RSE Workshop - Edinburgh 6/2/02

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CP Violation & Flavour-Changing Physics

- The Flavour Puzzle
- The CKM Model
- Flavour Oscillations
- CP Violation in Mixing
- Direct CP Violation
- Flavour-Changing Neutral Currents
- The Lepton Sector

The Pattern of Flavour

Elementary fermions come in 12 flavours which are grouped into three generations:

Quark Flavour	Mass	Charge
Down (d)	$\approx$ 10 MeV	-1/3
Up (u)	$\approx$ 5 MeV	+2/3
Strange (s)	$\approx$ 100 MeV	-1/3
Charm (c)	$\approx$ 1.3 GeV	+2/3
Bottom (b)	$\approx$ 4.5 GeV	-1/3
Top (t)	$\approx$ 180 GeV	+2/3

Lepton Flavour	Mass	Charge
Electron (e)	0.511 MeV	-1
e Neutrino (ν_e)	$<$ 10 eV	0
Muon (μ)	105 MeV	-1
μ Neutrino (ν_μ)	$<$ 0.17 MeV	0
Tau (τ)	1.78 GeV	-1
τ Neutrino (ν_τ)	$<$ 24 MeV	0

Neutrino mass differences are 10^{-3} and 10^{-5} eV^2

Flavour-Changing Decays

Weak interactions change flavour through charged current couplings to W bosons:

Flavour Change	Coupling Strength
$e \longrightarrow \nu_e$	1
$\mu \longrightarrow \nu_\mu$	1
$\tau \longrightarrow \nu_\tau$	1
$u \longrightarrow d$	$V_{ud} = 0.975$
$c \longrightarrow s$	$V_{cs} = 0.975$
$t \longrightarrow b$	$V_{tb} \approx 1$
$s \longrightarrow u$	$V_{us} = 0.220$
$c \longrightarrow d$	$V_{cd} = 0.220$
$b \longrightarrow c$	$V_{cb} = 0.04$
$t \longrightarrow s$	$V_{ts} \approx 0.04$
$b \longrightarrow u$	$V_{ub} = 0.003$
$t \longrightarrow d$	$V_{td} \approx 0.010$

Lepton charged current interactions only occur within a generation

Baryogenesis and CP Violation

The universe contains almost no antimatter

The matter density is small:

$$\frac{N(baryons)}{N(photons)} \approx 3 \times 10^{-10}$$

Sakharov conditions in the early universe:

- Baryon number violating transitions (Δ B = 1)
- CP violation in Δ B = 1 transitions
  CP = Charge Conjugation + Parity Reversal
- Δ B = 1 transitions occur out of thermal equilibrium

CP violation has only been observed in weak decays of K and B mesons

Observed CP violation cannot account for Baryogenesis

No experimental evidence for Δ B = 1 transitions

The CKM Model

The Cabibbo-Kobayashi-Maskawa Matrix:

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

Wolfenstein parametrisation to order λ^4:

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

In the Standard Model the complex phase η gives rise to the observed CP violation

$$\lambda = 0.221 \pm 0.002 \qquad A = 0.78 \pm 0.04$$

Unitarity Triangles

If the CKM Matrix is a 3×3 Unitary matrix:

$$\Sigma_i V_{ij}^* V_{ik} = \delta_{jk} \qquad \text{Rows}$$

$$\Sigma_j V_{ij}^* V_{kj} = \delta_{ik} \qquad \text{Columns}$$

There are 6 equations where $\Sigma = 1$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.997 \pm 0.002$$

...leaves some room for a fourth generation!

The error on this sum is dominated by:

$$V_{ud} = 0.9736 \pm 0.0010 \quad \text{from} \quad \beta \quad \text{decay}$$

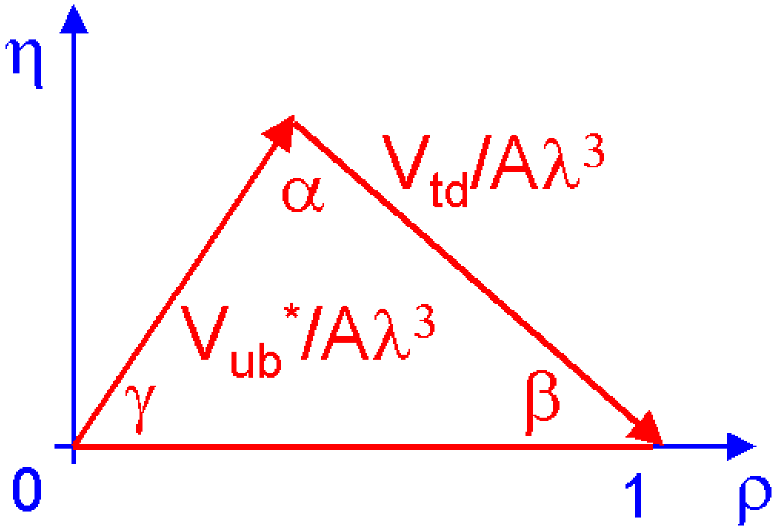
There are 6 equations where $\Sigma = 0$ These are known as the Unitarity triangles.

Most important one for CP violation:

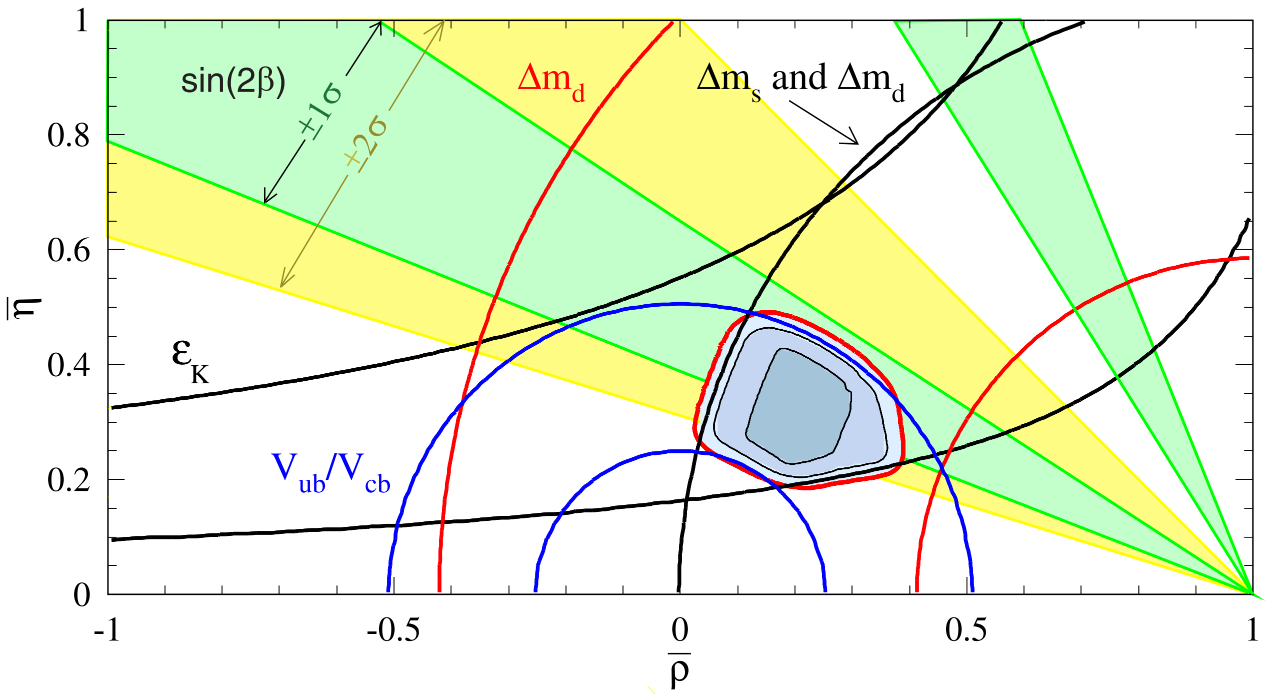
$$V_{cb}^* V_{cd} + V_{tb}^* V_{td} + V_{ub}^* V_{ud} = 0$$

Constraints in $\rho - \eta$ plane

Unitarity triangle in $\rho - \eta$ plane:

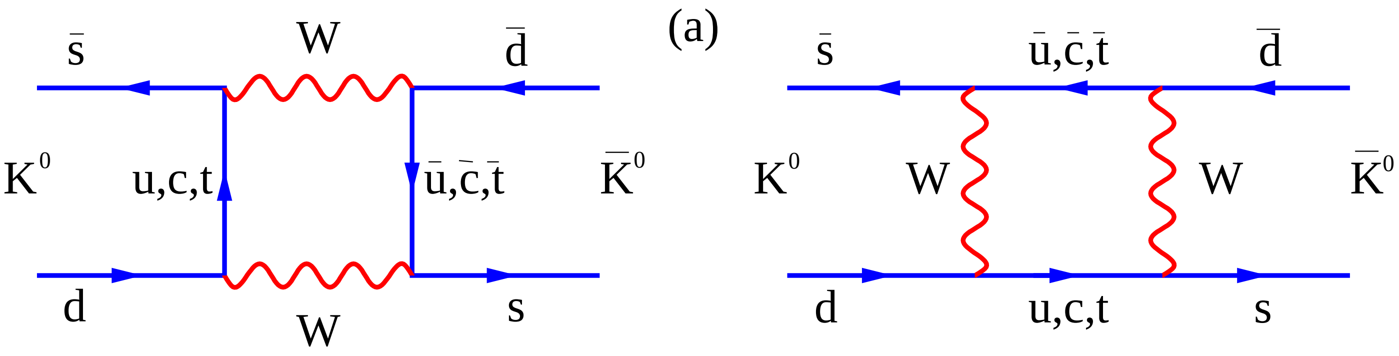


... and the current constraints on it:



Flavour Oscillations

Neutral mesons oscillate between particle and antiparticle states through second order weak interactions ("box" diagrams)



Time evolution of state:

$$\psi(t) = a(t)|K^0 > + b(t)|\bar{K}^0 >$$

$$i\hbar \frac{d\psi}{dt} = \mathcal{H}\psi$$

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

Off diagonal terms lead to mixing of flavour eigenstates

$K^0 - \bar{K}^0$ Mixing

Decay eigenstates are K_S and K_L

$$|K_S> = \frac{p|K^0> + q|\bar{K}^0>}{\sqrt{p^2+q^2}} \qquad |K_L> = \frac{p|K^0> - q|\bar{K}^0>}{\sqrt{p^2+q^2}}$$

$$\tau_S = 0.893 \times 10^{-10} s \qquad \tau_L = 5.15 \times 10^{-8} s$$

$$\Delta\Gamma_K = \Gamma_L - \Gamma_S = 7.28 \times 10^{-12} \mathrm{MeV}$$

$$\Delta M_K = M_L - M_S = 3.48 \times 10^{-12} \mathrm{MeV}$$

Probability of finding K^0 in initially pure K^0 beam:

$$P = \frac{1}{4}\left[e^{-\Gamma_L t} + e^{-\Gamma_S t} + 2e^{-\frac{1}{2}(\Gamma_S+\Gamma_L)t}\cos\Delta M_K t\right]$$

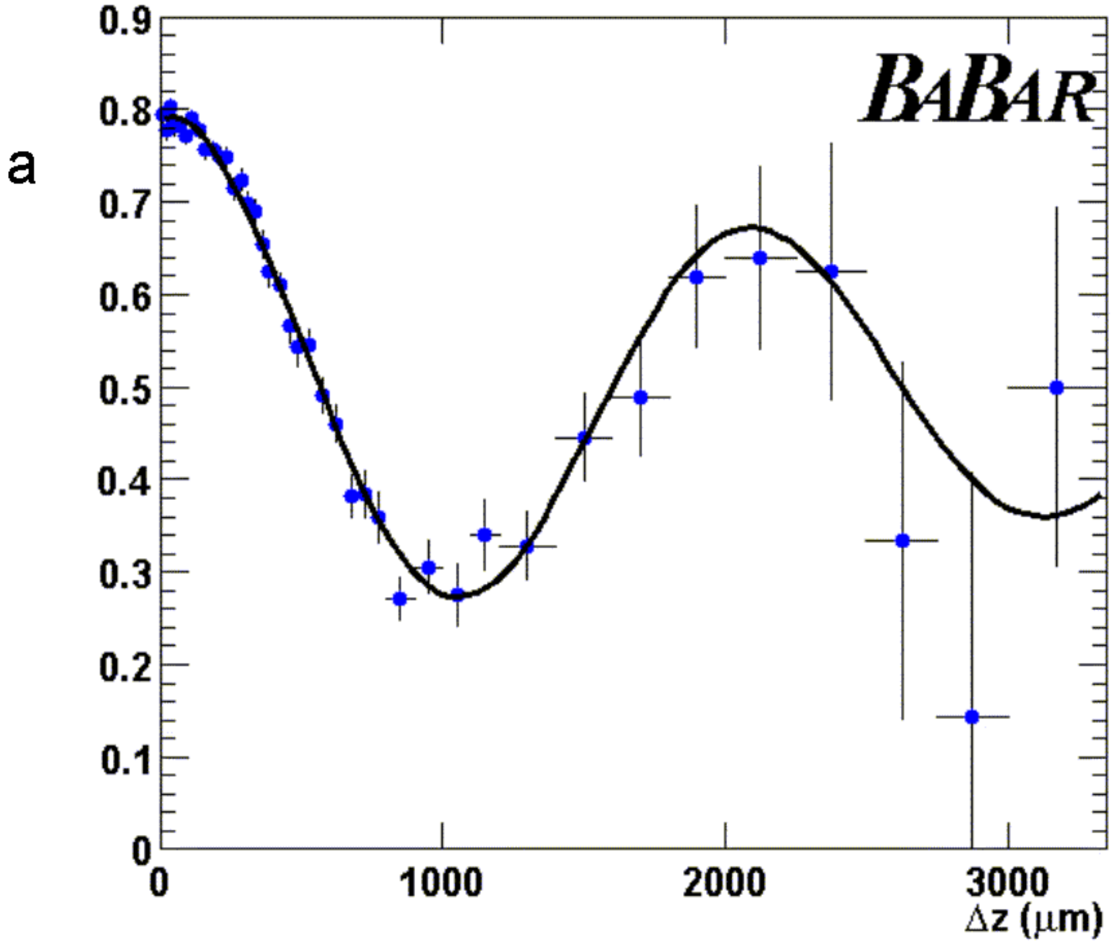
Probability of finding $\bar{K}^0$ in initially pure K^0 beam:

$$\bar{P} = \frac{1}{4}\left[e^{-\Gamma_L t} + e^{-\Gamma_S t} - 2e^{-\frac{1}{2}(\Gamma_S+\Gamma_L)t}\cos\Delta M_K t\right]$$

B_d Mixing

The mixing of B^0 and $\bar{B}^0$ mesons is being precisely measured using Υ(4S)$\rightarrow B^0\bar{B}^0$ at B factories.

Measure oscillations as a function of time-difference $\Rightarrow$ z decay vertex separation of the two B mesons.



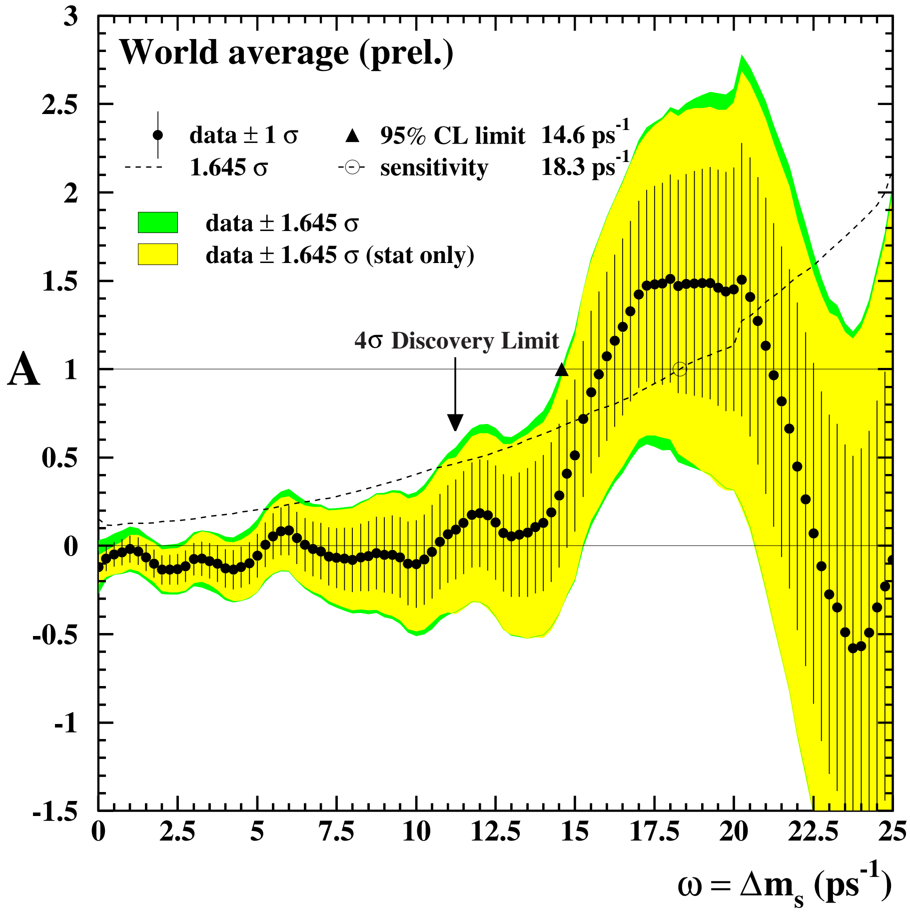
World average from many experiments:

$$\Delta m_d = 0.488 \pm 0.008 \mathrm{ps}^{-1}$$

$$\tau_{B^0} = 1.55 \pm 0.02 \mathrm{ps}$$

B_s Mixing

Searches for B_s oscillations at LEP, SLD and CDF have not observed a signal. The combined world data set limits on the possible oscillation frequency:



The oscillation frequency is very high...

$$\Delta m_s > 14.6\text{ps}^{-1}$$

$$\tau_{B_s} = 1.49 \pm 0.06\text{ps}$$

B Mixing in Standard Model

From the box diagram containing top quarks and W bosons:

$$\Delta m_d = C_d |V_{tb}^* V_{td}|^2 F\left(\frac{m_t^2}{M_W^2}\right) \eta_{QCD}$$

$$\Delta m_s = C_s |V_{tb}^* V_{ts}|^2 F\left(\frac{m_t^2}{M_W^2}\right) \eta_{QCD}$$

$$C_d = G_F^2 B_{Bd} f_{Bd}^2 m_b$$

$$C_s = G_F^2 B_{Bs} f_{Bs}^2 m_b$$

Lattice calculations are needed for C_d and C_s
Accuracy $\approx 20\%$ limits determination of V_{td} and V_{ts} from mixing measurements.

Ratio of B_d to B_s mixing is understood to a few %

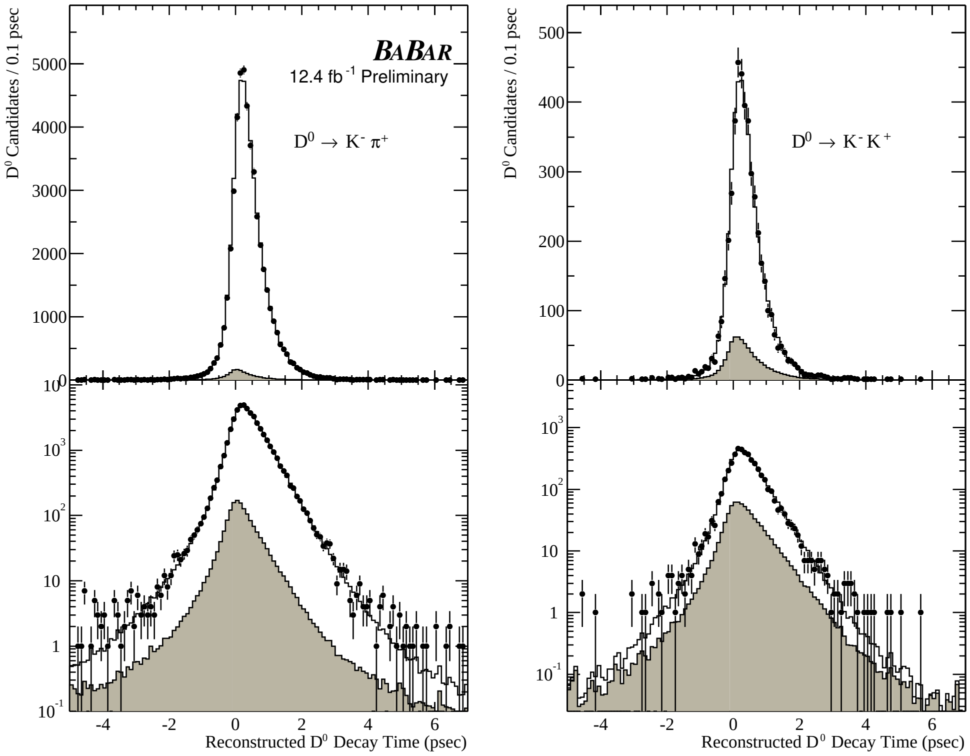
Standard Model prediction $\Delta m_s \approx 20$

Discovery expected at Tevatron for $\Delta m_s < 50$

D^0 Lifetime and Mixing

CP even/odd D^0 decays may have different lifetimes

(Equal mix) $D^0 \to K^-\pi^+$ $\quad$ $D^0 \to K^+K^-$ (CP-even)



$$y = \frac{\Delta\Gamma}{2\Gamma} = (-1.0 \pm 2.2 \pm 1.7)\%$$

$$\tau_{D^0} = 412 \pm 2 fs \qquad (\mathrm{PDG} : 412.6 \pm 2.8 fs)$$

$D^0 - \bar{D}^0$ mixing can be searched for using the time evolution of $D^0 \to K^-\pi^+$ and $D^0 \to K^+\pi^-$

$$\frac{D^0 \to K^+\pi^-}{D^0 \to K^-\pi^+} = (0.38 \pm 0.04 \pm 0.02)\%$$

Standard Model predictions for D mixing are very small

CP Violation in K^0 Mixing

CP violation manifests itself as a difference between the decay rates of K^0 and $\bar{K}^0$

$$|K^0>= \frac{\sqrt{p^2+q^2}}{2p}(|K_S> + |K_L>)$$

$$|\bar{K}^0>= \frac{\sqrt{p^2+q^2}}{2q}(|K_S> - |K_L>)$$

There is CP violation in $K^0 - \bar{K}^0$ mixing if:

$$|\frac{q}{p}| \neq 1$$

CP violation is observed in semileptonic decays of K_L mesons:

$$\delta = \frac{(K_L \to \pi^- \ell^+ \nu) - (K_L \to \pi^+ \ell^- \nu)}{(K_L \to \pi^- \ell^+ \nu) + (K_L \to \pi^+ \ell^- \nu)} = 2Re(\epsilon_K)$$

$$\epsilon_K = \frac{p-q}{p+q}$$

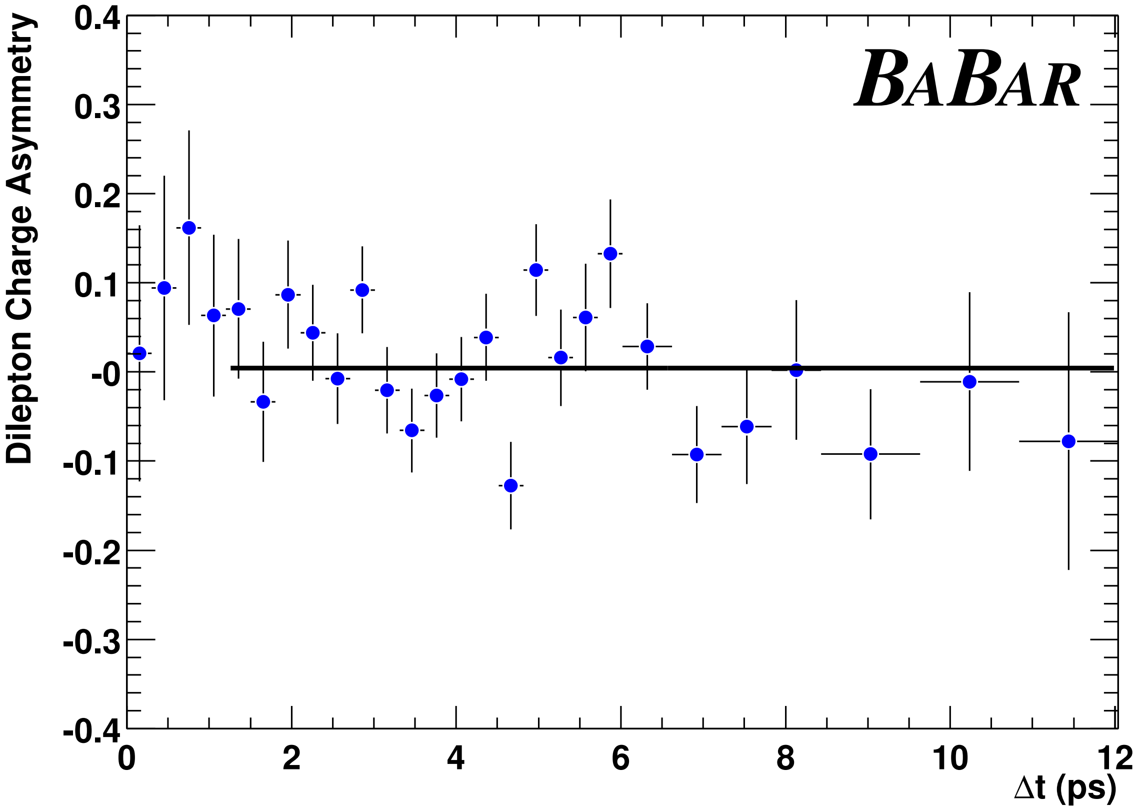
$Re(\epsilon_K) = 1.6 \times 10^{-3}$ $\qquad$ $|\epsilon_K| = (2.28 \pm 0.02) \times 10^{-3}$

Shown to be consistent with Time reversal (T) violation as required by the CPT theorem

CP Violation in B_d Mixing

At the B factories the equivalent measurement of CP violation in mixing is made with dilepton events (two semileptonic B decays):

$$A_{CP} = \frac{(B\bar{B} \to \ell^+\ell^+) - (B\bar{B} \to \ell^-\ell^-)}{(B\bar{B} \to \ell^+\ell^+) + (B\bar{B} \to \ell^-\ell^-)} = 4Re(\epsilon_B)$$



$$\epsilon_B = \frac{p-q}{p+q} \qquad Re(\epsilon_B) = (1.2 \pm 2.9 \pm 3.6) \times 10^{-3}$$

Time dependent CP Violation

For a B decay to a CP eigenstate, f, the CP asymmetry is given by:

$$A_{CP} = \frac{\bar{A}(\bar{B}^0 \to f) - A(B^0 \to f)}{\bar{A}(\bar{B}^0 \to f) + A(B^0 \to f)}$$

This asymmetry has a time dependence due to mixing:

$$A_{CP}(t) = \frac{(1 - |\lambda|^2)\cos \Delta m t - 2Im(\lambda)\sin \Delta m t}{1 + |\lambda|^2}$$

At the B factories, t is the **time difference** between the B^0 and $\bar{B}^0$ decays

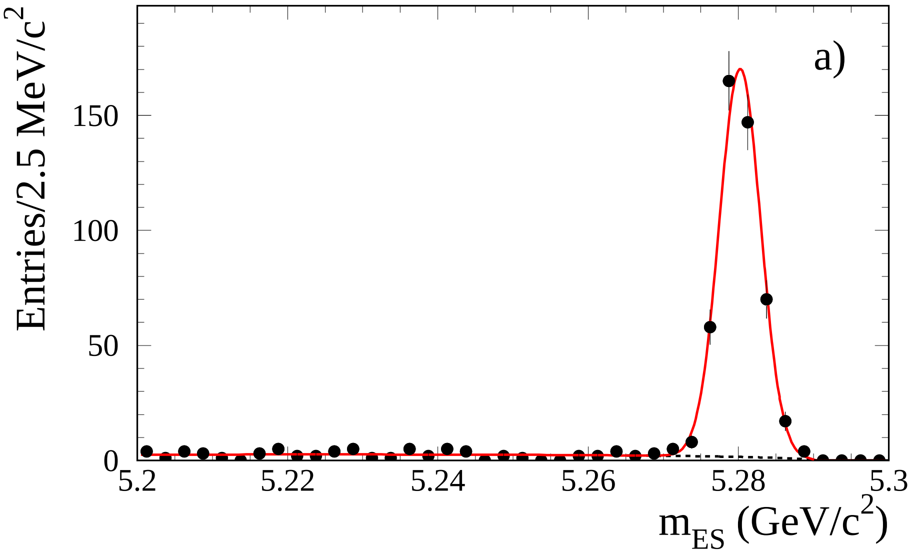
The critical parameter is:

$$\lambda = \left(\frac{q}{p}\right)\left(\frac{\bar{A}}{A}\right)$$

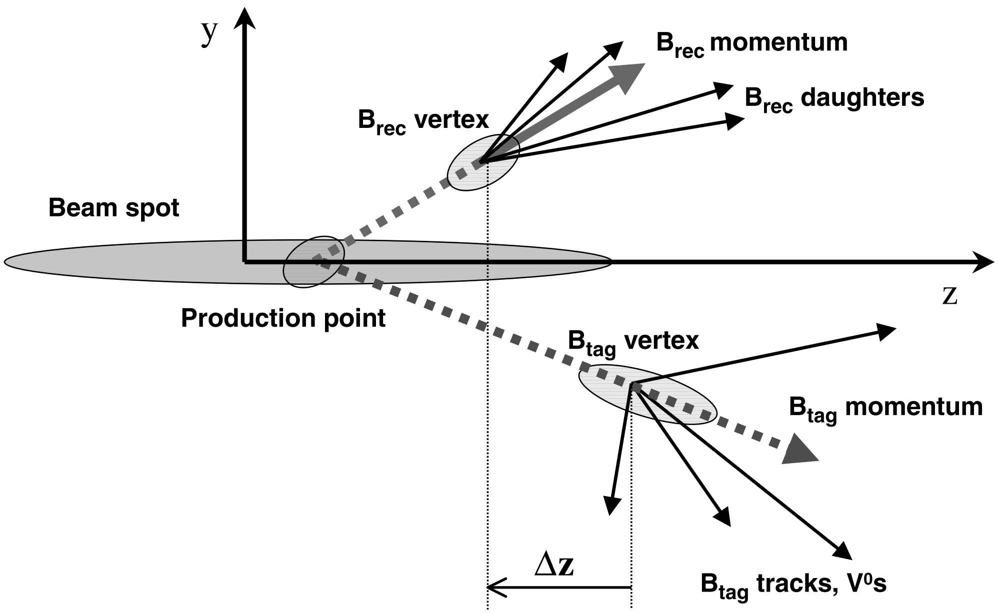
- CP violation via mixing is $|q/p| \neq 1$
- Direct CP violation is $|\bar{A}/A| \neq 1$
- CP violation via interference is $Im(\lambda) \neq 0$

Measurement of $A_{CP}(t)$

1. Reconstruct a B decay to a CP eigenstate:
   $B \to \psi K_S$



2. Tag the flavour using the decay of the other B



3. Measure the separation of the decay vertices (Δz)

4. Fit the results to a $\sin \Delta m t$ distribution

Tagging B Flavour at BaBar

Flavour specific tags for other B are:

- High momentum leptons
- Charged Kaons
- Partially reconstructed charm vertices (handled by a neural network)

Category	Efficiency	Mistags	Separation Power
Leptons	10.9%	8.9%	7.4%
Kaons	35.8%	17.6%	15.0%
Neural Net 1	7.8%	22.0%	2.5%
Neural Net 2	13.8%	35.1%	1.2%
Total	68.4%	19.2%	26.1%

The **separation power** defines the statistical accuracy of the measurement:

$$< s^2 >= efficiency * (1 - 2 * mistags)^2$$

Tagging performance is measured using Flavour specific final states , e.g. $B \to \psi K^{*0}, K^{*0} \to K^+\pi^-$

Vertexing at BaBar

PEP-II collides 9 GeV electrons with 3.1 GeV positrons

$$E_{CM} = 10.58\ GeV \qquad \Upsilon(4S) \qquad \gamma\beta = 0.56$$

At the interaction point the beamsize is:

$$\Delta x = 150\mu m \qquad \Delta y = 6\mu m \qquad \Delta z = 1cm$$

The B decays occur along the z axis after:

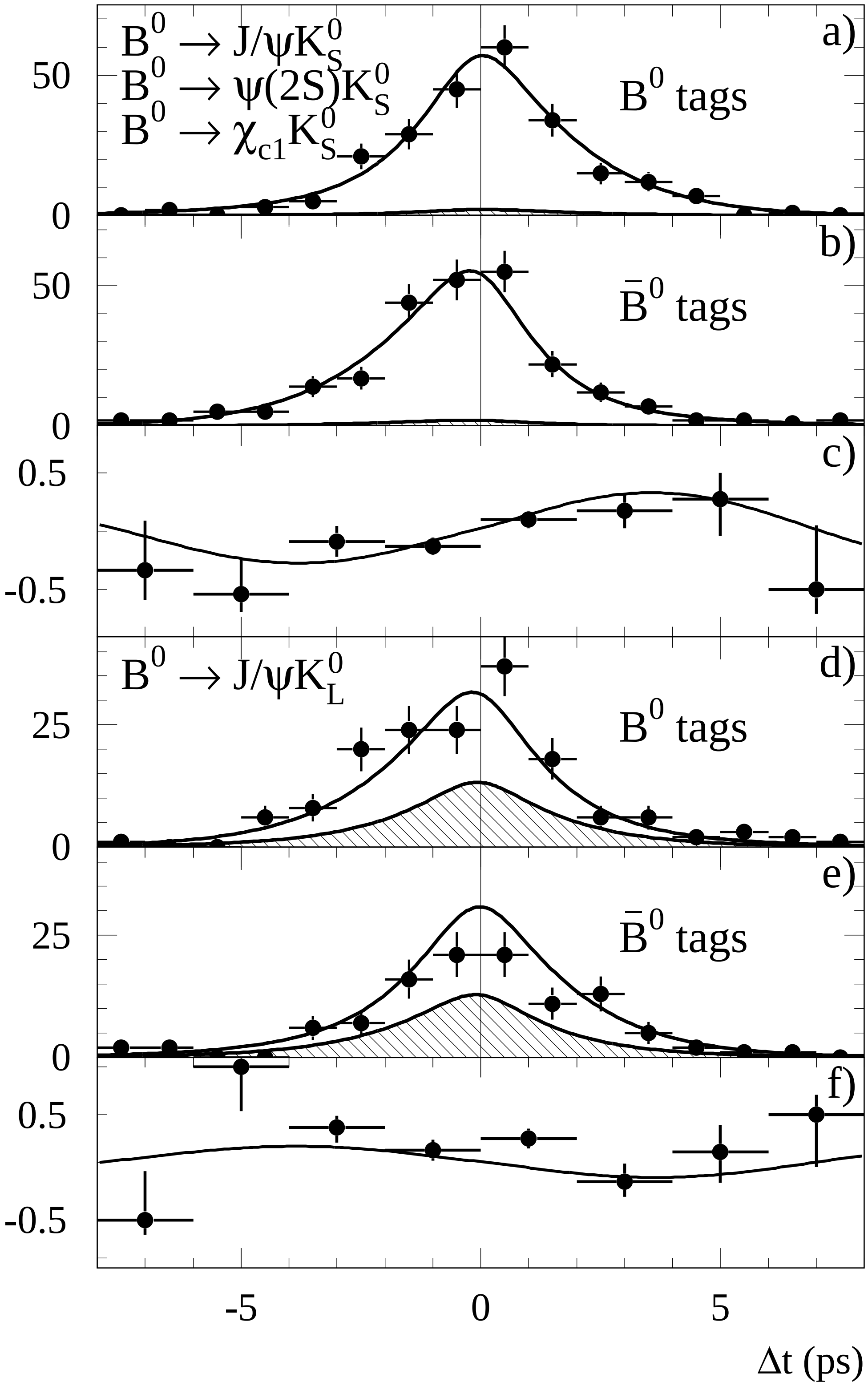
$$\tau_B = 1.55ps \qquad \gamma\beta c\tau \approx 270\mu m$$

The vertex resolutions in BaBar are:

1. The CP vertex ($B \to \psi K_S$)
   $\sigma_z = 50\mu m$
2. The tag vertex (the other B)
   $\sigma_z = 65\mu m$ (lepton or Kaon tag)

Need to understand non-Gaussian tails of distribution using control samples

Observation of CP Violation in B decays



Measurements of $\sin 2\beta$

Standard Model prediction for $B \to \psi K_S$:

$$\lambda = \frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}} \frac{V_{td}V_{tb}^*}{V_{td}^*V_{tb}} \frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}$$

Amplitude of CP asymmetry is $Im\lambda = \sin 2\beta$

Direct CP violation is small because one diagram dominates the decay amplitude

BABAR - 2001

$$\sin 2\beta = 0.59 \pm 0.14 \pm 0.05$$

BELLE - 2001

$$\sin 2\beta = 0.99 \pm 0.14 \pm 0.06$$

CDF - 2000

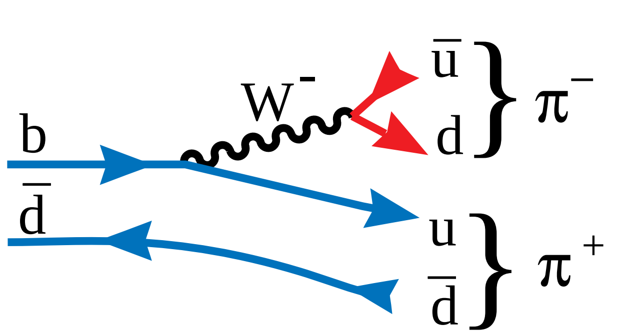
$$\sin 2\beta = 0.79^{+0.45}_{-0.41}$$

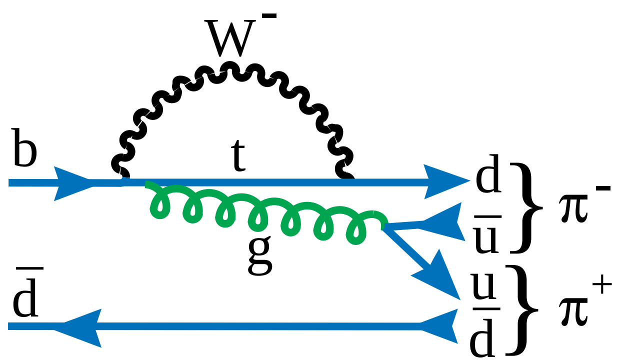
Unfortunately these are consistent with the Standard Model expectation of ≈ 0.70

Rare Hadronic B Decays

With large numbers of B mesons, these decays will be the main focus of measurements over the next few years

Two diagrams contribute to the amplitudes for $B \to \pi\pi$:



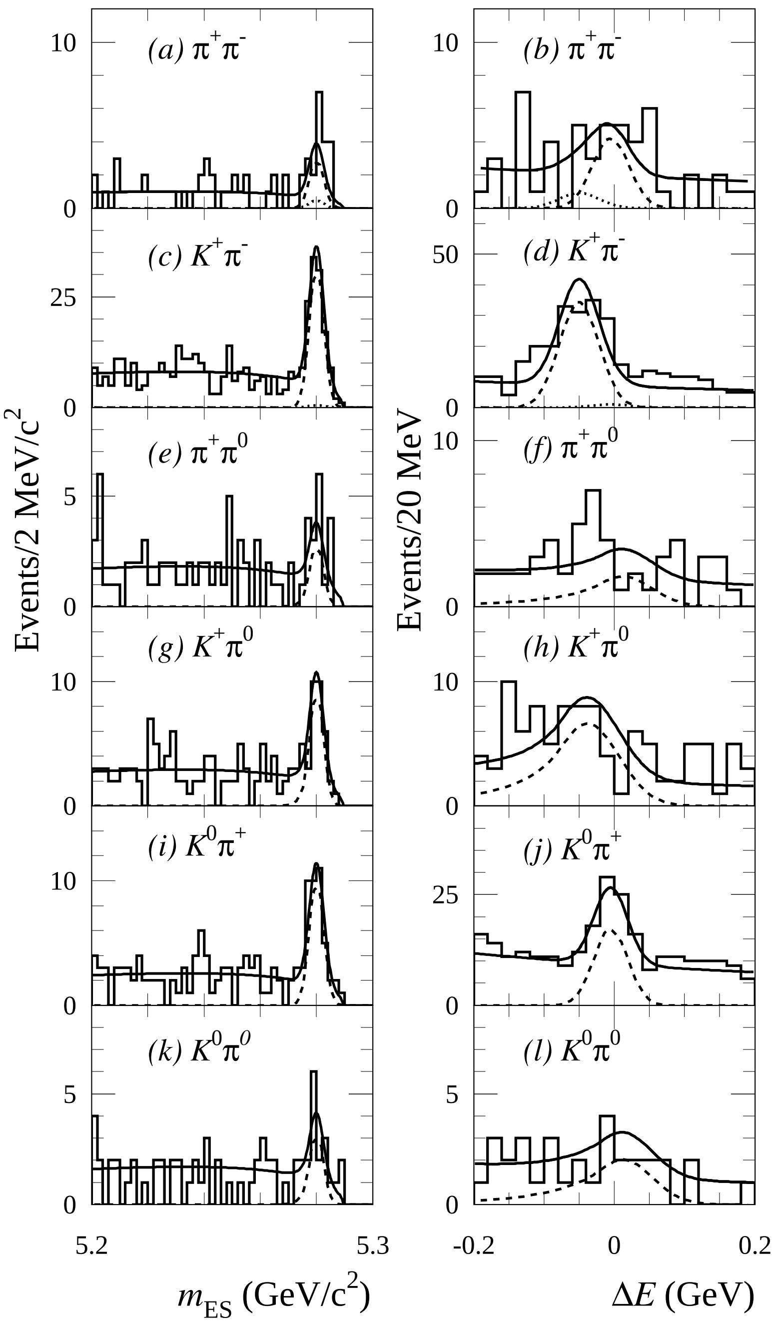


Tree Diagram **Penguin Diagram**

The decays $B \to K\pi$ are mostly due to $b \to s$ penguin diagrams

BaBar Measurements of Rare Hadronic B Decays

Branching Fractions are given $\times 10^{-6}$



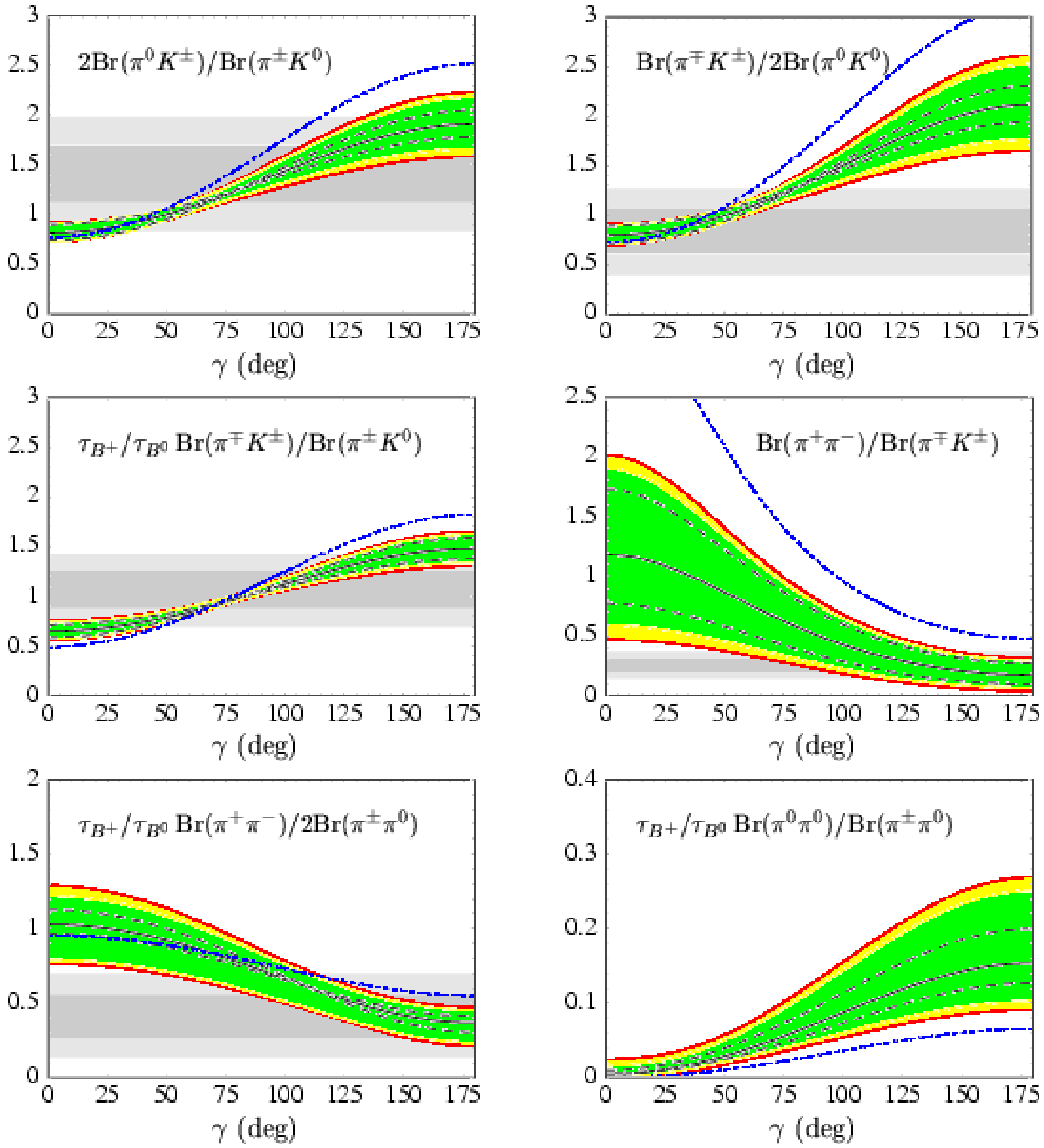
Decay Mode	Branching Fraction
$\pi^+\pi^-$	4.1 ± 1.2
$K^+\pi^-$	16.7 ± 2.1
K^+K^-	< 2.5

$\pi^+\pi^0$	5.1 ± 2.2
$K^+\pi^0$	10.8 ± 2.2
$K^+\bar{K}^0$	< 2.4

$K^0\pi^+$	18.2 ± 3.7
$K^0\pi^0$	8.2 ± 3.1
$K^0\bar{K}^0$	< 7.3

QCD Factorization

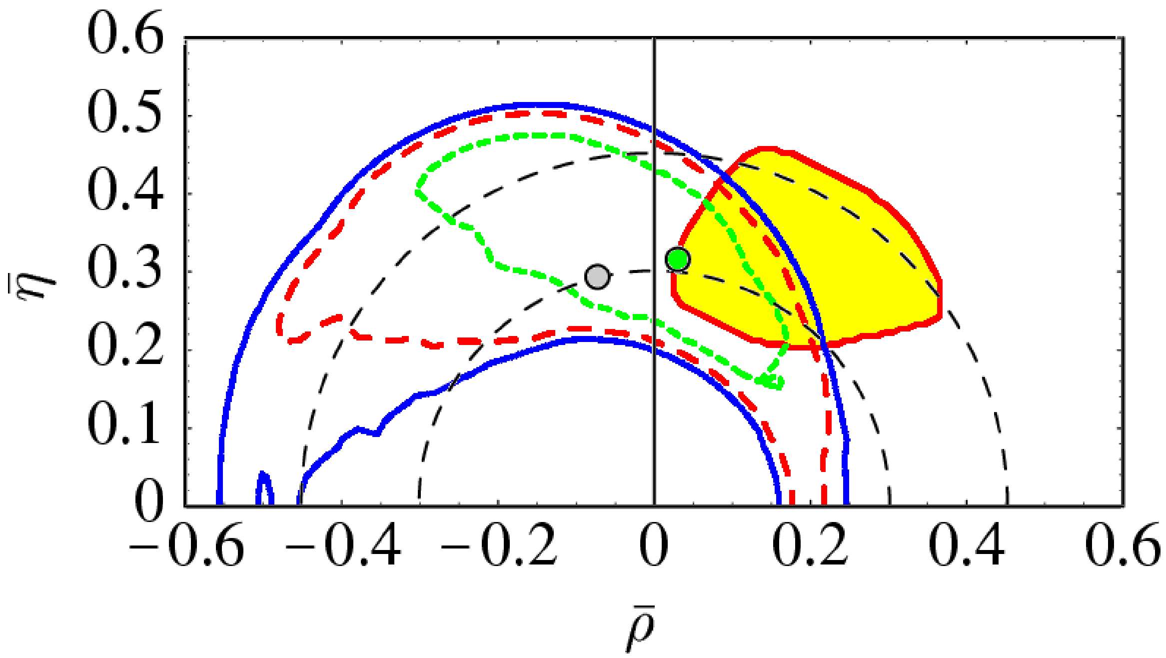
Ratios of Branching Fractions are sensitive to the phase of V_{ub} (the angle γ)



Beneke,Buchalla,Neubert & Sachradja hep-ph/0104110

Constraints in ρ/η plane

Using QCD Factorization and the Branching Fractions for $B \to \pi\pi$ and $K\pi$, a region in the ρ/η plane is constrained:



Solid Blue Line 95% C.L.

Dashed Red Line 90% C.L.

Dotted Green Line 68% C.L.

Black dashed lines are V_{ub} constraint

Yellow zone from ϵ_K, V_{td}, V_{ts}, V_{ub} constraints

CP Violation in $B \to \pi^+\pi^-$

CP asymmetries are due to:

- Interference between mixing and decay
- Interference between penguin and tree diagrams

$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left[1 \pm S_{\pi\pi} \sin \Delta m \Delta t \mp C_{\pi\pi} \cos \Delta m \Delta t\right]$$

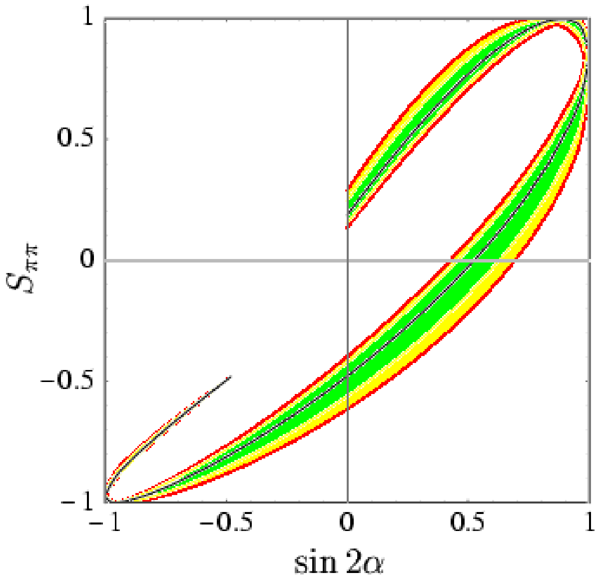
$$S_{\pi\pi} = \frac{2Im(\lambda)}{1+|\lambda|^2} \qquad C_{\pi\pi} = \frac{1-|\lambda|^2}{1+|\lambda|^2}$$

With no penguin contribution:

$$S_{\pi\pi} = \sin 2\alpha \qquad C_{\pi\pi} = 0$$

QCD Factorization
gives $S_{\pi\pi}$ and $C_{\pi\pi}$
with penguin diagram

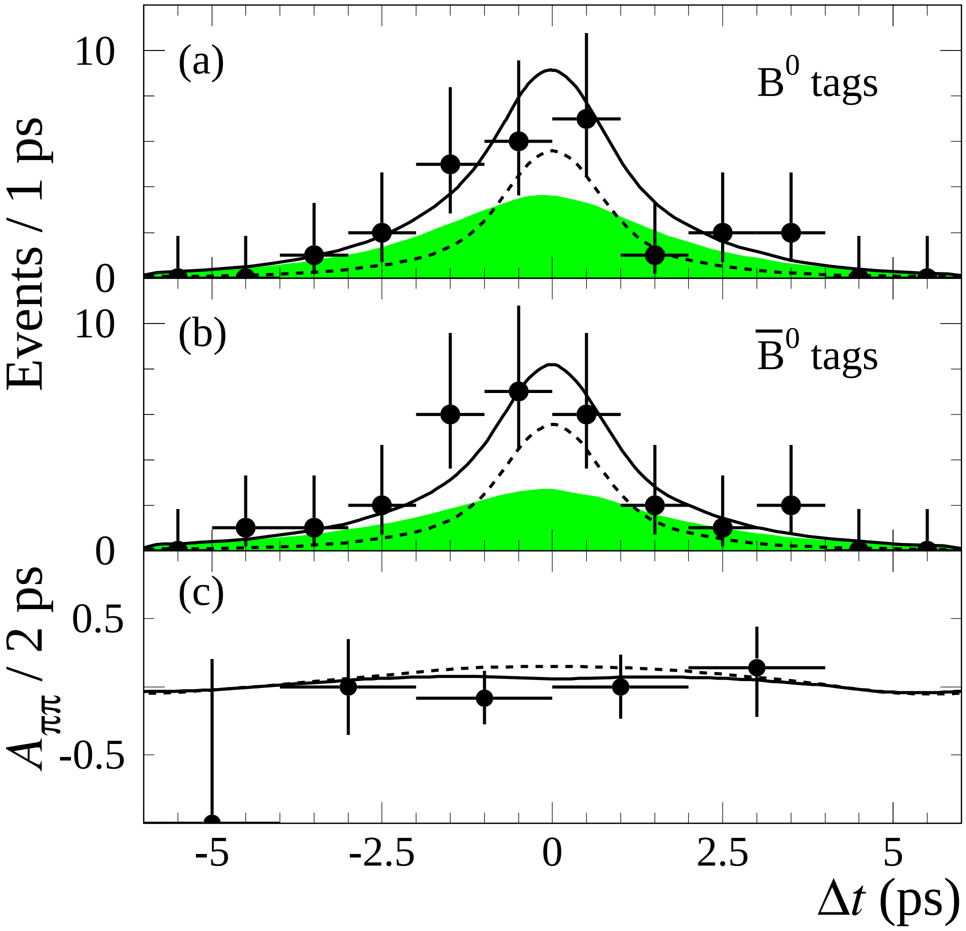
Beneke, Buchalla
Neubert & Sachradja
hep-ph/0104110



First Result on $\sin 2\alpha$

BaBar has published the first results on time-dependent CP asymmetry in $B \to \pi^+\pi^-$

Uses tagging and vertexing algorithms developed for the $\sin 2\beta$ analysis



$$S_{\pi\pi} = 0.03^{+0.53}_{-0.56} \pm 0.11$$

$$C_{\pi\pi} = -0.25^{+0.45}_{-0.47} \pm 0.14$$

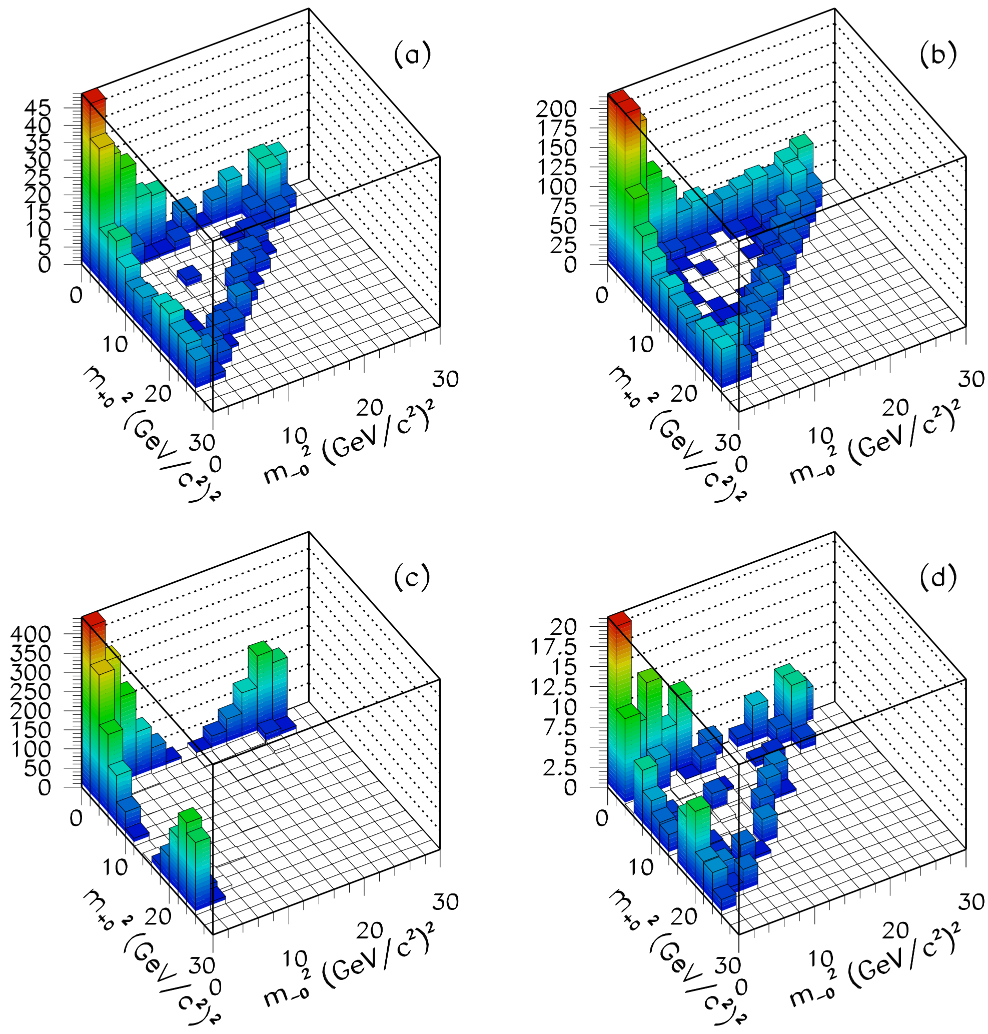
hep-ex/0110062, to appear in PRD

Future Measurements in B Decays

- $A_{CP}(t)$ measurement in $B^0 \to D^{(*)}D^{(*)}$ decays
  Should also give $\sin 2\beta$
- Observation of the decay $B^0 \to \pi^0\pi^0$
  Isospin analysis of $\pi^+\pi^-$, $\pi^+\pi^0$, $\pi^0\pi^0$
  can resolve penguin contribution
- Dalitz plot analysis of $B^0 \to \pi^\pm\rho^\mp$
  including time dependent CP analysis!
  Another way to determine $\sin 2\alpha$
- $A_{CP}(t)$ measurement in $B^0 \to \phi K_S$
  Decay described by gluonic penguin diagram
  In Standard Model also gives $\sin 2\beta$
- Direct CP violation in B^0 and B^+ decays
  particularily the $K\pi$ channels
  Best way to determine γ?
- Measurements of B_s decays at the LHC
  Examples are $B_s \to D_s K$ and K^+K^-

Observation of $B \to \pi\rho$

Data (Signal region) Data (Sideband)



Monte Carlo (Signal) Background-Subtracted Data

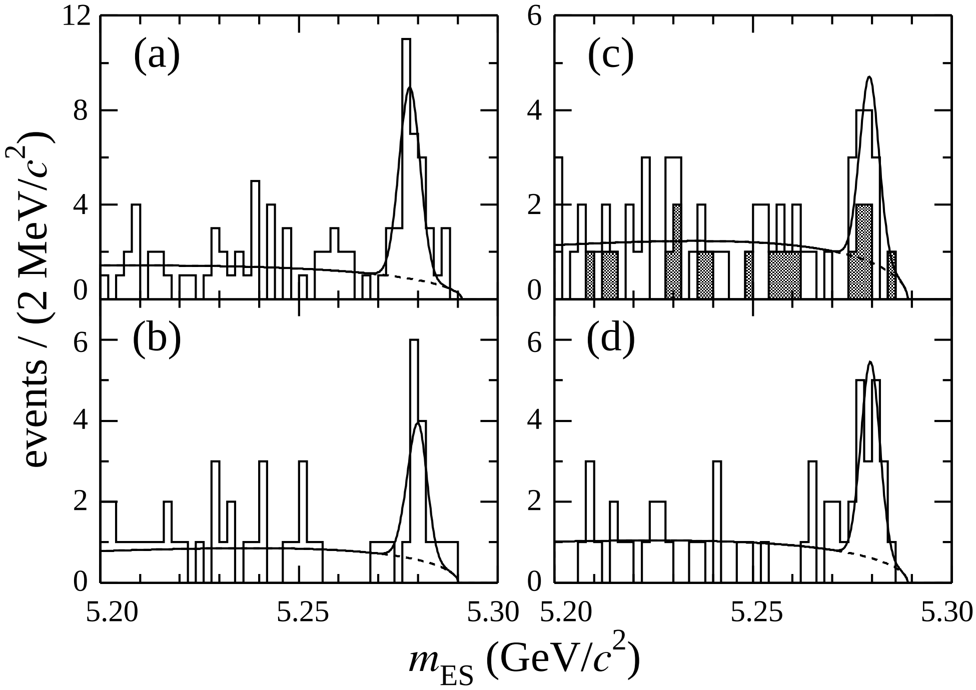
$$\mathcal{B}(B^0 \to \pi^\pm \rho^\mp) = (28.9 \pm 5.4 \pm 4.3) \times 10^{-6}$$

Gluonic Penguin Decays $B \to \phi K^{(*)}$

$B \to \phi K_s$ is a CP eigenstate. $A_{CP}(t) \propto \sin 2\beta$

If different from $\psi K_s \Rightarrow$ New Physics

BaBar has observed all four decay modes:



Decay Mode	Signal Events	Branching Fraction
(a) $B^+ \to \phi K^+$	$31.4^{+6.7}_{-5.9}$	$7.7^{+1.8}_{-1.6} \times 10^{-6}$
(b) $B^0 \to \phi K^0$	$10.8^{+4.1}_{-3.3}$	$8.1^{+3.2}_{-2.6} \times 10^{-6}$
(c) $B^+ \to \phi K^{*+}$	$11.5^{+5.1}_{-3.9}$	$9.7^{+4.5}_{-3.8} \times 10^{-6}$
(d) $B^0 \to \phi K^{*0}$	$20.8^{+5.9}_{-5.1}$	$8.7^{+2.7}_{-2.4} \times 10^{-6}$

PRL 87, 151801 (2001),hep-ex/0105001

Direct CP Violation in $K^0 \to \pi\pi$

Direct CP violation manifests itself as a difference between the decay rates to $\pi^+\pi^-$ and $\pi^0\pi^0$

$$A(K^0 \to \pi^+\pi^-) = \frac{1}{\sqrt{3}}\left(A_2 e^{i\delta_2} + \sqrt{2}A_0 e^{i\delta_0}\right)$$

$$A(K^0 \to \pi^0\pi^0) = \sqrt{\frac{2}{3}}\left(-\sqrt{2}A_2 e^{i\delta_2} + A_0 e^{i\delta_0}\right)$$

$$\frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \eta_{+-} = \epsilon + \epsilon'$$

$$\frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \eta_{00} = \epsilon - 2\epsilon'$$

$$\epsilon' \approx \frac{1}{\sqrt{2}} Im(\frac{A_2}{A_0}) e^{-i(\delta_2 - \delta_0)}$$

Measurements are of the double ratio:

$$\frac{\eta_{00}}{\eta_{+-}} = 1 - 6Re(\frac{\epsilon'}{\epsilon})$$

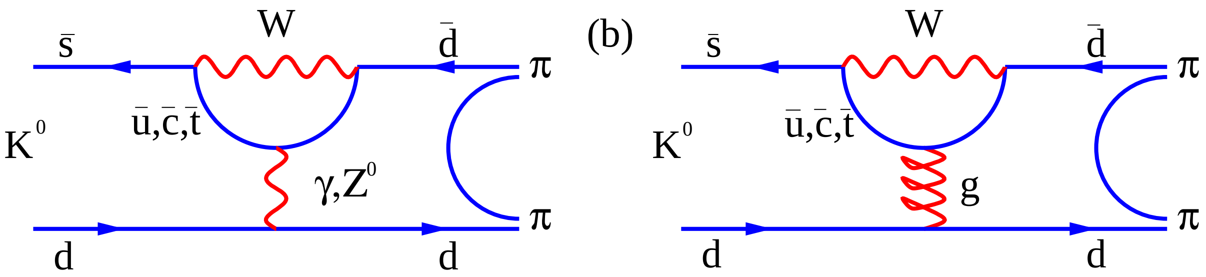
Definite observation in 2001 by NA48 & kTeV

$$\frac{\epsilon'}{\epsilon} = (17.2 \pm 1.8) \times 10^{-4}$$

First evidence for Direct CP violation!

Theoretical interpretation of ϵ'

Direct CP violation is the result of a small interference between gluonic and electroweak penguin diagrams:



Very difficult to calculate theoretically!

Before the measurements most calculations predicted:

$$\epsilon'/\epsilon \approx 5 \times 10^{-4}$$

A recent review by Buras et al gives a larger range:

$$1.5 \times 10^{-4} < \epsilon'/\epsilon < 28.8 \times 10^{-4}$$

It is hoped that reliable hadronic matrix elements can be obtained from lattice calculations

Direct CP Violation in Rare B Decays

All results are statistics limited

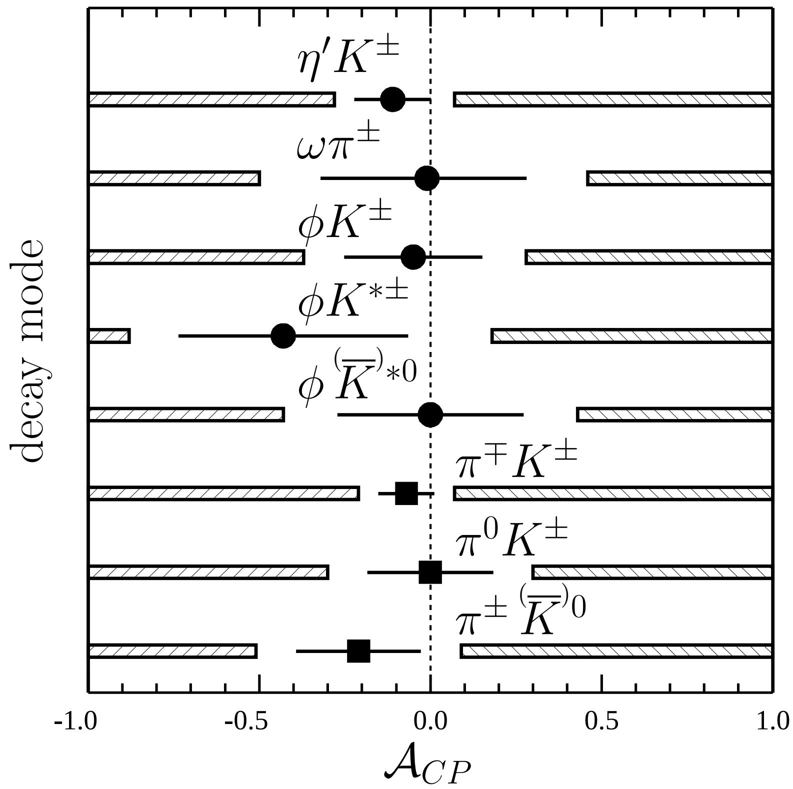
Detector asymmetries are small

Strategy is to look everywhere...

No evidence yet for Direct CP violation other than ϵ'

The best constraint comes from $K^+\pi^-$

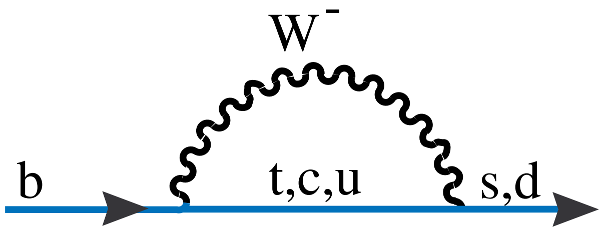
$$\mathcal{A}_{CP}(K\pi) = -0.07 \pm 0.08 \pm 0.02$$



Flavour-Changing Neutral Currents

Penguin graphs lead to FCNC decays

Clear signals have been seen for the radiative penguin decay $b \to s\gamma$:



The inclusive Branching Fraction for $b \to s\gamma$ has been calculated to next-to-leading order:
Chetyrkin, Misiak & Münz hep-ph/9612313

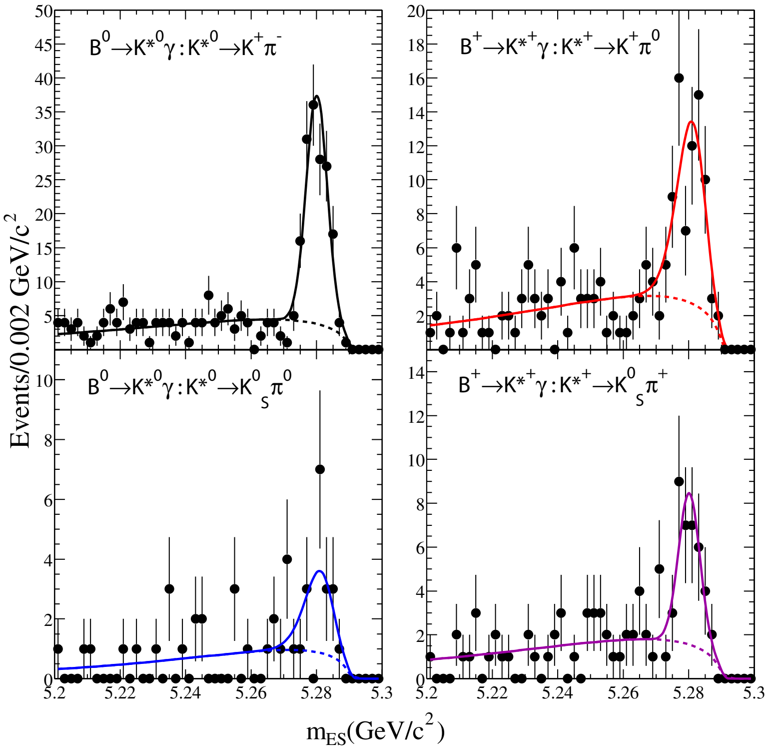
$$\mathcal{B}(b \to s\gamma) = (3.28 \pm 0.33) \times 10^{-4}$$

Experimental measurements give important constraints on new physics contributions in penguin diagrams (Charged Higgs, SUSY particles etc.)

ALEPH	$3.11 \pm 0.80 \pm 0.72$
BELLE	$3.36 \pm 0.53 \pm 0.44 \pm 0.52$
CLEO	$3.21 \pm 0.43 \pm 0.27 \pm 0.14$
Average	$(3.2 \pm 0.3 \pm 0.3) \times 10^{-4}$

Exclusive Decay $B \to K^*\gamma$

BaBar results on $B \to K^*\gamma$:



Decay Mode	Signal Events	Branching Fraction
$B^0 \to K^{*0}(K^+\pi^-)\gamma$	135.7 ± 13.3	$4.24 \pm 0.47 \times 10^{-5}$
$B^0 \to K^{*0}(K_s\pi^0)\gamma$	14.8 ± 5.6	$4.10 \pm 1.76 \times 10^{-5}$
$B^+ \to K^{*+}(K_s\pi^+)\gamma$	28.1 ± 6.6	$3.01 \pm 0.79 \times 10^{-5}$
$B^+ \to K^{*+}(K^+\pi^0)\gamma$	57.6 ± 10.4	$5.52 \pm 1.14 \times 10^{-5}$

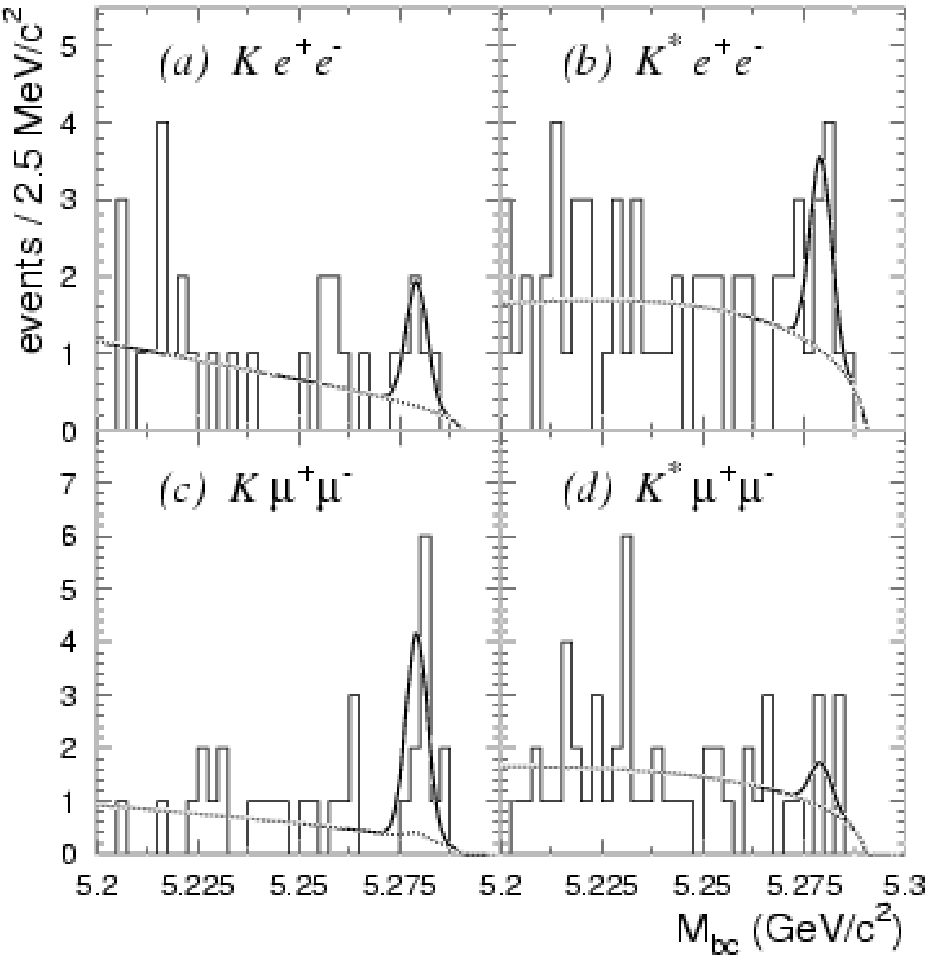
Direct CP violation search:

$$\mathcal{A}_{CP}(K^*\gamma) = -0.044 \pm 0.076 \pm 0.012$$

Observation of $B \to K\ell^+\ell^-$ by BELLE

Described by sum of electromagnetic penguin,
Z penguin and W^+W^- box diagrams

Branching fraction, dilepton mass and F/B Asymmetry are all sensitive to New Physics



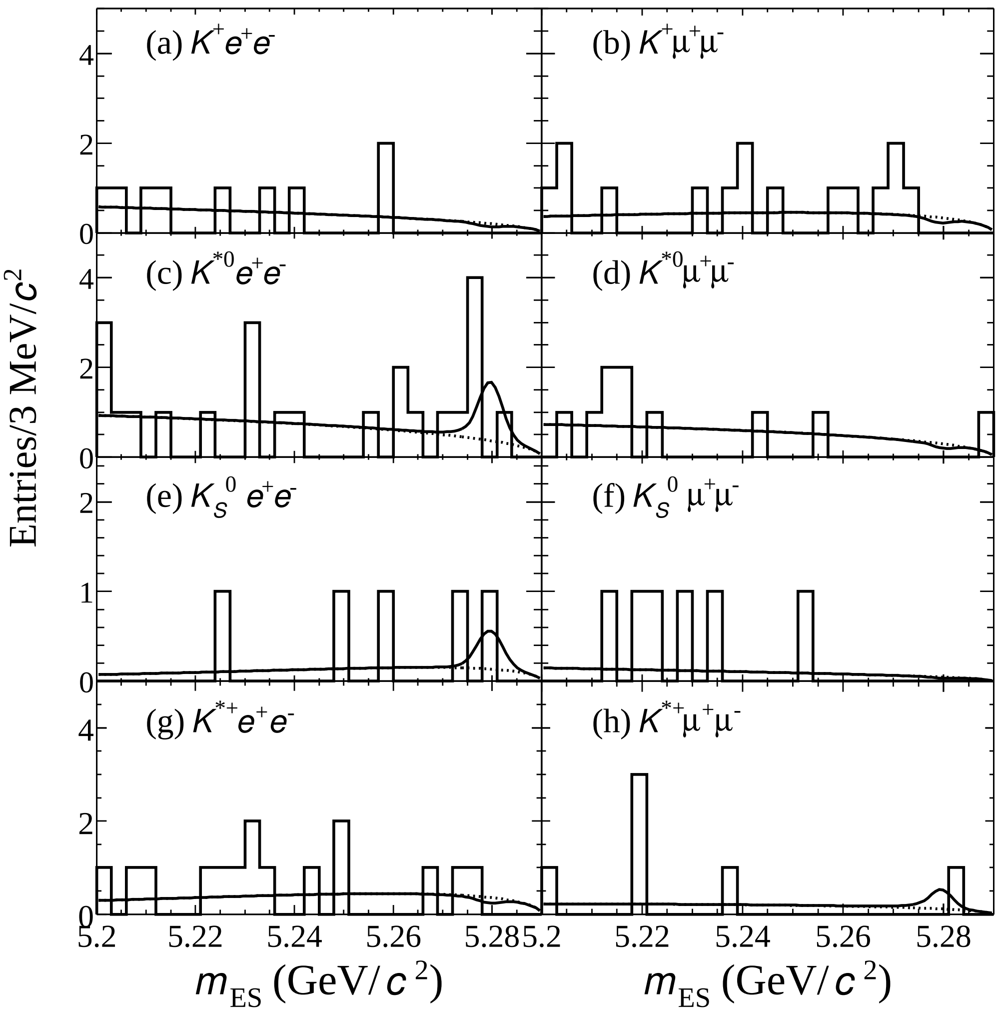
$$B \to K\ell^+\ell^- = (0.75^{+0.25}_{-0.21} \pm 0.09) \times 10^{-6} \qquad (5.3\sigma)$$

No evidence for $B \to K^*\ell^+\ell^-$?

PRL 88, 021801 (2002),hep-ex/0109026

BaBar results on $B \to K^{(*)}\ell^+\ell^-$

No evidence for these decays!



$B \to K\ell^+\ell^- < 0.50\times 10^{-6}$ $\quad$ $B \to K^*\ell^+\ell^- < 2.9\times 10^{-6}$

Upper limits close to Standard Model predictions:

$B \to K\ell^+\ell^- = 0.35\times 10^{-6}$ $\quad$ $B \to K^*e^+e^- = 1.6\times 10^{-6}$

Ali, Lunghi, Greub & Hiller, hep-ph/0112300

Rare Decays $K \to \pi\nu\bar{\nu}$

These decays are cleanly related to V_{td}

...but very difficult to measure experimentally!

Brookhaven experiment E787 has just reported a second candidate for $K^+ \to \pi^+\nu\bar{\nu}$ from data taken in 1995-1998:

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$$

This is about twice the Standard Model prediction

There are plans to search for $K_L \to \pi^0\nu\bar{\nu}$

... and for $B \to K\nu\bar{\nu}$

Lepton Flavour-Changing Decays

Since 1945 experimental limits have improved by an order of magnitude every 5 years!

Still no evidence for these decays:

$$\mathcal{B}(\mu \to e\gamma) < 1.2 \times 10^{-11}$$

$$\mathcal{B}(\mu \to e^+e^-e^+) < 1.0 \times 10^{-12}$$

Best sensitivity comes from SINDRUM-II experiment on $\mu \to e$ conversion on nuclei:

$$\mathcal{B}(\mu^- \to e^-) < 6.1 \times 10^{-13}$$

...and from the B factories:

$$\mathcal{B}(\tau \to \mu\gamma) < 1.1 \times 10^{-6}$$

Some supersymmetric theories predict branching fractions just below these limits

Future experiments on μ decays are planned at PSI (MEG) and Brookhaven (MECO)

Neutrino Oscillations

The neutrino flavour eigenstates, ν_e, ν_μ, ν_τ, can mix into three mass eigenstates, ν_1, ν_2, ν_3:

$$\nu_\ell = V_{MNS}\nu_m$$

where V_{MNS} is a 3×3 matrix similar to V_{CKM}

Simple 2×2 Mixing of ν_μ and ν_τ:

$$\nu_\mu = \nu_2 \cos\theta_{23} + \nu_3 \sin\theta_{23}$$

$$\nu_\tau = -\nu_2 \sin\theta_{23} + \nu_3 \cos\theta_{23}$$

Leads to flavour oscillations of neutrinos

An initial ν_μ beam has a probability of being observed as a ν_μ given by:

$$P_\mu = 1 - \sin^2\theta_{23} \sin^2 \frac{1.27\Delta m_{23}^2 L}{E_\nu}$$

where Δm_{23} is the neutrino mass difference

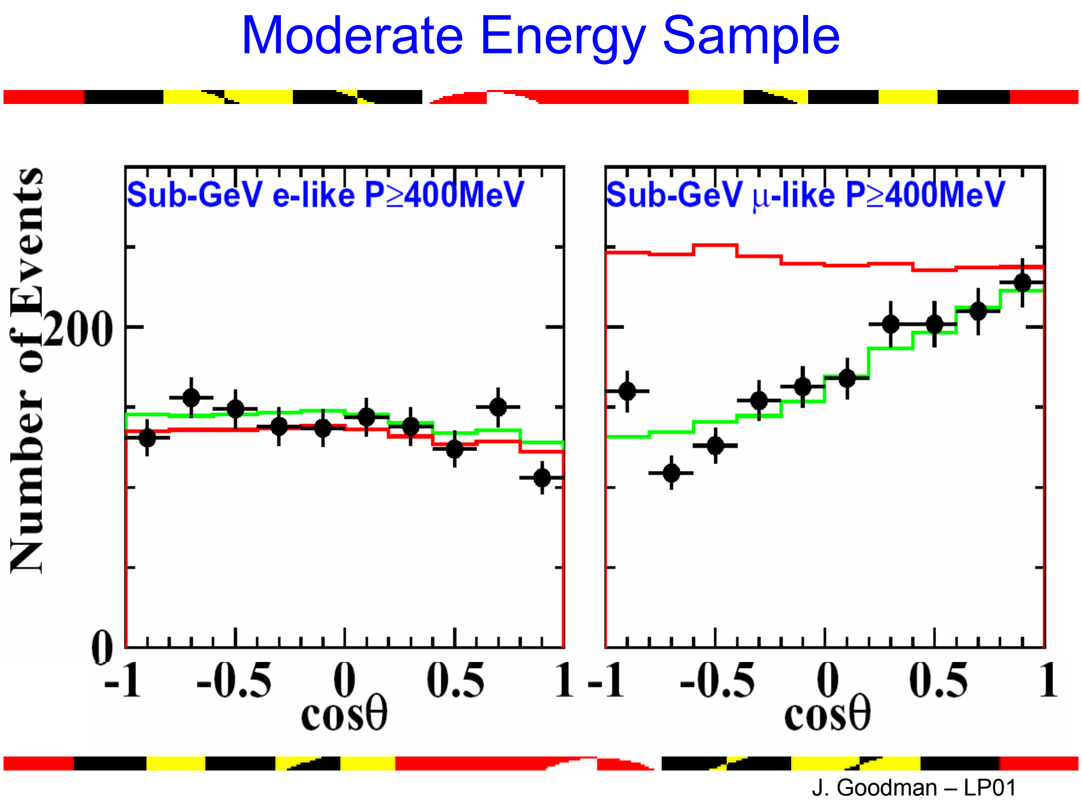
L is the oscillation length or "baseline"

E_ν is the neutrino energy

Atmospheric Neutrinos

Cosmic rays produce exactly twice as many ν_μ as ν_e in the upper atmosphere

SuperKamiokande observes differences between upward and downward neutrinos which are consistent with disappearance of ν_μ due to oscillations into ν_τ

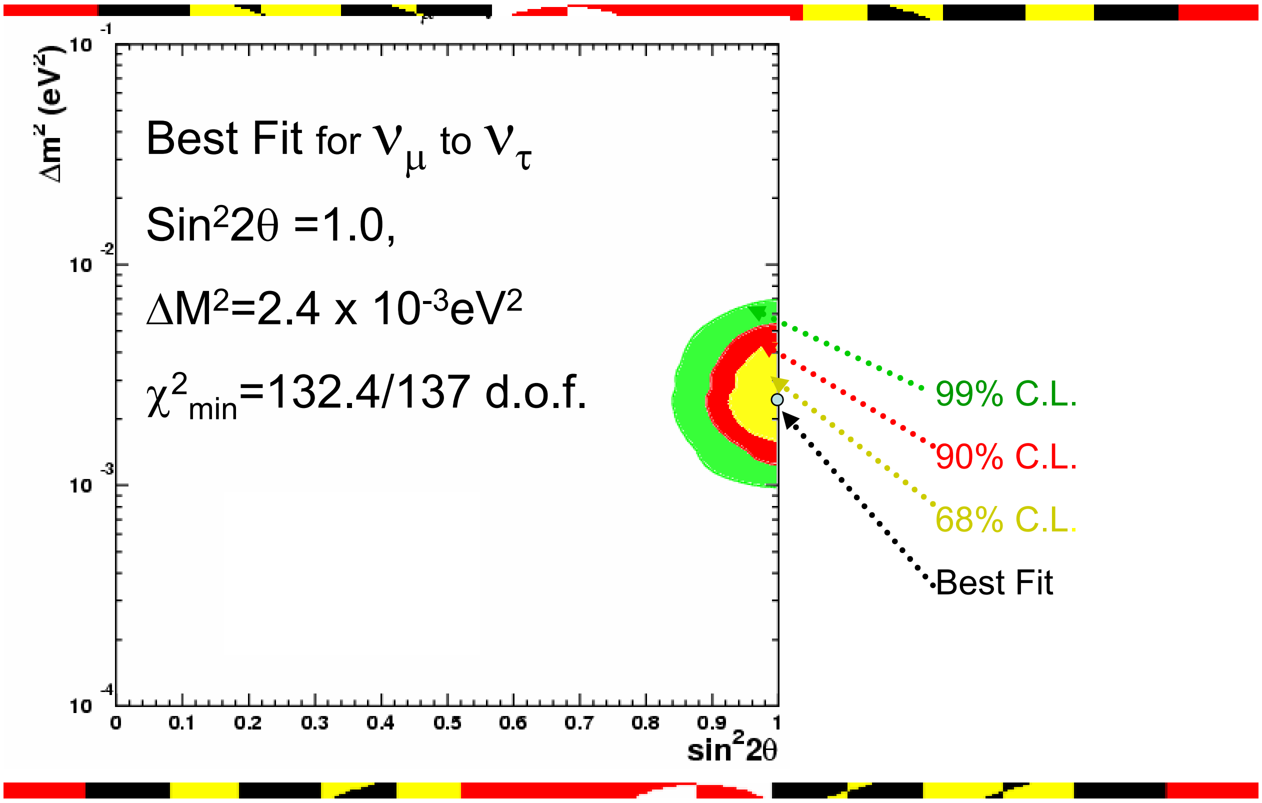


One of many plots showing evidence of this effect

Neutrino Oscillation Parameters

Constraints on $\sin^2\theta_{23}$ and Δm^2_{23} from atmospheric neutrino data:

Summary of Atmospheric Results



J. Goodman – LP01

$\sin 2\theta_{23} \approx 1 \Rightarrow$ maximal mixing!

Solar Neutrinos

The sun produces low energy ν_e which have been detected by several experiments

Spectrum and flux are predicted by
Solar models (John Bahcall)

Experiments:

GALLEX and SAGE - pp neutrinos

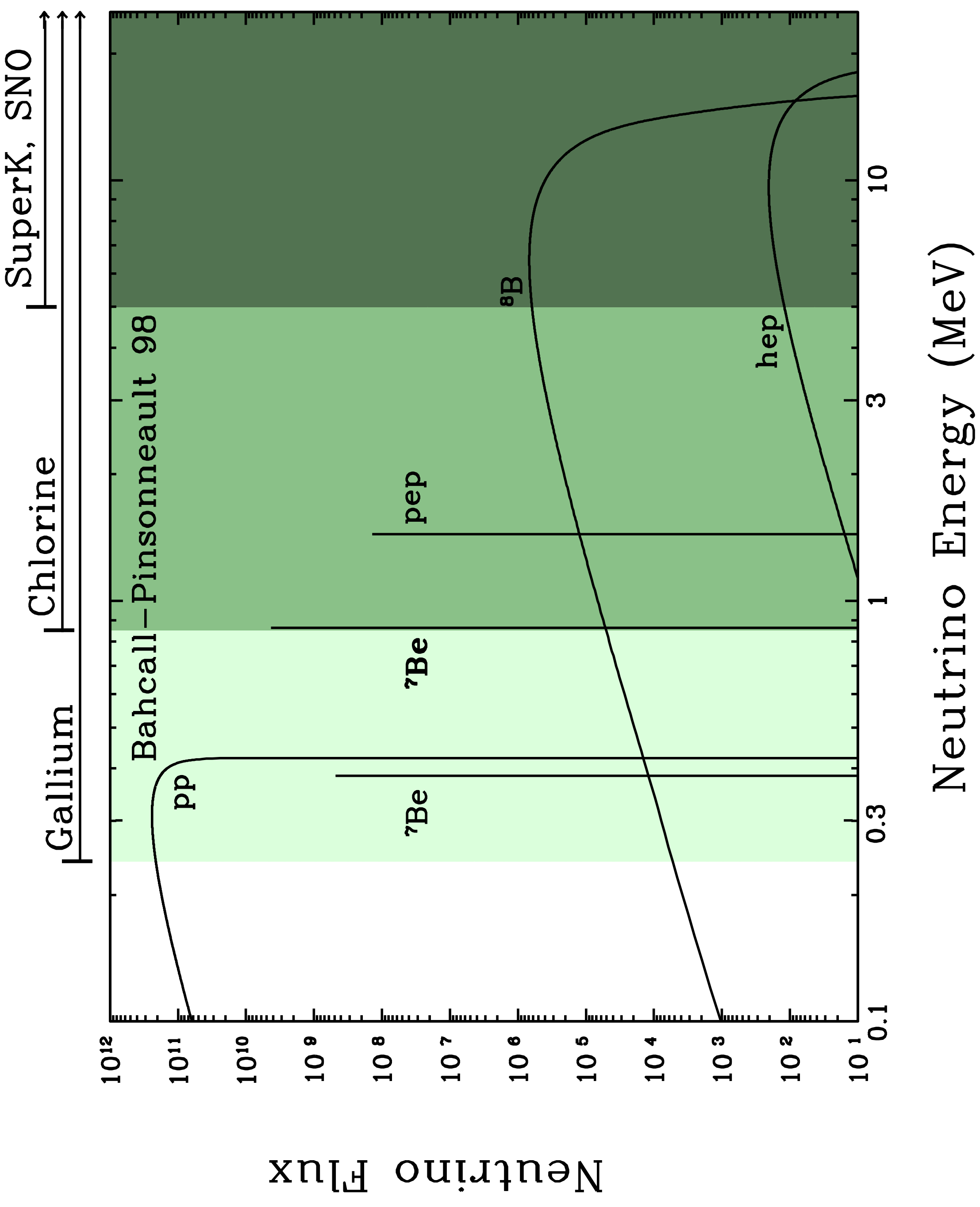
Davis (Chlorine) - Be and B neutrinos

SuperKamiokande - B neutrinos
(charged current interactions)

SNO (Heavy Water) - B neutrinos
(neutral and charged currents)

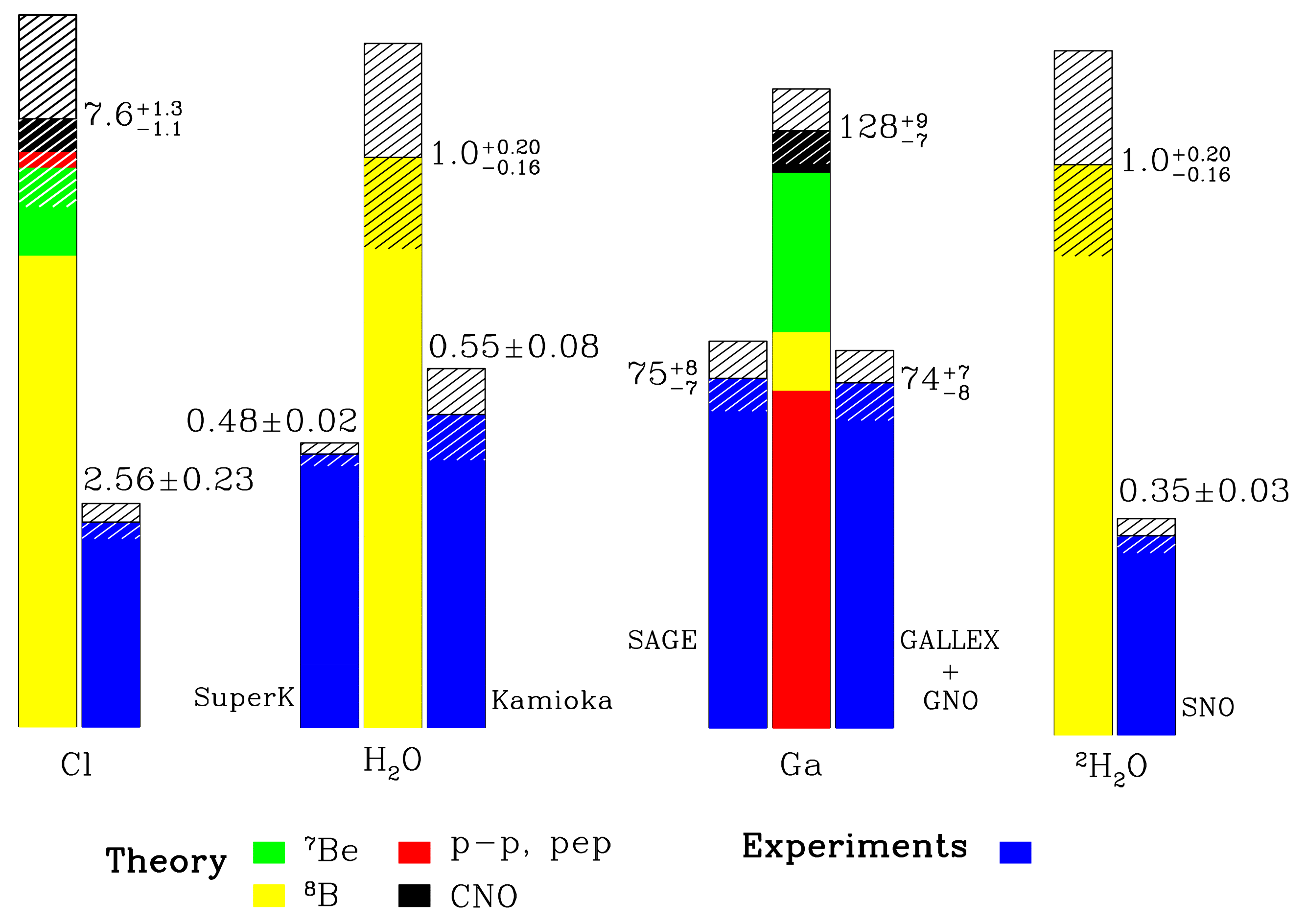
Solar neutrino problem!
All experiments see too low a flux

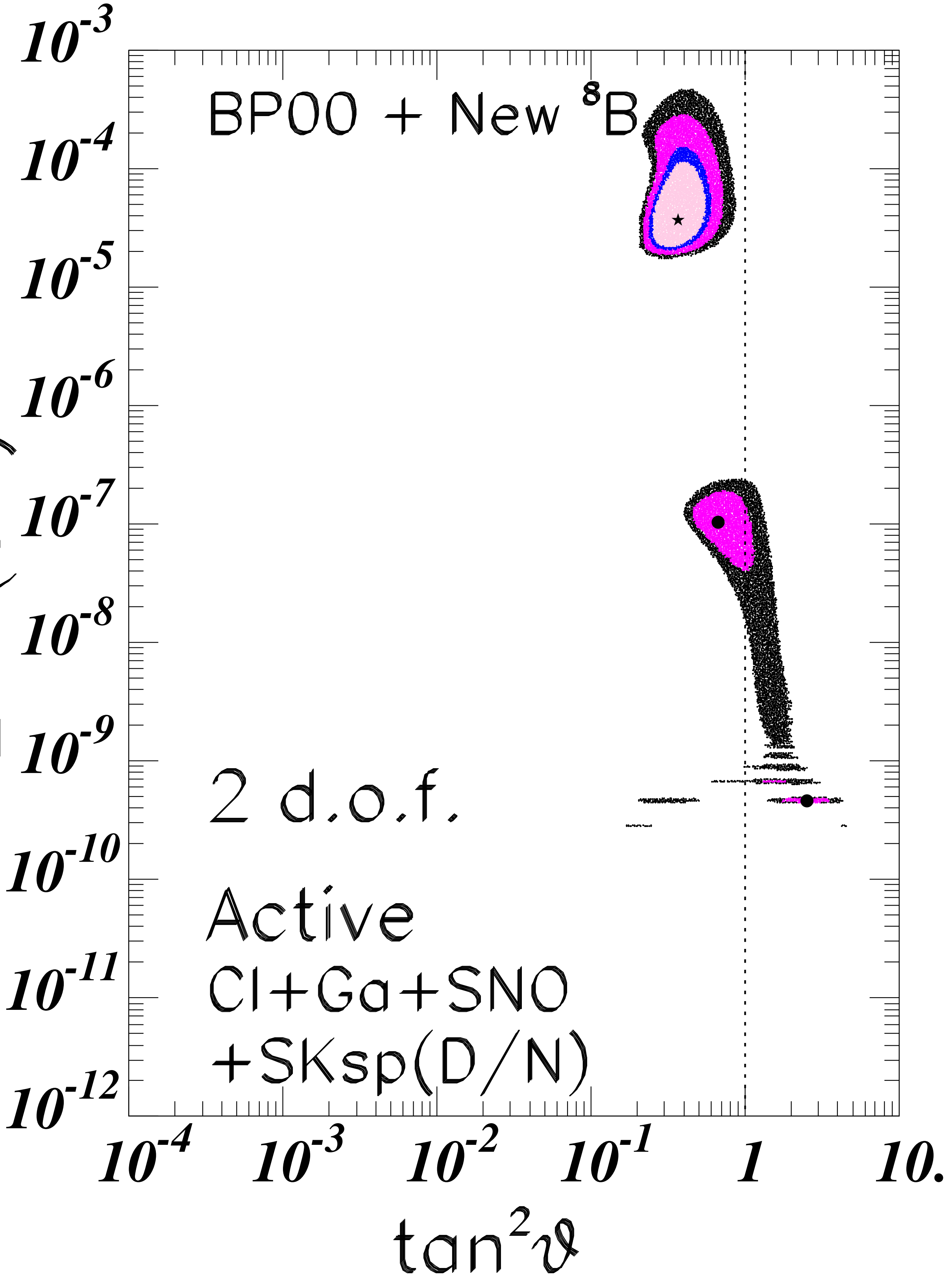
Interpreted as evidence for ν_e oscillations to ν_μ or ν_τ



Gallium
Chlorine
SuperK, SNO
Bahcall–Pinsonneault 98
pp
⁷Be
pep
⁸B
hep
Neutrino Flux
Neutrino Energy (MeV)
0.1
0.3
1
3
10

Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000




BP00 + New ^{8}B
2 d.o.f.
Active
Cl+Ga+SNO
+SKsp(D/N)
Δm^2 (eV^2)
$\tan^2\vartheta$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10.

CP Violation in Lepton Sector?

$$V_{MNS} =$$

Atmospheric

$$\begin{pmatrix} 1 & & \\ & 1/\sqrt{2} & 1/\sqrt{2} \\ & -1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix} \times$$

CP Violating via δ?

$$\begin{pmatrix} cos\theta_{13} & & \sin\theta_{13}e^{-i\delta} \\ & 1 & \\ -\sin\theta_{13}e^{i\delta} & & \cos\theta_{13} \end{pmatrix} \times$$

Solar

$$\begin{pmatrix} 0.85 & 0.51 & \\ -0.51 & 0.85 & \\ & & 1 \end{pmatrix}$$

Possible link between **Leptogenesis** and **Baryogenesis** in early universe