B Physics at the Tevatron: Physics of the B_s Meson

- Introduction to B_s Physics
- Tevatron, CDF and DØ
- Selected B_s Results
- Conclusion

Matthew Herndon, July 2006
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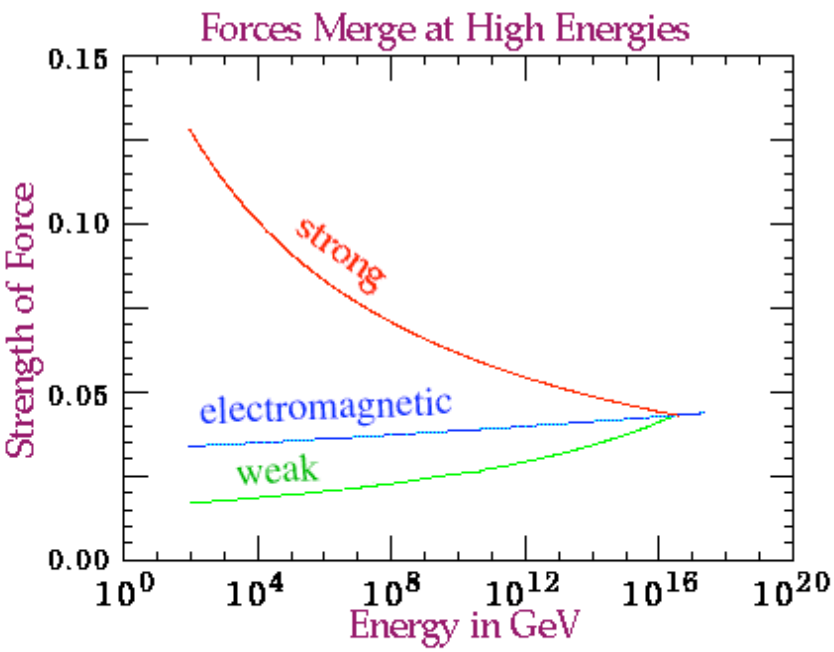
Why *B* Physics?

- To look for physics beyond the Standard Model

Standard Model fails to answer many fundamental questions

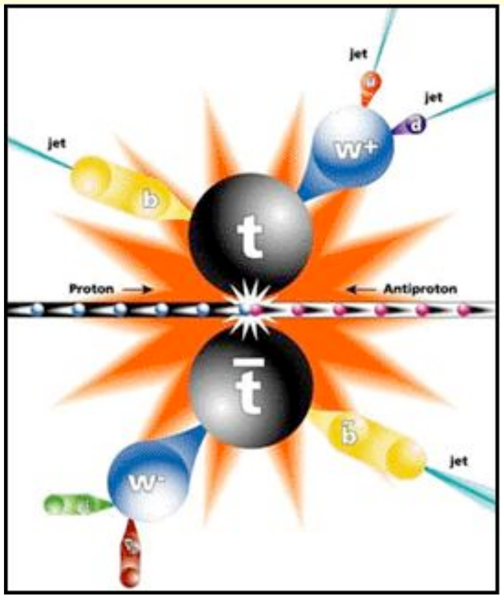
- Gravity not a part of the SM
- What is the very high energy behaviour?
  - At the beginning of the universe?
  - Grand unification of forces?
- Where is the Antimatter?
  - Why is the observed universe mostly matter?
- Dark Matter?
  - Astronomical observations of gravitational effects indicate that there is more matter than we see



Look for new physics that would explain these mysteries:
SUSY, Extra Dimensions ...

Searches For New Physics

- How do you search for new physics at a collider?
  - Direct searches for production of new particles
    - Particle-antipartical annihilation
    - Example: the top quark
  - Indirect searches for evidence of new particles
    - Within a complex process new particles can occur virtually



- Tevatron is at the energy frontier and

  a data volume frontier: 1 billion B and Charm events on tape
  - So much data that we can look for some very unusual processes
- Where to look
  - Many weak processes involving *B* hadrons are very low probability
  - Look for contributions from other low probability processes – Non Standard Model

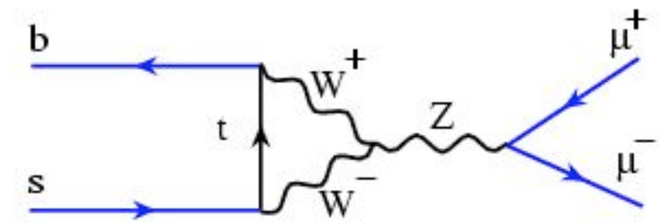
Rare Decays, CP Violating Decays and Processes such as Mixing
Present unique window of opportunity to find new physics before the LHC

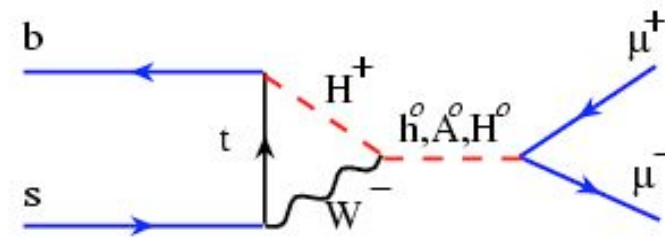
Physics of the B_s Meson

- Look at processes that are suppressed in the SM
- $B_{s(d)} \rightarrow \mu^+\mu^-$: FCNC to leptons
  - SM: No tree level decay, loop level suppressed
  - BF($B_{s(d)} \rightarrow \mu^+\mu^-$) = $3.5\mathrm{x}10^{-9}(1.0\mathrm{x}10^{-10})$

    G. Buchalla, A. Buras, Nucl. Phys. B398,285
  - NP: 3 orders of magnitude enhancement $\propto \tan^6\beta/(M_A)^4$

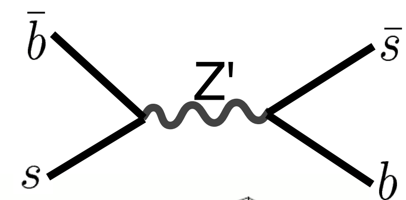
    Babu and Kolda, PRL 84, 228

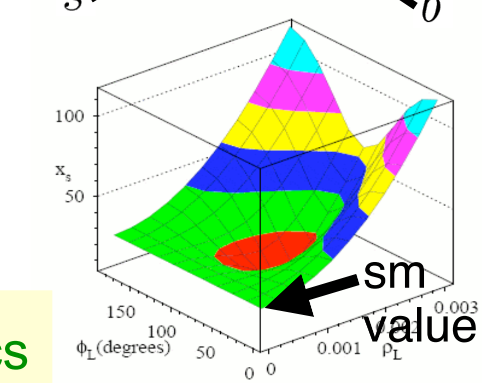




- B_s Oscillations
  - SM: Loop level box diagram
  - Oscillation frequency can be calculated using electroweak SM physics and lattice QCD
  - NP can enhance the oscillation process, higher frequencies

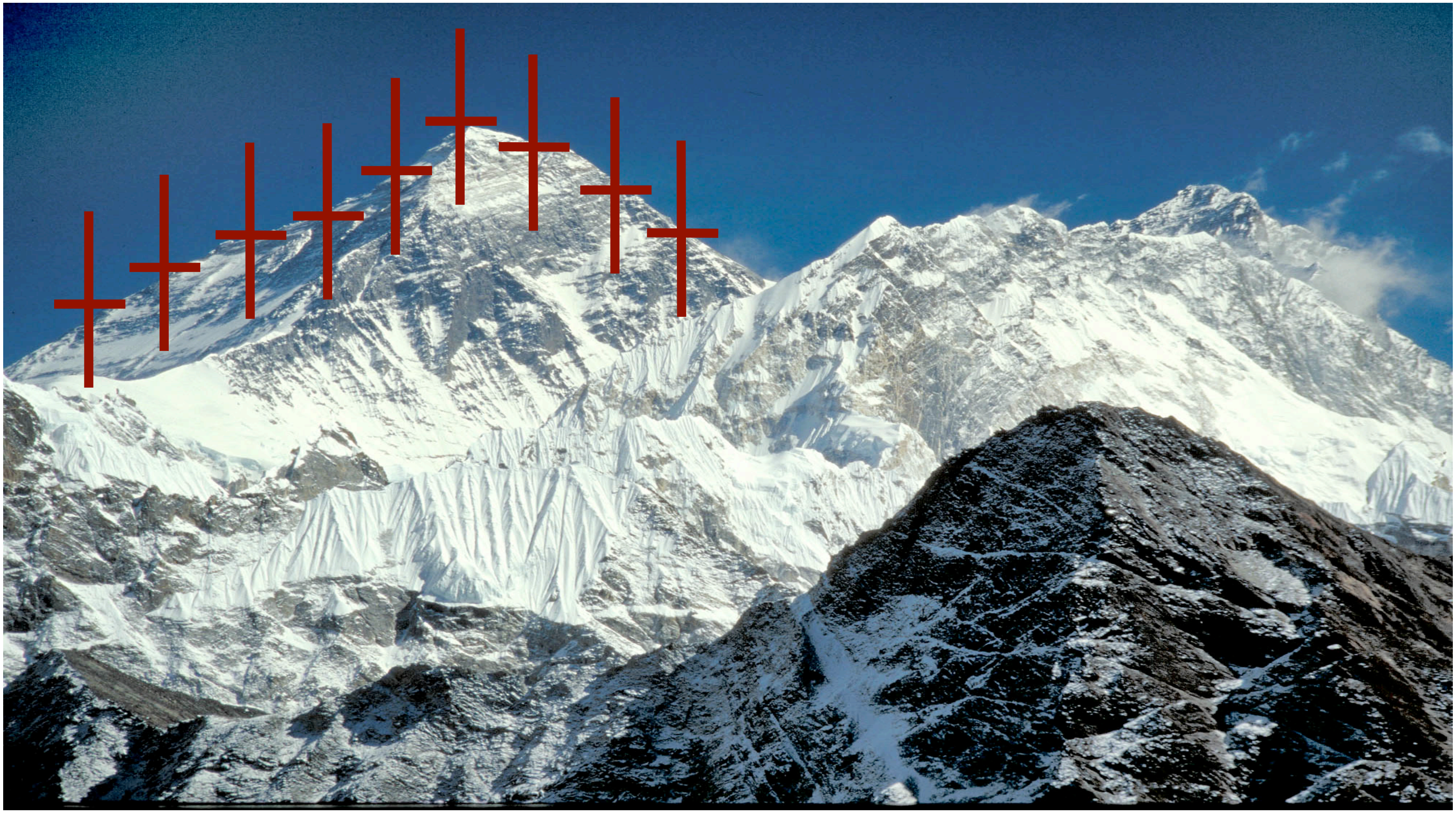
    Barger et al., PL B596 229, 2004, one example of many
  - Related: $\Delta\Gamma$ and CP violation





Tevatron has many opportunities to look for New Physics

The Real Motivation

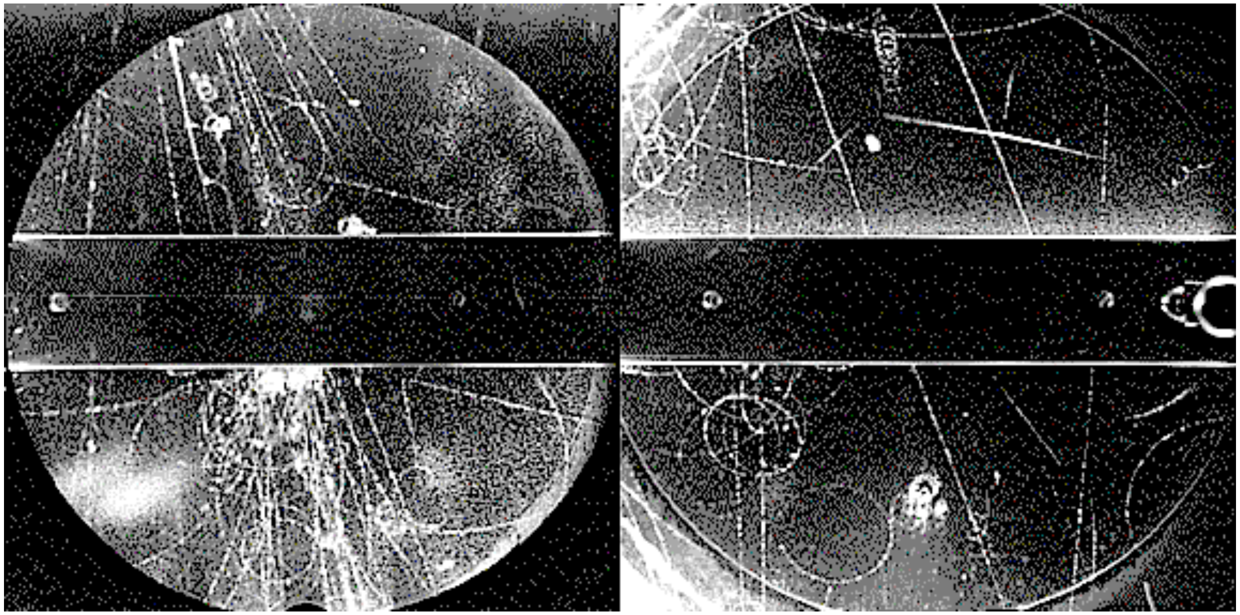


Because it's there

Mallory

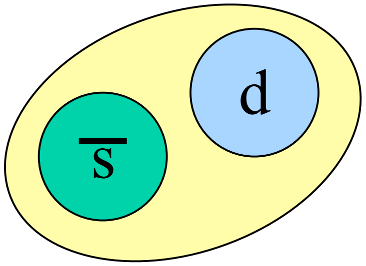
A Little History

- Everything started with kaons
  - Flavor physics is the study of bound states of quarks.
  - Kaon: Discovered using a cloud chamber in 1947 by Rochester and Butler.
  - Could decay to pions and had a very long lifetime. 10^{-10} sec



- Bound state of up or down quarks with with a new particle: the strange quark!
  - Needed the weak force to understand it's interactions.
  - Neutron kaons were some of the most interesting kaons

K^0



Rich ground for studying new physics

Physics of Neutral Mesons

- New physics(at the time) of neutral particles and antiparticles
- K^0 and $\bar{K}^0$
- Interacted differently with weak and strong force. Different eigenstates
  - Strong force quark eigenstates: K^0 and $\bar{K}^0$
  - Weak force mass and CP eigenstates: K^0_S and K^0_L

Weak force violated C and P thought to conserve CP

- The Schrödenger equation
  - H not diagonal
  - K^0 and $\bar{K}^0$ not mass eigenstates

$$i\frac{\partial}{\partial t}\psi = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & 0 \\ 0 & \Gamma \end{pmatrix}\psi$$

- Treat the particle and antipaticle as one two state system(Gellman, Pais)

$$|K_1\rangle = \frac{1}{\sqrt{2}}(|K_0\rangle - |\bar{K}_0\rangle)$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}(|K_0\rangle + |\bar{K}_0\rangle)$$

$CP|K^0\rangle = -|\bar{K}^0\rangle$ and $CP|\bar{K}^0\rangle = -|K^0\rangle$:

$$CP|K_1\rangle = +|K_1\rangle \quad \text{CP} - \text{even}$$

$$CP|K_2\rangle = -|K_2\rangle \quad \text{CP} - \text{odd}$$

- New states mass eigenstates $K^0_S = K_1 \to \pi\pi$ $\quad K^0_L = K_2 \to \pi\pi\pi$
  - $\Delta m = 2M_{12}$, width difference $\Delta\Gamma$, also predicted conversion of matter to antimatter

Neutral Kaons

Observation of Long-Lived Neutral *V* Particles*

K. Lande, E. T. Booth, J. Impeduglia, and L. M. Lederman,
Columbia University, New York, New York
and
W. Chinowsky, *Brookhaven National Laboratory, Upton, New York*

(Received July 30, 1956)

PR 103, 1901 (1956)

1954: Mixing Predicted

1956: CP Eigenstates Observed

1964: CP Violation Observed

PHYSICAL REVIEW VOLUME 97, NUMBER 5 MARCH 1, 1955

Behavior of Neutral Particles under Charge Conjugation

M. Gell-Mann,* *Department of Physics, Columbia University, New York, New York*
and
A. Pais, *Institute for Advanced Study, Princeton, New Jersey*

(Received November 1, 1954)

Volume 13, Number 4 PHYSICAL REVIEW LETTERS 27 July 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey

(Received 10 July 1964)

New Physics in a rare decay: CP violating $K_L(\text{odd}) \rightarrow 2\pi(\text{even})$

- Very Rare decays observed in the Kaon system:

$BF(K^0_L \rightarrow \pi^+\pi^-) = 2.1\text{x}10^{-3}$

$BF(K^0_L \rightarrow \mu^+\mu^-) = 7.3\text{x}10^{-9}$

B_s CKM Physics

- Our knowledge of the flavor physics can be expressed in the CKM matrix
  - Translation between mass(strong) and flavor(weak) eigenstantes

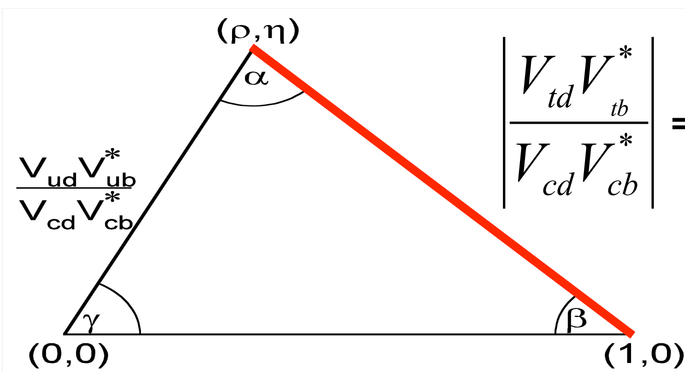
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

CP violating phase

Also in higher order terms

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

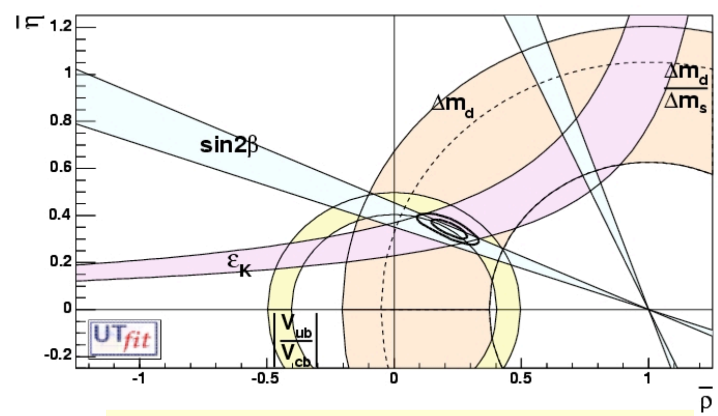
Unitarity relationship for b quarks



$$\left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| = \frac{|V_{td}|}{|V_{ts}|} \times \frac{1}{|V_{cd}|}$$

$$\sim \sqrt{\frac{\Delta m_d}{\Delta m_s}}$$

Some theoretical errors cancel out in the ratio

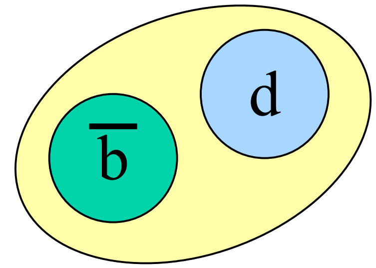


$$\frac{\Delta\Gamma B_s}{\Delta m_s} = 3.9 \times 10^{-3}$$

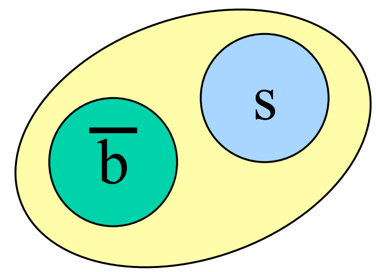
Several important B_s CKM Measurements

Neutral *B* Mesons

- The B^0 and B_s meson
  - Very interesting place to look for new physics(in our time)
    Higgs physics couples to mass so *B* mesons are interesting
  - Same program. Rare decays, CP violation, oscillations



- First evidence for *B* meson oscillations
  How the B_s meson was found
  - 1987: UA1 Integrated mixing measurement
  - $\bar{\chi}$: Compare charges of leptons from two B decays: opposite(unmixed) same(mixed)
  - 1987: Argus measured B_0 meson mixing frequency
  - UA1 and Argus measurements disagreed!



$$\chi = \frac{x^2}{2(1+x^2)} \qquad x = \frac{\Delta m}{\Gamma} = \Delta m \cdot \tau$$

$$\bar{\chi} = f_d \chi_d + f_s \chi_s = \mathbf{0.18} f_d + \mathbf{0.50} f_s$$

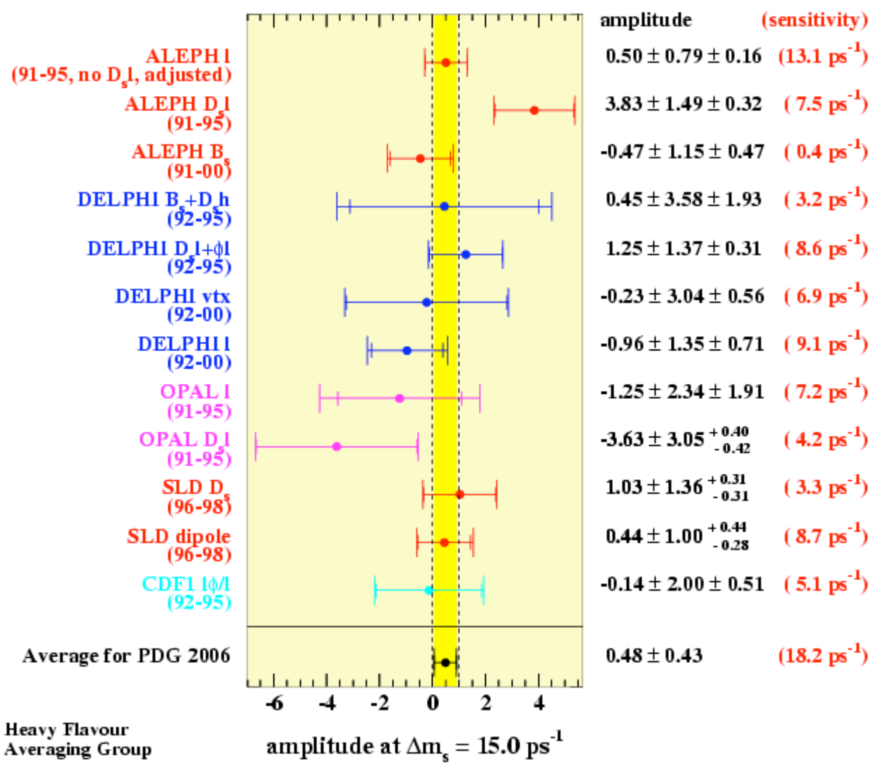
First evidence for the B_s meson - Also could tell it oscillated fast!

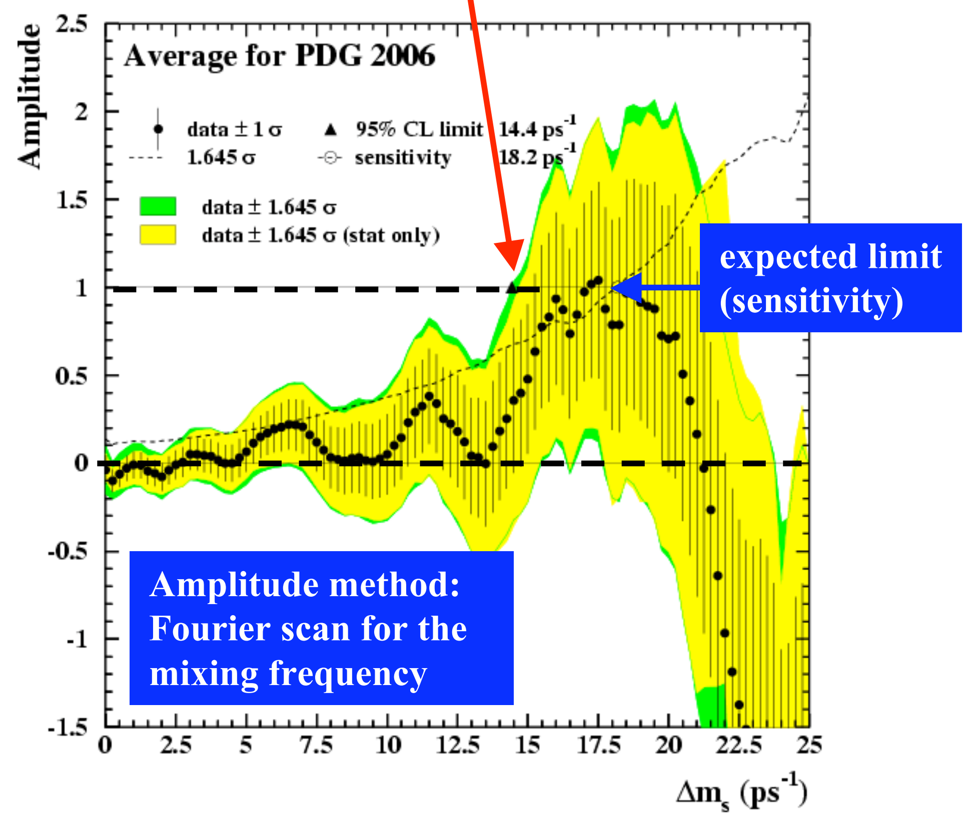
B_s Oscillations

- With the first evidence of the B_s meson we knew it oscillated fast.
  - How fast has been a challenge for a generation of experiments.

> 2.3 THz

$\Delta m_s > 14.4\ ps^{-1}$ 95% CL





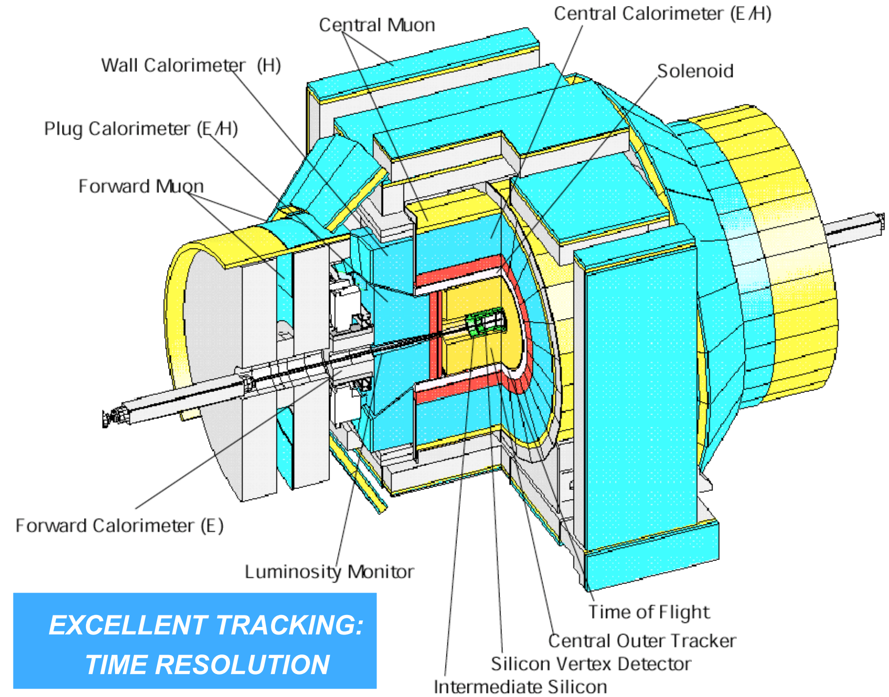
Run 2 Tevatron experiments built to meet this challenge

CDF and DØ Detectors

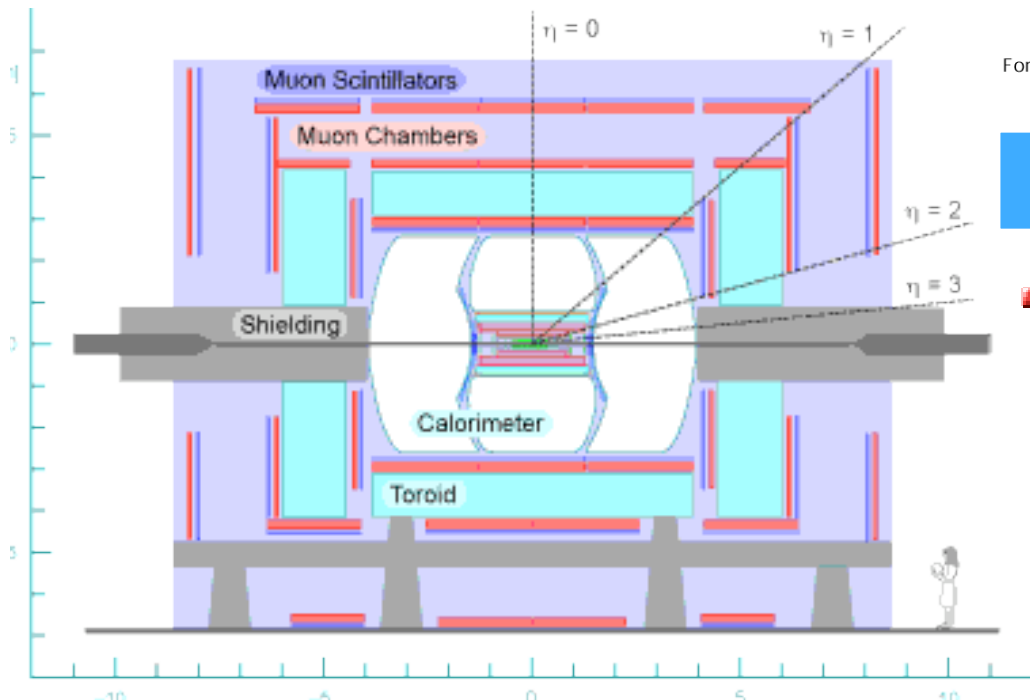
- CDF Tracker
  - Silicon |η|<2, 90cm long, r_{L00} =1.3 - 1.6cm
  - 96 layer drift chamber 44 to 132cm

EXCELLENT TRACKING: MASS RESOLUTION

- Triggered Muon coverage: |η|<1.0



EXCELLENT TRACKING: TIME RESOLUTION



- DØ Tracker
  - Silicon and Scintillating Fiber
  - Tracking to |η|<2

EXCELLENT TRACKING: EFFICIENCY

  - New L0 on beam pipe
- Triggered Muon coverage: |η|<2.0

The Trigger

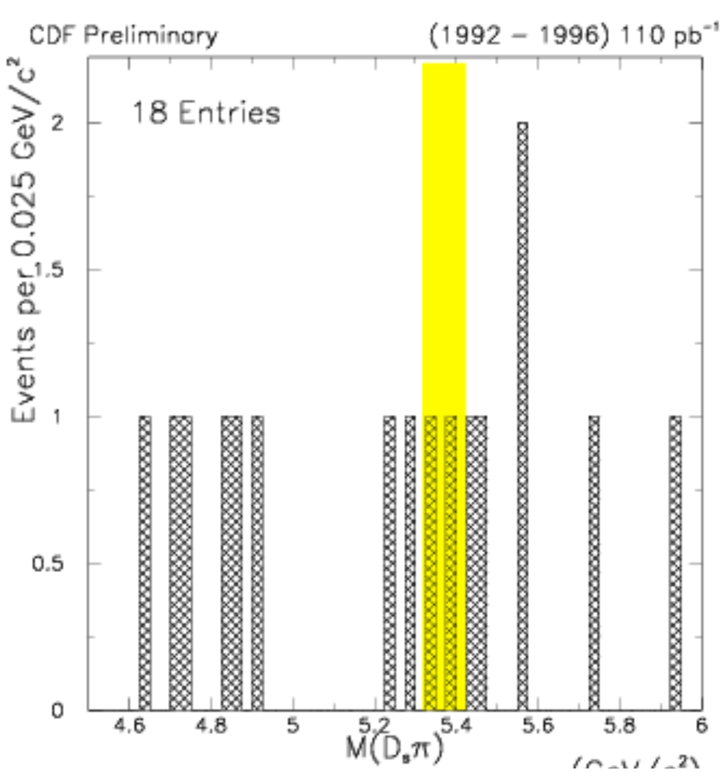
- Hadron collider: Large production rates
  - $\sigma(pp \rightarrow bX, |y| < 1.0, p_T(B) > 6.0\text{GeV/c}) = \sim 30\mu b, \sim 10\mu b$

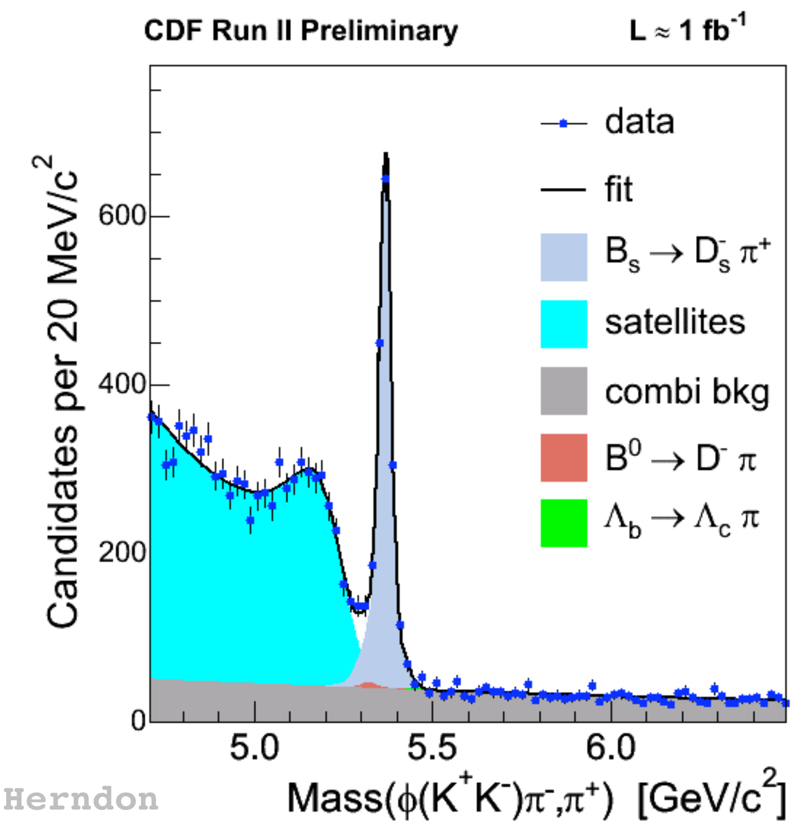
TRIGGERS ARE CRITICAL

- Backgrounds: > 3 orders of magnitude higher
  - Inelastic cross section ~100 mb

1 Billion B and Charm Events on Tape

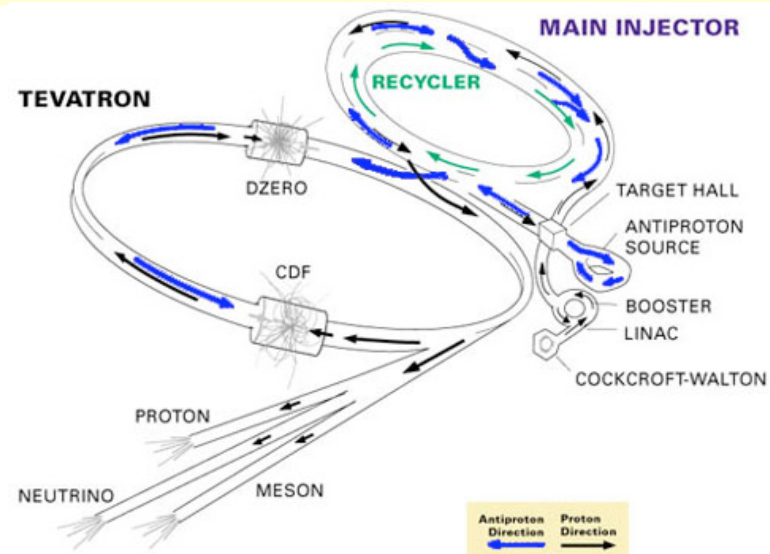
- Single and double muon based triggers and displaced track based triggers

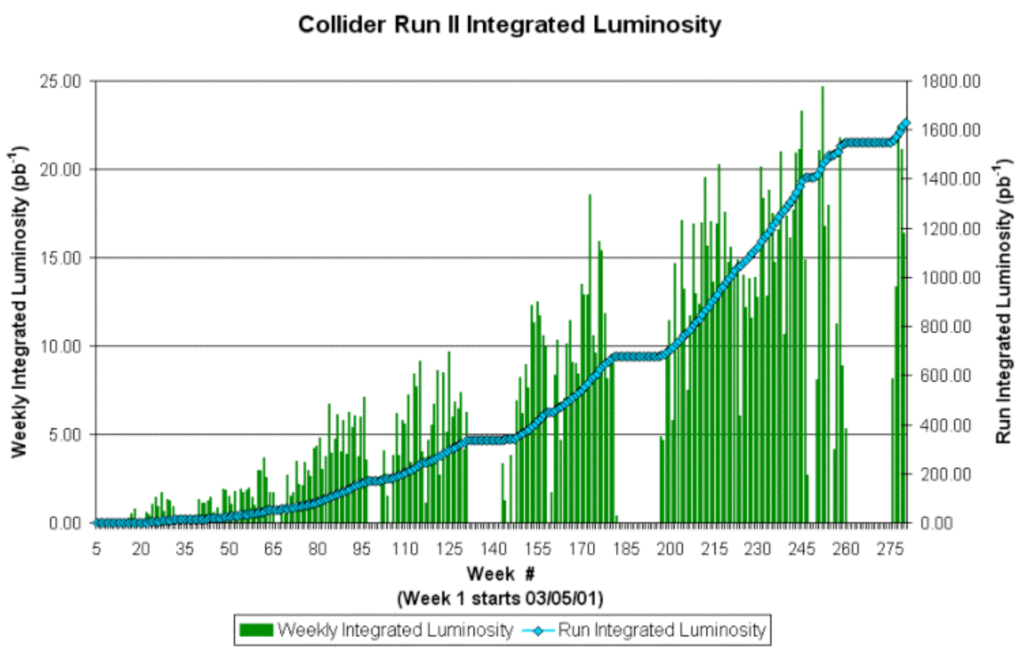




The Tevatron

- 1.96TeV $p\bar{p}$ collider
  - Excellent performance and improving each year
  - Record peak luminosity in 2006: $1.8 \times 10^{32} sec^{-1} cm^{-2}$





CDF/DØ Integrated Luminosity

- ~$1 fb^{-1}$ with good run requirements through 2005
  - All critical systems operating including silicon
- Doubled data in 2005, predicted to double again in 2006

B_s physics benefits from more data

The Results!

- Combining together excellent detectors and accelerator performance
- Ready to pursue a full program of B_s physics

- Today…

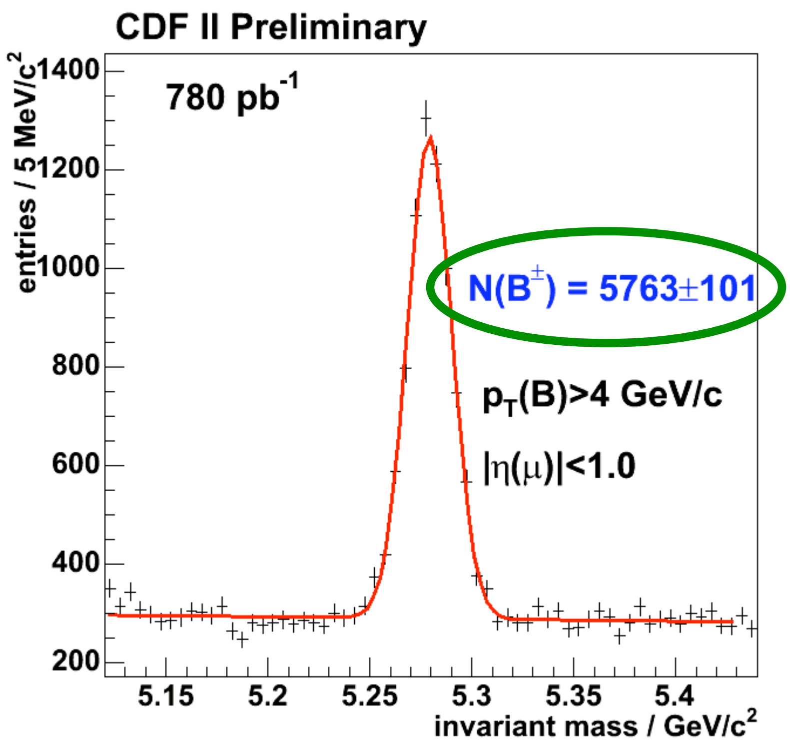
$B_s \rightarrow \mu\mu$

$\Delta\Gamma$ B_s and CP violation

B_s Oscillations

$B_{s(d)} \rightarrow \mu^+\mu^-$ Method

- Relative normalization search
  - Measure the rate of $B_{s(d)} \rightarrow \mu^+\mu^-$ decays relative to $B \rightarrow J/\psi K^+$
  - Apply same sample selection criteria
  - Systematic uncertainties will cancel out in the ratios of the normalization
  - Example: muon trigger efficiency same for J/ψ or B_s μs for a given p_T



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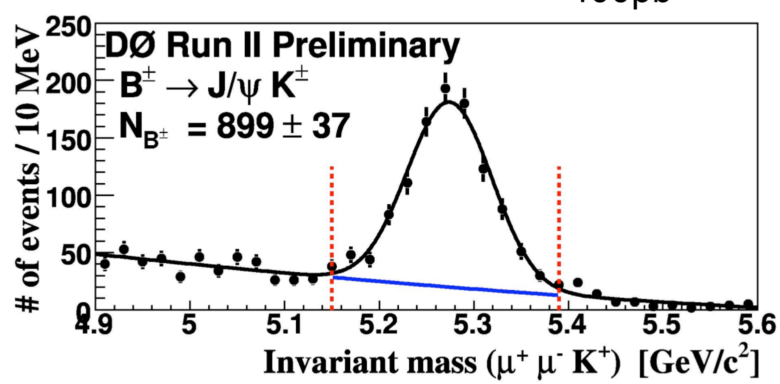

$$BF(B_s \rightarrow \mu^+\mu^-) = \frac{(N_{cand} - N_{bg})}{\alpha_{Bs}\varepsilon_{Bs}} \bullet \frac{\alpha_{B^+}\varepsilon_{B^+}}{N_{B^+}} \bullet \frac{f_u}{f_u} \bullet$$
$$BR(B^+ \rightarrow J/\psi K^+) \bullet BR(J/\psi \rightarrow \mu^+\mu^-)$$

$B_{s(d)} \to \mu^+\mu^-$ Method

- Relative normalization search
  - Measure the rate of $B_{s(d)} \to \mu^+\mu^-$ decays relative to $B \to J/\psi K^+$
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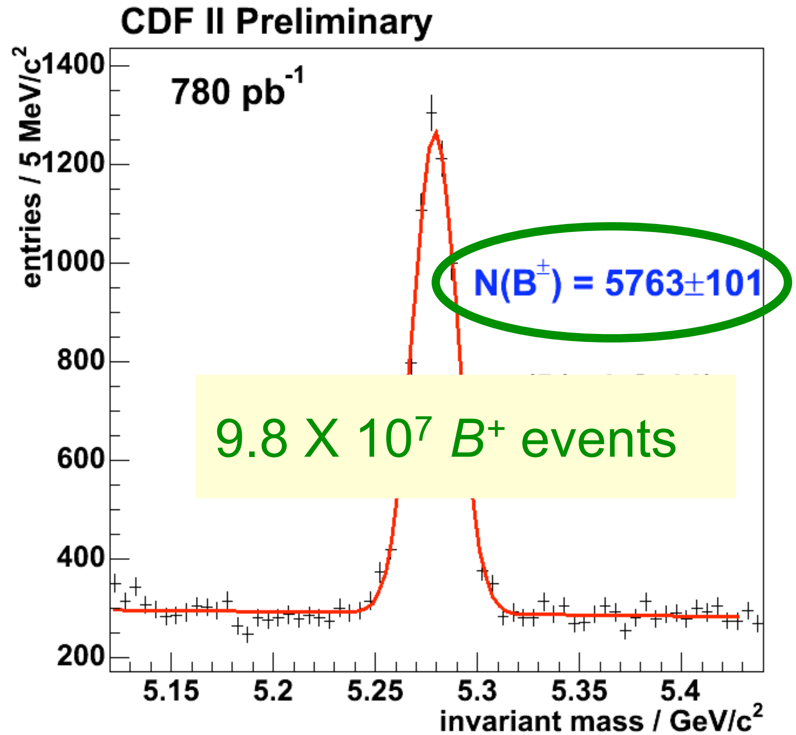

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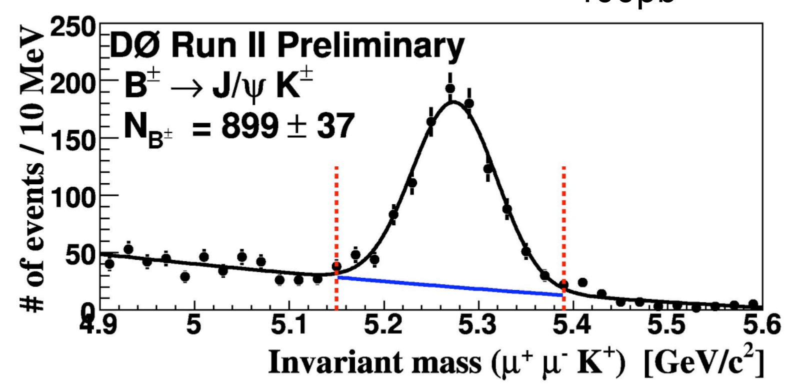
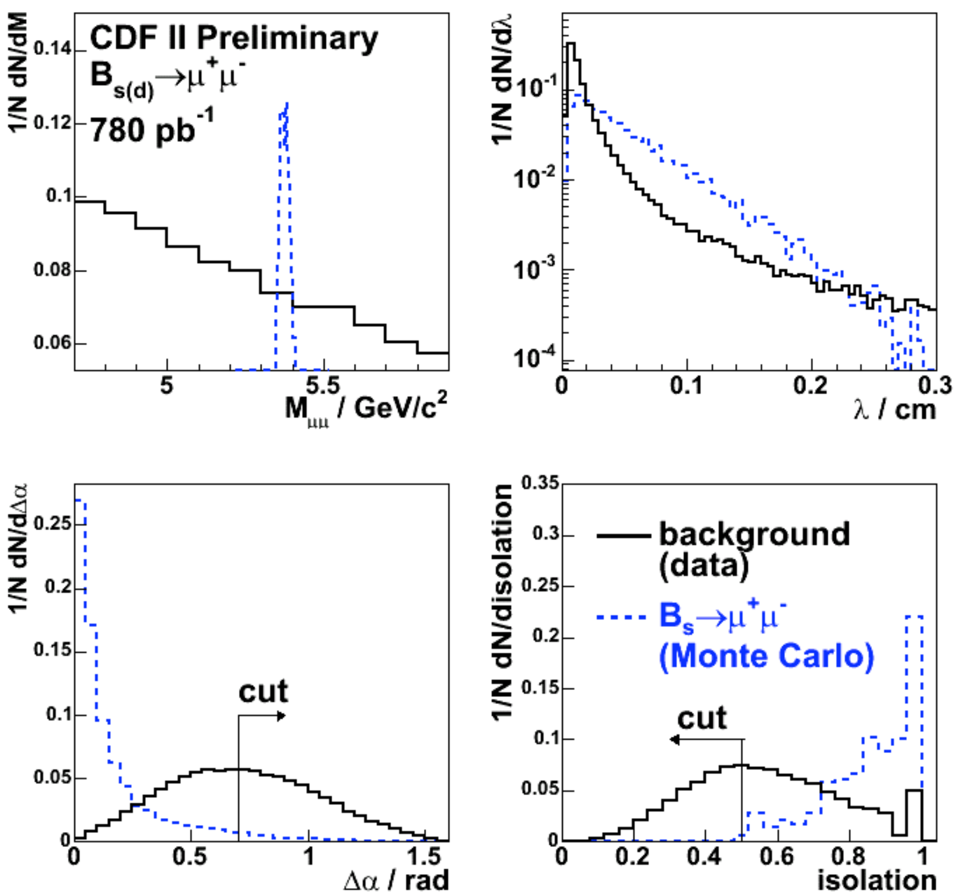


$$BF(B_s \to \mu^+\mu^-) = \frac{(N_{cand} - N_{bg})}{\alpha_{Bs}\varepsilon_{Bs}} \bullet \frac{\alpha_{B^+}\varepsilon_{B^+}}{N_{B^+}} \bullet \frac{f_u}{f_u} \bullet$$

$$BR(B^+ \to J/\psi K^+) \bullet BR(J/\psi \to \mu^+\mu^-)$$

Discriminating Variables

- 4 primary discriminating variables



- Mass $M_{\mu\mu}$
  - CDF: 2.5σ window: σ = 25*MeV/c*^{2}
  - DØ: 2σ window: σ = 90*MeV/c*^{2}
- CDF $\lambda = c\tau/c\tau_{Bs}$, DØ L_{xy}/σ_{Lxy}
- $\Delta\alpha$: $|\varphi_B - \varphi_{vtx}|$ in 3D
- Isolation: $p_{TB}/(\Sigma trk + p_{TB})$
- CDF, λ, Δα and Iso: used in likelihood ratio
- D0 uses optimized cuts
- Optimization
  - Unbiased optimization
  - Based on simulated signal and data sidebands

$B_{s(d)} \to \mu^+\mu^-$ Search Results

- CDF Result: 1(2) $B_{s(d)}$ candidates observed consistent with background expectation

$BF(B_s \to \mu^+\mu^-) < 1.0\text{x}10^{-7}$ at 95% CL

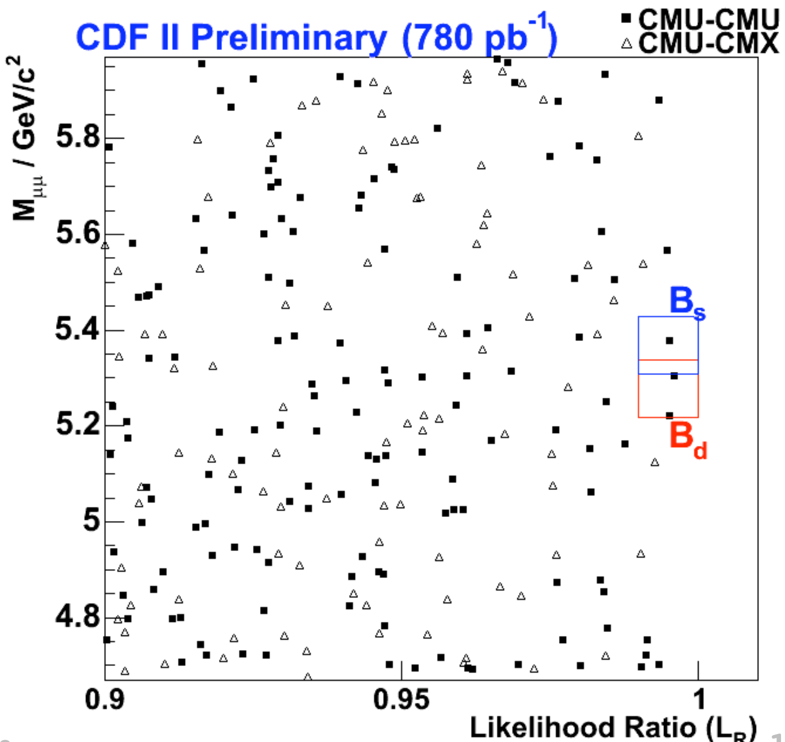
$BF(B_d \to \mu^+\mu^-) < 3.0\text{x}10^{-8}$ at 95% CL

Worlds Best Limits!

- D0 Result: with 300pb^{-1} 4 events. 700pb^{-1} still blind - expected limit:

$BF(B_s \to \mu^+\mu^-) < 2.3\text{x}10^{-7}$ at 95% CL

Decay	Total Expected Background	Observed
CDF B_s	1.27 ± 0.36	1
CDF B_d	2.45 ± 0.39	2
D0 B_s	4+2.2 ± 0.7	4+??



- CDF 1 B_s result: 3.0×10^{-6}
  PRD 57, 3811 1998
- BaBar B_d result: 8.3×10^{-8}(90%)
  PRL 94, 221803 2005

New Physics in $\Delta\Gamma$ B_s

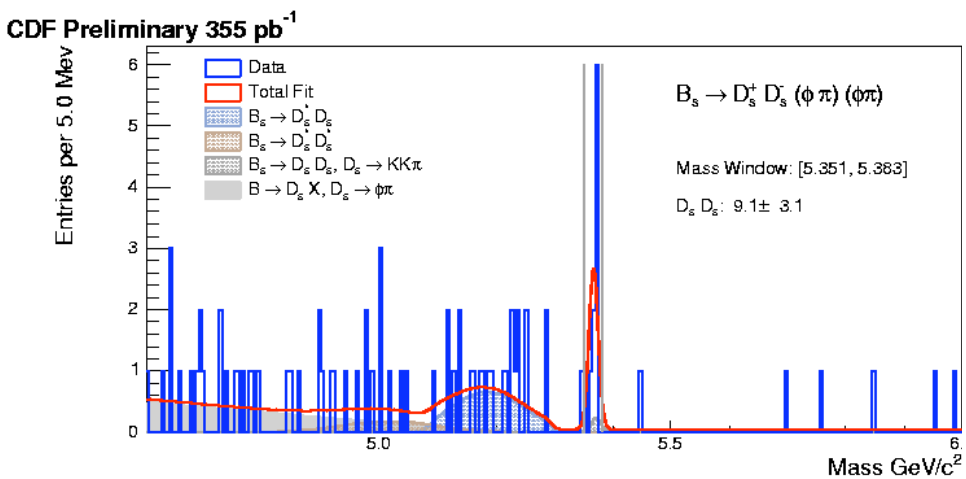
- $\Delta\Gamma$ B_s Width-lifetime difference between eigenstantes

  $B_{s,Short,Light} \rightarrow$ *CP even* $B_{s,Long,Heavy} \rightarrow$ *CP odd*

- New physics can contribute in penguin diagrams

$$\Delta\Gamma_{Bs}^{meas} = \Delta\Gamma_{Bs}^{SMCPCons} \bullet \cos(\phi^{SM} + \phi^{NP})$$

- Measurements
  - Directly measure lifetimes in $B_s \rightarrow J/\psi\phi$
    Separate CP states by angular distribution and measure lifetimes
  - Measure lifetime in $B_s \rightarrow K^+ K^-$
    CP even state
  - Search for $B_s \rightarrow D_s^{(*)} D_s^{(*)}$
    CP even state
    May account for most of the lifetime-width difference

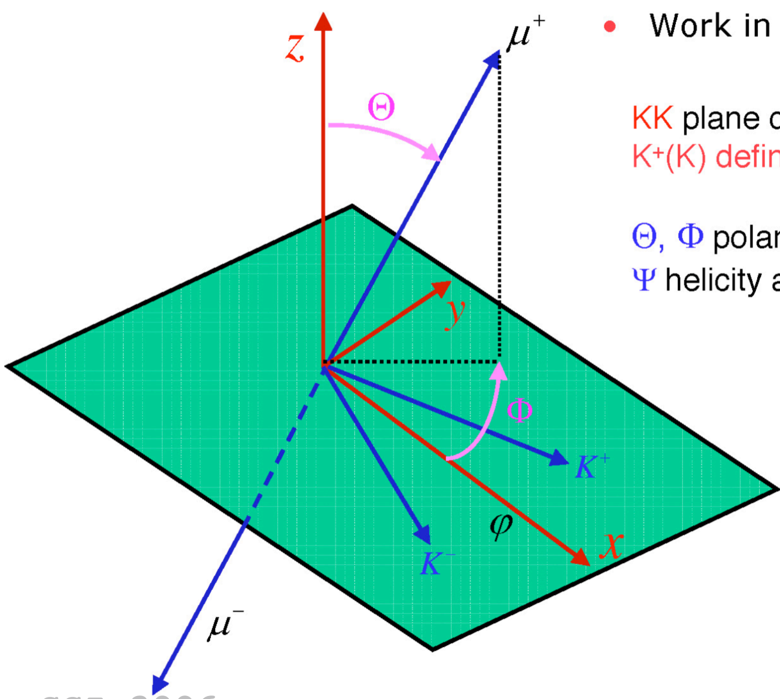


Many Orthogonal Methods!

$\Delta\Gamma$ B_s Method: $B_s \rightarrow J/\psi\phi$

- Directly measure lifetimes in $B_s \rightarrow J/\psi\phi$
  - Separate CP states by angular distribution and measure lifetimes
  - A_0 = S + D wave → P even
  - $A_{||}$ = S + D wave → P even
  - $A_\perp$ = P wave → P odd
  - $B_{s,Short,Light}$ → *CP even*
  - $B_{s,Long,Heavy}$ → *CP odd*

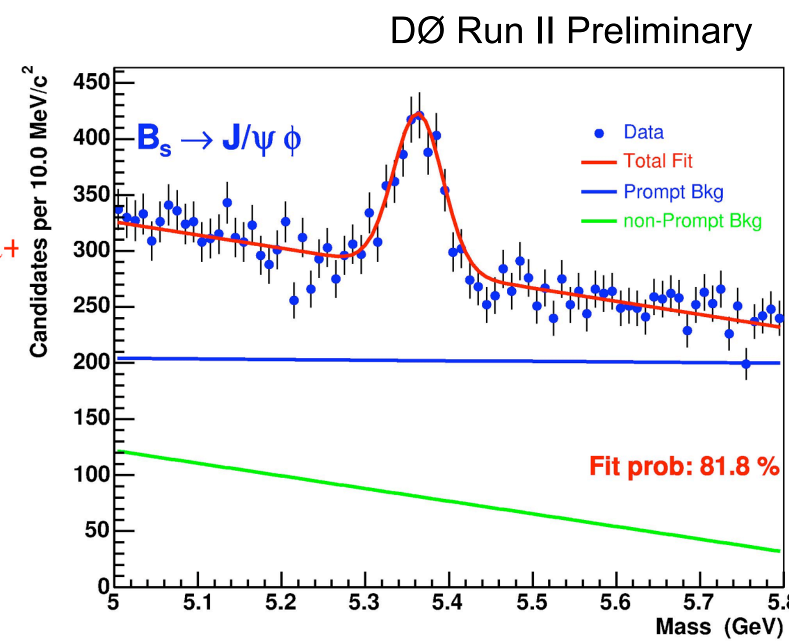
CP Violation will change this picture



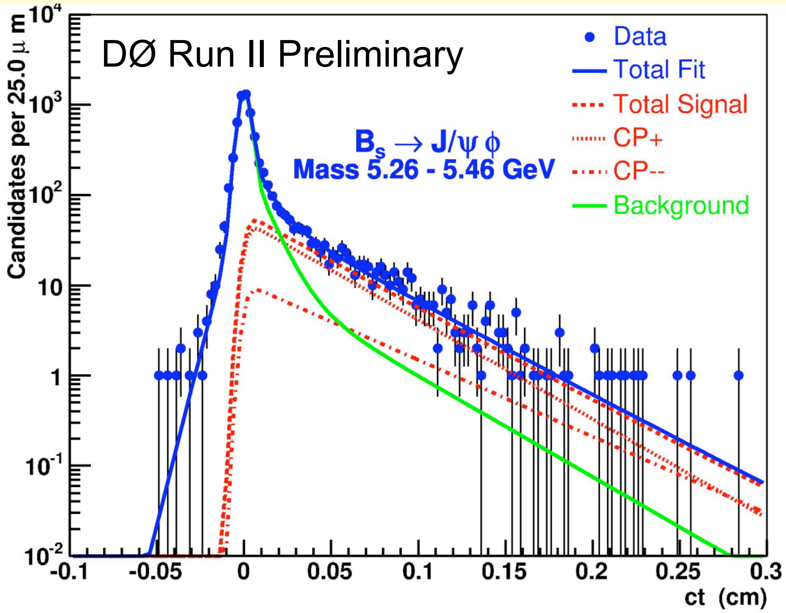
- Work in J/Ψ rest Frame

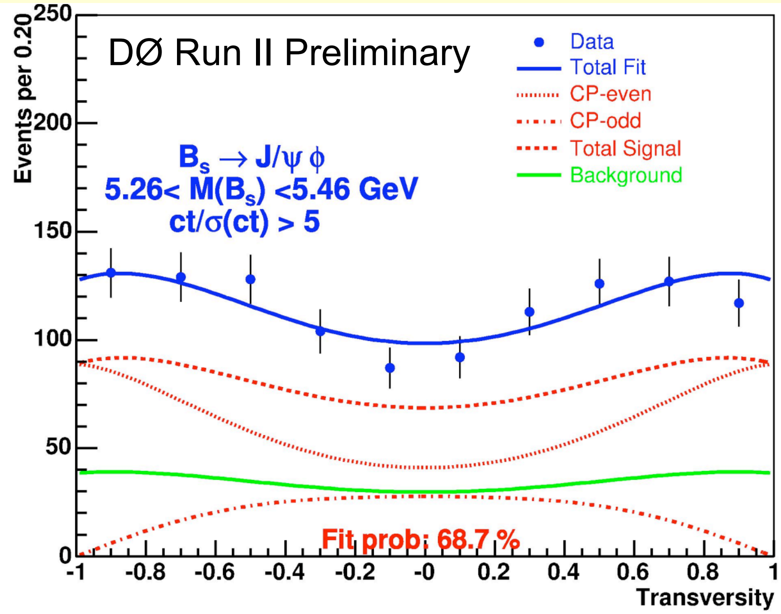
KK plane defines (x,y) plane
K+(K) defines +y direction

Θ, Φ polar & azimuthal angles of μ+
Ψ helicity angle of ϕ (K*)



$\Delta\Gamma$ B_s Results: $B_s \to J/\psi\phi$



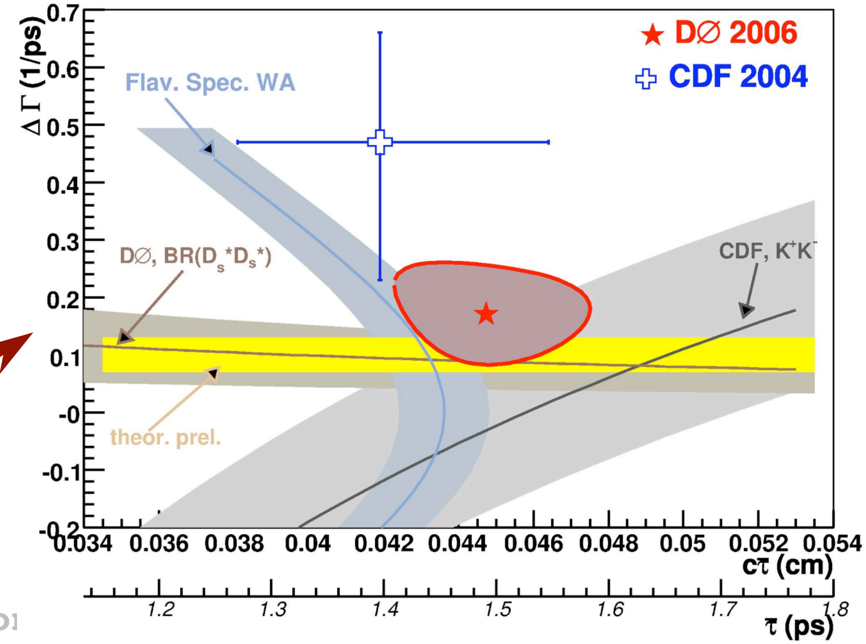


- Assuming no CP violation

$\Delta\Gamma$ B_s = 0.12 ± 0.08 ± 0.03 ps^{-1}

Non 0 $\Delta\Gamma$ B_s

- Putting all the measurements together



$\Delta\Gamma$ B_s CP Violation Results

- Allowing for CP Violation

$$\Delta\Gamma_{Bs}^{meas} = \Delta\Gamma_{Bs}^{SMCPCons} \bullet \cos(\phi^{SM} + \phi^{NP})$$

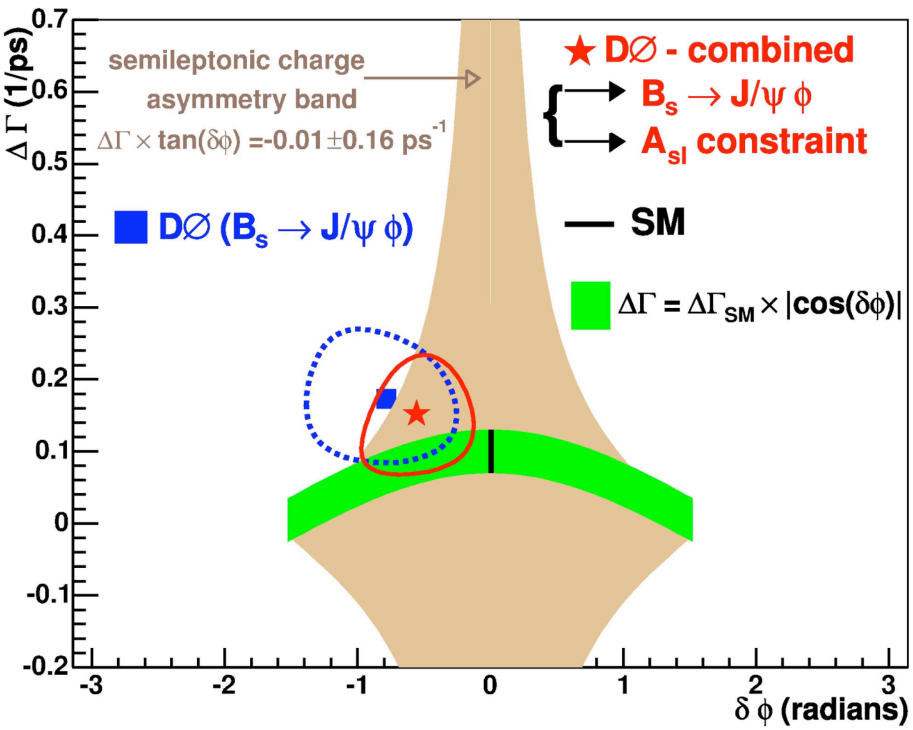
$\Delta\Gamma$ B_s = 0.17 ± 0.09 ± 0.03 ps^{-1}

$\phi = \phi^{NP} + \phi^{SM}$ = -0.79 ± 0.56 ± 0.01

- Combine with searches for CP violation in semileptonic *B* decays

$\Delta\Gamma$ B_s = 0.15 ± 0.08 ± 0.03 ps^{-1}

$\phi = \phi^{NP} + \phi^{SM}$ = -0.56 ± 0.40 ± 0.01

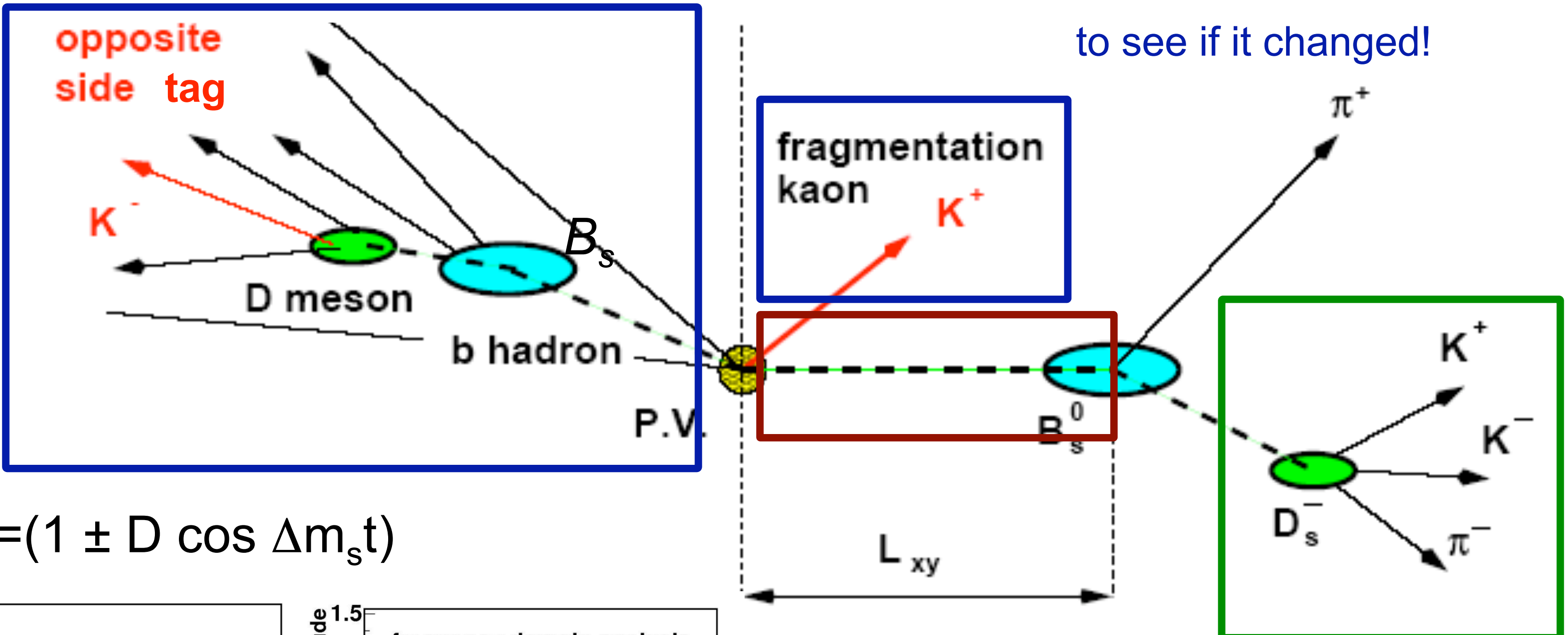


- Consistent with SM $\Delta\Gamma$ B_s = 0.10 ± 0.03 ϕ^{SM} = -0.03 - +0.005

U. Nierste hep-ph/0406300

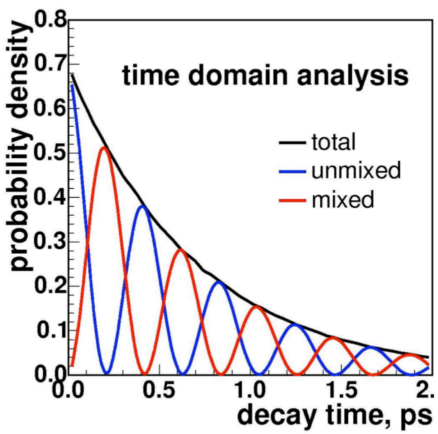
B_s Mixing: Overview

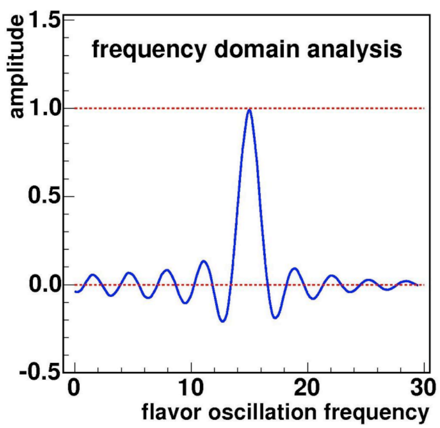
- Measurement of the rate of conversion from matter to antimatter: $B_s \Leftrightarrow \bar{B}_s$
  - Determine b meson flavor at production, how long it lived, and flavor at decay to see if it changed!



$p(t)=(1 \pm D \cos \Delta m_s t)$

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



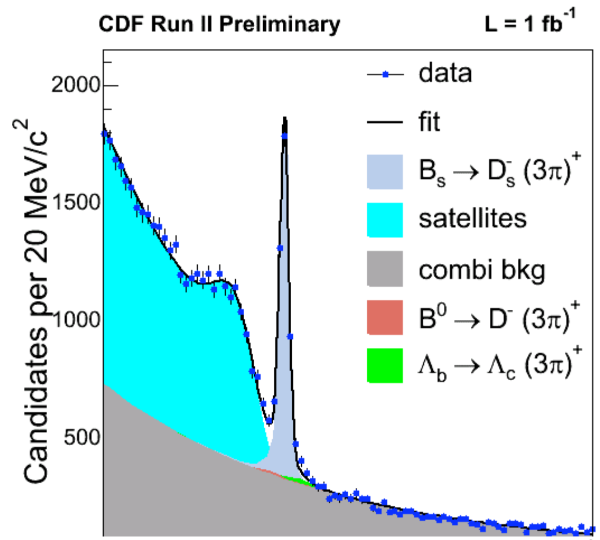


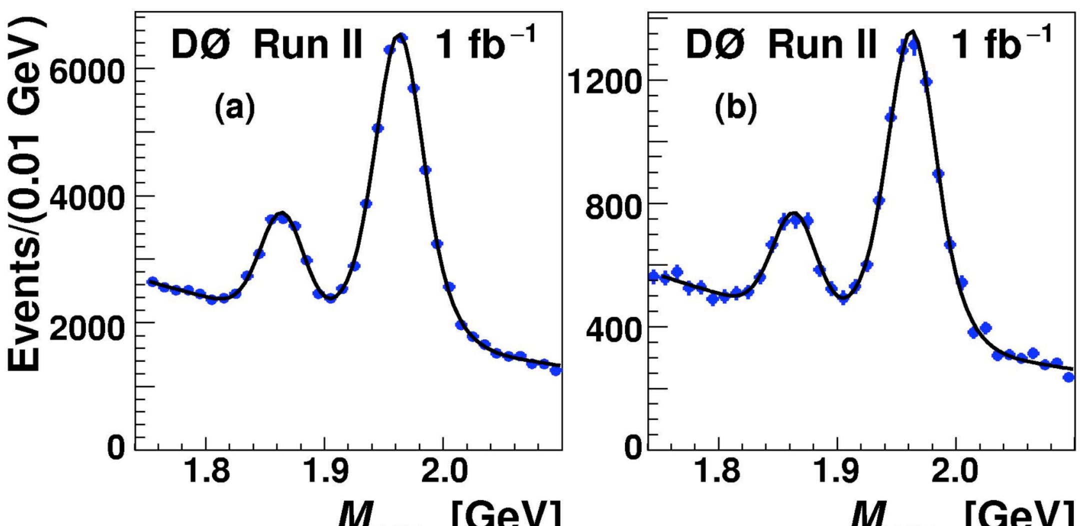
$$\frac{1}{\sigma_A} = \sqrt{S\epsilon D^2} \times \sqrt{\frac{S}{S+B}} \times e^{-\frac{1}{2}(\sigma_t \Delta m_s)^2}$$

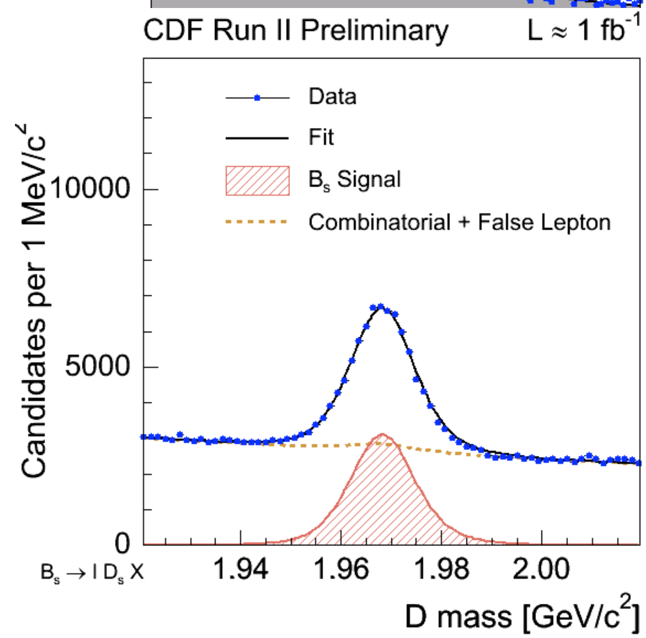
B_s Mixing: Signals

- Fully reconstructed decays: $B_s \to D_s\pi(2\pi)$, where $D_s \to \phi\pi$, K^*K, 3π
- Semiletonic decays: $B_s \to D_s l X$, *where* $l = e,\mu$

Decay	Candidates
CDF $B_s \to D_s\pi(2\pi)$	3600
CDF $B_s \to D_s l X$	37,000
D0 $B_s \to D_s l X$	27,000



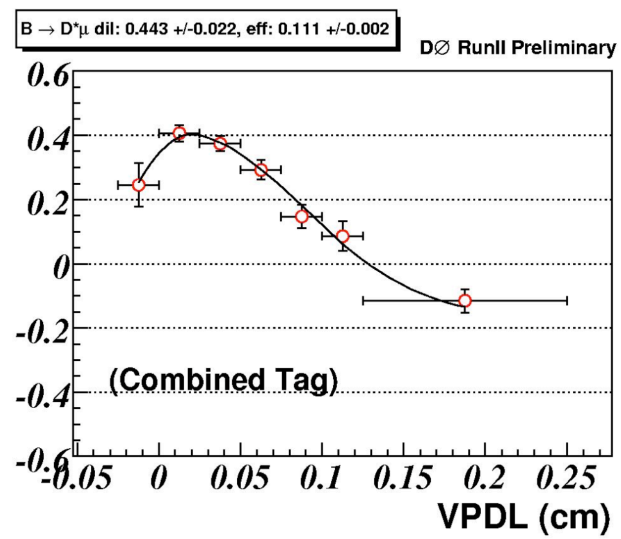




B_s Mixing: Flavor Tagging

- D0 Opposite side tag(OST): Combined Jet finding, b vertex and lepton tag
  - Information combined in a likelihood ratio
- CDF OST: Separate Jet with b vertex and lepton tags
  - Hierarchy of tags with most accurate tag taken first
- CDF Same side tag(SST): Kaon PID
- Taggers calibrated in data where possible
  - OST tags calibrated using B^+ data and by performing a B^0 oscillation analysis
  - SST calibrated using MC and kaon finding performance validated in data

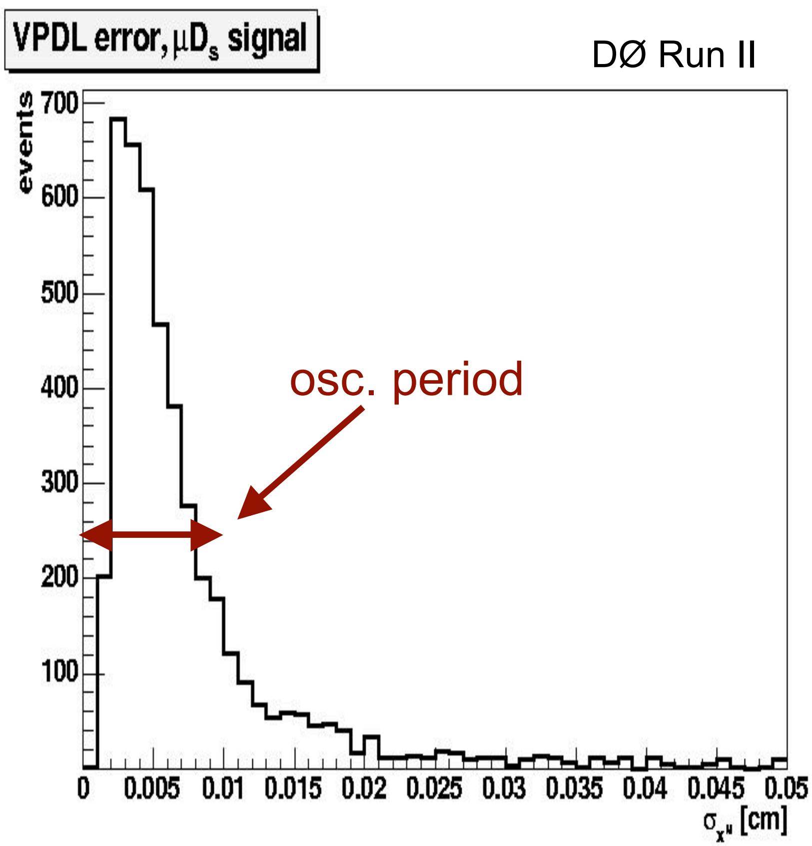
Tag	Performance(εD^2)
D0 OST	2.48 ± 0.21 ± 0.07%
CDF OST	1.5 ± 0.01%
CDF SST	3.5 ± 0.87%(4.0%)

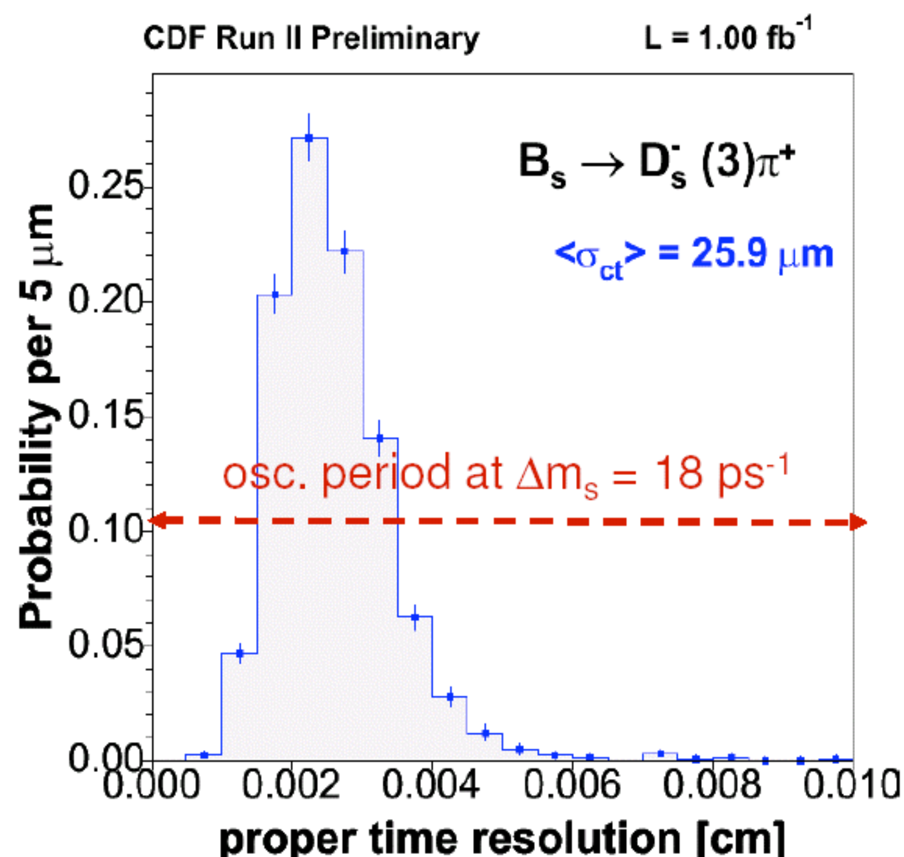


B_s Mixing: Proper Time Resolution

- Measurement critically dependent on proper time resolution
  - Full reconstructed events have excellent proper time resolution
  - Semileptonic events have worse resolution
  - Momentum necessary to convert from decay length to proper time

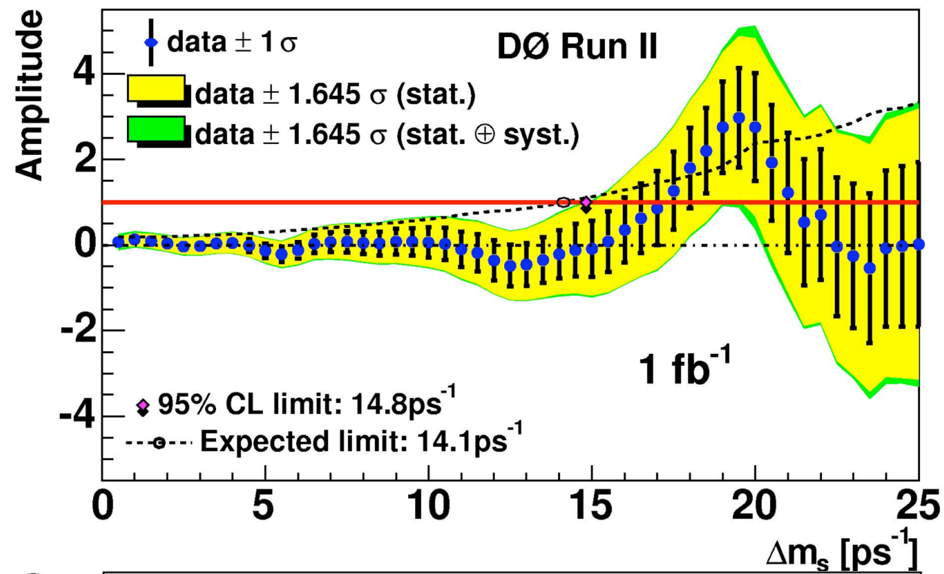
$$ct = L_{xy}\frac{m_b}{p_T}$$





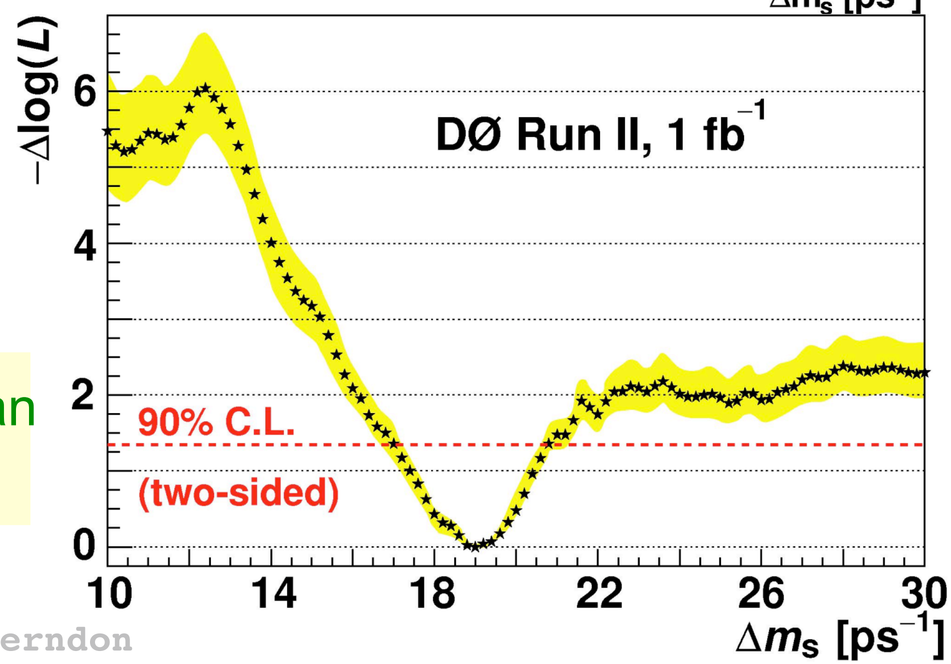
B_s Mixing: DØ Results

Key Features	Result
Sen: 95%CL	14.1ps^{-1}
Sen: σ_A(@17.5ps^{-1})	0.91
A/σ_A	2.5
Prob. Fluctuation	5%
Peak value: Δm_s	19ps^{-1}



Limits: 17-21ps^{-1} @90CL

One experiment with more sensitive than a whole generation of experiments!



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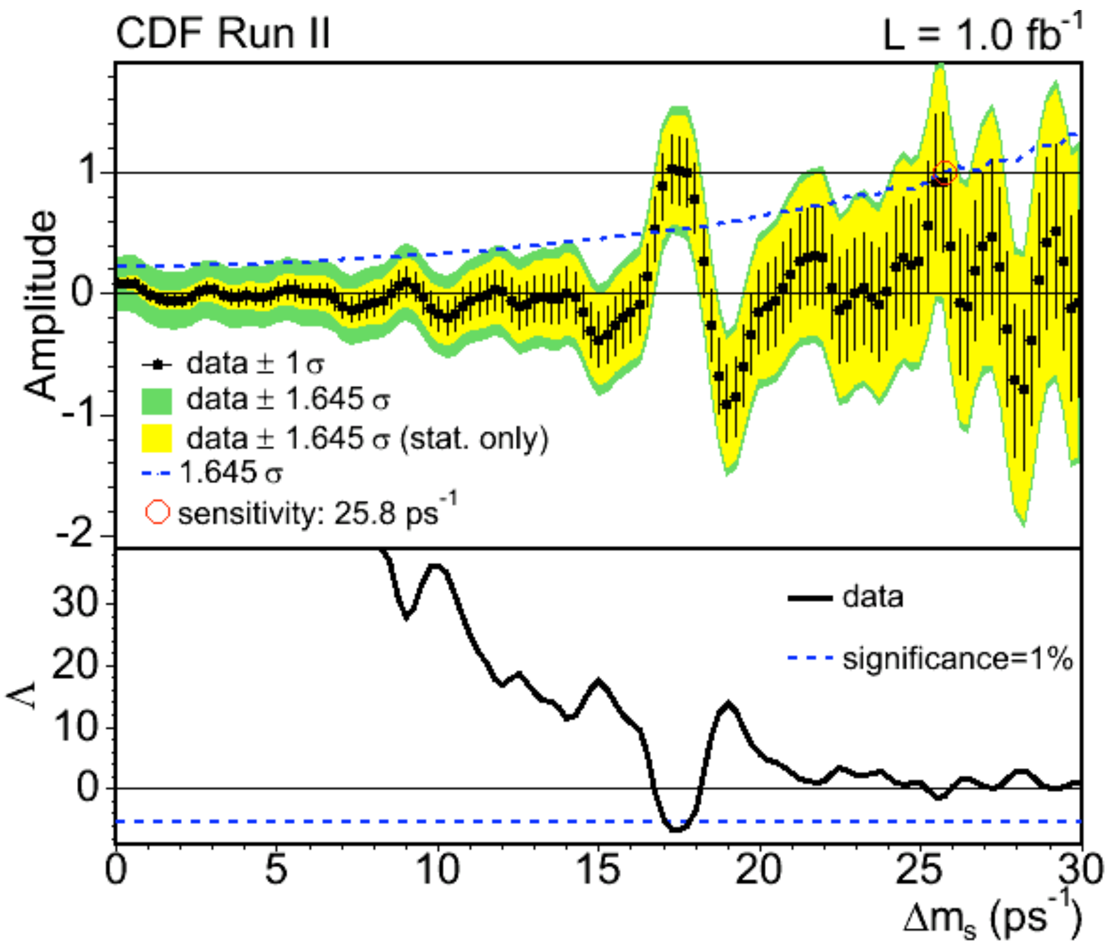
B_s Mixing: CDF Results

Key Features	Result
Sen: 95%CL	$25.8 ps^{-1}$
Sen: σ_A(@$17.5 ps^{-1}$)	0.28
A/σ_A	3.7
Prob. Fluctuation	0.2%
Peak value: Δm_s	$17.3 ps^{-1}$



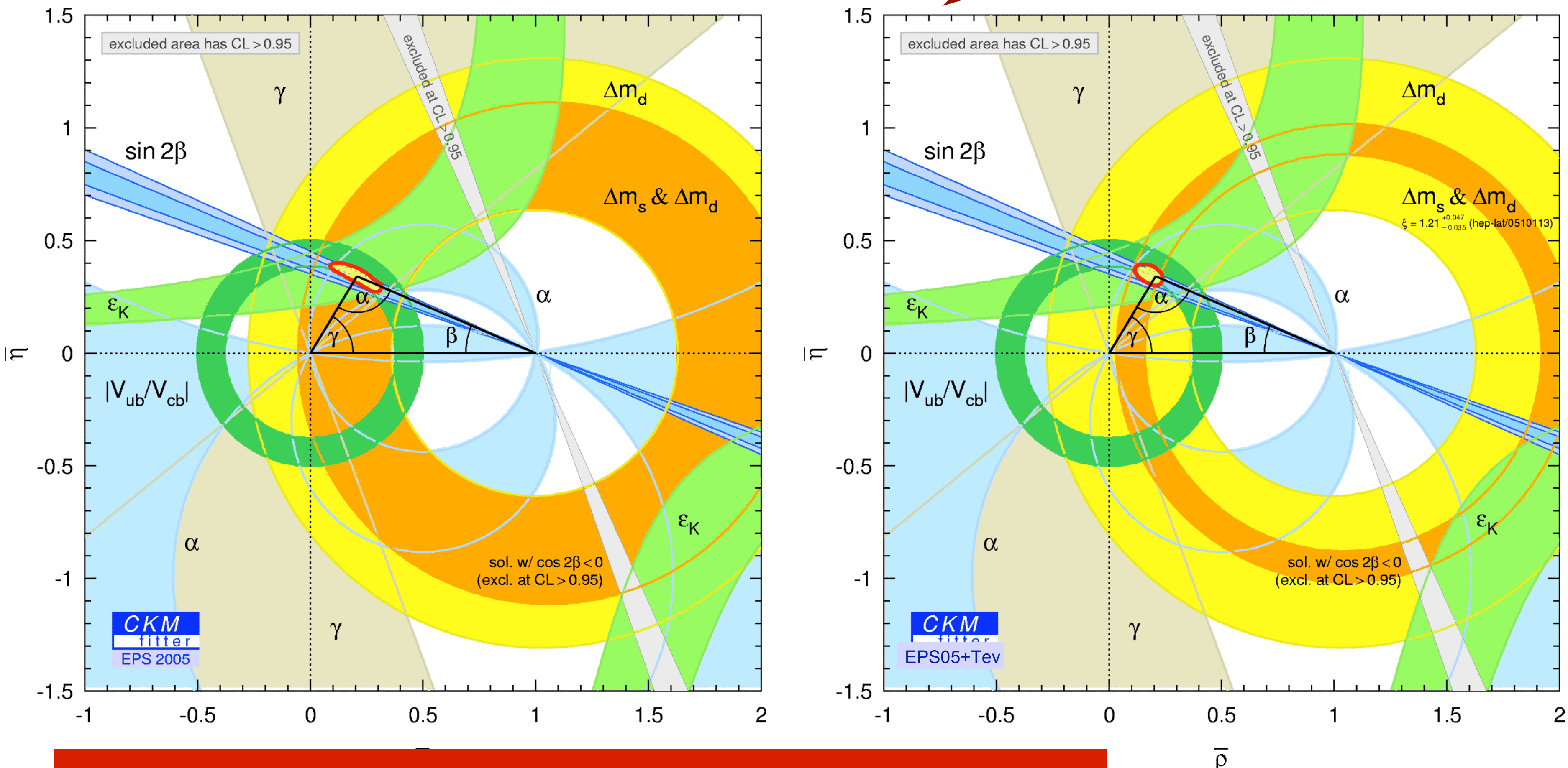
Limits: $16.96\text{-}17.91 ps^{-1}$ @90CL

0.2% is 3σ evidence: Let's measure Δm_s and V_{ts}

Accepted by PRL

B_s Mixing: CKM Triangle

Tevatron

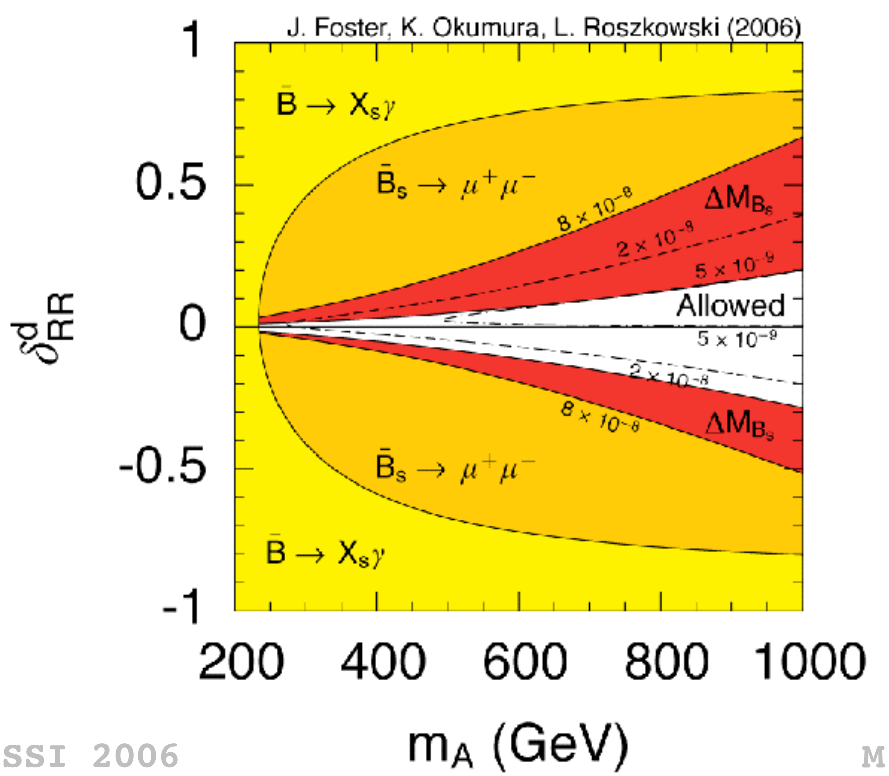


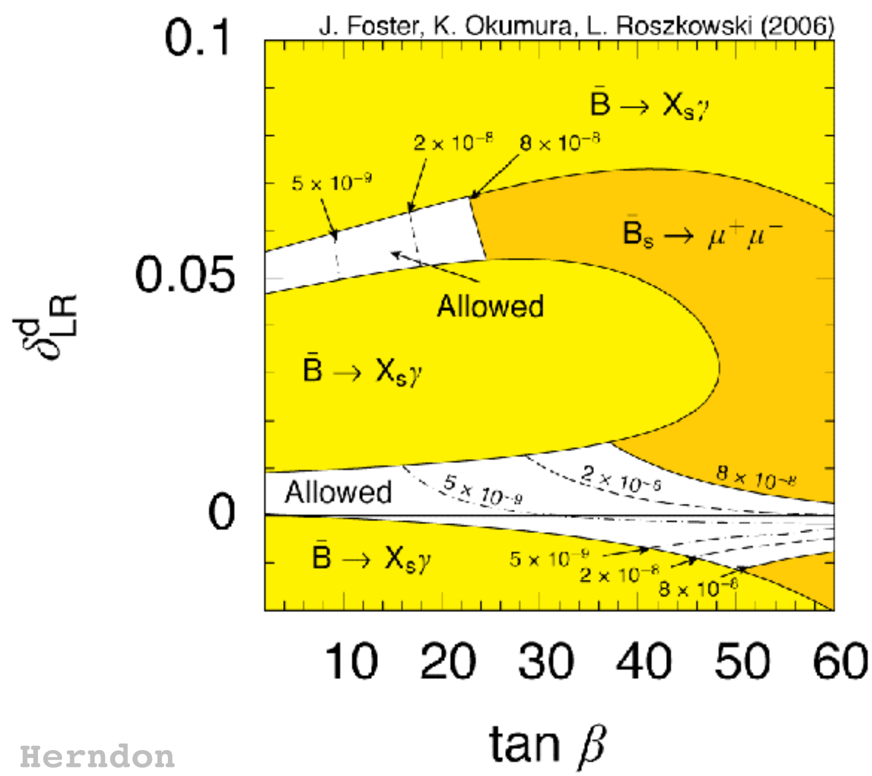
$\Delta m_s = 17.31\ ^{+0.33}_{-0.18}\ \text{(stat)} \pm 0.07\ \text{(syst) ps}^{-1}$

$|V_{td}|\ /\ |V_{ts}| = 0.208\ ^{+0.001}_{-0.002}\ \text{(stat + syst)}\ ^{+0.008}_{-0.007}$

B_s Results - New Physics

- Many new physics models that predict observable effects in flavor physics
- Consider a SUSY GFV model: general rather than minimal flavor violation
  - Makes predictions for Non Standard model $BF(B_s \rightarrow \mu^+\mu^-)$ and Δm_s
  - Basically corrects quark mass terms with sqark-gluino loop terms in a general way
  - Size of effects depends on $\tan\beta$ and m_A hep-ph/0604121





B_s Physics Conclusion

- Tevatron making large gains in our understanding of B_s Physics
- Concentrating on areas where there might be hints of new physics
- New stringent limits on rare decays:

$BF(B_s \rightarrow \mu^+\mu^-) < 1.0\text{x}10^{-7}$ at 95% CL

Factor of 30 improvement over run 1

- Precise measurement of $\Delta\Gamma\ B_s$

$\Delta\Gamma\ B_s = 0.12 \pm 0.08 \pm 0.03\ \text{ps}^{-1}$

And first look at the CP violating phase

- First measurements of Δm_s

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

Signal at 3σ level. Signal seen by both experiments

Study of the B_s meson well on its way