The Asymmetry between Matter and Antimatter

In the Universe

and

in the laws of physics

In the Universe

Now

Lots of matter

Very little antimatter

At the beginning?

Does starting condition matter?

If no conservation law protects it,

then thermal equilibrium rules give equality

Pauli 1933 –letter to Heisenberg

I do not believe in the hole theory, since I would like to have the asymmetry between positive and negative electricity in the laws of nature (it does not satisfy me to shift the empirically established asymmetry to one of the initial state).

After the discovery of positrons!

In the laws of physics

Until 1964 we thought there was exact symmetry

Experiment told us otherwise

We know one tiny difference affecting quark decays

Maybe there is a similar effect in neutrinos

C, P and T operations

C converts every particle to its antiparticle

P reverses all coordinates (mirror reflection plus rotation)

C and P   conserved in strong and e-m interactions
Maximally violated in weak interactions – 1956

T reverses in and out (initial and final) states

CPT – product of all three operations

Exact symmetry of all field theories with

Hermitian Lagrangian

Lorentz invariance

In any simple (few particle) theory this also gives CP and T symmetry separately

Example --QED

Gauge theory –one universal coupling

$$g\overline{\psi}\gamma_\mu A^\mu\psi + g^*\overline{\psi}\gamma_\mu A^\mu\psi$$

Hermitian lagrangian: g+g* is real

Adding mass term:

$$\overline{\psi}(a + b\gamma_5 b)\psi + \overline{\psi}(a * - b^*\gamma_5)\psi = \overline{\psi}[(a + a^*) + (b - b^*)\gamma_5]\psi$$

Make this real by chiral rotation $\psi' = e^{i\phi\gamma_5}\psi$

CP Symmetry violating effects

CP conjugate rates differ

or

Mass eigenstates are not CP eigenstates

for neutral but flavoured mesons K, D and B

Neutral flavoured mesons

Produced and decay as states of definite flavour

$$K^0 = \overline{s}d \qquad \overline{K}^0 = \overline{d}s$$

$$D^0 = \overline{u}c \qquad \overline{D}^0 = \overline{c}u$$

$$B^0 = \overline{b}d \qquad \overline{B}^0 = \overline{d}b$$

$$B_s = \overline{b}s \qquad \overline{B}_s = \overline{s}b$$

States of definite CP are mixtures

$$K_{even} = \frac{K^0 + \overline{K}^0}{\sqrt{2}} \qquad K_{odd} = \frac{K^0 - \overline{K}^0}{\sqrt{2}}$$

1964 - CP violation in K decays

Long lived neutral K decays to two pions

CP symmetry forbids this decay

$$K_{long} = p_K K^0 - q_K \overline{K}^0 \quad \approx \quad K_{odd} + \tilde{\epsilon} K_{even}$$

Not a CP eigenstate

$$\tilde{\epsilon} \approx 10^{-3}$$

Why was this a surprise?

In 1964 what field theories were known?

QED

Four- Fermi theory for beta decay

strong force from pi meson

Yukawa couplings

All have automatic CP symmetry

CP Violation in decays

An interference effect, if

$$A = g_1 e^{i\phi_1} r_1 e^{i\delta_1} + g_2 e^{i\phi_2} r_2 e^{i\delta_2}$$

CP conjugate process

$$\overline{A} = g_1 e^{-i\phi_1} r_1 e^{i\delta_1} + g_2 e^{-i\phi_2} r_2 e^{i\delta_2}$$

Rate difference

$$|A|^2 - |\overline{A}|^2 = 2 g_1 g_2 r_1 r_2 \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)$$

Both phases must differ!

Redefining fields can make most couplings real

For a simple field theory hermiticity alone does it.

Quark weak couplings

$$g V_{ij}\ \overline{q}_i \gamma_\mu W^\mu q_j + g V_{ij}^*\ \overline{q}_j \gamma_\mu W^{\mu *} q_i$$

$$\frac{g^2}{8 M_W^2} = \frac{G_F}{\sqrt{2}}$$

Redefining the phases of quark fields

$$q_i \longrightarrow e^{i\alpha_i} q_i'$$

Gives

$$g e^{i(\alpha_j - \alpha_i)} V_{ij}\ \overline{q}_i' \gamma_\mu W^\mu q_j' \quad + \quad g e^{i(\alpha_i - \alpha_j)} V_{ij}^*\ \overline{q}_j' \gamma_\mu W^{\mu *} q_i'$$

$$= g V_{ij}'\ \overline{q}_i' \gamma_\mu W^\mu q_j' \quad + \quad g V_{ij}'^*\ \overline{q}_j' \gamma_\mu W^{\mu *} q_i'$$

3 generation Standard Model

One phase left after all possible phase changes

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

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

Special case: Neutral flavored mesons

Mass eigenstates not CP eigensates

---- seen in K decays

Interference between decay before mixing and decay after mixing –seen in B decays

Both also require two relatively-complex couplings

B decays: Time evolving admixture

Produced state is not definite mass state

$$B_{Light} = pB^0 + q\overline{B}^0 \qquad B_{Heavy} = pB^0 - q\overline{B}^0$$

State that at time t=0 is pure B^0

evolves in time

$$B^0(t) = \frac{e^{i(M+i\Gamma)t/2}}{2p}[e^{i(\Delta M+i\Delta\Gamma)t/4}B_{Heavy} + e^{-i(\Delta M+i\Delta\Gamma)t/4}B_{Light}]$$

Time dependant CP asymmetry

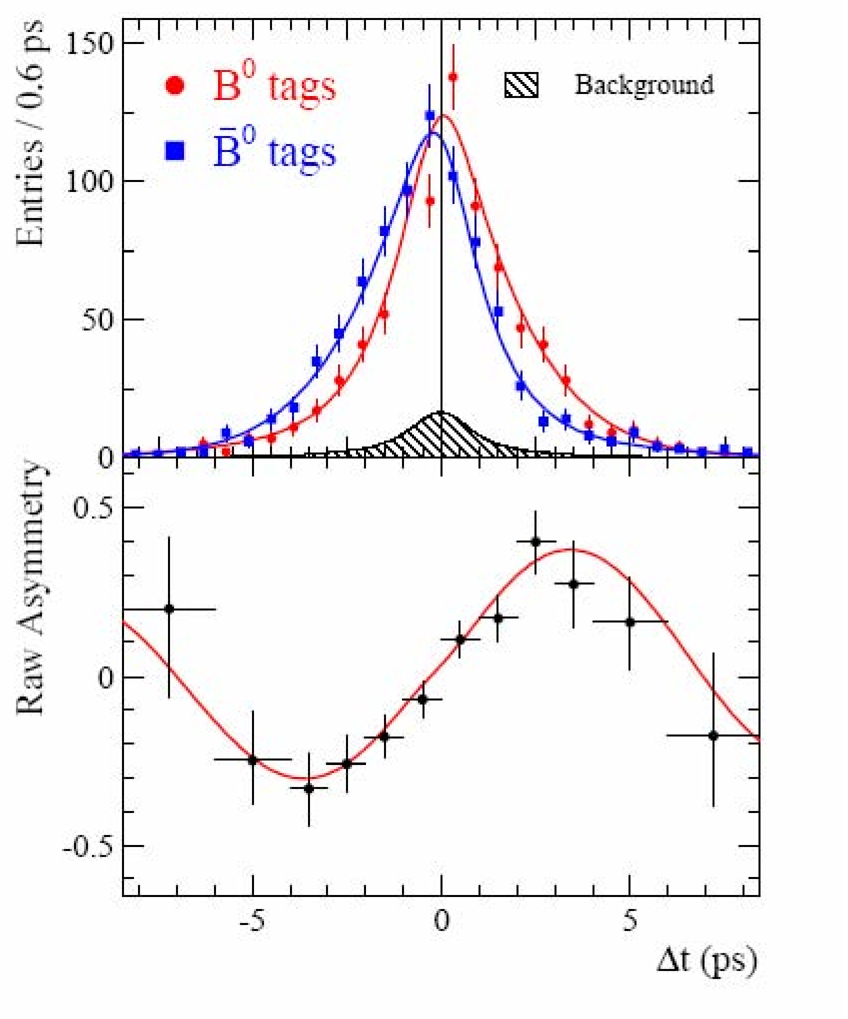
Data from BaBar

$$e^+e^- \to B^0 + \overline{B}^0$$

One B is 'tag'

Other B decays via

$$B(t) \to J/\psi K_S$$



Clean prediction from Standard Model

Asymmetry in $B(t) \to J/\psi K_S$

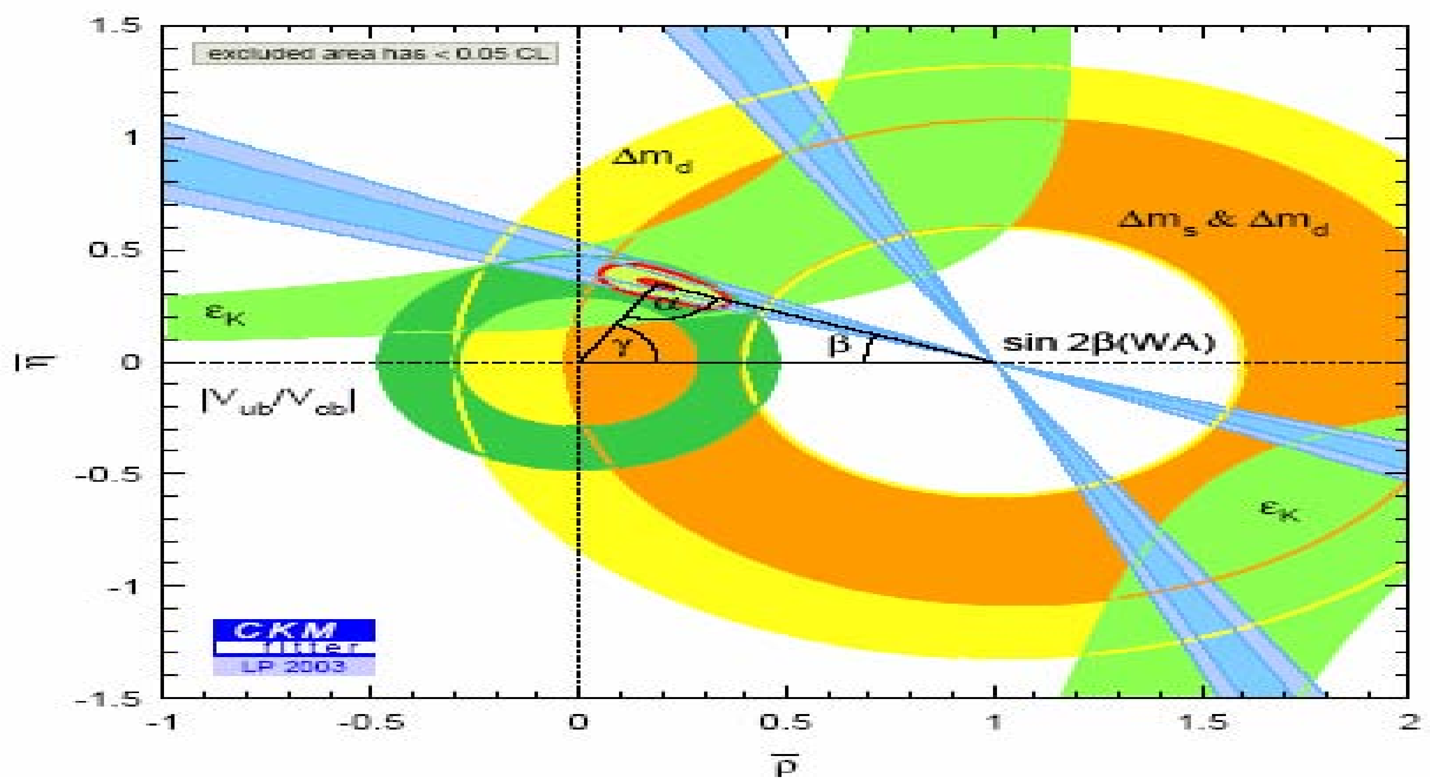
$A_f = A(B^0 \to f)$ $\overline{A}_f = A(\overline{B}^0 \to \overline{f}) = \eta_f A(\overline{B}^0 \to f)$

$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}$ $|q/p| = 1$ $|\frac{\overline{A}_f}{A_f}| = 1$

$$R(t_{\rm tag}, t_f) \propto \left\{ \frac{1+|\lambda_f|^2}{2} \mp \cos \Delta m(t_f - t_{\rm tag}) \left(\frac{1-|\lambda_f|^2)}{2} \right) \right.$$

$$\left. \pm \sin \Delta m(t_f - t_{\rm tag}) \,\mathrm{Im}\, \lambda_f \right\}$$

Standard Model – Fits all data



Ongoing experimental program

Look at multiple other decay channels

Many interlocking predictions

Does full pattern fit?

New physics can change many predictions!

But what about the Universe?

Sakharov's 3 conditions:

Baryon number non-conservation

CP violation

Out of equilibrium condition

Quark scenario

Phase transition in Higgs field vacuum value

our universe = inside bubble

Matter and antimatter penetrate bubble wall differently

Two BIG problems:

Higgs mass too heavy –no phase transition

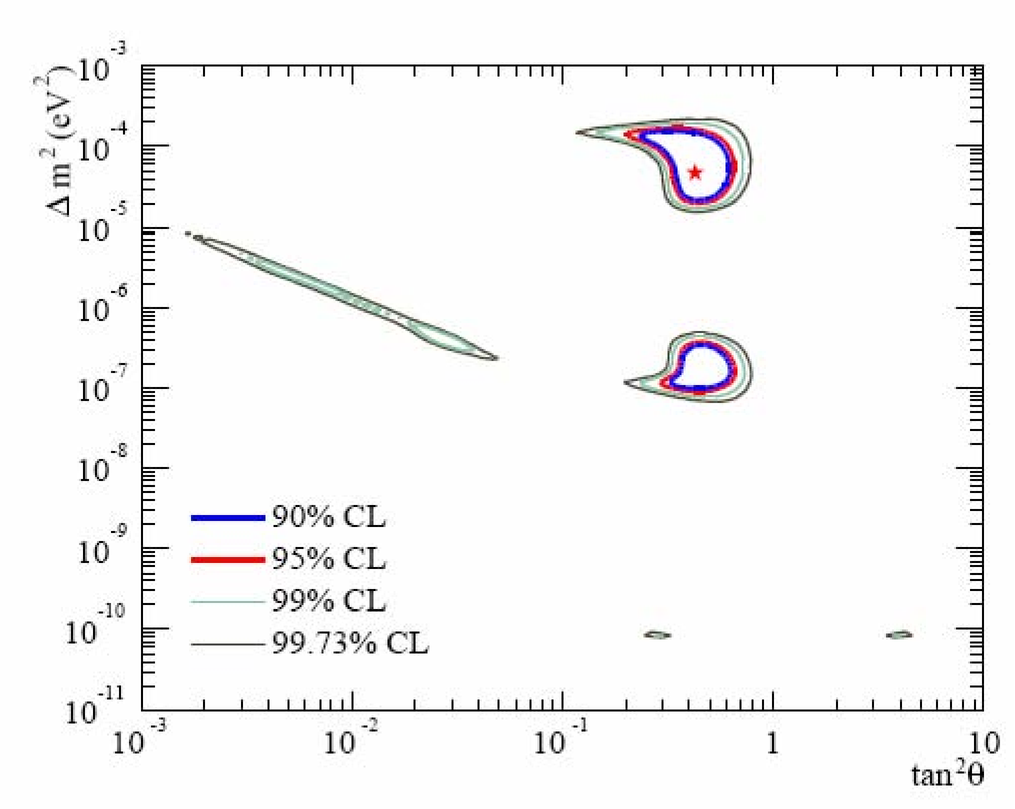
Even if we fix that –imbalance much too small to give observed baryon to photon ratio

Neutrinos have mass and ‘mix’ 1

Solar neutrinos

-- SNO data

-- e and tau

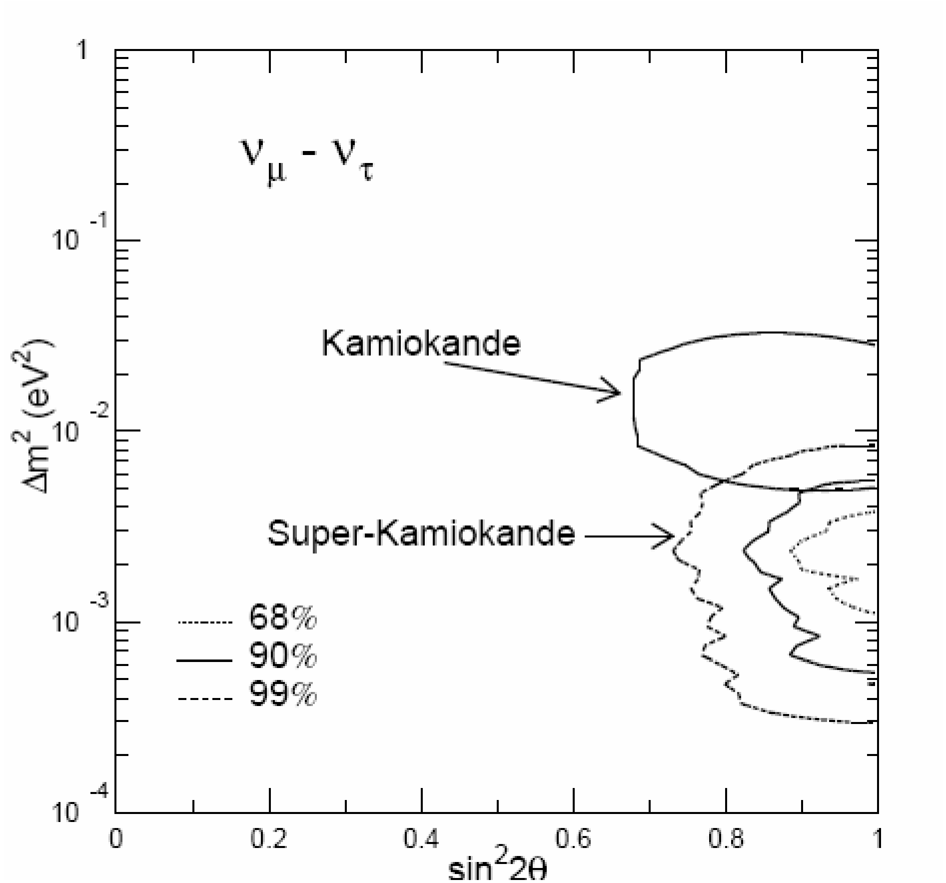


Neutrinos have mass and ‘mix’ - 2

Atmospheric

(Cosmic ray)

Mu and tau



Neutrino mass and `mixing’

Produced and decay in association with a lepton flavour: e-type, mu-type, tau-type

Mass eigenstates are mixtures of flavours

Thus in mass basis neutrinos have a matrix of couplings – like that for quarks

Neutrino CP violation ?

Formalism allows it

So far we only have an upper limit on the term that mixes generations 1 and 3

- target of next generation experiments

Size of that term will determine whether we can see neutrino CP violation

Very massive neutrino states

- Massless neutrinos were pure left handed
- Massive neutrinos are not!
- Almost all theories to add neutrino mass also add extra very massive neutrino states
- Very little interaction with known particles

Neutrino scenario

Heavy neutrino states

produced in hot early Universe

decouple from other matter early

CP Violation in their decays gives

matter-antimatter imbalance

3 viable (?) answers to the puzzle

1. Initial condition + Conservation Law
   (B-L conservation)

2. CP violation in quark sector
   + extended theory

3. CP violation in neutrino sector
   + extended theory