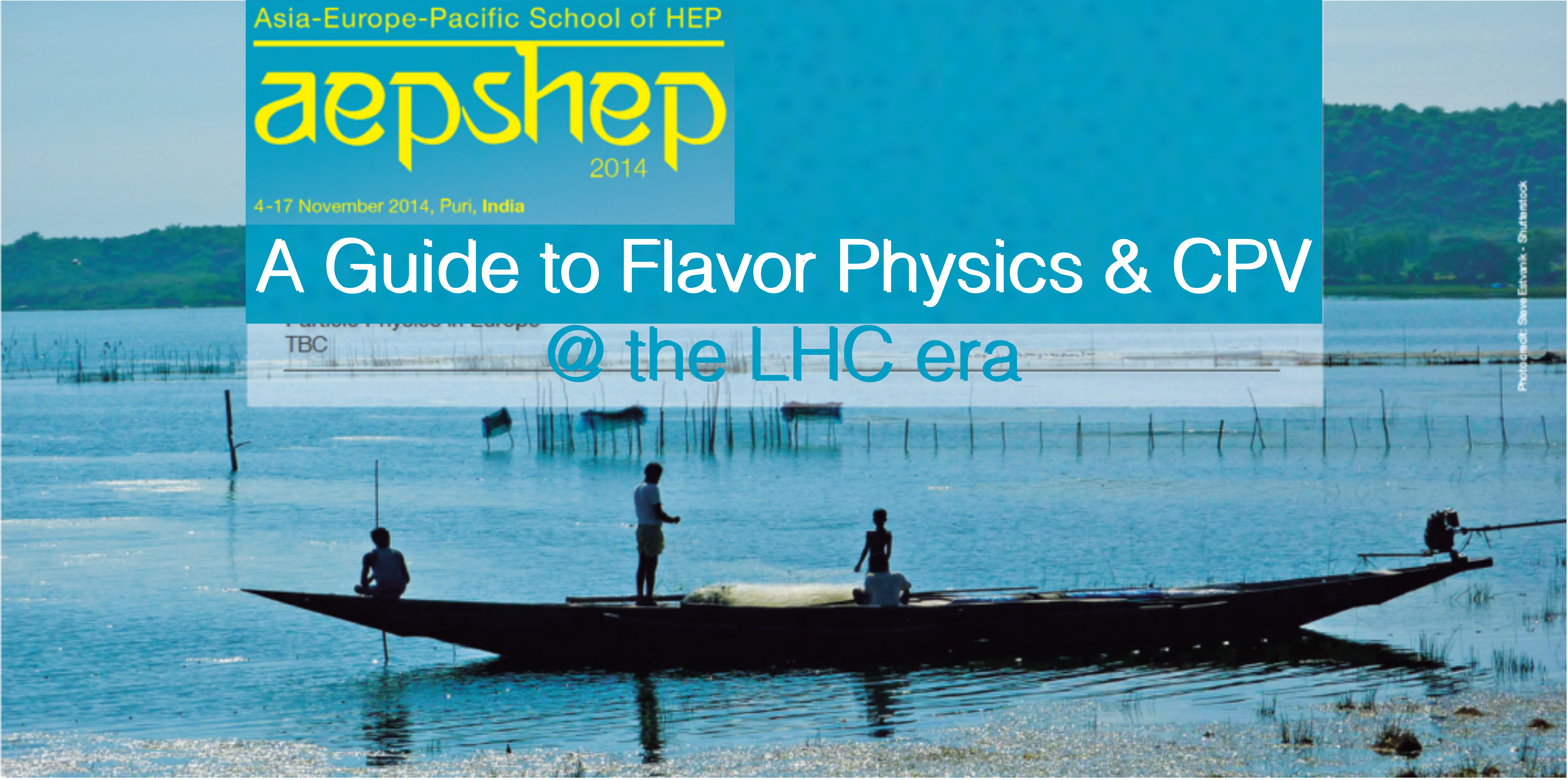


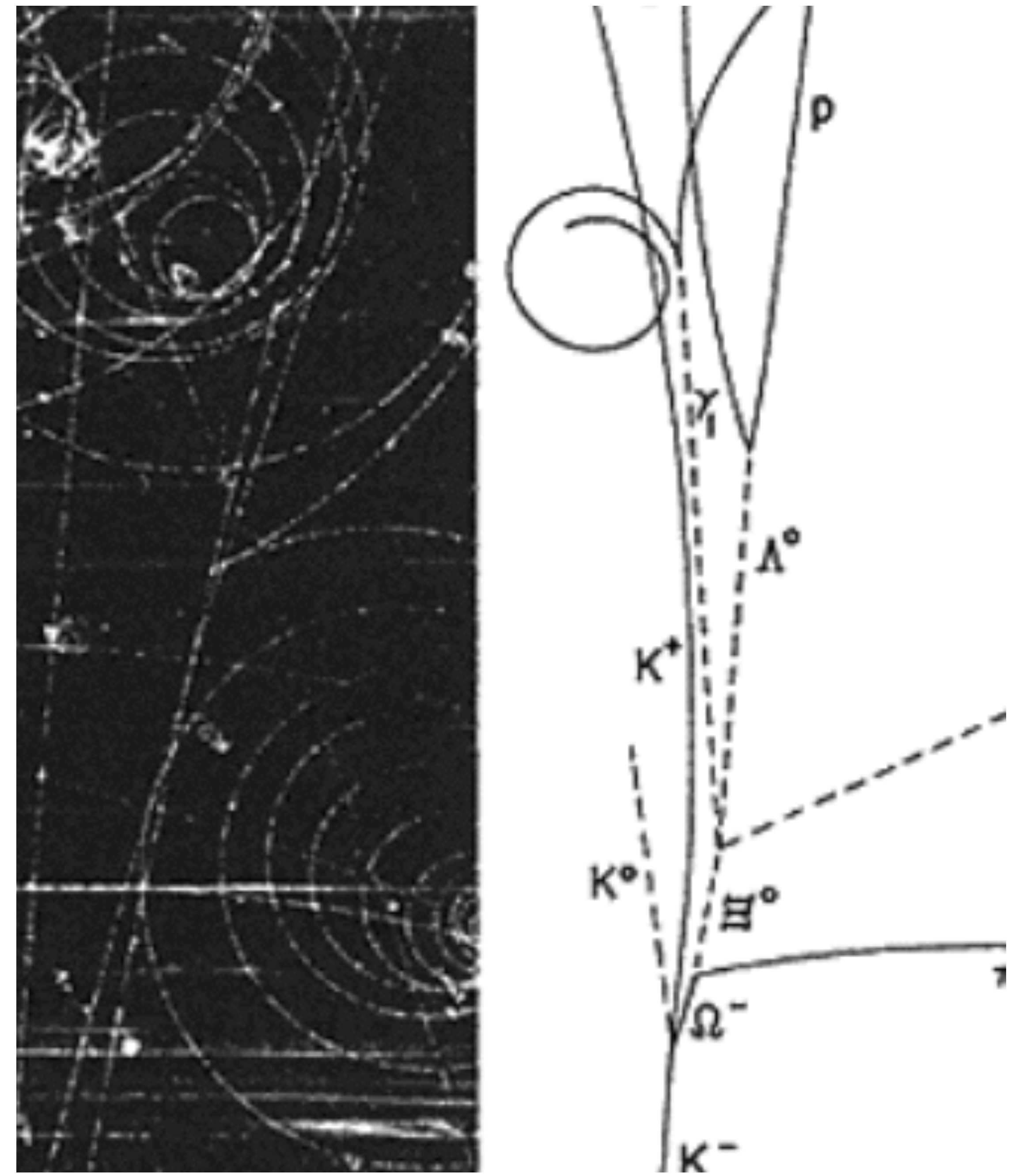
A Guide to Flavor Physics & CPV @ the LHC era

Seung J. Lee
KAIST

Lecture 1

Outline

- Lecture I: Motivation, and Basic Introduction to Flavor Physics
- Lecture 2: Flavor and CP Violation in the meson mixings and decays
- Lecture 3: OPE, Effective Theories for heavy flavors.
- Lecture 4: New Physics Puzzle & Implication on BSM flavor structure. Flavor Physics at the LHC era



references: Y. Nir, hep-ph/0510413
A. Buras, hep-ph/9806471
Branco, Lavora, and Silva, "CP violation"
Y. Grossman, arXiv:1006.3534

Lecture I

- Introduction to the Flavor Physics
- The Role of Flavor Physics (historical)
- Flavor Physics (current issues)
- Flavor Structure of the SM

Introduction: What is flavor physics?

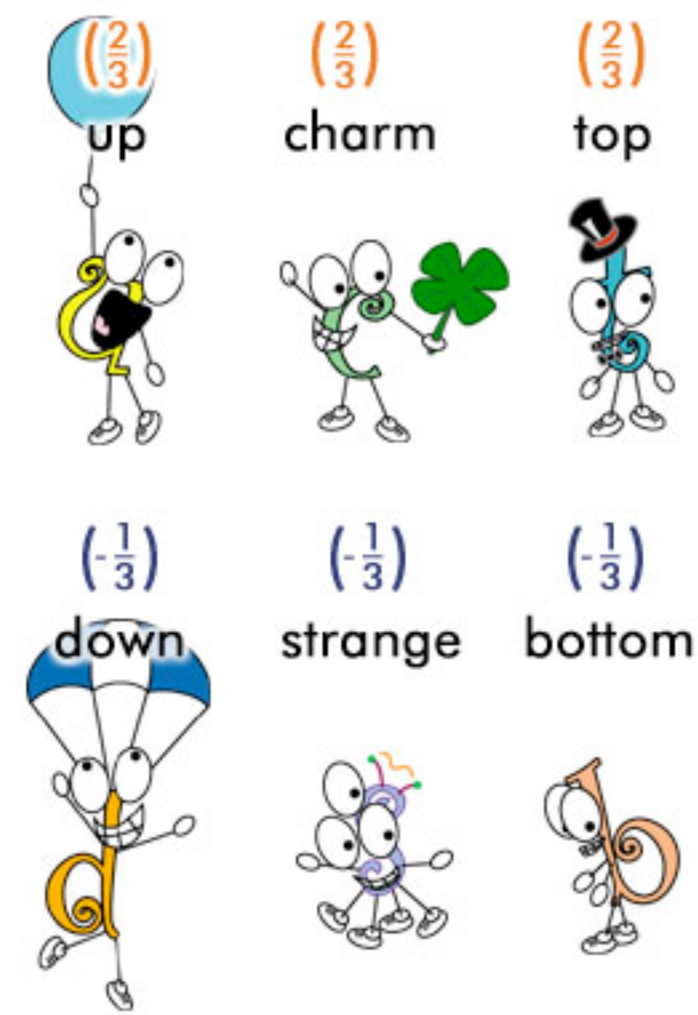
- What is flavor? several copies of the same gauge representation, i.e. several fields that are assigned the same quantum charges

- "Flavor physics" describes interactions that distinguish between flavors.

- Interactions for fermions:

  1) Gauge interactions- interactions that are related to unbroken symmetries and mediated therefore by massless gauge bosons, do not distinguish among the flavors and do not constitute part of flavor physics.

  2) Yukawa interactions, where 2 fermions couple to a scalar -> source of flavor and CP violation.



Introduction: What is flavor physics?

- What is flavor? several copies of the same gauge representation, i.e. several fields that are assigned the same quantum charges

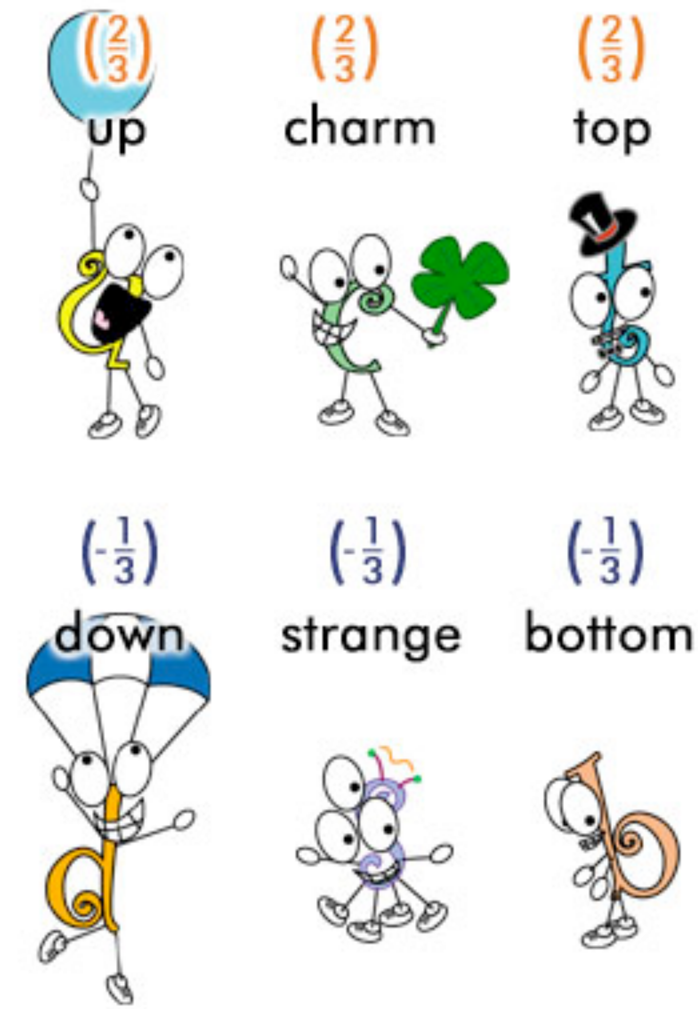
- "Flavor physics" describes interactions that distinguish between flavors

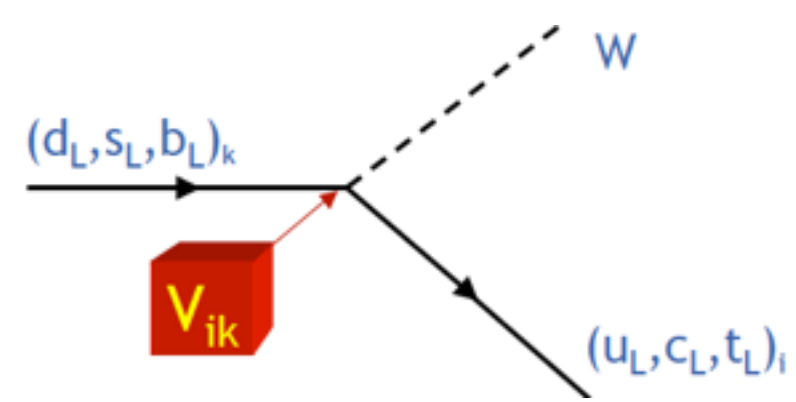
- Interacti

  1) Gauge lated to unbrok re by massless g ng the flavors and do not constitu part of flavor physics.

  2) Yukawa interactions, where 2 fermions couple to a scalar -> source of flavor and CP violation.

Within the SM, flavor-physics refers to the weak and Yukawa interactions





The Role of Flavor Physics (historical)

* Flavor physics can predicted New Physics before it's directly observed

s before it's directly observed

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

echanism (Phys Rev D 1970)

ι^- very suppressed?

- Estimation of $m_c \sim 1.5$ GeV (Gaillard and Lee, Phys Rev D 1974)

→ Charm discovery with hadron and e^+e^- machines

Aubert et al. and Augustin et al., 1974

Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

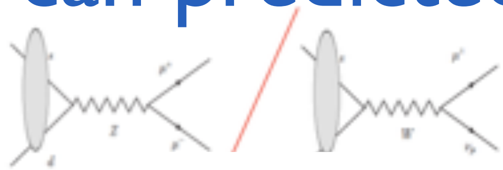
and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

The Role of Flavor Physics (historical)

- Flavor physics can predicted New Physics before it’s directly observed



$\mathrm{Br}(K^+ \to \mu^+\nu) = 64\%$ $\mathrm{Br}(K_L \to \mu^+\mu^-) = 7 \times 10^{-9}$

- smallness of $\frac{\Gamma(K_L \to \mu^+\mu^-)}{\Gamma(K^+ \to \mu^+\nu)}$ ➡ prediction of charm quark
- the size of Δm_K ➡ charm mass prediction
- The measurement of ε_K ➡ prediction of the third generation
- the size of Δm_B ➡ prediction of top mass (~150 GeV) 81`
- The measurement of neutrino flavor transitions led to the discovery of neutrino masses.

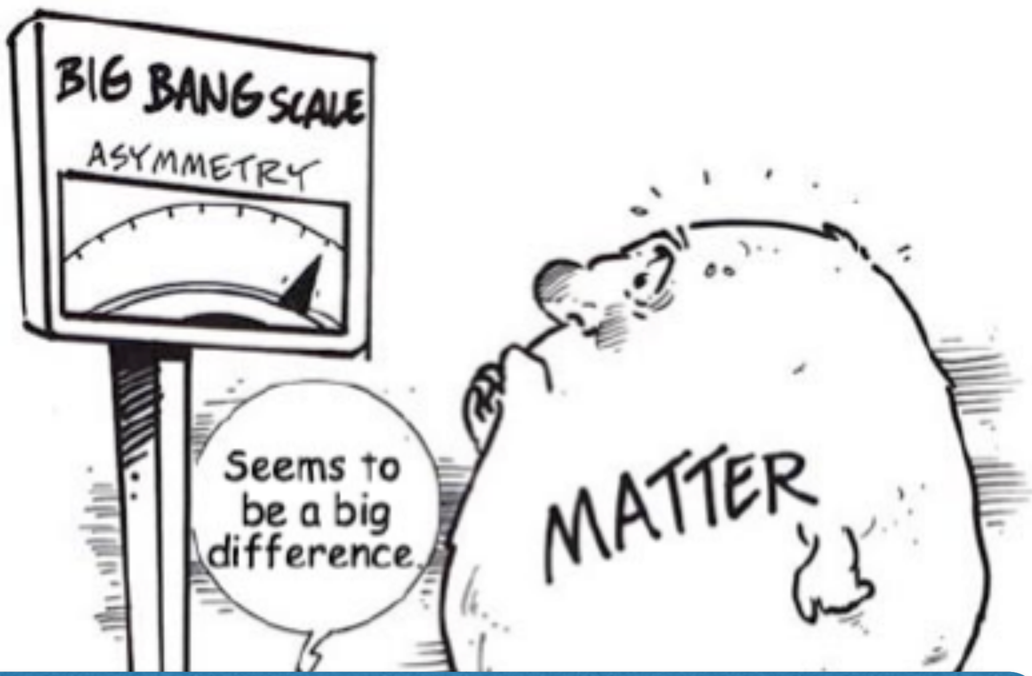
- Flavor physics (CP Violation) predicts that there should be New Physics beyond the SM:

Flavor Physics (current issues): The Baryon Asymmetry

("otherwise we would not be here")

$$\boxed{Y_B \equiv \frac{n_b - n_{\bar{b}}}{s} = (8.75 \pm 0.23) \times 10^{-11}}$$

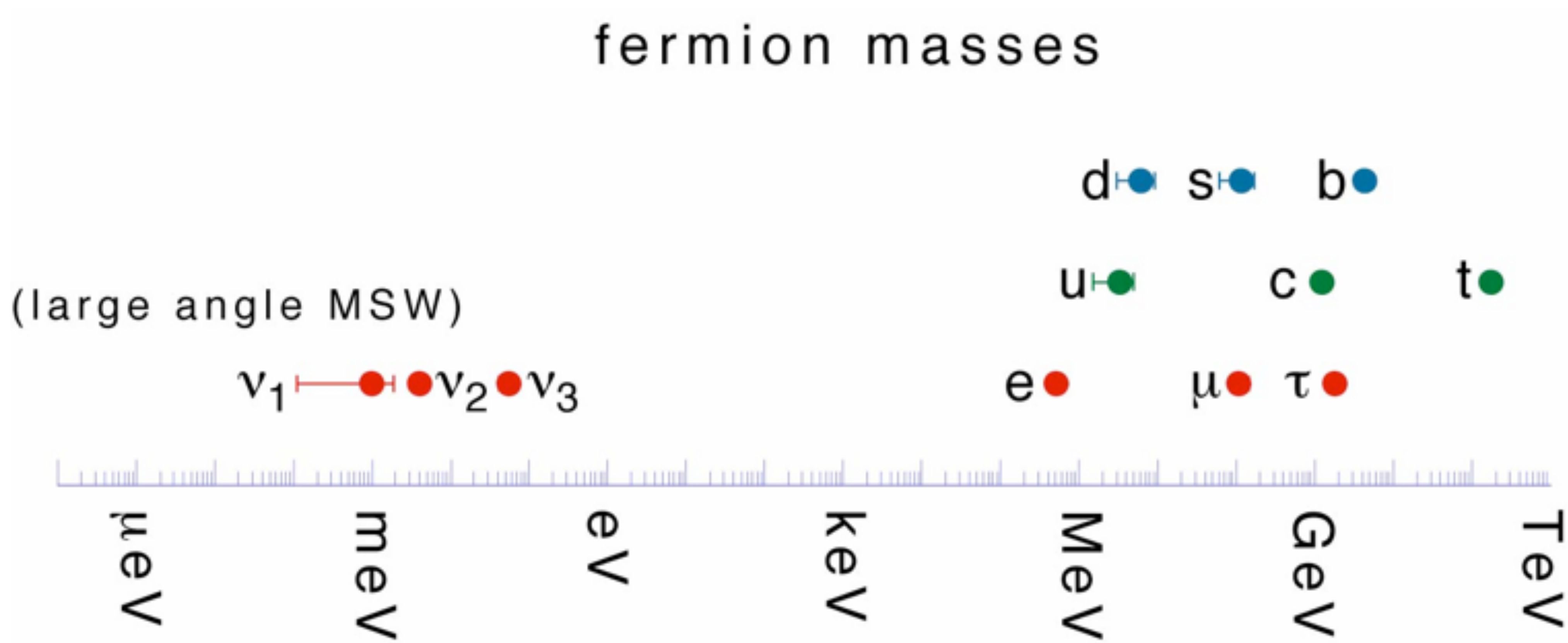
- Antimatter disappeared from the Universe: $n_{\bar{b}}/s \approx 0$
- Matter has survived: $n_b/s \sim 10^{-10}$
- The baryon asymmetry can be dynamically generated ('baryogenesis') provided that
    1. Baryon number is violated
    2. CP and C are violated
    3. Departure from thermal equilibrium



CP Violation from the SM (via CKM phase) cannot produce large enough baryon asymmetry
=> There must exist sources of CPV beyond the SM

Flavor Physics (current issues)

- Flavor physics can predicted New Physics before it's directly observed
- Flavor physics (CP Violation) predicts that there should be New Physics beyond the SM
- SM flavor problem: hierarchy of masses and mixing angles; why neutrinos are different



Flavor Puzzle (hierarchy) vs. Fine-tuning (naturalness)

- SM flavor problem: hierarchy of masses and mixing angles; why neutrinos are different

Is it fine tuned?

- Technically it's still natural: according to the definition of t'Hooft, a parameter is natural if there is an enhanced symmetry when the parameter is set to zero

- If we set fermion masses to zero, we will see that there will be enhanced global $U(3)^5$ symmetries

→ flavor sector is tunned, but not fine-tuned!

Flavor Structure of the SM

- Symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y$
- irreps: 3 copies of QudLe fermions

$$Q_L(3,2)_{1/6}\ u_R(3,1)_{2/3}\ d_R(3,1)_{-1/3}$$

$$L_L(1,2)_{-1/2}\ e_R(1,1)_{-1}$$

- SSB: one scalar

$$\phi(1,2)_{+1/2} \qquad \langle\phi\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

$$\Rightarrow \quad SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$$

- This model has a $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$ global symmetry
- The most renormalizable Lagrangian

$$\mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$

Flavor Structure of the SM

generation index

violated by the Yukawa couplings of the fermions to
the Higgs field

$$Q_L^i = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} c_L \\ s_L \end{pmatrix}$$

$$(u^c)_L^i = \quad (u^c)_L \quad (c^c)_L \quad (t^c)_L \quad \bar{3} \quad 1 \quad -\tfrac{2}{3}$$

$$(d^c)_L^i = \quad (d^c)_L \quad (s^c)_L \quad (b^c)_L \quad \bar{3} \quad 1 \quad \tfrac{1}{3}$$

U(3) flavor-independent phase: U(3)[5]
U(N)=SU(N)xU(1)

$$L_L^i = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$$

$$1$$

$$G_{\text{global}}(Y^{u,d,e}=0) = SU(3)_q^3 \times SU(3)_\ell^2 \times U(1)^5,$$

$$\begin{aligned} SU(3)_q^3 &= SU(3)_Q \times SU(3)_U \times SU(3)_D, \\ SU(3)_\ell^2 &= SU(3)_L \times SU(3)_E, \\ U(1)^5 &= U(1)_B \times U(1)_L \times U(1)_Y \times U(1)_{\text{PQ}} \times U(1)_E. \end{aligned}$$

$$\begin{aligned} Q_L^i &\to U_{Q_L}^{ij} Q_L^j \\ u_R^i &\to U_{u_R}^{ij} u_R^j \\ d_R^i &\to U_{d_R}^{ij} d_R^j \\ L_L^i &\to U_{L_L}^{ij} L_L^j \\ e_R^i &\to U_{e_R}^{ij} e_R^j \,. \end{aligned}$$

Flavor Structure of the SM

- U(3)[5] symmetry is broken by the Yukawa terms; most general, gauge invariant and renormalizable interactions of Higgs and matter fields

$$\mathcal{L}_{Yukawa} = -Y_u^{ij}\bar{Q}_L^i\tilde{\phi}u_R^j - Y_d^{ij}\bar{Q}_L^i\phi d_R^j - Y_e^{ij}\bar{L}_L^i\phi e_R^j$$

$$\phi(1,2)_{+1/2} \qquad \langle\phi\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \qquad \tilde{\phi} = i\tau_2\phi^\dagger$$

- The Yukawa matrix, Y_f : arbitrary 3x3 complex matrix
- After the EWSB, Yukawa terms provide masses to fermions. ($Q_L \rightarrow u_L$ and d_L)
- If Y_f is not diagonal, flavor is violated
- If Y_f carries a phase, CP is violated

Flavor Structure of the SM

- CP Violation from Yukawa terms: a "hand-waving" argument:

  Since the Lagrangian is hermitian,

$$\mathcal{L}_{Yukawa} \supset -Y_d^{ij} \bar{Q}_L^i \phi d_R^j - Y_d^{ji*} \bar{d}_R^j \phi^\dagger Q_L^i$$

- Under the CP transformation,

$$\mathcal{L}_{Yukawa} \supset -Y_d^{ij} \bar{d}_R^i \phi^\dagger Q_L^j - Y_d^{ji*} \bar{Q}_L^j \phi d_R^i$$

→ CP is violated if $Y^{ij} \neq Y^{ij*}$

- This is not a full story, since we have a choice for basis, but the basic idea follows from it

Flavor Structure of the SM

$$\mathcal{L}_{Yukawa} = -Y_u^{ij}\bar{Q}_L^i\tilde{\phi}u_R^j - Y_d^{ij}\bar{Q}_L^i\phi d_R^j - Y_e^{ij}\bar{L}_L^i\phi e_R^j$$

- Gauge principle allows arbitrary generation changing interactions, since fermions of different generations have equal gauge charges!

- Usually such couplings are eliminated by field redefinitions (unitary rotation in generation space):

$$\Psi^i \to U^{ij}\Psi^j$$

We have seen this for the global symmetries for kinetic terms

Flavor Structure of the SM

- We can diagonalize Yukawa matrices using bi-unitary transformations, e.g.:

$$Y_d = V_L^d \lambda_d V_R^{d\dagger} \qquad \lambda_d = \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix}$$

unitary

$$\bar{u}_L M_u u_R + \bar{d}_L M_d d_R$$

$$V_L^{u\dagger} V_L^u \quad V_R^{u\dagger} V_R^u \qquad V_L^{d\dagger} V_L^d \quad V_R^{d\dagger} V_R^d$$

$$\Rightarrow \bar{u'}_L M_u^{diag} u'_R + \bar{d'}_L M_d^{diag} d'_R$$

$u'_L{}^{mass} = V_L \, u_L{}^{interaction}$

- Under the following field redefinition, we can diagonalize the mass matrices (moving from the interaction basis to the mass basis):

$$e_L \to V_L^e e_L \qquad e_R \to V_R^e e_R$$

$$u_L \to V_L^u u_L \qquad u_R \to V_R^u u_R$$

$$d_L \to V_L^d d_L \qquad d_R \to V_R^d d_R$$

$\Rightarrow$ fermion masses are generated with $m_f = y_f v/\sqrt{2}$

Flavor Structure of the SM

$e_L \to V_L^e e_L$ e_R

$u_L \to V_L^u u_L$ u_R

$d_L \to V_L^d d_L$ d_R

Adding quarks of different irreps
generate tree level
FCNC Z couplings

* The coupling to neutral gauge boson (γ, Z, g) is not modified by this field redefinition

$$\mathcal{L}_\gamma \sim \bar{d}_i \delta_{ij} d_j \to \bar{d}_k (V_d)_{ki} \delta_{ij} (V_d^\dagger)_{jl} d_l \sim \bar{d}_i \delta_{ij} d_j$$

The absence of FCNC for γ and g is due to the gauge invariance.

$$g^{Zff} = g \cos\theta_W T_3 - g' \sin\theta_W Y.$$

* The absence of tree-level FCNC for Z (gauge inv. is broken) is from different reason: $Q = T_3 + Y$. In the SM all quarks with the same electric charge Q also have the same T_3 and therefore also the same Y. Z coupling only depends on these quantities =>Z coupling is universal for each of the up-type and down-type quarks for SM

Flavor Structure of the SM

$e_L \to V_L^e e_L \qquad e_R \to V_R^e e_R$

$u_L \to V_L^u u_L \qquad u_R \to V_R^u u_R$

$d_L \to V_L^d d_L \qquad d_R \to V_R^d d_R$

- The coupling to neutral gauge boson (γ, Z, g) is not modified by this field redefinition

$$\mathcal{L}_\gamma \sim \bar{d}_i \delta_{ij} d_i \;\to\; \bar{d}_i V \delta_{ij} V^\dagger d \sim \bar{d}_i \delta_{ij} d_i$$

- The absence of FCNC for Higgs: $Y_d^{ij} \bar{Q}^i \phi d^j \to Y_d^{ij} \bar{Q}^i (v + i\, h) d^j$

  Alignment: Higgs couplings to the fermions are aligned with the mass matrices, since Yukawa coupling is proportional to fermion masses matrices => Higgs coupling is diagonal in the mass basis => if multiple higgses, than generically FCNC (usual two higgs doublet is exception ~ like single higgs for each up and down sector)

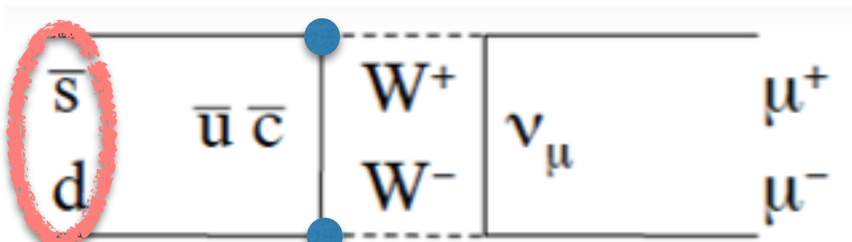
Flavor Structure of the SM

$$e_L \to V_L^e e_L \qquad e_R \to V_R^e e_R$$
$$u_L \to V_L^u u_L \qquad u_R \to V_R^u u_R$$
$$d_L \to V_L^d d_L \qquad d_R \to V_R^d d_R$$

- The coupling to neutral gauge boson (γ, Z, g) is not modified by this field redefinition

$$\mathcal{L}_\gamma \sim \bar{d}_i \delta_{ij} d_i \;\to\; \bar{d}_i V \delta_{ij} V^\dagger d \sim \bar{d}_i \delta_{ij} d_i$$

- In SM, FCNC is only via loop effect



→ FCNC suppressed by loop, GIM, CKM

$$V_{us} \sim V_{cd} \sim 0.22$$

Flavor Structure of the SM

$e_L \to V_L^e e_L \qquad e_R \to V_R^e e_R$

$u_L \to V_L^u u_L \qquad u_R \to V_R^u u_R$

The point is that we cannot have Y_U, Y_D and the couplings to the W diagonal at the same basis

=>In the mass basis, flavor is violated by W interaction!

- The cou ... ed by this fi

- But, the rotation modifies the coupling to charged gauge boson (W)

$$\mathcal{L}_W \sim \bar{u}_L^i \delta_{ij} d_L^j \to \bar{u}_L^k (V_L^u)_{ki} \delta_{ij} (V_L^{d\dagger})_{jl} d_L^l \sim \bar{u}_L^i (V_{\rm CKM})_{ij} d_L^j$$

$$\boxed{V_{\rm CKM} = V_L^u V_L^{d\dagger}}$$

CKM matrix:

$$\boxed{V_{\mathrm{CKM}} = V_L^u V_L^{d\dagger}}$$

- V_{CKM} is unitary by construction
- Unitary 3x3 matrix V can by parameterized by 3 Euler angles and 6 phases
- Not all phases are observable, since under phase redefinitions $q_L \to e^{i\phi_q} q_L$ of the quark fields:

$$V \to \begin{pmatrix} e^{-i\varphi_u} & 0 & 0 \\ 0 & e^{-i\varphi_c} & 0 \\ 0 & 0 & e^{-i\varphi_t} \end{pmatrix} V \begin{pmatrix} e^{i\varphi_d} & 0 & 0 \\ 0 & e^{i\varphi_s} & 0 \\ 0 & 0 & e^{i\varphi_b} \end{pmatrix}, \qquad V_{ij} \to e^{i(\varphi_d^i - \varphi_u^j)} V_{ij}$$

→ 5 of 6 phases can be eliminated by suitable choices of phase differences! ("Unphysical" parameters are those that can be set to zero by a basis rotation)

How many physically relevant parameters?

Quark Sector

- Number of parameters contained in the Yukawa matrices Y_u and Y_d is: $2 \times 3 \times 3 \times 2 = 36$
- The unitary symmetries U_Q, U_u U_d (untitary 3 x 3 matirces) are the subset of quark field redefinitions: degree of freedom = $3 \times 3 \times 3 = 27$
- Baryon number is a symmetry of the Yukawa Lagrangian, so it cannot be used to diagonalize the mass matrices => 1 less degree of freedom
- Number of physical parameters:
  $(2 \times 3 \times 3 \times 2) - (3 \times 3 \times 3 - 1) = 10$

(Total # of parameter) - (# of broken generators) = # of physical parameter

How many physically relevant parameters?

Quark Sector

- Number of parameters contained in the Yukawa matrices Y_u and Y_d is: $2 \times 3 \times 3 \times 2 = 36$

10 physical parameters =

6 quark masses
+ 4 parameters from the CKM matrix

- 3 mixing angles (the orthogonal part of the mixing)
- One phase (CP violating)

mass matrices => 1 less degree of freedom

- Number of physical parameters:
$$(2 \times 3 \times 3 \times 2) - (3 \times 3 \times 3 - 1) = 10$$

(Total # of parameter) - (# of broken generators) = # of physical parameter

CKM matrix:

$$\boxed{V_{\rm CKM} = V_L^u V_L^{d\dagger}}$$

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \bar{u}_L V \gamma^\mu d_L W_\mu^+ + \text{h.c.}$$

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

- CKM is unitary

$$\sum V_{ij} V_{ik}^* = \delta_{jk}$$

- Experimentally, $V \sim 1$. Off diagonal terms are small
- Many ways to parametrize the matrix

CKM matrix:

- Form of V is not unique
  - The standard parametrization $s_{13} \ll s_{23} \ll s_{12} \ll 1$.

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

  where $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$.
  - In general there are 5 entries that carry a phase
  - Experimentally: (will explain later how these measurements were done)

$$|V| \approx \begin{pmatrix} 0.97383 & 0.2272 & 3.96 \times 10^{-3} \\ 0.2271 & 0.97296 & 4.221 \times 10^{-2} \\ 8.14 \times 10^{-3} & 4.161 \times 10^{-2} & 0.99910 \end{pmatrix}$$

CKM matrix:

* Form of V is not unique: a very useful one is due to Wolfenstein (1983):

$\lambda = s_{12}$ is approximately the Cabibbo angle.

$$V \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- Jarlskog determinant:
  for arbitrary choice of i,j,k,l the quantity

$$\boxed{\mathrm{Im}(V_{ij}V_{kl}V_{il}^{*}V_{kj}^{*}) = J \sum_{m,n} \varepsilon_{ikm}\, \varepsilon_{jln}}$$

$$J = c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13} \sin\delta_{KM} \approx \lambda^6 A^2 \eta.$$

  is an invariant of the CKM matrix (independent of phase conventions)

- CP invariance is broken if and only if J≠0
- Wolfenstein parameterization:

$$J = O(\lambda^6) = O(10^{-4}) \quad \text{rather small}$$

The flavor parameters span many order magnitudes and have a clear hierarchy. why? Is it natural?

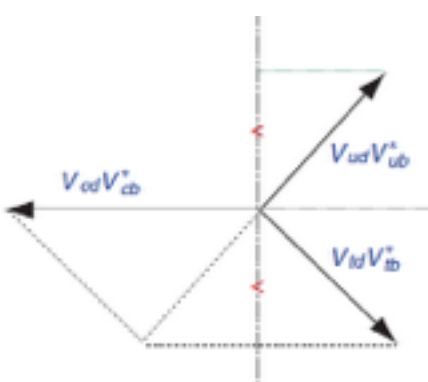
The Unitarity Triangle

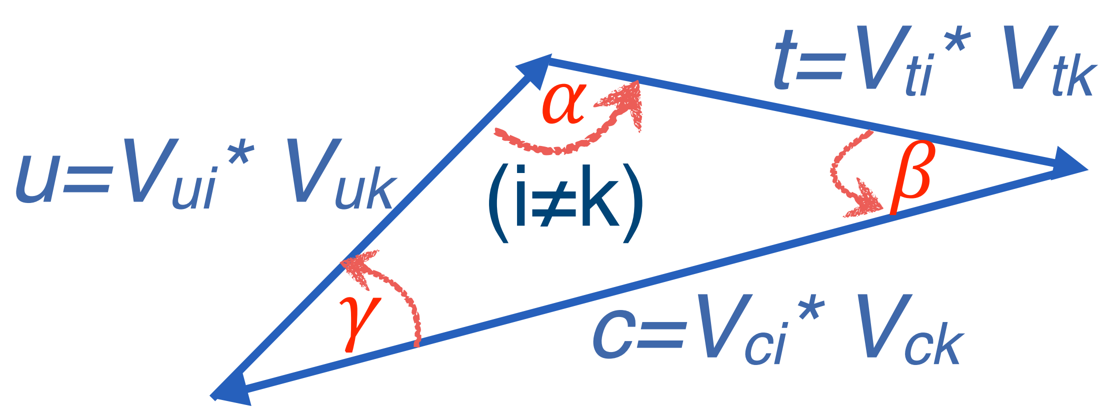
- Unitarity relation $V_{ji}^{*} V_{jk} = \delta_{ik}$ and $V_{ij}^{*} V_{kj} = \delta_{ik}$:

  For i≠k this gives 6 triangle relations.

  Unitarity triangle is a geometrical presentation of 3 complex numbers adds up to zero (e.g. $V_{ub}^{*}V_{ud} + V_{tb}^{*}V_{td} + V_{cb}^{*}V_{cd} = 0$)

  => 3 vectors in complex plane form a triangle





area = J/2

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^{*}}{V_{ud}V_{ub}^{*}}\right)$$

$$\beta = \arg\left(\frac{V_{cd}V_{cb}^{*}}{V_{td}V_{tb}^{*}}\right)$$

$$\gamma = \arg\left(\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right).$$

- Rescale by the c size and rotated

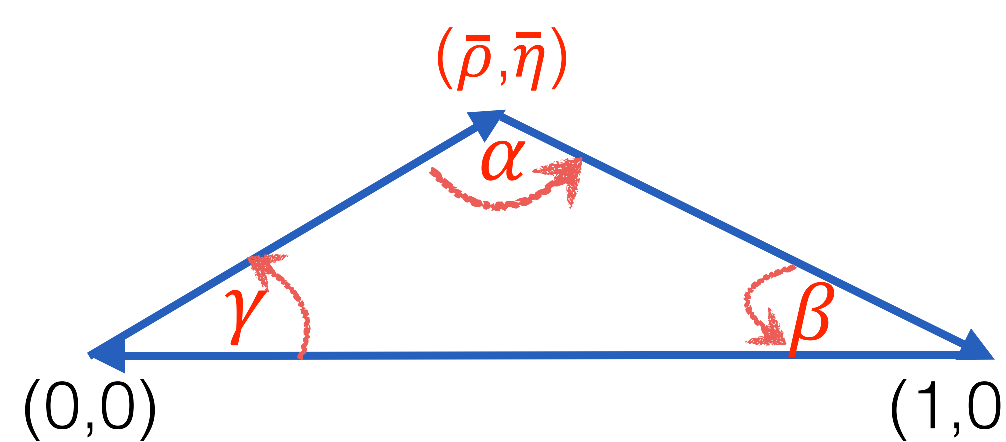
$$A\lambda^3\left[(\rho + i\eta) + (1 - \rho - i\eta) + (-1)\right] = 0$$

$\bar{\rho} = \rho(1 - \lambda^2/2)$ and $\bar{\eta} = \eta(1 - \lambda^2/2)$

$V_{ud}\, V^{*}_{ub} = A\lambda^3(1 - \lambda^2/2)(\rho + i\eta)$

$V_{cd}\, V^{*}_{cb} = - A\lambda^3$

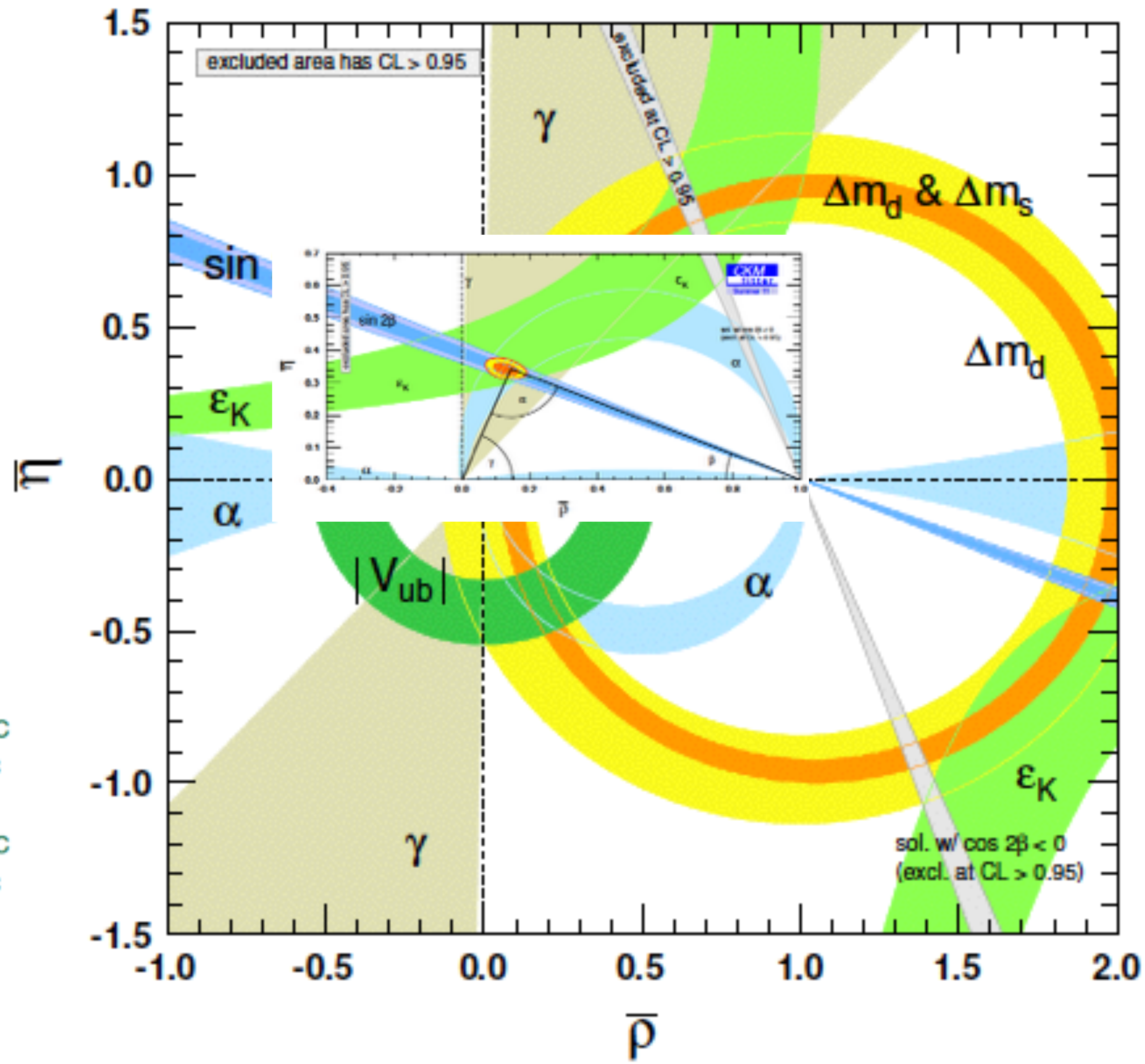
$V_{td}\, V^{*}_{tb} = A\lambda^3(1 - \rho - i\eta)$



The Unitarity Triangle

λ known from K → $\pi\ell\nu$
A known from b → $c\ell\nu$

Many observables are f(ρ, η):
b → $u\ell\nu \Rightarrow \propto |V_{ub}/V_{cb}|^2$
$\propto \rho^2 + \eta^2$
$\Delta m_{B_d}/\Delta m_{B_s} \Rightarrow \propto |V_{td}/V_{ts}|^2$
$\propto (1-\rho)^2 + \eta^2$
$S_{\psi K_S} \Rightarrow 2\eta(1-\rho)/((1-\rho)^2+\eta^2)$
$S_{\rho\rho}(\alpha)$
$A_{DK}(\gamma)$
ϵ_K



Sides:

V_{ud}	β-decay	$(A,Z) \to (A,Z+1) + e^- + \bar{\nu}_e$	$\cos\vartheta_C$
V_{us}	K-decay	$K^+ \to \pi^0 + \ell^+ + \nu_\ell$	$\sin\vartheta_C$
		$K^0 \to \pi^- + \ell^+ + \nu_\ell$	
V_{cd}	ν-production of c's	$\nu_\ell + d \to \ell^- + c$	$\cos\vartheta_C$
V_{cs}		$D^\pm \to K^0 + \ell^\pm + \nu_\ell$	$\sin\vartheta_C$
V_{ub}	B-decay	$b \to u + \ell^- + \bar{\nu}_\ell$	
V_{cb}		$b \to c + \ell^- + \bar{\nu}_\ell$	
V_{td}	Δm in B^0-$\bar{B}^0$		

LHCb: Measure asymmetries in B-decay: $V_{tb}^* V_{td} V_{cb}^* V_{cd} = |V_{tb}^* V_{td} V_{cd}^* V_{cb}|\, e^{-i\beta}$

$B^0_d \to J/\Psi\, K_S$	sin 2β
$B^0_d \to \pi^+\pi^-$	sin 2α
$B^0_s \to D_s^\pm K^\mp$	sin 2γ

Discrete Symmetries

- C, P, T
  - Any Local Lorentz invariant QFT conserves CPT
  - No theoretical reason for C, P or T to be conserved separately
  - In the SM the weak interaction breaks them all.
  - Any chiral theory break C and P (QED and QCD are vectorial and so preserve P and C separately).
  - The condition for CP violation is more complicated: a phase in the Lagrangian

Discrete Symmetries

- **Parity, P:** $e^-_L \leftrightarrow e^-_R$

  $(\vec{x}, t) \to (-\vec{x}, t)$

  $$P\psi(t,x)P^{-1} = \eta_p \gamma^0 \psi(t,-x)$$

  - The vector and axial-vector fields transform as

    $$V_\mu(\vec{x},t) \to V^\mu(-\vec{x},t) \text{ and } A_\mu(\vec{x},t) \to -A^\mu(-\vec{x},t).$$

  - Left-handed components of fermions transform into right-handed ones and vice-versa.

- **Charge Conjugation, C:** $e^-_R \leftrightarrow e^+_R$

  $$C\psi C^{-1} = i\eta_c(\bar{\psi}\gamma^0\gamma^2)^T$$

  - Under C, the currents transform as:

    $$\bar{\Psi}_1\gamma_\mu\Psi_2 \to -\bar{\Psi}_2\gamma_\mu\Psi_1 \quad \text{and} \quad \bar{\Psi}_1\gamma_\mu\gamma_5\Psi_2 \to \bar{\Psi}_2\gamma_\mu\gamma_5\Psi_1$$

Discrete Symmetries: CP

- CP: $e_L^- \leftrightarrow e_R^+$ A symmetry between a particle and its anti-particle
  - Under CP, the currents transform as:

$$\bar{\psi}_1 \gamma_\mu \psi_2 \to -\bar{\psi}_2 \gamma^\mu \psi_1 \quad \text{and} \quad \bar{\psi}_1 \gamma_\mu \gamma_5 \psi_2 \to -\bar{\psi}_2 \gamma^\mu \gamma_5 \psi_1$$

  - For a charged current interaction:

$$(W_\mu^1 - iW_\mu^2)\,\bar{U}^i \gamma^\mu (1-\gamma^5) V_{ij} D^j + (W_\mu^1 + iW_\mu^2)\,\bar{D}^j \gamma^\mu (1-\gamma^5) V_{ij}^* U^i,$$

  - Under CP, the above transforms to:

$$(W_\mu^1 + iW_\mu^2)\,\bar{D}^j \gamma^\mu (1-\gamma^5) V_{ij} U^i + (W_\mu^1 - iW_\mu^2)\,\bar{U}^i \gamma^\mu (1-\gamma^5) V_{ij}^* D^j$$

Discrete Symmetries: CP

- CP: $e_L^- \leftrightarrow e_R^+$ A symmetry between a particle and its anti-particle

In the SM, CP is violated only if V_{CKM} is complex:

=> at least 3 generations for CPV => third generation was predicted and found!

(Nobel Prize for Kobayashi and Maskawa, 2008`)

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Discrete Symmetries: CP

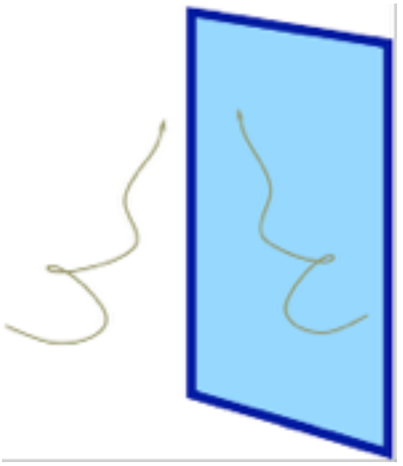
- CP: $e_L^- \leftrightarrow e_R^+$ A symmetry between a particle and its anti-particle
  - CP is violated if

$$\Gamma(A \to B) \neq \Gamma(\bar{A} \to \bar{B})$$

  - It is a very small effect in nature, and thus sensitive to new physics
  - In the SM it is closely related to flavor
  - We do not discuss the strong CP problem that is not directly related to flavor

CP Violation

Is anti-matter the exact mirror of matter?



- 1964 discovery of CP violation
  - If CP is a good symmetry:
    - Mass eigenstates = CP eigenstates
    - Two neutral kaon states: $K_S = K_{CP=+}$, $K_L = K_{CP=-}$
    - $K_S \Rightarrow \pi\pi$, $K_L \not\Rightarrow \pi\pi$
  - 1964, Cronin and Fitch:
    - Experimental discovery of $K_L \Rightarrow \pi\pi$

$$|\pi^0\rangle = |q \uparrow \bar{q} \downarrow\rangle - |q \downarrow \bar{q} \uparrow\rangle + |\bar{q} \uparrow q \downarrow\rangle - |\bar{q} \downarrow q \uparrow\rangle$$

$$P|\pi^0\rangle = |\bar{q} \downarrow q \uparrow\rangle - |\bar{q} \uparrow q \downarrow\rangle + |q \downarrow \bar{q} \uparrow\rangle - |q \uparrow \bar{q} \downarrow\rangle = -1\,|\pi^0\rangle$$

$$C|\pi^0\rangle = |\pi^0\rangle$$

$$CP|\pi^0\rangle = -1\,|\pi^0\rangle$$

$$CP|\pi^0\pi^0\rangle = (-1)^2\,|\pi^0\pi^0\rangle = +1\,|\pi^0\pi^0\rangle$$

CP Violation

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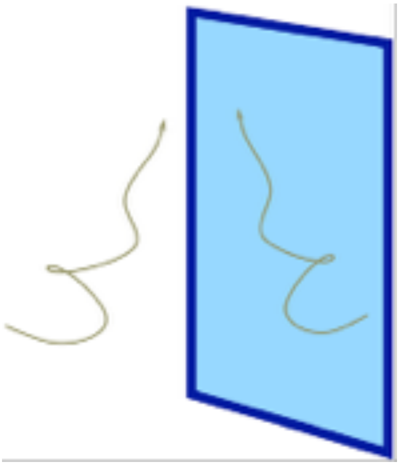

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- Since then, many CPV observables

- But CP violation observed so far is too small by a factor of 10^{-16} to explain the absence of anti-matter
  - BSM must exist. But at which scale?

Flavor Physics (current issues)

- Flavor physics can predicted New Physics before it's directly observed
- Flavor physics (CP Violation) predicts that there should be New Physics beyond the SM
- SM flavor problem: hierarchy of masses and mixing angles; why neutrinos are different
- NP flavor problem: TeV scale (hierarchy problem) << flavor & CPV scale

$$\epsilon_K: \frac{(s\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^4\,\mathrm{TeV}, \quad \Delta m_B: \frac{(b\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^3\,\mathrm{TeV}, \quad \Delta m_{B_s}: \frac{(b\bar{s})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^2\,\mathrm{TeV}$$

– Many extensions of the SM have new sources of CP and flavor violation

Clues for the subtle structure of the NP?

Flavor Physics (current issues)

- NP flavor problem: TeV scale (hierarchy problem) << flavor & CPV scale

$$\epsilon_K\colon \frac{(s\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^4\,\text{TeV}, \quad \Delta m_B\colon \frac{(b\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^3\,\text{TeV}, \quad \Delta m_{B_s}\colon \frac{(b\bar{s})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^2\,\text{TeV}$$

– Many extensions of the SM have new sources of CP and flavor violation

What kind of new physics can survive?

$$\Delta\mathcal{L}^{\Delta F=2} = \sum_{i\neq j} \frac{c_{ij}}{\Lambda^2}(\overline{Q}_{Li}\gamma^\mu Q_{Lj})^2$$

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}
$(\bar{t}_L\gamma^\mu u_L)^2$					same sign t's

Summary

- In the SM, fermions come in 3 generations of quarks and leptons; flavor physics is all about them
- Flavor is violated by the charged current weak interactions only; unique structure and prediction
- There is no FCNC at tree level. Not trivial, and very important for New Physics
- All flavor violation is from the CKM matrix
- CPV in SM is small, and comes from flavor
- Often we have seen the indirect evidence of New particles in flavor physics before directly discovering them