Flavour Physics and CP violation

Lecture 1 of 3

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- Part 1
  - Why is flavour physics & CP violation interesting?
- Part 2
  - What do we know from the previous generation of experiments?
- Part 3
  - What do we hope to learn from current and future heavy flavour experiments?

What is flavour physics?

WIKIPEDIA
The Free Encyclopedia

Flavour (particle physics)

From Wikipedia, the free encyclopedia

In particle physics, **flavour** or **flavor** is a quantum number of elementary particles. In quantum chromodynamics, flavour is a global symmetry. In the electroweak theory, on the other hand, this symmetry is broken, and flavour-changing processes exist, such as quark decay or neutrino oscillations.

Flavour in particle physics

Flavour quantum numbers:

- Baryon number: B
- Lepton number: L
- Strangeness: S
- Charm: C
- Bottomness: B'
- Topness: T
- Isospin: **I** or I_3
- Weak isospin: **T** or T_3
- Electric charge: Q
- X-charge: X

Combinations:

- Hypercharge: Y
  - $Y = (B + S + C + B' + T)$
  - $Y = 2 (Q - I_3)$
- Weak hypercharge: Y_W
  - $Y_W = 2 (Q - T_3)$
  - $X + 2Y_W = 5 (B - L)$

Flavour mixing

- CKM matrix
- PMNS matrix
- Flavour complementarity

"The term flavor was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena. Just as ice cream has both color and flavor so do quarks."

RMP 81 (2009) 1887

What is flavour physics?

The original flavour symmetry

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

masses almost identical

coupling to the strong interaction identical

Heisenberg (in 1932 – a big year for flavour physics) proposed (p,n) form a doublet of a global SU(2) symmetry "isospin"

p: $(I;I_z) = (½; +½)$ n: $(I,I_z) = (½; –½)$

Later extended to other particles

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

We know much more almost 100 years later, but isospin remains an excellent approximation

What is flavour physics?

Fermions ("matter")	Bosons ("forces")
Quarks: $u u u$ $c c c$ $t t t$ / $d d d$ $s s s$ $b b b$; Leptons: e μ τ / ν_e ν_μ ν_τ	$g g g g g g g g$
$\times$ { MATTER / ANTIMATTER }	γ, W^+, W^-, Z, H

$$\left\{ \begin{array}{ccc} & \text{Quarks} & \\ uuu & ccc & ttt \\ ddd & sss & bbb \\ & & \\ & \text{Leptons} & \\ e & \mu & \tau \\ \nu_e & \nu_\mu & \nu_\tau \end{array} \right\} \times \left\{ \begin{array}{c} \text{MATTER} \\ \text{ANTIMATTER} \end{array} \right\}$$

Bosons: $gggggggg$, 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 Dirac neutrino masses

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CKM matrix

PMNS matrix

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CKM matrix

PMNS matrix

FLAVOUR PARAMETERS

( ) = with Dirac neutrino masses

Mysteries of flavour physics

- Why are there so many different fermions?
- What is responsible for their organisation into generations / families?
- Why are there 3 generations / families each of quarks and leptons?
- Why are there flavour symmetries?
- What breaks the flavour symmetries?
- What causes matter–antimatter asymmetry?

Difficult questions!

Reducing the scope

- Flavour physics includes
  - Neutrinos
  - Charged leptons
  - Kaon physics
  - Charm & beauty physics
  - (Some aspects of) top physics

see lectures by Pilar Hernandez

see lectures by John Ellis and Sinead Farrington

- My focus will be on charm & beauty
  - will touch on others when appropriate

Heavy quark flavour physics

- Focus in these lectures will be on
  - flavour-changing interactions of charm and beauty quarks
- But quarks feel the strong interaction and hence hadronise
  - various different charmed and beauty hadrons
  - many, many possible decays to different final states
- The hardest part of quark flavour physics is learning the names of all the damned hadrons!
- On the other hand, hadronisation greatly increases the observability of CP violation effects
  - the strong interaction can be seen either as the "unsung hero" or the "villain" in the story of quark flavour physics

I. Bigi, hep-ph/0509153

Why is heavy flavour physics interesting?

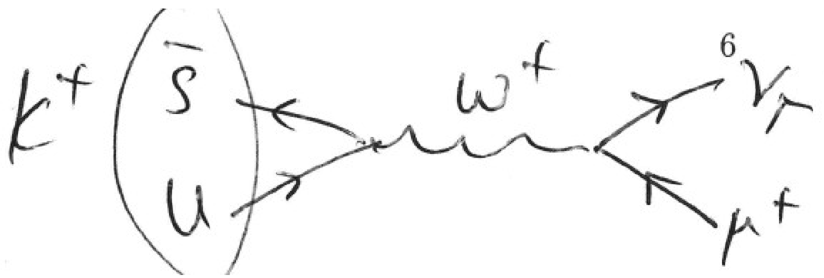
- Hope to learn something about the mysteries of the flavour structure of the Standard Model
- CP violation and its connection to the matter–antimatter asymmetry of the Universe
- Discovery potential far beyond the energy frontier via searches for rare or SM forbidden processes

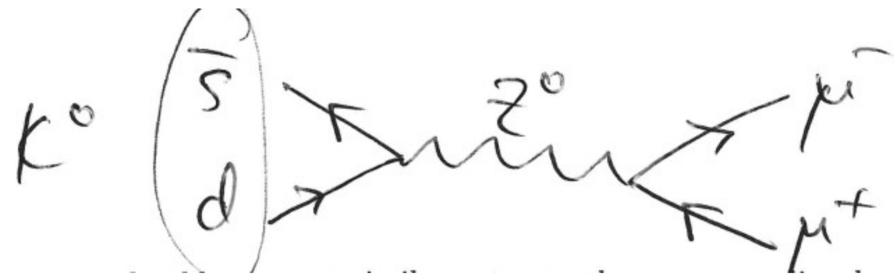
What breaks the flavour symmetries?

- In the Standard Model, the vacuum expectation value of the Higgs field breaks the electroweak symmetry
- Fermion masses arise from the Yukawa couplings of the quarks and charged leptons to the Higgs field (taking $m_\nu=0$)
- The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks
- Consequently, the only flavour-changing interactions are the charged current weak interactions
  - no flavour-changing neutral currents (GIM mechanism)
  - not generically true in most extensions of the SM
  - flavour-changing processes provide sensitive tests

The GIM mechanism

Glashow–Iliopoulos–Maiani (1970)





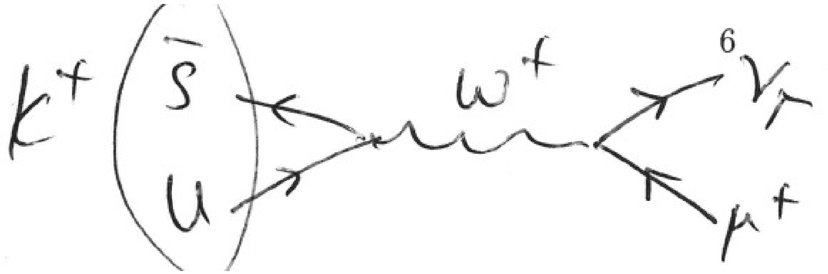
$B(K^+ \to \mu^+\nu_\mu) \approx 64\%$

$B(K_L^0 \to \mu^+\mu^-) = (6.8 \pm 0.1) \times 10^{-9}$

Why so different?

The GIM mechanism

Glashow–Iliopoulos–Maiani (1970)



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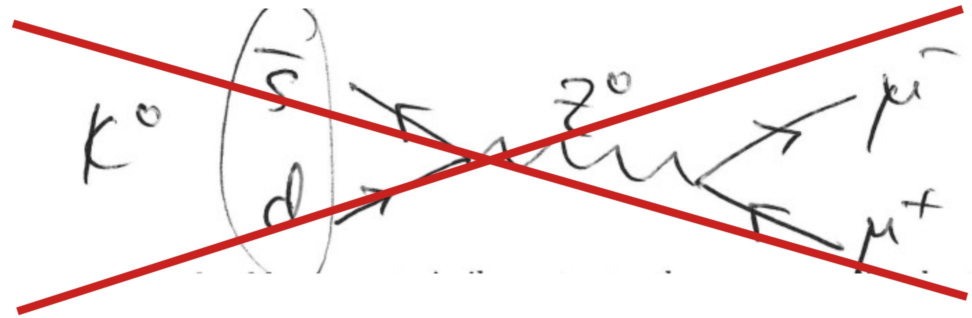
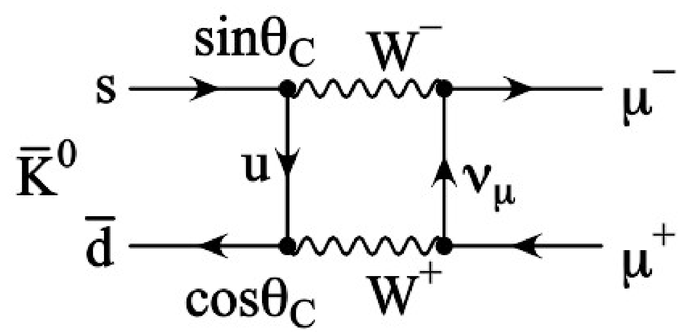


$B(K_L^0 \to \mu^+\mu^-) = (6.8 \pm 0.1) \times 10^{-9}$

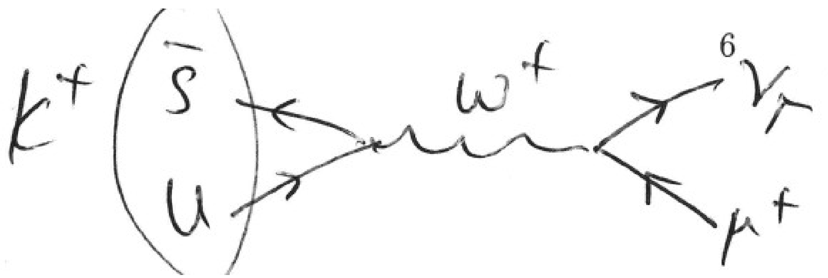
Why so different?

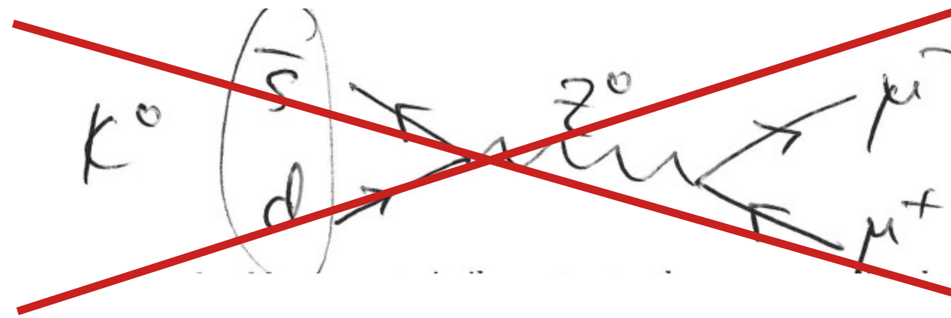
- No tree-level FCNC
- But still a loop diagram



The GIM mechanism

Glashow–Iliopoulos–Maiani (1970)



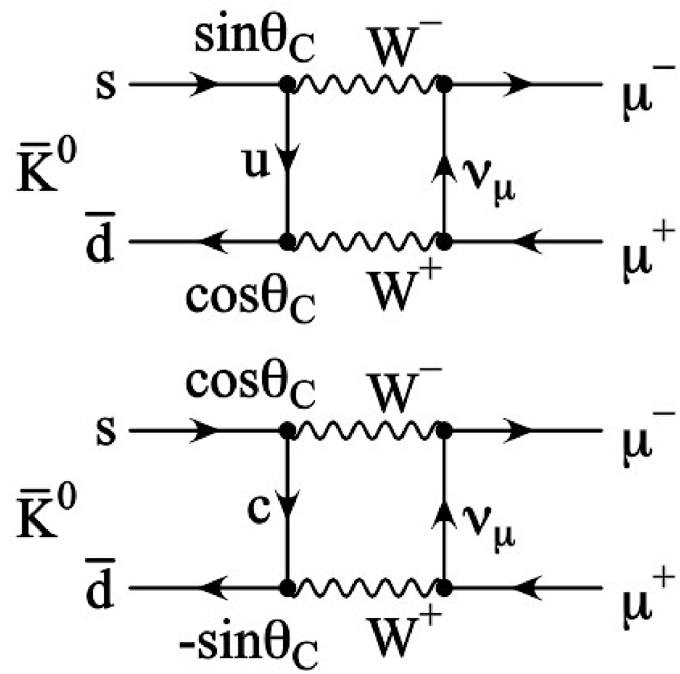


$B(K^+ \to \mu^+\nu_\mu) \approx 64\%$

$B(K_L^0 \to \mu^+\mu^-) = (6.8 \pm 0.1) \times 10^{-9}$

Why so different?

- No tree-level FCNC
- But still a loop diagram
- Cancels almost exactly with similar diagram with u $\leftrightarrow$ c if fourth quark introduced
- (Cancellation exact if $m_u = m_c$)



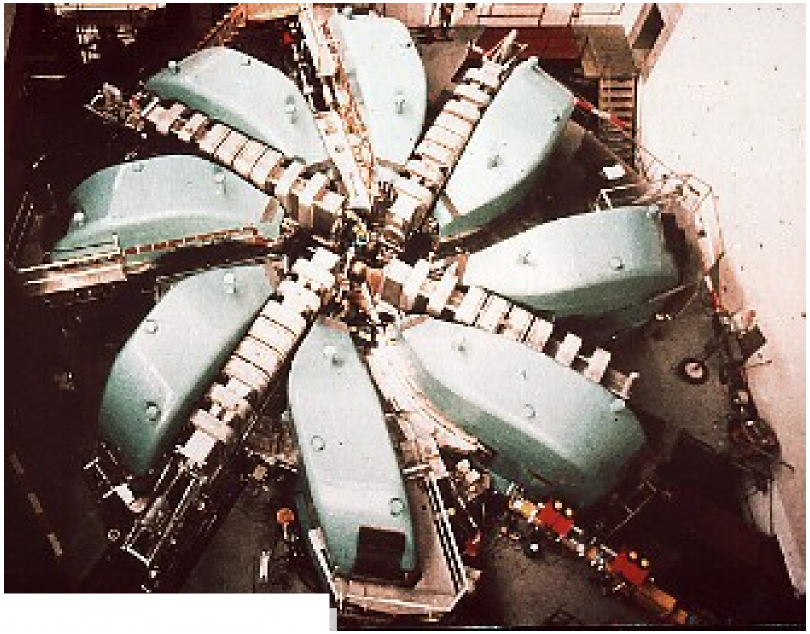
Lepton flavour violation

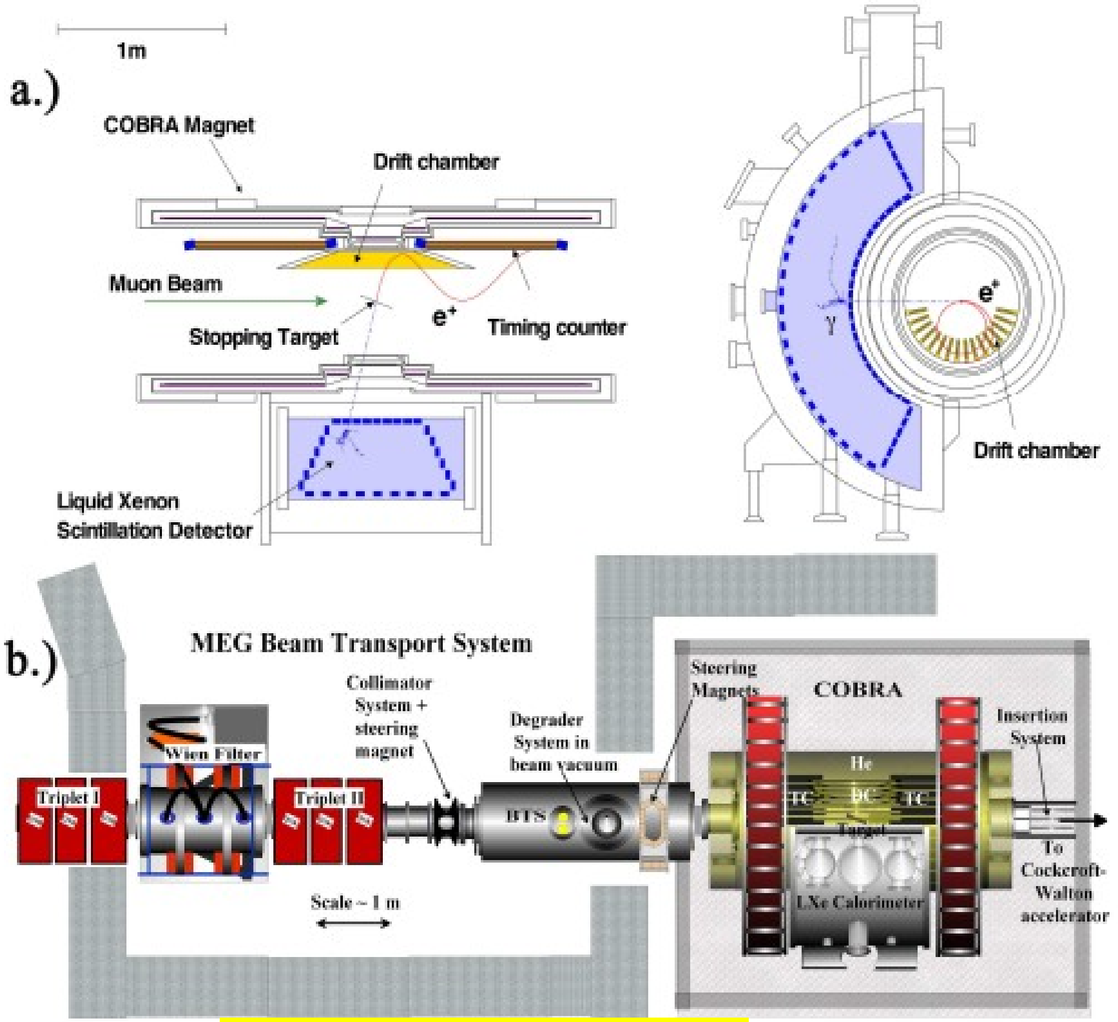
- Why do we not observe the decay $\mu \rightarrow e\gamma$?
  - exact (but accidental) lepton flavour conservation in the SM with $m_\nu=0$
  - SM loop contributions suppressed by $(m_\nu/m_W)^4$
  - but new physics models tend to induce larger contributions
    - unsuppressed loop contributions
    - generic argument, true in most common models

The muon to electron gamma (MEG) experiment at PSI

$\mu^+ \to e^+\gamma$

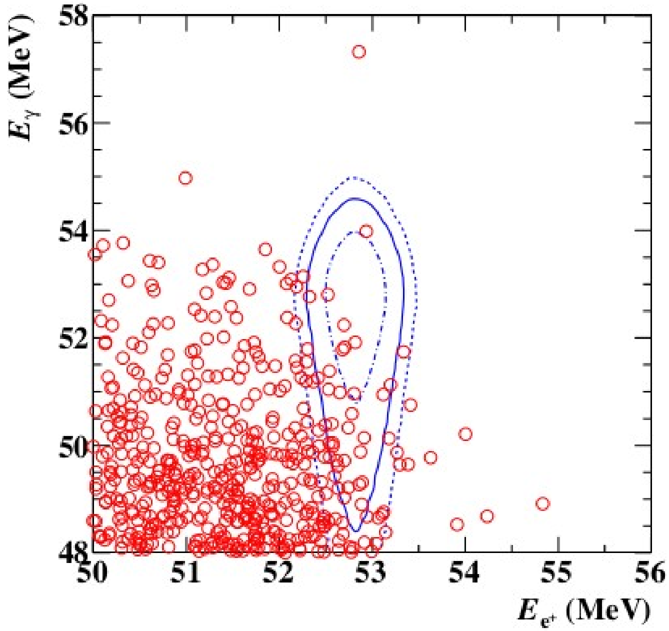
- positive muons → no muonic atoms
- continuous (DC) muon beam → minimise accidental coincidences

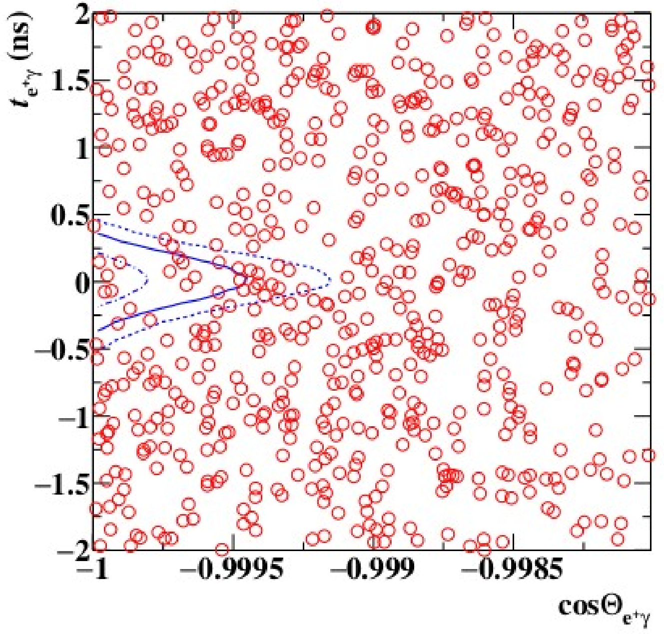


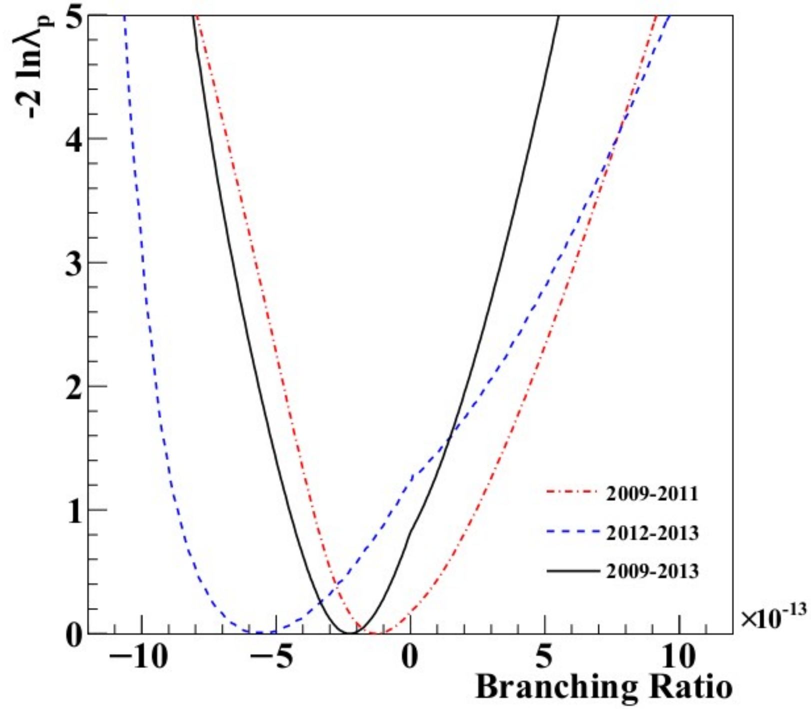


NPB 834 (2010) 1

MEG results



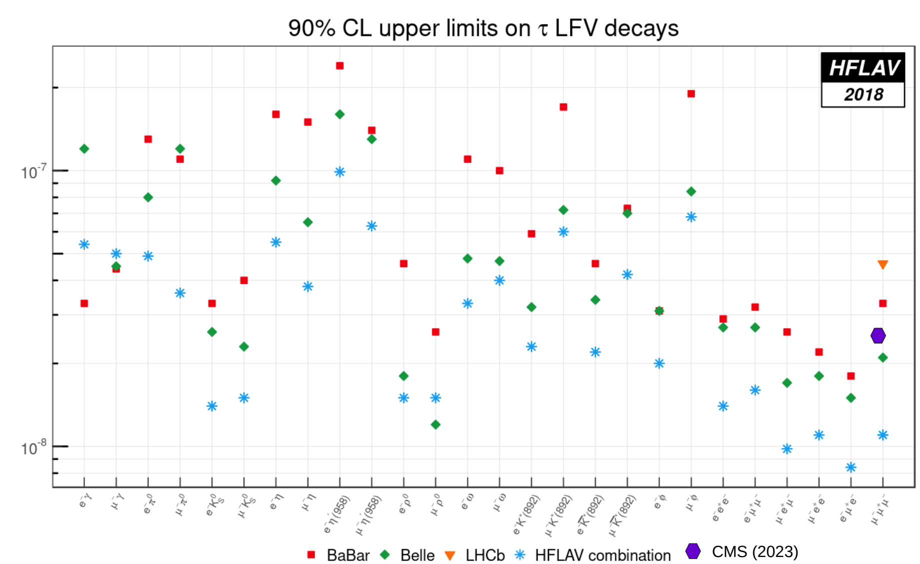




$B(\mu^+ \rightarrow e^+\gamma) < 4.2\ 10^{-13}$ @ 90% CL
EPJ C76 (2016) 434

Prospects for Lepton Flavour Violation

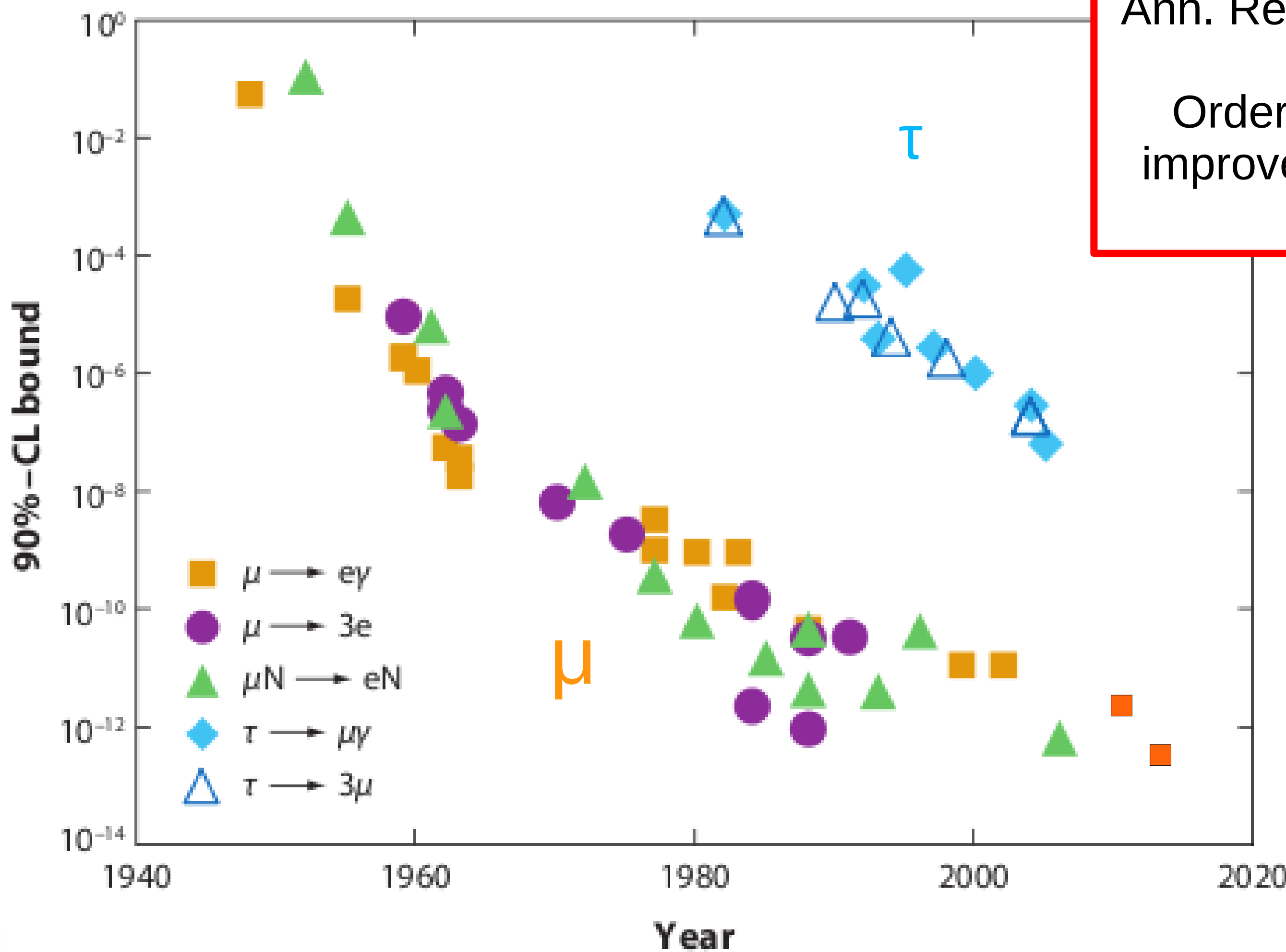
- MEG upgrade (MEGII); also $\mu \to eee$ (Mu3e) both as PSI
- New generations of μ – e conversion experiments
  - COMET at J-PARC; mu2e at FNAL
  - Potential improvements of $O(10^4)$ – $O(10^6)$ in sensitivities!
- τ LFV a priority for current & future experiments
  - SuperKEKB/Belle2 at KEK, LHCb, ATLAS & CMS at CERN
  - O(100) improvements in luminosity $\to$ O(10) – O(100) improvements in sensitivity (depending on background)



Charged lepton flavour violation

Modified from
Ann. Rev. 58 (2008) 315

Order of magnitude improvement every ~8 years



Well worth pushing down a few more orders of magnitude

What causes the difference between matter and antimatter?

- The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks

$$V_{CKM} = U_u U_d^+$$

U matrices from diagonalisation of mass matrices

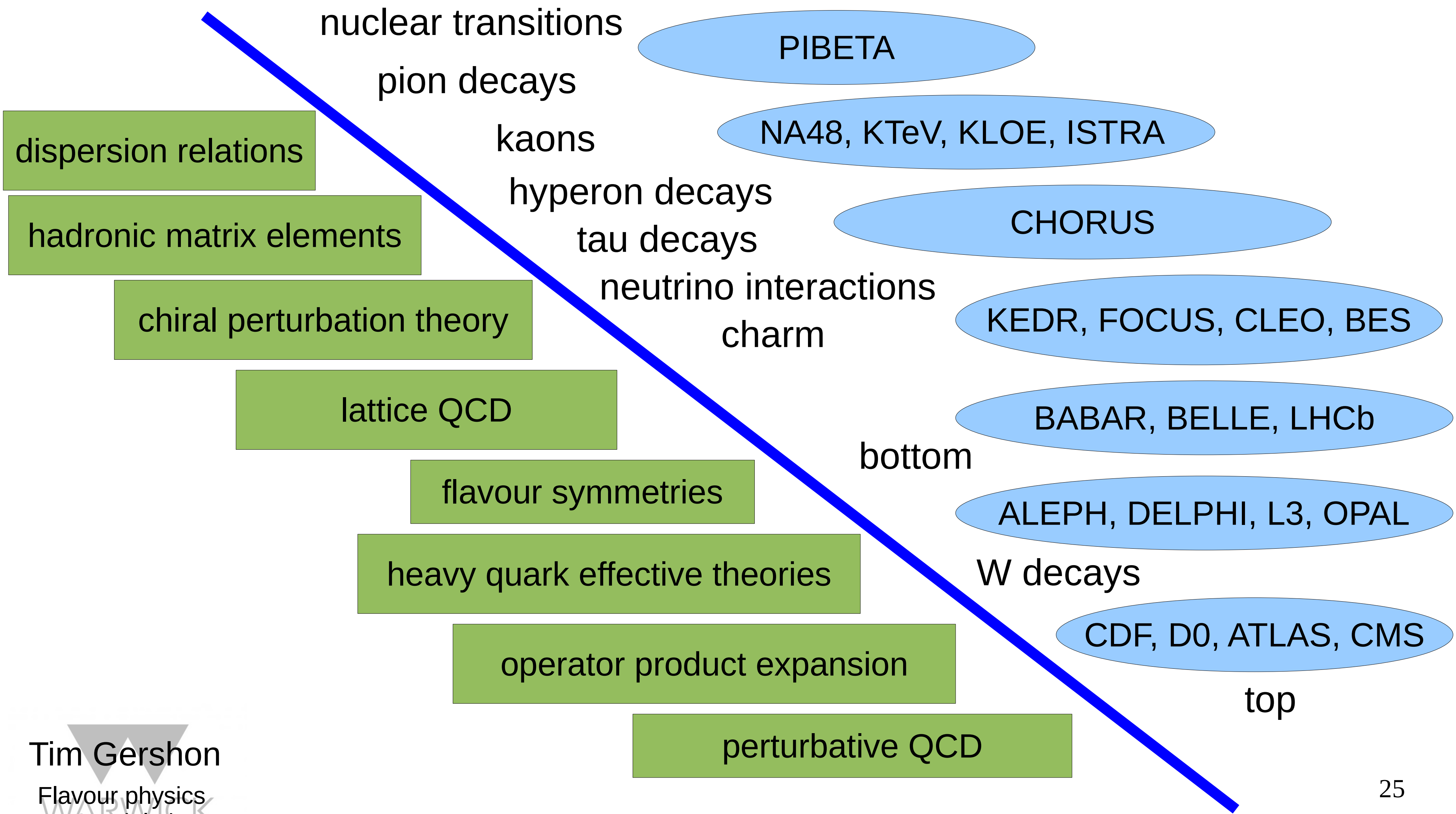
- It is a 3x3 complex unitary matrix
  - described by 9 (real) parameters
  - 5 can be absorbed as phase differences between the quark fields
  - 3 can be expressed as (Euler) mixing angles
  - the fourth makes the CKM matrix complex (i.e. gives it a phase)
    - weak interaction couplings differ for quarks and antiquarks
    - CP violation

The Cabibbo-Kobayashi-Maskawa Quark Mixing Matrix

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

- A 3x3 unitary matrix
- Described by 4 real parameters – allows CP violation
  - PDG (Chau-Keung) parametrisation: θ_{12}, θ_{23}, θ_{13}, δ
  - Wolfenstein parametrisation: λ, A, ρ, η
- Highly predictive

Range of CKM phenomena



What is CP violation?

The θ – τ puzzle:

- two strange charged particles discovered
  - the "θ" decaying to $\pi^+\pi^0$
  - the "τ" decaying to $\pi^+\pi^-\pi^+$
- parities of 2π and 3π are opposite, but masses and lifetimes of θ & τ found to be the same

Parity violation discovered 1957 (C.N.Wu et al, then many others, all following T.D.Lee and C.N.Yang)

θ & τ are the same particle: " K^+ "

From P to CP

P is maximally violated in beta decay (no right-handed neutrinos), however, C is also maximally violated (no left-handed antineutrinos)

- C : charge conjugation (swap particle for antiparticle)
- the product CP is conserved (Landau 1957)

Or so thought, until $K_L \to \pi^+\pi^-$ [CP(–1)→CP(+1)] was observed (Cronin & Fitch, 1964)

- CP violation distinguishes absolutely matter from antimatter

N.B. CPT is conserved in any Lorentz invariant gauge field theory

A brief history of CP violation and Nobel Prizes

- 1964 – Discovery of CP violation in K^0 system
  PRL 13 (1964) 138
- 1973 – Kobayashi and Maskawa propose 3 generations
  Prog.Theor.Phys. 49 (1973) 652
- 1980 – Nobel Prize to Cronin and Fitch

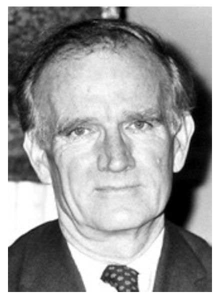
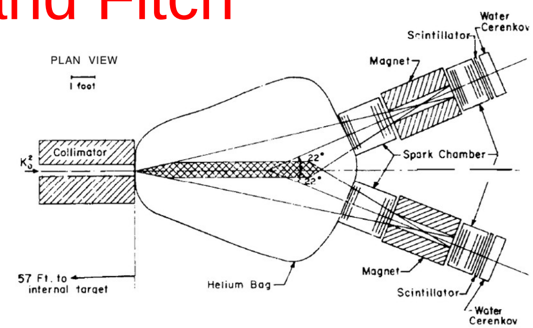




Fig. I. Plan view of the apparatus as located at the A. G. S.

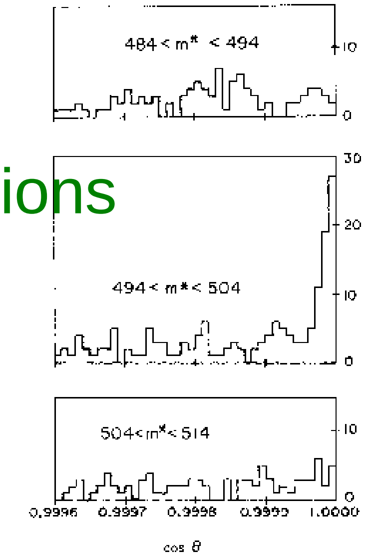
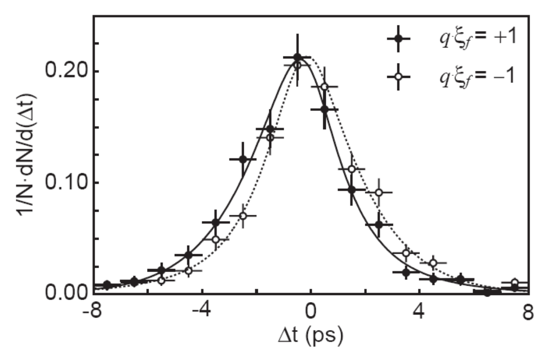
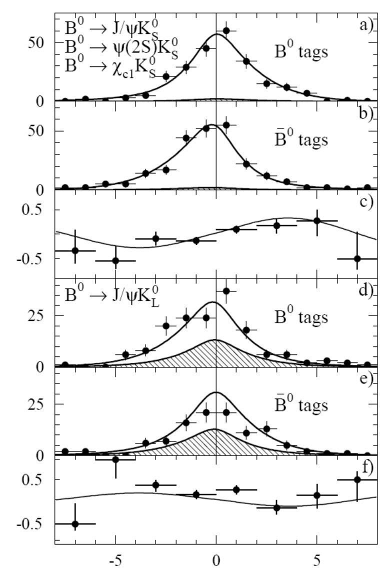


FIG. 3. Angular distribution in three mass ranges for events with cos θ > 0.9995.

- 2001 – Discovery of CP violation in B_d system
- 2008 – Nobel Prize to Kobayashi and Maskawa







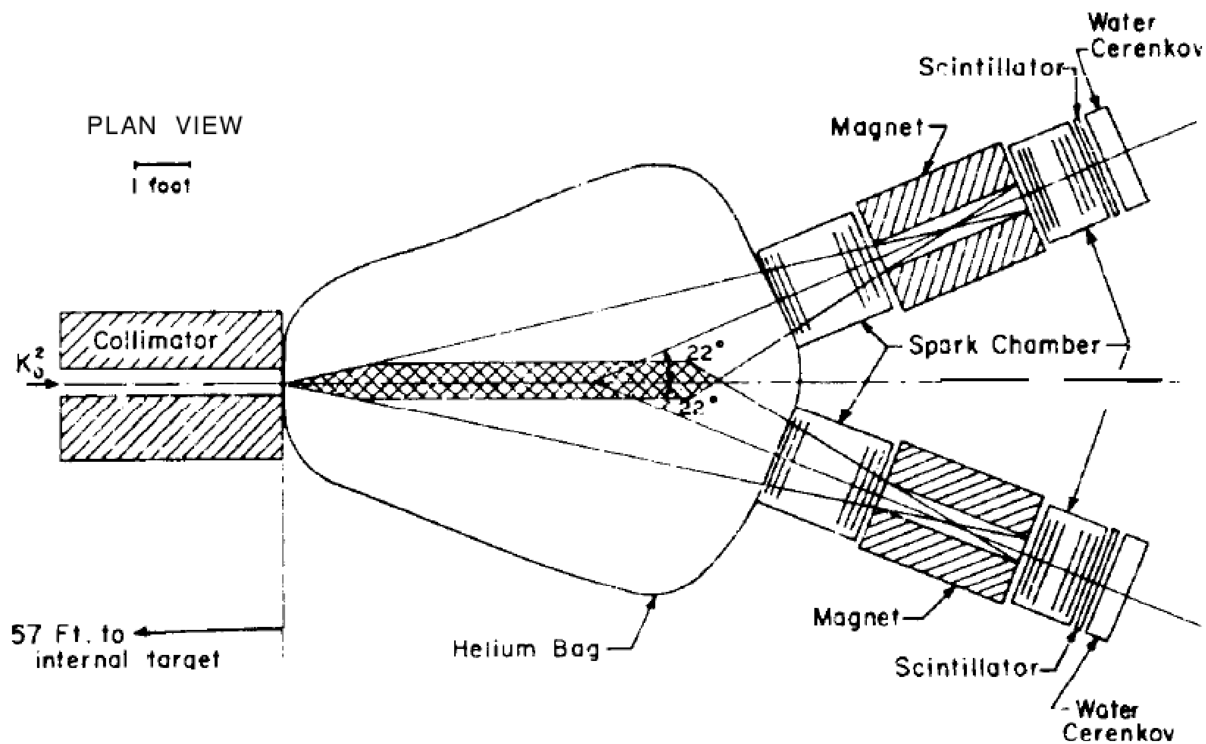
Belle PRL 87 (2001) 091802

BABAR PRL 87 (2001) 091801

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

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)



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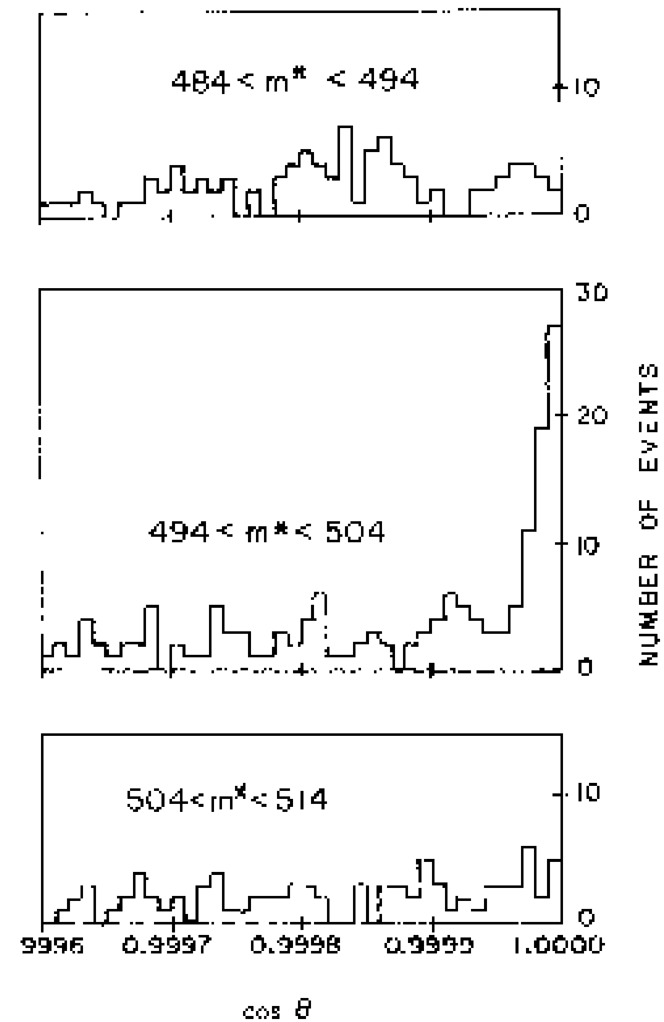
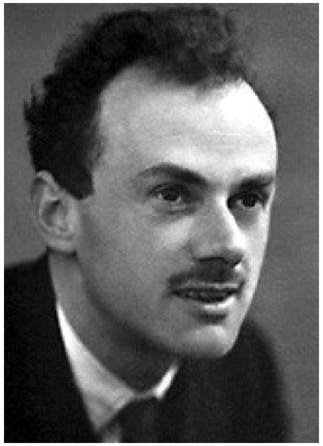


FIG. 3. Angular distribution in three mass ranges for events with cos θ > 0.9995.

Sakharov conditions

- Proposed by A.Sakharov, 1967
- Necessary for evolution of matter dominated universe, from symmetric initial state
  - (1) baryon number violation
  - (2) C & CP violation
  - (3) thermal inequilibrium
- No significant amounts of antimatter observed
- $\Delta N_B/N_\gamma$ = (N(baryon) – N(antibaryon))/$N_\gamma \sim 10^{-10}$

Dirac's prescience

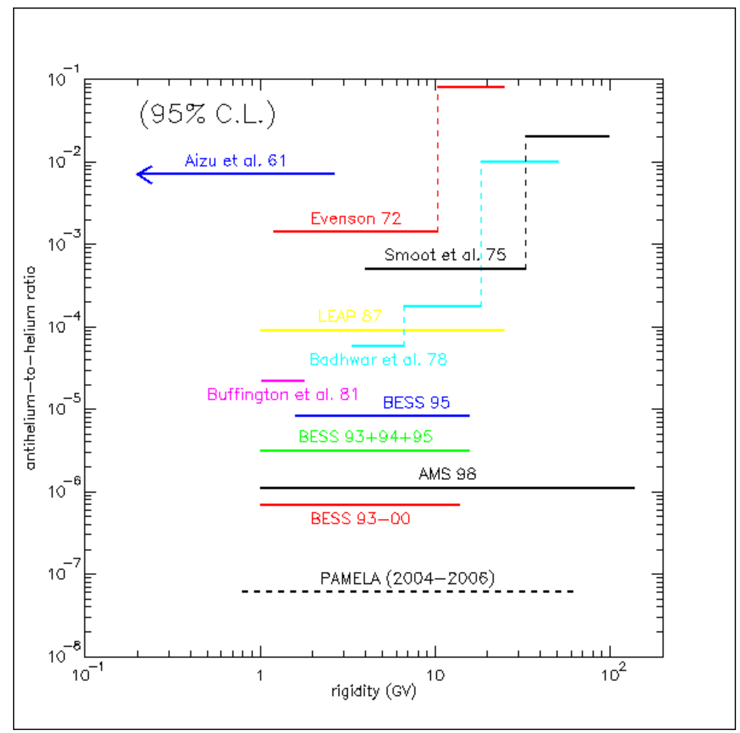


Concluding words of 1933 Nobel lecture

"If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods."

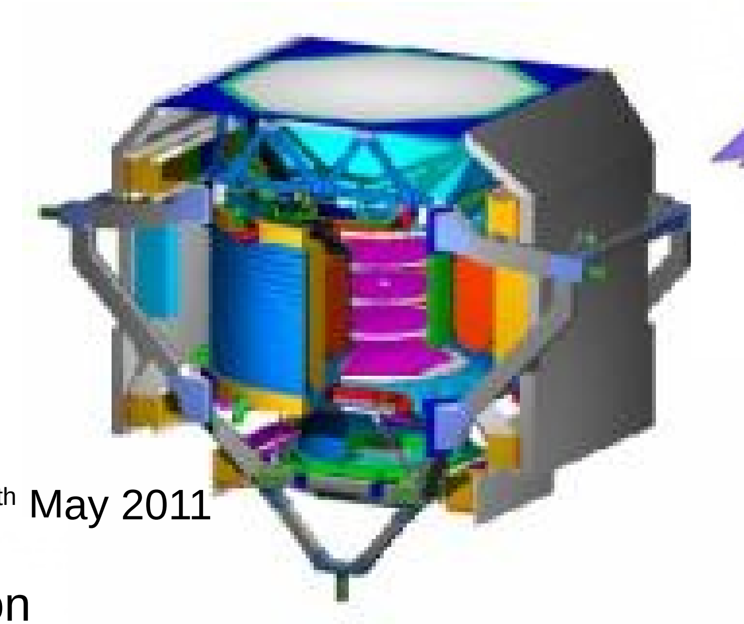
Digression: Are there antimatter dominated regions of the Universe?

- Possible signals:
  - Photons produced by matter-antimatter annihilation at domain boundaries – not seen
    - Nearby anti-galaxies ruled out
  - Cosmic rays from anti-stars
    - Best prospect: Anti-^{4}He nuclei
    - Searches ongoing ...



Searches for astrophysical antimatter

Alpha **M**agnetic **S**pectrometer Experiment on board the International Space Station



launched 16th May 2011

Payload for **A**nti**M**atter **E**xploration and **L**ight-nuclei **A**strophysics Experiment on board the Resurs-DK1 satellite

launched 15th June 2006

Dynamic generation of BAU

- Suppose equal amounts of matter (X) and antimatter ($\overline{X}$)
- X decays to
  - A (baryon number N_A) with probability p
  - B (baryon number N_B) with probability (1–p)
- $\overline{X}$ decays to
  - $\overline{A}$ (baryon number $-N_A$) with probability $\overline{p}$
  - $\overline{B}$ (baryon number $-N_B$) with probability $(1-\overline{p})$
- Generated baryon asymmetry:
  - $\Delta N_{TOT} = N_A p + N_B(1-p) - N_A\overline{p} - N_B(1-\overline{p}) = (p-\overline{p})(N_A-N_B)$
  - $\Delta N_{TOT} \neq 0$ requires $p \neq \overline{p}$ & $N_A \neq N_B$

CP violation

Baryon number violation

CP violation and the BAU

- We can estimate the magnitude of the baryon asymmetry of the Universe caused by KM CP violation

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx \frac{n_B}{n_\gamma} \sim \frac{J \times P_u \times P_d}{M^{12}}$$

N.B. Vanishes for degenerate masses

$$J = \cos(\theta_{12})\cos(\theta_{23})\cos^2(\theta_{13})\sin(\theta_{12})\sin(\theta_{23})\sin(\theta_{13})\sin(\delta)$$
$$P_u = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)$$
$$P_d = (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)$$

PRL 55 (1985) 1039

- The Jarlskog parameter J is a parametrization invariant measure of CP violation in the quark sector: J ~ $O(10^{-5})$
- The mass scale M can be taken to be the electroweak scale O(100 GeV)
- This gives an asymmetry $O(10^{-17})$
  - much much below the observed value of $O(10^{-10})$

We need more CP violation!

- Widely accepted[(*)] that SM CPV insufficient to explain observed baryon asymmetry of the Universe
- To create a larger asymmetry, require
  - new sources of CP violation
  - that occur at high energy scales
- Where might we find it?
  - lepton sector: CP violation in neutrino oscillations
  - quark sector: discrepancies with KM predictions
  - gauge sector, extra dimensions, other new physics: precision measurements of flavour observables are generically sensitive to additions to the Standard Model

[(*)] But not necessarily true! Don't forget the 3rd Sakharov condition of thermal inequilibrium. A very rapid phase transition could be a part of the solution to the BAU problem.

The neutrino sector

- Enticing possibility that neutrinos may be Majorana particles
  - provides connection with high energy scale (seesaw)
  - CP violation in leptons could be transferred to baryon sector (via B-L conserving processes)
- Requires
  - Determination of PMNS matrix
    - All mixing angles and CP phase must be non-zero
    - All mixing angles now measured; “only” δ_{CP} to go
  - Experimental proof that neutrinos are Majorana

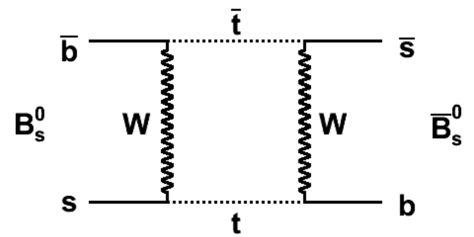
Flavour for new physics discoveries

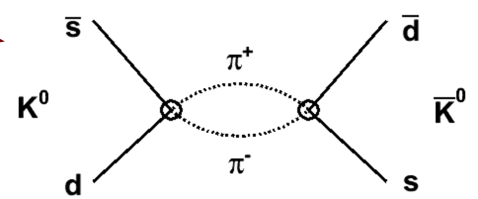
A lesson from history

- New physics shows up at precision frontier before energy frontier
  - GIM mechanism before discovery of charm
  - CP violation / CKM before discovery of bottom & top
  - Neutral currents before discovery of Z
- Particularly sensitive – loop processes
  - Standard Model contributions suppressed / absent
  - flavour changing neutral currents (rare decays)
  - CP violation
  - lepton flavour / number violation / lepton universality

Neutral meson oscillations

- We have flavour eigenstates M^0 and $\overline{M}^0$
  - M^0 can be K^0 ($\bar{s}d$), D^0 ($c\bar{u}$), B_d^0 ($\bar{b}d$) or B_s^0 ($\bar{b}s$)
- These can mix into each other
  - via short-distance or long-distance processes





- Time-dependent Schrödinger eqn.

$$i\frac{\partial}{\partial t}\begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix} = H \begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix} = \left(M - \frac{i}{2}\Gamma \right) \begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix}$$

  - H is Hamiltonian; M and Γ are 2x2 Hermitian matrices
- CPT theorem: $M_{11} = M_{22}$ & $\Gamma_{11} = \Gamma_{22}$

particle and antiparticle have equal masses and lifetimes

Solving the Schrödinger equation

- Physical states: eigenstates of effective Hamiltonian

$$M_{S,L} = p\, M^0 \pm q\, \overline{M}^0$$

p & q complex coefficients that satisfy $|p|^2 + |q|^2 = 1$

label as either S,L (short-, long-lived) or L,H (light, heavy) depending on values of Δm & $\Delta\Gamma$ (labels 1,2 usually reserved for CP eigenstates)

  – CP conserved if physical states = CP eigenstates ($|q/p| = 1$)

- Eigenvalues

$$\lambda_{S,L} = m_{S,L} - \tfrac{1}{2}i\Gamma_{S,L} = (M_{11} - \tfrac{1}{2}i\Gamma_{11}) \pm (q/p)(M_{12} - \tfrac{1}{2}i\Gamma_{12})$$

$$\Delta m = m_L - m_S \qquad \Delta\Gamma = \Gamma_S - \Gamma_L$$

$$(\Delta m)^2 - \tfrac{1}{4}(\Delta\Gamma)^2 = 4(|M_{12}|^2 + \tfrac{1}{4}|\Gamma_{12}|^2)$$

$$\Delta m \Delta\Gamma = 4\mathrm{Re}(M_{12}\Gamma_{12}^*)$$

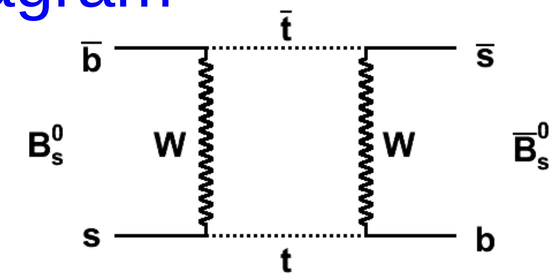
$$(q/p)^2 = (M_{12}^* - \tfrac{1}{2}i\Gamma_{12}^*)/(M_{12} - \tfrac{1}{2}i\Gamma_{12})$$

Simplistic picture of mixing parameters

- Δm: value depends on rate of mixing diagram
  - together with various other constants ...

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{tb}|^2 |V_{td}|^2$$

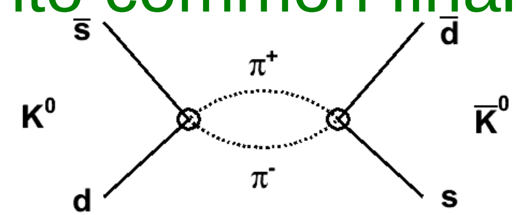
  - that can be made to cancel in ratios



$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

remaining factors can be obtained from lattice QCD calculations

- ΔΓ: value depends on widths of decays into common final states (CP-eigenstates)
  - large for K^0, small for D^0 & B_d^0



- $q/p \approx 1$ if $\arg(\Gamma_{12}/M_{12}) \approx 0$ ($|q/p| \approx 1$ if $M_{12} \ll \Gamma_{12}$ or $M_{12} \gg \Gamma_{12}$)
  - CP violation in mixing when $|q/p| \neq 1$

$$\left(\epsilon = \frac{p-q}{p+q} \neq 0 \right)$$

Simplistic picture of mixing parameters

	Δm ($x = \Delta m/\Gamma$)	$\Delta\Gamma$ ($y = \Delta\Gamma/2\Gamma$)	q/p ($\varepsilon = (p-q)/(p+q)$)
K^0	large ~ 500	~ maximal ~ 1	small 2×10^{-3}
D^0	small $(0.41 \pm 0.04)\%$	small $(0.65 \pm 0.02)\%$	small 0.006 ± 0.016
B^0	medium 0.775 ± 0.006	small 0.001 ± 0.005	small -0.0007 ± 0.0009
B_s^0	large 26.79 ± 0.08	medium 0.061 ± 0.005	small -0.0038 ± 0.0021

Simplistic picture of mixing parameters

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More precise measurements needed (SM prediction well known)

Constraints on NP from mixing

- All measurements of Δm & ΔΓ consistent with SM
  - K^0, D^0, B_d^0 and B_s^0
- This means $|A_{NP}| < |A_{SM}|$ where $\mathcal{A}_{\rm SM}^{\Delta F=2} \approx \frac{G_F^2 m_t^2}{16\pi^2} (V_{ti}^* V_{tj})^2 \times \langle \overline{M} | (\overline{Q}_{Li} \gamma^\mu Q_{Lj})^2 | M \rangle \times F\left(\frac{M_W^2}{m_t^2}\right)$
- Express NP as perturbation to the SM Lagrangian
  - couplings c_i and scale $\Lambda > m_W$ $\quad \mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields})$
- For example, SM like (left-handed) operators $\quad \Delta\mathcal{L}^{\Delta F=2} = \sum_{i \neq j} \frac{c_{ij}}{\Lambda^2} (\overline{Q}_{Li} \gamma^\mu Q_{Lj})^2$

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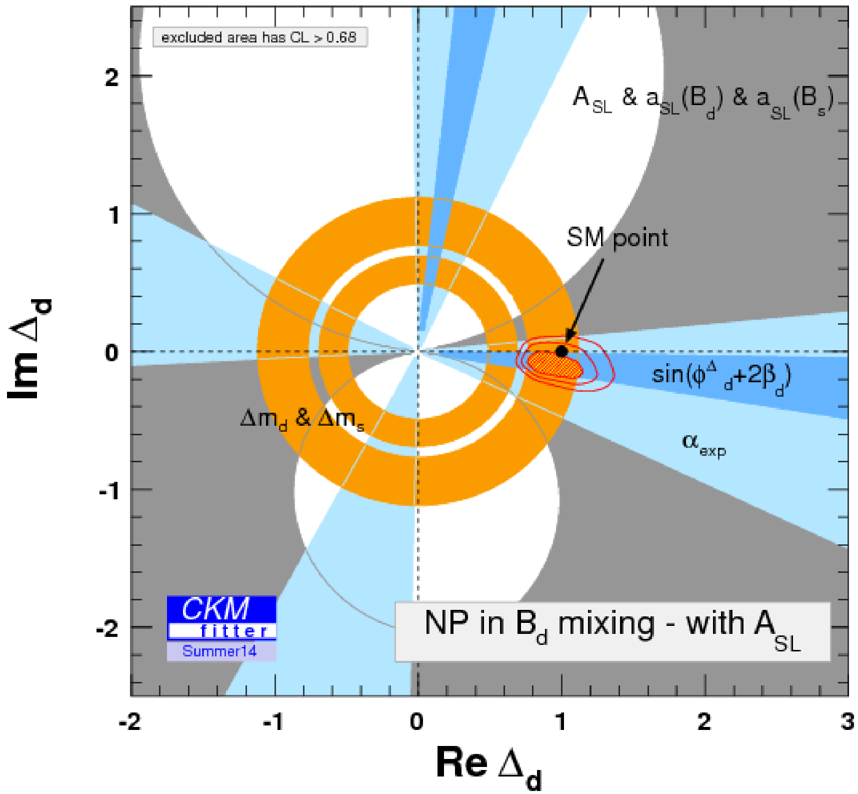
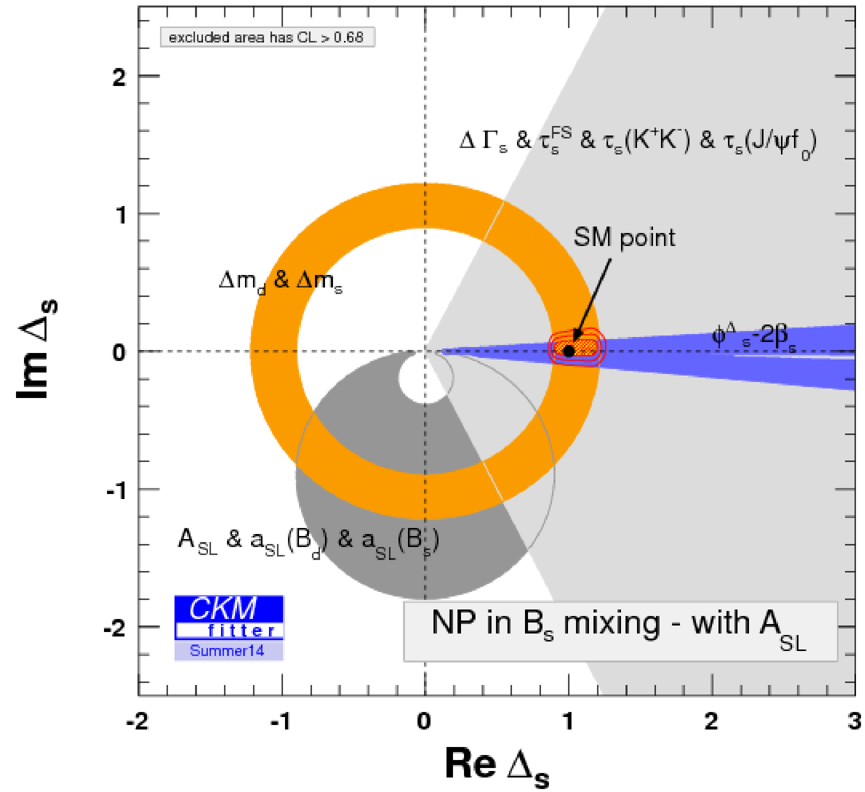
Operator	Bounds on Λ in TeV ($c_{ij} = 1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

Same table but bigger ...

Operator	Bounds on Λ in TeV ($c_{ij} = 1$) Re	Bounds on Λ in TeV ($c_{ij} = 1$) Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Bounds on c_{ij} ($\Lambda = 1$ TeV) Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

Similar story – but including more (& more up-to-date) inputs, and in pictures





arXiv:1501.05013

New Physics Flavour Problem

- Limits on NP scale at least 100 TeV for generic couplings
  - model-independent argument, also for rare decays
- But we need NP at the ~TeV scale to solve the hierarchy problem (and to provide DM candidate, etc.)
- So we need NP flavour-changing couplings to be small
- Why?
  - minimal flavour violation?
    - perfect alignment of flavour violation in NP and SM
  - some other approximate symmetry?
  - flavour structure tells us about physics at very high scales

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… are still important observables that are not yet well-tested