Heavy Flavors

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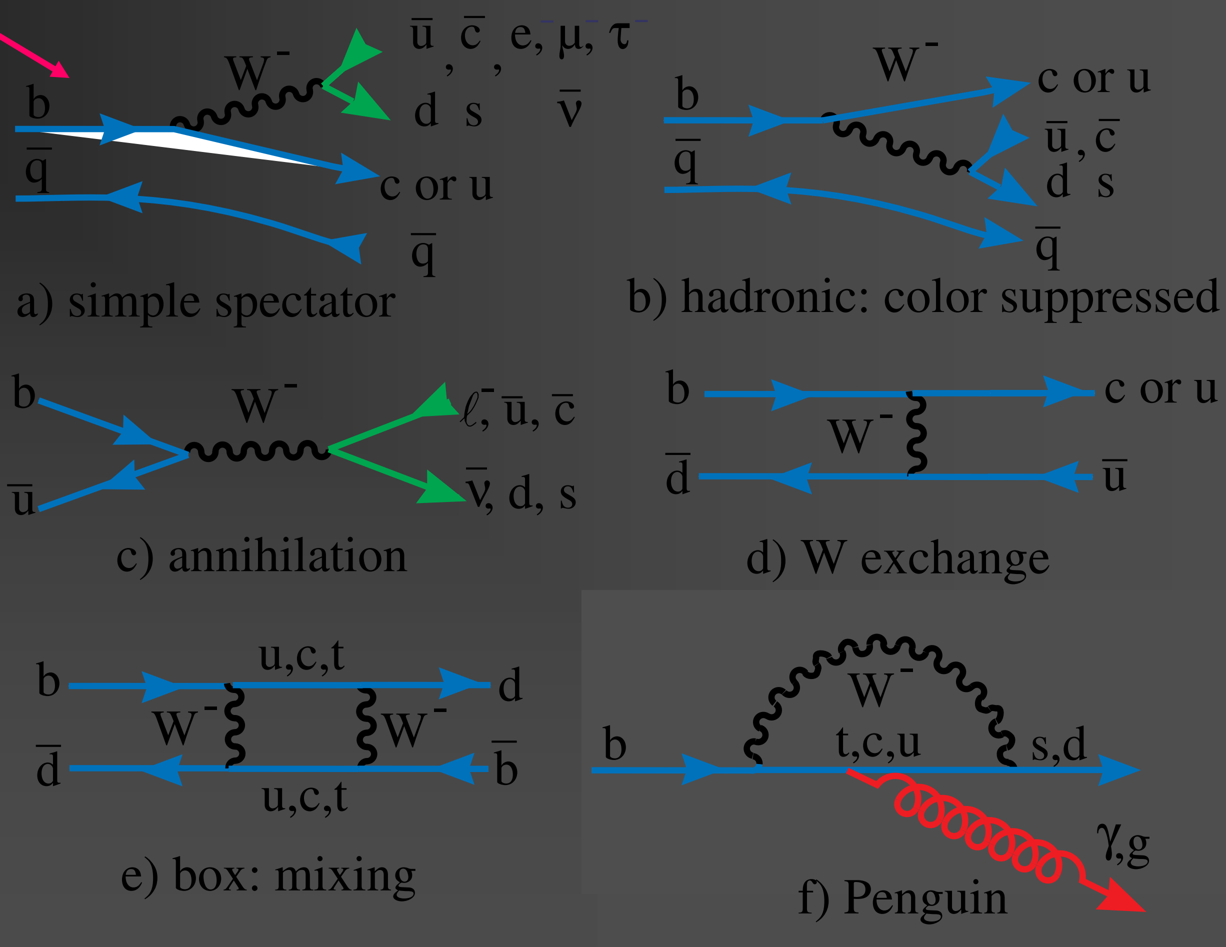
Introduction

- "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

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

  - The gauge bosons: $W^{\pm}$, γ & Z^o and the Higgs H^o
  - Lagrangian for charged current weak decays

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

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

The CKM Matrix

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

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

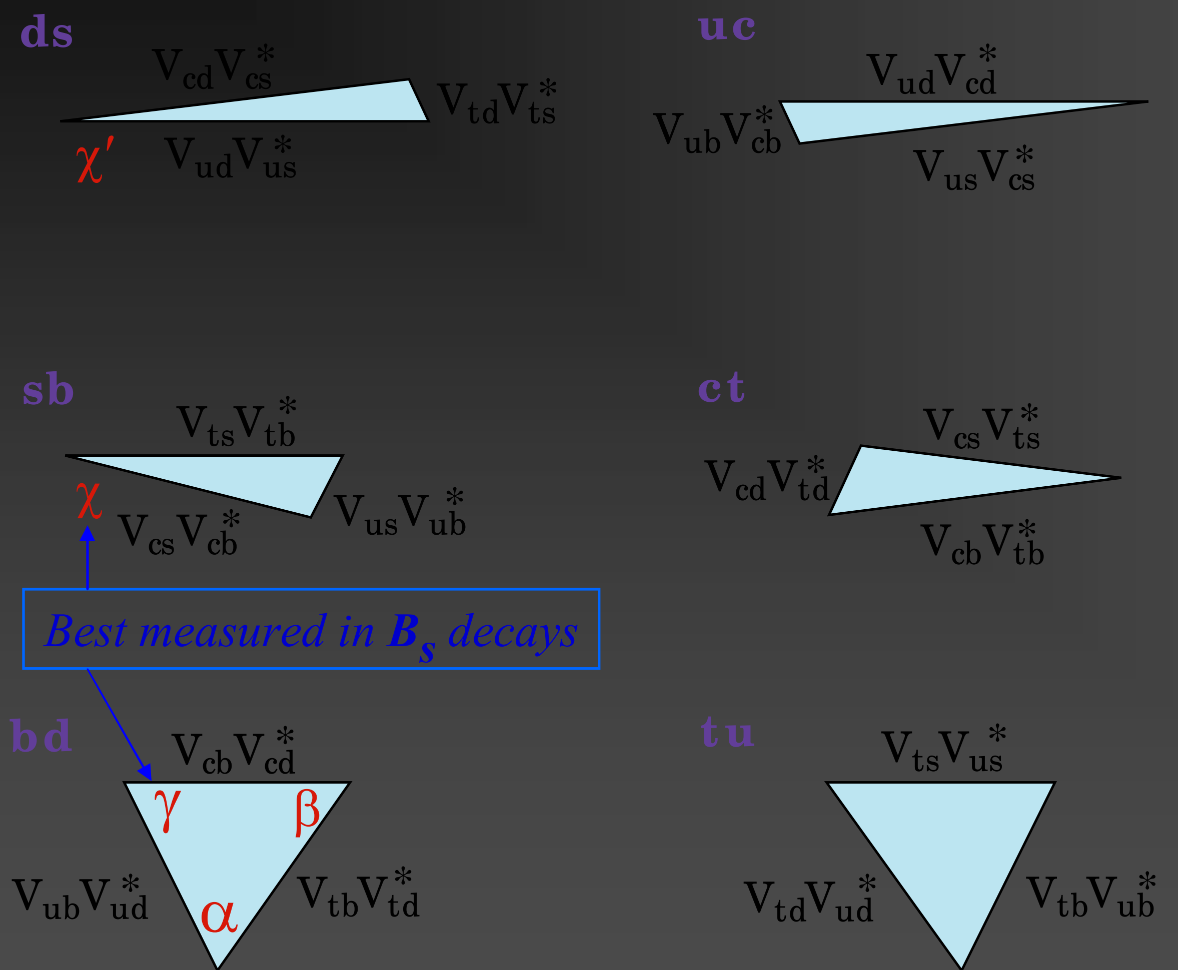
The Basics: Quark Mixing & the CKM Matrix

$$
\begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \longrightarrow \text{mass} \\
\begin{array}{c} u \\ c \\ t \end{array} & V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \end{array}
$$

↓ mass

- A, λ, ρ and η are in the Standard Model fundamental constants of nature like G, or α_{EM}
- η multiplies i and is responsible for CP violation
- We know λ=0.22 (V_{us}), A~0.8; constraints on ρ & η

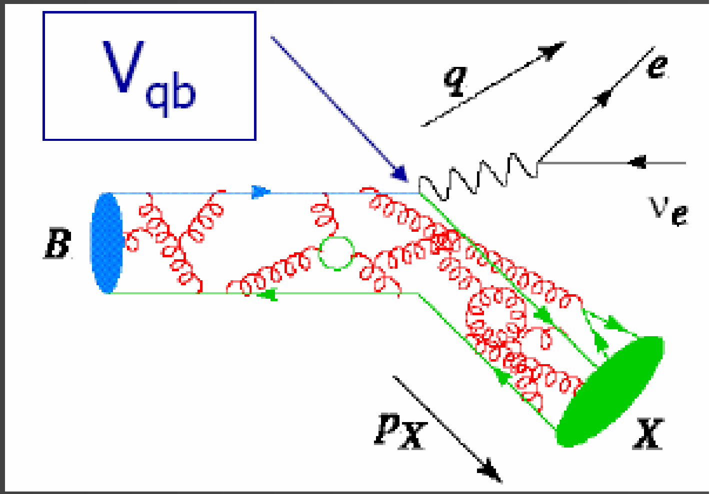
The 6 CKM Triangles



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

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

$|V_{cb}|$



- 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~10%or exclusive $B \rightarrow D^* \ell^- \nu$ with B~6%
- $|V_{cb}|=(41.96 \pm 0.23 \pm 0.35 \pm 0.59) \times 10^{-3}$ inclusive
- $|V_{cb}|=\left(39.4 \pm 0.9^{+1.6}_{-1.2}\right) \times 10^{-3}$ exclusive

(see Kowalewski ICHEP 2006)

Very well based theoretically (HQET)

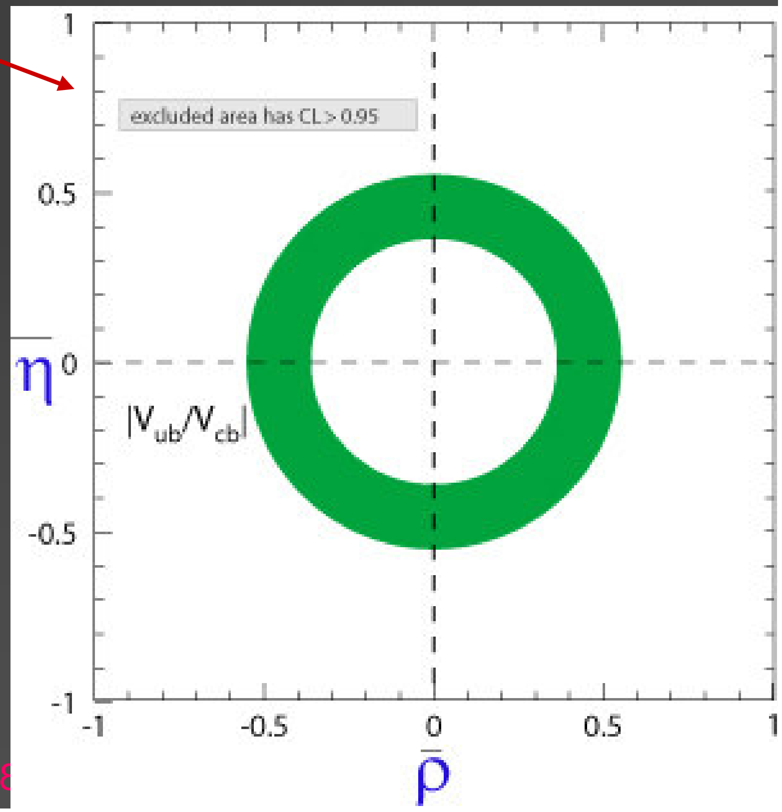
- Note difference is 2.6×10^{-3}, much larger than quoted theoretical errors!

$|V_{ub}|$

- This is much more difficult because the b→u rate is so much smaller than b→c
- Inclusive decays are studied with severe cuts to reduce b→u background
- $|V_{ub}|=(4.49\pm0.19\pm0.27)\times10^{-3}$
- For exclusive decays use $B\rightarrow\pi\ell^{-}\nu$ (in principle also $\rho\,\ell^{-}\nu$)
-

FF calc	Vub [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	$3.54 \pm 0.23\ ^{+1.36}_{-0.63}$

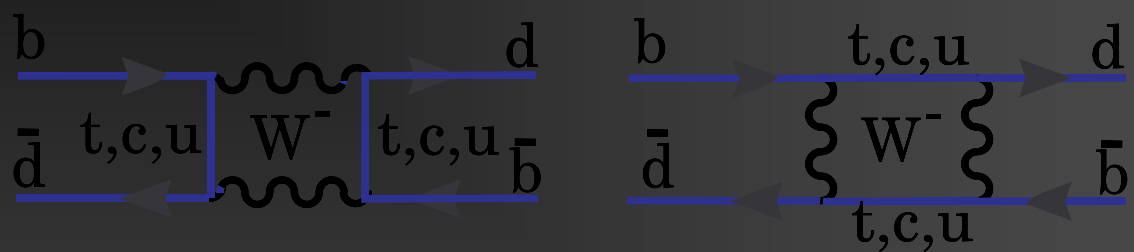
Again difference between inclusive & exclusive



Measurements of B^o & B_S mixing

B^o-$\bar{B}^o$ Mixing

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

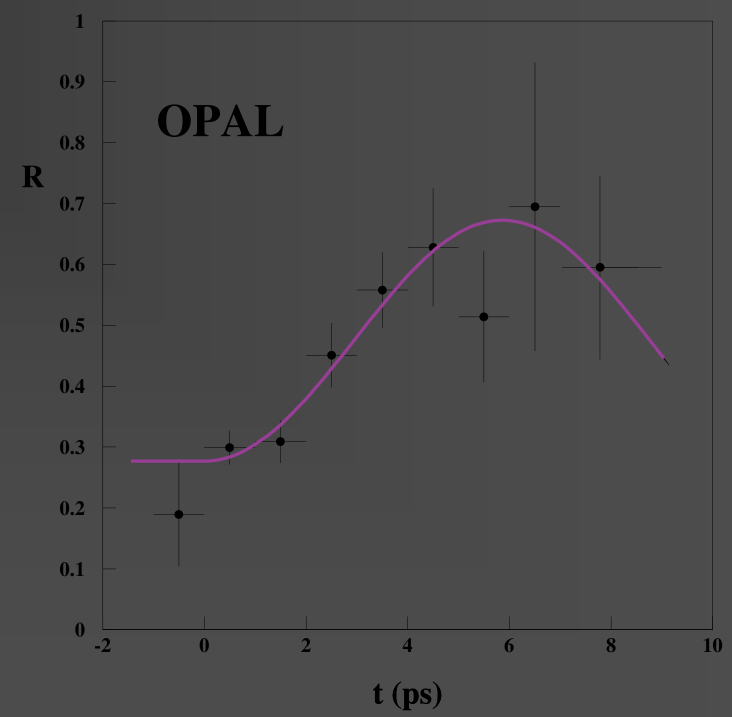


- The eigenstates of flavor, degenerate in pure QCD mix under the weak interactions. Let QM basis be $\{|1\rangle,|2\rangle\} \equiv \{|B^o\rangle,|\bar{B}^o\rangle\}$, then

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

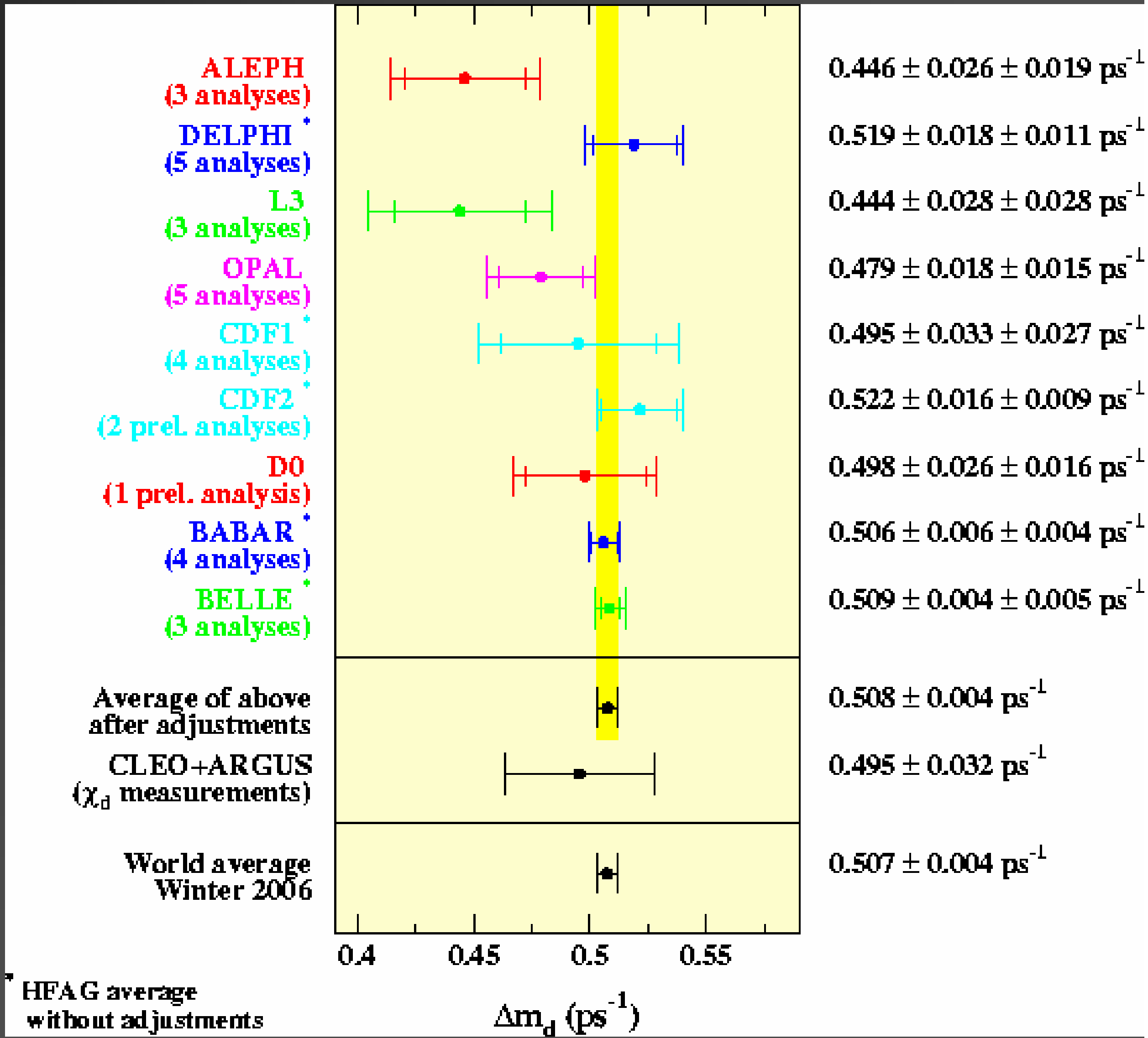
Mixing Measurements

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



Δm_d Measurements

- Δm_d average
  $0.507 \pm 0.004\ ps^{-1}$
- Accuracy better than 1%



B_d Mixing in the Standard Model

- Relation between B mixing & CKM elements:

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

- F is a known function, η_{QCD}~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

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

- 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 (ρ,η) plane centered at (1,0)
- To relate constraints on CKM matrix in terms of say ρ & η need to use theoretical estimates of $\xi = f_{B_s}^2 B_{B_s} / f_{B_d}^2 B_{B_d}$

CDF Measurement of Δm_s

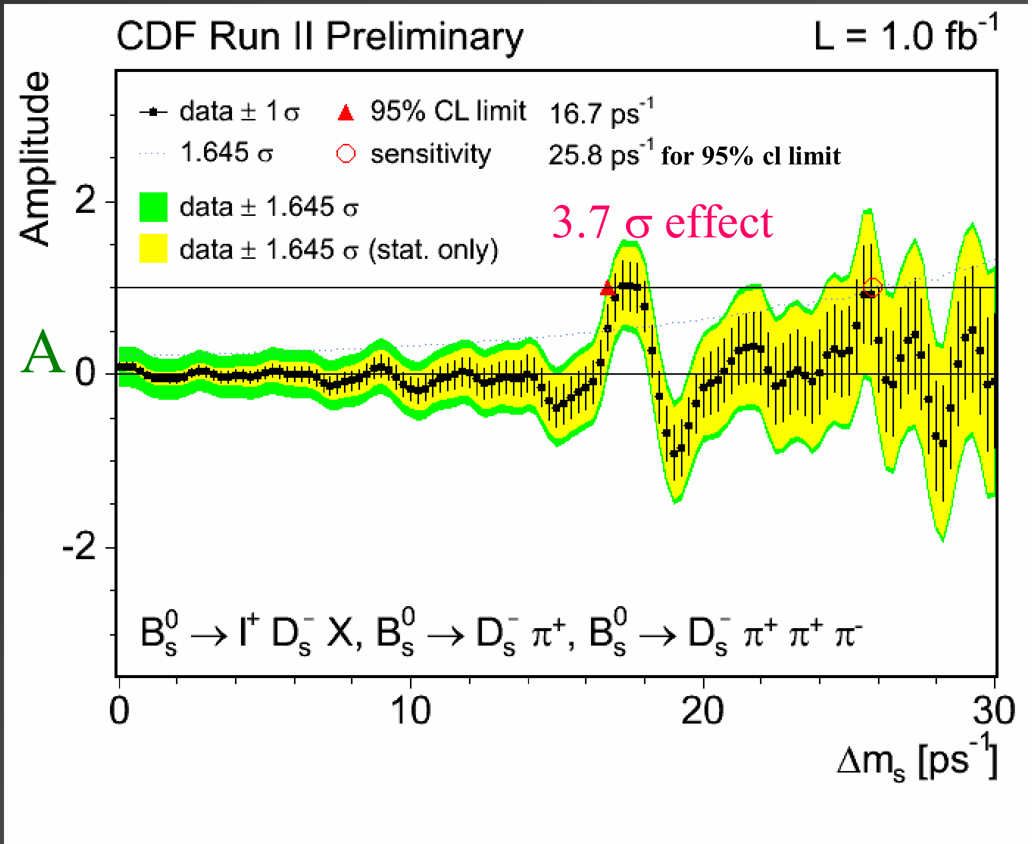
- $P(B_S \to \bar{B}_S) = 0.5 x$

  $\Gamma_S e^{-\Gamma_S t}[1+\cos(\Delta m_S t)]$
- It is useful to analyze the data as a function of a test frequency ω
- $g(t) = 0.5\, \Gamma_S$

  $e^{-\Gamma_S t}[1+A\cos(\omega t)]$
- CDF:

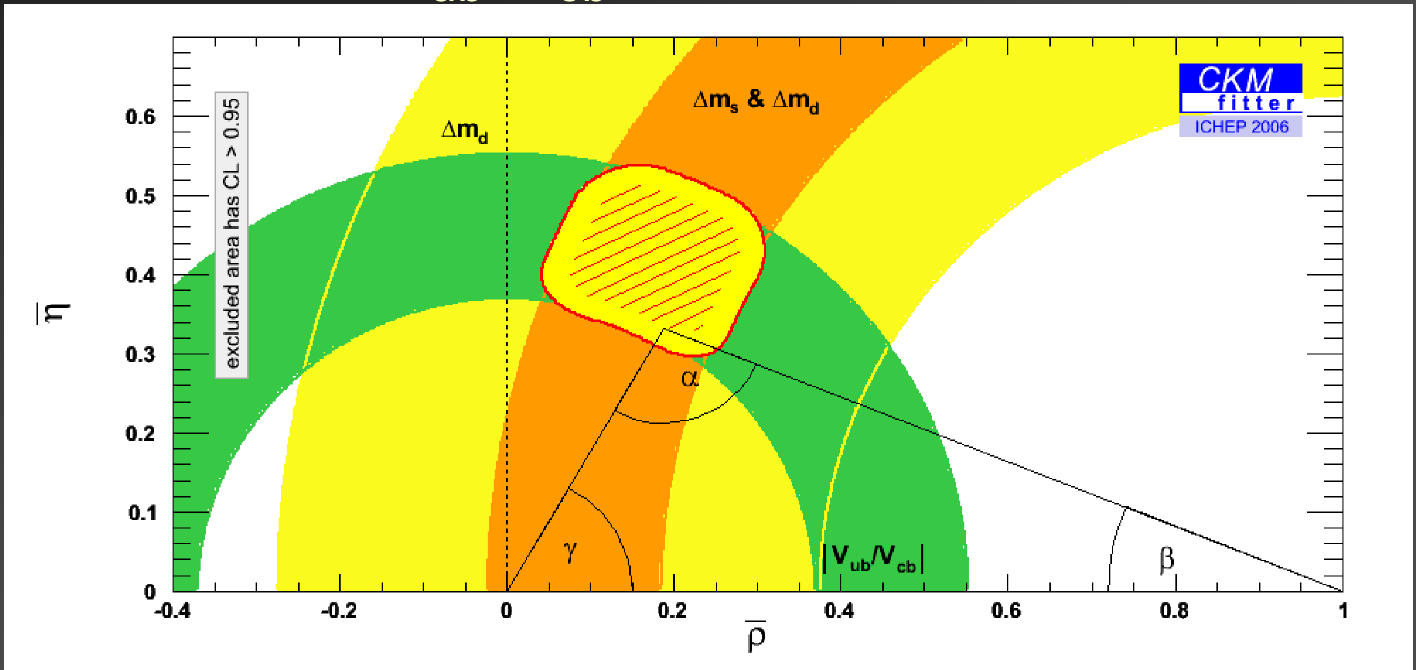
  $\Delta m_S = 17.22^{+0.33}_{-0.18} \pm 0.07\ ps^{-1}$
- D0 90% cl bounds

  $21 > \Delta m_S > 17\ ps^{-1}$



Constraint on ρ – η 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



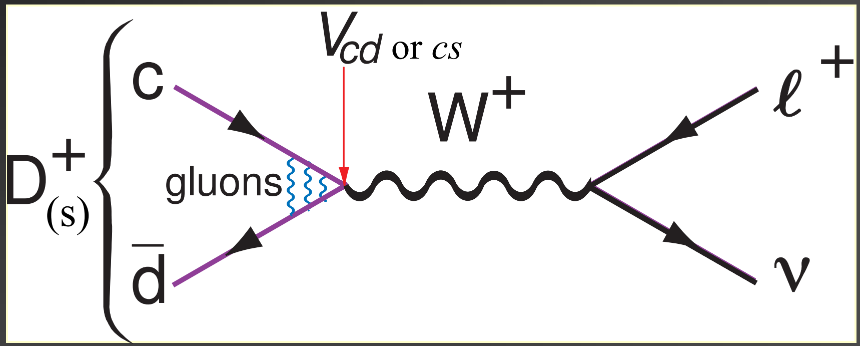
See http://ckmfitter.in2p3.fr/

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

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

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

Diagram:



In general for all pseudoscalars:

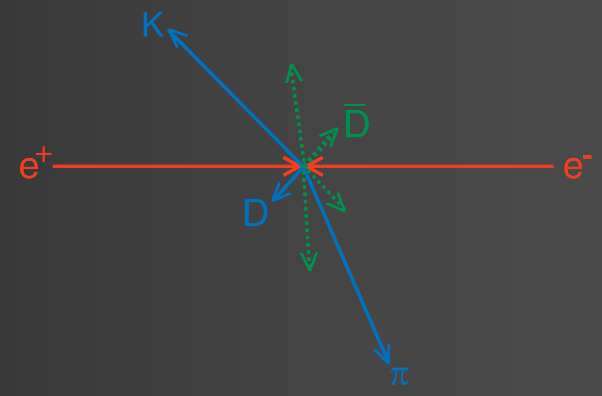
$$\Gamma(P^+ \to \ell^+ \nu) = \frac{1}{8\pi} G_F^2 f_P^2 m_\ell^2 M_P \left(1 - \frac{m_\ell^2}{M_P^2}\right)^2 |V_{Qq}|^2$$

Calculate, or measure if V_{Qq} is known

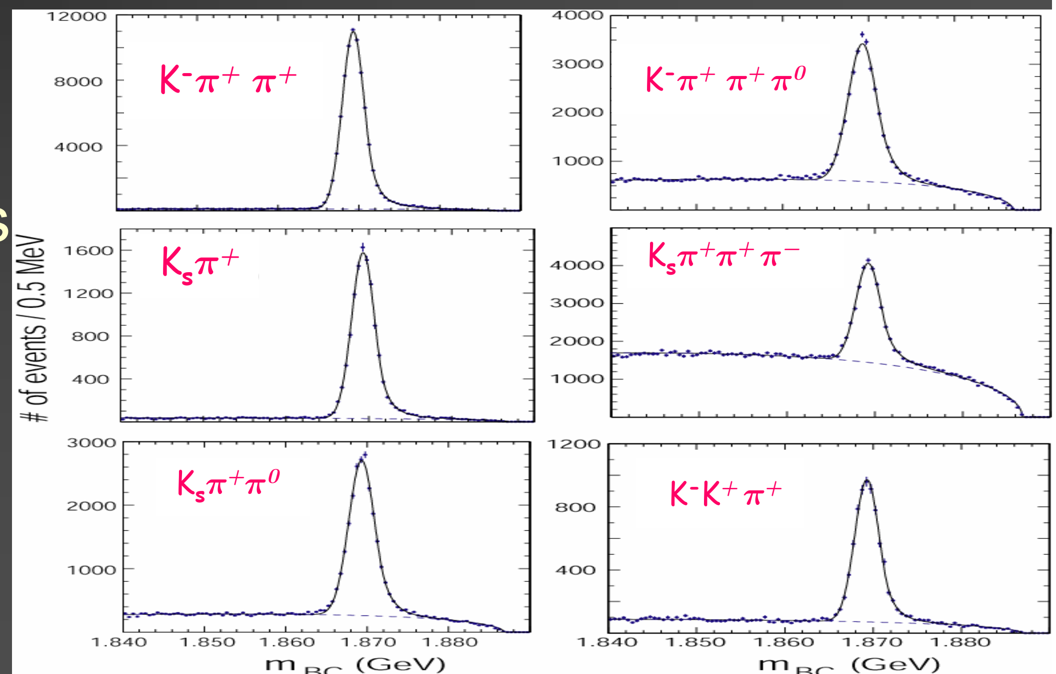
Measuring Charm at Threshold

- $D\bar{D}$ 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"
  - $\mathcal{B}$A = # of A/# of D's
- Beam Constrained Mass

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



CLEO-c



Measurement of f_{D^+}

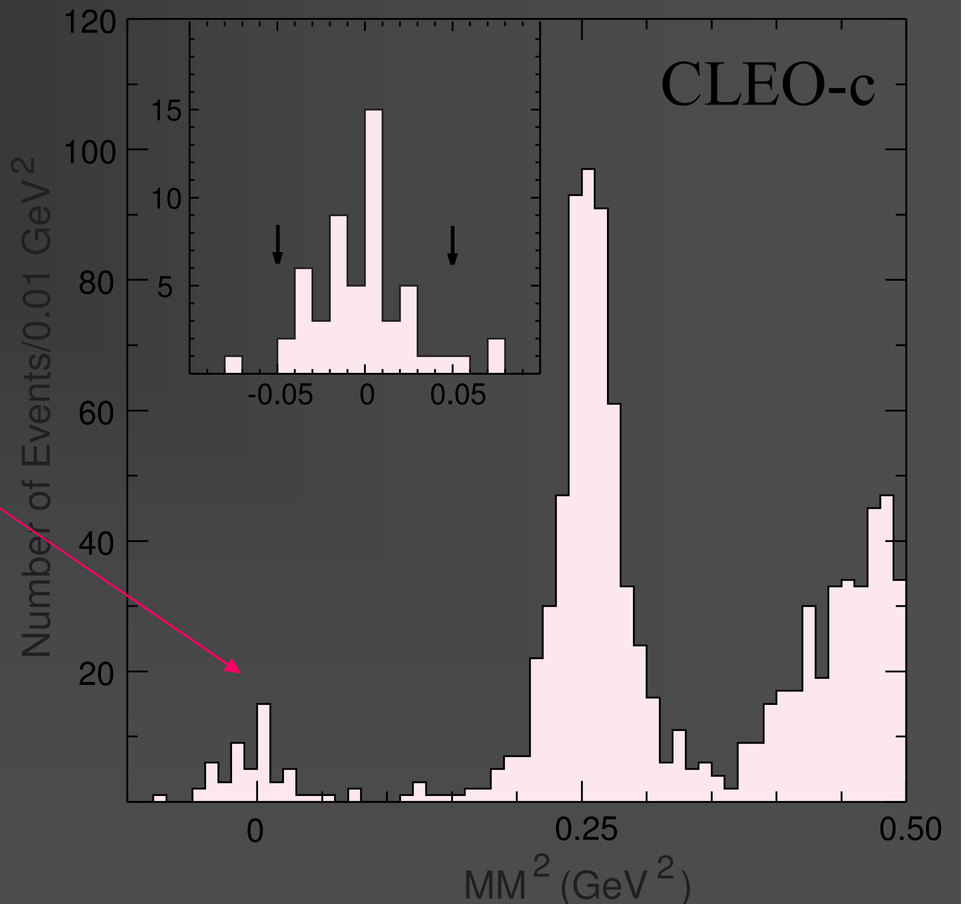
- To find signal, look for events consistent with one μ^+ track opposite a D^- tag with a missing ν
- Compute

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

- Find

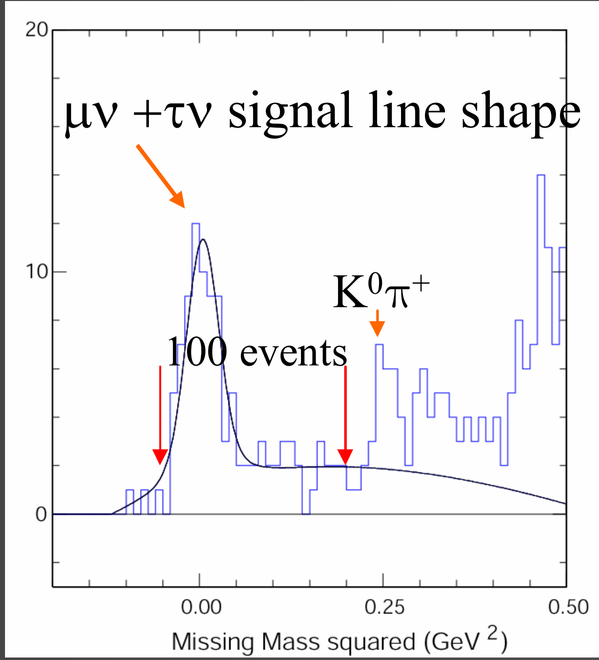
$$f_{D^+} = (222.6 \pm 16.7^{+2.3}_{-3.4})\ \text{MeV}$$

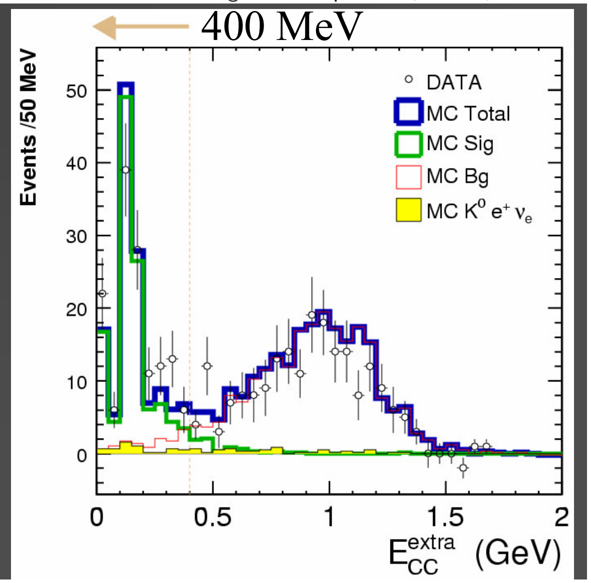
Data have 50 signal events in 281 pb^{-1}



$D_S^+ \to \mu^+\nu + \tau^+\nu,\ \tau \to \pi^+\nu$

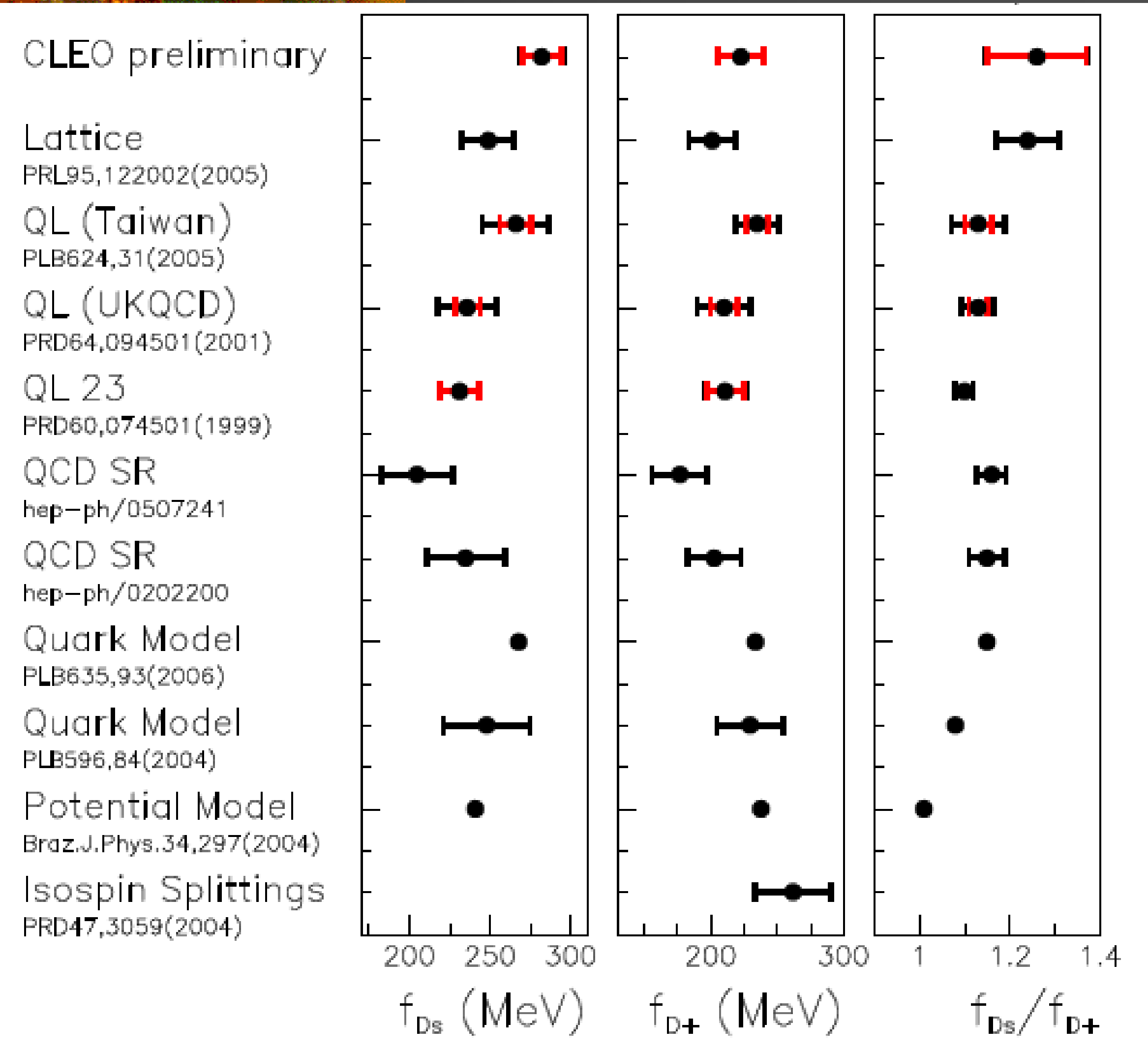
- $D_S^+ \to \mu^+\nu + \tau^+\nu,\ \tau \to \pi^+\nu$ Sum contains 100 $\mu^+\nu + \tau^+\nu$ events for $MM^2 < 0.2\ GeV^2$
- Also, $D_S^+ \to \tau^+\nu,\ \tau \to e^+\nu\nu$
- Weighted Average: $f_{Ds}=280.1\pm11.6\pm6.0$ MeV, the systematic error is mostly uncorrelated between the measurements
- Thus $f_{Ds}/f_{D^+}=1.26\pm0.11\pm0.03$ (CLEO-c)





Comparisons with Theory

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



Measurements of CP Violating Angles

Formalism of CP Violation

- CP Eigenstates:

$$\left|B_1^o\right\rangle=\left(\left|B^o\right\rangle+\left|\bar{B}^o\right\rangle\right)/\sqrt{2},\ CP\left|B_1^o\right\rangle=+\left|B_1^o\right\rangle$$

$$\left|B_2^o\right\rangle=\left(\left|B^o\right\rangle-\left|\bar{B}^o\right\rangle\right)/\sqrt{2},\ CP\left|B_2^o\right\rangle=-\left|B_2^o\right\rangle$$

- Because of mixing mass eigenstates are a superposition of $a|B^o\rangle+b|\bar{B}^o\rangle$ 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^o CP Formalism II

- For CP not being conserved, instead of B_1 & B_2

$$\left|B_1^o\right\rangle = \frac{1}{\sqrt{2}}\left|B^o\right\rangle + \frac{1}{\sqrt{2}}\left|\overline{B}^o\right\rangle$$

$$\left|B_L\right\rangle = p\left|B^o\right\rangle + q\left|\overline{B}^o\right\rangle, \left|B_H\right\rangle = p\left|B^o\right\rangle - q\left|\overline{B}^o\right\rangle$$

- 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

$$\left|B_L(t)\right\rangle = e^{-\Gamma_L t/2} e^{i m_L t/2}\left|B_L(0)\right\rangle, \left|B_H(t)\right\rangle = e^{-\Gamma_H t/2} e^{i m_H t/2}\left|B_H(0)\right\rangle$$

B^o CP Formalism III

- This leads to the time evolution of flavor amplitudes as

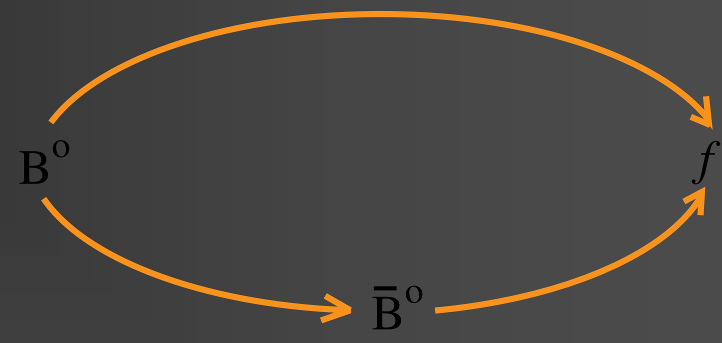
$$\left|B^o(t)\right\rangle = e^{-(i\Delta m+\Gamma/2)t}\left(\cos\frac{\Delta mt}{2}\left|B^o(0)\right\rangle + i\frac{q}{p}\sin\frac{\Delta mt}{2}\left|\bar{B}^o(0)\right\rangle\right)$$

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

- $\Delta m = m_H - m_L$, $\Gamma \approx \Gamma_L \approx \Gamma_H$ *(true for B_d, not necessarily for B_s)*
- Probability of a B^o decay is given by $\langle B^o(t)|B^o(t)^*\rangle$ & 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=<f|H|B°>
  - Ā=<f|H|B̄°>
  - |A/A|≠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

$$a_f(t) = \frac{\Gamma\left(B^o(t) \to f\right) - \Gamma\left(\bar{B}^o(t) \to f\right)}{\Gamma\left(B^o(t) \to f\right) + \Gamma\left(\bar{B}^o(t) \to f\right)}$$

- for |q/p| = 1

$$a_f(t) = \frac{\left(1-|\lambda|^2\right)\cos(\Delta m t) - 2\,\mathrm{Im}\,\lambda\sin(\Delta m t)}{1+|\lambda|^2}$$

- When there is only one decay amplitude, λ=1 then $a_f(t) = -\mathrm{Im}\,\lambda\sin(\Delta m t)$
- Time integrated

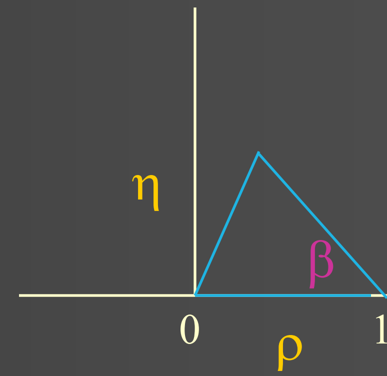
$$a_f(t) = -\frac{x}{1+x^2}\mathrm{Im}\,\lambda = -0.48\,\mathrm{Im}\,\lambda$$

good luck, maximum is –0.5

CPV using CP eigenstates III

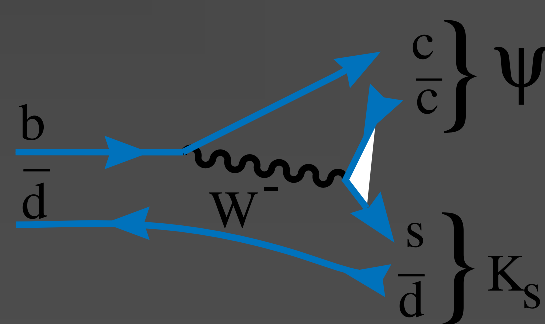
- For B_d, $$\frac{q}{p}=\frac{\left(V_{tb}^{*}V_{td}\right)^{2}}{\left|V_{tb}^{*}V_{td}\right|^{2}}=\frac{\left(1\text{-}\rho\text{-}i\eta\right)^{2}}{\left(1\text{-}\rho+i\eta\right)\left(1\text{-}\rho\text{-}i\eta\right)}=e^{-2i\beta}$$

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



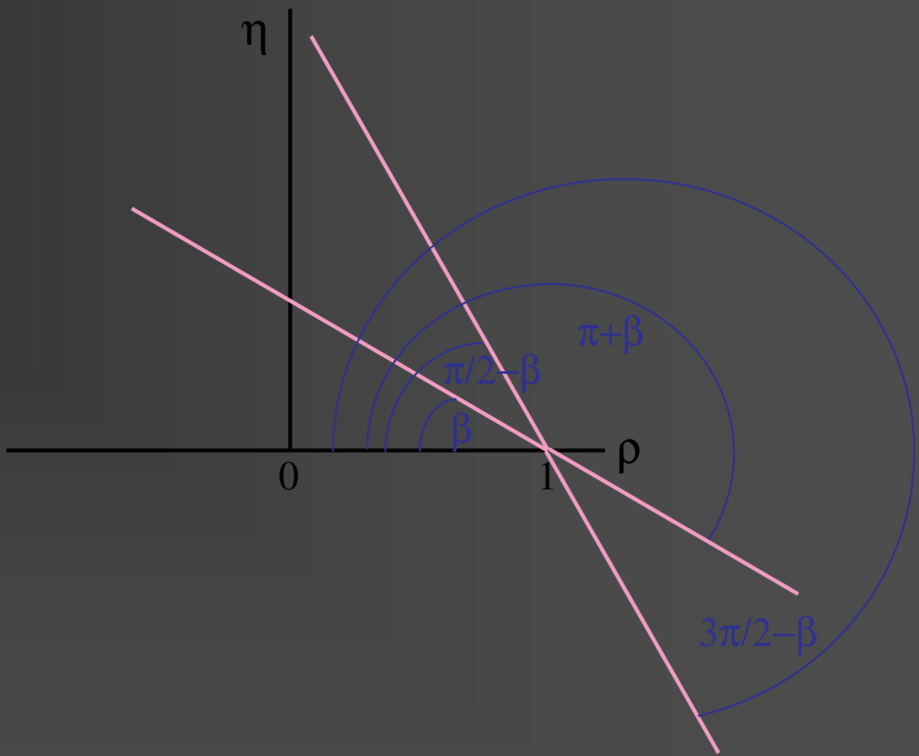
- Now need to add $\bar{A}/A$
  - for $J/\psi\ K_s$:

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



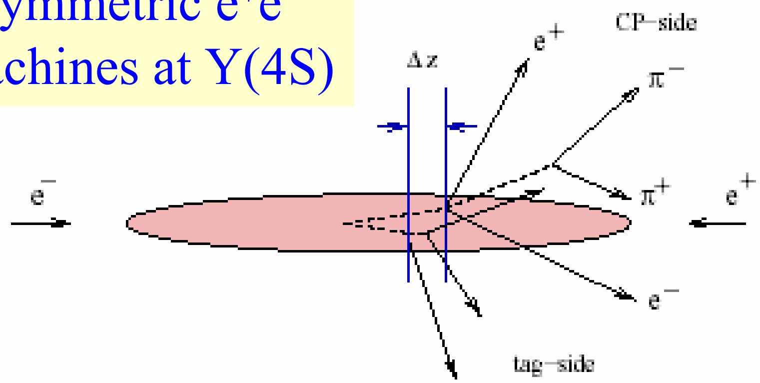
Ambiguities

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



B Kinematics at the Υ(4S) (Babar & Belle)

Asymmetric e^+e^- machines at Υ(4S)



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

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

$\Delta t \simeq (z_{cp} - z_{\rm tag})/(\gamma\beta c)$
B flight-length in x-y: only $\sim 30\mu$

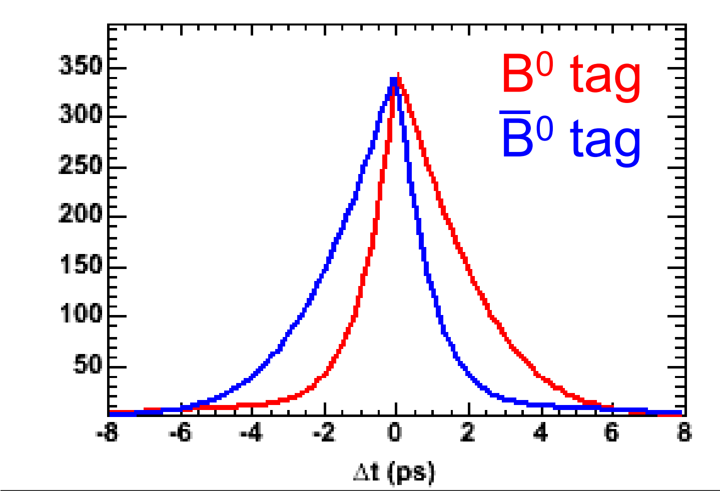
$(z_{cp} - z_{\rm tag}) \ll e^+e^-$ interaction region

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

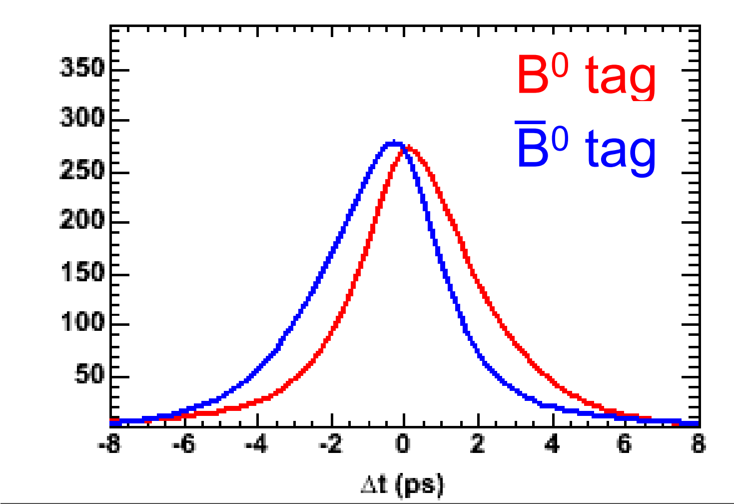
Parameters	BaBar	Belle
e^+e^- energy	$3.1 \times 9\,\mathrm{GeV}$	$3.5 \times 8.5\,\mathrm{GeV}$
$\gamma\beta$	0.56	0.425
Interaction region ($h \times v \times l$)	$120\,\mu\mathrm{m} \times 5\,\mu\mathrm{m} \times 8.5\,\mathrm{mm}$	$80\,\mu\mathrm{m} \times 2\,\mu\mathrm{m} \times 3.4\,\mathrm{mm}$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

From Abe

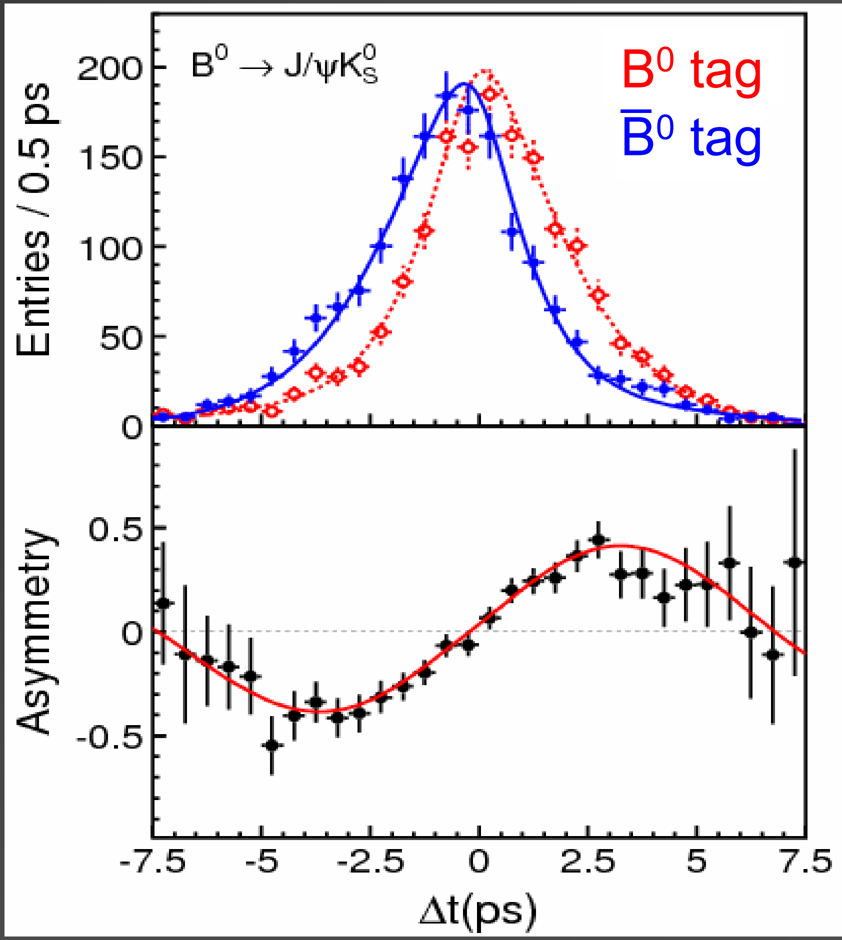
Fit to Δt Distributions



τ resolution, wrong tags

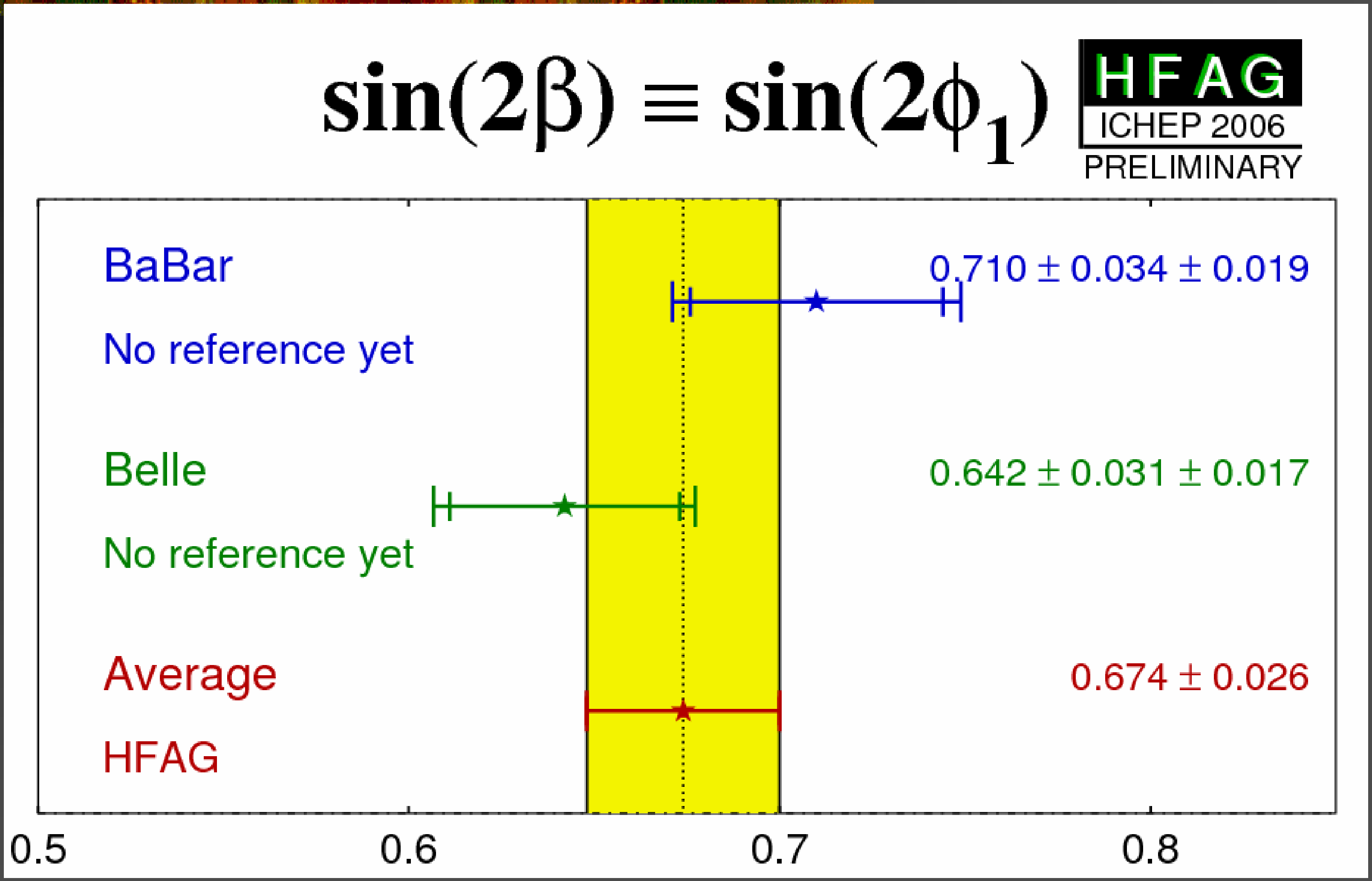


$B^0 \to J/\psi K_S^0$



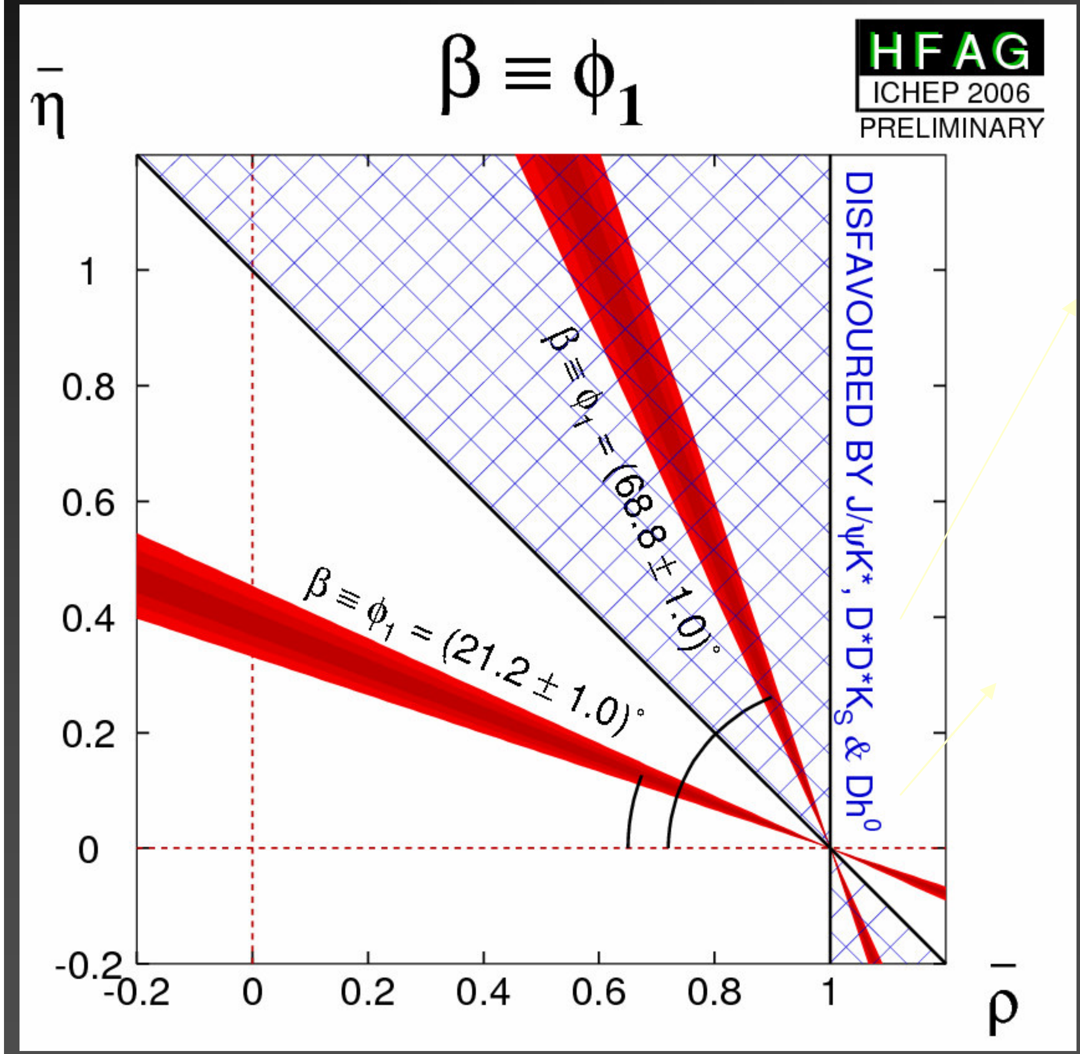
Asym. = $-\xi_{CP}\sin 2\beta \sin \Delta m \Delta t$

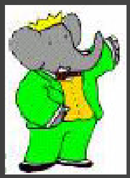
2006: BaBar + Belle



From Hazumi ICHEP 2006

β (not sin2β) measurements

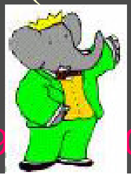




Preliminary

$B^0 \to D^{*+}D^{*-}Ks$
Time-dependent Dalitz analysis
(T.Browder, A. Datta et al. 2000)
→ $\cos 2\beta > 0$
(94%CL, model-dependent)

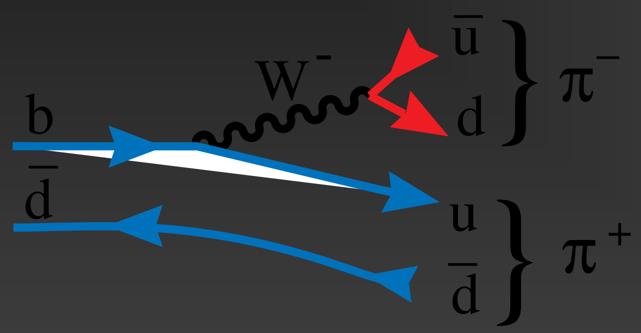
$B^0 \to Dh^0$ ($h^0 = \pi^0$ etc.)
Time-dependent Dalitz analysis
→ $\cos 2\beta > 0$
Belle: 98.3%CL
(hep-ex/0605023, accepted by PRL)
BaBar 87% CL
(BABAR-CONF06/017)

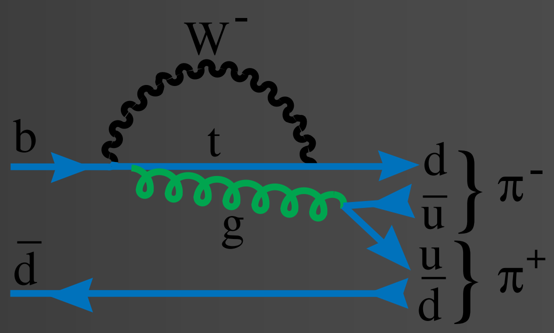


CPV in Charmless B Decays

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

Tree *Penguin*

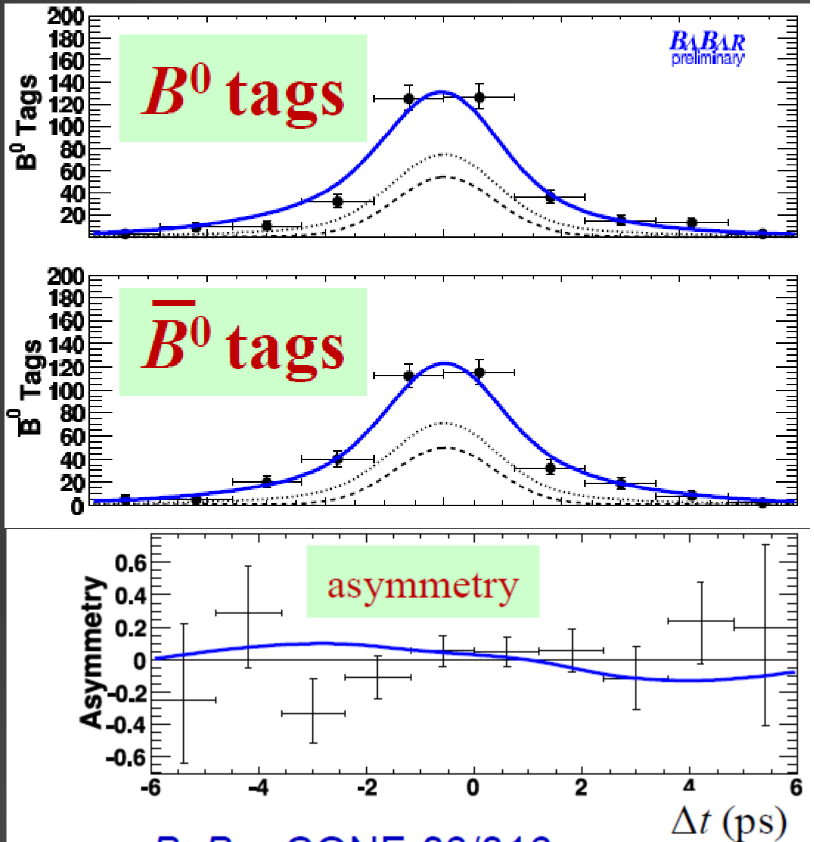




- The weak phase in the tree graph is γ. The weak phase in the Penguin is different. Therefore, the Penguin can (and does) mess up CP via mixing in $\pi^+\pi^-$
- Penguin is unmasked by evidence of $\pi^o\pi^o$

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
  - $f_L = 0.978 + 0.024^{+0.015}_{-0.013}$ (BaBar)
- However, Penguin pollution revealed at 3σ level (BaBar):
- $\mathcal{B}(\rho^o\rho^o) = (1.2 \pm 0.4 \pm 0.3) \times 10^{-6}$
- $\mathcal{B}(\rho^+\rho^-) = (23.5 \pm 2.2 \pm 4.1) \times 10^{-6}$



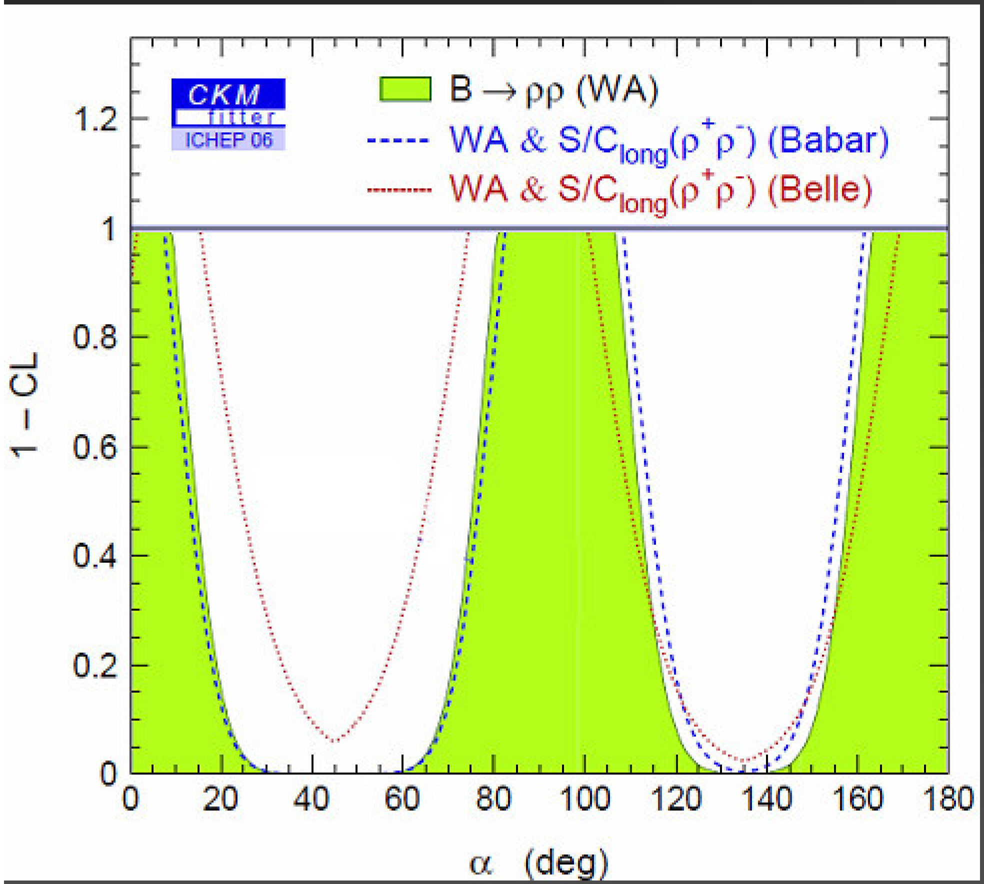
BaBar-CONF-06/016

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

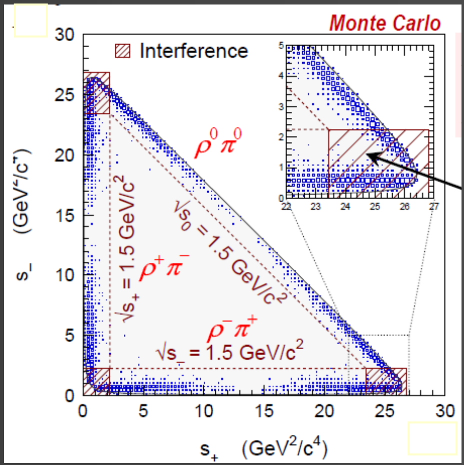
$$C_{\text{long}} = -0.07 \pm 0.15 \pm 0.06$$

CPV in $B \to \rho^+\rho^-$ II

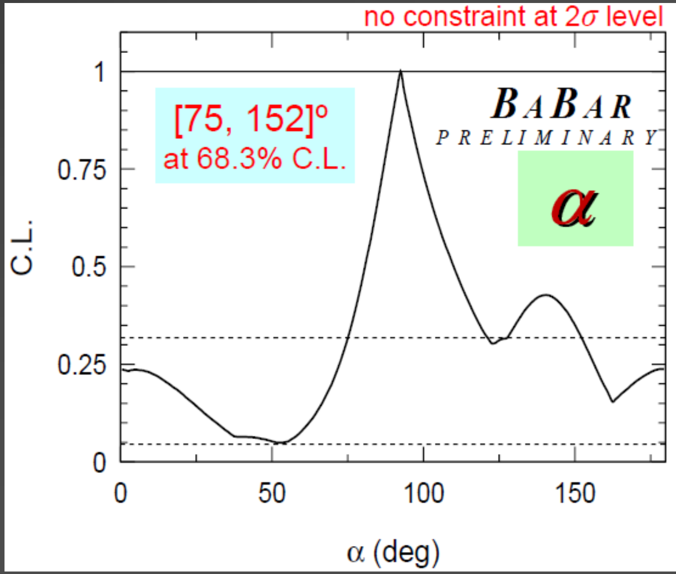
- Constraints on α



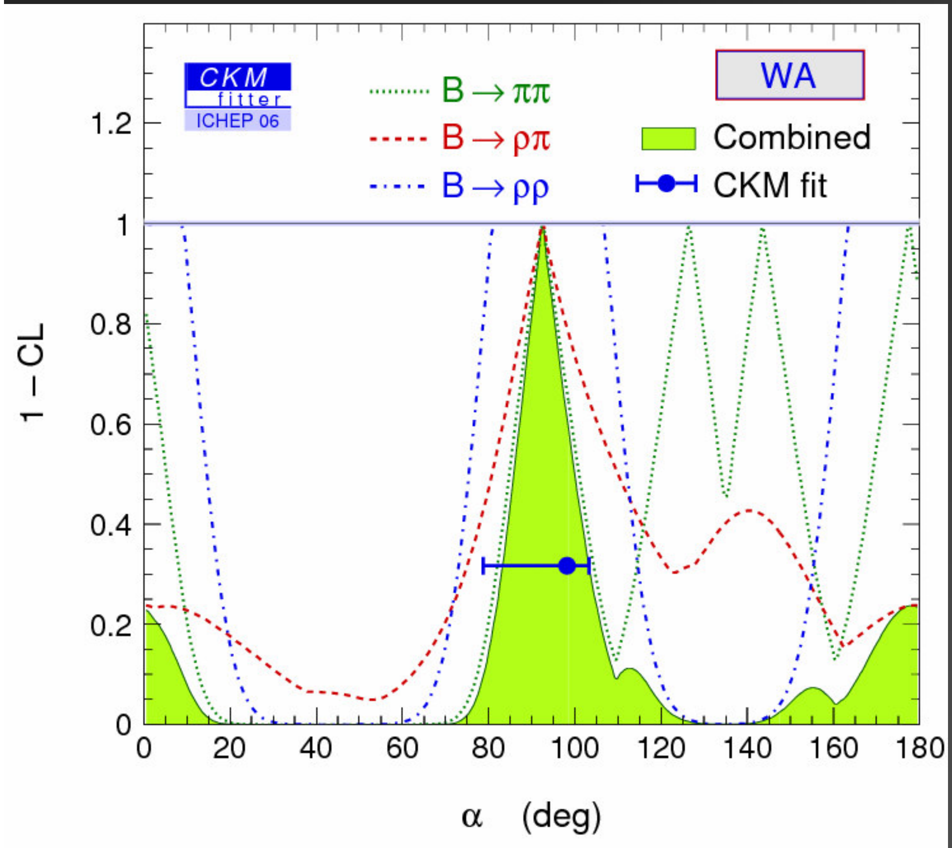
- Add $B \to \rho\pi \to \pi^+\pi^-\pi^o$

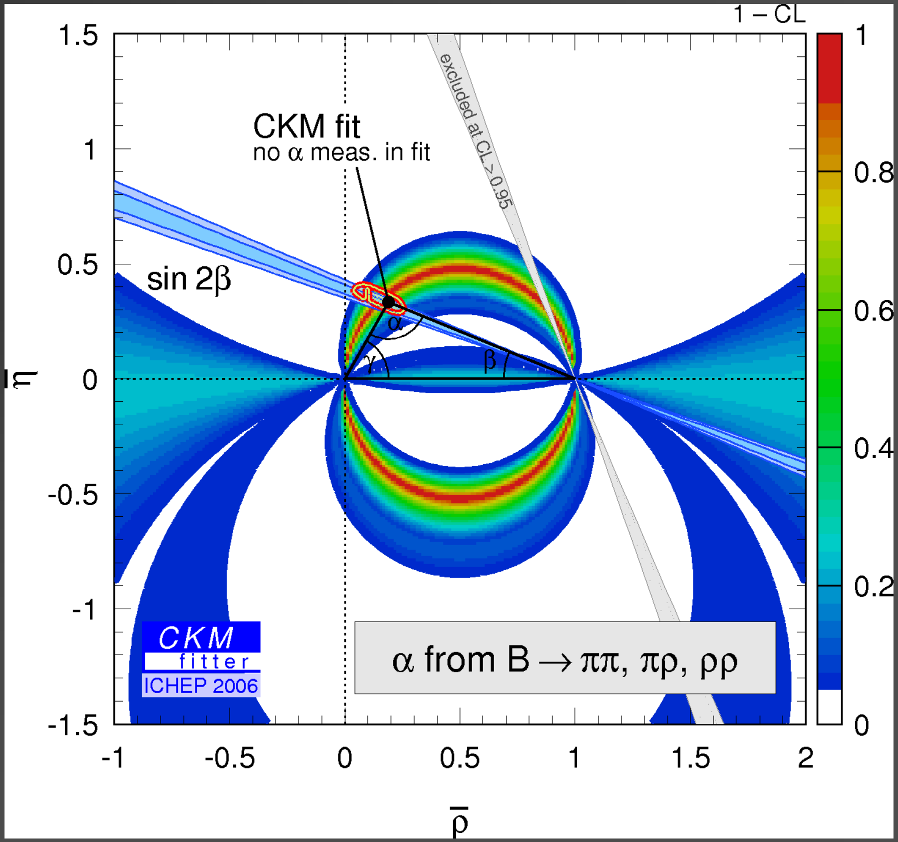


Dalitz plot analyses suggested by Snyder & Quinn



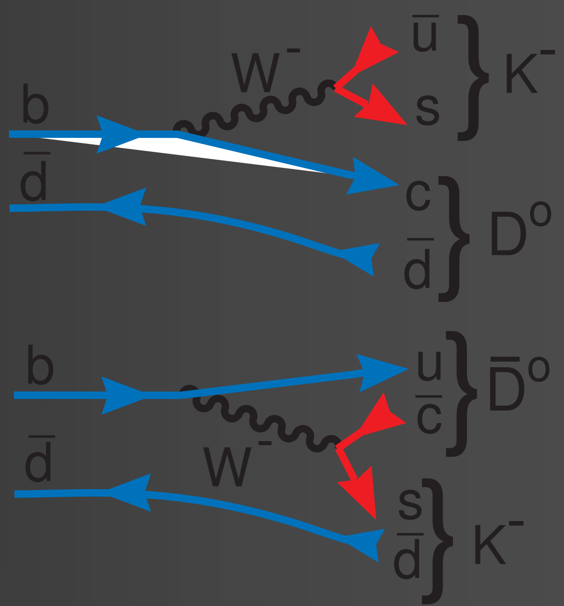
Results on α


CKM fitter
ICHEP 06
B → ππ
B → ρπ
B → ρρ
WA
Combined
CKM fit
1 – CL
α (deg)


1 – CL
CKM fit
no α meas. in fit
excluded at CL > 0.95
sin 2β
CKM fitter
ICHEP 2006
α from B → ππ, πρ, ρρ

γ: $B^{\pm}\rightarrow D^{o}K^{\pm}$ decays, $D^{o}\rightarrow K_{s}\pi^{+}\pi^{-}$

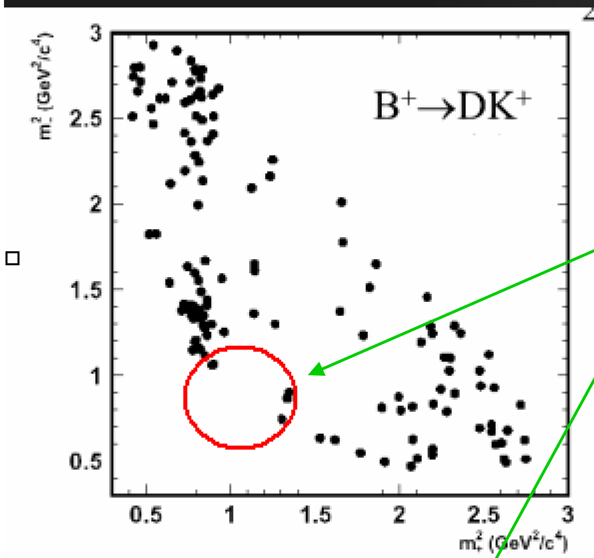
- Can have CPV in B decays
  Just need two interfering amplitudes



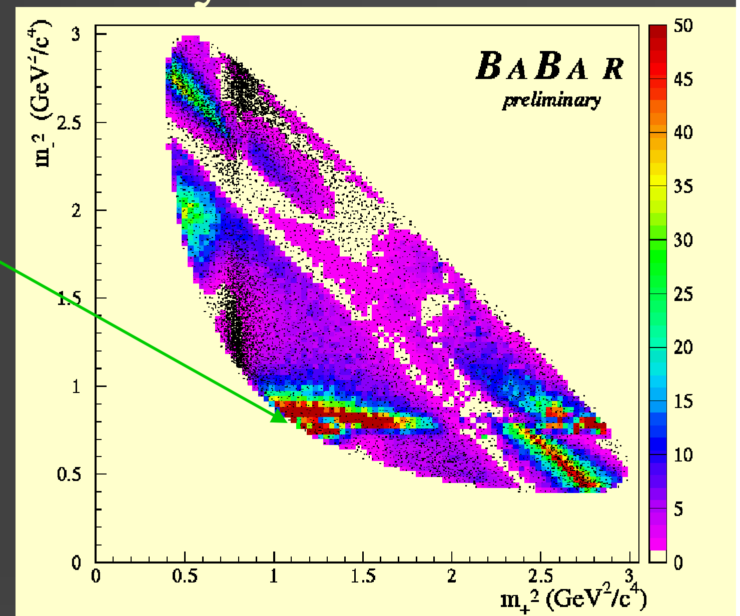
- For the B^{-} decay:
  $A(B^{-}\rightarrow D^{o}K^{-}) \equiv A_{B}$
  $A(B^{-}\rightarrow \bar{D}^{o}K^{-}) \equiv A_{B}r_{B}e^{i(\delta_{B}-\gamma)}$
- Use modes where the D^{o} is indistinguishable from the $\bar{D}^{o}$. Then use Daltiz plot analysis to find γ see A. Giri et al., [hep-ph/0303187]

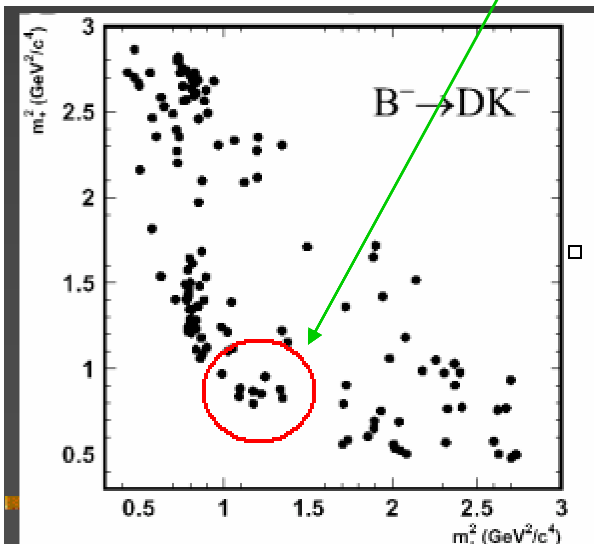
γ from $B \to D^o K^-$, $D^o \to K_s \pi^+ \pi^-$

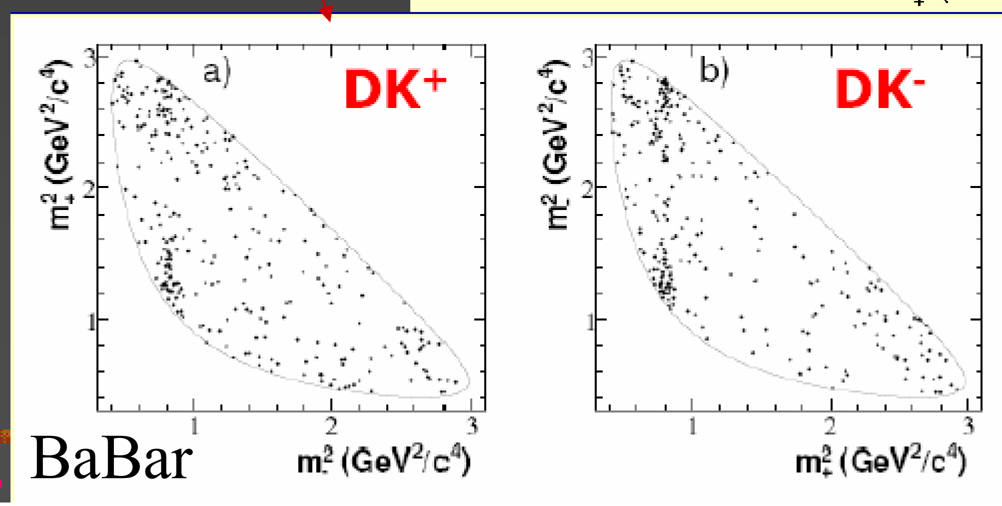
$d^2 \ln L / d^2\gamma$ sensitivity



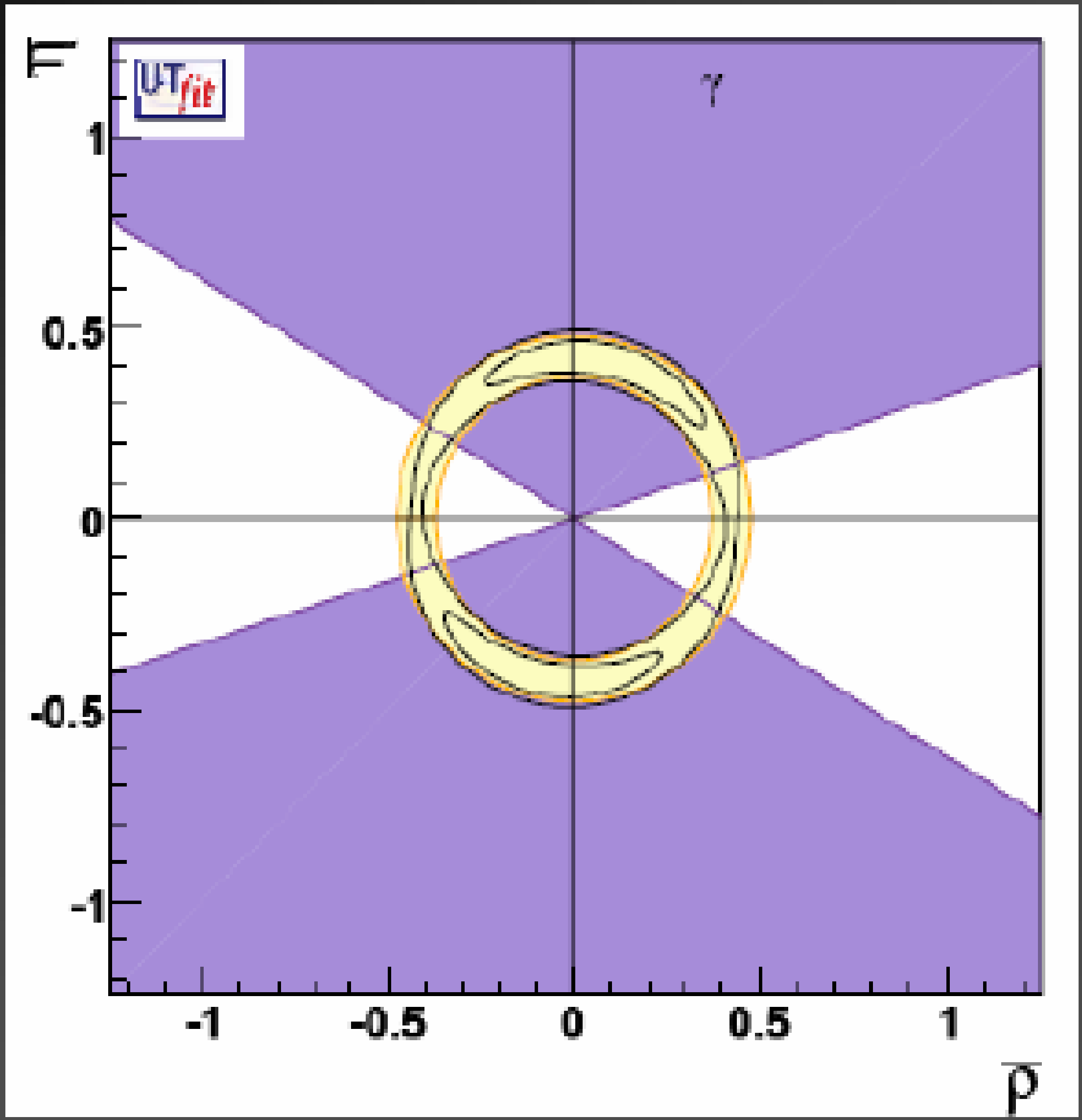
- Belle first saw a clear difference
- Now data show a smaller effect







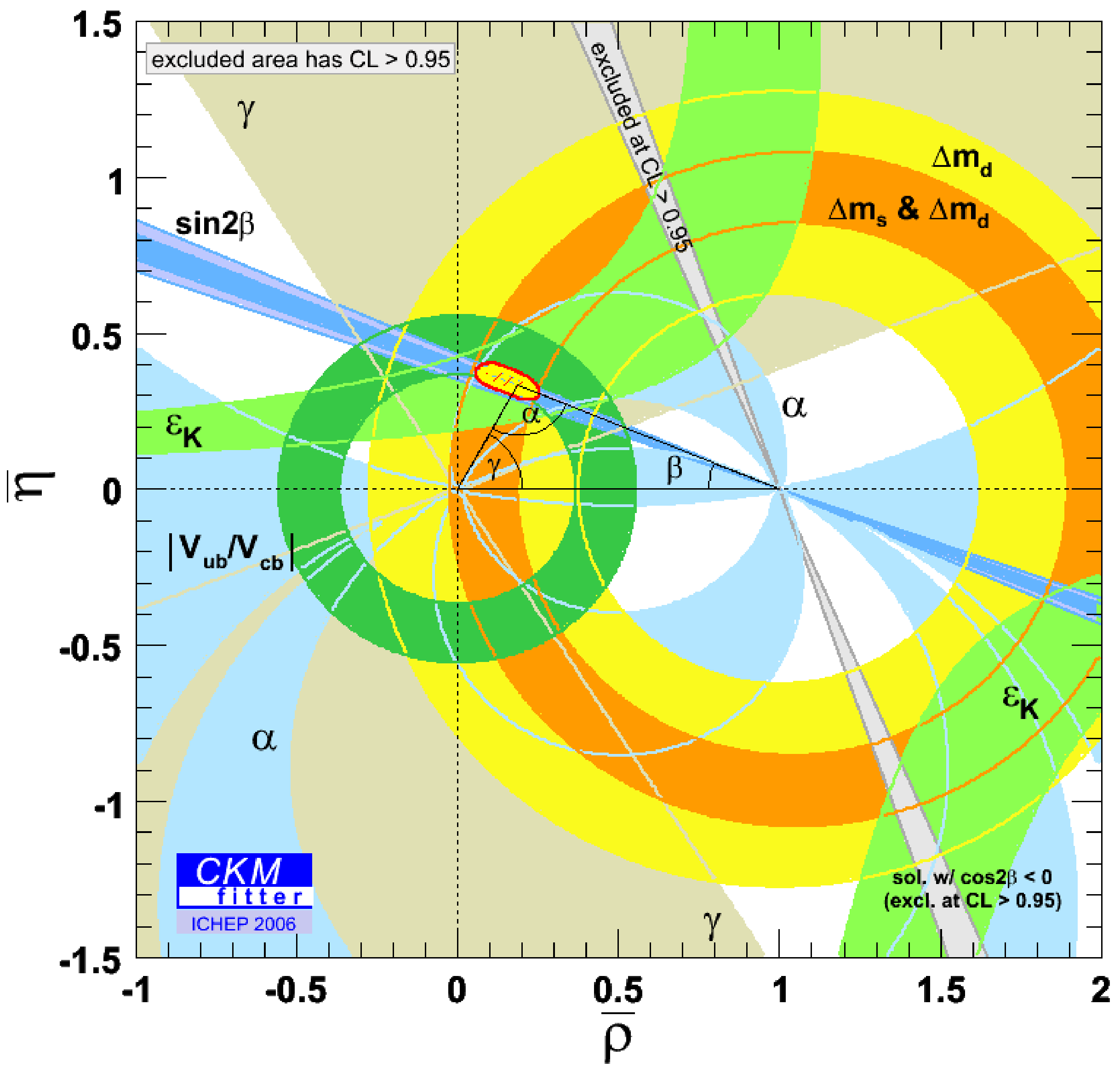
Poor Constraints on γ



See http://www.utfit.org/

Putting It All Together: Status

- Global fit using all available inputs
- ε_K is from CP violation in K^o system



Reasons for Further B Physics Studies

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

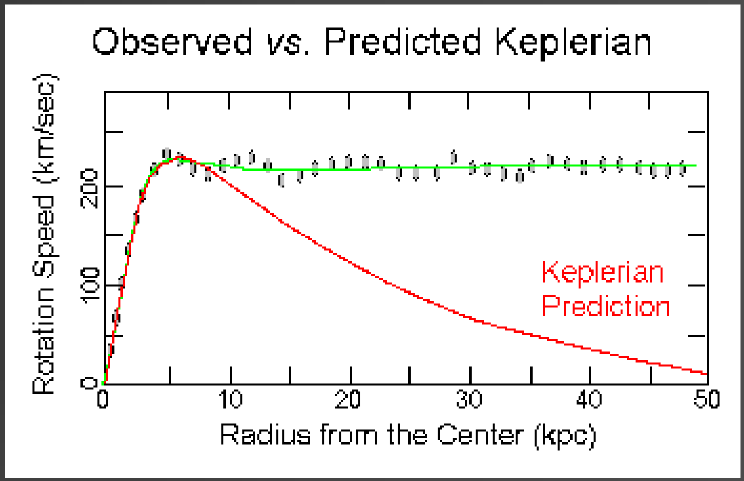
- When the Universe began, the Big Bang, there was an equal amount of matter & antimatter
- Now we have most matter. How did it happen?
- Sakharov criteria
  - Baryon (B) number violation
  - Departure from thermal equilibrium
  - C & CP violation

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

- Physics at the Planck scale ~10^{19} GeV is much larger than at the ~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

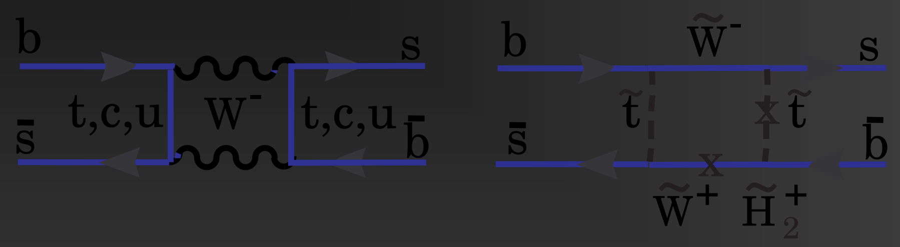
Effects of New Particles on B Decays

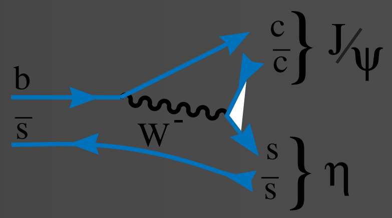
These decays are suppressed, so New Particles can show enhanced effects

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

- Contributions to B_s mixing

$B_s \rightarrow J/\psi\eta$



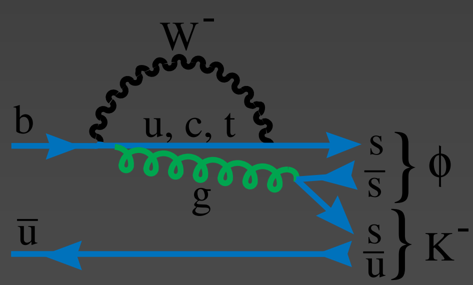


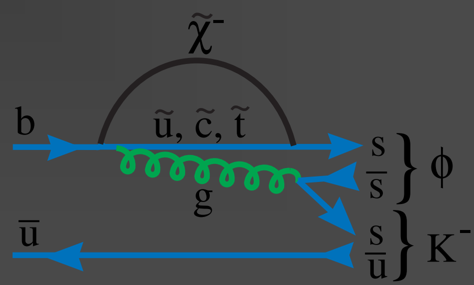
$$\text{CP asymmetry} \approx 0.1\sin\phi_\mu\cos\phi_A\sin(\Delta m_s t), \sim 10 \text{ x SM}$$

- Contributions to direct CP violating decay

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

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



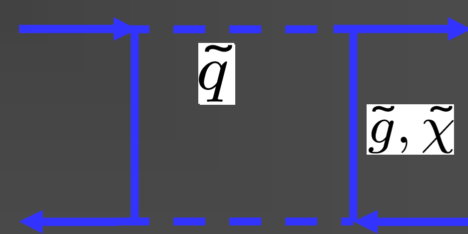


$$\text{Asym} = (M_W/m_{squark})^2\sin(\phi_\mu), \sim 0 \text{ in SM}$$

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.

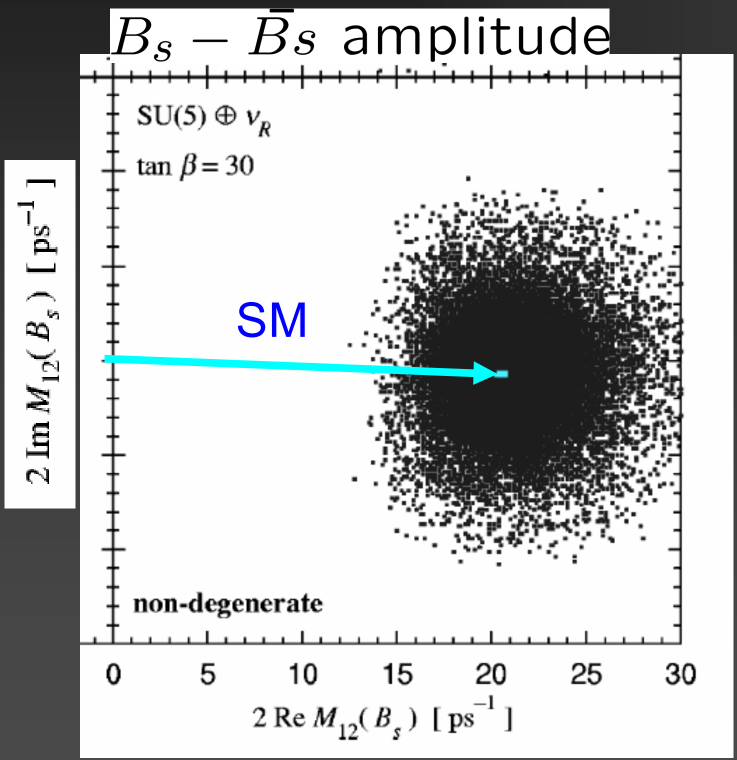
$$(m^2_{\tilde{q}})_{ij} = \begin{pmatrix} m^2_{11} & m^2_{12} & m^2_{13} \\ m^2_{21} & m^2_{22} & m^2_{23} \\ m^2_{31} & m^2_{32} & m^2_{33} \end{pmatrix}$$



Examples

SUSY GUT & B_S Mixing

CP Violation in B_S



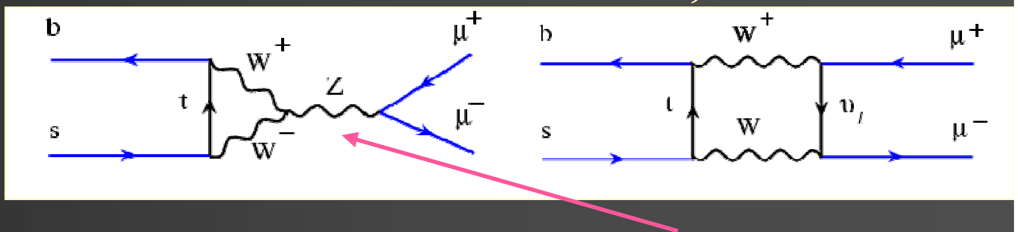
B_S mixing

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

From Okada ICHEP 2006

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

SM $\mathcal{B}$~3.4×10^{-9}, via



SUSY adds A°, H°, h°

$$B(B_S \to \mu^+\mu^-) = 5\times10^{-7}\left(\frac{\tan\beta}{50}\right)^6\left(\frac{300\ \text{GeV}}{M_{A^o}}\right)^4$$

Current CDF limits

	$B^0_s \to \mu^+\mu^-$	$B^0_d \to \mu^+\mu^-$
$\mathcal{B}$ @ 95% cl	$<1.0\times10^{-7}$	$<3.0\times10^{-8}$

SO(10)

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

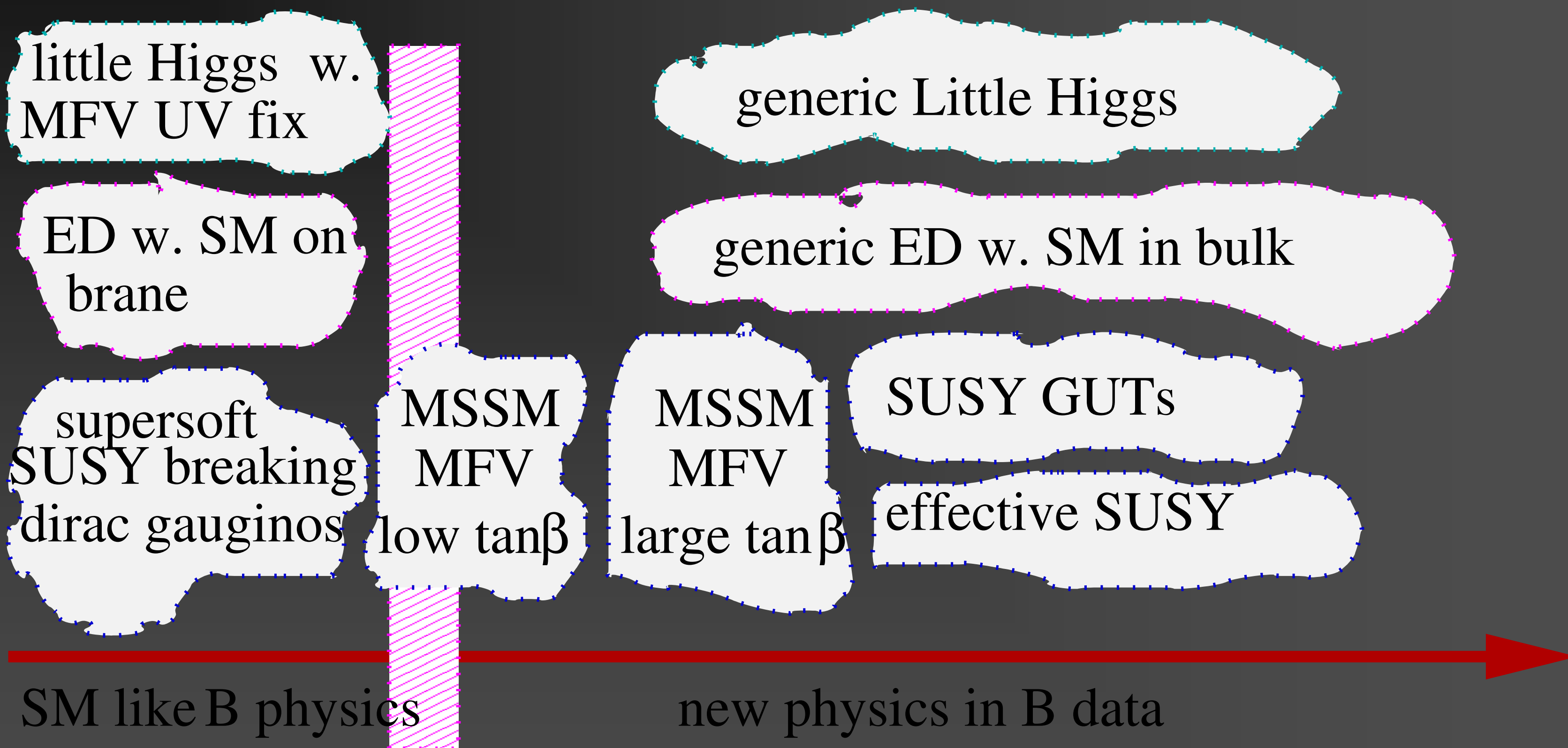
- Large mixing between ν_τ and ν_μ (from atmospheric ν oscillations) can lead to large mixing between $\tilde{b}_R$ and $\tilde{s}_R$.
- This does not violate any known measurements
- Leads to large CPV in B_s mixing, deviations from $\sin(2\beta)$ in $B^o \rightarrow \phi K_s$ and changes in the phase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

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	-	$B \to (D)\tau\nu$ $b \to s\ell^+\ell^-$	$B_s \to \mu\mu$ B_s mixing
SUSY GUT with ν_R	-	$B \to \phi K_S$ $B \to K^*\gamma$	-	B_s mixing τ LFV, n EDM
Effective SUSY	B_d mixing	$B \to \phi K_S$	$A_{CP}^{b\to s\gamma}$, $b \to s\ell^+\ell^-$	B_s mixing
KK graviton exchange	-	-	$b \to s\ell^+\ell^-$	-
Split fermions in large extra dimensions	B_d mixing	-	$b \to s\ell^+\ell^-$	$K^0\overline{K}^0$ mixing $D^0\overline{D}^0$ mixing
Bulk fermions in warped extra dimensions	B_d mixing	$B \to \phi K_S$	$b \to s\ell^+\ell^-$	B_s mixing $D^0\overline{D}^0$ mixing
Universal extra dimensioins	-	-	$b \to s\ell^+\ell^-$ $b \to s\gamma$	$K \to \pi\nu\overline{\nu}$

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

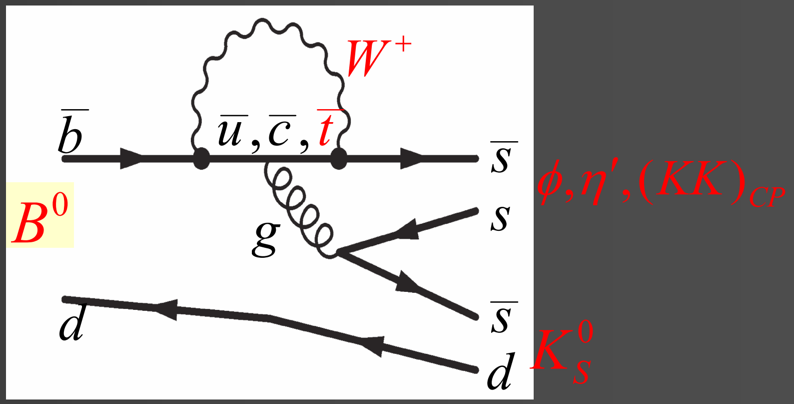
Possible Size of New Physics Effects



- From Hiller hep-ph/0207121

$b \rightarrow s$ Transitions (Penguins)

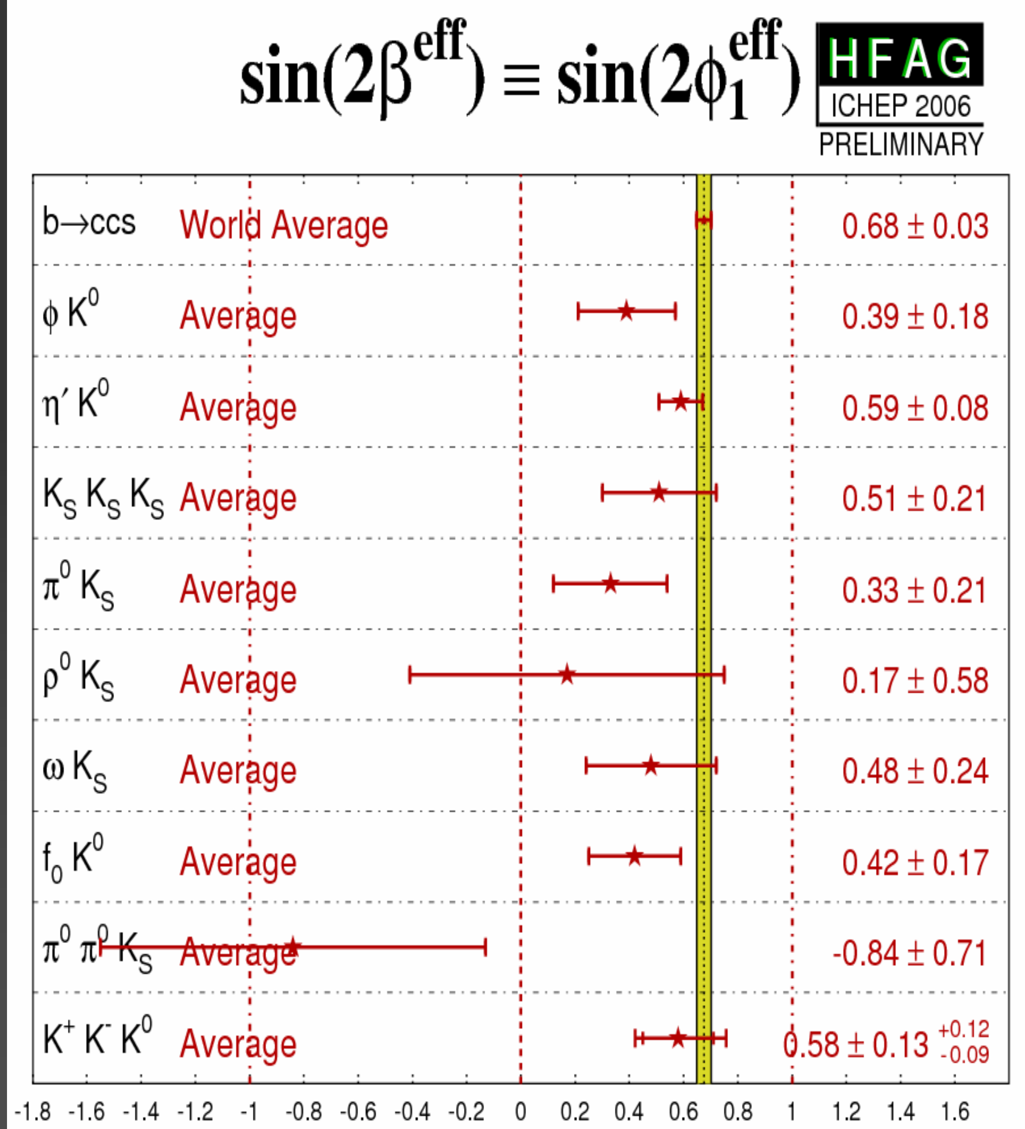
- In SM t in loop dominates and CP asymmetry should be equal to that in $J/\psi K_s$



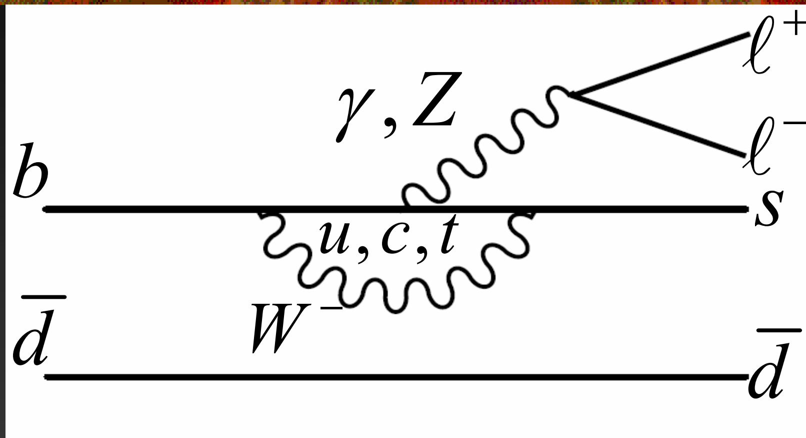
- Other objects in loop, new virtual particles, could interfere
- So this process is sensitive to new physics

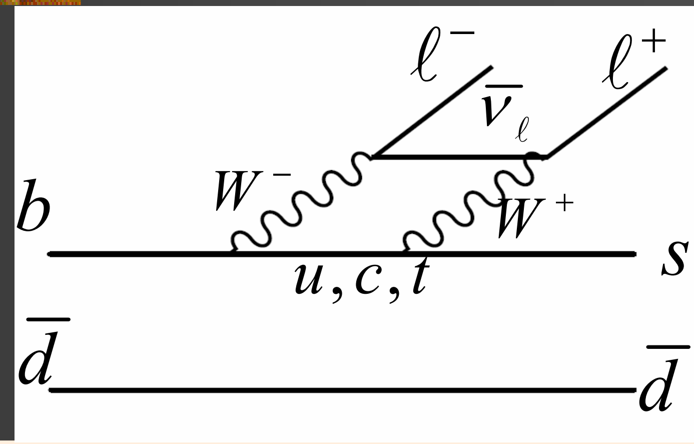
CPV Measurements In b→s

- We cannot just average these modes, but ....
- <S>=sin2β
  =0.50±0.06
- ΔS=.52±.05-.68±.03 = -0.16 ±0.06
- Does u & c parts of Penguin contribute? Yes but ΔS >0, ~0.1
- New Physics???



Electroweak penguins B→K$^{(*)}\ell^+\ell^-$

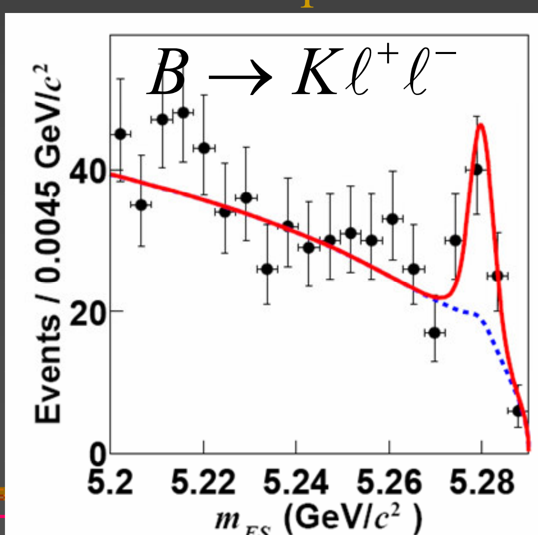


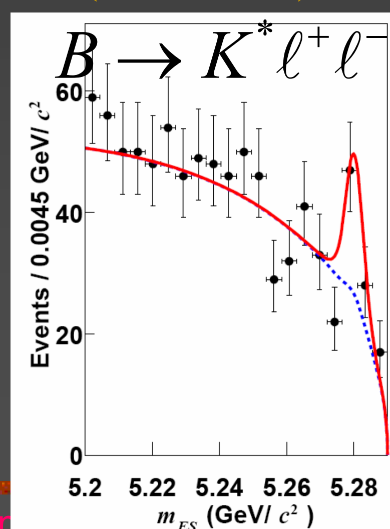


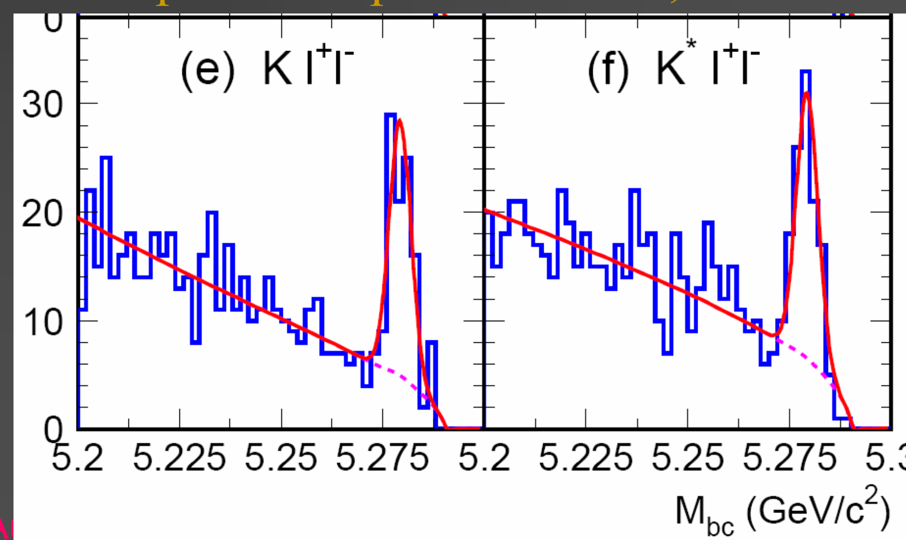
- With l^+l^- pair, can have either pseudoscalar or vector mesons
- New physics can affect both rates and kinematic distributions.

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

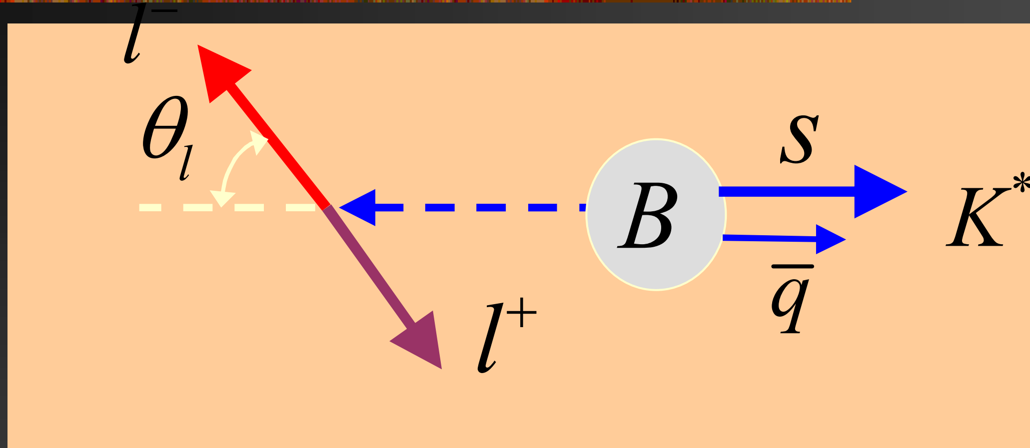
Belle prelim. hep-ex/0410006, 0508009



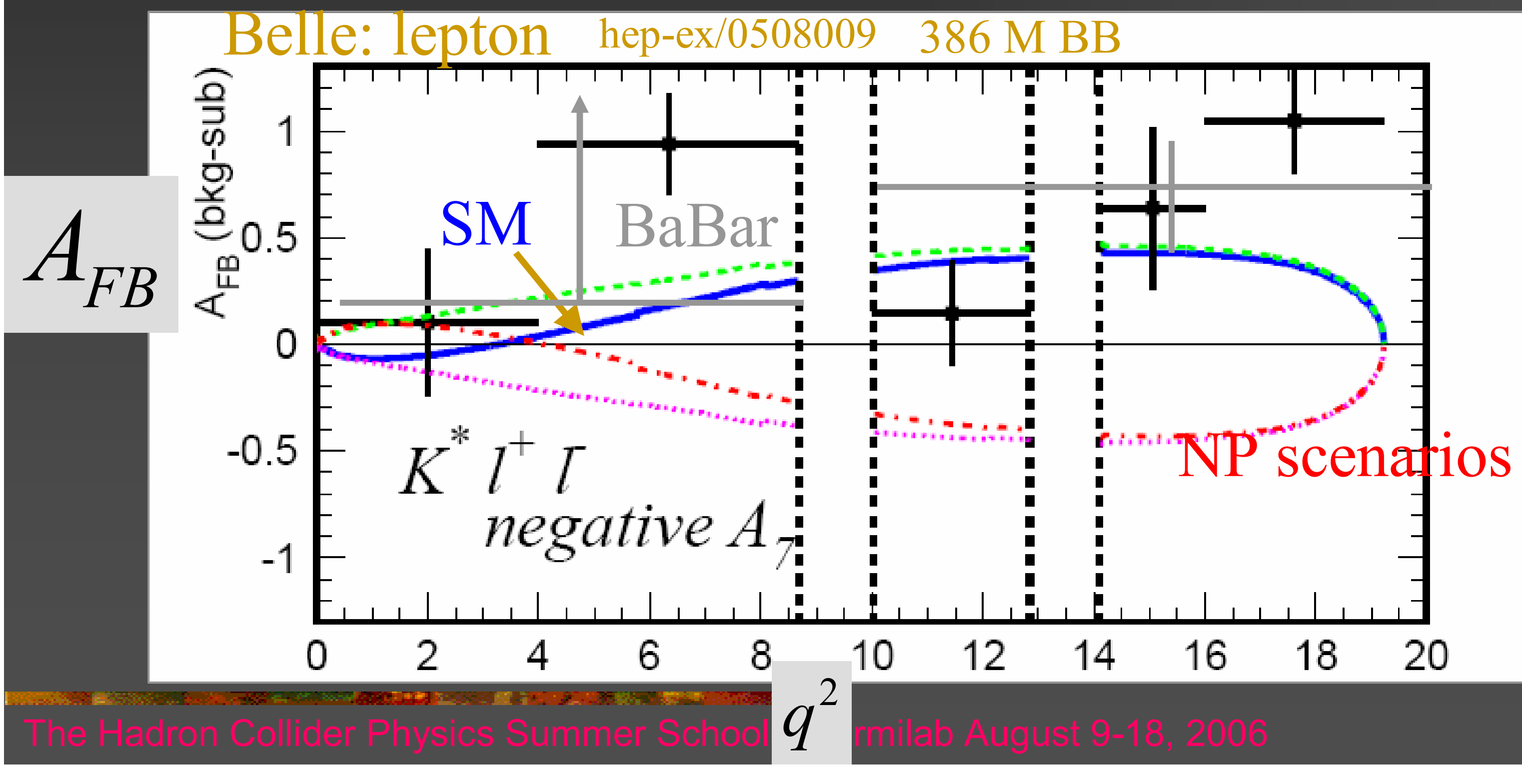




B→K$^{(*)}\ell^+\ell^-$: Lepton F-B Asymmetry



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



But large errors & somewhat contradictory data from BaBar

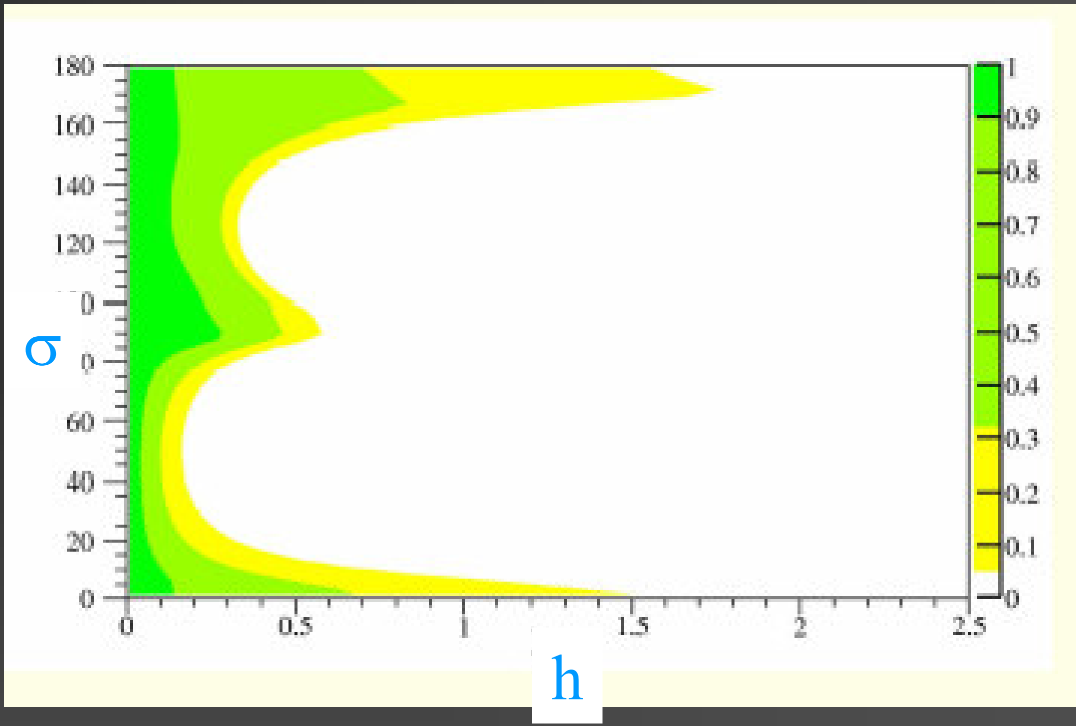
Constraints on New Physics

- Next to Minimal Flavor Violation construction
- Assume NP in tree decays is negligible
- Is there NP in B^o-$\overline{B}^o$ mixing?
- $$r_d^2 e^{2i\theta_d} = 1 + h e^{i\sigma} = \frac{\langle B^o | H^{full} | \overline{B}^o \rangle}{\langle B^o | H^{SM} | \overline{B}^o \rangle}$$
- Use V_{ub}, A_{DK}, $S_{\psi K}$, $S_{\rho\rho}$, Δm_d, A_{SL} = semileptonic asymmetry $= \frac{\Gamma(\overline{B}^o \to X\ell^- \nu) - \Gamma(B^o \to X\ell^+ \overline{\nu})}{\Gamma(\overline{B}^o \to X\ell^- \nu) + \Gamma(B^o \to X\ell^+ \overline{\nu})}$
- Fit to η, ρ, r_d, θ_d (or h, σ)

Agashe, Papucci, Perez, & Pirjol hep-ph/0509117

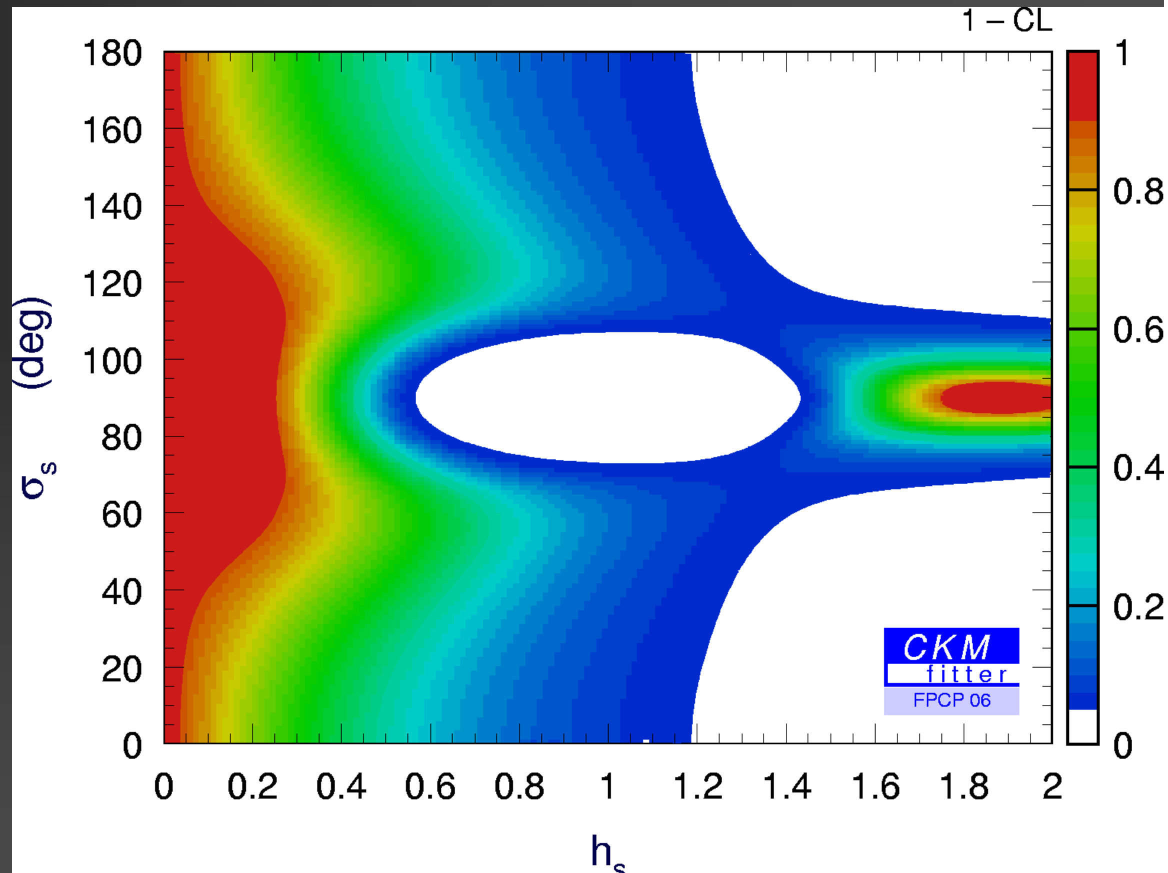
New Physics Constraints

- Amplitudes ~20% of SM still allowed in any region, more near 0º
- 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^o & B^o (i.e. $\pi^+\pi^-$)
  - $B_S \rightarrow D_S^{+(*)} D_S^{-(*)}$, where CP+ outweighs CP- B_S (recall CDF measured Δm_S), CDF & D0 have measurements, order of $\mathcal{B}(B\rightarrow D^{(*)}D_S^{(*)})$~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 ϕ_S is the CP violating phase in B_S mixing, expected to be tiny in SM ~$-2\lambda^2\eta=-.04$ rad but effected by NP
- Can measure $\Delta\Gamma$ using τ measurements

Measuring ϕ Phase of B_S mixing

- CP violation in B_S mixing

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

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

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

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

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

$$\Gamma(B^o \to f) \sim e^{-t/\tau}[1 + A^{dir}\cos\Delta mt + \sin\phi\Delta mt]$$

Measuring ϕ Without Flavor Tagging

- Sum

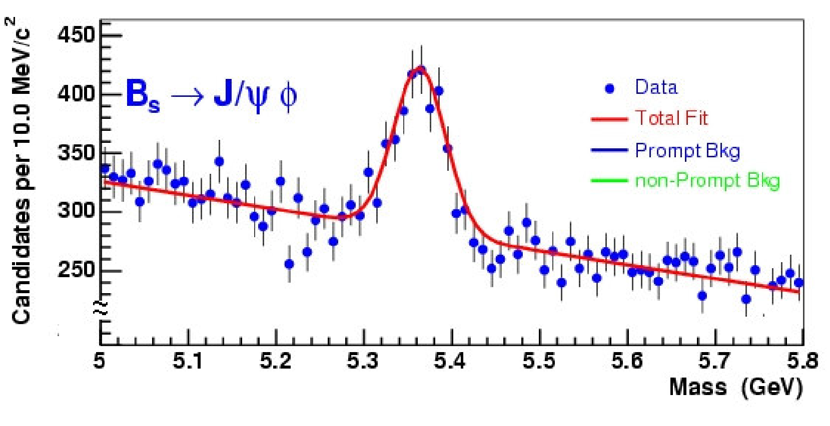
$$\Gamma(B_S(t) \rightarrow f) + \Gamma(\bar{B}_S(t) \rightarrow f) \sim e^{-t/\tau}\left[\cosh\frac{\Delta\Gamma t}{2} - \eta_f \sinh\frac{\Delta\Gamma t}{2}\cos\varphi\right]$$

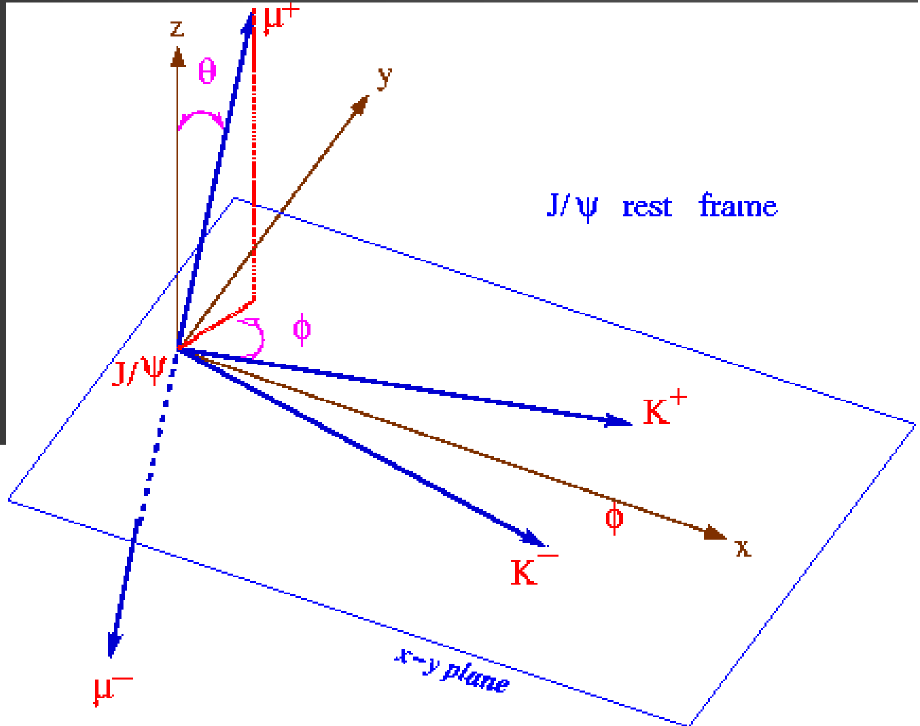
- Some sensitivity to ϕ without flavor tagging

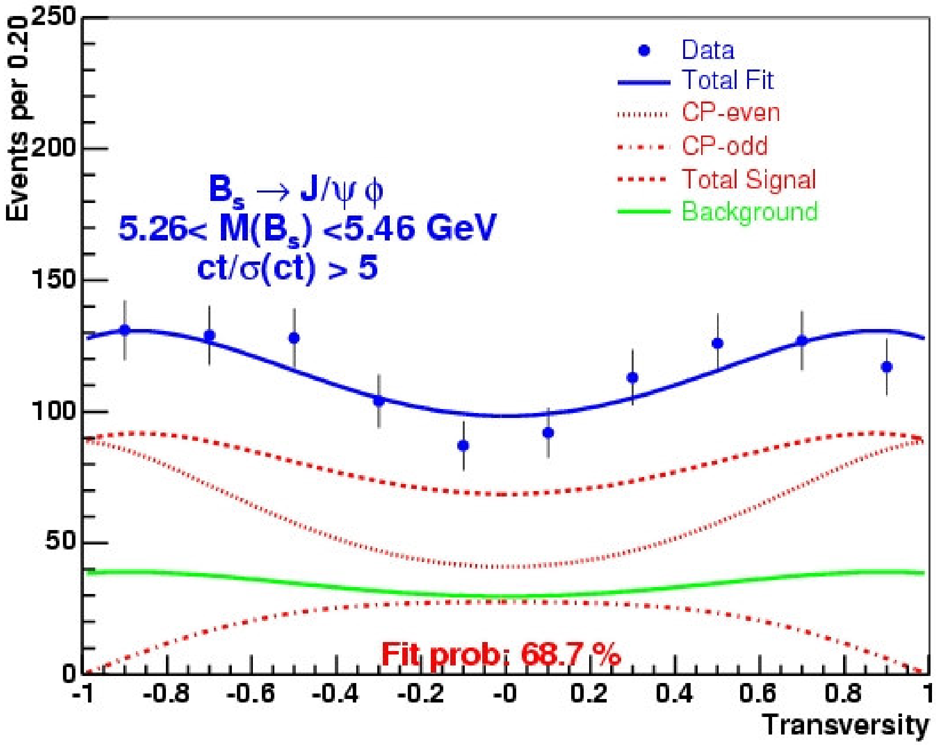
Measuring ϕ with $B_S \rightarrow J/\psi\ \eta$ (or ϕ)

- $B_S \rightarrow J/\psi\ \eta$ (where $\eta \rightarrow \gamma\gamma$ or $\pi^+\pi^-\pi^o$) is a CP eigenstate similar to $B^o \rightarrow J/\psi\ K_S$. However, detecting the η 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



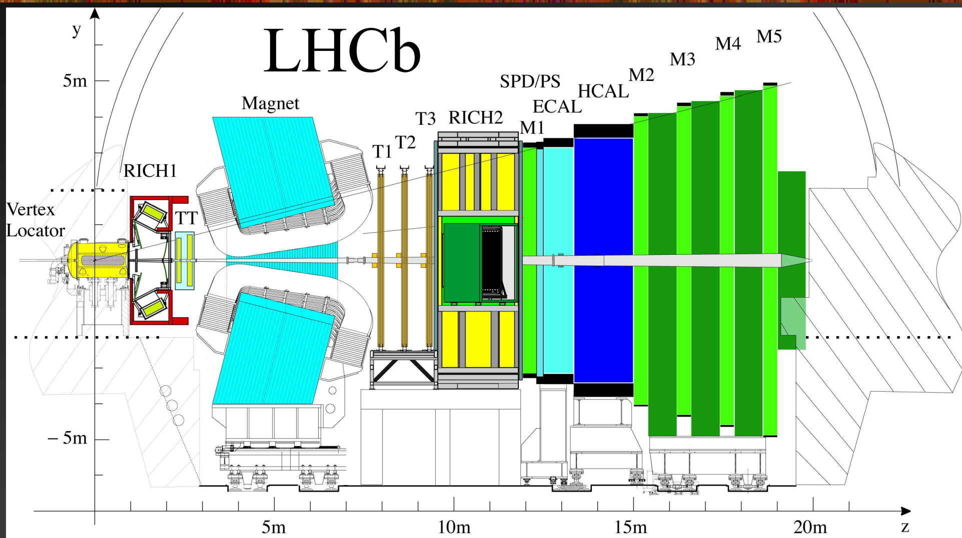




- D0 has 978±45 events
- ϕ_S=-0.79±0.56±0.01 (rad)
- $\Delta\Gamma_S$=0.17±0.09±0.04 ps^{-1}
- $\Rightarrow\Delta\Gamma/\Gamma$~0.25±0.13

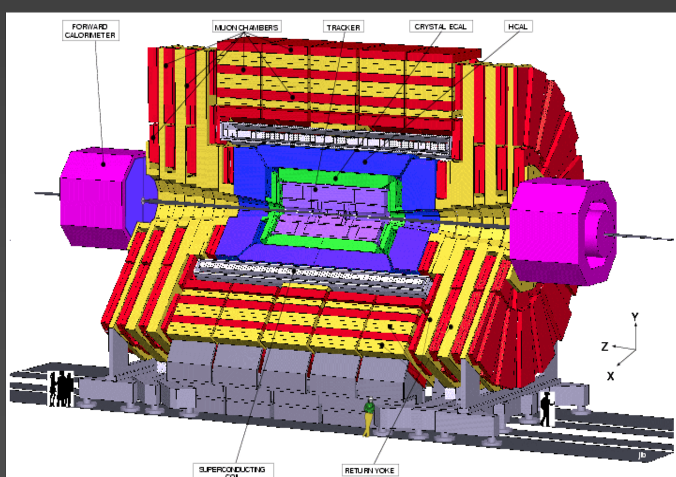
Future Experiments

B experiments at the LHC

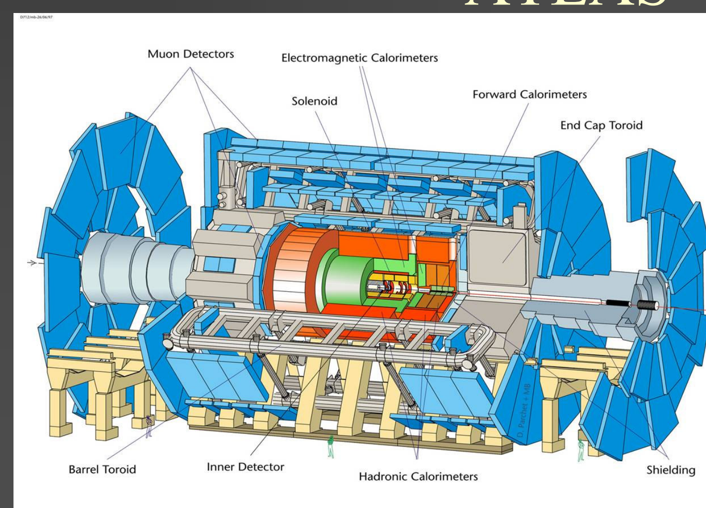


- LHCb: first dedicated b experiment at a hadron collider, the LHC
  - Excellent vertexing
  - Excellent particle id
- Super B? Two efforts, one at Frascati and SuperBelle in Japan

CMS



ATLAS



LHCb Projections

	Det. eff. (%)	Tot. eff. (%)	Vis. BR (10^6)	Annual signal yield	B/S from bb bkg.	Parameter	Error
$B^0 \to \pi^+\pi^-$	12.2	0.69	4.8	26k	< 0.7	γ	6^0
$B_s \to K^+K^-$	12.0	0.99	18.5	37k	0.3		
$B_s \to D_s^{\pm}K^{\pm}$	5.4	0.27	10.	5.4k	< 1.0	γ	14^0
$B^0 \to D^{\sim 0}(K\pi)K^{*0}$	5.3	0.35	1.2	3.4k	< 0.5	γ	8^0
$B^0 \to J/\psi\, K^0_S$	6.4	1.26	20.	216k	0.8	β	0.9^0
$B_s \to J/\psi\, \phi$	7.5	1.45	31.	131k	0.12	Φ_S	1.2^0 (0.02 rad)
$B^0 \to \rho\,\pi$	6.0	0.07	20.	14k	< 1.0	α	$<10^0_{stat}$
$B^0 \to K^{*0}\gamma$	9.5	0.16	29.	35k	< 0.7	A_{DIR}	<1%
$B^0 \to K^*\mu^+\mu^-$			0.8	4.4k	< 2.5	A_{FB}	±0.5GeV/c²
$B_s \to D_s^-\pi^+$	5.4	0.34	120.	80k	0.3	Δm_s	$68ps^{-1}$
$B_s \to \mu^+\mu^-$		2.4	0.0035	17	<5.7	BR	$<10^{-8}$

U-spin symmetry

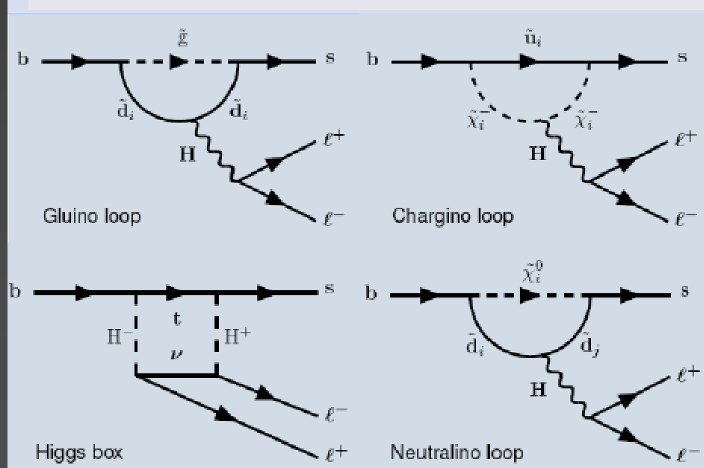
Zero x-ing $10fb^{-1}$

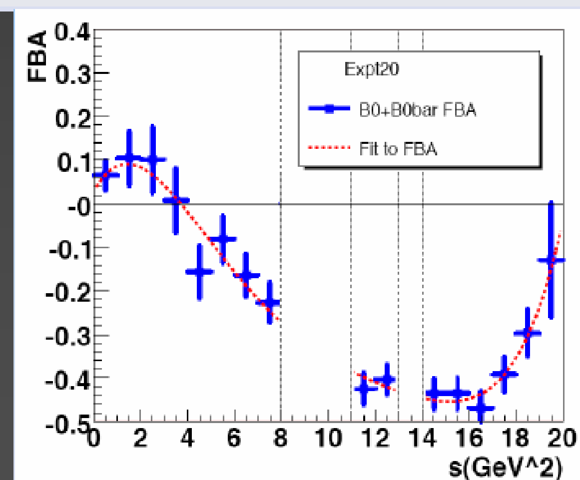
reach

-

- $K^*\mu^+\mu^-$

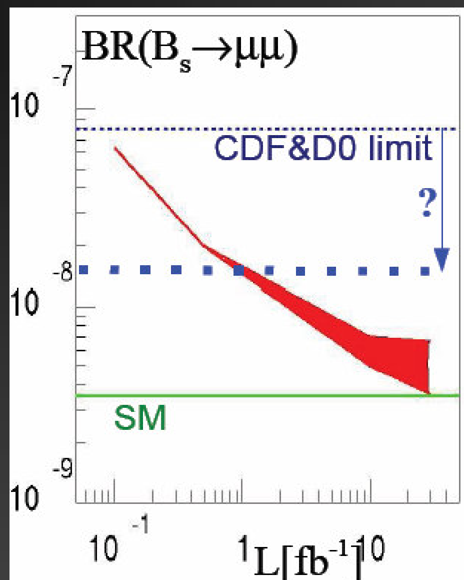
  2 fb^{-1}





Also ATLAS & CMS

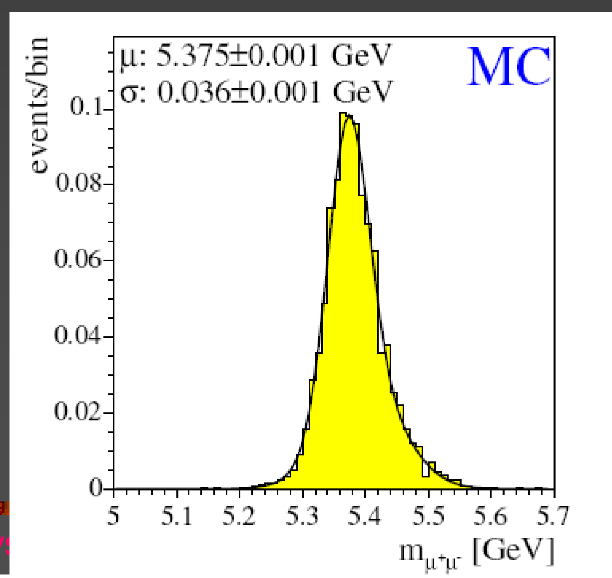
- ATLAS



$B_S \to J/\psi\ \phi$

	ATLAS after 30fb^{-1} (270 000 events)
$\sigma_{\Delta\Gamma}/\Delta\Gamma$	13%
σ_{Γ}/Γ	1%
$\sigma_{\phi s}$	0.046 for Δms=20ps-1

- CMS

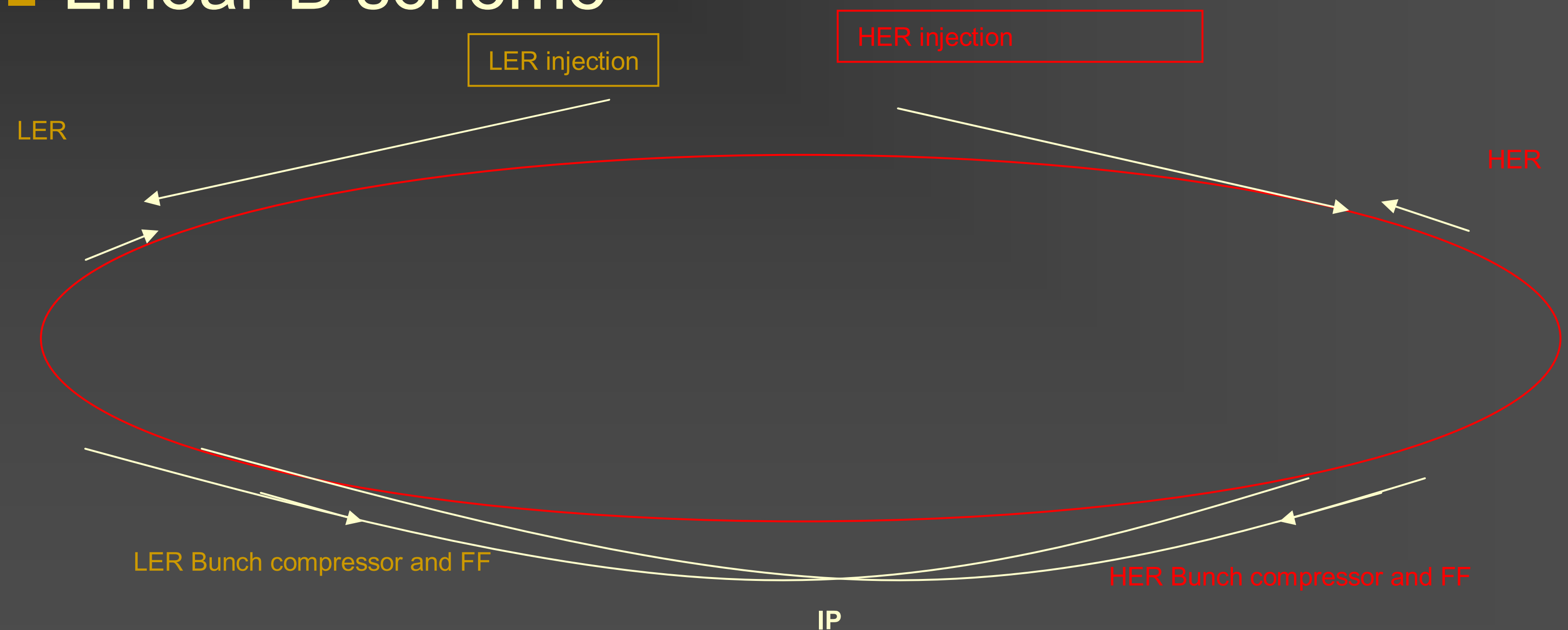


$B(B_S \to \mu^+\mu^-) < 1.4\text{x}10^{-8}$

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

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

- Two proposals currently being pursued to make $L \sim 10^{36}$, ~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