Flavour Physics

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Outline

Lecture 1

- what is flavour physics?
- some history, some concepts, some theory
- charged lepton physics

What is flavour physics?

Fermions (“matter”)	Bosons (“forces”)
$\left\{\begin{array}{ccc} & \text{Quarks} & \\ uuu & ccc & ttt \\ ddd & sss & bbb \\ & & \\ & \text{Leptons} & \\ e & \mu & \tau \\ \nu_e & \nu_\mu & \nu_\tau \end{array}\right\} \times \left\{\begin{array}{c} \text{MATTER} \\ \text{ANTIMATTER} \end{array}\right\}$	$gggggggg$ γ W^+ W^- Z H

Parameters of the Standard Model

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

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FLAVOUR PARAMETERS

What isn't flavour physics?

QCD: the strong interaction

- though intimately related to quark flavour physics

Electroweak physics

- though intimately related to charged couplings & suppression of flavour changing neutral currents
- quark masses and mixings generated via the Higgs mechanism

“Energy frontier physics” a.k.a “high-p_T physics”

- though important complementarity between searches for on-shell new particles and searching for their quantum effects in loop processes

Aspects of flavour physics

Families / generations

3 pairs of quarks (are we sure?)

3 pairs of leptons (are we sure?)

Hierarchies

$m(t) > m(c) > m(u)$ $m(b) > m(s) > m(d)$

$m(\tau) > m(\mu) > m(e)$ $m(\nu_\tau) > m(\nu_\mu) > m(\nu_e)$?

Mixings & couplings

hierarchy in quark mixings

what about lepton mixings?

Aspects of flavour physics

Mixings & couplings

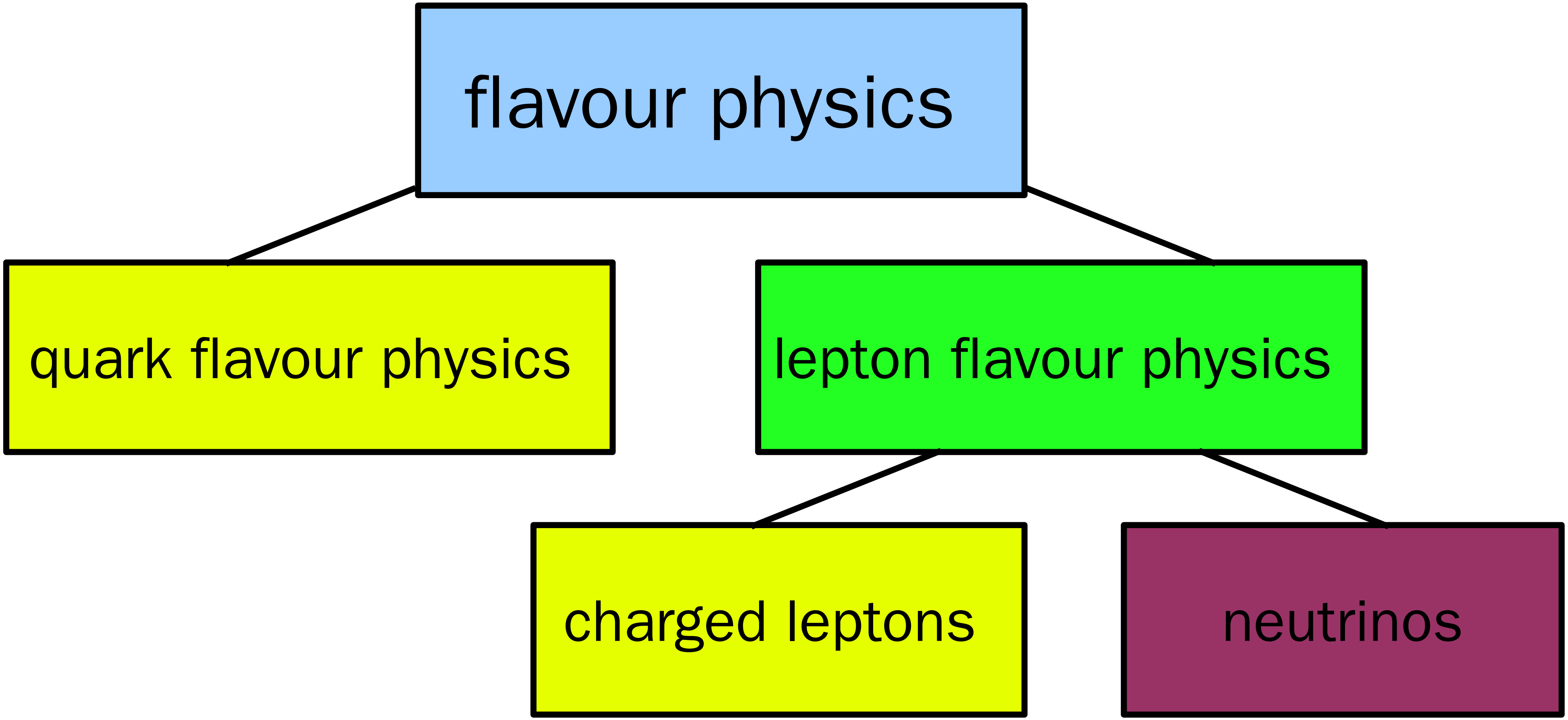
- universality
- (no) flavour changing neutral currents

Symmetry principles & their violation

- P violation / C violation
- CP violation / T violation
  - baryon asymmetry of the universe
- lepton flavour violation

Unification

Divisions



flavour physics

quark flavour physics

lepton flavour physics

charged leptons

neutrinos

What's special about neutrinos?

Parity violation

- neutrinos only left-handed (chirality)
- antineutrinos only right-handed (chirality)

YET, not massless

- where are the right-handed neutrinos?

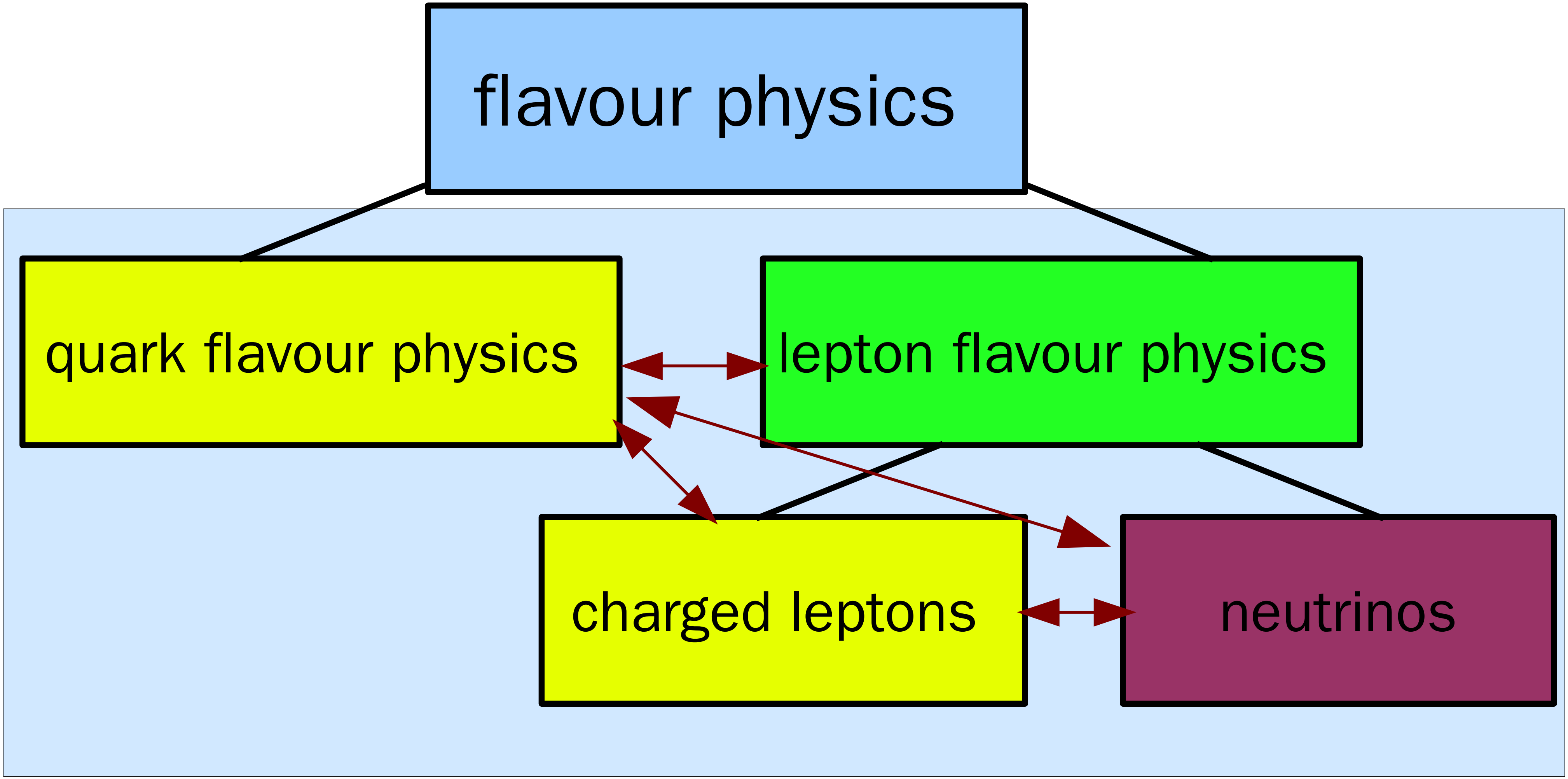
Could be a completely new type of field

Physics beyond the Standard Model

Possible probes of grand unification

See Steve Boyd's lectures

Goal



flavour physics

quark flavour physics

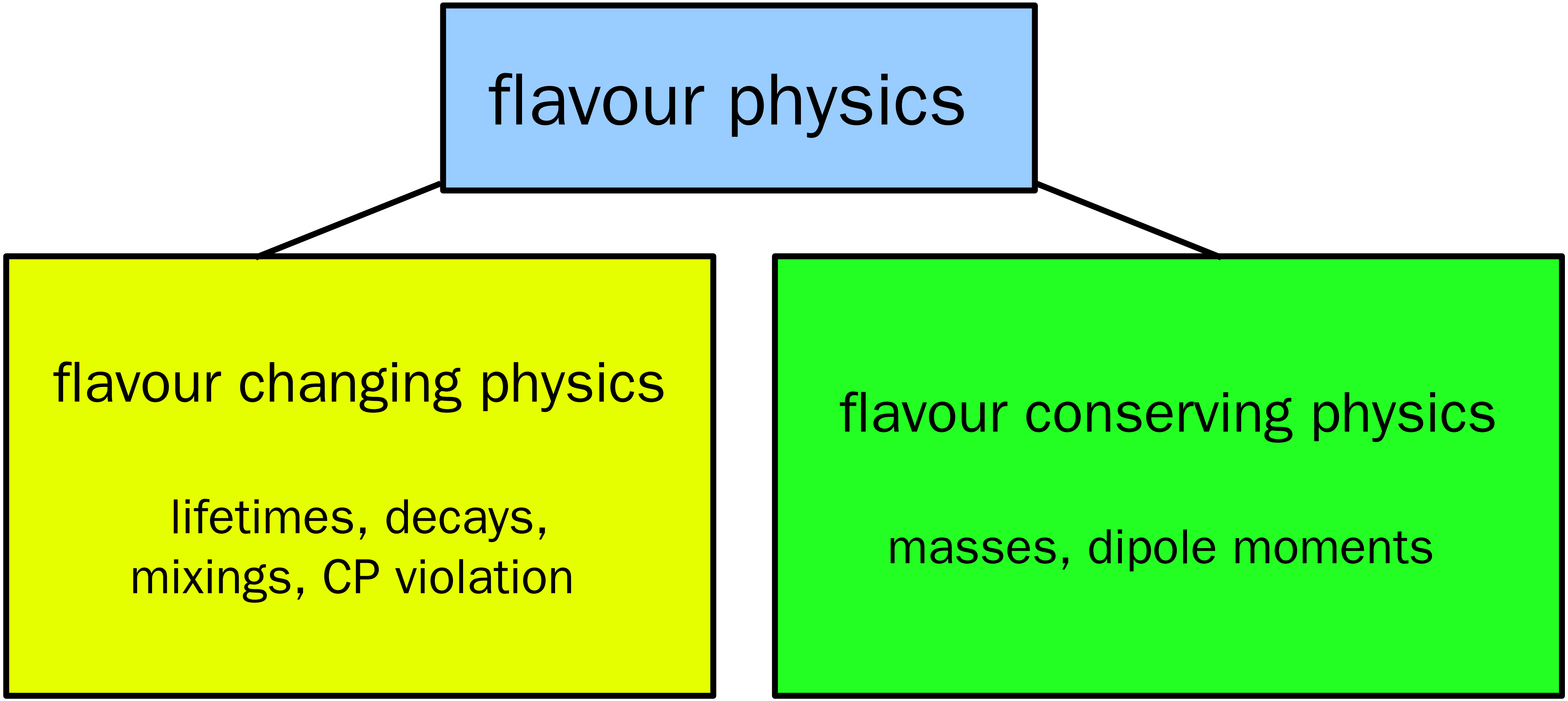
lepton flavour physics

charged leptons

neutrinos

Unified understanding of flavour physics!

Alternative Divisions



flavour physics

flavour changing physics

lifetimes, decays,
mixings, CP violation

flavour conserving physics

masses, dipole moments

History

Isospin

What is the difference between the proton (charge = +1) and the neutron (neutral)?

masses almost identical

coupling to the strong interaction identical

Heisenberg (1932) proposed (p,n) members of isospin doublet:

p: $(I,I_z) = (1/2,+1/2)$ n: $(I,I_z) = (1/2,-1/2)$

pions form an isospin triplet $\pi^{+,0,-}$: $(I,I_z) = (1, +1,0,-1)$

Isospin symmetry

Strong interaction same for proton & neutron

- Hamiltonian invariant under global SU(2) rotation
- pions thought to be Yukawa particles
  - gauge bosons responsible for mediating strong force (related to local SU(2) symmetry ... not correct description of strong interaction)

Isospin is not an exact symmetry

- nonetheless, v. useful concept
- successful because $m_u \sim m_d$ & $m_u, m_d < \Lambda_{QCD}$

Discovery of strangeness

1947, G. D. Rochester and C. C. Butler

- neutral particle (no track) → two charged pions
- charged particle (track) → charged pion + something
- lifetimes O(10^{-10}s) – long-lived : “strange”

Gell-Mann & Pais: “strangeness”

- conserved in strong interactions (production)
  - quark-antiquark pairs produced
- violated in weak interactions (decay)

Gell-Mann, Nishijima & Ne'eman

- “the eight-fold way”: SU(3)
- quarks

Note on the “quark model”

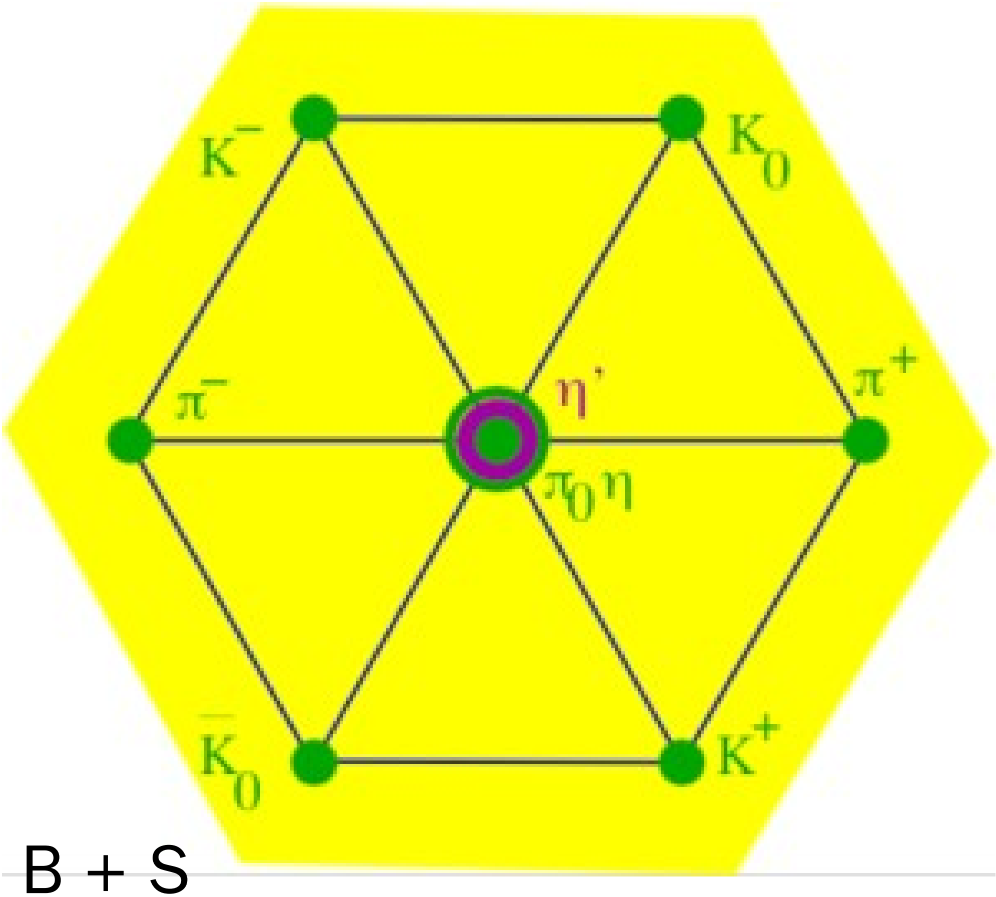
Nowadays, accepted that quarks are real, physical entities

Originally introduced as a *model* with which to explain the particle “zoo”

Acceptance of quarks not until after discovery of charm

Pseudoscalar meson nonet

S
(strangeness)



Hypercharge:

$Y = B + S$

(baryon number + strangeness)

Gell-Mann/Nishijima Law: $Q = e(I_z + Y/2)$

I_z

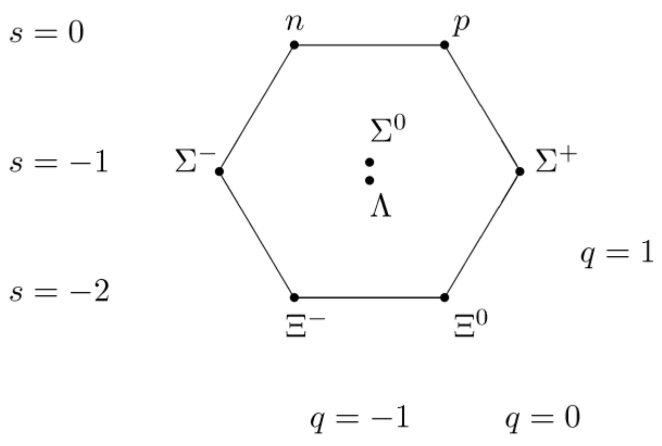
The Quark Model circa 1960s

Many new particles discovered

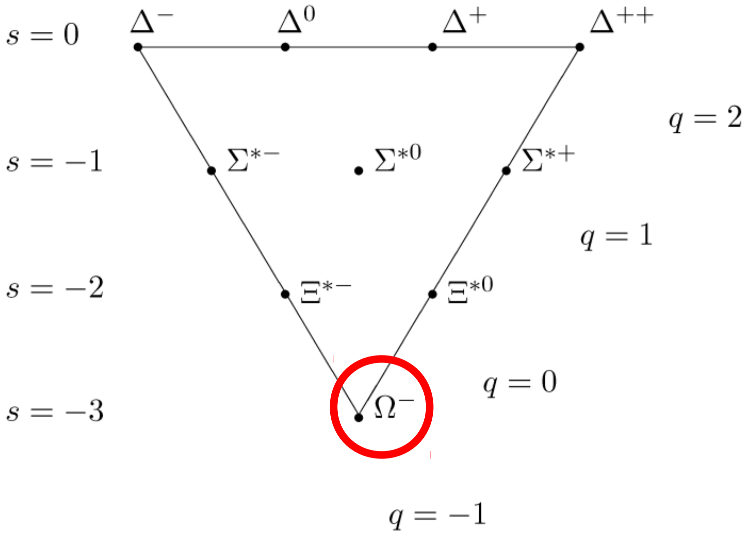
"The eight-fold way" – flavour SU(3) – provides elegant scheme for categorisation

discovery of Ω⁻ (sss) [1964] in particular vindicates theory

Baryon multiplets



spin = 1/2



spin = 3/2

The θ – τ puzzle

The particle decaying to $\pi^+\pi^0$ was originally called the θ

“Another” particle (called τ) decaying to $\pi^+\pi^-\pi^+$ was also discovered

parities of 2π and 3π are opposite

but masses and lifetimes of θ & τ same

Parity violation discovered 1957 (C.N.Wu, following T.D.Lee and C.N.Yang)

θ & τ are the same particle: “ K^+ ”

P and CP

Now understood that P is maximally violated in beta decay

- no right-handed neutrinos

However, C is also maximally violated

- no left-handed antineutrinos

Product CP is conserved (Landau 1957)

- CP distinguishes absolutely between matter and antimatter

Note that CPT is conserved in any Lorentz invariant gauge field theory (Luders, Pauli)

Cabibbo

Compare rates of

$s \rightarrow u$ eg. $K^+ \rightarrow \mu^+\nu_\mu$, $\Lambda \rightarrow p\pi^+$, $\Sigma^- \rightarrow ne^+\nu_e$

$d \rightarrow u$ eg. $\pi^+ \rightarrow \mu^+\nu_\mu$, $n \rightarrow pe^+\nu_e$

$s \rightarrow u$ transitions suppressed by a factor ~ 20

Small differences in values of Fermi constant measured from $d \rightarrow u$ compared to muon decay

Cabibbo (1963) proposed:

$(u,d)_c = (u, d \cos \theta_c + s \sin \theta_c)$

$\sin \theta_c = 0.22$ (empirically)

Neutral kaon mixing

Physical states turn out to be almost equal admixtures of strangeness eigenstates

$$K_S \simeq \frac{1}{\sqrt{2}}(K^0 + \overline{K^0}) \qquad K_L \simeq \frac{1}{\sqrt{2}}(K^0 - \overline{K^0})$$

$K_S \rightarrow \pi^+\pi^-, \pi^0\pi^0$ (CP even)

$K_L \rightarrow \pi^+\pi^-, \pi^0\pi^0$ forbidden by CP symmetry

$K_L \rightarrow \pi^+\pi^-\pi^0, \pi^0\pi^0\pi^0, \pi^{+-}e^{-+}\nu, \pi^{+-}\mu^{-+}\nu$

The GIM mechanism

$K^+ \to \mu^+ \nu_\mu$ so why not $K^0 \to \mu^+ \mu^-$?

$K^+ \to \pi^0 \mu^+ \nu_\mu$ so why not $K^0 \to \pi^0 \mu^+ \mu^-$?

$BR(K_L \to \mu^+ \mu^-) \sim 7\ 10^{-9}$ $BR(K_L \to e^+ e^-) \sim 10^{-11}$

$BR(K^0 \to \pi^0 \mu^+ \mu^-) <\sim 10^{-10}$

GIM (Glashow, Iliopoulos, Maiani) mechanism (1970)

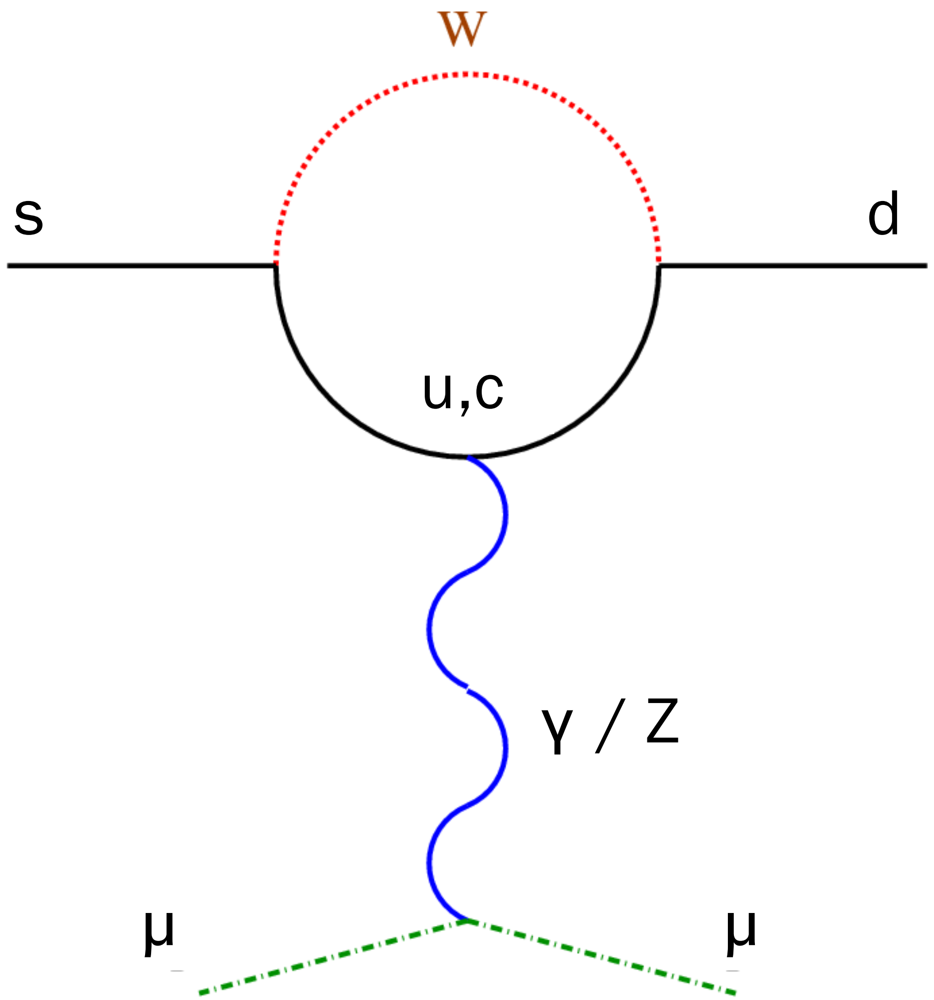
no tree level flavour changing neutral currents

suppression of FCNC via loops

Requires that quarks come in pairs (doublets)

predicts existence of charm quark

GIM suppression of loops



$A = V_{us} V_{ud}^* \, f(m_u/m_W) + V_{cs} V_{cd}^* \, f(m_c/m_W)$

2x2 unitarity:

$V_{us} V_{ud}^* + V_{cs} V_{cd}^* =$

$\sin(\theta_c)\cos(\theta_c) - \cos(\theta_c)\sin(\theta_c) = 0$

$m_u, m_c < m_W \therefore f(m_u/m_W) \sim f(m_c/m_W)$

$\therefore A \sim 0$

kaon mixing ⇒ predict m_c

CP Violation

In 1964, Christensen, Cronin, Fitch & Turlay, unexpectedly observe $K_L \rightarrow \pi^+\pi^-$

$CP(-1) \rightarrow CP(+1)$

Numerous explanations proposed

1973: Kobayashi & Maskawa demonstrate that CP violation arises naturally from quark mixing if there are 3 generations of quarks

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey

(Received 10 July 1964)

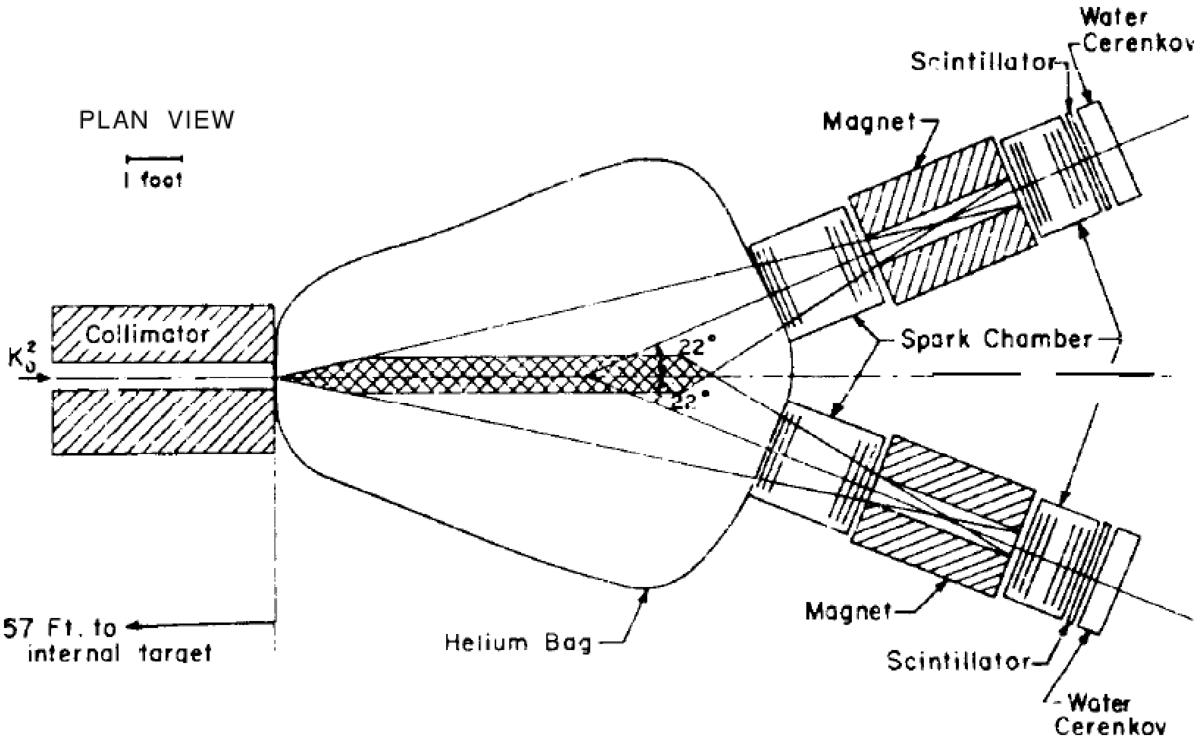


Fig. I. Plan view of the apparatus as located at the A. G. S.

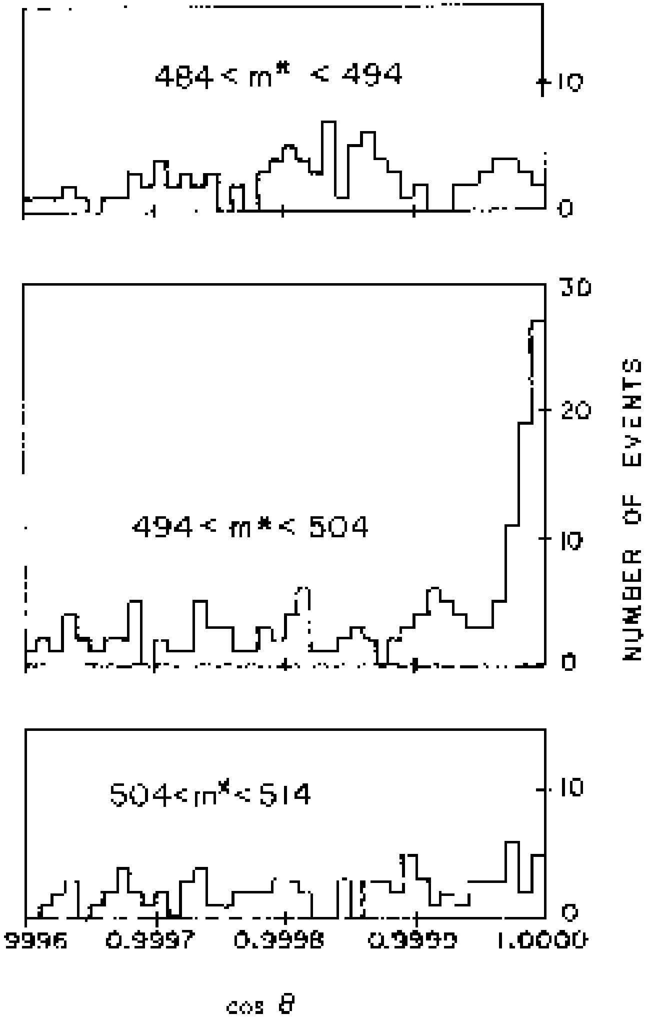


FIG. 3. Angular distribution in three mass ranges for events with $\cos\theta > 0.9995$.

CKM Matrix / KM mechanism

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

3x3 matrix of complex numbers ⇒ 18 parameters

Unitary ⇒ 9 parameters

Quark fields absorb unobservable phases

⇒ 4 parameters

3 mixing angles and 1 phase (V_{CKM} complex)

CP-Violation in the Renormalizable Theory of Weak Interaction

Progress of Theoretical Physics, Vol. 49 No. 2 pp. 652-657

Makoto Kobayashi and Toshihide Maskawa
Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of CP-violation are studied. It is concluded that no realistic models of CP-violation exist in the quartet scheme without introducing any other new fields. Some possible models of CP-violation are also discussed.

Sakharov conditions

Proposed by A.Sakharov, 1967

Necessary for evolution of matter dominated universe, from symmetric initial state

- baryon number violation
- C & CP violation
- thermal inequilibrium

No significant amounts of antimatter observed

$\Delta N_B/N_\gamma$ = (N(baryon) – N(antibaryon))/$N_\gamma \sim 10^{-10}$

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:

$$\Delta N_{TOT} = N_A p + N_B(1-p) - N_{\underline{A}}\underline{p} - N_B(1-\underline{p}) = (p - \underline{p})\,(N_A - N_B)$$

Require $p \neq \underline{p}$ & $N_A \neq N_B$

CHARGED LEPTONS

Charged leptons

Focus of these lectures is on quark flavour physics

Neutrinos covered elsewhere

What about charged leptons?

- precision tests of the lepton flavour sector
  - lepton flavour violation
  - electric dipole moments
  - magnetic moments (g-2)

Lepton flavour violation

- Essentially forbidden in the Standard Model
- Muon sector limits
  - BR(μ→eγ) < 5.7×10^{-13}
    - MEG Collaboration (PSI; Switzerland)
      - PRL 110 (2013) 201801
  - BR(μ→eee) < 1.0×10^{-12}
    - SINDRUM Collaboration (PSI)
      - NPB 299, 1 (1998)
  - μ→e conversion
    - various limits (capture on ^{32}S,Cu,Ti,Pb)
    - best is σ(μTi → eTi)/σ(μTi → capture) < 4.3×10^{-12}

Further improvements and upgrades expected from MEG experiment

New μ→eee experiment proposed @ PSI

COMET/PRISM (JPARC) & mu2e (FNAL) proposed to improve on this limit

τ lepton flavour violation

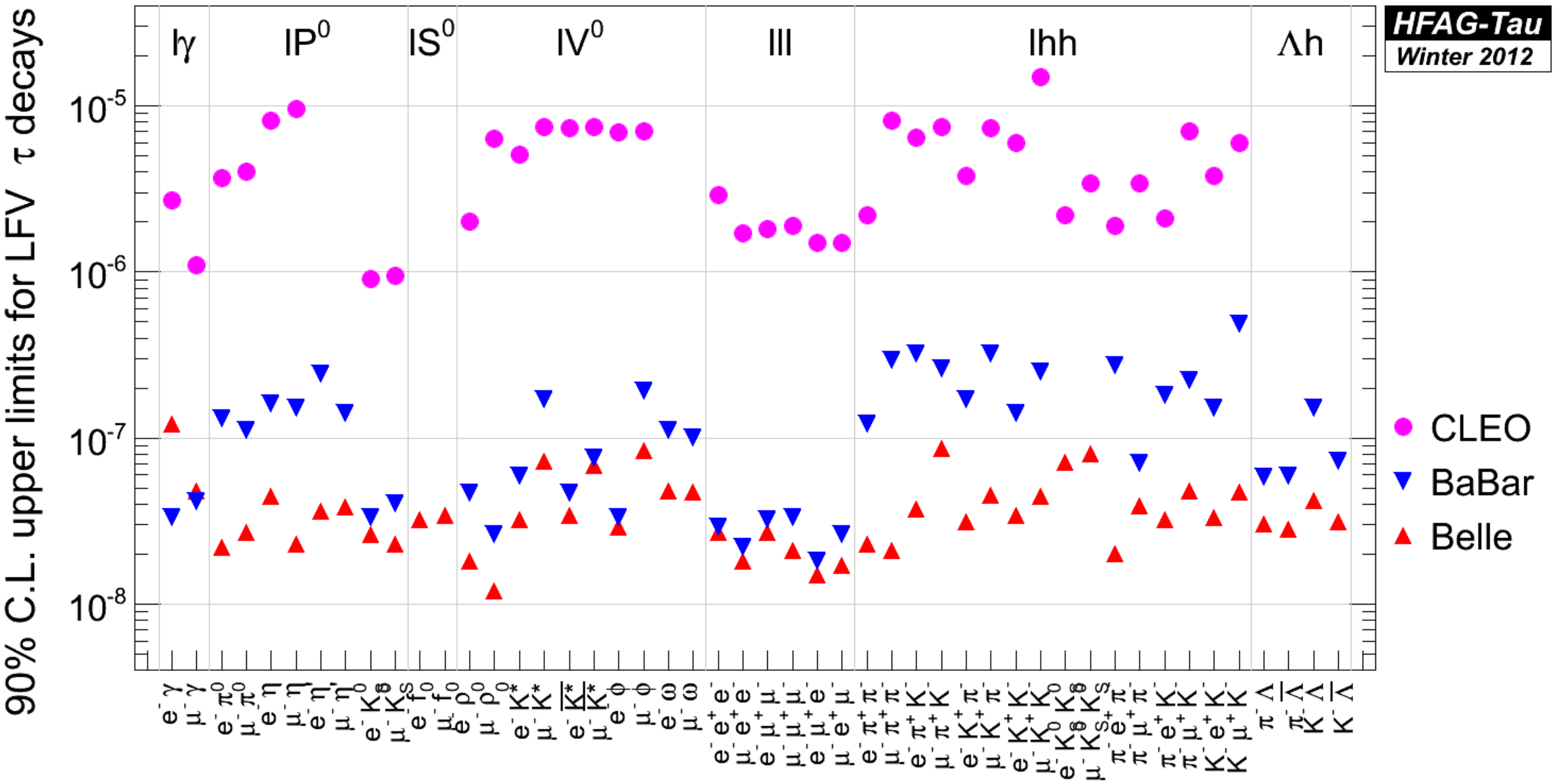
τ has many more possible decay channels

- $BR(\tau \to \mu\gamma)$, $BR(\tau \to e\gamma) <\sim 10^{-8}$
- $BR(\tau \to \mu\pi^0)$, $BR(\tau \to e\pi^0) <\sim 10^{-7}$
- $BR(\tau \to \mu K_S)$, $BR(\tau \to e K_S) <\sim 10^{-8}$
- $BR(\tau \to \mu\mu\mu)$, $BR(\tau \to e\mu\mu)$, $BR(\tau \to \mu ee)$, ... $<\sim 10^{-8}$

All these limits from “B factories”

- $e^+e^- \to \tau^+\tau^-$ at $E_{CM} = m(Y(4S))$
- CLEO, BaBar, Belle

τ lepton flavour violation



Main message: no sign of LFV

Belle2 (KEK) will significantly improve on these limits

(LHCb also has potential for τ→μμμ and some other modes)

Electric dipole moments

EDMs are both P violating and T violating

$|d_e| < 8.7 \times 10^{-29}$ e cm [Science 343 (2014) 6168, 269]

- significant & continuing progress in last few years

$|d_\mu| < 1.9 \times 10^{-19}$ e cm [PRD 80, 052008 (2009)]

- proposal to reach down to $O(10^{-24})$ e cm

τ EDM limits [Belle, PLB 551, 16 (2003)]

$\mathrm{Re}(d_\tau) = (1.2 \pm 1.7) \times 10^{-17}$ e cm

$\mathrm{Im}(d_\tau) = (-0.8 \pm 0.9) \times 10^{-17}$ e cm

Many other EDMs also measured (proton, neutron, deuteron, various nuclei, ...)

EDM measurement sensitivity

For neutron EDM:

$|d_n| < 3.0 \times 10^{-26}$ e cm [PRL 97, 131801 (2006)]

"If neutron were the size of the earth, current limit corresponds to a charge separation of ~ 10 μm"

Anomolous magnetic moments

$(g\text{-}2)_e$ famous test of the precision of QED

$(g\text{-}2)_e/2 = (1159.652186 \pm 0.000004) \times 10^{-6}$

Can also be tested for μ and τ, though theoretical corrections are larger and harder to calculate (includes also QCD effects)

$(g\text{-}2)_\mu/2 = (11659208 \pm 6) \times 10^{-10}$

[PRL 92, 161802 (2004)]

$-0.052 < (g\text{-}2)_\tau/2 < 0.013$

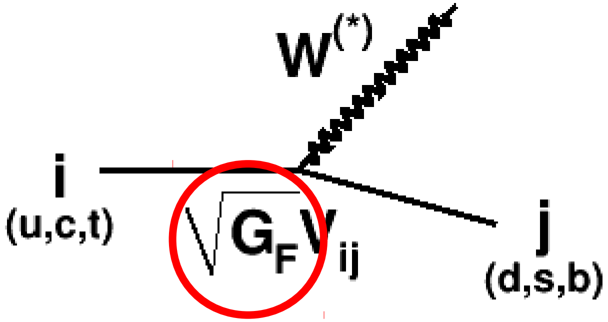
[EPJ C35, 437 (2004)]

See EPJ C66, 1 (2010) for interpretation
or Phys. Rept. 477 (2009) 1110 for a detailed review

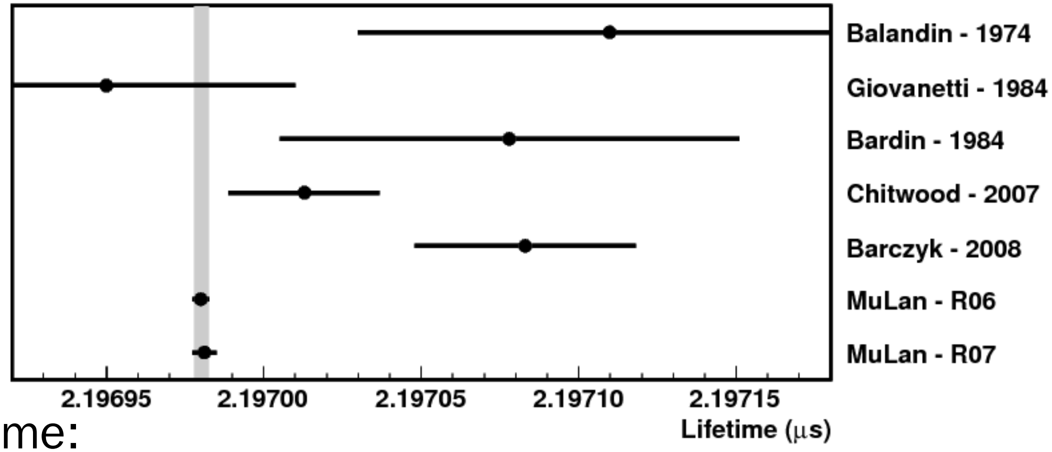
The muon lifetime & the Fermi constant

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1+\Delta q)$$

phase-space, QED & hadronic radiative corrections



MuLan experiment
PRL 106 (2011) 079901



World's best measurement of the muon lifetime:

$$\tau_{\mu^+} = (2196980.3 \pm 2.2)\, ps$$

$$G_F = (1.1663788 \pm 7) \times 10^{-5}\, GeV^{-2}$$

< 1 part per million precision!

Summary

Development of quark model & flavour physics

Key roles of

- mixing, flavour changing neutral currents
- symmetries, CP violation

Flavour physics probes high energy scales

- prediction of existence and <u>properties</u> of charm, bottom and top quarks
- link to matter-antimatter asymmetry of the Universe

Charged lepton physics

- new physics probes in both flavour-conserving and flavour-changing interactions

Hadron multiplets – SU(4)