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

Guillelmo Gómez-Ceballos

Instituto de Física de Cantabria

On behalf of the CDF Collaboration

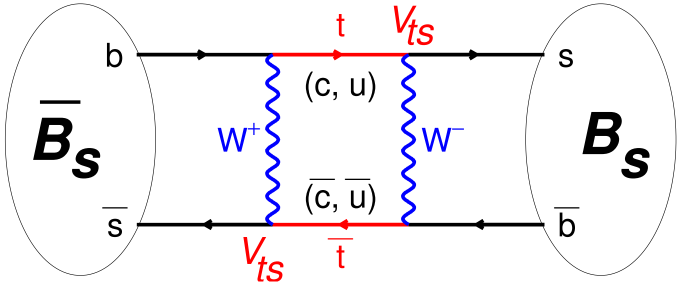
FPCP 2006, Vancouver, Canada

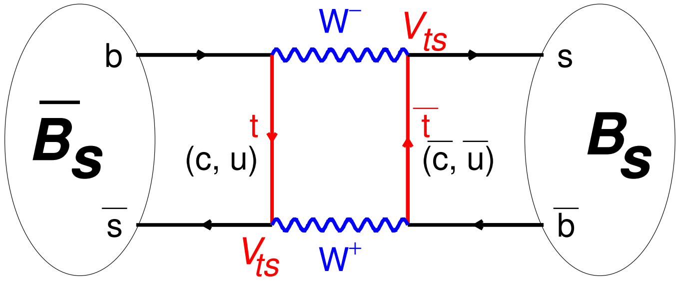
A Brief History of the Δm_s Search at CDF

Just a few “old” results to start with...

Date	Sensitivity (ps^{-1})	95% C.L. Limit (ps^{-1})
Run I	5.1	6.0
February 2005	8.4	7.9
October 2005	13.0	8.6
Now!	???	???

Neutral B Meson Mixing

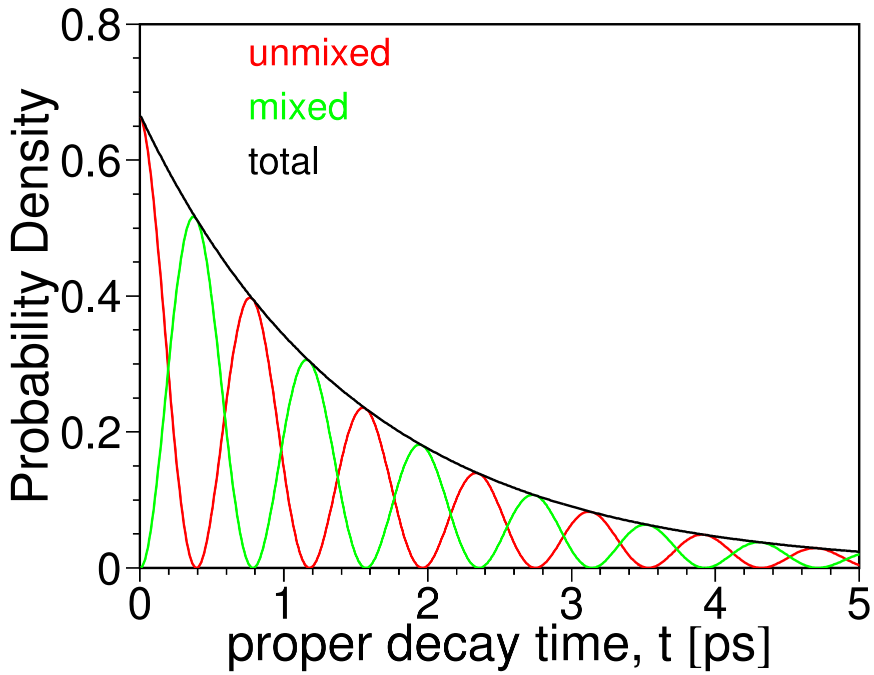




Two-state mixing system

- "heavy" and "light" weak eigenstates
- B and $\overline{B}$ mass eigenstates

$$|B_s\rangle = \frac{1}{\sqrt{2}}(|B_{s,H}\rangle + |B_{s,L}\rangle)$$
$$|\overline{B}_s\rangle = \frac{1}{\sqrt{2}}(|B_{s,H}\rangle - |B_{s,L}\rangle)$$



Solution in proper time

$$P(t)_{B^0\to B^0} = \frac{1}{2\tau}e^{-t/\tau}(1+\cos\Delta m t)$$
$$P(t)_{B^0\to \overline{B^0}} = \frac{1}{2\tau}e^{-t/\tau}(1-\cos\Delta m t)$$

- mixing par. $\Delta m = m_H - m_L$

Theoretical Predictions for Δm

B^0/B^0_s mix through box diagram:

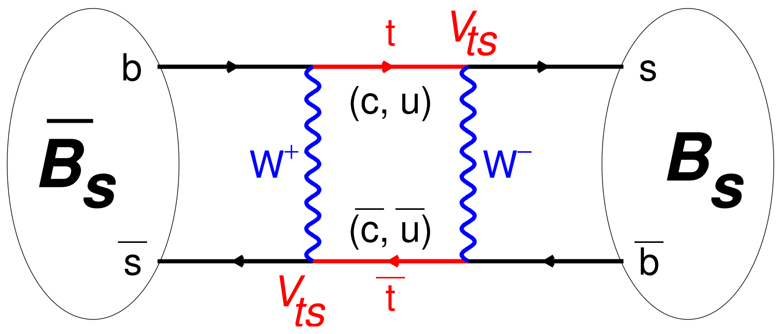
$$\Delta m_q \propto m_{B_q} \hat{B}_{B_q} f^2_{B_q} \left| V_{tb} V^*_{tq} \right|^2$$
$$q = s, d$$

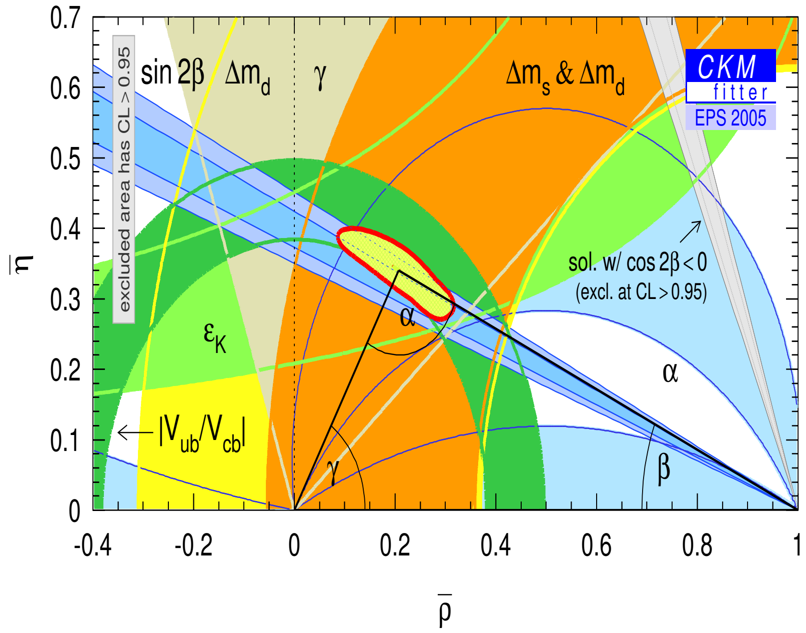
Uncertainties cancel in ratio:

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

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

(Okamoto, Lattice 2005)



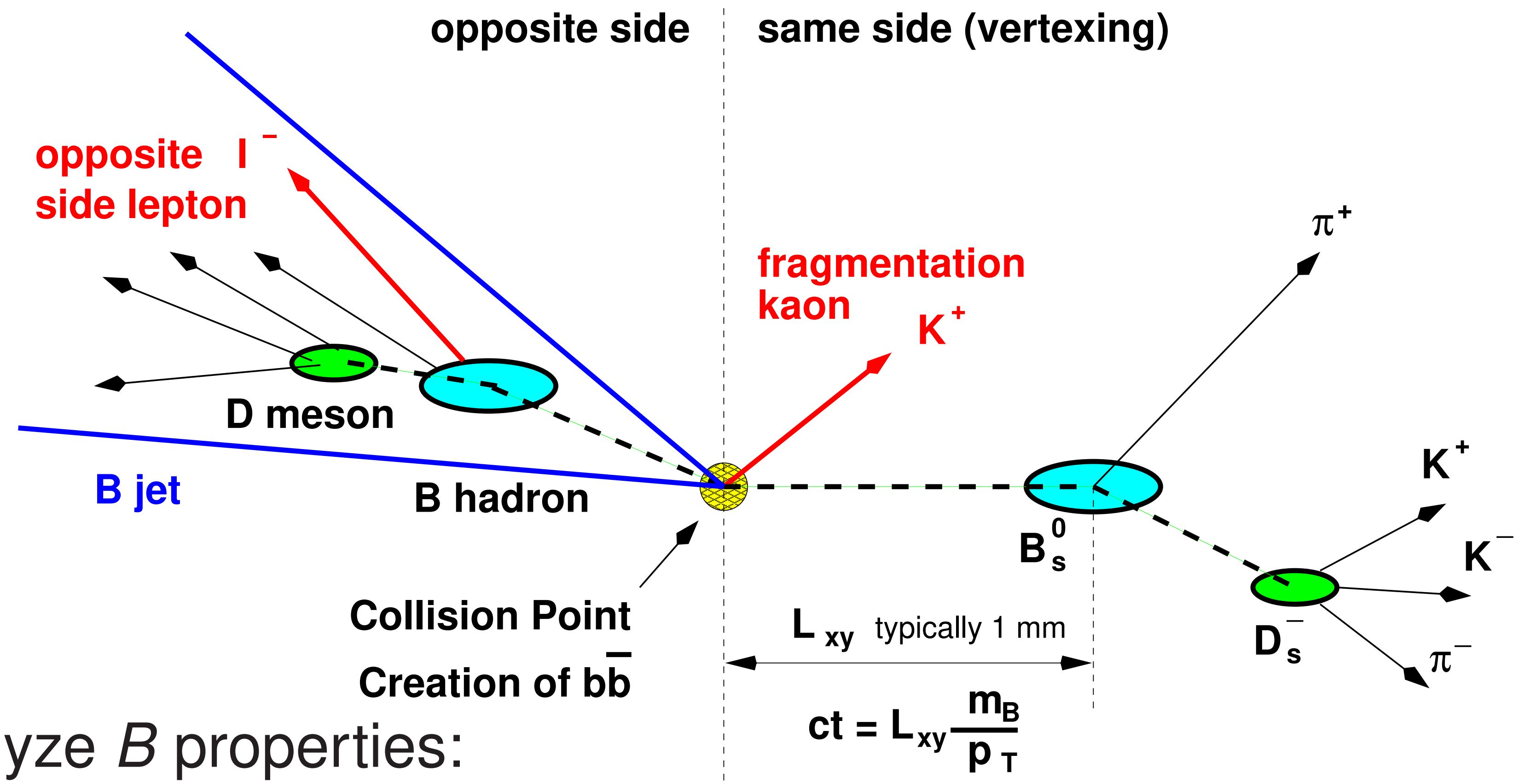


- ☞ measure $\frac{\Delta m_s}{\Delta m_d} \Rightarrow$ find $\frac{|V_{ts}|^2}{|V_{td}|^2}$ to 2.5%
- ☞ Δm_d measured to high precision
- ☞ Δm_s not measured yet
- ☞ Standard Model CKM fit:

$$\Delta m_s = 18.3 \,^{+6.5}_{-1.5}\ \text{ps}^{-1}$$

- ☞ potential new physics discovery

Understanding Single B_s^0 Meson Candidate



Analyze *B* properties:

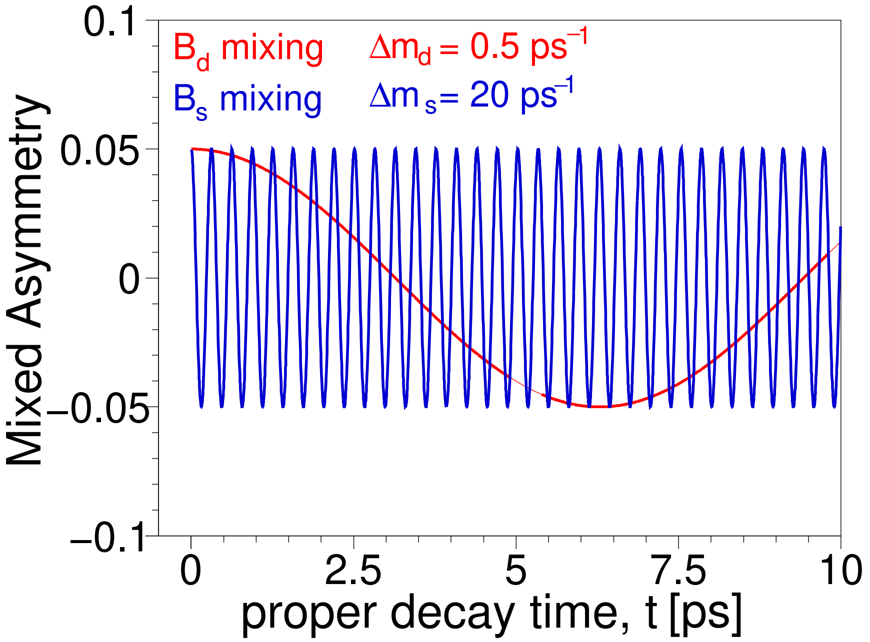
- flavor at decay: from final state
- proper decay length *ct*: in *B* rest frame
- flavor at production: from flavor tagging
- other properties (mass, etc): minimize backgrounds

Δm_s Measurement

Why is this measurement so difficult?:
B_s Mesons Mix much faster than B_d Mesons!

In order to measure:

$$\mathcal{A}_{mix}(t) = \frac{N_{unmix}(t) - N_{mix}(t)}{N_{unmix}(t) + N_{mix}(t)} = \mathcal{D} * cos(\Delta m_s t)$$



$$1/\sigma = \sqrt{S\varepsilon\mathcal{D}^2/2}\sqrt{\frac{S}{S+B}}e^{-\Delta m_s^2 \sigma_t^2/2}$$

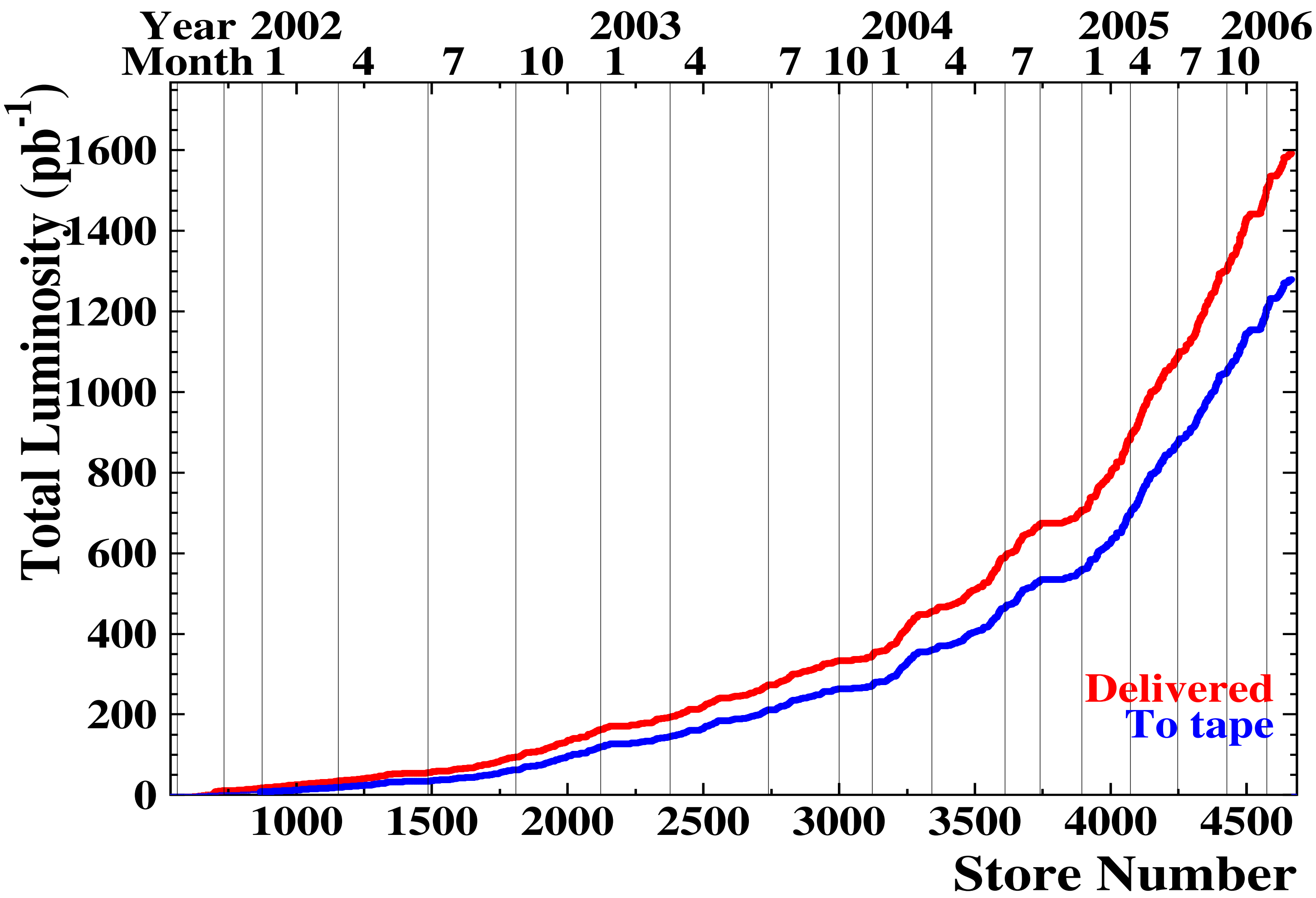
Key elements of the analysis:

- Statistics:
  - hadronic modes
  - semileptonic modes
- Proper decay time resolution: fully reconstructed modes provide better accuracy
- Production flavor (the -key- problem in a hadron collider!): effective statistics, $S\varepsilon\mathcal{D}^2$
  Efficiency: $\varepsilon = \frac{N_{wrong}+N_{right}}{N}$; Dilution: $\mathcal{D} = 1 - 2\frac{N_{wrong}}{N_{wrong}+N_{right}}$

CDF Detector: Critical Components for Δm_s

- Reconstruct B_s signal: low background, high statistics
  - Trigger system: displaced Track Trigger
  - Central Outer Chamber (COT): momentum resolution
  - Silicon tracker (SVX/ISL/L00)
  - Muon Chambers and Calorimeters: lepton identification
- Proper decay time resolution:
  - L00 (mounted on beam pipe): ~ 10-20% improvement in the impact parameter resolution of tracks
- *b* flavor tagging: separation of kaons versus pions
  - dE/dx information from the COT
  - Time-Of-Flight detector:
    - significantly improves Same-Side Kaon Tagging

Data



$\mathcal{L}$(tape) ~ 1.2 fb^{-1}, $\mathcal{L}$(silicon+core components) ~ 1.0 fb^{-1}

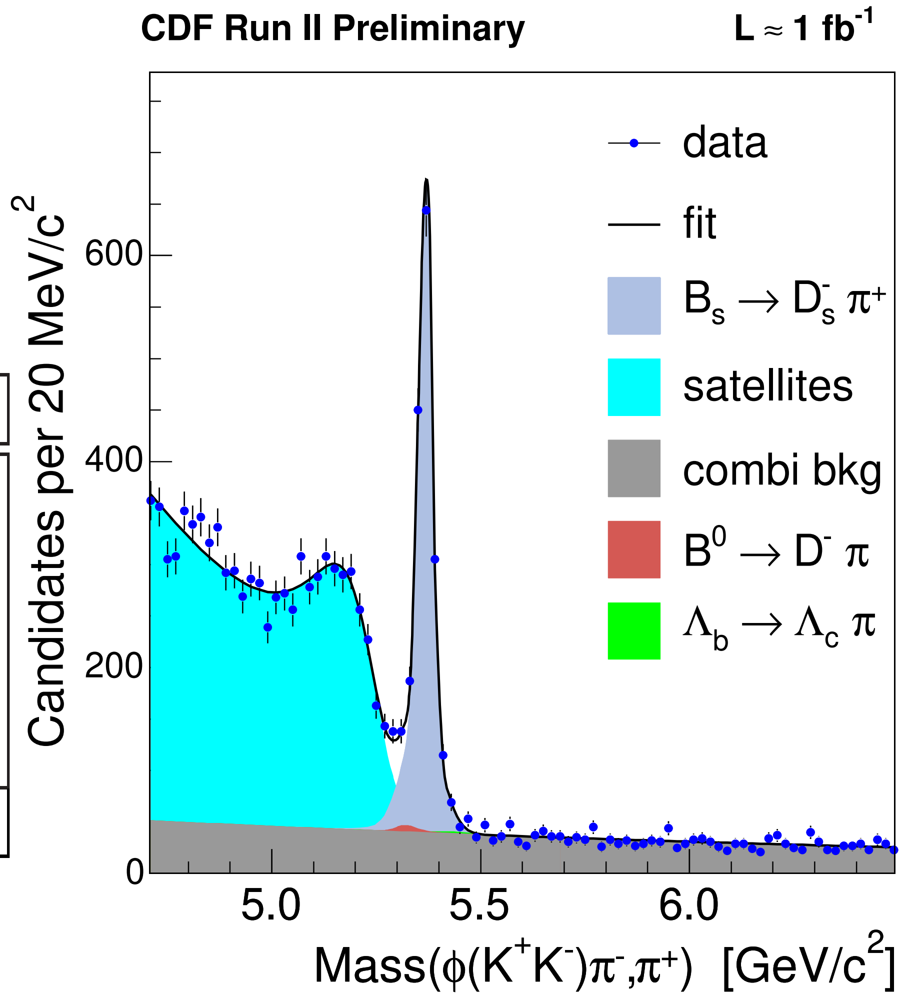
Reconstructing B_s Mesons

Reconstruct B_s signal

- Fully reconstructed modes: $B_s \to D_s(\pi\pi)\pi,\, D_s \to \phi\pi/K^*K/3\pi$
  - relatively small branching ratios
  - all daughters reconstructed
  - "Two Displaced Track Trigger" used to collect those events
- Semileptonic modes: $B_s \to D_s\ell X,\, D_s \to \phi\pi/K^*K/3\pi$
  - large branching ratios
  - missing momentum (neutrino & neutrals)
  - "Two Displaced Track Trigger" & "lepton + Displaced Track Trigger" used to collect those events

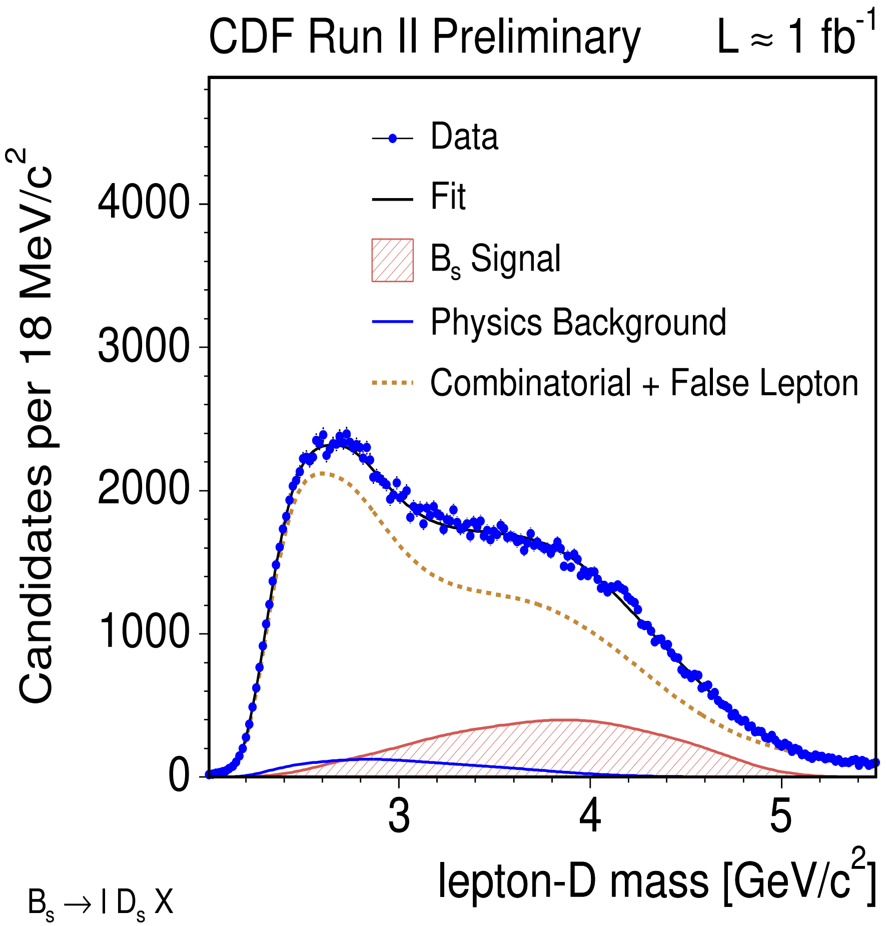
Fully Reconstructed Decays

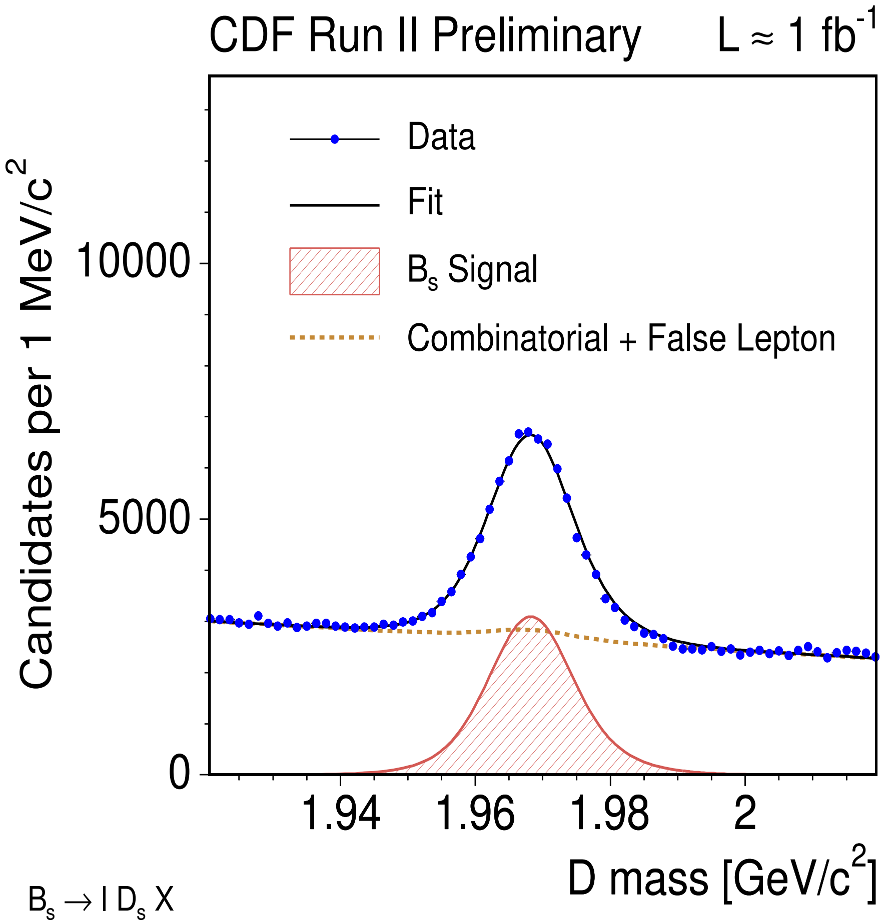
Decay	Candidates
$B_s \to D_s\pi, D_s \to \phi\pi$	1600
$B_s \to D_s\pi, D_s \to K^*K$	800
$B_s \to D_s\pi, D_s \to \pi\pi\pi$	600
$B_s \to D_s 3\pi, D_s \to \phi\pi$	500
$B_s \to D_s 3\pi, D_s \to K^*K$	200
Total	3700



Low background under
B_s mass peak

Semileptonic Decays





$m(\ell D_s)$

New powerful variable used in the unbinned likelihood fit

$B_s \rightarrow D_s \ell X$

~53K Candidates

Proper Decay Time
&
Proper Decay Time Resolution

Proper Decay Time Reconstruction

- Fully reconstructed decays:

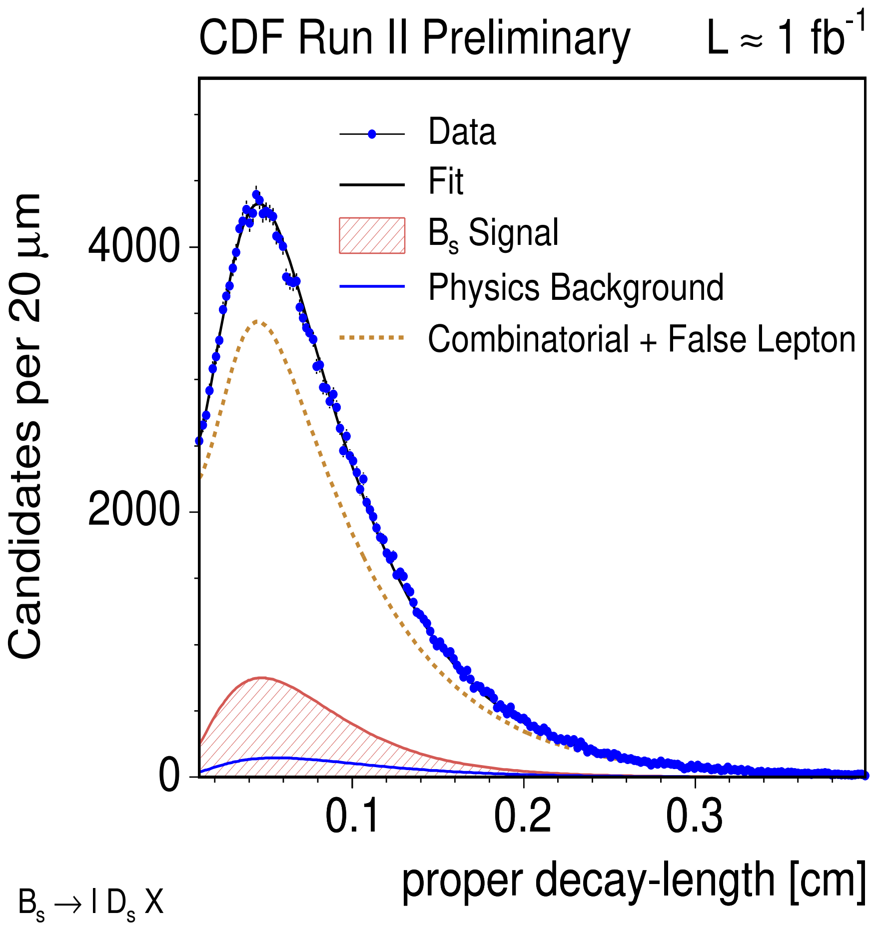
$$ct = L_{xy}^{B} \frac{m_B}{p_T^B}$$

- Semileptonic decays:

$$ct = L_{xy}^{\ell D} \frac{m_B}{p_T^{\ell D}} \cdot k$$

$$k = \left\langle \frac{p_T^{\ell D}}{p_T^B} \frac{L_{xy}^B}{L_{xy}^{\ell D}} \right\rangle \text{ from MC}$$

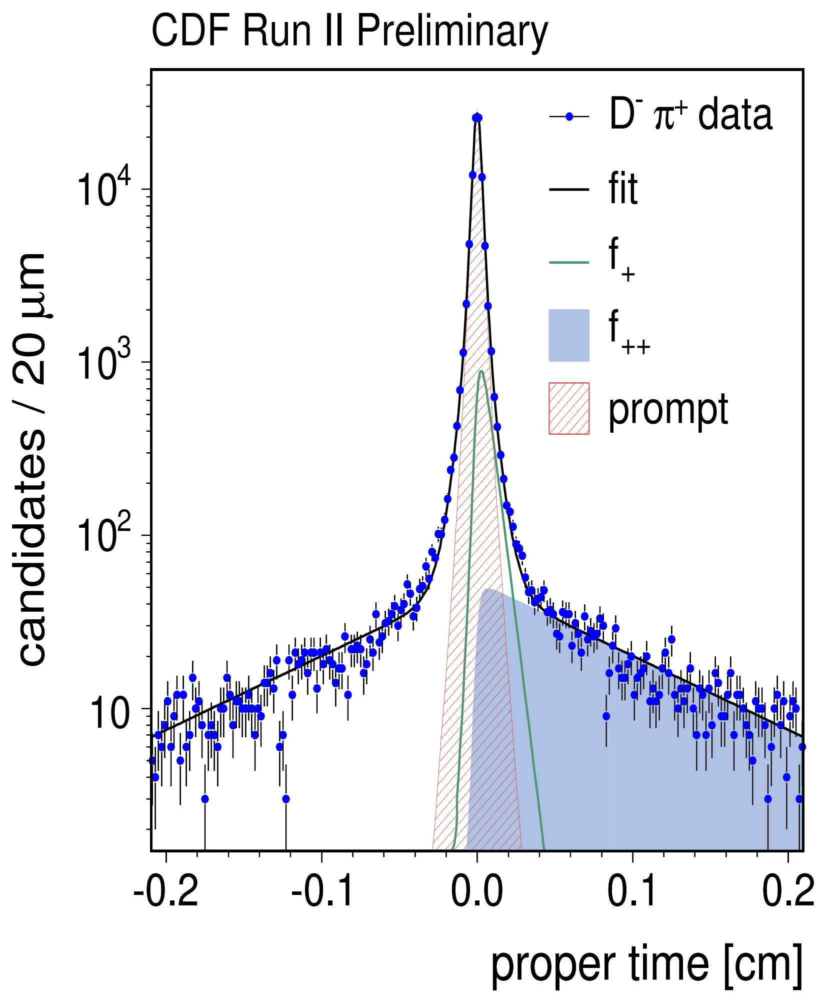
Model from well studied $B^{+/0}$ semileptonic decays



Lifetime measurements consistent with PDG (see other CDF talks)

Proper Decay Time Resolution (I)

Critical aspect of the analysis, limiting factor at high Δm_s



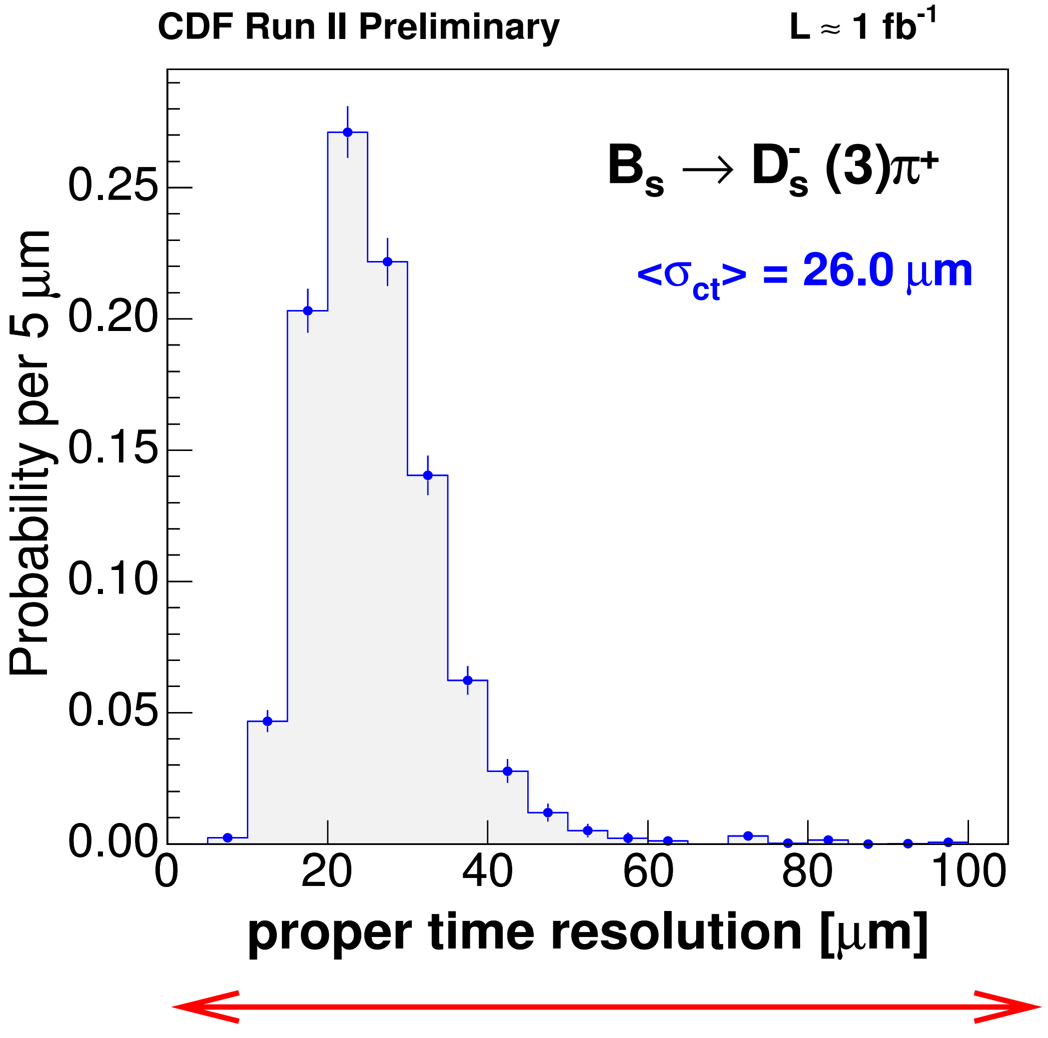
Use prompt D^+ and track

- ☞ large sample of prompt D^+
- ☞ most tracks from PV
- ☞ same topology as signal
- ☞ measure of *ct* resolution

Calibrated on our data

Proper Decay Time Resolution (II)

Critical aspect of the analysis, limiting factor at high Δm_s



one oscillation at Δ m_s = 18/ps

Proper Decay Time Resolution (III)

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

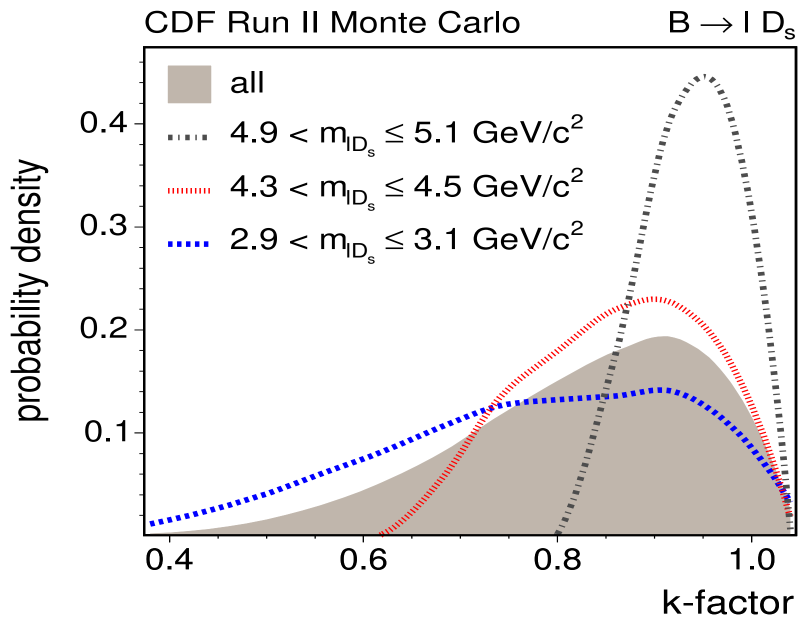
Hadronic $B_s \rightarrow D_s(3)\pi$:

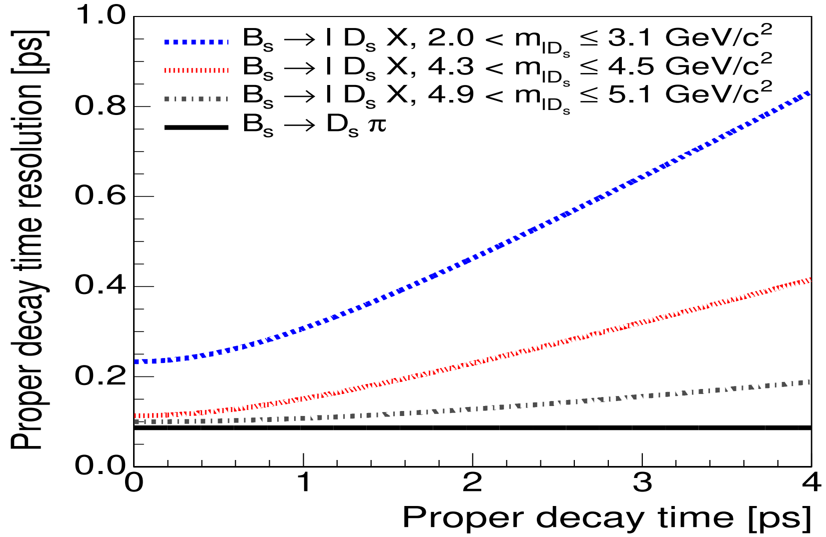
- ☞ $\sigma^0_{ct} \sim 26\ \mu m\ (87\ fs)$
- ☞ $\sigma_p/p < 1\%$

Semileptonic $B_s \rightarrow D_s \ell X$:

- ☞ $\sigma^0_{ct} \sim$ 30-70 μm (100-230 fs)
- ☞ $\sigma_p/p \sim$ 3-20%

Variation of k-factor with $m(\ell D)$ significantly improves decay time resolution in semileptonic





b Flavor Tagging

b Flavor Tagging (I)

Opposite Side Tagging:

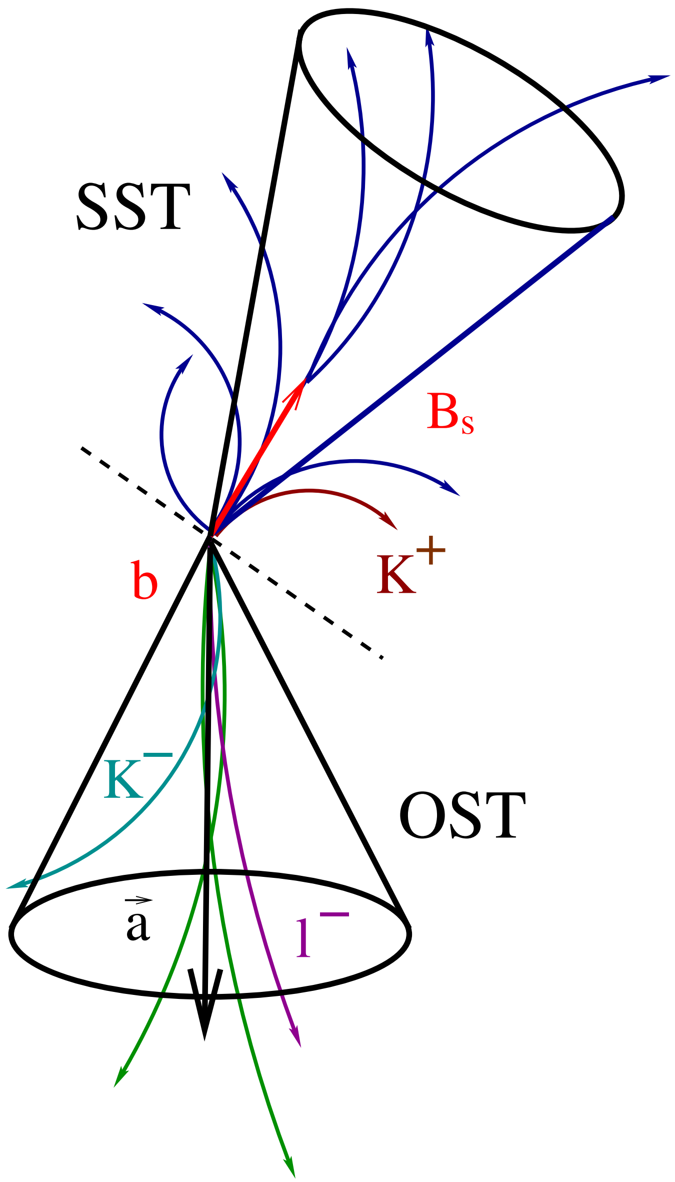
- Jet-Charge-Tagging
  sign of the weighted average charge of opposite B-Jet

- Soft-Lepton-Tagging
  identify soft lepton (e, μ) from semileptonic decay of opposite B: $b \to l^- X$ (BR $\approx$ 20%),

  Dilution due to $\bar{b} \to \bar{c} \to l^- X$ and oscillation

- Applicable to both B^0 and B_s: can use high statistics ℓD samples to calibrate the taggers

- Other b not always in the acceptance



b Flavor Tagging (II)

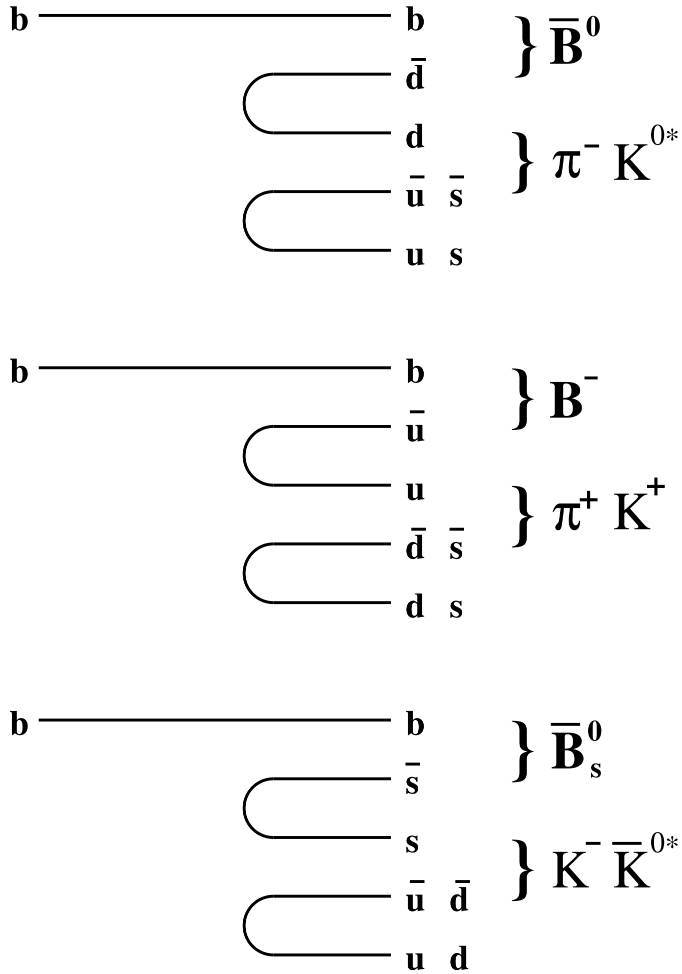
Same Side (Kaon) Tagging : (recently added)

- $B_{d/u}$ is likely to be accompanied close by a π^+/π^-
- B_s is likely to be accompanied close by a K^+

Particle ID helps a lot to improve εD^2:

TOF and dE/dx are very important!

There is no straightforward way to measure the tagger dilution on data unless we observe Mixing, we need to rely on MC (details given in J. Piedra's talk last Sunday)



b Flavor Tagging (III)

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

More details about b flavor tagging and Δm_d measurement already given in J. Piedra's talk

B_s Oscillation Analysis

Fourier analysis

Two domains to fit for oscillation:

Time domain:

☞ fit for Δm_s in $P(t) \sim (1 \pm D \cos \Delta m_s t)$

Frequency domain: amplitude scan

☞ introduce amplitude:

$P(t) \sim (1 \pm \mathcal{A} D \cos \Delta m_s t)$

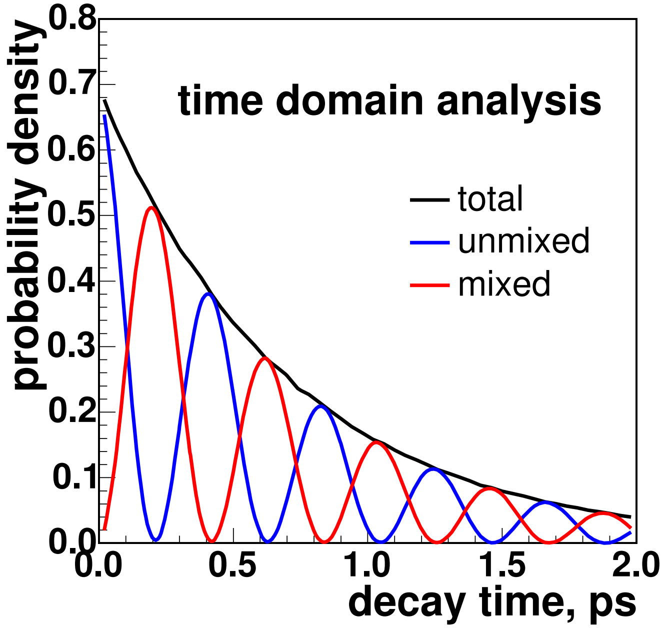
☞ fit for $\mathcal{A}$ at different Δm_s

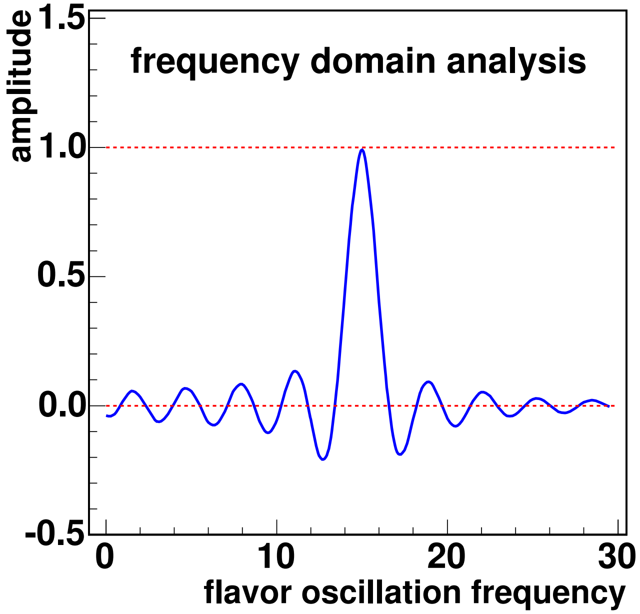
$\Rightarrow$ obtain frequency spectrum

☞ true $\Delta m_s \Rightarrow \mathcal{A} = 1$, else $\mathcal{A} = 0$

☞ traditionally used for B_s^0 mixing search

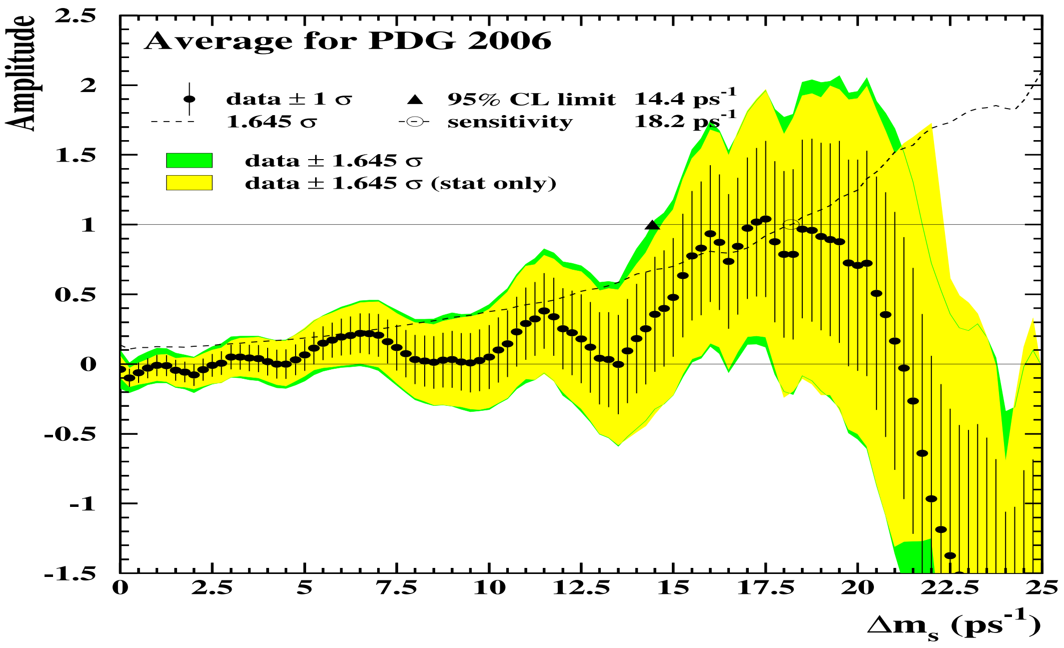
$\Rightarrow$ easy to combine experiments





Amplitude scan notations

- amplitude error bars: come from unbinned likelihood fit
- yellow: 1.645σ around data points defines 95% CL region
- Δm values where $\mathcal{A} + 1.645\sigma < 1$ are excluded at 95% CL
- dashed line: 1.645σ as a function of Δm
- sensitivity: the Δm where $1.645\sigma = 1$
- on average, we expect to observe mixing within sensitivity



Sensitivity

- Average PDG 2006: 18.6 ps^{-1}
- Latest DØ analysis: 14.1 ps^{-1}
- New CDF analysis: 25.3 ps^{-1}

One single experiment has more sensitivity than the world average combination!

Be prepared for measurement (finally !!)

Procedure

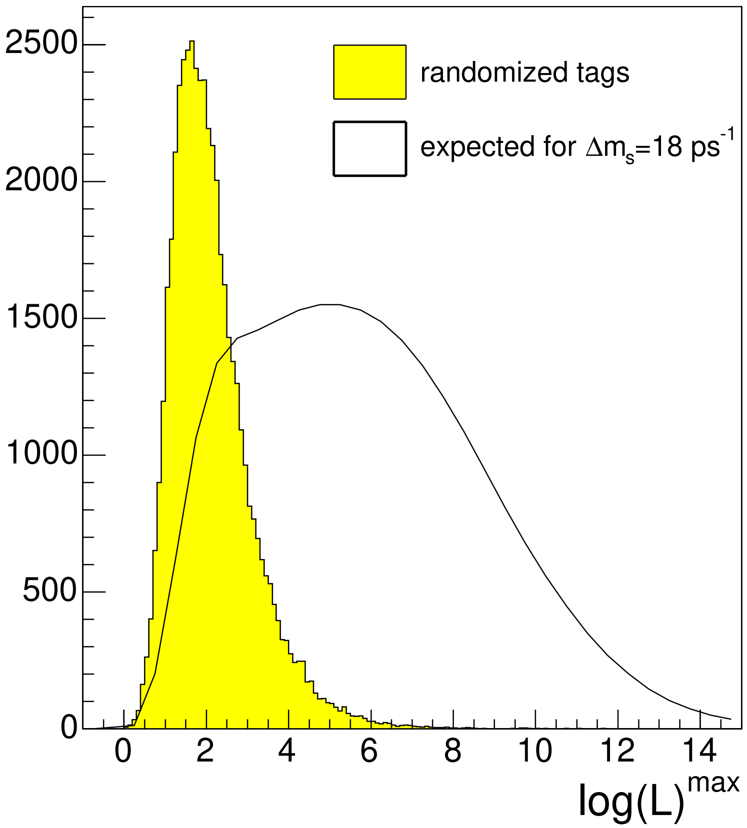
Before un-blinding the full data sample, we decided what to do:

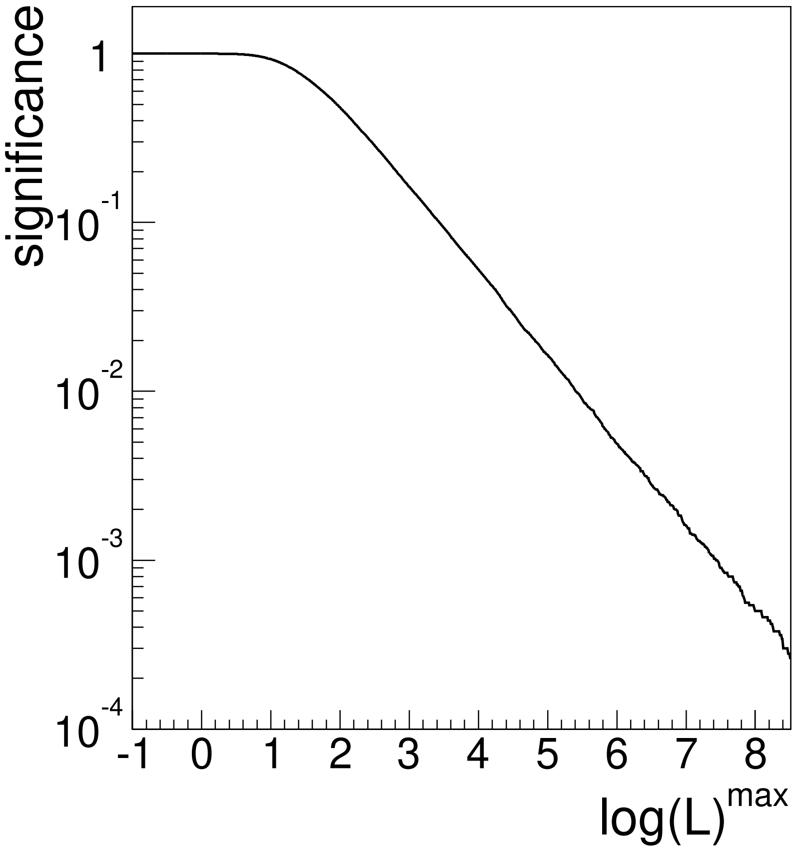
☞ to be estimated using $\Delta log(LR)$ method:
$\Delta log(LR) = log[L(A=1)/L(A=0)]$

☞ p-value: probability that background (random tags) could fluctuate to mimic such a signature

- If p-value $> 1\%$
  * use the usual amplitude scan
  * set 95% C.L. limit on Δm_s
- If p-value $< 1\%$
  * make double-sided confidence interval on Δm_s from $\Delta log(LR)$
  * measure Δm_s

Likelihood Ratio





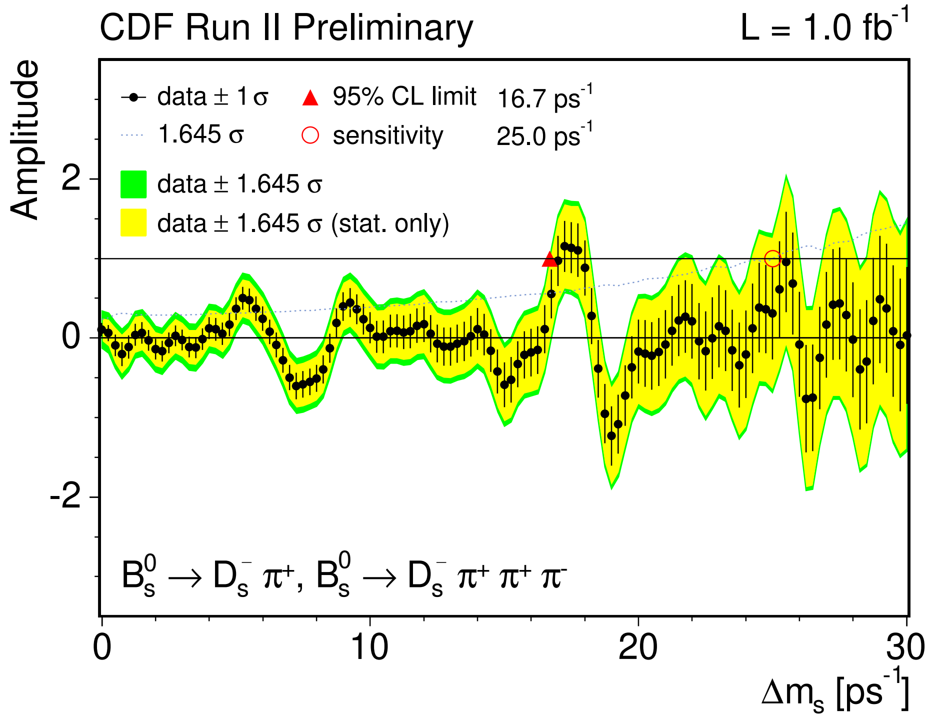
$$\Delta log(LR) = log[L(A=1)/L(A=0)]$$

p-value: probability that background (random tags) could fluctuate to values greater than a given value

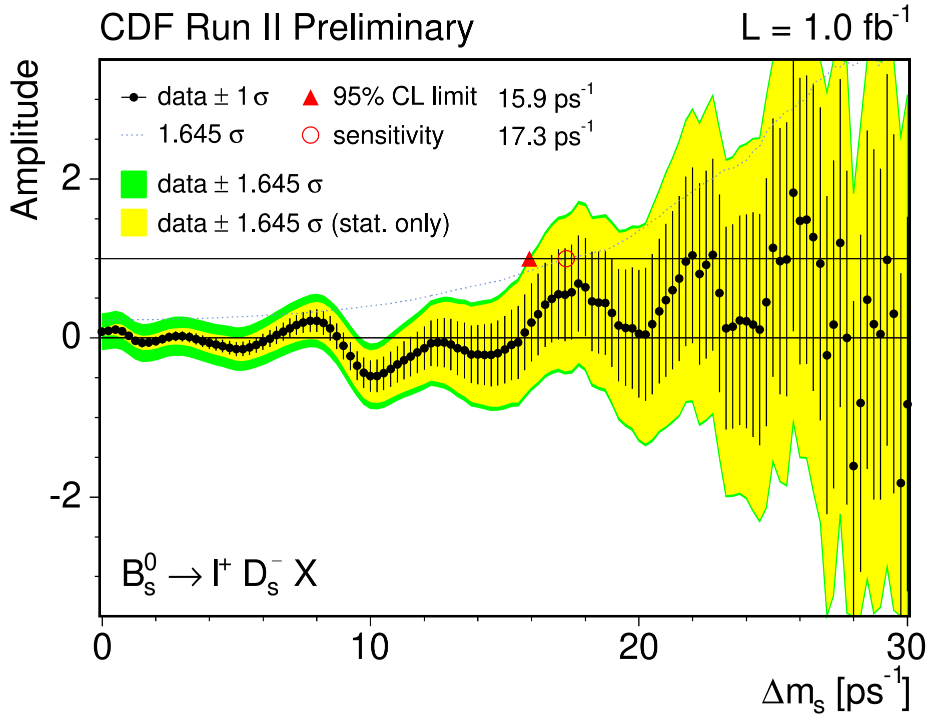
The Data

Amplitude Scans

Hadronic



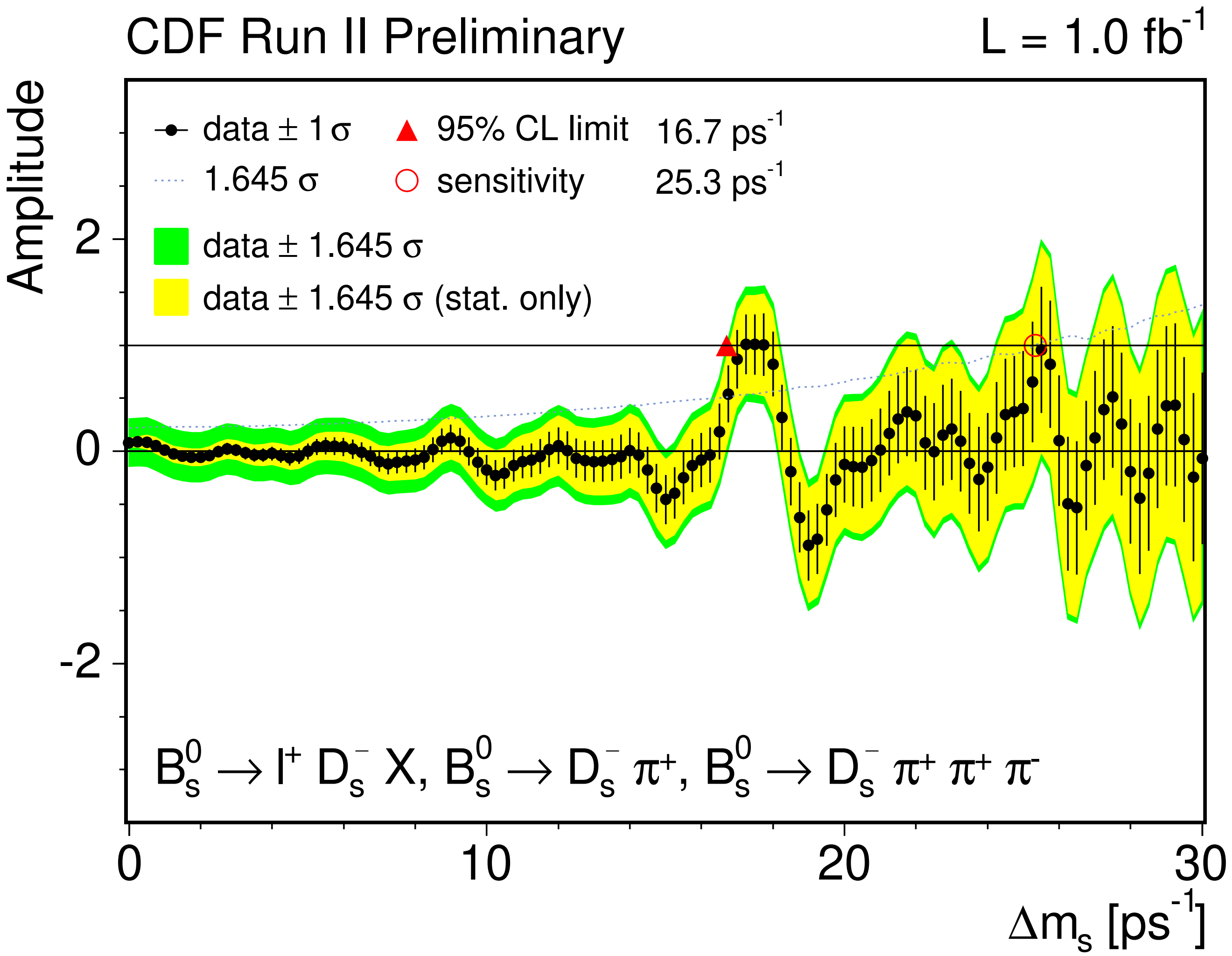
Semileptonic



Note that they have the best (hadronic) and 2nd best (semileptonic) sensitivity!

$\mathcal{A}$ compatible with 1 for $\Delta m_s \sim 17.25$ ps^{-1}!

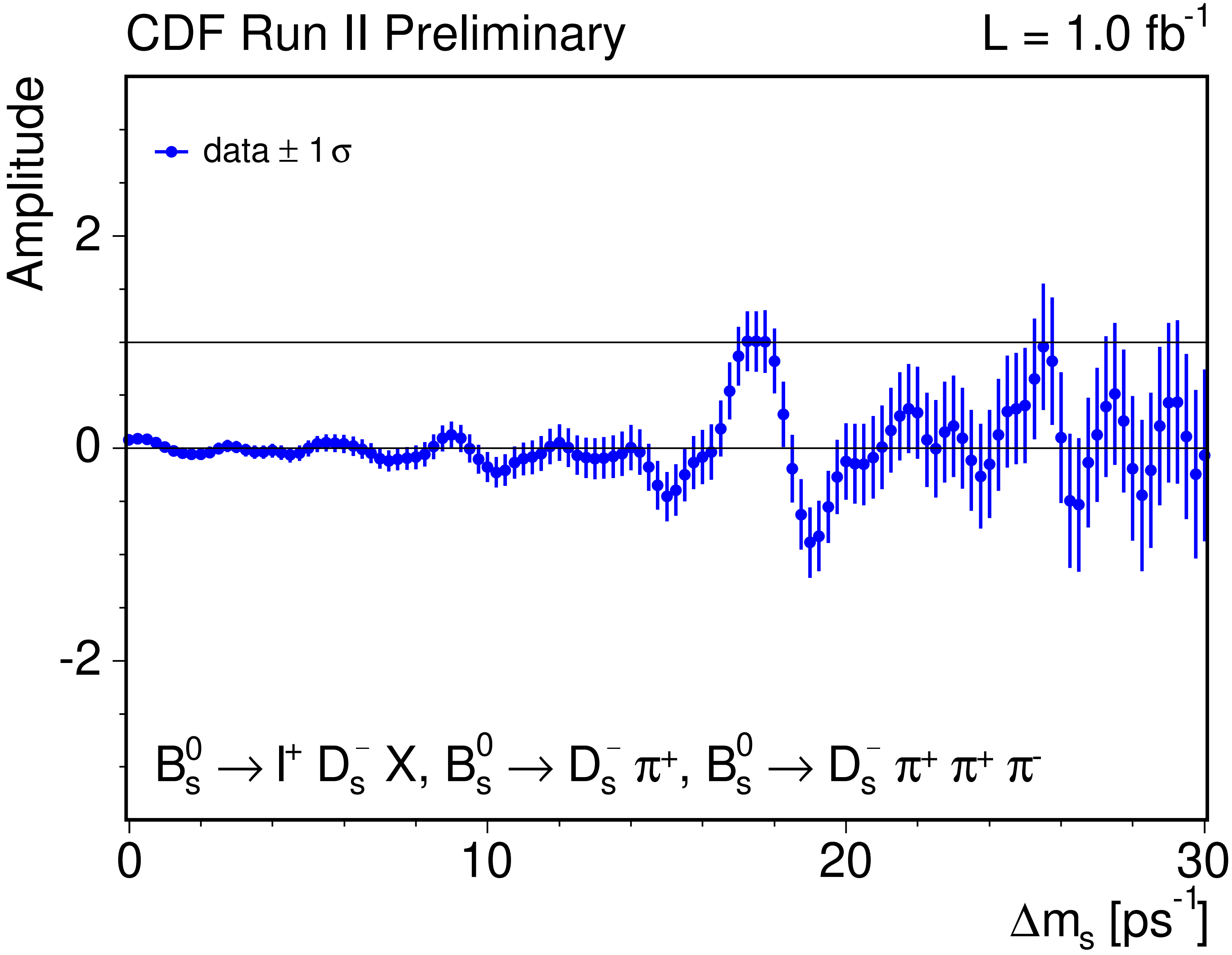
Combined Amplitude Scan



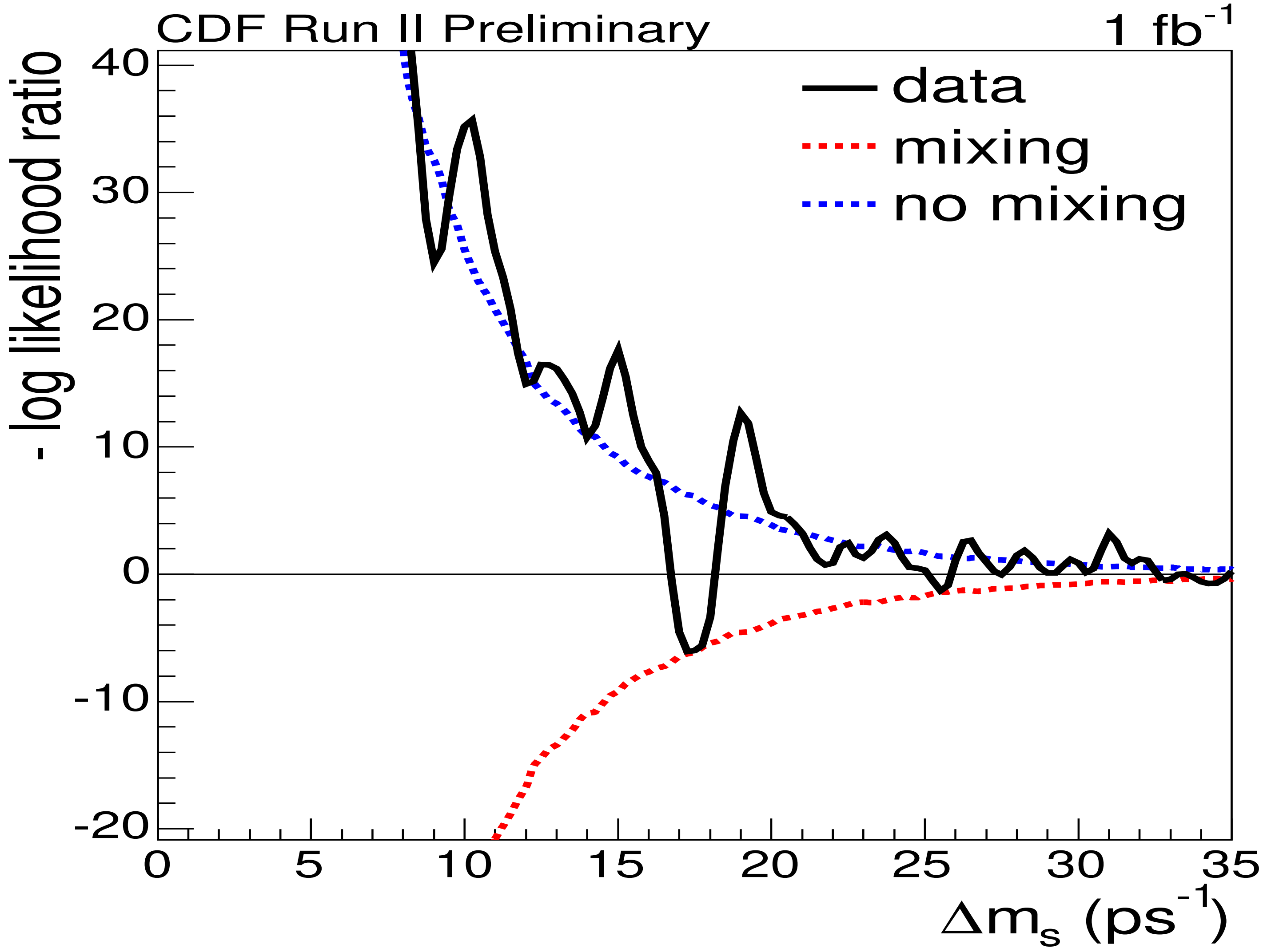
$\mathcal{A}$ compatible with 1 for $\Delta m_s \sim 17.25\ \mathrm{ps}^{-1}$!

$\mathcal{A}/\sigma_{\mathcal{A}}(\Delta m_s = 17.25\ \mathrm{ps}^{-1}) \sim 3.5$, but what is the p-value?

Combined Amplitude Scan

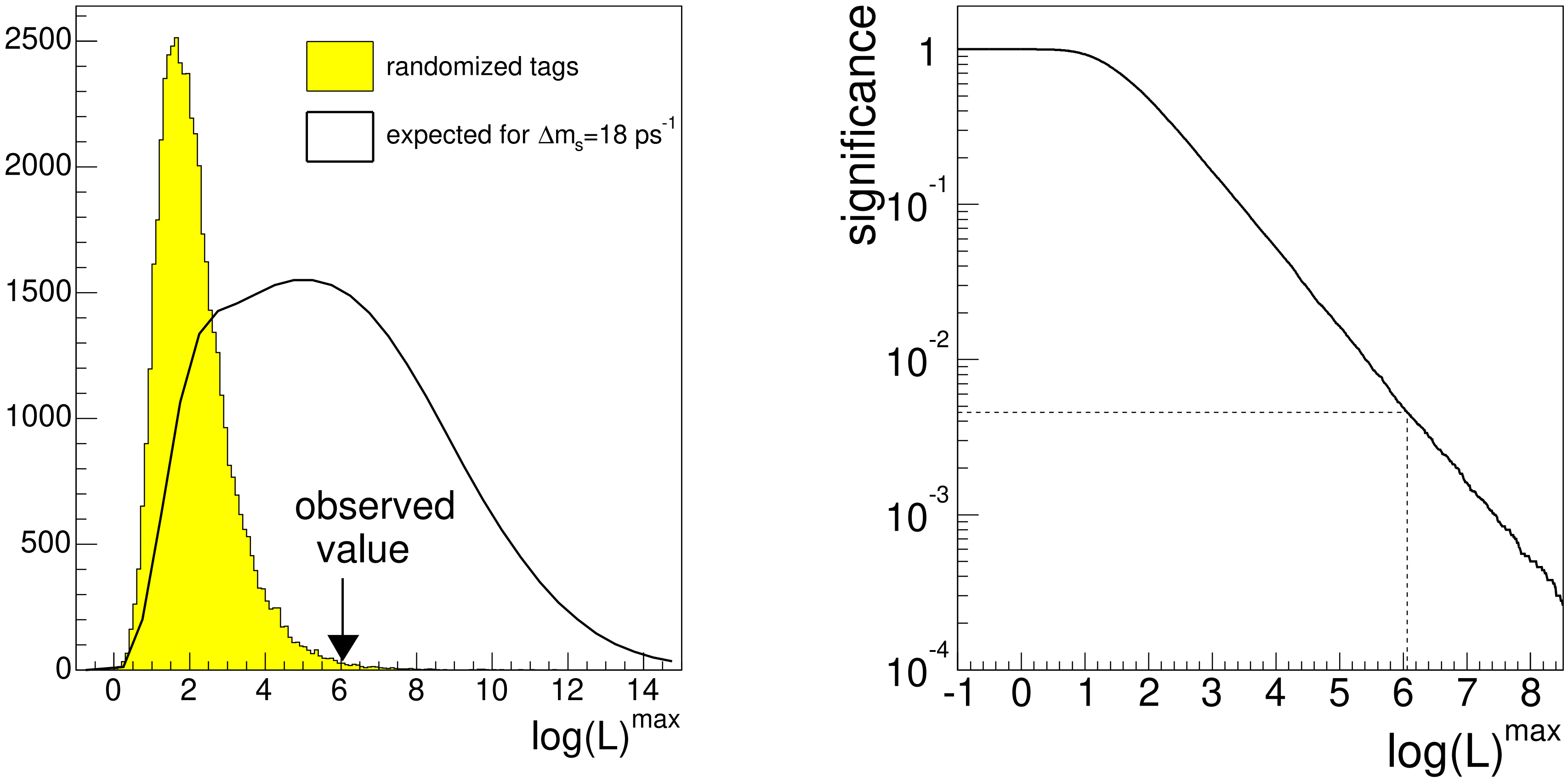


Likelihood Profile



How often can random tags produce a likelihood minimum this deep?

Likelihood Significance

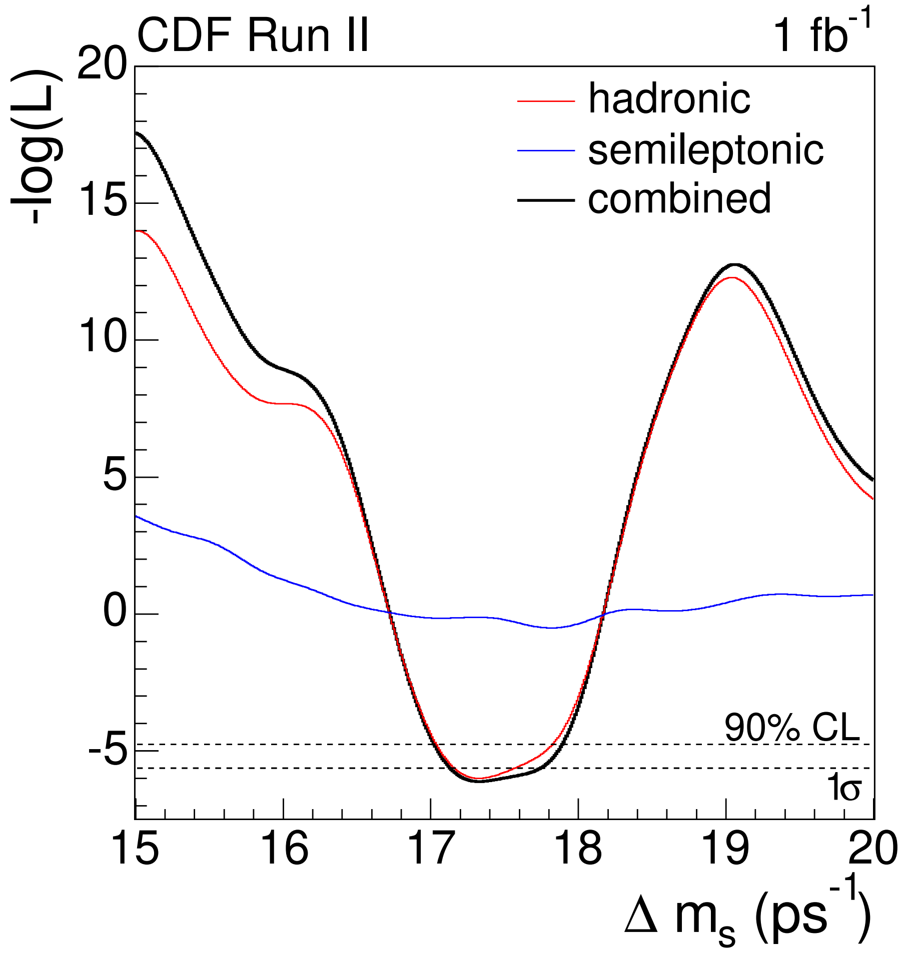


p-value ~ 0.5%

Very small probability of being background fluctuation

→→→ Measure Δm_s

Δm_s Measurement



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

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

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

Systematic dominated by the *ct* scale, any other effect very small

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

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

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

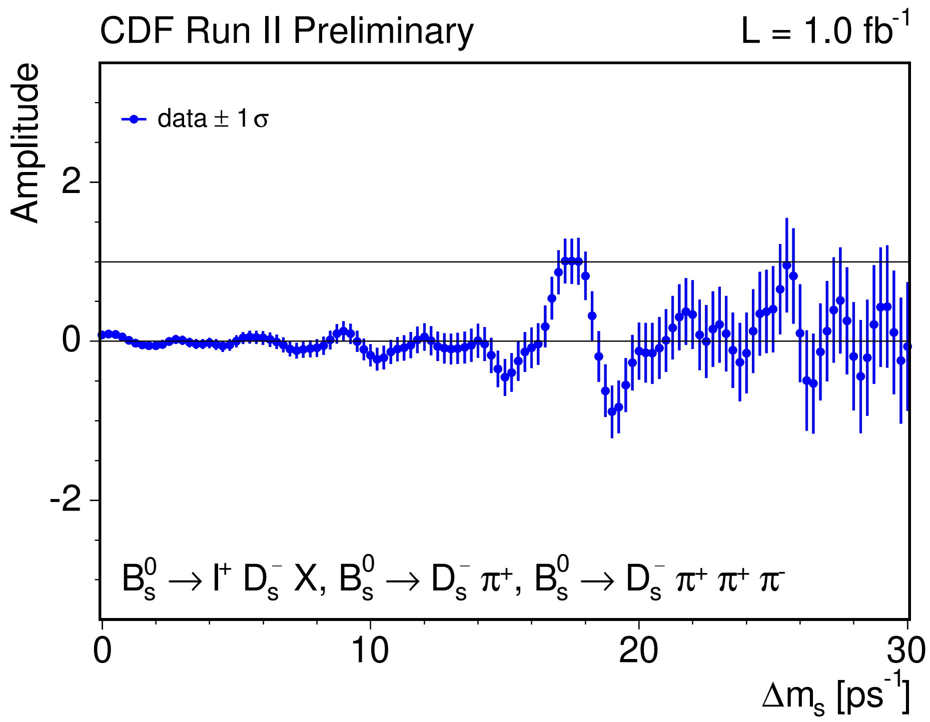
Belle measurement $b \to d\gamma$: $|V_{td}|/|V_{ts}| = 0.200\ ^{+0.026}_{-0.025}(exp.)\ ^{+0.038}_{-0.029}(theo.)$

Summary

- Found a signature consistent with $B_s^0 - \bar{B}_s^0$ oscillations
- Probability of random tag fluctuation ~ 0.5%
- First direct measurement of the $B_s^0 - \bar{B}_s^0$ oscillation frequency:

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

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



Back Up Slides

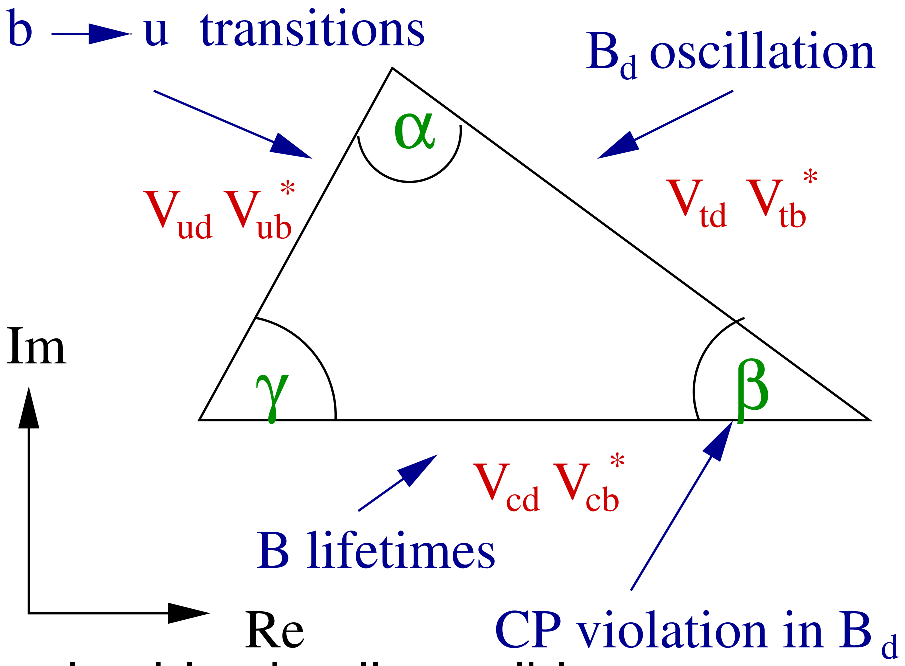
CKM Matrix

What is the origin of flavor symmetry breaking?
$\rightarrow$ quark mixing, CKM matrix

quark mass eigenstates
$\neq$ weak interaction eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$V * V^{\dagger} = 1$



CKM elements not predicted by SM

Goal: Measure sides/angles of CKM triangle sides in all possible ways

B-Physics at Hadron Colliders

☞ Large production rates

$\sigma(p\bar{p} \to bX, |y| < 0.6) \approx 18\mu b$

10^3 higher than at $\Upsilon(4S)$

☞ Heavy and excited B states currently uniquely at Tevatron:

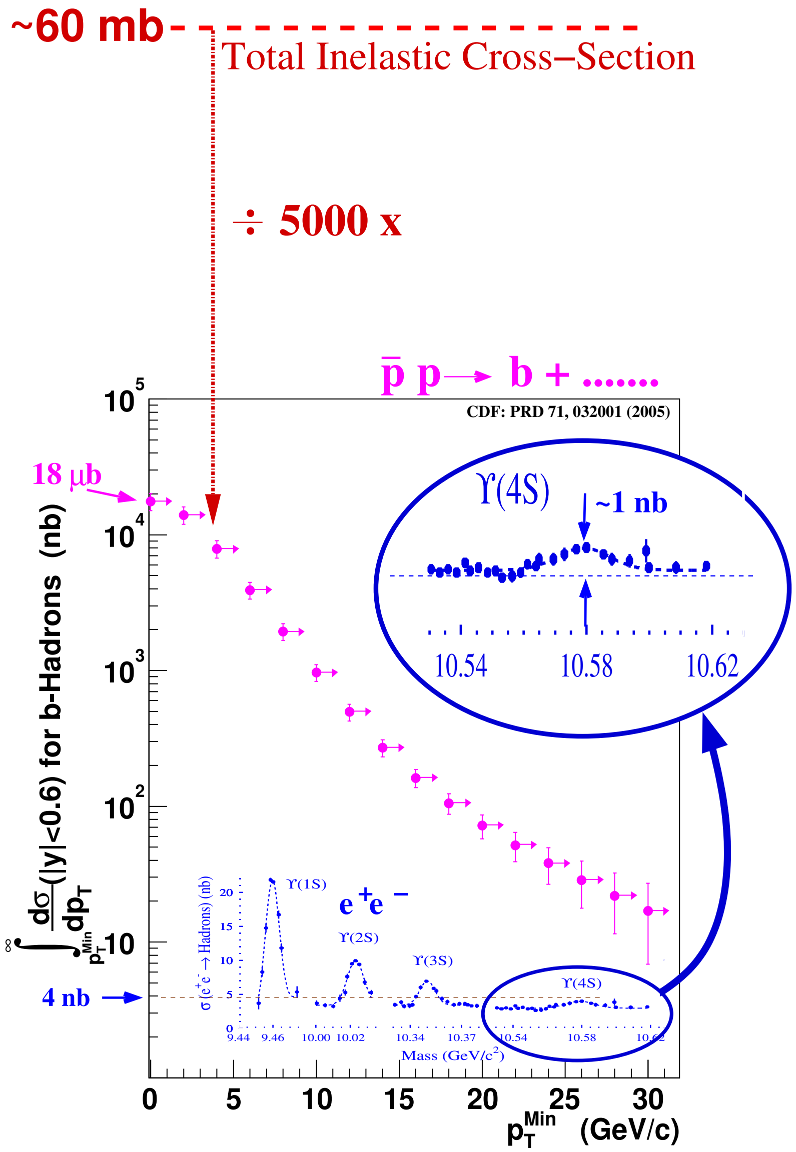
$B_s, B_c, \Lambda_b, \Xi_b, B^{**}, B_s^{**}, \ldots$

☞ But QCD background is 10^3 higher than signal

Triggers are critical

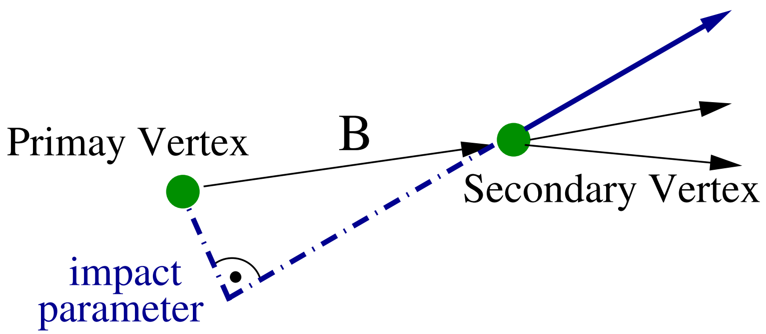
☞ Event signature polluted by many fragmentation tracks;

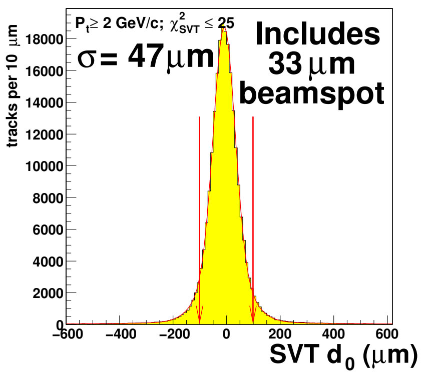
High precision vertex tracker + dedicated reconstruction algorithms needed



B Triggers

- B decays to $J/\psi \to \mu^+\mu^- \to$ Di-muon trigger
  - easy trigger
  - clean signature
- Semileptonic B decays $\to$ lepton + displaced track trigger
  - large branching ratio
  - missing momentum (neutrino & neutrals)

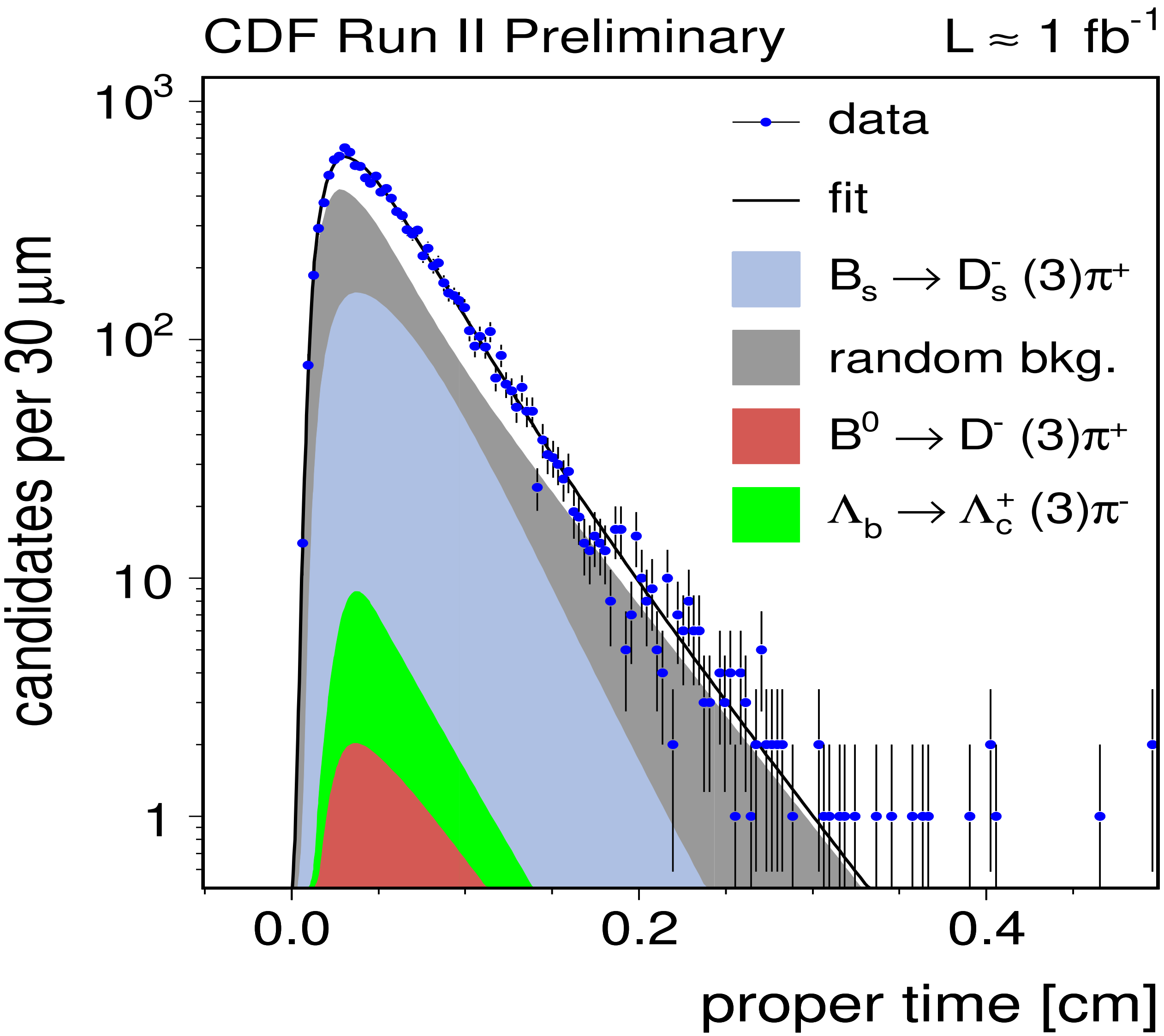




- Fully hadronic B decays $\to$ Two Track trigger
  - requires displaced track trigger
  - requires fast online tracking

Proper Decay Time Reconstruction

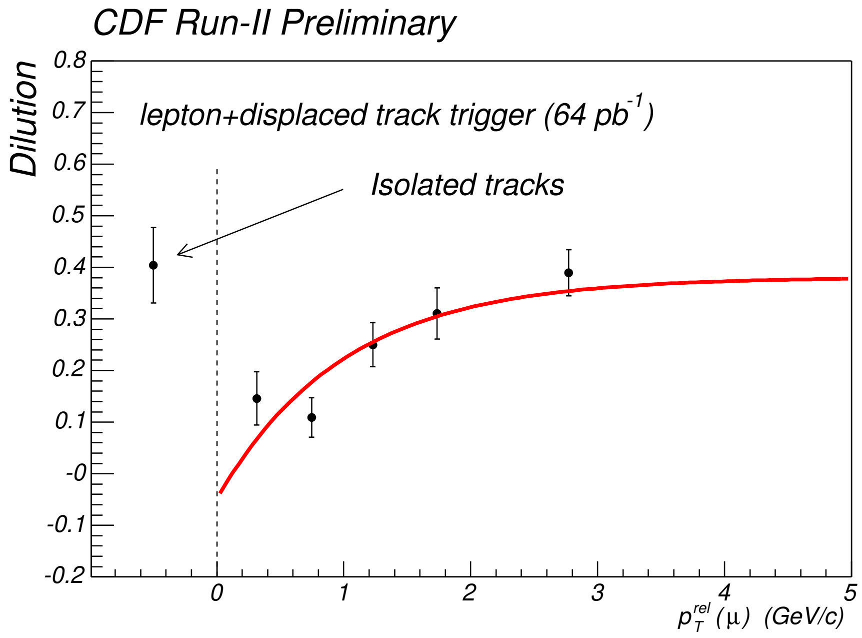
ct distribution of all combined fully reconstructed modes



Opposite Side Taggers

Combined Tagger:

- ☞ Soft Muon Tagger
- ☞ Soft Electron Tagger
- ☞ Jet Charge Tagger



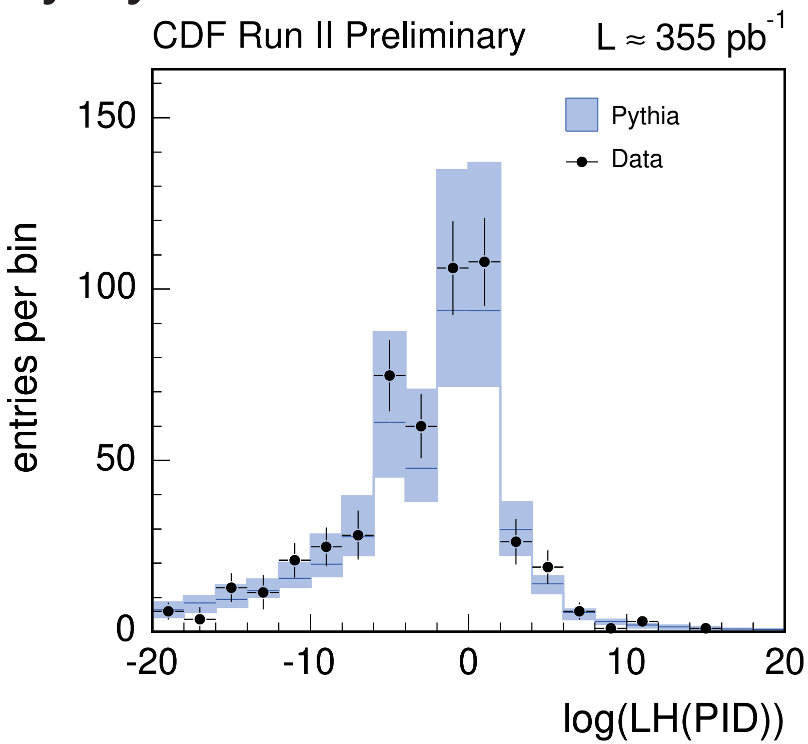
Opposite Side Taggers calibrated in our very high statistics $\ell + SVT$ samples
Dependence on several variables used to increase the tagging power

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

Similar performace of semileptonic hadronic modes

Same Side Kaon Tagger (I)

Small discrepancies covered by systematics



Systematic studies cover:

- Fragmentation Model
- $b\bar{b}$ 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)

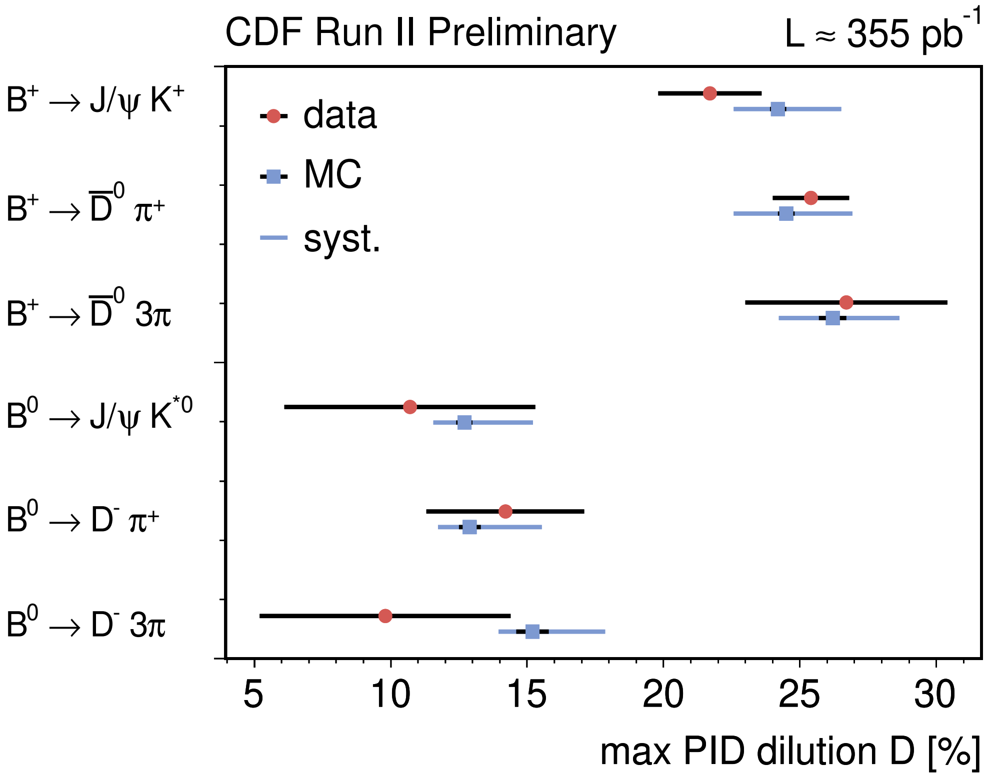
*) TOF & dE/dx are used for particle identification

Same Side Kaon Tagger (II)

Have to rely on Monte Carlo for prediction of SS(K)T performance for B_s decays!

- ☞ Extensive data/MC comparisons on all tagging related quantities
- ☞ Different tagging algorithms probe different aspects of the fragmentation

Very good agreement in high statistics B^+ and B^0 modes in all checks!



Δm_d Measurement

Combined all taggers, all semileptonic modes, all datasets:

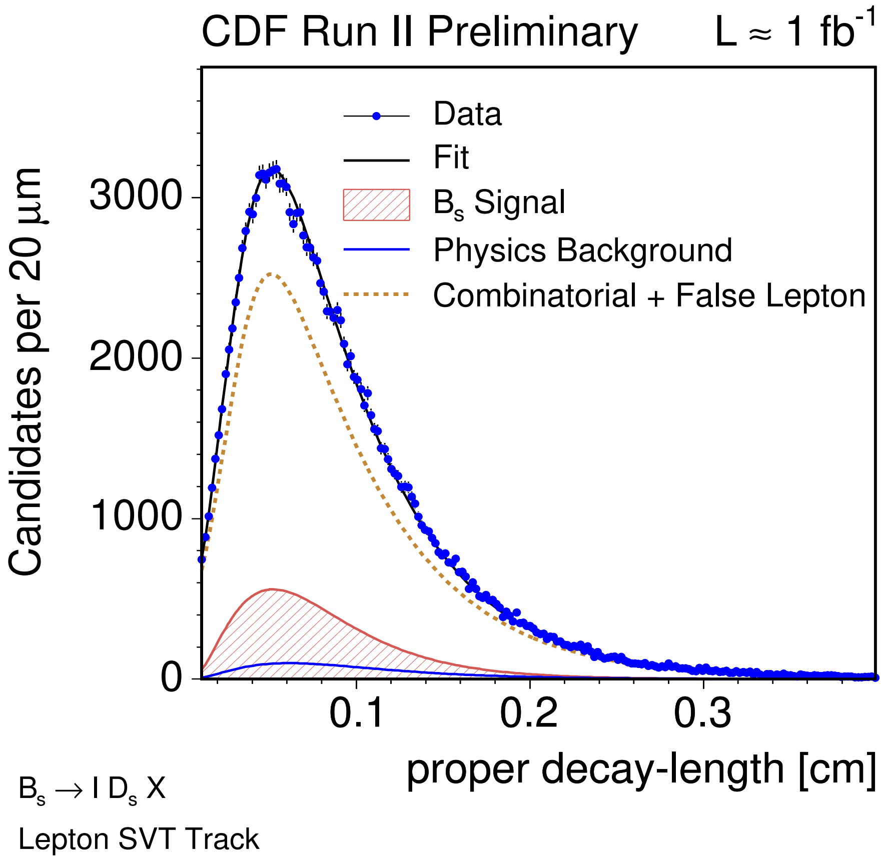
$$\Delta m_d = 0.509 \pm 0.010\ (\text{stat.}) \pm 0.016\ (\text{syst.})\ \text{ps}^{-1}$$

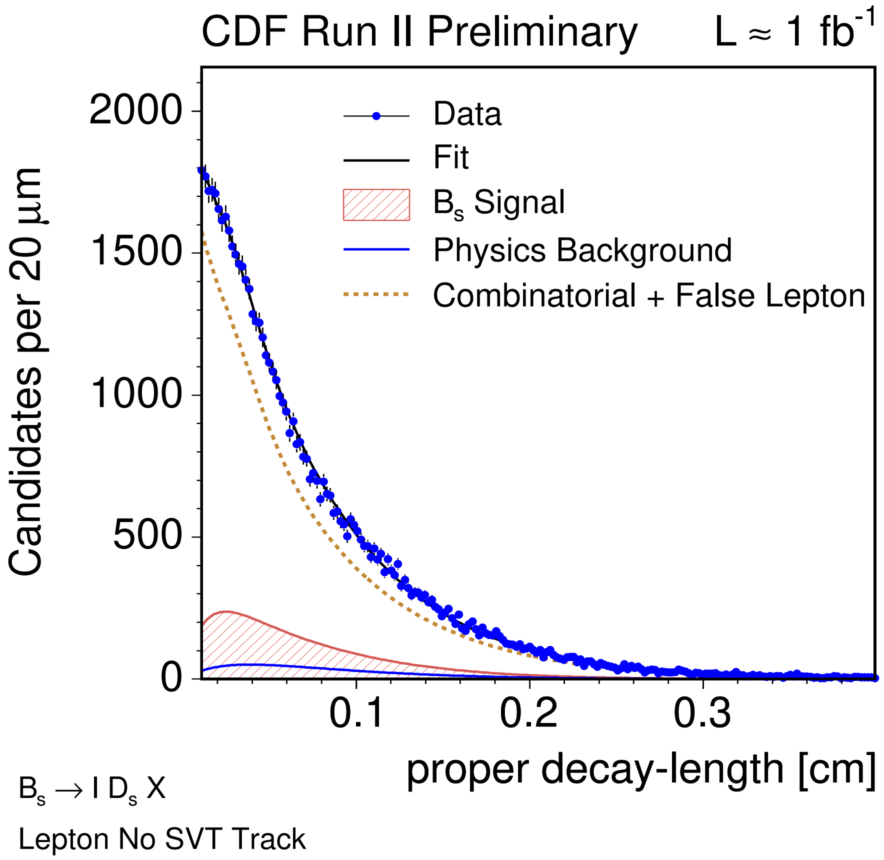
We cannot be competitive with B factories, but result is compatible

But already systematic limited!

Results consistent with world average ($\Delta m_d = 0.505 \pm 0.005$)
The whole framework ready to fit for B_s Oscillations...

Two Types of Semileptonic Candidates





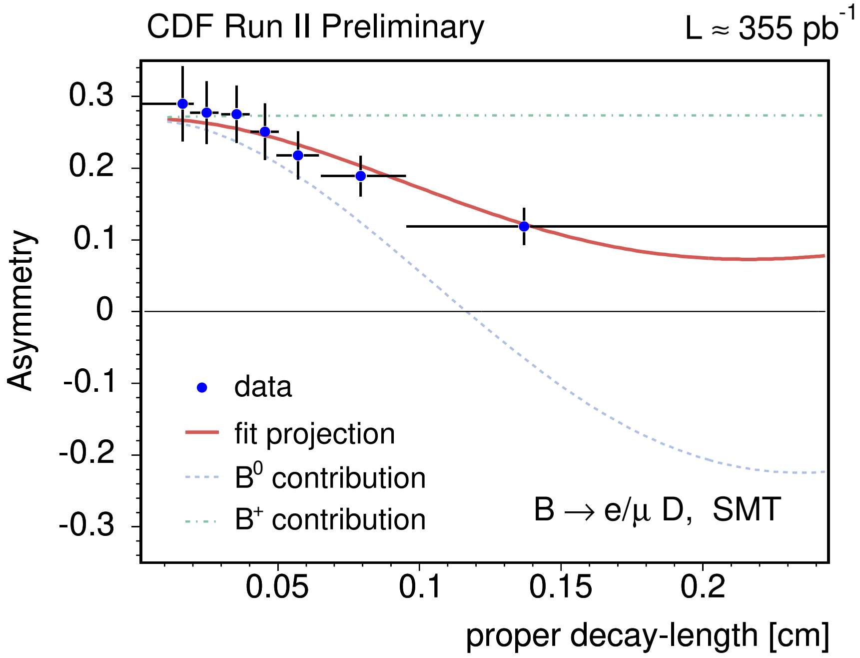
Lepton SVT Track

Lepton no SVT Track

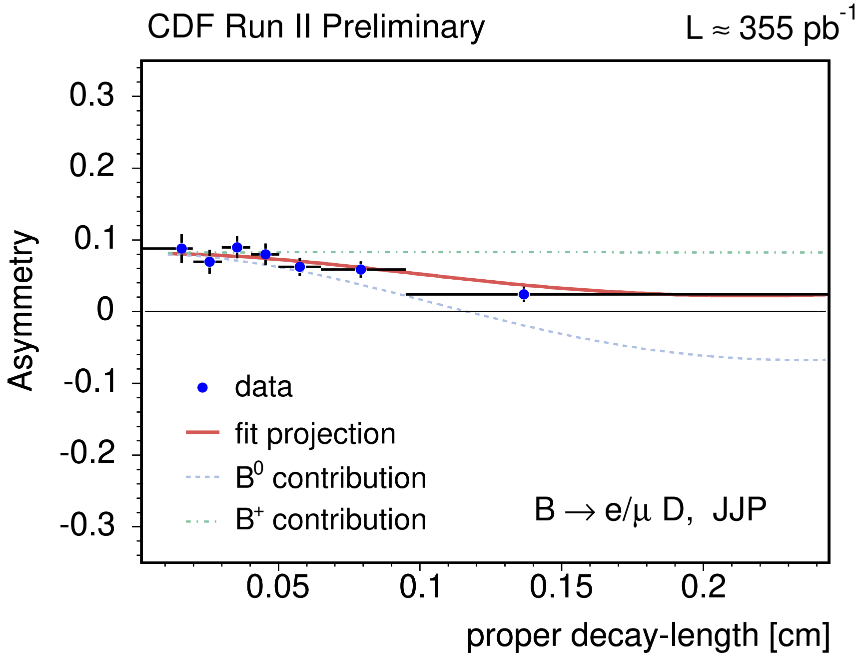
Crucial Test of the Whole "Machinery": B_d Mixing

- For setting limit on Δm_s, knowledge of tagger performance is crucial $\rightarrow$ measure tagging dilution in kinematically similar B^0/B^+ samples (for OST)
- Δm_d and Δm_s fits are very complex
  - combining several B flavor and several decay modes
  - combining several taggers
  - mass and lifetime templates for various backgrounds

Δm_d measurement is very important to test the fitter

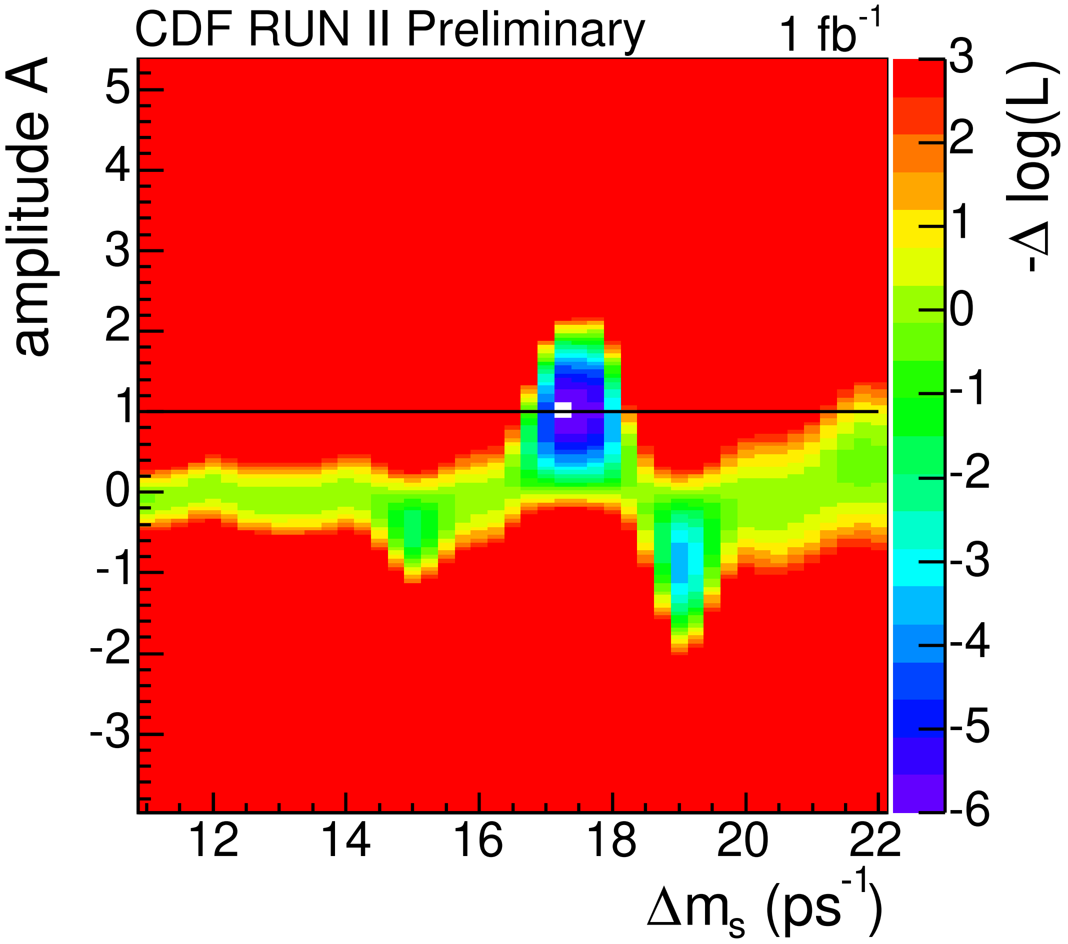


Soft Muon Tagger



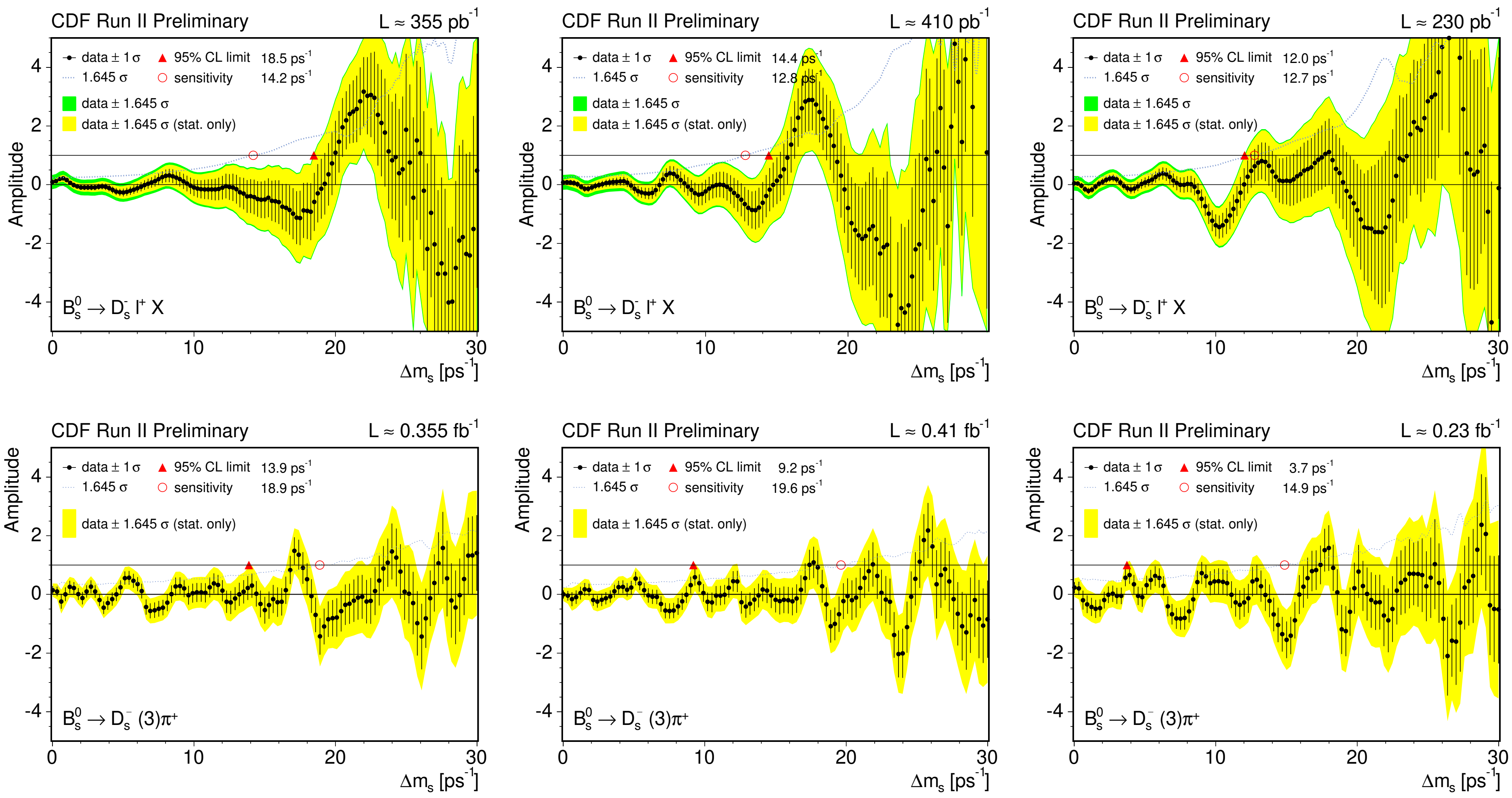
Jet Charge Tagger-Jet Probability

Amplitude vs. Δm_s



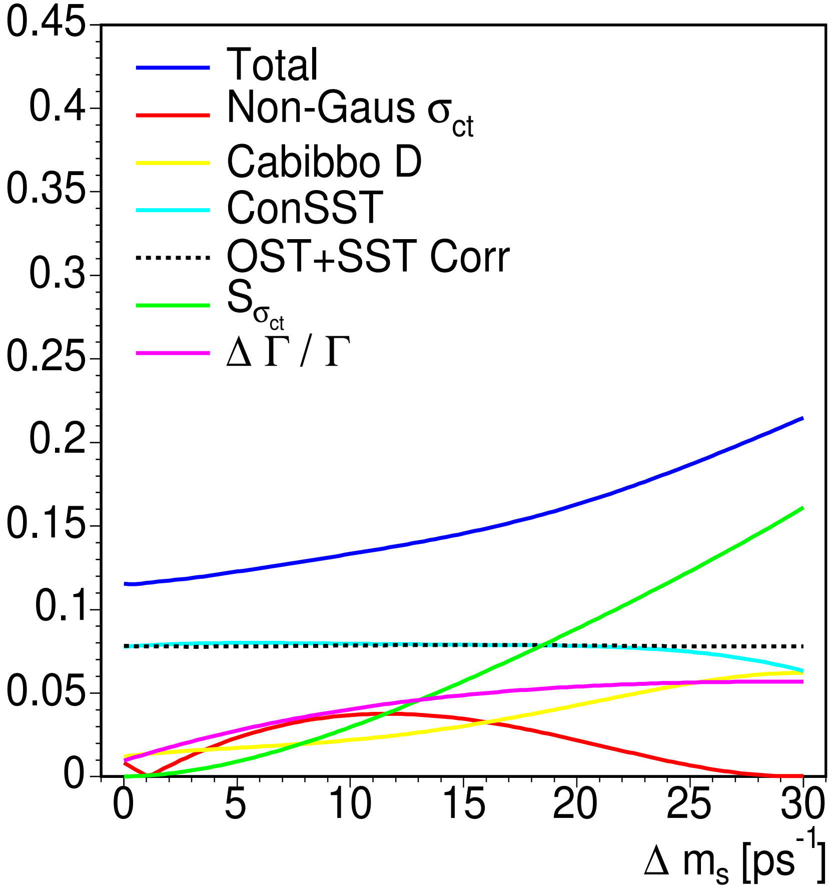
Clear deep in $\mathcal{A} \sim 1$ and $\Delta m_s \sim 17.25$ ps^{-1}

Amplitude Scan per Period, Semi/Had

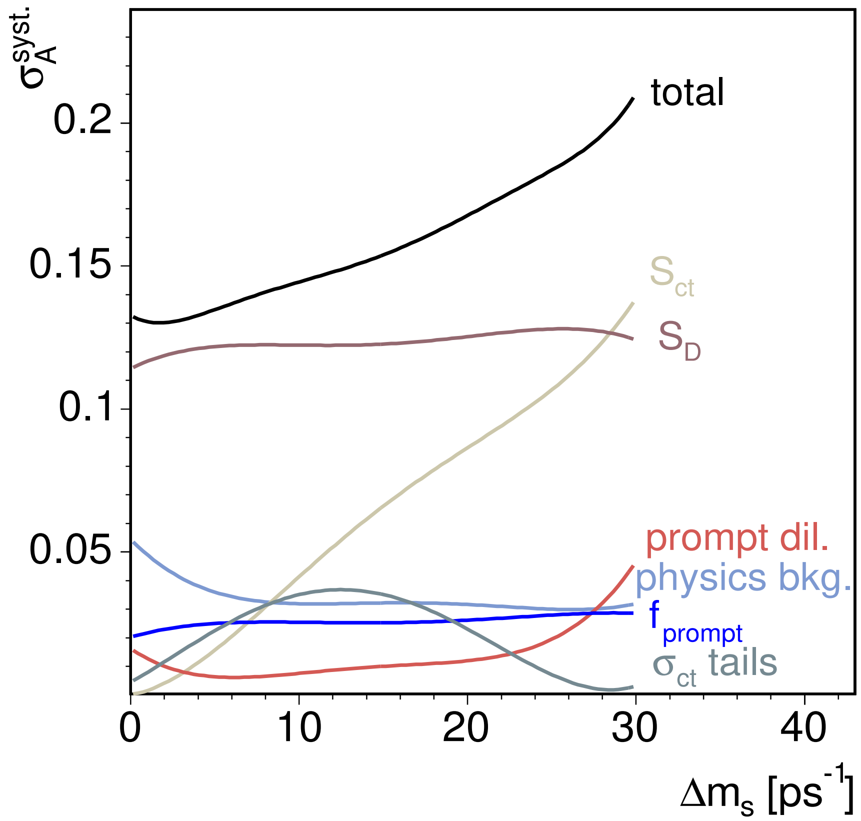


Systematic Uncertainties on A

Hadronic



Semileptonic



Systematic uncertainties ~0.15-0.20 at high Δm_s

Analysis is statistical limited

Systematic on Δm_s

Source	Value (ps^{-1})
SVX alignment	0.04
Track fit bias	0.05
P.V. bias from tagging	0.02
Others	< 0.01
Total	0.07

All relevant systematic uncertainties:

☞ related to *ct* scale

☞ common between hadronic and semileptonic samples