IoP Masterclass

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FLAVOUR PHYSICS

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The Standard Model

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Fermions ("matter")	Bosons ("forces")
$\left\{ \begin{array}{c} \text{Quarks} \\ u u u \quad c c c \quad t t t \\ d d d \quad s s s \quad b b b \\ \\ \text{Leptons} \\ e \quad \mu \quad \tau \\ \nu_e \quad \nu_\mu \quad \nu_\tau \end{array} \right\} \times \left\{ \begin{array}{c} \text{MATTER} \\ \text{ANTIMATTER} \end{array} \right\}$	$g g g g g g g g$ γ W^+ W^- Z H

Some Questions

- What is antimatter?
- Why are there three “colours” of quarks?
- Why are there so many bosons?

These questions have well-understood answers

Some More Questions

- Why are there so many fermions?
- Why are there three “generations” of both quarks and leptons?

  (“flavour”)
- Why are matter and antimatter different?

  (“CP violation”)

We do not know the answers to these questions!

Matter *vs.* antimatter

- In the Big Bang, matter and antimatter should have been produced in equal quantities
- In the Universe today, we observe only matter

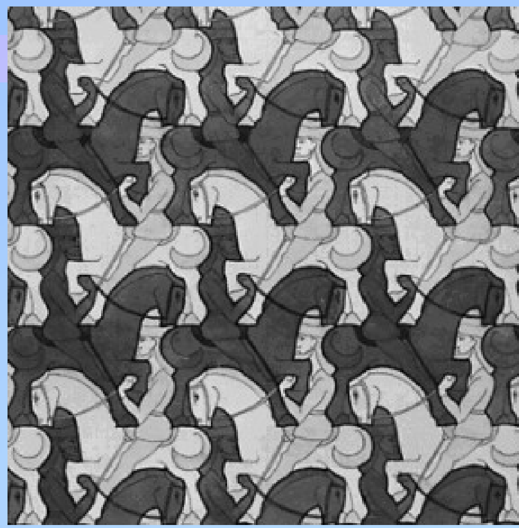
$\Rightarrow$ need *CP violation*

What is CP Violation?

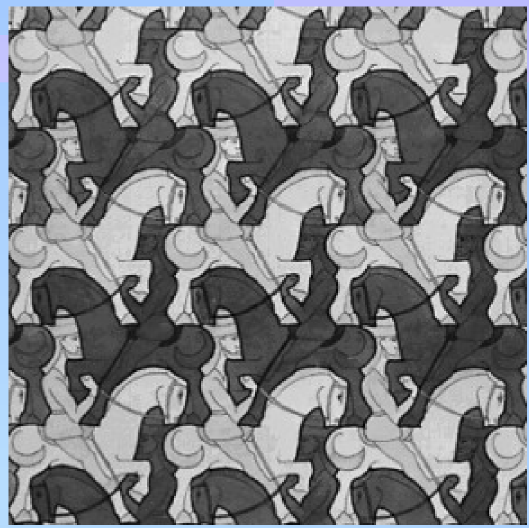
- Symmetries are powerful tools to understand nature
- Two important discrete symmetries are
  - C : charge conjugation
    (exchange particle and antiparticle)
  - P : parity
    (mirror transform all spatial coordinates)

Need violation of combined CP symmetry to distinguish absolutely between matter & antimatter

CP Symmetry



P



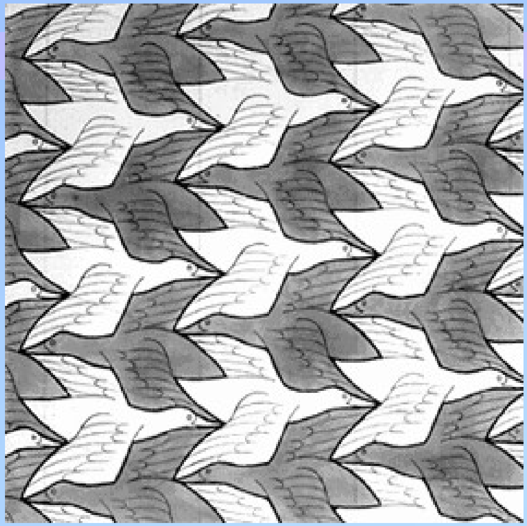
C

CP

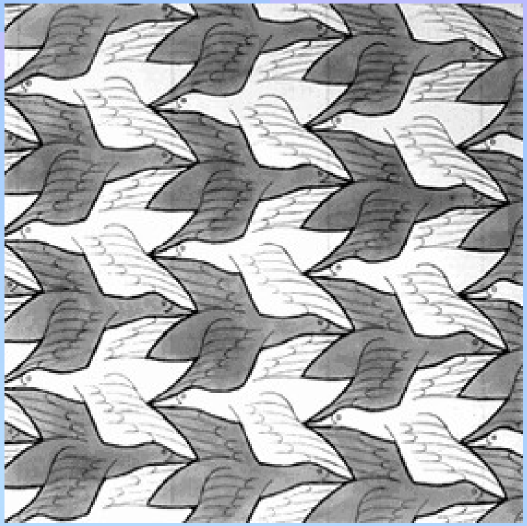
Combined CP transformation
⇒ pictures look the same

Illustrated using the images of MC Escher

CP Violation



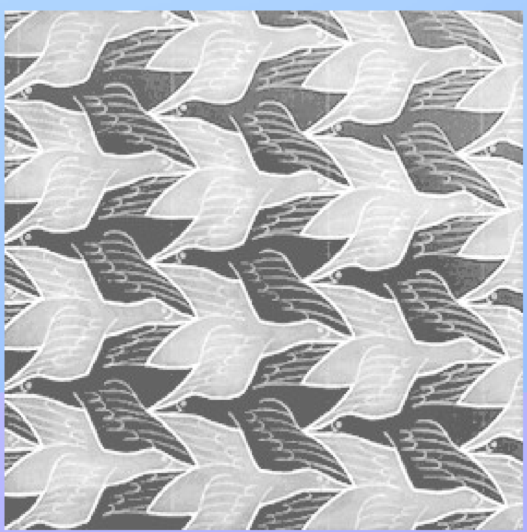
P



C

CP

Combined CP transformation
$\Rightarrow$ pictures look different!



Illustrated using the images of MC Escher

Addressing the questions

- Questions discussed above appear to be fundamental
- Unfortunately, we do not know how to answer them
- Do not give up! Instead:
  - Measure related processes
    - flavour changes
    - CP violation

    both quark & lepton sectors
  - Look for clues

The CKM Matrix

- Quark mixing described by Cabibbo-Kobayashi-Maskawa matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

down-type quarks as seen by the weak interaction

physical down-type quarks (with well-defined masses)

- Matrix elements are complex numbers
  - interactions of quarks and antiquarks can be different

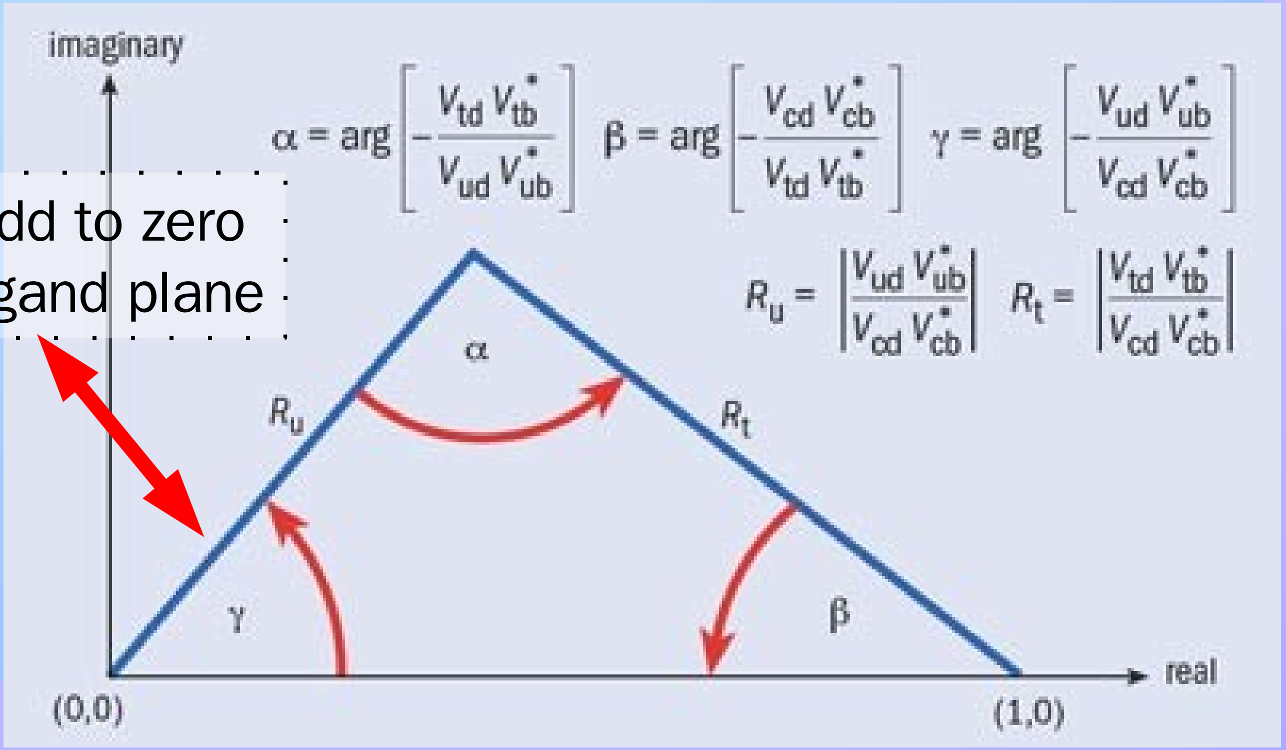
$\Rightarrow$ CP violation!

The Unitarity Triangle

- Squares of CKM matrix elements describe probabilities
  $\Rightarrow$ matrix must be *unitary*

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

Three complex numbers add to zero
$\Rightarrow$ triangle in Argand plane

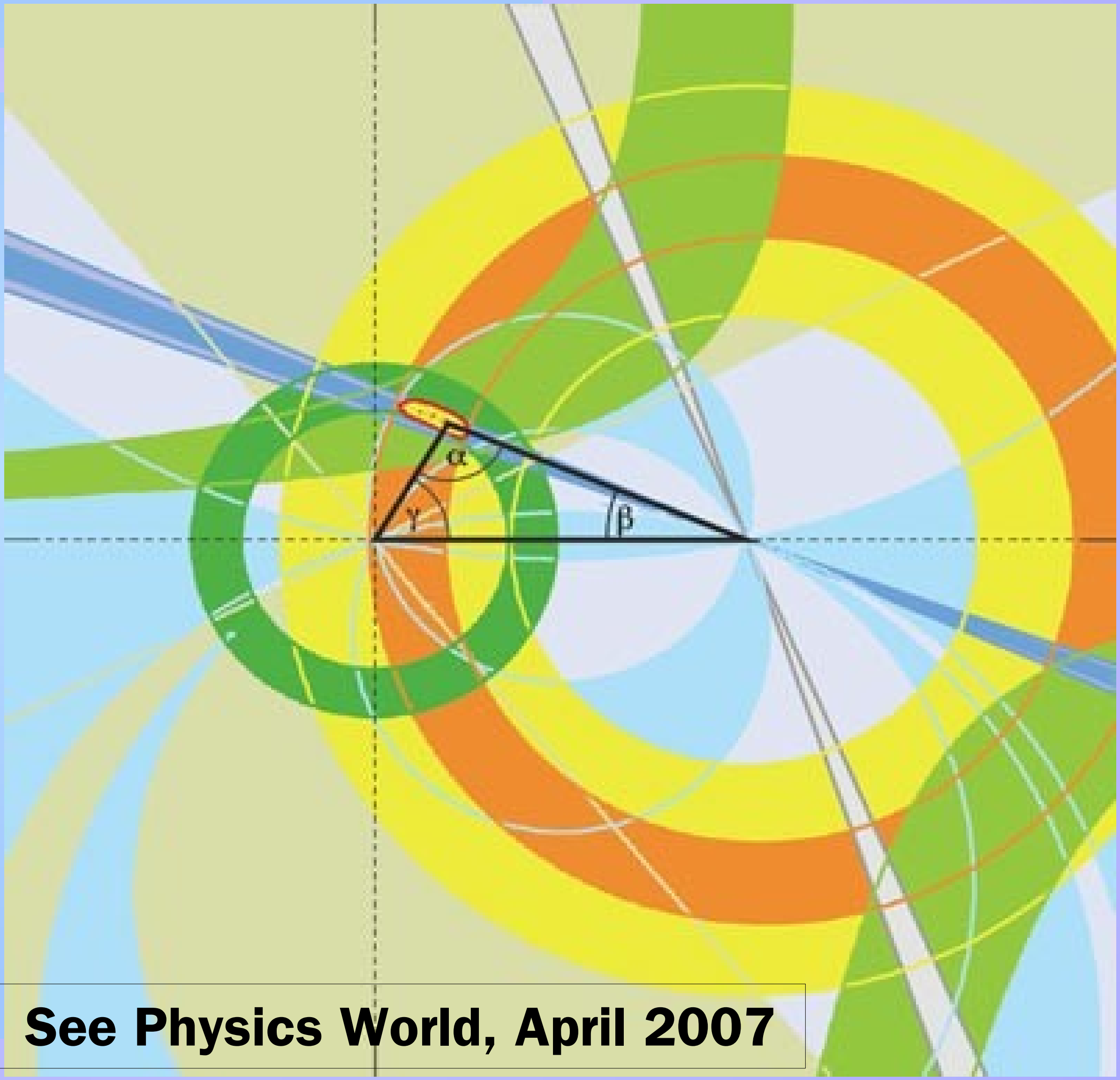


Current Status

- Measurements of Unitarity Triangle parameters test CKM picture
  $\Rightarrow$ BABAR experiment

- So far, all results are consistent

- Ongoing effort to improve precision



See Physics World, April 2007

Neutrino Physics

- Leptons mix just like quarks
  - mixing pattern described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) lepton mixing matrix
- Yet study of lepton flavours remarkably different
  - leptons are not bound by the strong interaction
  - neutrinos do not interact electromagnetically
  - neutrinos are much lighter than other particles

Neutrino Physics Questions

- Until recently biggest question was
  - "Do neutrinos have mass?"

    Observation of neutrino oscillations $\Rightarrow$ YES!
- Biggest questions now
  - what are the neutrino mixing parameters?

    $\Rightarrow$ T2K experiment
  - is the neutrino its own antiparticle?

    $\Rightarrow$ COBRA experiment
- Big question for the future:
  - is there CP violation in leptons?

    $\Rightarrow$ neutrino factory

Neutrino oscillations

- Leptons mix just like the quarks

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

neutrinos as seen by the weak interaction

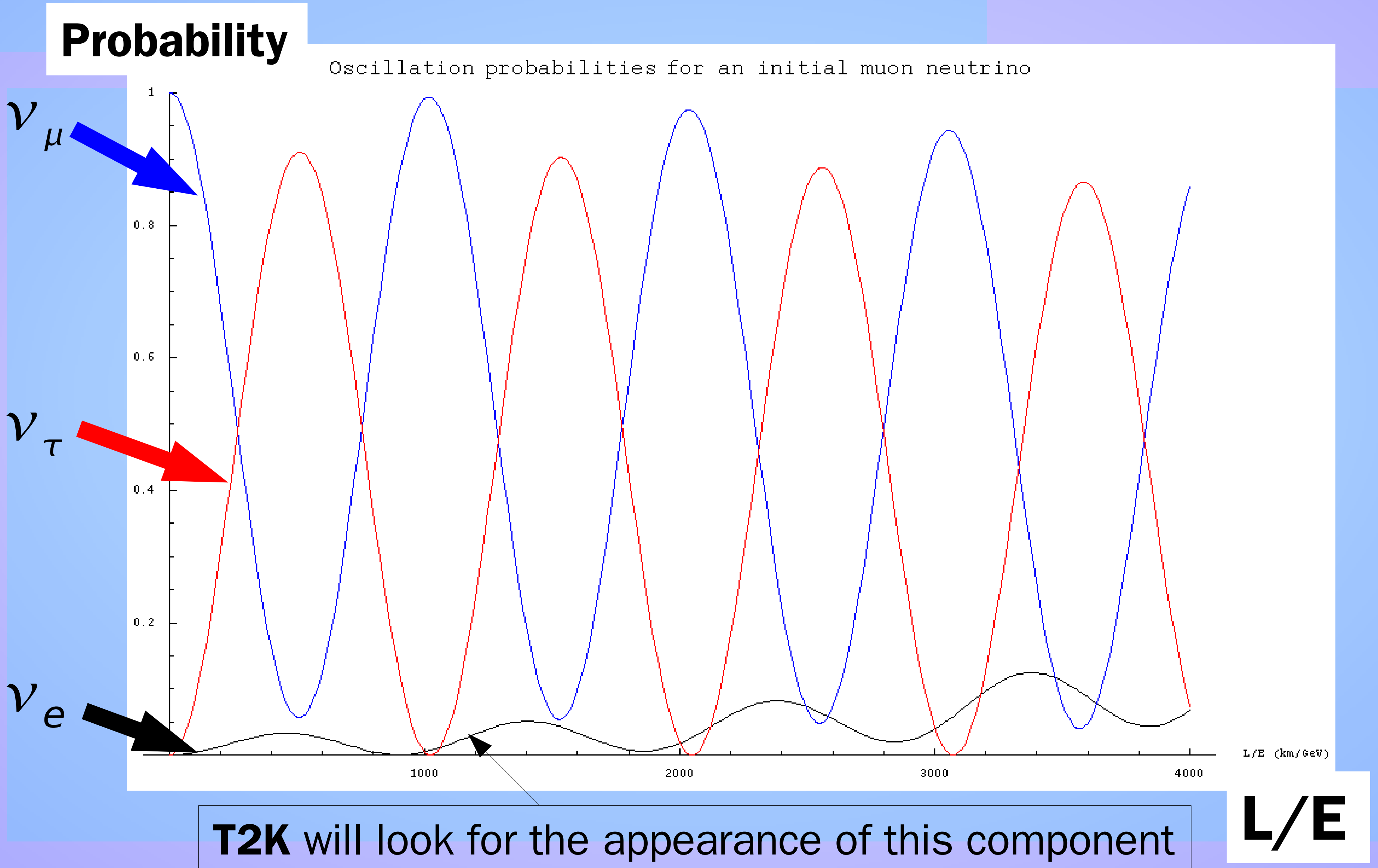
physical neutrinos (with well-defined masses)

- Neutrinos
  - must be produced and interact as flavour states
  - *but* travel as a mixture of the physical states

  $\therefore$ flavour composition can change

$\Rightarrow$ neutrino oscillation!

Neutrino oscillations



T2K will look for the appearance of this component

Summary

- Flavour physics addresses some of the fundamental questions of our current knowledge of nature
- We may not find answers to these questions soon, but the experimental program improves our understanding and takes us in the right direction
- Ultimately expect that studies of quarks, charged leptons and neutrinos will lead to a theory of flavour

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Parameter Counting

- 3 gauge couplings
- 2 Higgs parameters
- 6 quark masses
- 3 quark mixing angles + 1 phase
- 3 (+3) lepton masses
- (3 lepton mixing angles + 1 phase)

( ) = with neutrino mass

"FLAVOUR" PARAMETERS

Dynamic generation of BAU

- Suppose equal amounts of matter (X) and antimatter ($\underline{X}$)
- X decays to
  - A (baryon number N_A) with probability p
  - B (baryon number N_B) with probability $(1-p)$
- $\underline{X}$ decays to
  - $\underline{A}$ (baryon number $-N_A$) with probability $\underline{p}$
  - $\underline{B}$ (baryon number $-N_B$) with probability $(1-\underline{p})$
- Generated baryon asymmetry:
  - $\Delta N_{TOT} = N_A p + N_B(1-p) - N_A \underline{p} - N_B(1-\underline{p}) = (p - \underline{p})\,(N_A - N_B)$
  - Require $p \neq \underline{p}$ & $N_A \neq N_B$

The BABAR Experiment

- PEP-II accelerator collides electrons and positrons at energies tuned to produce pairs of B mesons
- Electron/positron energies are *asymmetric* – produced B particles are moving → time to decay can be measured
- BABAR detector reconstructs decay products of B mesons