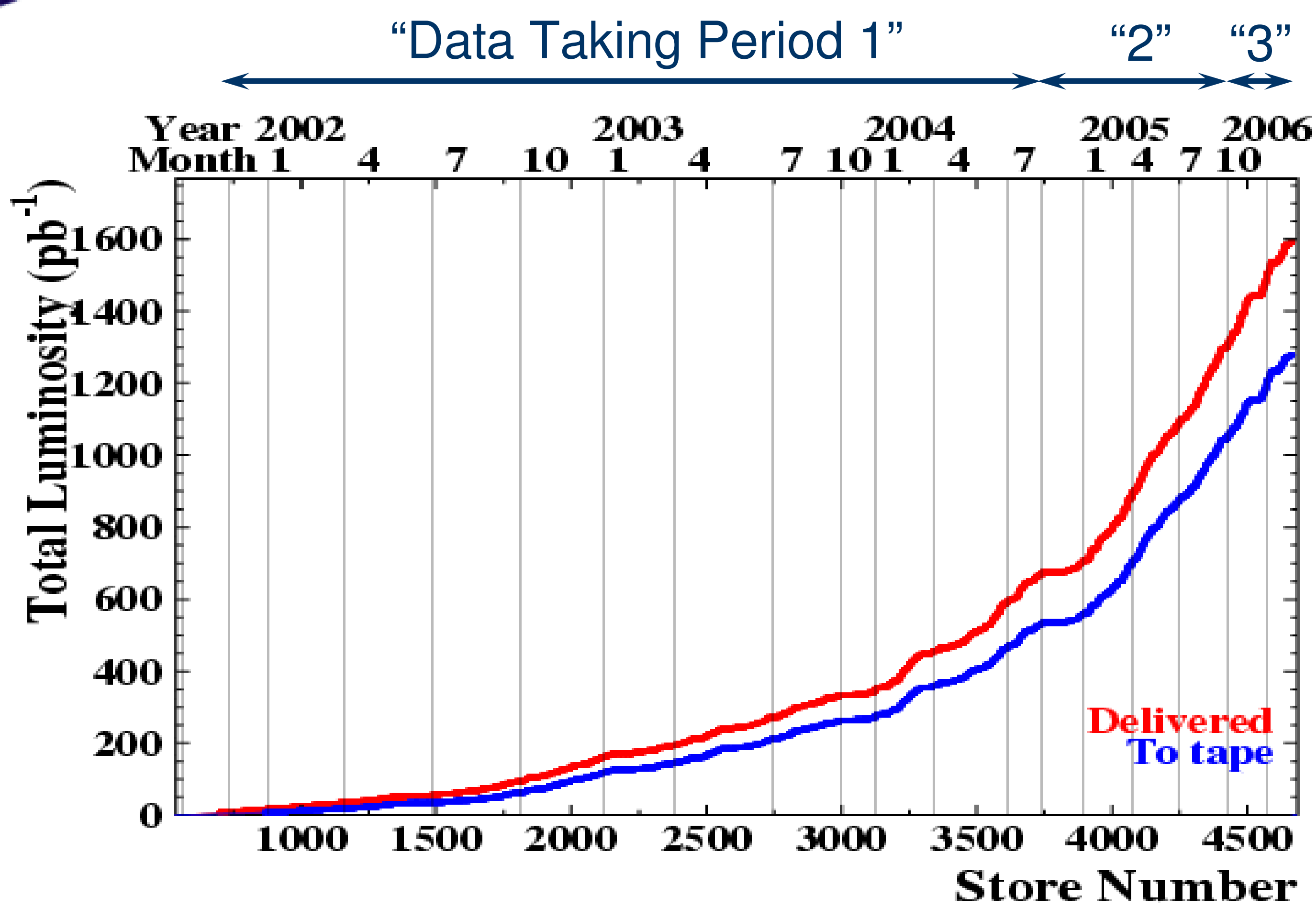
Samples of B_s Decays

The CDFII Detector

- multi-purpose detector
- excellent momentum resolution $\sigma(p)/p<0.1\%$
- Yield:
  - SVT based triggers
- Tagging power:
  - TOF, dE/dX in COT
- Proper time resolution:
  - SVXII, L00



Tevatron Luminosity



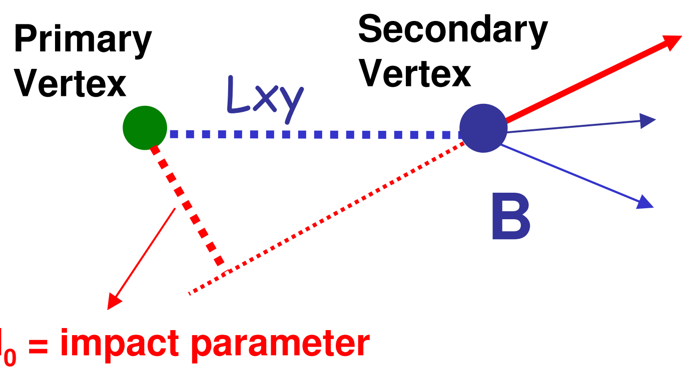
- Delivered Lum. >1 fb^{-1}
- This analysis: Feb 2002 – Jan 2006 → 1 fb^{-1}

Celebration of the first 1 fb Delivered to CDF!

Thank You Accelerator Division

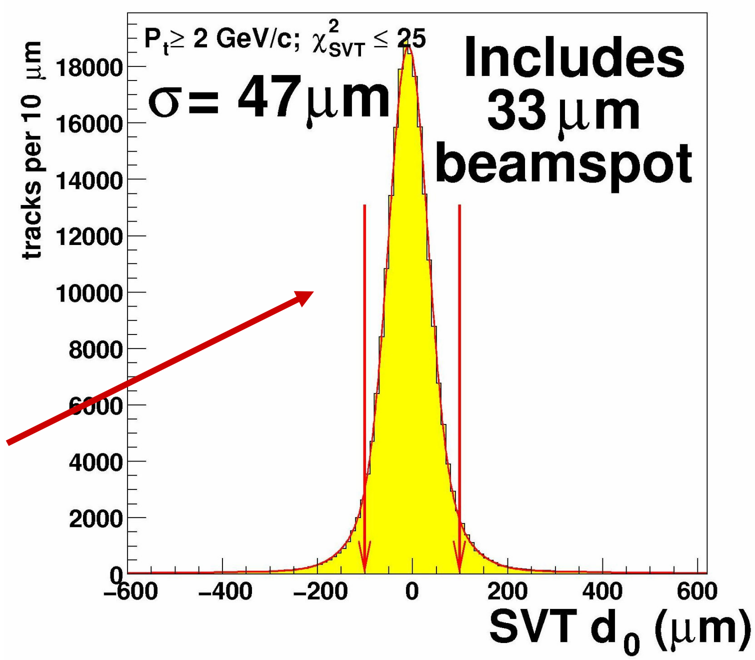
Triggering On Displaced Tracks

- trigger $B_s \to D_s^-\pi$, $B_s \to D_s^- l^+$

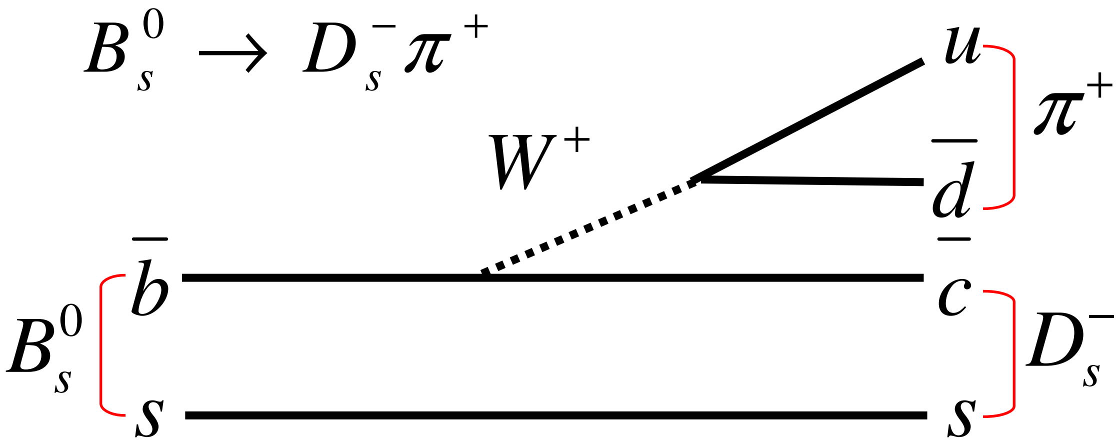


- trigger extracts 20 TB /sec
- "unusual" trigger requirement:
  - two displaced tracks:

  (p_T > 2 GeV/c, 120 μm<$|d_0|$<1mm)
- requires precision tracking in SVX



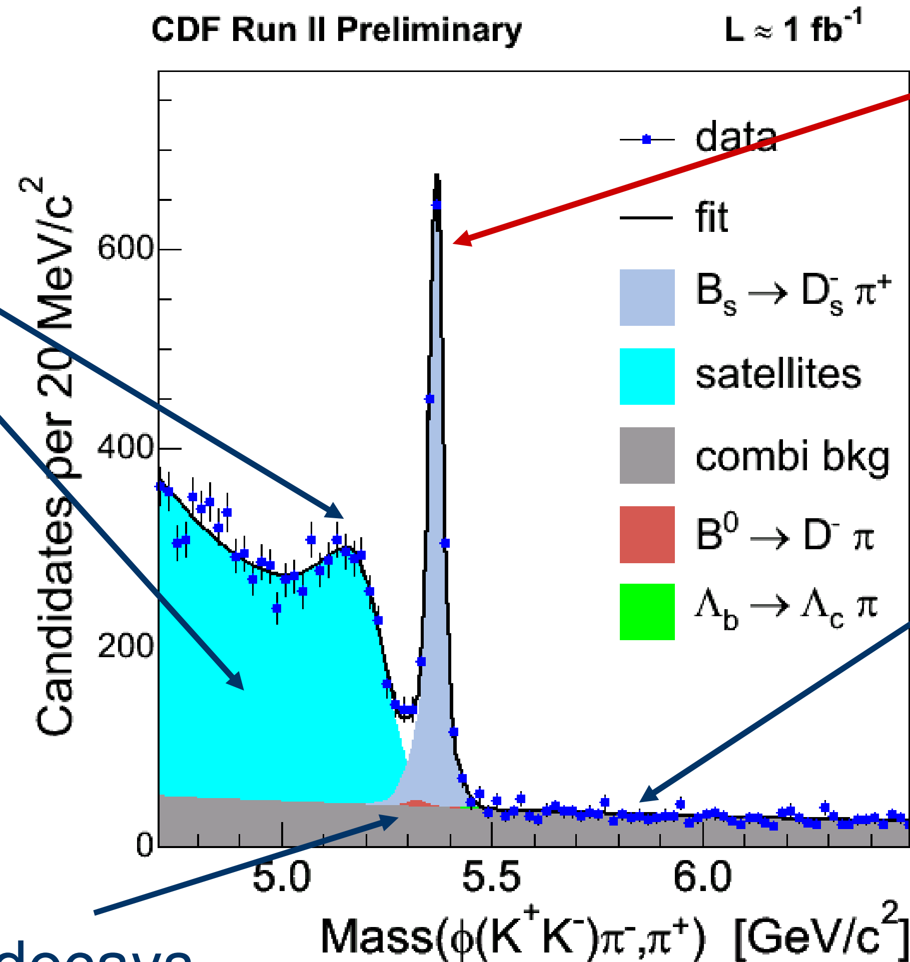
Hadronic B_s Decays



- relatively small signal yields (few thousand decays)
- momentum completely contained in tracker
- superior sensitivity at higher Δm_s

Example Mass Spectrum

partially reconstructed B mesons (satellites)



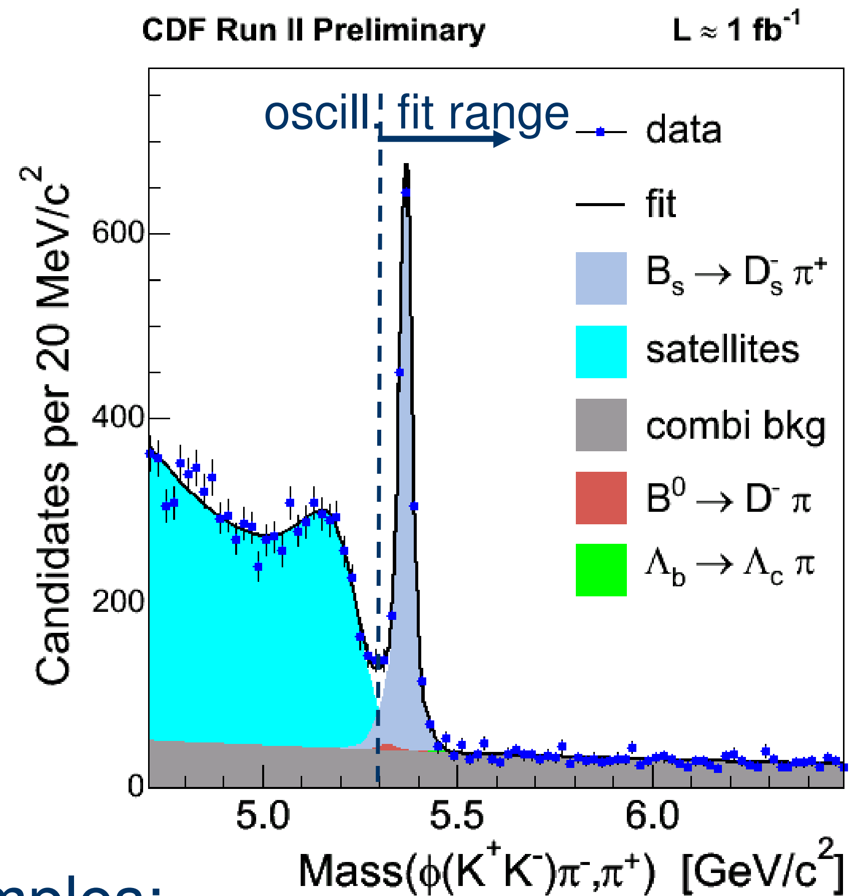
signal
$B_s \rightarrow D_s\pi$,
$D_s \rightarrow \phi\pi$,
$\phi \rightarrow K^+K^-$

combinatorial background

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

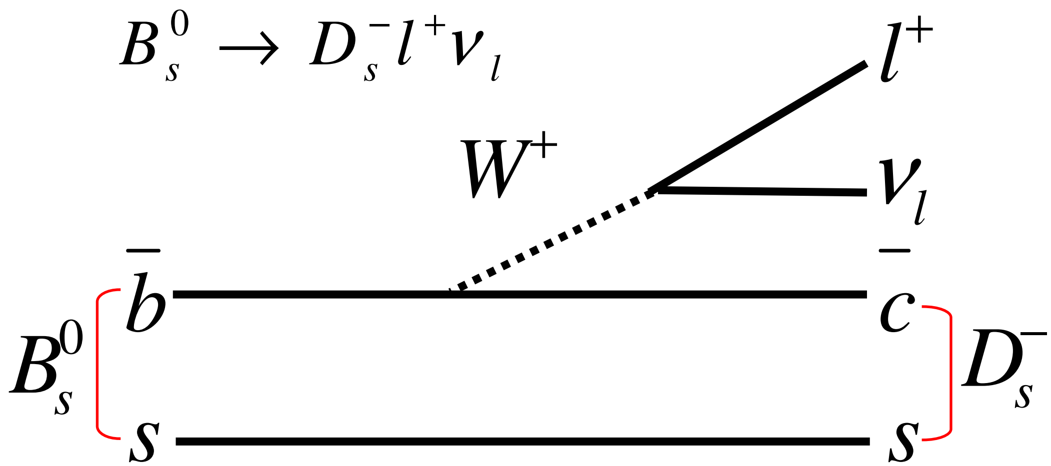
Signal Yield Summary: Hadronic

	Yield
$B_s \to D_s\pi\ (\phi\pi)$	1600
$B_s \to D_s\pi\ (K^* K)$	800
$B_s \to D_s\ \pi\ (3\pi)$	600
$B_s \to D_s 3\pi\ (\phi\ \pi)$	500
$B_s \to D_s 3\pi\ (K^* K)$	200
Total	3700



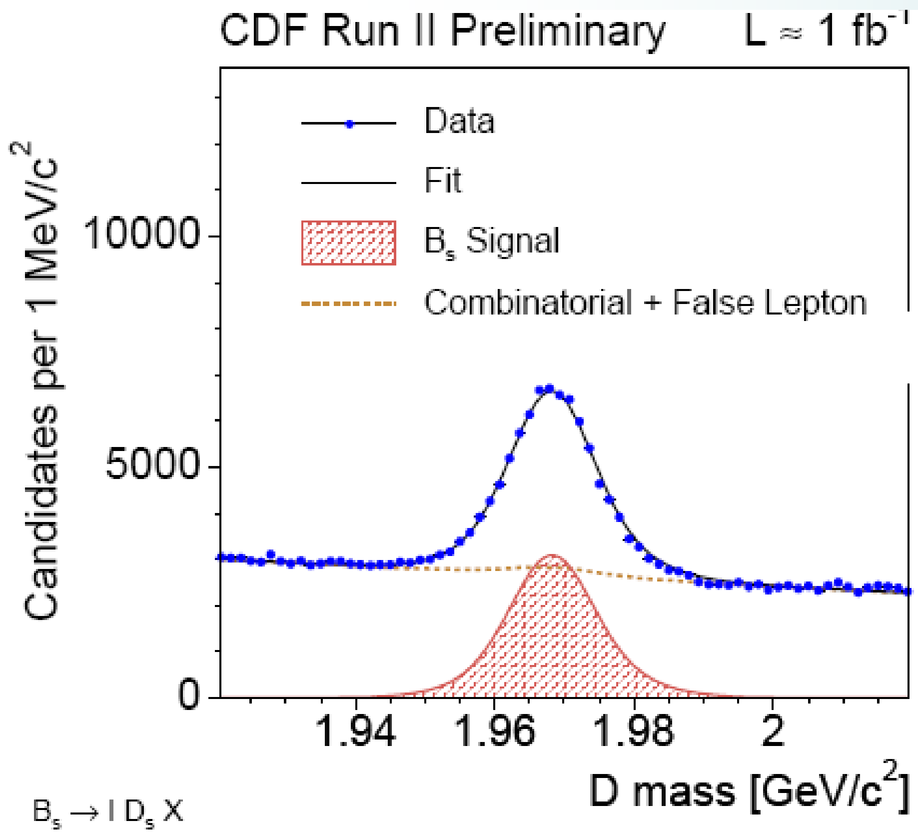
- high statistics light B meson samples:
  B^+ ($D^0\pi$): 26k events
  B^0 ($D^-\pi$): 22k events

Semileptonic B_s Decays



- relatively large signal yields (several 10’s of thousands)
- correct for missing neutrino momentum on average
- loss in proper time resolution
- superior sensitivity in lower Δm_s range

Semileptonic Samples: $D_s^- l^+ X$



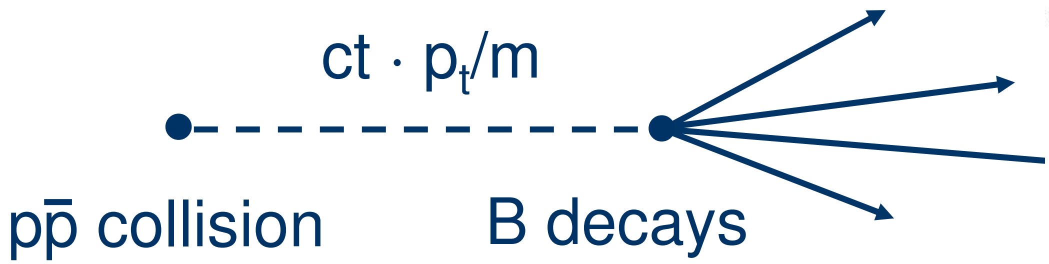
~53 K events

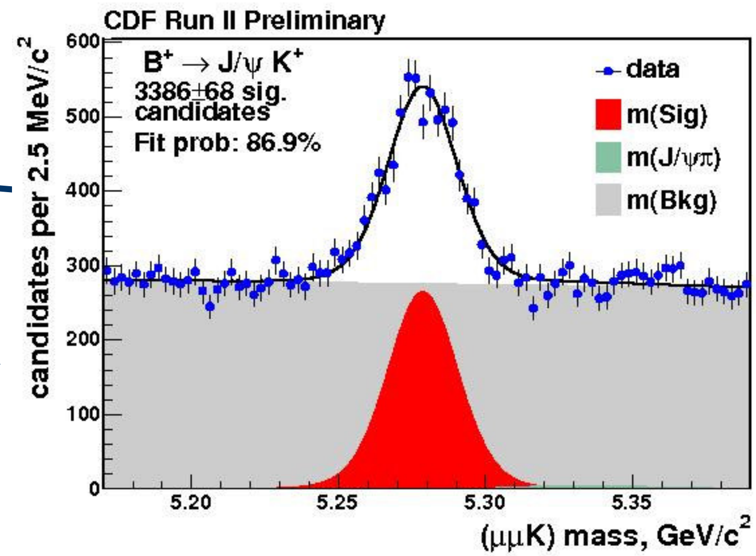
D_s: $D_s \to \phi\pi$	32 K
D_s: $D_s \to K^*K$	11 K
D_s: $D_s \to \pi\pi\pi$	10 K

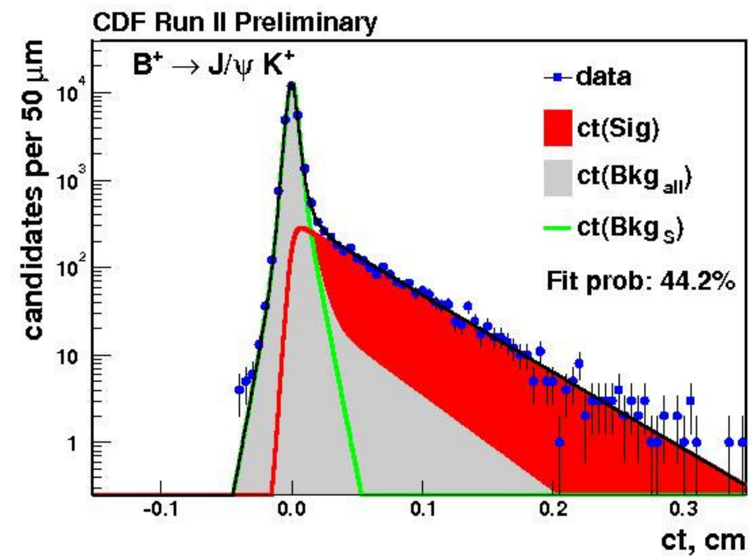
D^0: $D^0 \to K\pi$	540 K
D^{*-}: $D^0 \to K\pi$	75 K
D^-: $D^- \to K\pi\pi$	300 K

B Lifetime Measurements

“Classic” B Lifetime Measurement







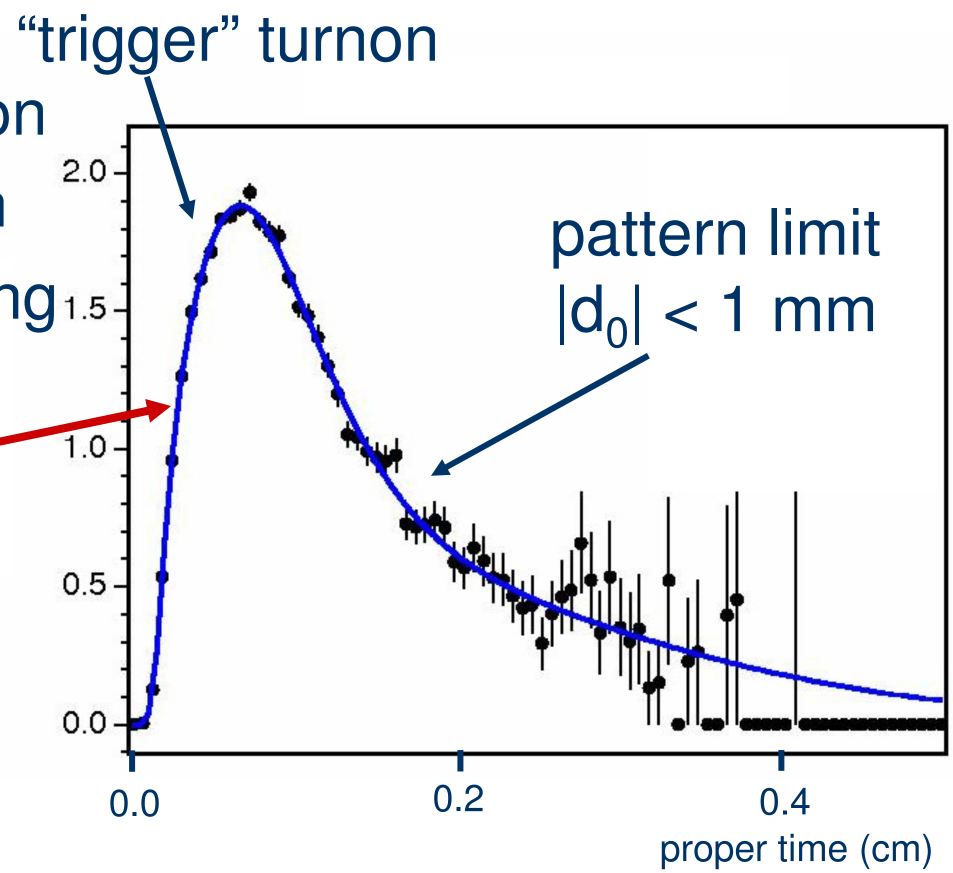
- reconstruct B meson mass, p_T, L_{xy}
- calculate proper decay time (ct)
- extract $c\tau$ from combined mass+lifetime fit
- signal probability: $p_{signal}(t) = e^{-t'/\tau} \otimes R(t',t)$
- background $p_{bkgd}(t)$ modeled from sidebands

Hadronic Lifetime Measurement

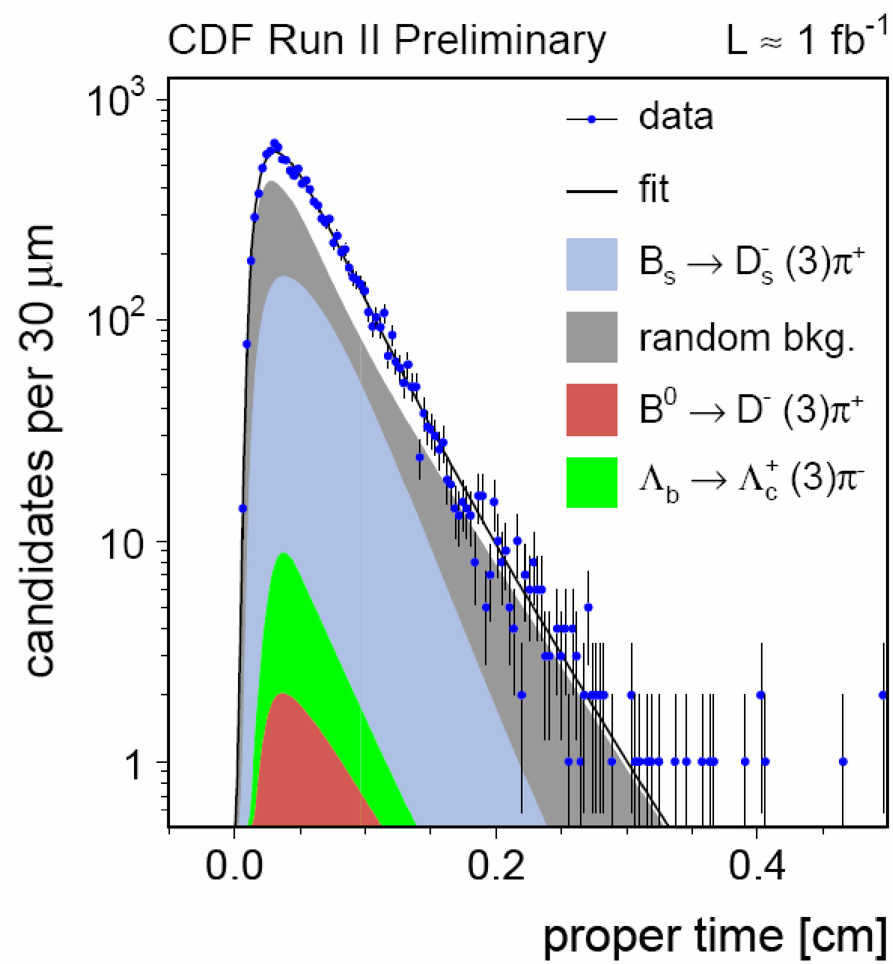
- SVT trigger, event selection sculpts lifetime distribution
- correct for on average using efficiency function:

$p = e^{-t'/\tau} \otimes R(t',t) \cdot \varepsilon(t)$

- efficiency function shape contributions:
  - event selection, trigger
- details of efficiency curve
  - important for lifetime measurement
  - inconsequential for mixing measurement



Hadronic Lifetime Results



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:

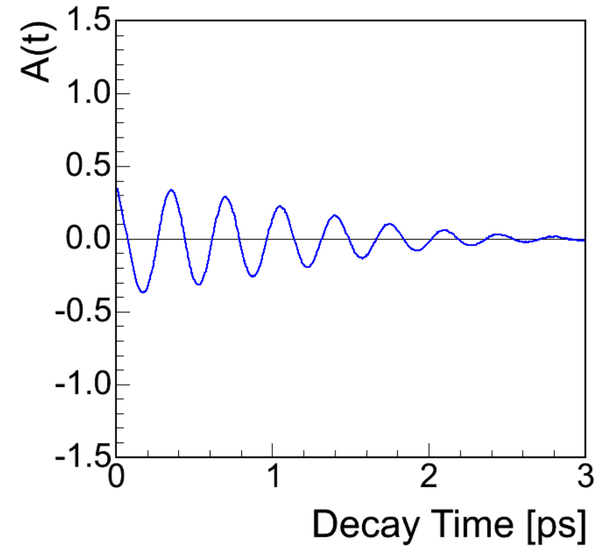
$B^0 \to 1.534 \pm 0.013$ ps^{-1}
$B^+ \to 1.653 \pm 0.014$ ps^{-1}
$B_s \to 1.469 \pm 0.059$ ps^{-1}

Excellent agreement!

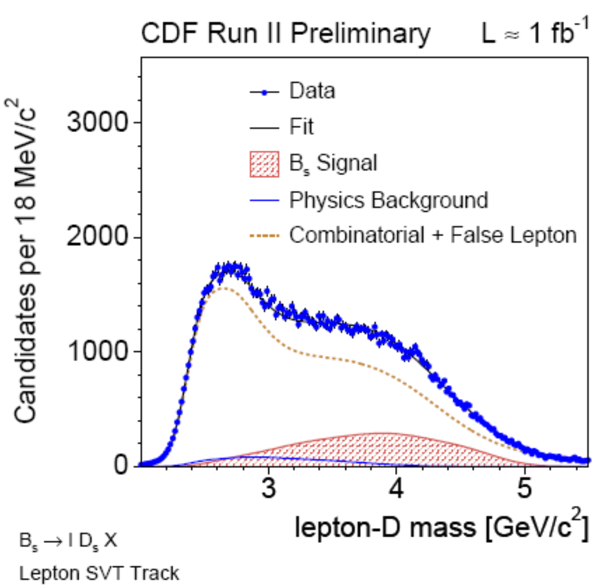
Semileptonic Lifetime Measurement

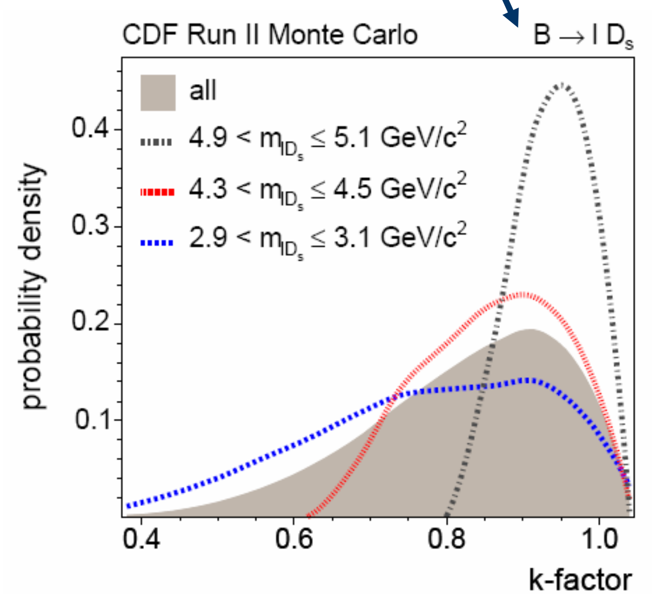
- neutrino momentum not reconstructed

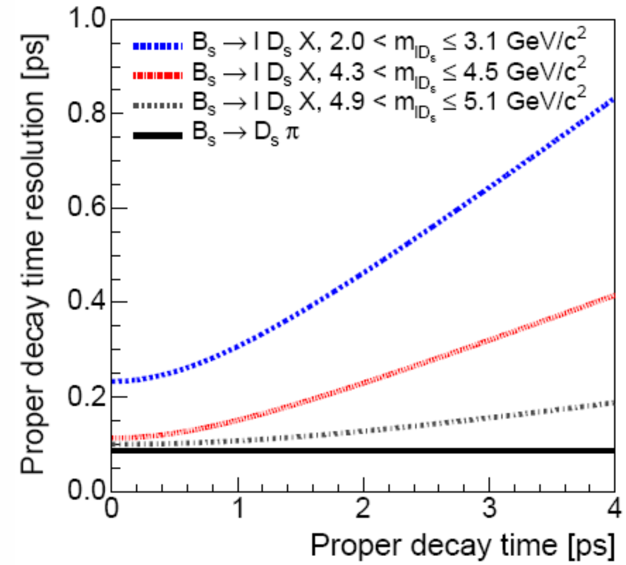
$$K = \frac{p_T(lD)}{p_T(B)} \cdot \frac{L(B)}{L(lD)}$$



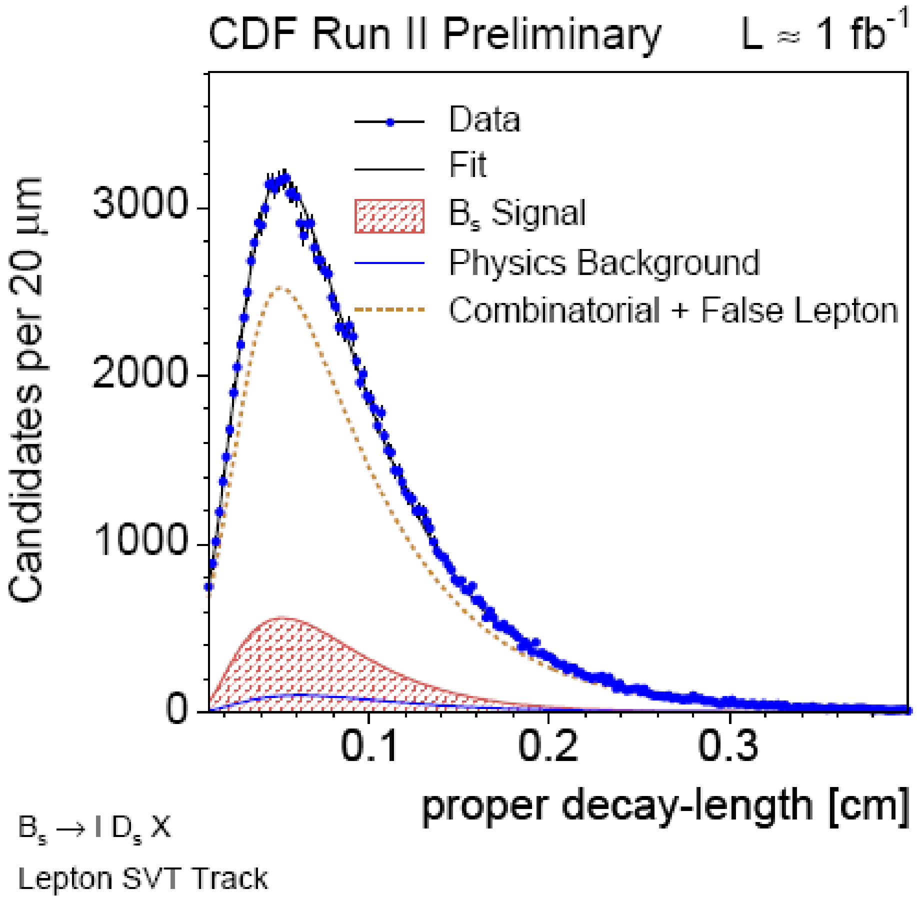
- correct for neutrino on average



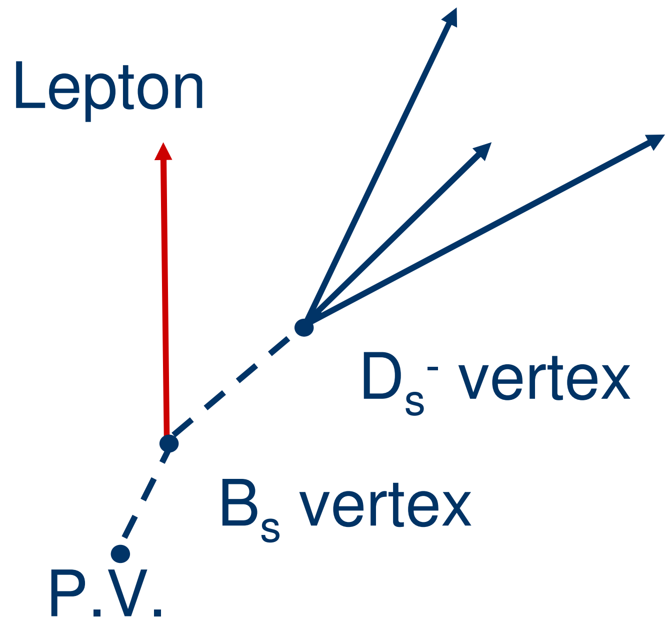




lD_s ct* Projections



$$ct^* = \frac{L(lD) \cdot m(B)}{p_T(lD)}$$



B_s lifetime in 355 pb^{-1}: 1.48 $\pm$ 0.03 (stat) ps

World Average value: 1.469 $\pm$ 0.059 ps

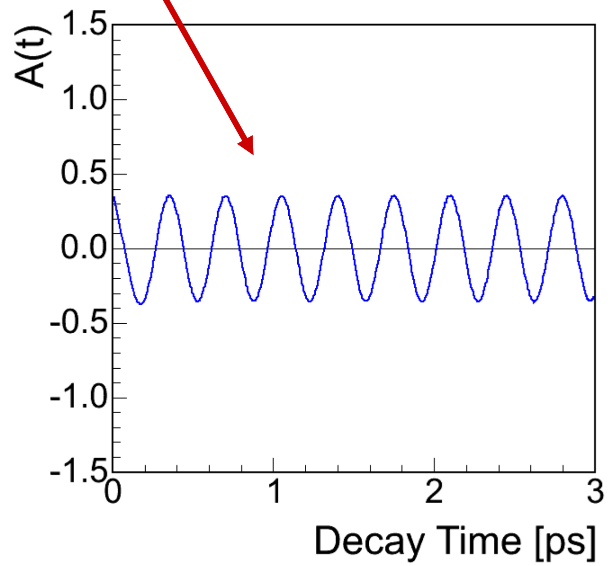
Proper Time Resolution

Proper Time Resolution

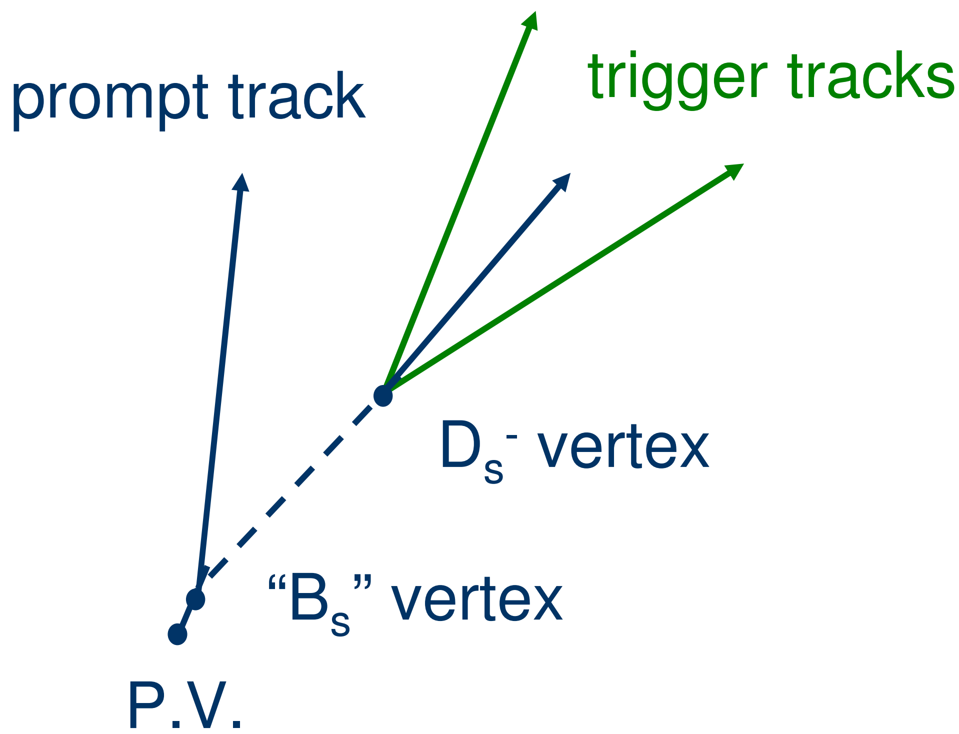
- Reminder, measurement significance:

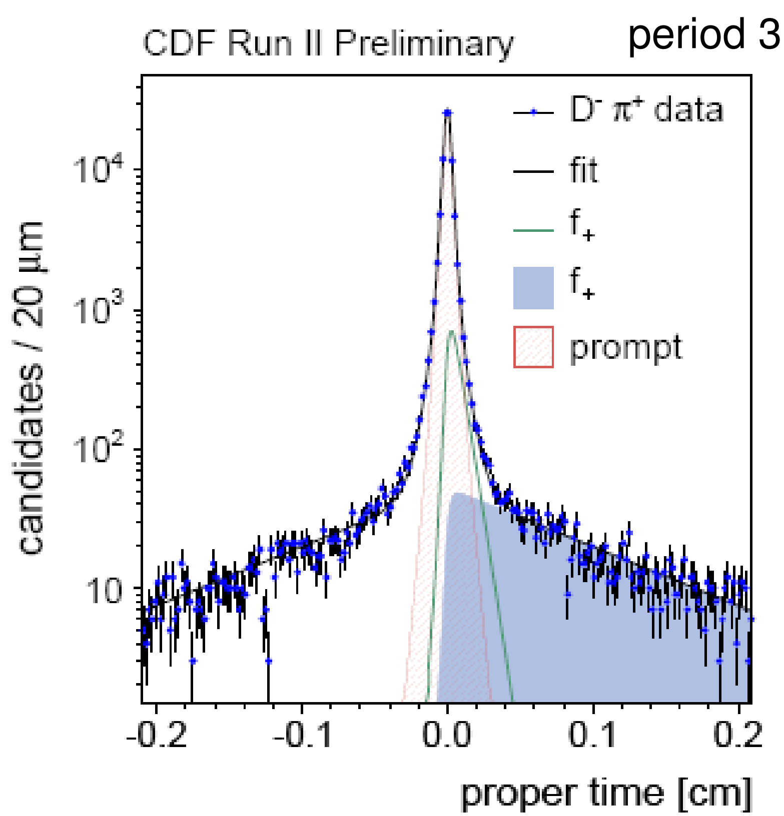
$$\text{Signif} = \sqrt{\frac{N\epsilon D^2}{2}} e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

- significant effect
- fitter has to correctly account for it
- lifetime measurements not very sensitive to resolution
- a dedicated calibration is needed!



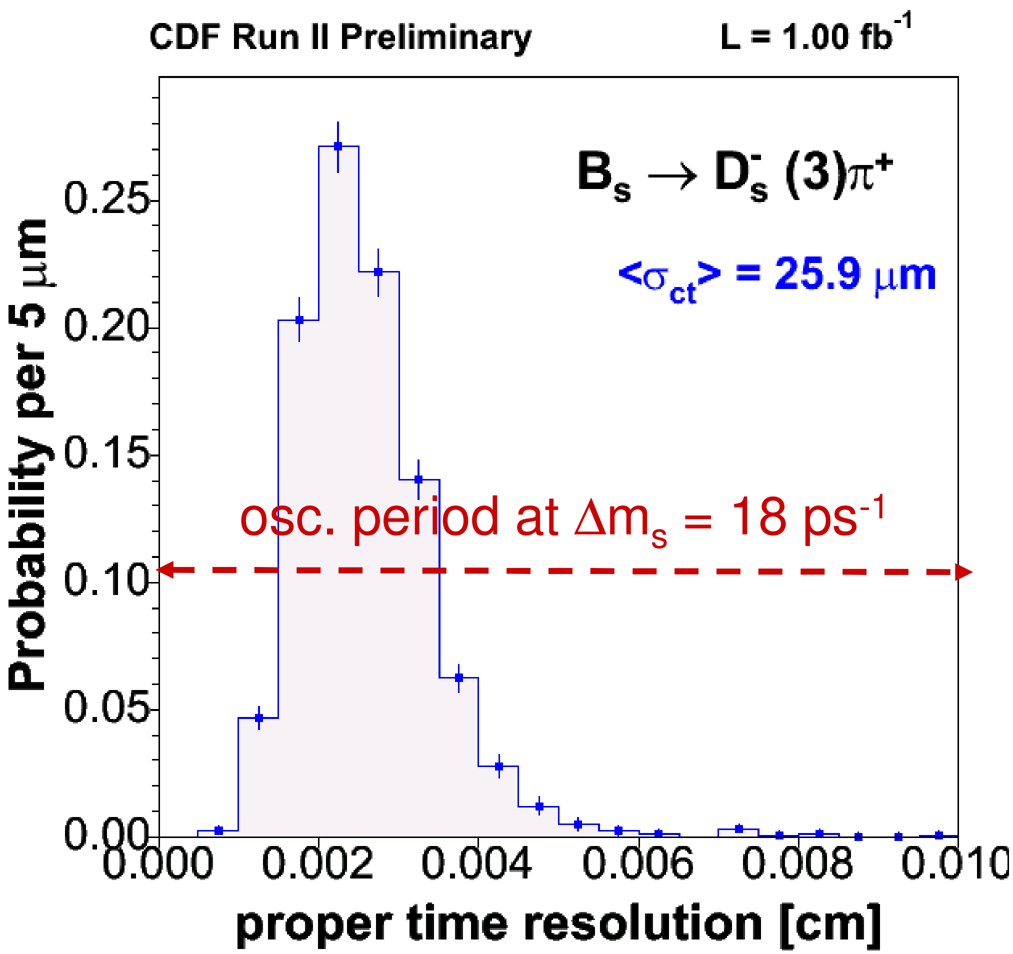
Calibrating the Proper Time Resolution





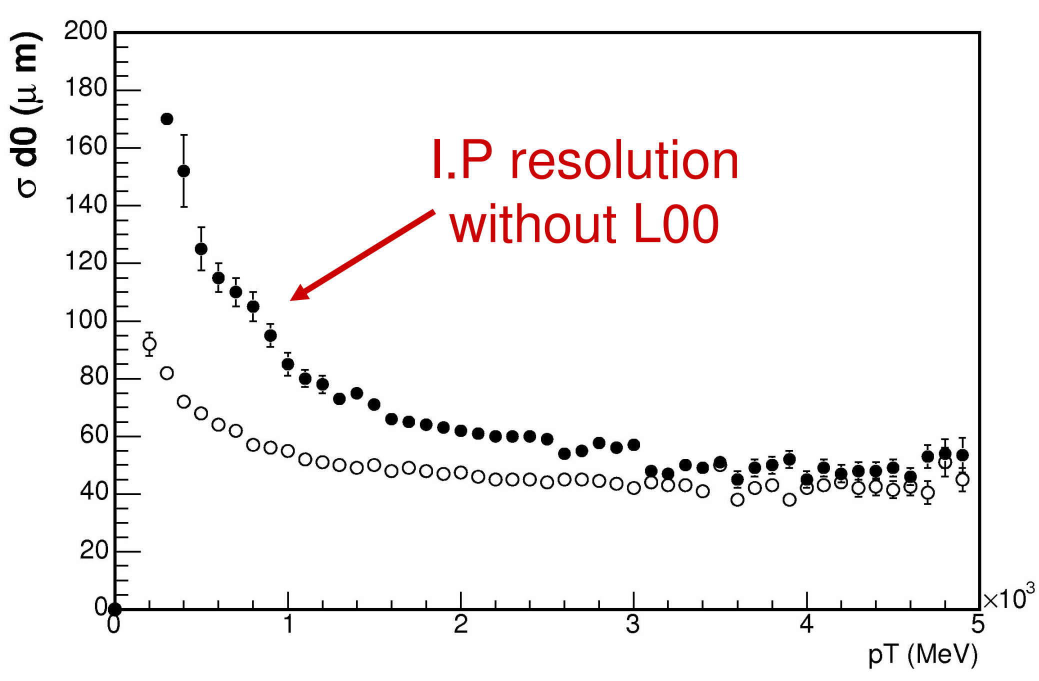
- utilize large prompt charm cross section
- construct “B^0-like” topologies of prompt D^- + prompt track
- calibrate ct resolution by fitting for “lifetime” of “B^0-like” objects

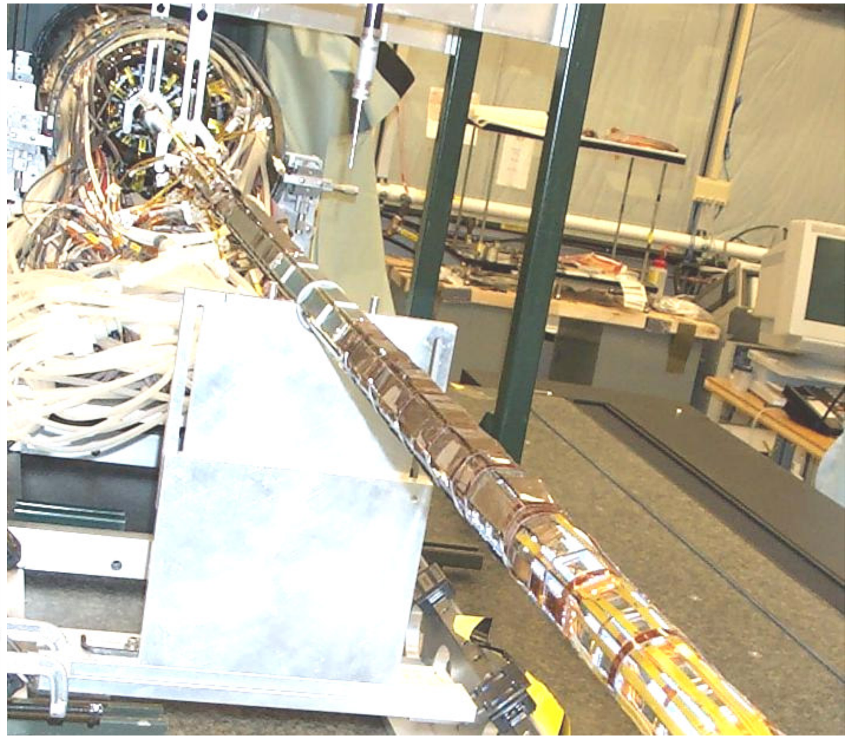
B_s Proper Time Resolution



- event by event determination of primary vertex position used
- average uncertainty ~ 26 μm
- this information is used per candidate in the likelihood fit

Layer "00"

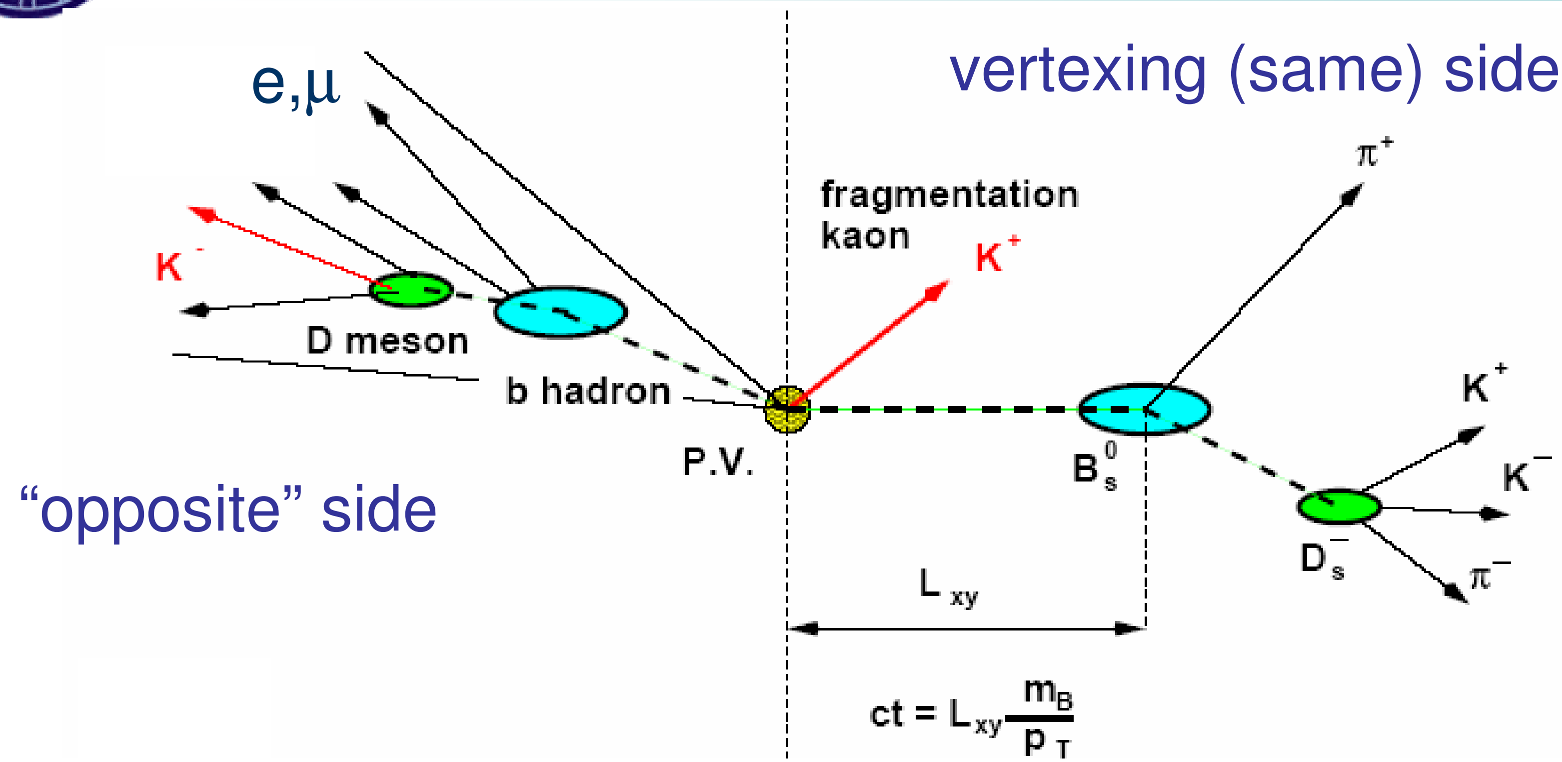




- layer of silicon placed directly on beryllium beam pipe
- radial displacement from beam ~1.5 cm
- additional impact parameter resolution, radiation hardness

Flavor Tagging

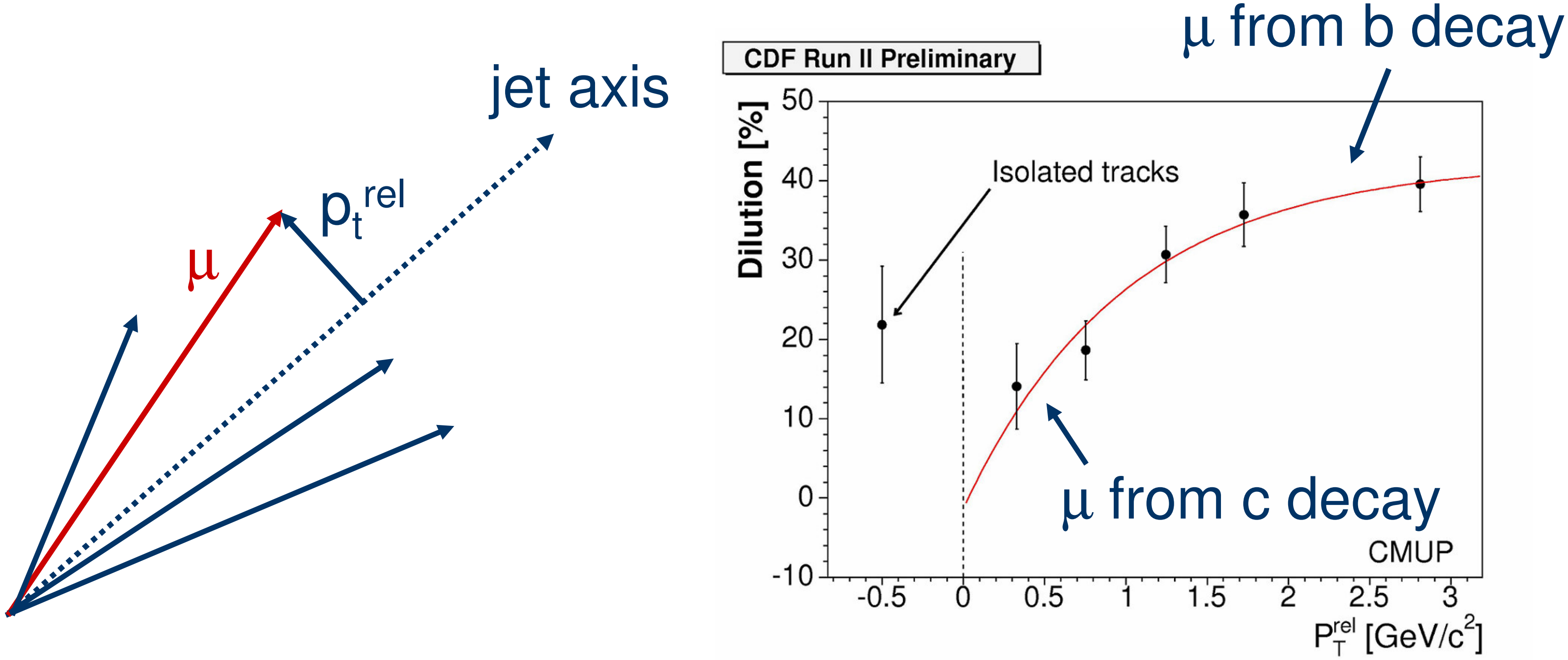
Tagging the B Production Flavor



- use a combined same side and opposite side tag!
- use muon, electron tagging, jet charge on opposite side
- jet selection algorithms: vertex, jet probability and highest p_T
- particle ID based kaon tag on same side

Parametrizing Tagger Decisions

- use characteristics of tags themselves to increase their tagging power, example: muon tags

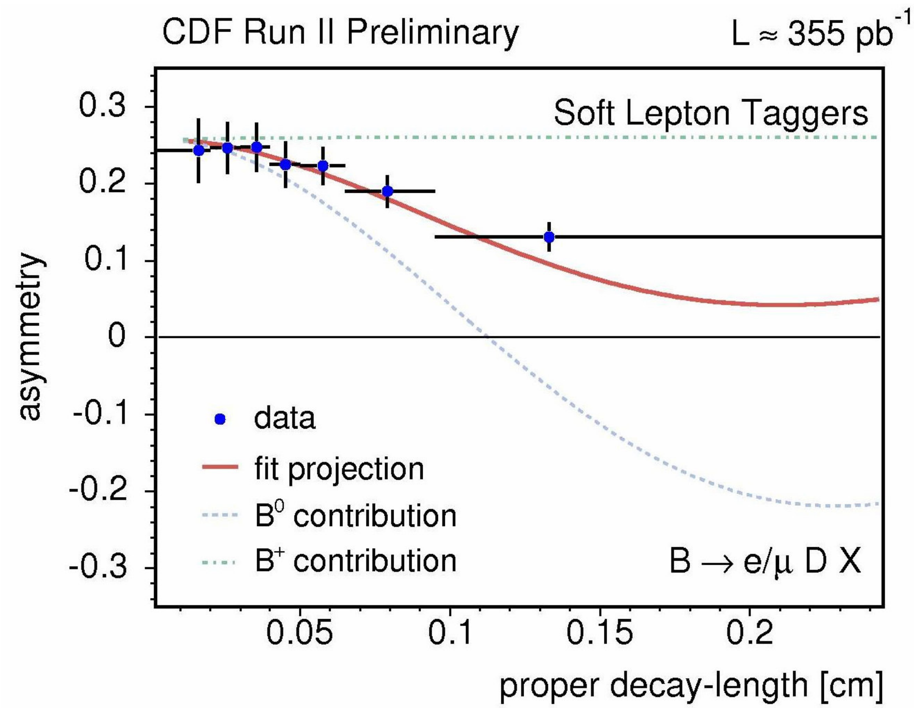


- tune taggers and parametrize event specific dilution
- technique in data works with opposite side tags

Unbinned Likelihood Δm_d Fits

- fit separately in hadronic and semileptonic sample
- per sample, simultaneously measure
  - tagger performance
  - Δm_d
- projection incorporates several classes of tags

semileptonic, ID^-, muon tag



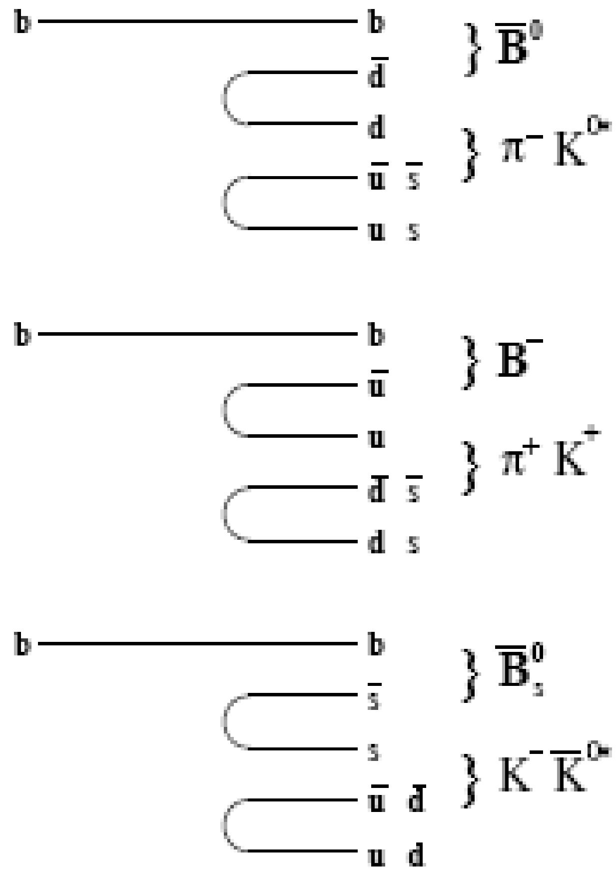
hadronic: $\Delta m_d = 0.536 \pm 0.028\ (\text{stat}) \pm 0.006\ (\text{syst})\ \text{ps}^{-1}$

semileptonic: $\Delta m_d = 0.509 \pm 0.010\ (\text{stat}) \pm 0.016\ (\text{syst})\ \text{ps}^{-1}$

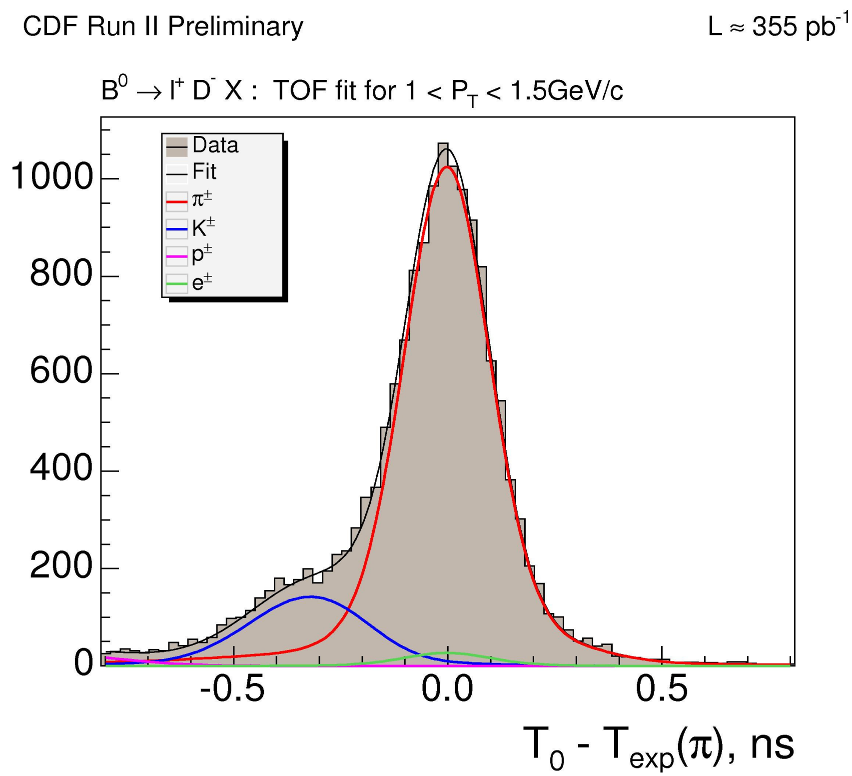
world average: $\Delta m_d = 0.507 \pm 0.005\ \text{ps}^{-1}$

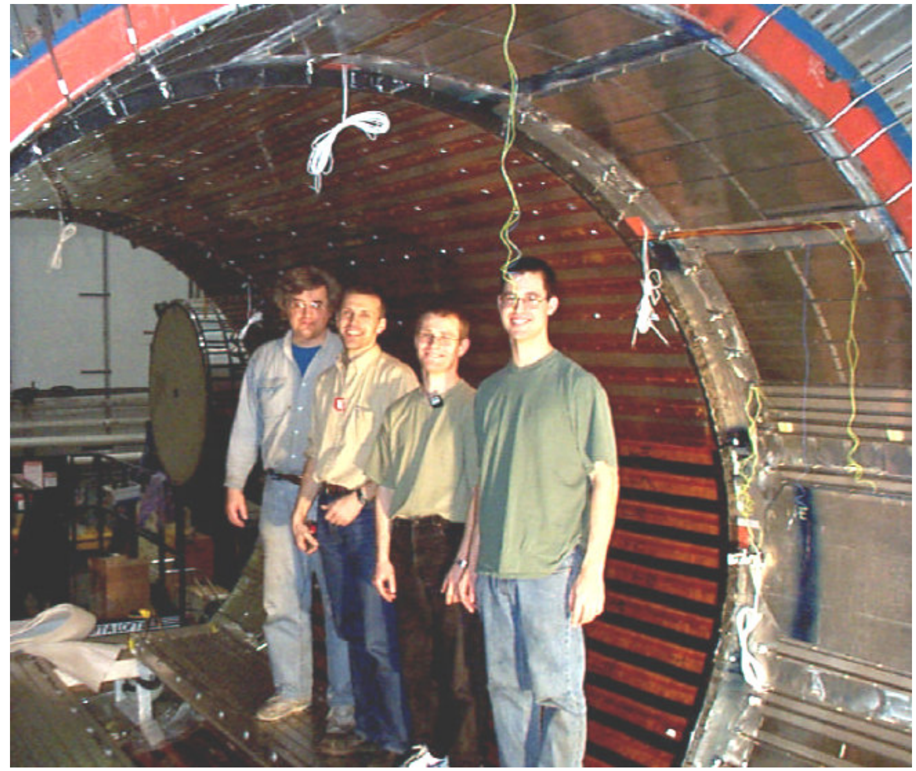
Same Side Kaon Tags

- exploit b quark fragmentation signatures in event
- B^0/B^+ likely to have a π^-/π nearby
- B_s^0 likely to have a K^+
- use TOF and COT dE/dX info. to separate pions from kaons
- problem: calibration using only B^0 mixing will not work
- tune Monte Carlo simulation to reproduce B^0, B^- distributions, then apply directly to B_s^0



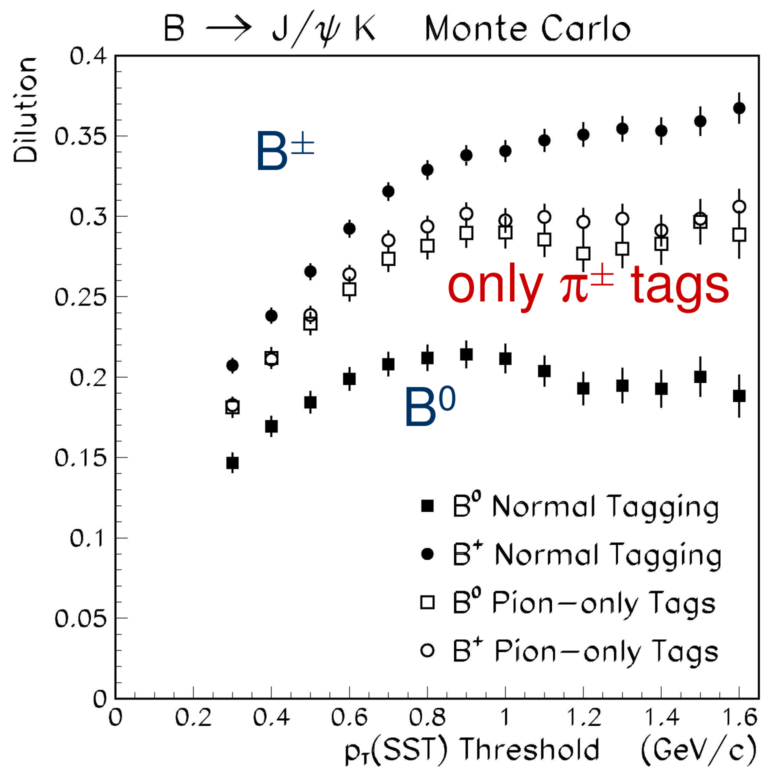
Time Of Flight System

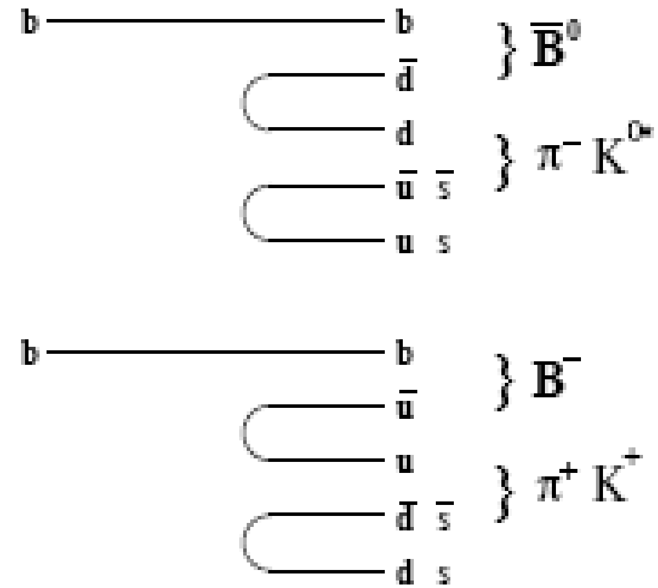




- timing resolution ~100 ps → resolves kaons from pions up to p ~ 1.5 GeV/c
- TOF provides most of the Particle ID power for SSKT

Kaons Matter in Light B's!

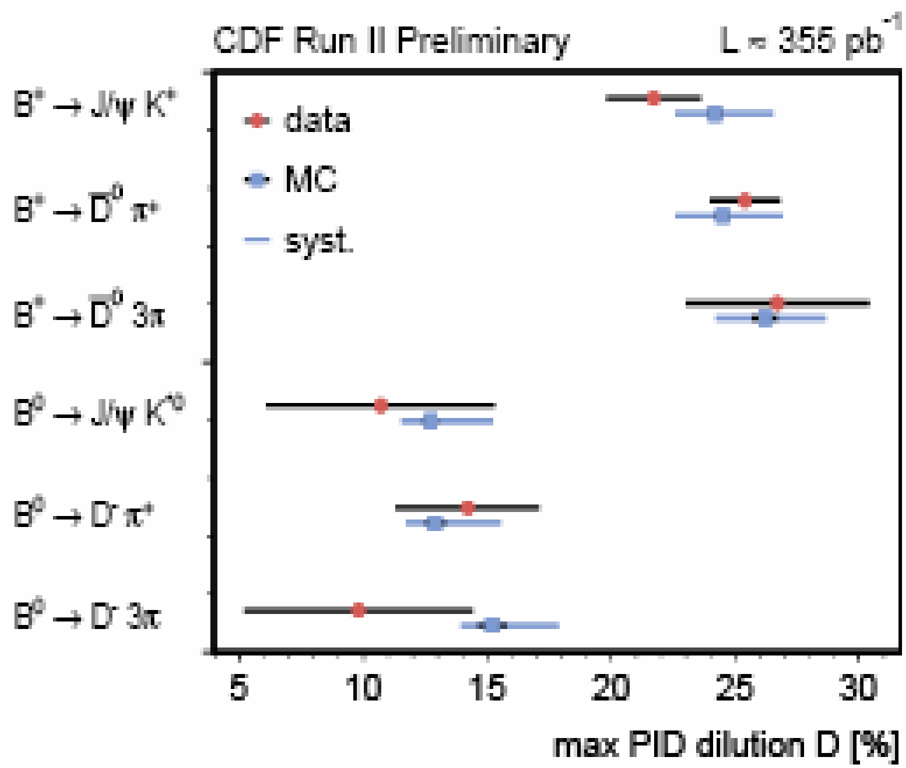




- kaons participate differently in tagging $B^{\pm}$, B^0
- Monte Carlo simulation has to have correct kinematics AND particle content to get the dilution right!

Calibrating SSKT

- Analogous to transfer scale factor in Opposite Side Tags
- Check dilution in light B meson decays



Data/MC agreement is the largest systematic uncertainty → O(14%)

Tagger Performance

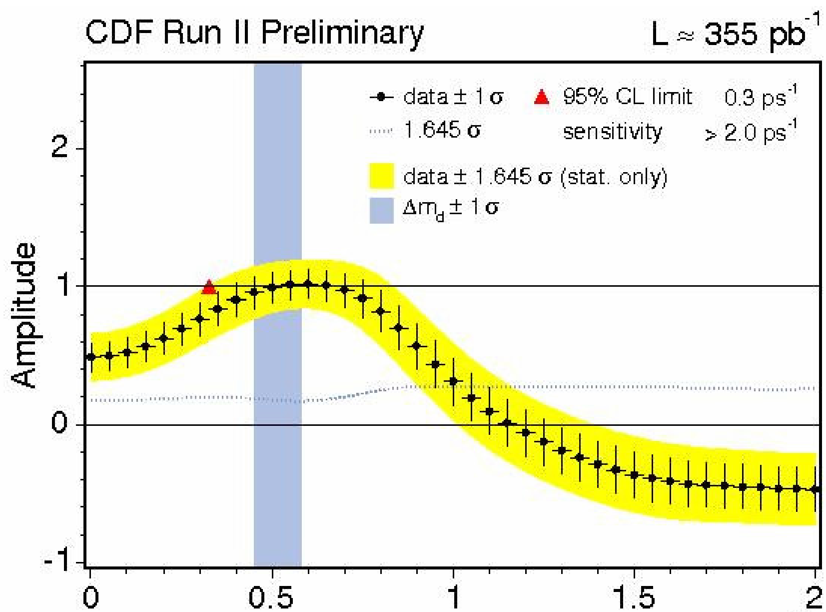
	εD^2 Hadronic (%)	εD^2 Semileptonic (%)
Muon	0.48 ± 0.06 (stat)	0.62 ± 0.03 (stat)
Electron	0.09 ± 0.03 (stat)	0.10 ± 0.01 (stat)
JQ/Vertex	0.30 ± 0.04 (stat)	0.27 ± 0.02 (stat)
JQ/Prob.	0.46 ± 0.05 (stat)	0.34 ± 0.02 (stat)
JQ/High p_T	0.14 ± 0.03 (stat)	0.11 ± 0.01 (stat)
Total OST	1.47 ± 0.10 (stat)	1.44 ± 0.04 (stat)
SSKT	3.42 ± 0.49 (syst)	4.00 ± 0.56 (syst)

- use exclusive combination of tags on opposite side
- same side – opposite side combination assumes independent tagging information

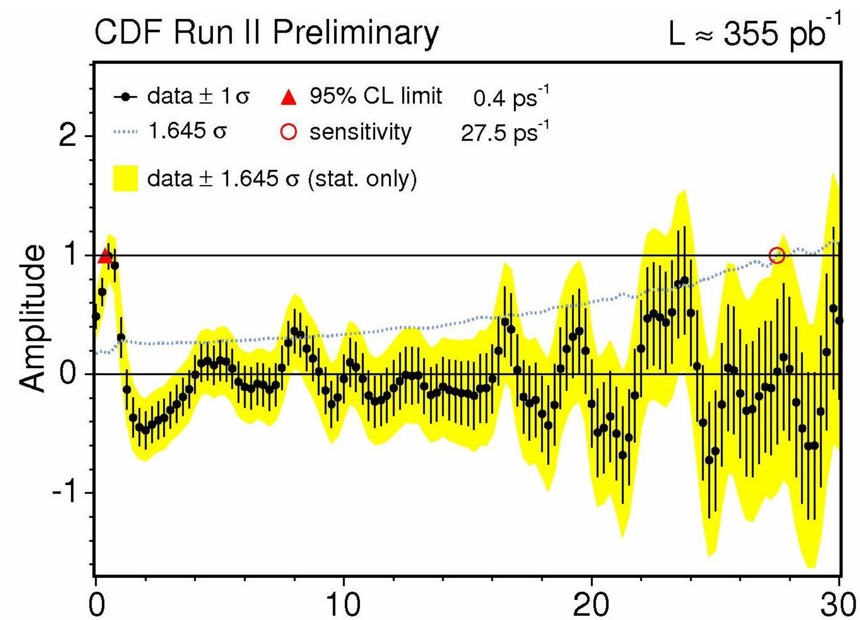
The Procedure

Amplitude Scans

- example: B^0 Mixing signal in hadronic decays
- points: $A \pm \sigma(A)$ from likelihood fit for different Δm
- yellow band: $A \pm 1.645\ \sigma(A)$
- Δm values where $A + 1.645\ \sigma(A) < 1$ are excluded at 95% C.L.
- dashed line: $1.645\ \sigma(A)$ as function of Δm
- measurement sensitivity: $1.645\ \sigma(A) = 1$

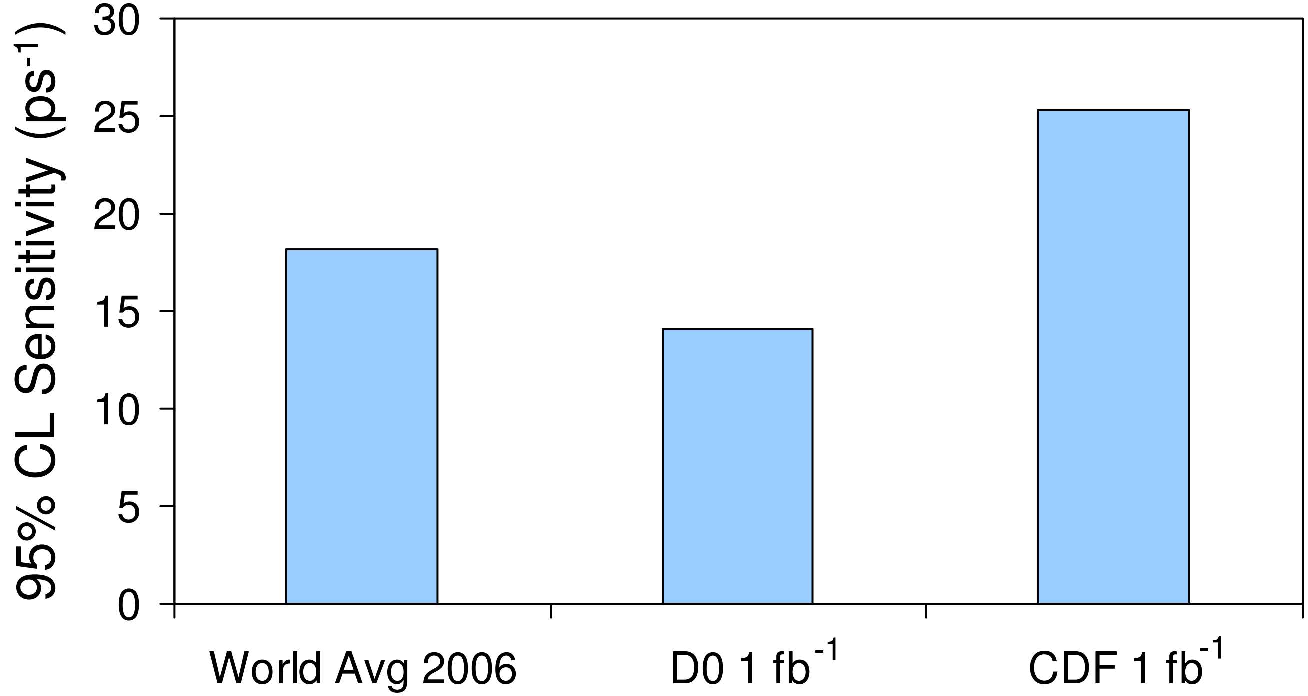


narrow Δm_s range



wide Δm_s range

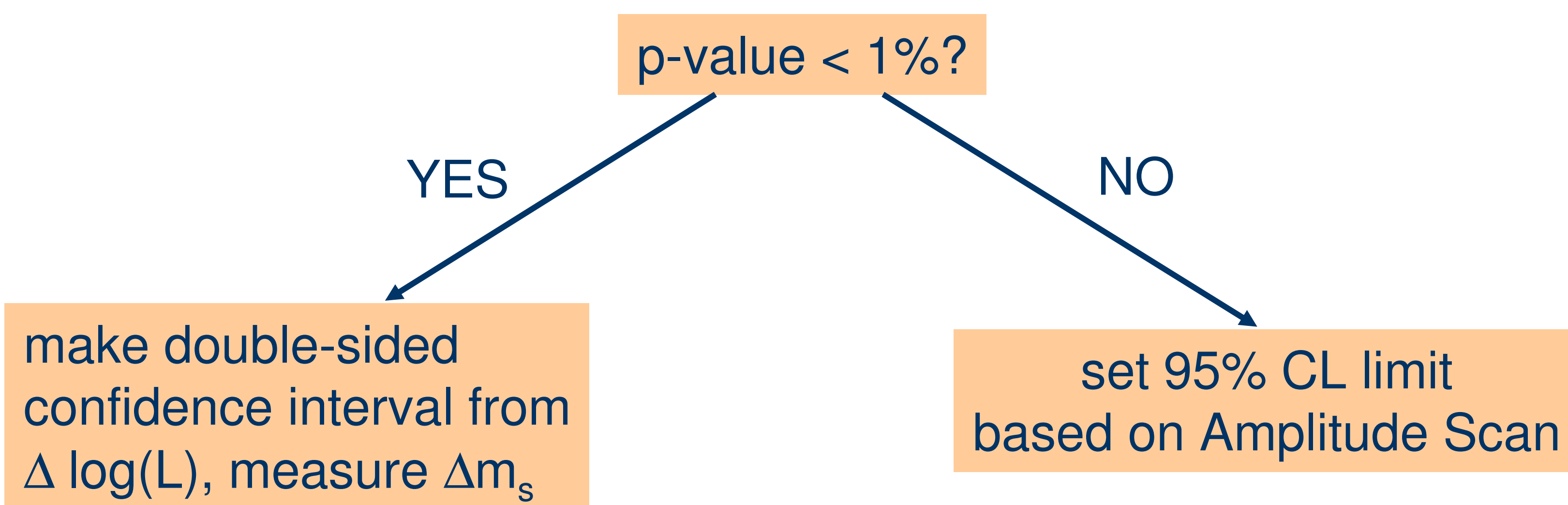
Measurement Sensitivity



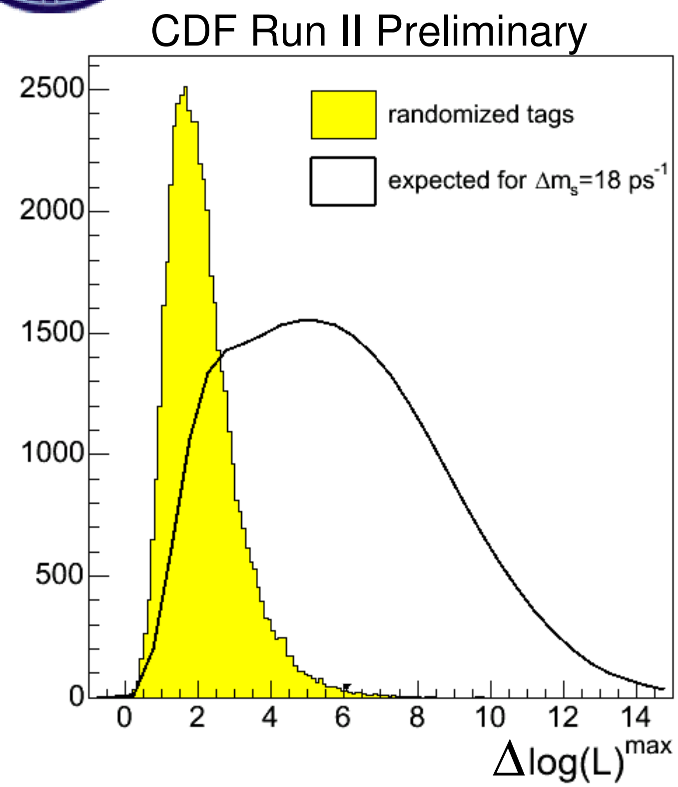
- estimated from data
- unusual situation – one single measurement more sensitive than the world average knowledge!

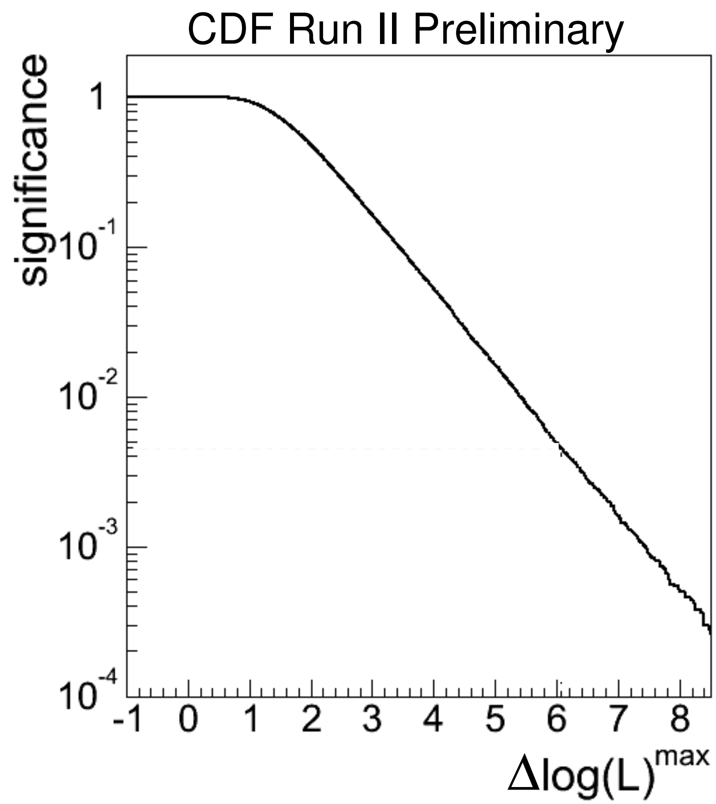
A Priori Procedure

- decided upon before un-blinding the 1 fb^{-1} of data
- p-value: probability that observed effect is due to background fluctuation
- p-value to be estimated using $\Delta(\ln L)$ method
- no search window to be used



p-value Estimation

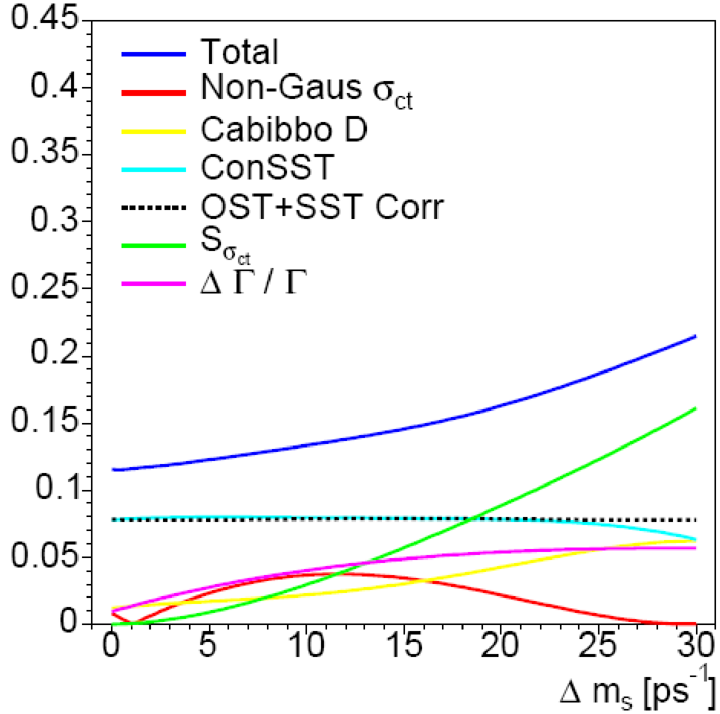




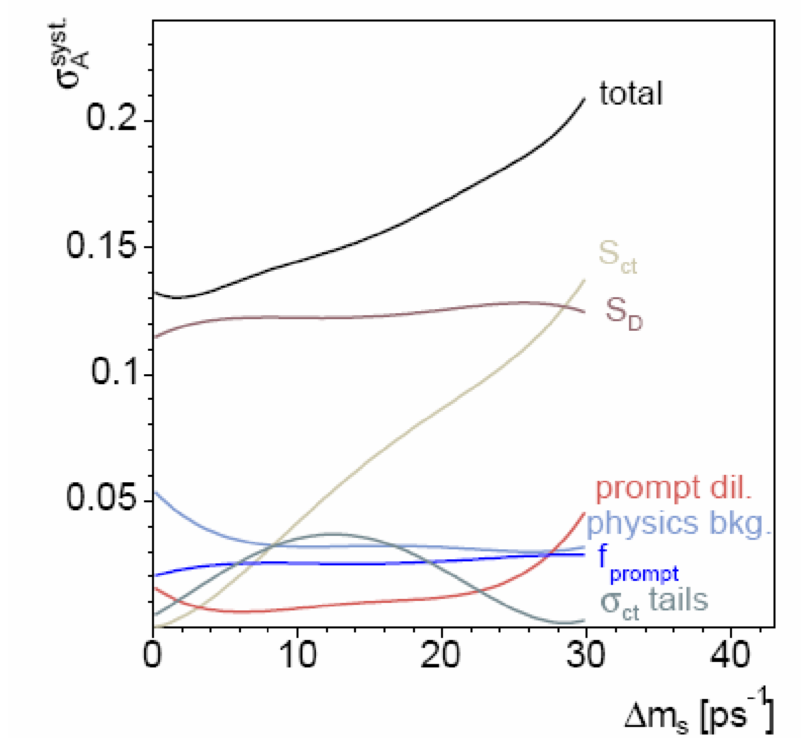
- Δlog(L) = log[L(A=1) / L(A=0)] → likelihood "dip" at signal
- more powerful discriminant than A/σ(A)
- probability of random tag fluctuations evaluated on data
  (with randomized tags) → checked that toy Monte Carlo gives same answer

Systematic Uncertainties

Hadronic



Semileptonic



- related to absolute value of amplitude, relevant only when setting limits
  - cancel in A/σ_A, folded in in confidence calculation for observation
  - systematic uncertainties are very small compared to statistical

Systematic Uncertainties on Δm_s

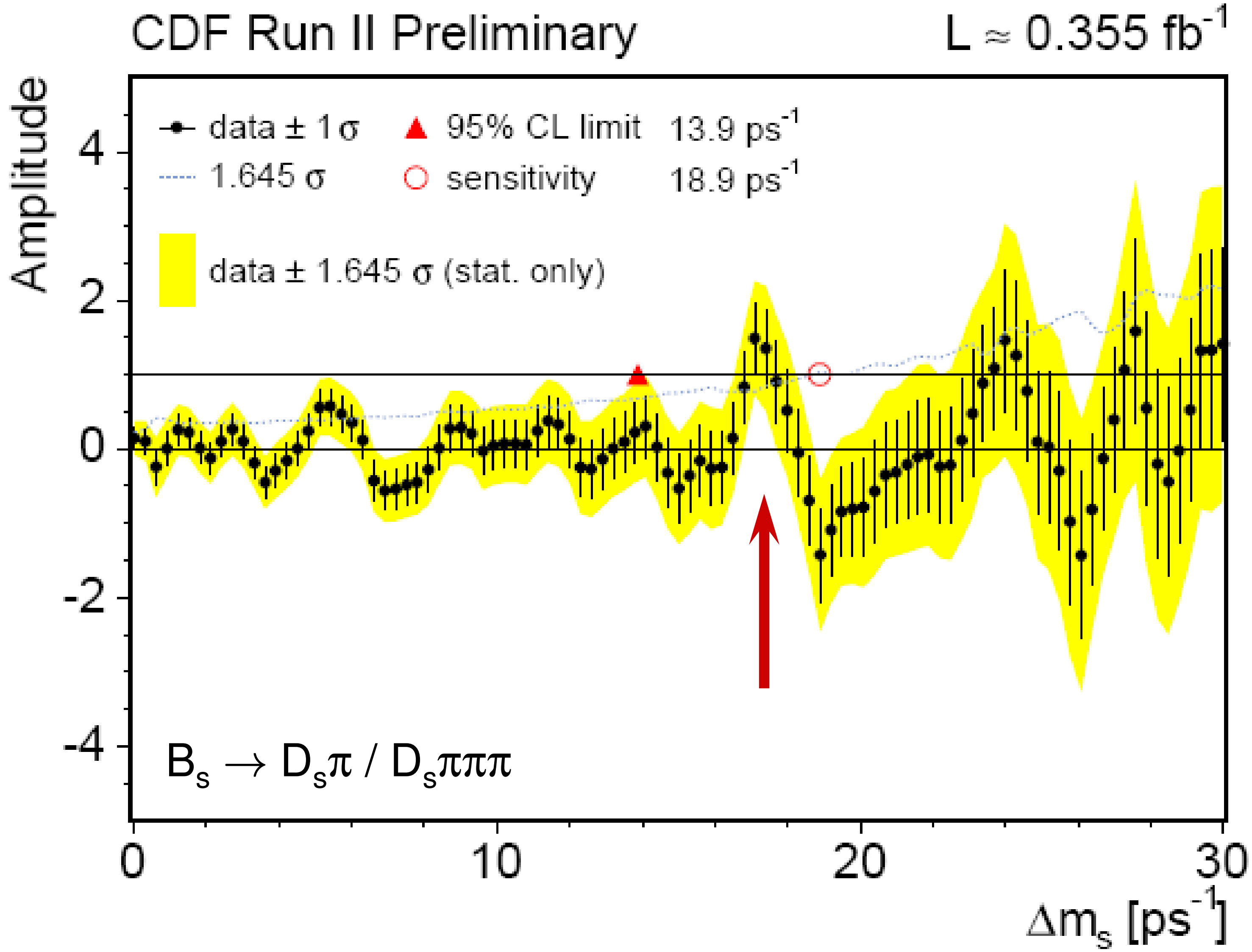
- systematic uncertainties from fit model evaluated on toy Monte Carlo
- have negligible impact
- relevant systematic unc. from lifetime scale

	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}

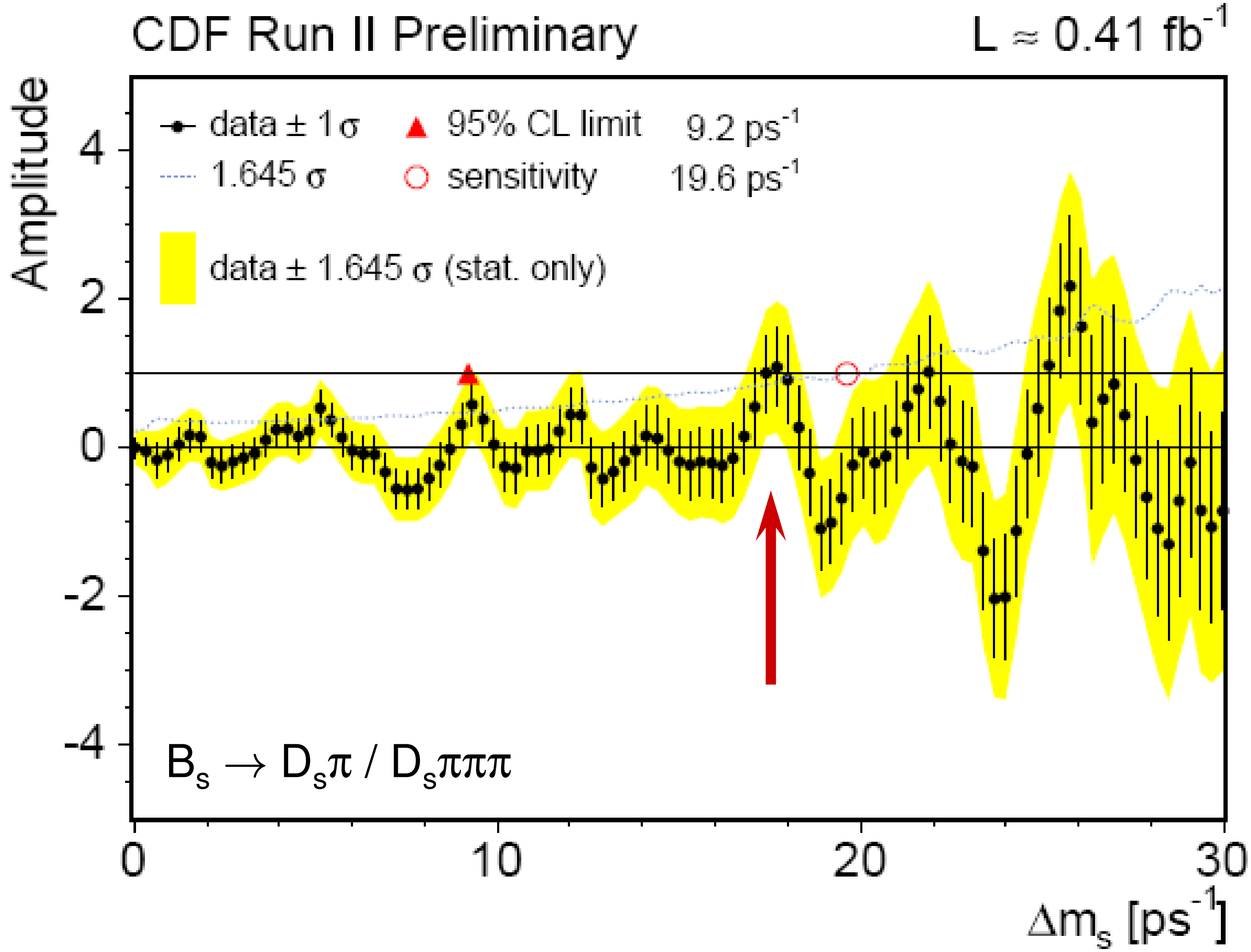
All relevant systematic uncertainties are common between hadronic and semileptonic samples

The Data

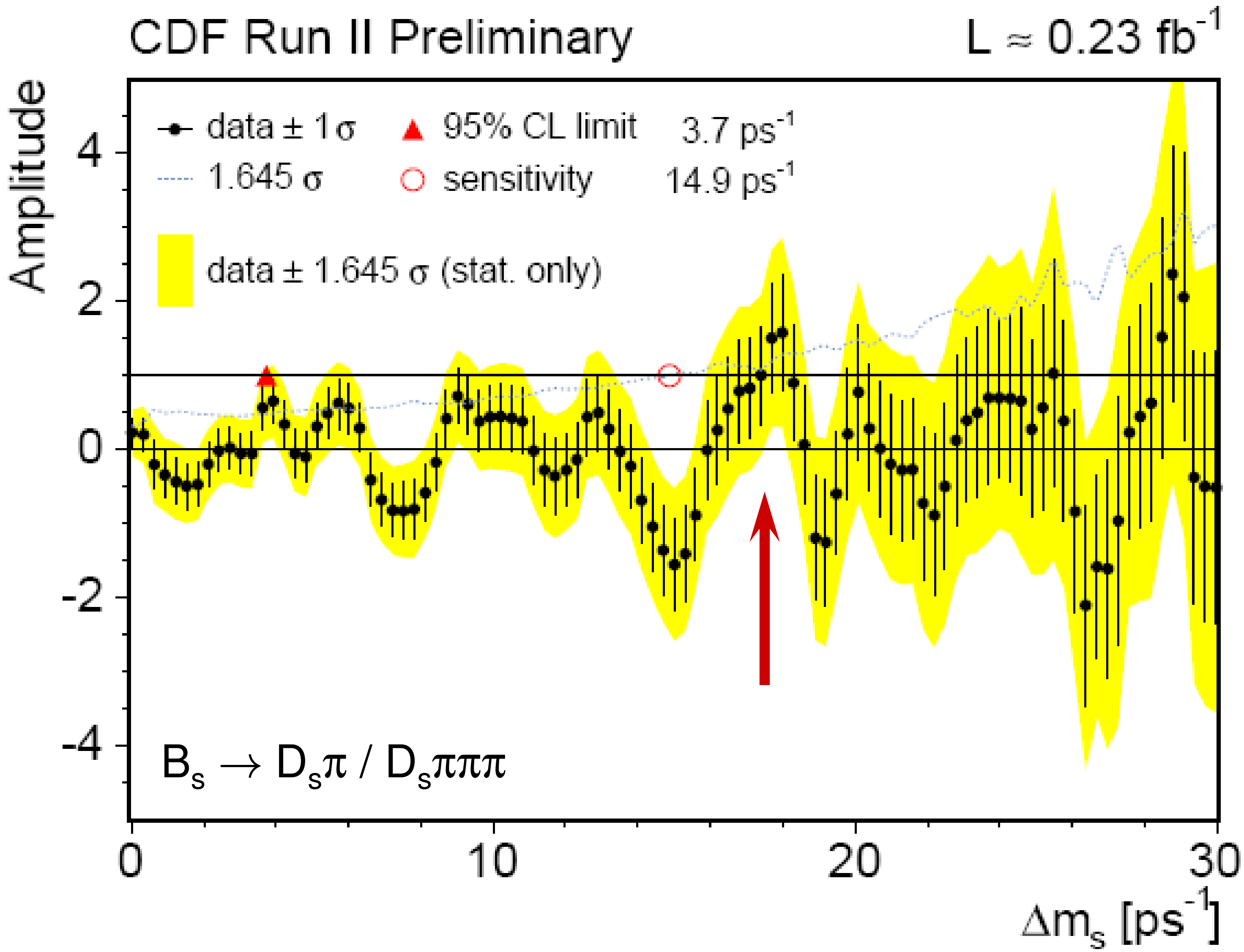
Amplitude Scan: Hadronic Period 1



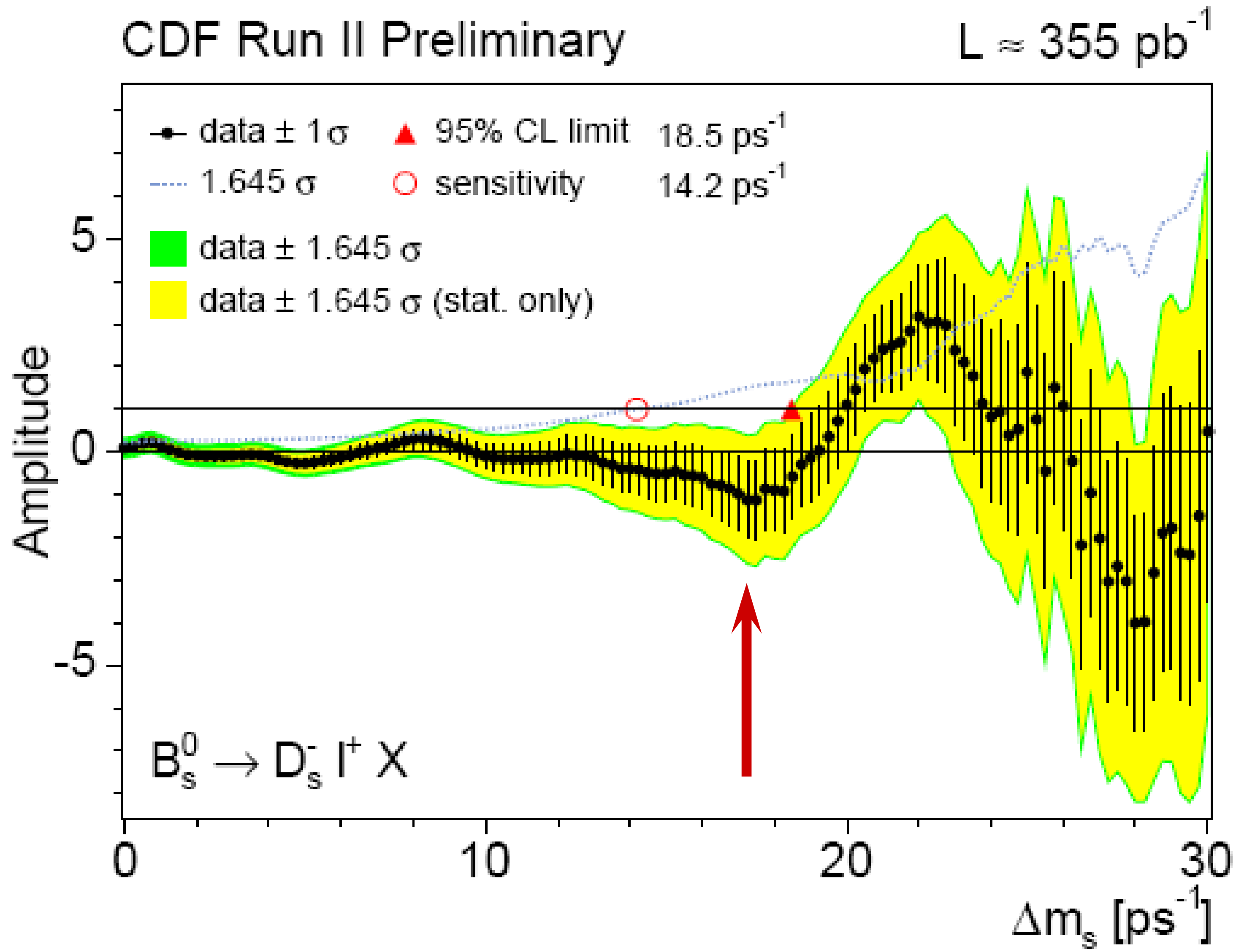
Amplitude Scan: Hadronic Period 2



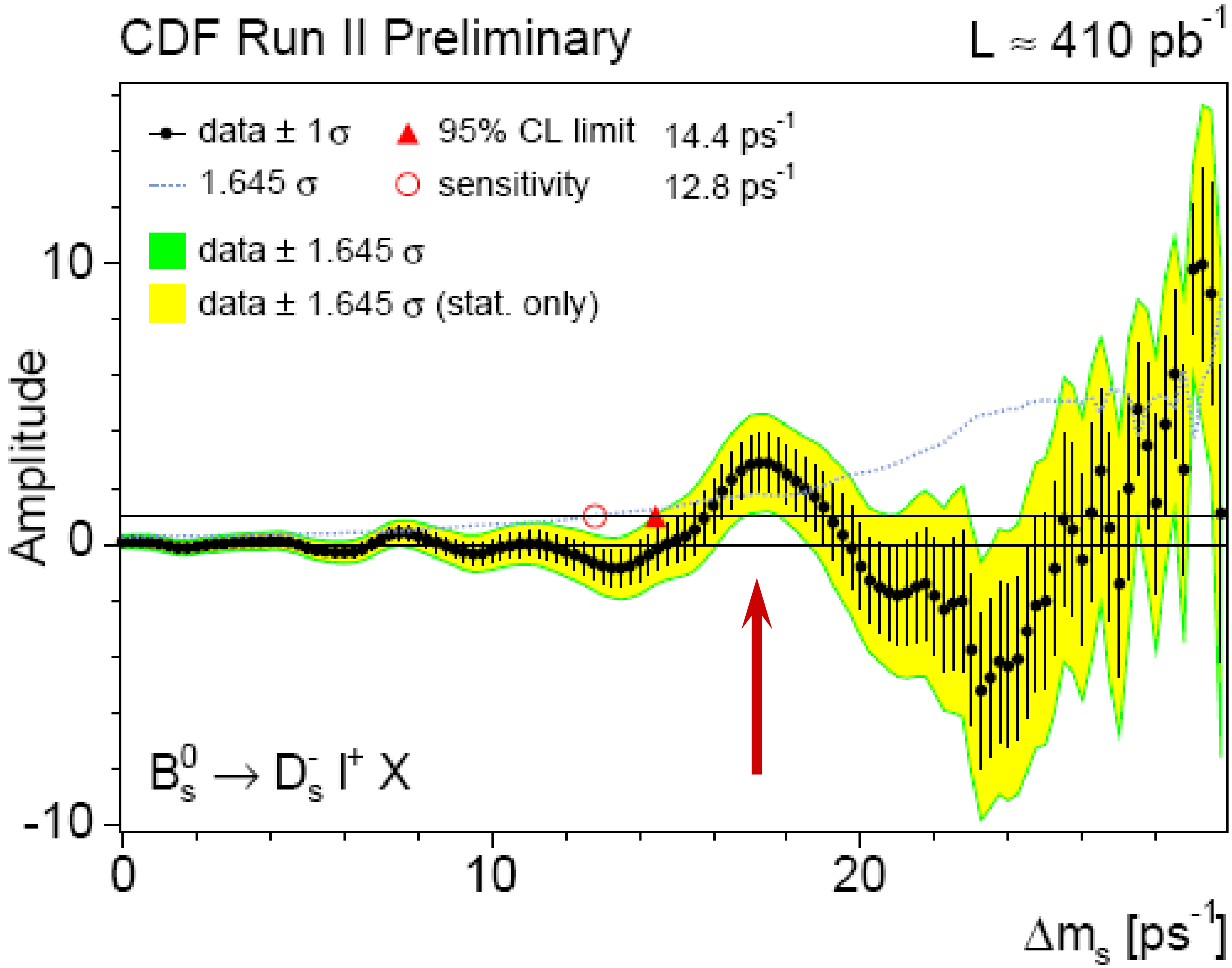
Amplitude Scan: Hadronic Period 3



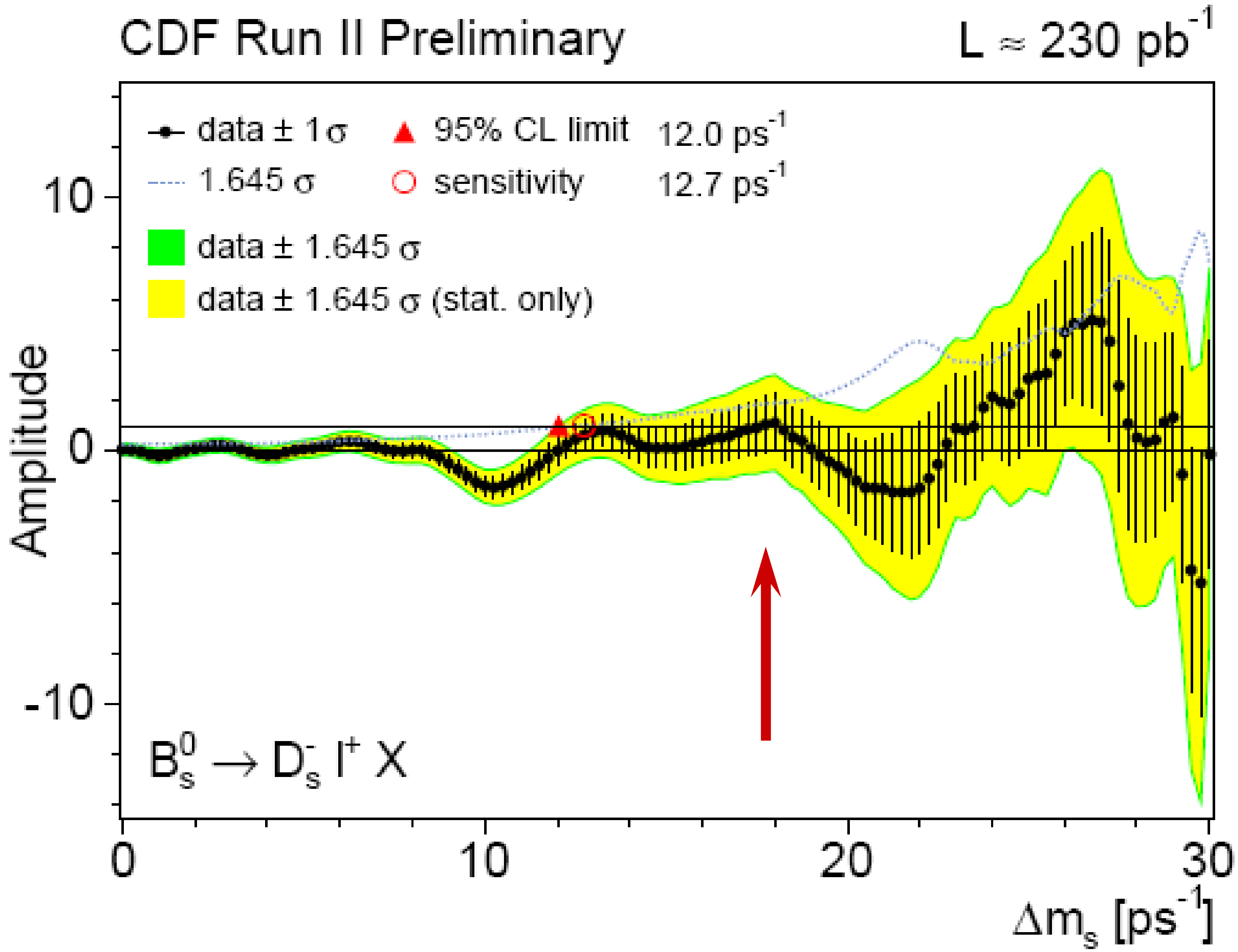
Semileptonic Scan: Period 1



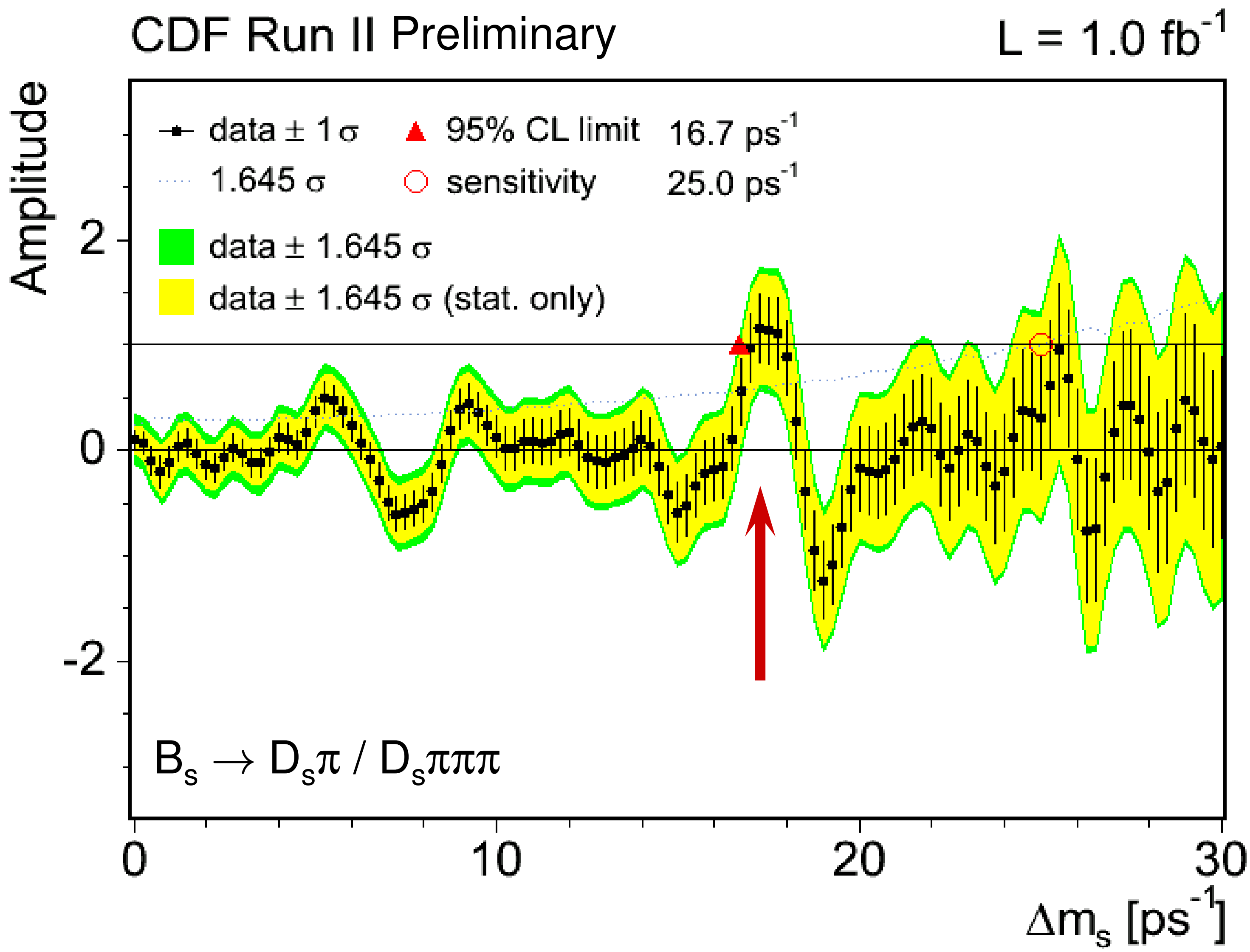
Semileptonic Scan: Period 2



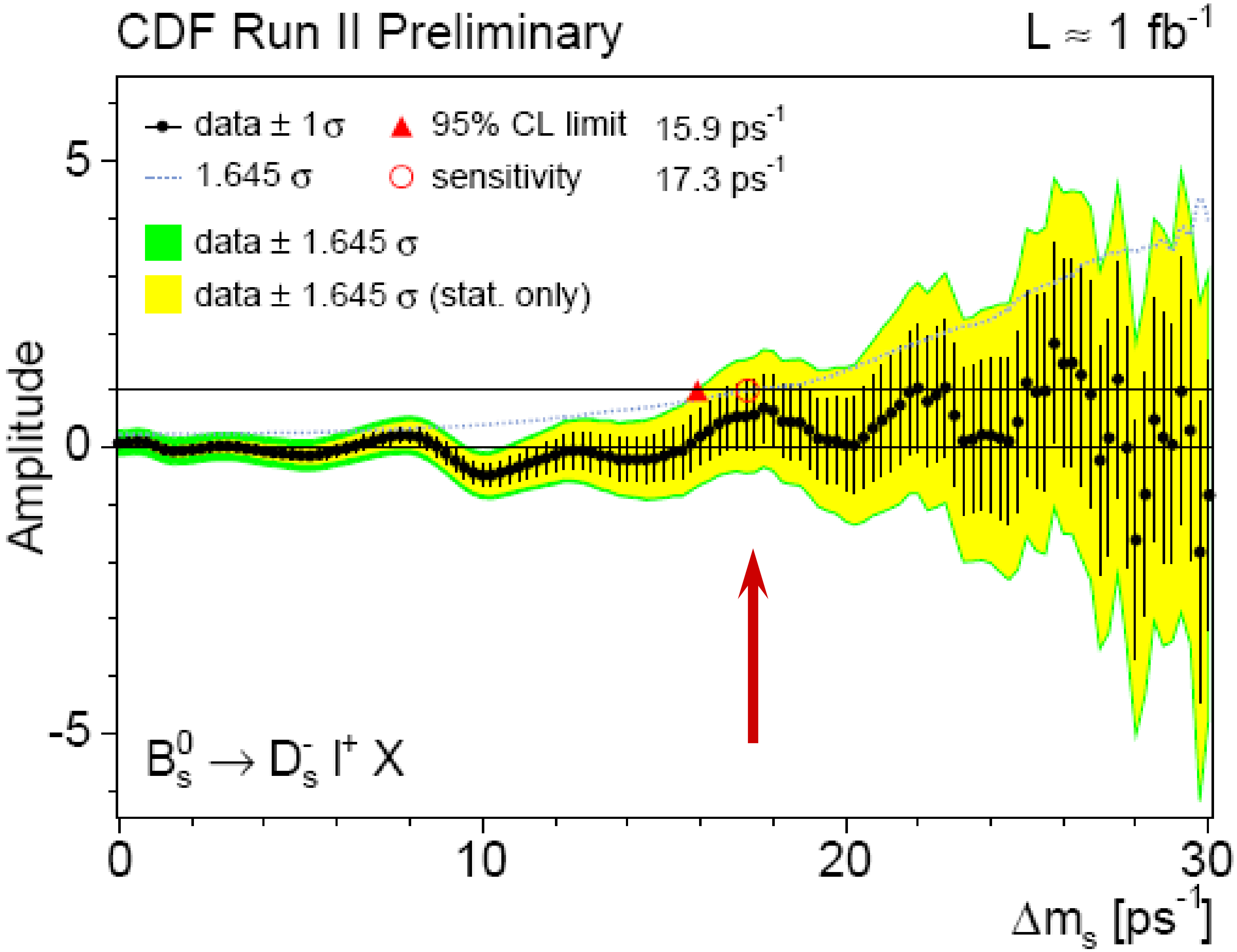
Semileptonic Scan: Period 3



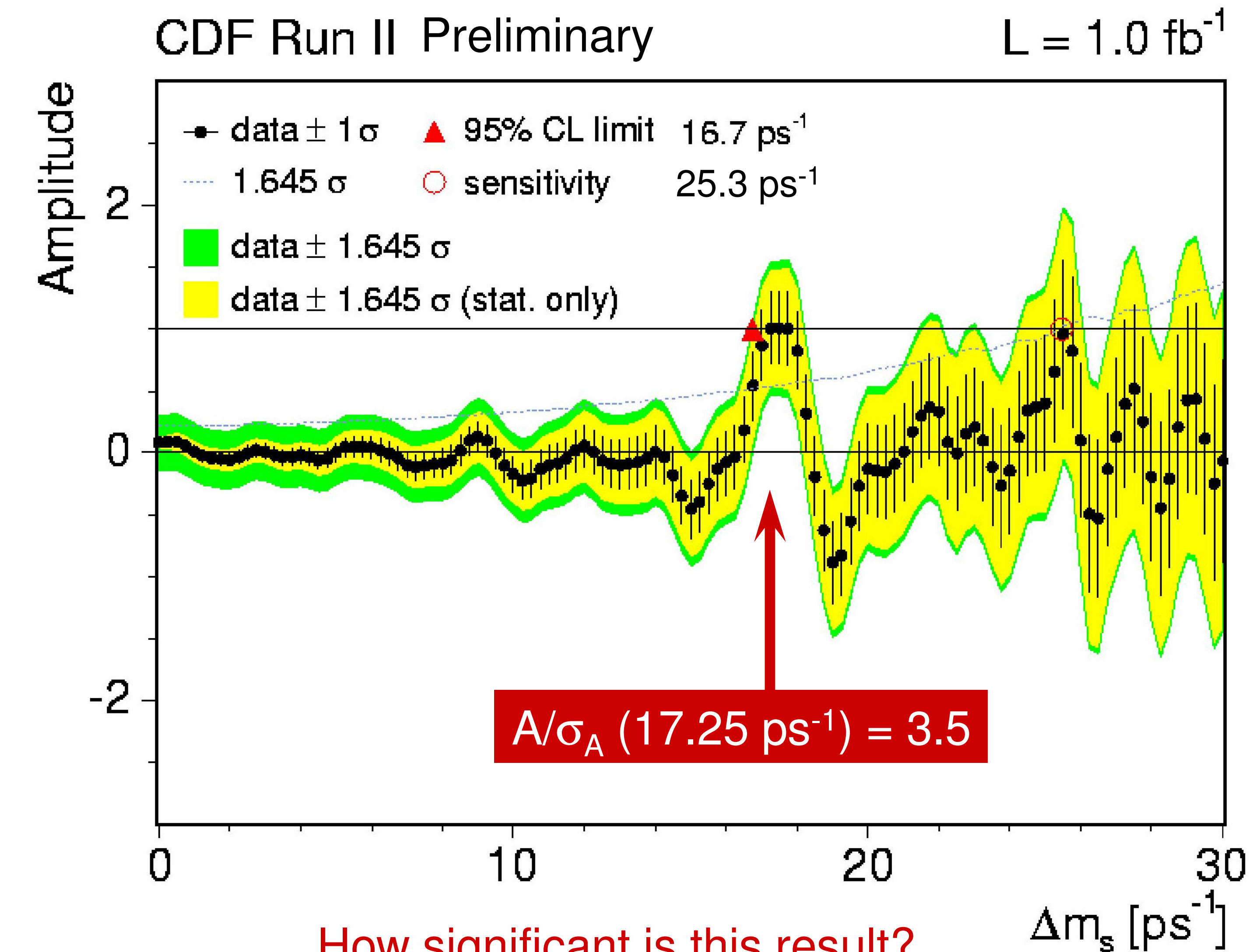
Hadronic Scan: Combined



Semileptonic Scan: Combined

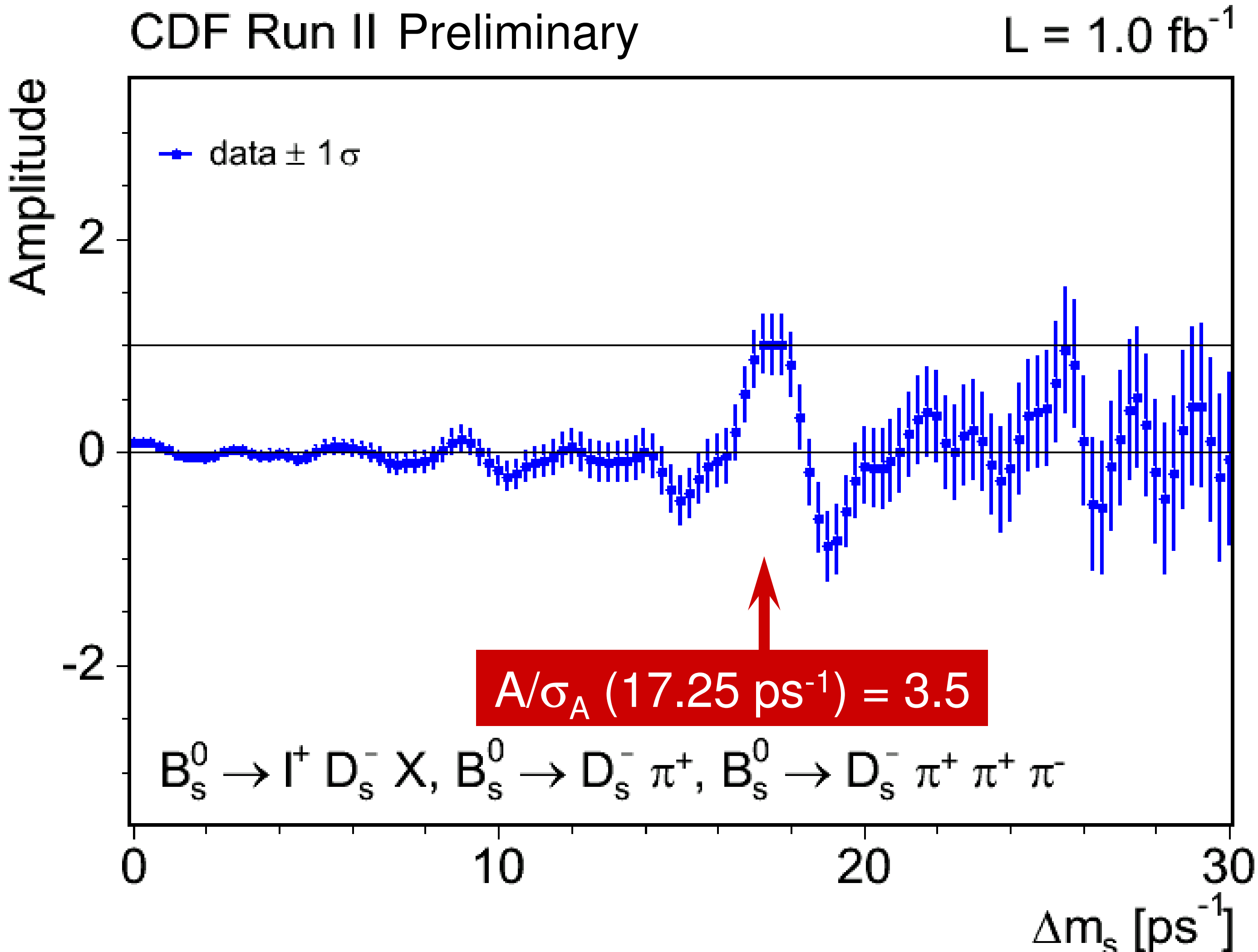


Combined Amplitude Scan



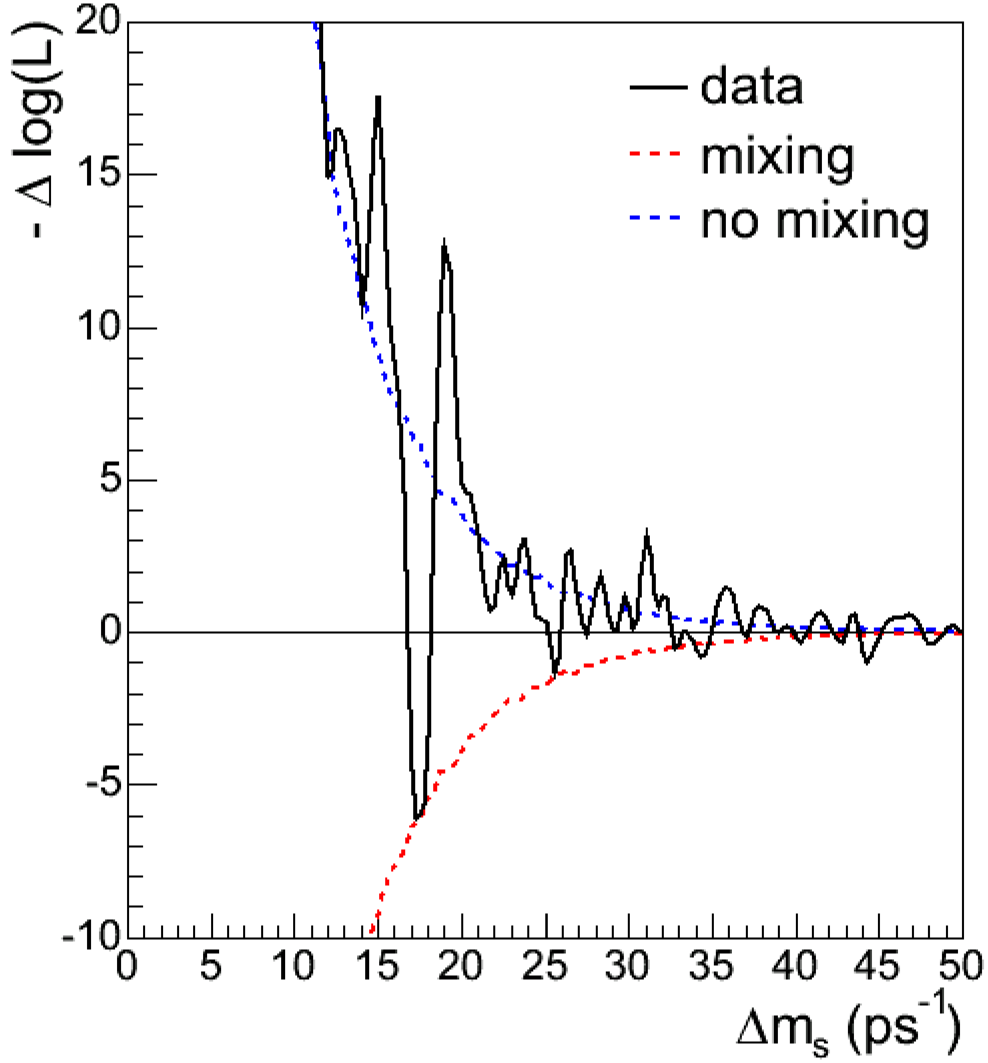
How significant is this result?

Combined Amplitude Scan



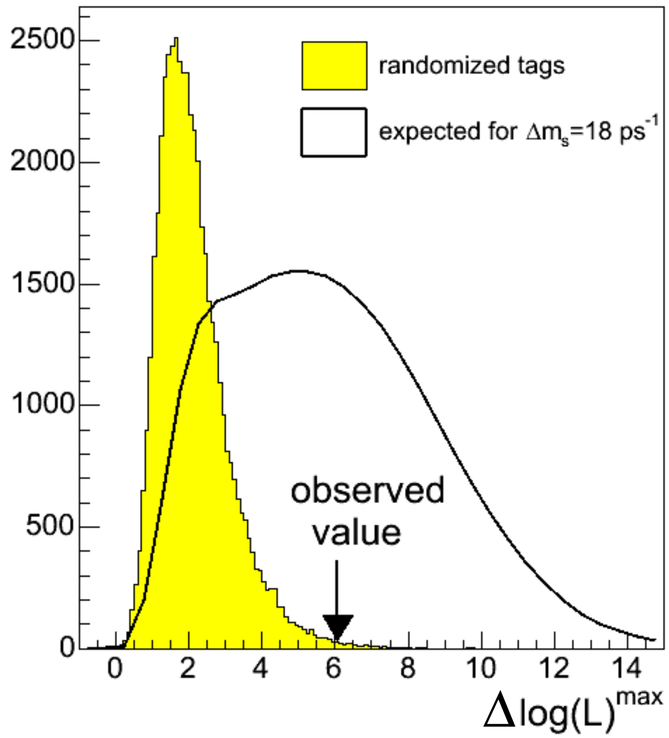
How significant is this result?

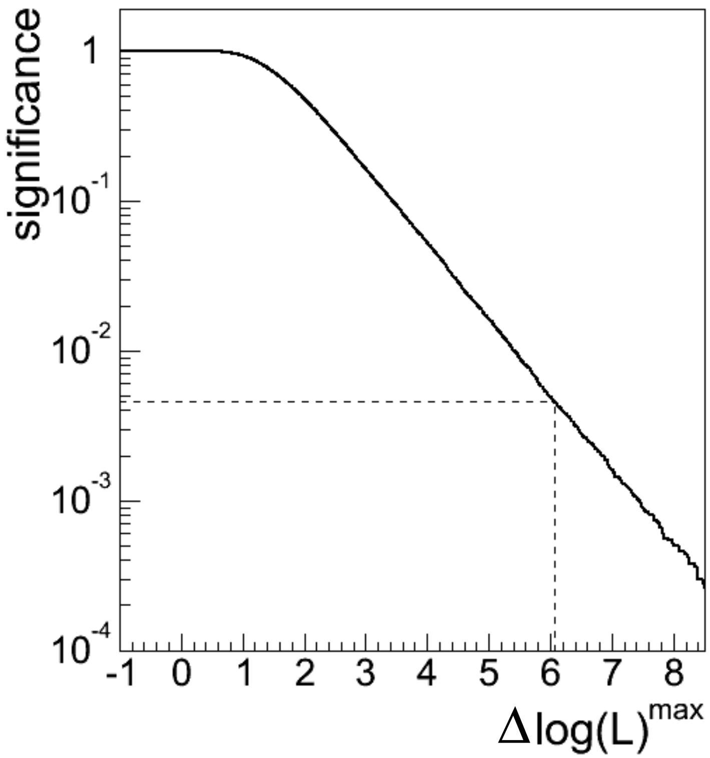
Likelihood Profile



Q: How often can random tags produce a likelihood dip this deep?

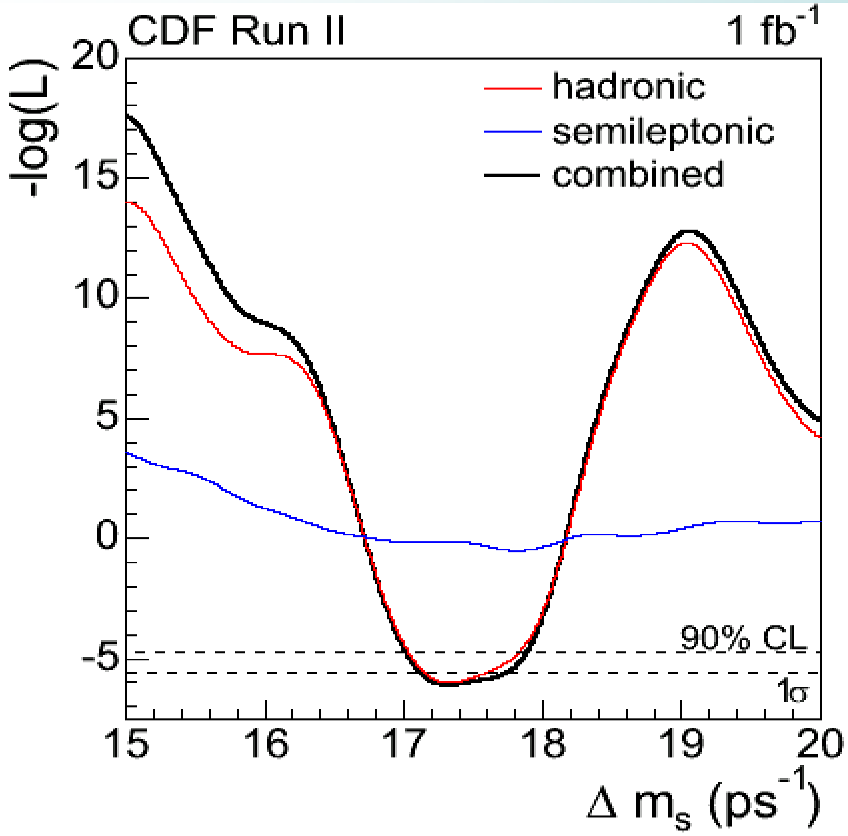
Likelihood Significance





- randomize tags 50 000 times in data, find maximum $\Delta\log(L)$
- in 228 experiments, $\Delta\log(L) \geq 6.06$
- probability of fake from random tags = 0.5% $\rightarrow$ measure Δm_s!

Measurement of Δm_s



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

the measurement is already very precise! (at 2.5% level)

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

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

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

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

- inputs:
  - → $m(B^0)/m(B_s) = 0.9830$ (PDG 2006)
  - → $\xi = 1.21\,^{+0.47}_{-0.35}$ (M. Okamoto, hep-lat/0510113)
  - → $\Delta m_d = 0.507 \pm 0.005$ (PDG 2006)

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

- compare to Belle $b \rightarrow s\gamma$ (hep-ex/0506079):

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

Conclusions

- found signature consistent with B_s - B_s oscillations
- probability of fluctuation from random tags is 0.5%
- presented first direct measurement of the B_s - $\bar{B}_s$ oscillation frequency:

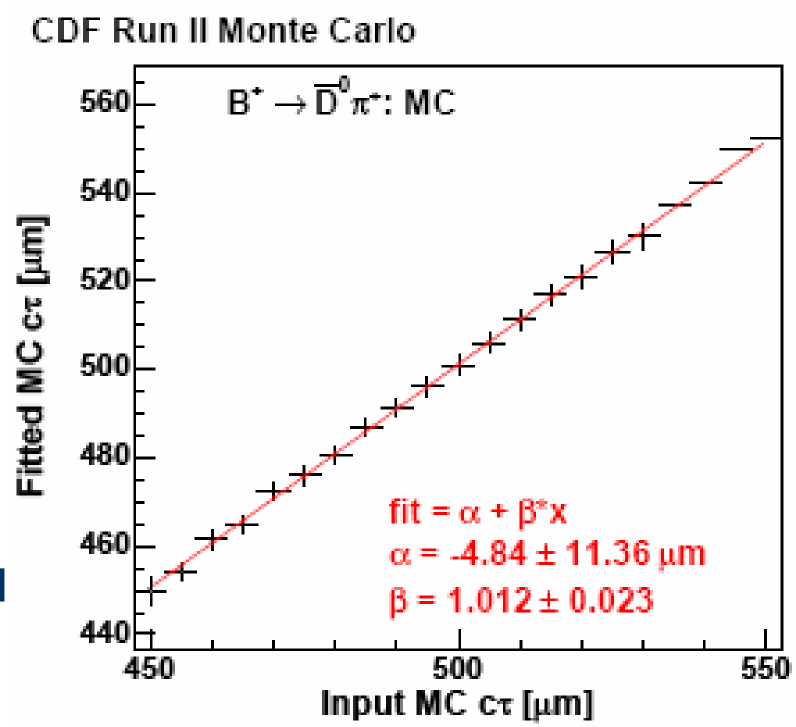
$$\Delta m_s = 17.33\,^{+0.42}_{-0.21}\,(\text{stat}) \pm 0.07\,(\text{syst})\ \text{ps}^{-1}$$

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

Backup Slides

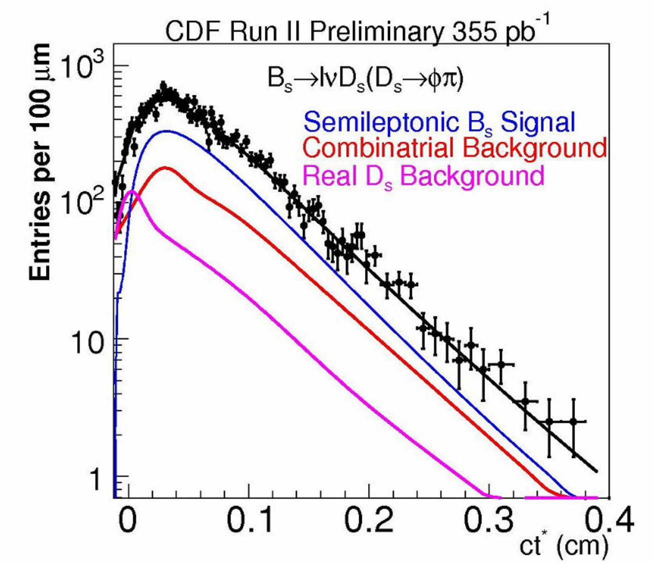
Does the MC bias the answer?

- efficiency function is derived from Monte Carlo
- the Monte Carlo is derived with an input lifetime
- does the input lifetime bias the fit outcome?
- test: fit many Monte Carlos with various input lifetimes
- derive efficiency function using one lifetime (500 μm)
- compare fit result to input lifetime
- observe no bias for ±50 μm
- measurement stat error ~7μ



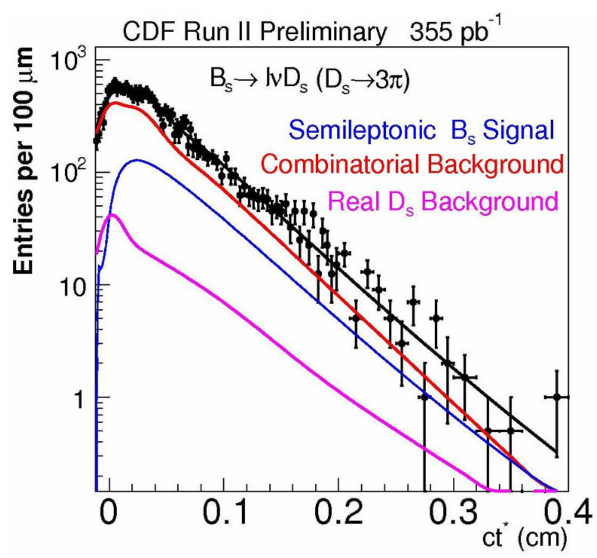
Semileptonic Lifetime Fits (Winter '05)

$D_s^- \to \phi\pi^-$



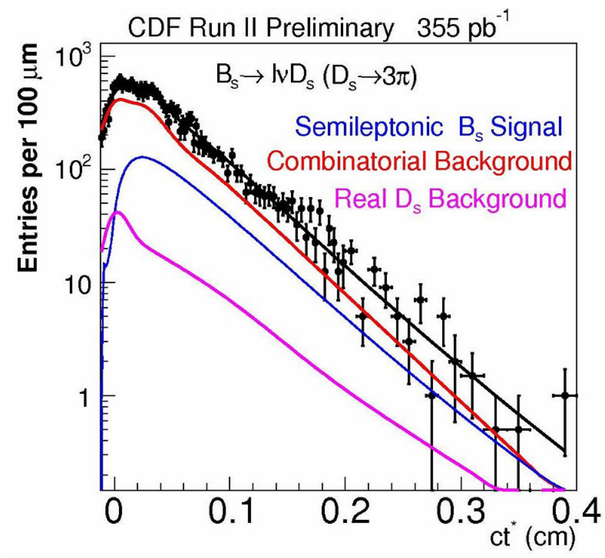
$c\tau = 455.9 \pm 11.9\ \mu m$

$D_s^- \to K^* K$



$c\tau = 413.8 \pm 20.1\ \mu m$

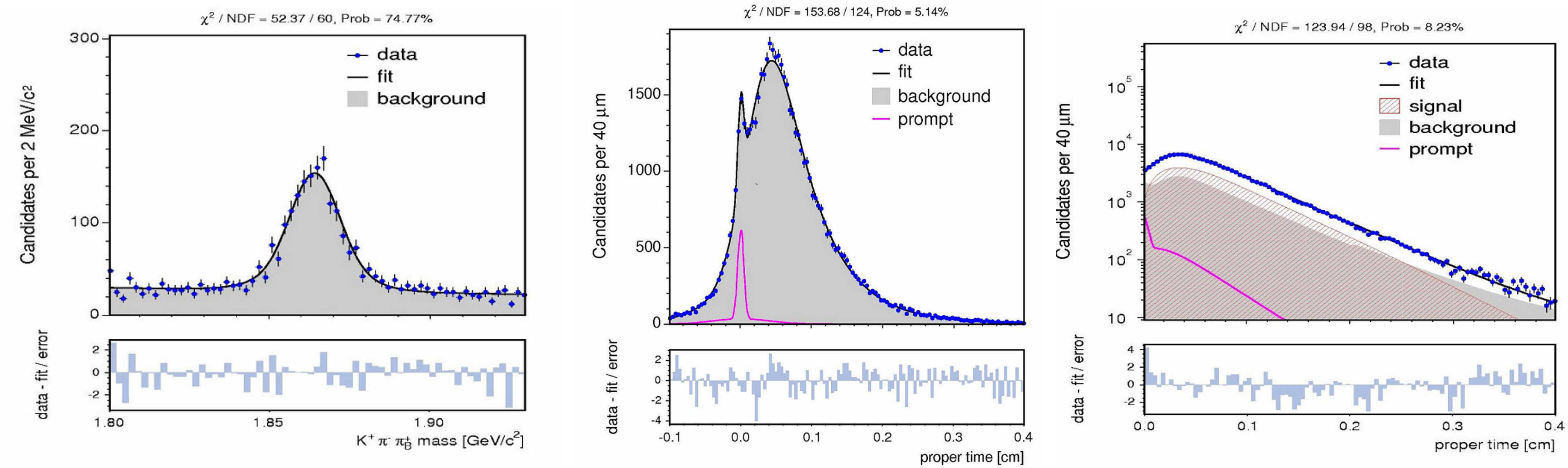
$D_s^- \to \pi^+\pi^-\pi^-$



$c\tau = 422.6 \pm 25.7\ \mu m$

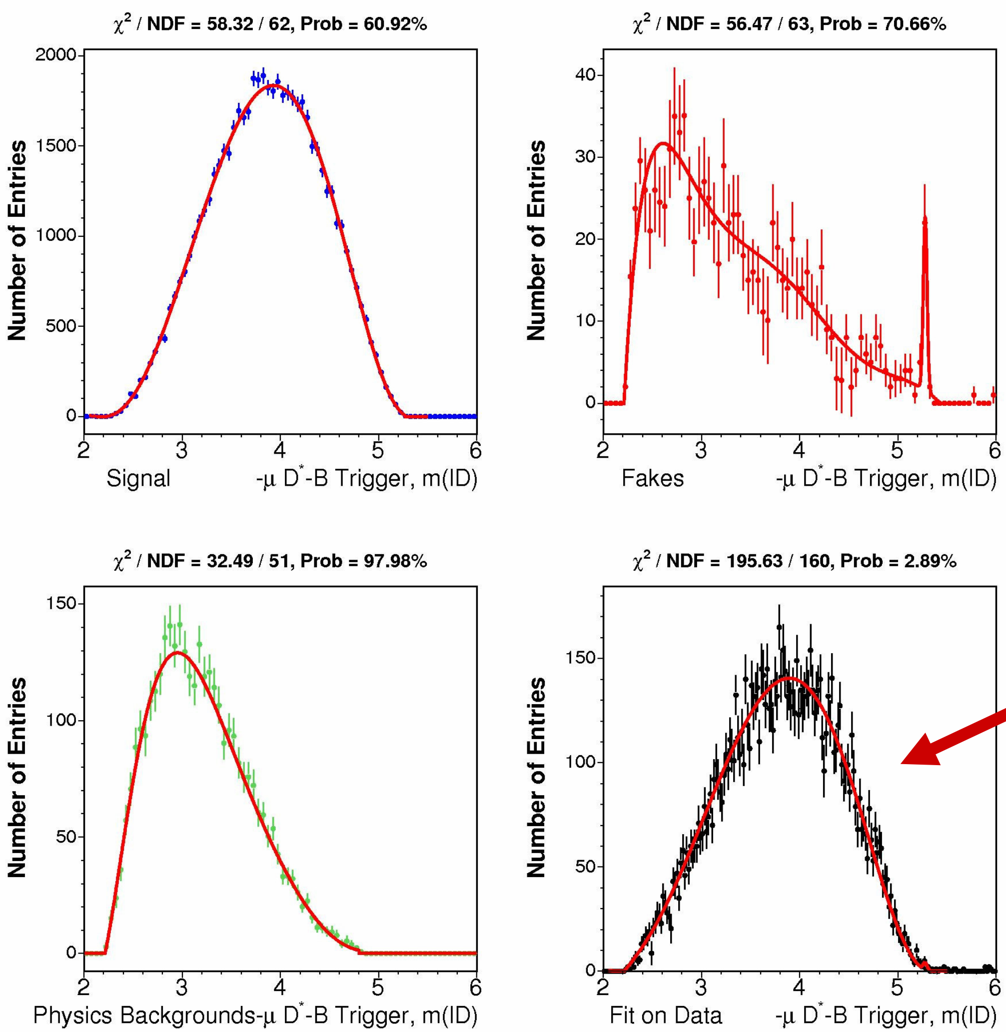
- B^0, B^+ lifetimes within 20 μm of world average values
- combined lD_s^- lifetime fit result: 445 ± 9.5 (stat) μm
- world average value: 438 ± 17 μm

“Prompt” Charm Background



- due to fake leptons, reconstruct some amount of prompt charm (D^-, D^0, D^{*-}) as B signal (in D mass signal region)
- can not disentangle from signal in any variable
- need to account for in lifetime, mixing fits
- extract shape from wrong-sign l^-D^- sample, use in fit

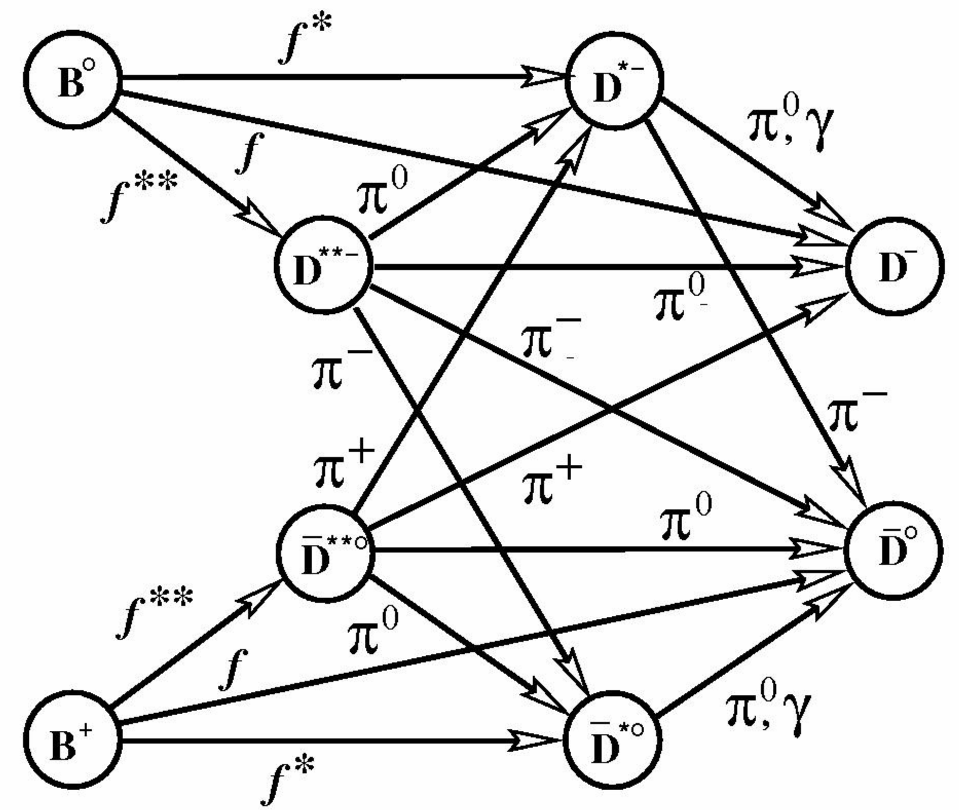
m(ID) fits



- signal distribution from Monte Carlo
- distribution for "fake" leptons from data
- physics background distribution from MC
- fit linear combination to sideband subtracted data to extract fractions

Cross-Talk

- problem:
- D^-, D^0 are a mixture of B^+, B^0
- when fitting for lifetimes and mixing amplitude, account for this effect in fitter

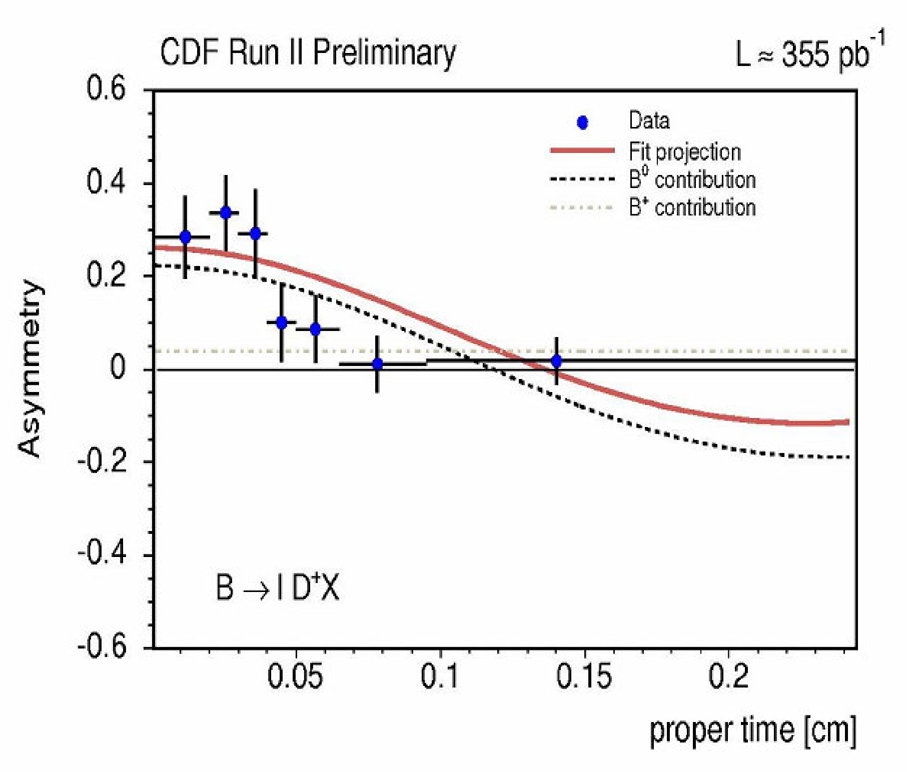


Tagger Calibration

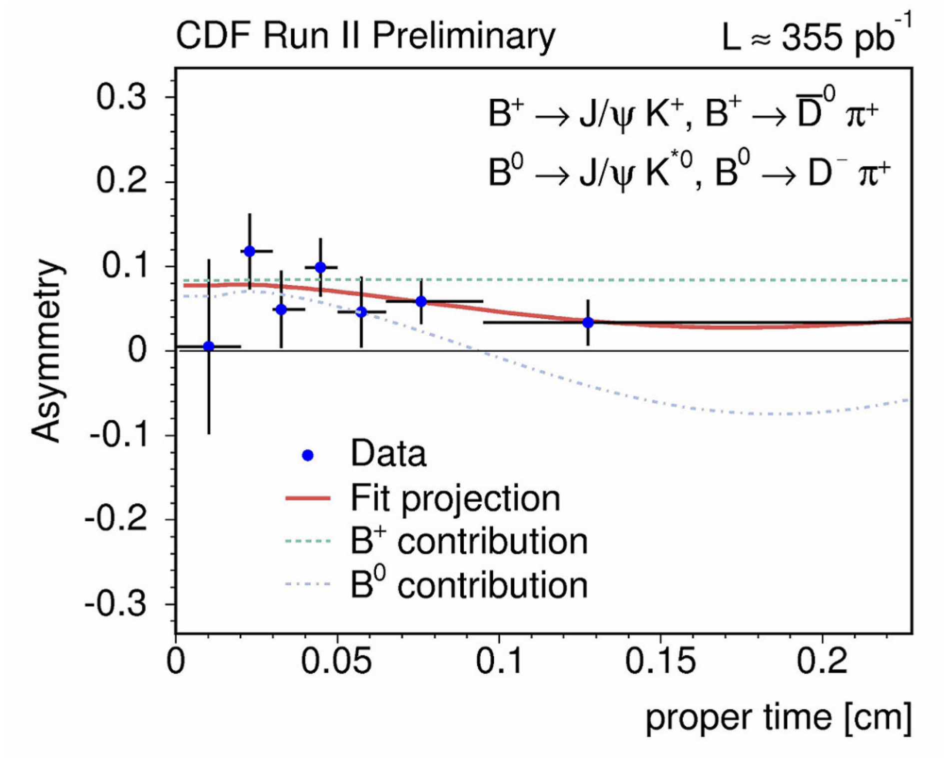
- taggers are parametrized in l+track sample
- kinematically different from final ($D_s\ \pi$, $l+D_s^-$)
- final tagger calibration:
- perform B^0 mixing fit in hadronic and semi-leptonic sample
- use per-event dilution, extract tagger scale factor:
- $p \sim \frac{1}{2}\,[1 \pm S_D\, D_i \cos(\Delta m_D\, t)]$
- use per-event corrected dilutions in $\Delta\, m_s$ fit
- for hadronic sample, final calibration in $D^{-/0}\pi$, $J/\psi\ K^{(*)}$
- for semileptonic sample, final calibration in $D^{-/0}\ l$, $D^{*-}\ l$

Δm_d Fits

semileptonic, lD^-, muon tag



hadronic, all channels, all tags

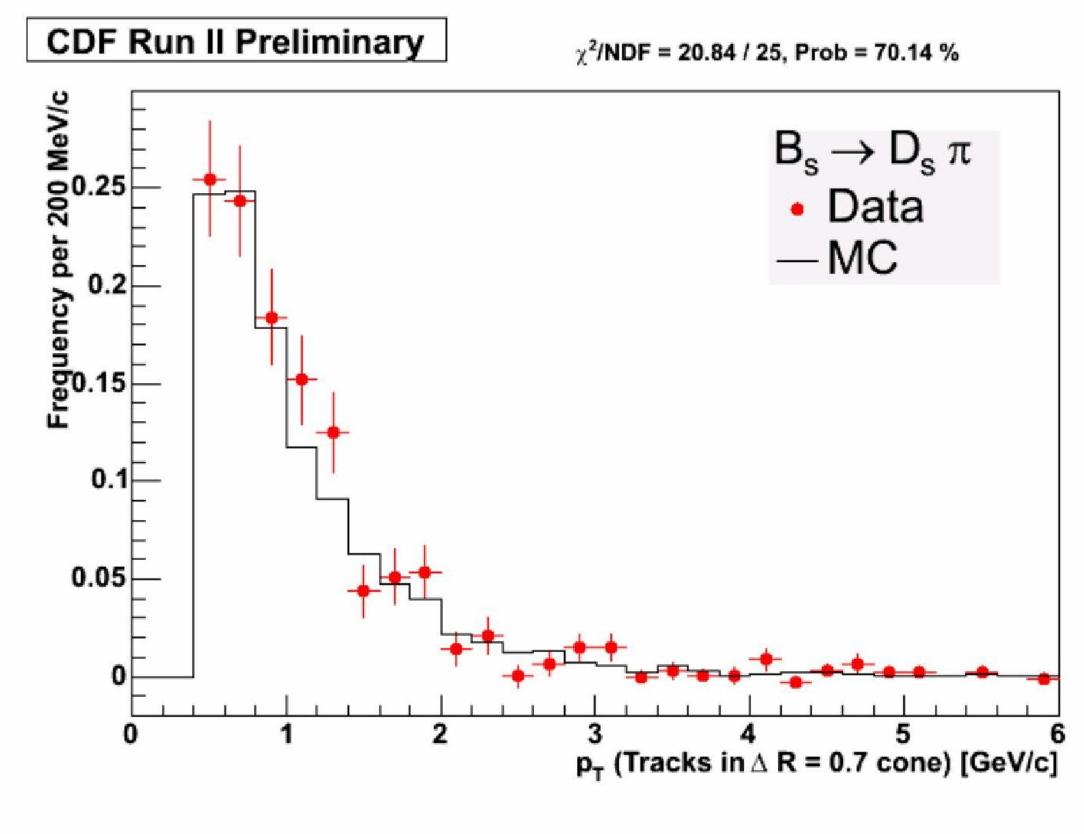


hadronic: $\Delta m_d = 0.503 \pm 0.063$ (stat) ± 0.015 (syst) ps^{-1}

semileptonic: $\Delta m_d = 0.497 \pm 0.028$ (stat) ± 0.015 (syst) ps^{-1}

Kaon Tagging

- no straight way to determine tagger dilution from data unless B_s mixing is observed
- but we need to know
- must use MC to measure dilution
- tune MC on B^0, B^+
- predict B_s



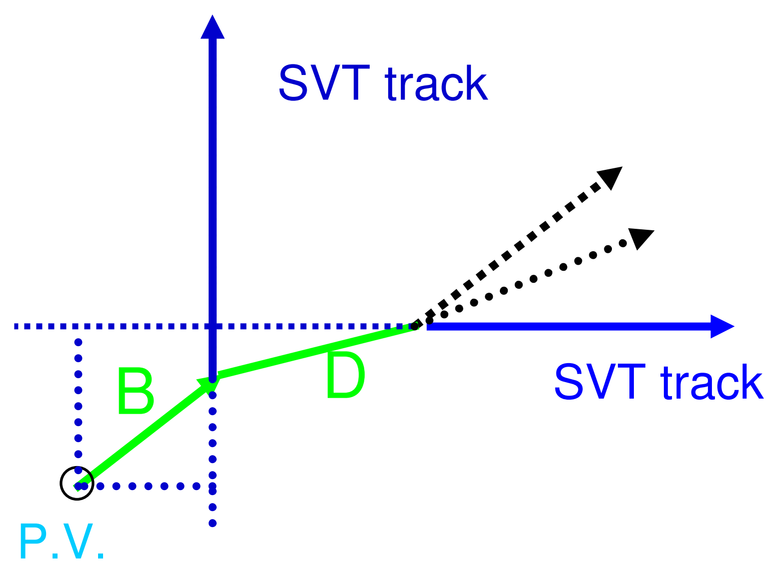
Roadmap of B_s Mixing Analysis

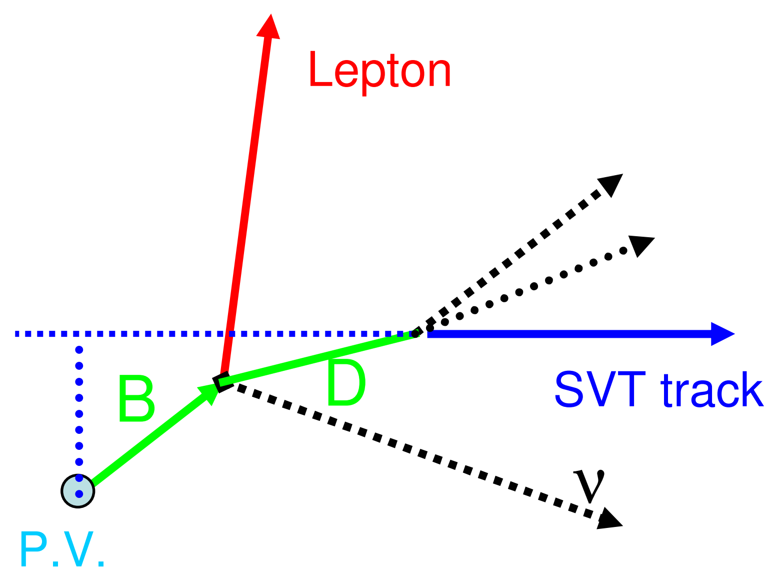
- Samples:
  - reconstruct B_s signals in samples triggered by SVT
  - optimize for $S/\sqrt{(S+B)}$
- Lifetimes:
  - SVT trigger sculpts lifetime distribution
  - develop method to correct for lifetime sculpting effects
  - fit for lifetimes in B^0, B^+, $B_s \rightarrow D\pi$
- Taggers
  - calibrate opposite side taggers to parametrize tagger D
  - use calibrated tagger D in fit for mixing
- Amplitude scan for B_s mixing - unbinned likelihood fit, utilizes:
  - per candidate estimate of proper decay time resolution
  - per candidate estimate of tagging power

SVT based Triggers

- hadronic channel
- require two SVT tracks
  - p_T>2GeV/c
  - $p_{T1}+p_{T2}$ > 5.5 GeV/c
  - opposite charge
  - 120 μm < SVT IP < 1 mm
  - Lxy > 200 μm

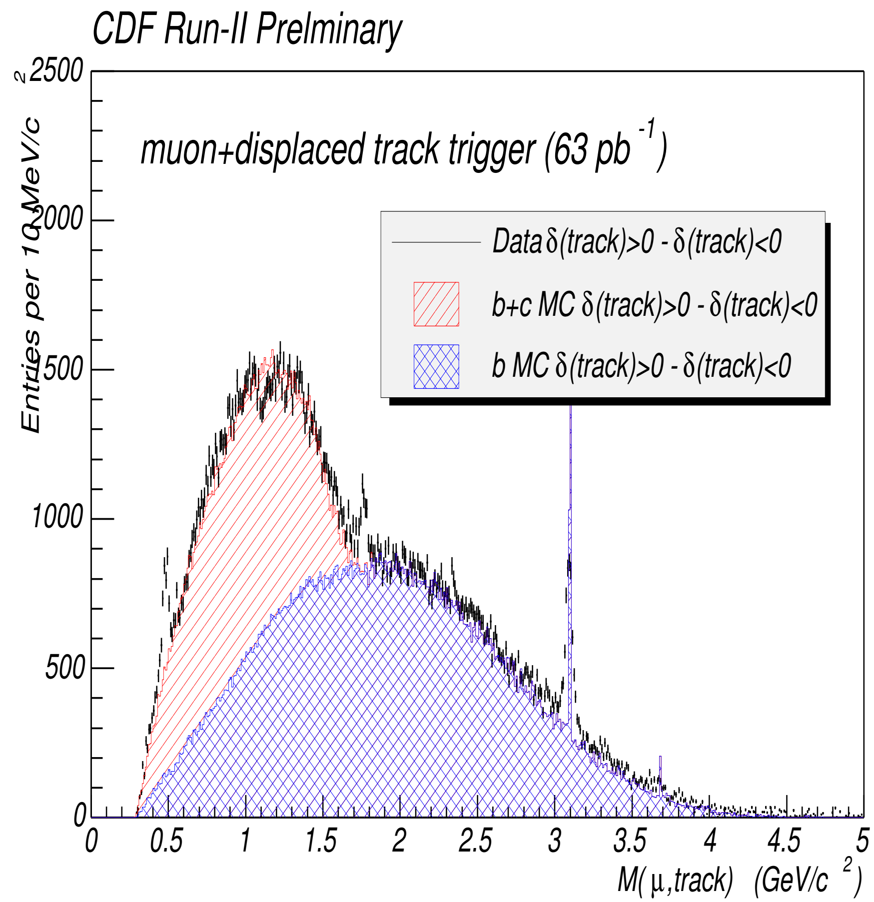
- semileptonic channel
- require 1 Lepton + 1 SVT track
  - 1 muon/electron p_T> 4 GeV
  - 1 additional SVT track with
    - p_T > 2 GeV
    - 120 μm < SVT IP < 1 mm





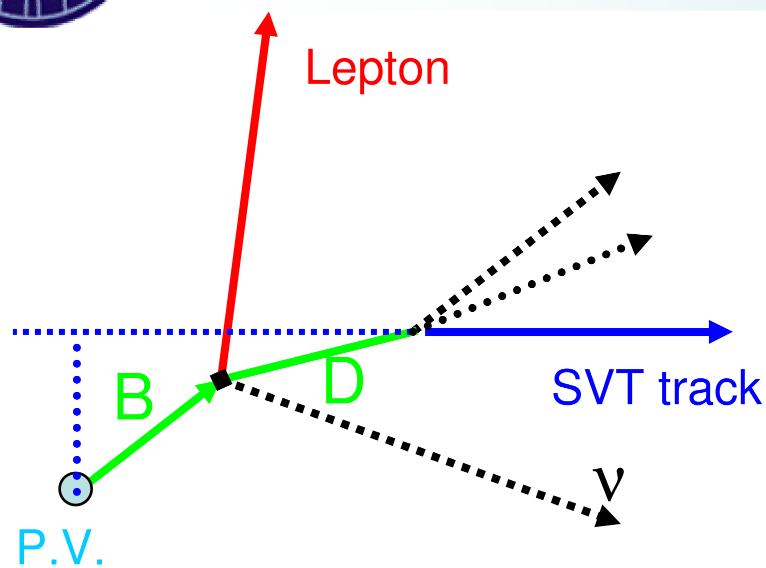
Calibrating Opposite Side Tags

- Statistical Power of the tag: εD^2
  - Tagging efficiency (ε)
  - Tagging dilution ($D = 1-2w$)
    - w = mistag rate
- "Binned Tagger"
  - Tag1: ε_1=50%, $D_1 = 0.5$
  - Tag2: ε_2=50%, $D_2 = 0.1$
  - $\langle D \rangle = (D_1 + D_2)/2 = 0.3$
  - $\sqrt{\langle D^2 \rangle} = 0.36$
- Dividing events into different classes based on tagging power improves εD^2
- Calibration the tagger performance requires high statistics



- inclusive B →track+lepton
- 1.4 M events of flavor specific B

Hadronic vs Semileptonic Signals

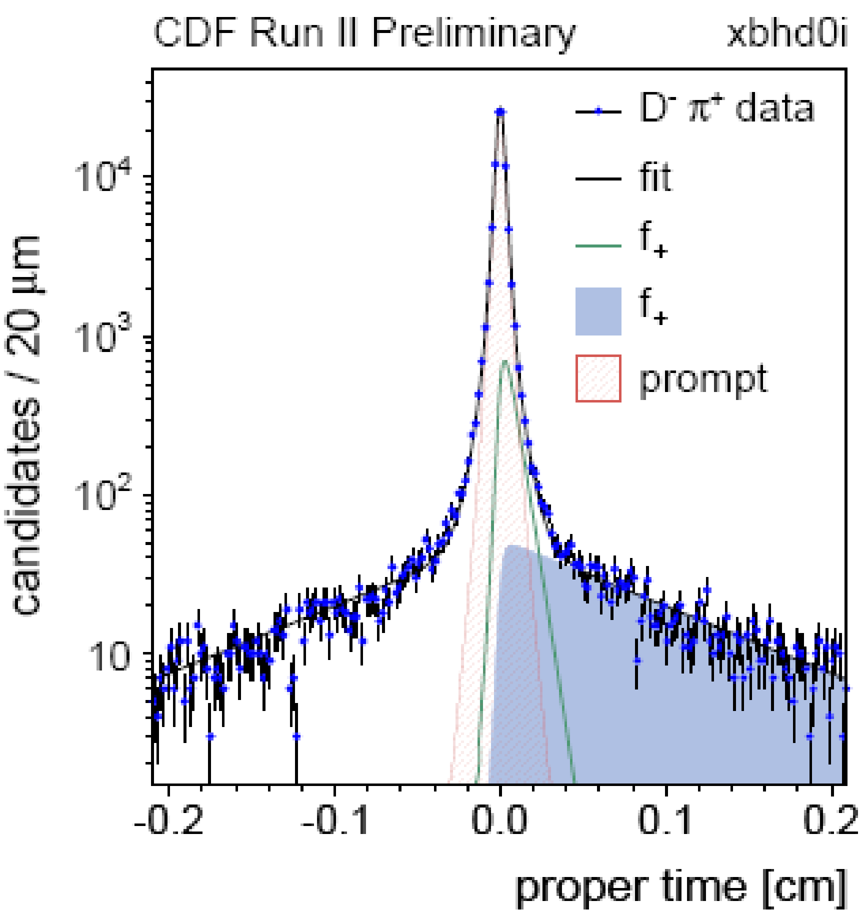


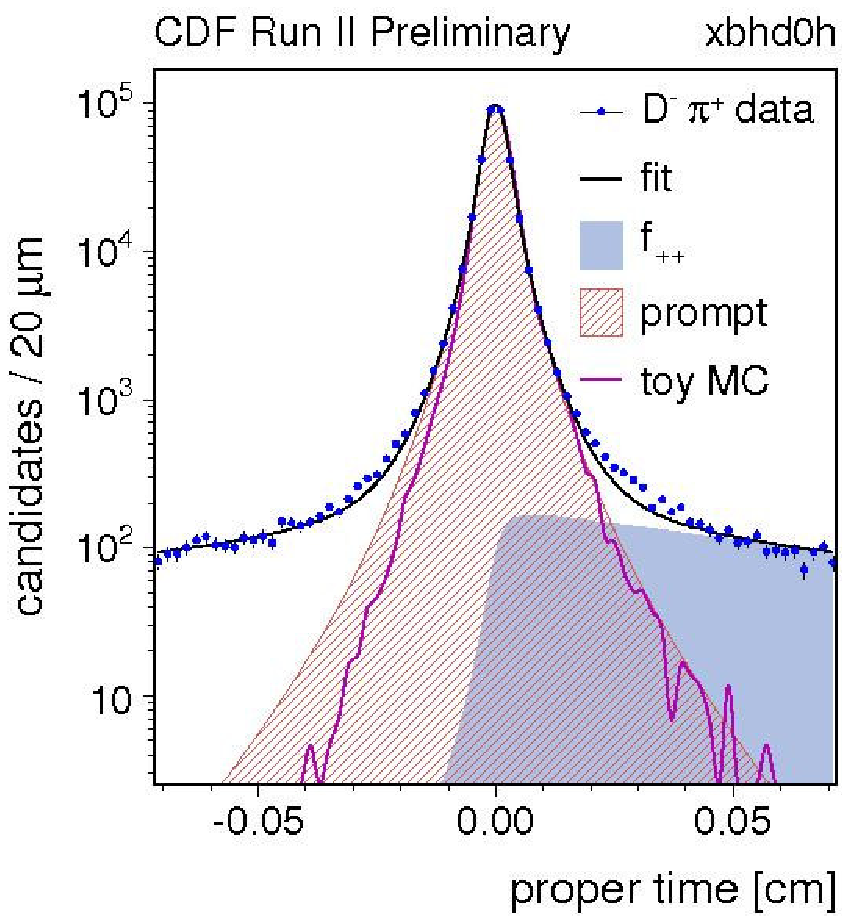
- Hadronic decays:
- full B momentum available
- signature: mass of B decay

- Semileptonic decays:
- part of B momentum "missing"
- signature: l + mass of D decay
- correct l,D charge correlations
- "hidden" contributions from:
  - real D meson + fake lepton
  - real D meson + unrelated lepton
- hadronic trigger sample:
- require lepton ID on decay track
- "B Trigger" – lepton triggered SVT
- "D Trigger" – D daughters trigger

- B^0, B^+ decays: high statistics, calibrate lifetimes, taggers
- B_s decays: low statistics, Bs mixing sample

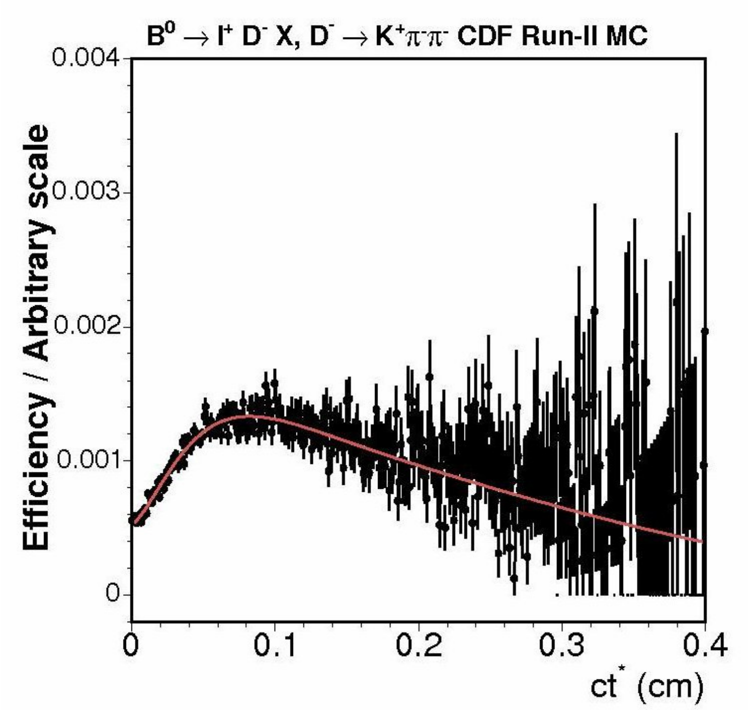
Non-Gaussian Tails

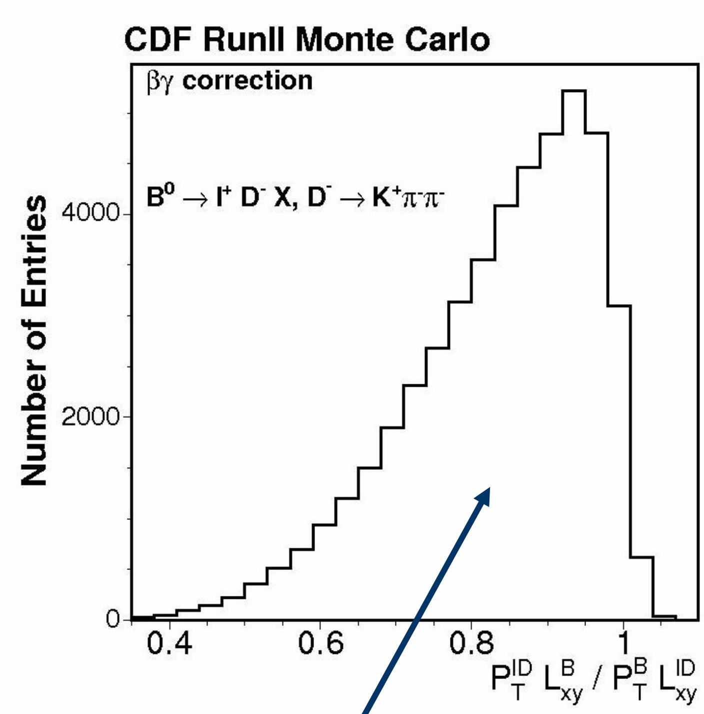




- amplitude corrected for effects of non-Gaussian tails
- correction derived from toy Monte Carlo, tuned to reproduce data

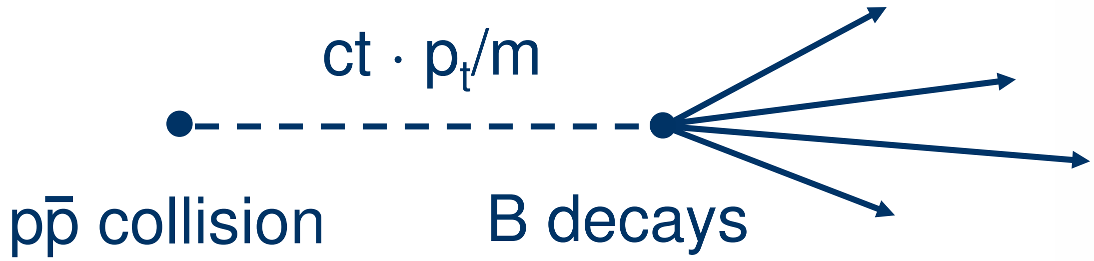
Lifetime Measurement: Semileptonic Subsample

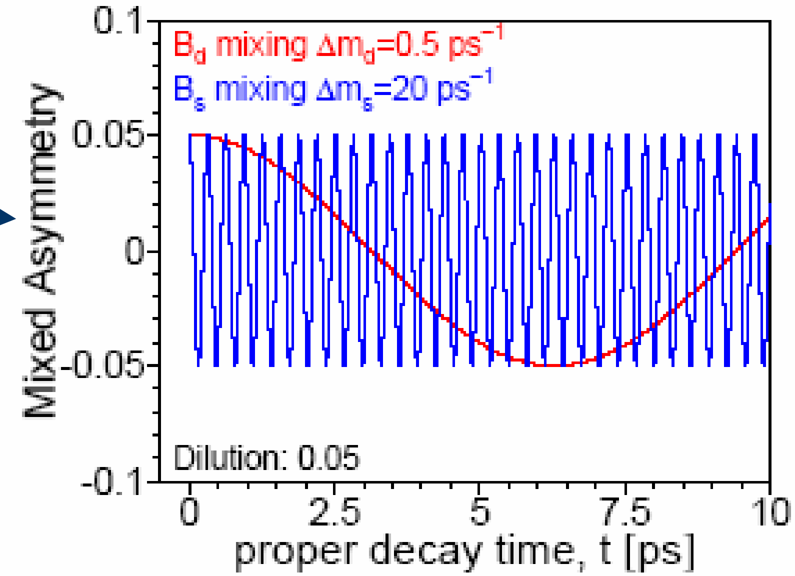




- in addition to SVT bias, correct for missing energy (K-factor)
- bin K-factor in l+D invariant mass to obtain narrow K-factor distributions

B Mixing Measurement





- determine decay flavor
- identify B_s production flavor
- measure proper decay time

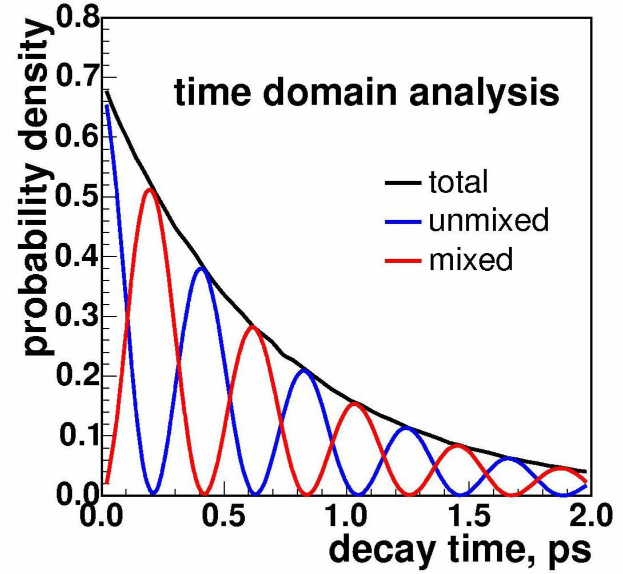
$$A_{mix}(t) = \frac{N_{unmix}(t) - N_{mix}(t)}{N_{unmix}(t) + N_{mix}(t)} = D \cdot \cos(\Delta m t)$$

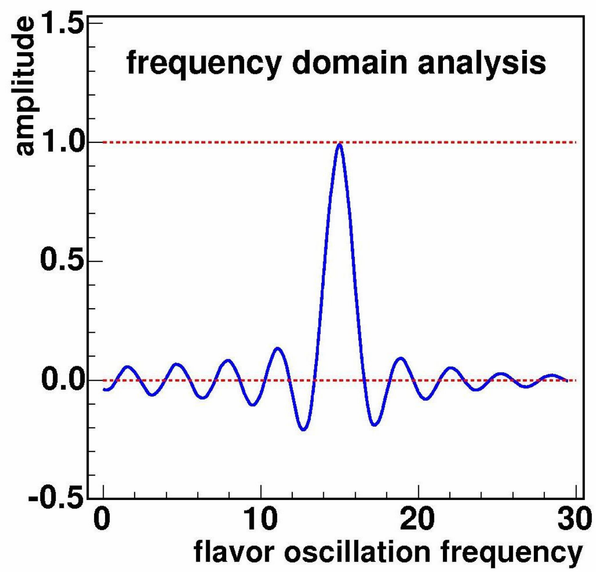
- oscillation amplitude D = 1 – 2w, w = mistag rate
- Moser, Roussarie (NIMA 384 491):

$$\text{Signif} = \sqrt{\frac{N\epsilon D^2}{2}e^{-\frac{(\Delta m_s \sigma_t)^2}{2}}}\sqrt{\frac{S}{S+B}}$$

Fourier Analysis

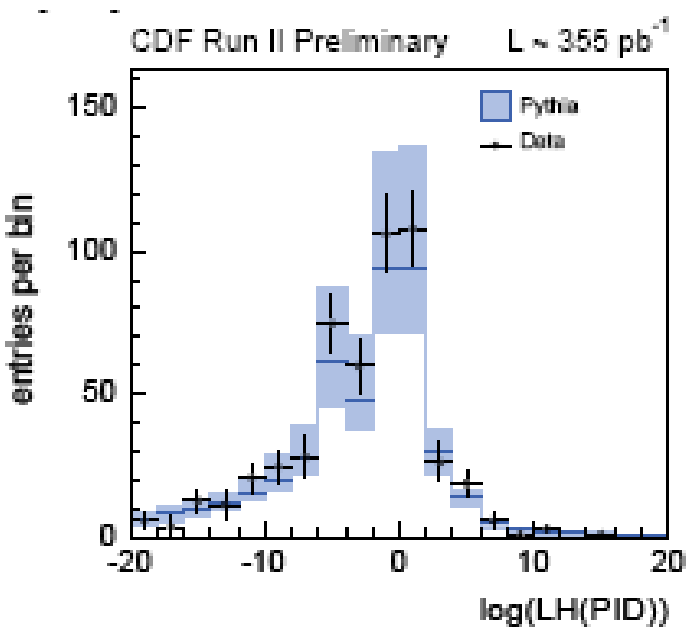
- two domains for mixing fit:
  - time: fit for cosine wave
  - frequency: examine spectrum
- Time Domain Approach:
  - fit for Δm_s in $p(t) \sim (1 \pm D \cos \Delta m_s t)$
  - good for measuring Δm_s
- Frequency Domain Approach:
  - fit for A in $p(t) \sim (1 \pm A\, D \cos \Delta\, m_s t)$
  - "scan" through different values of Δm_s
  - signal: Δm_s for which A = 1
  - good for exclusion, combining measurements





Calibrating SSKT (1)

- use combined PID likelihood, select most “kaon-like” track as tagging track
- parametrize dilution based on maximum PID likelihood value
- verify kinematic distributions (p_T, tagging track p_T, multiplicity, isolation) of light B mesons in Pythia simulation
- verify particle ID simulation
- test for dependences on:
  - fragmentation model
  - bb production mechanisms
  - detector/PID resolution
  - multiple interactions
  - pid content around B meson
  - data/MC agreement



- Final test: cross-check tagging power against high statistics light B decays

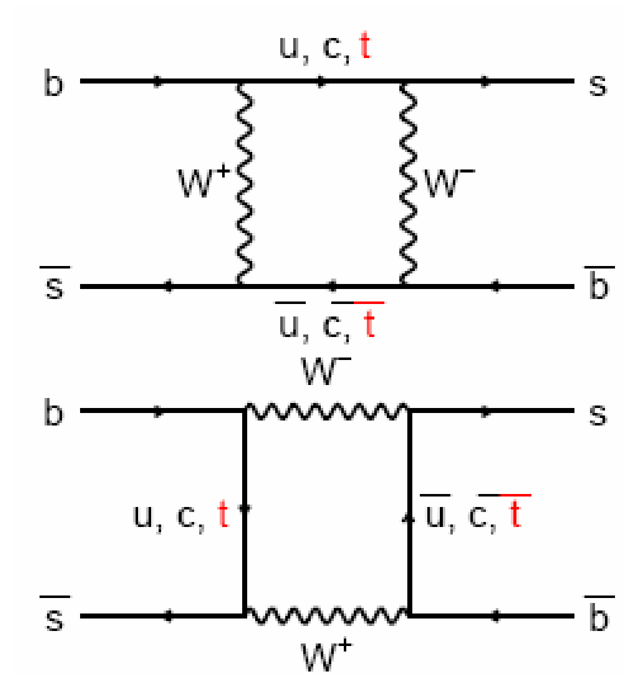
B Mixing in the Standard Model

- Within the SM
  - B_s mixing: box diagram

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

- $\Delta m_d = 0.510 \pm 0.005\ ps^{-1}$ (HFAG 2005)
  - $f^2_{Bd} B_{Bd} = (228 \pm 30 \pm 10\ \text{MeV})^2$
  - Lattice QCD calculation
  - $|V_{td}|$ determination limited at ~15%
- Ratio between Δm_s and Δm_d

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



- Many theoretical uncertainties are cancelled in the ratio
  - $\xi = 1.21 \pm 0.04 \pm 0.05$
  - Determine $|V_{ts}|/|V_{td}|$~5% precision

Unitarity Triangle

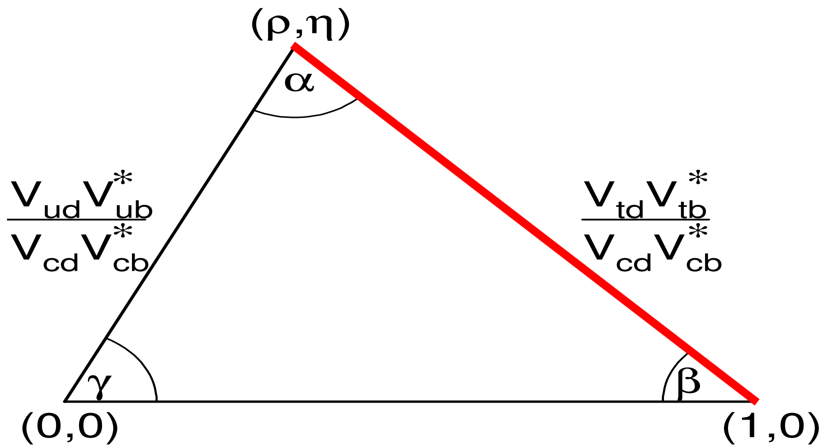
- CKM Matrix (Wolfenstein parameterization)

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

- Unitarity of CKM Matrix

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

- Unitarity Triangle



- $|V_{cb}|=|V_{ts}|$

$$\left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| = \frac{|V_{td}|}{|V_{ts}|} \times \frac{1}{|V_{cd}|}$$

- $|V_{cd}|$ is known to ~5% precision
  - 0.224 ± 0.012
- Primary goal: precise determination of one side of the Unitarity Triangle

Semileptonic Lifetime Results

	Lifetime (ps)
B_s:$D_s \rightarrow \phi\pi$	1.51 $\pm$ 0.04 stat. only
B_s:$D_s \rightarrow K^*K$	1.38 $\pm$ 0.07 stat. only
B_s:$D_s \rightarrow \pi\pi\pi$	1.40 $\pm$ 0.09 stat. only
B_s combined	1.48 $\pm$ 0.03 stat. only

- lifetimes measured on first 355 pb^{-1}
- compare to World Average: B_s: (1.469 $\pm$ 0.059) ps

Introduction

- matter – antimatter oscillation
- extremely fast process: ~2.8 trillion Hz
- process speed makes it challenging
- Tevatron experiments are the current world authority

- quark flavor mixing process $\rightarrow$ measurement contributes to our understanding of the CKM matrix