B_s^0 Mixing at CDF

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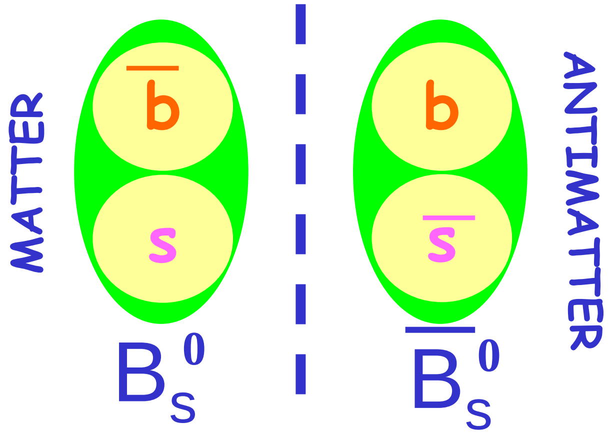
For the CDF Collaboration

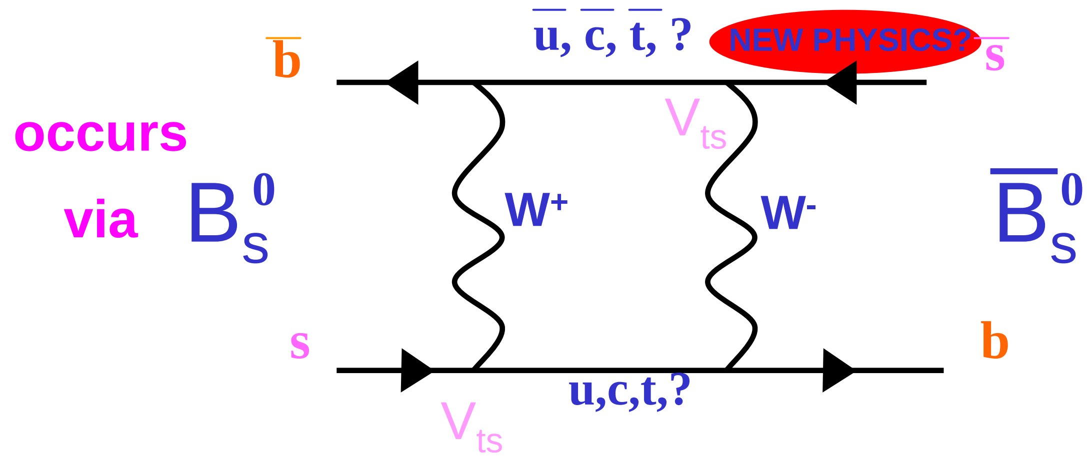
IOP HEPP 2006

B_s^0 Physics

Bound states:



Matter↔antimatter:



- Physical states, H and L, evolve as superpositions of B_s^0 and $\bar{B}_s^0$
- System characterised by 4 parameters:
  masses: m_H, m_L lifetimes: Γ_H, Γ_L ($\Gamma = 1/\tau$)
- Predicted Δm_s around 20ps^{-1}

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

- No measurements of Δm_s have been made:
  - B factories do not produce Bs Mesons
  - Limits set by LEP, SLD, Tevatron

Why is Δm_s interesting?

1) Probe of New Physics
   - may enter in box diagrams

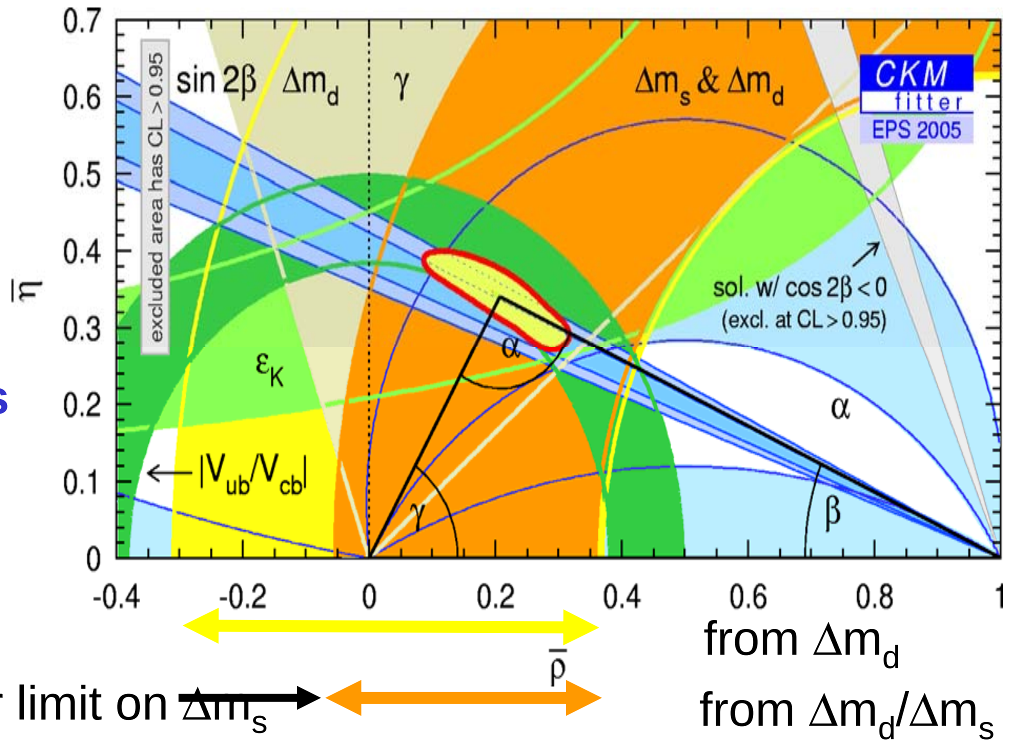
2) Measure CKM matrix element:

Δm_d known accurately from B factories

- V_{td} known to 15%
- Ratio $V_{td}/V_{ts} \propto \Delta m_d/\Delta m_s$ related by constants:

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

- ξ (from lattice QCD) known to 2%
- So: measure Δm_s gives V_{ts}



•CKM Fit result:

Δm_s: 18.3+6.5 (1s) : +11.4 (2σ) ps-1

Standard Model Predicts rate of mixing, $\Delta m = m_H - m_L$, so Measure rate of mixing $\Rightarrow V_{ts}$ (or hints of NEW physics)

Measuring Δm_s

In principle: **Measure asymmetry of number of matter and antimatter decays:**

$$A(t) \equiv \frac{N(B_s^0 \to B_s^0)(t) - N(B_s^0 \to \overline{B}_s^0)(t)}{N(B_s^0 \to B_s^0)(t) + N(B_s^0 \to \overline{B}_s^0)(t)} \propto \cos(\Delta m t)$$

In practice: **use amplitude scan method**

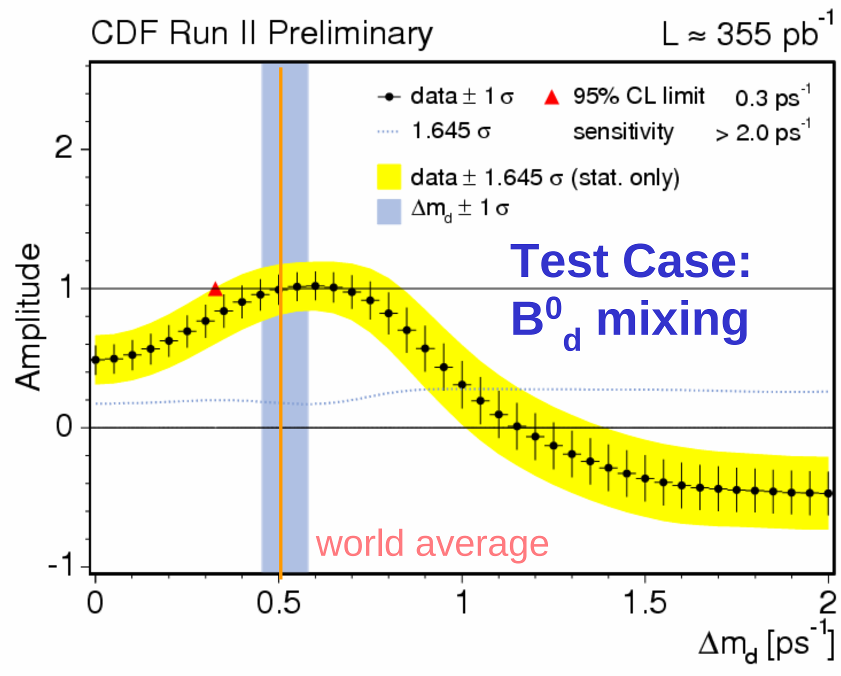
- **introduce amplitude to mixing probability formula**

$$P_{unmix}^{B_s} = \frac{1}{2}\Gamma_{B_s} e^{-\Gamma_{B_s} t}(1 + A\cos\Delta m_s t)$$

$$P_{mix}^{B_s} = \frac{1}{2}\Gamma_{B_s} e^{-\Gamma_{B_s} t}(1 - A\cos\Delta m_s t)$$

- **evaluate at each Δm point**
- **Amplitude=1 if evaluated at correct Δm**
- **Allows us to set confidence limit when 1.645σ=1**

H. G. Moser, A. Roussarie, NIM **A384** (1997)



Mixing Ingredients

1) Signal samples
   - semileptonic and hadronic modes

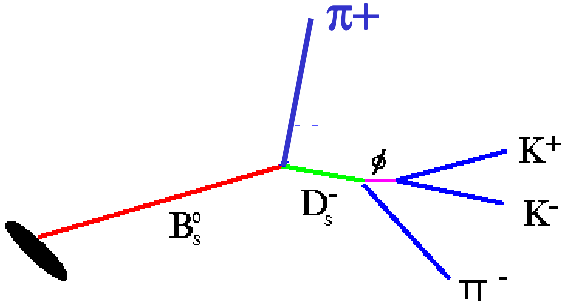
2) Time of Decay
   - and knowledge of Proper decay time resolution

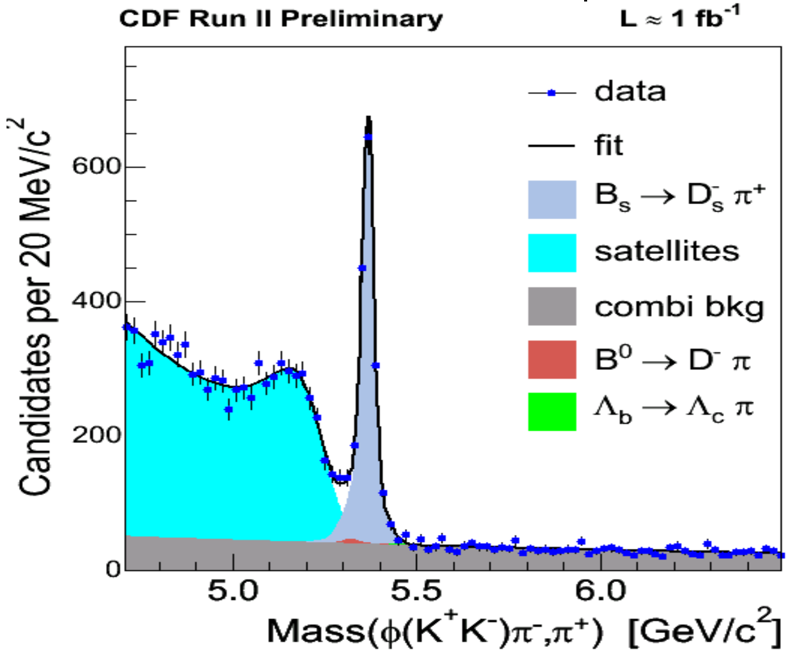
$$\sigma_{ct} = \sqrt{\left(\sigma_{ct}^{0}\right)^2 + \left(ct \times \frac{\sigma_p}{p}\right)^2}$$

3) Flavour tagging
   - opposite side (can be calibrated on B^0 and B^+)
   - same side (cannot be calibrated on B^0 and B^+, used for the first time now)

1) Signal Samples for B_s Mixing

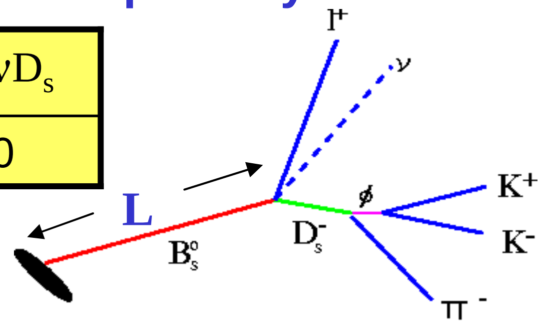
Hadronic: fully reconstructed

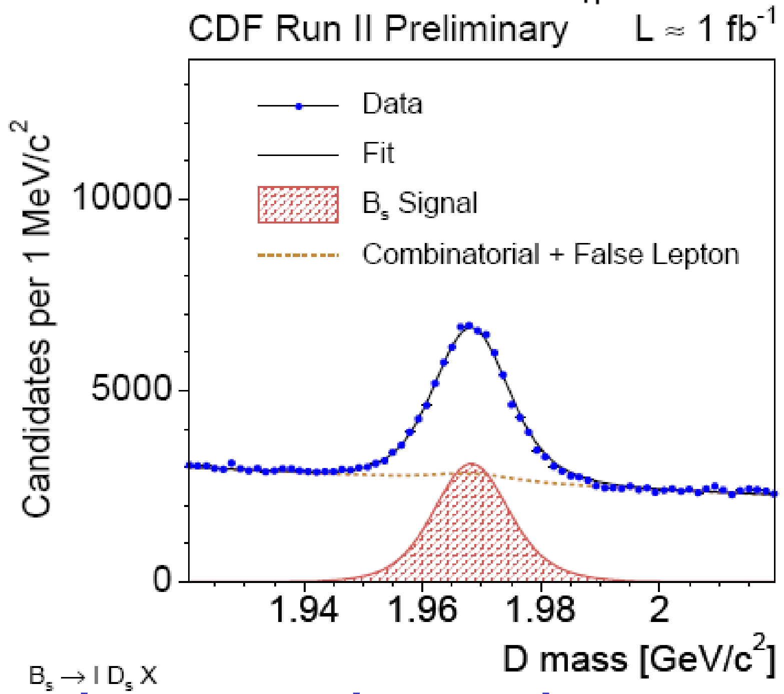




	$B_s \to D_s \pi$	$B_s \to l\nu D_s$
Yield	3700	53000

Semileptonic: partially reconstructed





These modes are flavour specific: the charges tag the B at decay

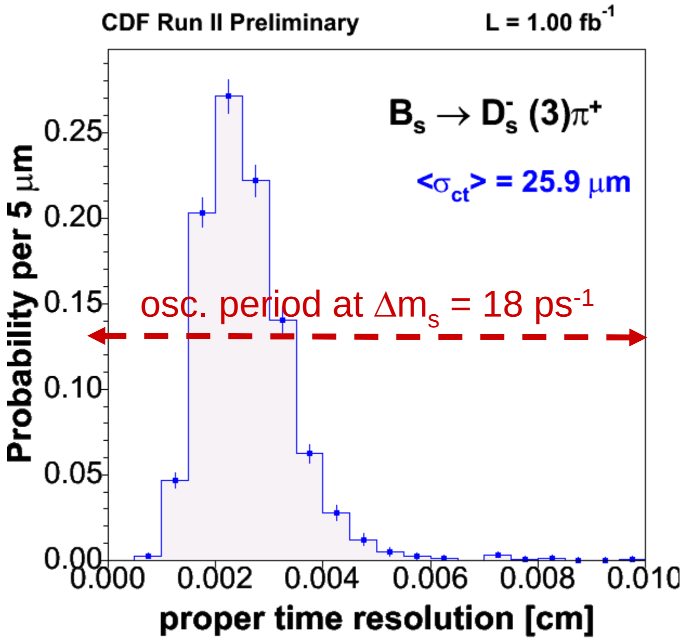
Crucial: Triggering using displaced track trigger
(Silicon Vertex Trigger)

2) Time of Decay

- Reconstruct decay length by vertexing
- Measure p_T of decay products

$$ct = \frac{L}{\beta\gamma} = L\frac{m(B)}{p(B)} = \frac{L_{xy}\,m(B)}{p_T(lD)}$$

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



Hadronic:

$$\sigma_{ct}^{0} \approx 59\mu m$$
$$\sigma_p / p \approx 15\%$$

Semileptonic:

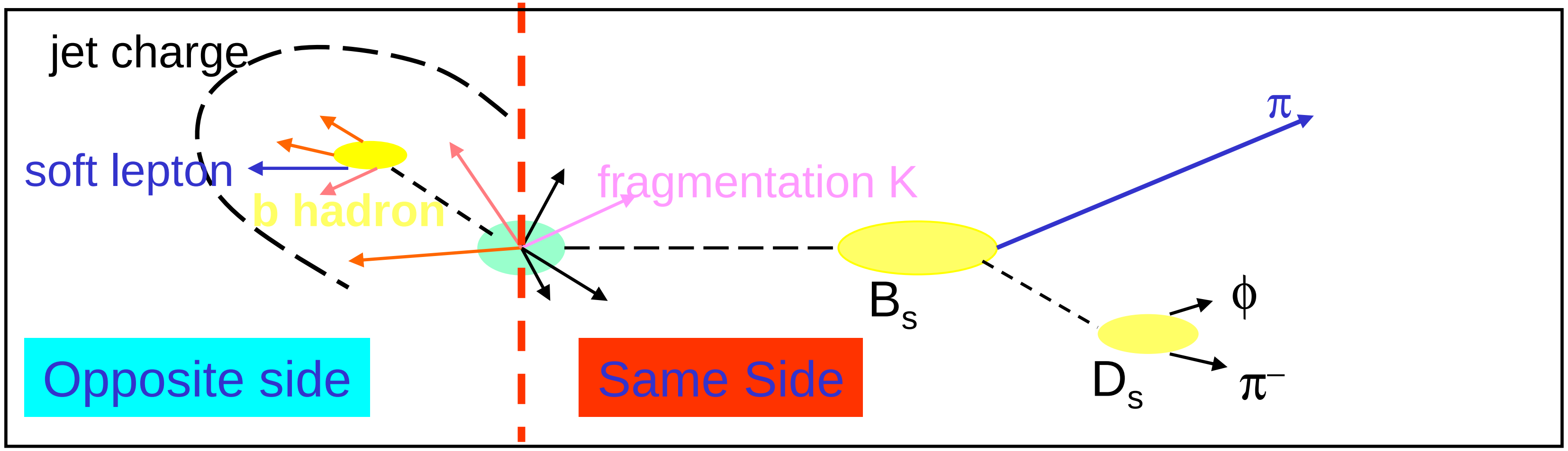
$$\sigma_{ct}^{0} \approx 30\mu m$$
$$\sigma_p / p \approx 0\%$$

Crucial: Vertex resolution
(Silicon Vertex Detector, in particular Layer00 very close to beampipe)

3) Flavour Tagging

To determine B flavour at production, use tagging techniques:

b quarks produced in pairs ⇒ only need to determine flavour of one of them



OPPOSITE SIDE
Soft Muon Tag
Soft Electron Tag
Jet charge tag
εD^2 = 1.44±0.04 % (semileptonic)
1.47±0.10 % (hadronic)

SAME SIDE
Same Side K Tag

εD^2 = 4.00±0.04 %(semileptonic)
3.42±0.06 % (hadronic)

Crucial: Particle Identification (Time of Flight Detector)

Putting Everything Together

- Amplitude scan performed on B_s candidates
- Inputs for each candidate:
  - Mass
  - Decay time
  - Decay time resolution
  - Tag decisions
  - Predicted dilution
  - Mass(lepton+D) if semileptonic

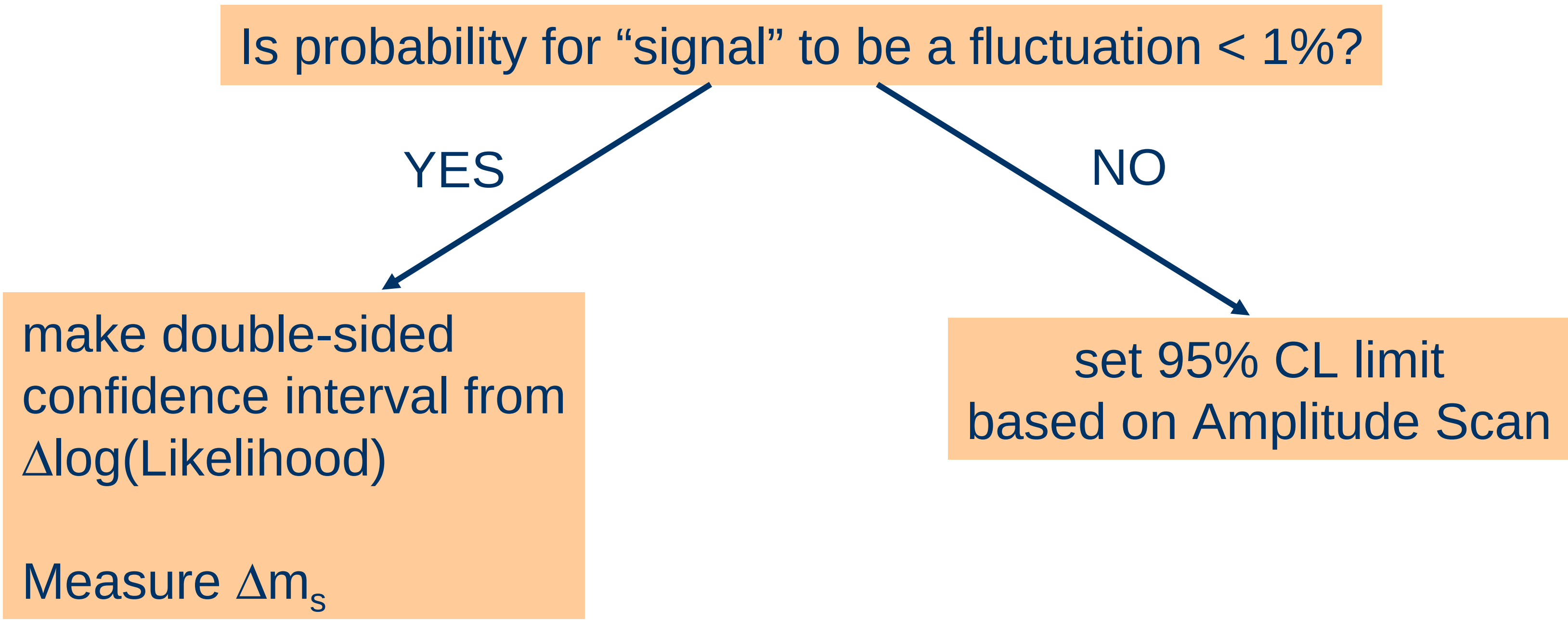
- All elements are then folded into the amplitude scan

$$\frac{1}{\tau} e^{-t/\tau}\left(1 \pm ADS_D \cos(\Delta m t)\right)$$

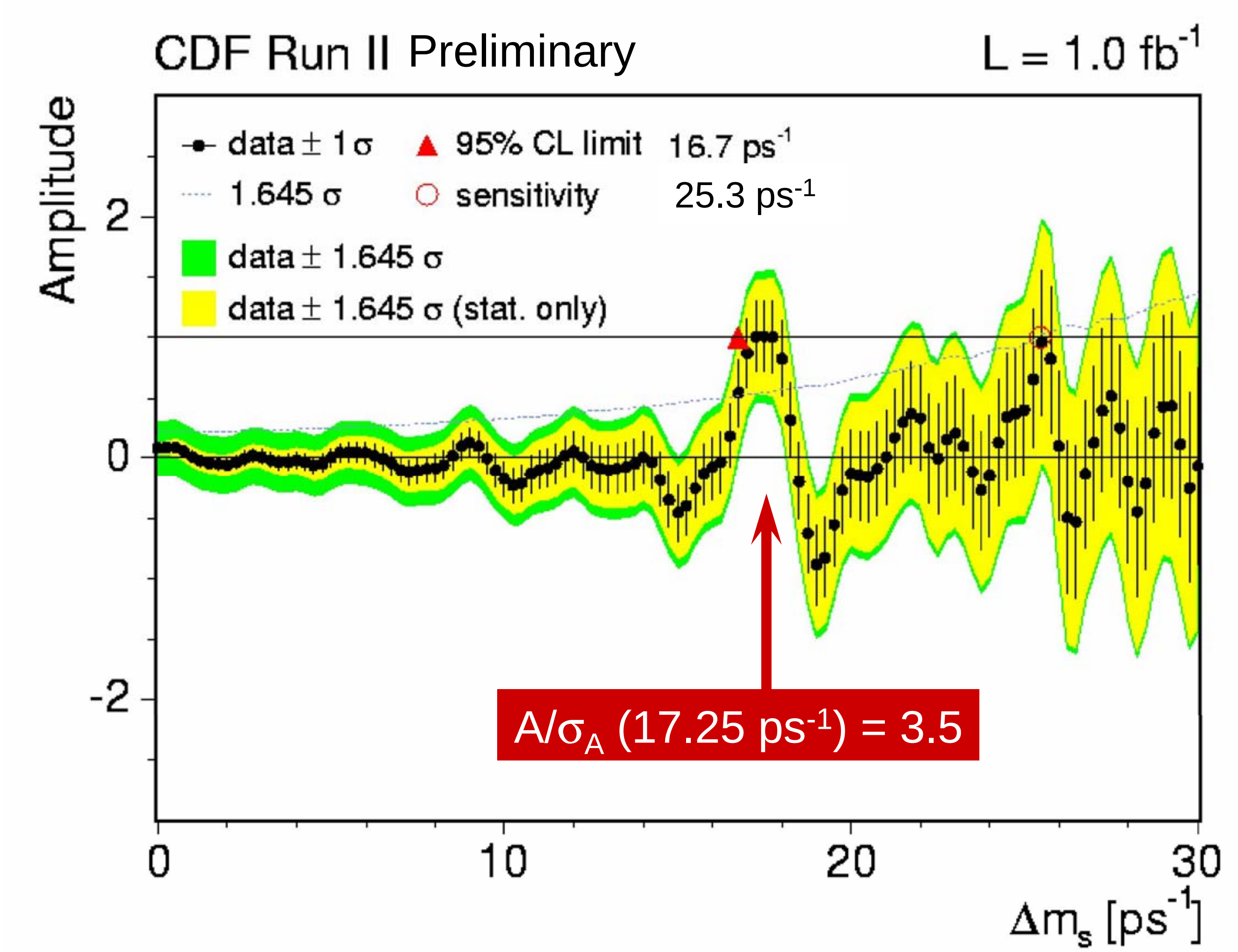
A Priori Procedure

Decided upon before un-blinding the data:
(everything blinded so far by scrambling tagger decision)

- **Find highest significant point on amplitude scan consistent with an amplitude of 1**
- **significance to be estimated using Δ(ln Likelihood) method**
- **effectively infinite Δm_s search window to be used**



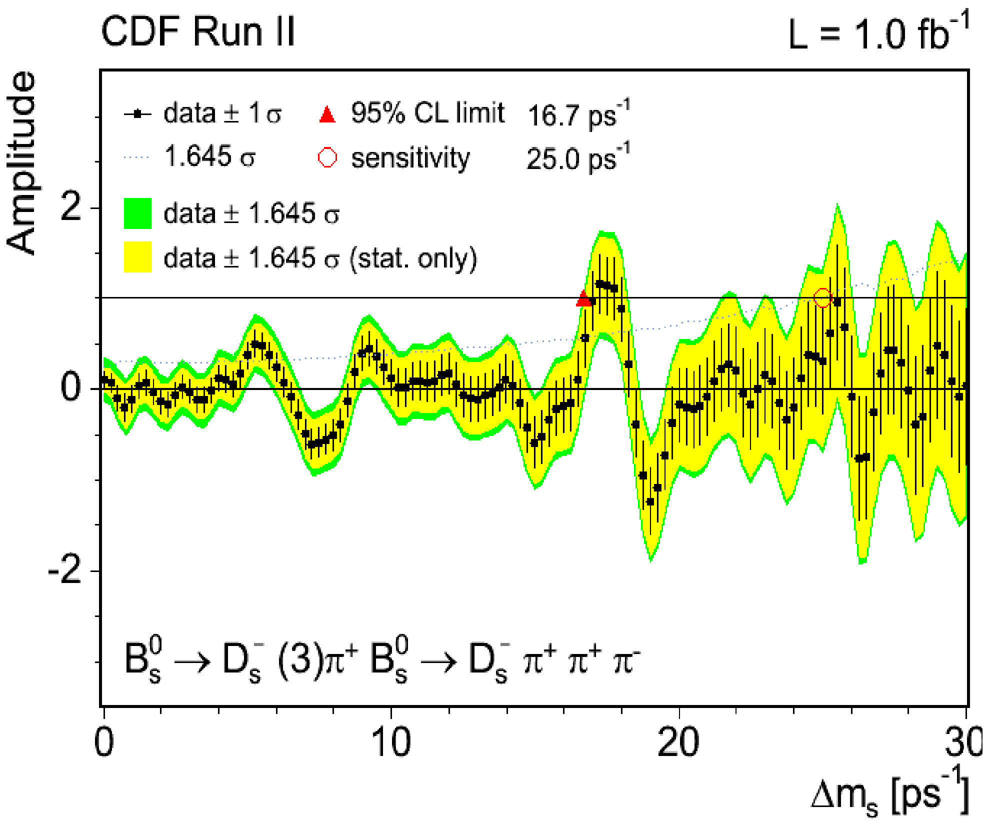
Combined Amplitude Scan



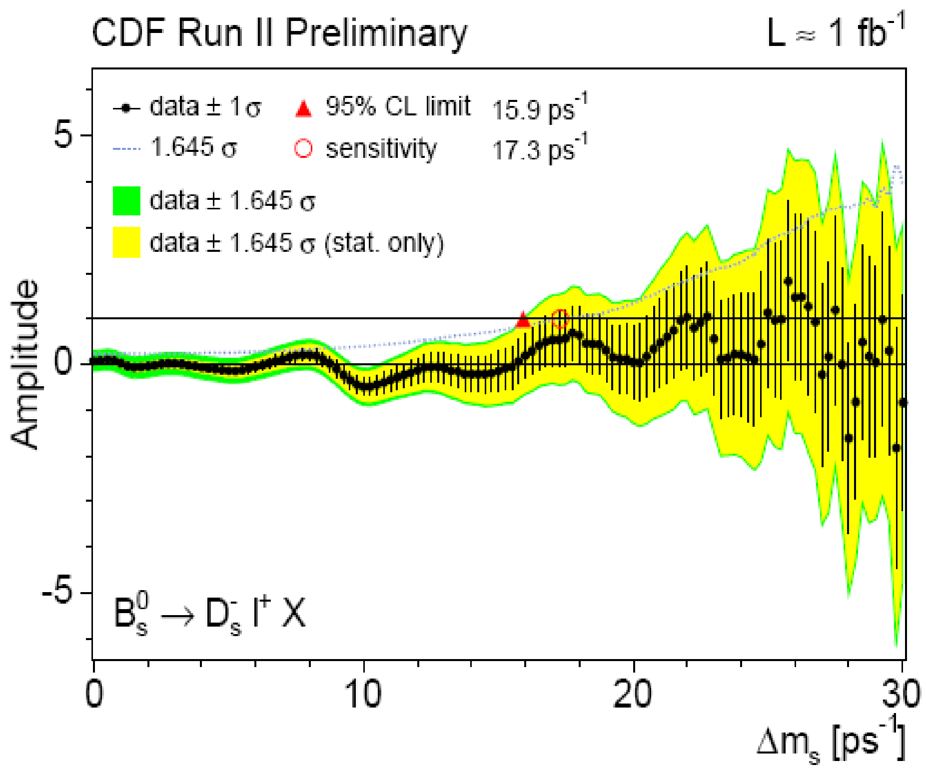
Q: How significant is this result?

Separate Samples

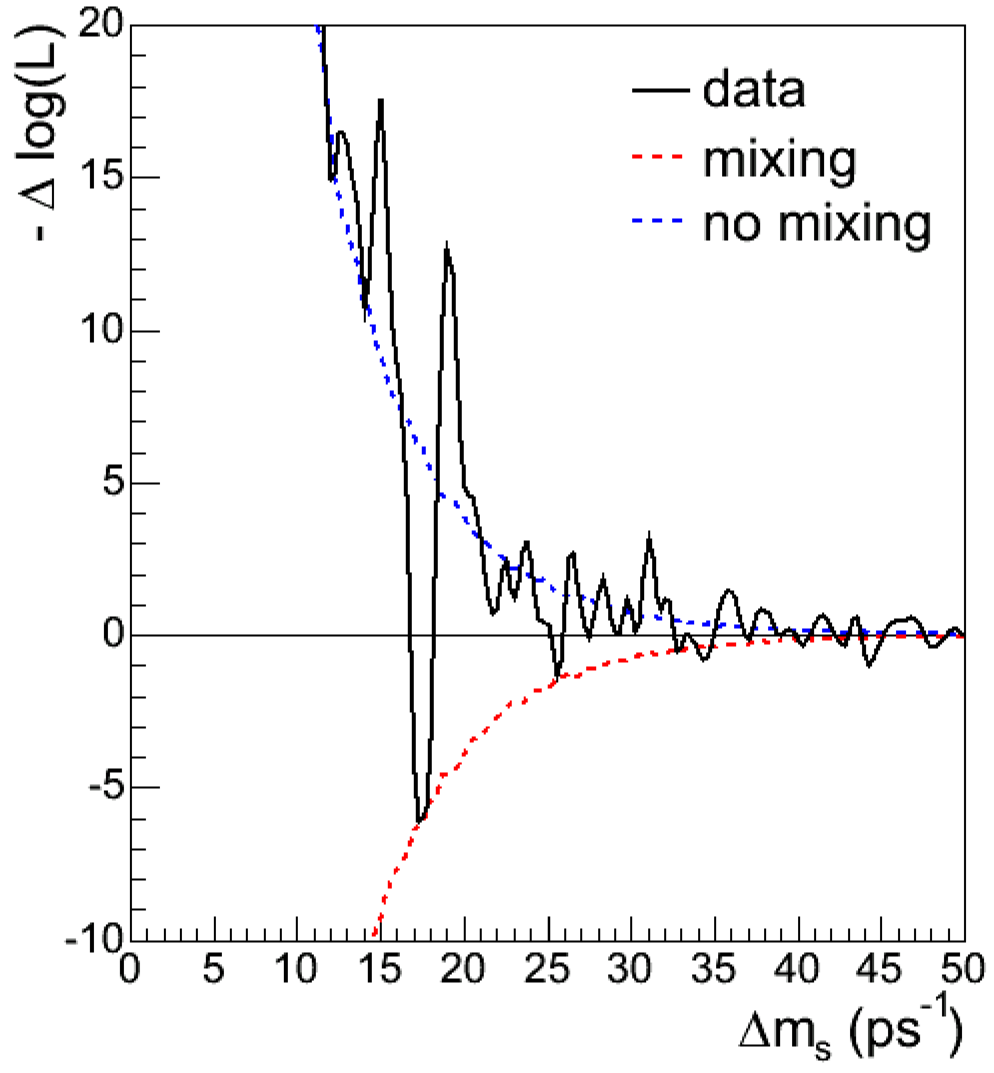
Hadronic



Semileptonic

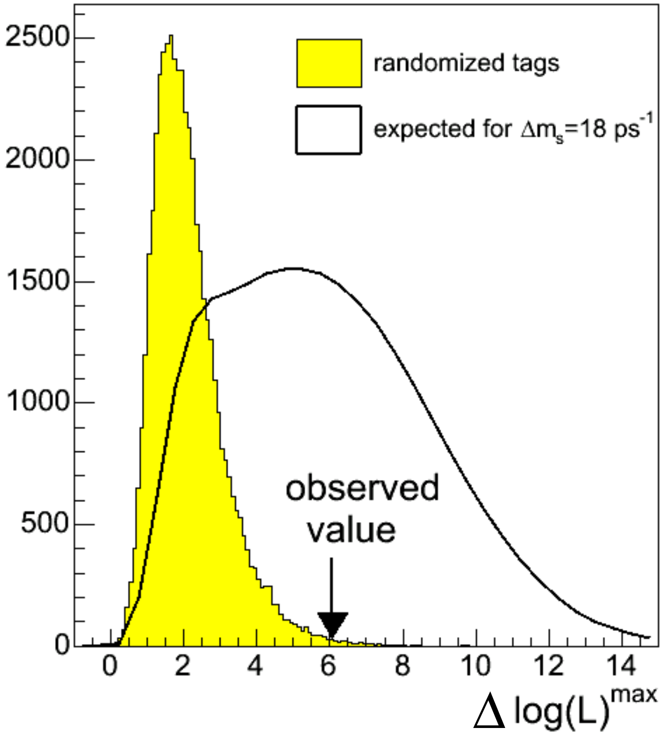


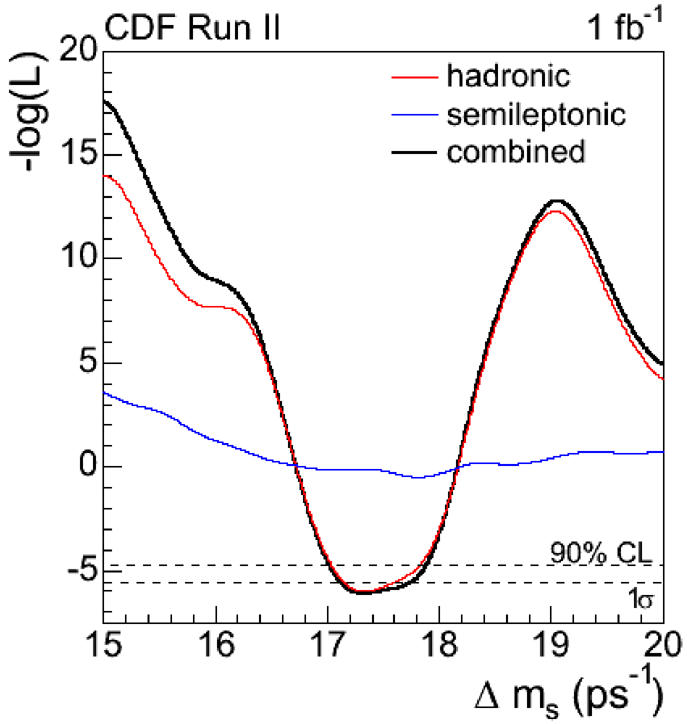
Likelihood Ratio Profile



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

Likelihood Significance





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

- probability of fake from random tags = 0.5% measure Δm_s!

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

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

- Can extract V_{ts} value

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

- compare to Belle b->sγ (hep-ex/050679):

  $|V_{td}| / |V_{ts}| = 0.199^{+0.026}$ (stat) $^{+0.018}$ (syst)

- our result: $0.208^{+0.008}_{-0.007}$ (stat + syst)

- inputs:
  - $m(B^0)/m(B_s) = 0.9832$ (PDG 2006)
  - $\xi = 1.21^{+0.40}_{-0.35}$ (Lattice 2005)
  - $\Delta m_d = 0.507 \pm 0.005$ (PDG 2006)

Conclusions

- CDF has found a signature consistent with B_s - $\overline{B}_s$ oscillations
- Probability of this being a fluctuation is 0.5%
- Presented first direct measurement of the B_s - $\overline{B}_s$ oscillation frequency:

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

$$V_{ts} / V_{td} = 0.208 + 0.008\ (stat + syst)$$

Systematic Uncertainties on Δm_s

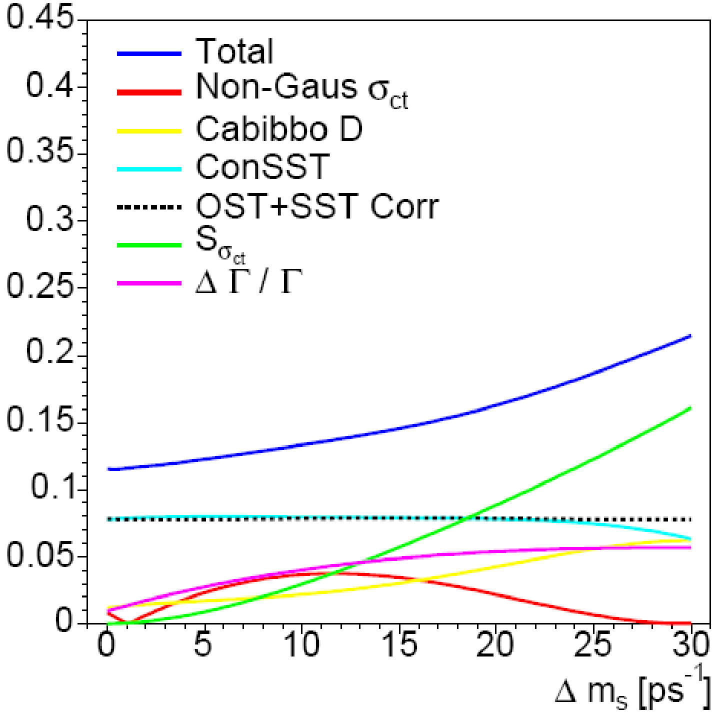
- systematic uncertainties from fit model evaluated on toy Monte Carlo
- have negligible impact
- relevant systematic unc. from lifetime scale

	Systematic Error
Fitting Model	$< 0.01 ps^{-1}$
SVX Alignment	$0.04\ ps^{-1}$
Track Fit Bias	$0.05\ ps^{-1}$
PV bias from tagging	$0.02\ ps^{-1}$
Total	$0.07\ ps^{-1}$

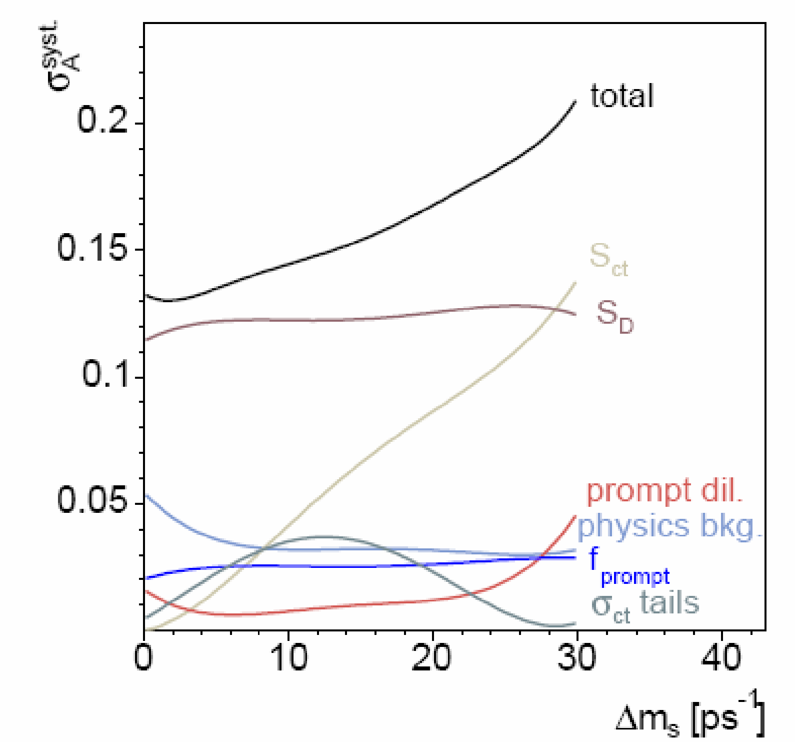
All relevant systematic uncertainties are common between hadronic and semileptonic samples

Systematic Uncertainties

Hadronic



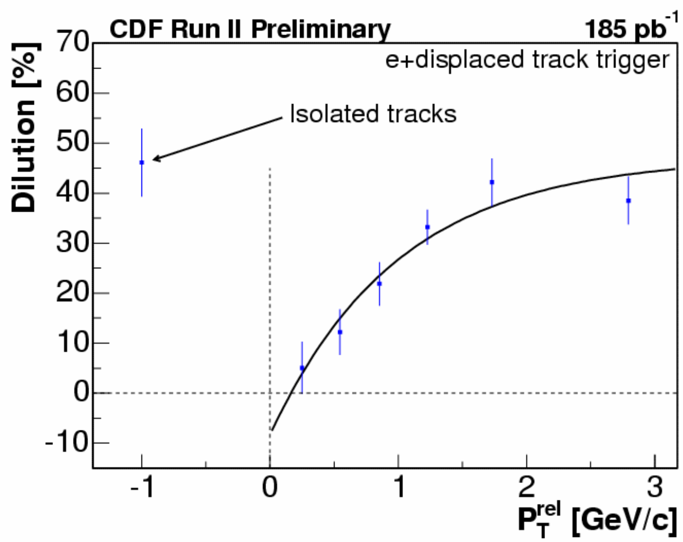
Semileptonic



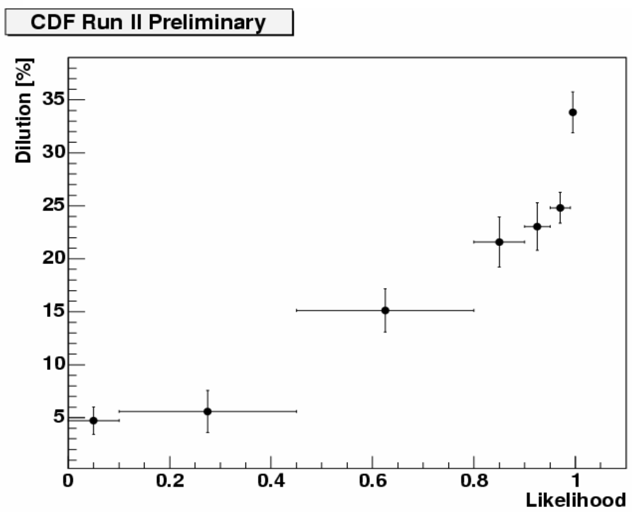
- **related to absolute value of amplitude, relevant only when setting limits**
  - **cancel in A/σ_A, folded in to confidence calculation for observation**
  - **systematic uncertainties are very small compared to statistical**

Opposite Side Taggers

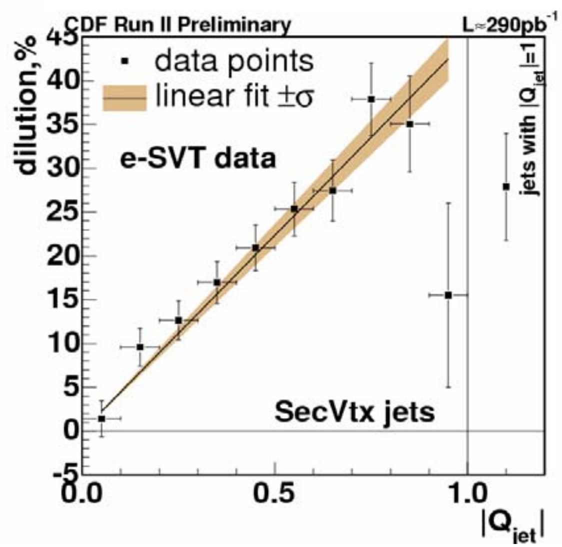
- Figure of merit is εD^2 ε = efficiency (% events tagger can be applied)
  D = dilution (% events tagger is correct)
- Performance studied in high statistics inclusive lepton+SVT trigger
  - Enables calibration of taggers
  - Can also parameterise tagging dilution as function of variables:
  - SLT: dilution parameterised as function of likelihood and p_t^{rel}
  - JQT: dilution parameterised as function of jet charge for a given jet



Soft Electron Tag



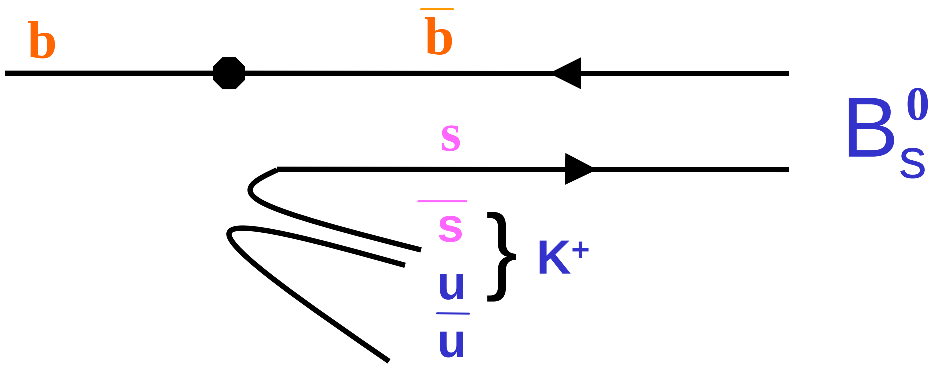
Soft Electron Tag



Jet Charge Tag

Same Side (Kaon) Tagger

- Now being used for the first time
- Principle: charge of B and K correlated

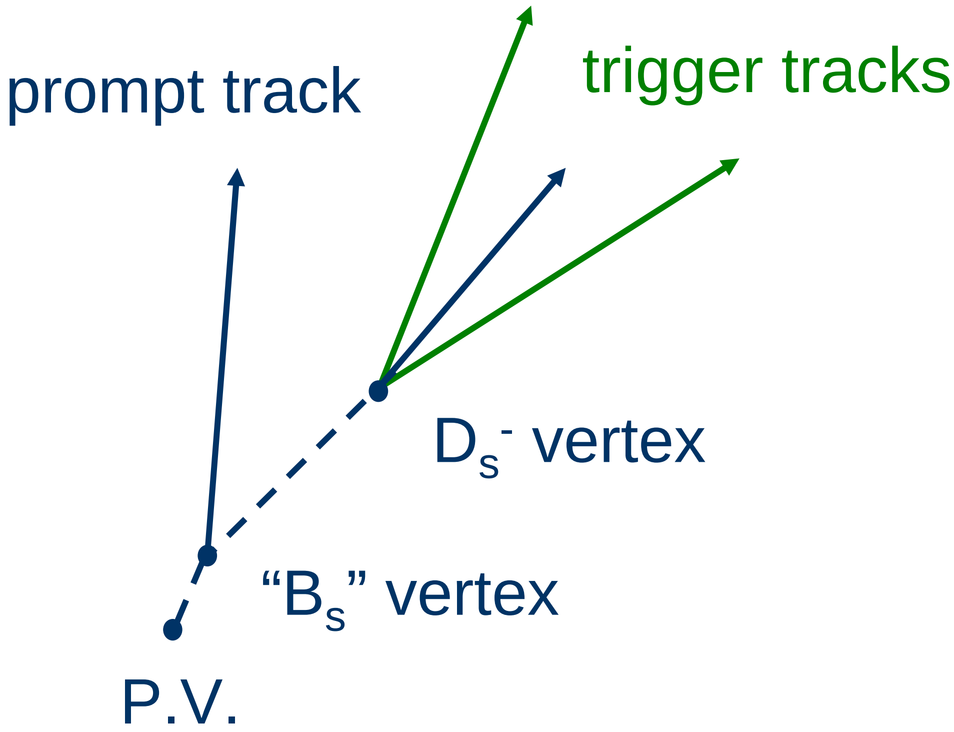


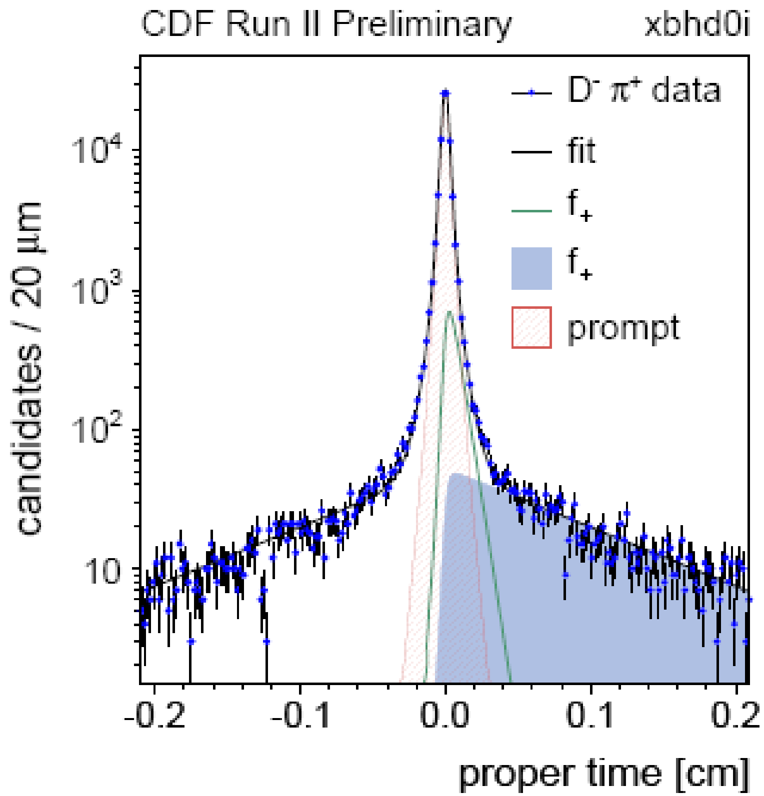
- Use TOF, dE/dx to select track
- Tagger εD^2 not measurable in data until B_s mixing frequency known

Very detailed study: (CDF Public note ****)

- If MC reproduces distributions well for B^0,B^+, then rely on it to extract tagger power in B_s (with appropriate systematic errors)
- High statistics B^0 and B^+ samples in which to make comparisons
- Systematics: production mechanism, fragmentation model, particle fraction around B, PID simulation, pile-up events

Calibrating the Proper Time Resolution

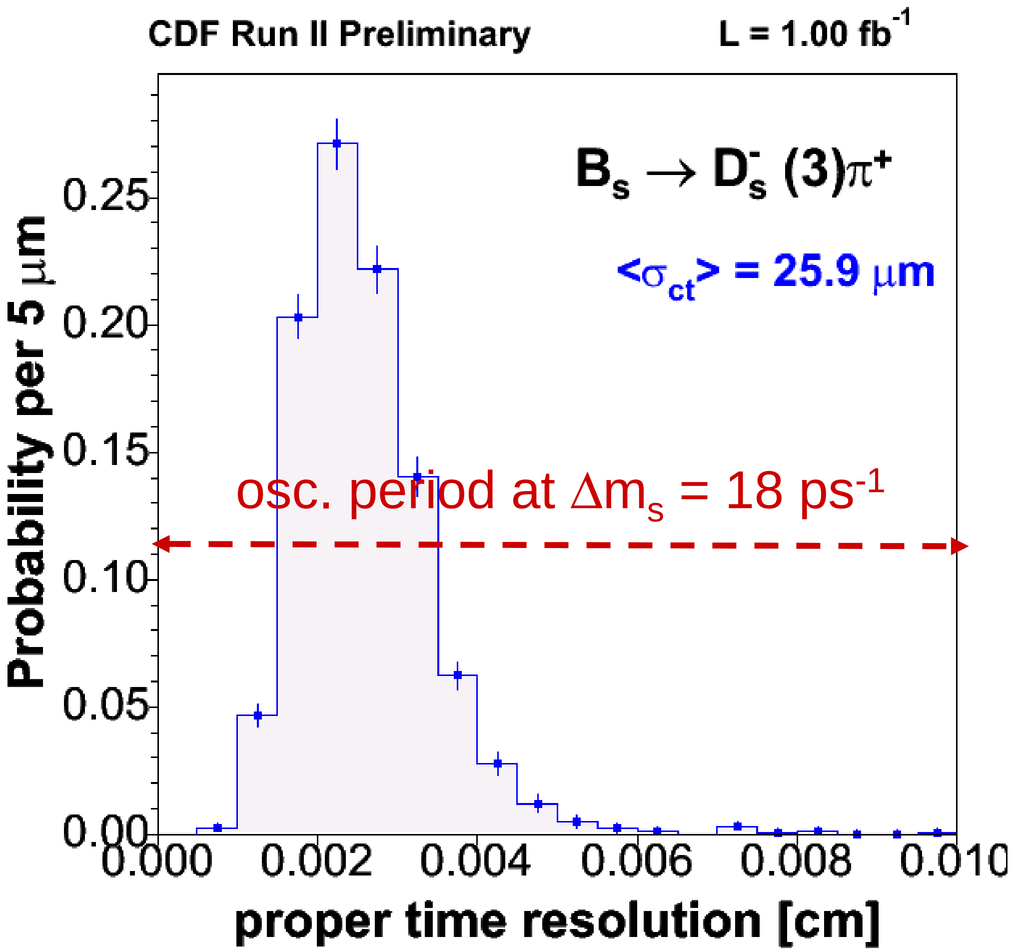




- utilize large prompt charm cross section
- construct "B_s-like" topologies of prompt D_s^- + prompt track

Proper Time Resolution

- utilize large prompt charm cross section
- construct "B_s-like" topologies of prompt D_s^- + prompt track
- calibrate ct resolution by fitting for "lifetime" of "B_s-like" objects



- event by event determination of primary vertex position used
- average uncertainty

  ~ 26 μm
- this information is used per

semileptonic:

$$\sigma_{ct}^0 \approx 59\mu m$$

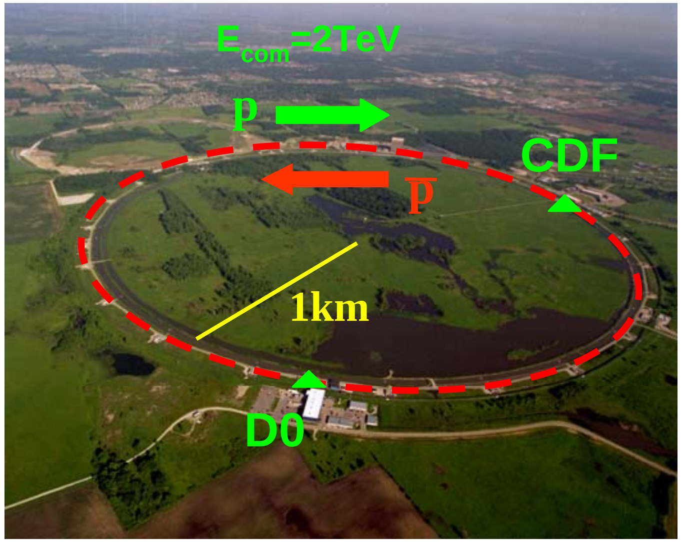
$$\sigma_p / p \approx 15\%$$

hadronic:

$$\sigma_{ct}^0 \approx 30\mu m$$

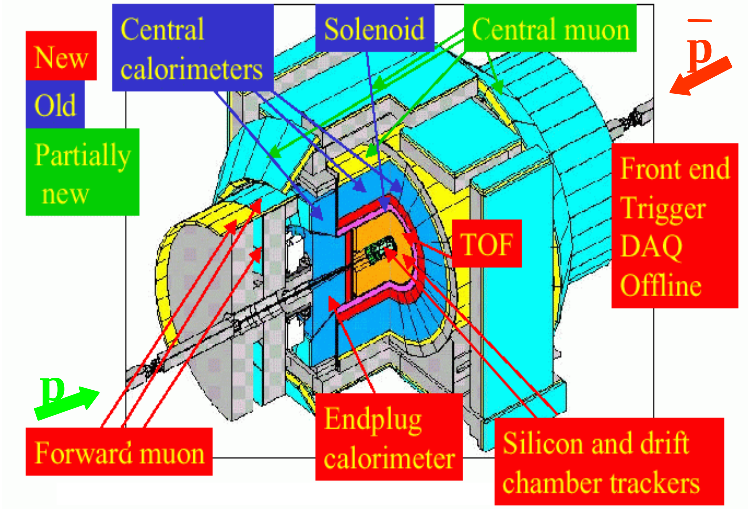
$$\sigma_p / p \approx 0\%$$

The Tevatron and CDF



Fermilab, Chicago

Currently the world's highest energy collider

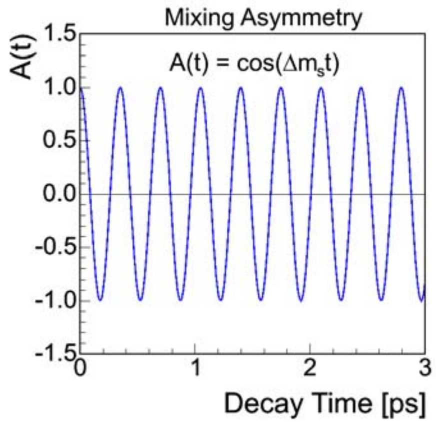


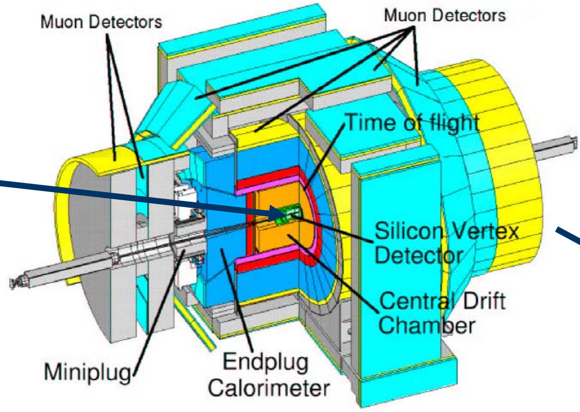
CDF Run I: 1992-1996 L= $0.1fb^{-1}$
Major Upgrades 1996-2001
CDF Run II: 2001-2006 L= $1fb^{-1}$

$p\bar{p}$ collisions can produce a wide spectrum of B hadrons in a challenging environment

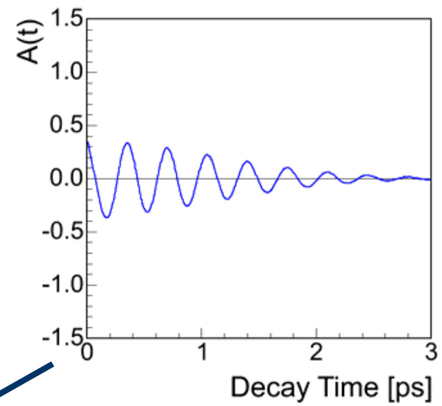
B_s cannot be produced at the B factories since Centre of Mass energy is below threshold

Real Measurement Layout





Data



momentum resolution
displacement resolution
flavor tagging power

scan for signal:

$A(\Delta m_s=[1 \ldots 30]\ ps^{-1}) = ?$

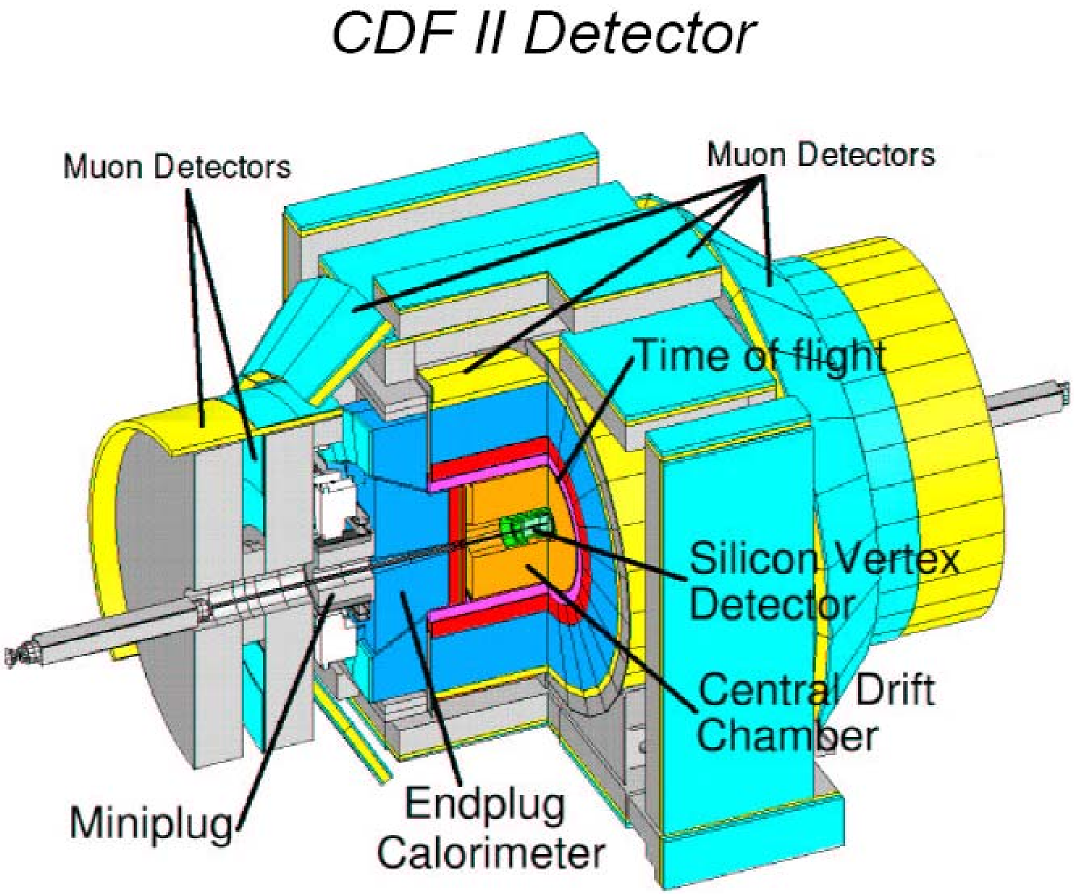
Unbinned Likelihood Fitter

measure frequency:

$\Delta\ m_s = ?$

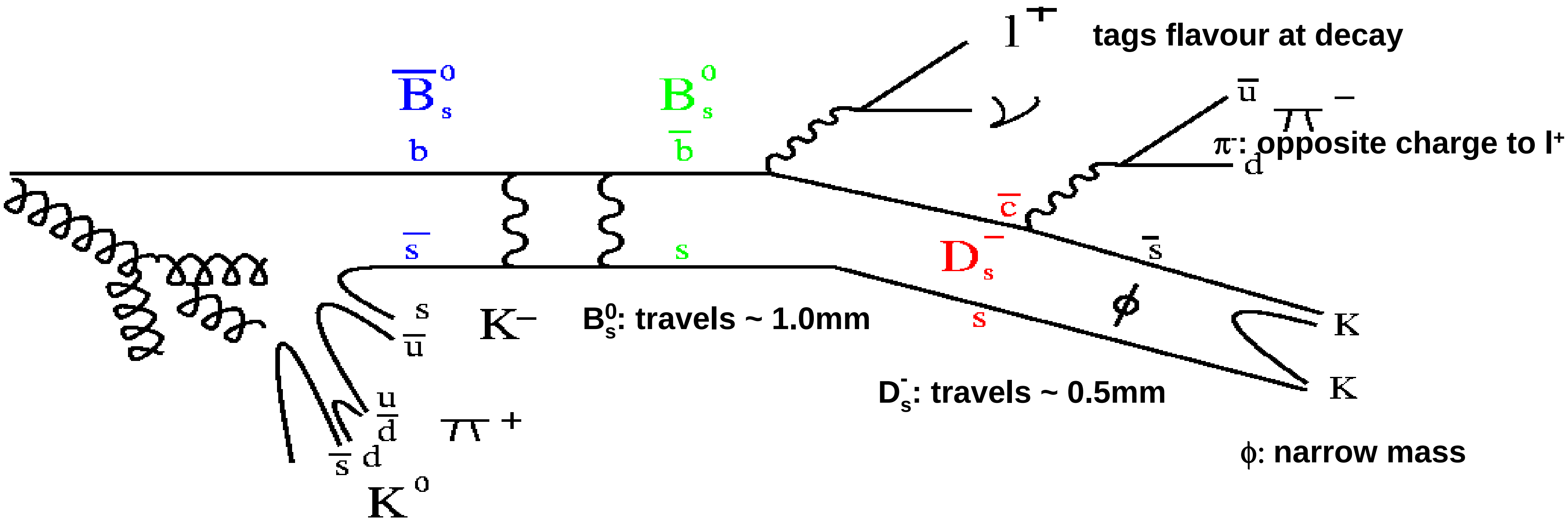
The CDFII Detector

- multi-purpose detector
- excellent momentum resolution $\sigma(p)/p<0.1\%$



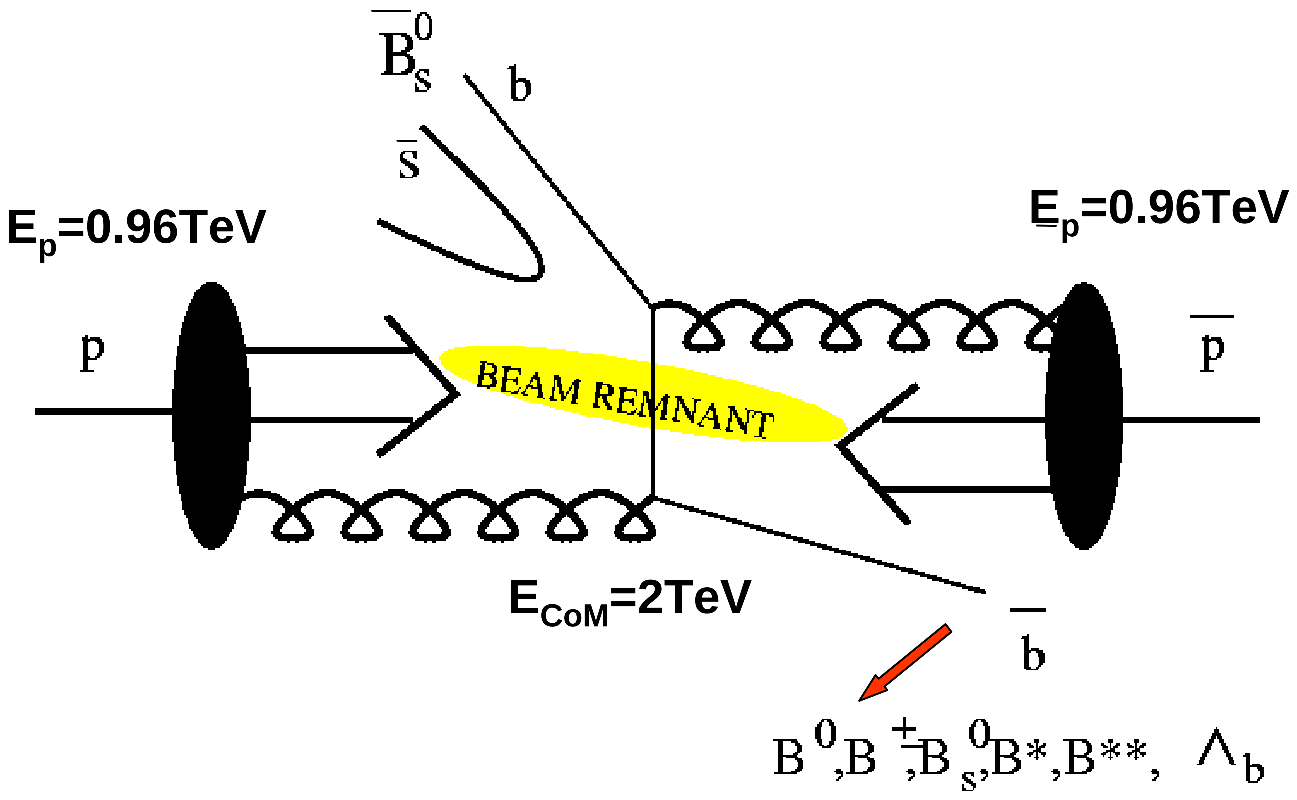
- Yield:
  - SVT based triggers
- Tagging power:

$B_s^0 - \overline{B}_s^0$ System

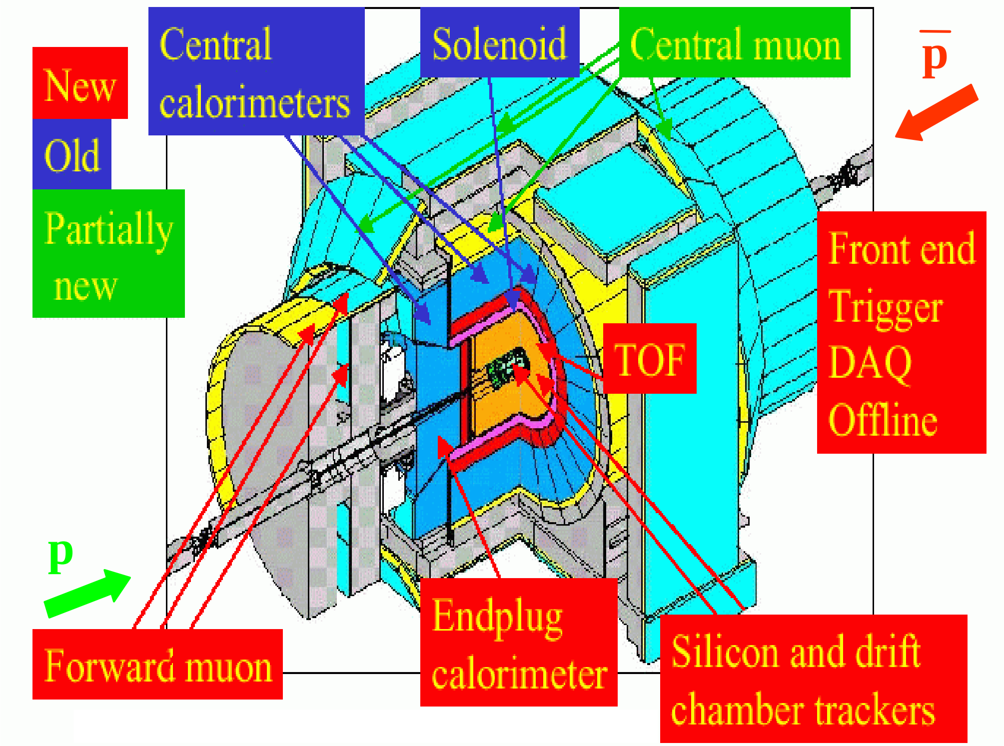


'neighbour' tags flavour at production

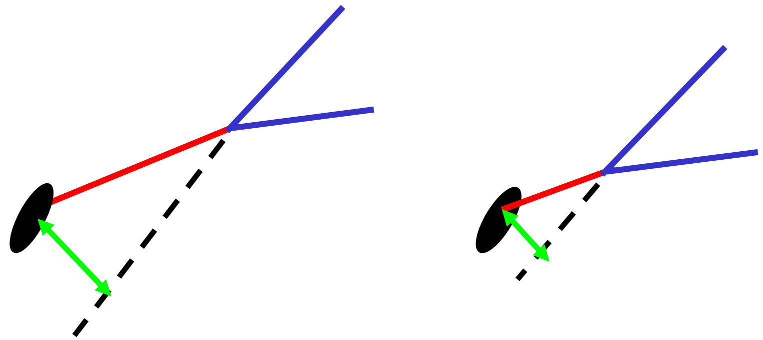
b Hadron Production at the Tevatron



The CDF Detector and Triggers



- $\sigma(b\bar{b}) << \sigma(p\bar{p})$ $\Rightarrow$ B events are selected with specialised triggers
- Displaced vertex trigger exploits long lifetime of B's
- Yields per pb^{-1} are 3x Run I



Semileptonic Decay Fit Model

Unbinned maximum likelihood fit to cτ(B)

- **Background is parameterised by delta function and positive exp convoluted with Gaussian resolution:**

$$F_{bkg} = \left[(1 - f_+)\delta(t - \Delta_D) + \frac{f_+}{\tau_+} \exp\left(\frac{\Delta_E - t}{\tau_+} \right) \right] \otimes G(t, \sigma_G)$$

Free parameters: Δ_D Δ_E λ_+ f_+ σ_G

- **Signal: exp convoluted with Gaussian resolution, K factor distribution, P(K), and bias function, ε**

$$F_{sig} = N \frac{K}{c\tau} \exp\left(\frac{-Kt}{\tau} \right) \varepsilon(Kt) \otimes G(t, s\sigma_i) \otimes P(K)$$

- **Maximum likelihood function:**

$$L = \prod_{i}^{N_{sig}} \left[(1 - f_{bkg}) F_{sig}^{i} + f_{bkg} F_{bkg}^{i} \right] \cdot \prod_{j}^{N_{bkg}} F_{bkg}^{j}$$

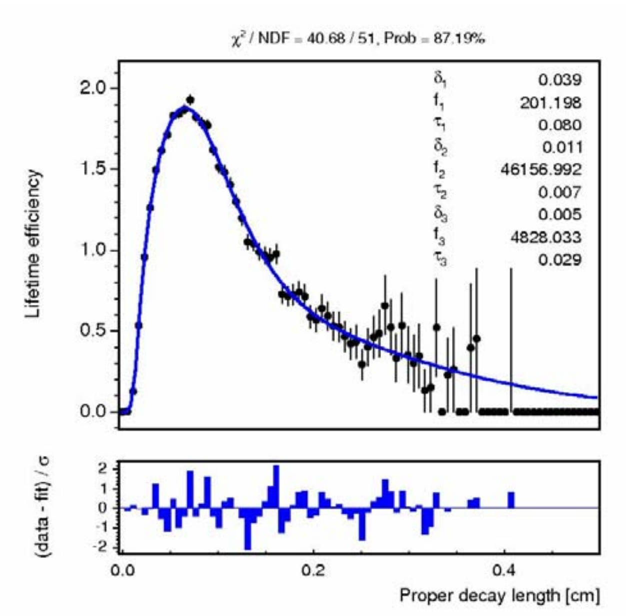
2) Time of Decay

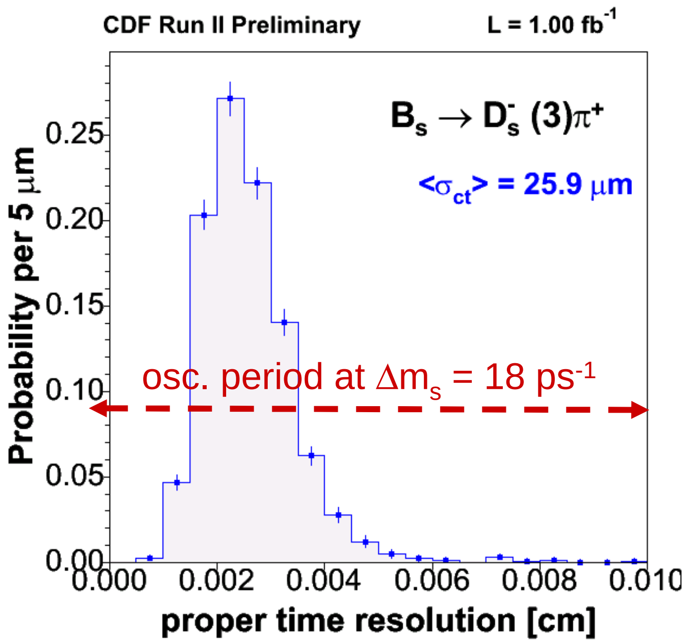
- **Reconstruct decay length by vertexing**
- **Measure p_T of decay products**

$$ct = \frac{L}{\beta\gamma} = L\frac{m(B)}{p(B)} = \frac{L_{xy}\, m(B)}{p_T\,(lD)} K$$

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

•Displaced Track Trigger imposes bias $\Rightarrow$ correct with efficiency function





$$\sigma_{ct}^0 \approx 59\mu m$$
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Crucial: Vertex resolution

(Silicon Vertex Detector, in particular Layer00 very close to beampipe)

$B_s^0 - \overline{B}_s^0$ System

Want to understand: - Average lifetime, Γ $= \frac{\Gamma_H + \Gamma_L}{2}$

- Lifetime difference, $\Delta\Gamma$ $= \Gamma_H - \Gamma_L$

- Rate of mixing, Δm $= m_H - m_L$

Current Status:	**Experiment**	**Theory**
$\Delta\Gamma/\Gamma$ (%)	**<0.29**	**≈0.15**
Δm (ps^{-1})	**>14.1**	**≈20**