Measurement of the B_s^0-$\bar{B}_s^0$ Oscillation Frequency

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Argonne National Laboratory, June 14th 2006

History *a 20 year quest*

1987

first B^0 mixing measurements: UA1 and Argus
CLEO confirms results 2 years after

1990's

inclusive B mixing measurements from LEP
establish B_s mixing

1993

First time dependent measurements
of Δm_d and lower limit on Δm_s by ALEPH

1999

CDF Run I result: $\Delta m_s > 5.8$ ps^{-1}, sens. 5.1 ps^{-1}

2000's

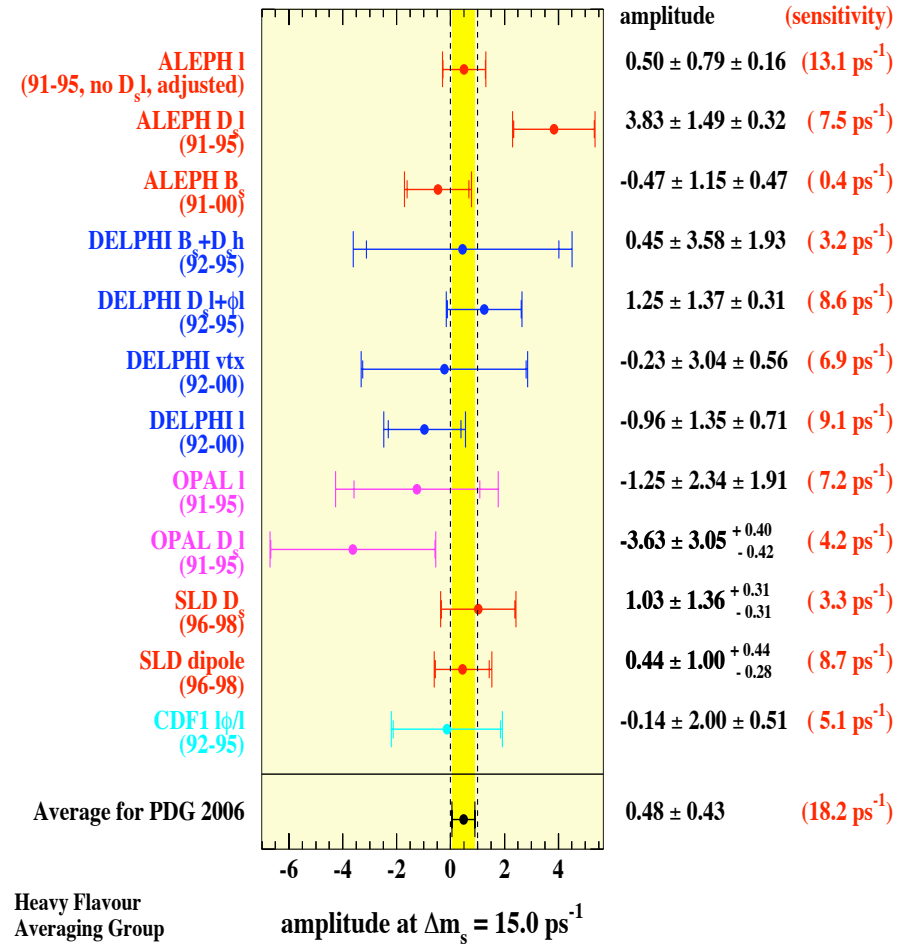
DØ recently reports direct bound

$\Delta m_s \in [17, 21]$ps^{-1} at 90% CL, sens. 14.1 ps^{-1}

CDF Run II

February 2005: sens. 8.4 ps^{-1} (limit 7.9 ps^{-1})
October 2005: sens. 13.0 ps^{-1} (limit 8.6 ps^{-1})
Now: sensitivity 25.8 ps^{-1} !

results from LEP, SLD, CDF I



$\Delta m_s > 14.4$ ps^{-1} @ 95%CL ↔ sensitivity 18.2 ps^{-1}

[PDG 2006]

Flavor Oscillations

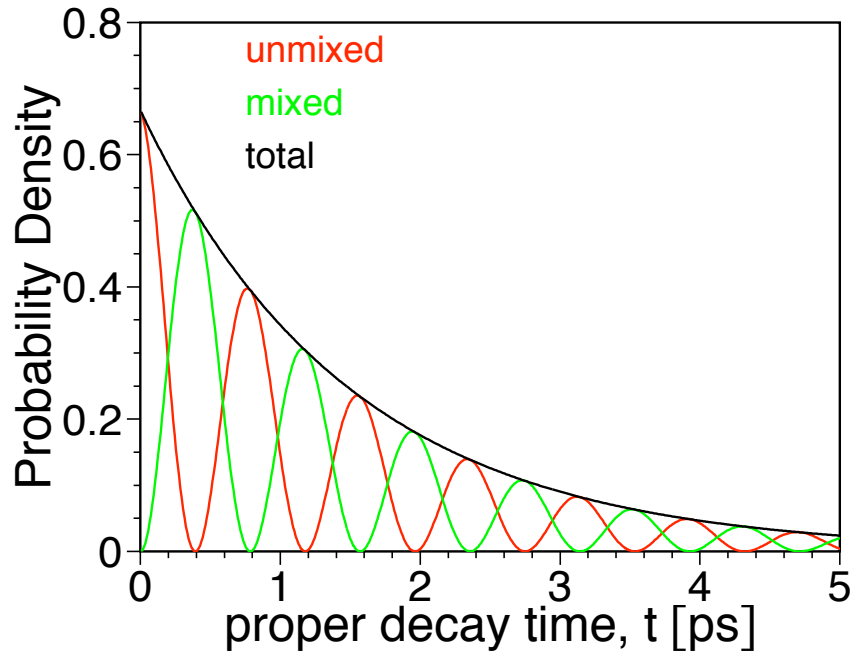
- neutral mesons undergo particle-antiparticle oscillations
- two-state system

$$\{|B(\bar{b}s)\rangle, |\bar{B}(b\bar{s})\rangle\}$$

- two mass eigenstates

$$\{|B_H\rangle, |B_L\rangle\}$$

  - separately evolve in time



- mass difference

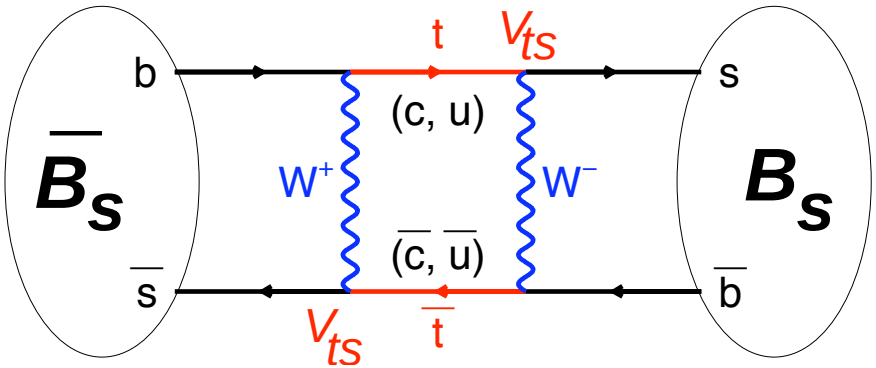
$$\Delta m = M_H - M_L$$

$$\mathcal{P}(B \to \bar{B}) \sim \frac{e^{-t/\tau}}{2\tau}(1 - \cos \Delta m\, t)$$

determines oscillation frequency of the system

In the Standard Model

- Mixing occurs via 2nd order flavor changing weak transitions



$$\Delta m_q \propto |V_{tq}|^2$$

- Ratio of B_s^0 and B_d^0 oscillation frequencies

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B^0}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

allows precise determination of CKM elements

- Δm_d measured to high precision
- Δm_s not been measured until now

Flavor Parameters CKM Matrix

CKM Matrix Wolfenstein parameterization

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

- CKM Matrix unitarity condition

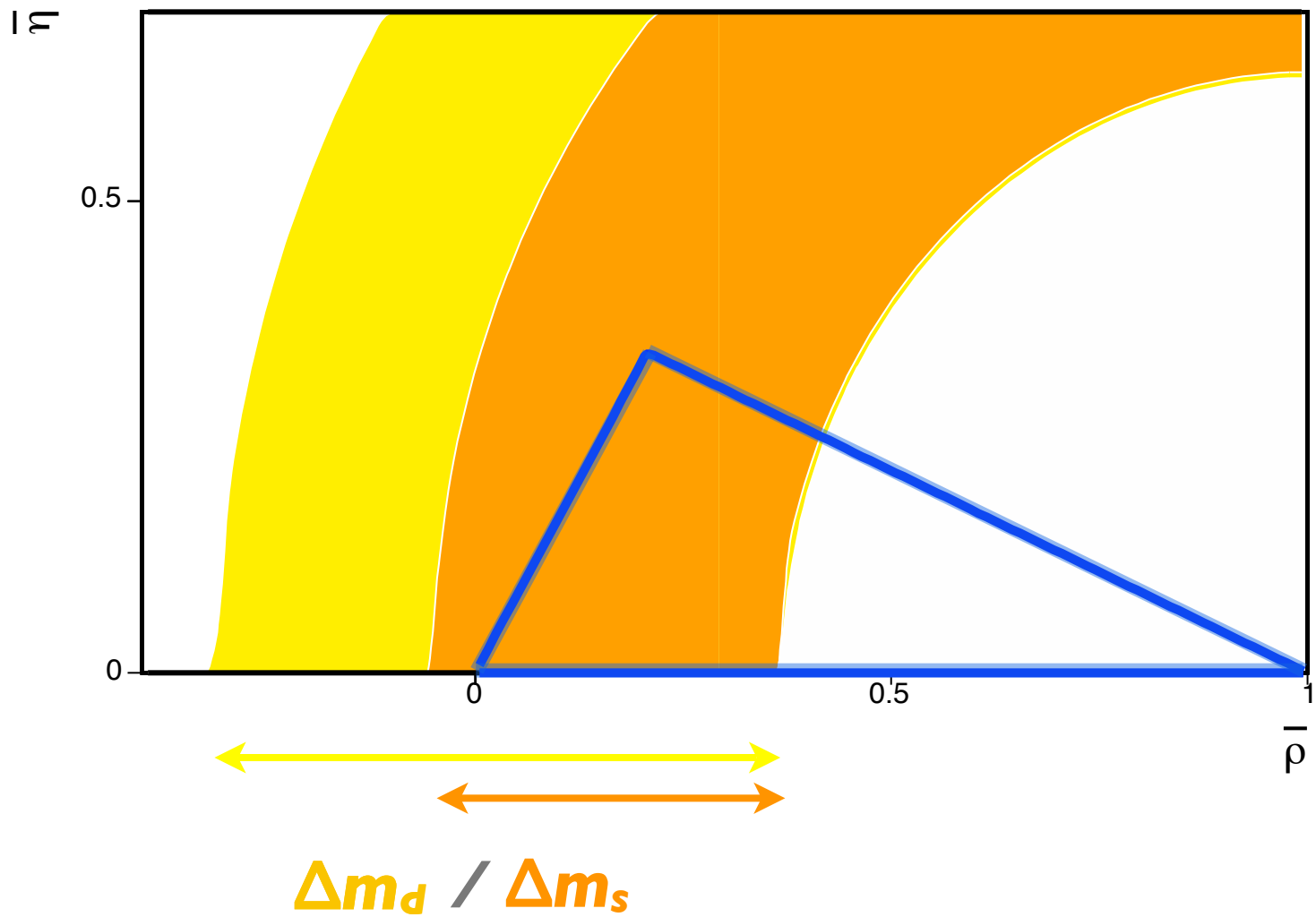
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

may be represented as a triangle in complex plane

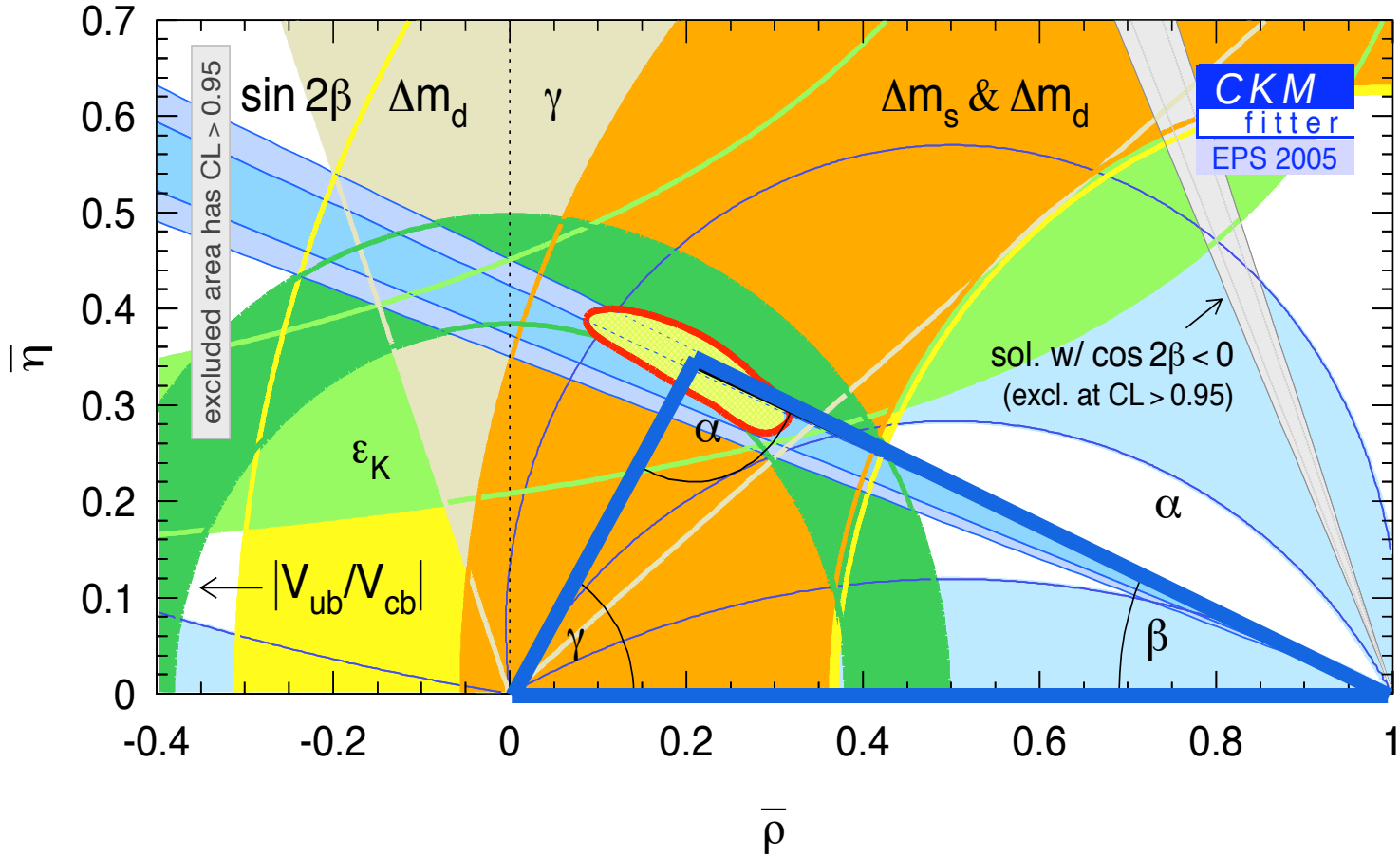
- in terms of re-scaled ρ and η parameters

$$\bar{\rho} = (1-\lambda^2/2)\,\rho \qquad \bar{\eta} = (1-\lambda^2/2)\,\eta$$

The Beauty Unitarity Triangle



Full UT/CKM Fit

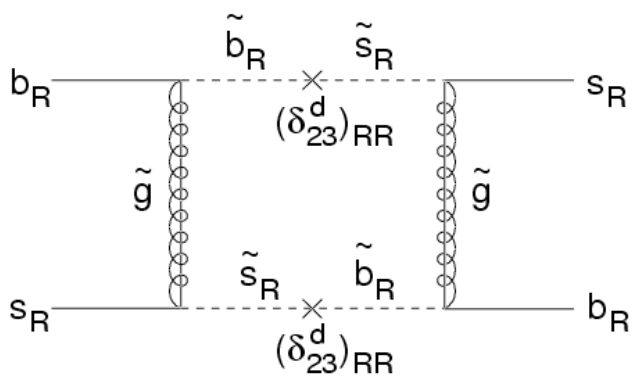


CKM Fit before Δm_s direct measurement

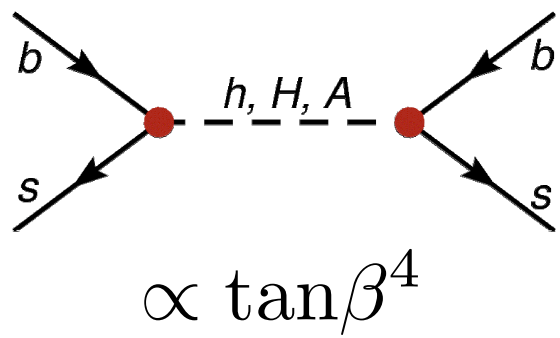
Probe of New Physics

- Additional virtual particles change Δm_s from SM expected value
- Measured value can be used to restrict model parameters

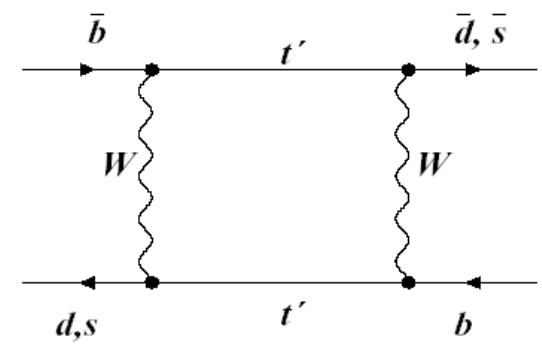
Examples:



[Phys. Rev. D **69** 0904024 (2004)]

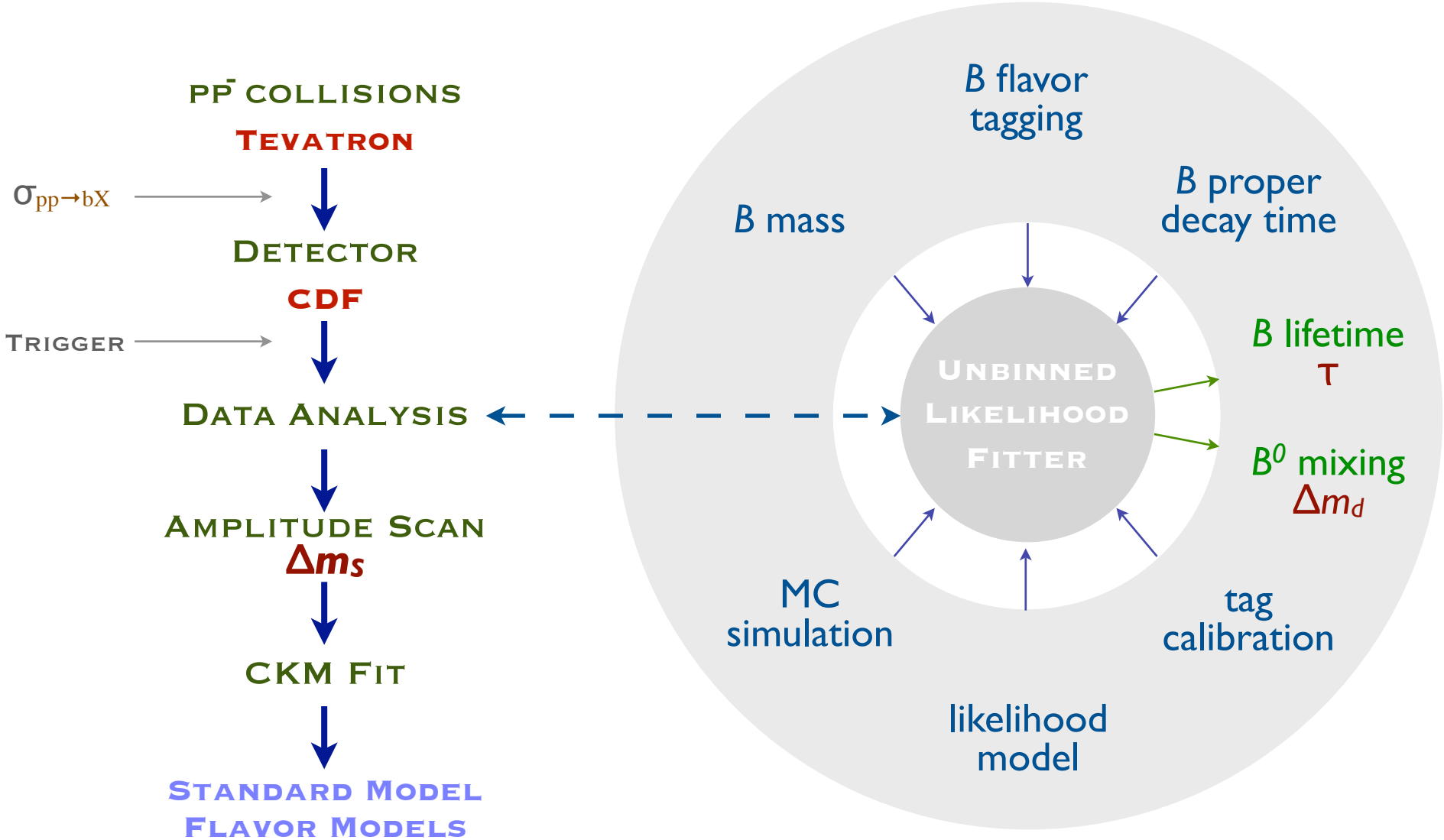


[hep-ph/0605177 (2006)]

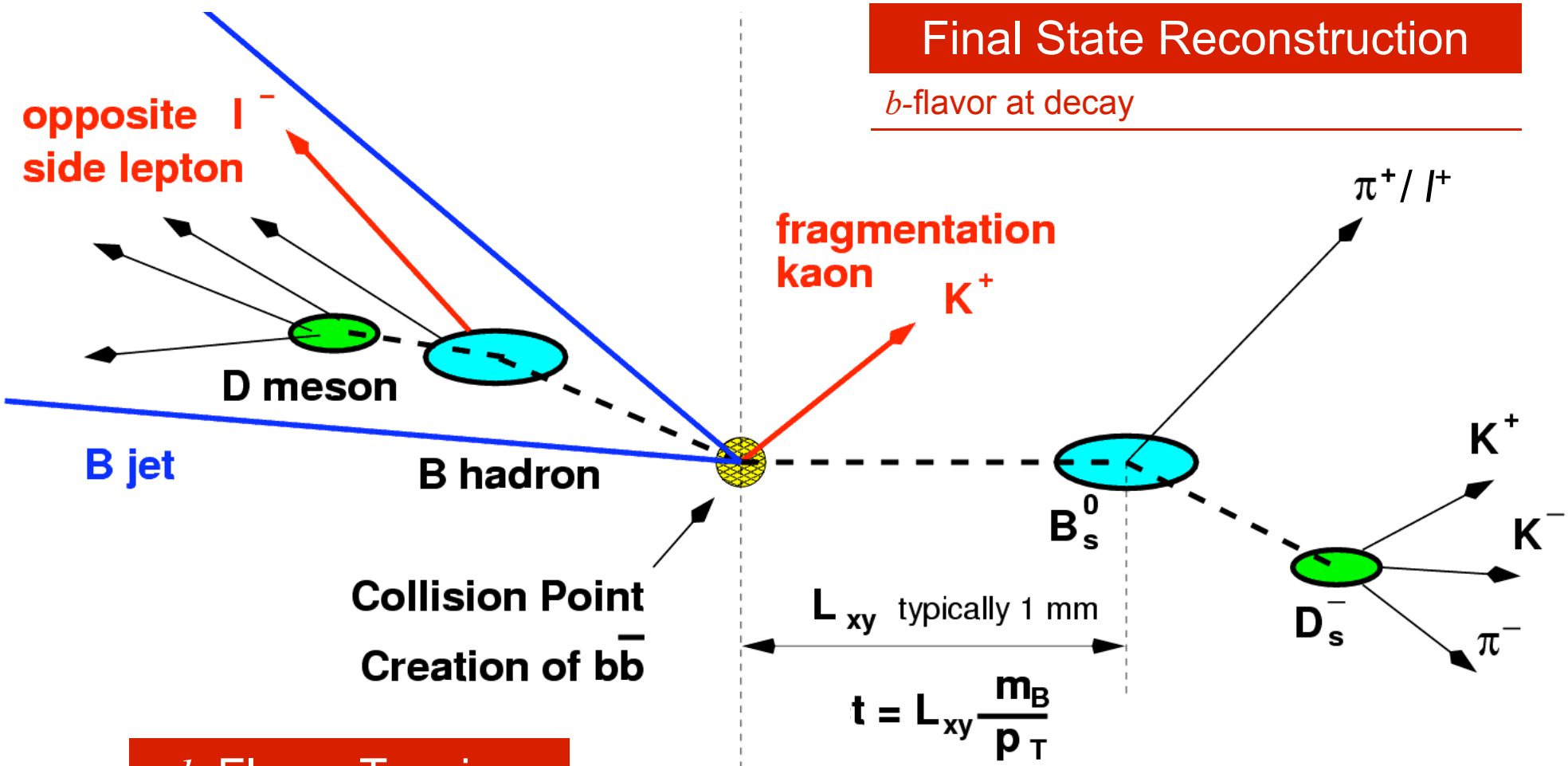


[Eur. Phys. J. C **24** 275 (2002)]

Scope & Overview



Analysis Ingredients



Final State Reconstruction

b-flavor at decay

***b*-Flavor Tagging**

b-flavor at production

Proper Decay Time

In *B* rest frame

Opposite Side

Trigger Side

Realistic Effects oscillation dampening

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

resolution of a mixing signal determined by

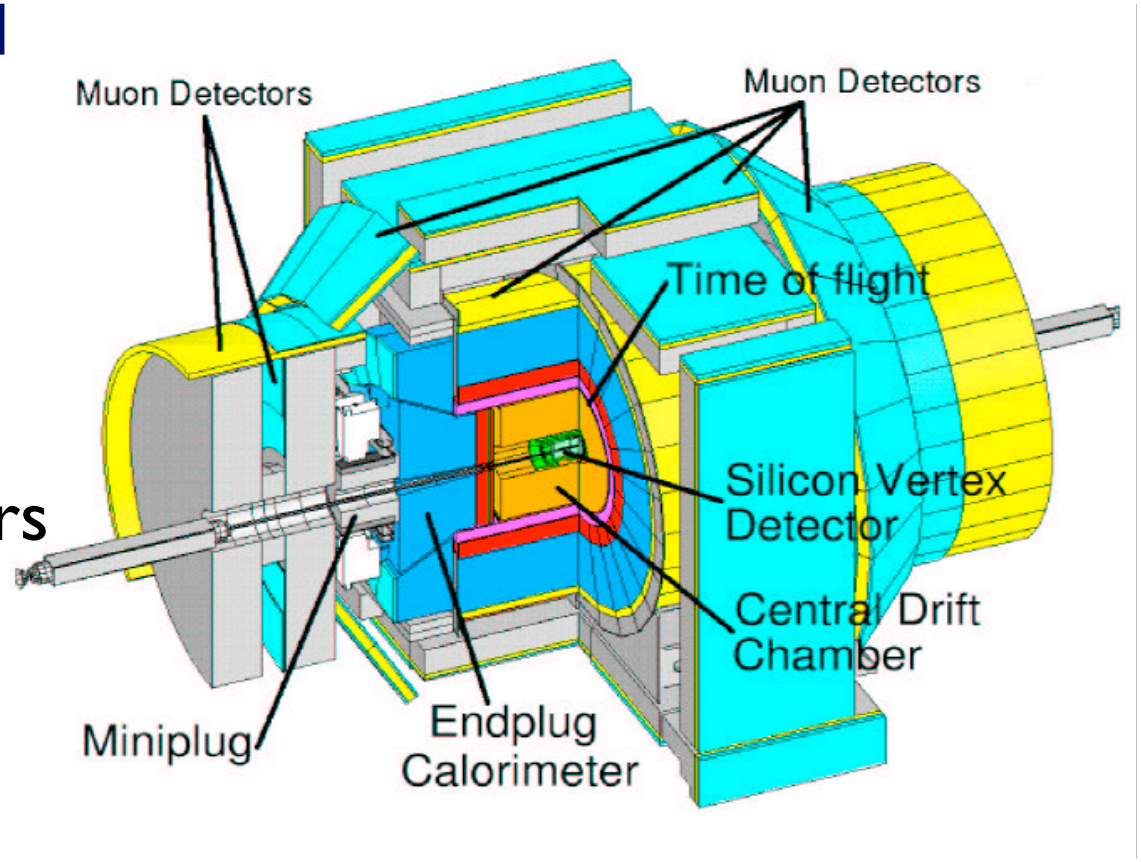
- signal yield, S
- purity, S/B
- flavor tagging power, ϵD^2
- proper decay time uncertainty, σ_t
  - decay-length resolution
  - effective momentum resolution

Getting the B_s samples

The CDF Detector

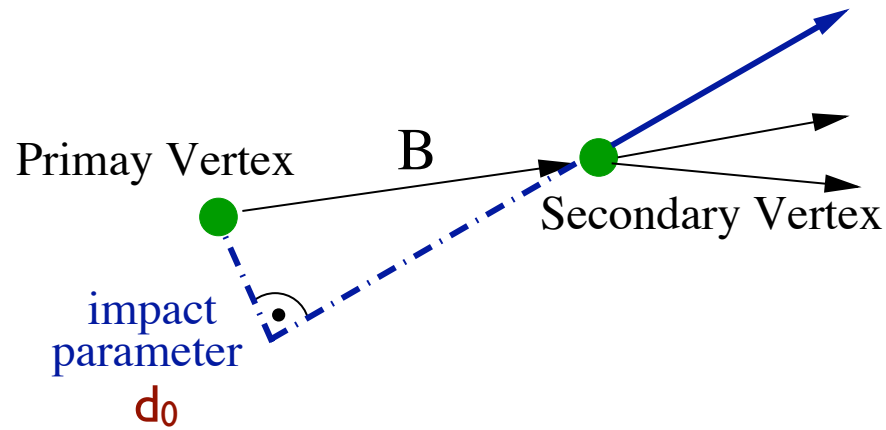
Key features for Δm_s

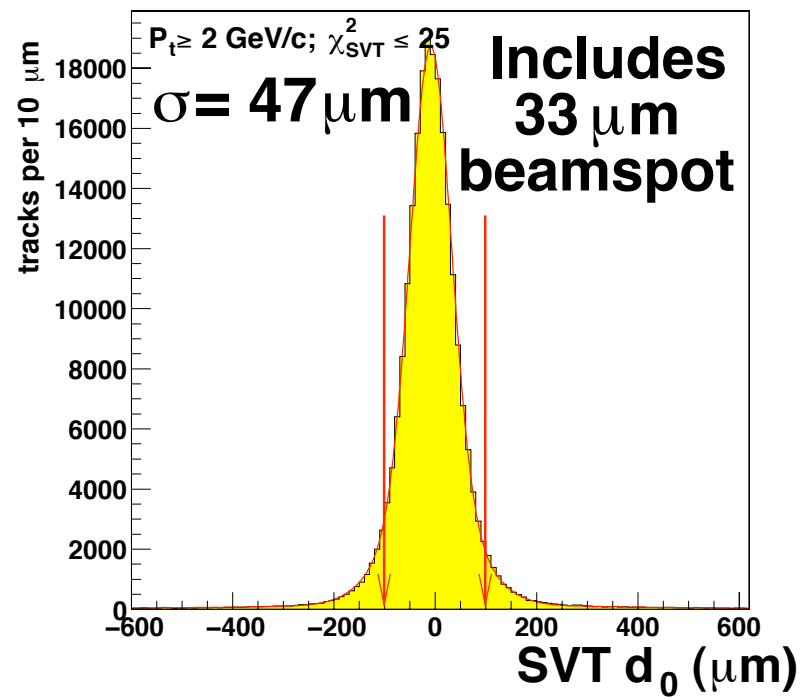
- excellent momentum and vertexing resolution
  - drift chamber, silicon
- particle identification
  - lepton id in calorimeters and muon chambers
  - time of flight
  - dE/dx in drift chamber
- 'deadtimeless' trigger system



Triggering on Displaced Tracks

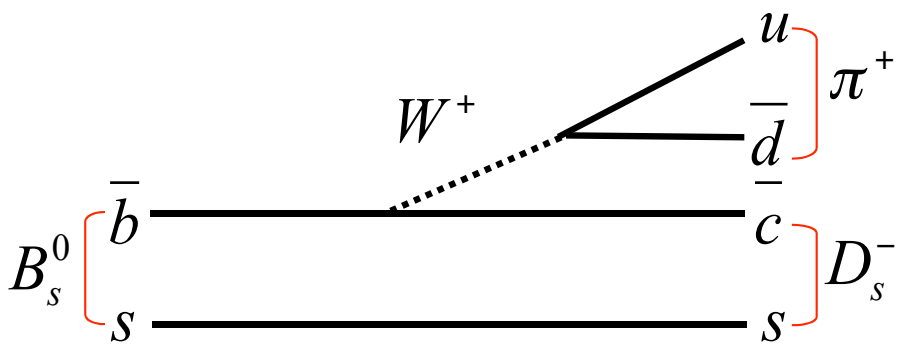
- Heavy flavor decays displaced from the primary vertex
  - daughter tracks tend to have large impact parameter
- trigger on displaced tracks
  - p_T>2GeV/c, 120μm<|d_0|<1mm
- requires precision tracking in silicon detector (SVT)



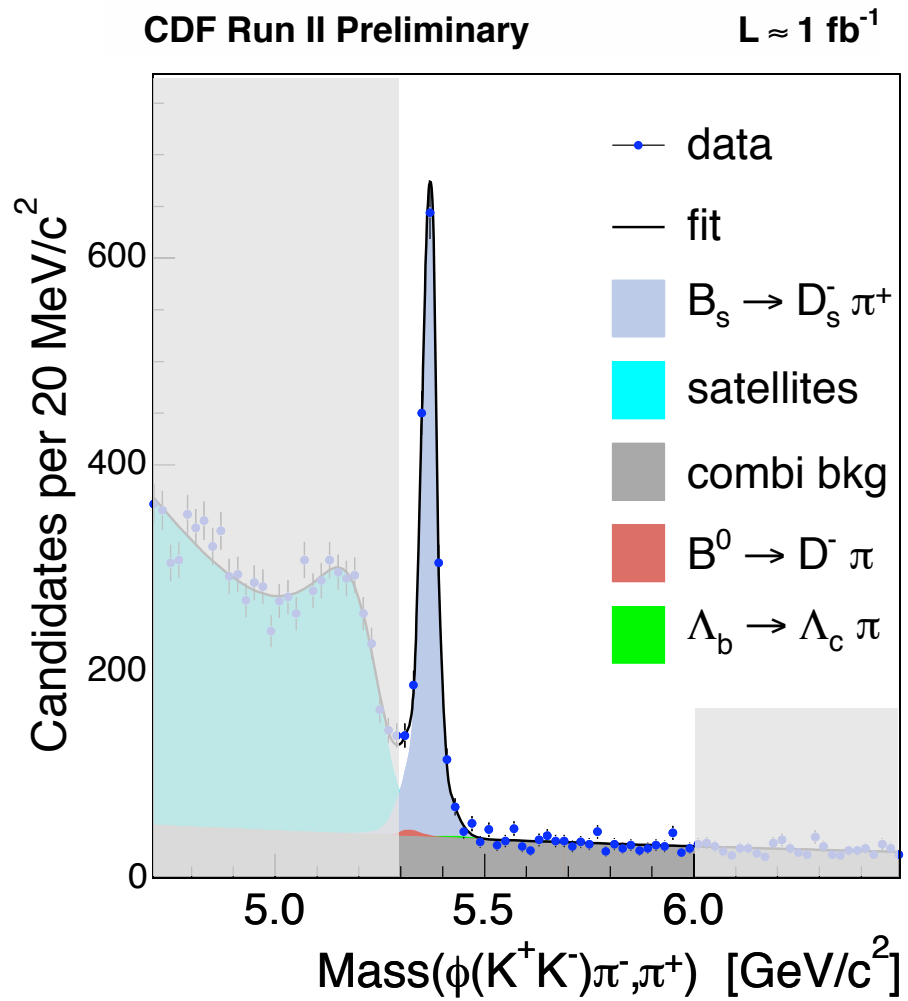


Fully Reconstructed Decays

Hadronic
$B_s \to D_s(3)\pi$



$$B_s \to D_s(\pi\pi)\pi,\ D_s \to \phi\pi/K^*K/\pi\pi\pi$$

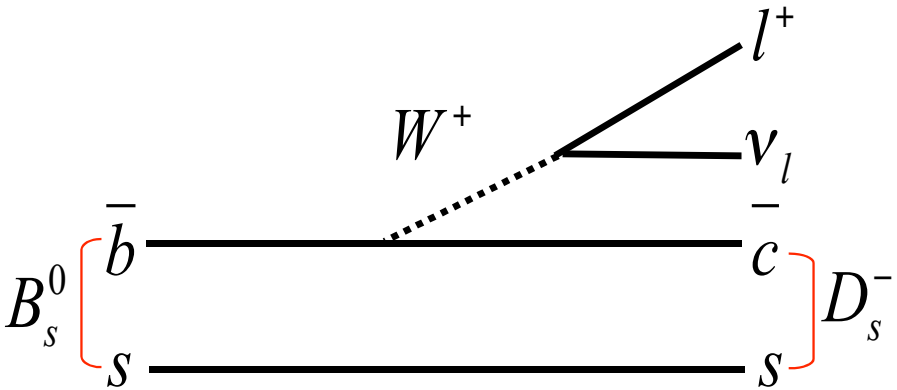


- relatively small BR's
- all daughters reconstructed
  - momentum completely contained in tracker
  - superior sensitivity at higher Δm_s
- signal yield: 3,600

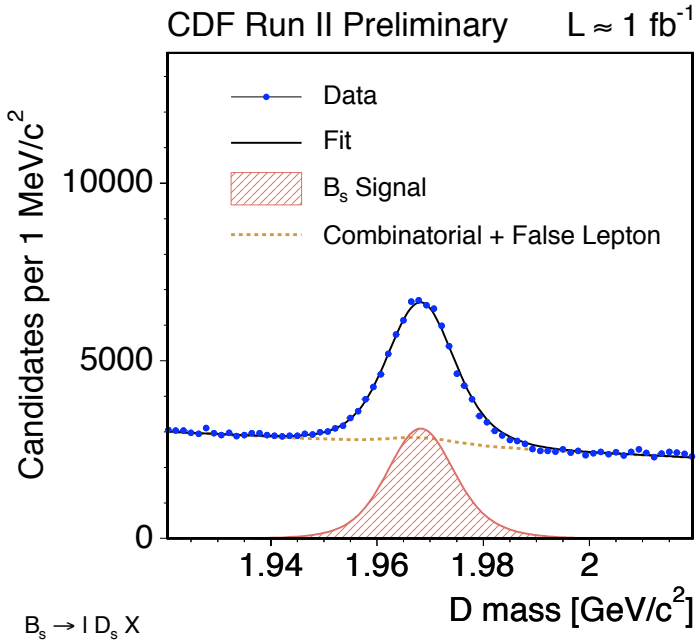
Partially Reconstructed Decays

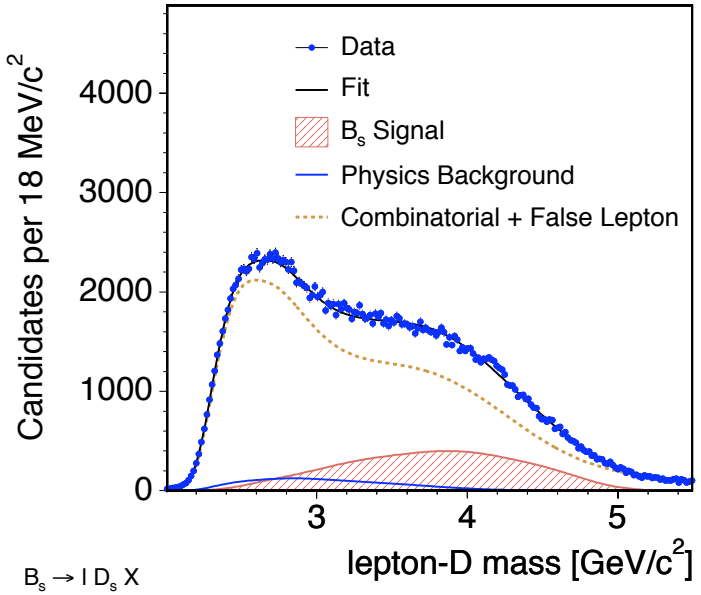
Semileptonic
$B_s \to D_s l X$

$$B_s \to D_s l X,\ D_s \to \phi\pi / K^* K / \pi\pi\pi$$



- large branching ratios
- missing neutrino and neutrals
  - need to correct for missing momentum on average
  - superior sensitivity in lower Δm_s range
- signal yield: 37,000





Proper Decay Time

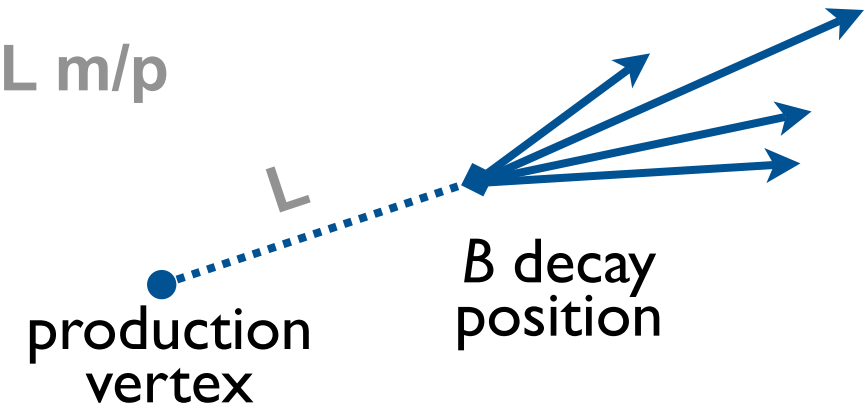
B Lifetime measurement

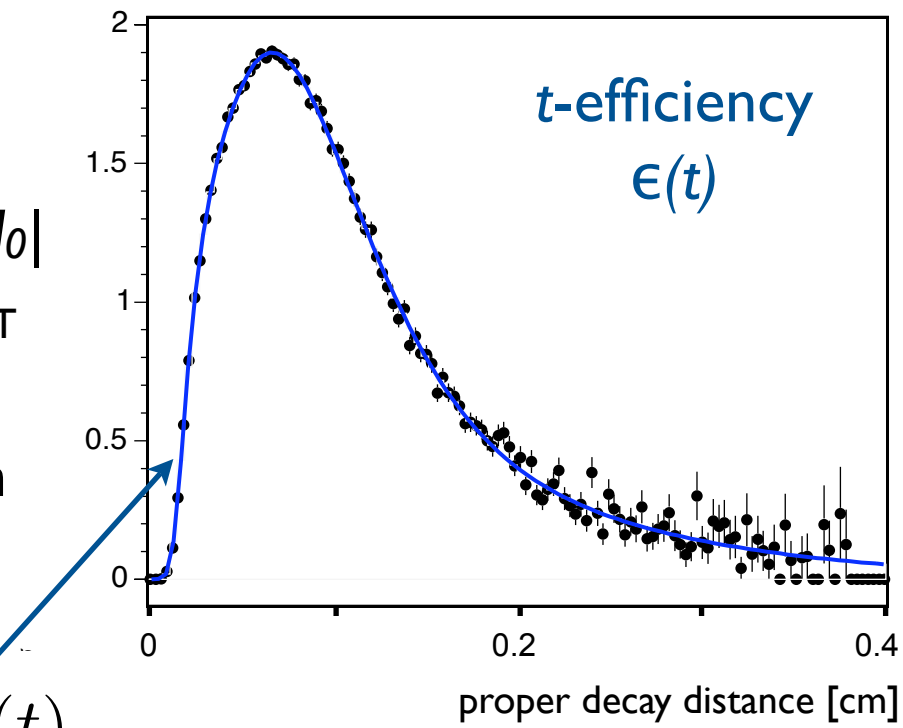
Proper Decay Time

Decay time in *B* rest frame: t = L m/p

t-distribution determined by

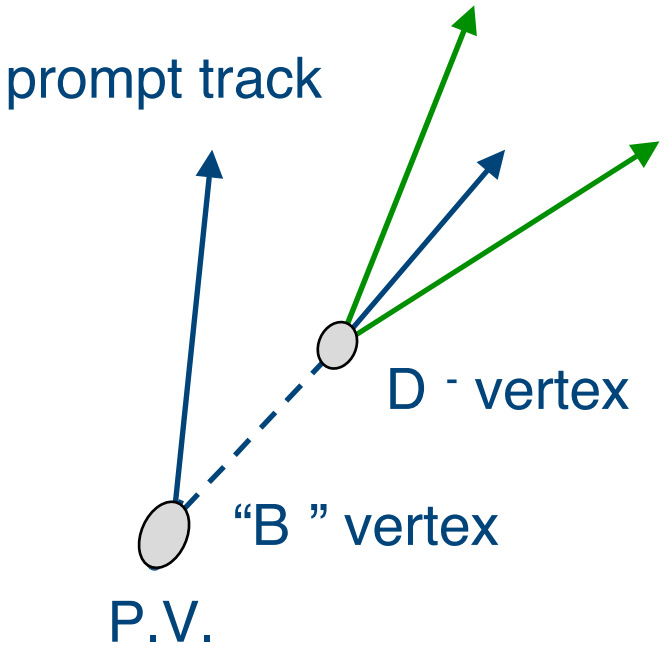
- *B* meson lifetime
- decay distance resolution
- trigger/selection sculpting
  - trigger (SVT) requirements on $|d_0|$ and event selection criteria on L_T modify PDF shape
  - described by *t*-efficiency function from Monte Carlo, $\epsilon_t(t)$

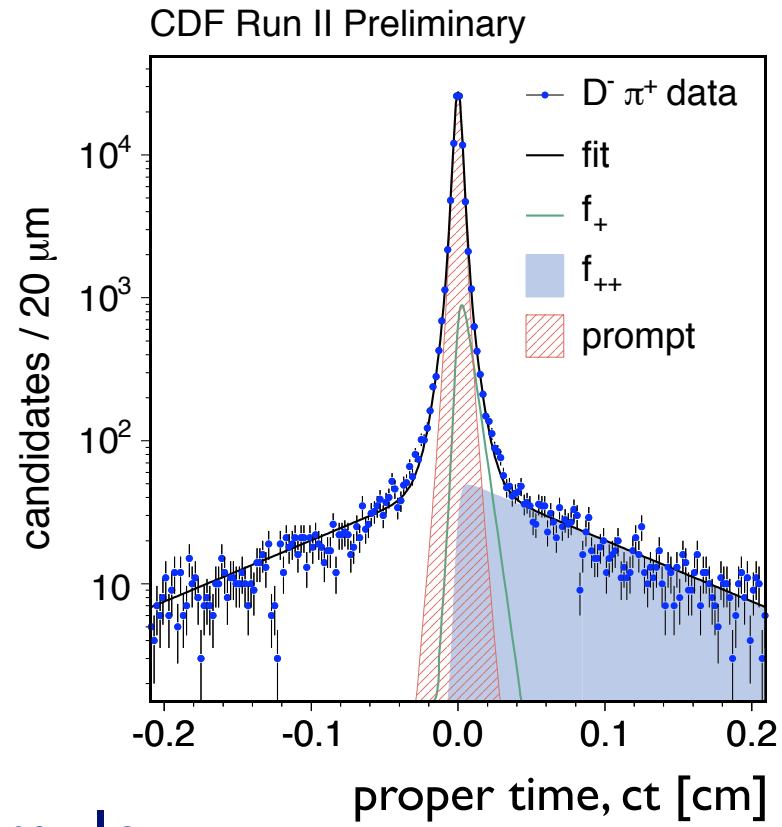




$$\mathcal{P}(t) \propto e^{-t'/\tau} \otimes R(t-t';\sigma_t) \cdot \mathcal{E}(t)$$

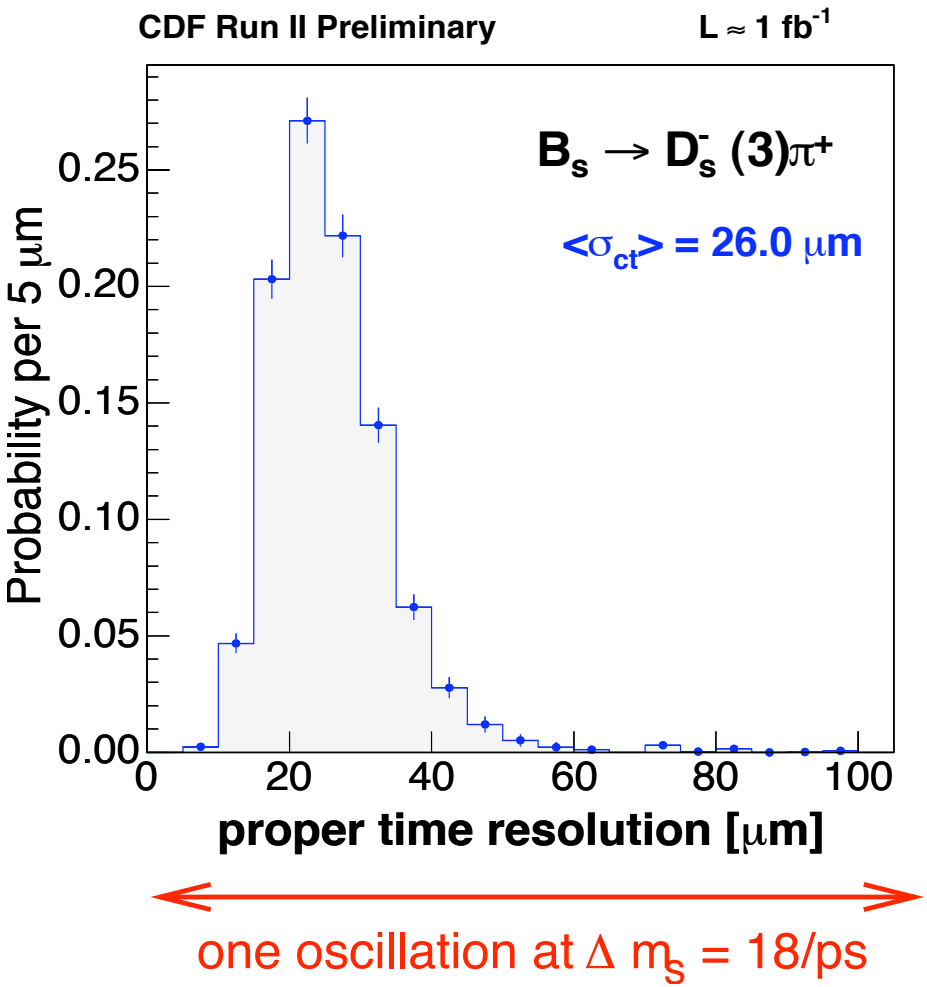
Calibrating Resolution in Data





- use large prompt *D* meson sample to construct *B*-like topologies of prompt *D*+track
- compare reconstructed decay point to interaction point
- calibrate *t*-resolution by fitting prompt *t*-distribution

B_s Decay Time Resolution



- candidate specific decay time resolution used in likelihood fit
- average uncertainty ~26 μm or 87 fs

  about 1/4 oscillation period at Δm_s=18ps^{-1}

  for hadronic decays

Superior decay time resolution gives CDF sensitivity at much higher frequencies than previous experiments

Kinematics correction in Semileptonics

- correct for missing momentum

$$t \mapsto t\,\kappa \qquad \kappa \equiv \frac{L_B}{L_{Dl}}\frac{p_{Dl}}{p_B}$$

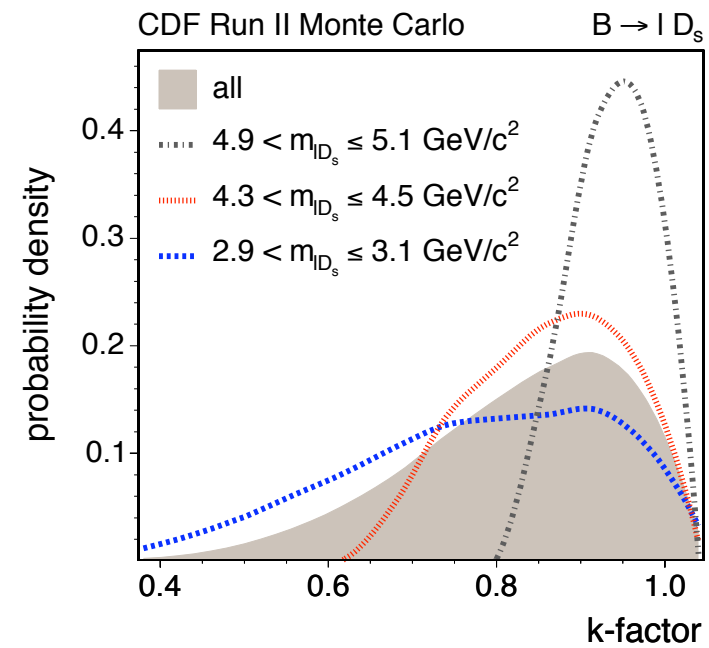
with κ-factor distribution (MC)

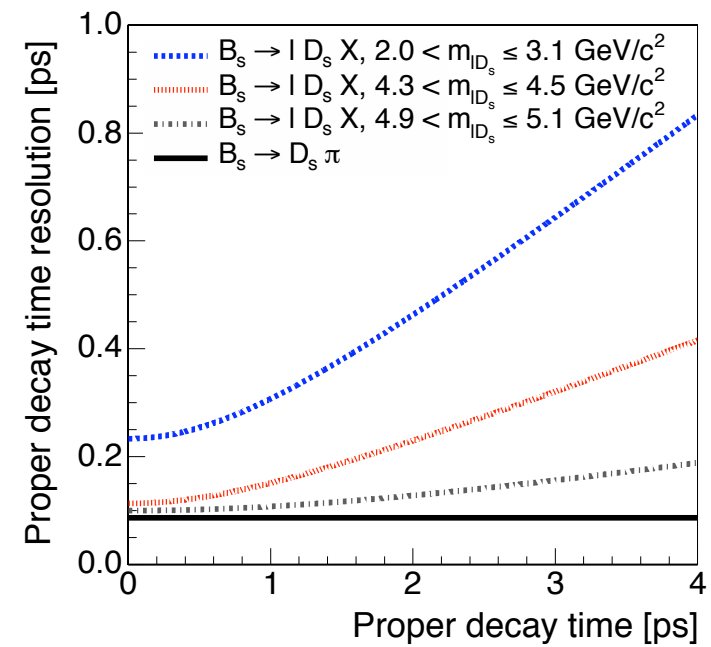
- explore dependence on lepton-*D* invariant mass

- effectively worsens *t*-resolution

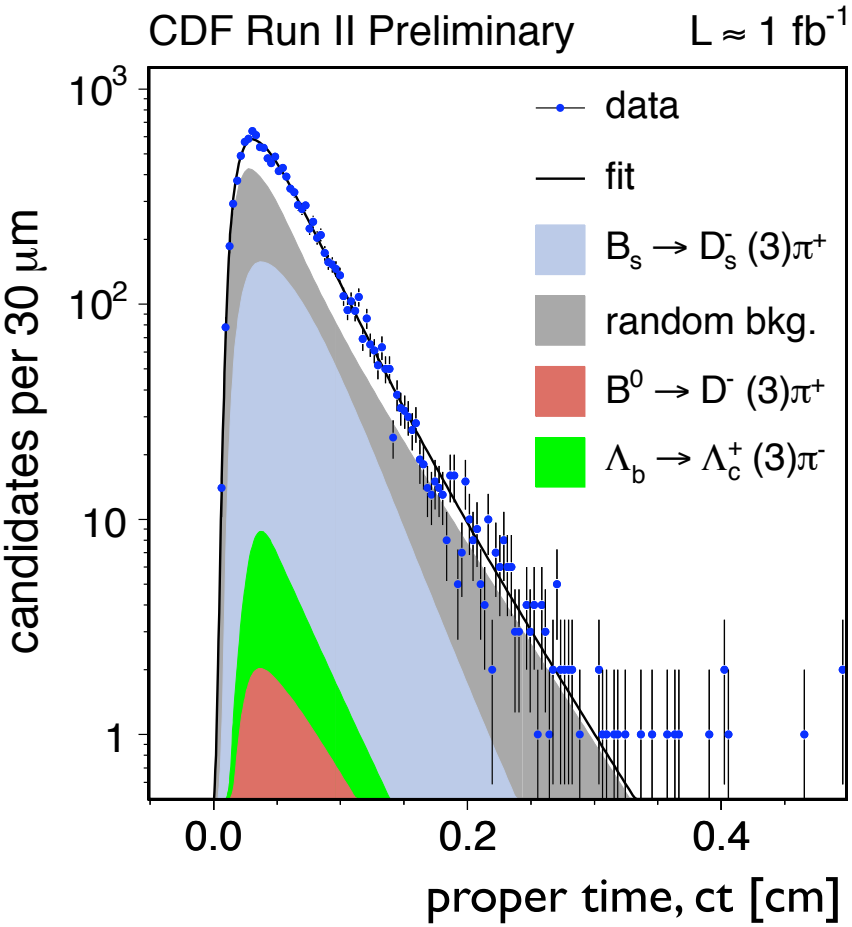
$$\sigma_t \mapsto \sigma_t^0 \oplus t\,\frac{\sigma_p}{p}$$

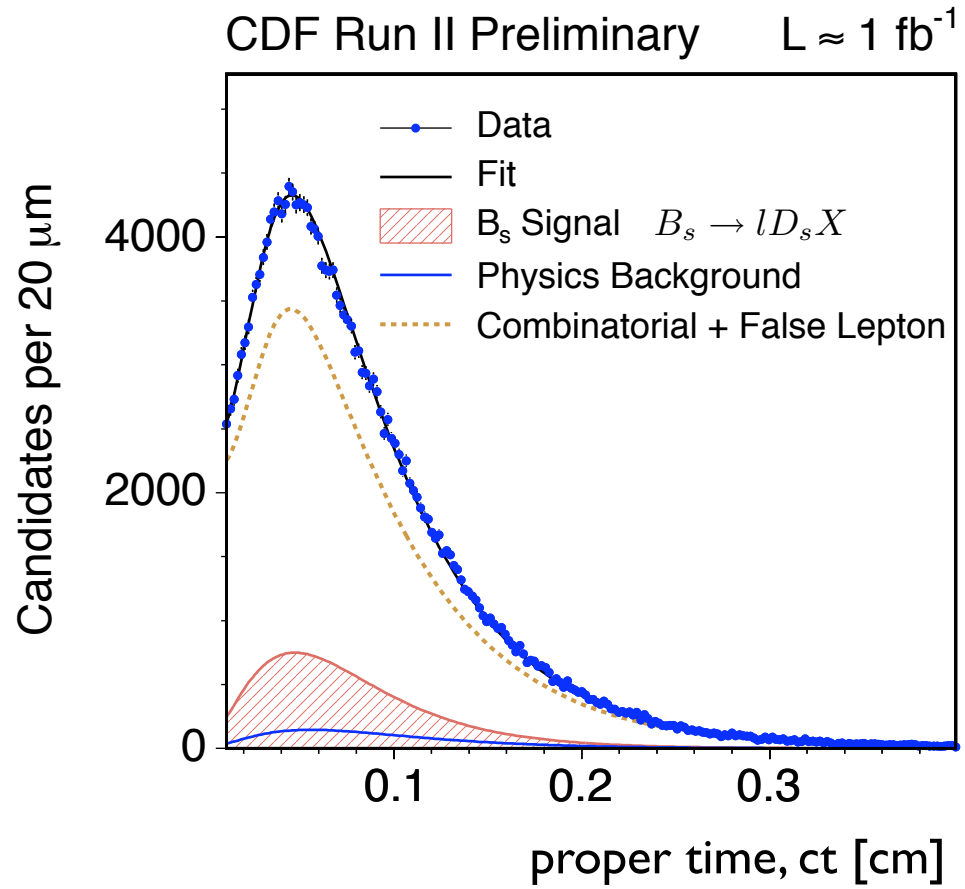
  - *limits semileptonics sensitivity at high* Δm_s





Lifetime Fits





Hadronic
1.54±0.04 ps^{-1}(stat)

Semileptonic (355pb^{-1})
1.48±0.03 ps^{-1} (stat)

Good agreement with World Average 1.469±0.059 ps^{-1}

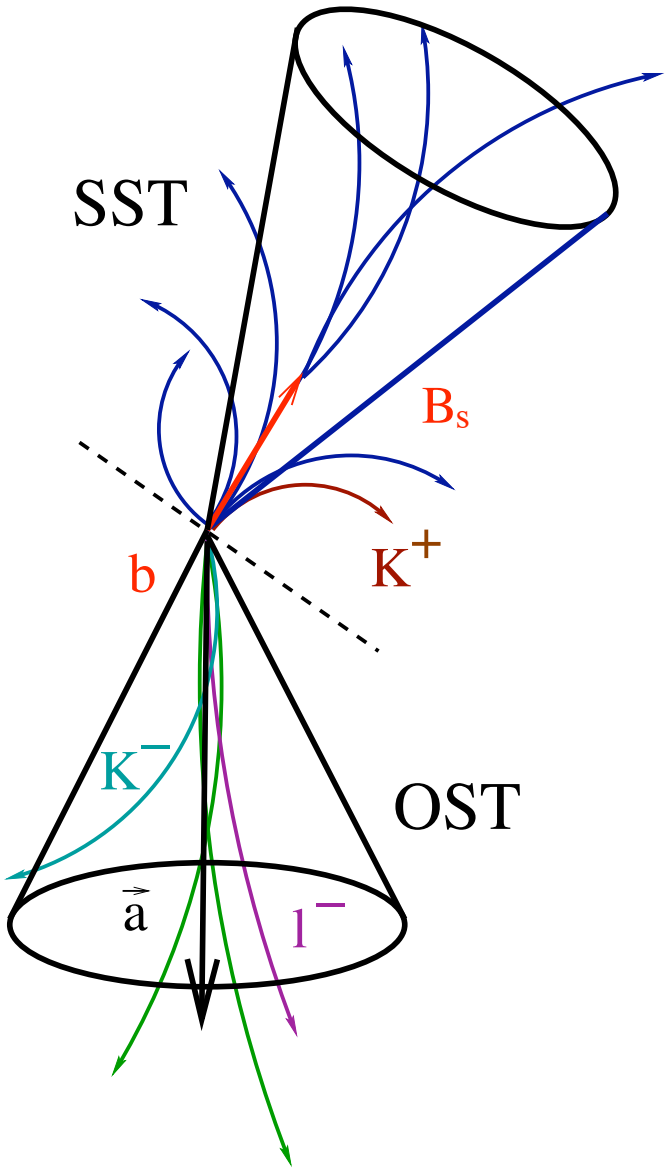
b Flavor Tagging

Δm_d measurement

Tagging *B* Production Flavor

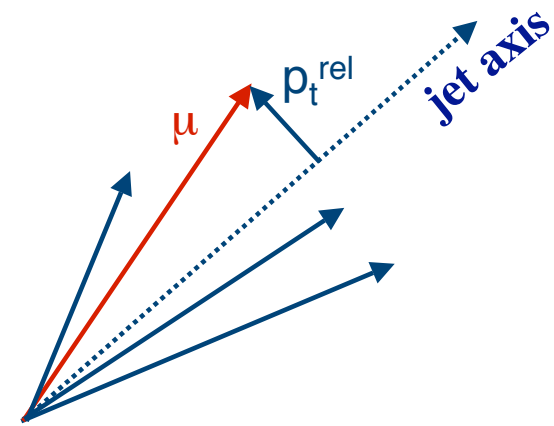
- produced $B(\bar{b})$ or $\bar{B}(b)$?
- use combined flavor taggers
  - Opposite-side
  - Same-side
- quantify performance with
  - *efficiency*, $\epsilon \equiv$ fraction of tagged events
  - *dilution*, $D \equiv 1 - 2 \times$ mistag probability
  - effective statistics for mixing becomes

    $N \Rightarrow N\,\epsilon D^2$
- for limit on Δm_s must *know* D

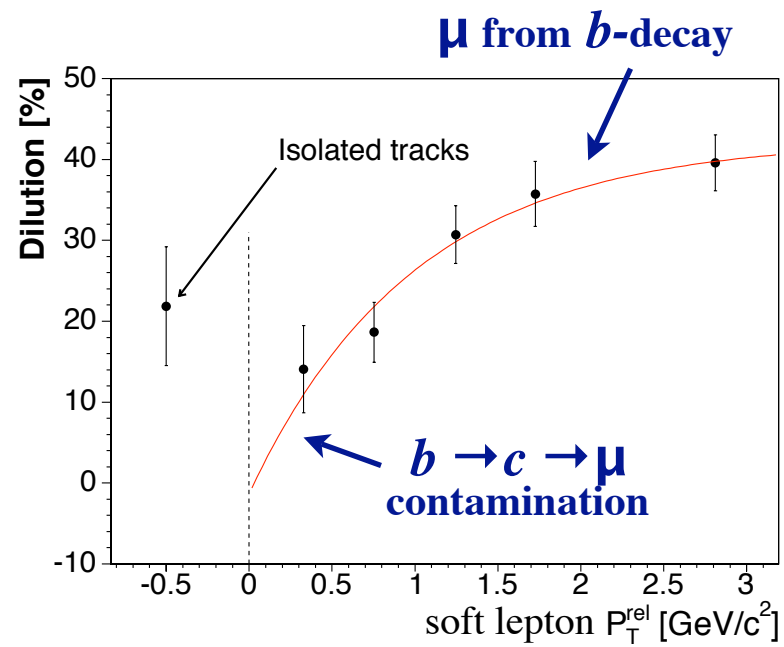


Opposite-Side Tagging

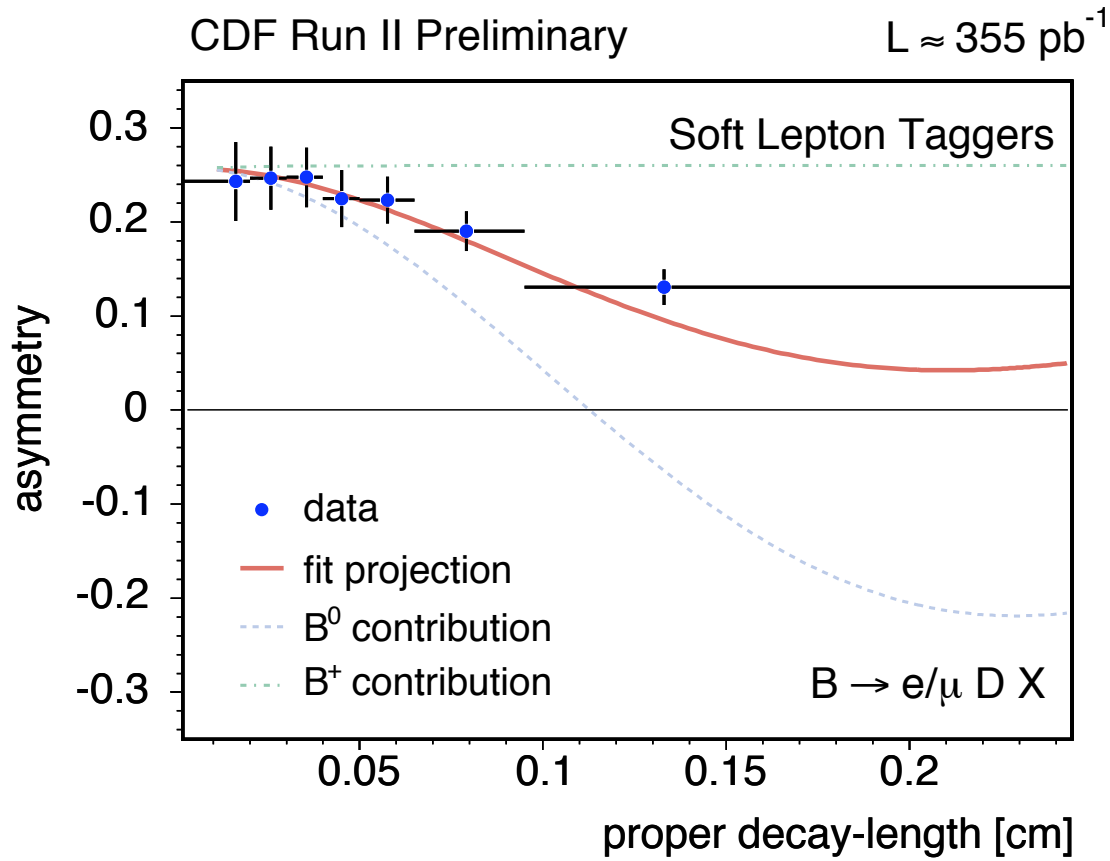
- soft lepton
  from semileptonic decay of opposite *b*
- jet charge
  momentum-weighted charge average of tracks in opposite side *b* jet



- use event specific dilution
  - dependence on p_t^{rel}, jet charge
- other *b* not always in the acceptance
- independent of *B* species
  - performance calibrated in high statistics samples of B^+ and B^0
  - results applicable directly to B_s



B^0 Mixing Fit Δm_d



$$\mathcal{P} \sim \frac{e^{-t/\tau}}{2\tau}(1 - S_D \cdot D \cdot \cos \Delta m_d\, t)$$

OST tagging power ϵD^2 [%]

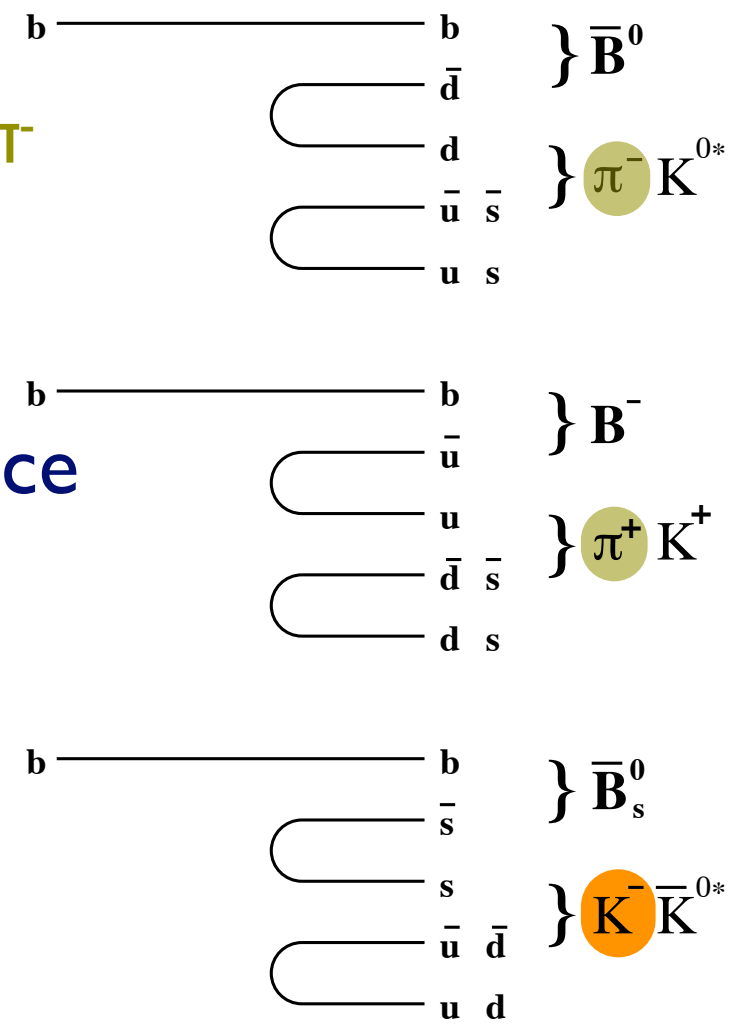
1.47 ± 0.10
(hadronic modes)

1.44 ± 0.04
(semileptonic modes)

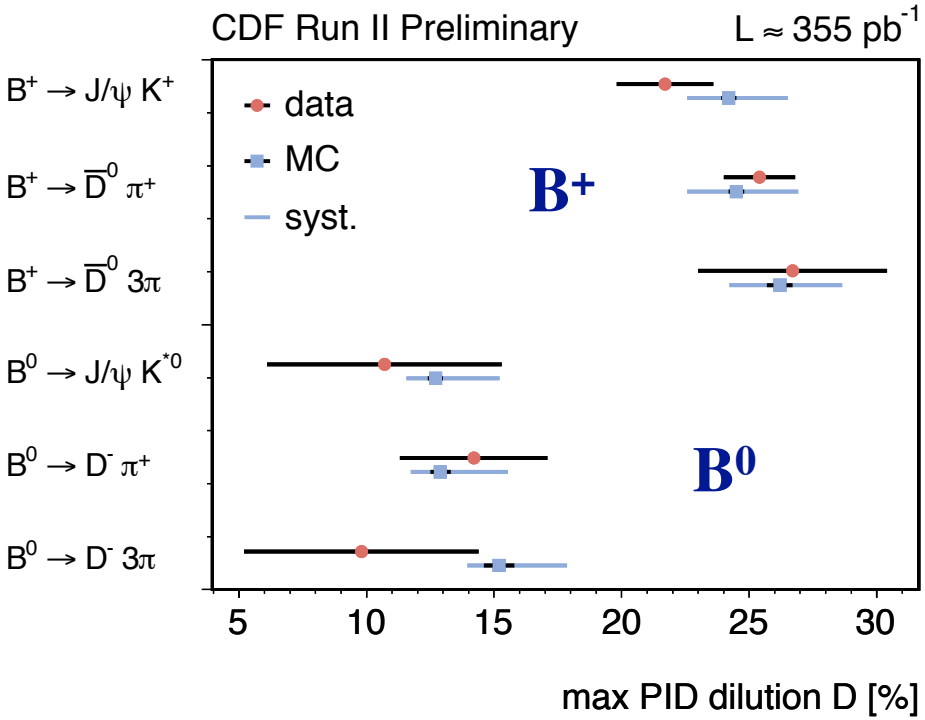
- Hadronic: $\Delta m_d = 0.536 \pm 0.028$ (stat) ± 0.006 (syst) ps^{-1}
- Semileptonic: $\Delta m_d = 0.509 \pm 0.010$ (stat) ± 0.016 (syst) ps^{-1}
- World average: $\Delta m_d = 0.505 \pm 0.005$ ps^{-1}

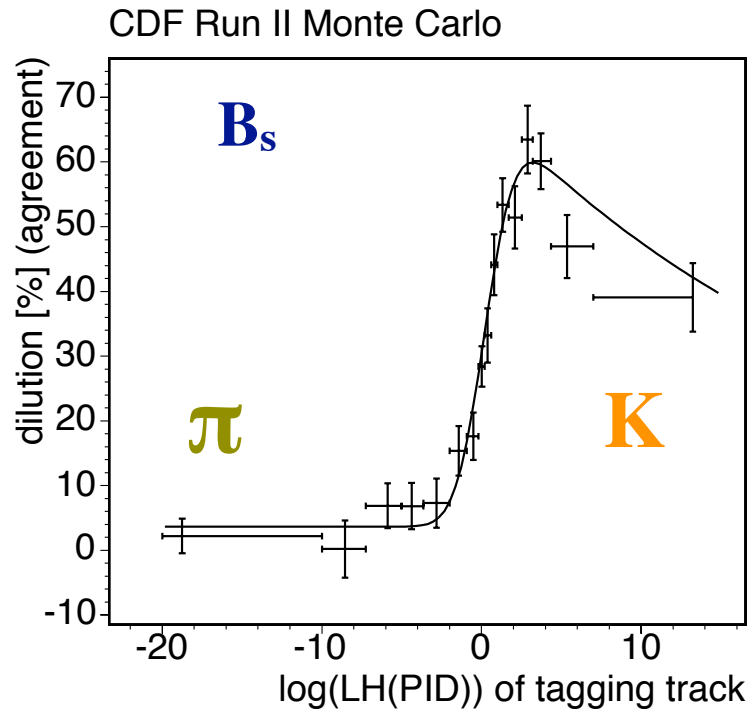
Same-Side Tagging

- exploit *b* quark fragmentation
  - B^0 / B^+ likely accompanied by π^+ / π^-
  - B_s likely accompanied by K^+
  - ➥ identify charge of leading track
- particle ID improves performance
  - separate kaons from pions
  - time-of-flight (TOF) & dE/dx
- dependent on *B* species
  - results in B^0/B^+ *not applicable* to B_s
- dilution for B_s needs to be estimated from Monte Carlo



SS(K)T Performance





Tagging power for B_s, ϵD^2 $\left\{ \begin{array}{l} 3.42 \pm 0.96\ \% \text{ (Hadronic)} \\ 4.00 \pm 1.12\ \% \text{ (Semileptonic)} \end{array} \right.$

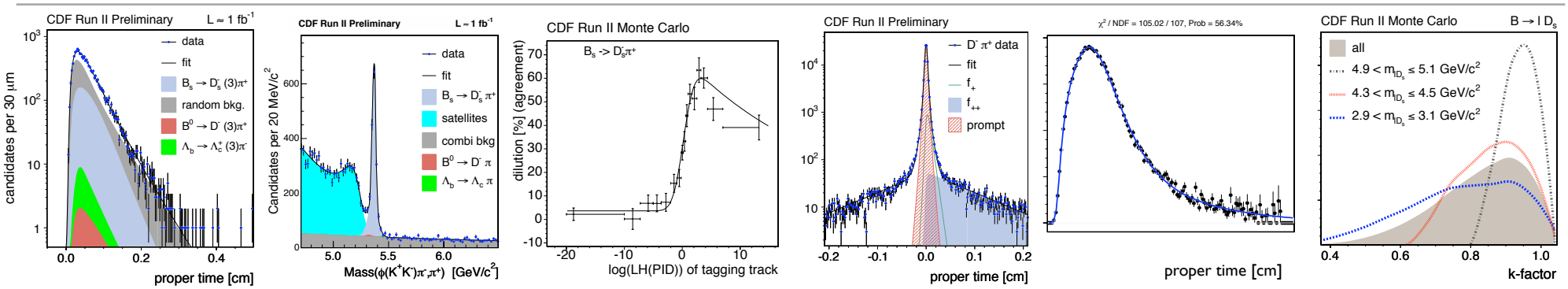
✓ overall tagging performance enlarged by x3-4!

Fit Procedure

Likelihood putting it all together

$$\mathcal{L} = \mathcal{L}_{mass} \cdot \mathcal{L}_t \cdot \mathcal{L}_{\sigma_t} \cdot \mathcal{L}_D$$

[for each sample component & event]



$$\mathcal{L}_t = \frac{1}{N}\,\kappa\,\frac{e^{-\frac{\kappa\, t'}{\tau}}}{\tau}\;\frac{1 \pm A\; S_D\, D\, \cos(\Delta m_s\, \kappa\, t')}{2} \otimes R(t-t'; S_{\sigma_t}\sigma_t)\cdot \mathcal{E}(t) \otimes F(\kappa)$$

analytical computation

Frequency Δm_s

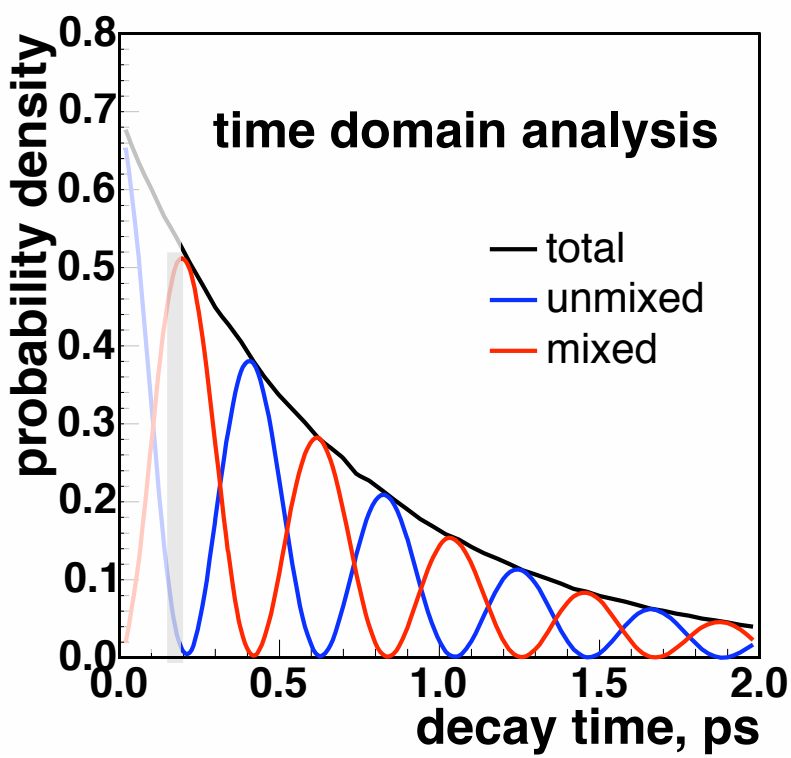
or

Amplitude (A, σ_A) for fixed Δm_s

Fit Strategy frequency/amplitude

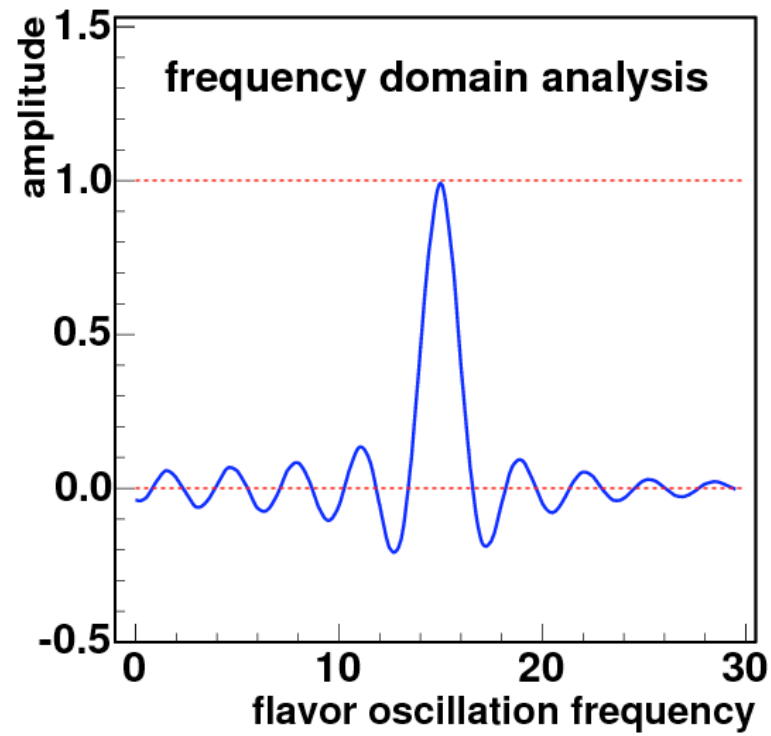
Time domain

$P(t) \sim 1 \pm D \cos \Delta m_s t$



Frequency domain

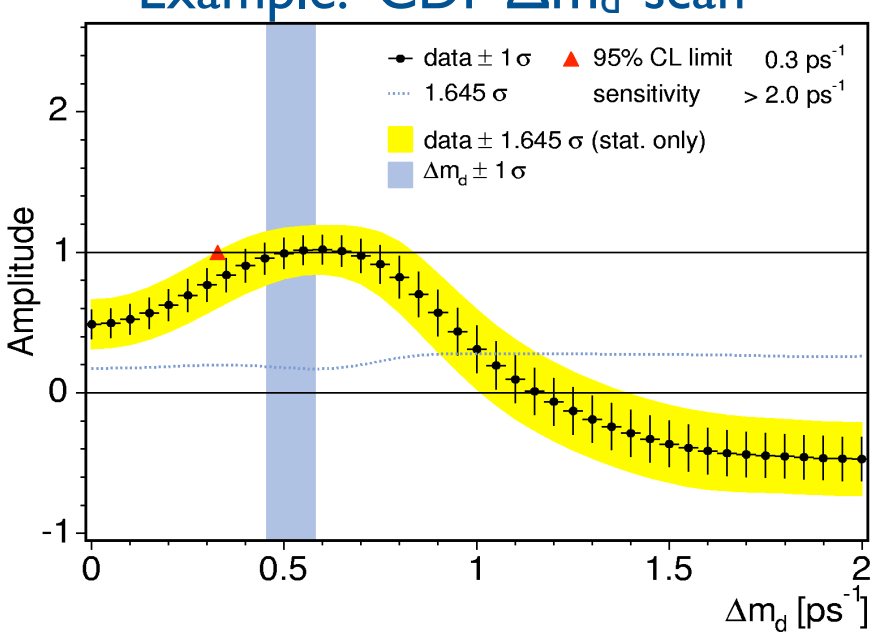
$P(t) \sim 1 \pm A\, D \cos \Delta m_s t$



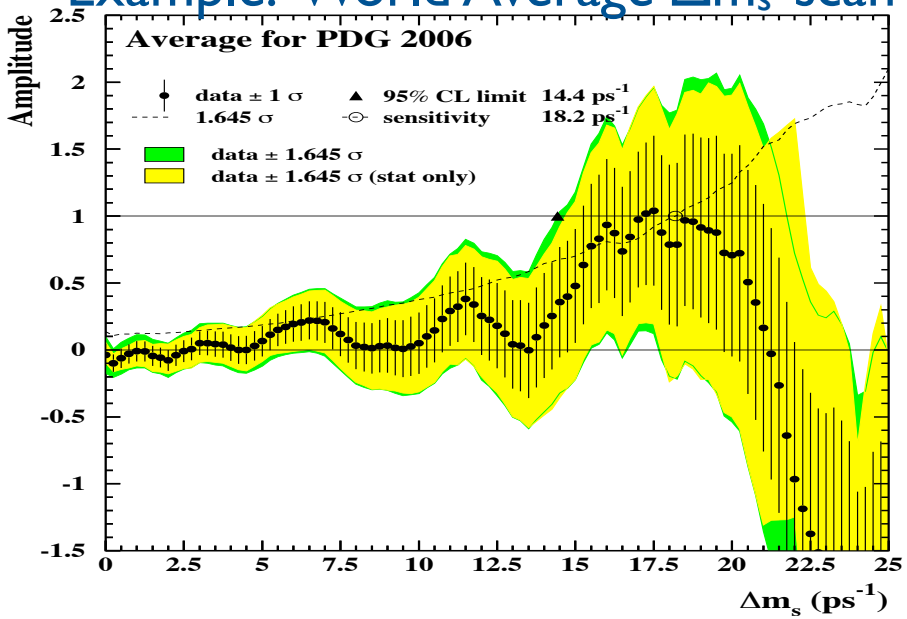
Amplitude Scan Notation

- procedure: repeat Amplitude fit for different Δm_s probe values
  - A~1 ⇐ true Δm_s value
  - A~0 ⇐ frequencies away from the true value
- frequency values where $A + 1.645\ \sigma_A < 1$ are excluded at 95% CL
- sensitive in Δm_s range where $1.645\ \sigma_A < 1$
  - examples: ☛ recent DØ result: 14.1 ps^{-1} ☛ average PDG 2006: 18.6 ps^{-1}

Example: CDF Δm_d scan

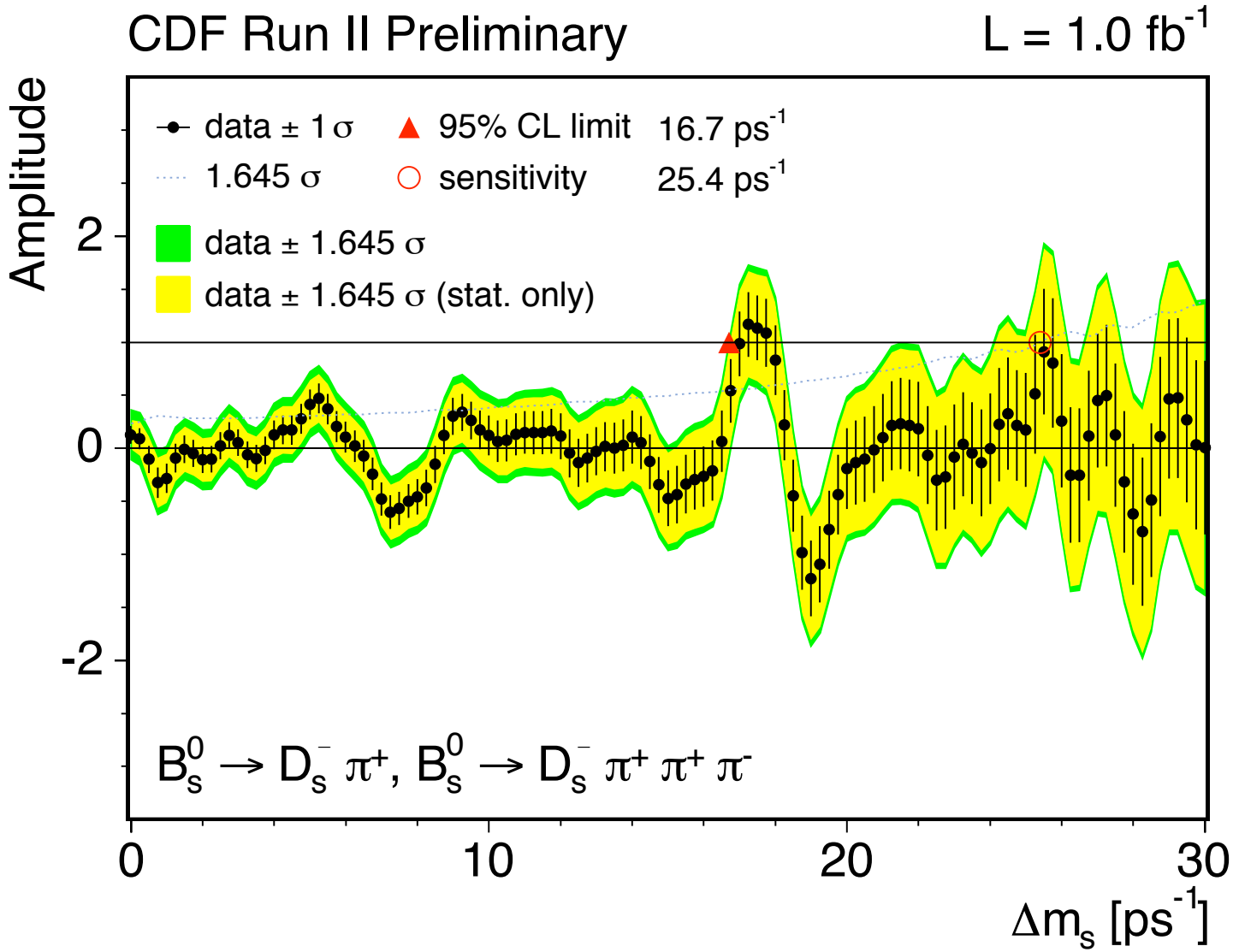


Example: World Average Δm_s scan

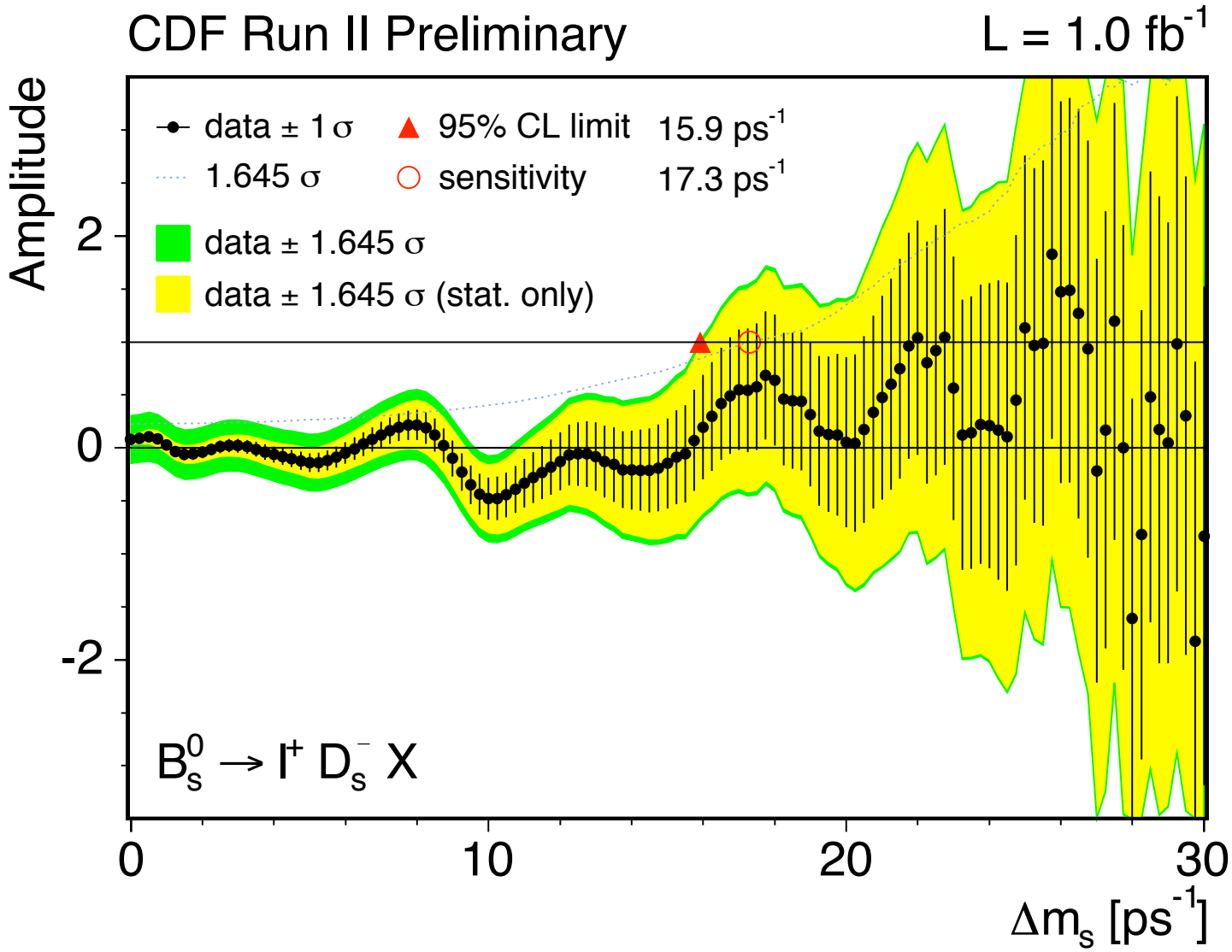


The Δm_s Results

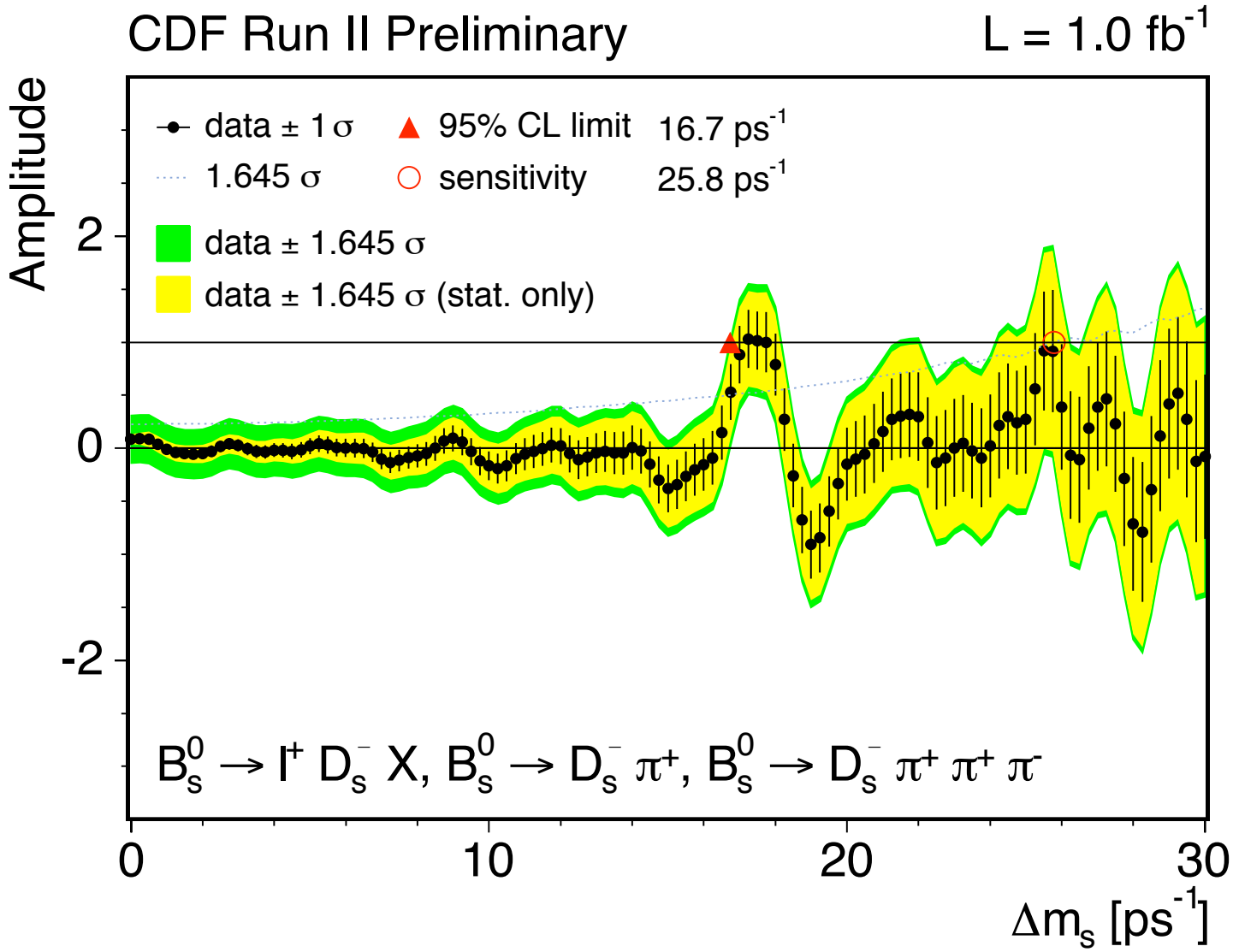
Amplitude Scan: Hadronic Decays



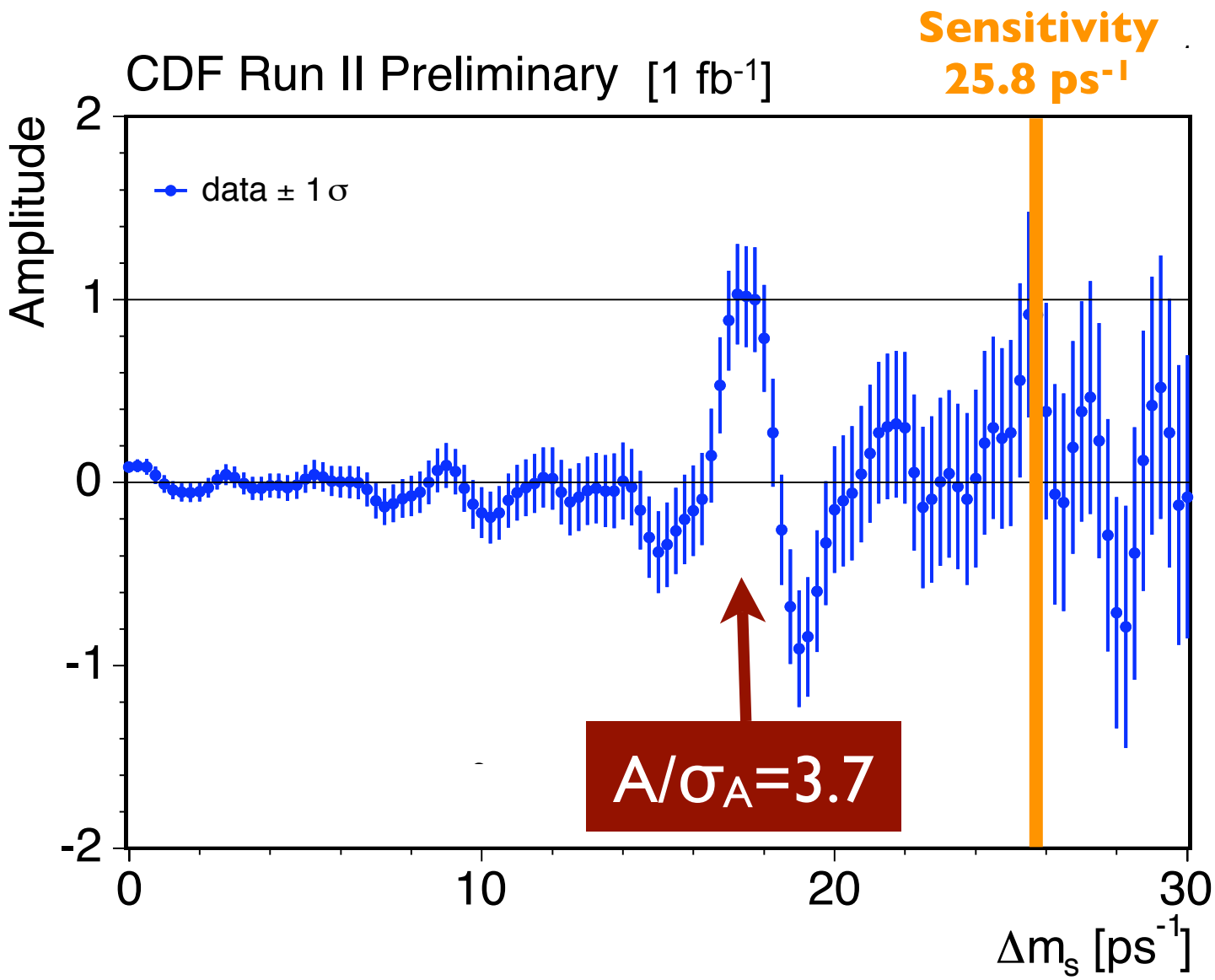
Amplitude Scan: Semileptonic Decays



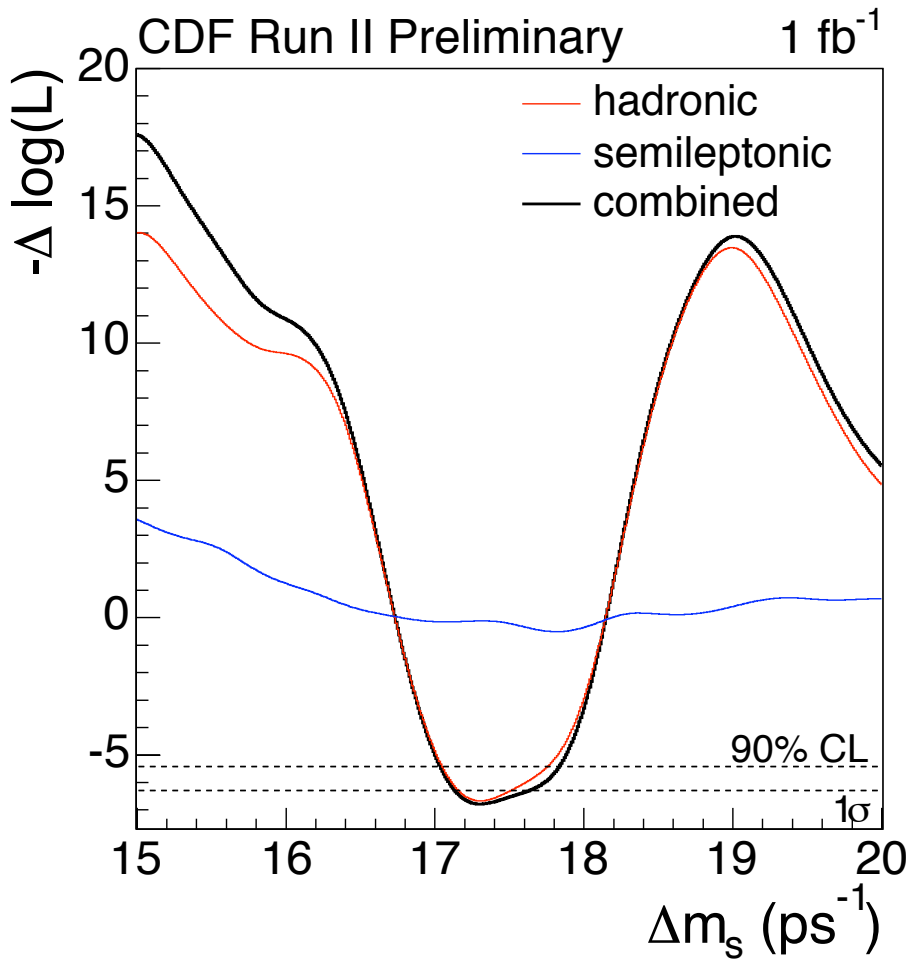
Combined Amplitude Scan



Results: Amplitude Scan



Measured Value of Δm_s



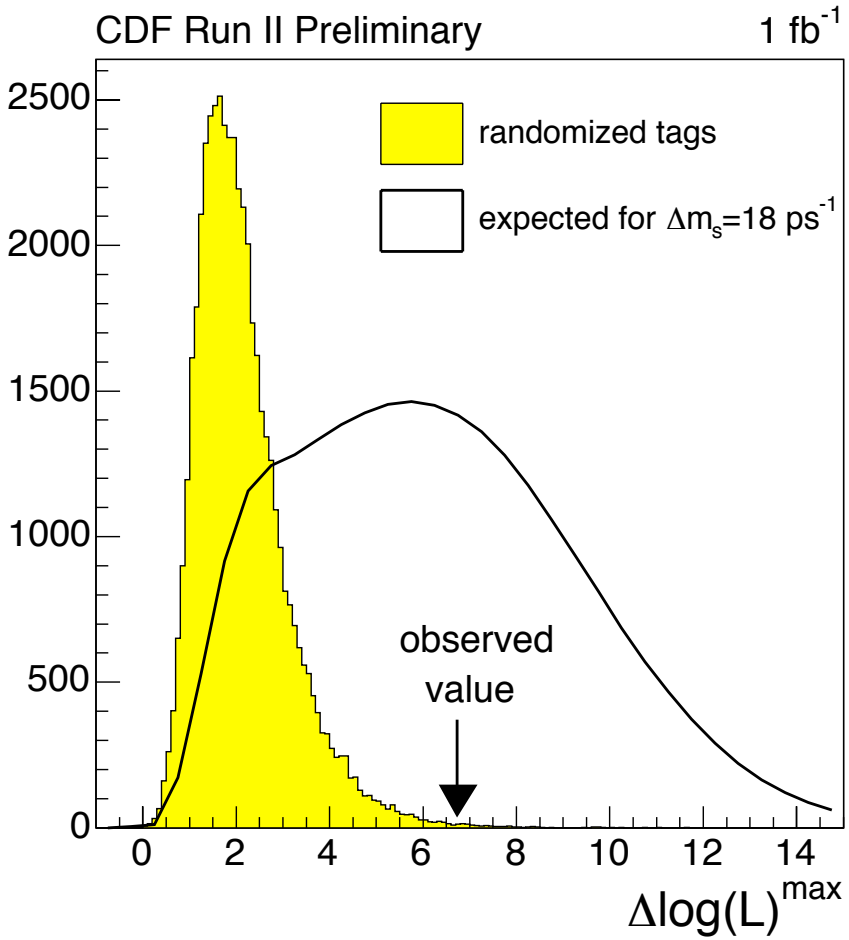
confidence intervals

90% CL
[17.01, 17.84] ps^{-1}

95% CL
[16.96, 17.91] ps^{-1}

$$\Delta m_s = 17.31^{+0.33}_{-0.18}\,(\text{stat}) \pm 0.07(\text{syst})\ ps^{-1}$$

Significance Probability of Fluctuation



- probability of random fluctuation determined from data
  - randomize tags many times
  - find how often max-Δlog(L) is larger than observed maximum for signal

$\Rightarrow$ 0.2% (3.7σ)

Impact on CKM

matrix elements determination

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

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B^0}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.208^{+0.001}_{-0.002}\,(\mathrm{exp})\,^{+0.008}_{-0.006}(\mathrm{theo})$$

other inputs:

$$\xi^2 = 1.21^{+0.047}_{-0.035}$$

[from M.Okamoto, hep-lat/0510113]

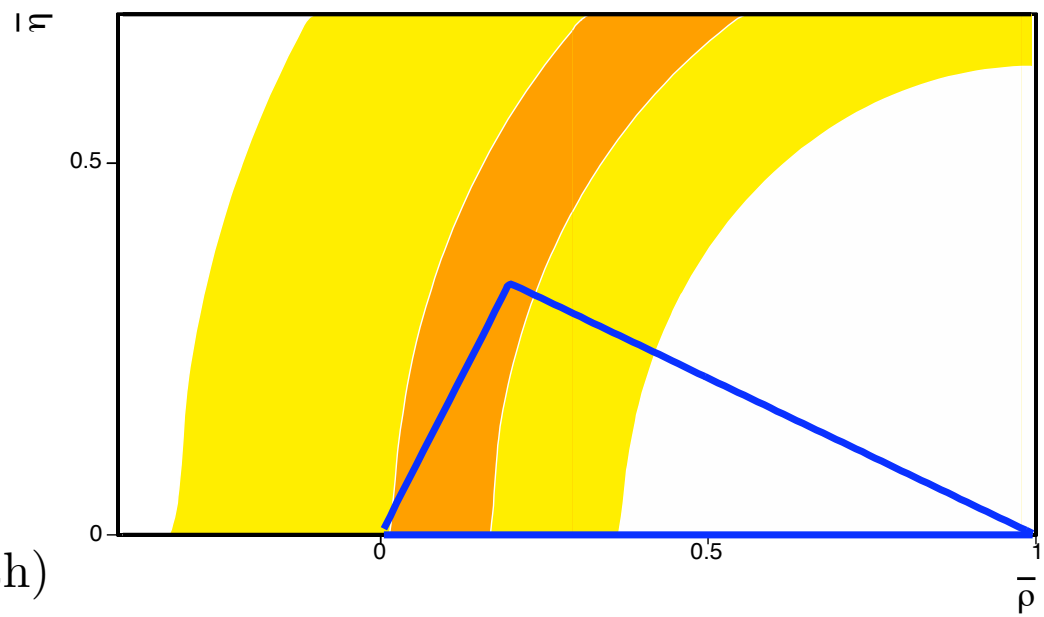
$$m_{B^0}/m_{B_s} = 0.983$$

[from PDG]

$$\Delta m_d = 0.505 \pm 0.005\ \mathrm{ps}^{-1}$$

[from PDG]

EPS'05 + CDF measurement



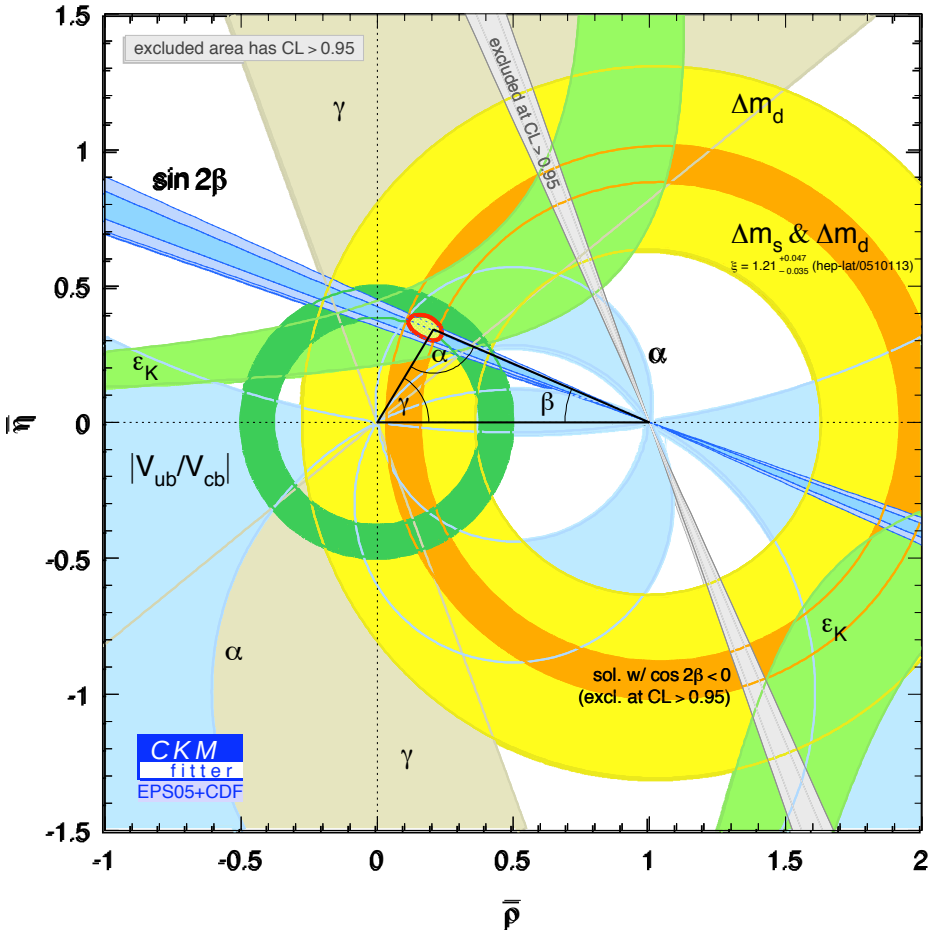
previous best result:

$$|V_{td}/V_{ts}| = 0.199^{+0.026}_{-0.025}(\mathrm{exp})^{+0.018}_{-0.015}(\mathrm{th})$$

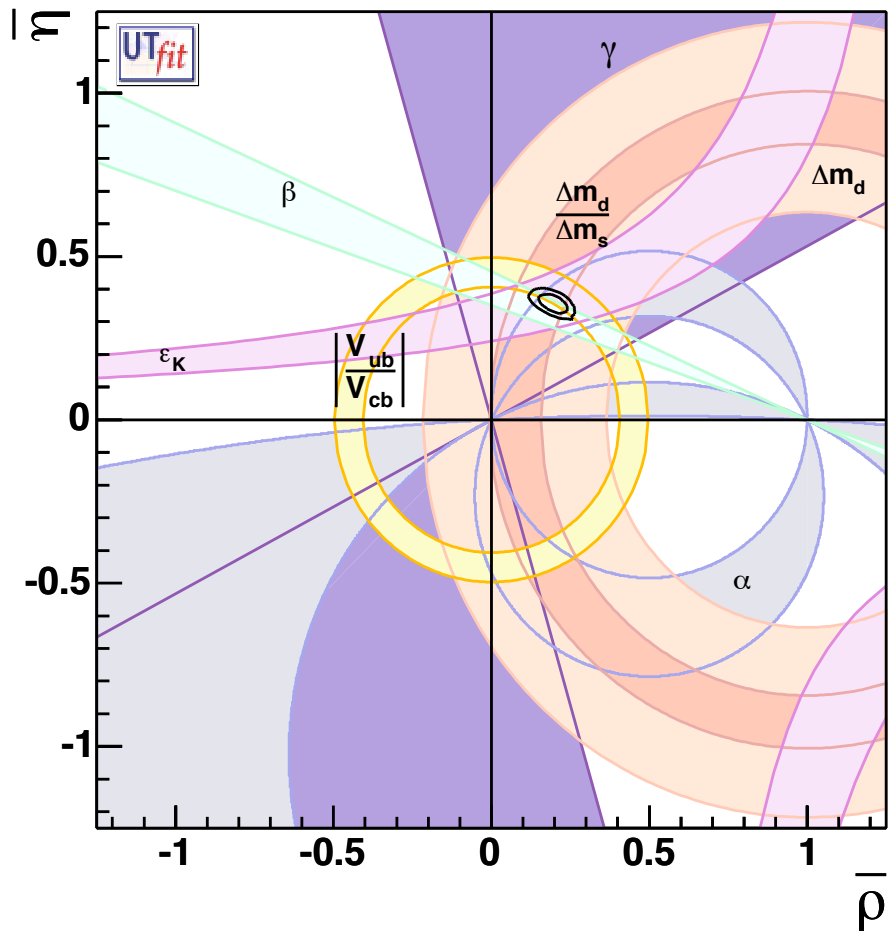
[Belle Collaboration, hep-ex/0506079]

Impact on Unitarity Triangle Fit

after



CKM Fit, with CDF measurement



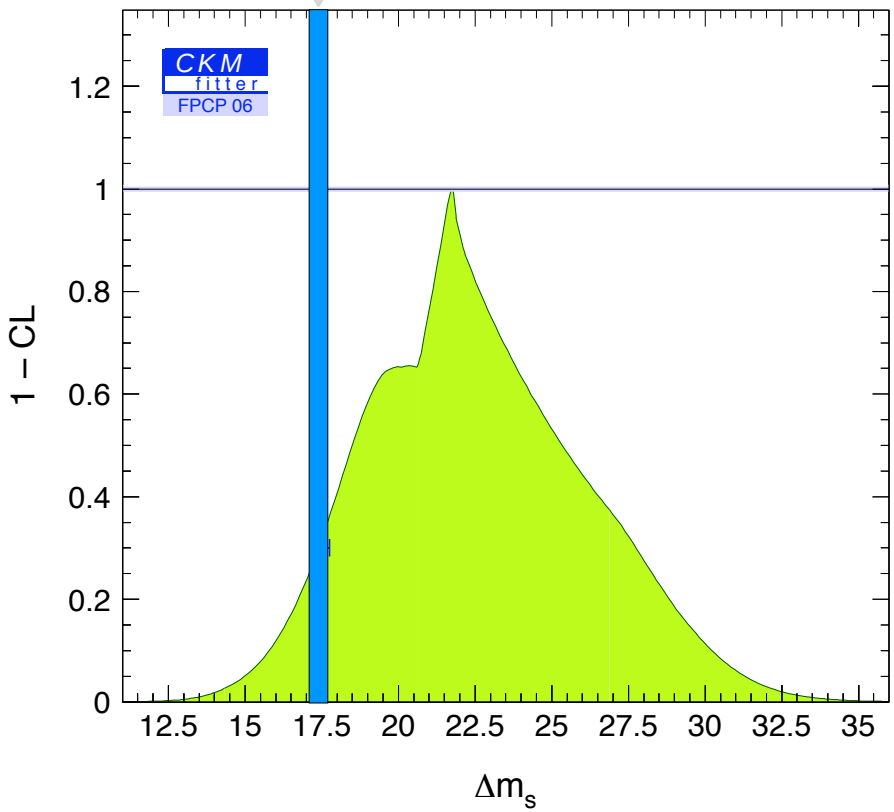
UT Fit, with CDF measurement

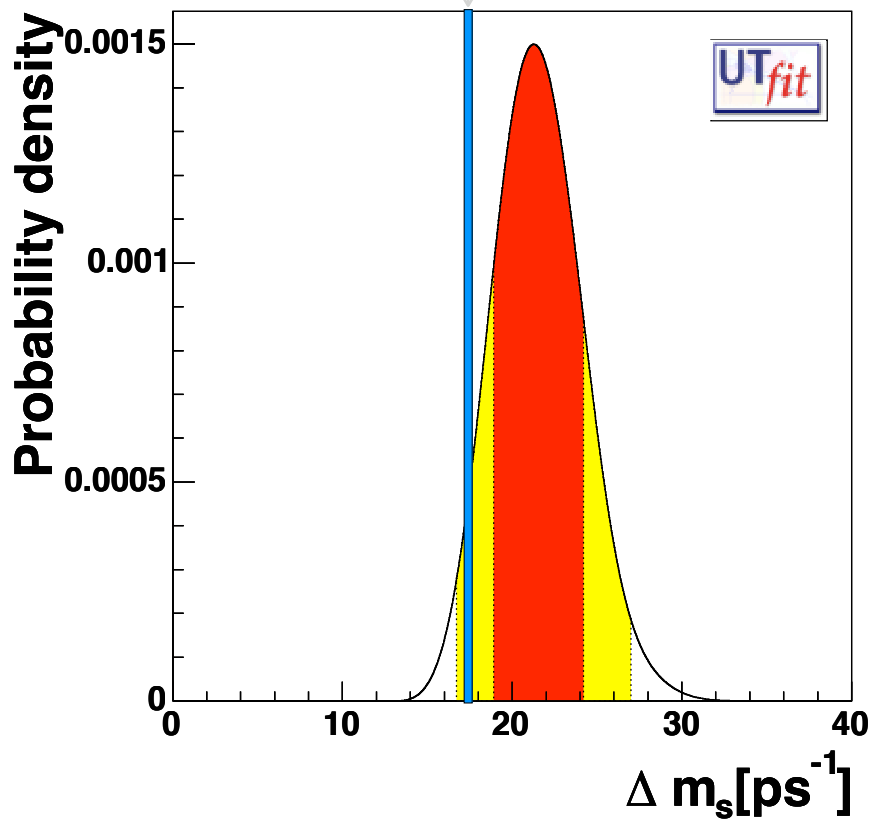
Measurement vs SM Expectation

CKM/UT Fit (SM) without Δms constraint

&

CDF Δm_s Measurement





Summary

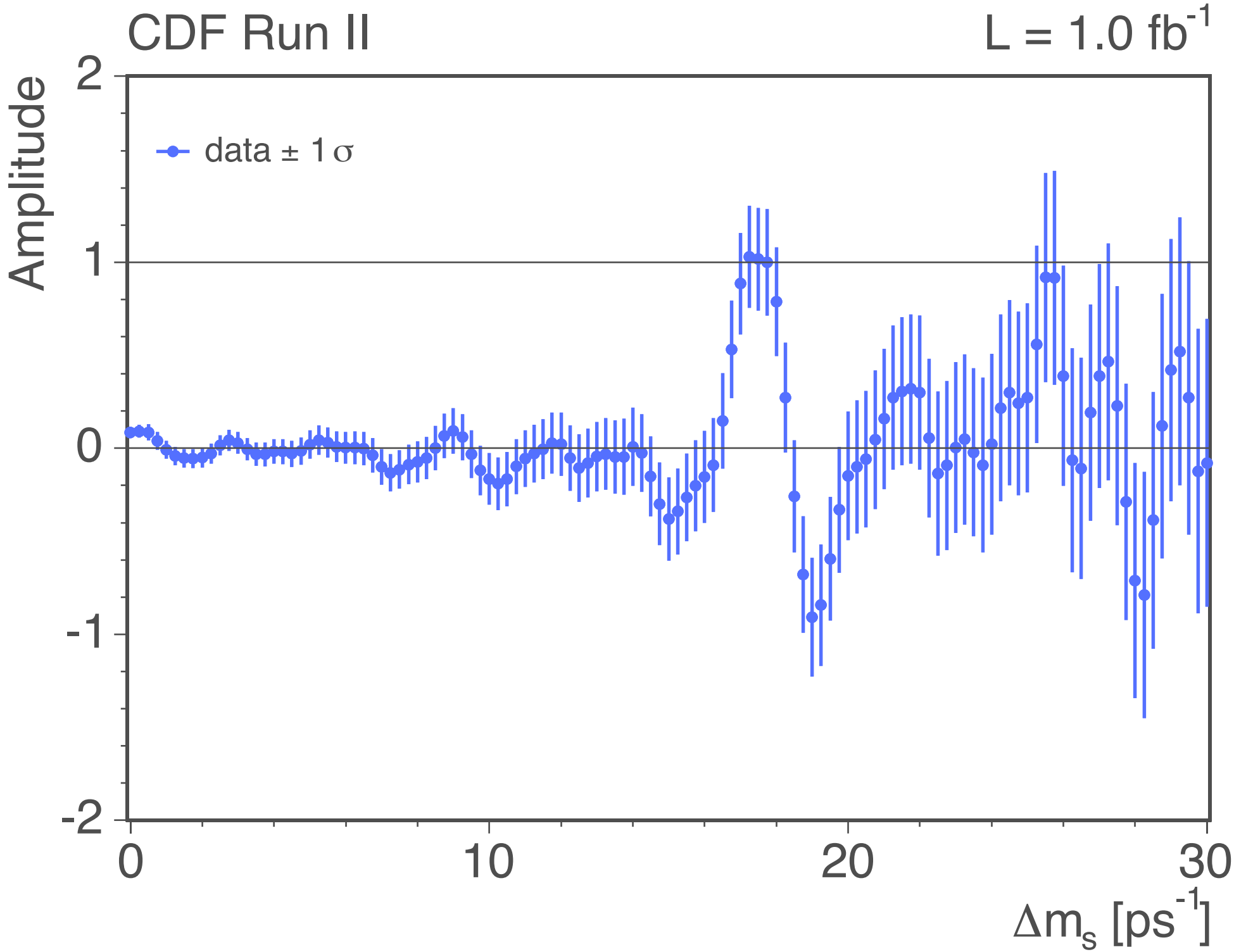
- first direct measurement of Δm_s

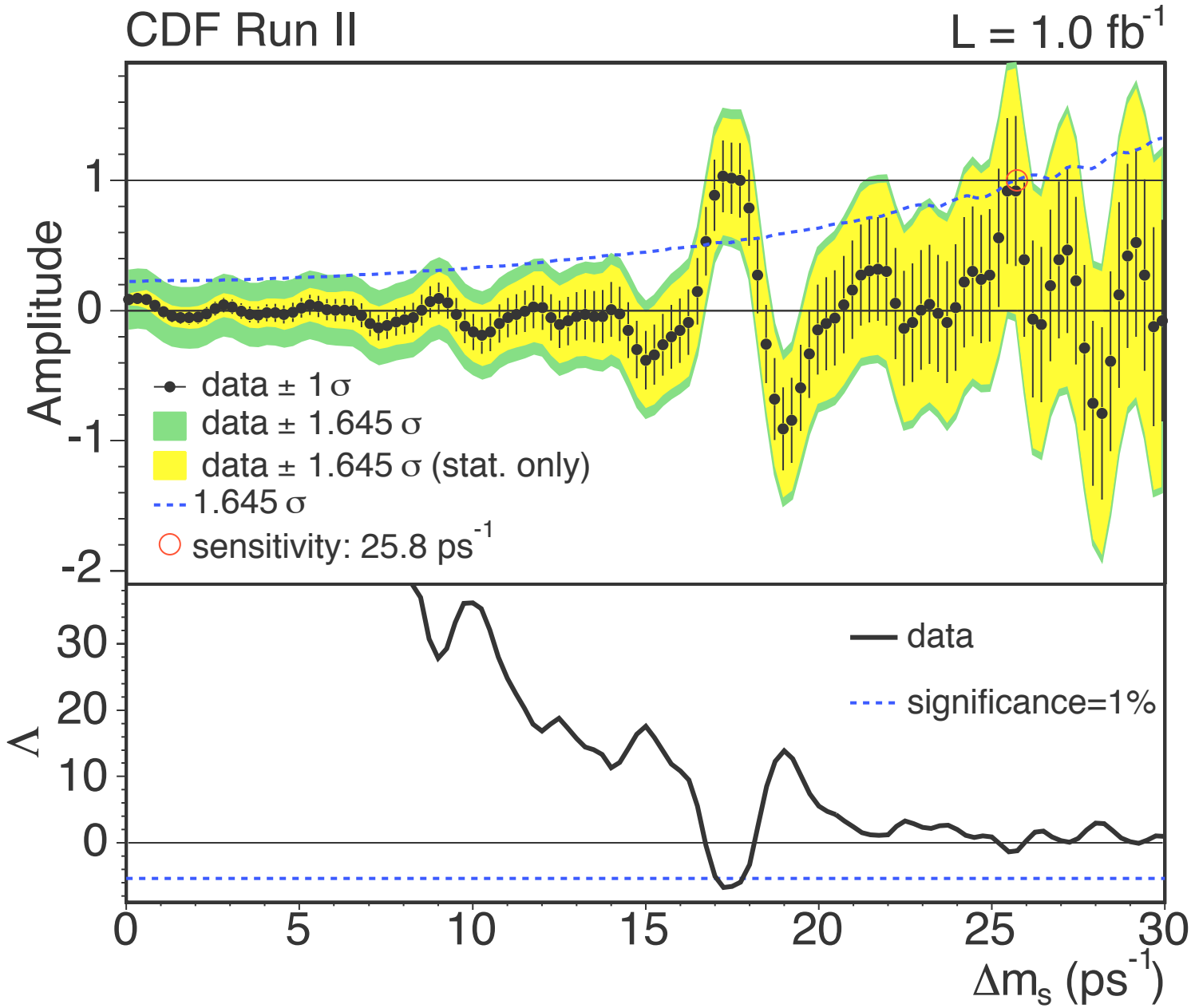
$$\Delta m_s = 17.31^{+0.33}_{-0.18}\,(\text{stat}) \pm 0.07(\text{syst})\ \text{ps}^{-1}$$

  - precision: 2% level
  - probability of random fluctuation: 0.2%

- impact on CKM fit
  - most precise measurement of $|V_{td}|/|V_{ts}|$

- publication just submitted
  - to *Physical Review Letters* | hep-ex/0606027

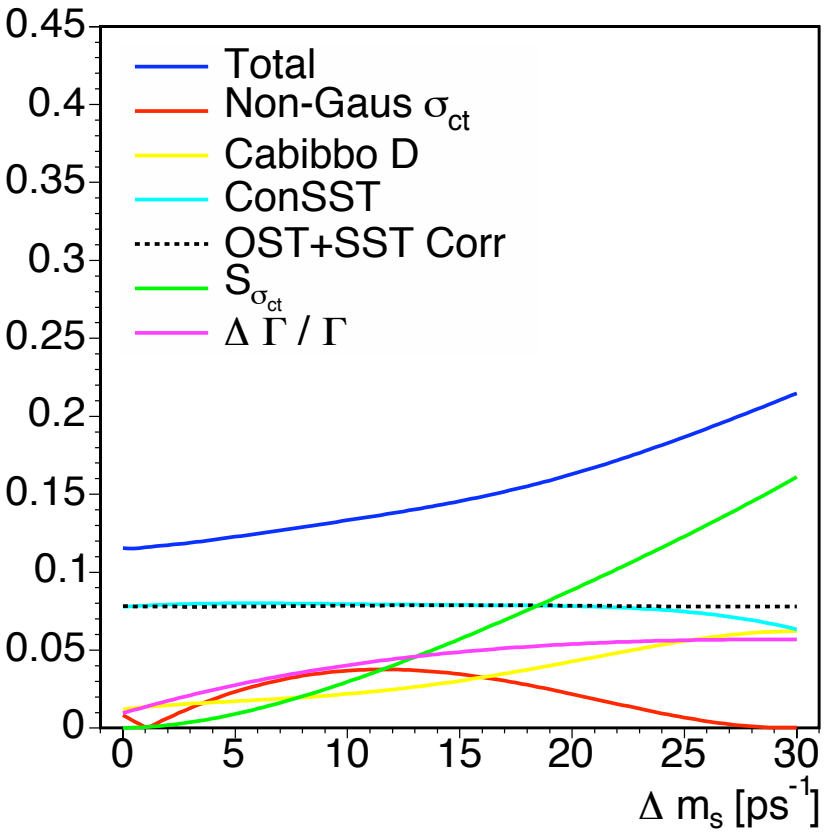

CDF Run II
L = 1.0 fb^{-1}
Amplitude
data ± 1 σ
2
1
0
-1
-2
0
10
20
30
Δm_s [ps^{-1}]


CDF Run II
L = 1.0 fb-1
Amplitude
data ± 1 σ
data ± 1.645 σ
data ± 1.645 σ (stat. only)
1.645 σ
sensitivity: 25.8 ps-1
Λ
data
significance=1%
Δms (ps-1)

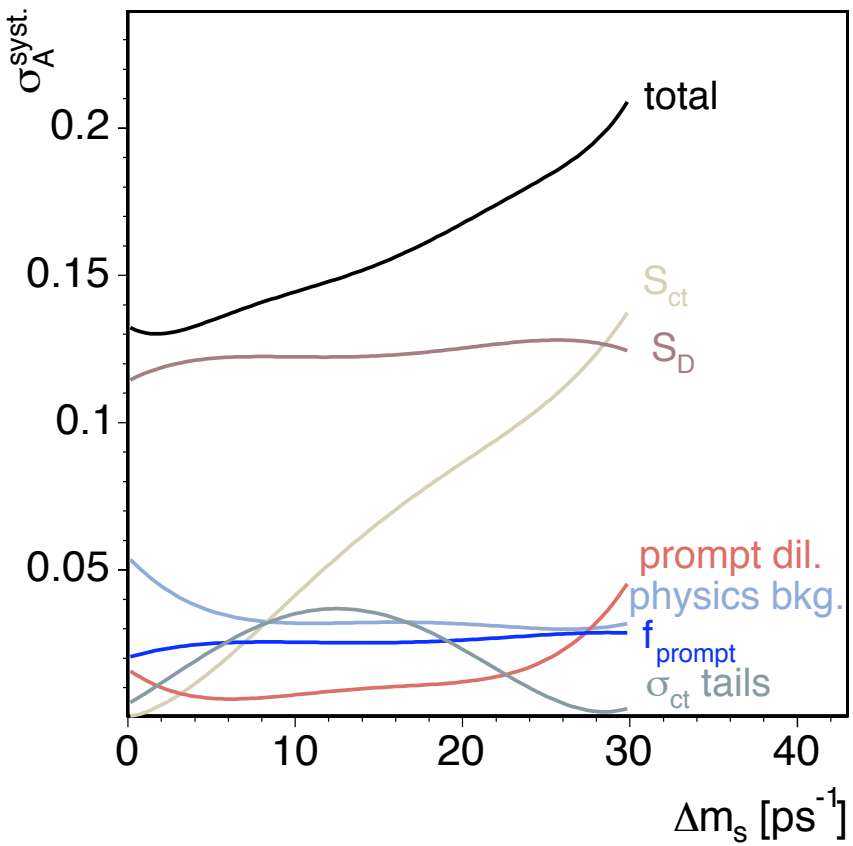
Additional Slides for Reference

Systematic Uncertainties Amplitude

Hadronic



Semileptonic



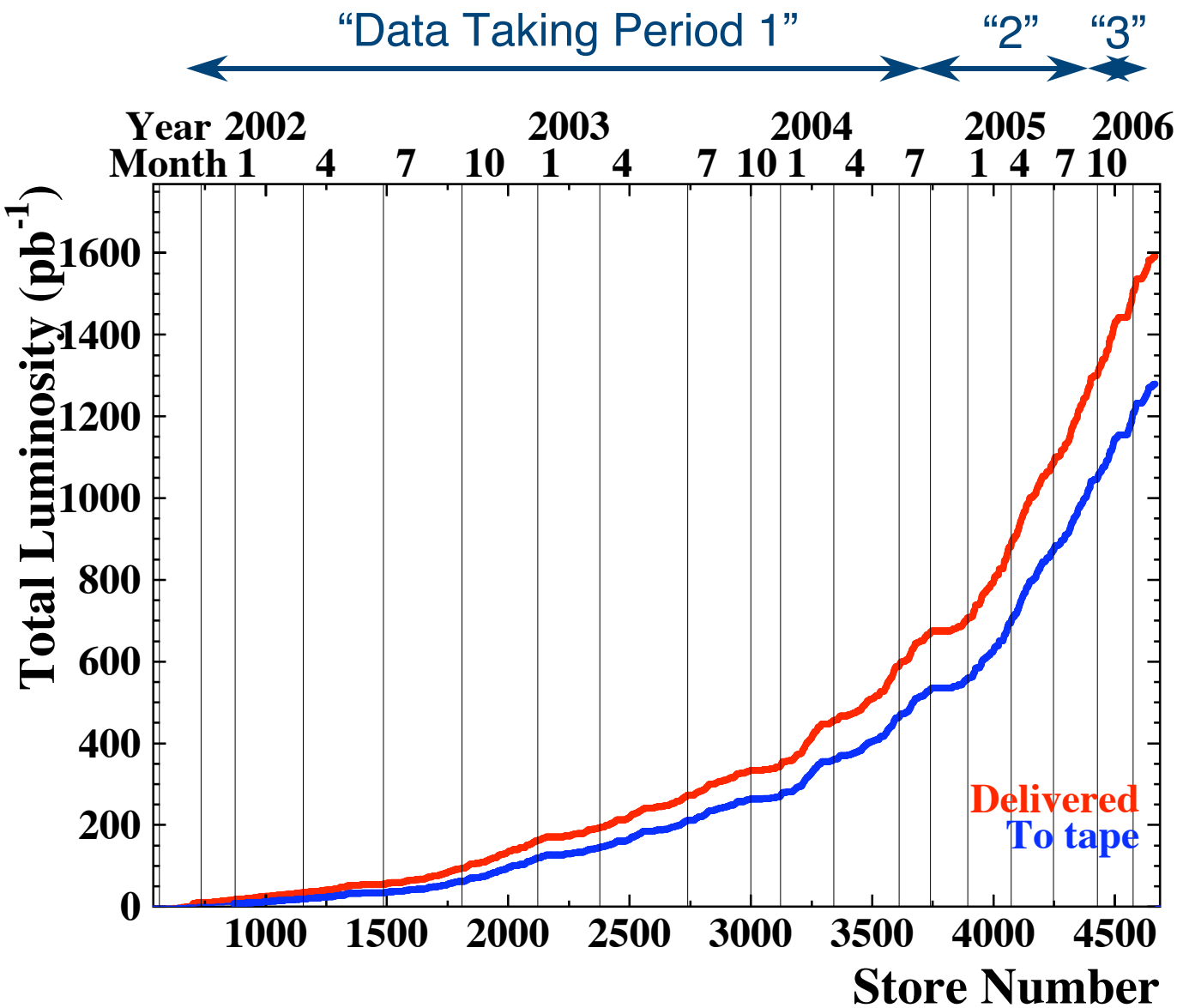
- evaluated on toy MC
- total systematic uncertainites very small compared to statistical
- relevant only for exclusion limits (cancel in ratio A/σ_A)

Systematic Uncertainties Δm_s

	syst. unc.
Silicon alignment	0.04 ps^{-1}
track fit bias	0.05 ps^{-1}
primary vertex	0.02 ps^{-1}
all other syst.	<0.01 ps^{-1}
total	0.07 ps^{-1}

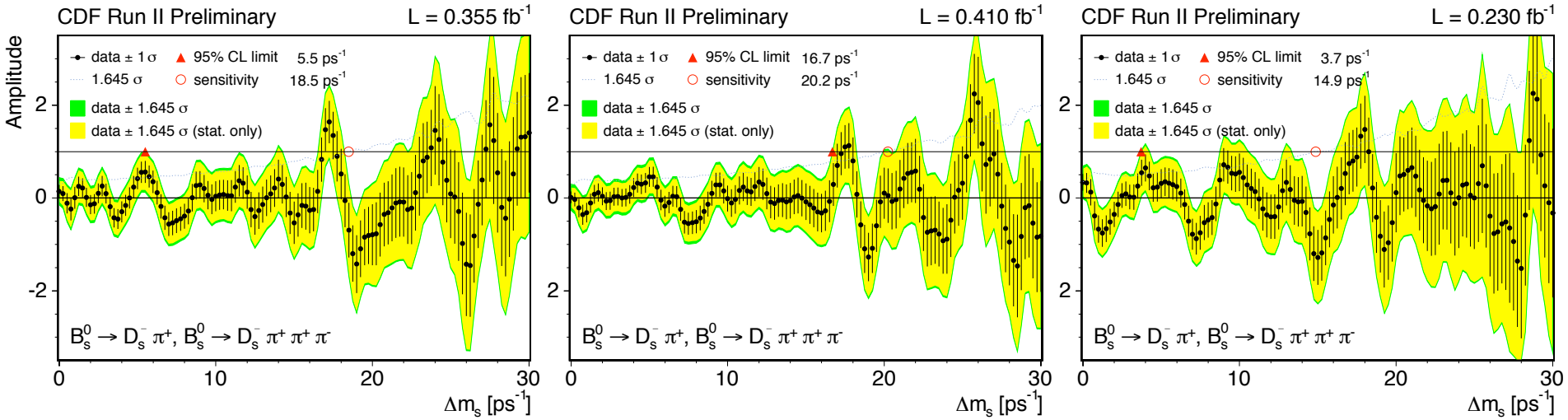
- evaluated on toy MC
- common between hadronic and semileptonic
- have negligible impact
  - relevant systematic uncertainties from proper time scale

Tevatron Luminosity Data Taking Periods

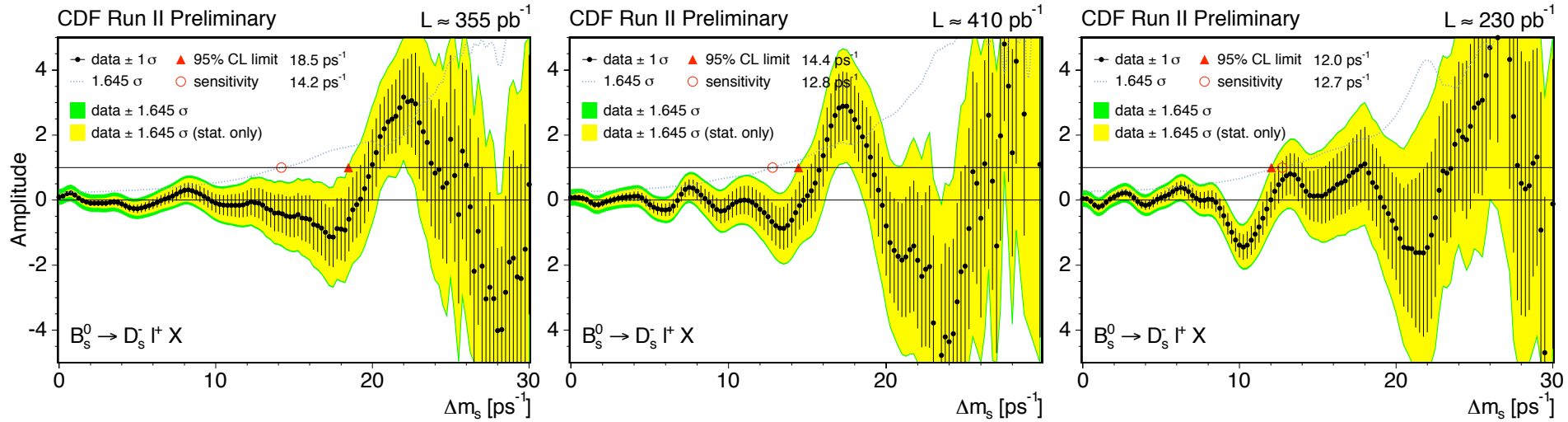


Amplitude Scans Data Taking Periods

Hadronic



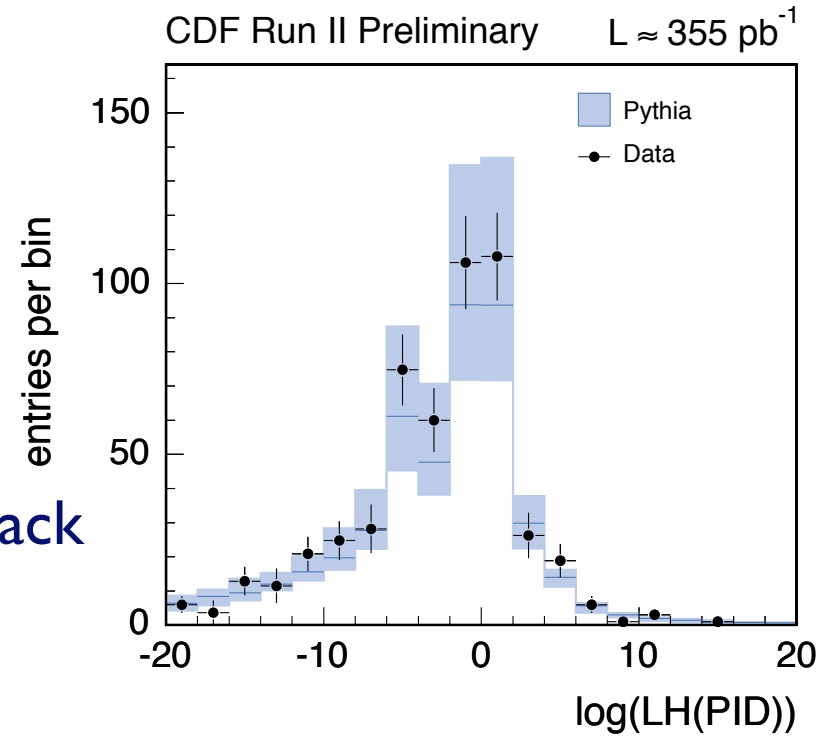
Semileptonic



Same Side Tagging simulation validation

- systematic variations covered
  - fragmentation model
  - *bb* production mechanisms
  - B^{**} content
  - detector/PID resolution
  - multiple interactions
  - PID content around the *B*
  - Data/MC agreement
- select most likely kaon track as tag track
  - use combined PID: TOF & dE/dx
- SST performance estimated from MC
  - $\epsilon D^2(B_s \rightarrow D_s(\phi\pi)\pi) = 4.0\ \%$

small discrepancies covered by systematic variations

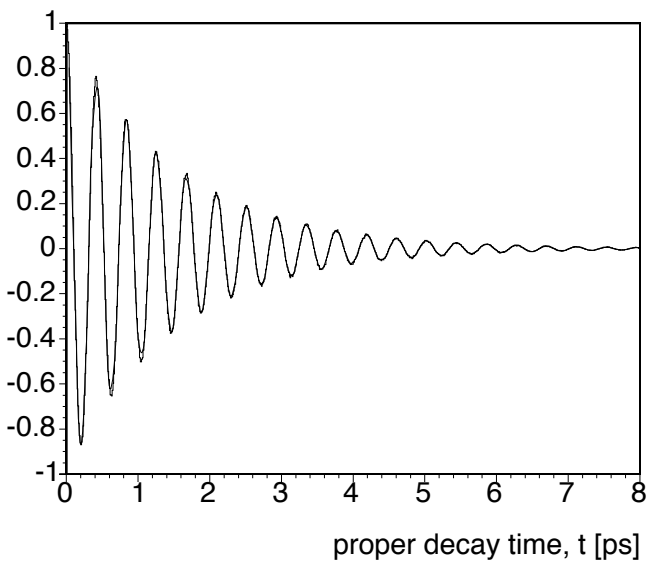


Fourier Transform amplitude peak shape

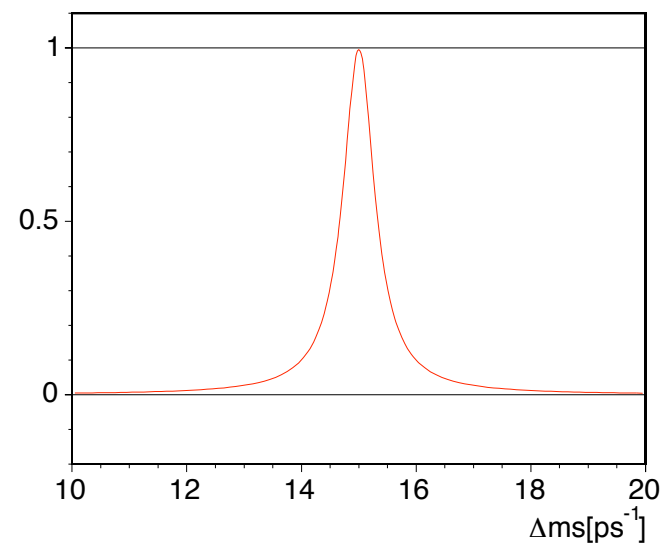
*un*biased proper time

$$A(t;w) = \frac{1}{\tau} e^{-\frac{t}{\tau}} \cos(wt)\,\theta(t)$$

Breit-Wigner



FT



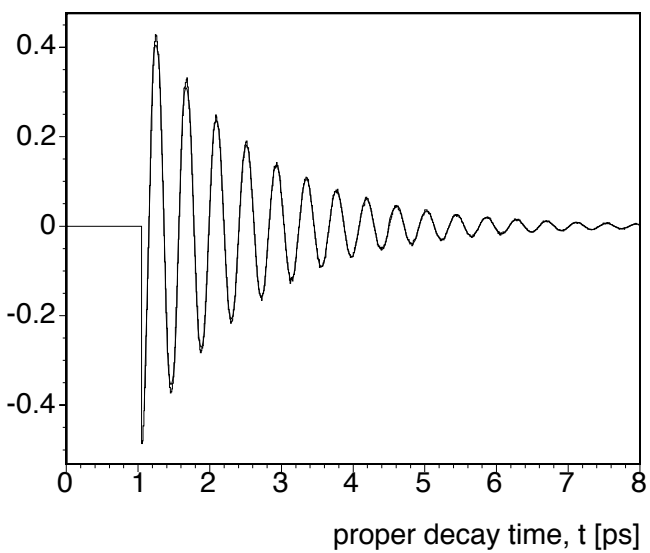
using simplest toy model for illustration purposes

Fourier Transform amplitude peak shape

biased proper time

$$A(t;w) = \frac{1}{\tau} e^{-\frac{t}{\tau}} \cos(wt)\, \theta(t-\zeta)$$

undershootings expected



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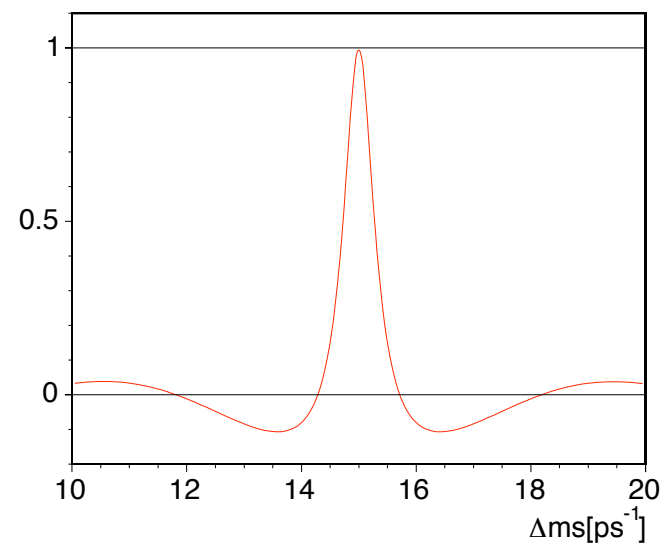

using simplest toy model for illustration purposes