Physics at the Tevatron

Lecture III

Beate Heinemann

University of California, Berkeley

Lawrence Berkeley National Laboratory

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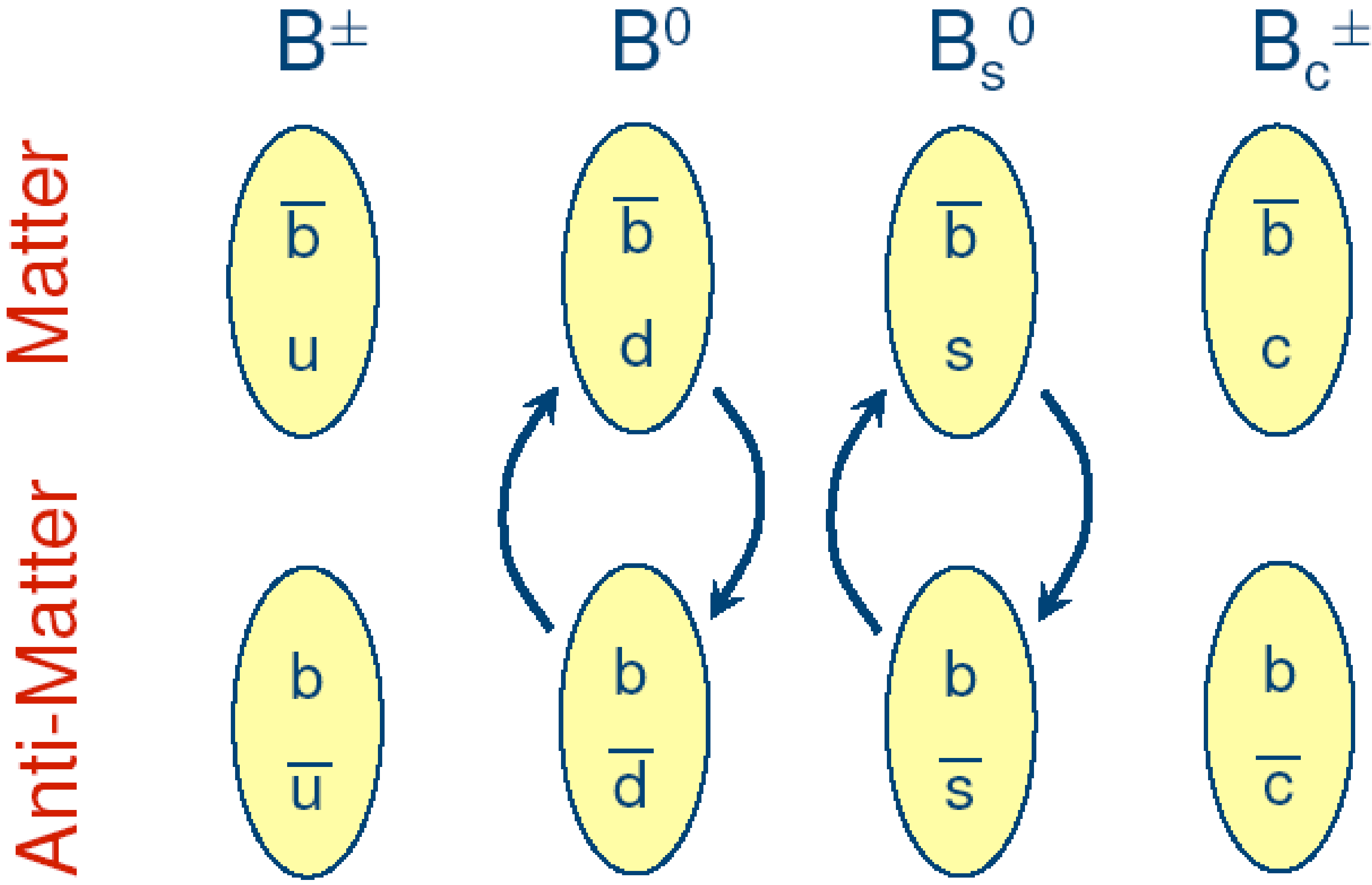
Outline

- Lecture I:
  - The Tevatron, CDF and DØ
  - Production Cross Section Measurements
- Lecture II:
  - The W boson mass, the Top Quark and the Higgs Boson
    - Lepton calibration, jet energy scale and b-tagging
- Lecture III
  - Lifetimes, B_s^0 and D^0 mixing, and $B_s \rightarrow \mu\mu$ rare decay
    - Vertex resolution and particle identification
- Lecture IV
  - Supersymmetry and High Mass Resonances
    - Missing E_T and background estimation strategies

All lectures available at:

http://www-atlas.lbl.gov/~heinemann/homepage/publictalk.html

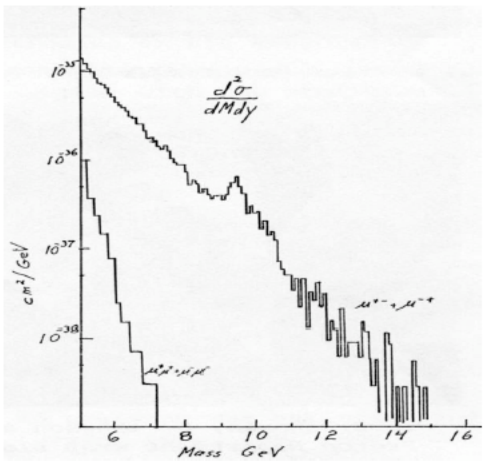
B mesons



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

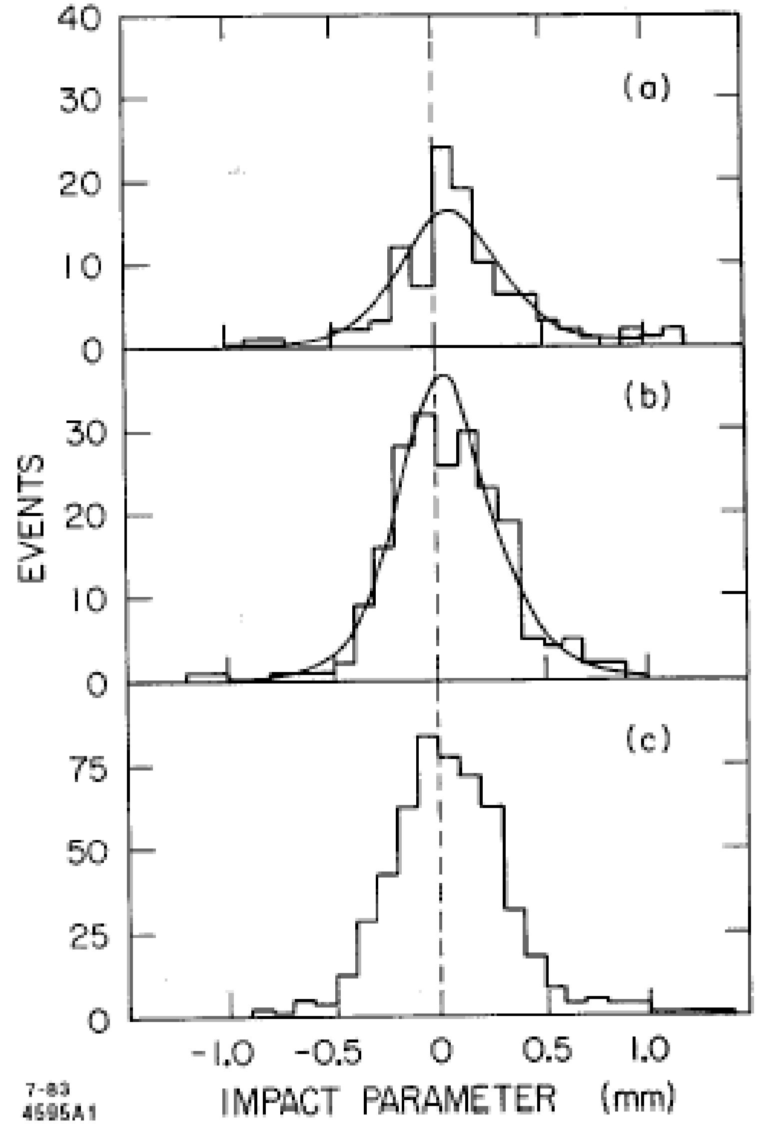
History: B Mass and Lifetime

- Upsilon observation 1978
  - 3rd generation exists
  - Mass about 5 GeV



- Lifetime observation 1983:
  - Lifetime = 1.5 ps^{-1}
  - Enables experimental techniques to identify B's

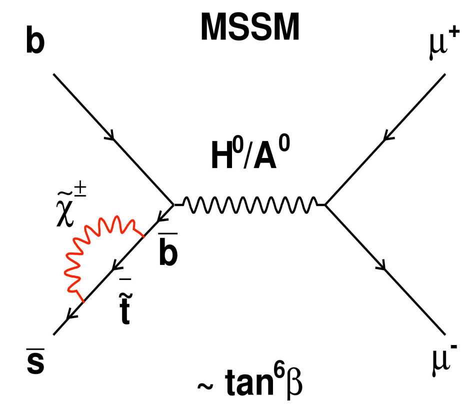
Phys.Rev.Lett.51:1316,1983

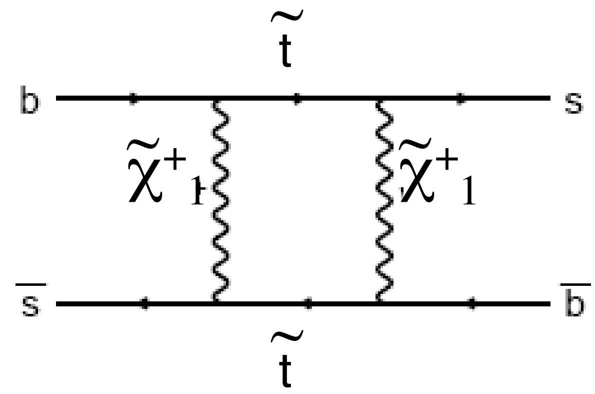


Why B Physics?

- New physics could contribute to B-decays
  - SUSY particles can contribute in addition to SM particles
  - Z' bosons could also alter the effective couplings

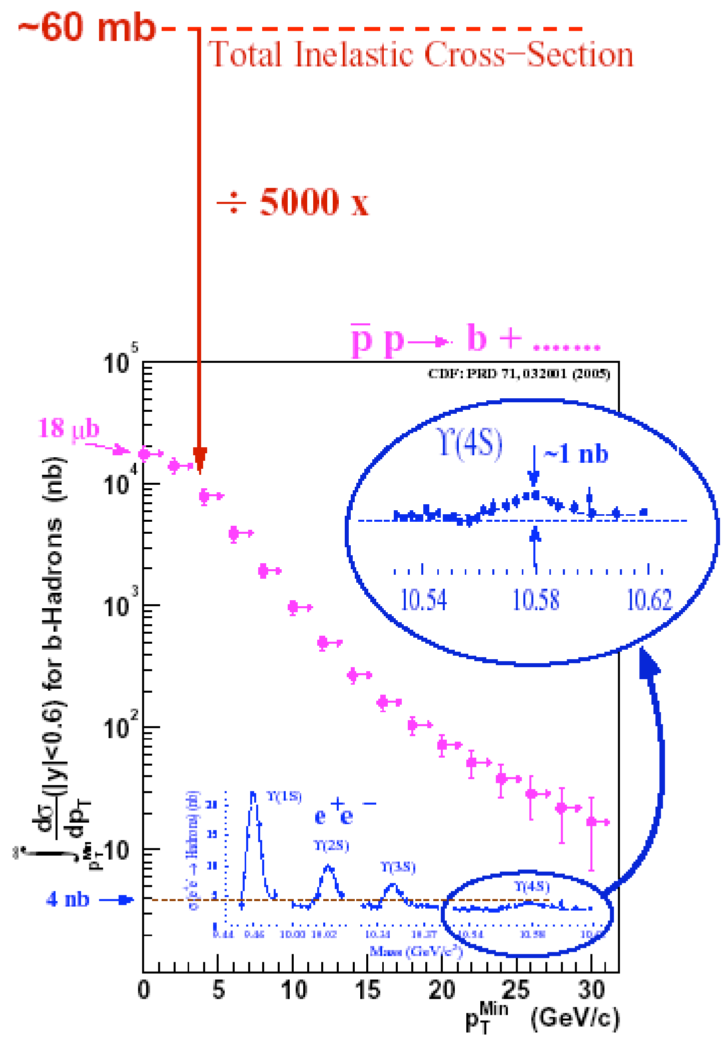
- Complementary to direct searches



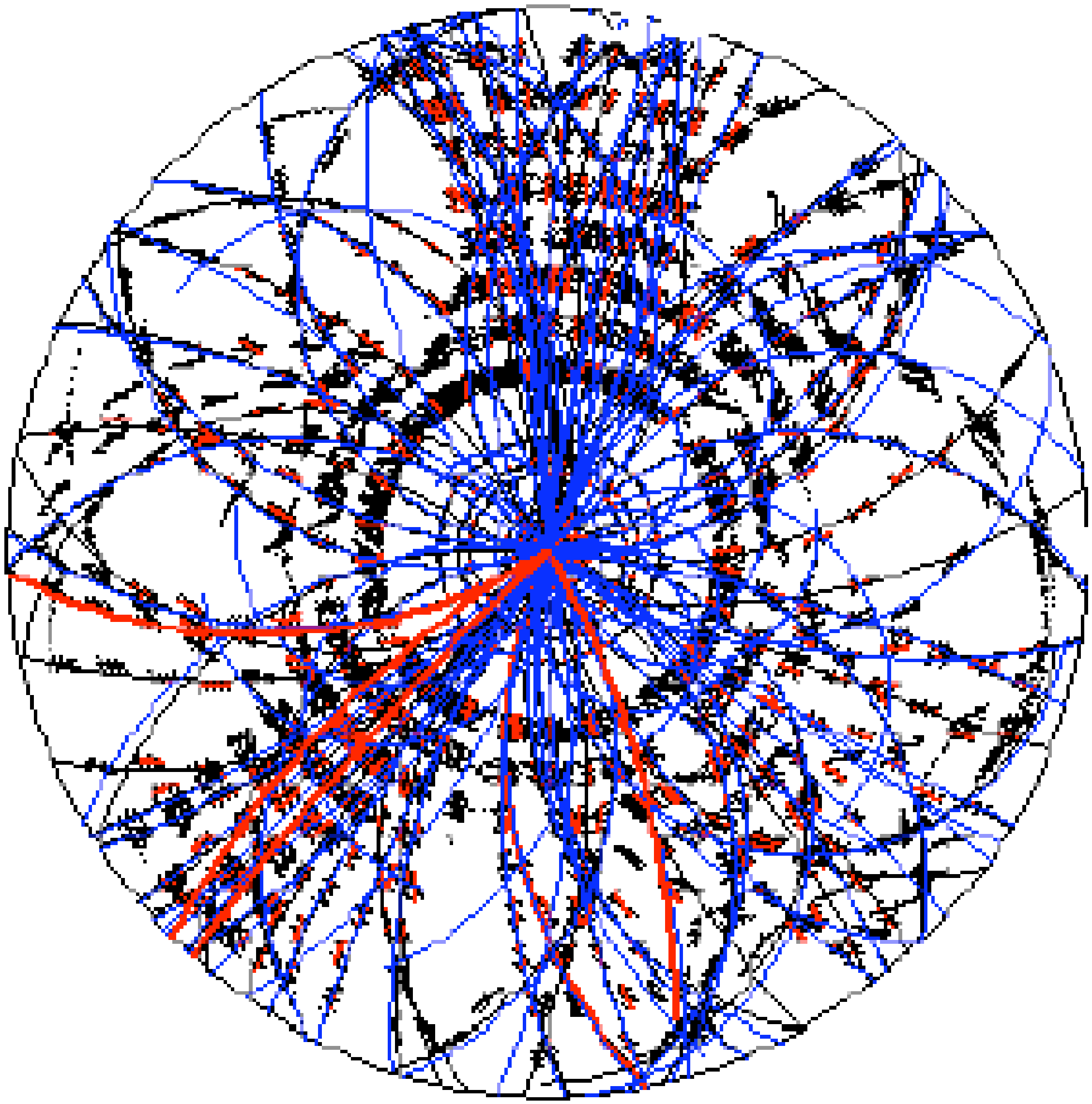


B Physics at Hadron Colliders

- Pro's
  - Large cross section: 18 μb
    - 1000 times larger than at B-factories
  - Produce all B-hadron species:
    - B^0, B_s^0, Λ_b, B_c,…
- Con's
  - No reconstruction of neutrals (photons, π^0's)
  - difficult to trigger, bandwidth restrictions
  - Messy environment

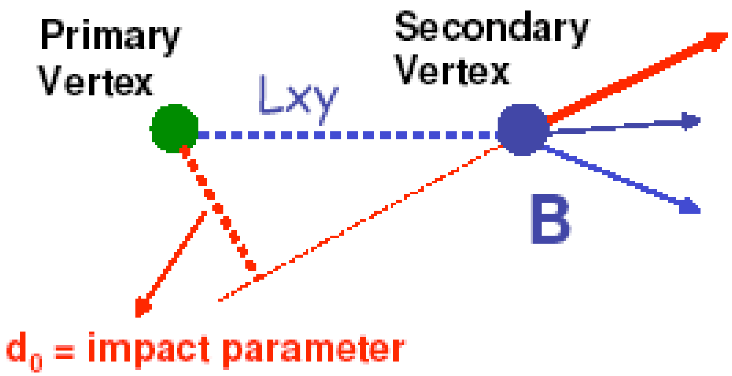


A typical B-decay event



The SVT Trigger at CDF

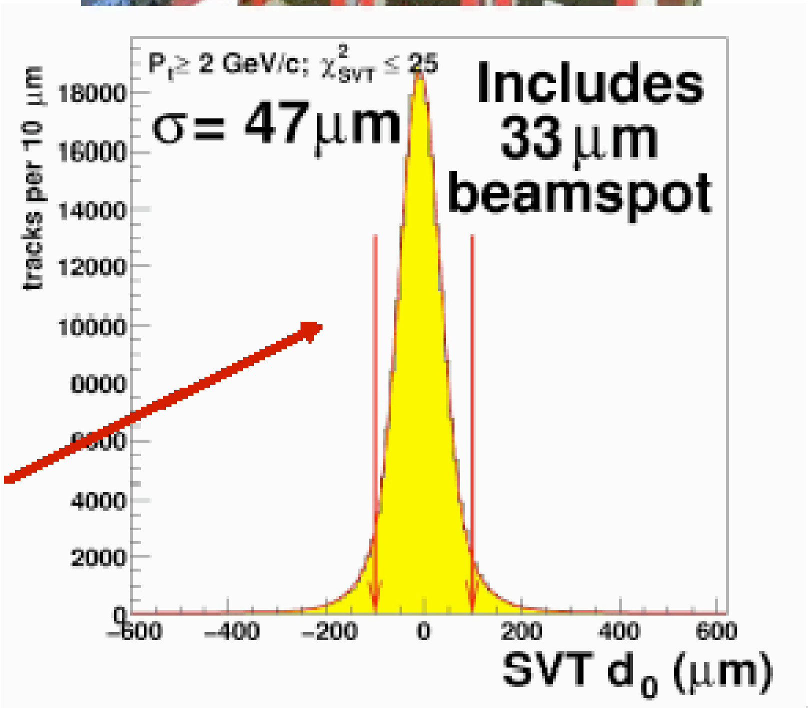
- trigger $B_s \to D_s^- \pi$, $B_s \to D_s^- l^+$



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

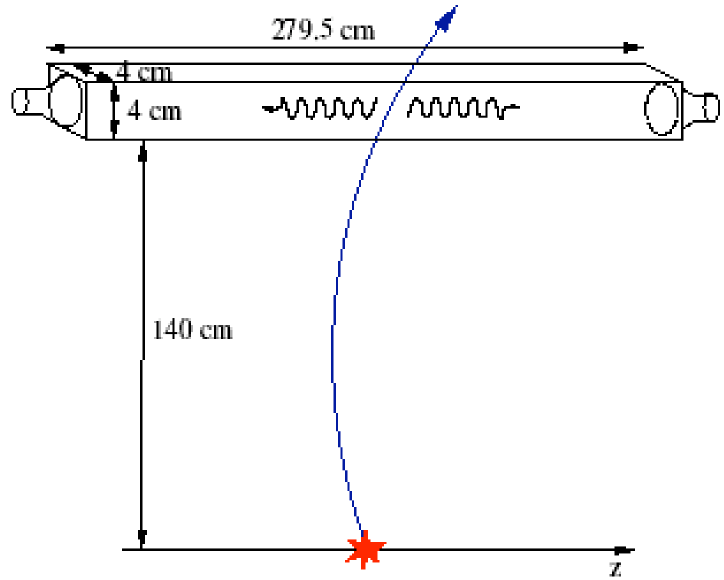
(p$_T$ > 2 GeV/c, 120 μm<|d$_0$|<1mm)

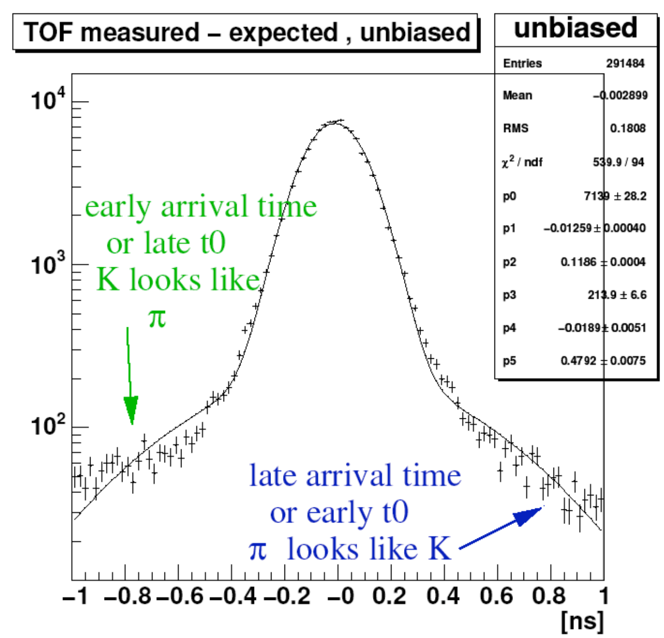
- requires precision tracking in SVX



Particle Identification

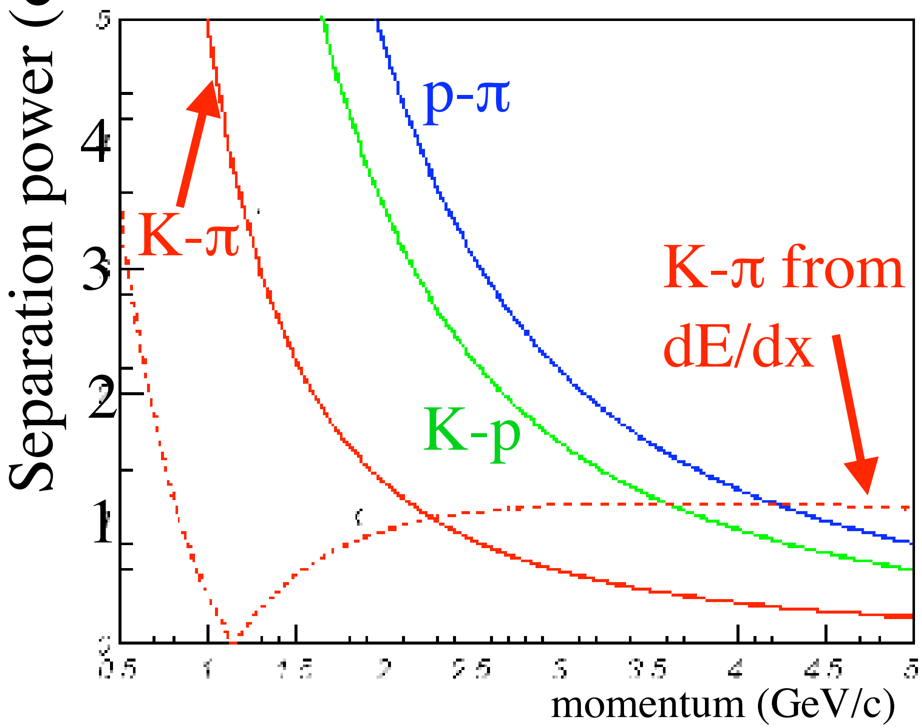
- TOF detector measures time of arrival at r=140cm
  - Resolution 119 ps
  - Time depends on particle mass:
    - For M>0: v≠c
- Measure pulse height in COT, dE/dx:
  - Ionization depends on particle species

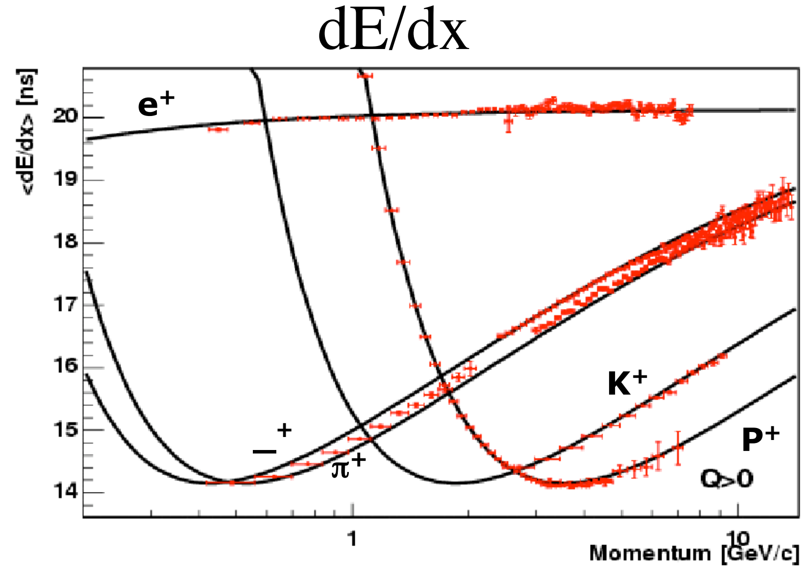


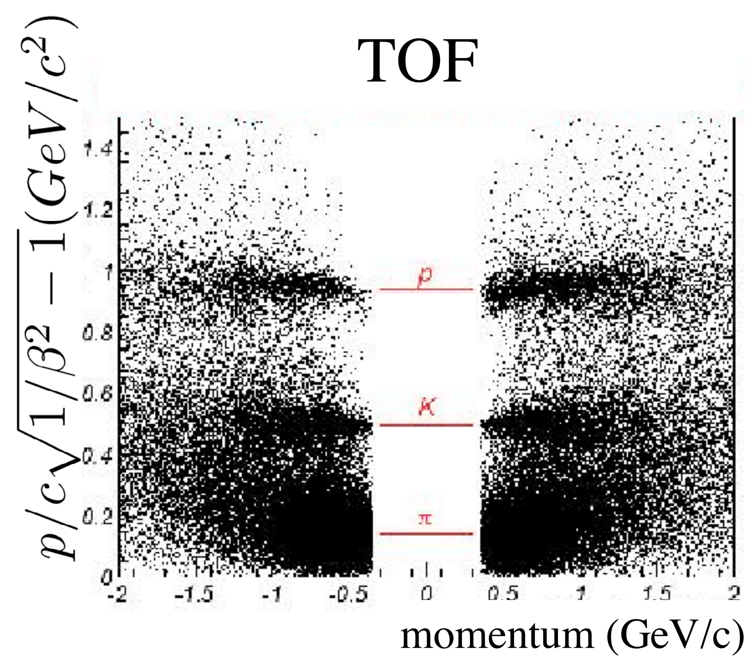


Particle Identification Calibration

- Separate kaons from pions
  - dE/dx gives 1σ separation for p>2 GeV
  - TOF gives better separation at low p
- Used for:
  - Kaon/pion separation
  - Electron tagging

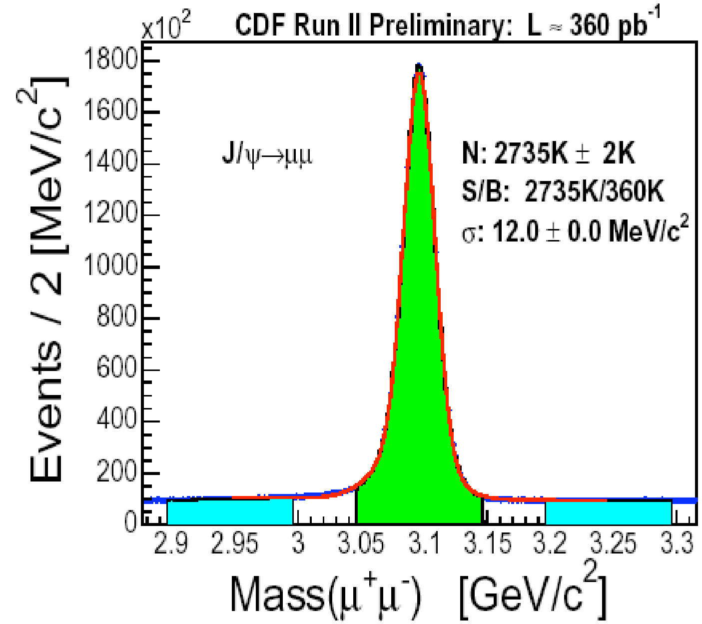


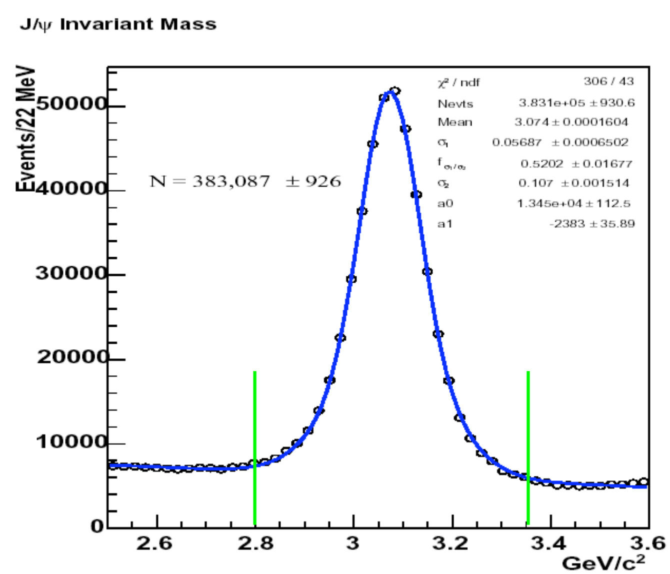




J/Psi signals

- Superb calibration signal
- Yields:
  - CDF 2.7M / 360 pb^{-1}
  - DØ: 0.4M / 250 pb^{-1}
- Mass resolution
  - CDF: 12 MeV
  - DØ: 60 MeV
- Used to calibrate:
  - Magnetic field
  - Detector material
  - Momentum resolution
  - Hadron calorimeter



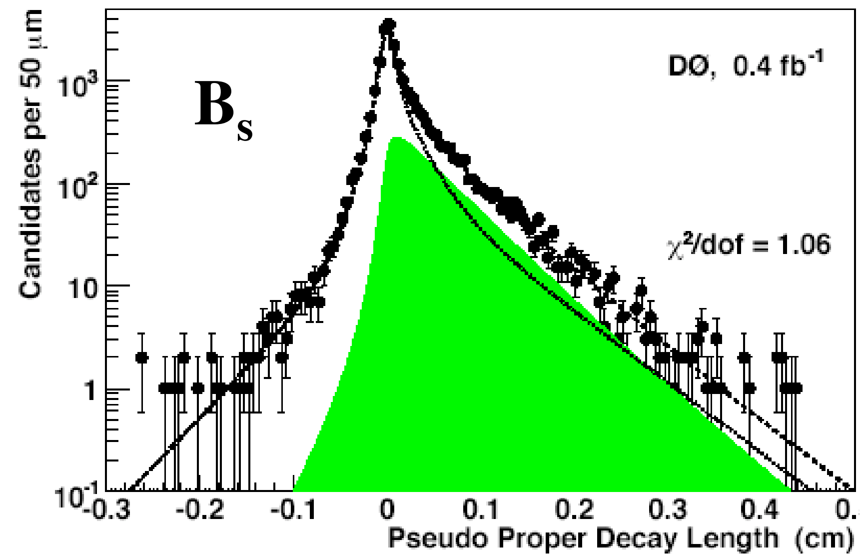


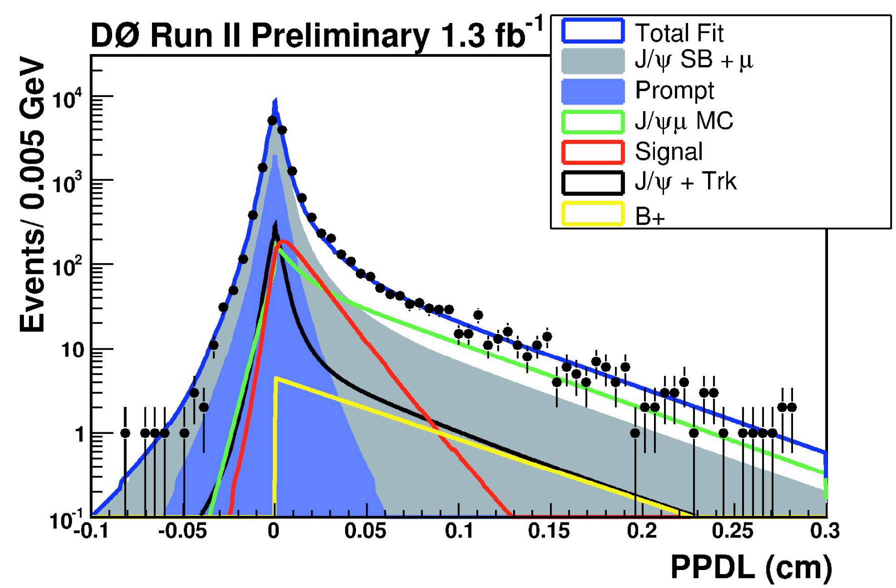
Lifetime Measurements: B_s^0, Λ_b, B_c

- Measure lifetimes of many b hadrons:

$$\lambda_B = \frac{L_{xy}}{(\beta\gamma)_T^B} = L_{xy}\frac{cM_B}{p_T}.$$

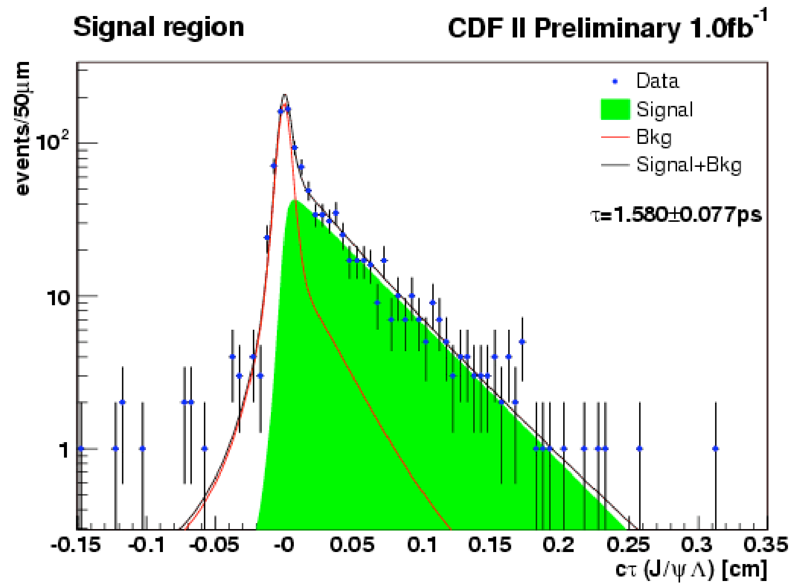
- Why?
  - Tests theoretical predictions:
    - Electroweak and strong sector play role
  - Demonstrates understanding of vertex resolution/detector
    - Important for both low and high P_T physics programme

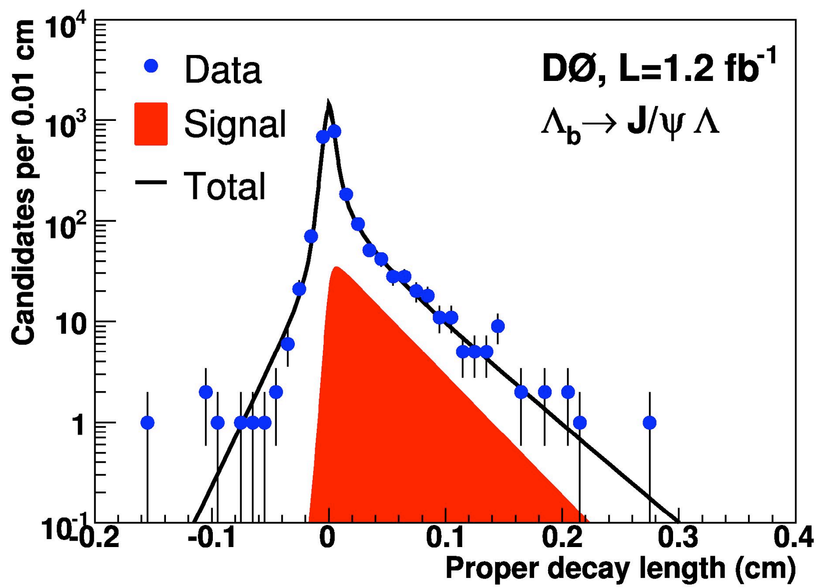




Λ_b Lifetime

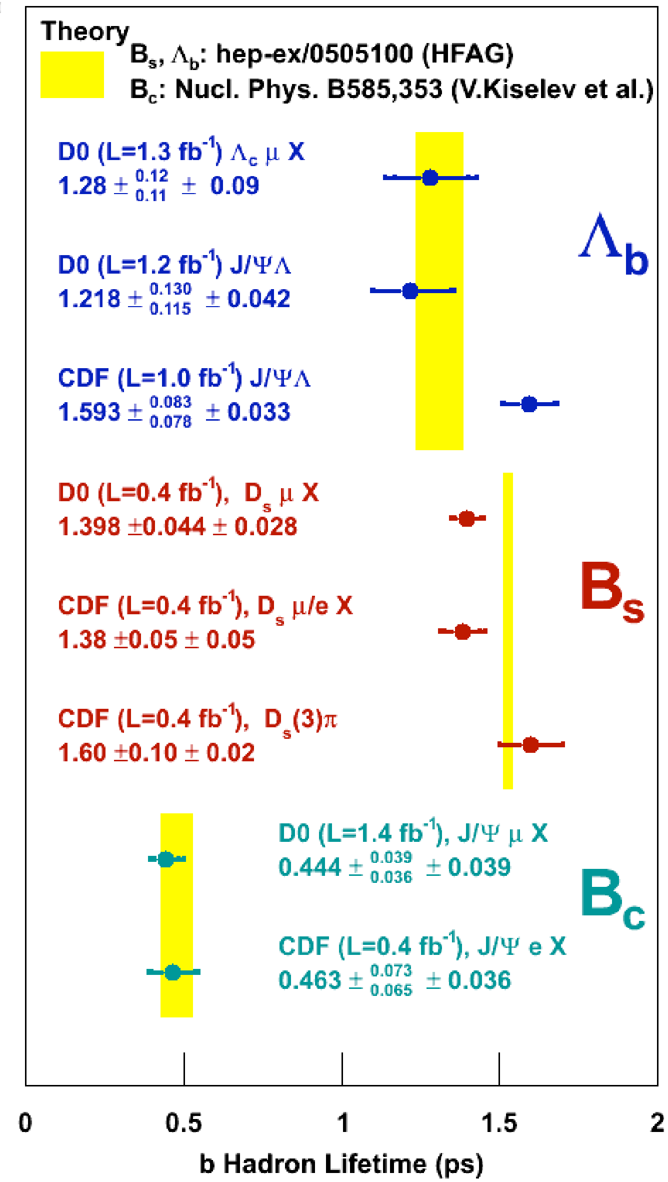
- Standing puzzle at LEP
  - Why is the lifetime so much shorter than that of the other B mesons
  - Measurement were mostly made in semileptonic decays due to low statistics
- New at Tevatron
  - Measurements in fully hadronic decay modes
- Are we missing anything in semileptonic decays
  - Other than the neutrino???





Summary of Lifetimes

- Measurements of similar precision as theory and/or world average
- Outstanding questions
  - Is B_s lifetime shorter than B_d lifetime?
  - Is Λ_b lifetime really shorter?
    - 2.3σ difference between CDF and DØ
- Will be answered with increasing data samples



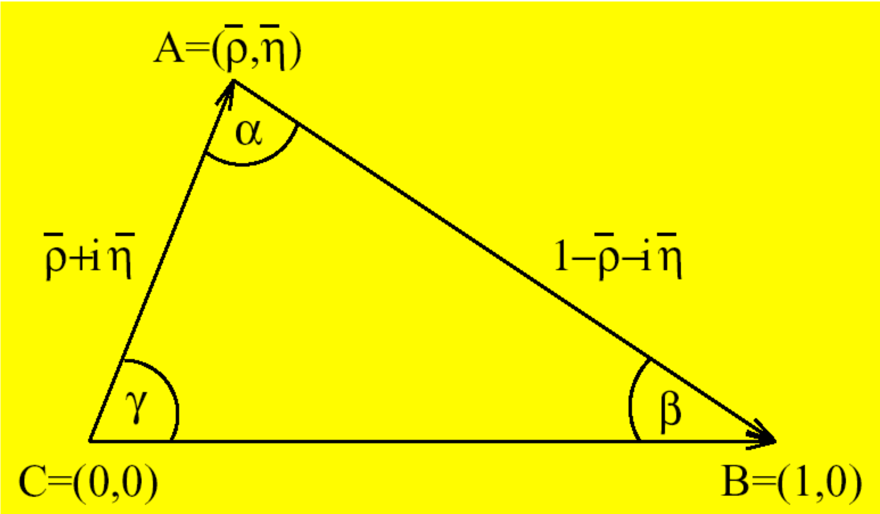
B_s mixing

Cabibbo-Kobayashi-Maskawa Matrix

CKM Matrix Wolfenstein parameterization

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

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



- Is this 3x3 matrix unitary?
  - 4th generation quarks?
  - New forces? E.g. SUSY?
- Measure each side and each angle:
  - Do all measurements cross at one point?

B Mixing

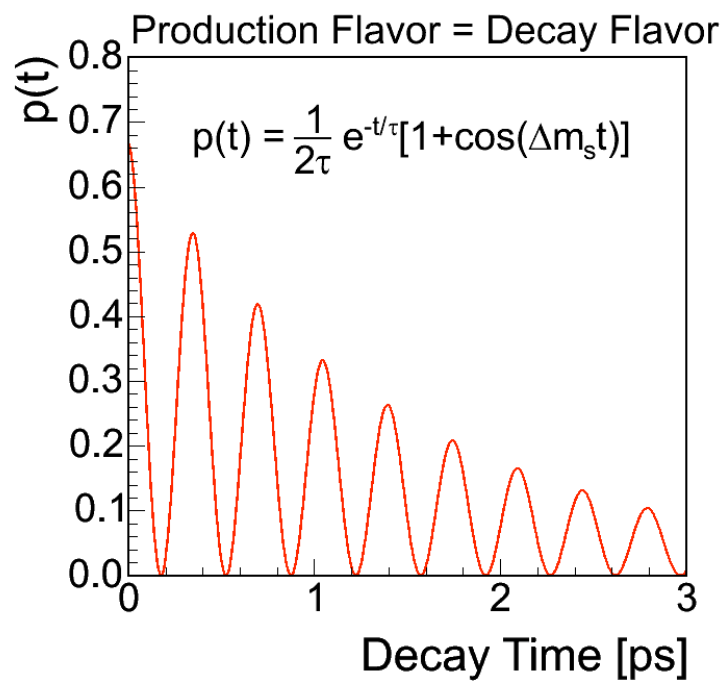
- Neutral B Meson system

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

- Mass eigenstates are mixture of CP eigenstates:

$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle$$
$$|B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$$

with $|p|^2 + |q|^2 = 1$

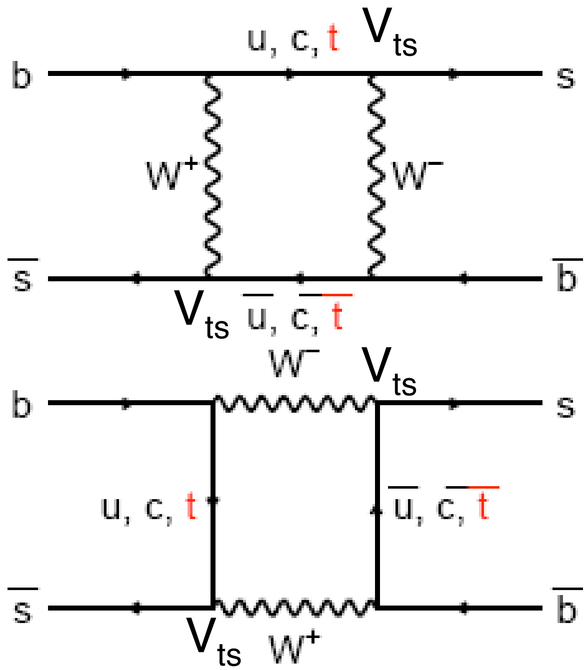


- B_H and B_L may have different mass and lifetime
  - $\Delta m = M_H - M_L$ (>0 by definition)
  - $\Delta\Gamma = \Gamma_H - \Gamma_L$ where $\Gamma = 1/\tau$

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

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

B_s mixing and the CKM Matrix



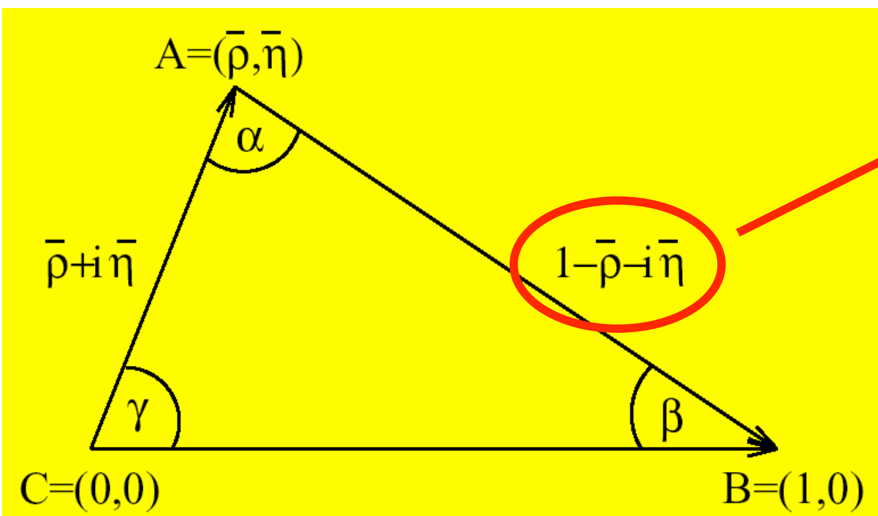
Ratio of frequencies for B^0 and B_s

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

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

(hep/lat-0510113)

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



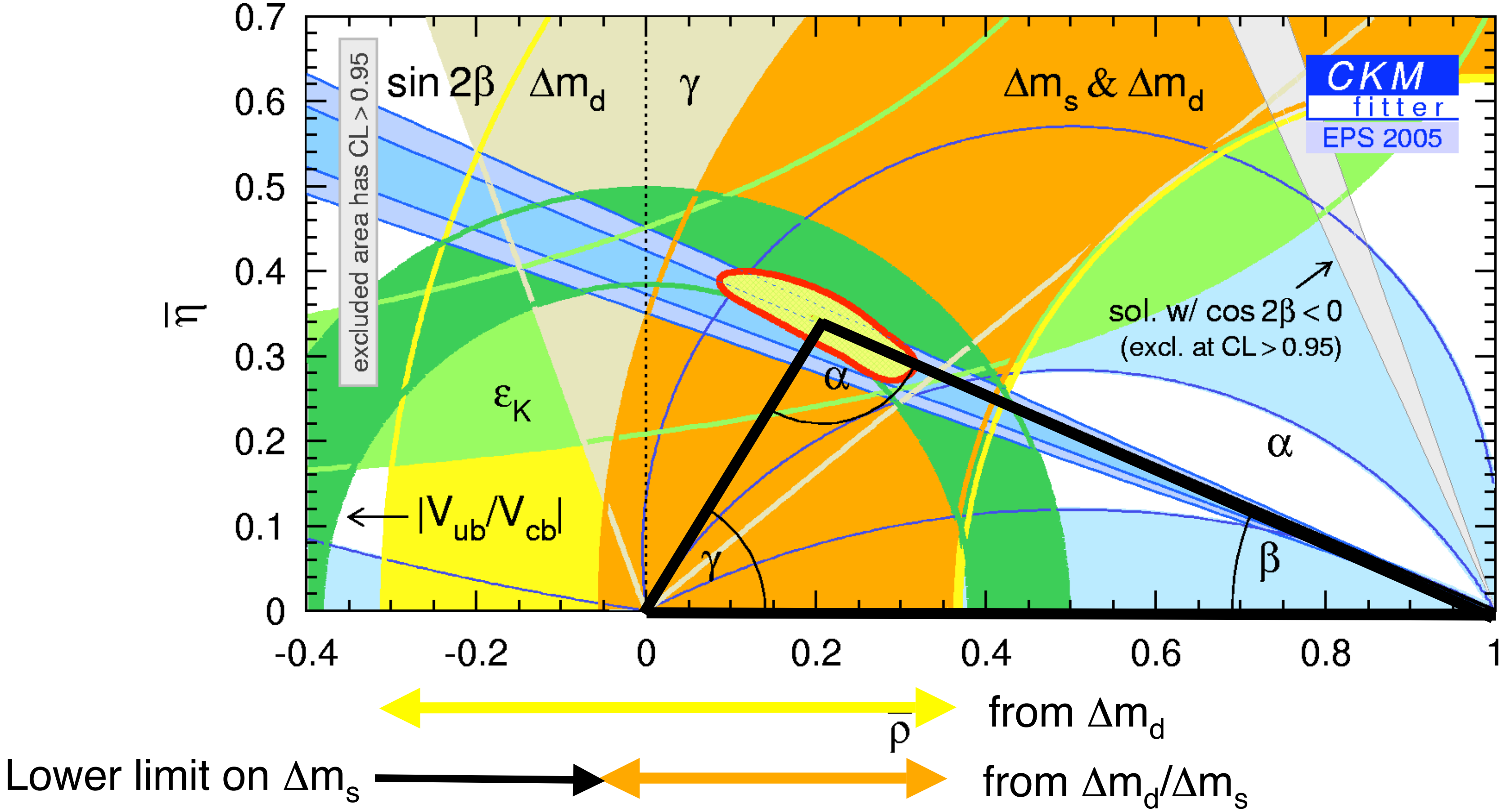
Constrain side of triangle:

$$|V_{td}|^2 = A^2\lambda^4\left[(1-\rho)^2+\eta^2\right]$$

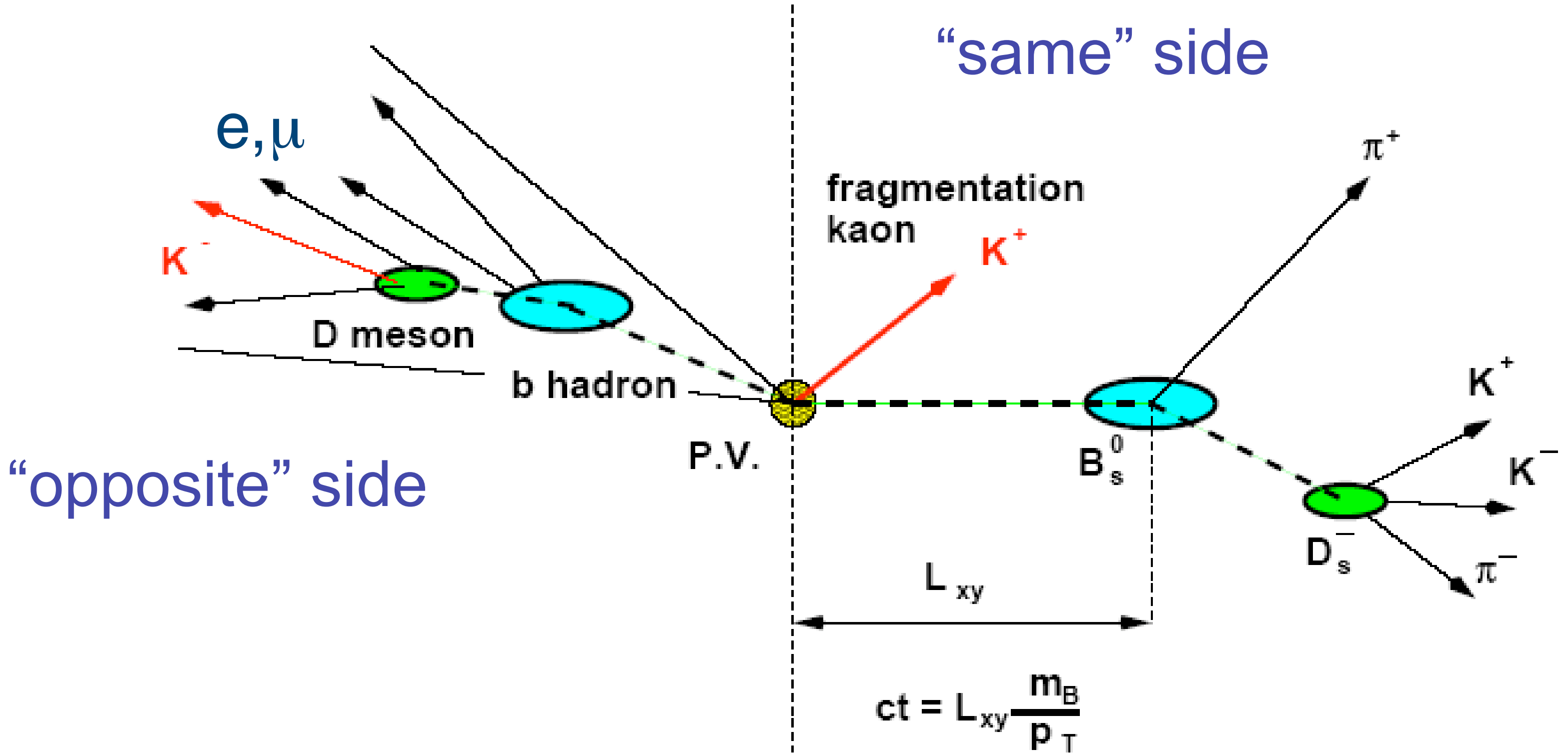
$$\frac{|V_{td}|^2}{|V_{ts}|^2} = (1-\rho)^2+\eta^2\ .$$

Unitarity Triangle Fit

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



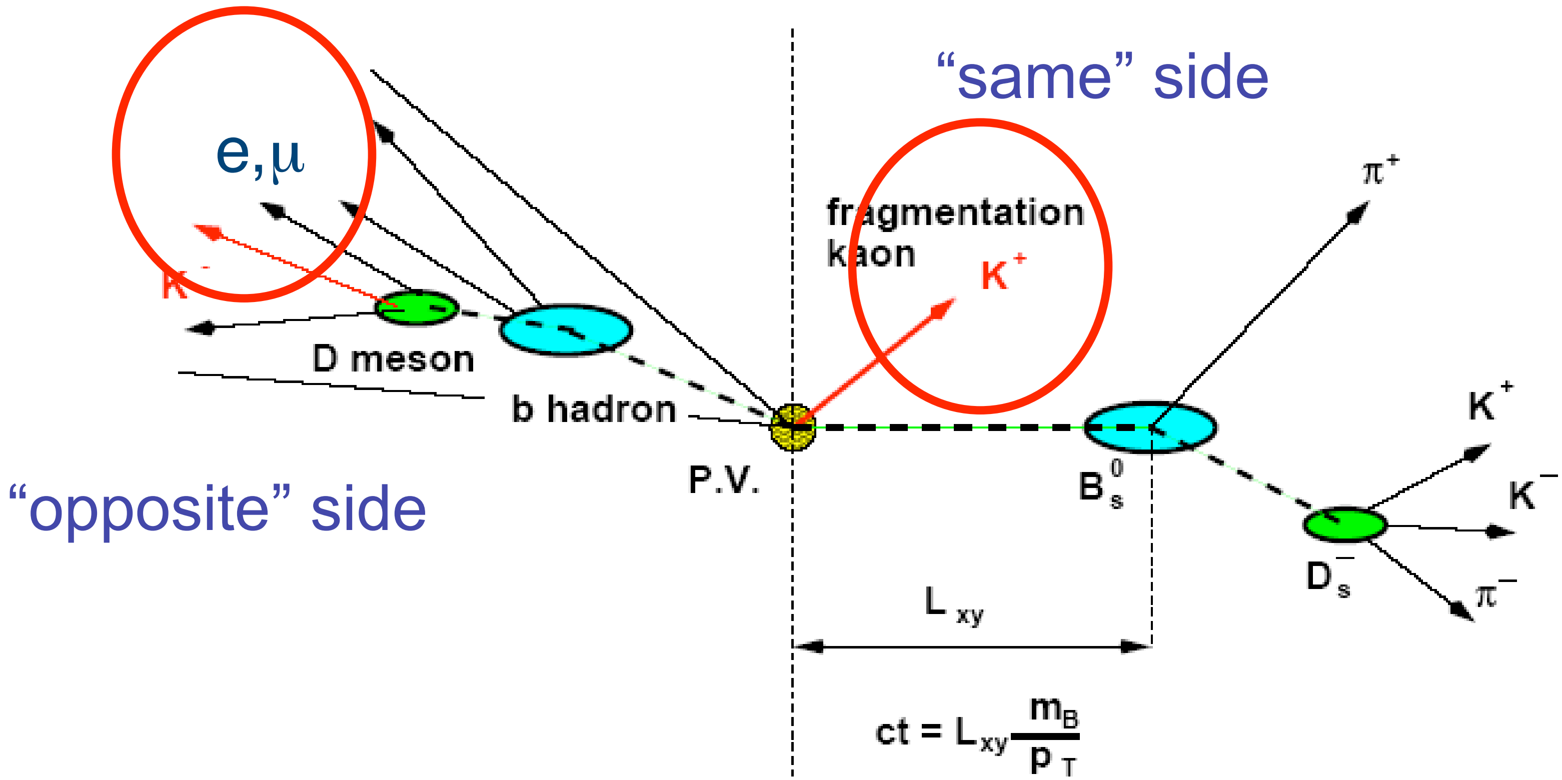
The “Big” Picture



significance of measurement

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

Flavour tagging



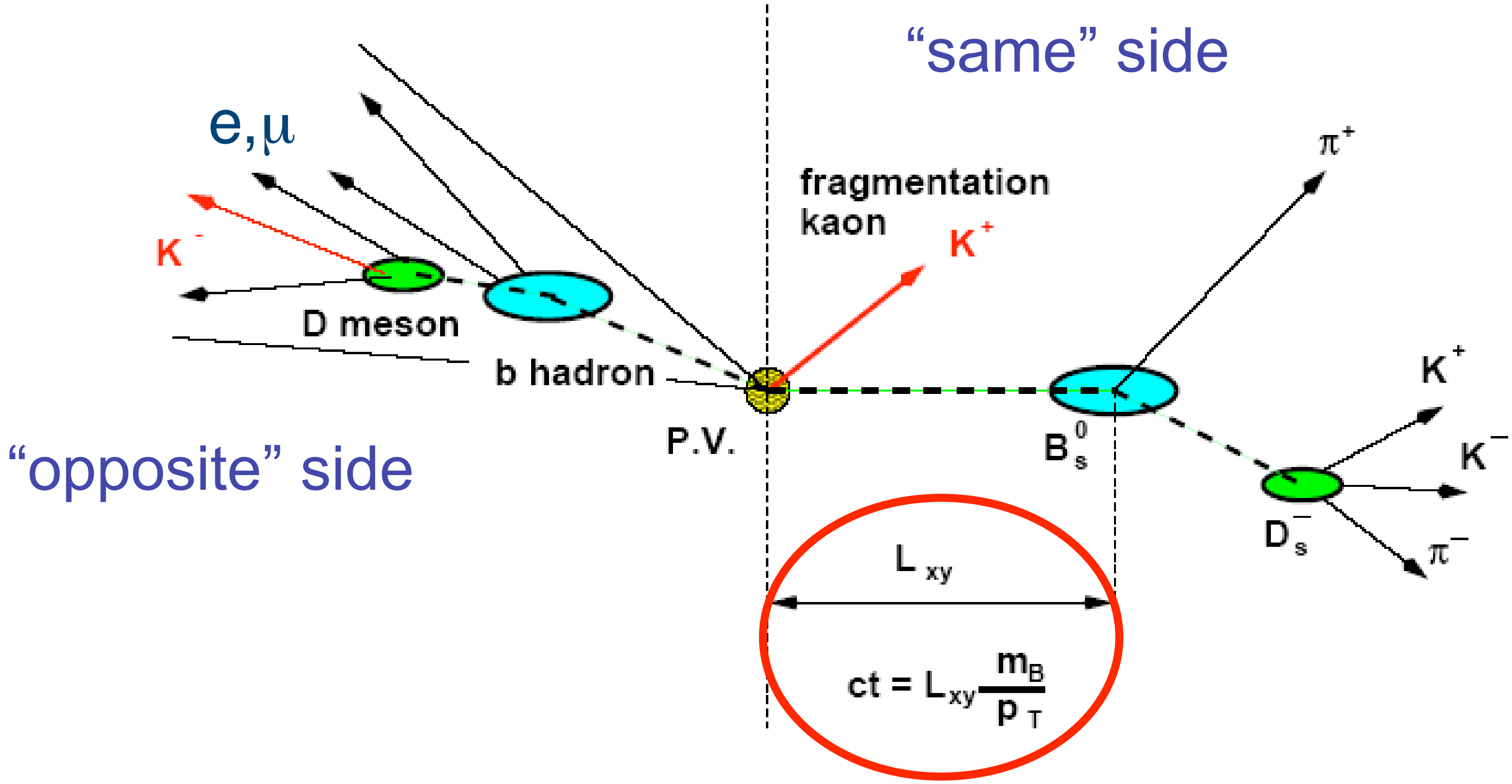
Time resolution

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

Flavour tagging

B signal efficiency

Time resolution

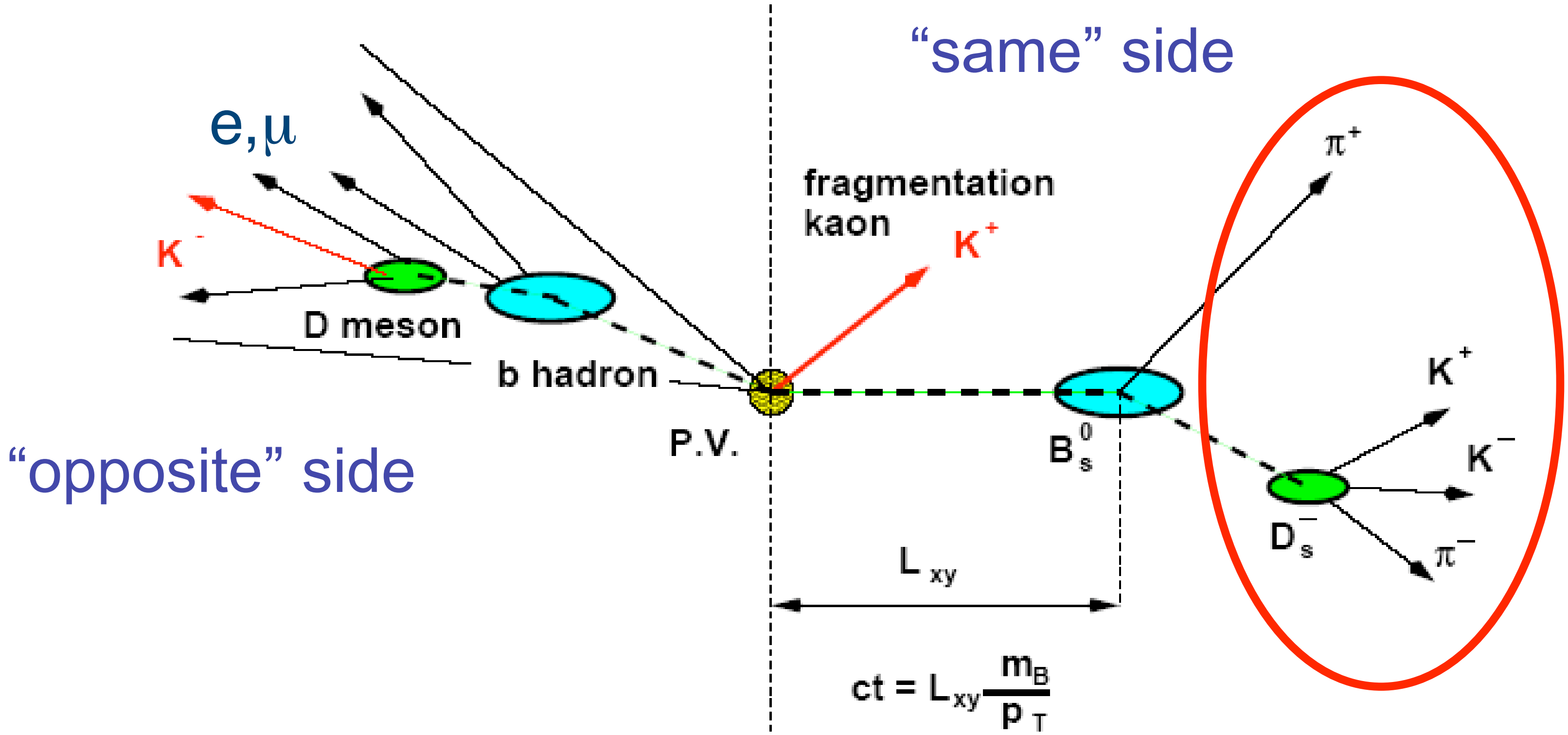


$$\frac{1}{\sigma} = \sqrt{\frac{S\epsilon D^2}{2} e^{-\frac{(\Delta m_s \sigma_t)^2}{2}}} \sqrt{\frac{S}{S+B}}$$

Time resolution

B signal efficiency

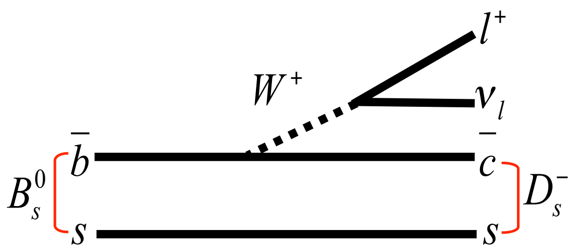
Signal Identification



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

B signal reconstruction

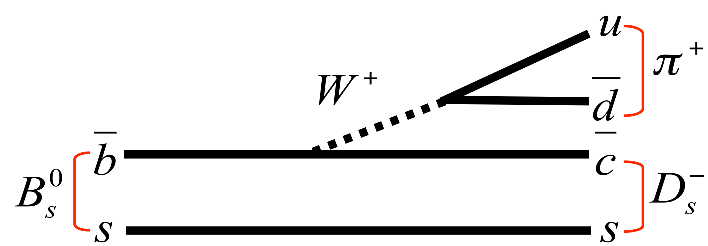
Semileptonic vs Hadronic Decays



- Semileptonic:
  - High statistics:
    - 50K events
  - B momentum not known
    - Neutrino missing
    - Requires average correction factor K

$$ct = L_{xy}\frac{m(B)}{p_T(B)} = L_{xy}\frac{m(B)}{p_T(\ell D)} \cdot K$$

  - Poorer time resolution



- Hadronic:
  - Lower statistics:
    - 4K events
  - Full reconstruction of B momentum

$$ct = L_{xy}\frac{m(B)}{p_T(B)}$$

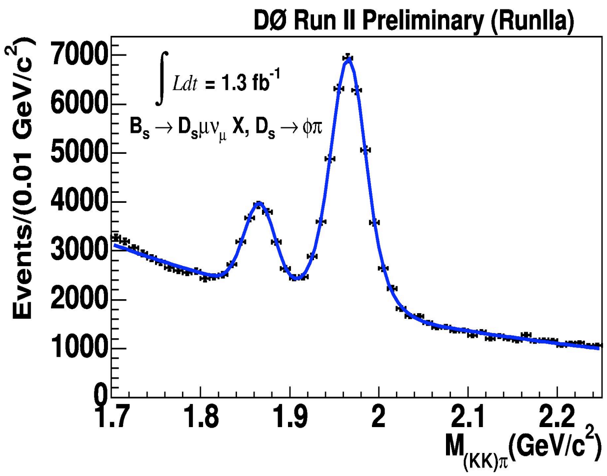
  - Excellent time resolution

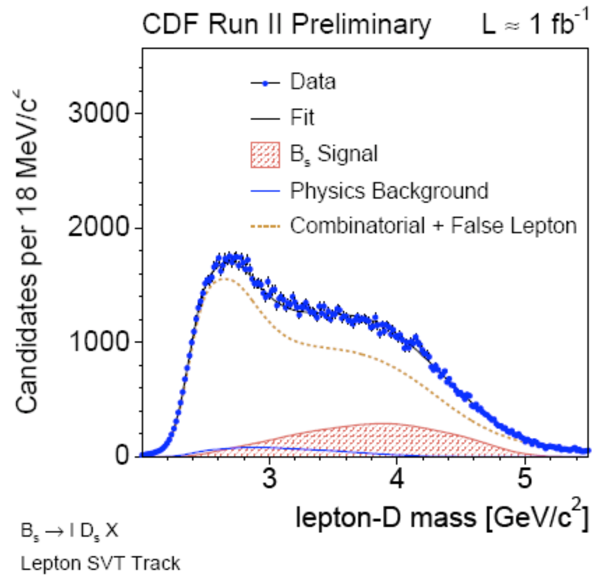
$$\sigma(ct) = \sqrt{(\sigma_0(ct))^2 + (ct \cdot \frac{\sigma(p)}{p})^2}$$

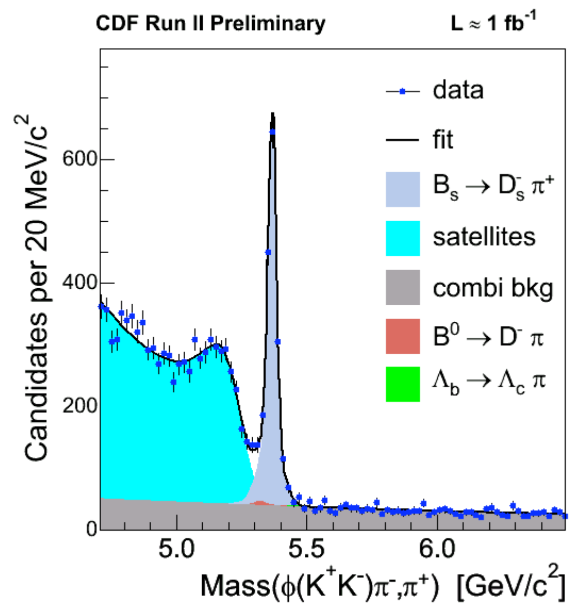
Semileptonic and Hadronic Signals

Semileptonic: $B_s \rightarrow l\nu D_s$

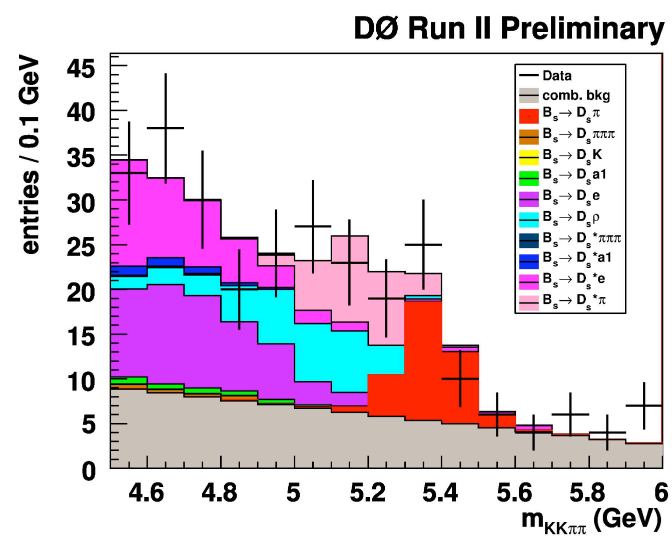
Hadronic: $B_s \rightarrow \pi D_s$



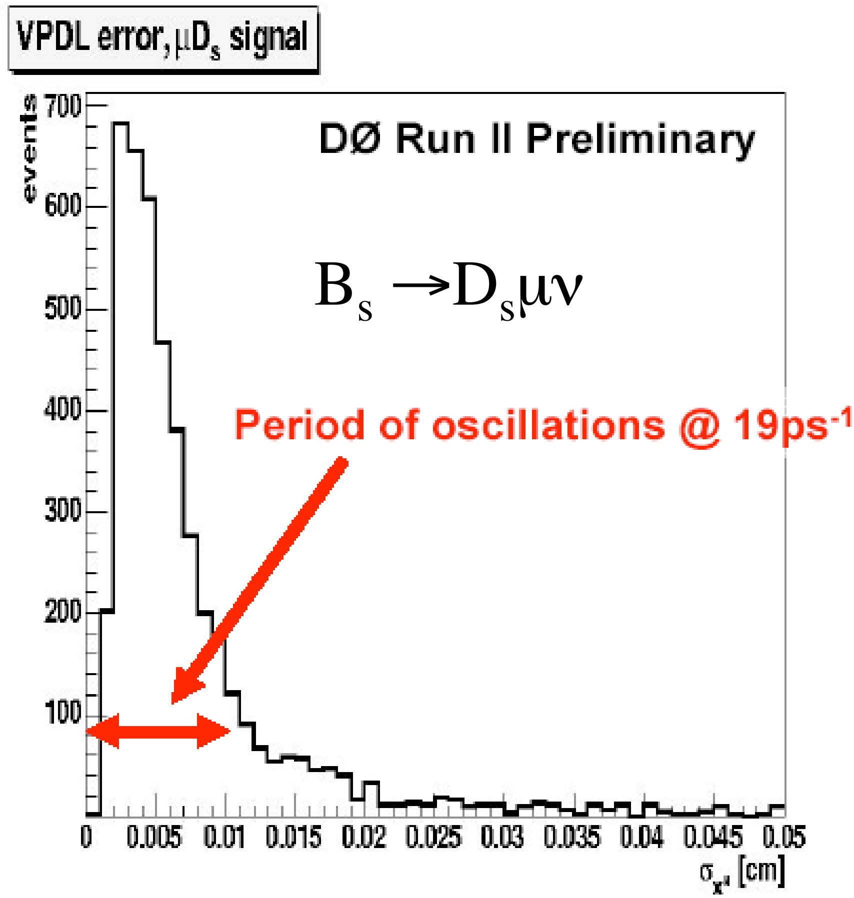


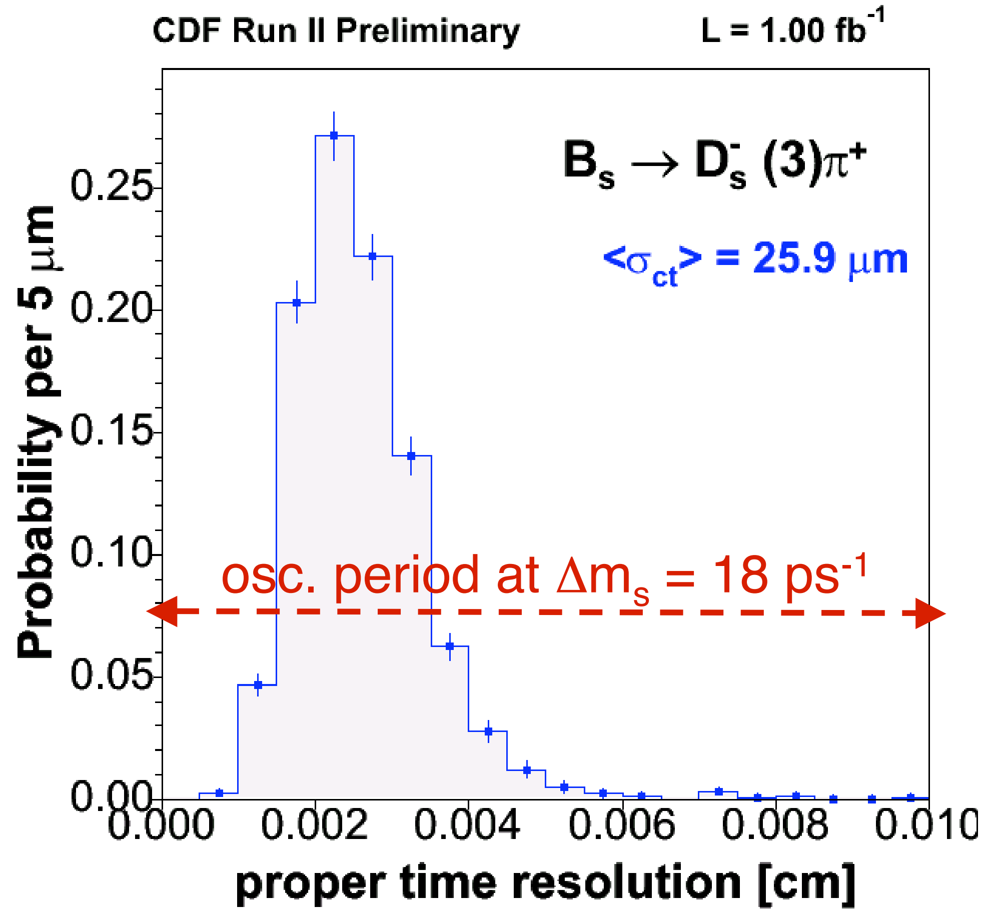


- Use for analysis:
  - Semileptonic decays
  - Hadronic Decays
  - Partially reconstructed decays
    - Escaping γ or π^0



Proper Time Resolution

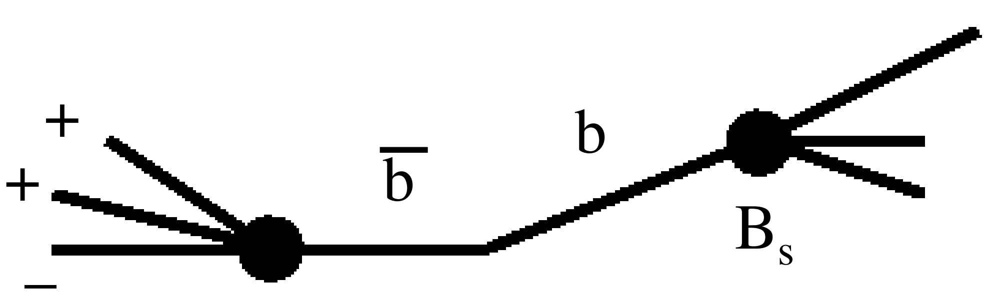




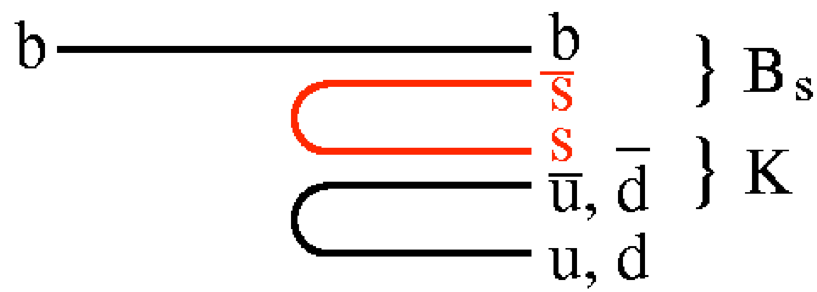
- Semileptonic Decays:
  - Resolution about 1 oscillation period
- Hadronic Decays:
  - Resolution 5 times better than 1 oscillation period
  - CDF also uses partially reconstructed decays

Production Flavour Tagging

Opposite side tagging



Same side tagging

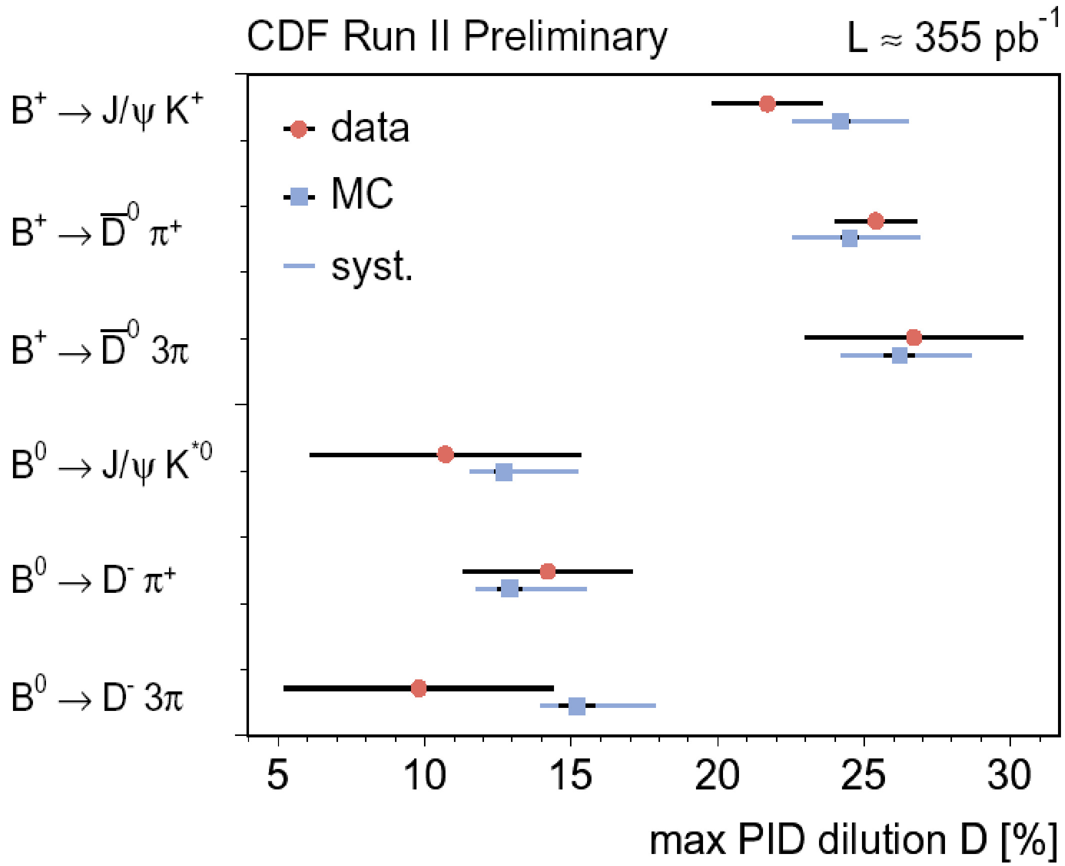


- Opposite side tags:
  - Only works for $b\bar{b}$ production mechanism
  - Used by CDF (εD^2=1.5%) and DØ (εD^2=2.5%):
    - Lepton (muon or electron) or jet charge
- Same side tags:
  - Identify Kaon from B_s fragmentation
  - CDF: εD^2=3.5-4.0%
- Figure that matters: εD^2
  - Efficiency ε of tagging (right or wrong)
  - Dilution D is fraction of correct tags

$$\epsilon = \frac{N_{tag}}{N_{all}}$$

$$D = \frac{N_{right} - N_{wrong}}{N_{tag}}$$

Same Side Kaon Tagger Crosschecks

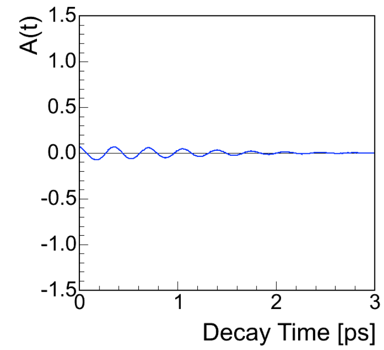


- Have to rely on MC to determine performance of Same Side Kaon Tagger
  – Extensive comparison of data and MC in high statistics B modes
- Good agreement between data and MC => confidence

"Amplitude Scan": Measuring Δm_s

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

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



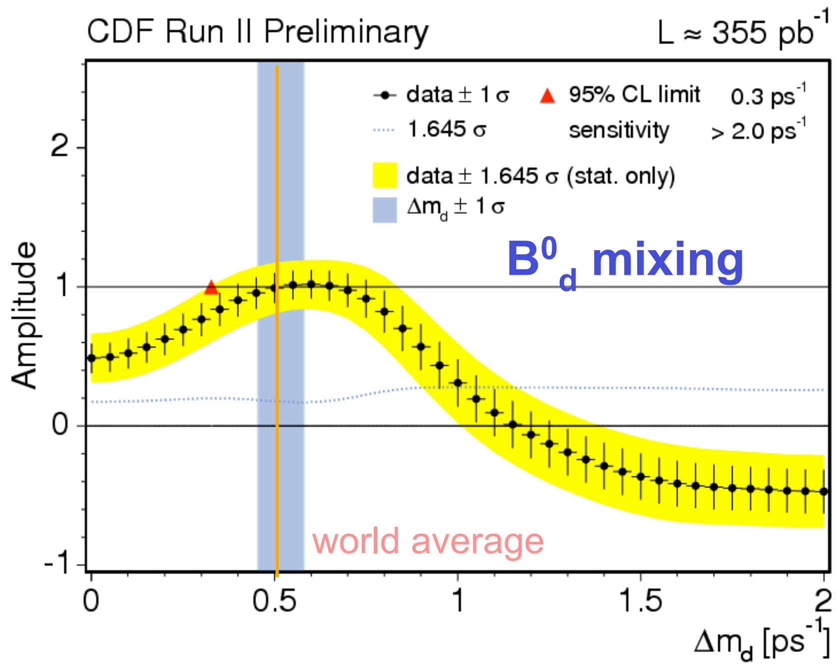
In practice: use amplitude scan method

- introduce amplitude to mixing probability formula

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

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

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



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

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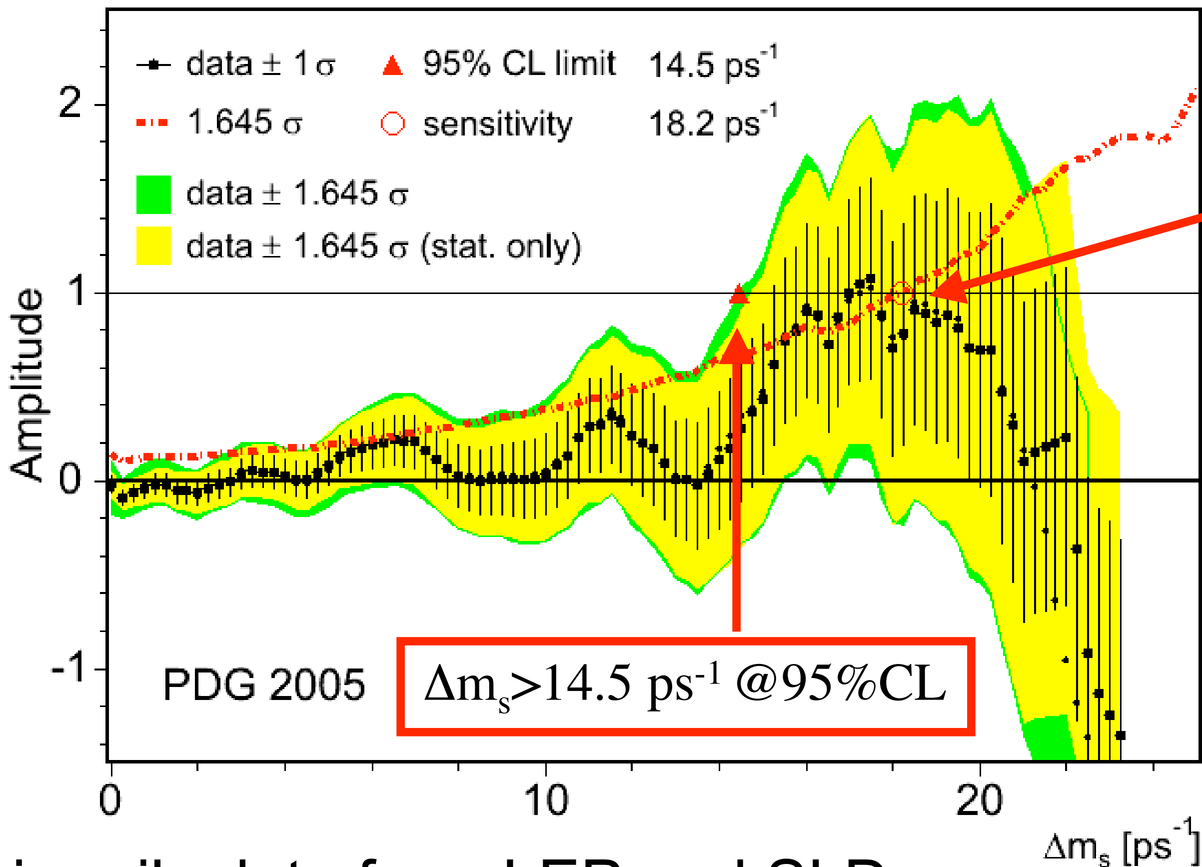
The World Data: PDG 2005

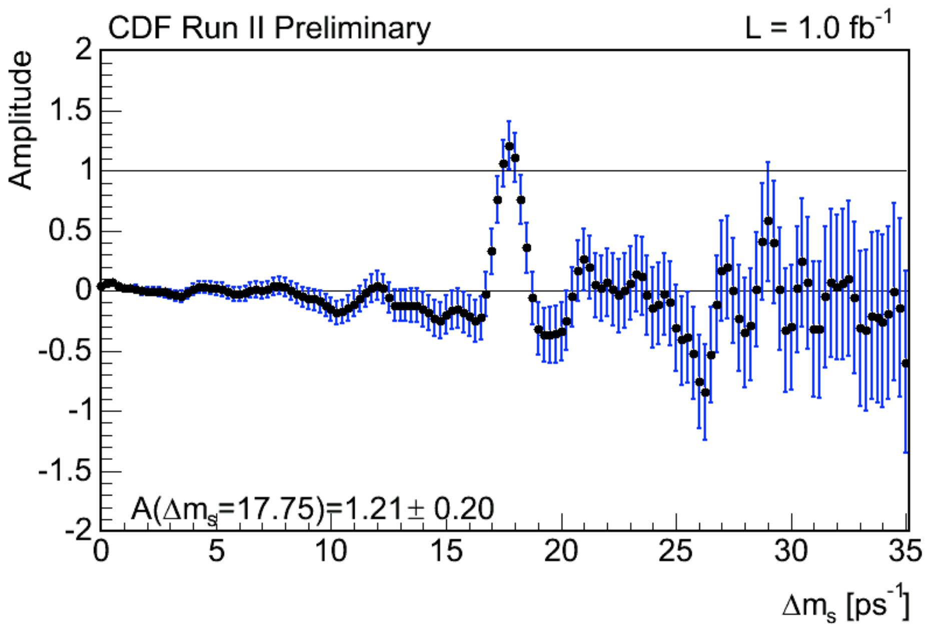


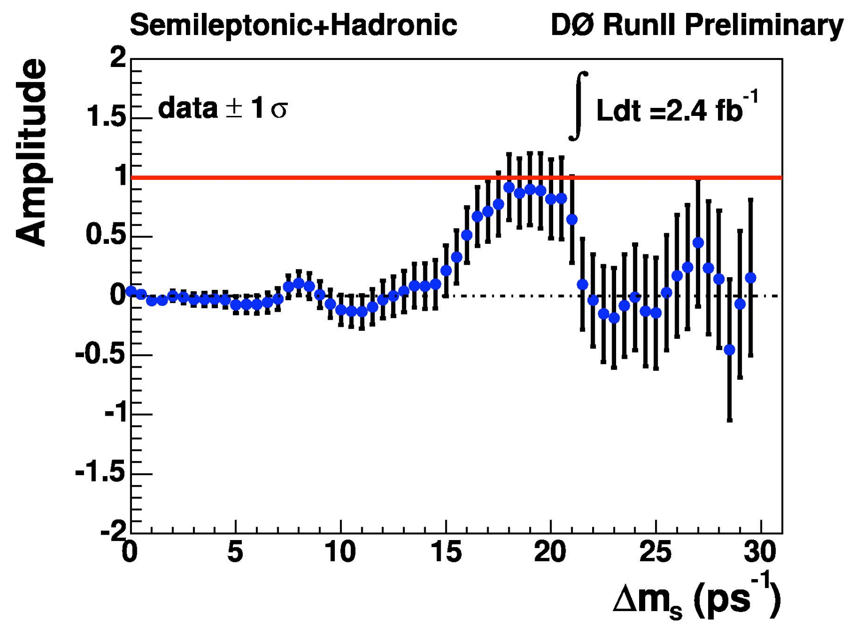
"Sensitivity": expected value in absense of stat. Fluctuations

⇒Shows power of experiment

- Primarily data from LEP and SLD:
  - Consistent with no mixing within 2σ everywhere
  - Consistent with mixing beyond 14.5 ps-1
    - Actual limit worse that sensitivity
    - either first hint of signal around 17-20 or statistical fluctuation
- Single best experiments sensitivity: ALEPH $\Delta m_s > 10.9\ ps^{-1}$

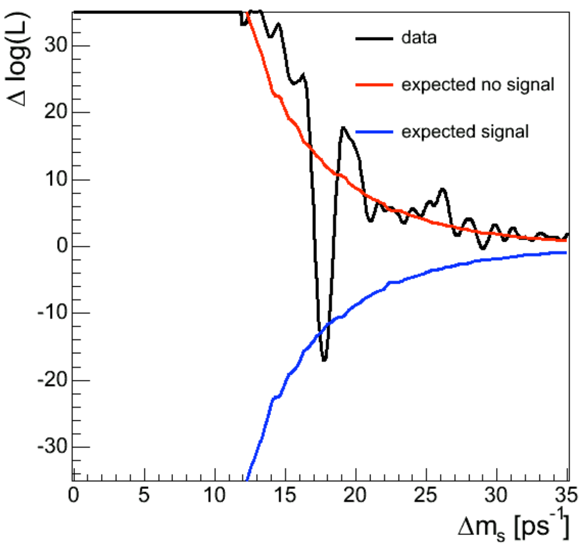
Amplitude Scan: Semileptonic+Hadronic

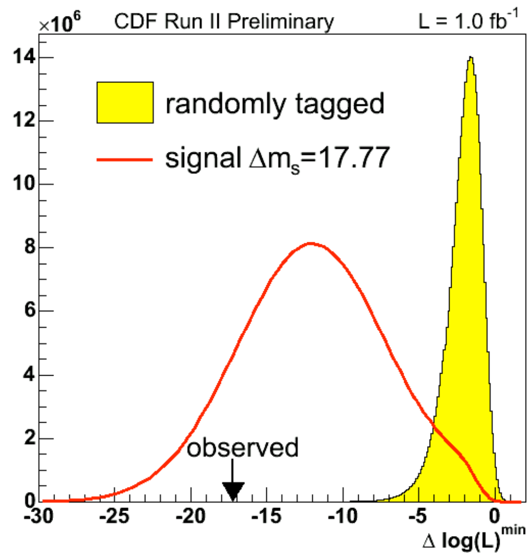




- Result:
  - Both experiments see result consistent with mixing and $\Delta m_s \approx 18$ ps^{-1}:
  - CDF:
    - Observation! Significance >5σ, published in Fall 2006
  - DØ:
    - significance 3.1σ, brand new in Summer 2007

Likelihood Ratio

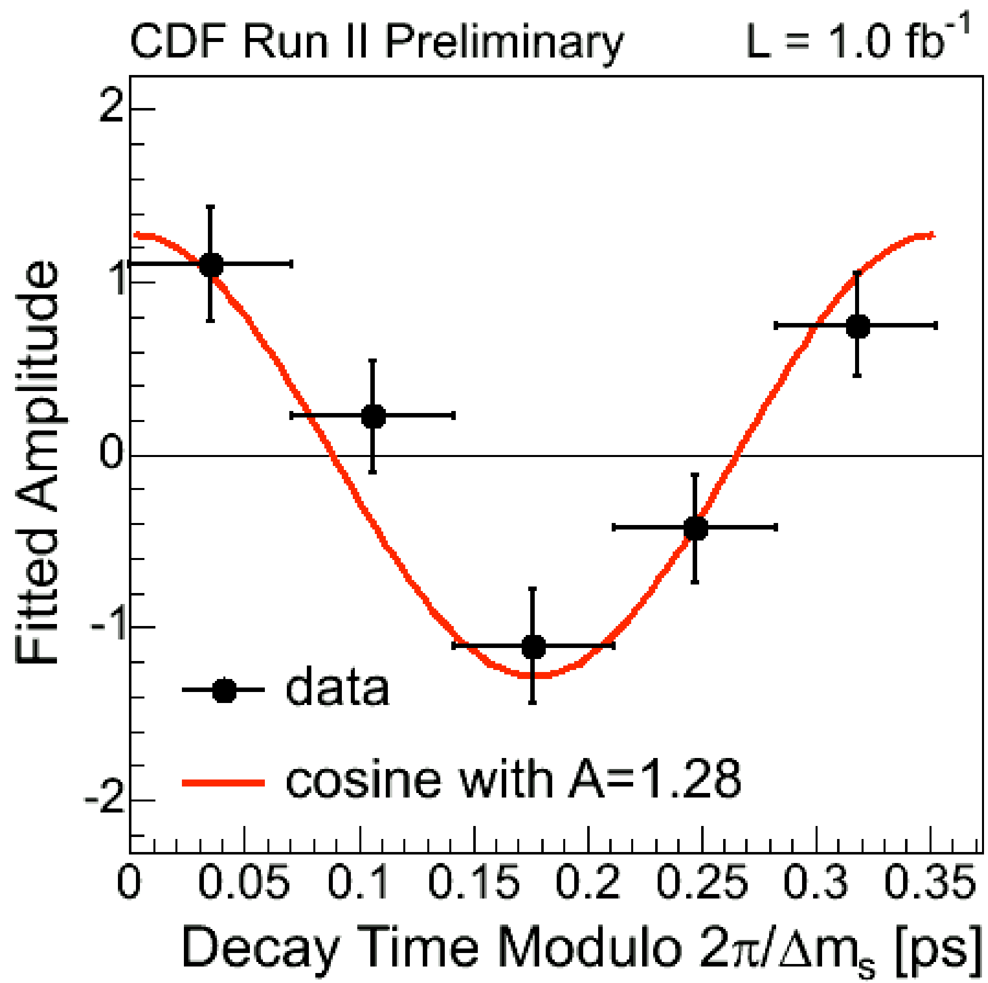




- Likelihood ratio tests between two hypotheses (A=1 and A=0):
  - Δlog(L) = log[L(A=1) / L(A=0)]
  - likelihood dips at signal frequency
- Pseudo-experiments tell us how often this happens randomly:
  - Probability: 8×10^{-8}
- Result:

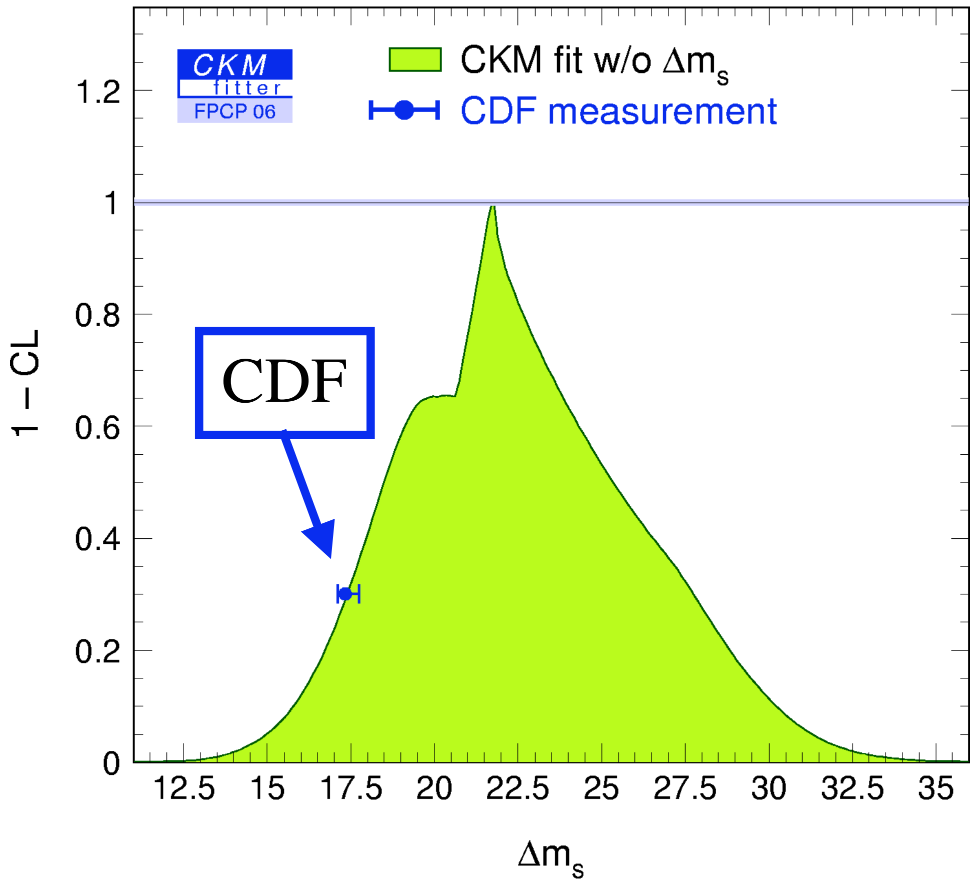
$$\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07\ (\text{syst})\ \text{ps}^{-1}$$

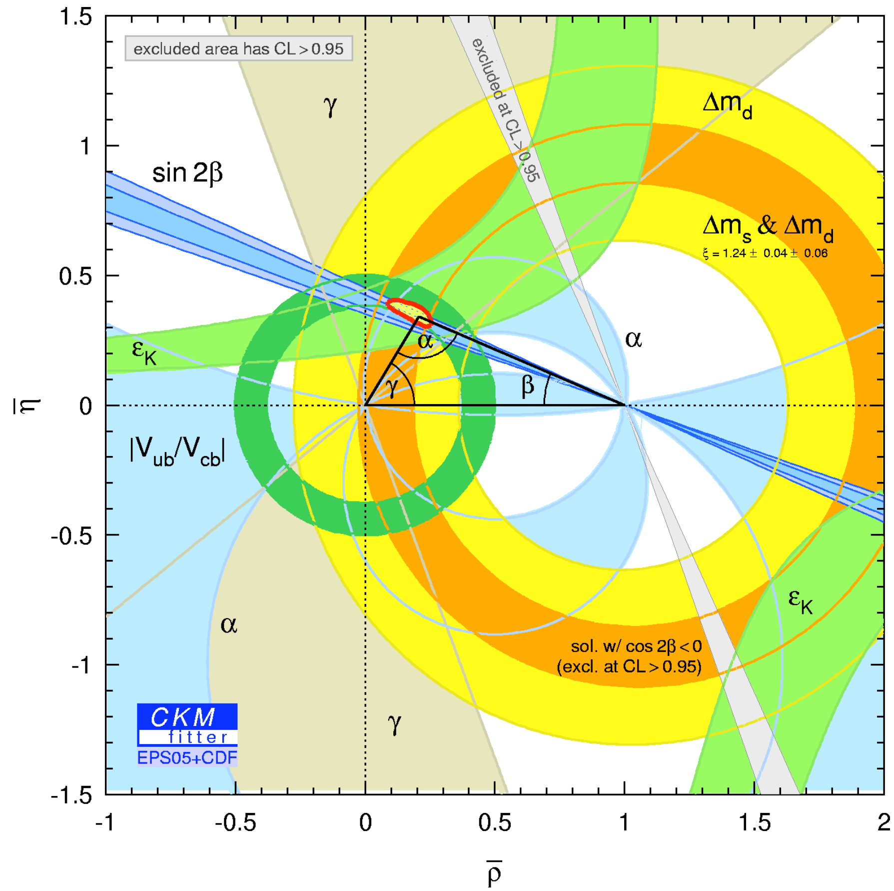
Amplitude versus Decay time



- Looks clearly like a nice oscillation!

New Unitarity Triangle Fit

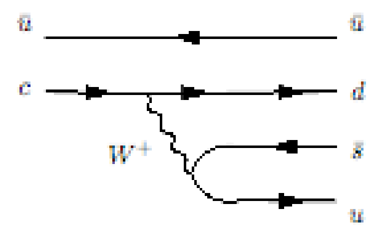


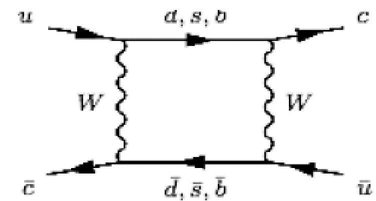


- Significant impact on unitarity triangle understanding
- So far CKM matrix consistent with Unitarity: $U^{+}U=1$

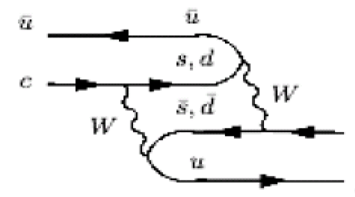
Charm mixes too since March 2007!

- Evidence from B-factories:
  - BaBar: compare $D^0 \to K^+\pi^-$ to $D^0 \to K^+\pi^-$
  - Belle: comparing $D^0 \to KK/\pi\pi$ to $D^0 \to K\pi$
- Large charm samples in CDF data
  - $D^* \to \pi_{soft} D^0$, $D^0 \to K\pi$
  - CDF's time resolution capability allows time dependent measurement
  - π_{soft} charge tags D flavour at production
- Asymmetry:
  - #wrong sign/#right sign events
    - Right sign: $D^{*+} \to \pi^+ D^0$, $D^0 \to K^-\pi^+$
    - Wrong sign: $D^{*+} \to \pi^+ D^0$, $D^0 \to K^+\pi^-$
  - Measure this as function of proper decay time

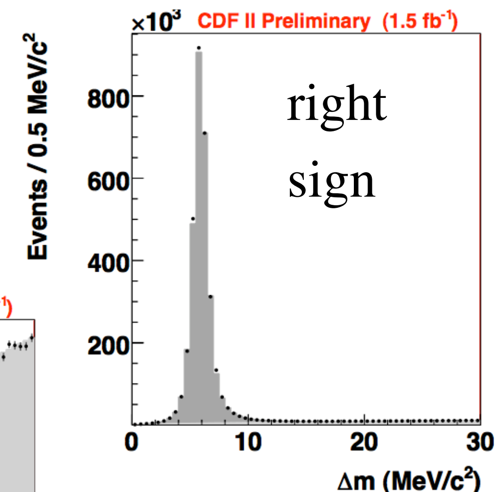


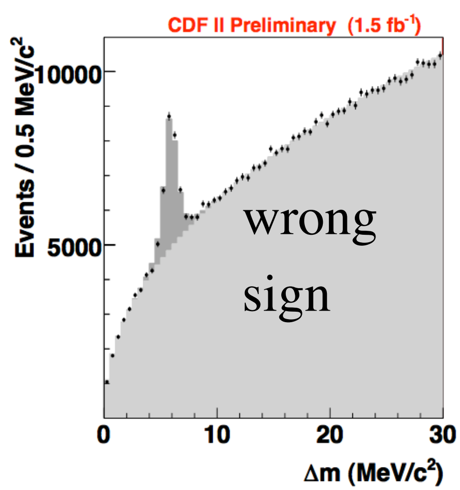


Mixing box diagram



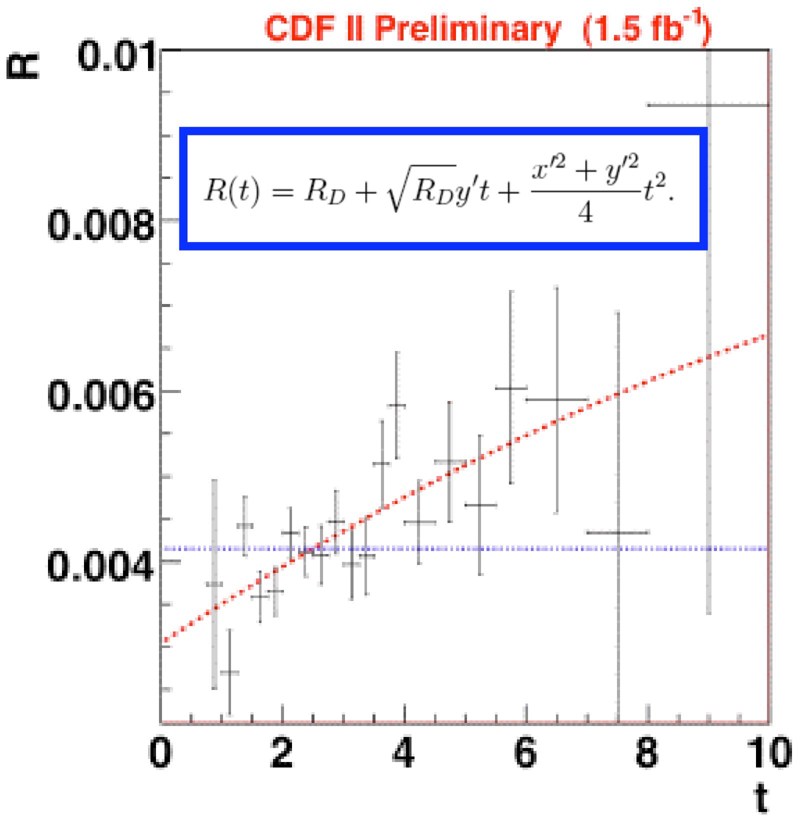
Mixing long distance diagram

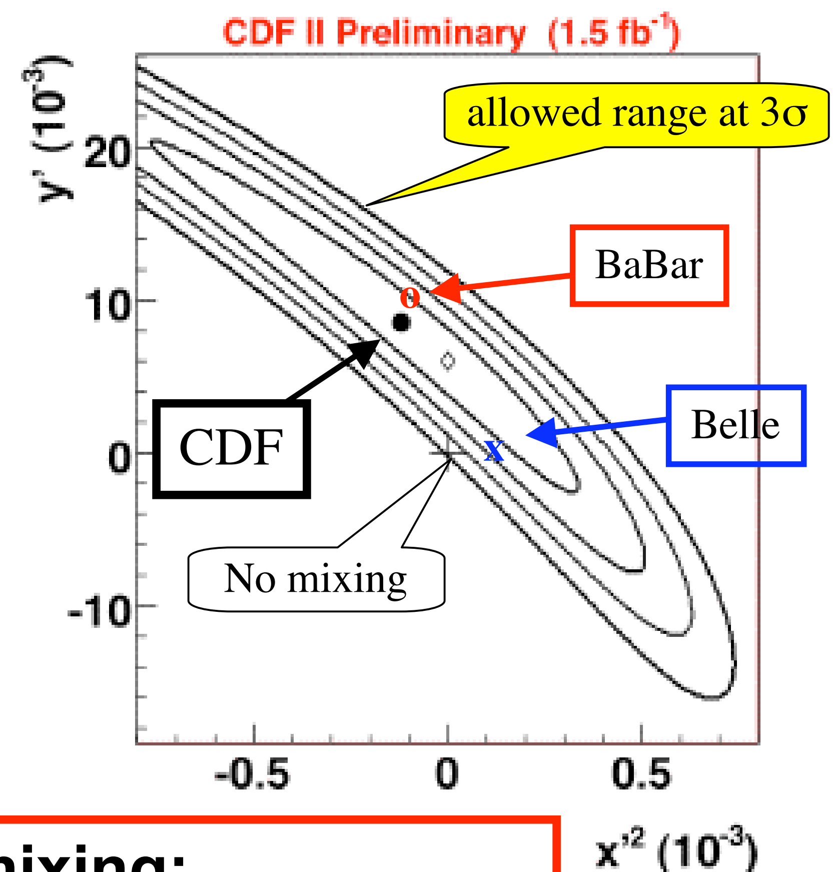




Evidence for Charm Mixing

- Define two parameters relative to average decay width:
  - Mass difference: **x'=Δm / Γ = 8.5 +/- 7.6**
  - Decay width difference: **y'= ΔΓ / 2Γ = -0.12 +/- 0.35**





- **3.8σ evidence for charm mixing:**
  - **Sensitivity similar to the B factories!**

Rare Decays: $B_s \rightarrow \mu^+\mu^-$

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- SM rate heavily suppressed:

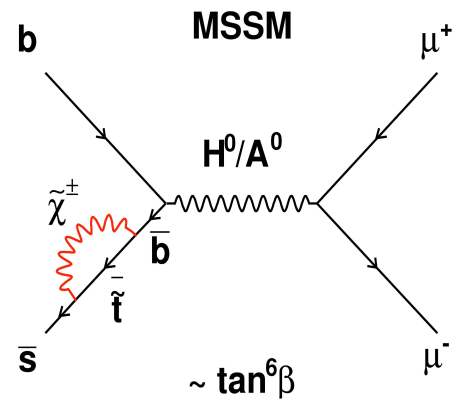
$$BR(B_s \rightarrow \mu^+\mu^-) = (3.5 \pm 0.9) \times 10^{-9}$$

(Buchalla & Buras, Misiak & Urban)

- SUSY rate may be enhanced:

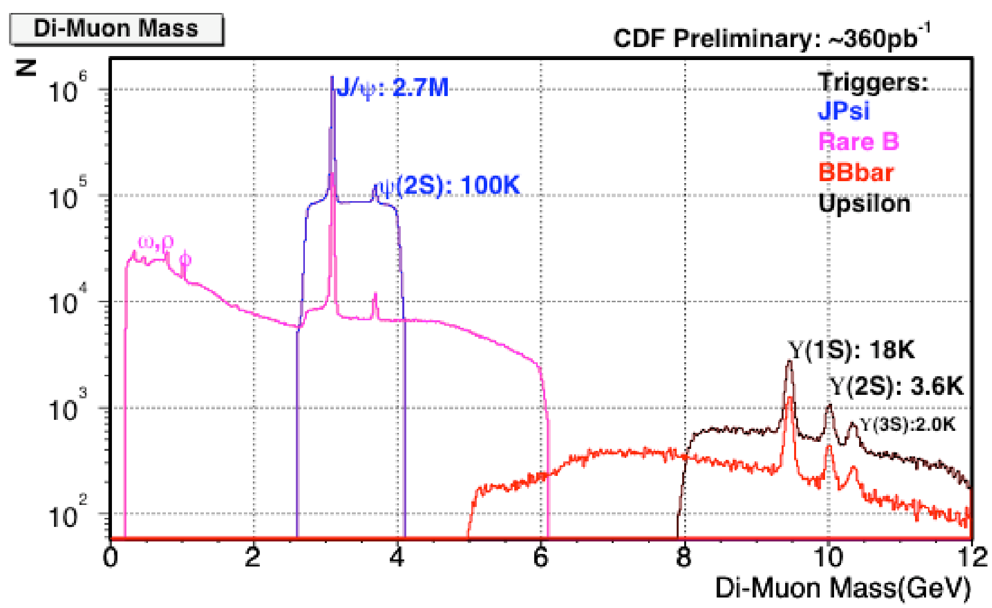
$$BR(B_s \to \mu^+\mu^-) \propto \tan^6 \beta / m_A^4$$

(Babu, Kolda: hep-ph/9909476+ many more)



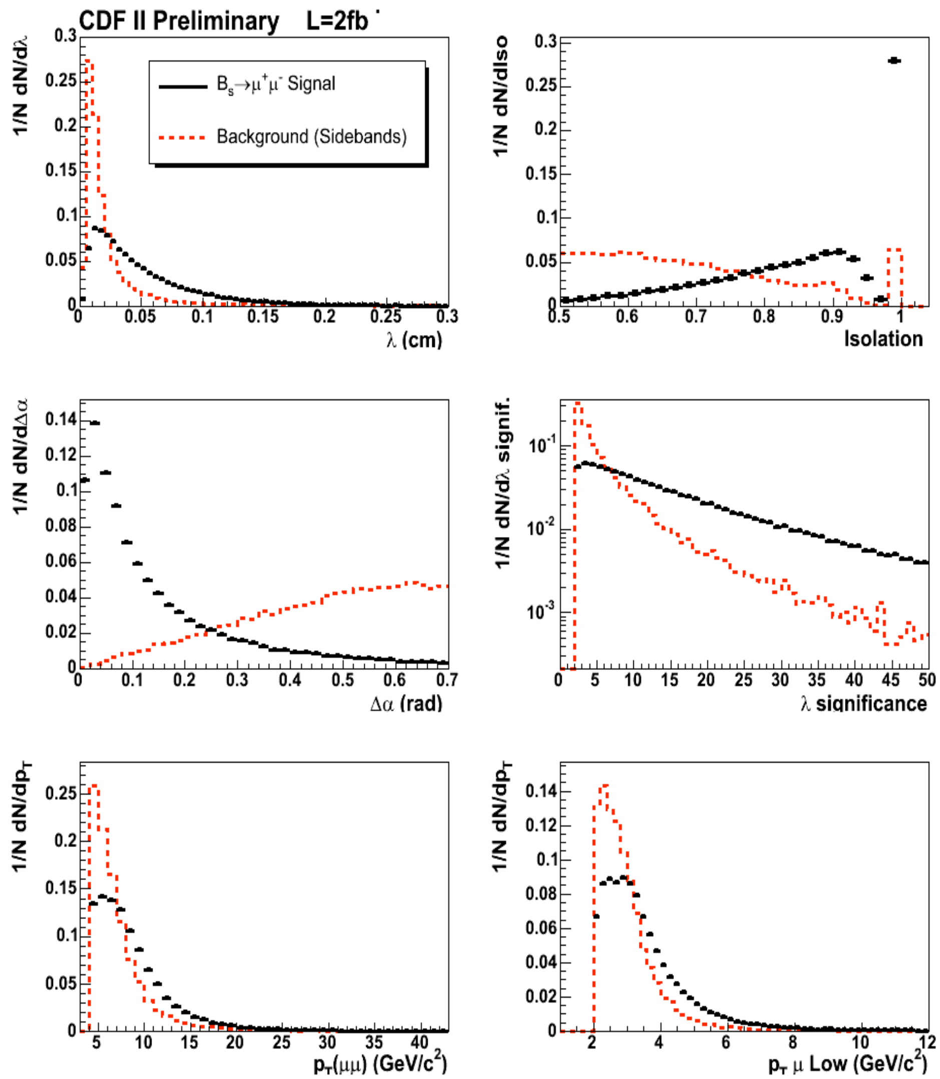
- Key problem:
  - Separate signal from huge background
- Analysis is performed "blind"
  - First finalise cuts and background estimates
  - Only then look at data!

- More details on SUSY theory in lecture tomorrow

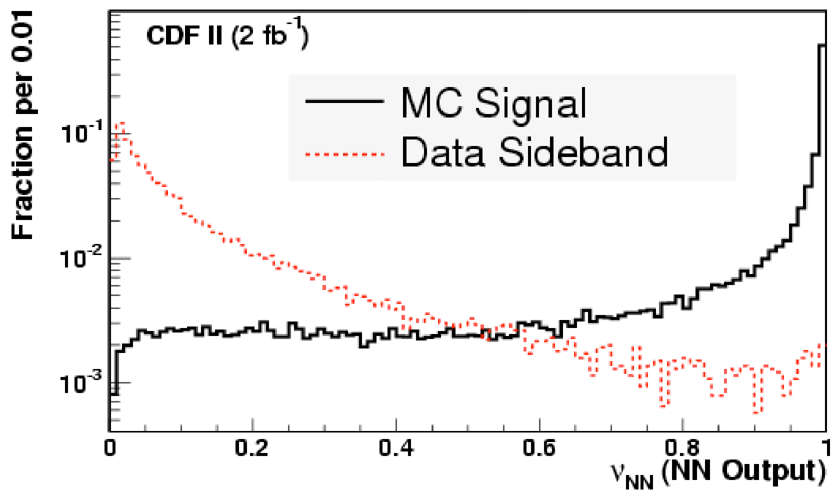


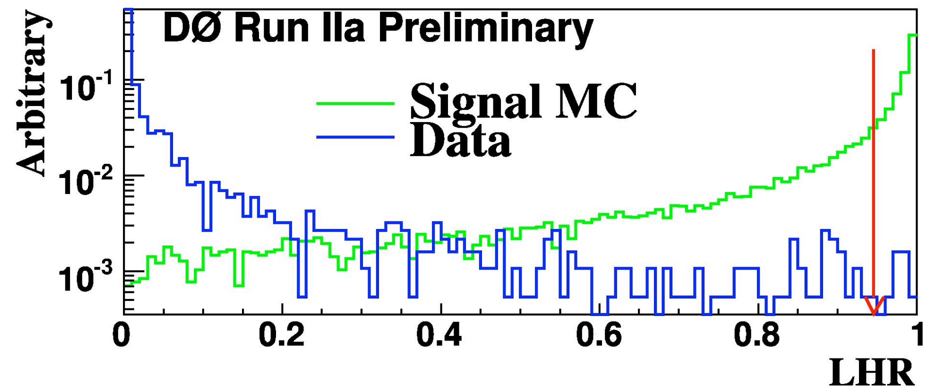
$B_s \rightarrow \mu^+\mu^-$: Cut Optimisation

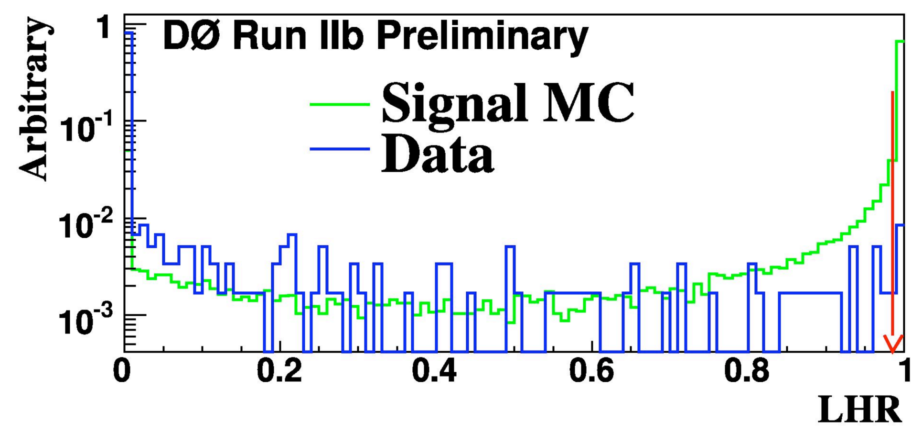
- Select events with
  - 2 muons with p_T>2 GeV
  - 4.669<M($\mu\mu$)<5.969 GeV
- Discriminating variables (CDF):
  1. Lifetime: λ=ct
  2. Isolation of B_s
  3. Opening angle between muons: $\Delta\alpha$
  4. Lifetime significance
  5. p_T of dimuon system
  6. p_T of lower p_T muon
- Construct likelihood ratio or Neural Network from those variables
  - Similar variables used by DØ



$B_s \to \mu^+\mu^-$: Discriminant against background



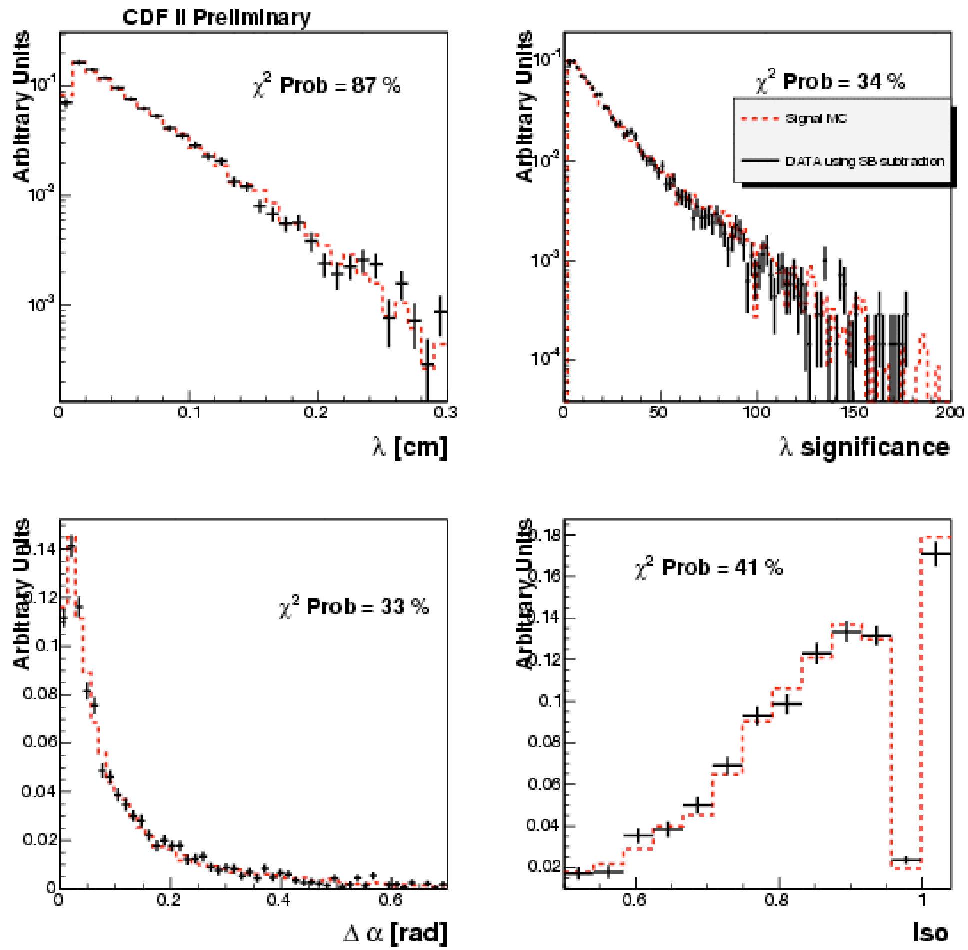




- Cut optimized to maximize sensitivity
- Optimization can depend on run period
  - E.g. DØ optimizes separately for data with L0 and without L0
    - L0 is silicon layer closest to beampipe

Checking the Signal Input Variables

$B^+ \rightarrow J/Psi\ K^+$

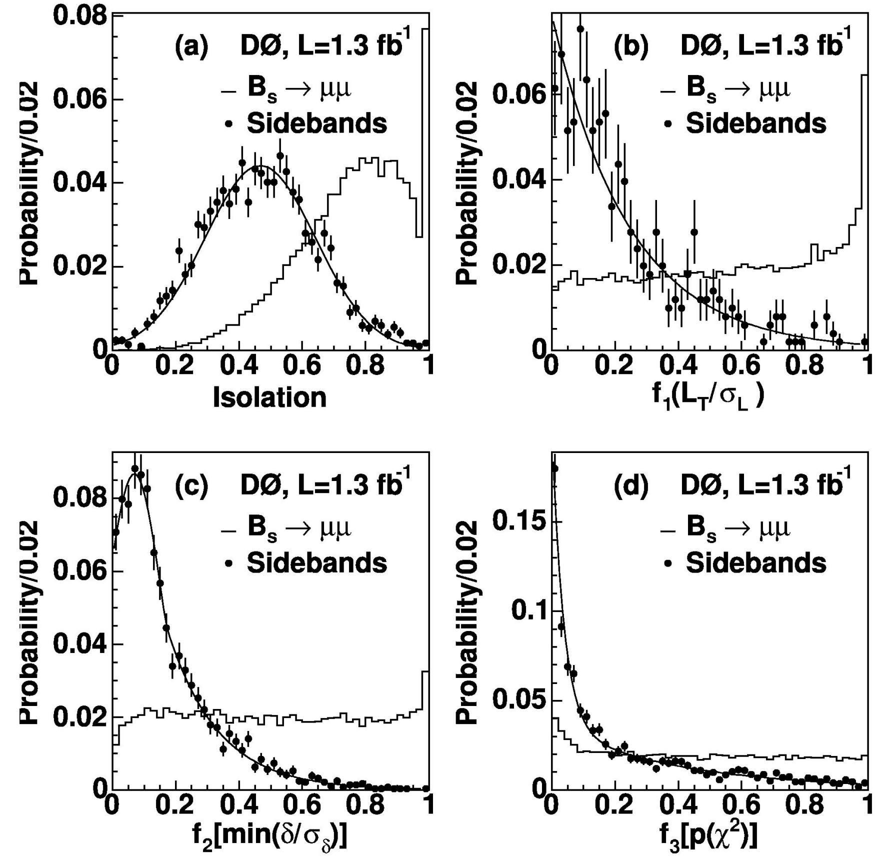


- Making sure that all variables are modeled correctly for the signal
  - Using high statistics $B^+ \rightarrow J/Psi\ K^+$ decays to understand modeling

Input Variables for the Background

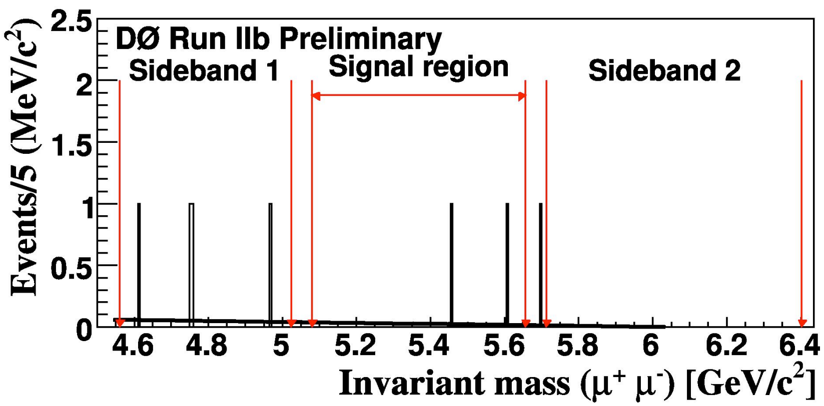
- Powerful technique:
  - Use “side bands” in mass
- Events that are close in mass but not exactly in the peak
  - They often give a representative background sample
  - Unless there are reflections or peaking background
- Also testing background using “control regions”, e.g.
  - 2 muons with same charge

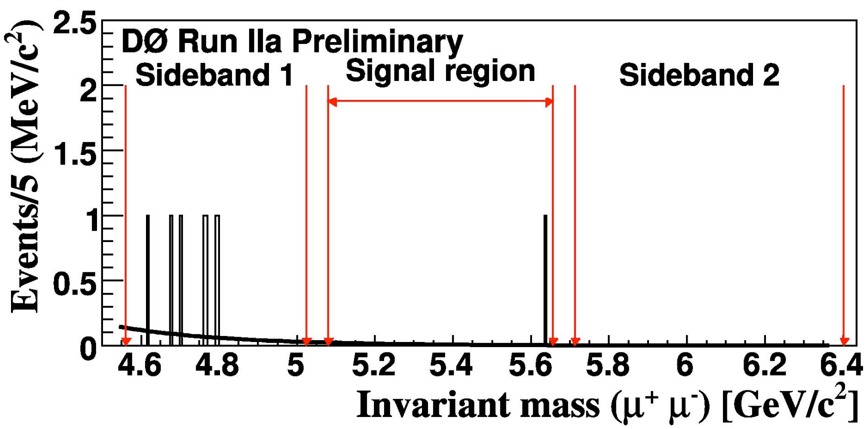
Backgrounds from Sidebands

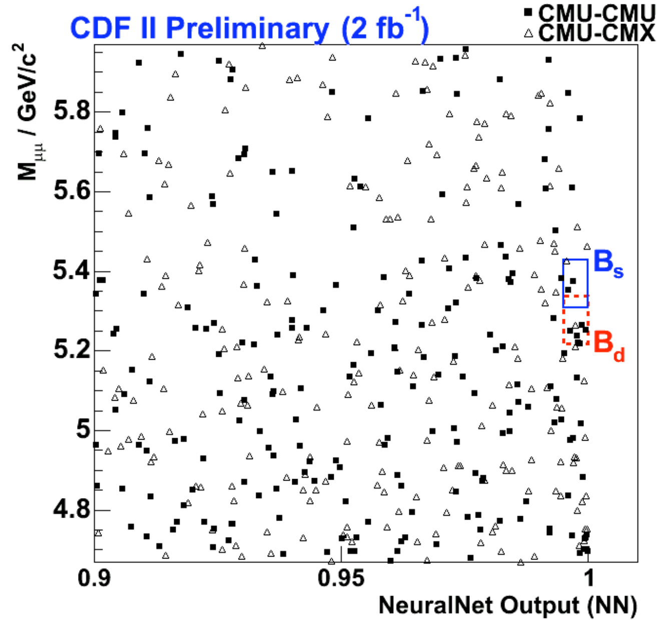


Background determined => Now, let’s look at the data

Opening the “Box”: $B_s \to \mu^+\mu^-$







Data agree with background estimate => constrain new physics

Calculating a limit

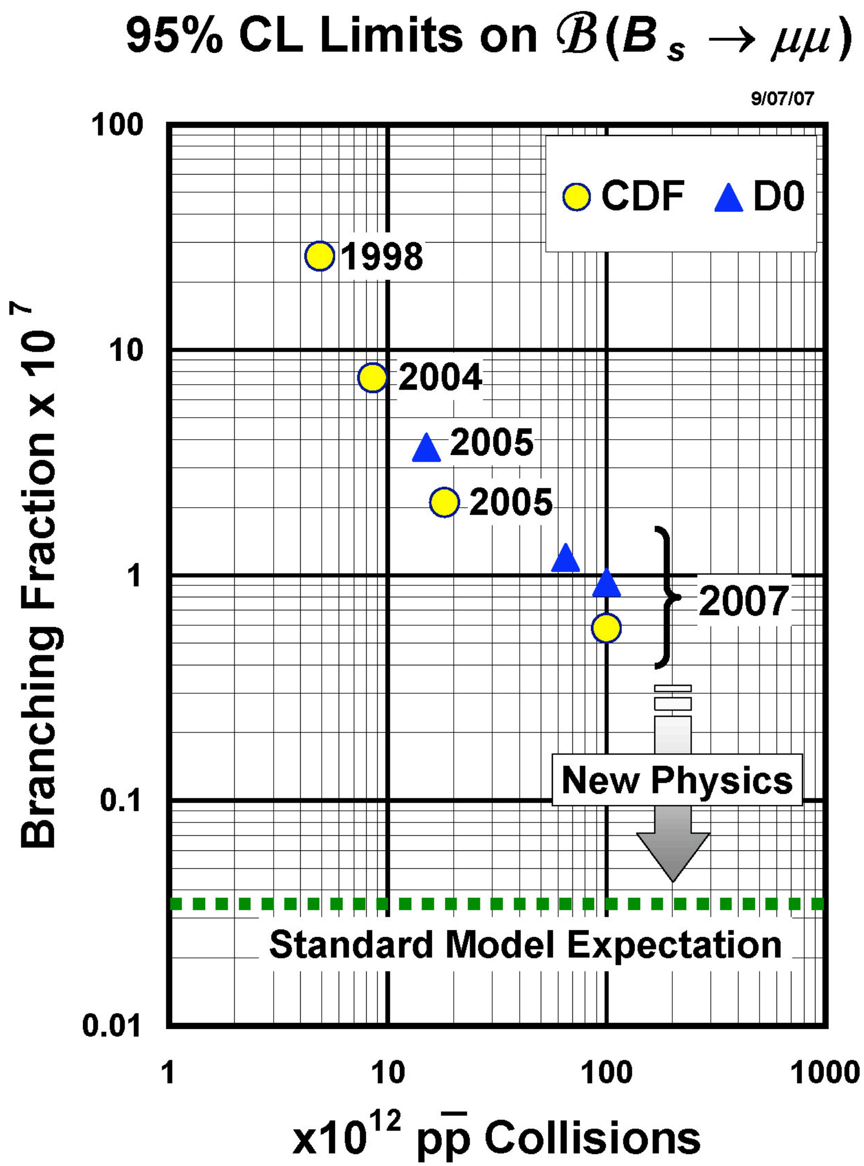
- Different methods:
  - Bayes
  - Frequentist
  - …
- Source of big arguments amongst statisticians:
  - Different method mean different things
  - Say what YOU have done
  - There is no “right” way
- Treatment of syst. Errors somewhat tricky
- But basically:
  - Calculate probability that data consistent with background + new physics:
    - $P=e^{-\mu}\mu^{N}/N!$
    - N = observed events
    - parameter μ is $N_{BG} + N_{new}$
    - P=5% => 95% CL upper limit on N_{new} and thus $\sigma xBR=N_{new}/(\alpha L)$
- E.g.:
  - 0 events observed means <2.7 events at 95%C.L.

Better to discover something than having to set a limit!

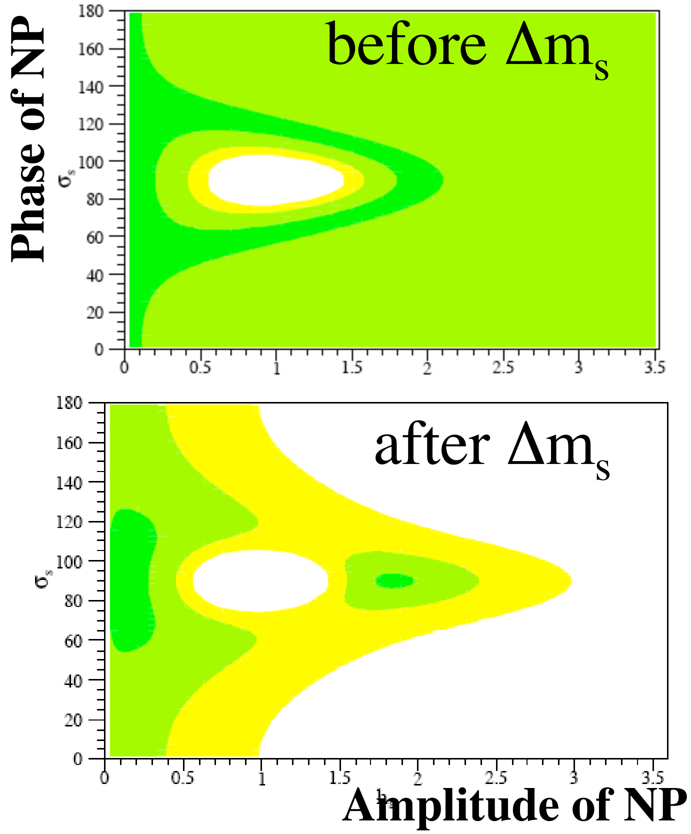
Limits on BR of $B_s \rightarrow \mu^+\mu^-$

- Fierce competition between the experiments!
  - Leads to great scientific results
  - Results improved linearly with increasing luminosity!
    - Usually they would improve as sqrt(L)
    - Better due to tireless efforts to improve analysis techniques and to understand data better

95% C. L. limits on branching ratio of $B_s \rightarrow \mu^+\mu^-$:
- DØ: BR < 9.3 x 10^{-8}
- CDF: BR < 5.8 x 10^{-8}

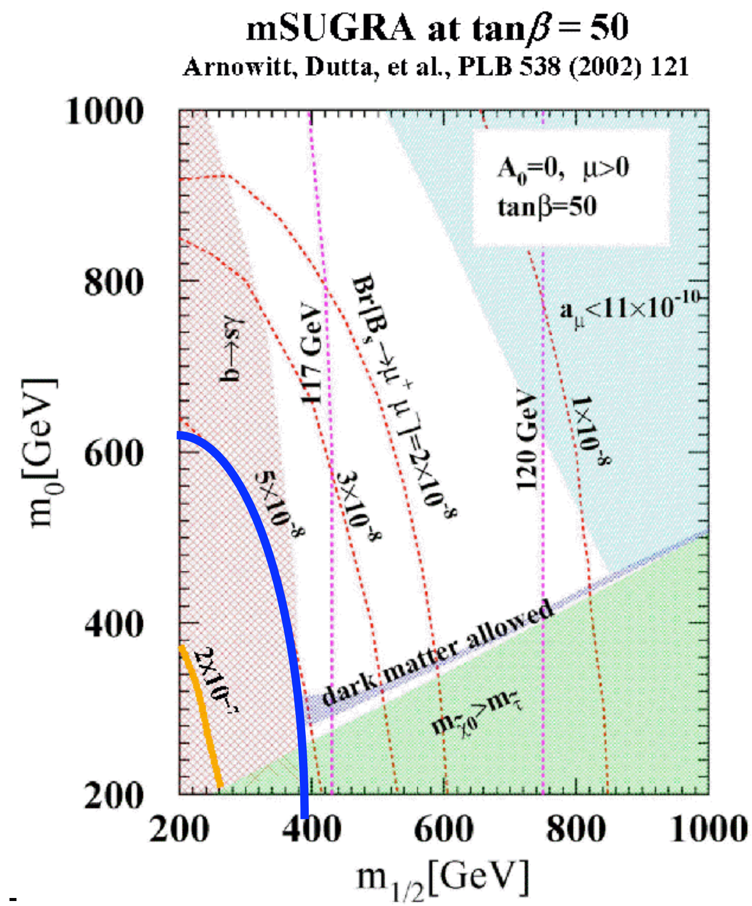


What did we learn about New Physics?



Z. Ligeti *et al.*

hep-ph/0604112



- SUSY contributions
  - affect both B_s mixing and $B_s \rightarrow \mu^+\mu^-$
  - Strong constraints on SUSY at large tanβ and small m_A
    - Corresponds e.g. to gluino mass of 1.1 TeV!

Conclusions

- New Physics could contribute to B hadron properties:
  - At hadron colliders
    - b-production cross section is 1000 times larger than at the B factories
    - all kinds of B hadrons are produced: B_d, B_s, Λ_b, B_c … Ξ_b
  - Observation of B_s meson oscillations:
    - Measurement **Δm_s = 17.77 +/- 0.10 (stat) +/- 0.07 (syst) ps^{-1}**
  - Evidence for D^0 mixing
    - Competitive with results from B factories
  - Search for $B_s \rightarrow \mu\mu$ yields strong limit
    - sensitive probe of New Physics
- No evidence for new physics contributions (yet)
  - Tomorrow's lecture: direct searches for the unknown