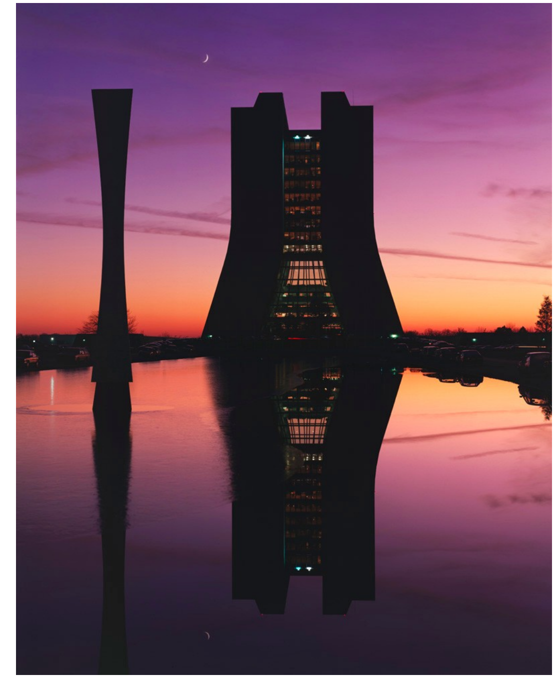
Heavy Quarks



Manfred Paulini

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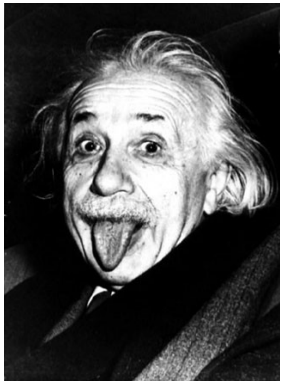
Hadron Collider Physics Summer School 2012
Fermilab, IL

August 6 - 17, 2012

Lecture 2
Aug 15, 2012

Lecture Outline

- **Lecture 1**
  - Introduction: Heavy Quarks
  - B Hadron Producers
  - Features of B Physics
  - B Hadron Properties
  - B Lifetimes
- **Lecture 2**
  - B_s^0 meson oscillations
  - CP Violation in B_s^0 system
  - Selected B Physics results



"God doesn't play dice with the universe."
(Albert Einstein)

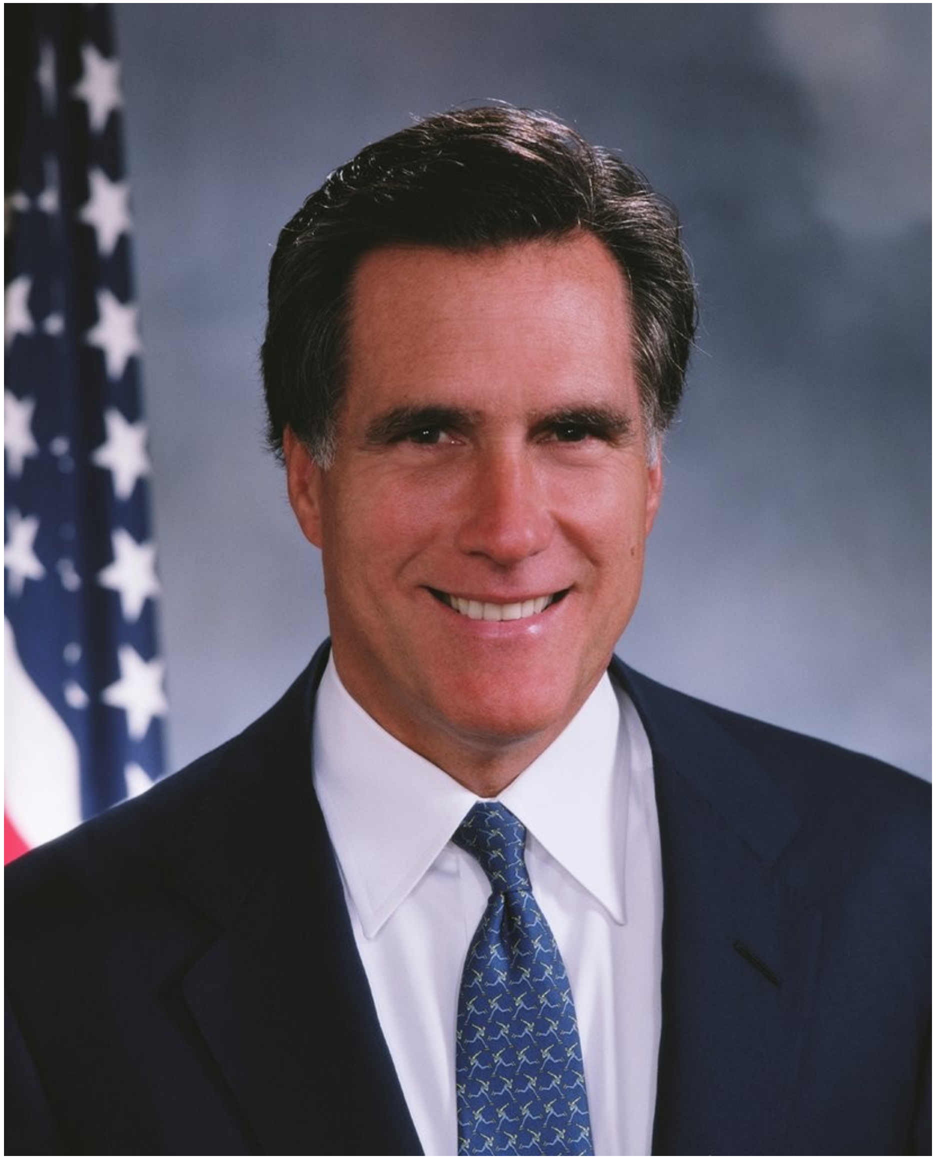
"If only god would give me some clear sign!
Like making a large deposit
in my name at a Swiss bank."
(Woody Allen)

B Meson Oscillations

What are Oscillations?

What are Oscillations?

What are Oscillations?



Particle-Antiparticle Oscillations

M. Gell-Mann & A. Pais, *Phys. Rev.*, **97**, 1387 (1955)

- Established phenomenon in neutral kaon system
- Basics of QM of particle oscillations given by ammonia molecule in Feynman Lectures

PHYSICAL REVIEW VOLUME 97, NUMBER 5 MARCH 1, 1955

Behavior of Neutral Particles under Charge Conjugation

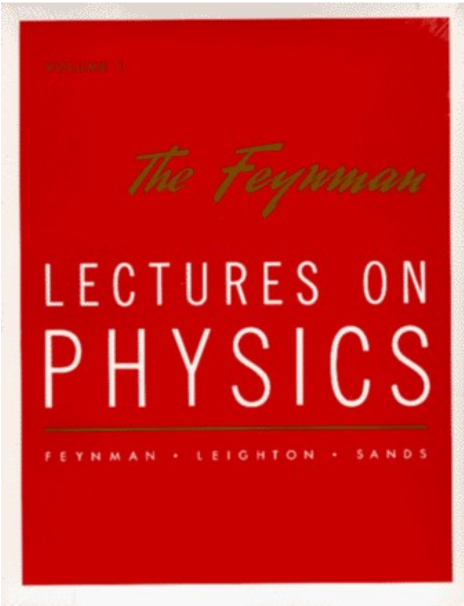
M. Gell-Mann,* *Department of Physics, Columbia University, New York, New York*

AND

A. Pais, *Institute for Advanced Study, Princeton, New Jersey*

(Received November 1, 1954)

Some properties are discussed of the θ^0, a heavy boson that is known to decay by the process $\theta^0 \to \pi^+ + \pi^-$. According to certain schemes proposed for the interpretation of hyperons and K particles, the θ^0 possesses an antiparticle $\bar{\theta}^0$ distinct from itself. Some theoretical implications of this situation are discussed with special reference to charge conjugation invariance. The application of such invariance in familiar instances is surveyed in Sec. I. It is then shown in Sec. II that, within the framework of the tentative schemes under consideration, the θ^0 must be considered as a "particle mixture" exhibiting two distinct lifetimes, that each lifetime is associated with a different set of decay modes, and that no more than half of all θ^0's undergo the familiar decay into two pions. Some experimental consequences of this picture are mentioned.



8–6 The ammonia molecule

We want now to show you how the dynamical equation of quantum mechanics can be used to describe a particular physical circumstance. We have picked an interesting but simple example in which, by making some reasonable guesses about the Hamiltonian, we can work out some important—and even practical—results. We are going to take a situation describable by two states: the ammonia molecule.

The ammonia molecule has one nitrogen atom and three hydrogen atoms located in a plane below the nitrogen so that the molecule has the form of a pyramid, as drawn in Fig. 8–1(a). Now this molecule, like any other, has an infinite number of states. It can spin around any possible axis; it can be moving in any direction; it can be vibrating inside, and so on, and so on. It is, therefore, not a two-state system at all. But we want to make an approximation that all other states remain fixed, because they don't enter into what we are concerned with at the moment. We will consider only that the molecule is spinning around its axis of symmetry (as shown in the figure), that it has zero translational momentum, and that it is vibrating as little as possible. That specifies all conditions except one: *there are still the two possible positions for the nitrogen atom*—the nitrogen may be on one side of the plane of hydrogen atoms or on the other, as shown in Fig. 8–1(a) and (b). So we will discuss the molecule as though it were a two-state system. We mean that there are only two states we are going to really worry about, all other things being assumed to stay put. You see, even if we know that it is spinning with a certain angular momentum around the axis and that it is moving with a certain momentum and vibrating in a definite way, there are still two possible states. We will say that the molecule is in the state $|\,1\rangle$ when the nitrogen is "up," as in Fig. 8–1(a), and is in the state $|\,2\rangle$ when the nitrogen is "down," as in (b). The states $|\,1\rangle$ and $|\,2\rangle$ will be taken as the set of base states for our analysis of the behavior of the ammonia molecule. At any moment, the actual state $|\,\psi\rangle$ of the molecule can be represented by giving $C_1 = \langle 1\,|\,\psi\rangle$, the amplitude to be in state $|\,1\rangle$, and $C_2 = \langle 2\,|\,\psi\rangle$, the amplitude to be in state $|\,2\rangle$. Then, using Eq. (8.8) we can write the state vector $|\,\psi\rangle$ as

$$|\,\psi\rangle = |\,1\rangle\langle 1\,|\,\psi\rangle + |\,2\rangle\langle 2\,|\,\psi\rangle$$

or

$$|\,\psi\rangle = |\,1\rangle C_1 + |\,2\rangle C_2. \tag{8.44}$$

Now the interesting thing is that if the molecule is known to be in some state at some instant, it will *not* be in the same state a little while later. The two C-coefficients will be changing with time according to the equations (8.43)—which hold for any two-state system. Suppose, for example, that you had made some observation—or had made some selection of the molecules—so that you *know* that the molecule is *initially* in the state $|\,1\rangle$. At some later time, there is some chance that it will be found in state $|\,2\rangle$. To find out what this chance is, we have to solve the differential equation which tells us how the amplitudes change with time.

8–11

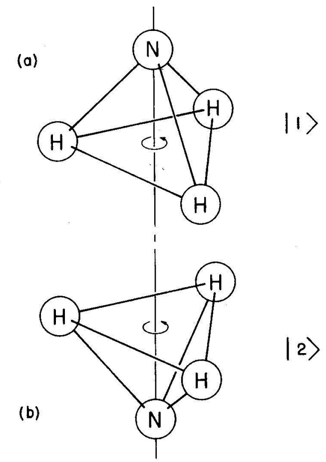
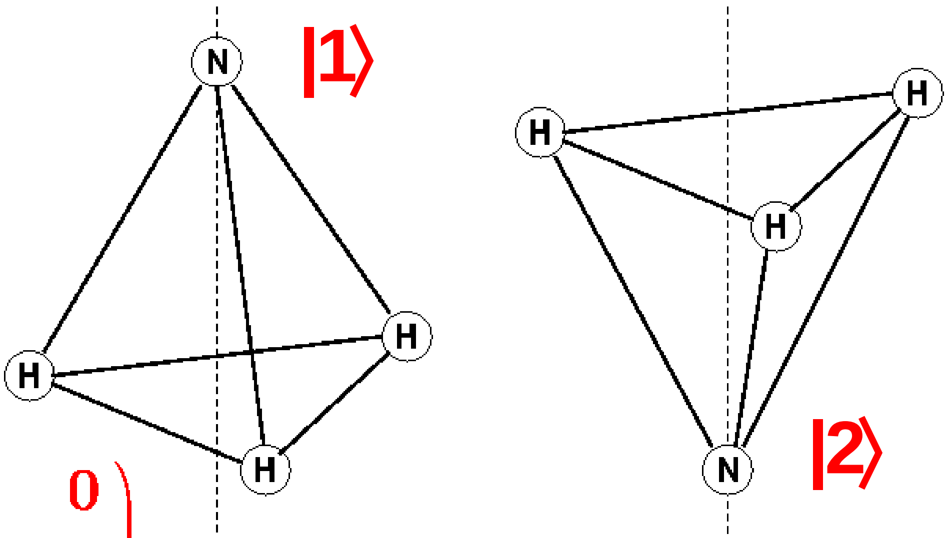


Fig. 8–1. Two equivalent geometric arrangements of the ammonia molecule.

Oscillations in Quantum Mechanics

Remember: Ammonia Molecule



Two state quantum mechanical system:

$$|1\rangle = |\mathrm{N\ above\ plane}\rangle$$
$$|2\rangle = |\mathrm{N\ below\ plane}\rangle$$

$$\hat{H} \rightarrow \begin{pmatrix} \langle 1|\hat{H}|1\rangle & \langle 1|\hat{H}|2\rangle \\ \langle 2|\hat{H}|1\rangle & \langle 2|\hat{H}|2\rangle \end{pmatrix} \quad \hat{H} \rightarrow \begin{pmatrix} E_0 & 0 \\ 0 & E_0 \end{pmatrix}$$

Energy eigenstates: $E_1 = E_2 = E_0$ (stationary states)

Allow tunneling between potential barrier of H-atoms: $\hat{H} \rightarrow \begin{pmatrix} E_0 & -A \\ -A & E_0 \end{pmatrix}$

Energy eigenvalues: $E_0 + A$, $E_0 - A$

Energy eigenstates:

$$|\mathrm{I}\rangle : E_I = E_0 - A \qquad |\mathrm{II}\rangle : E_{II} = E_0 + A$$
$$|\mathrm{I}\rangle = 1/\sqrt{2}(|1\rangle + |2\rangle) \qquad |\mathrm{II}\rangle = 1/\sqrt{2}(|1\rangle - |2\rangle)$$

Oscillations in Quantum Mechanics

Existence of tunneling has split energy eigenstates of NH_3

Note: Neither in $|\mathrm{I}\rangle$ nor $|\mathrm{II}\rangle$, N is above nor below plane but in superposition

$$|\mathrm{I}\rangle = \tfrac{1}{\sqrt{2}}|1\rangle + \tfrac{1}{\sqrt{2}}|2\rangle \qquad |\mathrm{II}\rangle = \tfrac{1}{\sqrt{2}}|1\rangle - \tfrac{1}{\sqrt{2}}|2\rangle$$

$$|1\rangle = \tfrac{1}{\sqrt{2}}|\mathrm{I}\rangle + \tfrac{1}{\sqrt{2}}|\mathrm{II}\rangle \qquad |2\rangle = \tfrac{1}{\sqrt{2}}|\mathrm{I}\rangle - \tfrac{1}{\sqrt{2}}|\mathrm{II}\rangle$$

Time dependence:

$$|\psi(0)\rangle = |1\rangle \;\Rightarrow\; |\psi(t)\rangle = e^{-i\hat{H}t/\hbar}\left(\frac{1}{\sqrt{2}}|\mathrm{I}\rangle + \frac{1}{\sqrt{2}}|\mathrm{II}\rangle\right) =$$

$$= \frac{e^{-i(E_0-A)t/\hbar}}{\sqrt{2}}|\mathrm{I}\rangle + \frac{e^{-i(E_0+A)t/\hbar}}{\sqrt{2}}|\mathrm{II}\rangle =$$

$$= \frac{e^{-iE_0t/\hbar}}{2}\left[e^{+iAt/\hbar}(|1\rangle + |2\rangle) + e^{-iAt/\hbar}(|1\rangle - |2\rangle)\right] =$$

$$= \frac{e^{-iE_0t/\hbar}}{2}\left[\left(e^{+iAt/\hbar} + e^{-iAt/\hbar}\right)|1\rangle + \left(e^{+iAt/\hbar} - e^{-iAt/\hbar}\right)|2\rangle\right] =$$

$$= \frac{e^{-iE_0t/\hbar}}{2}\left[2\cos\frac{At}{\hbar}|1\rangle + 2i\sin\frac{At}{\hbar}|2\rangle\right]$$

Probability to find $|\psi(t)\rangle$ as $|1\rangle$:

$$|\langle 1|\psi(t)\rangle|^2 = \cos^2\frac{At}{\hbar}$$

B Meson Oscillations

Ammonia: Two energy eigenstates which are superpositions of |1⟩ and |2⟩ :

$$|\mathrm{I}\rangle = \frac{1}{\sqrt{2}}|1\rangle + \frac{1}{\sqrt{2}}|2\rangle \qquad |\mathrm{II}\rangle = \frac{1}{\sqrt{2}}|1\rangle - \frac{1}{\sqrt{2}}|2\rangle$$

System of neutral B mesons $|B^0\rangle = |\bar{b}d\rangle \qquad |\bar{B}^0\rangle = |b\bar{d}\rangle$ ← anti-particle (anti-matter)

2 (energy-) mass eigenstates:

$$|B_H\rangle = \frac{1}{\sqrt{2}}|B^0\rangle + \frac{1}{\sqrt{2}}|\bar{B}^0\rangle \quad \text{(B heavy)}$$

$$|B_L\rangle = \frac{1}{\sqrt{2}}|B^0\rangle - \frac{1}{\sqrt{2}}|\bar{B}^0\rangle \quad \text{(B light)}$$

Write masses (mass-eigenvalues) as:

$$m_H = m + \frac{\Delta m}{2} - \frac{i}{2}\Gamma \qquad \Delta m = m_H - m_L$$

$$m_L = m - \frac{\Delta m}{2} - \frac{i}{2}\Gamma \qquad \Gamma = \frac{\hbar}{\tau_B}$$

Express B states through mass-eigenstates:

$$|B^0\rangle = \frac{1}{\sqrt{2}}|B_H\rangle + \frac{1}{\sqrt{2}}|B_L\rangle$$

$$|\bar{B}^0\rangle = \frac{1}{\sqrt{2}}|B_H\rangle - \frac{1}{\sqrt{2}}|B_L\rangle$$

B Meson Oscillations

Time evolution:

$$t = 0: \quad |\psi(0)\rangle = |B^0\rangle \;\Rightarrow$$

$$|\psi(t)\rangle = \frac{1}{\sqrt{2}} e^{-i(m+\frac{\Delta m}{2}-\frac{i}{2}\Gamma)t/\hbar}\,|B_H\rangle + \frac{1}{\sqrt{2}} e^{-i(m-\frac{\Delta m}{2}-\frac{i}{2}\Gamma)t/\hbar}\,|B_L\rangle =$$

$$= \frac{1}{\sqrt{2}} e^{-i(m+\frac{\Delta m}{2}-\frac{i}{2}\Gamma)t/\hbar}\left(\frac{1}{\sqrt{2}}|B^0\rangle + \frac{1}{\sqrt{2}}|\bar{B}^0\rangle\right) + \frac{1}{\sqrt{2}} e^{-i(m-\frac{\Delta m}{2}-\frac{i}{2}\Gamma)t/\hbar}\left(\frac{1}{\sqrt{2}}|B^0\rangle - \frac{1}{\sqrt{2}}|\bar{B}^0\rangle\right) =$$

$$= \frac{e^{-i(m-\frac{i}{2}\Gamma)t/\hbar}}{2}\left[\left(e^{-i\frac{\Delta m}{2}t/\hbar} + e^{-i(-\frac{\Delta m}{2})t/\hbar}\right)|B^0\rangle + \left(e^{-i\frac{\Delta m}{2}t/\hbar} - e^{-i(-\frac{\Delta m}{2})t/\hbar}\right)|\bar{B}^0\rangle\right] =$$

$$= e^{-i(m-\frac{i}{2}\Gamma)t/\hbar}\left[\cos\left(\frac{\Delta m}{2\hbar}t\right)|B^0\rangle - i\,\sin\left(\frac{\Delta m}{2\hbar}t\right)|\bar{B}^0\rangle\right]$$

$|B^0\rangle$ state oscillates between particle and anti-particle state:

Probability to find state as $|B^0\rangle$ at time t:

$$\cos^2 x = \frac{1}{2}(1+\cos 2x)$$

$$|\langle B^0|\psi(t)\rangle|^2 = \left|e^{-imt/\hbar}\right|^2 \left|e^{i\frac{i}{2}\Gamma\,t/\hbar}\right|^2 \cos^2\left(\frac{\Delta m}{2\hbar}t\right) =$$

$$= e^{-\Gamma\,t/\hbar}\cos^2\left(\frac{\Delta m}{2\hbar}t\right) = \frac{1}{2}e^{-t/\tau_B}\left[1+\cos\left(\frac{\Delta m}{\hbar}t\right)\right]$$

Exponential decay

particle - antiparticle oscillation

Oscillation frequency

B Meson Oscillations

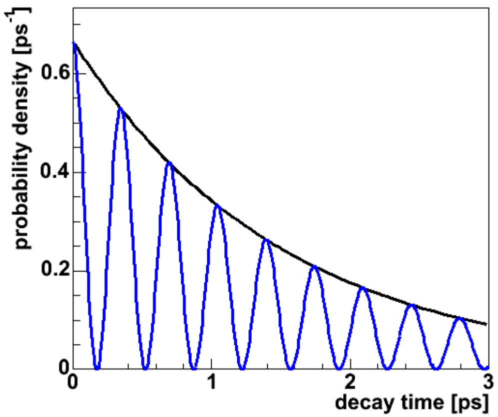
Pure particle $|\psi(0)\rangle = |B_s^0\rangle = \frac{B_{s,L} - B_{s,H}}{\sqrt{2}} \quad (\Delta\Gamma = 0)$

$$|\langle B_s^0|\psi(t)\rangle|^2 = \frac{\Gamma e^{-\Gamma t}}{2}[1 + \cos(\Delta m_s t)]$$

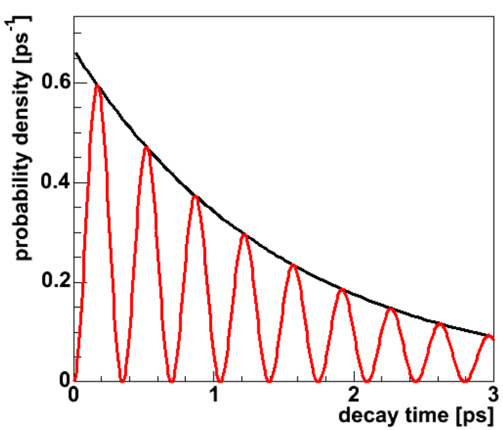
$$|\langle \bar{B}_s^0|\psi(t)\rangle|^2 = \frac{\Gamma e^{-\Gamma t}}{2}[1 - \cos(\Delta m_s t)]$$

antiparticle exists at time t > 0

Particle $|\langle B_s^0|\psi(t)\rangle|^2$

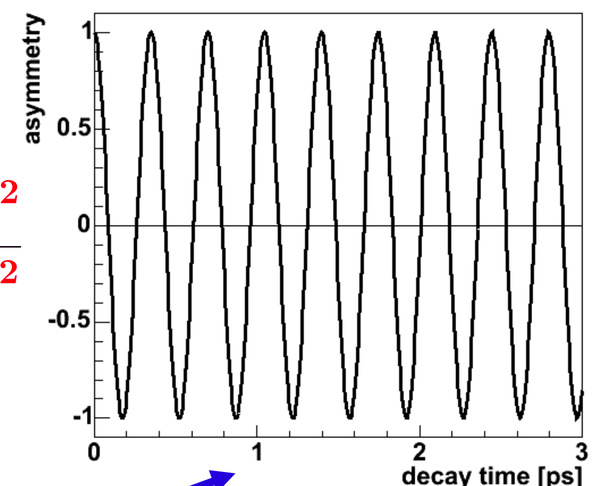


anti-Particle $|\langle \bar{B}_s^0|\psi(t)\rangle|^2$



Asymmetry

$$\frac{|\langle B_s^0|\psi(t)\rangle|^2 - |\langle \bar{B}_s^0|\psi(t)\rangle|^2}{|\langle B_s^0|\psi(t)\rangle|^2 + |\langle \bar{B}_s^0|\psi(t)\rangle|^2}$$



Δm_s is oscillation frequency

Pop-Quiz !!!

? ? ?

2008 Nobel Prize in Physics

The Nobel Prize in Physics 2008

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: SCANPIX

Yoichiro Nambu

1/2 of the prize

USA

Enrico Fermi Institute, University of Chicago
Chicago, IL, USA

b. 1921

Photo: University of Chicago

Makoto Kobayashi

1/4 of the prize

Japan

High Energy Accelerator Research Organization (KEK)
Tsukuba, Japan

b. 1944

Photo: Kyoto University

Toshihide Maskawa

1/4 of the prize

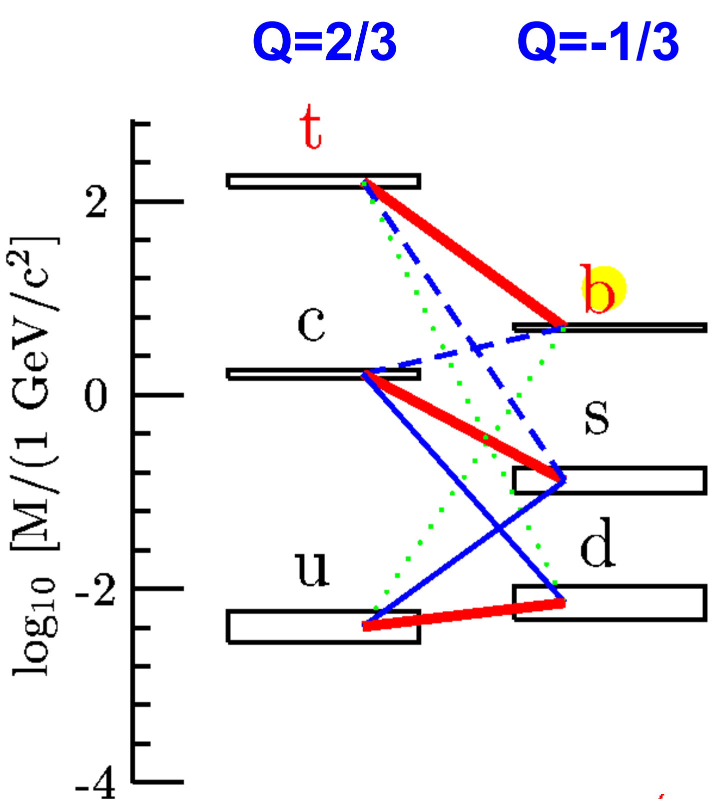
Japan

Kyoto Sangyo University; Yukawa Institute for Theoretical Physics (YITP), Kyoto University
Kyoto, Japan

b. 1940

Quark Transitions

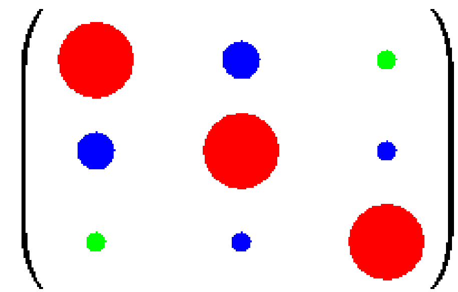
Quark spectrum:



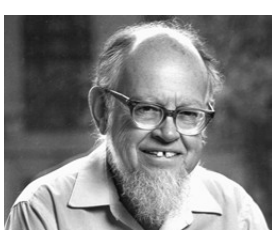
Quark transition described by CKM matrix V_{CKM}:

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$|V_{\rm CKM}| =$



Wolfenstein:



$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Particular importance of b quark: Couples to all other quarks directly or via loops

Wolfenstein Parametrization

VOLUME 51, NUMBER 21 PHYSICAL REVIEW LETTERS 21 NOVEMBER 1983

Parametrization of the Kobayashi-Maskawa Matrix

Lincoln Wolfenstein
Department of Physics, Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
(Received 22 August 1983)

The quark mixing matrix (Kobayashi-Maskawa matrix) is expanded in powers of a small parameter λ equal to $\sin\theta_c = 0.22$. The term of order λ^2 is determined from the recently measured B lifetime. Two remaining parameters, including the CP-nonconservation effects, enter only the term of order λ^3 and are poorly constrained. A significant reduction in the limit on ϵ'/ϵ possible in an ongoing experiment would tightly constrain the CP-nonconservation parameter and could rule out the hypothesis that the only source of CP nonconservation is the Kobayashi-Maskawa mechanism.

PACS numbers: 11.30.Er, 12.10.Ck, 13.25.+m

The quark mixing of the weak-interaction current in the standard model is described by the 3×3 Kobayashi-Maskawa (KM) matrix[1]

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}. \quad (1)$$

The element V_{us} is quite well determined to be equal to 0.22. This and other information suggest that V differs from unity by a small quantity. Here we set

$$0.22 = V_{us} = \lambda \quad (2)$$

and consider an expansion of V in powers of λ. A recent measurement of the lifetime τ_B of B particles yields the result[2]

$$V_{cb} \approx 0.06. \quad (3)$$

This suggests to us that V_{cb} is of order λ^2 rather than λ so that we set

$$V_{cb} = A\lambda^2$$

with $A \approx \frac{5}{4}$. To order λ^2 the KM matrix can then be written

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & 0 \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ 0 & -A\lambda^2 & 1 \end{pmatrix}.$$

We now want to go to order λ^3. Unitarity then prescribes the following form:

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix} \quad (4)$$

where two new parameters ρ and η must be introduced. Equation (4) can be derived from the standard KM form by assuming that s_2 and s_3 are of order λ^2 and making the replacements[3]

$$\lambda = s_1, \quad (5a)$$

$$A\lambda^2 = (s_2^2 + s_3^2 + 2s_2 s_3 \cos\delta)^{1/2}, \quad (5b)$$

$$A^2\lambda^4\eta = s_2 s_3 \sin\delta, \quad (5c)$$

$A\lambda^2(\rho^2 ...$ (5d)

or

$A\lambda^2[(1 - ...$

Only three ... pendent. T... from the st... tion enters ...
Given the ... ical constr... nonconserv... order λ^4 (w... the $\lambda^2 A$ ter... given expe... Therefore ... present ana... now comes ... $b \to c$ transi...

$V_{ub}/V ...$

or

$\rho^2 + \eta^2 < ...$

From Eq. (...

$V_{td} < 2A ...$

I note in pa... sistency of the expansion in powers of λ because they limit the coefficients of the λ^3 terms. Many other experimental constraints on the KM matrix are discussed in the literature.[1] When we neglect CP nonconservation all of these are now of no significance. For example, an upper limit on

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UMBER 21 PHYSICAL REVIEW LETTERS 21 N

Parametrization of the Kobayashi-Maskawa Matrix

Lincoln Wolfenstein
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$$V_{\rm CKM} = \begin{matrix} \\ u \\ c \\ t \end{matrix} \begin{pmatrix} d & s & b \\ 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- $V_{us} = \lambda = \sin\theta_c$ θ_c : Cabibbo angle
- A, λ, ρ, η are real
- Only V_{td} and V_{ub} are complex $\longrightarrow$ link to CP violation

CKM Matrix

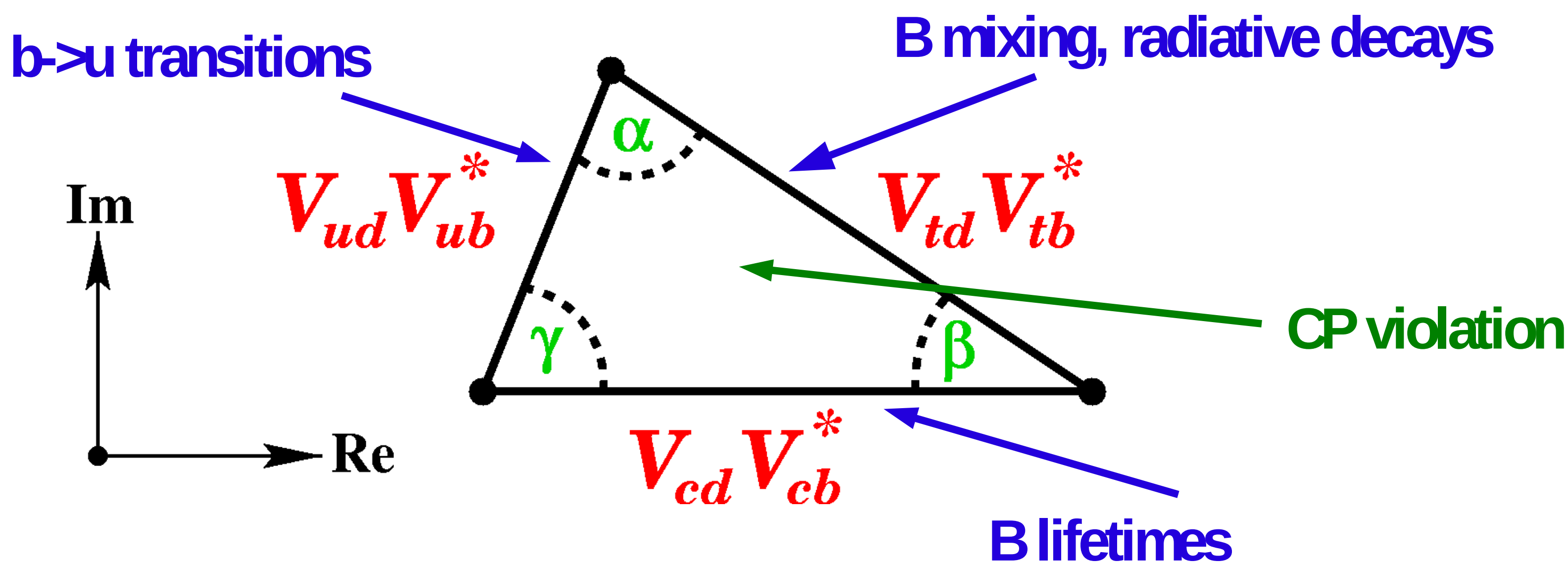
- Individual CKM matrix elements are not predicted by SM => have to be measured
- B decays determine 5 CKM matrix elements

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Unitarity of CKM matrix $(V^\dagger V = 1)$

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

- <u>CKM triangle:</u>



CKM Triangle and CP Violation

Recap:

- Flavour changing interactions generated by exchange of virtual W, Z and t
- No flavour changing neutral currents on tree level => loops
- In SM flavour changing processes depend on CKM matrix
- Phase of CKM mixing matrix explains CP violation in SM
- CP violation related to matter-antimatter asymmetry in universe
- CP violation in SM not sufficient to explain matter/photon ratio in universe

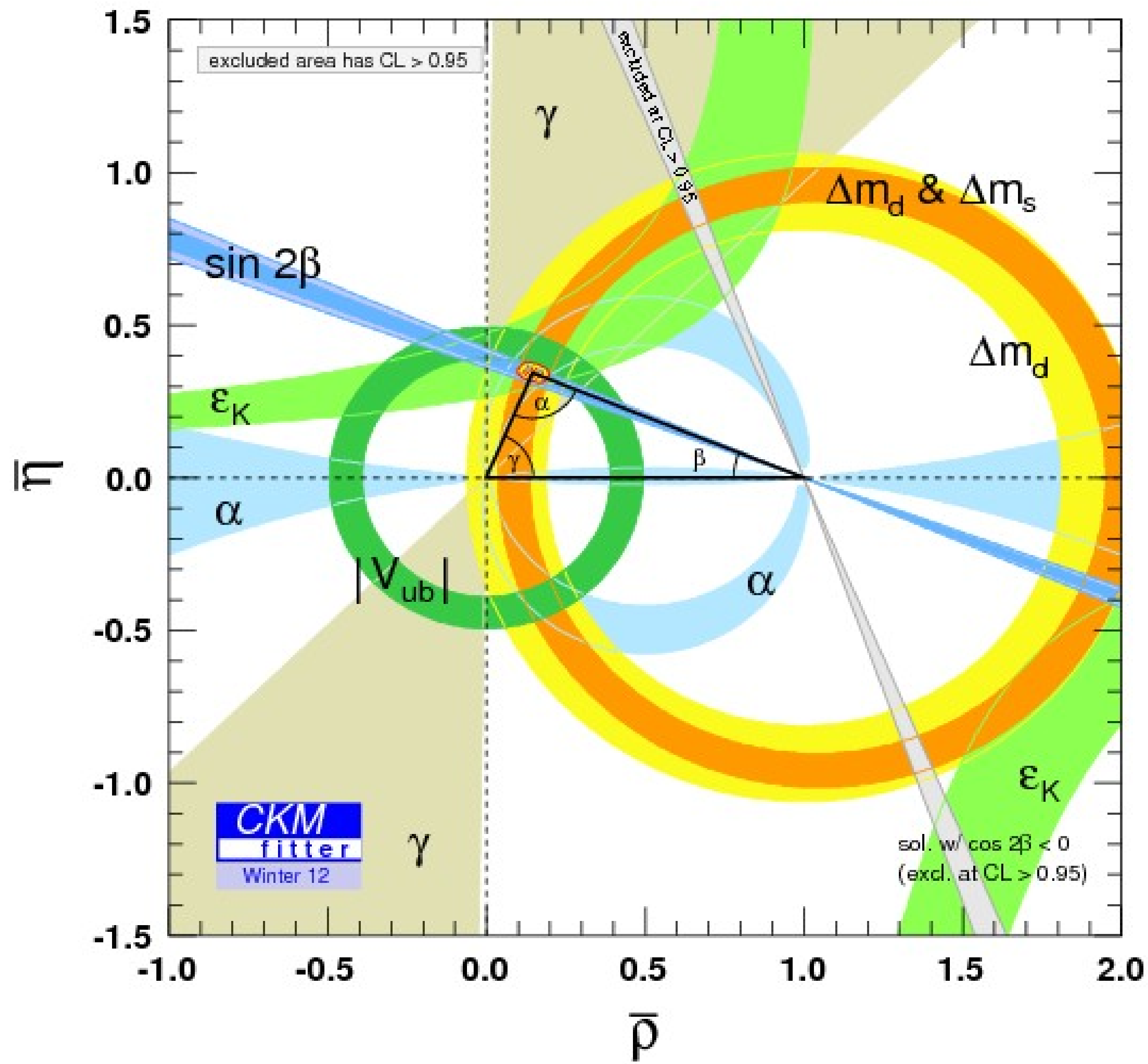
Goal of past, present and future B physics:

- Test flavour changing interactions in all possible ways

  => *Theoretically clean modes versus experimental accessibility*
- Measure sides and angles of CKM triangle in many ways

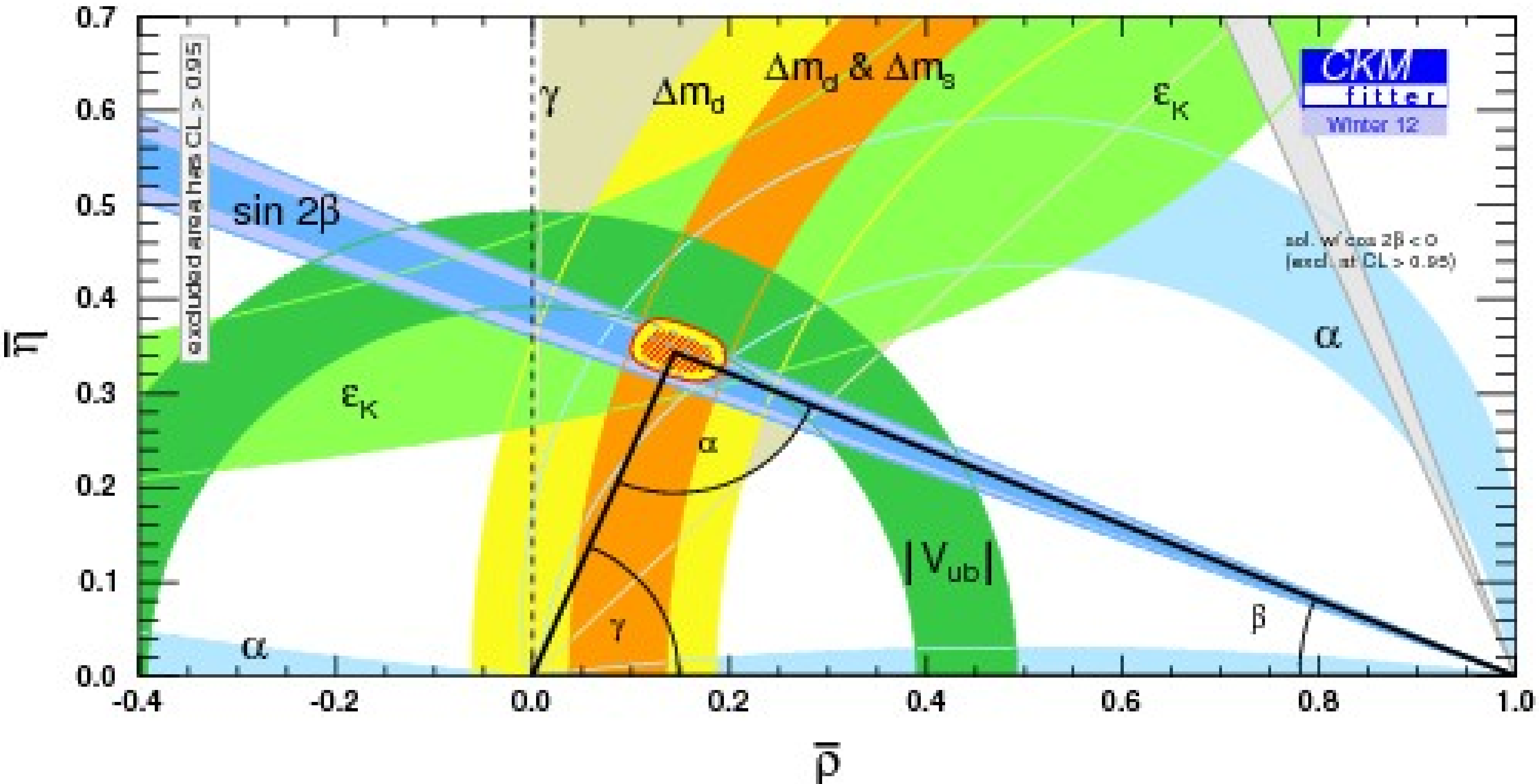
  => *Over-constrain triangle*

CKM Triangle Today



CKM Triangle Today

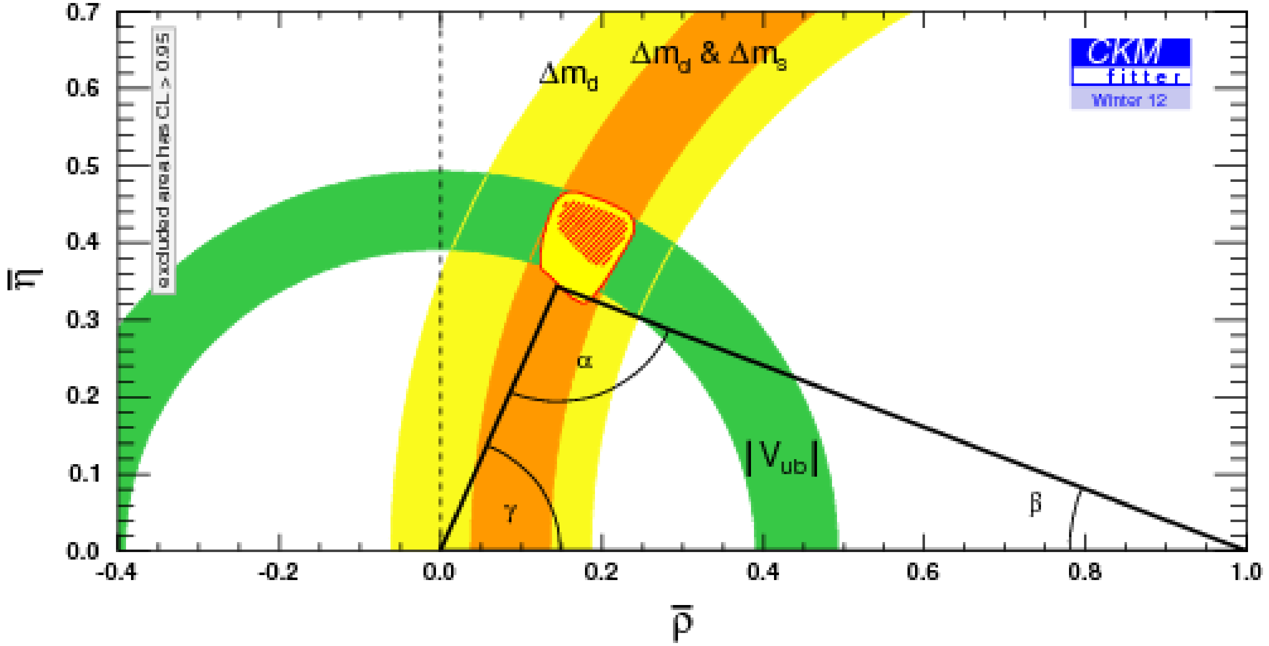
Zoomed in:



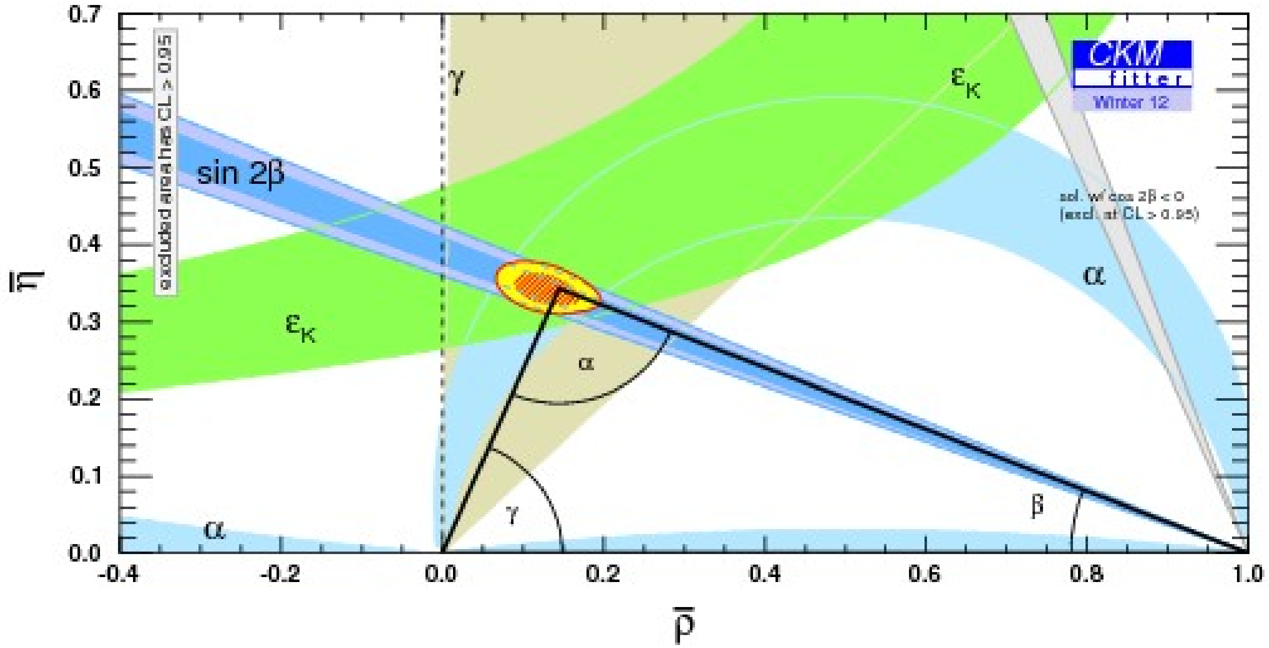
Overwhelming success of Standard Model!

CKM Triangle Today

CP conserving quantities:

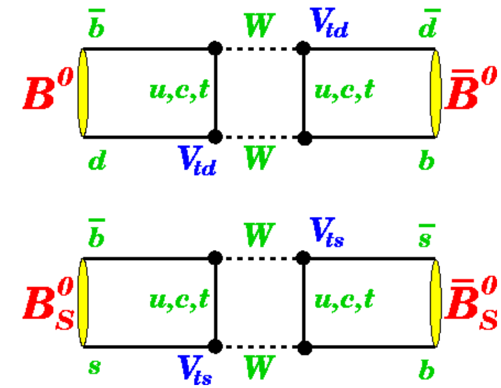


CP violating quantities:

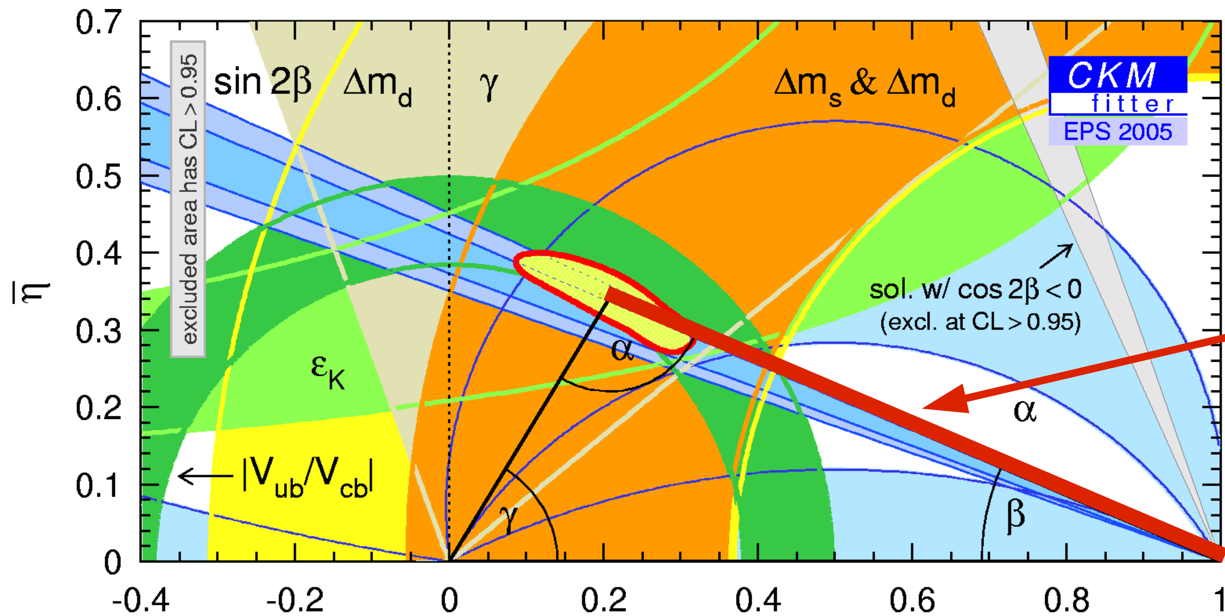


Back to
B Meson Oscillations

B Meson Oscillations



Why are we interested in B_S mixing?



$$\frac{|V_{td}|}{|V_{ts}|}$$

- **Theory:** In Standard Model

CKM element

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_B (f_B^2 B_B) \eta_B m_t^2 F\left(\frac{m_t^2}{m_W^2}\right) |V_{tb}^* V_{td}|^2$$

Experiment

Lattice QCD

Better to measure:

$$\frac{\Delta m_S}{\Delta m_d} = \frac{m_{B_S^0}}{m_{B^0}} \frac{f^2_{B_S^0} B_{B_S^0}}{f^2_{B^0} B_{B^0}} \frac{|V_{ts}|^2}{|V_{td}|^2}$$

ξ^2 from lattice QCD

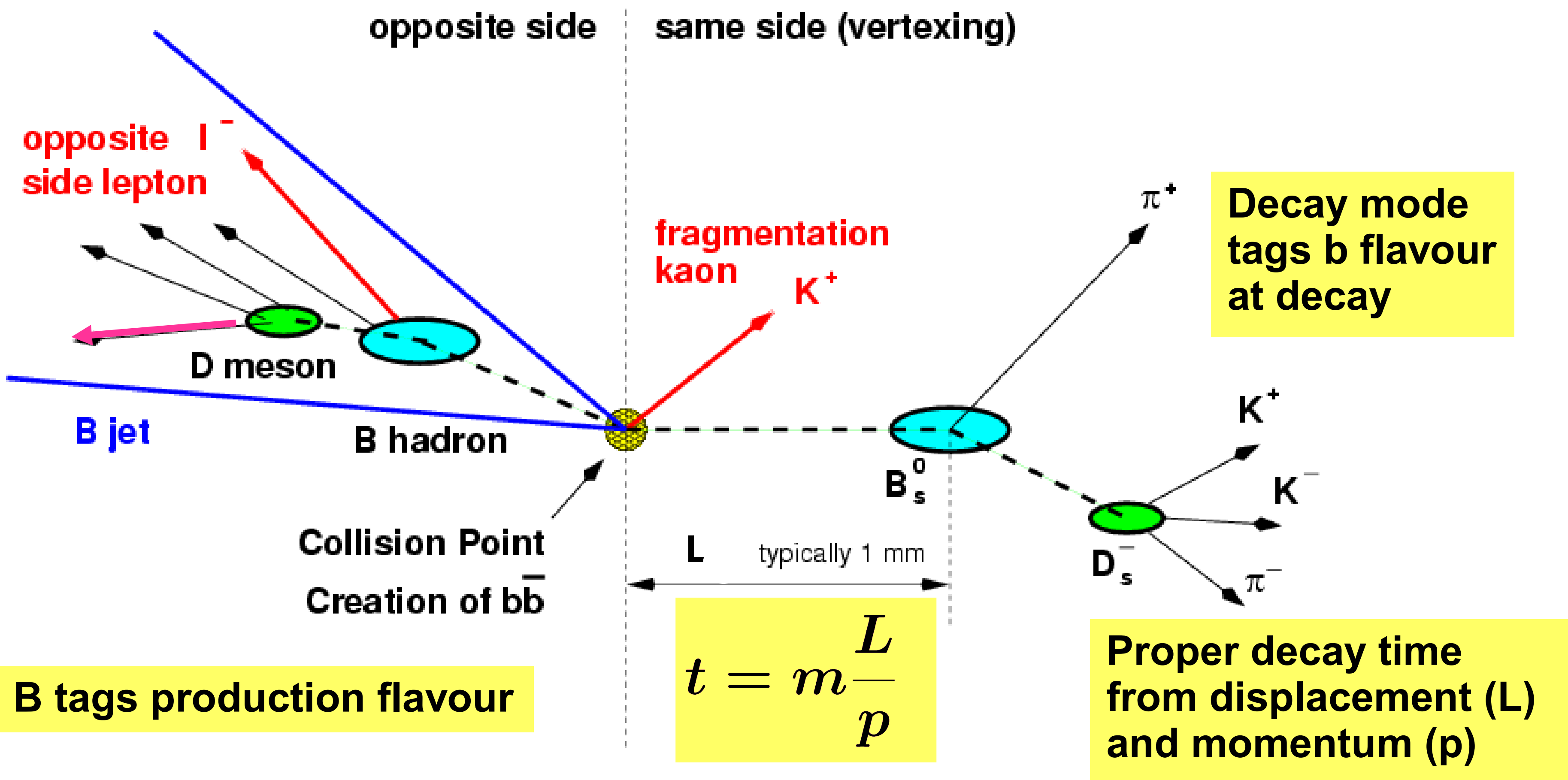
Analysis Strategy

What do we need for measurement of B_s mixing?

(1) B signal reconstruction

(2) Determination of B decay time from decay length and momentum

(3) Determination of B production flavour ("flavour tagging")



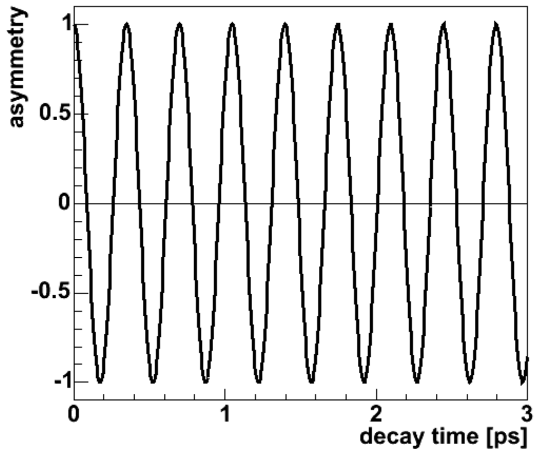
Measurement of B_S Mixing

- Two domains to measure oscillation:

Time domain:

- Fit for Δm_s in $\mathcal{P}_{\text{mix}}(t) \sim (1 - \mathcal{D} \cos \Delta m_s\, t)$

Time Domain



Measurement of B_s Mixing

- Two domains to measure oscillation:

Time domain:

- Fit for Δm_s in $\mathcal{P}_{\rm mix}(t) \sim (1 - \mathcal{D} \cos \Delta m_s\, t)$

Frequency domain:

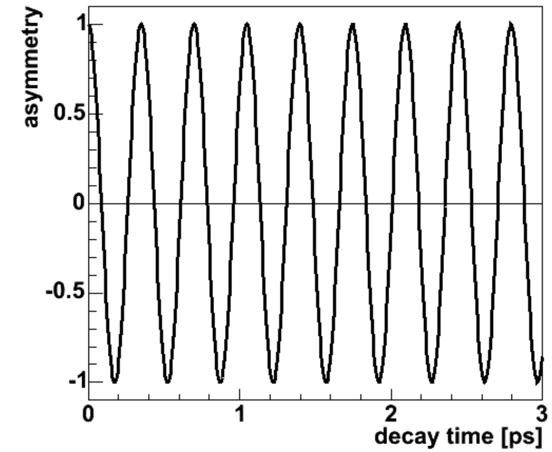
- Fourier transform $\mathcal{F}(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(t)\, e^{-i\omega t}\, dt$
- "Amplitude scan" method

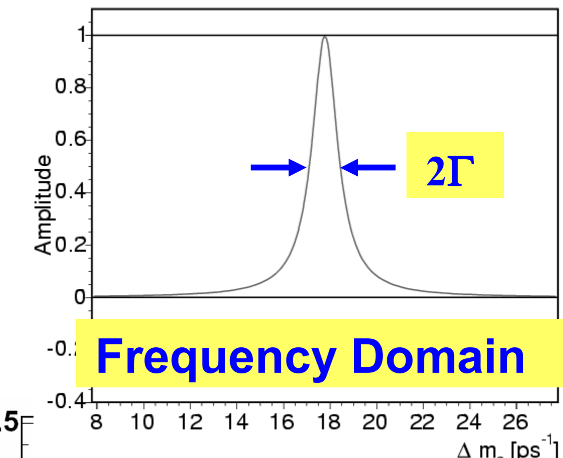
Introduce amplitude $\mathcal{A}$

$$\mathcal{P}_{\rm mix}(t) \sim (1 - \mathcal{D}\, \mathcal{A} \cos \Delta m_s\, t)$$

- Fit for $\mathcal{A}$ at different Δm_s :
- $\mathcal{A}$ = 1 for mixing at true Δm_s
- $\mathcal{A}$ = 0 else in case of no mixing

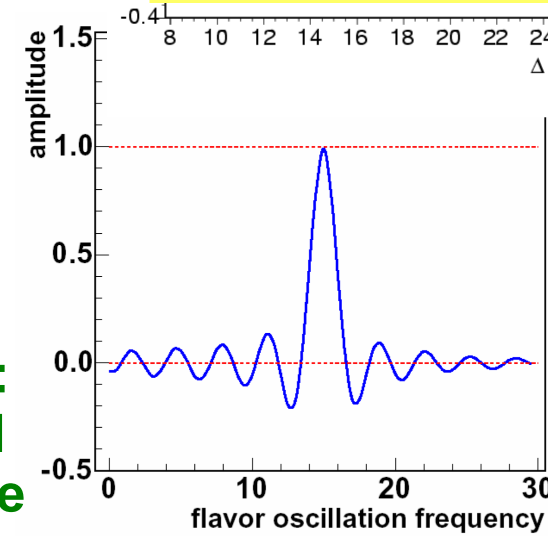
Time Domain





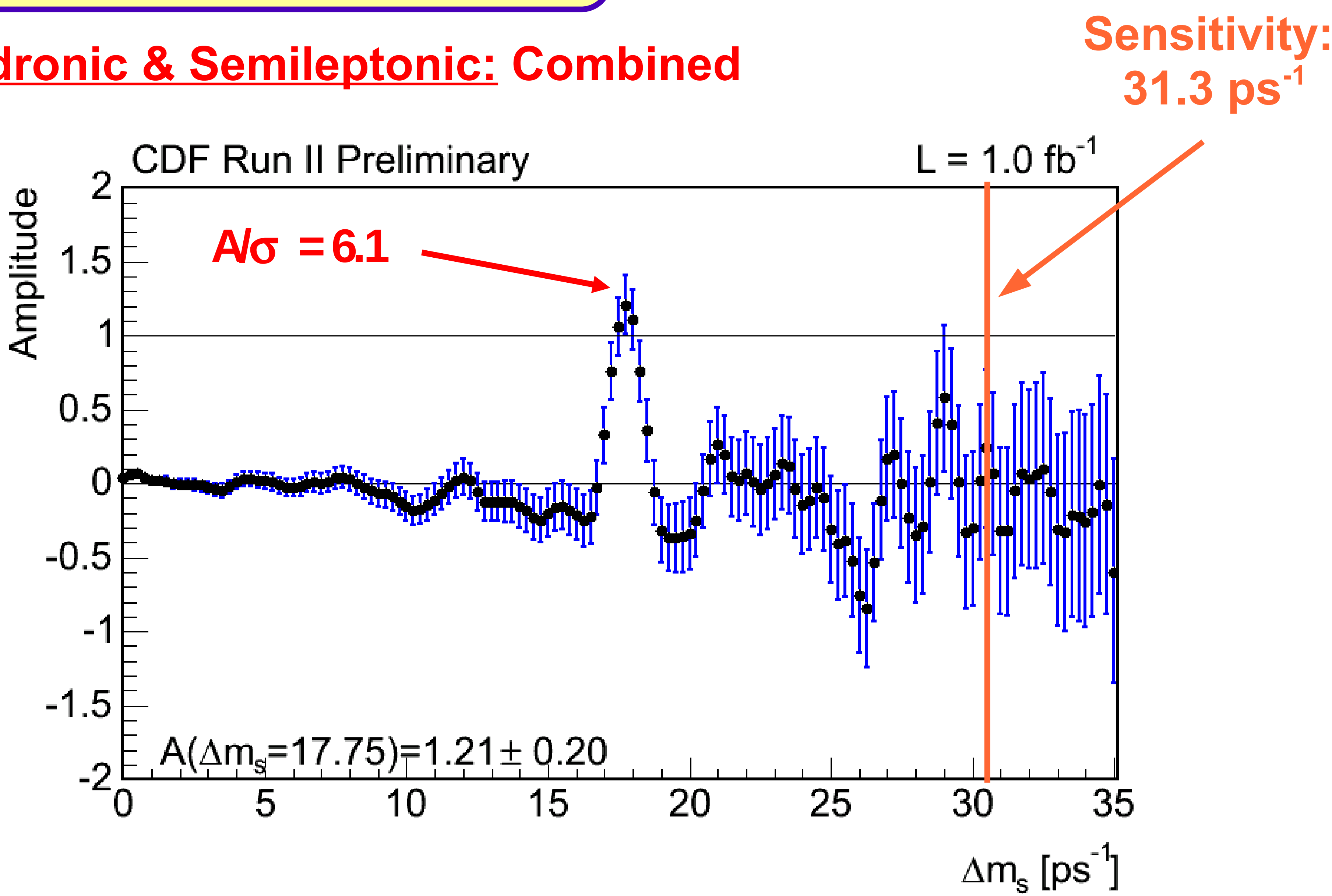
Frequency Domain

In reality: expected amplitude



Result: Amplitude Scan

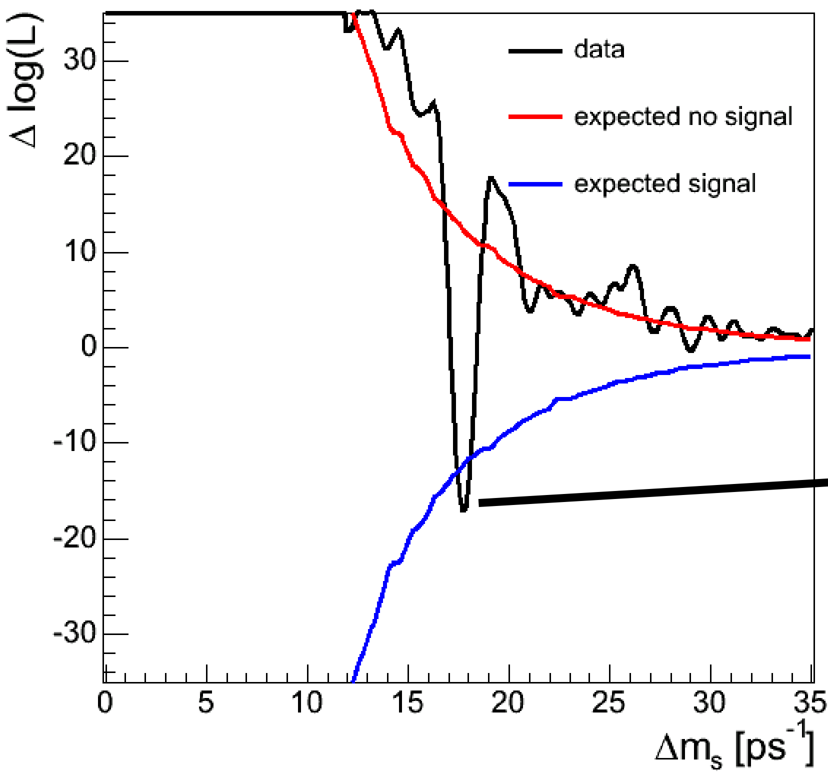
Hadronic & Semileptonic: Combined

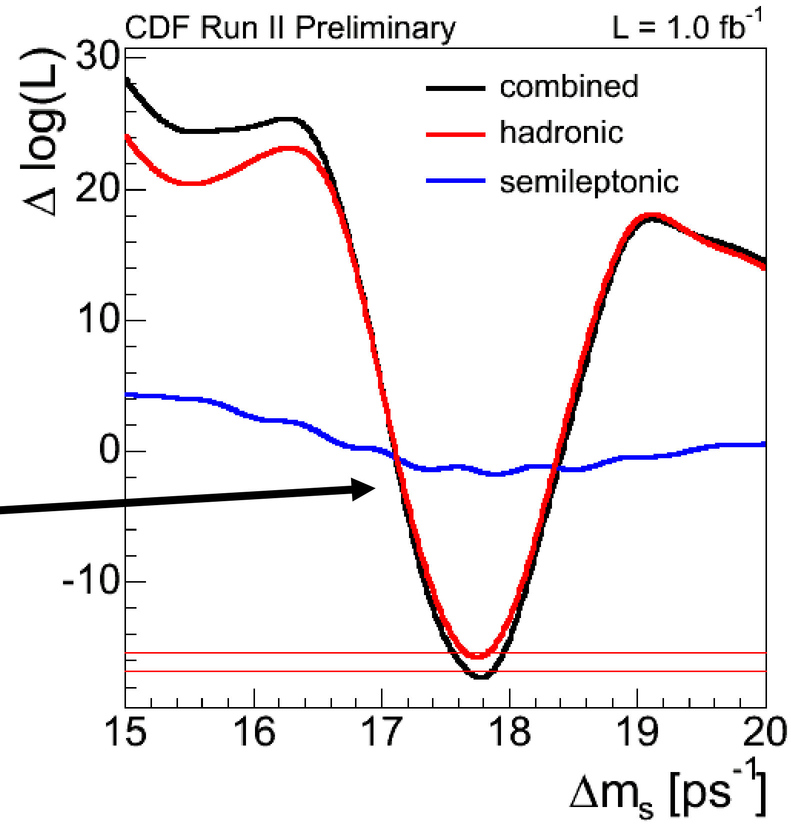


Result: Fit for Oscillation

Measured Value of Δm_s

Hypothesis of A=1 compared to A=0

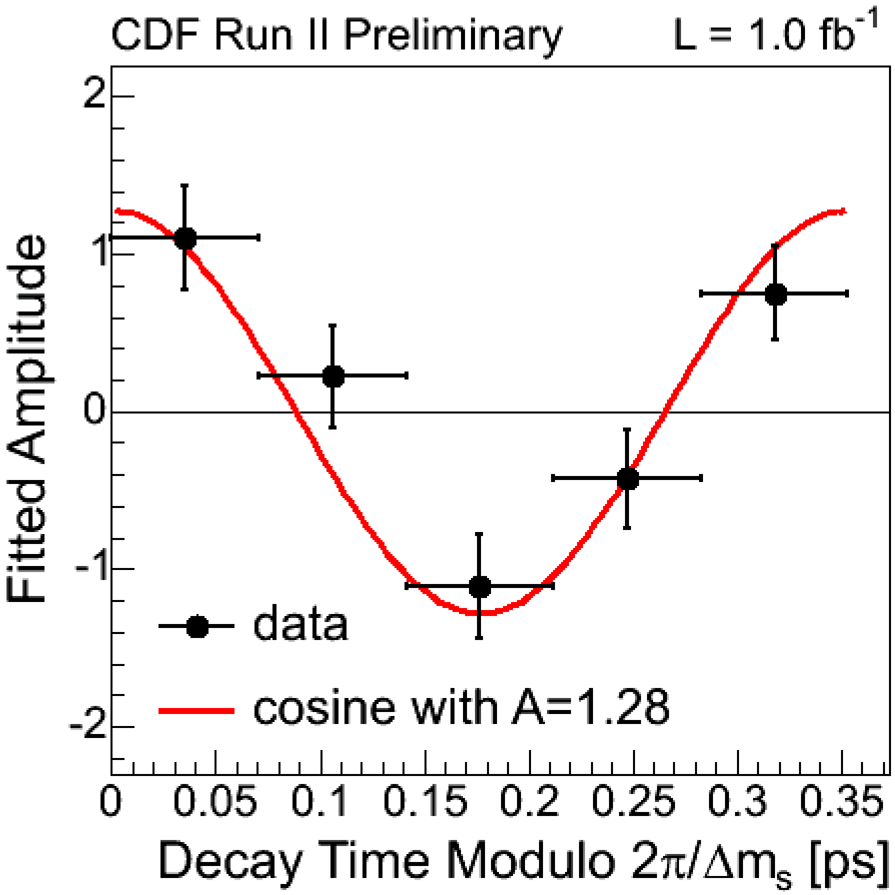




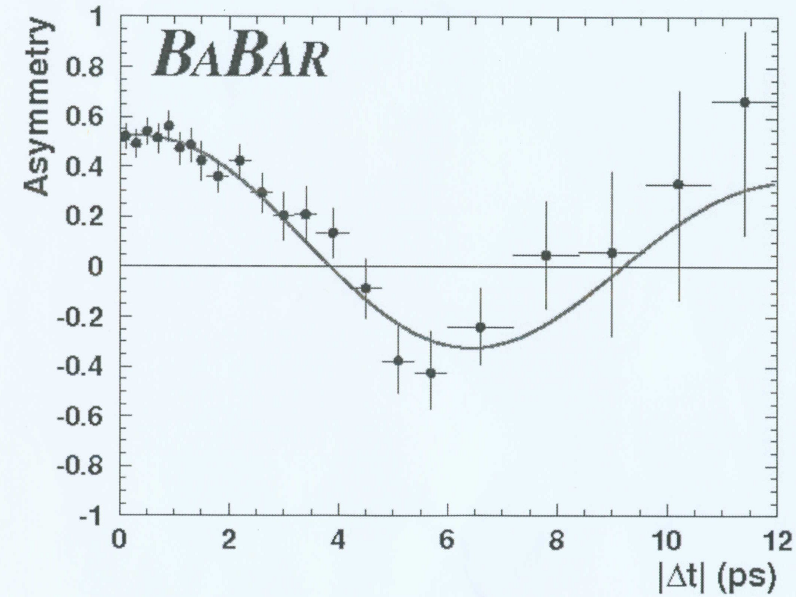
$$\Delta m_s = 17.77 \pm 0.10\,(\text{stat.}) \pm 0.07\,(\text{syst.})\ \text{ps}^{-1}$$

Corresponds to frequency of 3 trillion times a second

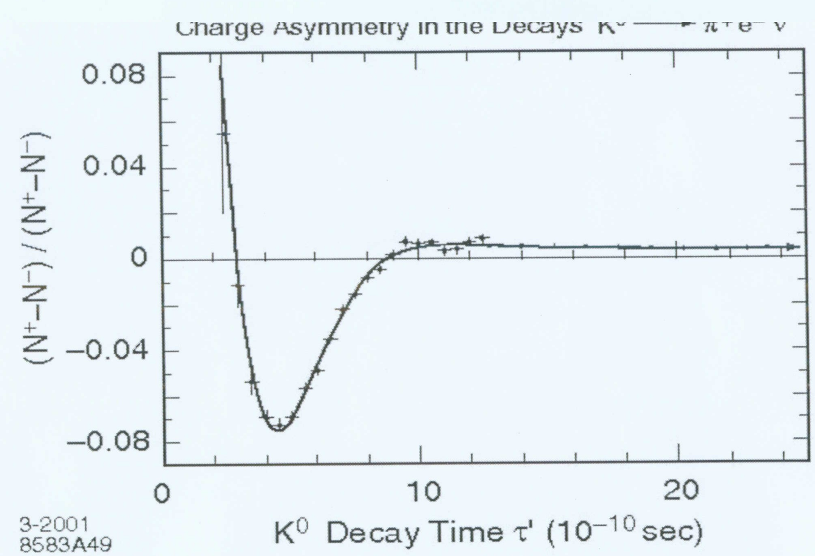
Oscillation in Time Domain



2006: B_S^0 oscillation: ~0.3 ps



2002: B^0 oscillation: ~10 ps



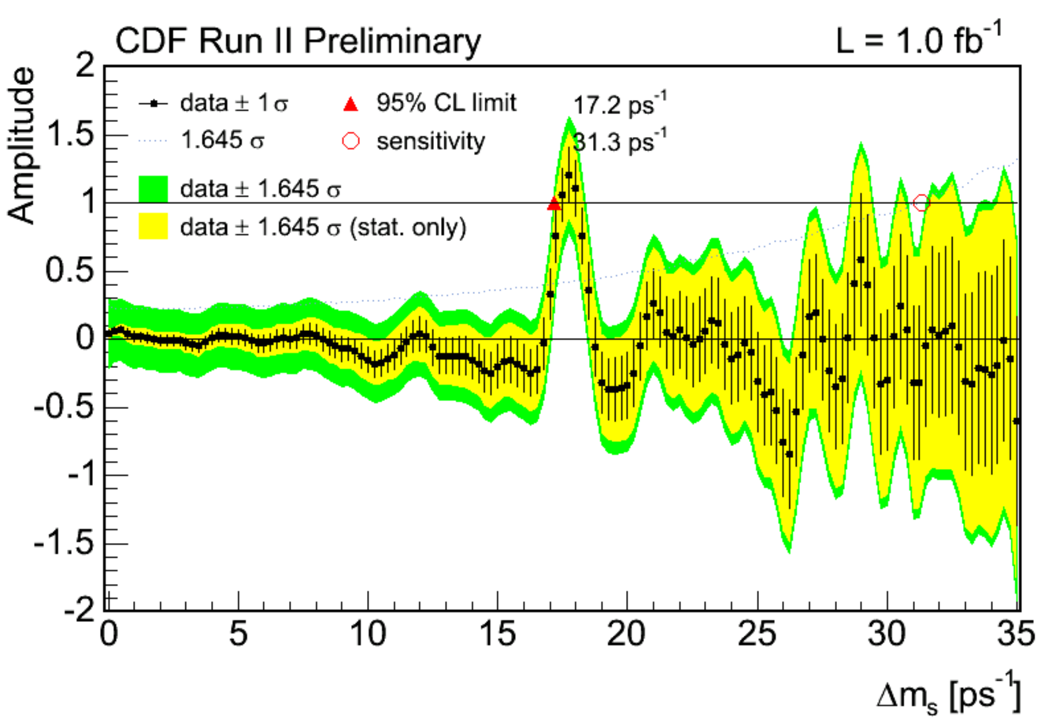
1974: K^0 oscillation: ~1000 ps

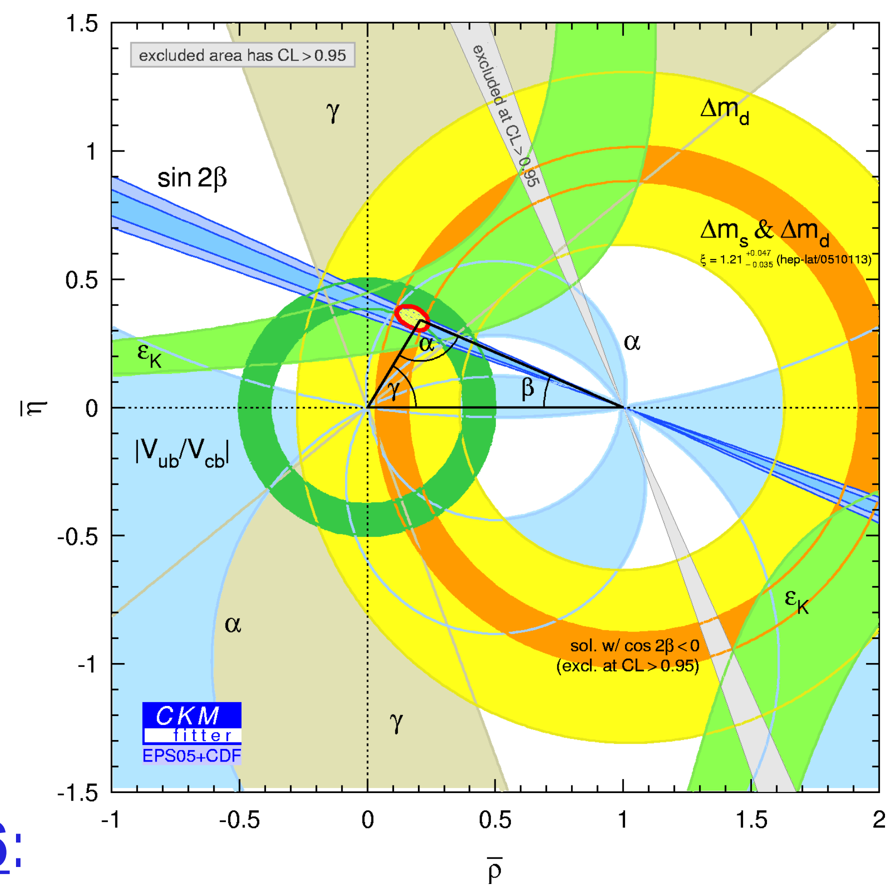
Measurement of CKM Matrix Elements

Determination of $|V_{ts}| / |V_{td}|$:

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

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2060 \pm 0.0007\,(\mathrm{exp.})^{+0.0081}_{-0.0060}\,(\mathrm{theo.})$$





The new world order in 2006:

CP Violation in B_s^0 Mesons

Neutral B_s^0 System

B_s^0 System: 2 flavour eigenstates: $B_s^0 = |\bar{b}s\rangle \quad \& \quad \bar{B}_s^0 = |b\bar{s}\rangle$

Time evolution of states governed by Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} = \left[\underbrace{\begin{pmatrix} M_0 & M_{12} \\ M_{12}^* & M_0 \end{pmatrix}}_{\text{mass matrix}} - \frac{i}{2} \underbrace{\begin{pmatrix} \Gamma_0 & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_0 \end{pmatrix}}_{\text{decay matrix}} \right] \begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix}$$

Mass eigenstates are admixture of B_s^0 flavour eigenstates:

$$|B_s^H\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle \qquad |B_s^L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle \qquad \frac{q}{p} = \frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}$$

where $\Delta m_s = m_H - m_L \sim 2|M_{12}|$ Oscillations between B_s^0 & $\bar{B}_s^0$

$\Delta\Gamma_s = \Gamma_L - \Gamma_H \sim 2\,|\Gamma_{12}|\cos(\phi_s)$ Lifetime / width difference

$\phi_s = \arg(-M_{12}/\Gamma_{12})$ CP phase

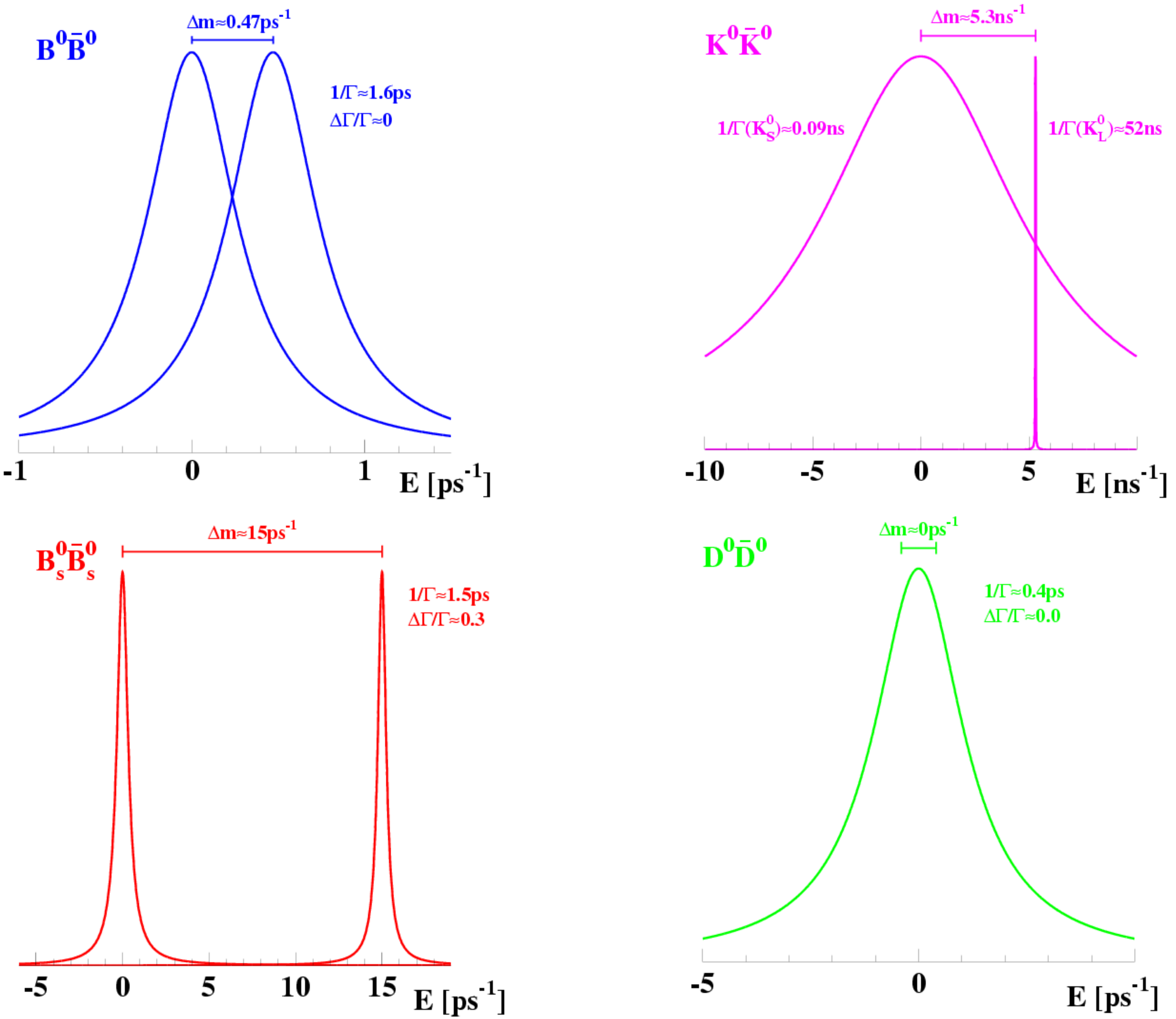
Assume no CP violation ($\phi_s^{SM} \sim 0.004$) => mass eigenstate = CP eigenstate

=> $\Gamma_L \sim$ CP even (short lived) & $\Gamma_H \sim$ CP odd (long lived)

Experimental observables describing system:

m_H, m_L => Δm_s, $\Gamma_s = (\Gamma_H + \Gamma_L)/2 = 1/\tau_s$, $\Delta\Gamma_s$, ϕ_s

ΔΓ and Δm in Neutral Meson Systems



Numbers just for illustration

B_s^0 Lifetimes

Since $\Delta\Gamma \neq 0$: Different measurements have different meanings

1) Flavour specific lifetime:

- Equal mix of B_s^H & B_s^L at t=0

  e.g. semileptonic decays $B_s^0 \to D_s l\nu X$

- Fit of single exponential measures

$$\tau(B_s^0)_{\text{fl.spec.}} = \frac{1}{\Gamma_s} \frac{1 + \left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}{1 - \left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}$$

- $\tau(B_s^0) = (1.463 \pm 0.032)$ ps [PDG 2012]

2) *CP* specific lifetime:

- Assumed to be either *CP* even or odd

  e.g. $B_s^0 \to K^+K^-$ or $D_s^+D_s^-$ assumed *CP* even or $B_s^0 \to \to J/\psi\ f_0(980)$ is *CP* odd

  => lifetime measures Γ_L or Γ_H

3) Disentangle mixed *CP* state

- e.g. $B_s^0 \to J/\psi\ \phi$: Fit for *CP* components

- $\tau(B_s^0) = (1.429 \pm 0.088)$ ps [PDG 2012]

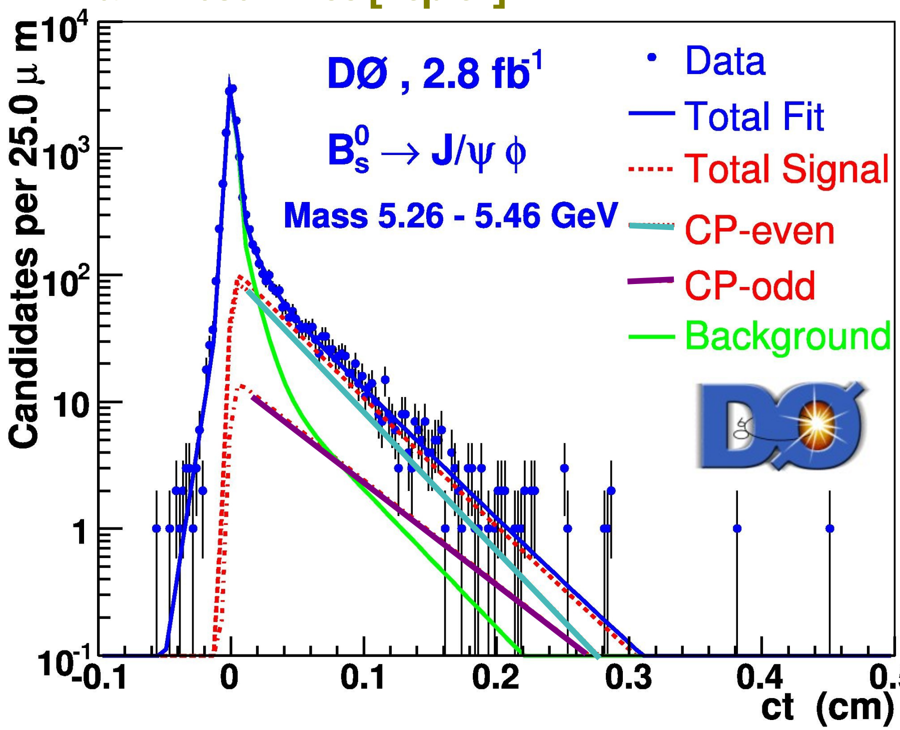
$B_s^0 \to J/\psi\ \phi$ Lifetime Example

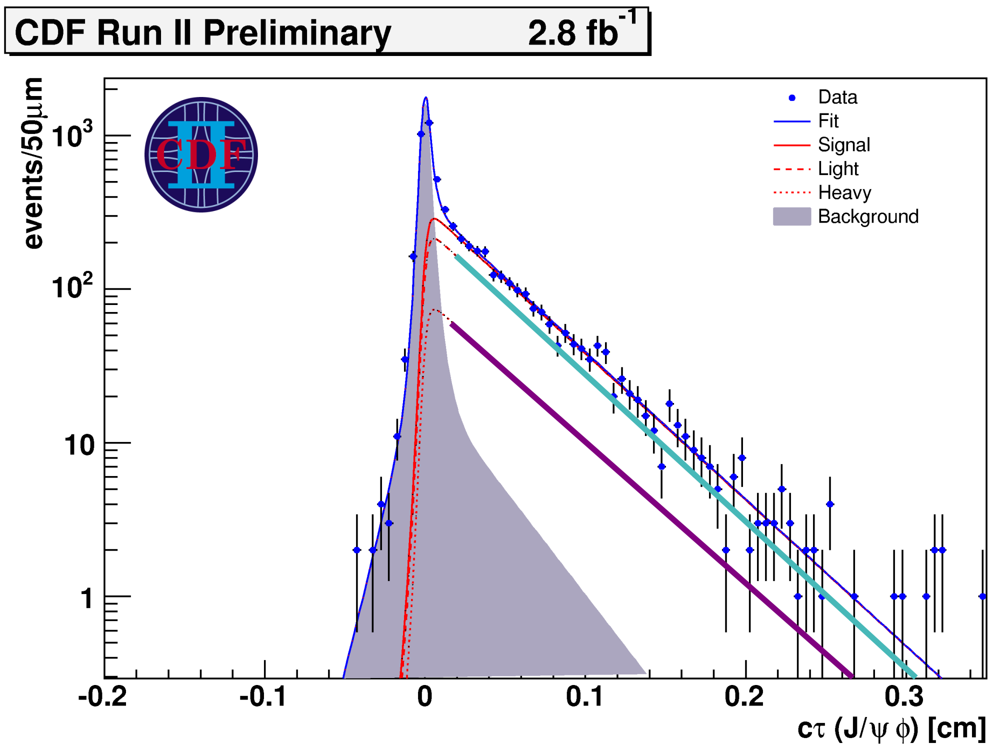
Results:

- **Measurement of lifetime and $\Delta\Gamma$**

CP even
CP odd

arXiv:0802.2255 [hep-ex]





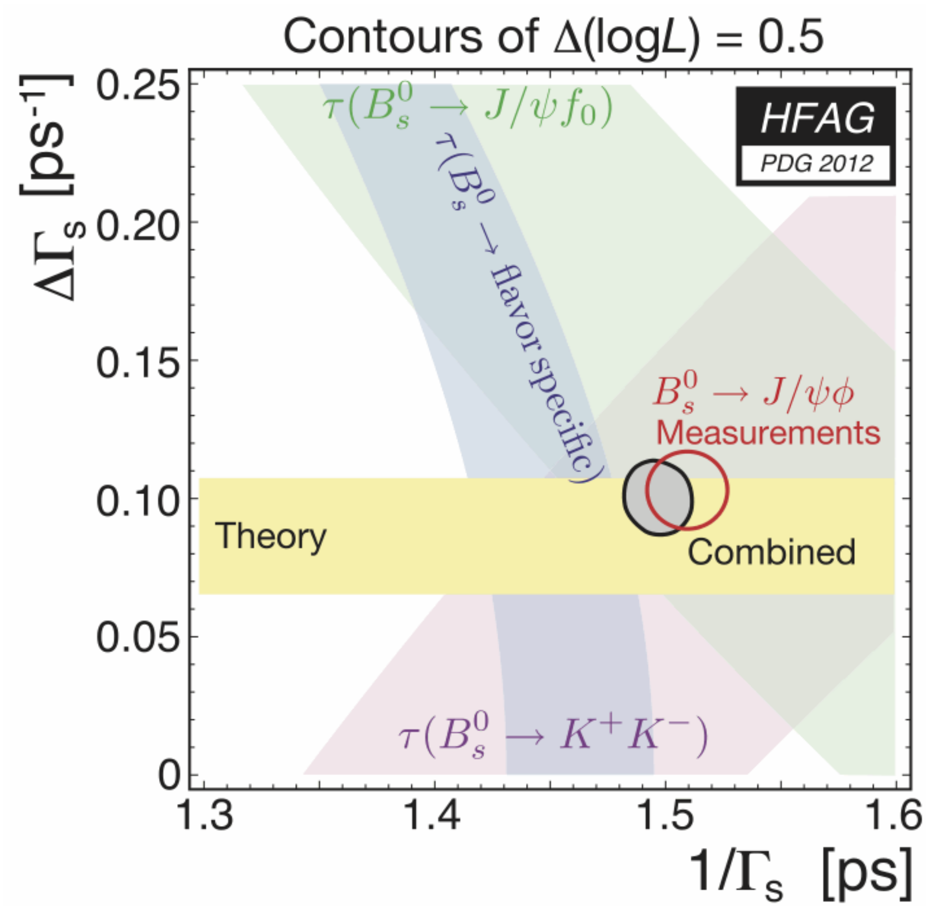
$\tau_s = 1/\Gamma_s = (1.53 \pm 0.06 \pm 0.01)$ ps
$\Delta\Gamma_s = (0.14 \pm 0.07 \pm 0.02)\ \text{ps}^{-1}$

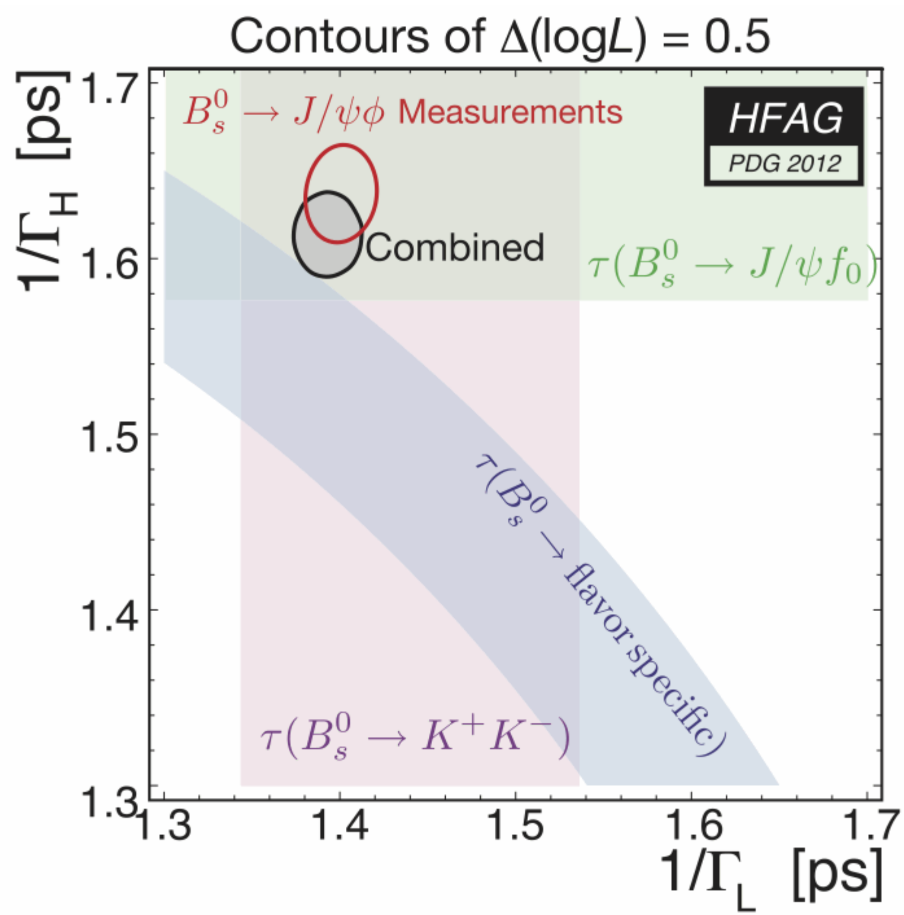
$\tau_s = 1/\Gamma_s = (1.53 \pm 0.04 \pm 0.01)$ ps
$\Delta\Gamma_s = (0.02 \pm 0.05 \pm 0.01)\ \text{ps}^{-1}$

$\Delta\Gamma_s$ Summary

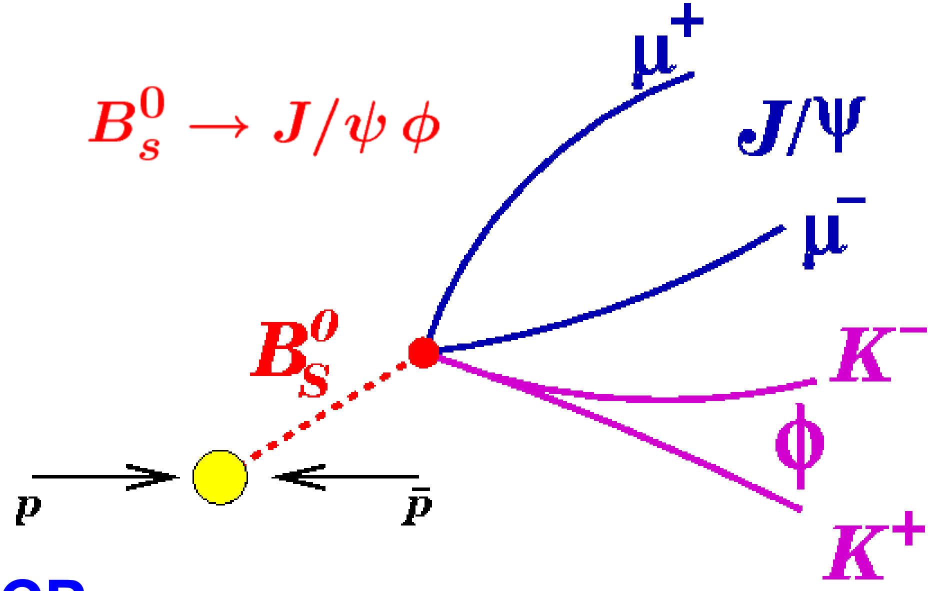
PDG 2012 averages:

$$\begin{aligned} 1/\Gamma_s &= (1.497 \pm 0.015)\ \text{ps} \\ \tau_{\text{short}} = 1/\Gamma_L &= (1.393 \pm 0.019)\ \text{ps} \\ \tau_{\text{long}} = 1/\Gamma_H &= (1.618 \pm 0.024)\ \text{ps} \\ \Delta\Gamma_s &= +(0.100 \pm 0.013)\ \text{ps}^{-1} \\ \Delta\Gamma_s/\Gamma_s &= +(0.150 \pm 0.020) \end{aligned}$$



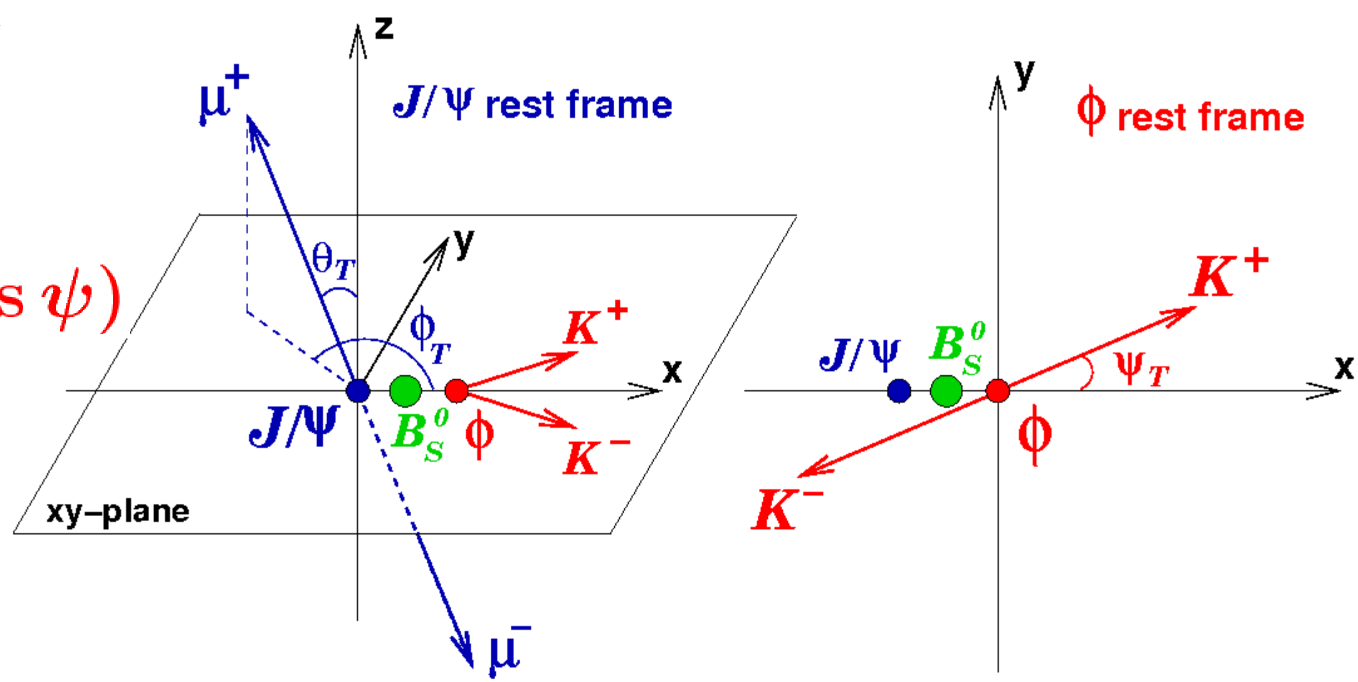


B_s^0 -> J/ψ φ Analysis



- **Decay $B_s^0 \to J/\psi\,\phi$**
  (spin-0 -> spin-1 + spin-1)
  leads to 3 different angular momentum final states:
  - L=0 (S-wave), L=2 (D-wave) -> CP even
  - L=1 (P-wave) -> CP odd

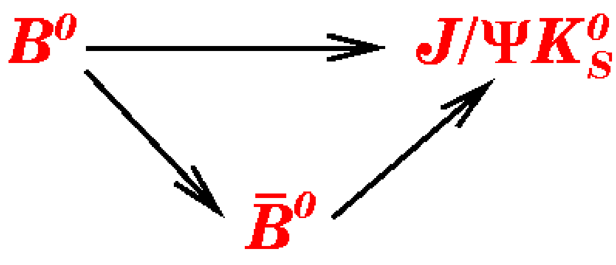
- **Use decay angular distribution in transversity basis**
  $\vec{\rho} = (\cos\theta,\ \phi,\ \cos\psi)$
  to disentangle CP states
  => mainly
  CP even !



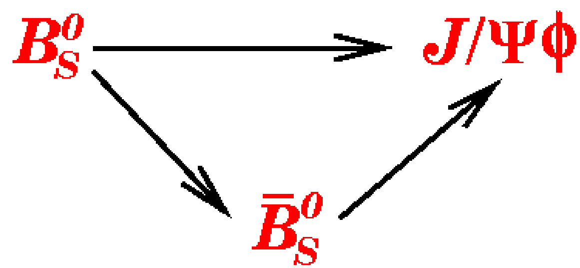
$B_s^0 \to J/\psi\ \phi$ Analysis

- With flavor tagging measure time dep. *CP* asym. => determ. β_s

  Analogy to measurement of CKM angle β in $B^0 \to J/\psi K_S^0$

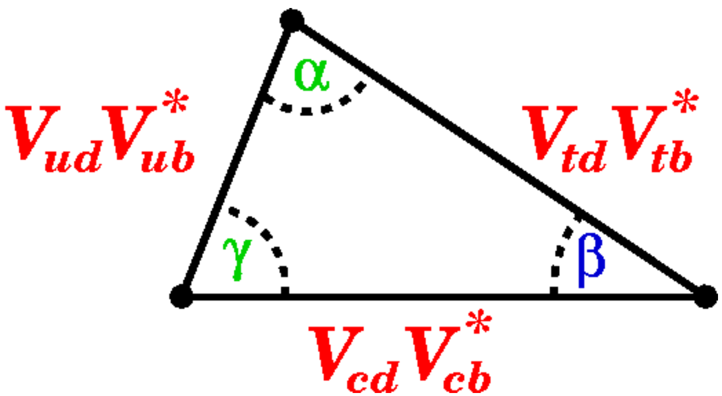


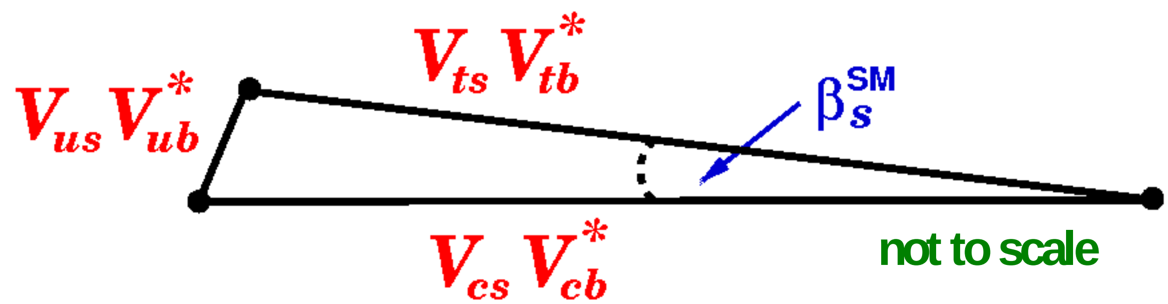
=> sin 2β



=> sin $2\beta_s^{SM}$

$$\beta_s^{\mathrm{SM}} = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$



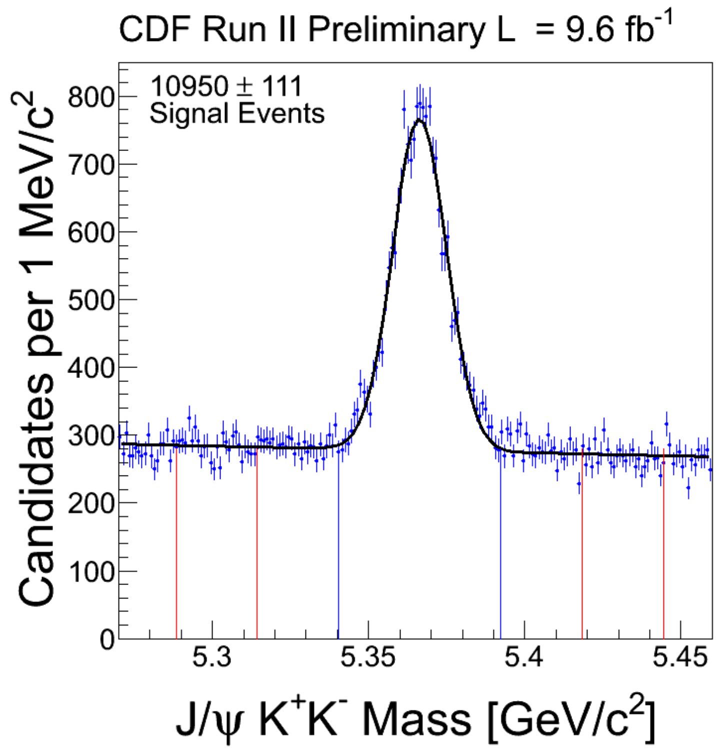


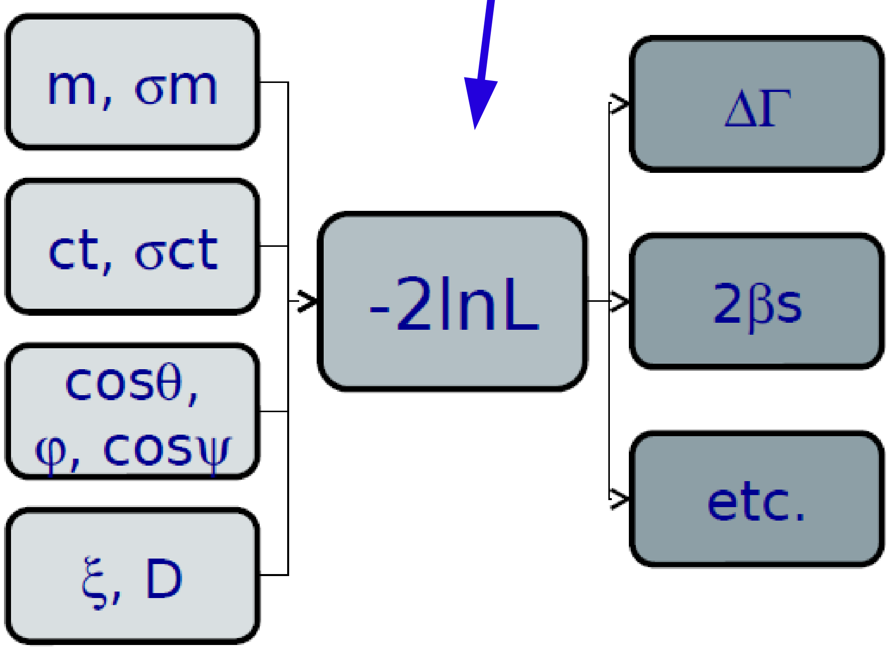
Expect β_s to be small in SM ($|\beta_s^{SM}| \approx 0.02$) - beyond current reach

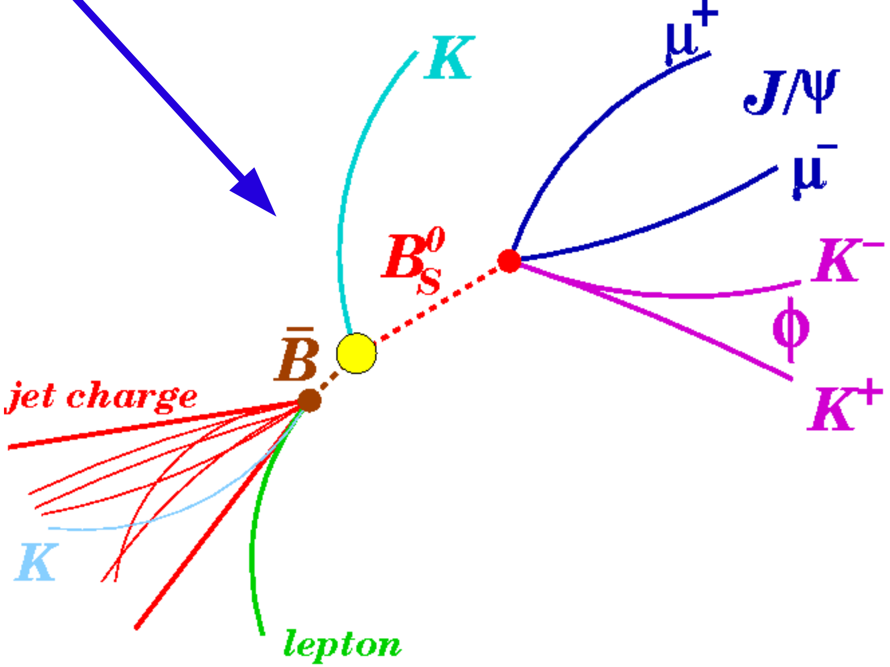
=> Current interest: Search for enhanced CP violation through new physics: $2\beta_s^{J/\psi\phi} = 2\beta_s^{\mathrm{SM}} - \phi_s^{\mathrm{NP}}$

Analysis Strategy

- **Reconstruct $B_s^0 \to J/\psi\phi$**
- **Use angular information to disentangle CP eigenstates**
- **Identify initial state of B_s^0 meson (flavour tagging)**
- **Perform unbinned maximum likelihood fit**







Some History

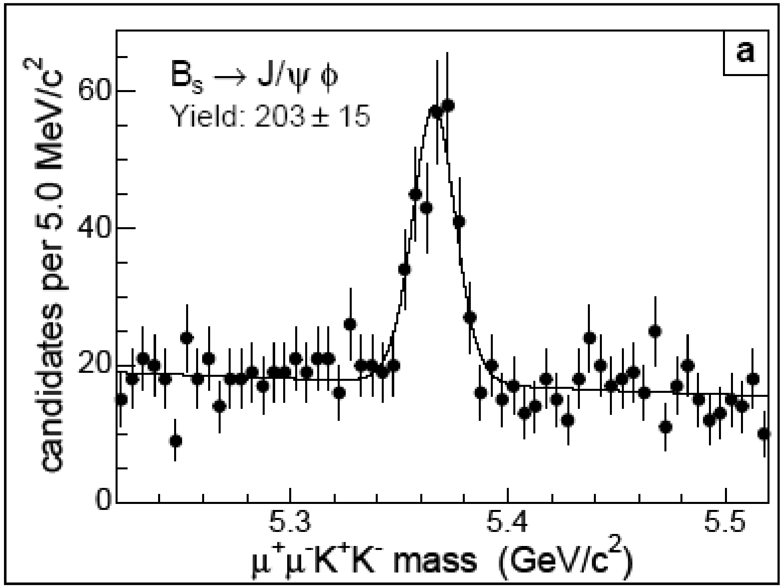
In the beginning: Measurement of $\Delta\Gamma_s$

Measurement of the Lifetime Difference Between B_s Mass Eigenstates

D. Acosta,[16] J. Adelman,[12] T. Affolder,[9] T. Akimoto,[54] M.G. Albrow,[15] D. Ambrose,[43] S. Amerio,[42] D. Amidei,[33] A. Anastassov,[50] K. Anikeev,[15] A. Annovi,[44] J. Antos,[1] M. Aoki,[54] G. Apollinari,[15] T. Arisawa,[56] J-F. Arguin,[32] A. Artikov,[13] W. Ashmanskas,[15] A. Attal,[7] F. Azfar,[41] P. Azzi-Bacchetta,[42] N. Bacchetta,[42] H. Bachacou,[28] W. Badgett,[15] A. Barbaro-Galtieri,[28] G.J. Barker,[25] V.E. Barnes,[46] B.A. Barnett,[24] S. Baroiant,[6] M. Barone,[17] G. Bauer,[31] F. Bedeschi,[44] S. Behari,[24] S. Belforte,[53] G. Bellettini,[44] J. Bellinger,[58] E. Ben-Haim,[15] D. Benjamin,[14] ...locker,[5] K. Bloom,[33] ...rtoletto,[46] J. Boudreau,[45]

We present measurements of the lifetimes and polarization amplitudes for $B_s^0 \to J/\psi\,\phi$ and $B_d^0 \to J/\psi\,K^{*0}$ decays. Lifetimes of the heavy (H) and light (L) mass eigenstates in the B_s^0 system are separately measured for the first time by determining the relative contributions of amplitudes with definite CP as a function of the decay time. Using 203 ± 15 B_s^0 decays we obtain $\tau_L = (1.05\,^{+0.16}_{-0.13} \pm 0.02)$ ps and $\tau_H = (2.07\,^{+0.58}_{-0.46} \pm 0.03)$ ps. Expressed in terms of the difference $\Delta\Gamma_s$ and average Γ_s, of the decay rates of the two eigenstates, the results are $\Delta\Gamma_s/\Gamma_s = (65\,^{+25}_{-33} \pm 1)\%$, and $\Delta\Gamma_s = (0.47\,^{+0.19}_{-0.24} \pm 0.01)\,\mathrm{ps}^{-1}$.

PRL 94, 101803 (2005)



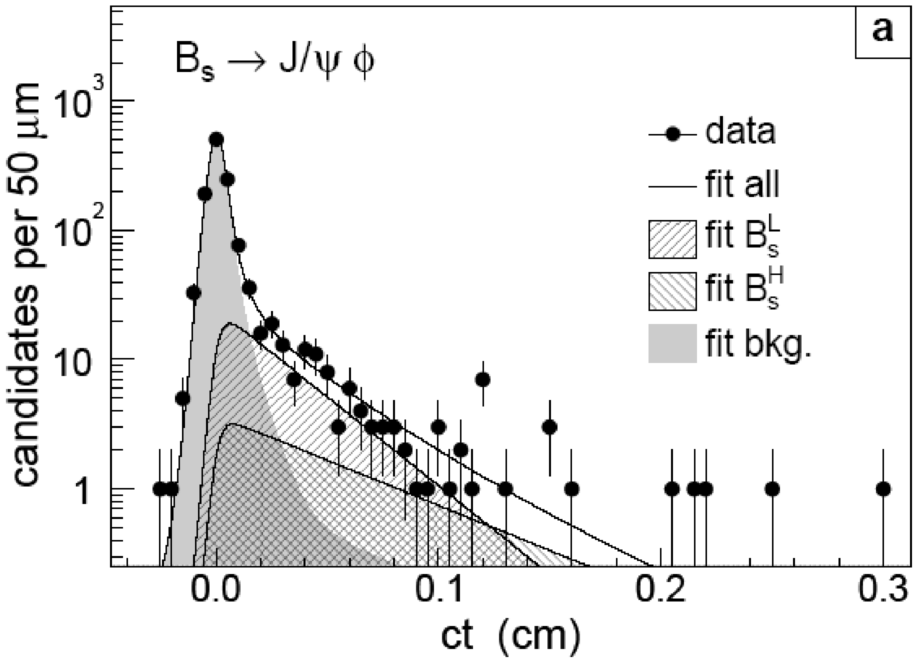
2004: CDF measures with 0.27 fb^{-1}:

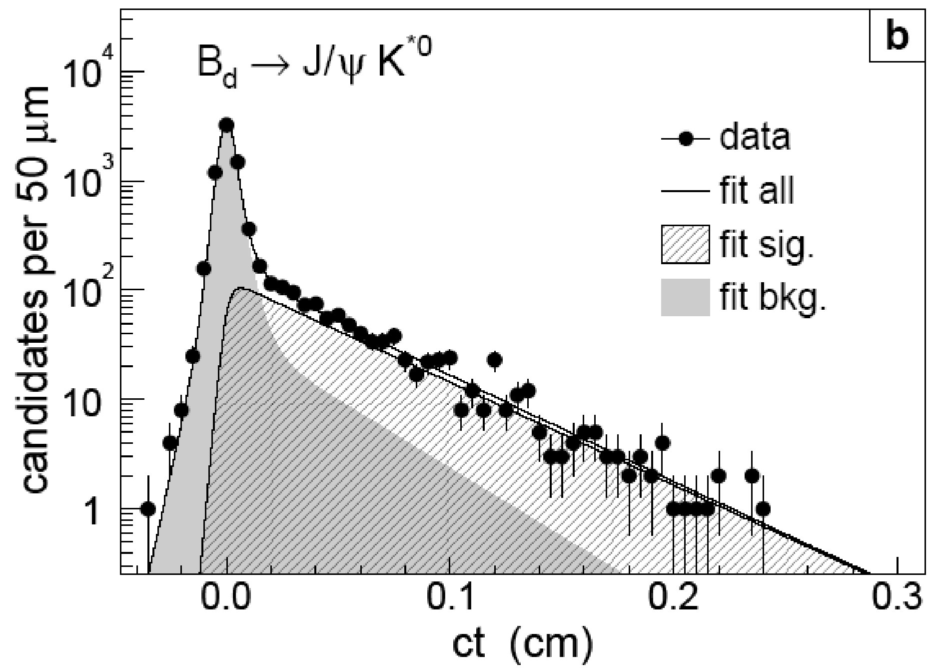
$\Delta\Gamma_s / \Gamma_s = 0.65\,^{+0.25}_{-0.33}$

=> $\Delta m_s \sim 125\ \mathrm{ps}^{-1}$!!

Some History

At that time life was simpler ….



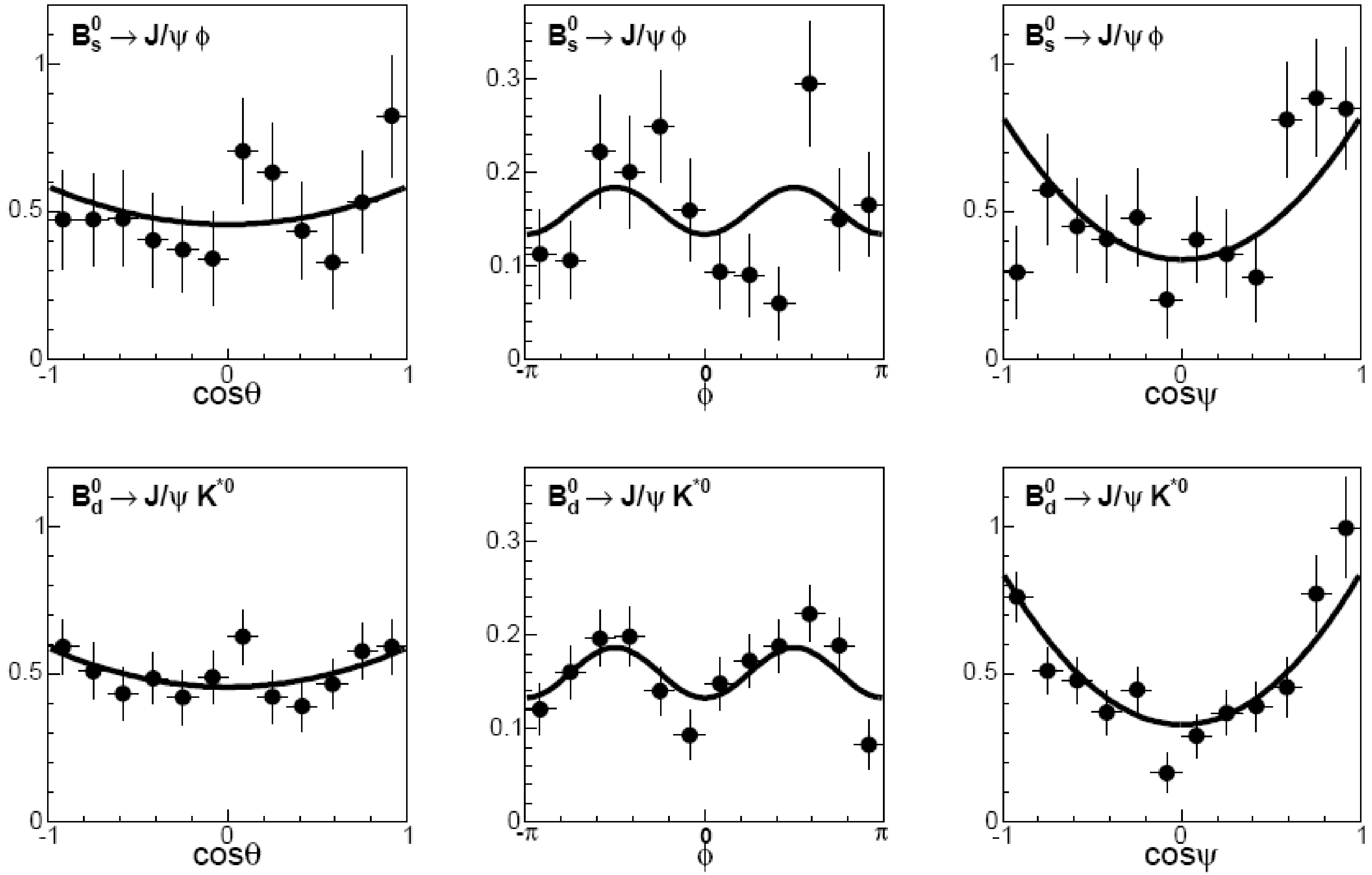


2004: Didn't know Δm_s => no need for flavour tagging

$$\frac{d^4\mathcal{P}(\vec{\rho},t)}{d\vec{\rho}\,dt} \propto |A_0|^2 e^{-\Gamma_L t}\cdot f_1(\vec{\rho}) + |A_{||}|^2 e^{-\Gamma_L t}\cdot f_2(\vec{\rho})$$
$$+ |A_\perp|^2 e^{-\Gamma_H t}\cdot f_3(\vec{\rho}) + \mathrm{Re}(A_0^* A_{||})\cdot f_5(\vec{\rho}) e^{-\Gamma_L t}$$

Some History

Check angular fit with $B^0 \rightarrow J/\psi K^{*0}$



Some History

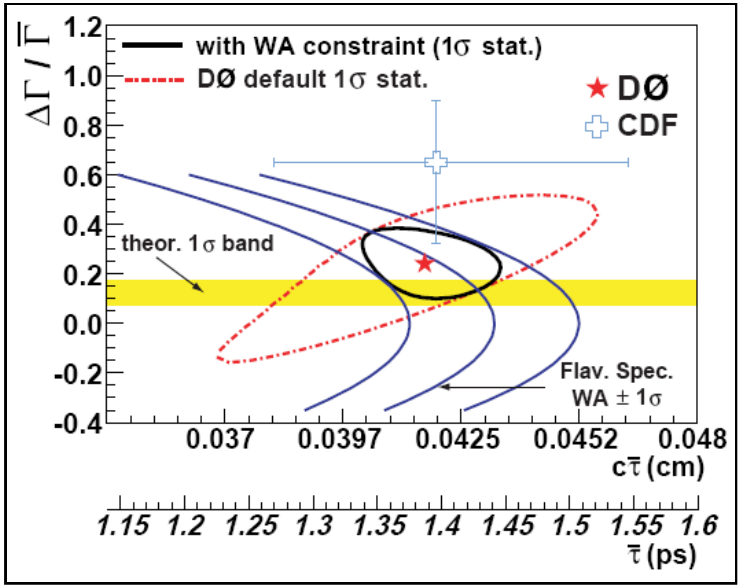
D0 measurement of $\Delta\Gamma_s$ followed soon

Measurement of the Lifetime Difference in the B_s^0 System

V.M. Abazov,[35] B. Abbott,[72] M. Abolins,[63] B.S. Acharya,[29] M. Adams,[50] T. Adams,[48] M. Agelou,[18] J.-L. Agram,[19] S.H. Ahn,[31] M. Ahsan,[57] G.D. Alexeev,[35] G. Alkhazov,[39] A. Alton,[62] G. Alverson,[61] G.A. Alves,[2] M. Anastasoaie,[34] T. Andeen,[52] S. Anderson,[44] B. Andrieu,[17] Y. Arnoud,[14] M. Arov,[51] A. Askew,[48] B. Åsman,[40] A.C.S. Assis Jesus,[3] O. Atramentov,[55] C. Autermann,[21] C. Avila,[8] F. Badaud,[13] A. Baden,[59] L. Bagby,[51] B. Baldin,[49] P.W. Balm,[33] P. Banerjee,[29] S. Banerjee,[29] E. Barberis,[61] P. Bargassa,[76] P. Baringer,[56] C. Barnes,[42] J. Barreto,[2] J.F. Bartlett,[49] U. Bassler,[17] D. Bauer,[53] A. Bean,[56] S. Beauceron,[17] M. Begalli,[3] M. Begel,[68] A. Bellavance,[65] S.B. Beri,[27] G. Bernardi,[17] R. Bernhard,[49,*] I. Bertram,[41] M. Besancon,[18] R. Beuselinck,[42] V.A. Bezzubov,[38] P.C. Bhat,[49] ler,[42] G. Blazey,[51] F. Blekman,[42] S. Blessing,[48] . Bolton,[57] F. Borcherding,[49] G. Borissov,[41]

We present a study of the decay $B_s^0 \to J/\psi\,\phi$. We obtain the CP-odd fraction in the final state at time zero, $R_\perp = 0.16 \pm 0.10$ (stat) $\pm$ 0.02 (syst), the average lifetime of the $(B_s^0, \overline{B}_s^0)$ system, $\overline{\tau}(B_s^0) = 1.39^{+0.13}_{-0.16}$ (stat) $^{+0.01}_{-0.02}$ (syst) ps, and the relative width difference between the heavy and light mass eigenstates, $\Delta\Gamma/\overline{\Gamma} \equiv (\Gamma_L - \Gamma_H)/\overline{\Gamma} = 0.24^{+0.28}_{-0.38}$ (stat) $^{+0.03}_{-0.04}$ (syst). With the additional constraint from the world average of the B_s^0 lifetime measurements using semileptonic decays, we find $\overline{\tau}(B_s^0) = 1.39 \pm 0.06$ ps and $\Delta\Gamma/\overline{\Gamma} = 0.25^{+0.14}_{-0.15}$. For the ratio of the B_s^0 and B^0 lifetimes we obtain $\frac{\overline{\tau}(B_s^0)}{\tau(B^0)} = 0.91 \pm 0.09$ (stat) $\pm$ 0.003 (syst).

PRL 95, 171801 (2005)



2005: D0 measures with 0.45 fb^{-1}:

$\Delta\Gamma_s / \Gamma_s = 0.24\ ^{+0.28}_{-0.38}$

closer to expectation of ~0.15

Some History

D0 includes fit to CP phase β_s

=> likelihood gets more complicated

$$\frac{d^4 P(\vec{\rho},t)}{d\vec{\rho}dt} \propto |A_0|^2 f_1(\vec{\rho})\mathcal{T}_+ + |A_{||}|^2 f_2(\vec{\rho})\mathcal{T}_+$$

$$+ |A_\perp|^2 f_3(\vec{\rho})\mathcal{T}_- + |A_0||A_{||}| f_5(\vec{\rho})\cos(\delta_{||})\mathcal{T}_+$$

$$+ |A_{||}||A_\perp| f_4(\vec{\rho})\cos(\delta_\perp - \delta_{||})$$

$$\sin(2\beta_s)(e^{-\Gamma_H t} - e^{-\Gamma_L t})/2$$

$$+ |A_0||A_\perp| f_6(\vec{\rho})\cos(\delta_\perp)$$

$$\sin(2\beta_s)(e^{-\Gamma_H t} - e^{-\Gamma_L t})/2$$

Previously ignored these, $2\beta_s$ ~ 0 in SM

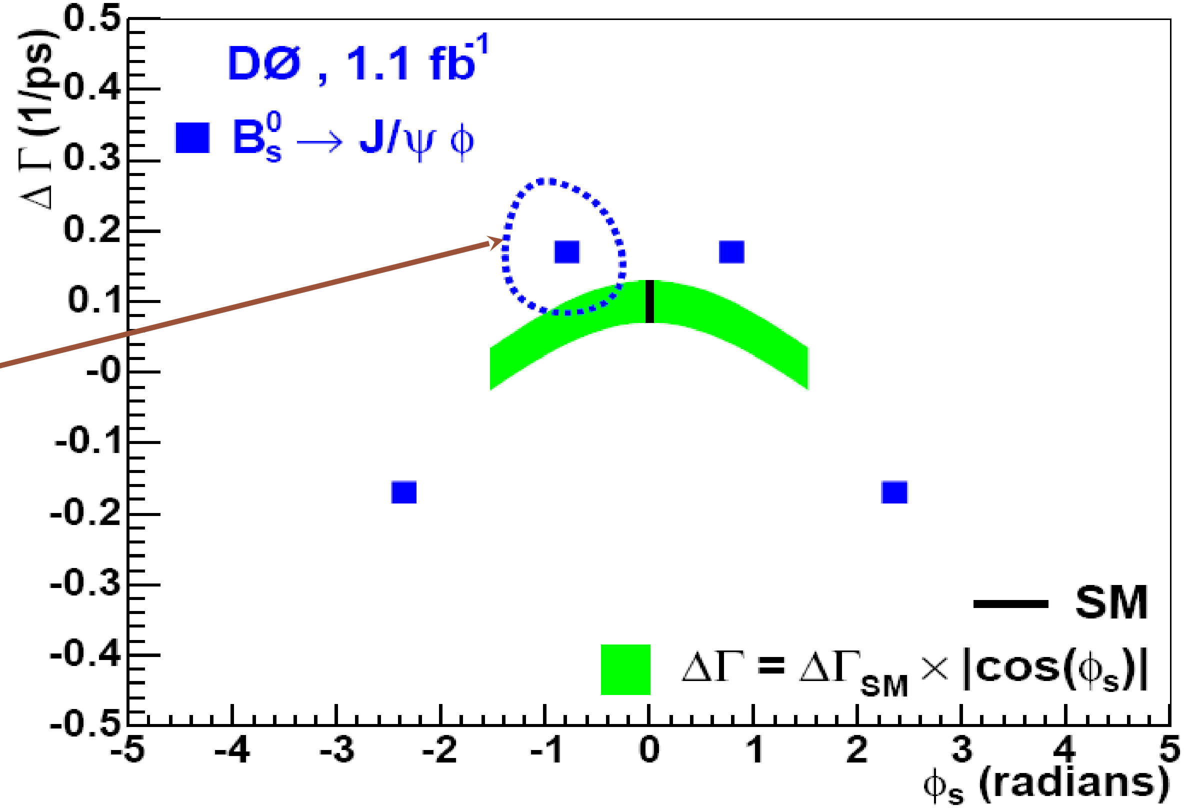
- δ‖ = arg(A‖(0) A0*(0))
- δ ⊥ = arg(A ⊥ (0) A0*(0))

$$\mathcal{T}_\pm = \left[(1 \pm \cos(2\beta_s))e^{-\Gamma_L t} + (1 \mp \cos(2\beta_s))e^{-\Gamma_H t}\right]/2$$

Some History

D0 includes fit to CP phase β_s

PRL 98, 121801 (2007)



Dotted line indicates 39% CL

No flavour tagging
=> four-fold ambiguity in determination of CP phase β_s

<u>2006:</u> D0 measures with 1.1 fb^{-1}:

$\Delta\Gamma_s = 0.17 \pm 0.08 \pm 0.01\ ps^{-1}$

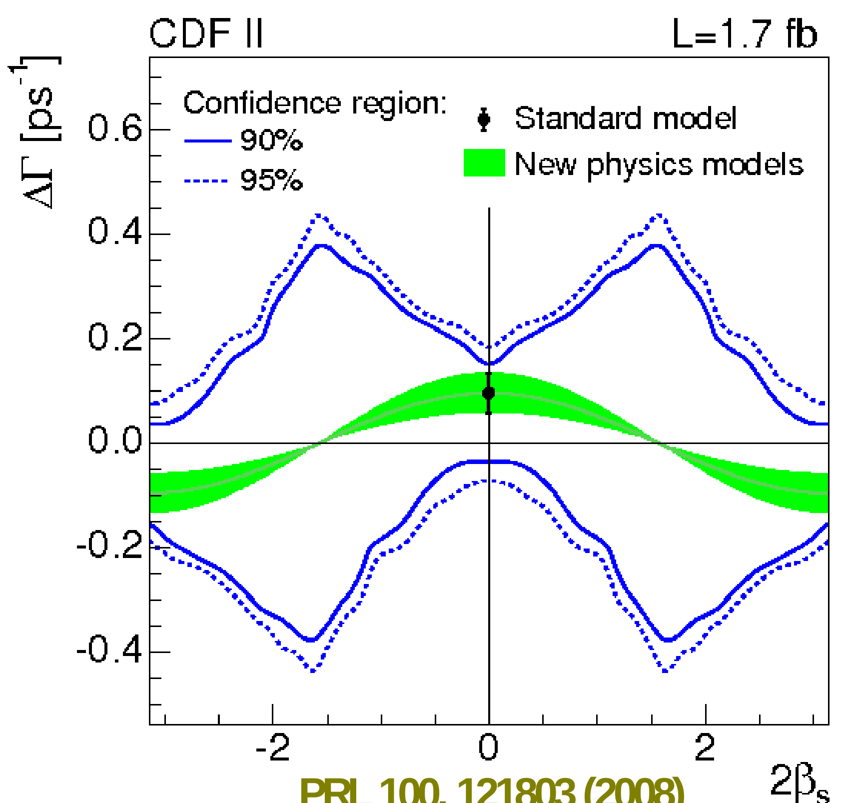
Some History

- CDF finds that things are not so simple:
- When $2\beta_s$ floats freely in fit, CDF sees significant biases and non-Gaussian errors in pseudo-experiments at low statistics
- Can reliably quote some point estimates only with $2\beta_s$ fixed to standard model prediction
- Quote confidence regions, rather than point estimates, when $2\beta_s$ floats freely

<u>2007:</u>

CDF measures with 1.7 fb^{-1} for CP phase $2\beta_s$ fixed to zero

$\Delta\Gamma_s = 0.076\ ^{+0.059}_{-0.063} \pm 0.01\ ps^{-1}$

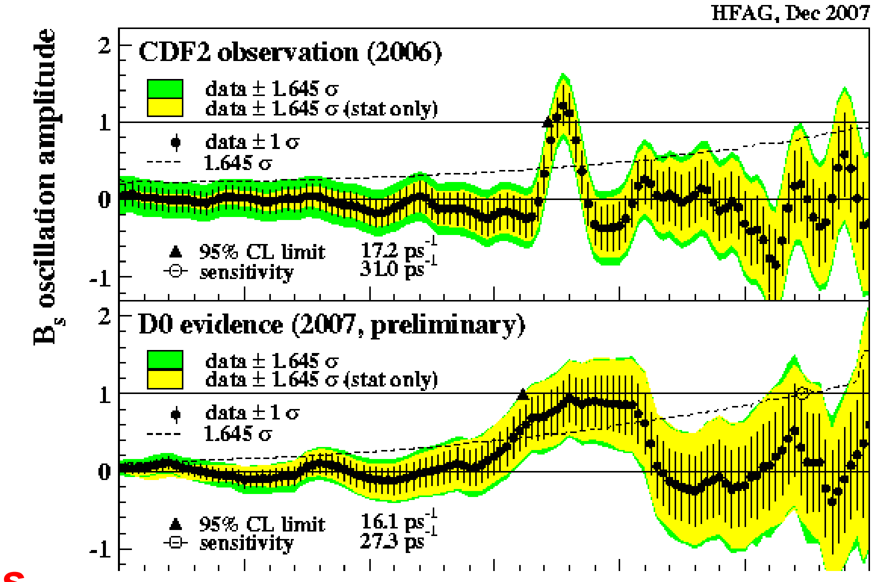


PRL 100, 121803 (2008)

Some History

- Meanwhile everything changes:
- CDF observes B_s mixing in 2006

  => measures Δm_s



- Time dependence on $\Delta\Gamma_s$, Δm_s, $2\beta_s$

$$\mathcal{T}_\pm = e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) \mp \cos(2\beta_s)\sinh\left(\frac{\Delta\Gamma}{2}t\right) \mp \eta\sin(2\beta_s)\sin(\Delta m_s t)\right]$$

CP asymmetry

η = +1 Bs0, η = -1 Bs0

$$\mathcal{U}_\pm = \pm e^{-\Gamma t} \times \left[\sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t) - \cos(\delta_\perp - \delta_\parallel)\cos(2\beta_s)\sin(\Delta m_s t) \pm \cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)\sinh\left(\frac{\Delta\Gamma t}{2}\right)\right]$$

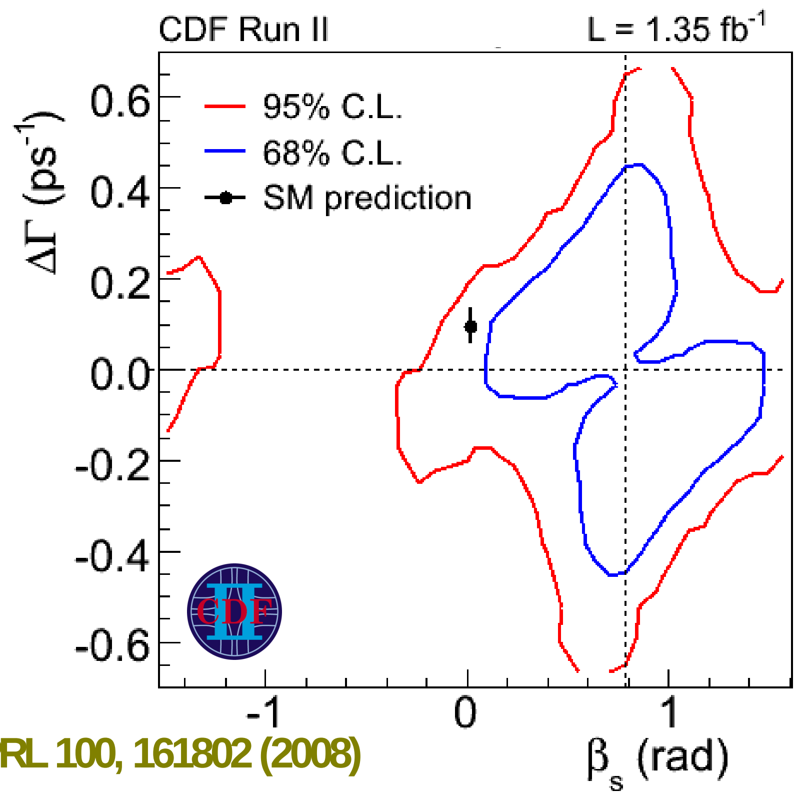
Dependence on $\cos(\Delta m_s t)$

$$\mathcal{V}_\pm = \pm e^{-\Gamma t} \times \left[\sin(\delta_\perp)\cos(\Delta m_s t) - \cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t) \pm \cos(\delta_\perp)\sin(2\beta_s)\sinh\left(\frac{\Delta\Gamma t}{2}\right)\right].$$

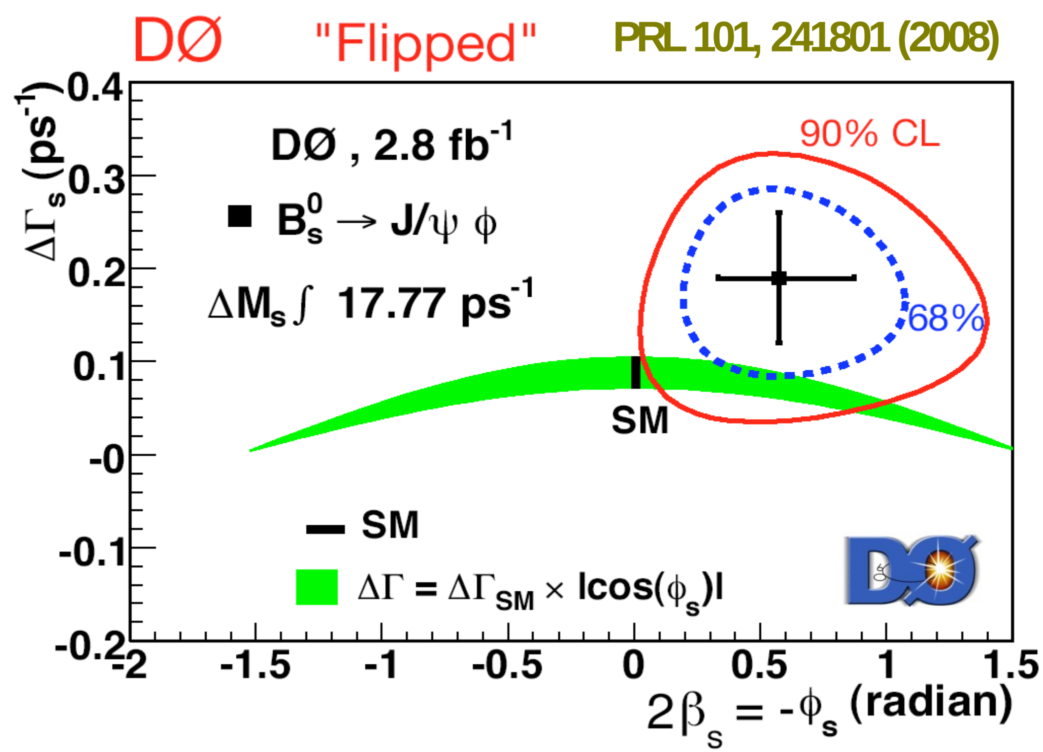
CP Violation in $B_s^0 \rightarrow J/\psi\ \phi$

Winter Conferences 2008:

- **First results from CDF (1.35 fb^{-1}) & D0 (2.8 fb^{-1}) presented**
- **Expressed as confidence regions in β_s-$\Delta\Gamma_s$ plane**



PRL 100, 161802 (2008)



PRL 101, 241801 (2008)

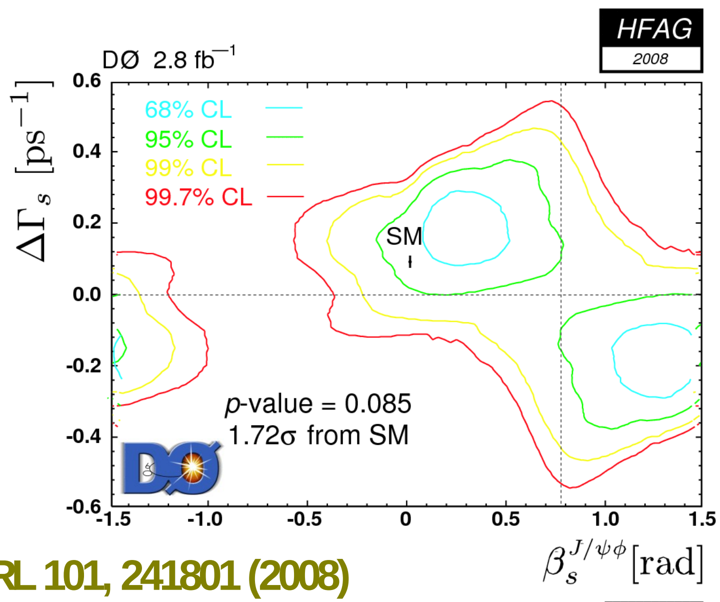
p-value(SM): 0.15 (~1.5σ)

Use external constraints on strong phases
p-value(SM): 0.066 (~1.8σ)

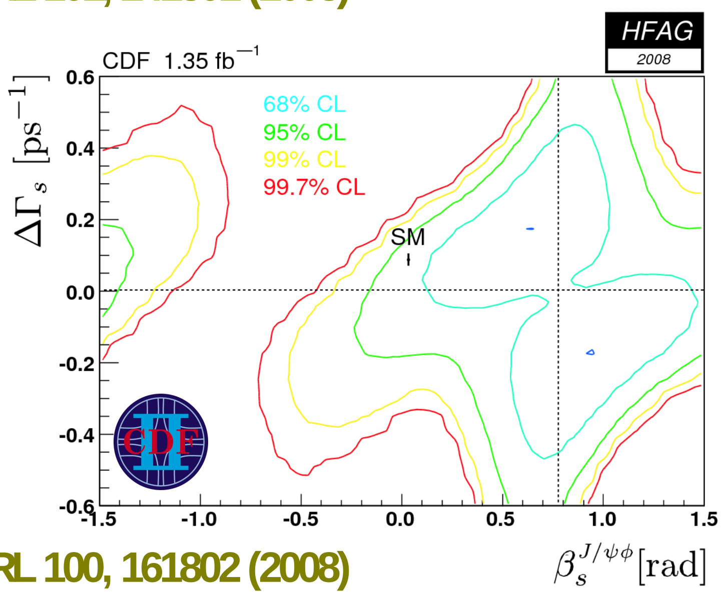
Mild inconsistency with SM (but in same direction)

CP Violation in $B_s^0 \to J/\psi\ \phi$

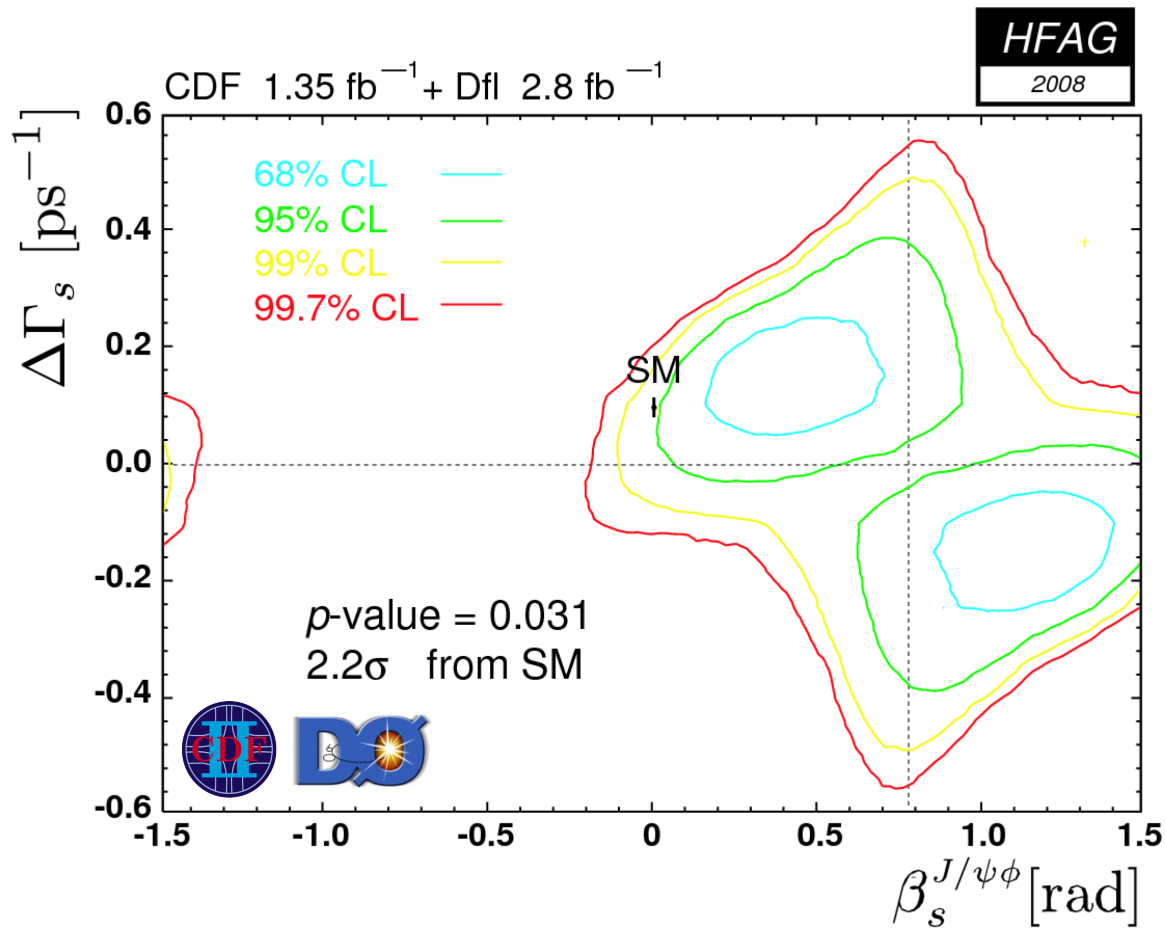
<u>Next:</u> D0 released data with no constraint for average with CDF



PRL 101, 241801 (2008)



PRL 100, 161802 (2008)



β_s in [0.14,0.73] or [0.83,1.42] at 90% CL

Combined p-value(SM): <u>0.031 (~2.2σ)</u>

Some History

- These results have created quite some excitement
- Utfit collaboration released a paper claiming evidence of new physics in Mar. 2008

FIRST EVIDENCE OF NEW PHYSICS IN $b \leftrightarrow s$ TRANSITIONS

(**UT***fit* Collaboration)

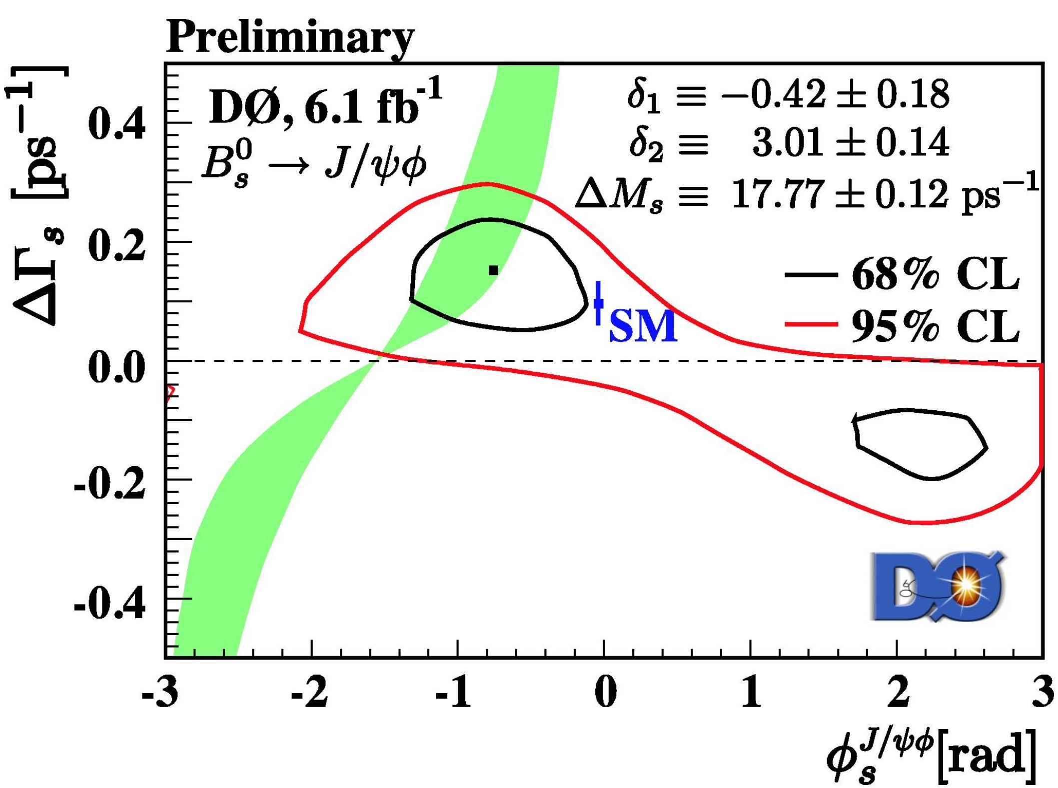
M. Bona,[1] M. Ciuchini,[2] E. Franco,[3] V. Lubicz,[2,4] G. Martinelli,[3,5] F. Parodi,[6]
M. Pierini,[1] C. Schiavi,[6] L. Silvestrini,[3] V. Sordini,[7] A. Stocchi,[7] and V. Vagnoni[8]

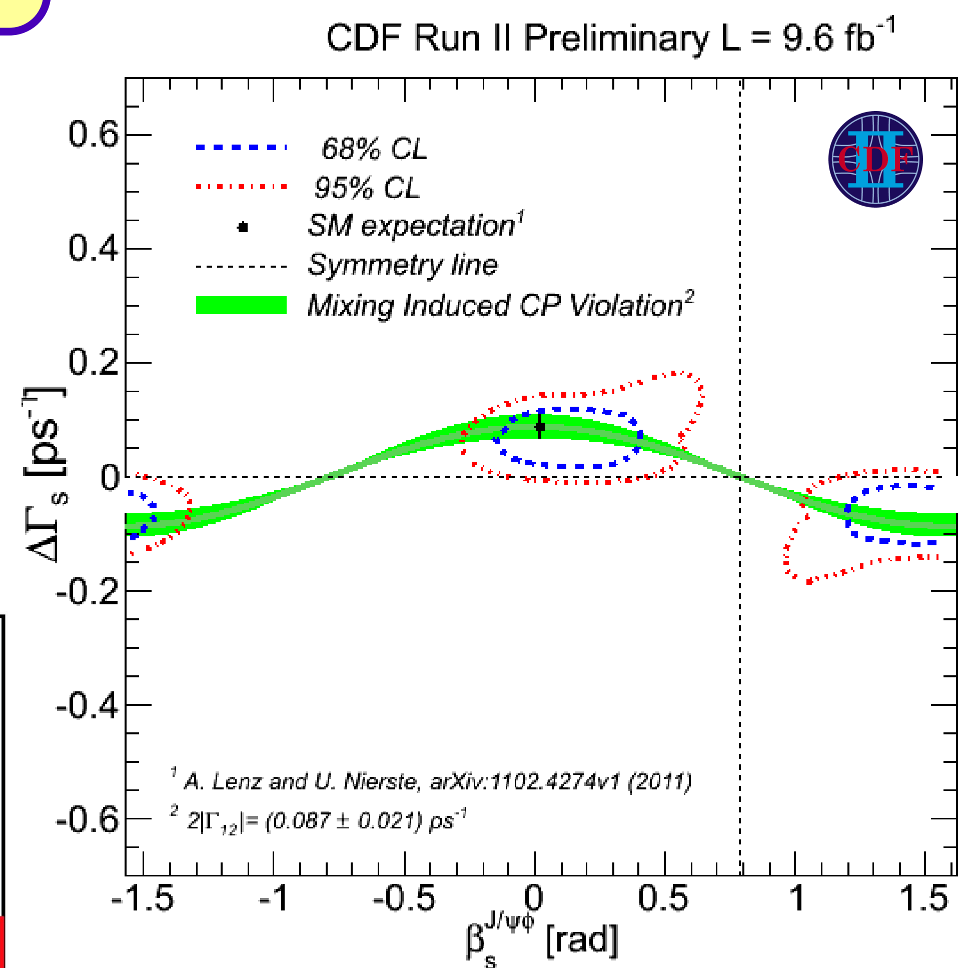
[1] *CERN, CH-1211 Geneva 23, Switzerland*
[2] *INFN, Sezione di Roma Tre, I-00146 Roma, Italy*
[3] *INFN, Sezione di Roma, I-00185 Roma, Italy*
[4] *Dipartimento di Fisica, Università di Roma Tre, I-00146 Roma, Italy*
[5] *Dipartimento di Fisica, Università di Roma "La Sapienza", I-00185 Roma, Italy*
[6] *Dipartimento di Fisica, Università di Genova and INFN, I-16146 Genova, Italy*
[7] *Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS et Université de Paris-Sud, BP 34, F-91898 Orsay Cedex, France*
[8] *INFN, Sezione di Bologna, I-40126 Bologna, Italy*

We combine all the available experimental information on B_s mixing, including the very recent tagged analyses of $B_s \to J/\Psi\phi$ by the CDF and DØ collaborations. We find that the phase of the B_s mixing amplitude deviates more than 3σ from the Standard Model prediction. While no single measurement has a 3σ significance yet, all the constraints show a remarkable agreement with the combined result. This is a first evidence of physics beyond the Standard Model. This result disfavours New Physics models with Minimal Flavour Violation with the same significance.

CP Violation in $B_s^0 \to J/\psi\ \phi$

Where things are today ….

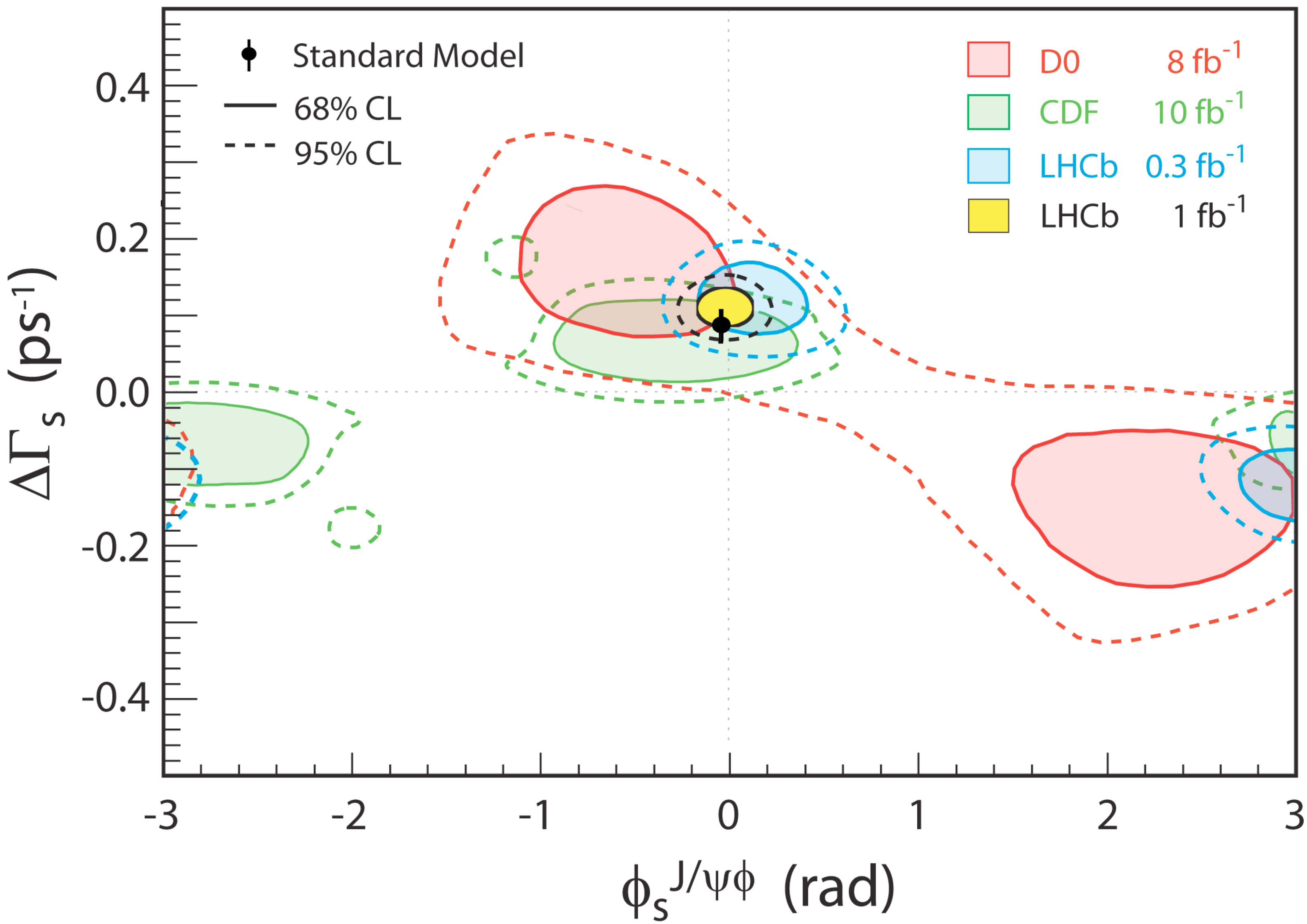




Much less disagreement with SM

CP Violation in $B_s^0 \to J/\psi\ \phi$

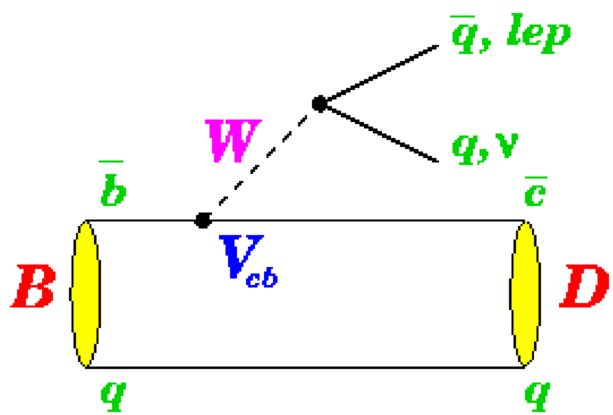
Where things are today …. LHCb dominates ...



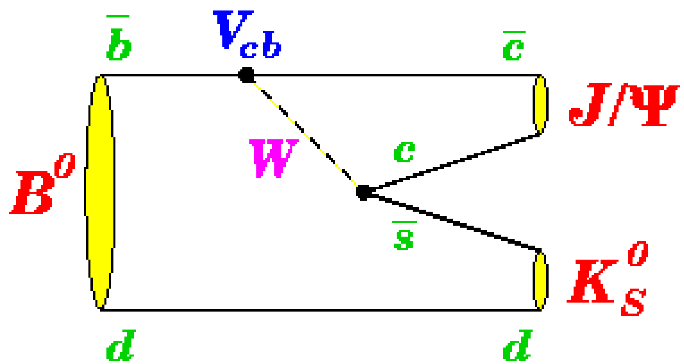
Another result in good agreement with SM ...

What's Next?

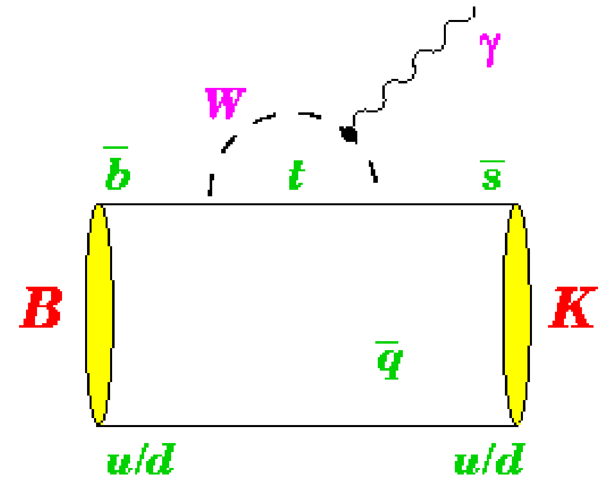
Back to B Decay Diagrams



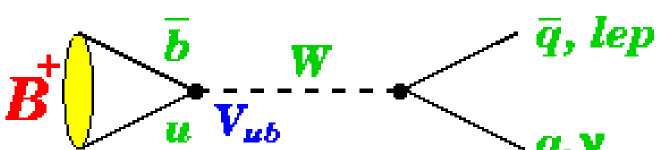
External spectator
(semileptonic, hadronic)



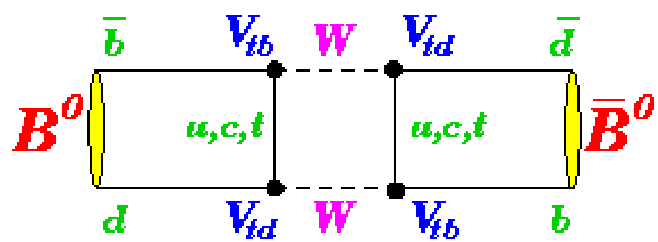
Internal spectator



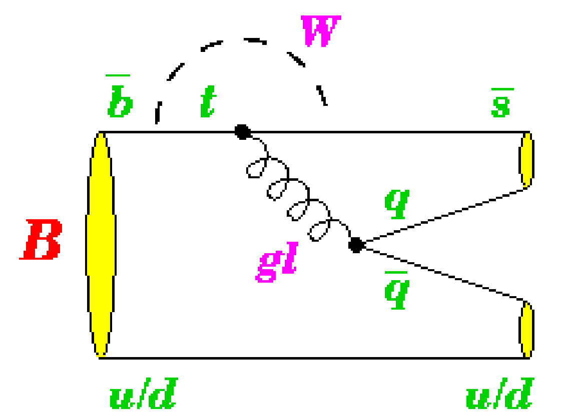
Penguin (radiative)



Annihilation

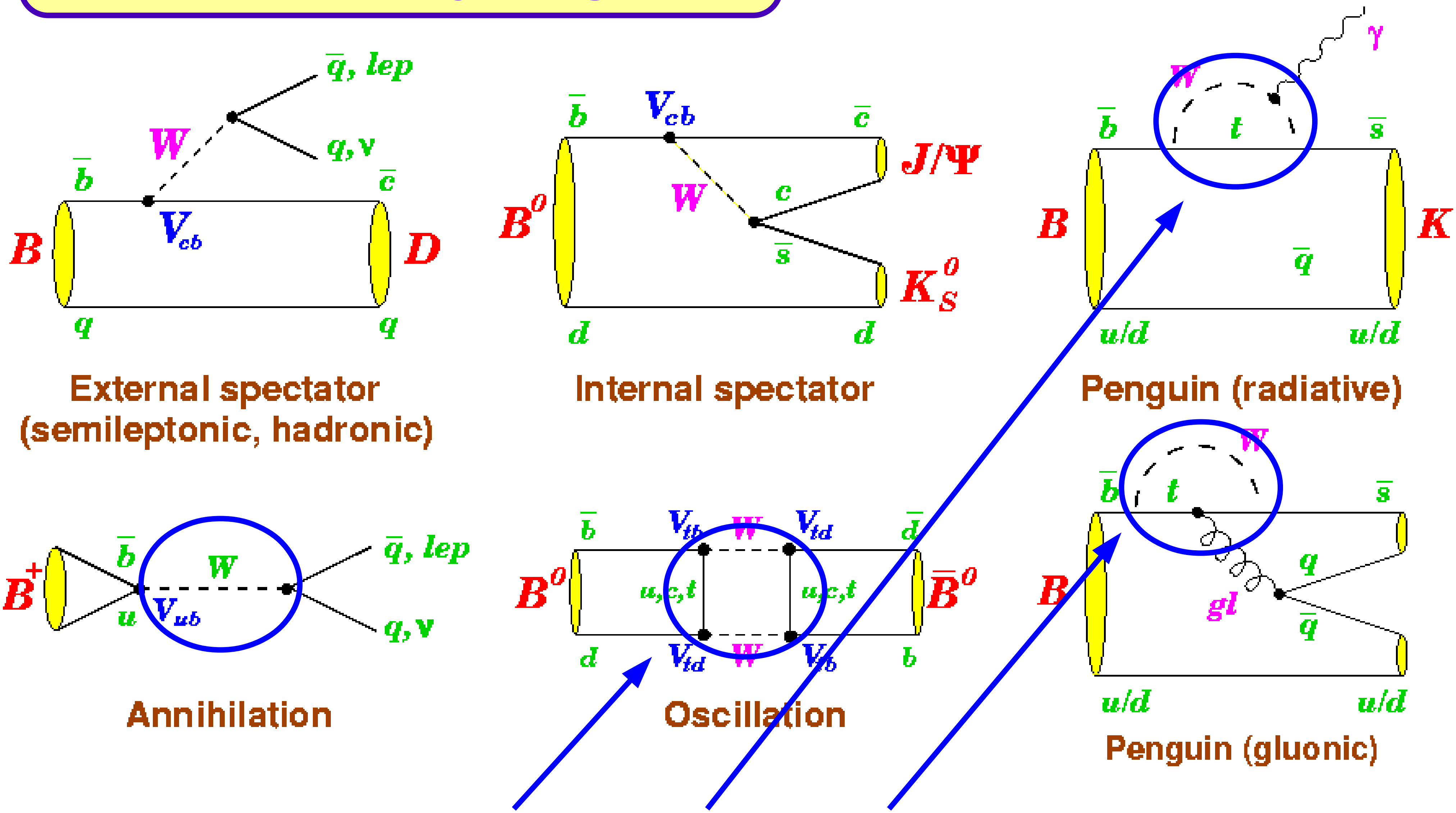


Oscillation



Penguin (gluonic)

Back to B Decay Diagrams



Loop diagrams:
Hiding place for new particles?

Loop Processes

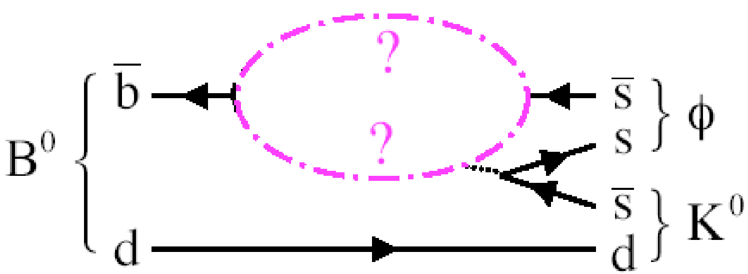
How to continue testing the Standard Model?

- **SM cannot be the ultimate theory**
  - **Must be a low-energy effective theory of a more fundamental theory at a higher energy scale, expected to be in the TeV region (accessible at LHC !)**
- **How can New Physics be discovered and studied ?**
  - **New physics models introduce new particles, dynamics and/or symmetries at the higher scale. These new particles could**
    - **Be produced and observed as real particles at energy frontier machines (e.g LHC)**
    - **Appear as virtual particles (e.g. in loop processes), leading to observable deviations from the pure SM expectations in flavour physics and CP violation**

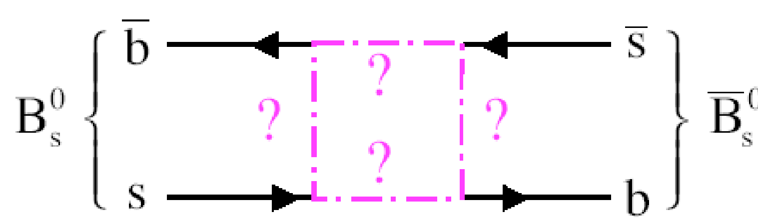
New Physics

$\Delta m_s \neq \Delta m_s^{SM} \propto |V_{ts}^2|$,

$\phi_s \neq \phi_s^{SM} = -\arg(V_{ts}^2) = -2\lambda\eta^2$



$B^0 \to \phi K^0$ decay: "Penguin" diagram



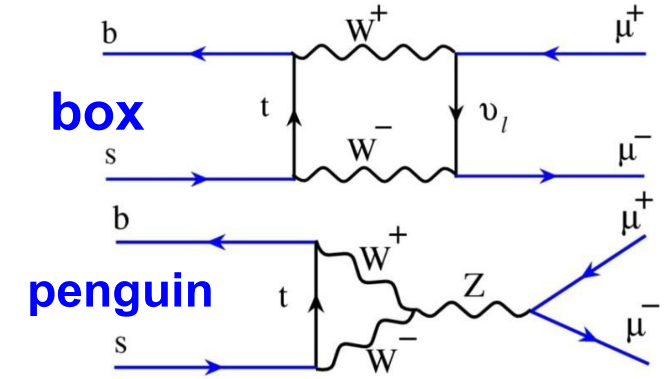
B_s–$\overline{B}_s$ oscillations: "Box" diagram

Strength of Indirect Approach

- Can in principle access higher scales & therefore see effect earlier:
  - Third quark family inferred by Kobayashi and Maskawa (1973) to explain small CP violation measured in kaon mixing (1964), but only directly observed in 1977 (b) and 1995 (t)
  - Neutral currents discovered in 1973, but real Z discovered in 1983
- Can in principle also access the phases of the new couplings:
  - New physics at TeV scale needs to have a "flavour structure" to provide the suppression mechanism for already observed FCNC processes => once NP is discovered, it is important to measure this structure, including new phases
- Complementarity with the "direct" approach:
  - If new physics is found in direct searches at LHC, B physics measurements will help understanding its nature and flavour structure

Rare Loop Processes

Rare Decays: $B_s^0 \to \mu^+\mu^-$

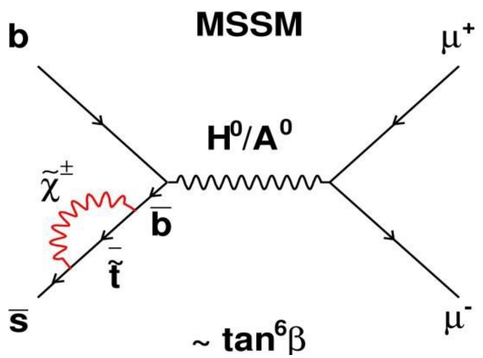


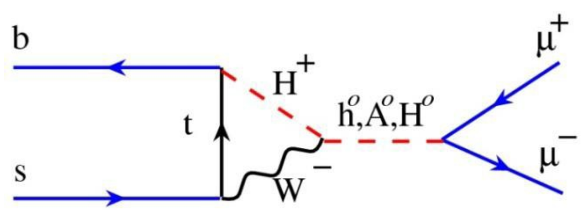
$B_s^0 \to \mu^+\mu^-$: FCNC, forbidden at tree level in SM

SM prediction for BR: $(3.2\pm0.2) \times 10^{-9}$

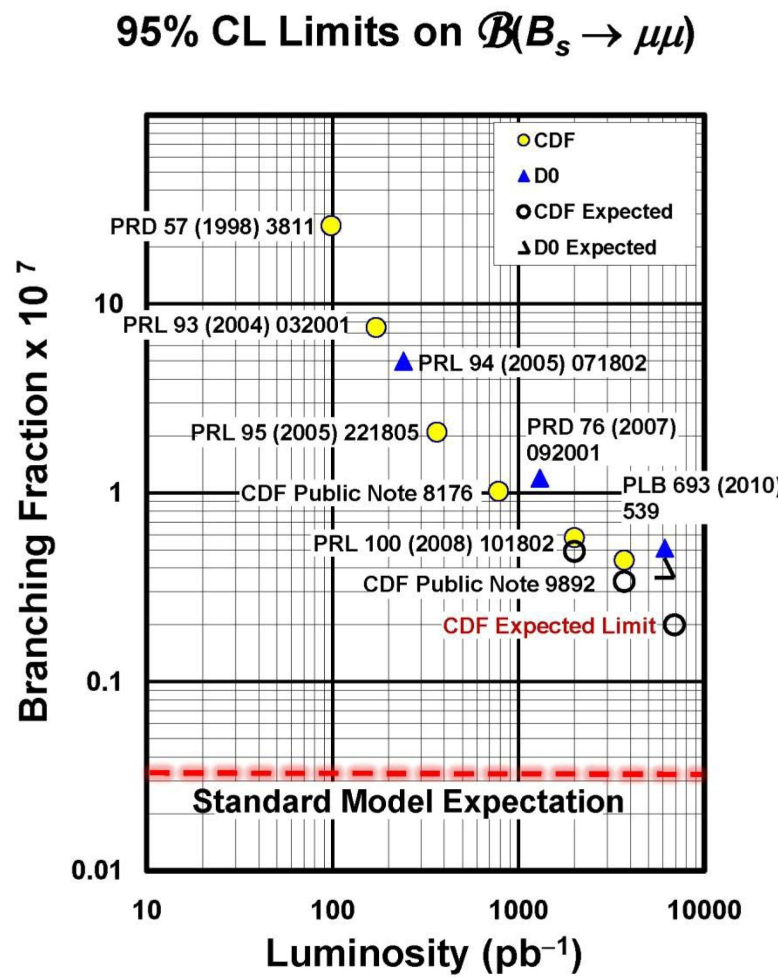
Enhancement to BR due to New Physics

=> powerful probe to NP





penguin enhancement

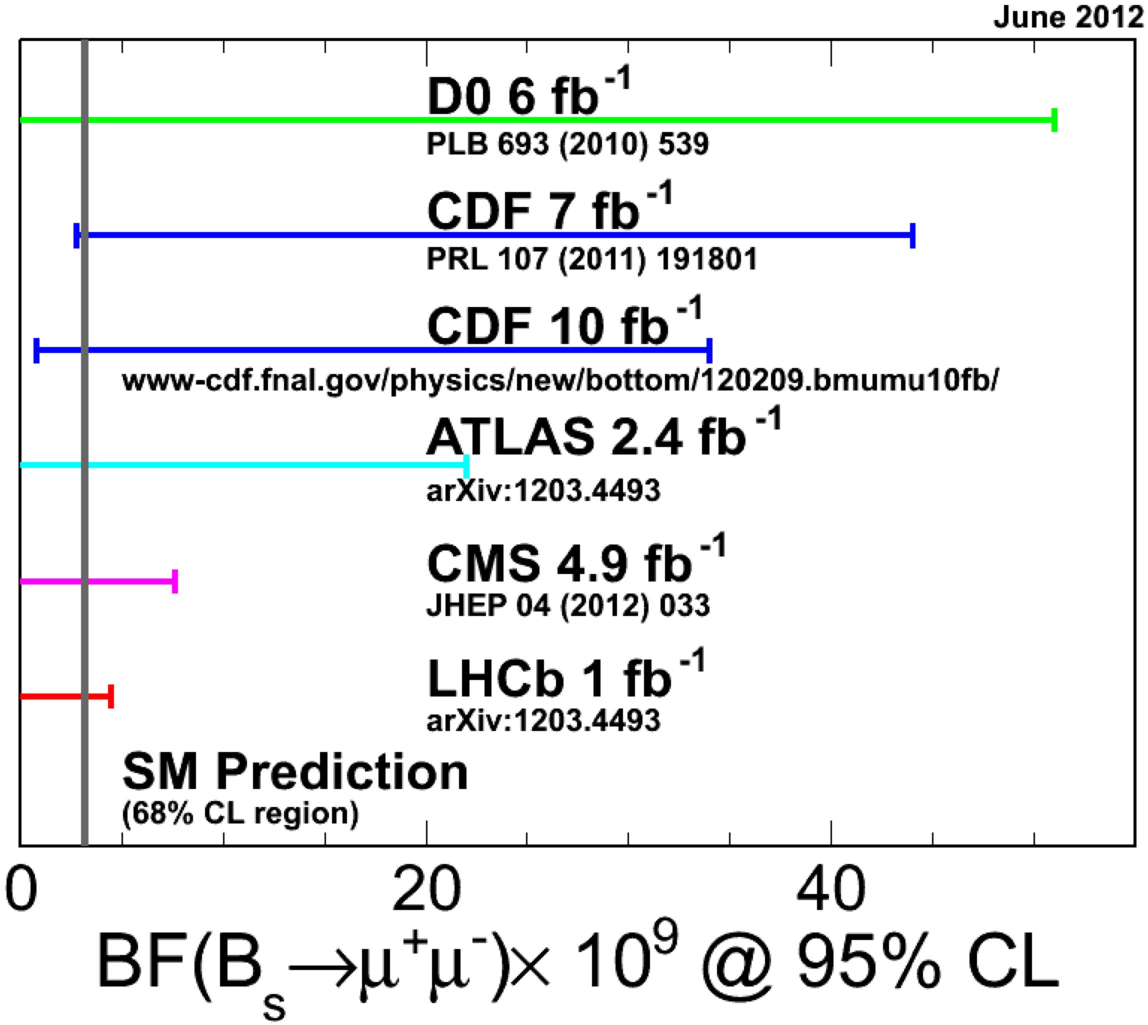


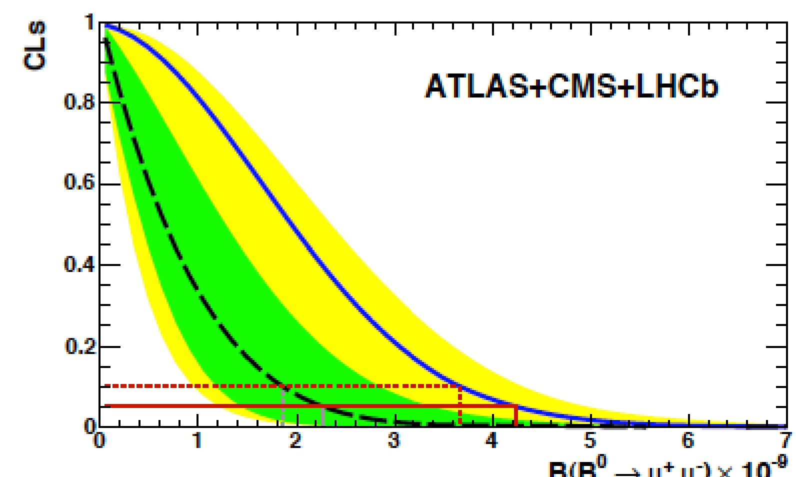
Analysis Strategy:

- CDF & LHCb use multivariate analysis and bin in m, topology, ...
- CDF & LHCb use $B \to hh$ to tune cuts
- Atlas and CMS use cut & count

Rare Decays: $B_s^0 \rightarrow \mu^+\mu^-$

<u>Current limits</u> on $BR(B_s^0 \rightarrow \mu^+\mu^-)$ @95% CL





<u>Atlas + CMS + LHCb:</u> $BR(B_s^0 \rightarrow \mu^+\mu^-) < 4.2 \times 10^{-9}$ @95% CL

Conclusions

- Tevatron & B factories offered rich heavy flavour program
- Many results from heavy quark physics (many not able to cover)
  - Lifetimes and $\Delta\Gamma$ in B_s^0 decays
  - Discovery of B_s^0 oscillations paved road to CP violation
  - CP violation excitement in $B_s^0 \to J/\psi\ \phi$ resolved
  - Rare loop processes as search tool for new physics
- Scene now dominated by LHC: LHCb plus Atlas & CMS
- Expect many more results from LHC in future
- **YOU ARE THE FUTURE !!!**

Conclusions II

"Anyone who keeps the ability
to see beauty
never grows old."

(Franz Kafka)

Conclusions II

"Anyone who keeps the ability
to see beauty
never grows old."

(Franz Kafka)

"You see things as they are
and ask 'Why'?
I see things as they never were
and ask 'Why not'? "

(George Bernard Shaw)