

# Heavy Flavors



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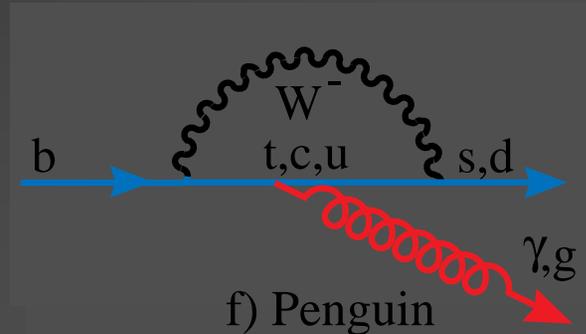
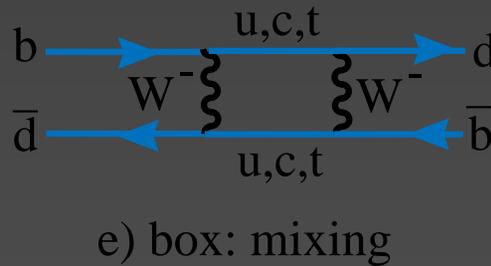
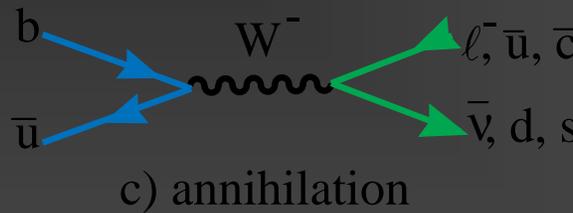
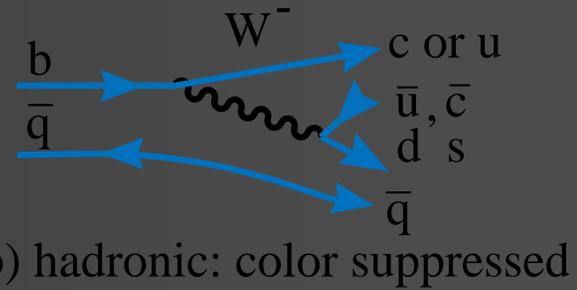
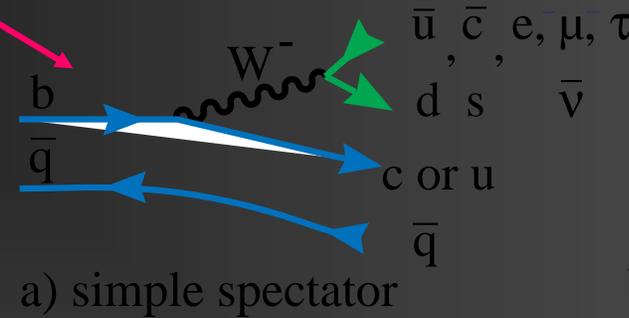


# Introduction

- “Heavy” flavors, defined as b & c quarks, not t, which is heavier, as the top doesn’t live long enough to form a meson and just decays ~100% directly to b quarks (In England we have “Heavy” flavours)
- Charm is interesting in several special areas, but I will concentrate on b’s
- First I will discuss some specific b phenomenology and then point out why these studies are extremely important and interesting

# Some B Meson Decay Diagrams

- a) is dominant
- b) is “color suppressed”
- a) & b) are called “tree” level diagrams



# The Standard Model

## ■ Theoretical Background

### ■ Physical States in the Standard Model

$$\begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} c \\ s \end{pmatrix}_L, \begin{pmatrix} t \\ b \end{pmatrix}_L, \dots, u_R, d_R, c_R, s_R, t_R, b_R$$

### ■ The gauge bosons: $W^\pm$ , $\gamma$ & $Z^0$ and the Higgs $H^0$

### ■ Lagrangian for charged current weak decays

$$L_{cc} = -\frac{g}{\sqrt{2}} J_{cc}^\mu W_\mu^\dagger + h.c.$$

### ■ Where

$$J_{cc}^\mu = (\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau) \gamma^\mu V_{MNS} \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix} + (\bar{u}_L, \bar{c}_L, \bar{t}_L) \gamma^\mu V_{CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

# The CKM Matrix

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

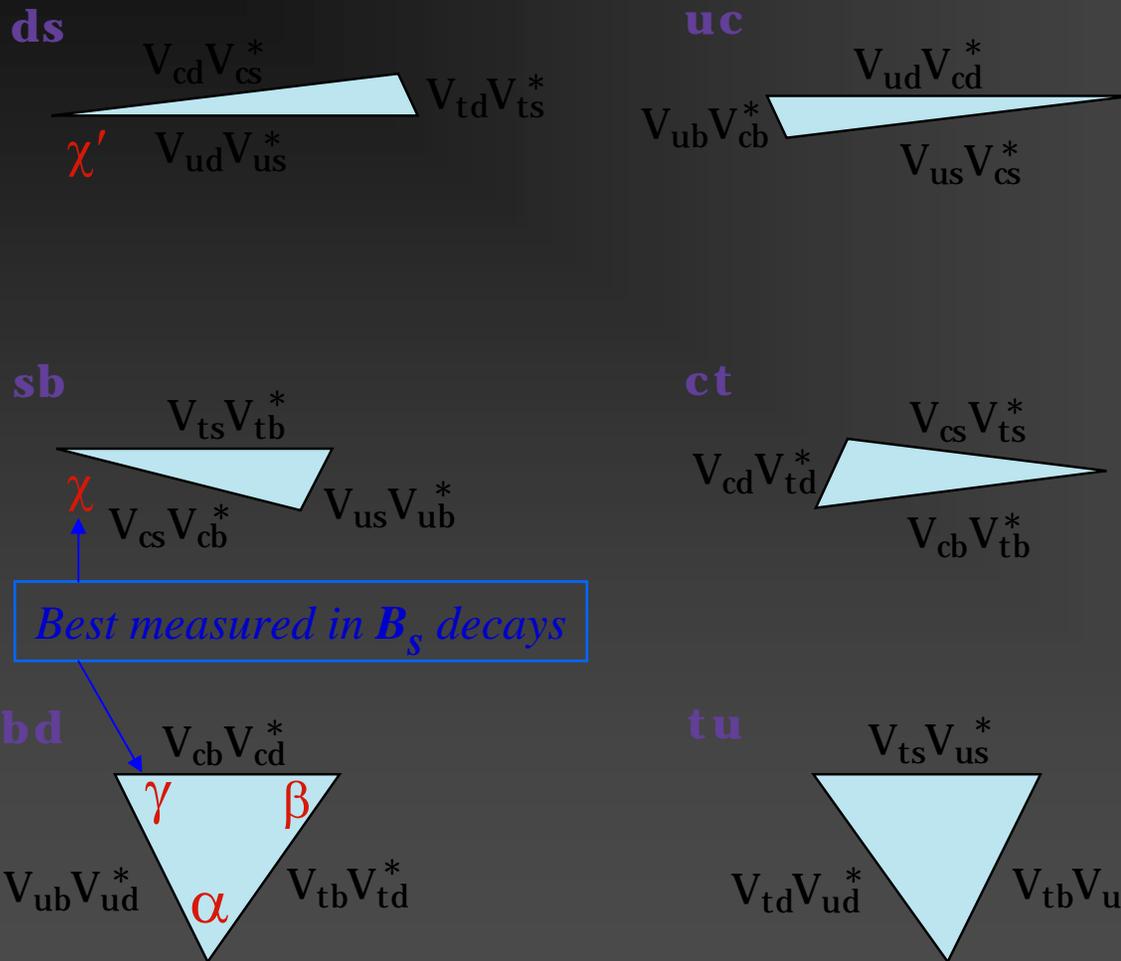
- Unitary with 9\*2 numbers → 4 independent parameters
- Many ways to write down matrix in terms of these parameters

# The Basics: Quark Mixing & the CKM Matrix

		d	s	b	→	mass
u	$V =$	$\begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$			↓	m
c						a
t						s
						s

- A,  $\lambda$ ,  $\rho$  and  $\eta$  are in the Standard Model fundamental constants of nature like G, or  $\alpha_{EM}$
- $\eta$  multiplies i and is responsible for CP violation
- We know  $\lambda=0.22$  ( $V_{us}$ ),  $A\sim 0.8$ ; constraints on  $\rho$  &  $\eta$

# The 6 CKM Triangles

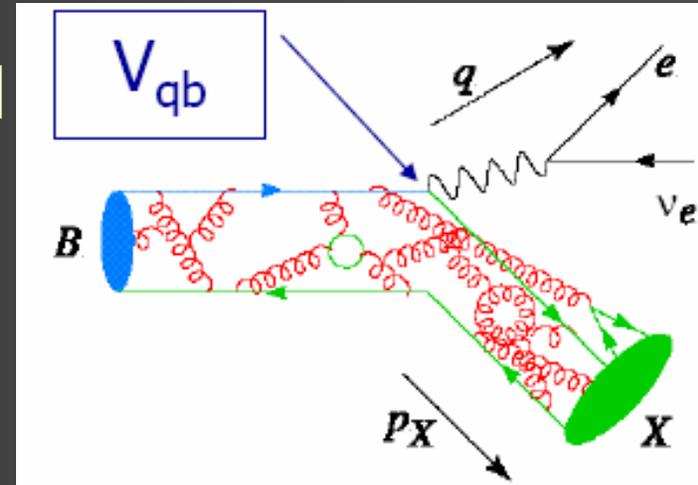


- From Unitarity
- “ds” - indicates rows or columns used
- There are 4 independent phases:  $\beta$ ,  $\gamma$ ,  $\chi$ ,  $\chi'$  ( $\alpha$  can be substituted for  $\gamma$  or  $\beta$ , as  $\alpha + \beta + \gamma = \pi$ )

Area of each  $\Delta = A^2 \lambda^6 \eta$ , the Jarlskog Invariant

# $|V_{cb}|$

- Both  $V_{cb}$  &  $V_{ub}$  can be determined using diagram (a) when  $W^- \rightarrow \ell^- \nu$
- Can use either inclusive decays  $B \rightarrow X \ell^- \nu$ , with  $B \sim 10\%$  or exclusive  $B \rightarrow D^* \ell^- \nu$  with  $B \sim 6\%$



- $|V_{cb}| = (41.96 \pm 0.23 \pm 0.35 \pm 0.59) \times 10^{-3}$  inclusive

- $|V_{cb}| = (39.4 \pm 0.9^{+1.6}_{-1.2}) \times 10^{-3}$  exclusive

(see Kowalewski ICHEP 2006)

Very well based theoretically (HQET)

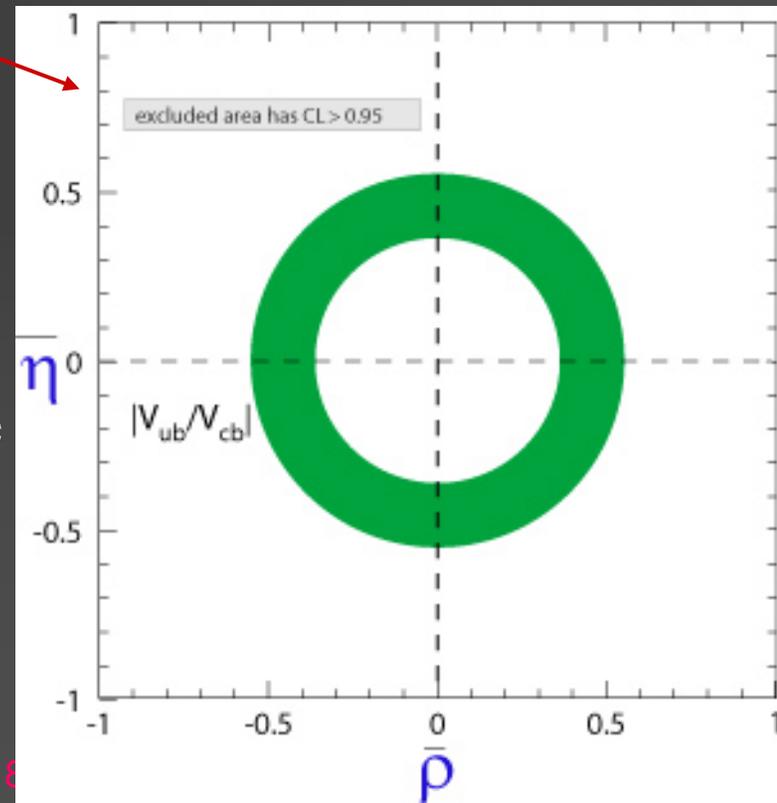
- Note difference is  $2.6 \times 10^{-3}$ , much larger than quoted theoretical errors!

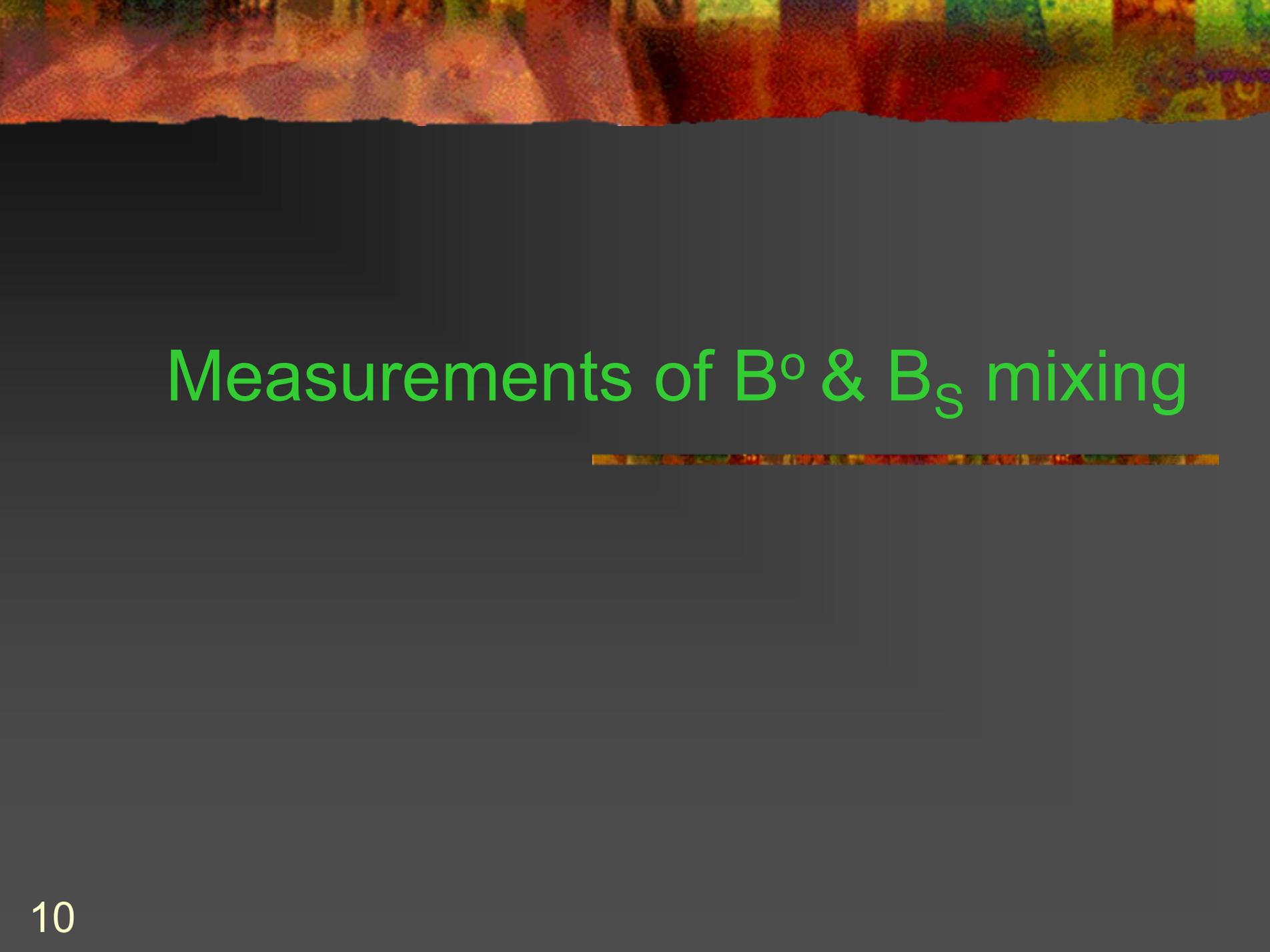
# $|V_{ub}|$

- This is much more difficult because the  $b \rightarrow u$  rate is so much smaller than  $b \rightarrow c$
- Inclusive decays are studied with severe cuts to reduce  $b \rightarrow u$  background
- $|V_{ub}| = (4.49 \pm 0.19 \pm 0.27) \times 10^{-3}$
- For exclusive decays use  $B \rightarrow \pi \ell^- \nu$  (in principle also  $\rho \ell^- \nu$ )

FF calc	$V_{ub}$ [ $10^{-3}$ ]
Ball-Zwicky	$3.38 \pm 0.12$ $^{+0.56}_{-0.37}$
HPQCD	$3.93 \pm 0.26$ $^{+0.59}_{-0.41}$
FNAL	$3.51 \pm 0.23$ $^{+0.61}_{-0.40}$
APE	$3.54 \pm 0.23$ $^{+1.36}_{-0.63}$

Again difference between inclusive & exclusive



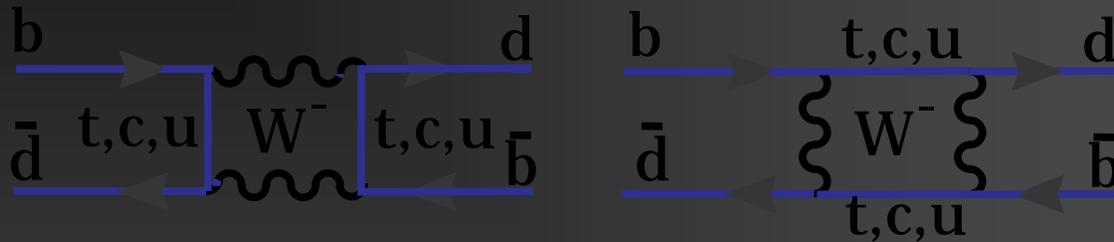


# Measurements of $B^0$ & $B_S$ mixing

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# $B^0-\bar{B}^0$ Mixing

- $B^0$  can transform to  $\bar{B}^0$ , like neutral K's

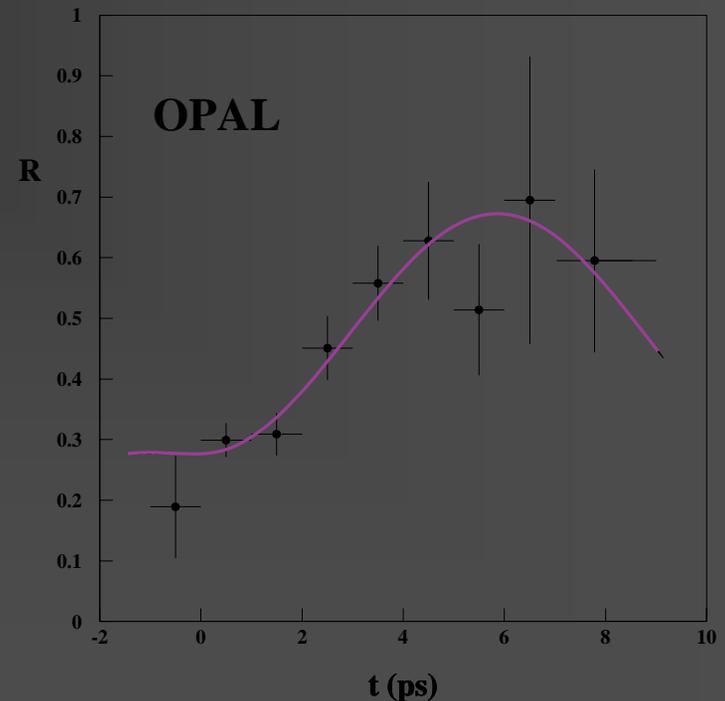


- The eigenstates of flavor, degenerate in pure QCD mix under the weak interactions. Let QM basis be  $\{|1\rangle, |2\rangle\} \equiv \{|B^0\rangle, |\bar{B}^0\rangle\}$ , then

$$H = M - \frac{i}{2}\Gamma = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

# Mixing Measurements

- Diagonalizing we have
$$\Delta m = m_{B_H} - m_{B_L} = 2|M_{12}|, \Delta\Gamma \sim 0$$
- $R = \text{prob } B^0 \rightarrow \bar{B}^0 / \text{prob } B^0 \rightarrow B^0$
- First seen by ARGUS
- $P(B^0 \rightarrow \bar{B}^0) =$ 
$$0.5\Gamma e^{-\Gamma t} \cdot [1 + \cos(\Delta m t)]$$
- Must “tag” the flavor of the of the decaying B at  $t=0$  using the other B

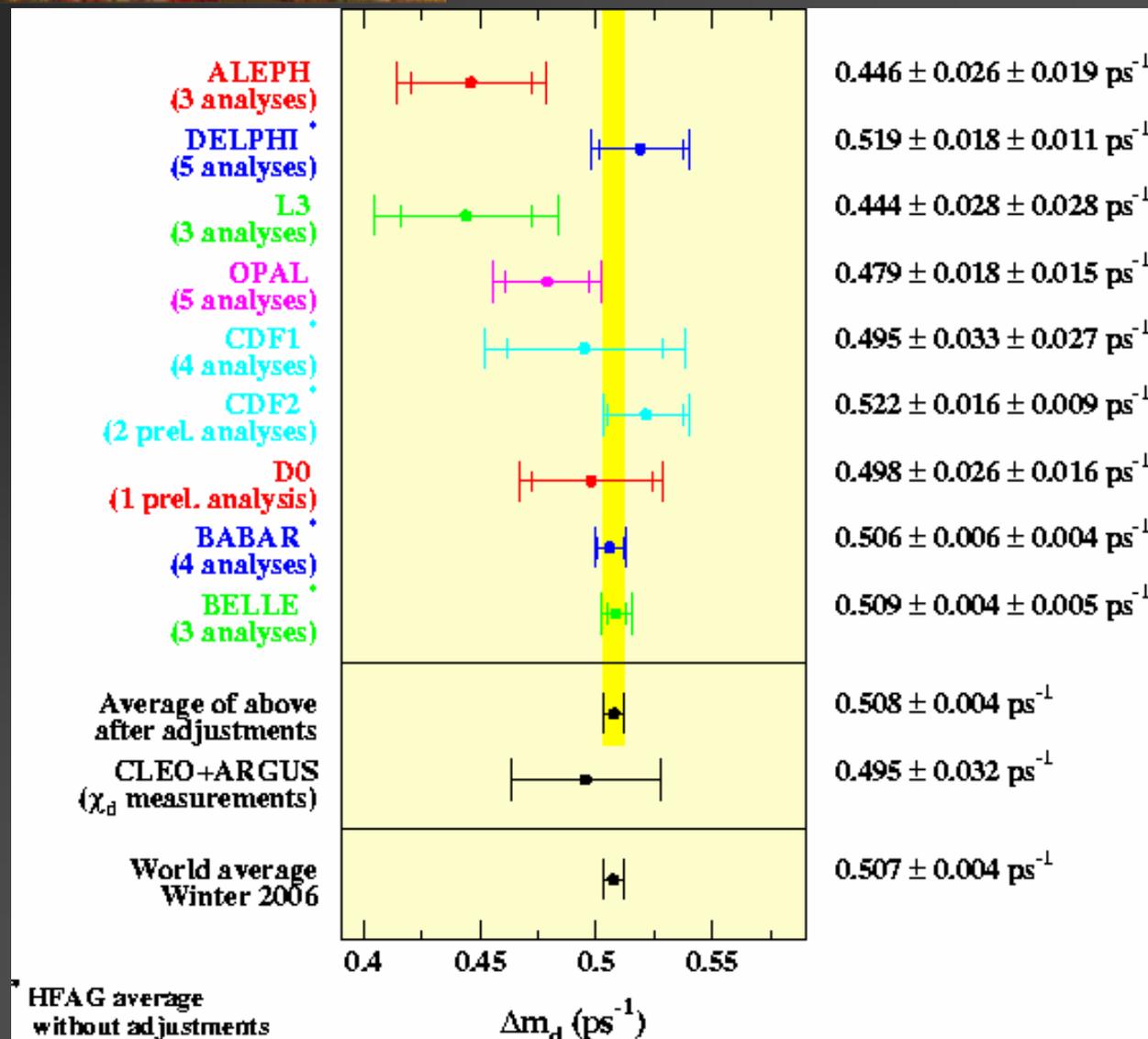


# $\Delta m_d$ Measurements

- $\Delta m_d$  average

$$0.507 \pm 0.004 \text{ ps}^{-1}$$

- Accuracy better than 1%



# $B_d$ Mixing in the Standard Model

- Relation between B mixing & CKM elements:

$$X \equiv \frac{\Delta m}{\Gamma} = \frac{G_F^2}{6\pi^2} B_B f_B^2 m_B \tau_B |V_{tb}^* V_{td}|^2 m_t^2 F\left(\frac{m_t^2}{m_W^2}\right) \eta_{\text{QCD}}$$

- F is a known function,  $\eta_{\text{QCD}} \sim 0.8$
- $B_B$  and  $f_B$  are currently determined only theoretically
  - in principle,  $f_B$  can be measured, but its very difficult, need to measure  $B^- \rightarrow \ell^- \nu$
  - Current best hope is Lattice QCD

# $B_s$ Mixing in the Standard Model

$$x_s \equiv \frac{\Delta m_s}{\Gamma_s} = \frac{G_F^2}{6\pi^2} B_{B_s} f_{B_s}^2 m_{B_s} \tau_{B_s} |V_{tb}^* V_{ts}|^2 m_t^2 F\left(\frac{m_t^2}{m_W^2}\right) \eta_{\text{QCD}}$$

- Measurement of  $B_s$  mixing provides the ratio of  $V_{td}/V_{ts}$  which gives the same essential information as  $B_d$  mixing alone, but with much better control of theory parameters
  - $|V_{td}|^2 = A^2 \lambda^4 [(1-\rho)^2 + \eta^2]$
  - $|V_{td}|^2 / |V_{ts}|^2 = [(1-\rho)^2 + \eta^2]$
  - Circle in  $(\rho, \eta)$  plane centered at  $(1, 0)$
- To relate constraints on CKM matrix in terms of say  $\rho$  &  $\eta$  need to use theoretical estimates of  $\xi = f_{B_s}^2 B_{B_s} / f_{B_d}^2 B_{B_d}$

# CDF Measurement of $\Delta m_s$

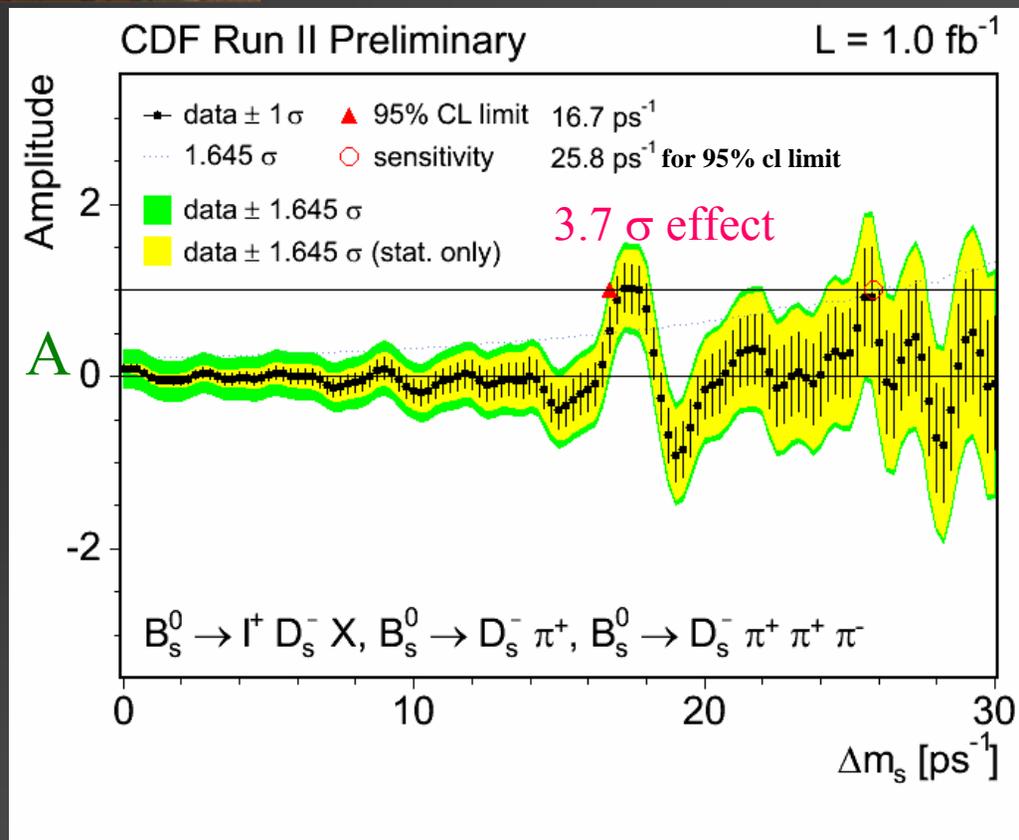
- $P(B_S \rightarrow \bar{B}_S) = 0.5 \times \Gamma_S e^{-\Gamma_S t} [1 + \cos(\Delta m_S t)]$
- It is useful to analyze the data as a function of a test frequency  $\omega$

- $g(t) = 0.5 \Gamma_S e^{-\Gamma_S t} [1 + A \cos(\omega t)]$

- CDF:

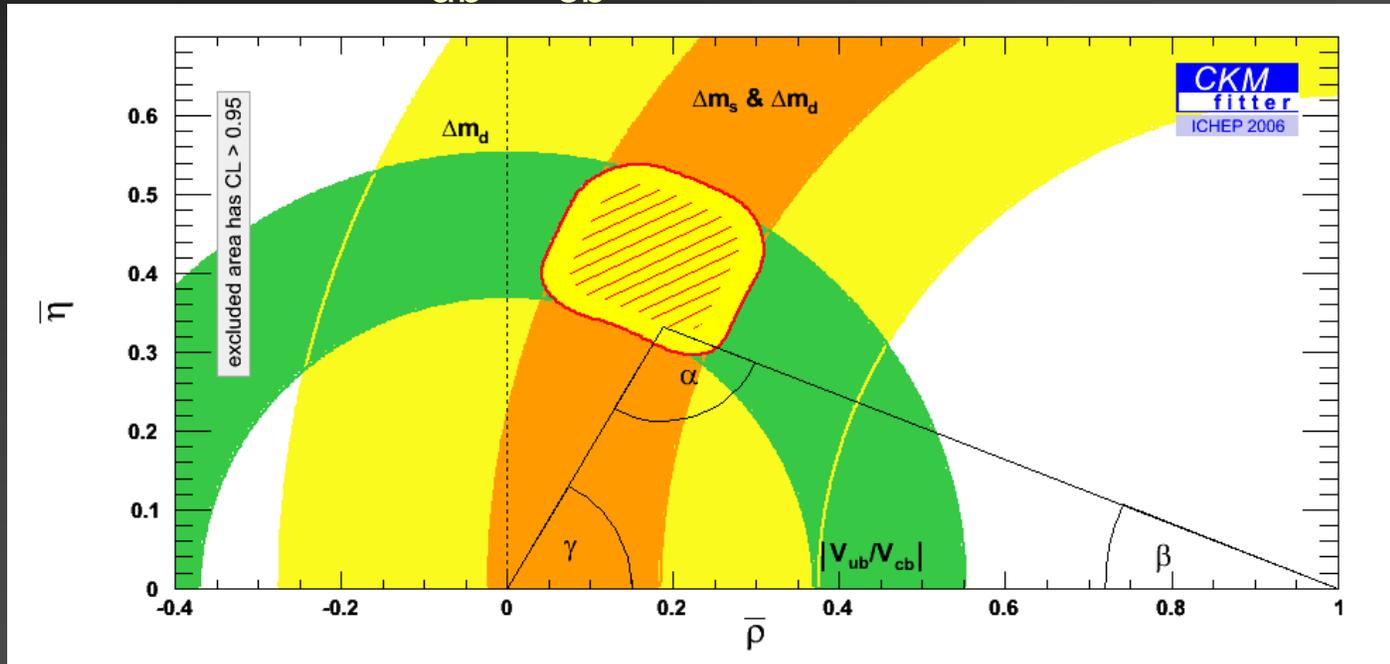
$$\Delta m_s = 17.22^{+0.33}_{-0.18} \pm 0.07 \text{ ps}^{-1}$$

- D0 90% cl bounds  
 $21 > \Delta m_s > 17 \text{ ps}^{-1}$



# Constraint on $\rho - \eta$ plane

- Need to use theory value for  $\xi = \frac{f_{B_s} \sqrt{B_{B_s}}}{f_{B_d} \sqrt{B_{B_d}}} = 1.24 \pm 0.04 \pm 0.06$
- Using both  $V_{ub}/V_{cb}$  & B mixing



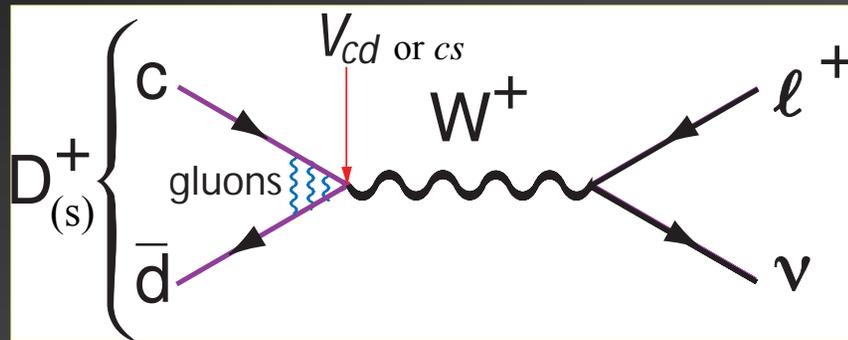
See <http://ckmfitter.in2p3.fr/>

- In principle, could measure  $f_B |V_{ub}|$  using  $B^- \rightarrow \tau^- \nu$ , but difficult: Belle “discovery” was “corrected” &  $V_{ub}$  error is significant, so use D decays

# Leptonic Decays: $D_{(s)} \rightarrow \ell^+ \nu$

$c$  and  $\bar{q}$  can annihilate, probability is  $\propto$  to wave function overlap

Diagram:



In general for all pseudoscalars:

$$\Gamma(P^+ \rightarrow \ell^+ \nu) = \frac{1}{8\pi} G_F^2 f_P^2 m_\ell^2 M_P \left(1 - \frac{m_\ell^2}{M_P^2}\right)^2 |V_{Qq}|^2$$

Calculate, or measure if  $V_{Qq}$  is known

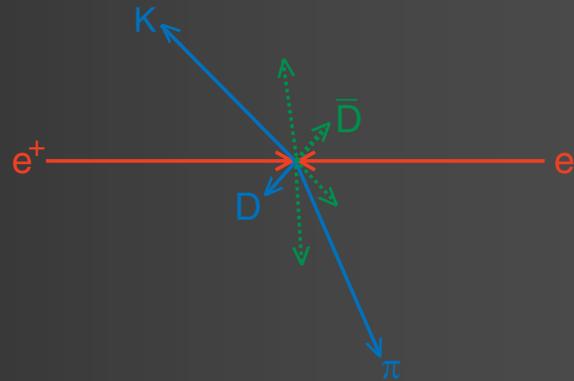
# Measuring Charm at Threshold

- $D\bar{D}$  production at threshold: used by Mark III, and more recently by CLEO-c and BES-II.

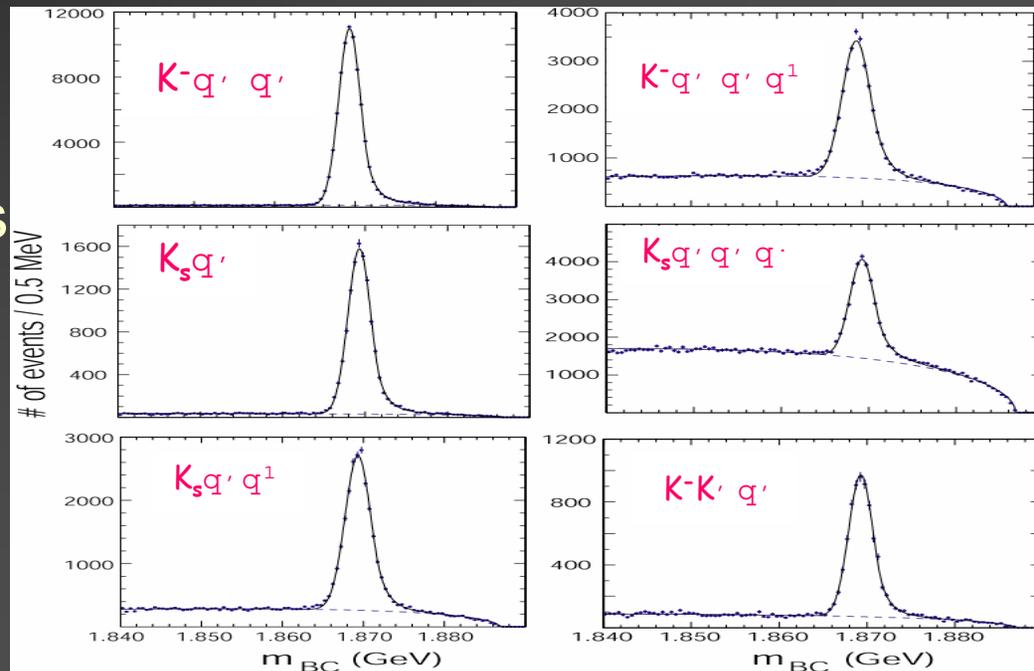
- Unique event properties
- Only  $D\bar{D}$  not  $D\bar{D}x$  produced
- Ease of B measurements using "double tags"
- $E_A = \# \text{ of } A / \# \text{ of } D\text{'s}$

- Beam Constrained Mass

$$m_{BC}^2 = \sum_i E_i^2 - \sum_i \vec{p}_i^2 = E_{\text{beam}}^2 - \sum_i \vec{p}_i^2$$



CLEO-c



# Measurement of $f_{D^+}$

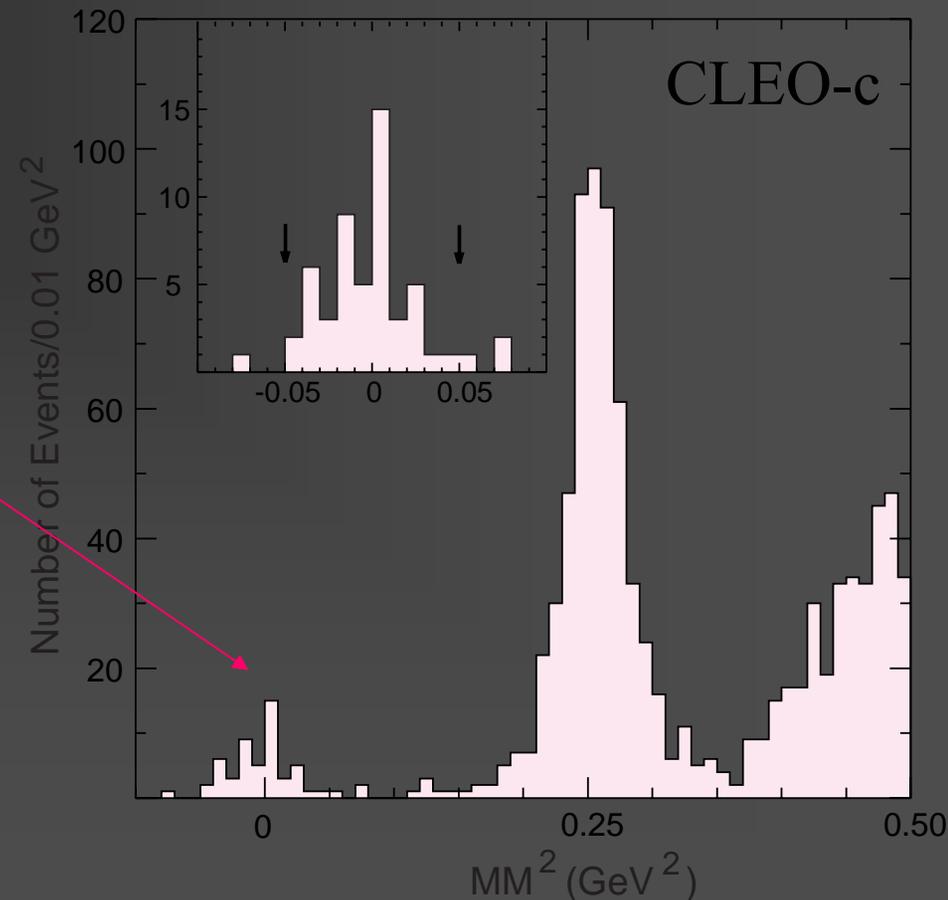
- To find signal, look for events consistent with one  $\mu^+$  track opposite a  $D^-$  tag with a missing  $\nu$
- Compute

$$\begin{aligned}MM^2 &= (E_{D^+} - E_{\ell^+})^2 - (\vec{p}_{D^+} - \vec{p}_{\ell^+})^2 \\ &= (E_{beam} - E_{\ell^+})^2 - (-\vec{p}_{D^-} - \vec{p}_{\ell^+})^2\end{aligned}$$

- Find

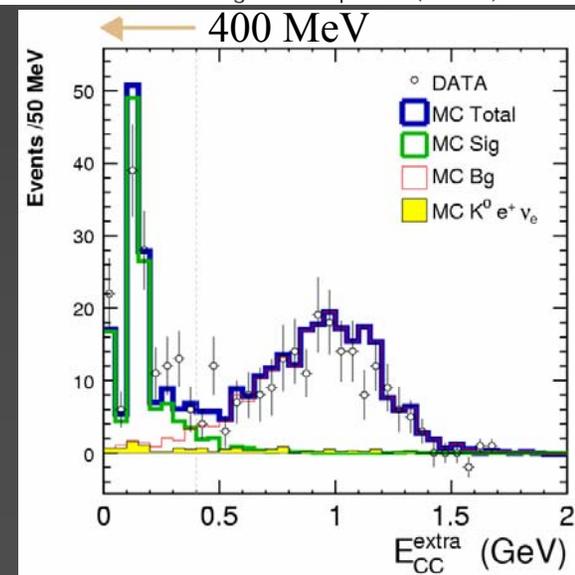
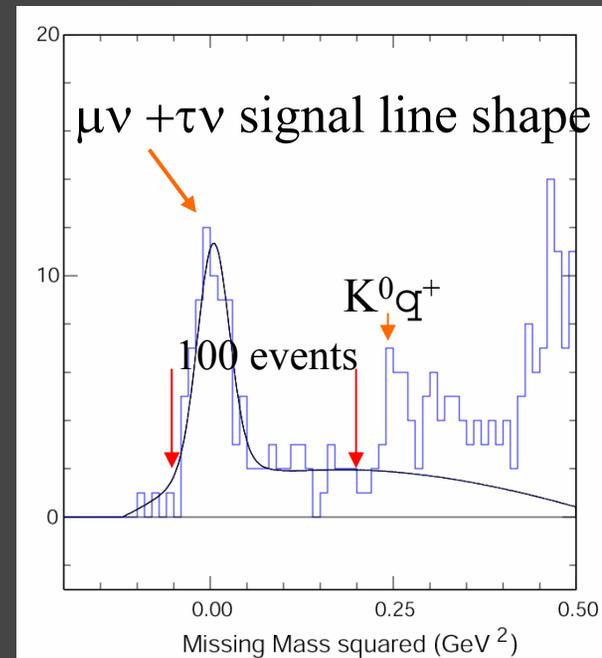
$$f_{D^+} = (222.6 \pm 16.7^{+2.3}_{-3.4}) \text{ MeV}$$

Data have 50 signal events in  $281 \text{ pb}^{-1}$



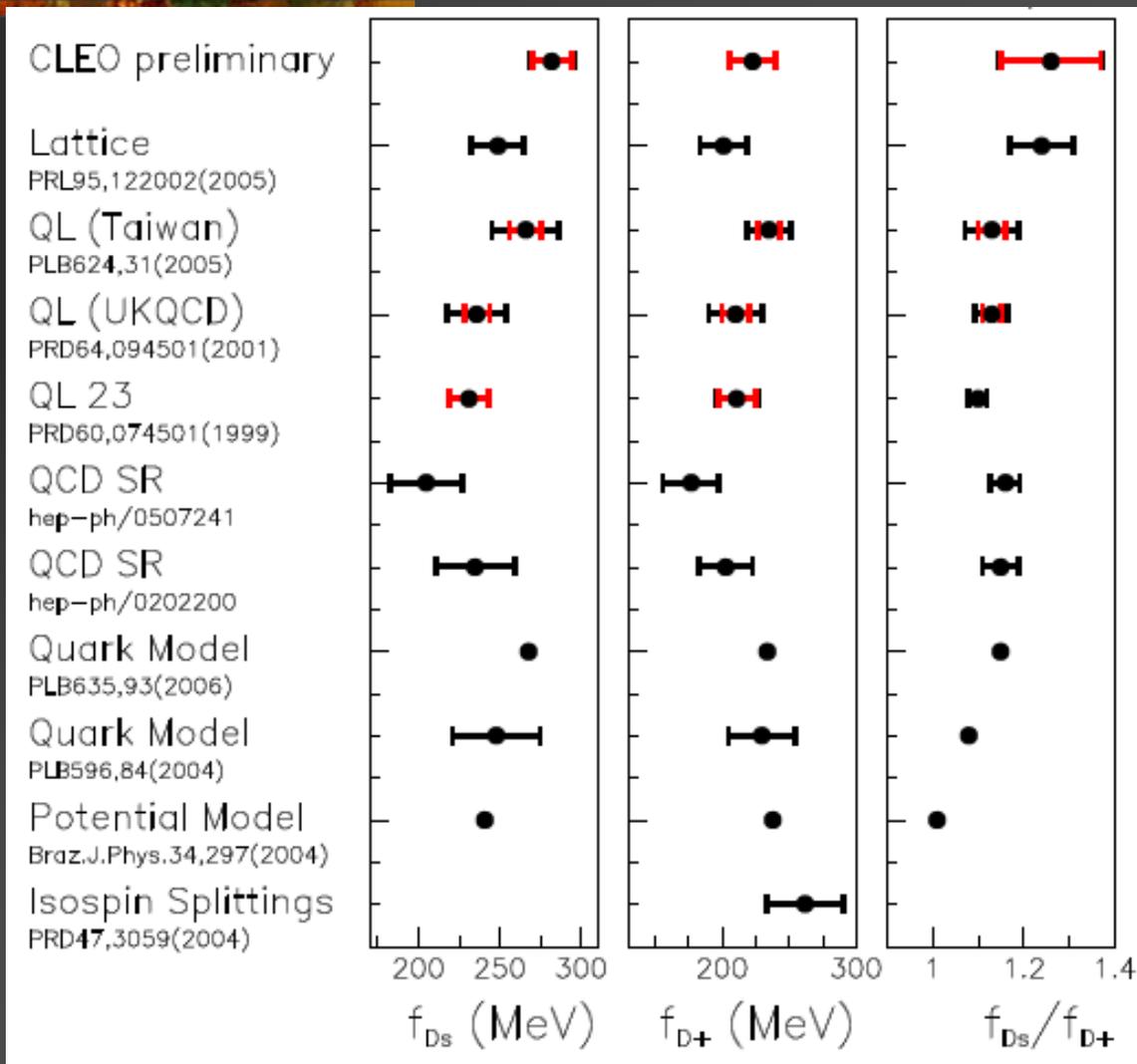
$$D_S^+ \rightarrow \mu^+ \nu + \tau^+ \nu, \quad \tau \rightarrow \pi^+ \nu$$

- $D_S^+ \rightarrow \mu^+ \nu + \tau^+ \nu, \tau \rightarrow \pi^+ \nu$  Sum contains 100  $\mu^+ \nu + \tau^+ \nu$  events for  $MM^2 < 0.2 \text{ GeV}^2$
- Also,  $D_S^+ \rightarrow \tau^+ \nu, \tau \rightarrow e^+ \nu \nu$
- **Weighted Average:**  
 $f_{D_S} = 280.1 \pm 11.6 \pm 6.0 \text{ MeV}$ ,  
 the systematic error is mostly uncorrelated between the measurements
- Thus  $f_{D_S}/f_{D^+} = 1.26 \pm 0.11 \pm 0.03$   
 (CLEO-c)



# Comparisons with Theory

- CLEO-c data are consistent with most models, more precision needed, for both





# Measurements of CP Violating Angles

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# Formalism of CP Violation

- CP Eigenstates:

$$|B_1^0\rangle = (|B^0\rangle + |\bar{B}^0\rangle) / \sqrt{2}, \quad CP |B_1^0\rangle = +|B_1^0\rangle$$

$$|B_2^0\rangle = (|B^0\rangle - |\bar{B}^0\rangle) / \sqrt{2}, \quad CP |B_2^0\rangle = -|B_2^0\rangle$$

- Because of mixing mass eigenstates are a superposition of  $a|B^0\rangle + b|\bar{B}^0\rangle$  that obey the Schrödinger equation

$$i \frac{d}{dt} \begin{pmatrix} a \\ b \end{pmatrix} = H \begin{pmatrix} a \\ b \end{pmatrix} = \left( M - \frac{i}{2} \Gamma \right) \begin{pmatrix} a \\ b \end{pmatrix}$$

See Bigi & Sanda  
“CP Violation,” Cambridge

# B<sup>0</sup> CP Formalism II

- For CP not being conserved, instead of B<sub>1</sub> & B<sub>2</sub>

$$|B_1^0\rangle = \frac{1}{\sqrt{2}}|B^0\rangle + \frac{1}{\sqrt{2}}|\bar{B}^0\rangle$$

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

- CP is violated if  $q/p \neq 1$

$$\frac{q}{p} = \pm \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

- Time dependence is given by

$$|B_L(t)\rangle = e^{-\Gamma_L t/2} e^{im_L t/2} |B_L(0)\rangle, \quad |B_H(t)\rangle = e^{-\Gamma_H t/2} e^{im_H t/2} |B_H(0)\rangle$$

# B<sup>0</sup> CP Formalism III

- This leads to the time evolution of flavor amplitudes as

$$\begin{aligned} |B^0(t)\rangle &= e^{-(i\Delta m + \Gamma/2)t} \left( \cos \frac{\Delta m t}{2} |B^0(0)\rangle + i \frac{q}{p} \sin \frac{\Delta m t}{2} |\bar{B}^0(0)\rangle \right) \\ |\bar{B}^0(t)\rangle &= e^{-(i\Delta m + \Gamma/2)t} \left( i \frac{p}{q} \sin \frac{\Delta m t}{2} |B^0(0)\rangle + \cos \frac{\Delta m t}{2} |\bar{B}^0(0)\rangle \right) \end{aligned}$$

- $\Delta m = m_H - m_L$ ,  $\Gamma \approx \Gamma_L \approx \Gamma_H$  (*true for B<sub>d</sub>, not necessarily for B<sub>s</sub>*)
- Probability of a B<sup>0</sup> decay is given by  $\langle B^0(t) | B^0(t)^* \rangle$  & is pure exponential in the absence of CP violation

# CP violation using CP eigenstates

- CPV requires the interference of two amplitudes. We use the direct decay for one amplitude and mixing for the other one

- Define

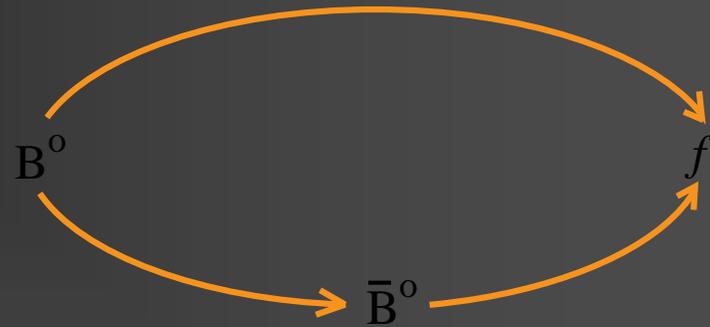
- $A = \langle f | H | B^0 \rangle$

- $\bar{A} = \langle f | H | \bar{B}^0 \rangle$

- $|A/\bar{A}| \neq 1$  is evidence of CP violation in the decay amplitude (“direct” CPV)

- With mixing included, we have CPV if

$$\lambda = \frac{q}{p} \frac{\bar{A}}{A} \neq 1$$



# CP V using CP eigenstates II

- CP asymmetry 
$$a_f(t) = \frac{\Gamma(B^0(t) \rightarrow f) - \Gamma(\bar{B}^0(t) \rightarrow f)}{\Gamma(B^0(t) \rightarrow f) + \Gamma(\bar{B}^0(t) \rightarrow f)}$$
- for  $|q/p| = 1$  
$$a_f(t) = \frac{(1 - |\lambda|^2) \cos(\Delta mt) - 2 \operatorname{Im} \lambda \sin(\Delta mt)}{1 + |\lambda|^2}$$
- When there is only one decay amplitude,  $\lambda=1$  then 
$$a_f(t) = -\operatorname{Im} \lambda \sin(\Delta mt)$$
- Time integrated

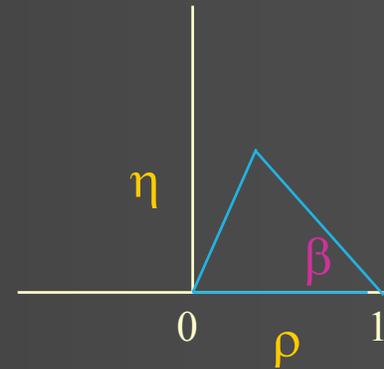
$$a_f(t) = -\frac{x}{1+x^2} \operatorname{Im} \lambda = -0.48 \operatorname{Im} \lambda$$

*good luck, maximum is -0.5*

# CPV using CP eigenstates III

■ For  $B_d$ ,  $\frac{q}{p} = \frac{(V_{tb}^* V_{td})^2}{|V_{tb}^* V_{td}|^2} = \frac{(1-\rho-i\eta)^2}{(1-\rho+i\eta)(1-\rho-i\eta)} = e^{-2i\beta}$

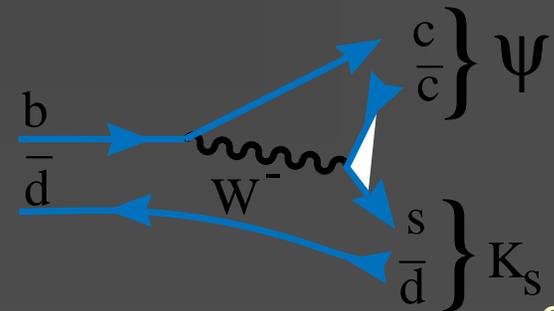
$$\text{Im}\left(\frac{p}{q}\right) = \frac{2(1-\rho)\eta}{(1-\rho)^2 + \eta^2} = \sin(2\beta)$$



■ Now need to add  $\bar{A}/A$

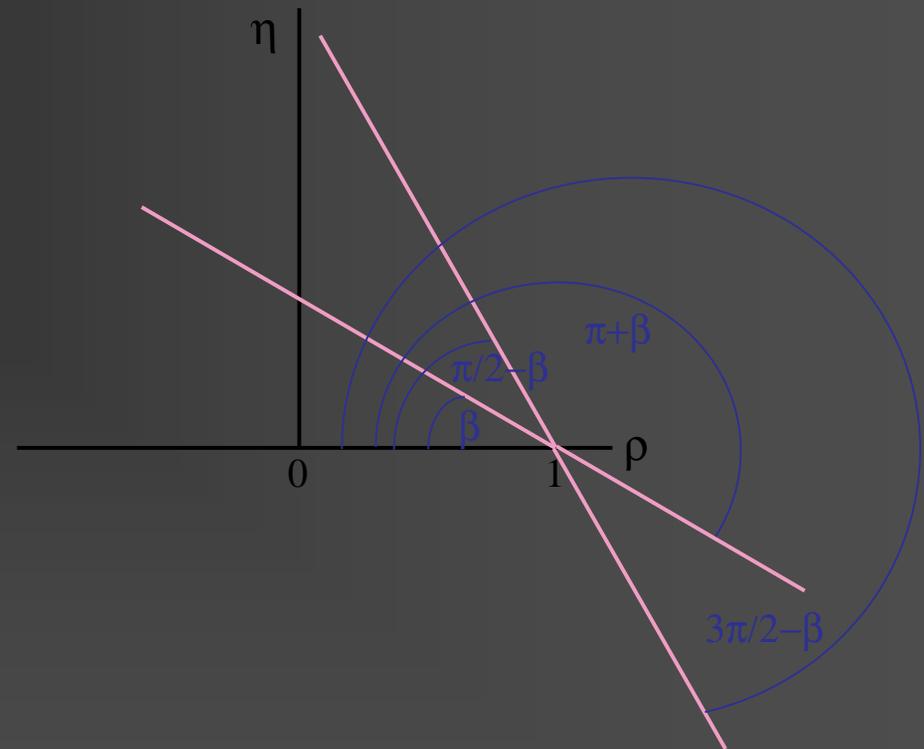
■ for  $J/\psi K_s$ :

$$\frac{\bar{A}}{A} = \frac{(V_{cb} V_{cs}^*)^2}{|V_{cb} V_{cs}^*|^2} \approx 1$$



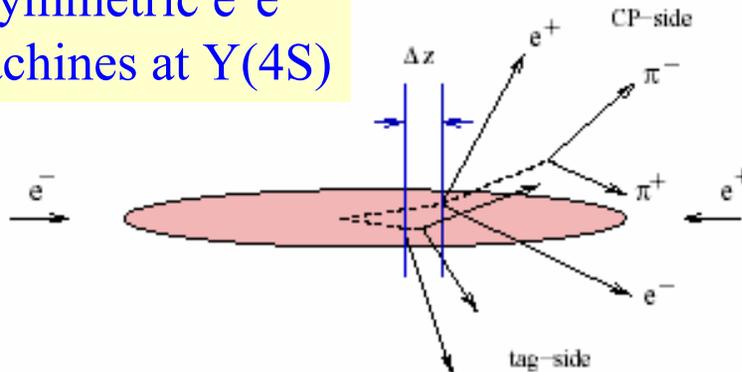
# Ambiguities

- Suppose we measure  $\sin(2\beta)$  using  $\psi K_s$ , what does that tell us about  $\beta$ ?
- Ans: 4 fold ambiguity-  
 $\beta$ ,  $\pi/2-\beta$ ,  $\pi+\beta$ ,  $3\pi/2-\beta$
- Only reason  $\eta > 0$ , is  $B_k > 0$  from theory, and related theoretical interpretation of  $\varepsilon'$



# B Kinematics at the $\Upsilon(4S)$ (Babar & Belle)

## Asymmetric $e^+e^-$ machines at $\Upsilon(4S)$



$$\psi(t) = |B_1^0\rangle |\bar{B}_2^0\rangle - |\bar{B}_1^0\rangle |B_2^0\rangle$$

When one is  $B^0$ , the other is  $\bar{B}^0$  at any  $t$   
( $C$  is conserved in  $\Upsilon(4S) \rightarrow BB$ )

$$\Delta t \simeq (z_{CP} - z_{tag}) / (\gamma\beta c)$$

$B$  flight-length in  $x$ - $y$ : only  $\sim 30\mu$

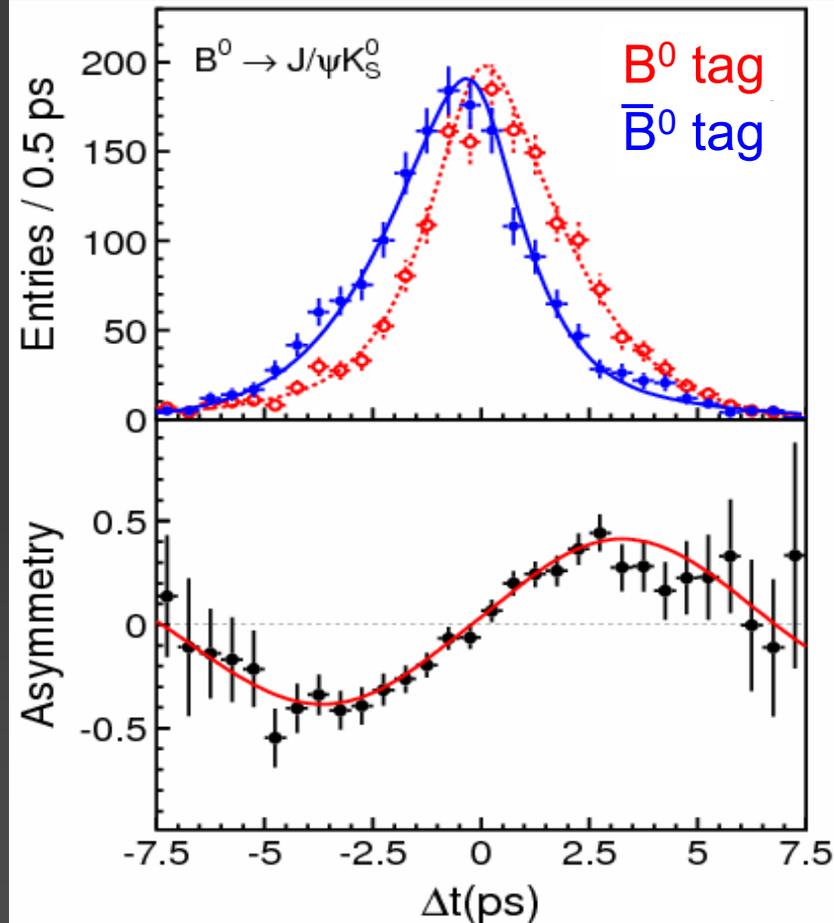
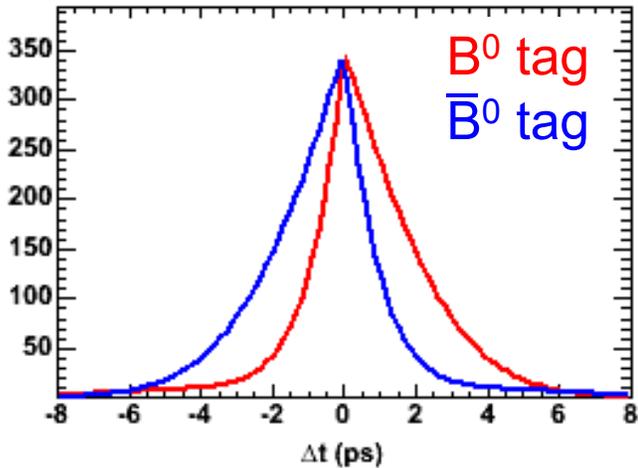
$$(z_{CP} - z_{tag}) \ll e^+e^- \text{ interaction region}$$

The other  $B$  (tag-side) provides a time reference and flavor tagging at  $\Delta t = 0$

Parameters	BaBar	Belle
$e^+e^-$ energy	$3.1 \times 9 \text{ GeV}$	$3.5 \times 8.5 \text{ GeV}$
$\gamma\beta$	0.56	0.425
Interaction region ( $h \times v \times l$ )	$120 \mu\text{m} \times 5 \mu\text{m} \times 8.5 \text{ mm}$	$80 \mu\text{m} \times 2 \mu\text{m} \times 3.4 \text{ mm}$
Typical ( $z_{CP} - z_{tag}$ )	$260 \mu\text{m}$	$200 \mu\text{m}$
$\sigma_z$ (CP-side)	$50 \mu\text{m}$	$75 \mu\text{m}$
$\sigma_z$ (tag-side)	$100 \sim 150 \mu\text{m}$	$140 \mu\text{m}$

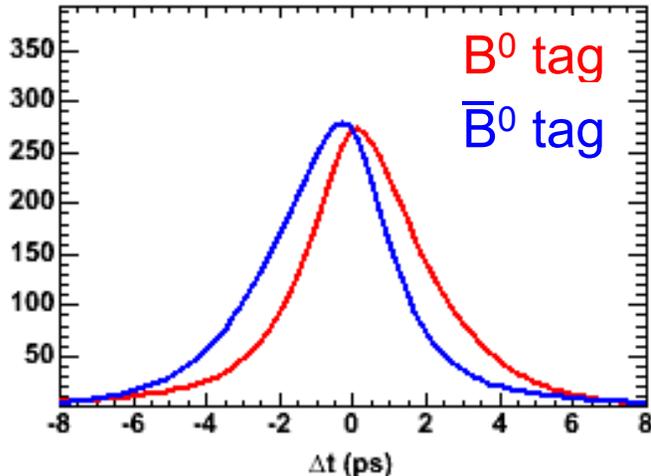
# Fit to $\Delta t$ Distributions

$B^0 \rightarrow J/\psi K_S^0$



$$\text{Asym.} = -\xi_{CP} \sin 2\beta \sin \Delta m \Delta t$$

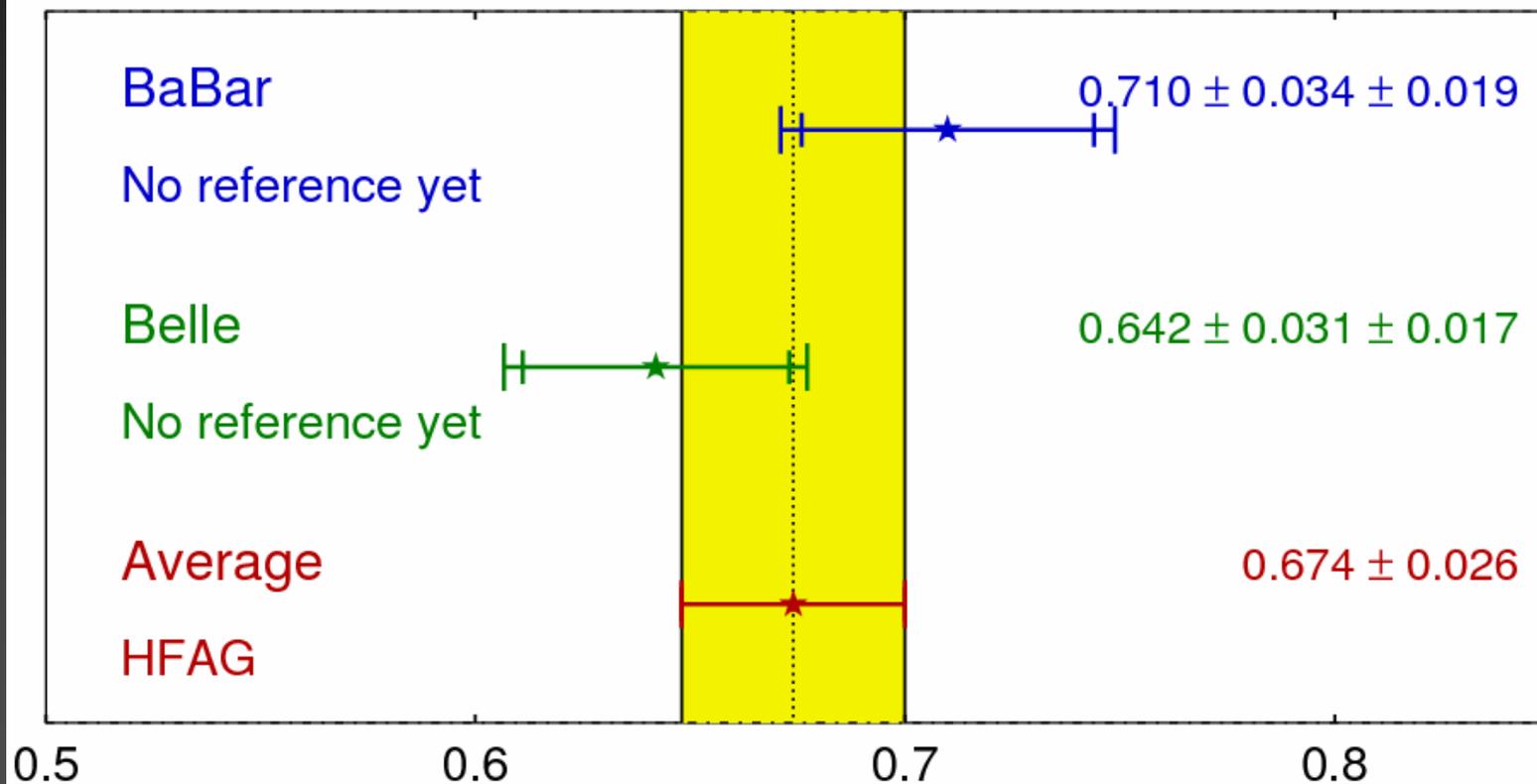
$\tau$  resolution, wrong tags



# 2006: BaBar + Belle

$$\sin(2\beta) \equiv \sin(2\phi_1)$$

**HFAG**  
ICHEP 2006  
PRELIMINARY



From Hazumi ICHEP 2006

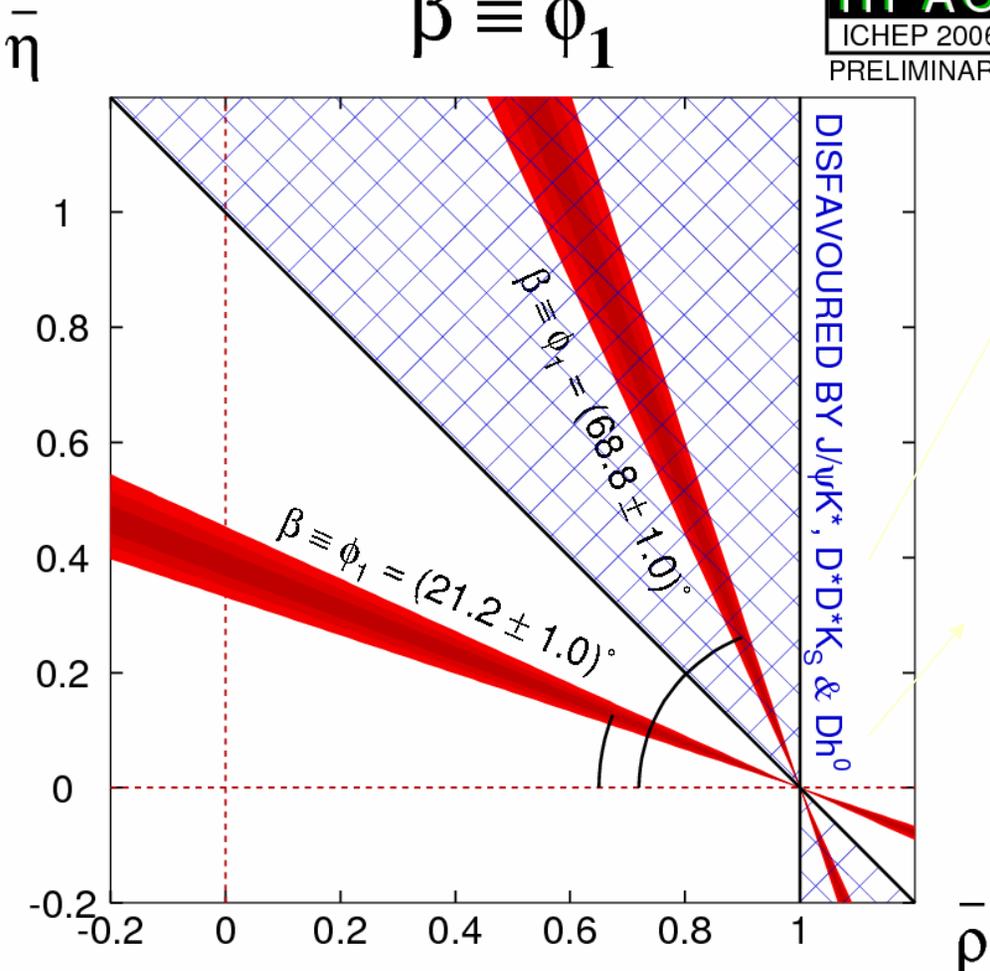
# $\beta$ (not $\sin 2\beta$ ) measurements



Preliminary

HFAG  
ICHEP 2006  
PRELIMINARY

$$\beta \equiv \phi_1$$



Time-dependent Dalitz analysis  
(T.Browder, A. Datta et al. 2000)

$\rightarrow \cos 2\beta > 0$   
(94%CL, model-dependent)



Time-dependent Dalitz analysis

$\rightarrow \cos 2\beta > 0$

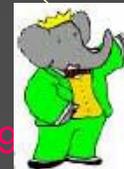
Belle: 98.3%CL



(hep-ex/0605023, accepted by PRL)

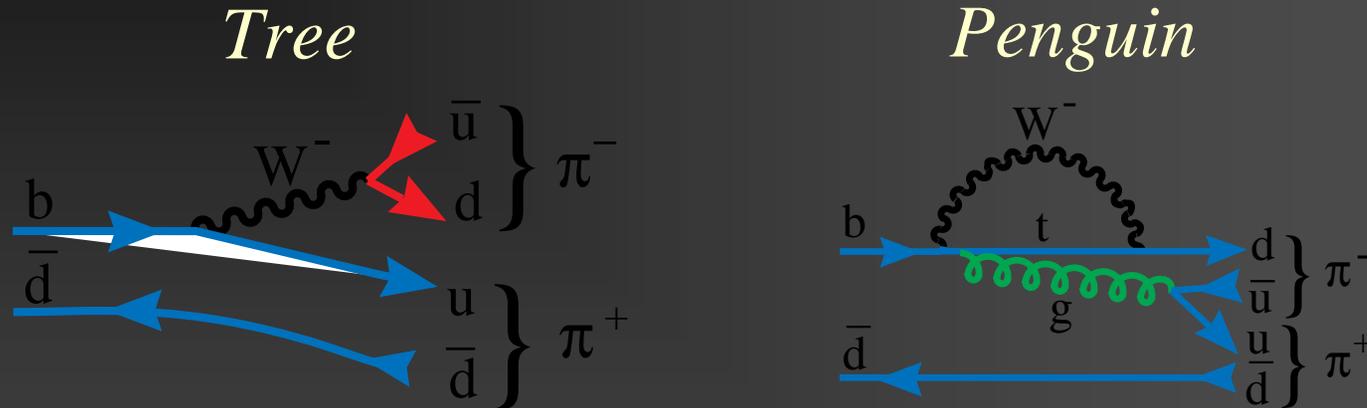
BaBar 87% CL

(BABAR-CONF06/017)



# CPV in Charmless B Decays

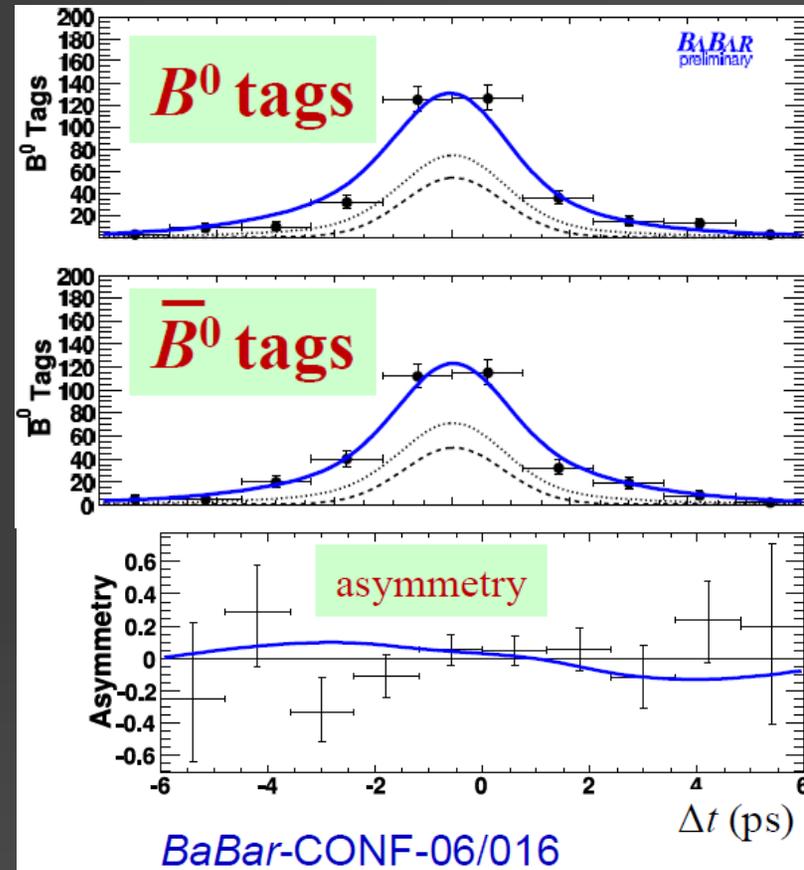
- Can have both tree & loop diagrams in  $\pi^+\pi^-$  (or  $\rho^+\rho^-$ )



- The weak phase in the tree graph is  $\gamma$ . The weak phase in the Penguin is different. Therefore, the Penguin can (and does) mess up CP via mixing in  $\pi^+\pi^-$
- Penguin is unmasked by evidence of  $\pi^0\pi^0$

# CPV in $B \rightarrow \rho^+ \rho^-$

- First done by BaBar confirmed by Belle
- Not a CP eigenstate, but final state is almost fully longitudinally polarized
  - $f_L = 0.978 \pm 0.024^{+0.015}_{-0.013}$  (BaBar)
- However, Penguin pollution revealed at  $3\sigma$  level (BaBar):
- $E(\rho^0 \rho^0) = (1.2 \pm 0.4 \pm 0.3) \times 10^{-6}$
- $E(\rho^+ \rho^-) = (23.5 \pm 2.2 \pm 4.1) \times 10^{-6}$

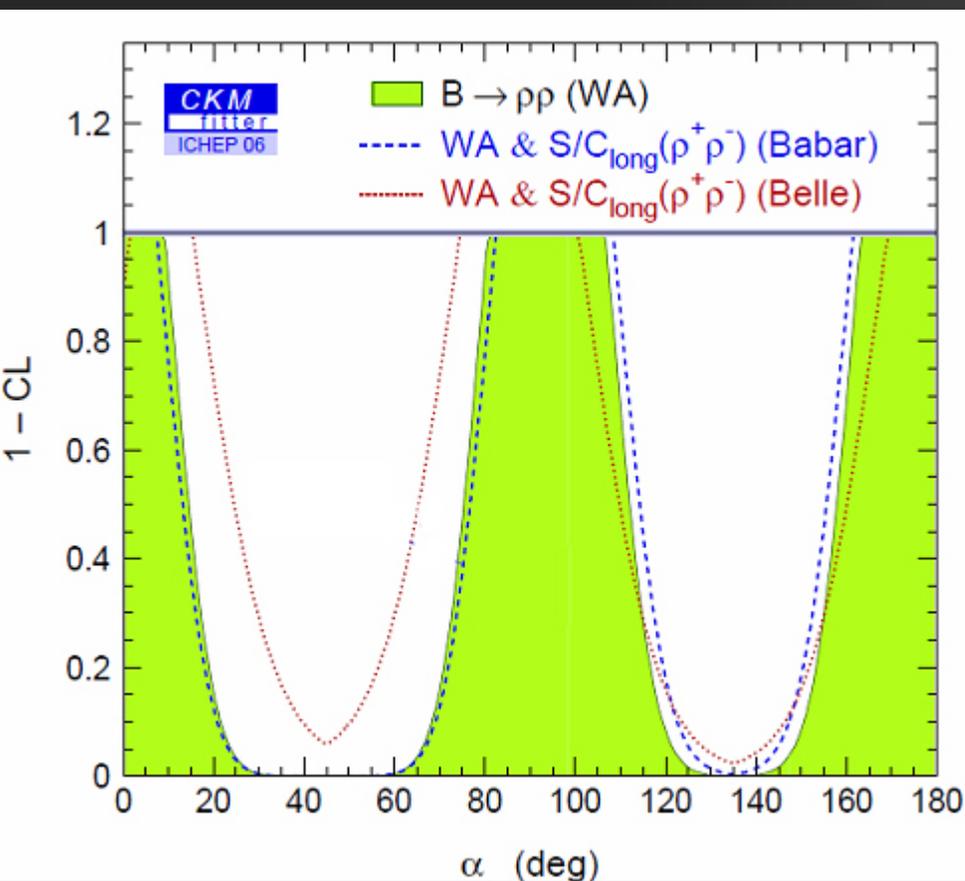


$$S_{\text{long}} = -0.19 \pm 0.21^{+0.05}_{-0.07}$$

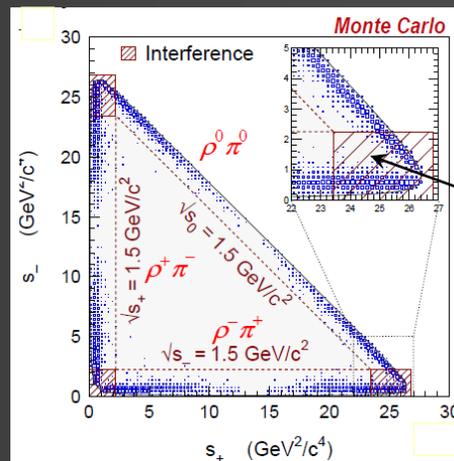
$$C_{\text{long}} = -0.07 \pm 0.15 \pm 0.06$$

# CPV in $B \rightarrow \rho^+ \rho^-$ II

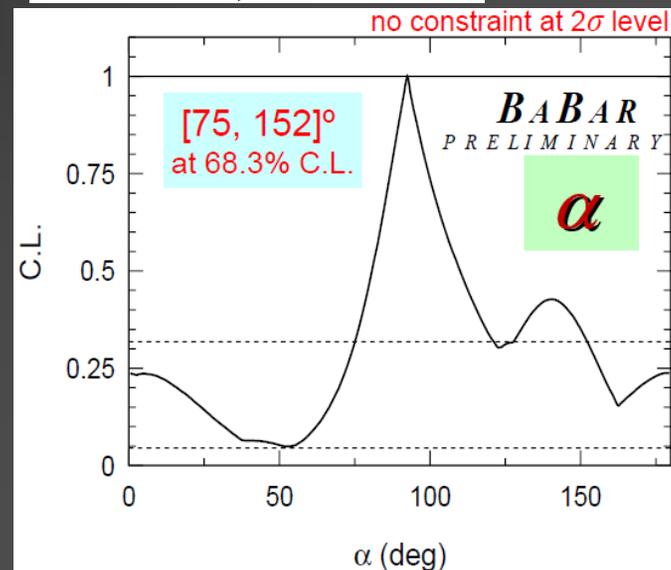
## ■ Constraints on $\alpha$



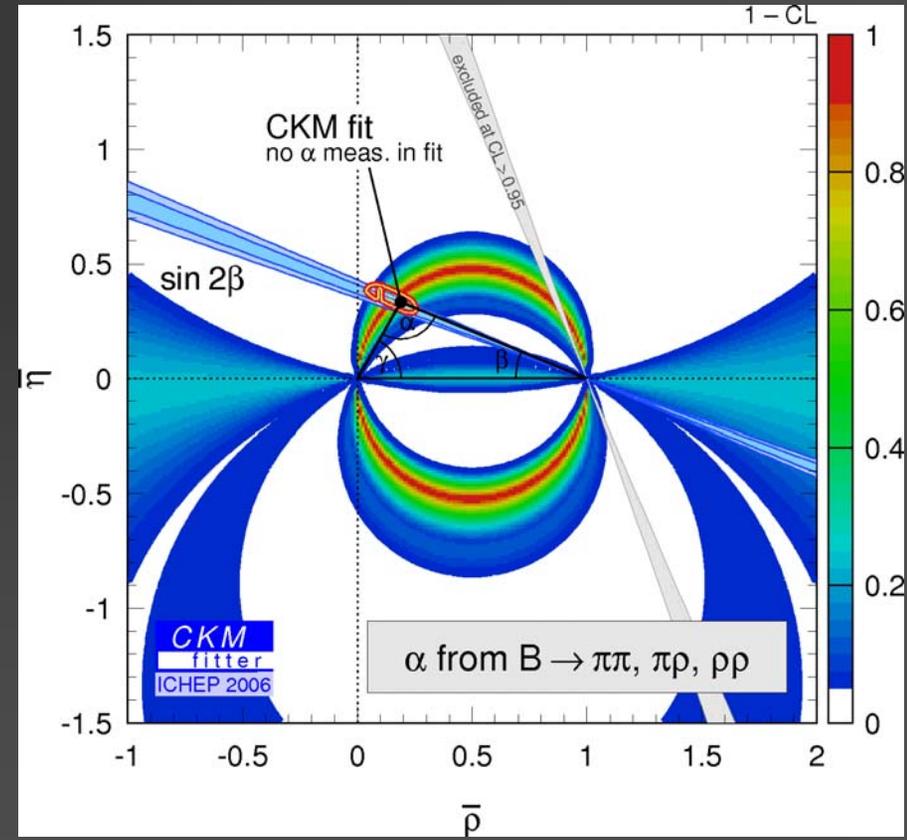
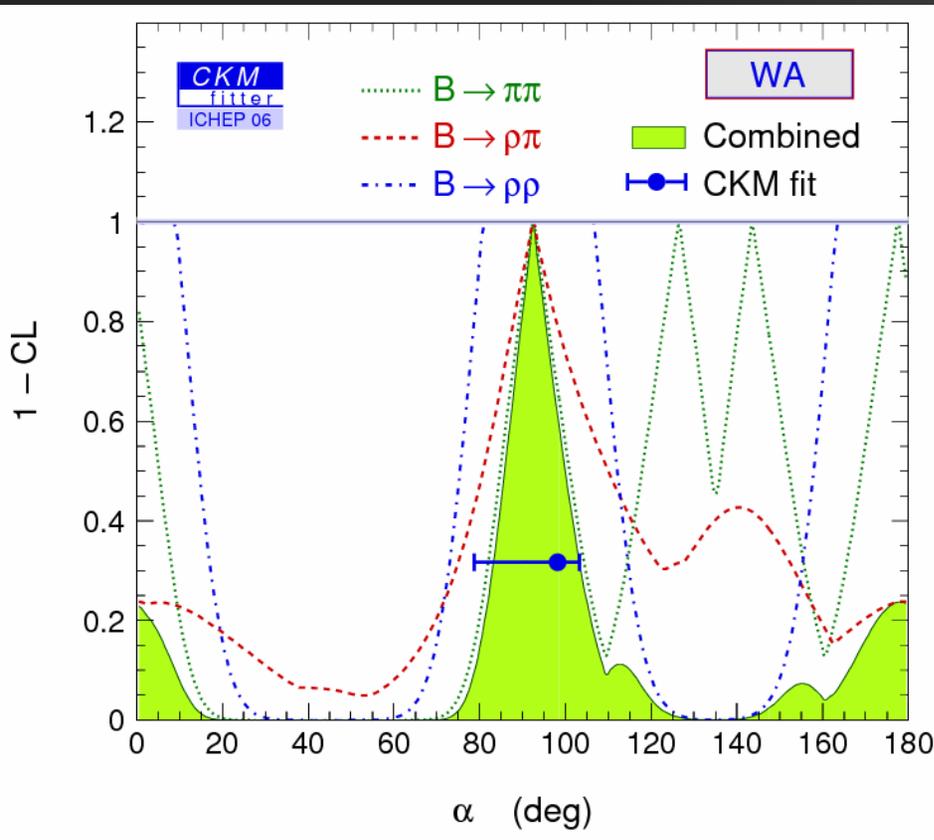
## ■ Add $B \rightarrow \rho\pi \rightarrow \pi^+ \pi^- \pi^0$



Dalitz plot analyses suggested by Snyder & Quinn



# Results on $\alpha$



# $\gamma$ : $B^\pm \rightarrow D^0 K^\pm$ decays, $D^0 \rightarrow K_S \pi^+ \pi^-$

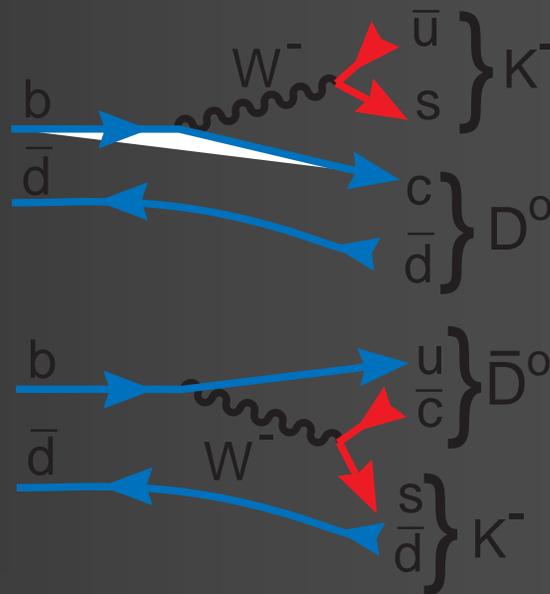
- Can have CPV in B decays  
Just need two interfering amplitudes

- For the  $B^-$  decay:

$$A(B^- \rightarrow D^0 K^-) \equiv A_B$$

$$A(B^- \rightarrow \bar{D}^0 K^-) \equiv A_B r_B e^{i(\delta_B - \gamma)}$$

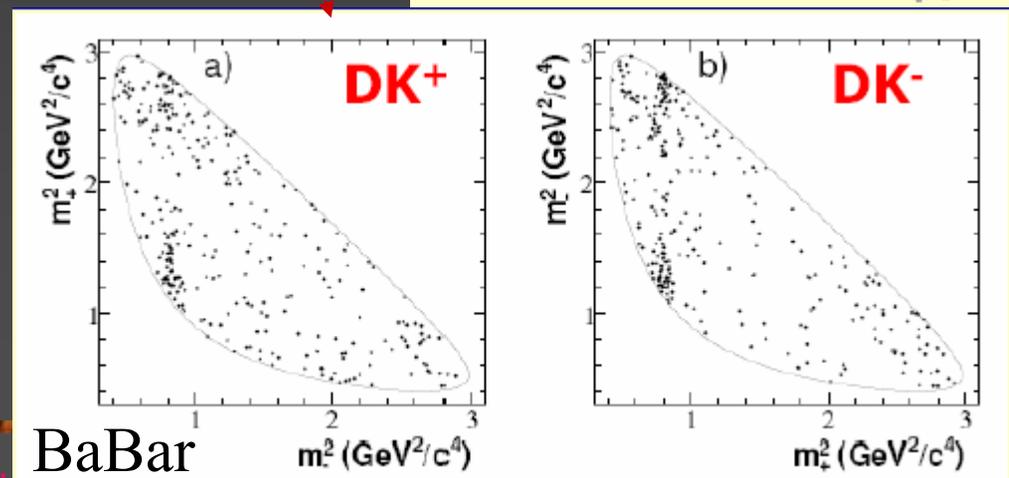
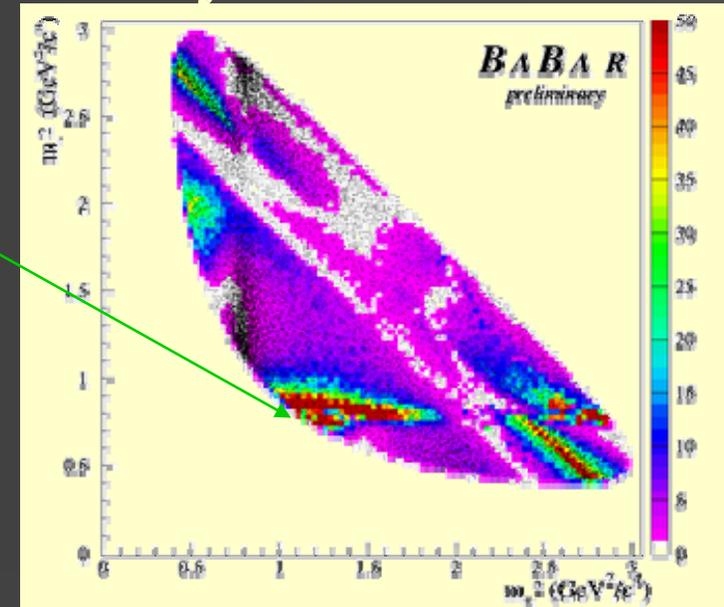
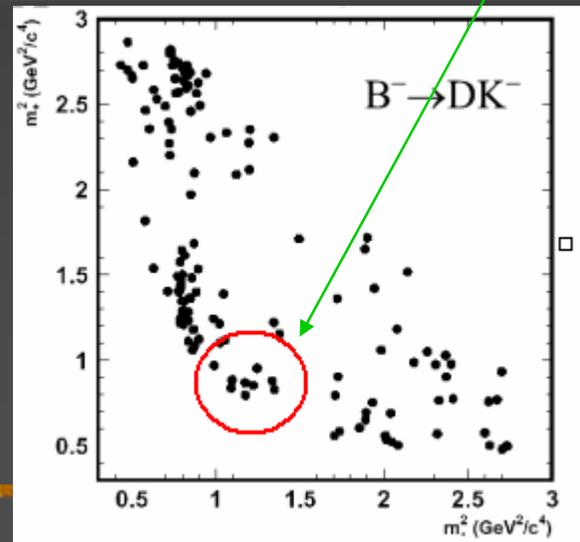
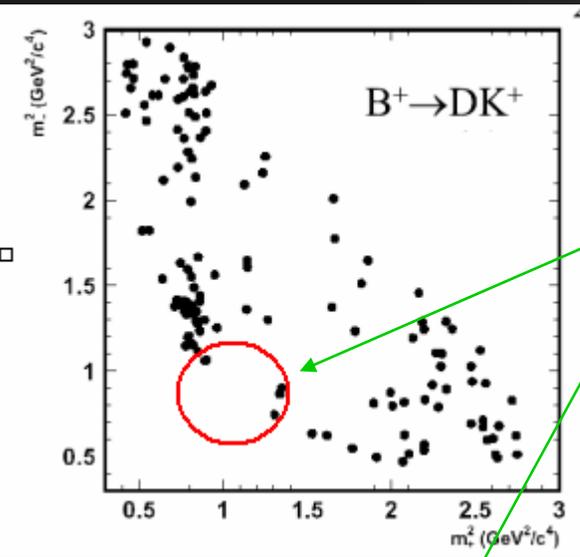
- Use modes where the  $D^0$  is indistinguishable from the  $\bar{D}^0$ . Then use Daltiz plot analysis to find  $\gamma$  see A. Giri et al., [hep-ph/0303187]



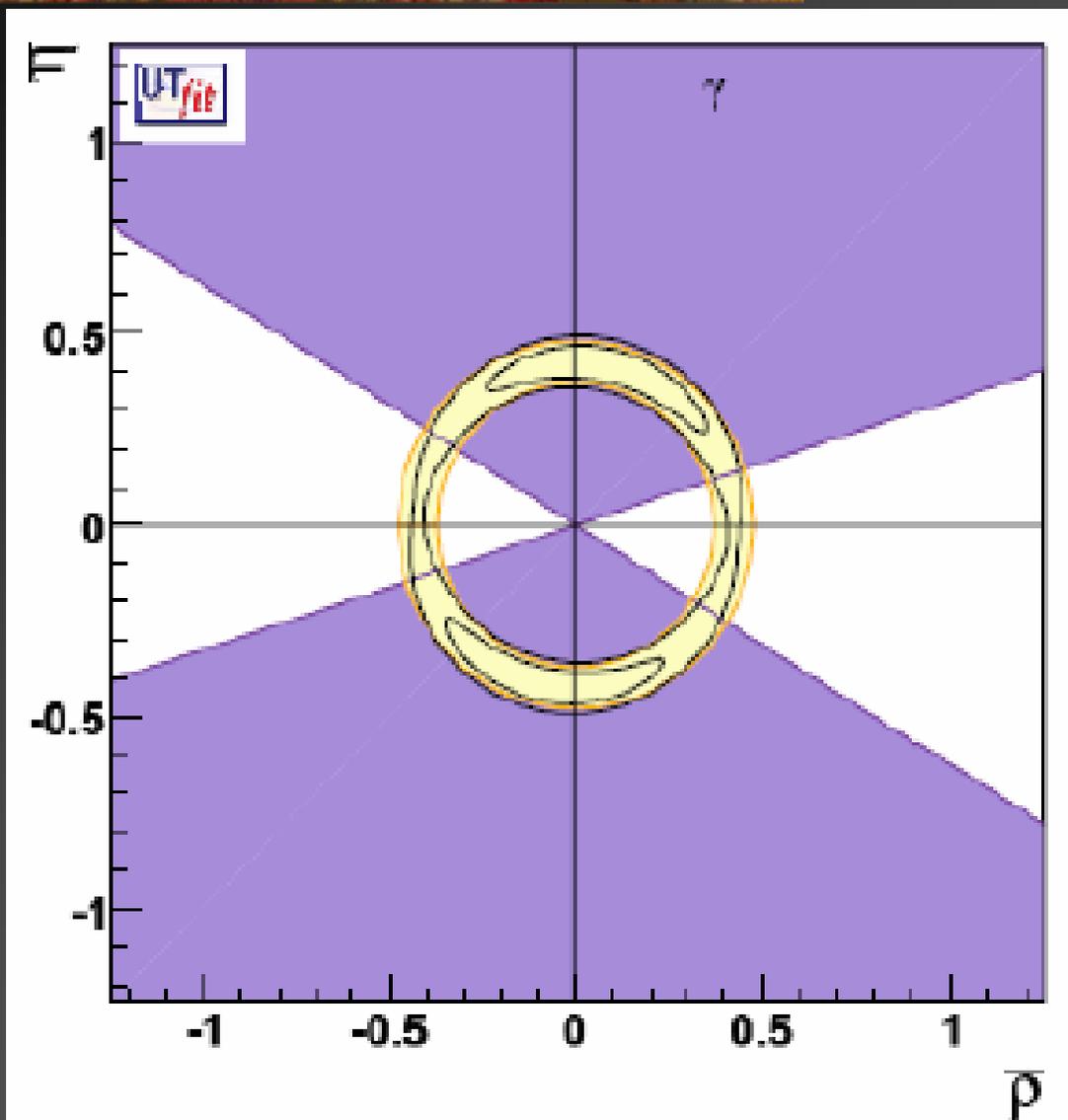
# $\gamma$ from $B \rightarrow D^0 K^-$ , $D^0 \rightarrow K_S \pi^+ \pi^-$

$d^2 \ln L / d^2 \gamma$  sensitivity

- Belle first saw a clear difference
- Now data show a smaller effect



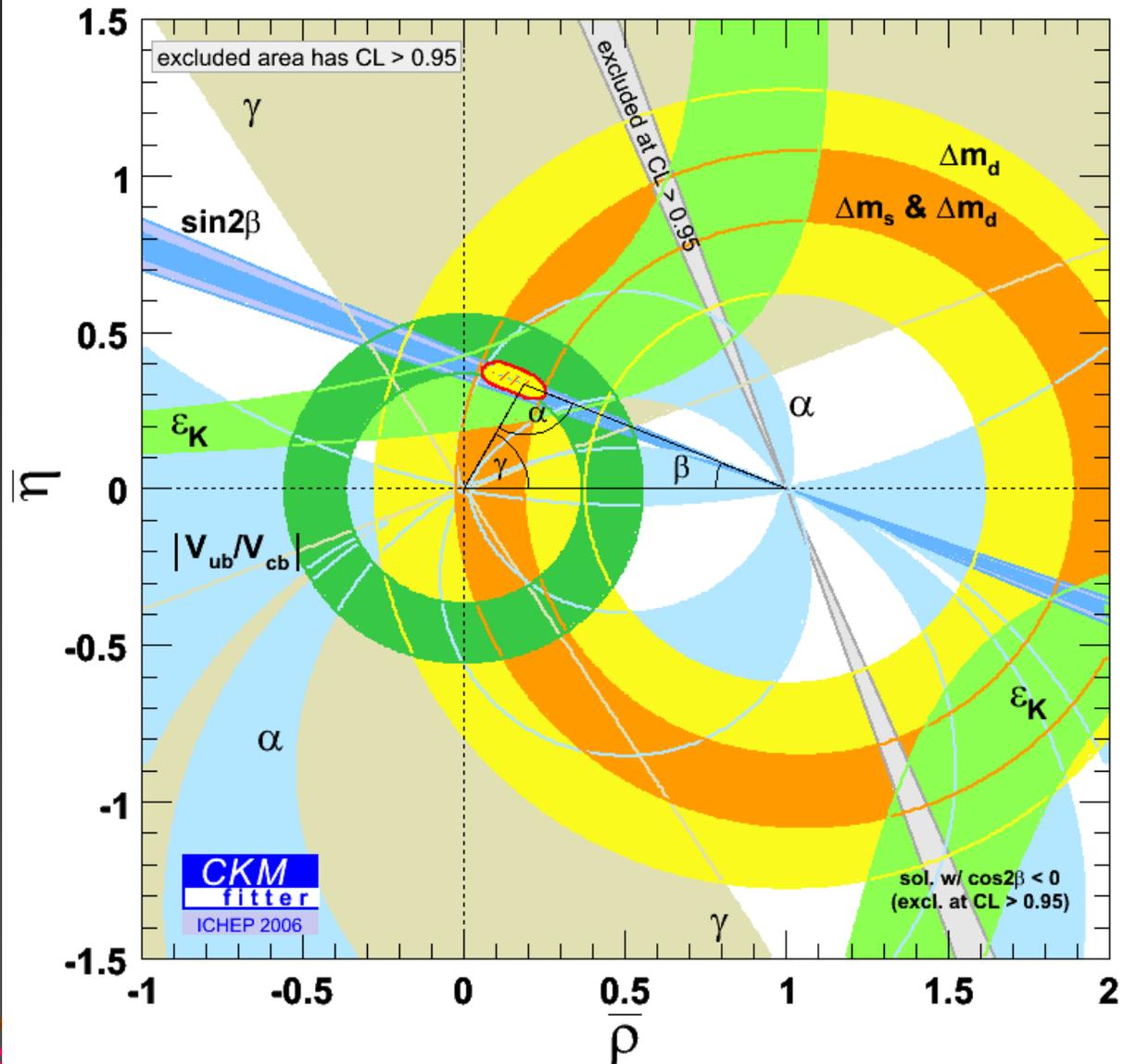
# Poor Constraints on $\gamma$



See  
<http://www.utfit.org/>

# Putting It All Together: Status

- Global fit using all available inputs
- $\varepsilon_K$  is from CP violation in  $K^0$  system





# Reasons for Further B Physics Studies

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There is New Physics out there:  
Standard Model is violated by the  
Baryon Asymmetry of Universe & by  
Dark Matter

I will show that B physics will be  
crucial towards interpreting New  
Physics found at the LHC

# The Enigma of Baryogenesis

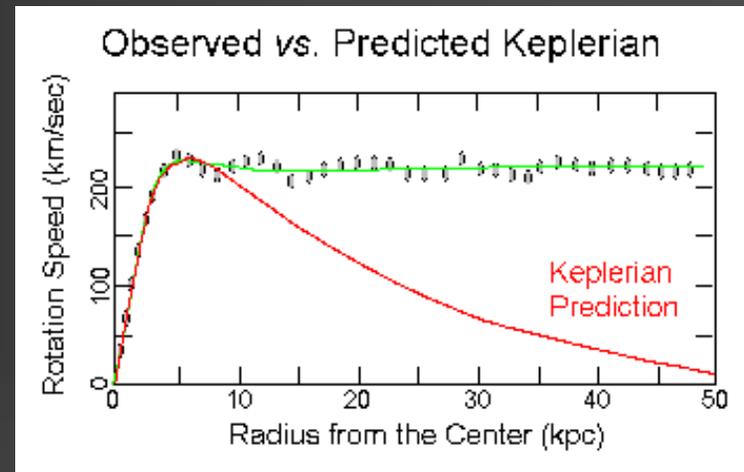
- When the Universe began, the Big Bang, there was an equal amount of matter & antimatter
- Now we have most matter. How did it happen?
- Sakharov criteria
  - Baryon (B) number violation
  - Departure from thermal equilibrium
  - C & CP violation

# Sakharov Criteria All Satisfied

- B is violated in Electroweak theory at high temperature, B-L is conserved (need quantum tunneling, powerfully suppressed at low T)
- Non-thermal equilibrium is provided by electroweak phase transition
- C & CP are violated by weak interactions. However the violation is too small!
  - $n_B - n_{\bar{B}}/n_\gamma = \sim 6 \times 10^{-10}$ , while SM can provide only  $\sim 10^{-20}$
- Therefore, there **must** be new physics

# Dark Matter

- Discovered by Zwicky in 1933 by measuring rotation curves of galaxies in the Coma cluster



- Also gravitational lensing of galaxy clusters

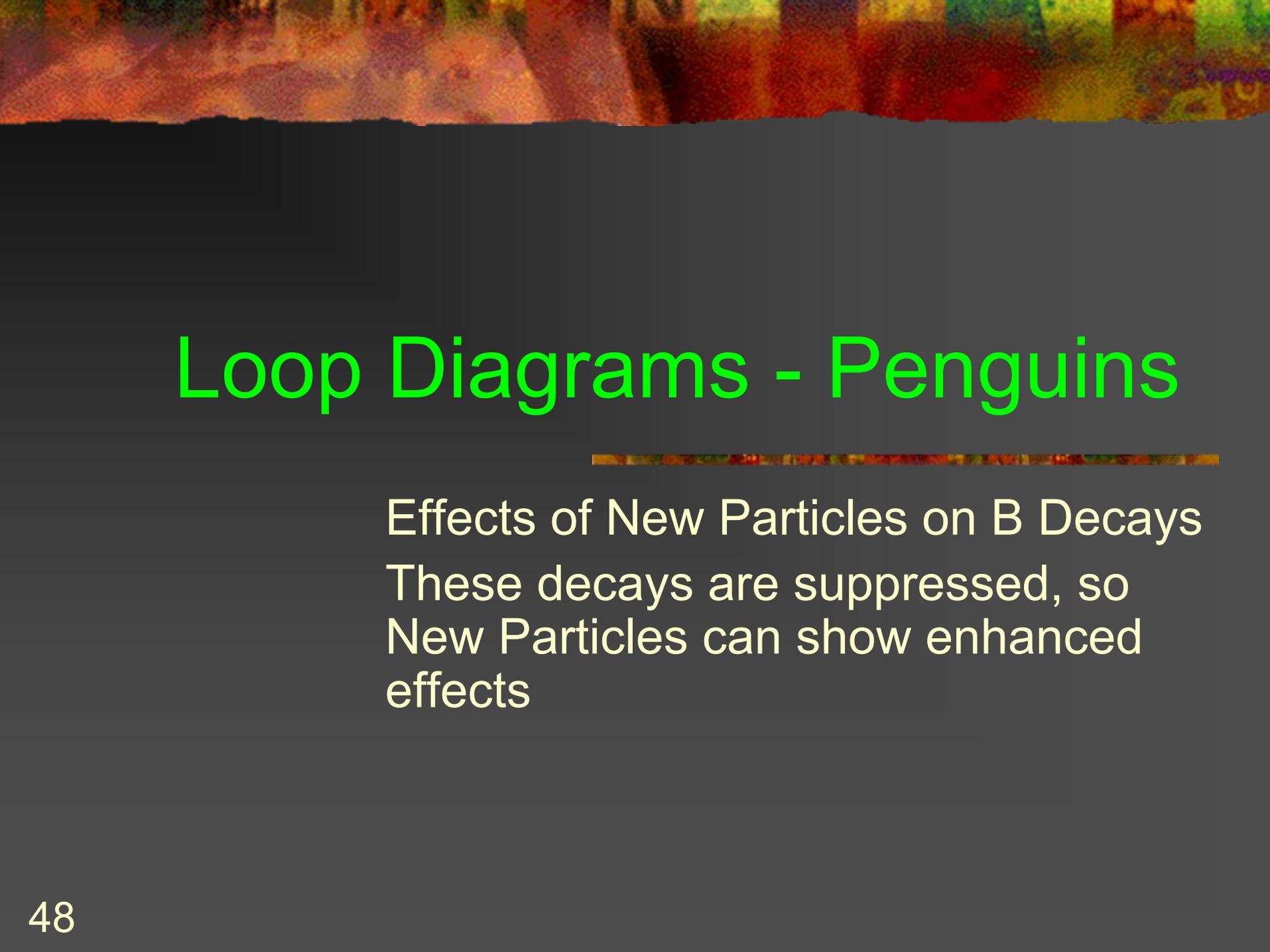
- Is dark matter composed of Supersymmetric particles?



# The Hierarchy Problem

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- Physics at the Planck scale  $\sim 10^{19}$  GeV is much larger than at the  $\sim 100$ - $1000$  TeV electroweak scale, requires delicate cancellations between fundamental quantities and quantum corrections.
- New Physics is needed to solve this problem



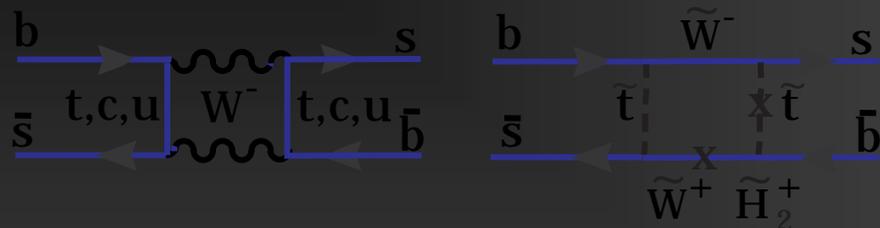
# Loop Diagrams - Penguins

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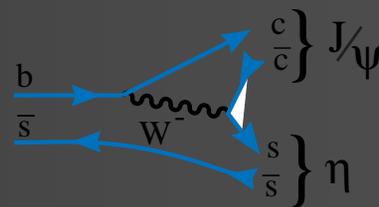
Effects of New Particles on B Decays  
These decays are suppressed, so  
New Particles can show enhanced  
effects

# MSSM Measurements, from Hinchcliff & Kersting (hep-ph/0003090)

## Contributions to $B_s$ mixing



## $B_s \rightarrow J/\psi \eta$

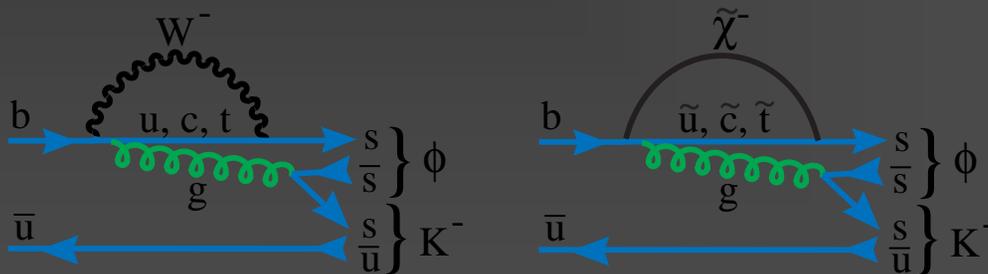


CP asymmetry ...  $0.1 \sin \phi_\mu \cos \phi_A \sin(\Delta m_s t)$ ,  $\sim 10 \times \text{SM}$

## Contributions to direct CP violating decay

$B^- \rightarrow \phi K^-$  vs

$B^+ \rightarrow \phi K^+$

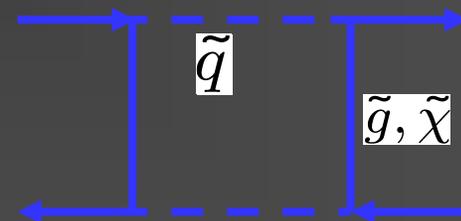


$A_{\text{sym}} = (M_W/m_{\text{squark}})^2 \sin(\phi_\mu)$ ,  $\sim 0$  in SM

# Supersymmetry

- Supersymmetry contains squarks and sleptons.
- Squark mass matrixes contain information on SUSY breaking mechanisms &/or GUT scale interactions.
- Quark flavor changing neutral current processes, e.g.  $B_s$  or  $D^0$  mixing, are sensitive to the off-diagonal elements of the squark mass matrix.

$$(m_{\tilde{q}}^2)_{ij} = \begin{pmatrix} m_{11}^2 & m_{12}^2 & m_{13}^2 \\ m_{21}^2 & m_{22}^2 & m_{23}^2 \\ m_{31}^2 & m_{32}^2 & m_{33}^2 \end{pmatrix}$$

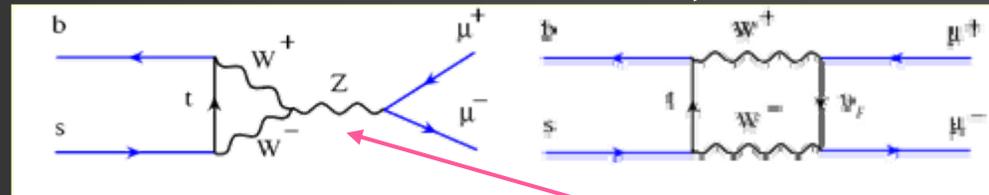


# Examples

## SUSY GUT & $B_S$ Mixing

## Enhancements to $B_S \rightarrow \mu^+ \mu^-$

SM  $\mathcal{E} \sim 3.4 \times 10^{-9}$ , via



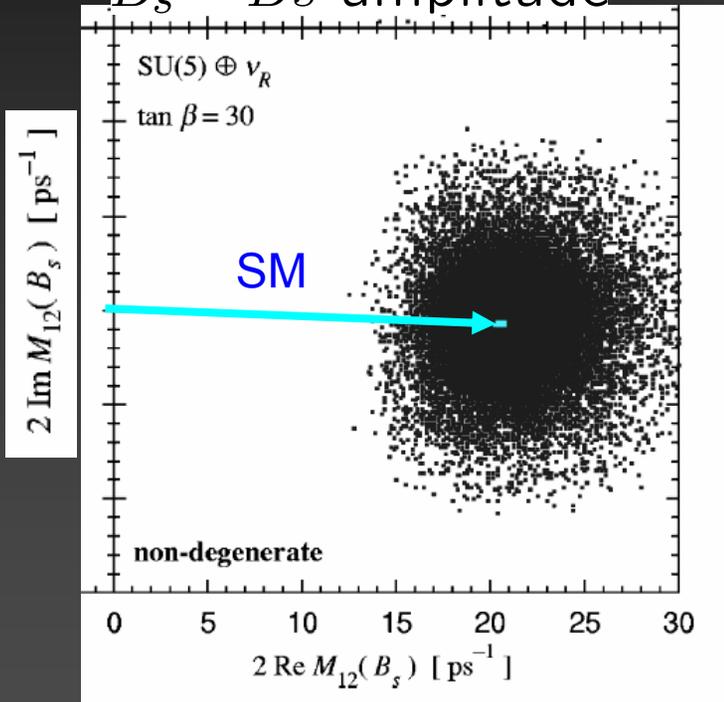
SUSY adds  $A^0, H^0, h^0$

$$B(B_S \rightarrow \mu^+ \mu^-) = 5 \times 10^{-7} \left( \frac{\tan \beta}{50} \right)^6 \left( \frac{300 \text{ GeV}}{M_{A^0}} \right)^4$$

Current CDF limits

	$B_S^0 \rightarrow \mu^+ \mu^-$	$B_d^0 \rightarrow \mu^+ \mu^-$
$\mathcal{E}$ @ 95% cl	$< 1.0 \times 10^{-7}$	$< 3.0 \times 10^{-8}$

$B_S - \bar{B}_S$  amplitude



$B_S$  mixing

T.Goto, Y.O.Y.Shimizu, Y.Shindou, and M.Tanaka, 2003

From Okada ICHEP 2006

# SO(10)

ala' Chang, Masiero & Murayama hep-ph/0205111

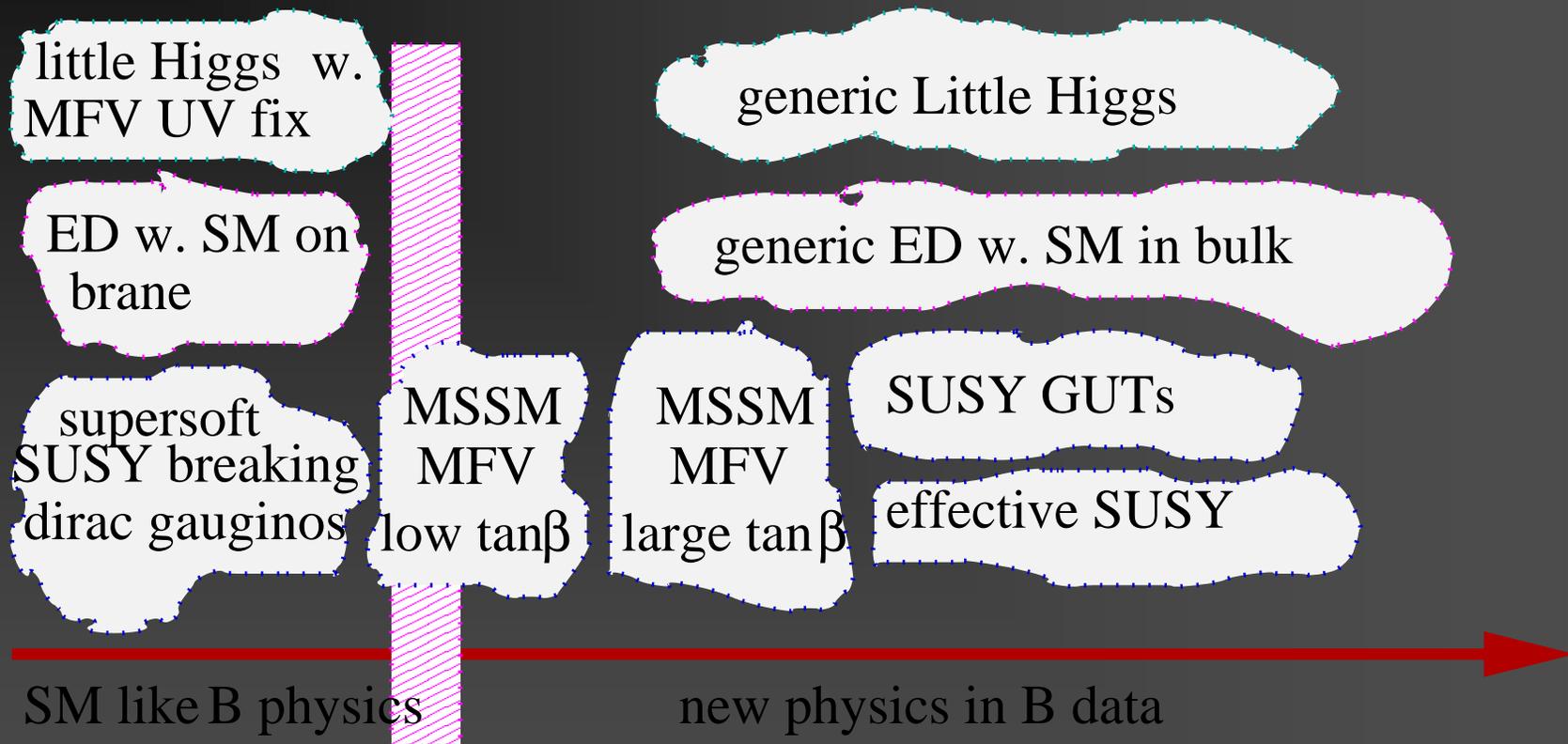
- Large mixing between  $\nu_\tau$  and  $\nu_\mu$  (from atmospheric  $\nu$  oscillations) can lead to large mixing between  $\tilde{b}_R$  and  $\tilde{s}_R$ .
- This does not violate any known measurements
- Leads to large CPV in  $B_s$  mixing, deviations from  $\sin(2\beta)$  in  $B^0 \rightarrow \phi K_s$  and changes in the phase  $\gamma$

# New Physics Effects in Some Different Models

Model	$B_d$ Unitarity	Time-dep. $CPV$	Rare $B$ decay	Other signals
mSUGRA(moderate $\tan \beta$ )	-	-	-	-
mSUGRA(large $\tan \beta$ )	$B_d$ mixing	-	$B \rightarrow (D)\tau\nu$ $b \rightarrow sl^+\ell^-$	$B_s \rightarrow \mu\mu$ $B_s$ mixing
SUSY GUT with $\nu_R$	-	$B \rightarrow \phi K_S$ $B \rightarrow K^*\gamma$	-	$B_s$ mixing $\tau$ LFV, $n$ EDM
Effective SUSY	$B_d$ mixing	$B \rightarrow \phi K_S$	$A_{CP}^{b \rightarrow s\gamma}, b \rightarrow sl^+\ell^-$	$B_s$ mixing
KK graviton exchange	-	-	$b \rightarrow sl^+\ell^-$	-
Split fermions in large extra dimensions	$B_d$ mixing	-	$b \rightarrow sl^+\ell^-$	$K^0\bar{K}^0$ mixing $D^0\bar{D}^0$ mixing
Bulk fermions in warped extra dimensions	$B_d$ mixing	$B \rightarrow \phi K_S$	$b \rightarrow sl^+\ell^-$	$B_s$ mixing $D^0\bar{D}^0$ mixing
Universal extra dimensions	-	-	$b \rightarrow sl^+\ell^-$ $b \rightarrow s\gamma$	$K \rightarrow \pi\nu\bar{\nu}$

- *Different models give different patterns* (2003 SLAC WS Proceedings)

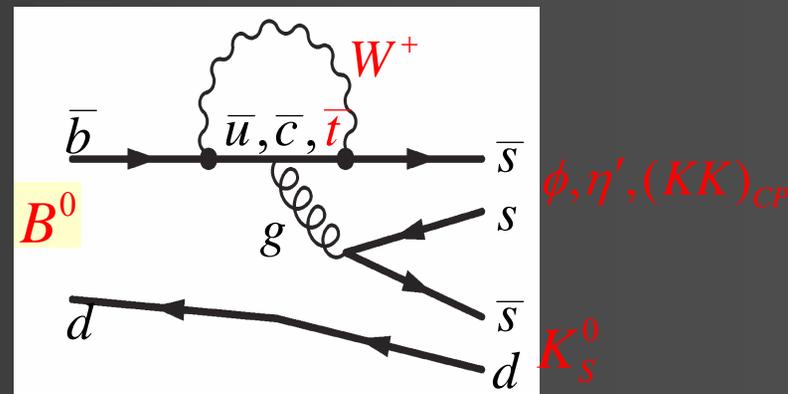
# Possible Size of New Physics Effects



■ From Hiller hep-ph/0207121

# $b \rightarrow s$ Transitions (Penguins)

- In SM  $t$  in loop dominates and CP asymmetry should be equal to that in  $J/\psi K_S$
- Other objects in loop, new virtual particles, could interfere
- So this process is sensitive to new physics

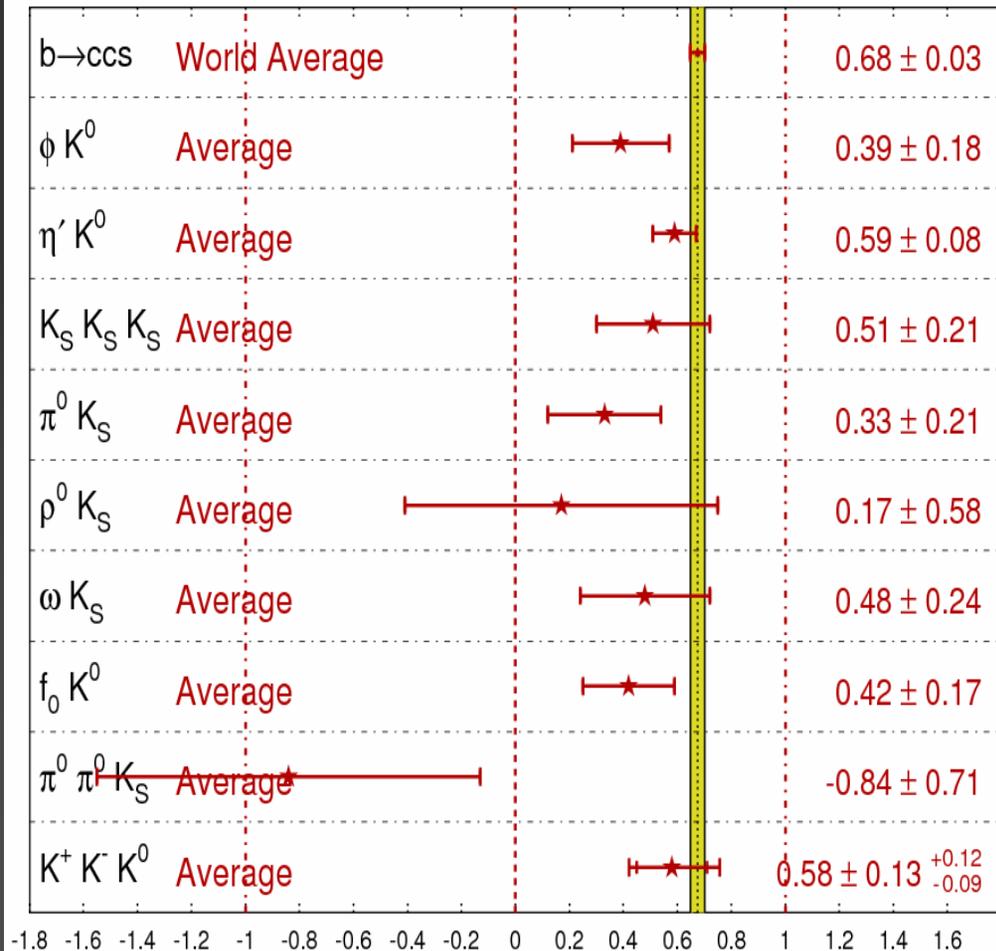


# CPV Measurements In $b \rightarrow s$

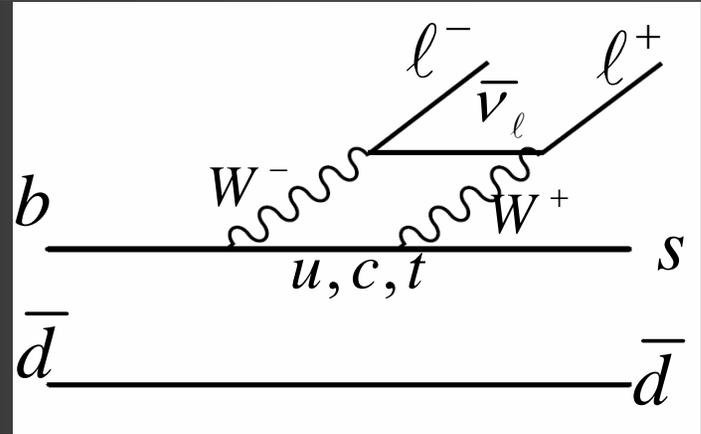
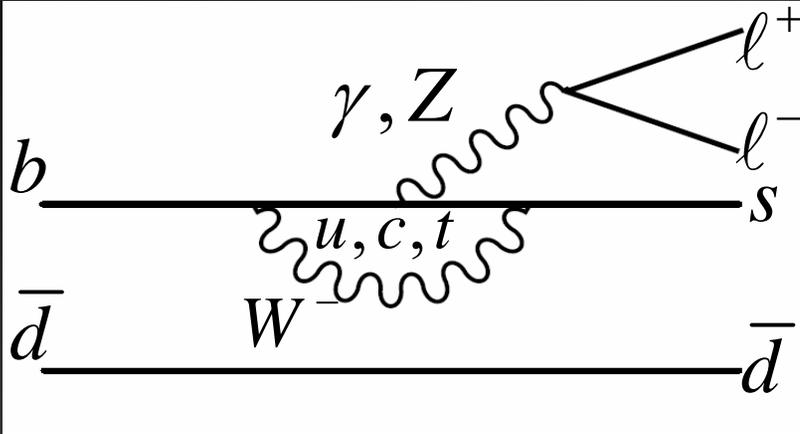
- We cannot just average these modes, but ....
- $\langle S \rangle = \sin 2\beta$   
 $= 0.50 \pm 0.06$
- $\Delta S = .52 \pm .05 - .68 \pm .03$   
 $= -0.16 \pm 0.06$
- Does u & c parts of Penguin contribute?  
 Yes but  $\Delta S > 0$ ,  $\sim 0.1$
- New Physics???

$$\sin(2\beta^{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}})$$

**HFAG**  
 ICHEP 2006  
 PRELIMINARY



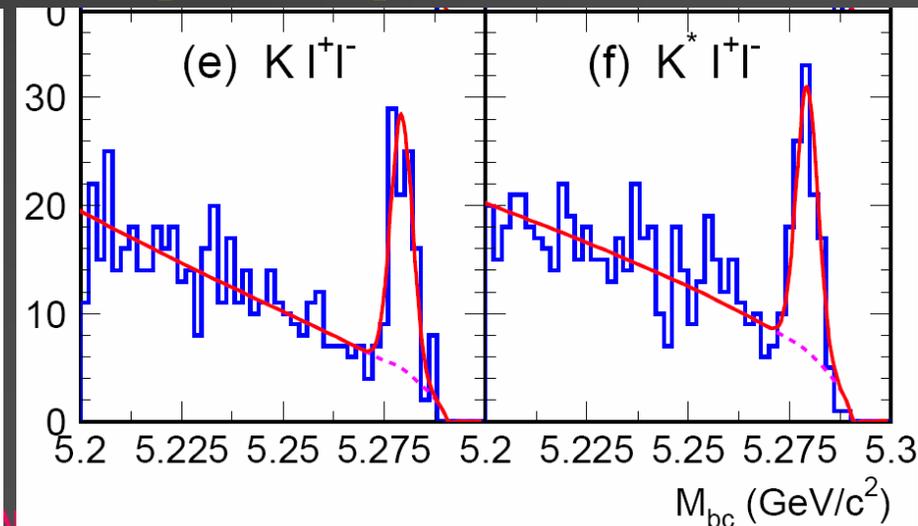
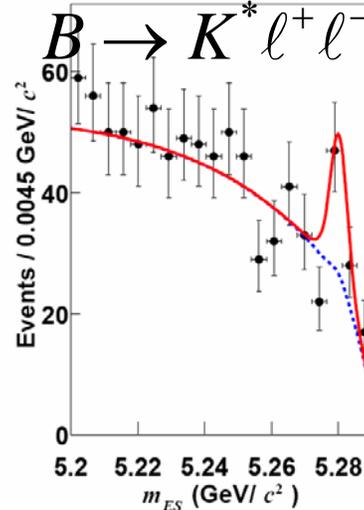
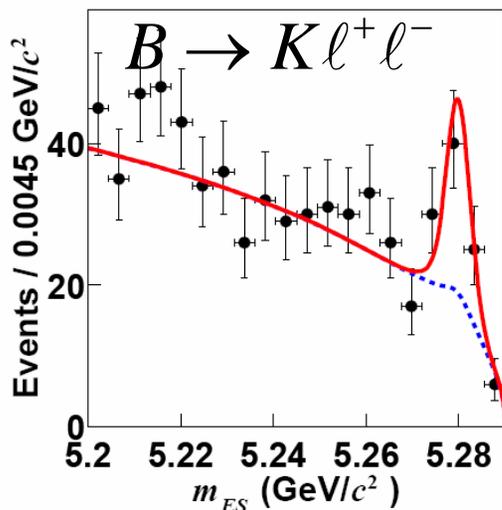
# Electroweak penguins $B \rightarrow K^{(*)} l^+ l^-$



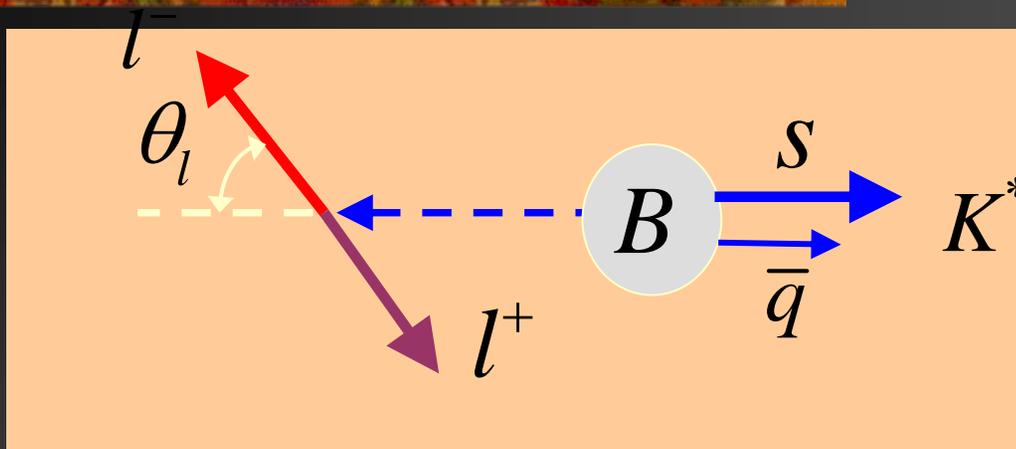
- With  $l^+ l^-$  pair, can have either pseudoscalar or vector mesons
- New physics can affect both rates and kinematic distributions.

BABAR hep-ex/0507005 (229M  $BB$ )

Belle prelim. hep-ex/0410006, 0508009



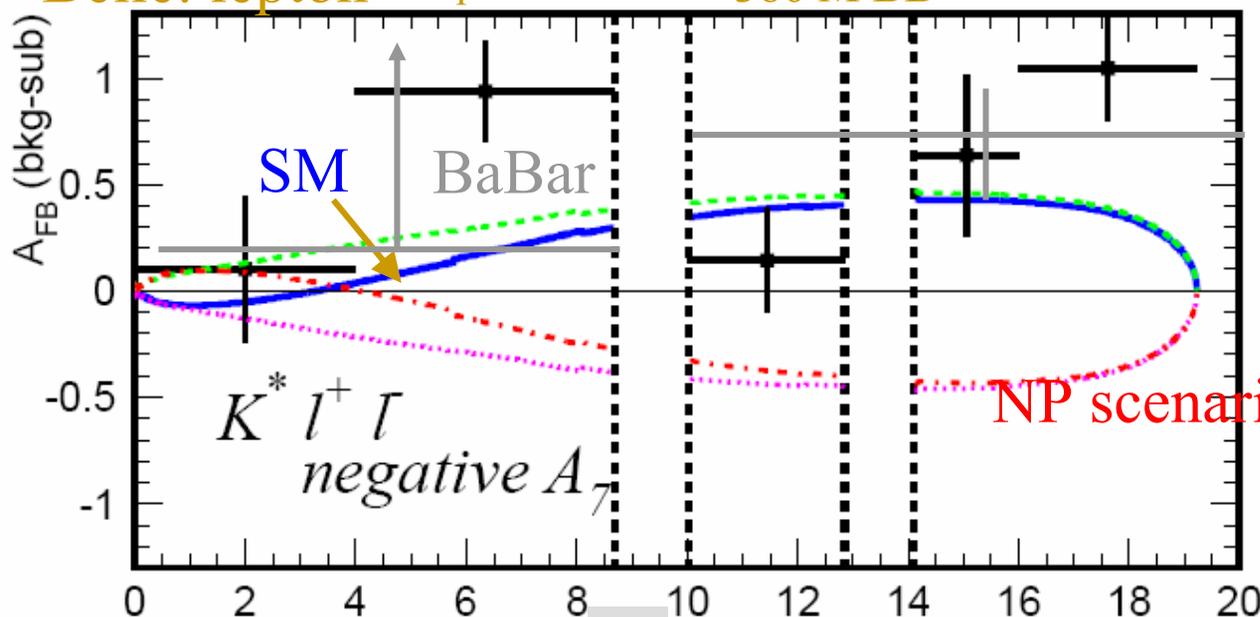
# $B \rightarrow K^{(*)} \ell^+ \ell^-$ : Lepton F-B Asymmetry



Lepton angular distribution in  $l^+ l^-$  rest frame

Belle: lepton hep-ex/0508009 386 M BB

$A_{FB}$



But large errors & somewhat contradictory data from BaBar

# Constraints on New Physics

- Next to Minimal Flavor Violation construction
- Assume NP in tree decays is negligible
- Is there NP in  $B^0$ - $\bar{B}^0$  mixing?

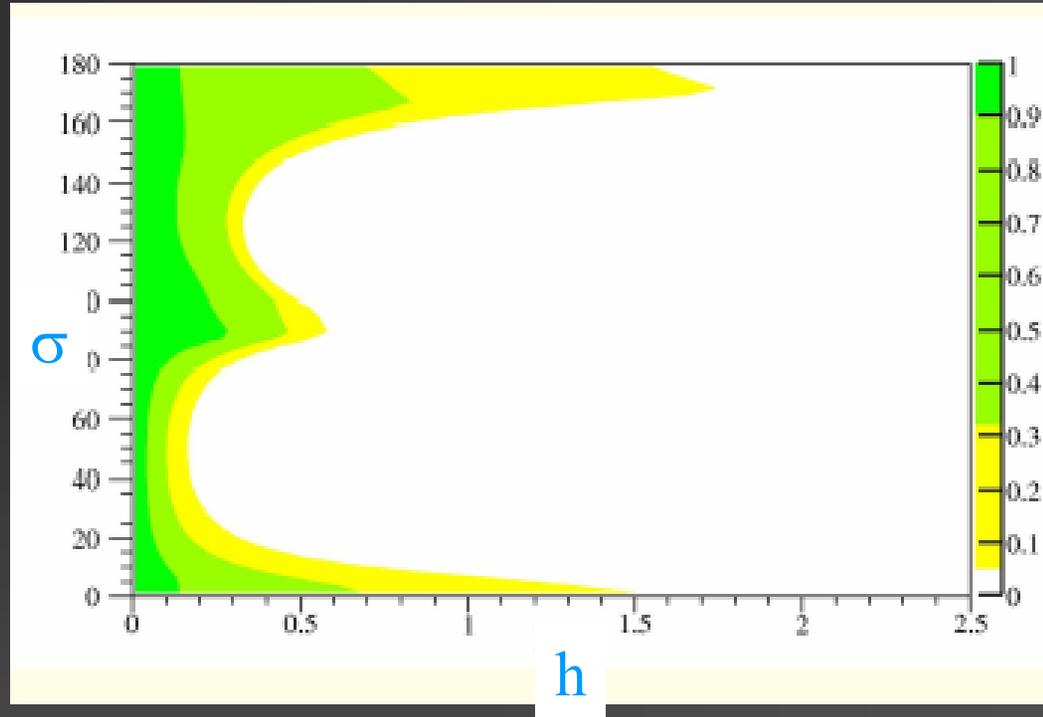
- $$r_d^2 e^{2i\theta_d} = 1 + h e^{i\sigma} = \frac{\langle B^0 | H^{\text{full}} | \bar{B}^0 \rangle}{\langle B^0 | H^{\text{SM}} | \bar{B}^0 \rangle}$$

- Use  $V_{ub}$ ,  $A_{\text{DK}}$ ,  $S_{\psi K}$ ,  $S_{\rho\rho}$ ,  $\Delta m_d$ ,  $A_{\text{SL}} =$   
 semileptonic asymmetry  $= \frac{\Gamma(\bar{B}^0 \rightarrow X l^- \bar{\nu}) - \Gamma(B^0 \rightarrow X l^+ \bar{\nu})}{\Gamma(\bar{B}^0 \rightarrow X l^- \bar{\nu}) + \Gamma(B^0 \rightarrow X l^+ \bar{\nu})}$
- Fit to  $\eta$ ,  $\rho$ ,  $r_d$ ,  $\theta_d$  (or  $h$ ,  $\sigma$ )

[Agashe, Papucci, Perez, & Pirjol hep-ph/0509117](#)

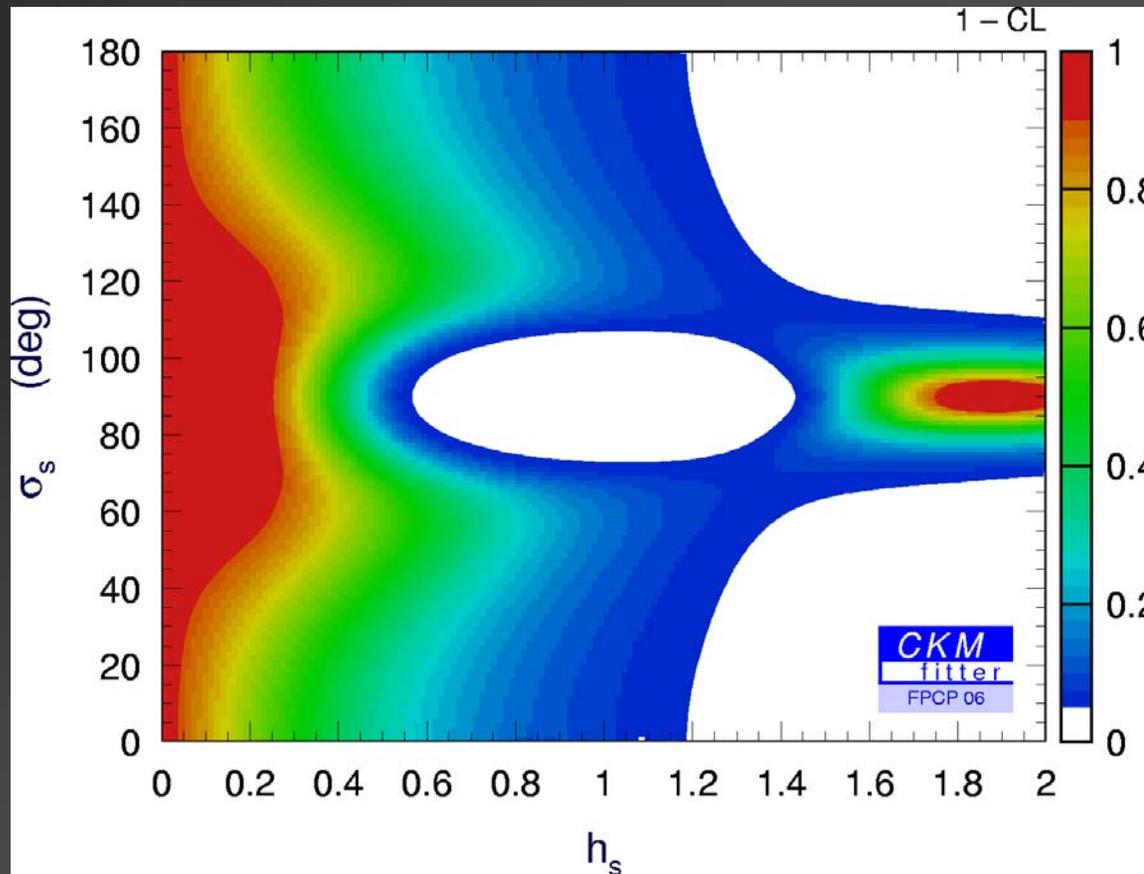
# New Physics Constraints

- Amplitudes  
~20% of SM  
still allowed in  
any region,  
more near  $0^\circ$
- Still a lot of  
room for New  
Physics in  $B_d$   
system



# $B_s$ System

- New Physics almost unconstrained



# $\Delta\Gamma$ in $B_S$ Decays

- $\Delta\Gamma = \Gamma_L - \Gamma_H$ , where  $\Gamma = 1/\tau$  of “light” vs “heavy”
  - In  $B_d$  system  $\Delta\Gamma$  is small, driven by common channels for  $B^0$  &  $\bar{B}^0$  (i.e.  $\pi^+\pi^-$ )
  - $B_S \rightarrow D_S^{+(*)} D_S^{-(*)}$ , where CP+ outweighs CP-  $B_S$  (recall CDF measured  $\Delta m_S$ ), CDF & D0 have measurements, order of  $\mathbb{E}(B \rightarrow D^{(*)} D_S^{(*)}) \sim 10\%$
  - Recall
 
$$i \frac{d}{dt} \begin{pmatrix} |B_S^0(t)\rangle \\ |\bar{B}_S^0(t)\rangle \end{pmatrix} = \left( M - i \frac{\Gamma}{2} \right) \begin{pmatrix} |B_S^0(t)\rangle \\ |\bar{B}_S^0(t)\rangle \end{pmatrix}$$
- $\Delta\Gamma = 2|\Gamma_{12}| \cos\phi_S$ , where  $\phi_S$  is the CP violating phase in  $B_S$  mixing, expected to be tiny in SM  $\sim -2\lambda^2\eta = -.04$  rad but effected by NP
- Can measure  $\Delta\Gamma$  using  $\tau$  measurements

# Measuring $\phi$ Phase of $B_S$ mixing

- CP violation in  $B_S$  mixing

$\Gamma(B_S(t) \rightarrow f)$

$$\sim \frac{1 + |\lambda_f|^2}{2} e^{-t/\tau} \left[ \cosh \frac{\Delta\Gamma t}{2} + A_{CP}^{\text{dir}} \cos(\Delta m_S t) - \eta_f \cos \phi \sinh \frac{\Delta\Gamma t}{2} + \eta_f \sin \phi \sin(\Delta m_S t) \right]$$

$\Gamma(\bar{B}_S(t) \rightarrow f)$

$$\sim \frac{1 + |\lambda_f|^2}{2} e^{-t/\tau} \left[ \cosh \frac{\Delta\Gamma t}{2} - A_{CP}^{\text{dir}} \cos(\Delta m_S t) - \eta_f \cos \phi \sinh \frac{\Delta\Gamma t}{2} - \eta_f \sin \phi \sin(\Delta m_S t) \right]$$

- $\eta_f = \pm 1$ , depending on  $f = CP+$  or  $CP-$
- Contrast with  $B^0$

$$\Gamma(B^0 \rightarrow f) \sim e^{-t/\tau} [1 + A^{\text{dir}} \cos \Delta m t + \sin \phi \Delta m t]$$

# Measuring $\phi$ Without Flavor Tagging

- Sum

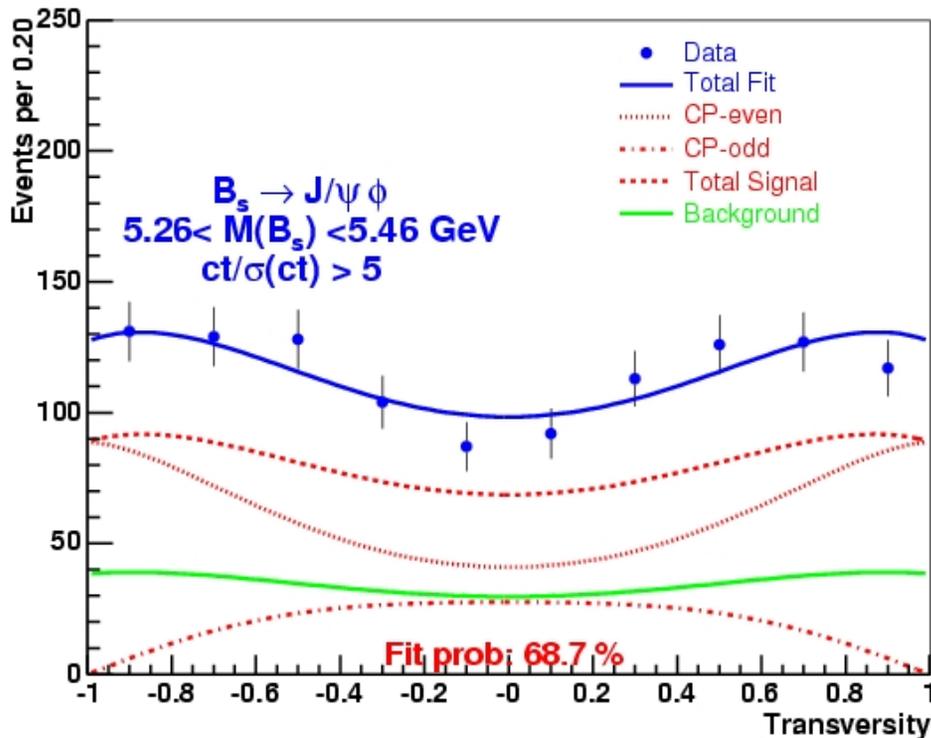
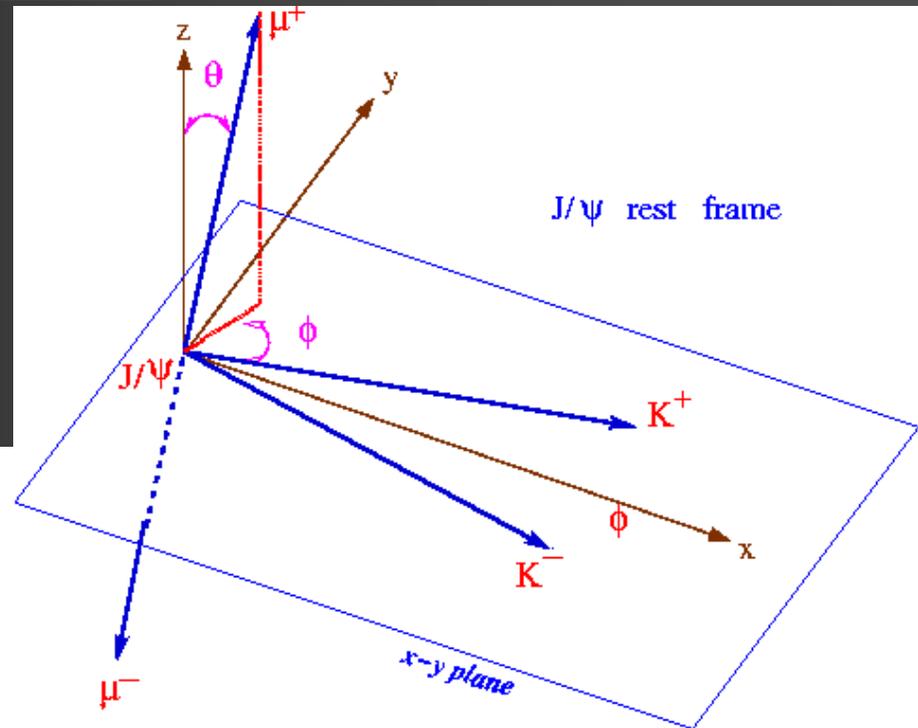
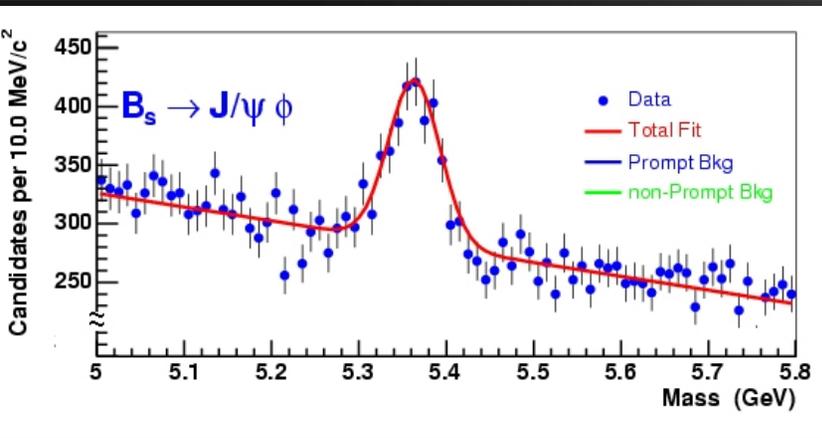
$$\Gamma(B_s(t) \rightarrow f) + \Gamma(\bar{B}_s(t) \rightarrow f) \sim e^{-t/\tau} \left[ \cosh \frac{\Delta\Gamma t}{2} - \eta_f \sinh \frac{\Delta\Gamma t}{2} \cos\phi \right]$$

- Some sensitivity to  $\phi$  without flavor tagging

# Measuring $\phi$ with $B_S \rightarrow J/\psi \eta$ (or $\phi$ )

- $B_S \rightarrow J/\psi \eta$  (where  $\eta \rightarrow \gamma\gamma$  or  $\pi^+\pi^-\pi^0$ ) is a CP eigenstate similar to  $B^0 \rightarrow J/\psi K_S$ . However, detecting the  $\eta$  is difficult for some hadron collider detectors
- $J/\psi \phi$  is not a CP eigenstate, but is very useful in all experiments. Must take into account different spins: S, P, D.
- $\therefore$  use Transversity analysis
- Most sensitivity expected using flavor tagged analysis

# D0 Untagged Analysis



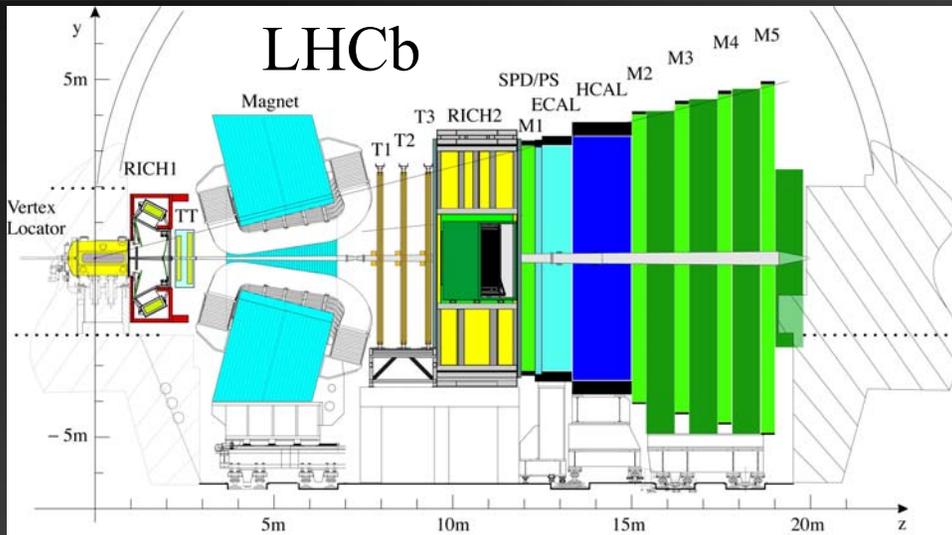
- D0 has  $978 \pm 45$  events
- $\phi_S = -0.79 \pm 0.56 \pm 0.01$  (rad)
- $\Delta\Gamma_S = 0.17 \pm 0.09 \pm 0.04$  ps<sup>-1</sup>
- $\Rightarrow \Delta\Gamma/\Gamma \sim 0.25 \pm 0.13$

The background features a vibrant, abstract pattern of colors including reds, oranges, yellows, and greens, which appears to be a textured surface like a painting or a collage. This pattern is partially obscured by a dark grey, semi-transparent rectangular overlay that covers the majority of the slide's background.

# Future Experiments

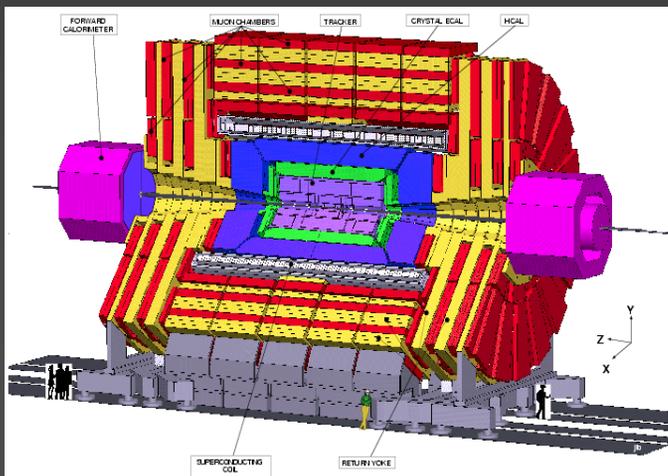
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# B experiments at the LHC

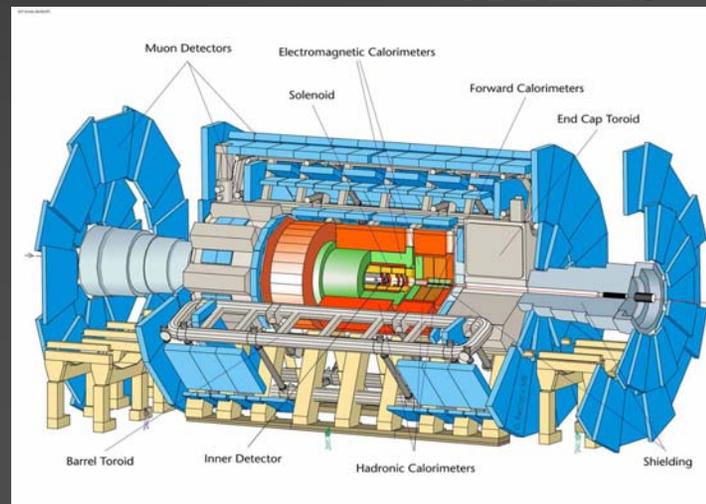


- LHCb: first dedicated b experiment at a hadron collider, the LHC
  - Excellent vertexing
  - Excellent particle id
- Super B? Two efforts, one at Frascati and SuperBelle in Japan

CMS



ATLAS

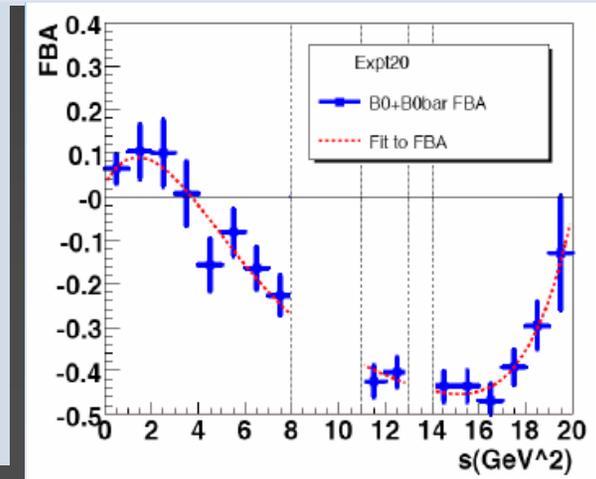
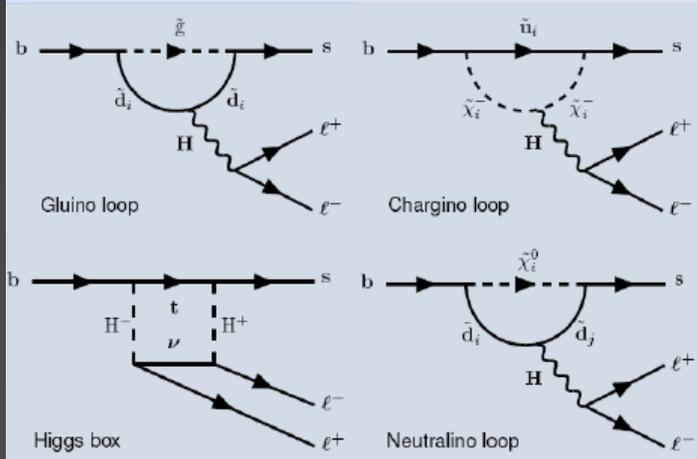


# LHCb Projections

	Det. eff. (%)	Tot. eff. (%)	Vis. BR (10 <sup>6</sup> )	Annual signal yield	B/S from bb bkg.	Parameter	Error
$B^0 \rightarrow \pi^+ \pi^-$	12.2	<b>0.69</b>	4.8	26k	< 0.7	$\gamma$	6 <sup>0</sup>
$B_s \rightarrow K^+ K^-$	12.0	<b>0.99</b>	18.5	37k	0.3		U-spin symmetry
$B_s \rightarrow D_s^\pm K^\pm$	5.4	<b>0.27</b>	10.	5.4k	< 1.0	$\gamma$	14 <sup>0</sup>
$B^0 \rightarrow D^{*0} (K\pi) K^{*0}$	5.3	<b>0.35</b>	1.2	3.4k	< 0.5	$\gamma$	8 <sup>0</sup>
$B^0 \rightarrow J/\psi K_s^0$	6.4	<b>1.26</b>	20.	216k	0.8	$\beta$	0.9 <sup>0</sup>
$B_s \rightarrow J/\psi \phi$	7.5	<b>1.45</b>	31.	131k	0.12	$\Phi_s$	1.2 <sup>0</sup> (0.02 rad)
$B^0 \rightarrow \rho \pi$	6.0	<b>0.07</b>	20.	14k	< 1.0	$\alpha$	< 10 <sup>0</sup> stat
$B^0 \rightarrow K^{*0} \gamma$	9.5	<b>0.16</b>	29.	35k	< 0.7	$A_{DIR}$	< 1%
$B^0 \rightarrow K^* \mu^+ \mu^-$			0.8	4.4k	< 2.5	$A_{FB}$	$\pm 0.5 \text{ GeV}/c^2$
$B_s \rightarrow D_s^- \pi^+$	5.4	<b>0.34</b>	120.	80k	0.3	$\Delta m_s$	68ps <sup>-1</sup>
$B_s \rightarrow \mu^+ \mu^-$		<b>2.4</b>	0.0035	17	< 5.7	BR	< 10 <sup>-8</sup>

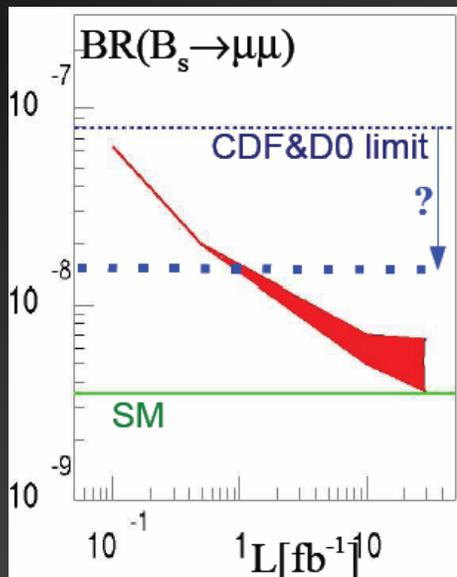
Zero x-ing  
10fb<sup>-1</sup>  
reach

$K^* \mu^+ \mu^-$   
2 fb<sup>-1</sup>



# Also ATLAS & CMS

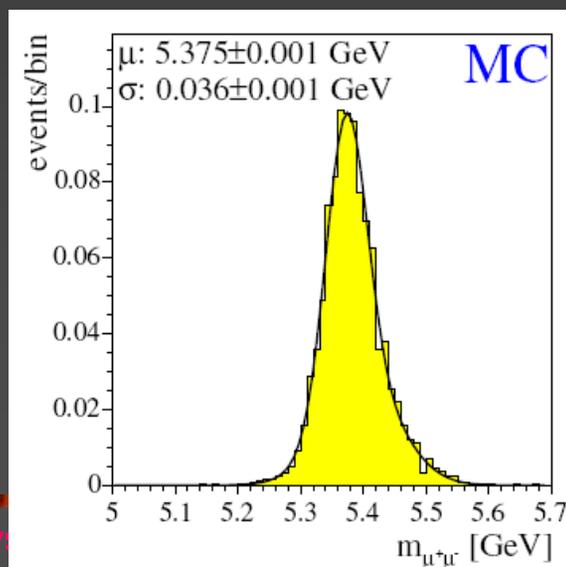
## ■ ATLAS



$$B_S \rightarrow J/\psi \phi$$

	ATLAS after $30\text{fb}^{-1}$ (270 000 events)
$\sigma_{\Delta\Gamma}/\Delta\Gamma$	13%
$\sigma_{\Gamma}/\Gamma$	1%
$\sigma_{\phi_S}$	0.046 for $\Delta m_S = 20\text{ps}^{-1}$

## ■ CMS

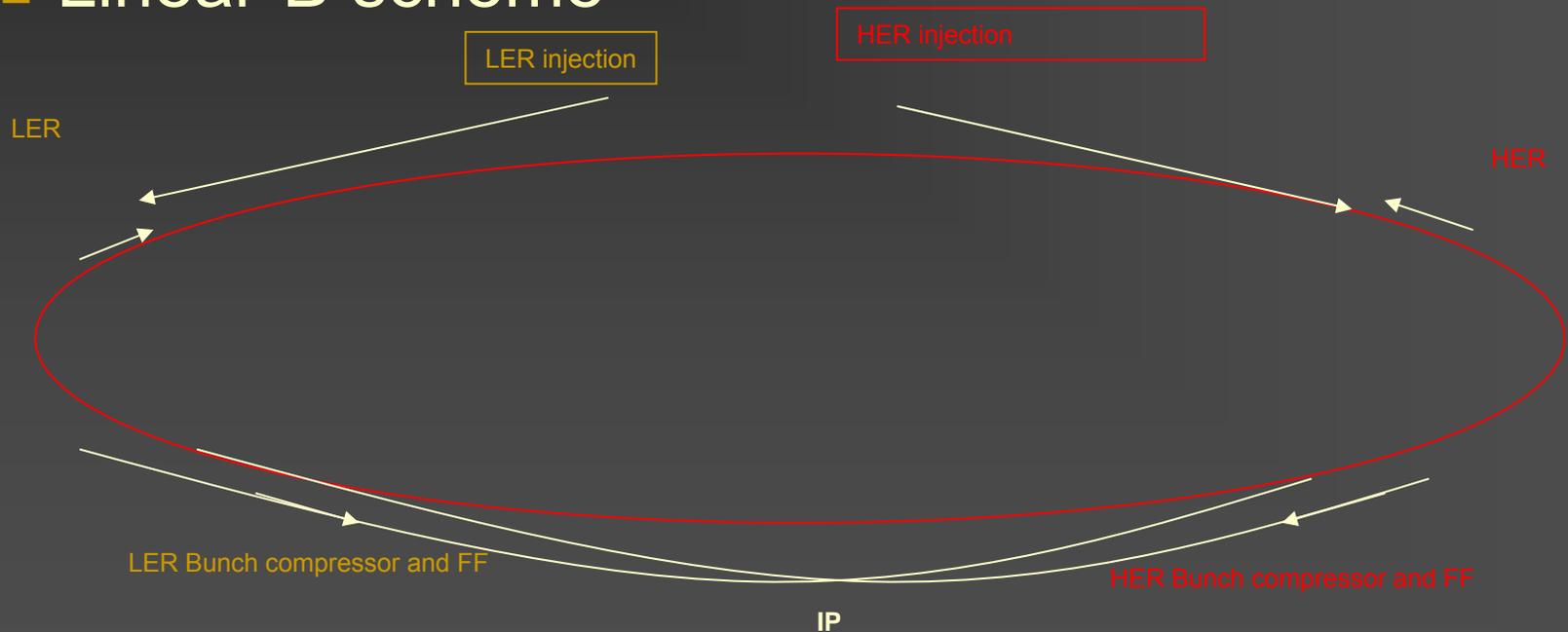


$$B(B_S \rightarrow \mu^+ \mu^-) < 1.4 \times 10^{-8}$$

$$@ 90\% \text{ cl in } 10 \text{ fb}^{-1}$$

# Will There Be a Super-B $e^+e^-$ Machine?

- Two proposals currently being pursued to make  $L \sim 10^{36}$ ,  $\sim 100$  times current B factories
  - Super Belle at KEK
  - Linear-B scheme



# Conclusions

- Much has been learned about the structure of matter & fundamental forces in nature using flavor decays; contributions from several generations of experiments at  $e^+e^-$ , fixed target and hadron colliders
- **b & c decays will be used as incisive probes of New Physics. These effects appear in loops. We already are probing the TeV scale. Flavor decays will be ever more important in understanding the nature of NP effects found at the LHC or Tevatron (i.e. SUSY, Extra Dimensions, Little Higgs etc...)**
- The next few years will see more results from BaBar, Belle, CDF & D0, but only Belle will remain post 2009
- LHCb will be the first dedicated B physics experiment at a Hadron Collider. ATLAS & CMS also have B physics capability. There may be a Super B factory, possibly at KEK or at Frascati