Measurement of B_s Oscillations at CDF

Sandro De Cecco

FNAL & INFN Roma

Outline

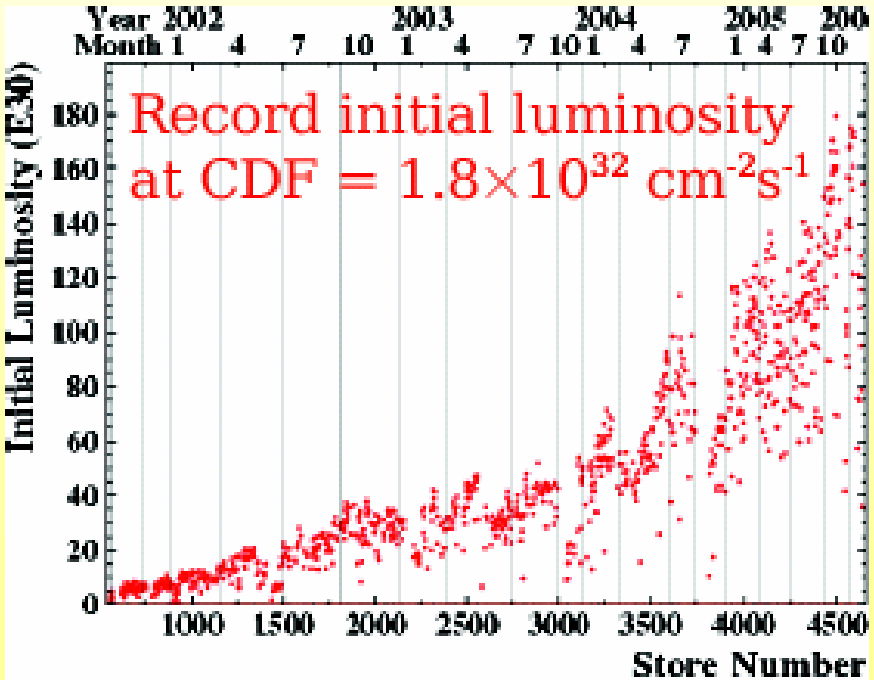
- CDF detector and B physics triggers
- B_s mixing analysis overview:
  - B_s signals
  - Proper decay time analysis
  - Initial state Flavour Tagging
  - Amplitude Scan for Δm_s
- **Measurement of Δm_s**
- *Summary and perspectives*

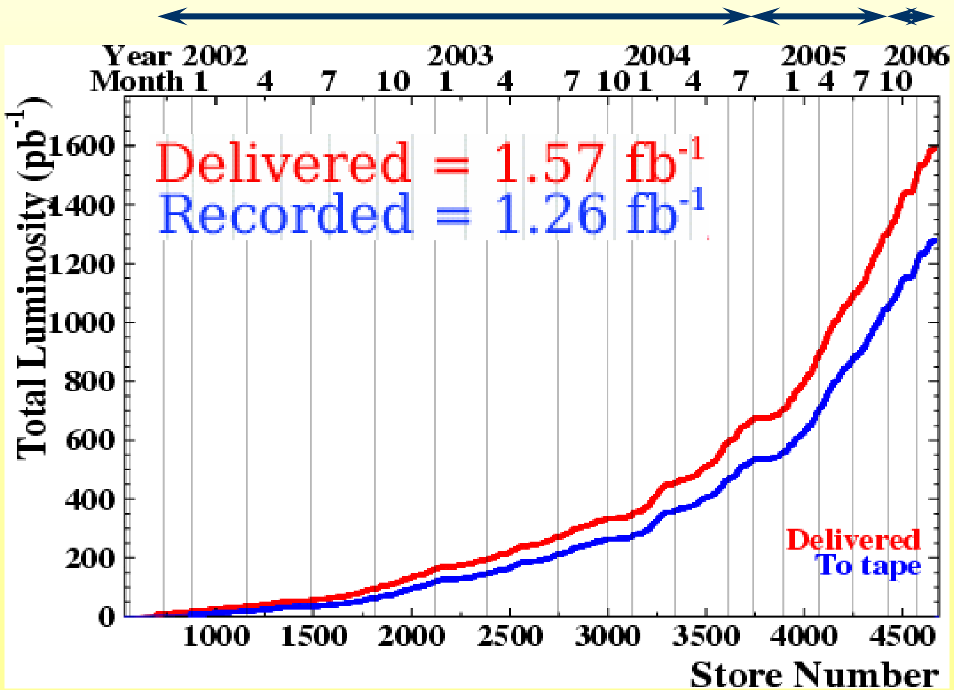
Tevatron performances

•CDF collected so far ~ 1.26 fb^{-1} out of 1.57 fb^{-1} delivered by Tevatron.

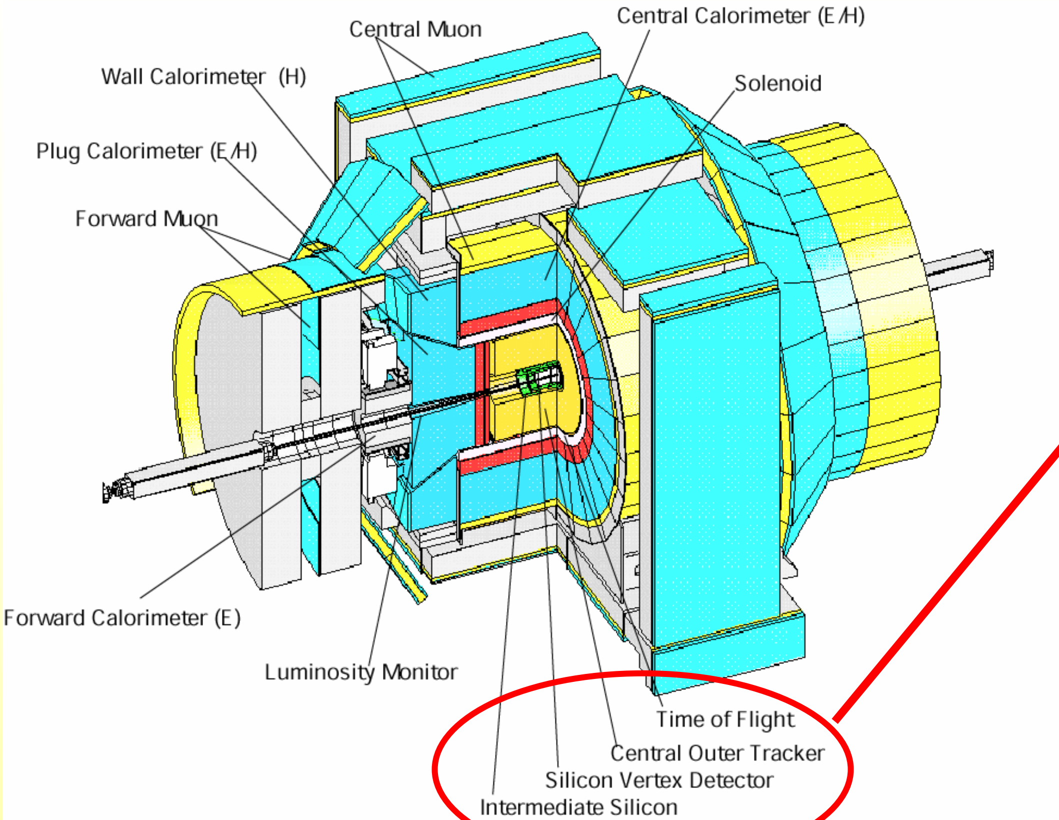
•Record peak luminosity is ~ $1.8 \cdot 10^{32}$ $cm^{-2}s^{-1}$

•B_s Mixing analysis performed with integrated Luminosity of 1 fb^{-1}

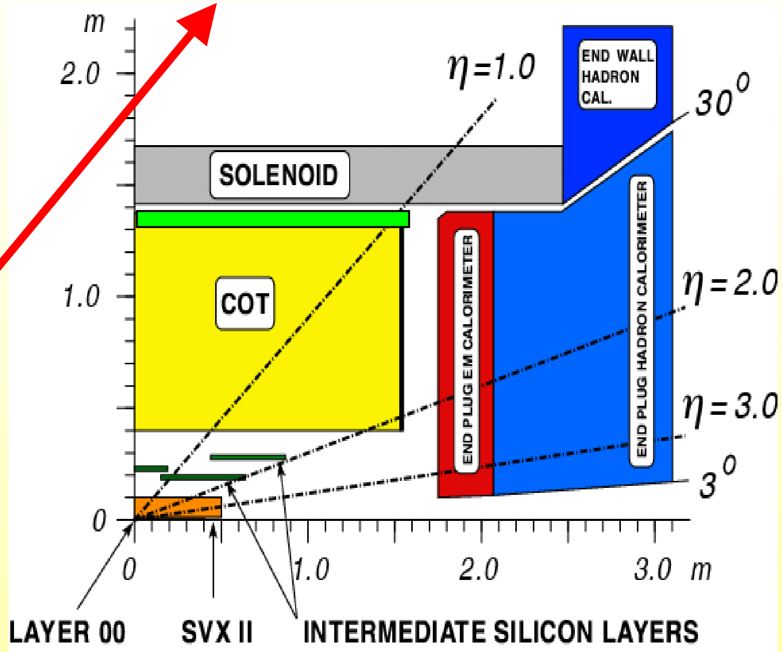




The CDF II detector



CDF Tracking System



Lepton ID

Muons: CMU, CMP, CMX ($|\eta|<1.1$)

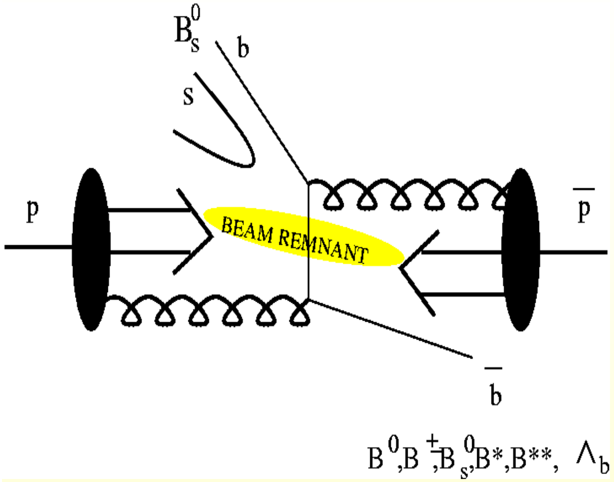
Electrons: CEM (EM calorimeter)
CPR (pre-shower detector)

Particle ID

•dE/dX in **COT**

•Time **O**f **F**light detector

B Physics at Collider



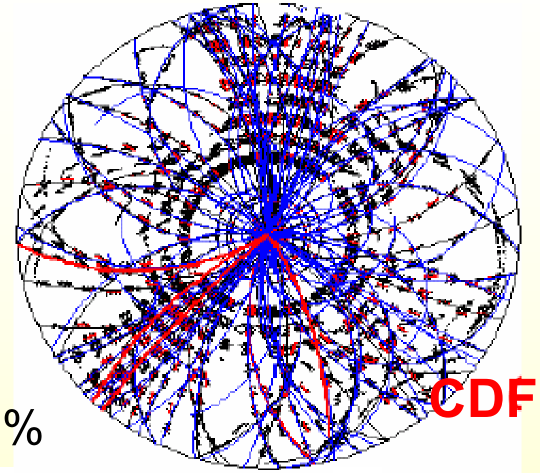
- All *B* species produced:

  $B_u, B_d, B_s, B_c, \Lambda_b, \Xi_b \ldots$

- With production fractions:

  $f_u : f_d : f_s : f_\Lambda \approx 4 : 4 : 1 : 1$

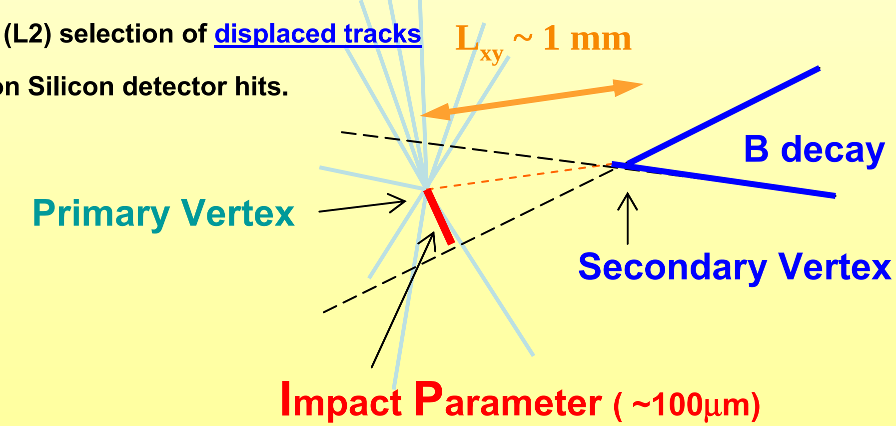
- Acceptance for other B is 20-40%

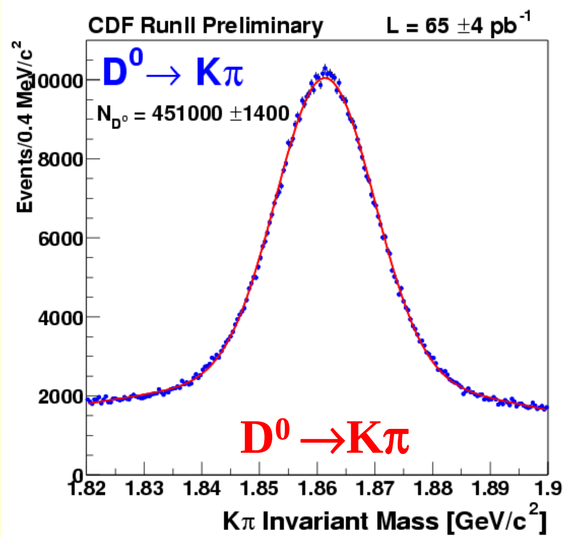


BUT: $\sigma(bb) \ll \sigma(pp)$ (~65 mb) ⇒ **B have to be selected with specific Triggers**

the CDF Secondary Vertex Trigger SVT

- **Online (L2) selection of displaced tracks based on Silicon detector hits.**





- b production is very large (~300 Hz @ 10^{32} cm^{-2} Hz) → trigger on specific decays

B physics triggers at CDF II

Conventional at colliders (Run I)

With SVT trigger

Di-Muon (J/ψ)

$Pt(\mu) > 1.5$ GeV

J/ψ modes down to low $Pt(J/\psi)\sim 0$ (Run II)

+

1-Displaced track + *lepton* (e, μ)

120 μm < I.P.(trk) < 1mm

$P_T(lepton) > 4$ GeV

Semileptonic modes

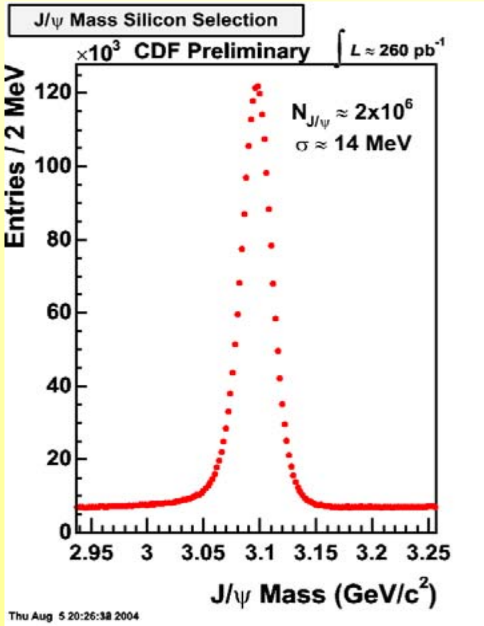
2-Displaced tracks

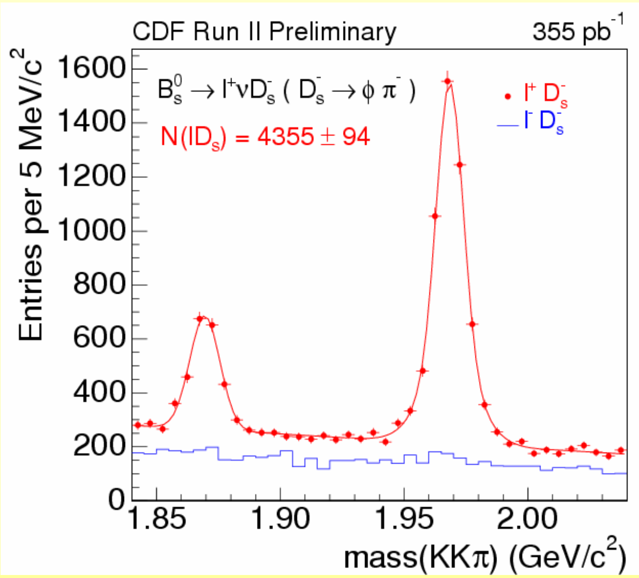
P_T(trk) > 2 GeV

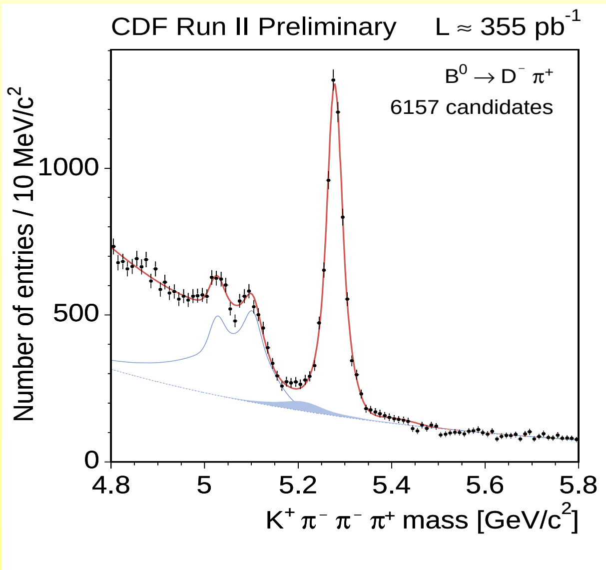
120 μm < I.P.(trk) < 1mm

$\Sigma p_T > 5.5$ GeV

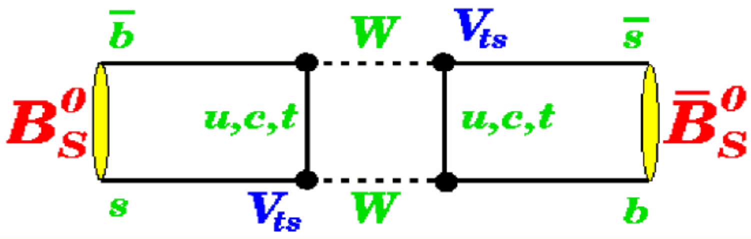
fully hadronic modes







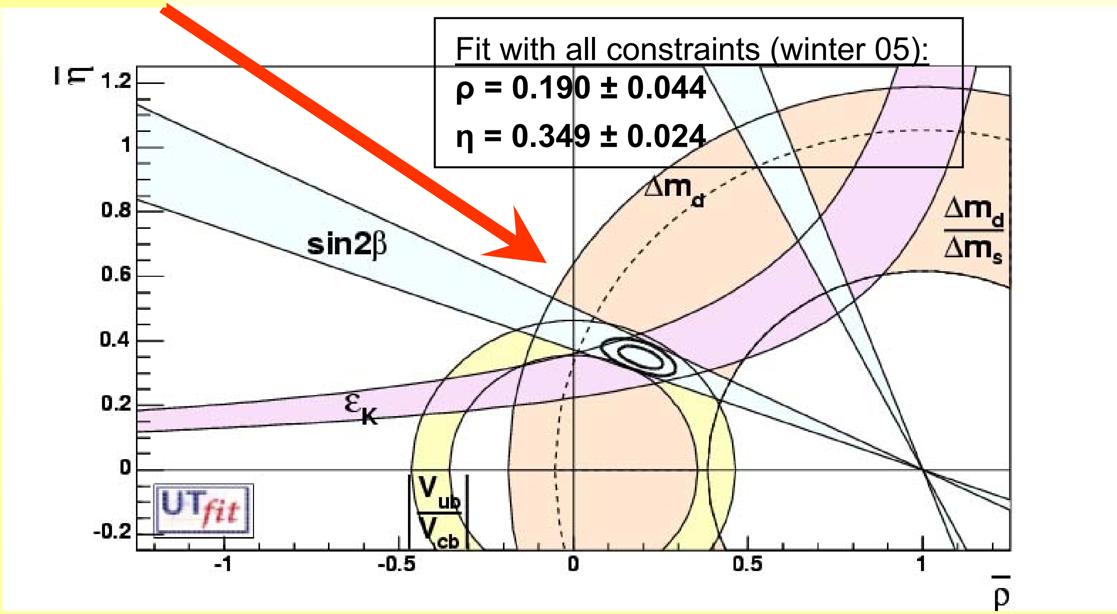
B_s Mixing



but: $|V_{ts}|>>|V_{td}| \rightarrow \Delta m_s >> \Delta m_d$

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

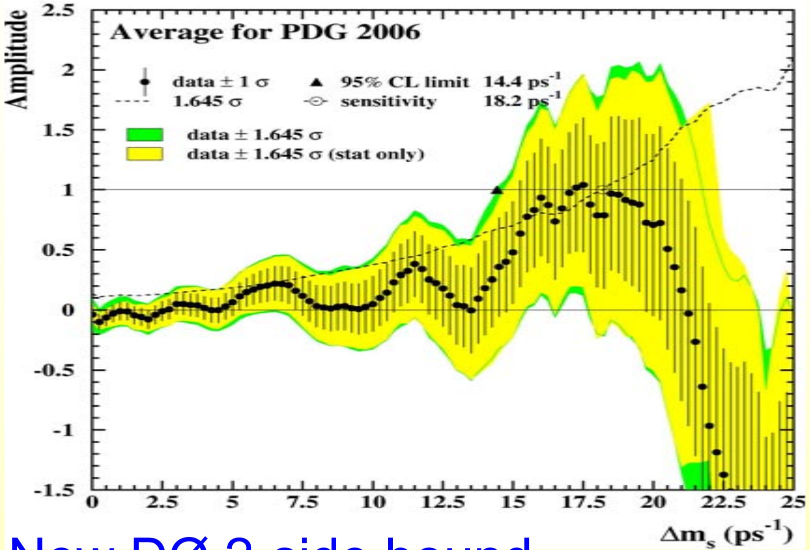
Measuring $\Delta m_s/\Delta m_d$ determines $|V_{ts}|/|V_{td}|$
Lattice calculation error O(5%)



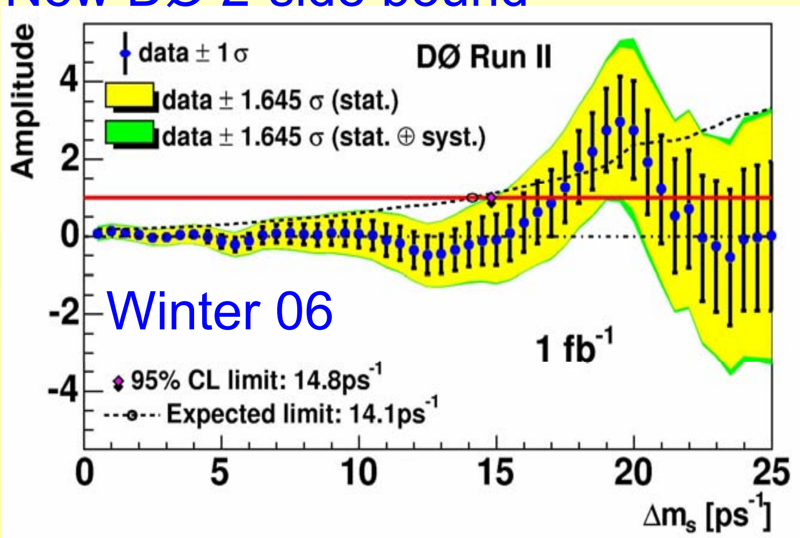
WA experimental limit:
$\Delta m_s > 14.5\ ps^{-1}$ (95%CL)
(LEP+SLD+CDF 1)

Status of Δm_s

WA experimental limit



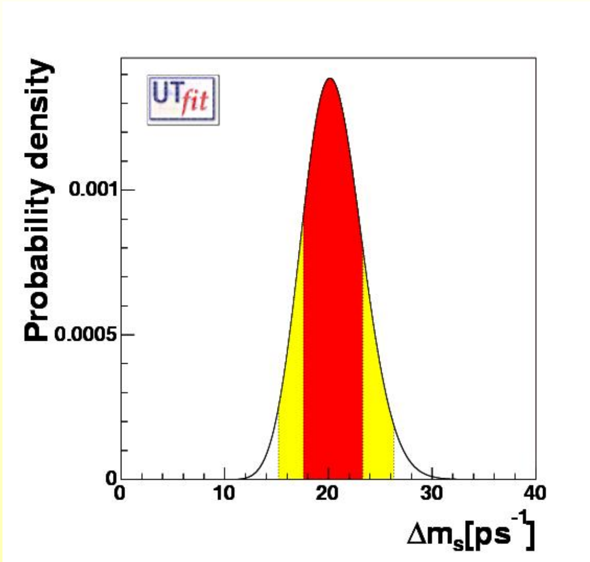
New DØ 2-side bound



Winter 06

CKM fit S.M. prediction

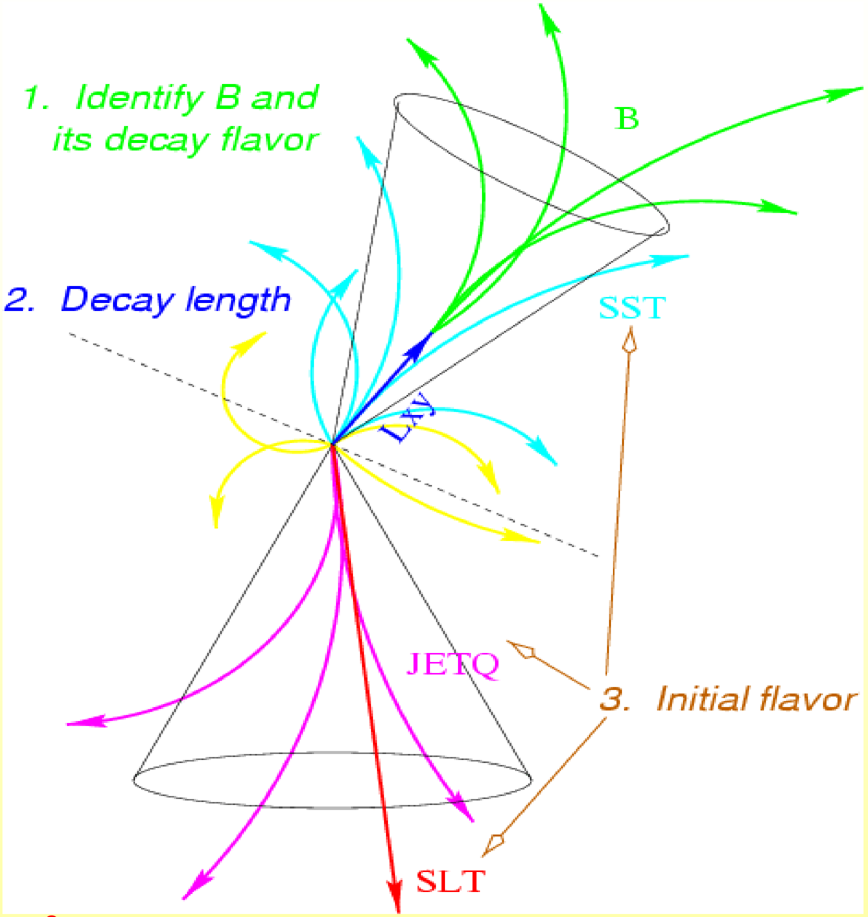
Δm_s not used (winter 2005)



Δm_s = 20.5 ± 3.2 ps^{-1}

[14.4, 27.1] @ 95% CL

Analysis Strategy

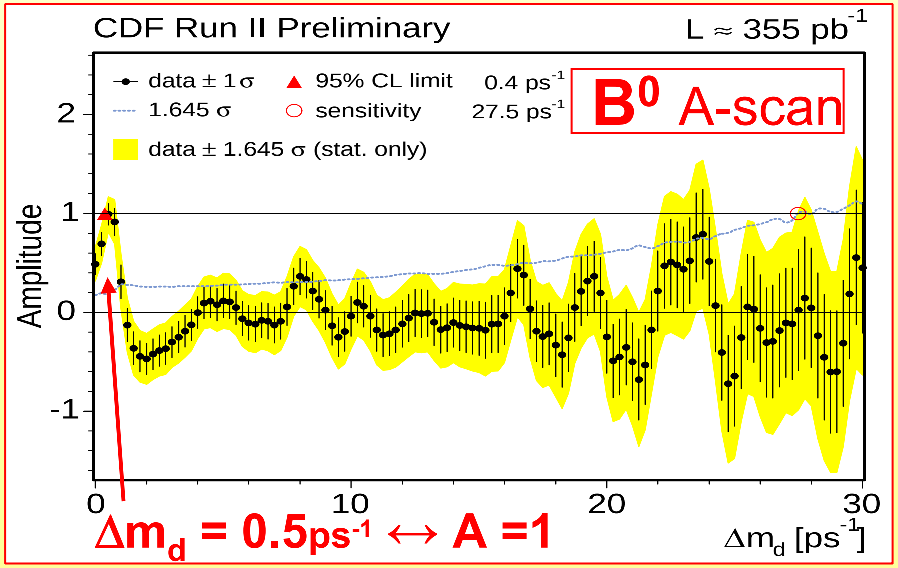


- **B_s signal reconstruction**
  - Flavour specific states
- **B_s decay time**
  - proper time reconstruction
  - **Lifetime** measurement
- **Initial flavour of the B_s**
  - **Flavour tagging** techniques
  - calibrate on B_d mixing

→B^0 Mixing

perform a "Blind AMPLITUDE SCAN":

$$L_{sig}^{t} = \frac{1}{\tau} e^{-t/\tau} \left(1 \pm A \cdot D \cdot S \cdot \cos(\Delta m t)\right)$$



Significance of B^0_s mixing measurement

•Since initial state flavour sign is "far from ideally" known → $A = \frac{P_{unmix} - P_{mix}}{P_{unmix} + P_{mix}} = D \cos \Delta mt$

where: $D = \frac{N^{right} - N^{wrong}}{N^{right} + N^{wrong}}$

$$Significance = \sqrt{\frac{S\varepsilon D^2}{2}} e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

Signal / Noise

<u>Effective tagging power:</u>

ε= efficiency of taggers

D = 1 – 2*w*   ***w*** = mistag prob.

→ **εD²** figure of merit

$$c\tau = \frac{L_{xy}}{\beta_T \gamma} = \frac{L_{xy} m(B)}{p_T(B)}$$

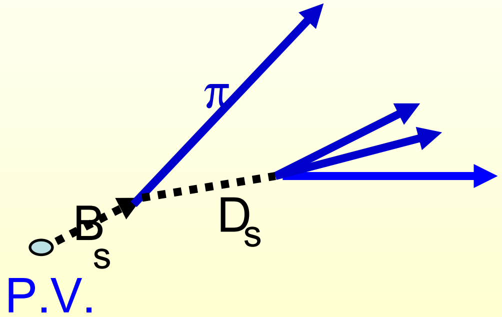
<u>vertexing and momentum resolution</u>

$$\sigma_{c\tau} = \left(\frac{\sigma_{L_{xy}} \cdot m(B)}{p_T(B)}\right) \oplus \left(\frac{\sigma_{p_T}}{p_T(B)}\right) \cdot c\tau$$

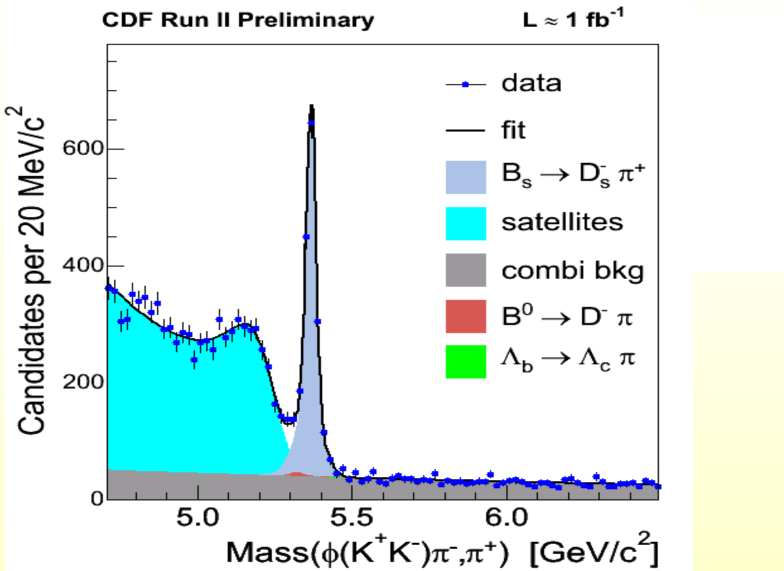
Two different B_s signatures:

Fully reconstructed HADRONIC modes:

- Good proper time resolution
- High B_s mass resolution
- Selected by Two Track Trigger (SVT)

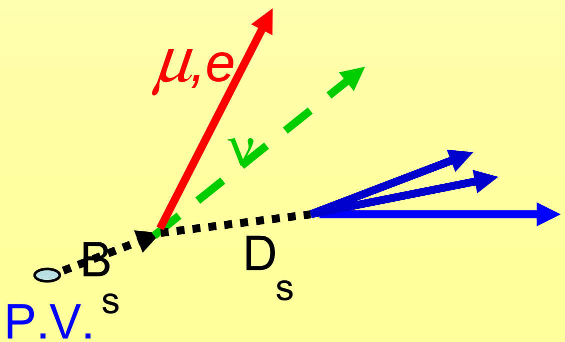


$$B_s^0 \rightarrow D_s^-(3)\pi^+$$

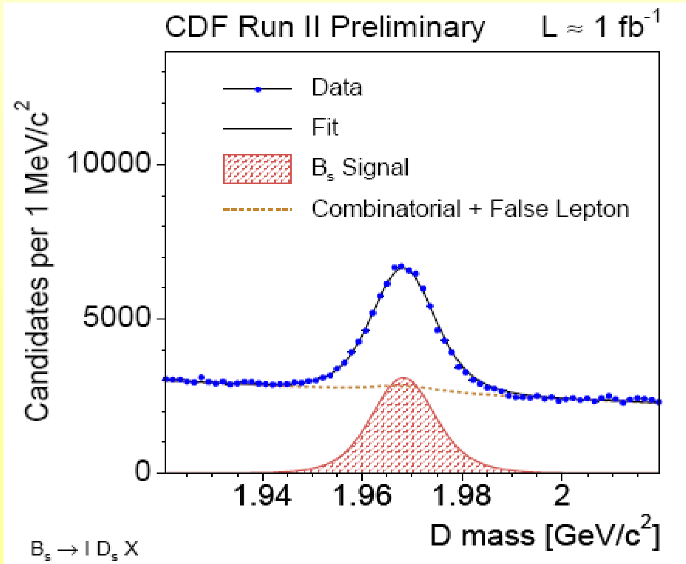


SEMILEPTONIC modes:

- Missing momentum carried by the ν
- Diluted proper time resolution
- Also selected by T.T.T. + offline μ or **e** ID



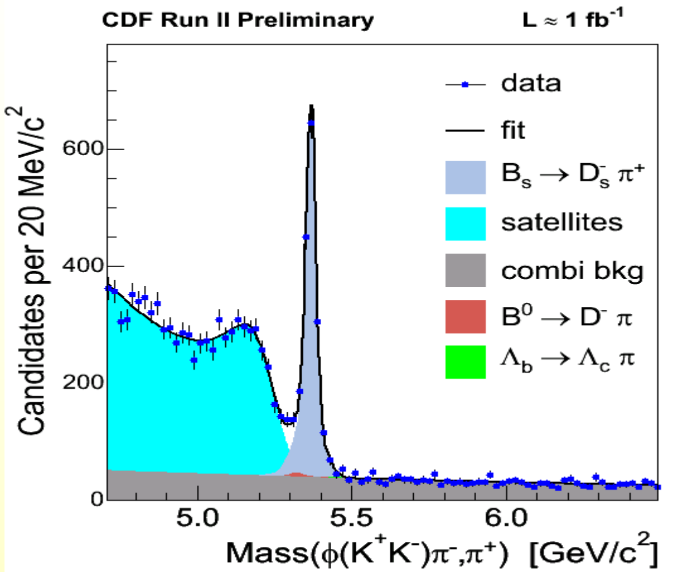
$$B_s^0 \rightarrow D_s^- l^+ \nu_l X$$



B_s yields:

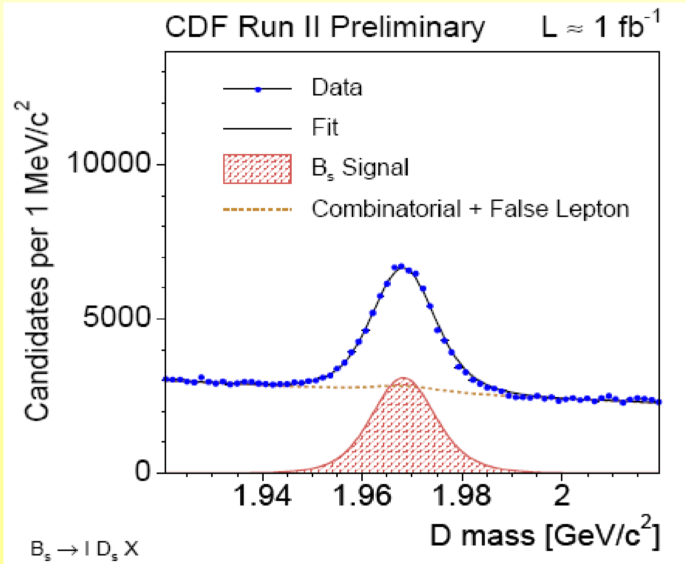
HADRONIC modes:

$B_s \to D_s\pi\ (\phi\pi)$	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**



SEMILEPTONIC modes:

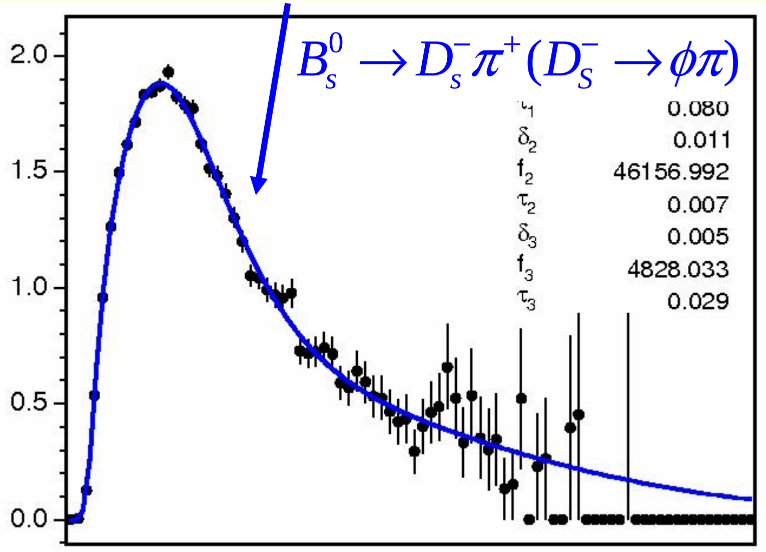
$B_s \to \ell\nu\ D_s(\phi\pi)X$	32000
$B_s \to \ell\nu\ D_s(K^*K)X$	11000
$B_s \to \ell\nu\ D_s\ (3\pi)X$	10000
Total	**53000**



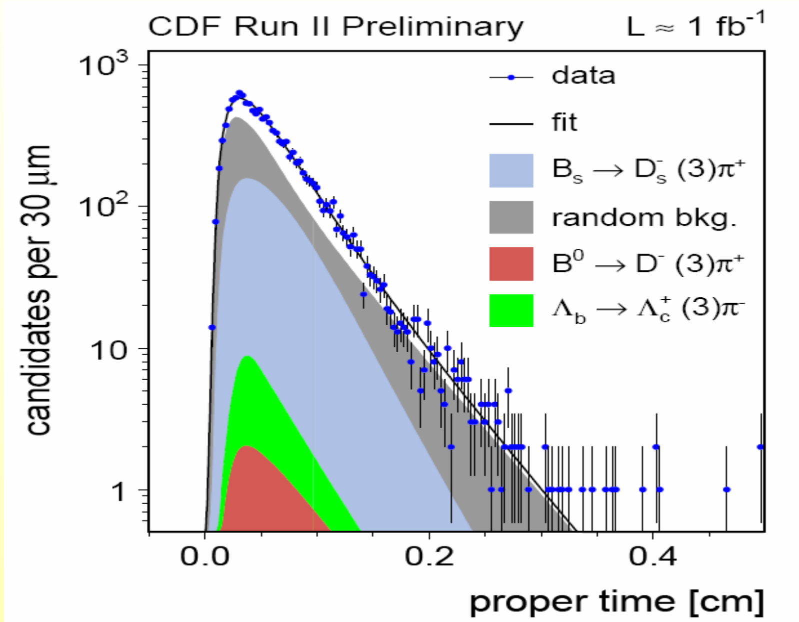
B_s proper decay time analysis

SVT cuts on track **I**mpact **P**arameter: 120 μm < **I.P.**(trk) < 1mm

Efficiency as a function of decay time is obtained from **M**onte**C**arlo



Proper time distribution is sculpted



CDF preliminary B lifetimes **in fully reconstructed hadronic modes (statistical error only !)**

$B^0 \to D^- \pi^+$	**1.508 ± 0.017 ps**
$B^- \to D^0 \pi^-$	**1.638 ± 0.017 ps**
$B_s \to D_s \pi(\pi\pi)$	**1.538 ± 0.040 ps**

W.A. $\tau(B_s)$ = 1.469 ± 0.059 ps

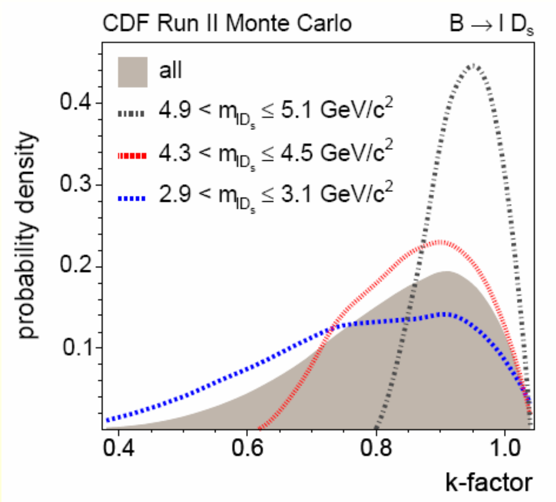
Lifetime in the semileptonic B_s sample

Measure the B decay distance L intersection of ℓ and $\mathbf{D_s}$

– Observable momentum p* = p(ℓ $\mathbf{D_s}$)

– Correct statistically for missing momentum factor (from MC)

$$K = \frac{p(lDs)}{p(B)}$$

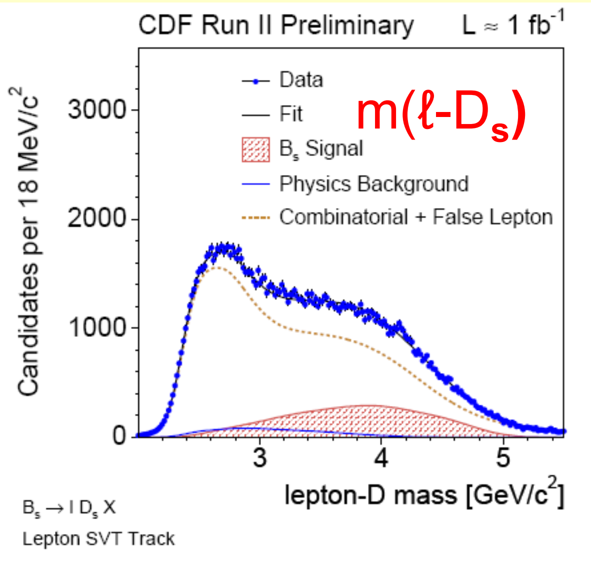


decay time

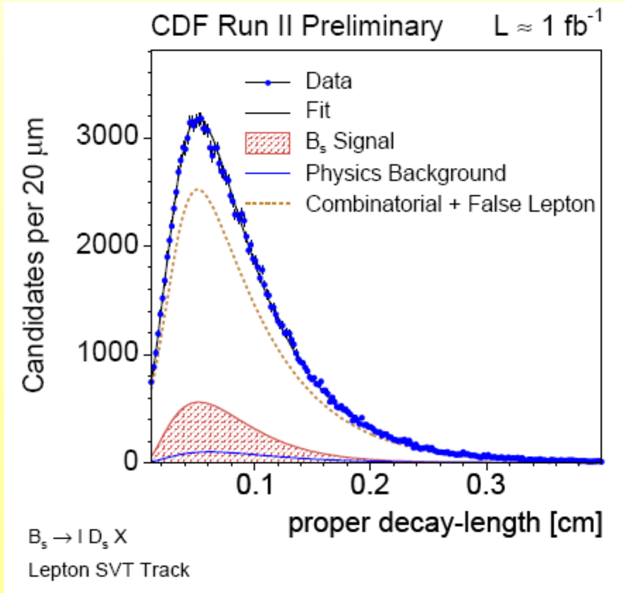
$$t = L \times \frac{m(B)}{p(B)}$$

pseudo decay time

$$t^* = L \times \frac{m(B)}{p(\ell D_s)} \otimes K$$



Use ℓ-D_s mass to separate S from B



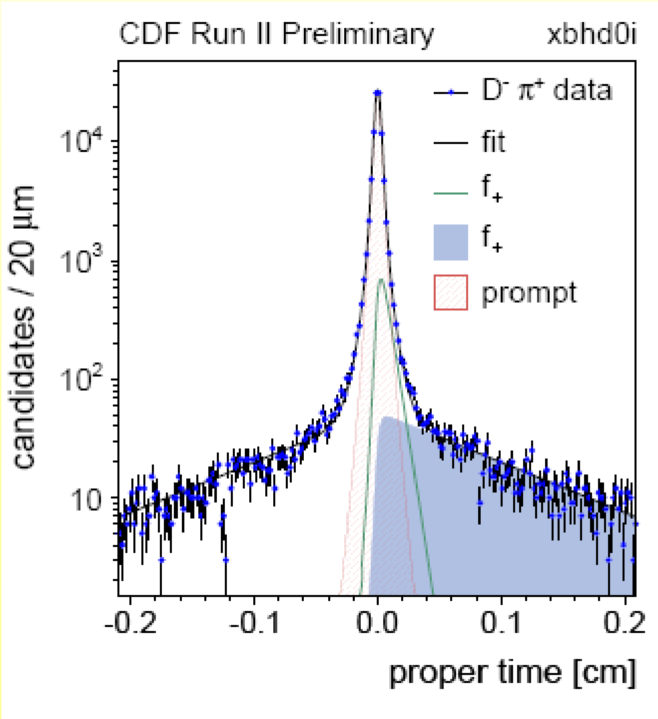
ct(B_s) = 1.48 ± 0.03 ps (stat only)

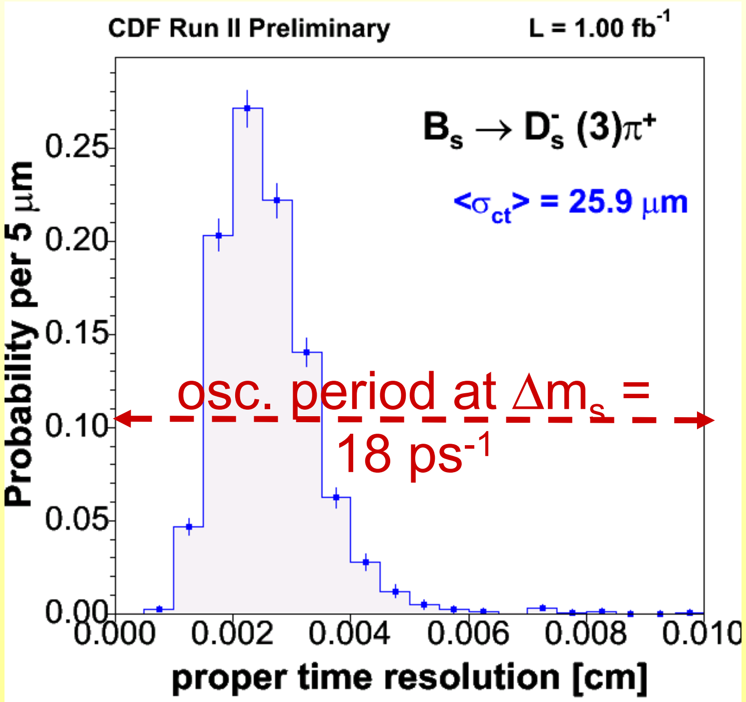
B_s Proper Time Resolution

Decay vertex error matrix overall correction for mis-knowledge of hit resolution

→ Apply a scale factor **S** to **σ(ct)** from vertex fit:

- Use large data control sample, real Ds + track from Primary Vertex
- Parameterize **S** in terms of several variables (P_T, Isolation,…)
- Correct **σ(ct)' = S·σ(ct)** event by event.

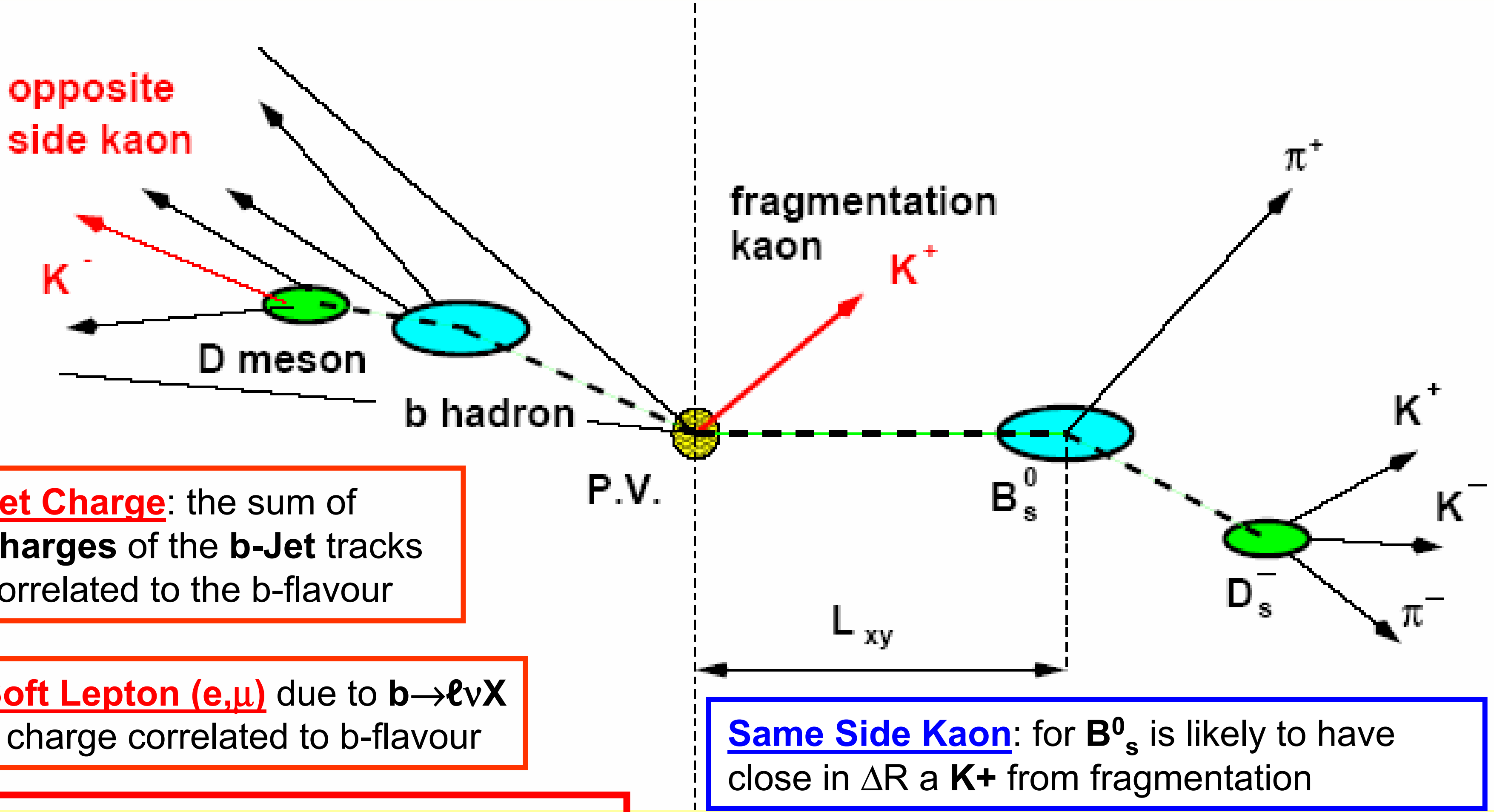




Flavour tagging

Opposite Side

Same Side



Jet Charge: the sum of **charges** of the **b-Jet** tracks correlated to the b-flavour

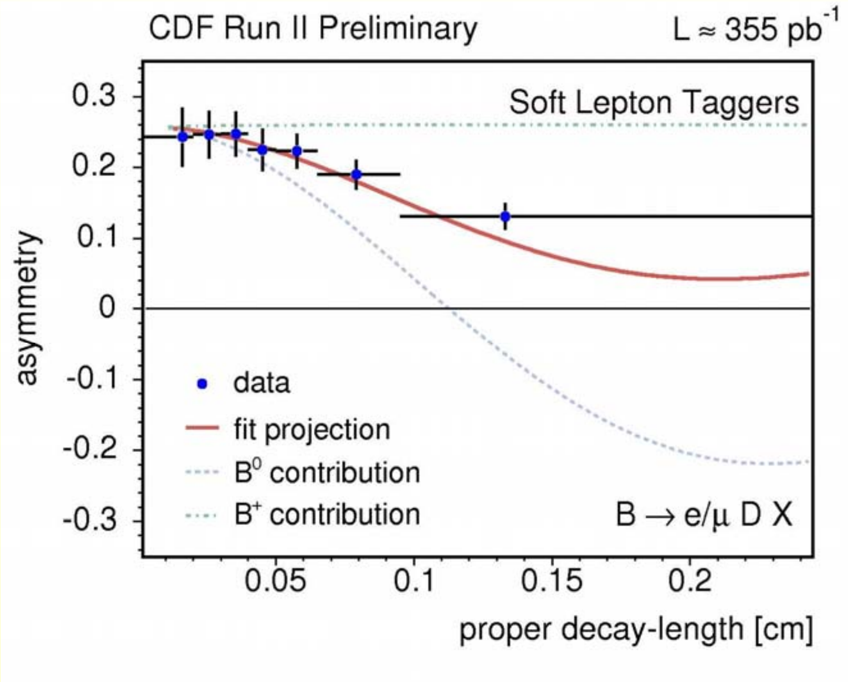
Soft Lepton (e,μ) due to **b→ℓνX**
ℓ charge correlated to b-flavour

Opposite Side K: due to **b→c→s**
→search for secondary **K** **(D ~ 0.3%)**

Same Side Kaon: for $\mathbf{B^0_s}$ is likely to have close in ΔR a **K+** from fragmentation

Caliration of OppositeTaggers

→ Perform **B^0 mixing** analysis:



- Use exclusive combination of:
  - 2 SLT (m, e)
  - 3 JQT categories
  - No OSKT

Total $\varepsilon D^2 = 1.55 \pm 0.08$

	HADRONIC (355 pb^{-1})	SEMILEPTONIC (1 fb^{-1})
Δm_d	$(0.536 \pm 0.028 \pm 0.006)$ ps^{-1}	$(0.509 \pm 0.010 \pm 0.016)$ ps^{-1}

Same Side Kaon Tagging

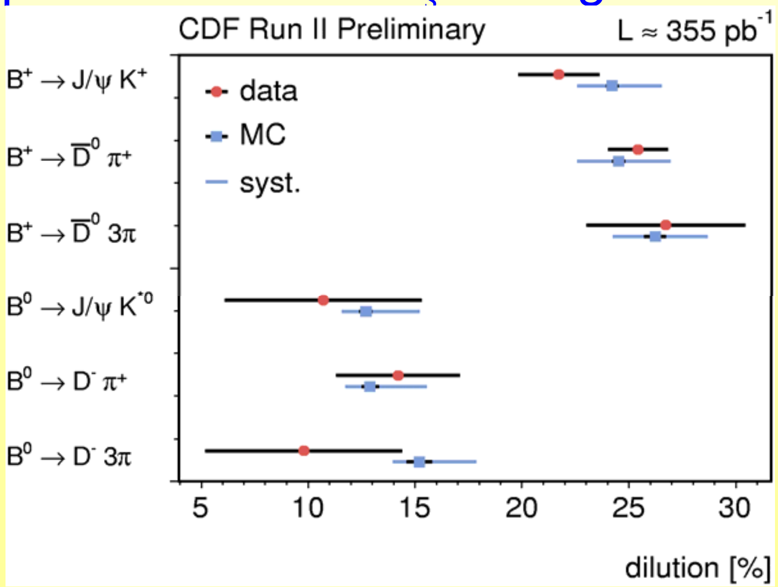
- Look for the fragmentation track that is charge correlated with the *B*

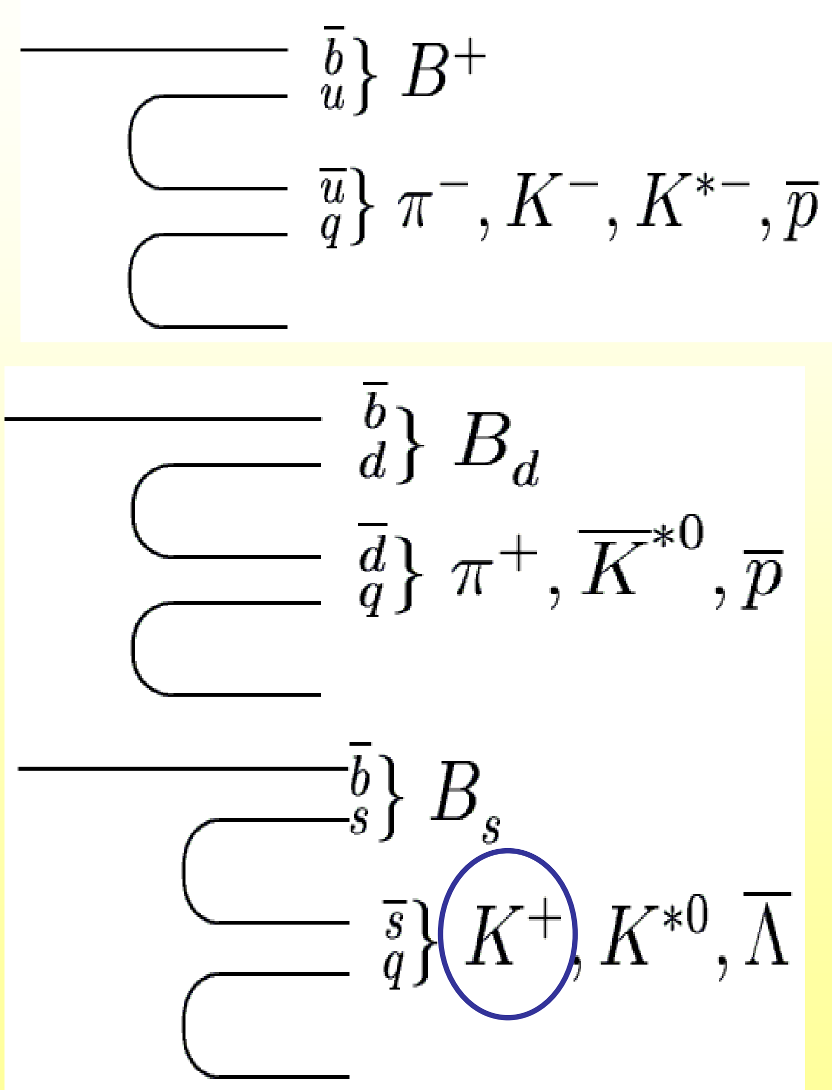
Δm_s not yet measured precisely

⇒ Parameterization from MC

- Detailed data/MC comparison on all tagging related quantities

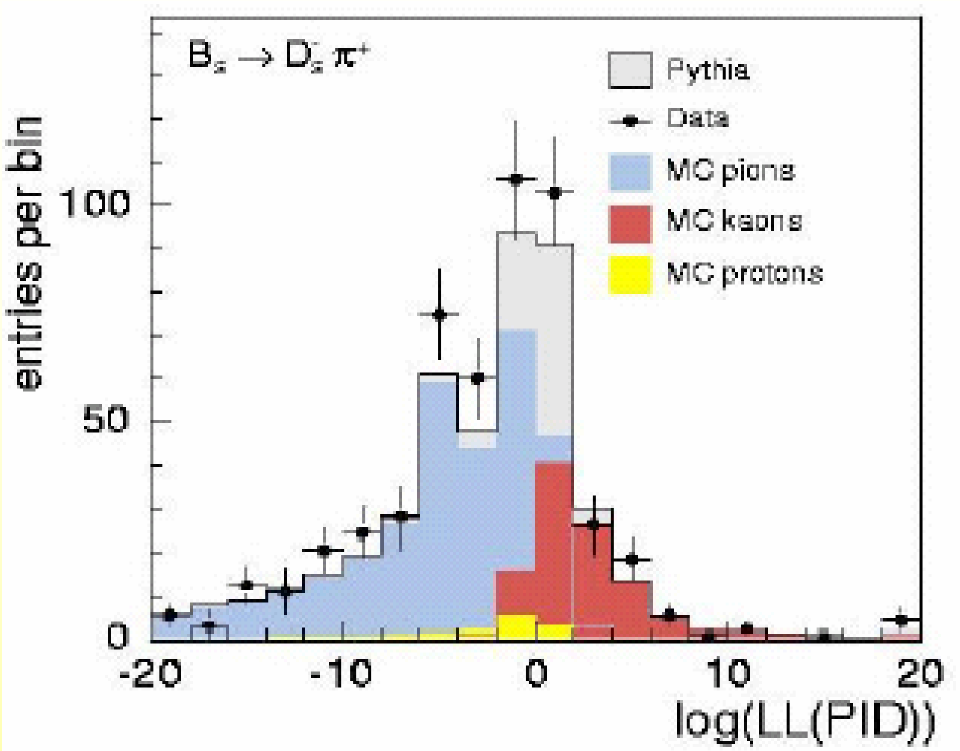
⇒ Rely on MC prediction of SSKT performance for B_s mixing





Evaluating SSKT performance

- Select tracks within a cone of $\Delta R_{b\bar{b}} < 0.7$ around *B*
- Chose the most likely to be a Kaon:
- Make use of PID based on *dE/dx* and T.O.F. information



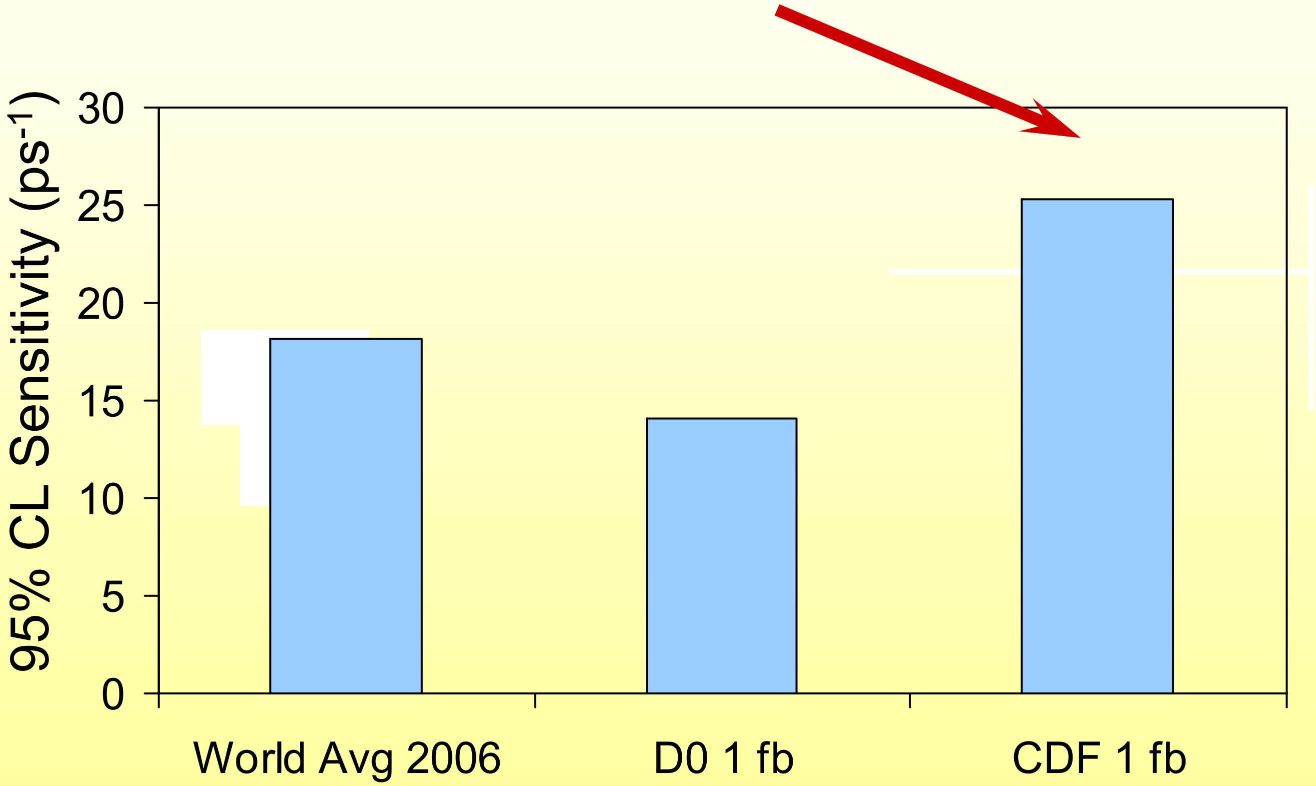
CDF *Pythia MC (msel=1, tune A) 355 pb^{-1}*

$$\varepsilon D^2_{SSKT}\left(B_s^0 \rightarrow D_s^- \pi^+\right) = 4.0^{+0.8}_{-1.2}\ \%$$

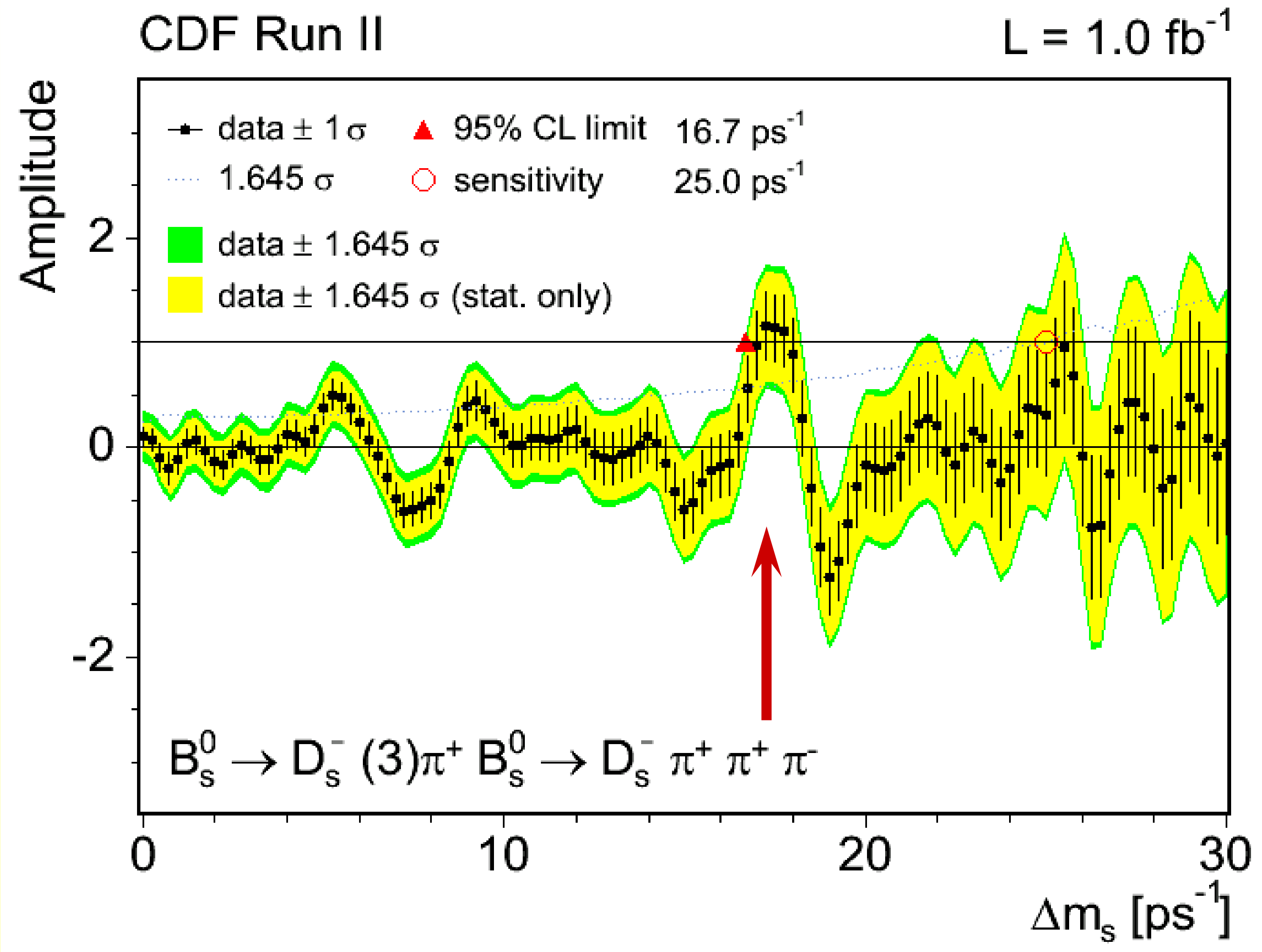
Amplitude Scan Results

Evaluate the average expected limit before unblind the A-Scan:

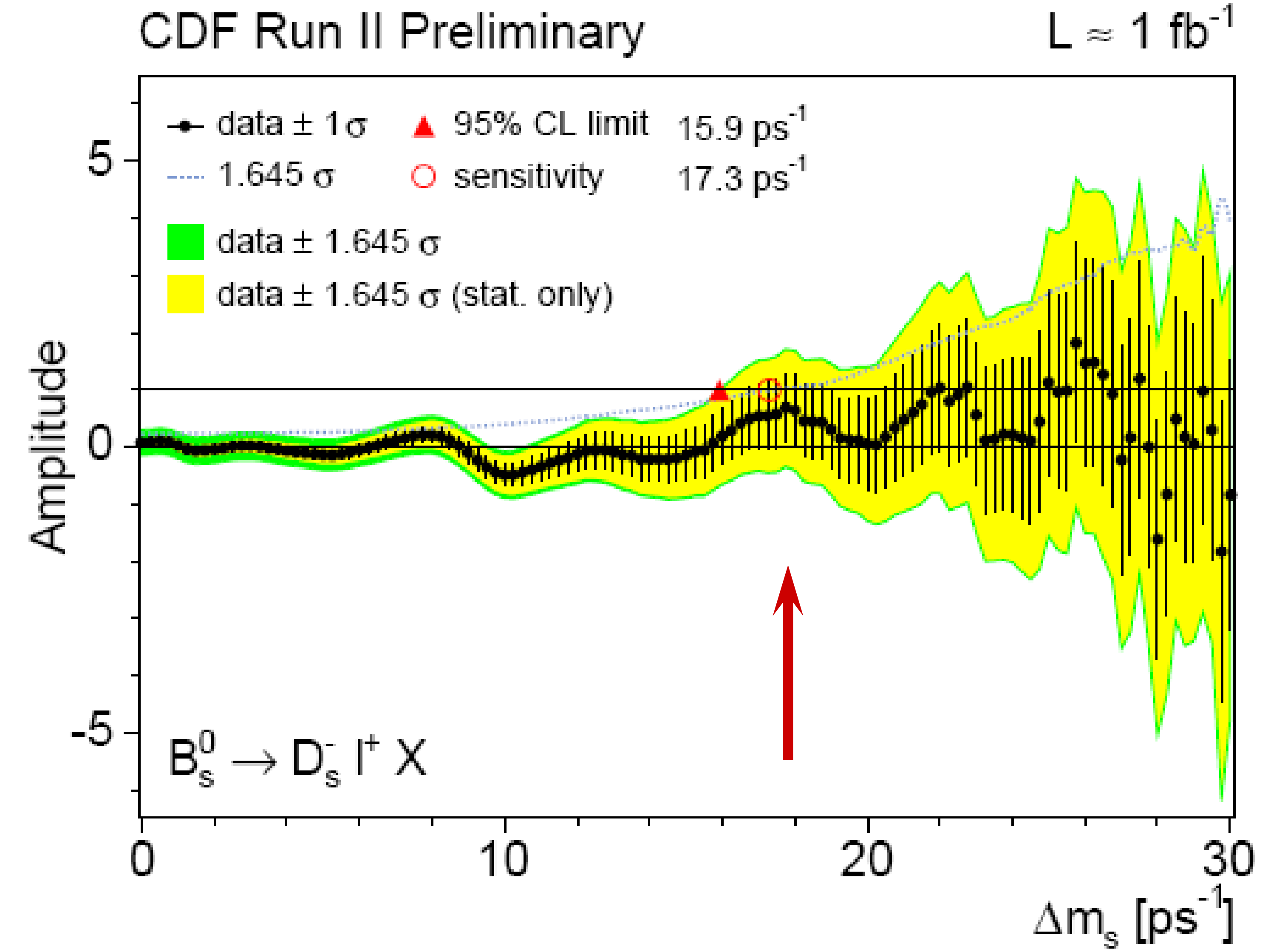
CDF 1fb^{-1} leads world sensitivity:



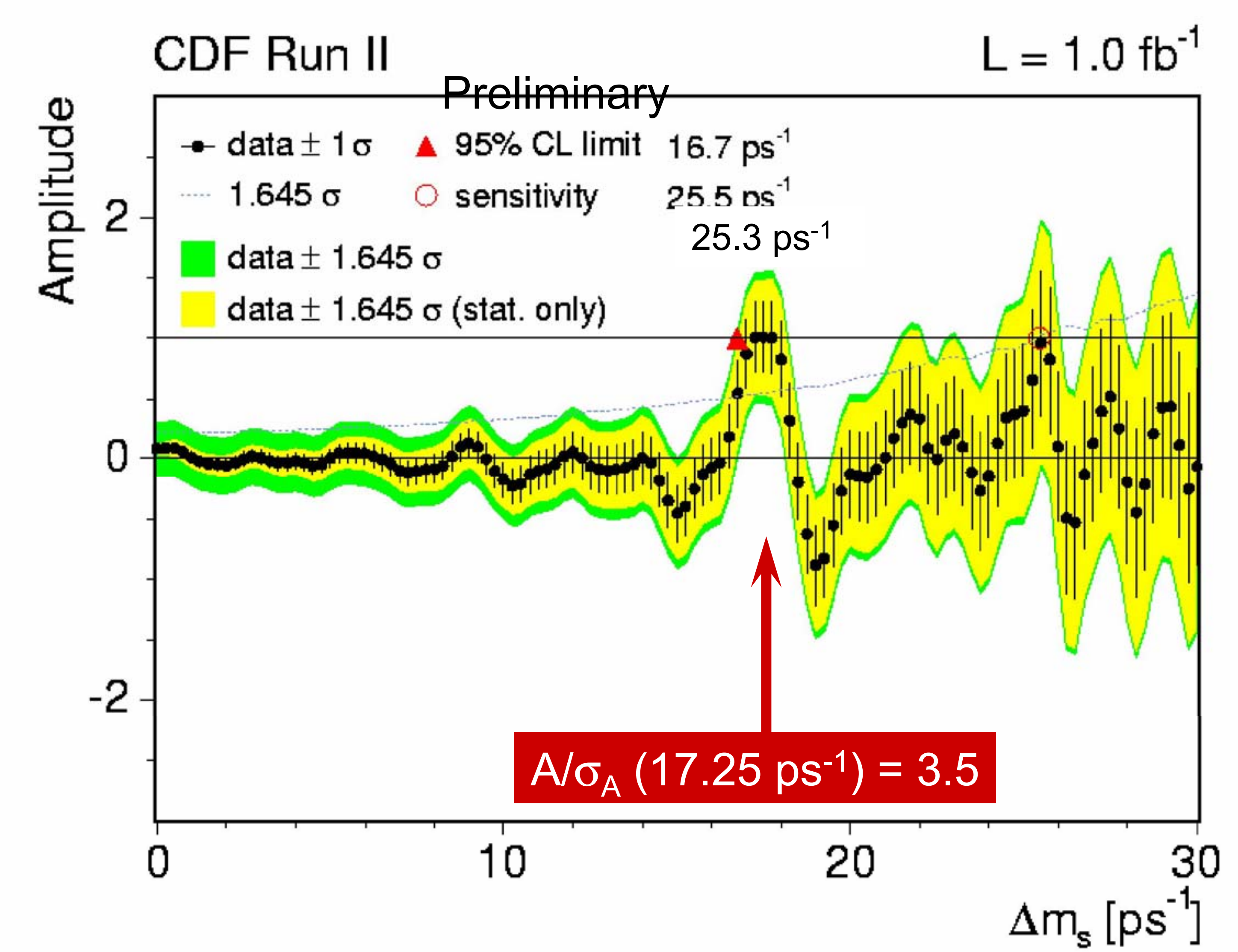
Result: Hadronic Scan



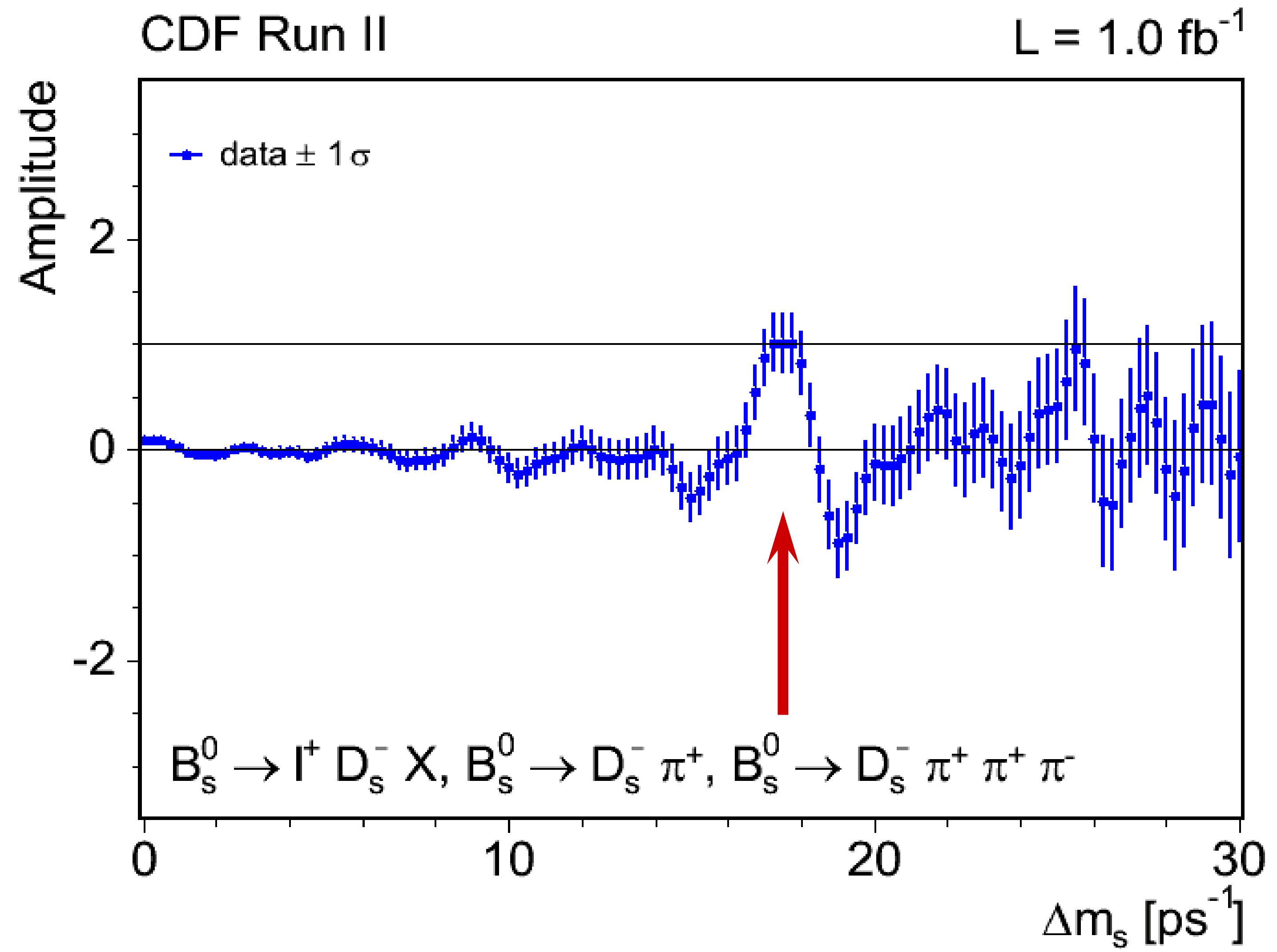
Result: Semileptonic Scan



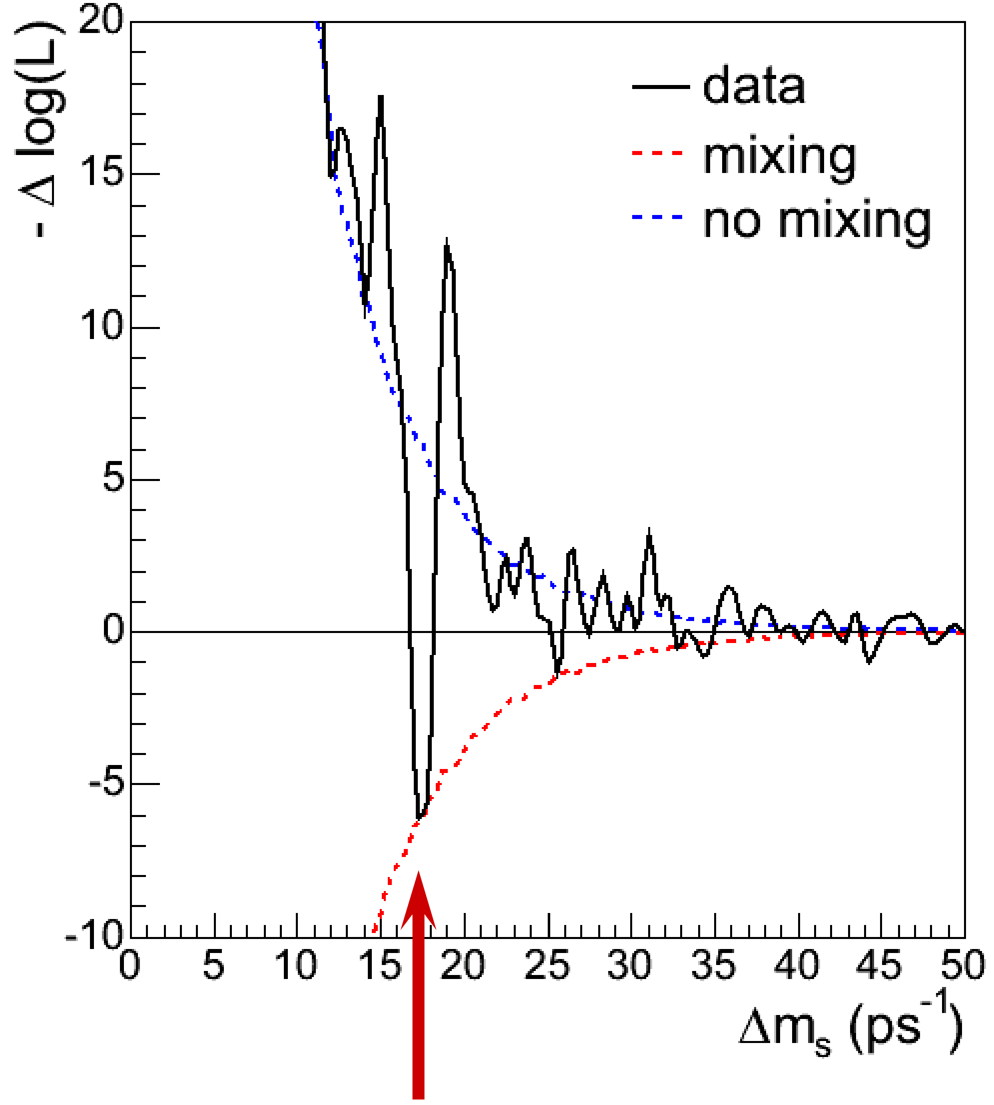
Combined Amplitude Scan



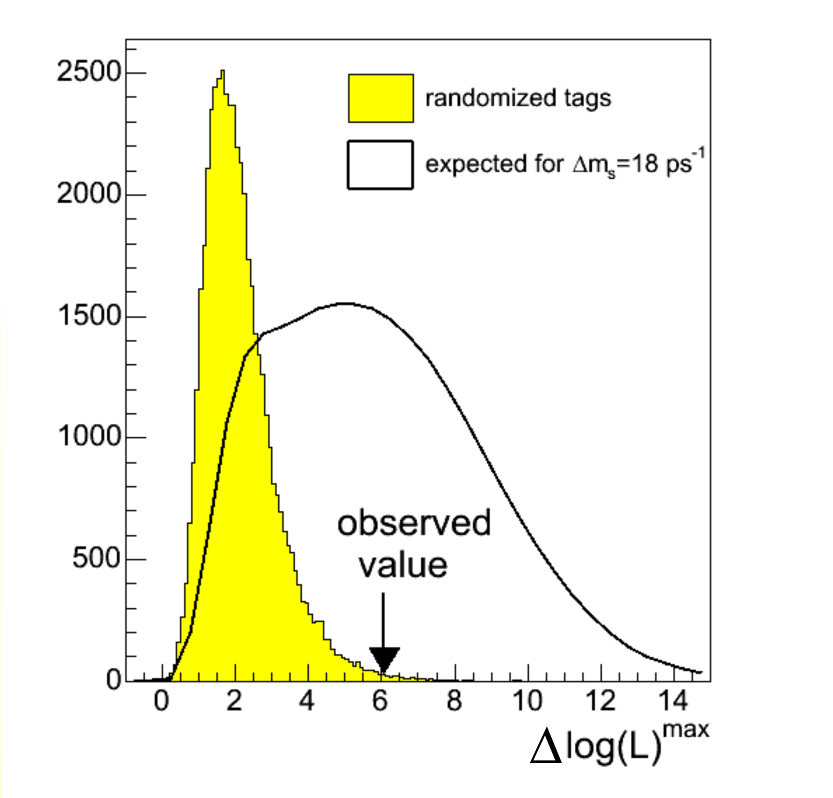
Combined Amplitude Scan

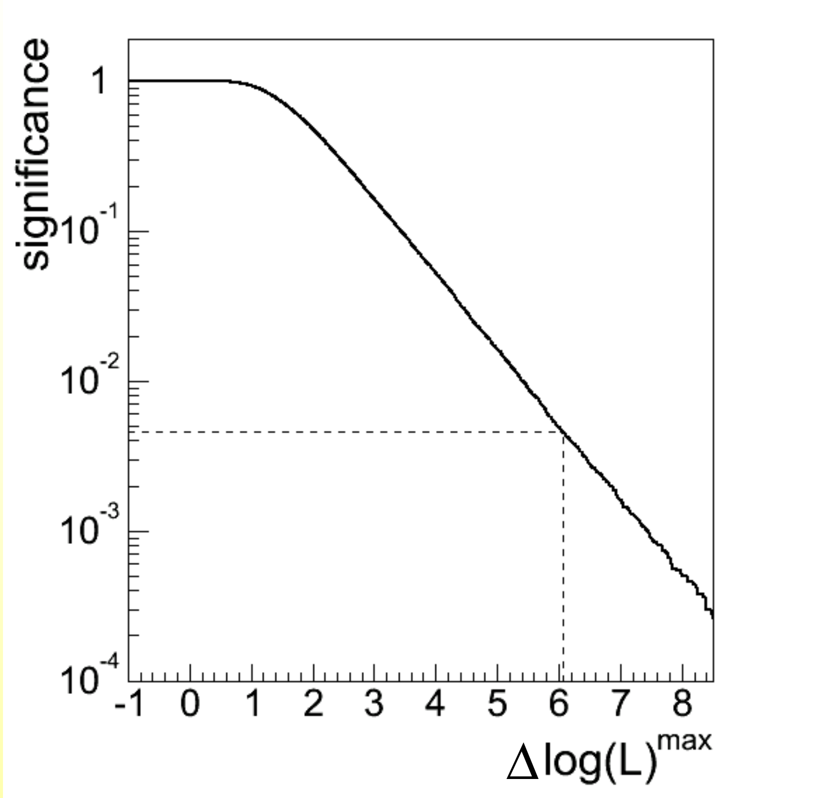


Likelihood Profile



Likelihood Significance





- randomize tags 50 000 times in data, find maximum Δlog(L)
- in 228 experiments, Δlog(L) ¸ 6.06
- probability of fake from random tags = 0.5% → measure Δm_s

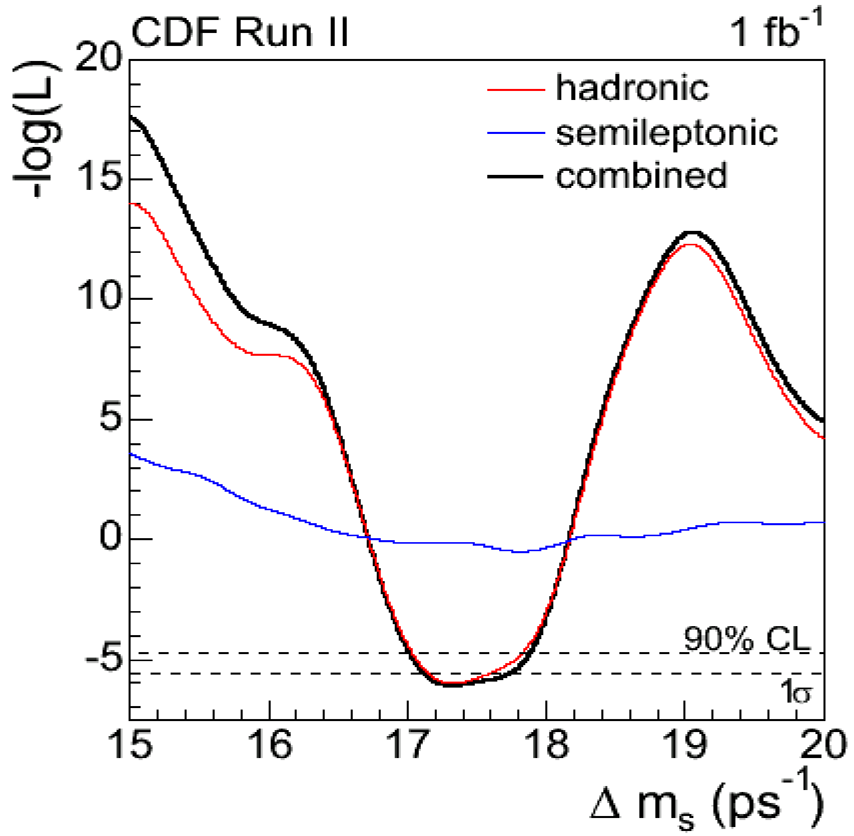
Systematic Uncertainties on Δm_s

- 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	$< 0.01 ps^{-1}$
Total	$0.07\ ps^{-1}$

All relevant systematic uncertainties are common between hadronic and semileptonic samples

Measurement of Δm_s



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

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)
  - → $\xi = 1.21^{+0.047}_{-0.035}$ (M. Okamoto, hep-lat/0510113)
  - → $\Delta m_d = 0.507$ ℓ 0.005 (PDG 2006)

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

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

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

Conclusions

- B_s - B_s oscillations signature found, frequency measured:

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

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

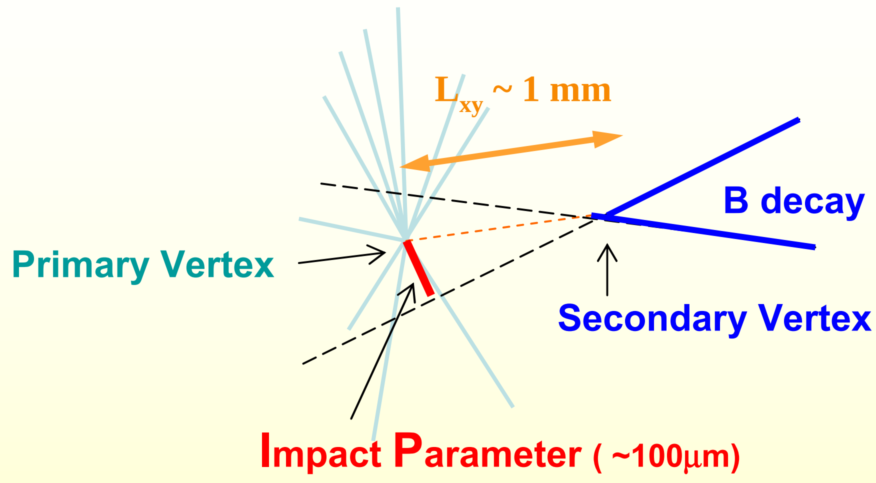
- Important new experimental input to SM test → see next discussion this morning

- BUT this is not the end of the story for CDF B physics:

  - Improved $\Delta\Gamma_s/\Gamma_s$ from $B_s \rightarrow J\Psi/\phi$ in the pipeline
  - Lifetime difference from penguin mode $B_s \rightarrow KK$
  - Look for CP Violation in $B_s \rightarrow J\Psi/\phi$
  - CP Asymmetry in $B_s \rightarrow KK$

Backup slides

SVT: the hadronic B trigger

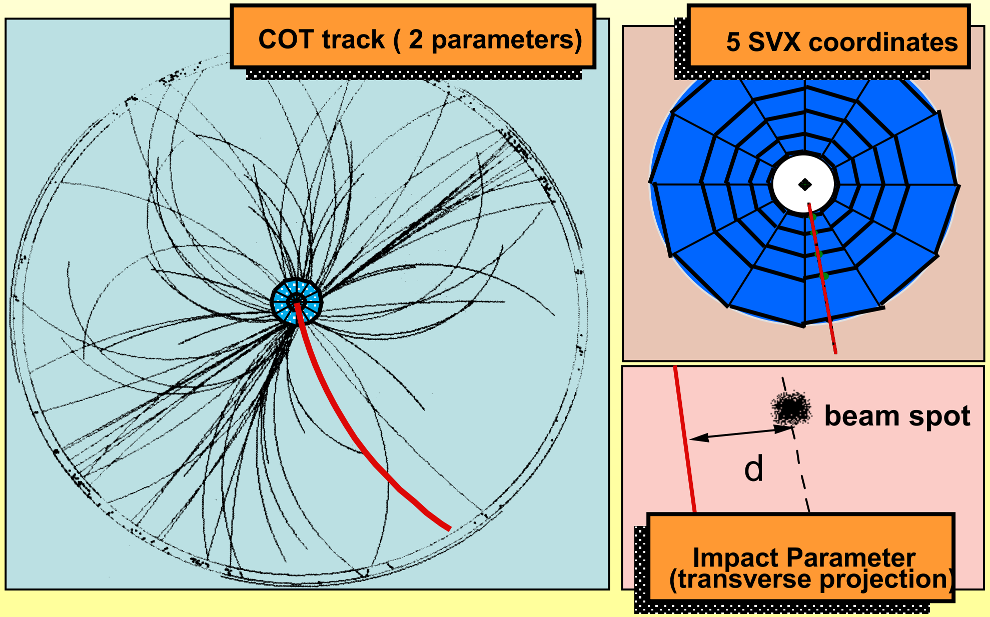


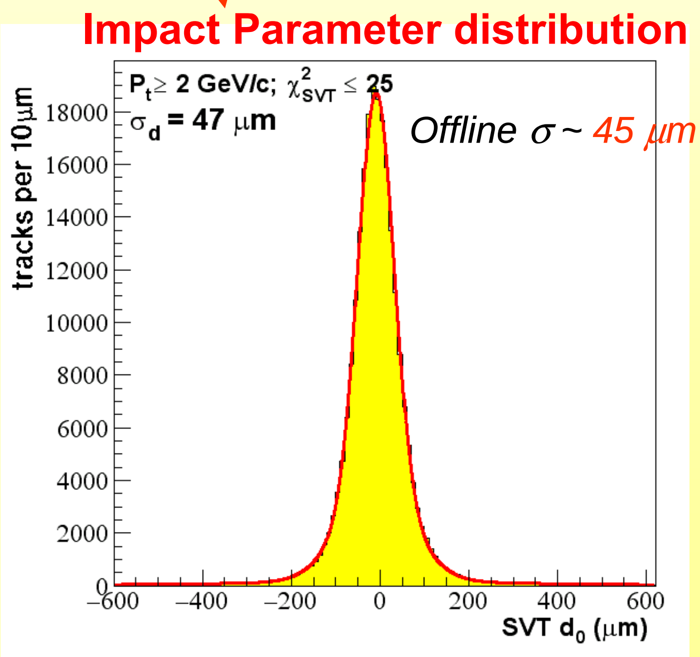
→Online Impact parameter
Available at Level 2 trigger (20μs latency)

→convolution of transverse size of the beam spot with the impact parameter resolution of the SVT:

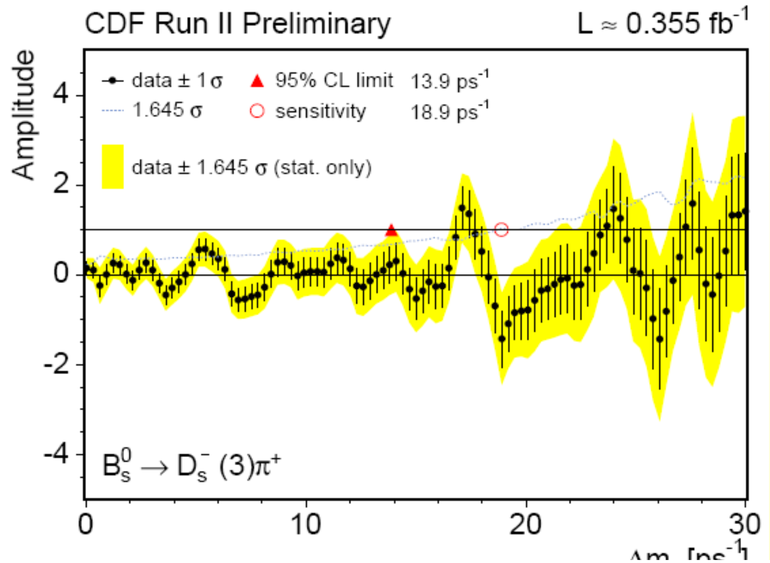
$\sigma \approx 47\ \mu m \approx 35\ \mu m \oplus 30\ \mu m$

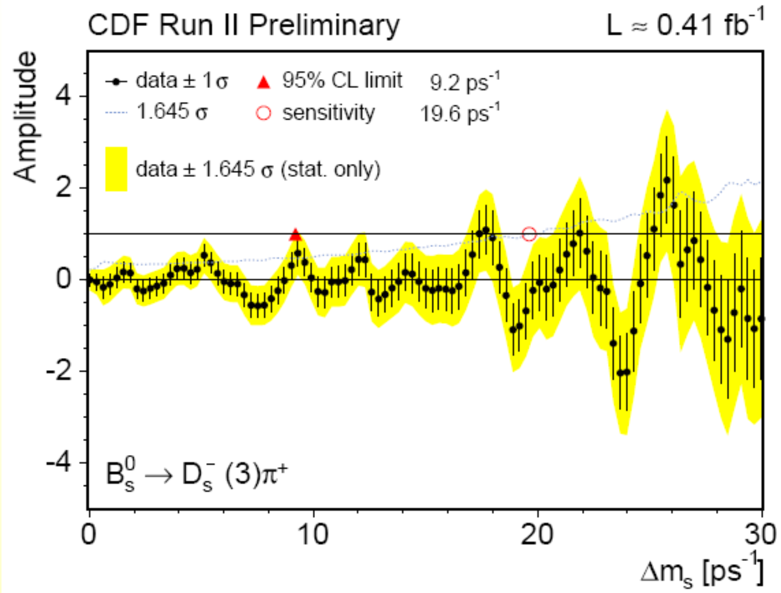
SVT resolution — Beam spot size

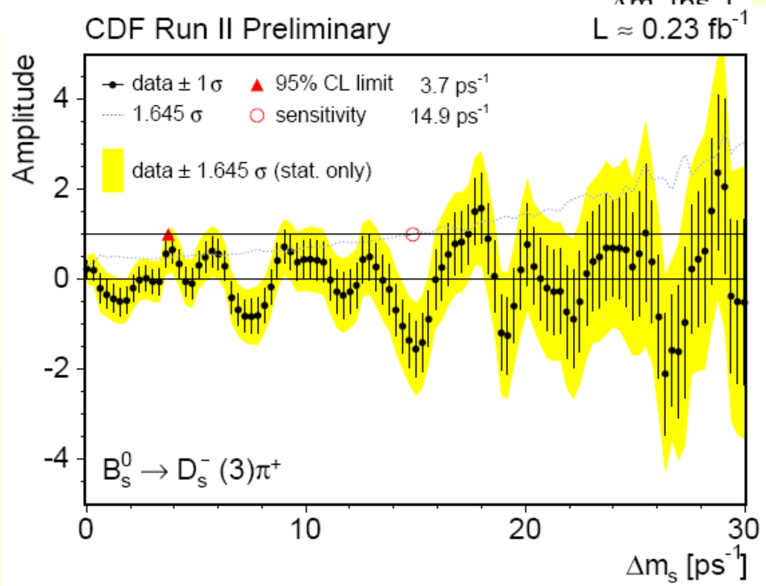




Hadronic Scans: 3 data tacking periods

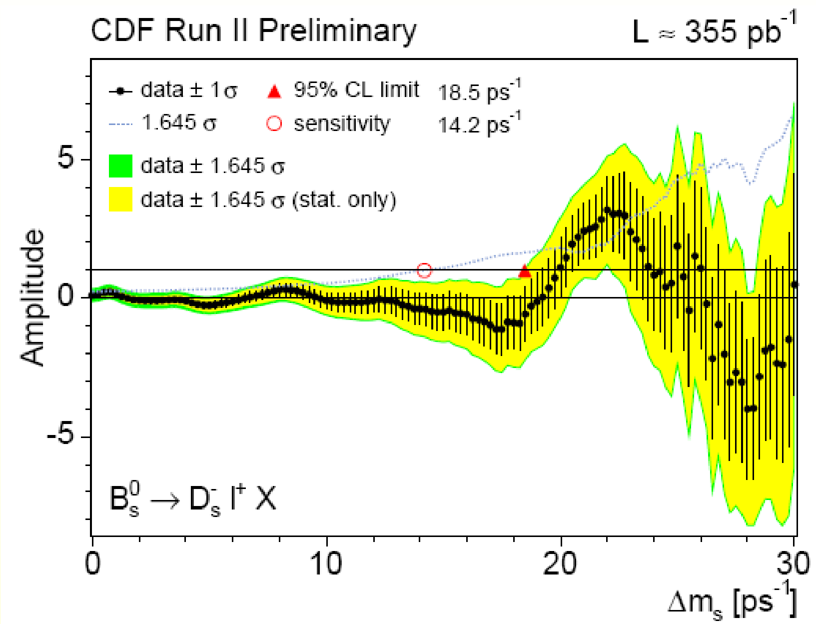


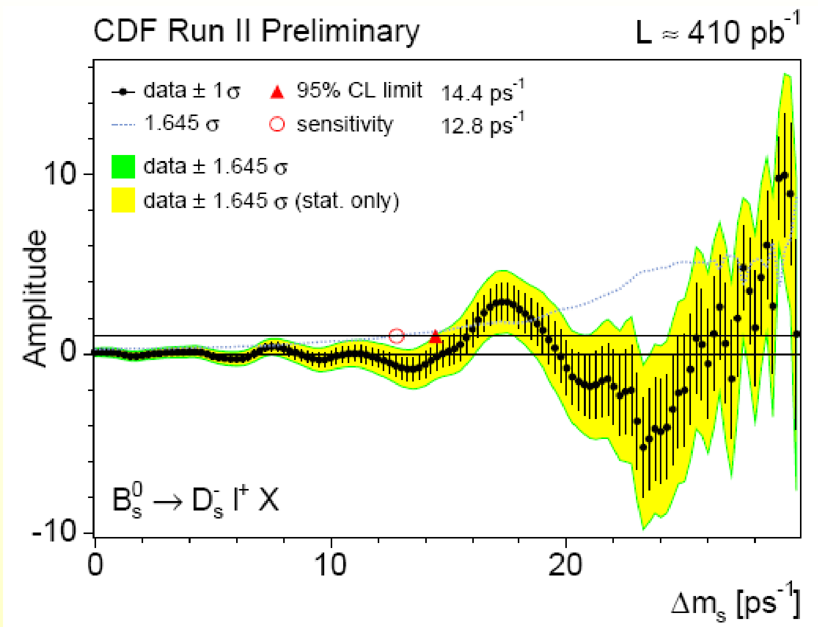


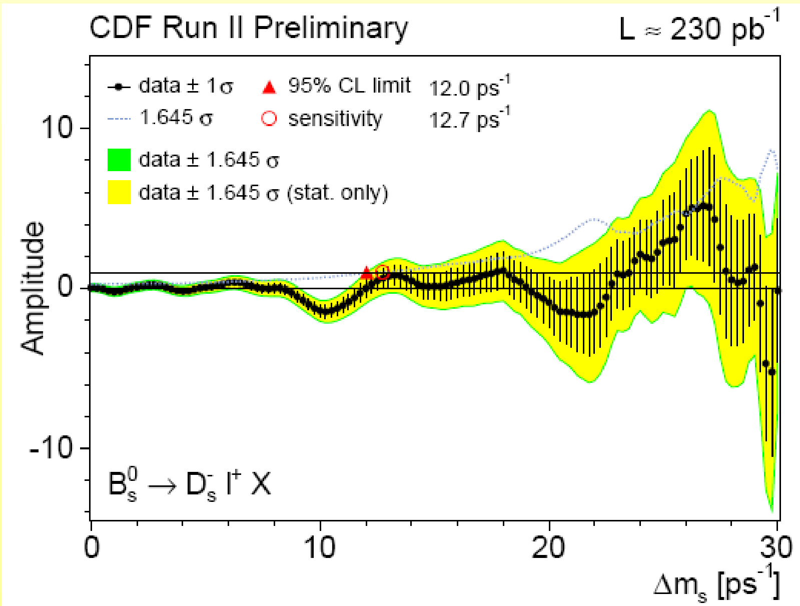


Typical fluctuations from ~3σ effect

Semileptonic Scans: 3 data tacking periods



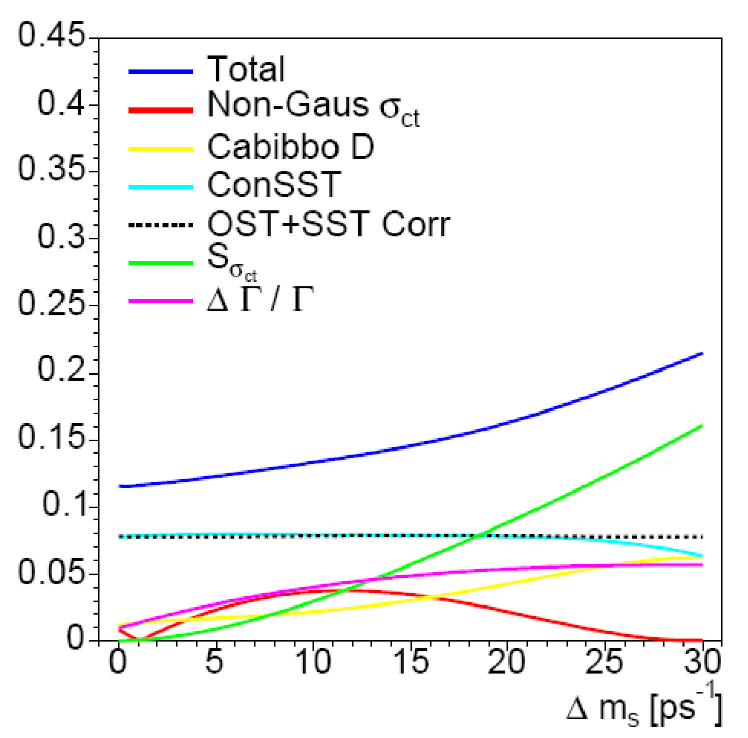




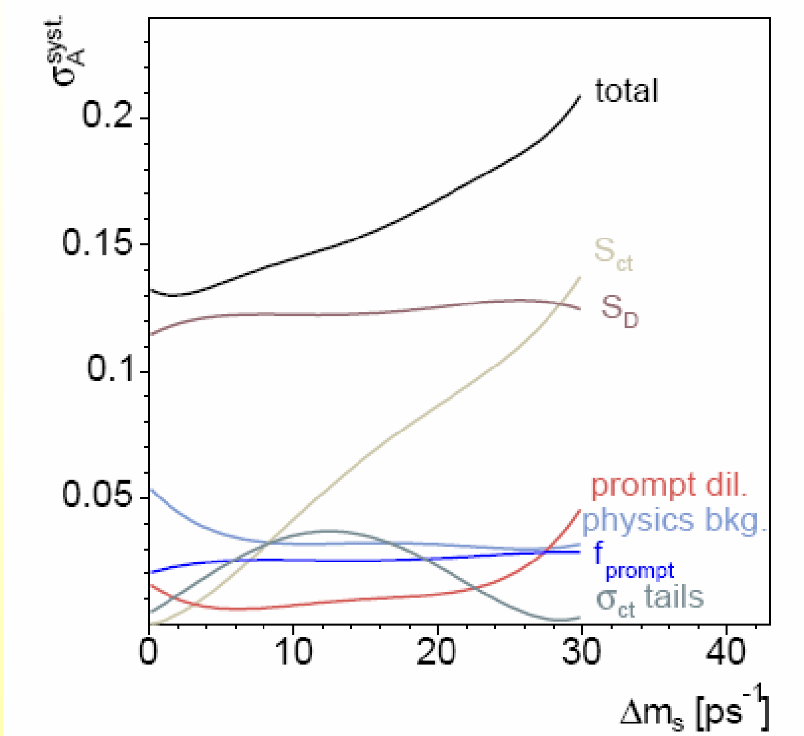
Typical fluctuations from ~1σ effect

Amplitude Systematic Uncertainties

Hadronic



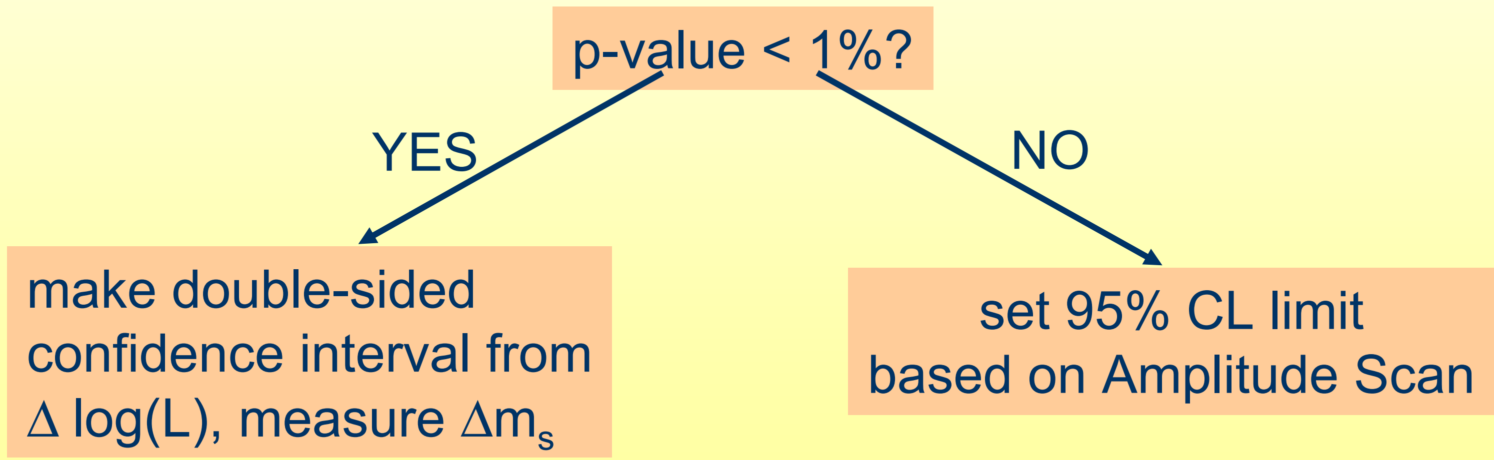
Semileptonic



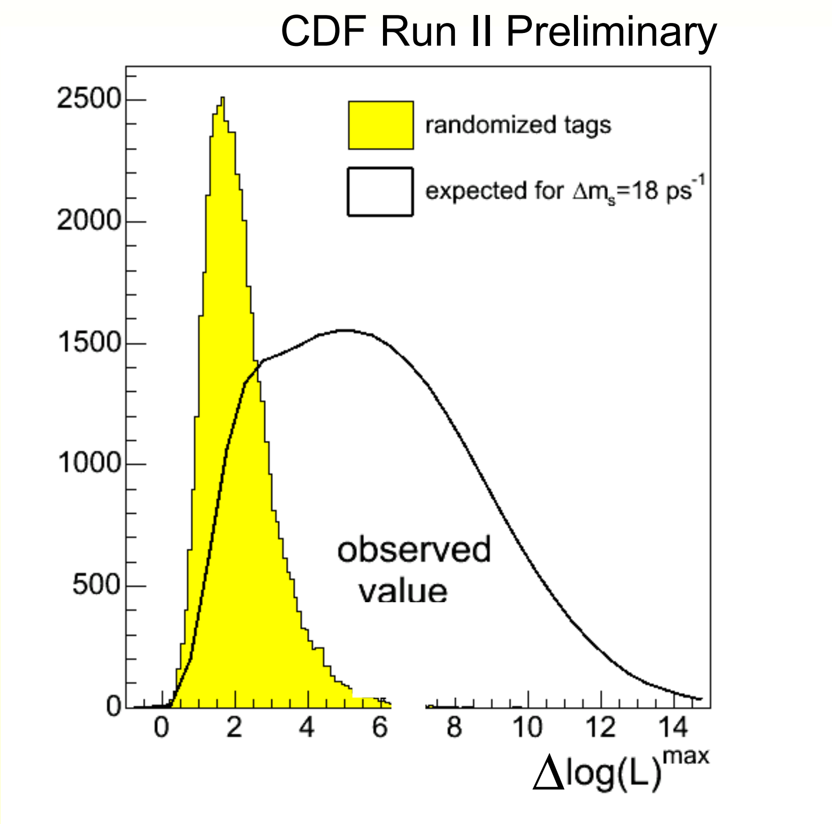
- related to absolute value of Amplitude, relevant only when setting limits
  - cancel in A/σ_A,
  - systematic uncertainties are very small compared to statistical

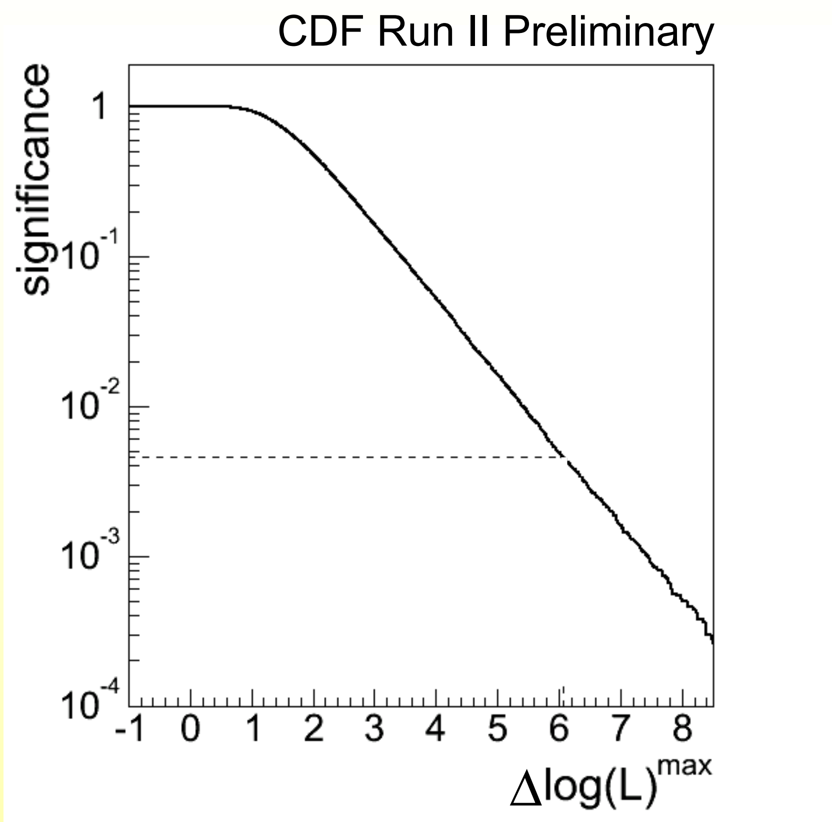
A Priori Procedure

- decided upon before un-blinding the 1 fb^{-1} of data
- p-value: probability that background fluctuation would produce observed effect
- 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