CP Violation and Beyond the Standard Model

Matter-anti-Matter-Asymmetry

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CP-violating effects in heavy-meson systems

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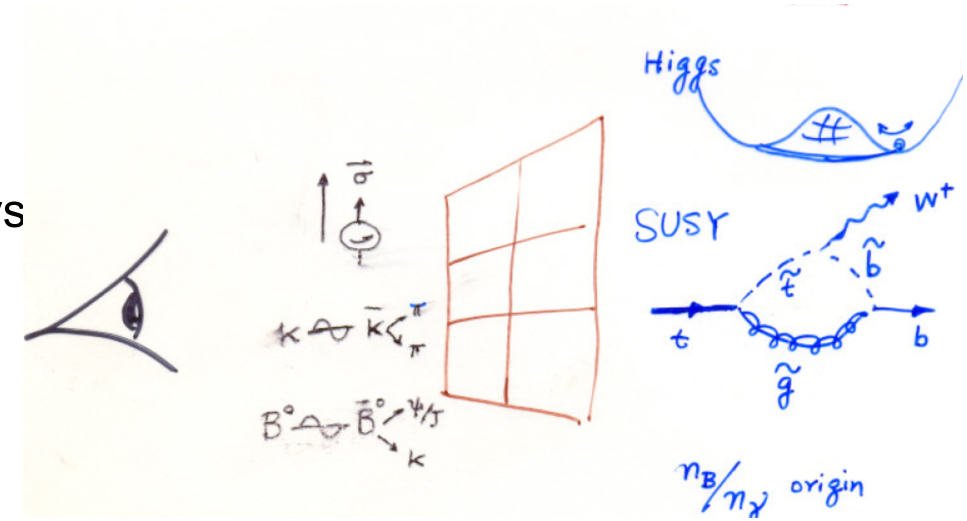
(Received 15 December 1981)

We calculate the dilepton charge asymmetry in the neutral-conjugate-heavy-meson systems produced in e^+e^- annihilation. This asymmetry, which is a measure of the intrinsic *CP* violation in the mass matrix, is calculated in the Kobayashi-Maskawa (KM) model as well as the Higgs-boson model of *CP* nonconservation. While the charge asymmetry is small for the D^0-$\bar{D}^0$ and B^0-$\bar{B}^0$ systems in both models, it is predicted to be quite large

Abstract

Review: the phenomenology of Matter-Anti-Matter Asymmetry, or CP Non-conservation,

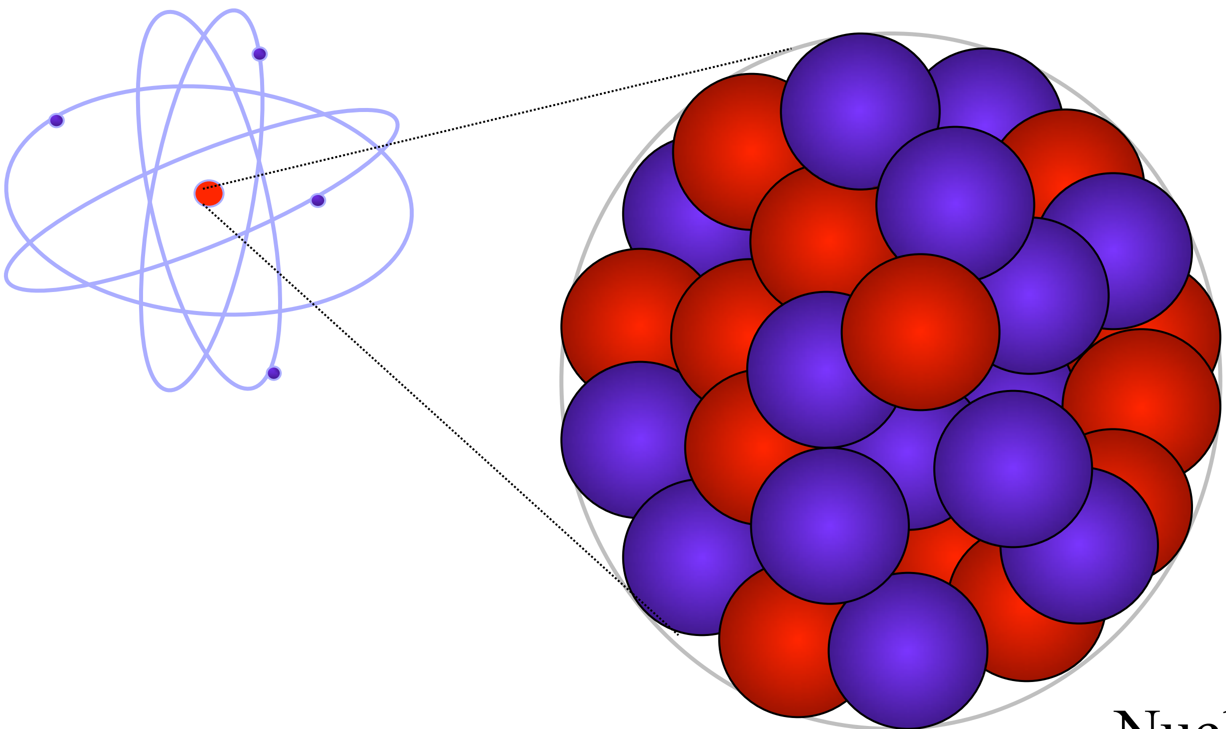
Pathway: to understand subnuclear phys within or beyond the standard model of fundamental interactions of the strong and the electroweak forces.



Research programs on the B meson physics, on the neutrino oscillations, and on the electric dipole moments of the electron and the neutron.

Relation of the CP non-conservation in subnuclear physics to the matter dominated structure of our universe.

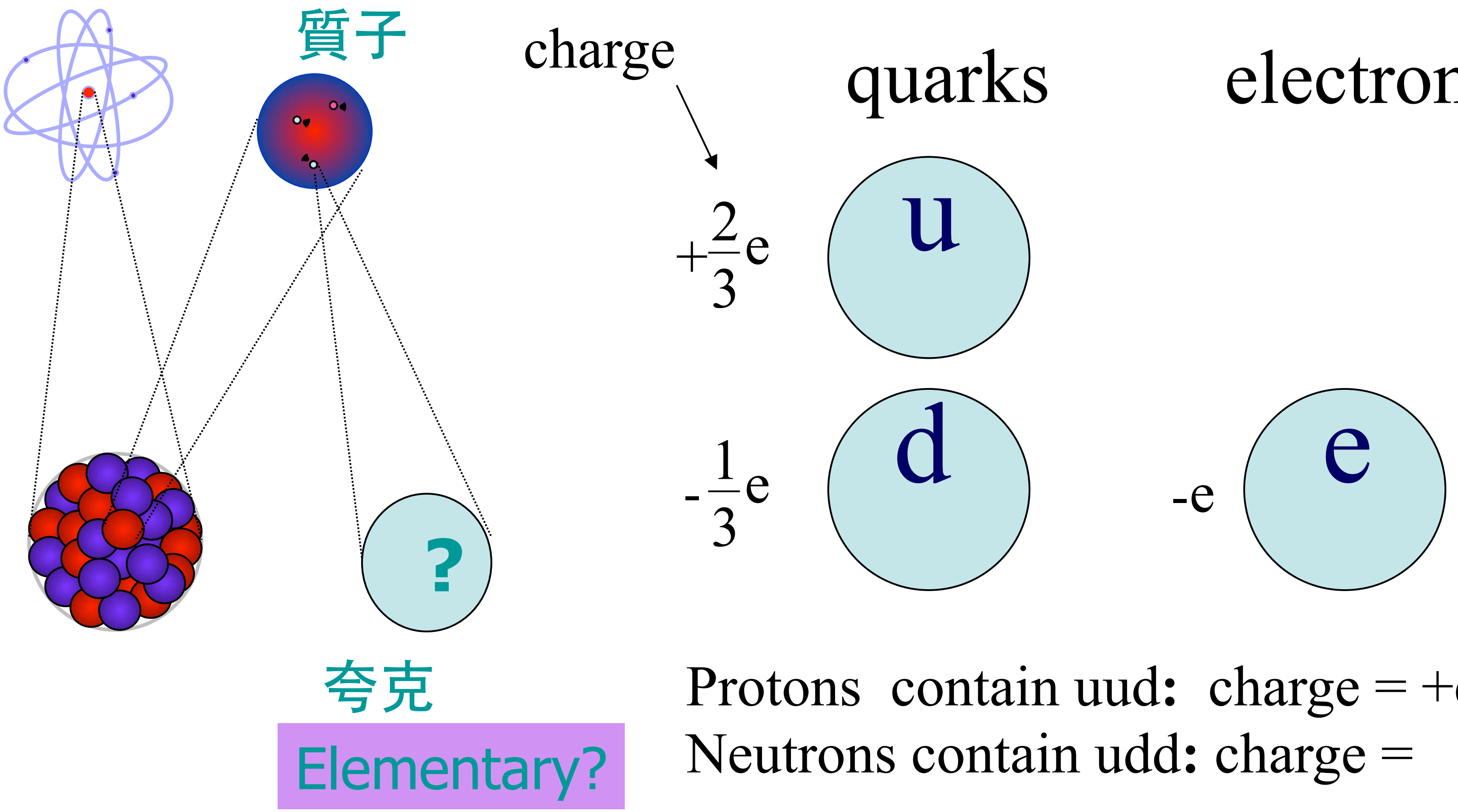
1st generation: e,p,n



N.B. **ν** proposed (Pauli), but "latent"

Nucleus:
protons and neutrons (1932)
bound thru Yukawa's (1935)
pions (theory)

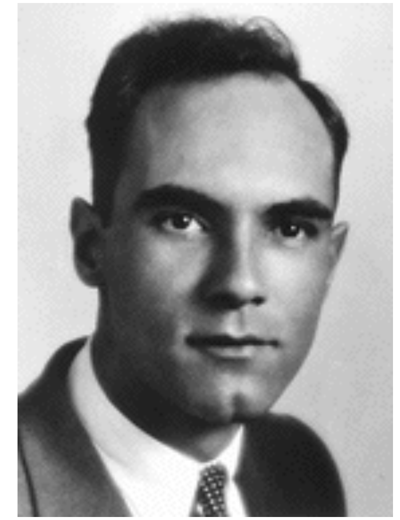
The Modern View



Protons contain uud: charge = +e
Neutrons contain udd: charge = 0

Prediction and Discovery of Antimatter

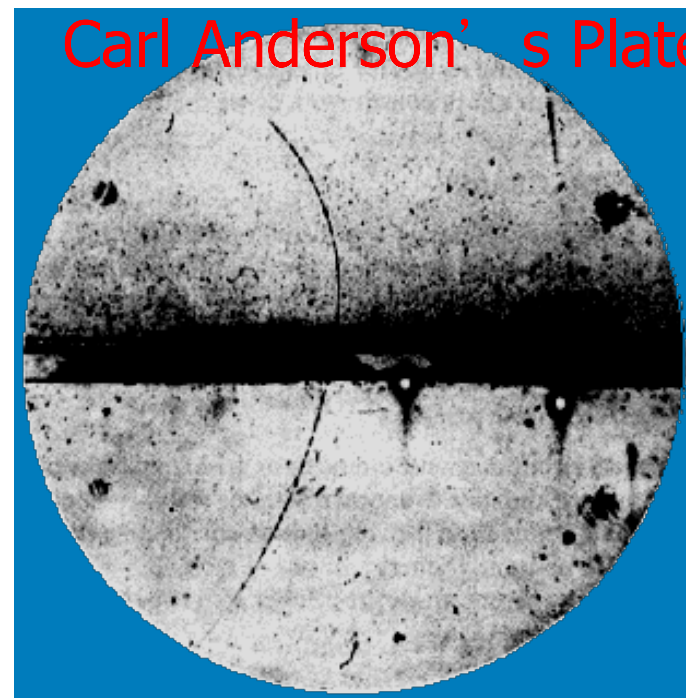
Paul Dirac predicted existence of the positron in 1928 by incorporating Special Relativity with Quantum Mechanics



Simplified:

$$E^2 = p^2c^2 + m^2c^4$$

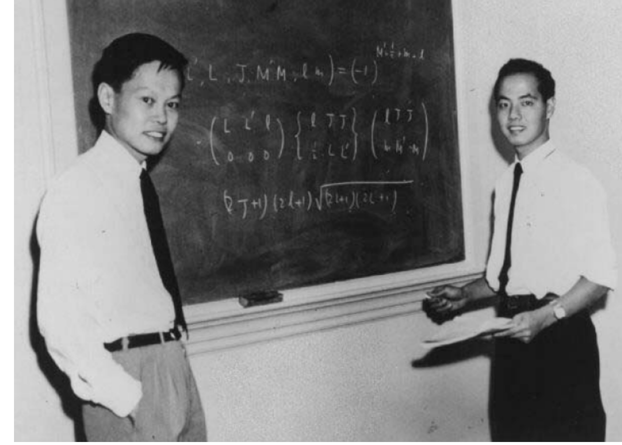
Has $E > 0$ & $E < 0$ Solutions



Dirac Equation implies:

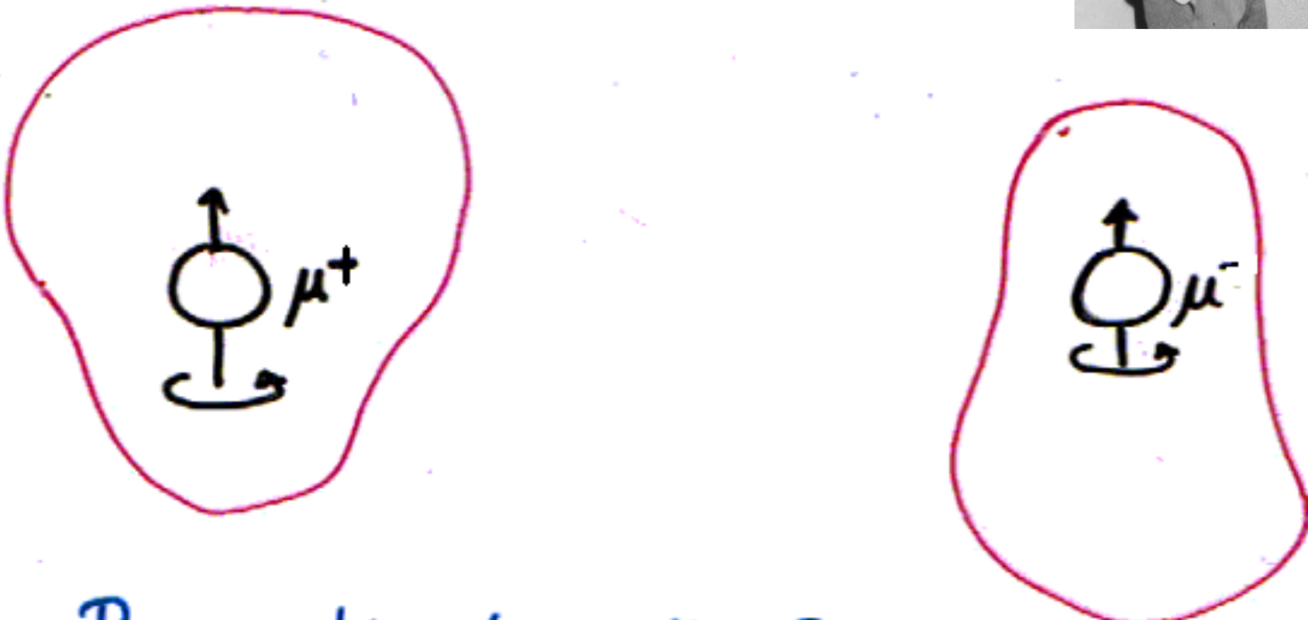
positron mass = electron mass

positron charge = - electron charge

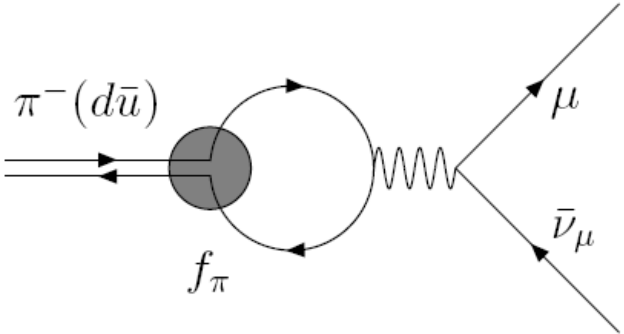


Weak decay

$$\mu \rightarrow e \, \nu \, \nu$$



but P combined with C , namely CP , is a valid symmetry.



$$K^+ \to \pi^+\pi^0$$

$$K^+ \to \mu^+\nu$$

$$K^+ \to \pi^0\mu^+\nu$$

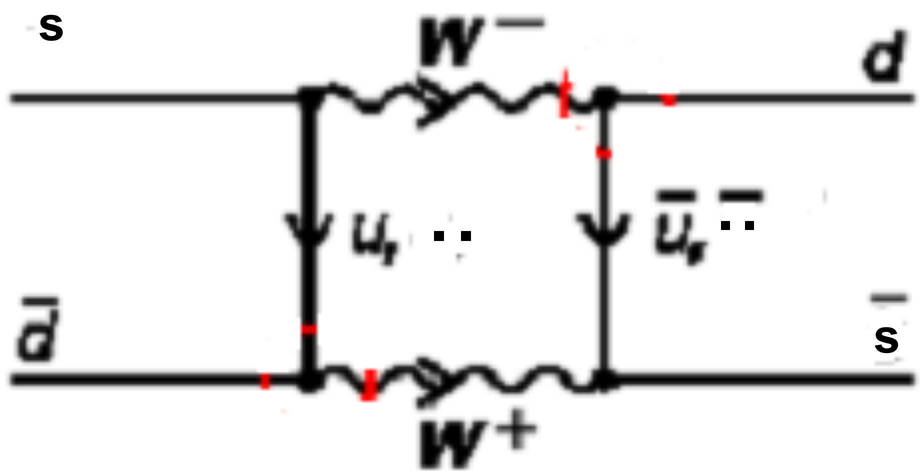
s: the "Strange"

*Strange*ness: Repeat of μ in Meson/Baryons

- Long Lifetime: $\tau_K/\tau_\pi \sim 0.5$, but $m_K^2/m_\pi^2 \sim 13$, *Strange*, should be shorter.
- Cabibbo Proposal:

Mixing:
$d_c = d \cos\theta_c + s \sin\theta_c$ with $\sin\theta_c \sim 0.22$

K^0-$\overline{K}^0$ *Not* eigenstate of full Hamiltonian (e.g. Weak Interaction)



$|K^0\rangle = \overline{s}\, d\,, \qquad |\overline{K}^0\rangle = \overline{d}\, s\,, \qquad CP|K^0\rangle = +|\overline{K}^0\rangle$ (convention dependent)

states of definite CP: $|K_{1,2}\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle \pm |\overline{K}^0\rangle)$

$$CP|K_1\rangle = |K_1\rangle\,, \qquad CP|K_2\rangle = -|K_2\rangle$$

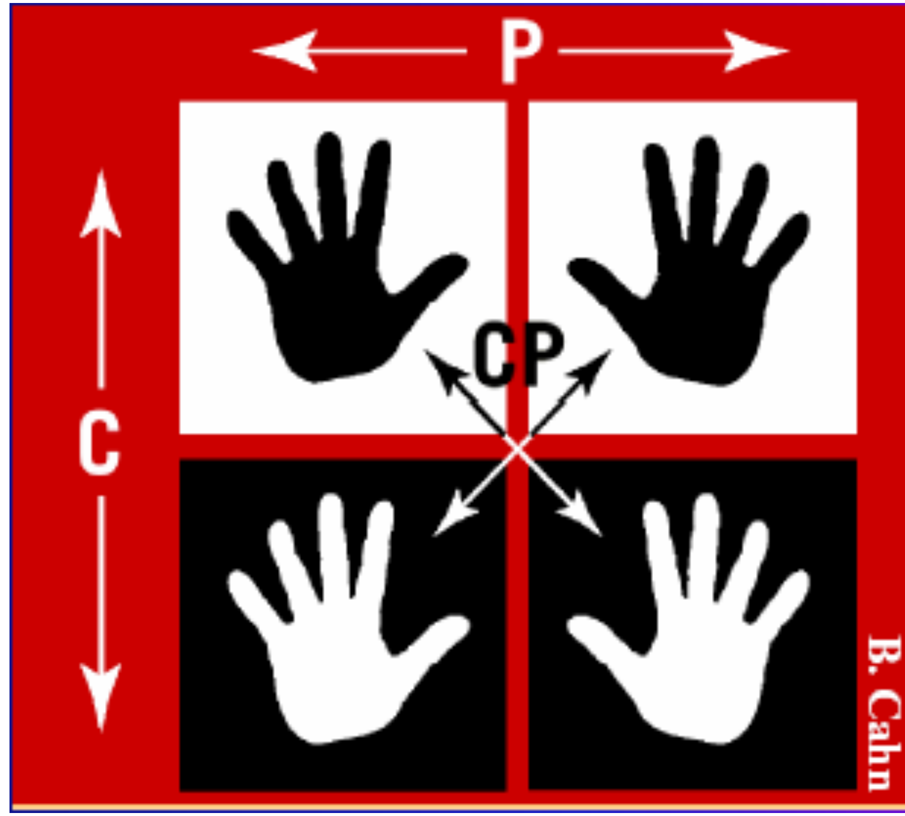
If CP were an exact symmetry:

CP	+	+

only $K_1 \to \pi\pi$
both $K_{1,2} \to \pi\pi\pi$ $\Rightarrow \tau(K_1) \ll \tau(K_2)$

Discrete symmetry, P, C, CP

$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} (\bar{e}\nu_e)_{V-A} \cdot (\bar{\nu}_\mu \mu)_{V-A}$$



$$V^\lambda \xrightarrow{C} -V^\lambda(*) \;,\; A^\lambda \xrightarrow{C} \; A^\lambda(*)$$

$$V^\lambda \xrightarrow{P} \begin{pmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{pmatrix} V^\lambda = V_\lambda$$

$$A^\lambda \xrightarrow{P} \begin{pmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{pmatrix} A^\lambda = -A_\lambda$$

Under CP, $V-A$ form remains unchanged.

CP violation only when couplings are complex.

Discovery of CP Violation

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)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have served[1,2] to set an upper limit of 1/300 for the fraction of K_2^0's which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit.

In this measurement, K_2^0 mesons were produced at the Brookhaven AGS in an internal Be target bombarded by 30-BeV protons. A neutral beam was defined at 30 degrees relative to the circulating protons by a $1\frac{1}{2}$-in.$\times 1\frac{1}{2}$-in.$\times$ 48-in. collimator at an average distance of 14.5 ft. from

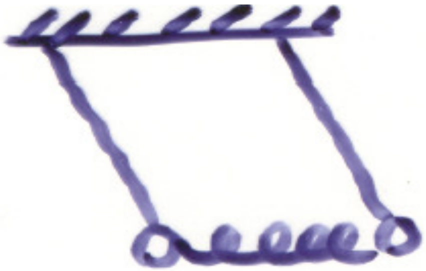
The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, m^*, assuming each charged particle had the mass of the charged pion. In this detector the K_{e3} decay leads to a distribution in m^* ranging from 280 MeV to ~536 MeV; the $K_{\mu 3}$, from 280 to ~516; and the $K_{\pi 3}$, from 280 to 363 MeV. We emphasize that m^* equal to the K^0 mass is not a preferred result when the three-body decays are analyzed in this way. In addition, the vector sum of the two momenta and the angle, θ, between it and the direction of the K_2^0 beam were determined. This

"K_2^0" $\rightarrow \pi\pi$ ~ 1/500 !

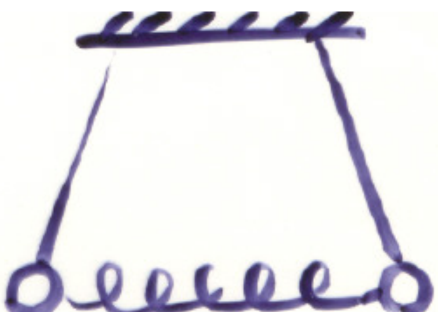
$\varepsilon_K \cong 2\times 10^{-3}$

CP - +

Swings



persisting motion



Rusty Spring

$$P(2\pi) = (-1)^2 = 1 \; ; \quad C(2\pi) = 1$$

$$\mathcal{A}(K \to 2\pi) = \mathcal{A}(\bar{K} \to 2\pi)$$

$$K_S : \frac{|K\rangle + |\bar{K}\rangle}{\sqrt{2}} \to |2\pi\rangle \; : \; \mathcal{A} + \mathcal{A} = 2\mathcal{A}$$

$$K_L : \frac{|K\rangle - |\bar{K}\rangle}{\sqrt{2}} \to |2\pi\rangle \; : \; \mathcal{A} - \mathcal{A} = 0$$

$$K_S \to 2\pi \quad (\sim 100\% \quad \tau = 0.89 \times 10^{-10}\,\text{sec})$$

$$K_L \not\to 2\pi \quad \left(\text{but} \;\; \begin{matrix} 3\pi & 34\% \\ \pi \ell \nu & 65\% \end{matrix} \quad \tau = 5.2 \times 10^{-8}\,\text{sec} \right)$$

If you wait for a long while, the spring still squeaks, why?

Charm Flavor

K^0-$\overline{K}^0$

- Long Lifetime: Cabibbo →
- Mixing:
- Rare *SCNC*:

$$\begin{pmatrix} u \\ d_c \end{pmatrix}, \begin{pmatrix} c \\ s_c \end{pmatrix} \qquad \begin{aligned} d_c &= d\cos\theta_c + s\sin\theta_c \\ s_c &= -d\sin\theta_c + s\cos\theta_c \end{aligned}$$

Charm!

2x2 Rotation!

- *CP* Violation: Discovered Experimentally 1964

3X3

*CP*V at 2×10^{-3} level

$$\begin{pmatrix} u \\ d_c \end{pmatrix}, \begin{pmatrix} c \\ s_c \end{pmatrix} \qquad \begin{aligned} d_c &= d\cos\theta_c + s\sin\theta_c \\ s_c &= -d\sin\theta_c + s\cos\theta_c \end{aligned}$$

2x2 Rotation!

Kobayashi-Maskawa (1973): *CP*V Emerge by generalizing

小林・益川

2x2 → 3x3

3 Generations !

$c/\tau/b/t$

Discovered 1974-1995: 3 Generation Completed

- c : GIM Mechanism (1970) and m_c from K^0-$\overline{K}^0$ Mixing

  Discovery — J/ψ (1974); D meson (1975)
- τ : KM (1973) predicts 3rd Generation from *CP* Violation

  Discovery (1975)
- b : Discovery, following c/τ

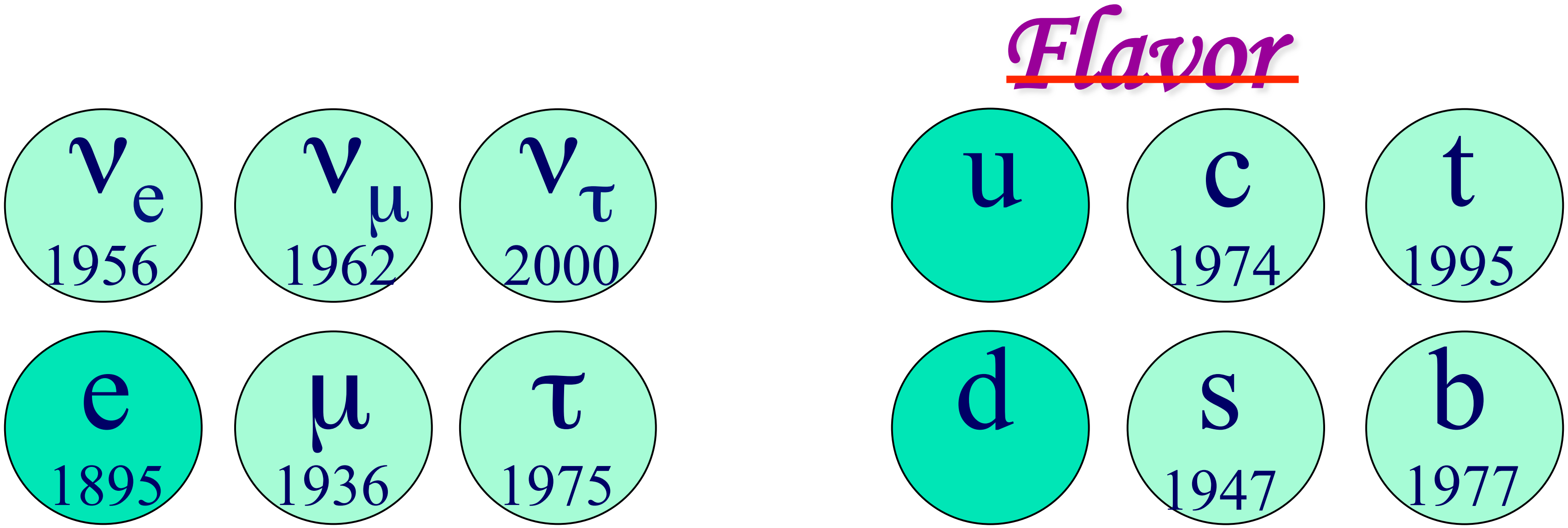
  "Repeat" J/ψ history — Υ (1977); B meson (1983)
- t : Long awaited, ...

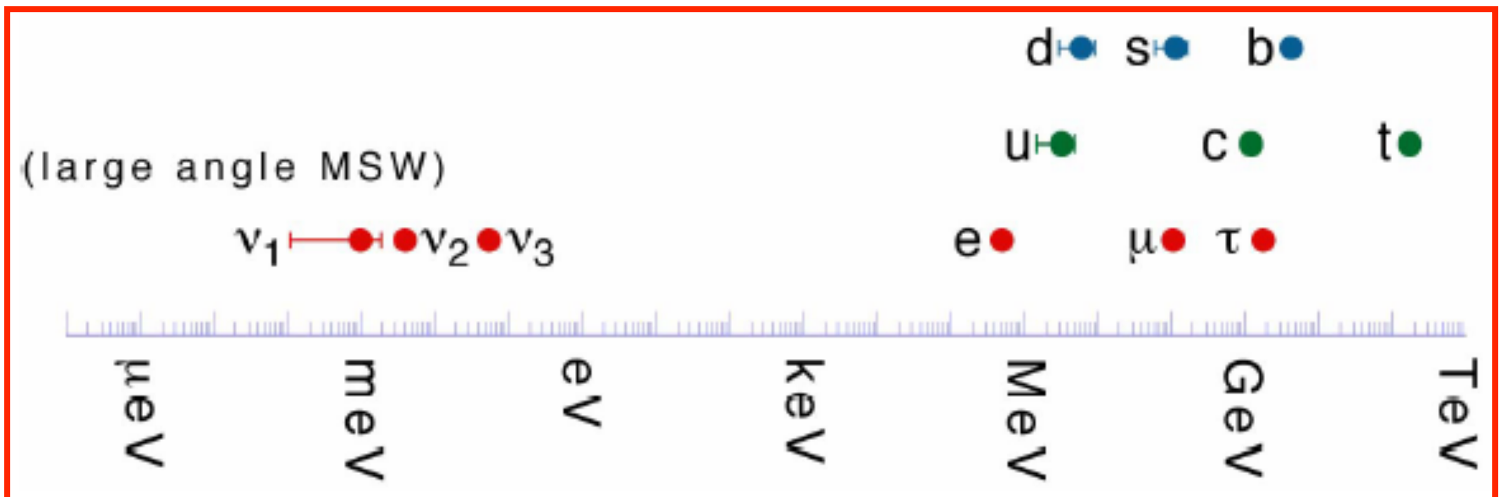
  Finally appeared 1995 (20th anniversary)

  — *Much Heavier* than expected *!*

Why *b physics* is interesting ?

The Fundamental Fermions





The Standard Model (SM)

Gauge symmetry: $SU(3)_c \times SU(2)_L \times U(1)_Y$ parameters

8 gluons $W^{\pm}, Z^0, \gamma$ 3

Particle content: 3 generations of quarks and leptons

$Q_L(3,2)_{1/6},\ u_R(3,1)_{2/3},\ d_R(3,1)_{-1/3}$ 10

$L_L(1,2)_{-1/2},\ \ell_R(1,1)_{-1}$ $3(+9)$

quarks: $\begin{pmatrix} u & c & t \\ d & s & b \end{pmatrix}$ leptons: $\begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \\ e & \mu & \tau \end{pmatrix}$

Symmetry breaking: $SU(2)_L \times U(1)_Y \rightarrow U(1)_{\rm EM}$

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

- The SM agrees (too well...) with all observed particle physics phenomena

Pattern of Flavor (*CP* V) Not Understood !

CKM Unitarity Triangle

Sides and Phases

In mass basis, charged current ($W^{\pm}$) weak interactions become complicated:

$$-\frac{g}{2}\overline{Q^I_{Li}}\,\gamma^\mu\,W^a_\mu\,\tau^a\,Q^I_{Li} + \text{h.c.} \;\Rightarrow\; -\frac{g}{\sqrt{2}}\left(\overline{u_L},\,\overline{c_L},\,\overline{t_L}\right)\gamma^\mu\,W^+_\mu\,(V_{uL}V^\dagger_{dL})\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}$$

$\Uparrow$

Cabibbo-Kobayashi-Maskawa matrix: V_{CKM}

Only source of CPV in flavor changing processes in the SM

only charged current interactions change flavor

i in Dynamics: *CP* V

ElectroMagnetism:

Charge ***e*** is *Real*.

"We" Understand: *Gauge* Charge is Real.

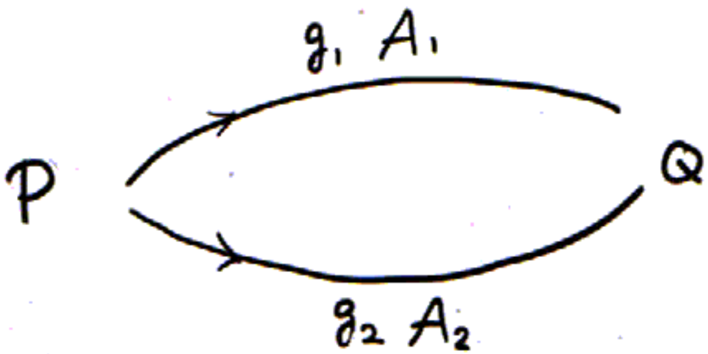
Imagine a ~~Complex Coupling~~ :

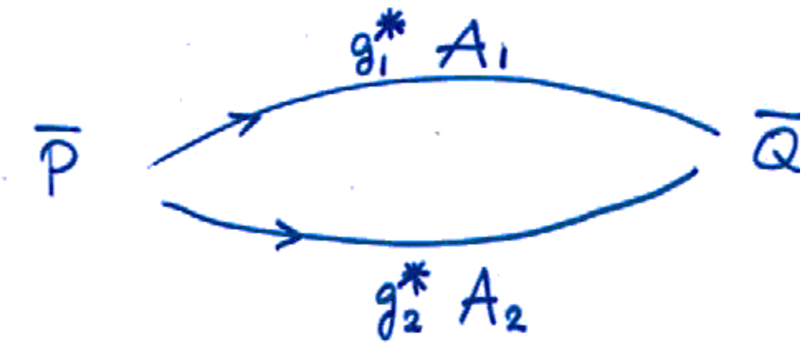
True, or, Possible, for Yukawa Coupling of quarks/leptons to Higgs boson(s)...

Quantum Interference in ***Amplitude*** More Interesting

⇒ How *CP* Violation Appears

Two phases





$$\mathrm{Amp}(P \to Q) = (\cdots \; g_i \; \cdots) \begin{pmatrix} \cdot \\ \cdot \\ \cdot \\ A_i \\ \cdot \\ \cdot \\ \cdot \end{pmatrix}$$

$$\mathrm{Prob}(P \to Q) = (\cdots \; A_j^* \; \cdots) \begin{pmatrix} \cdot \\ \cdot \\ \cdot \\ g_j^* \\ \cdot \\ \cdot \\ \cdot \end{pmatrix} (\cdots \; g_i \; \cdots) \begin{pmatrix} \cdot \\ \cdot \\ \cdot \\ A_i \\ \cdot \\ \cdot \\ \cdot \end{pmatrix}$$

$$|g_1 A_1| = |g_1^* A_1|$$

- One complex g not enough for ~~CP~~

$$\mathrm{Prob}(P \to Q) = g_i g_j^* A_i A_j^*$$

$$\mathrm{Prob}(\bar{P} \to \bar{Q}) = g_i^* g_j A_i A_j^*$$

$$\mathrm{diff} = -2\mathrm{Im}(g_i g_j^*)\mathrm{Im}(A_i A_j^*)$$

Efficient 3x3 complex matrix

VOLUME 53, NUMBER 19 PHYSICAL REVIEW LETTERS 5 NOVEMBER 1984

Comments on the Parametrization of the Kobayashi-Maskawa Matrix

Ling-Lie Chau and Wai-Yee Keung
Physics Department, Brookhaven National Laboratory, Upton, New York 11973
(Received 30 March 1984)

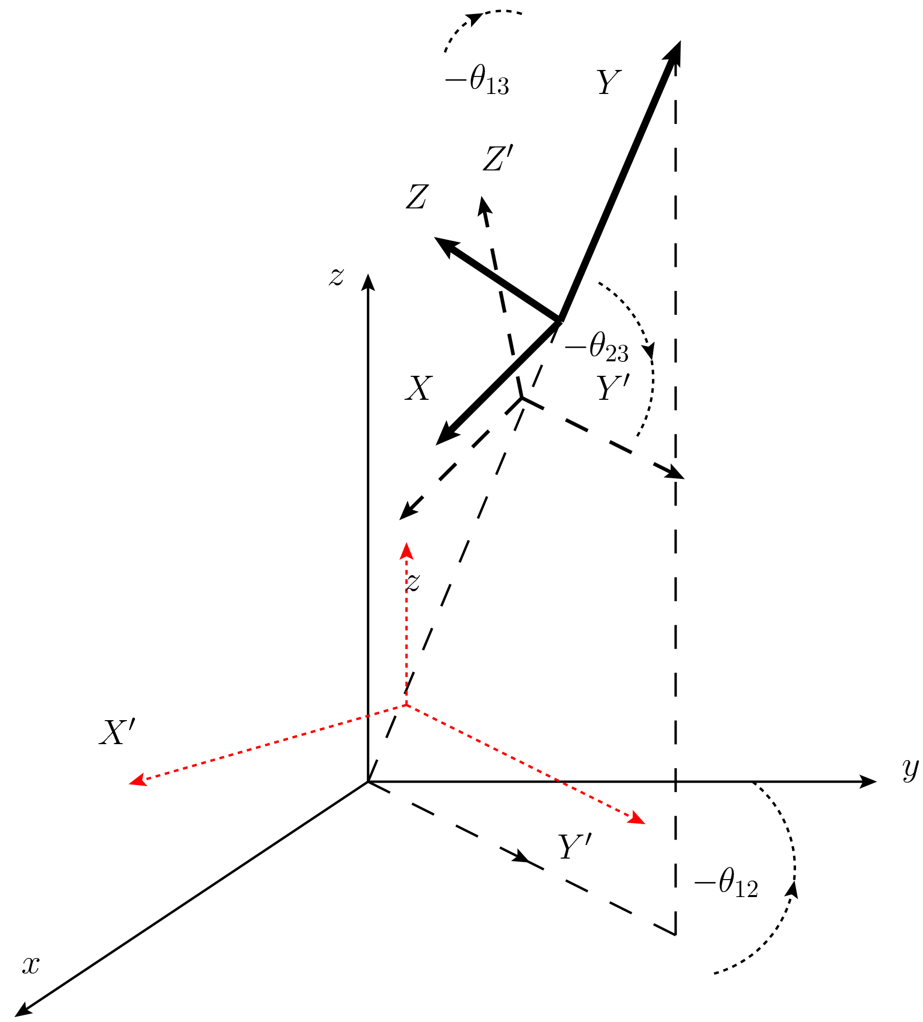
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_y & s_y \\ 0 & -s_y & c_y \end{pmatrix} \begin{pmatrix} c_z & 0 & s_z e^{-i\phi} \\ 0 & 1 & 0 \\ -s_z e^{i\phi} & 0 & c_z \end{pmatrix} \begin{pmatrix} c_x & s_x & 0 \\ -s_x & c_x & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} c_x c_z & s_x c_z & s_z e^{-i\phi} \\ -s_x c_y - c_x s_y s_z e^{i\phi} & c_x c_y - s_x s_y s_z e^{i\phi} & s_y c_z \\ s_x s_y - c_x c_y s_z e^{i\phi} & -c_x s_y - s_x c_y s_z e^{i\phi} & c_y c_z \end{pmatrix}$$

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

$$\begin{pmatrix} c_x & s_x & s_z e^{-i\phi} \\ -s_x - s_y s_z e^{i\phi} & c_x & s_y \\ s_x s_y - s_z e^{i\phi} & -s_y - s_x s_z e^{i\phi} & 1 \end{pmatrix}$$

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

Each term in 3X3 matrix is given by one leading term.



CKM matrix is hierarchical (empirical)

$$(u, c, t)\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

~ 1

$\sim \lambda$

$\sim \lambda^2$

$\sim \lambda^3$

V_{us}

$\lambda \sim 0.22$

Elements depend on 4 real parameters (3 angles + 1 CPV phase)

$V_{\rm CKM}$ is the only source of CPV in the SM

It is convenient to exhibit the hierarchical structure by expanding in $\lambda = \sin\theta_C$

Wolfenstein parameterization

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

$V_{cb} \rightarrow A$

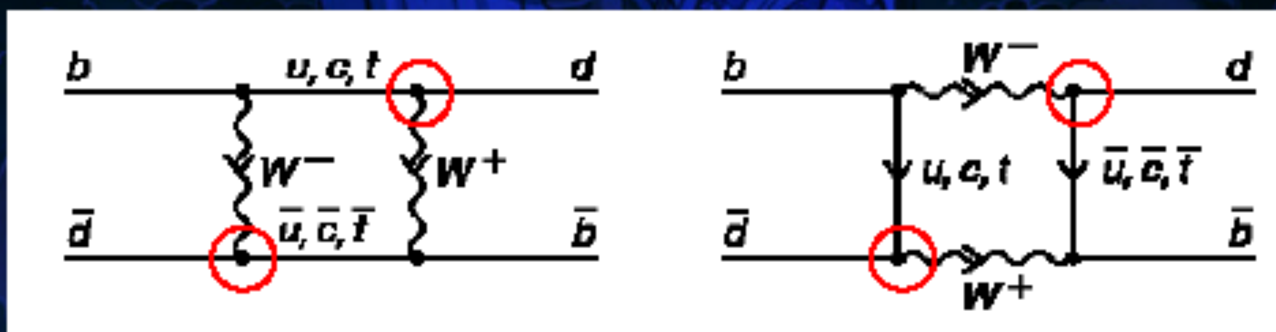
$V_{ub} \rightarrow \rho, \eta$

Present uncertainties: $\lambda \sim 1\%$, $A \sim 5\%$, $\sqrt{\rho^2+\eta^2} \sim 20\%$,

Ex. Use the upper right 3 elements as definition, and using unitarity of CKM matrix, verify Wolfenstein parametrization to $O(\lambda^4)$ [memorize it !], and derive to $O(\lambda^6)$.

B factories studying top quarks

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



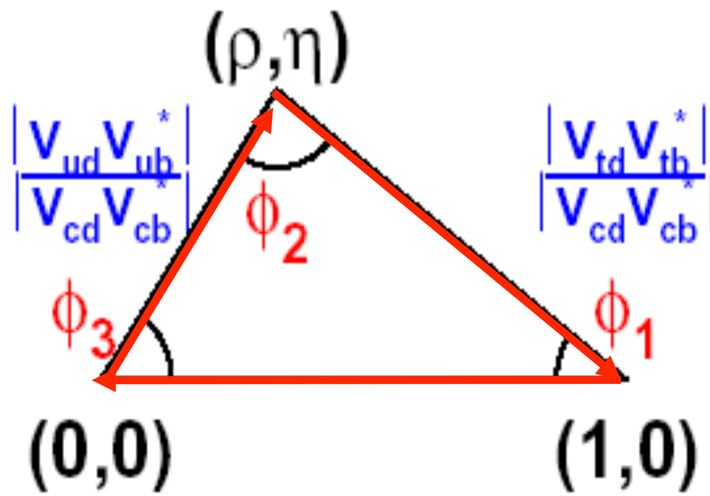
Top-quark physics
- Direct production, Mass, width etc. → CDF/D0
- Off-diagonal couplings, phase → BaBar/Belle

Unitarity Triangle and CKM Phases

From unitarity ($V_{CKM}^* V_{CKM} = 1$):

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

The Unitarity Triangle



Phases

$$\phi_1 \leftrightarrow \beta$$
$$\phi_2 \leftrightarrow \alpha$$
$$\phi_3 \leftrightarrow \gamma$$

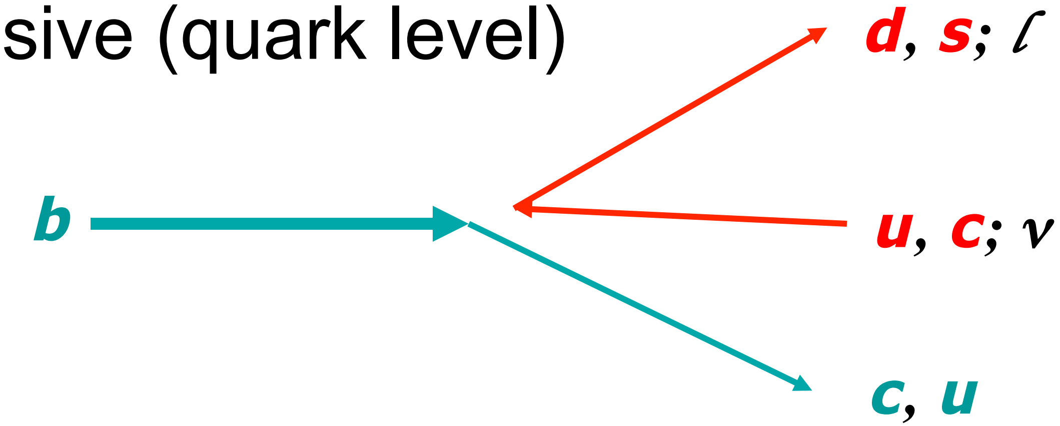
Sides

"Normalized" $|V_{ub}|$, $|V_{td}|$

Remarkable that we can ! [varying difficulty]

B Decays: "Tree" View

Inclusive (quark level)



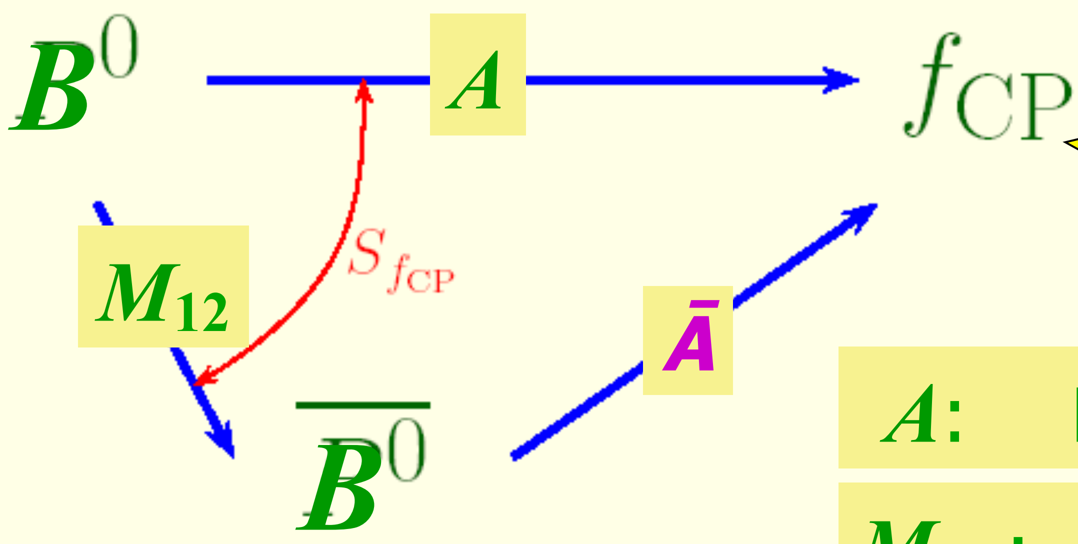
Dressed by QCD

		hadronic	semileptonic	
Leading Decays:	$b \to$	$c\bar{u}d,\ c\bar{c}s;$	$ce\bar{\nu},\ c\mu\bar{\nu},\ c\tau\bar{\nu}$	$\propto V_{cb}$
λ suppressed:	$b \to$	$c\bar{u}s,\ c\bar{c}d$		
V_{ub} suppressed:	$b \to$	$u\bar{u}d,\ u\bar{c}s;$	$ue\bar{\nu},\ u\mu\bar{\nu},\ u\tau\bar{\nu}$	
λV_{ub} suppressed:	$b \to$	$u\bar{u}s,\ u\bar{c}d$		

CPV Phase !

the Physics …

CPV in Mixing-Decay Interference



Double Slit Experiment

A: Decay Amplitude

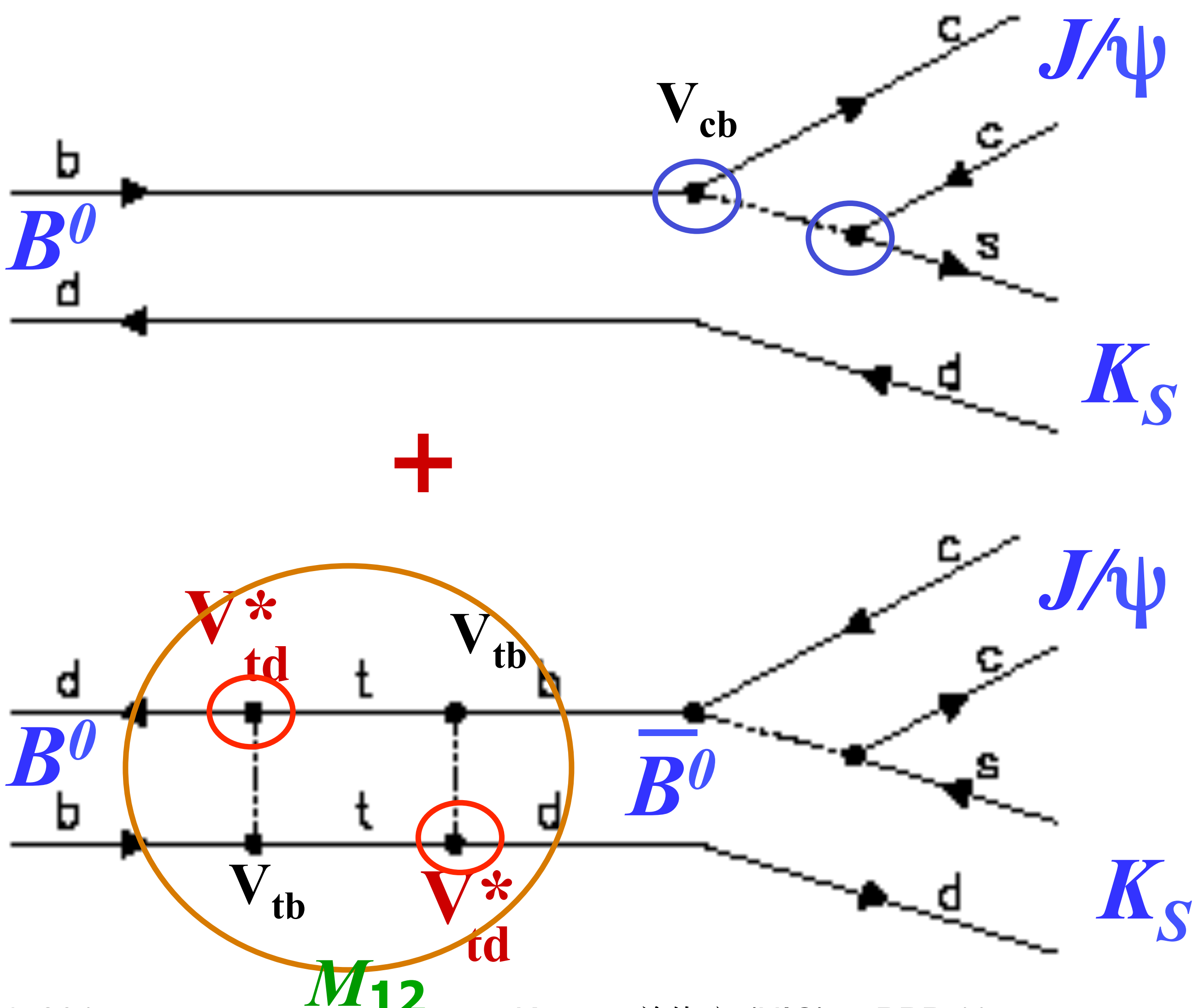
M_{12}: Mixing Amplitude

1. Decay dominated by a single CPV phase: $|\bar{A}/A| = 1$
2. CPV in mixing negligible: $|q/p| = 1$
3. The only remaining effect is

$$S_{f_{CP}} = \mathcal{I}m\lambda_{f_{CP}} \sim \sin[\arg(M_{12}) - 2\arg(A)]$$

CPV in $B^0 \to \overline{B}^0$ Mixing

No CPV in $B \to J/\psi K_S$ Decay

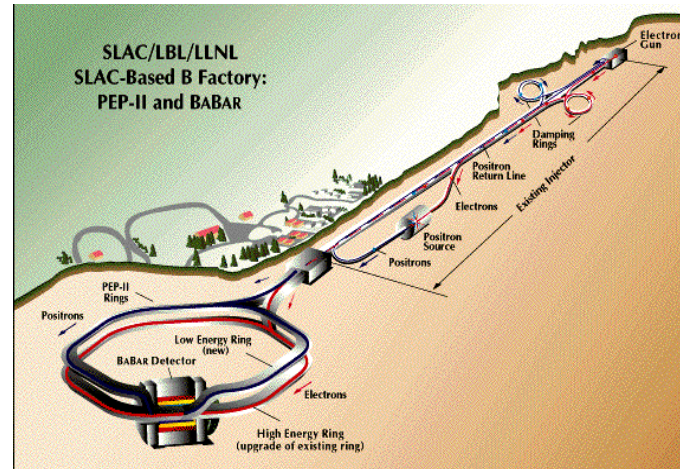


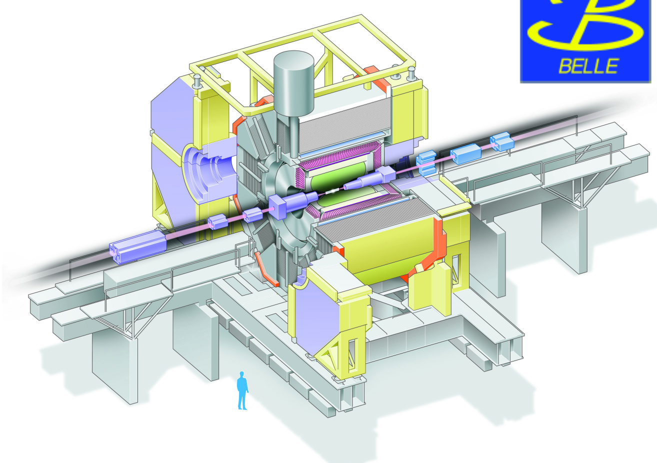
$\propto V_{td}^{*2}$

The Duel of the B Factories

KEK

SLAC





Belle

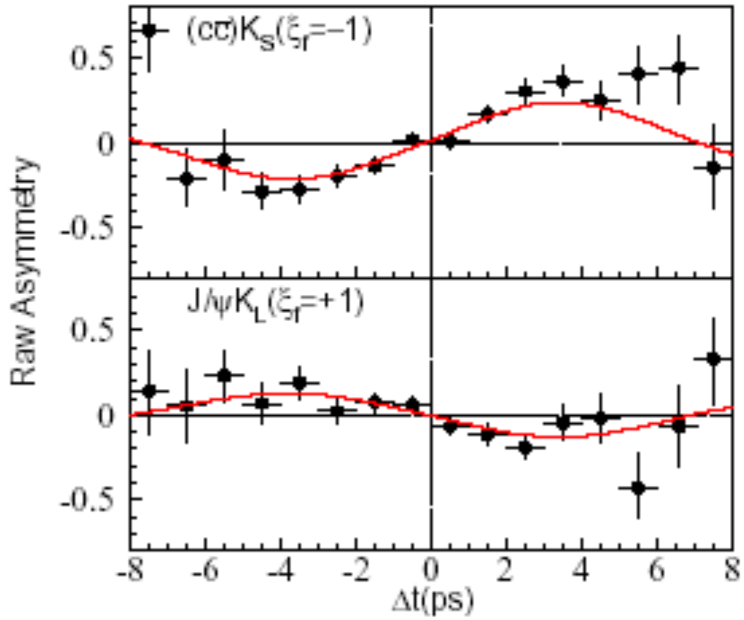
BaBar

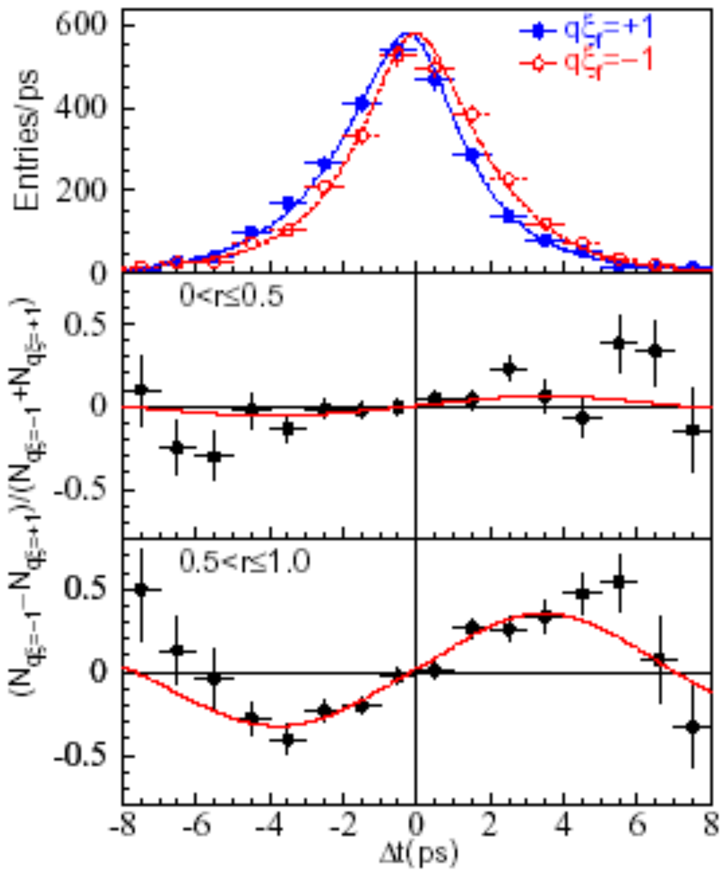
Time graphs

140 fb^{-1} ≅ 152M *B* pairs

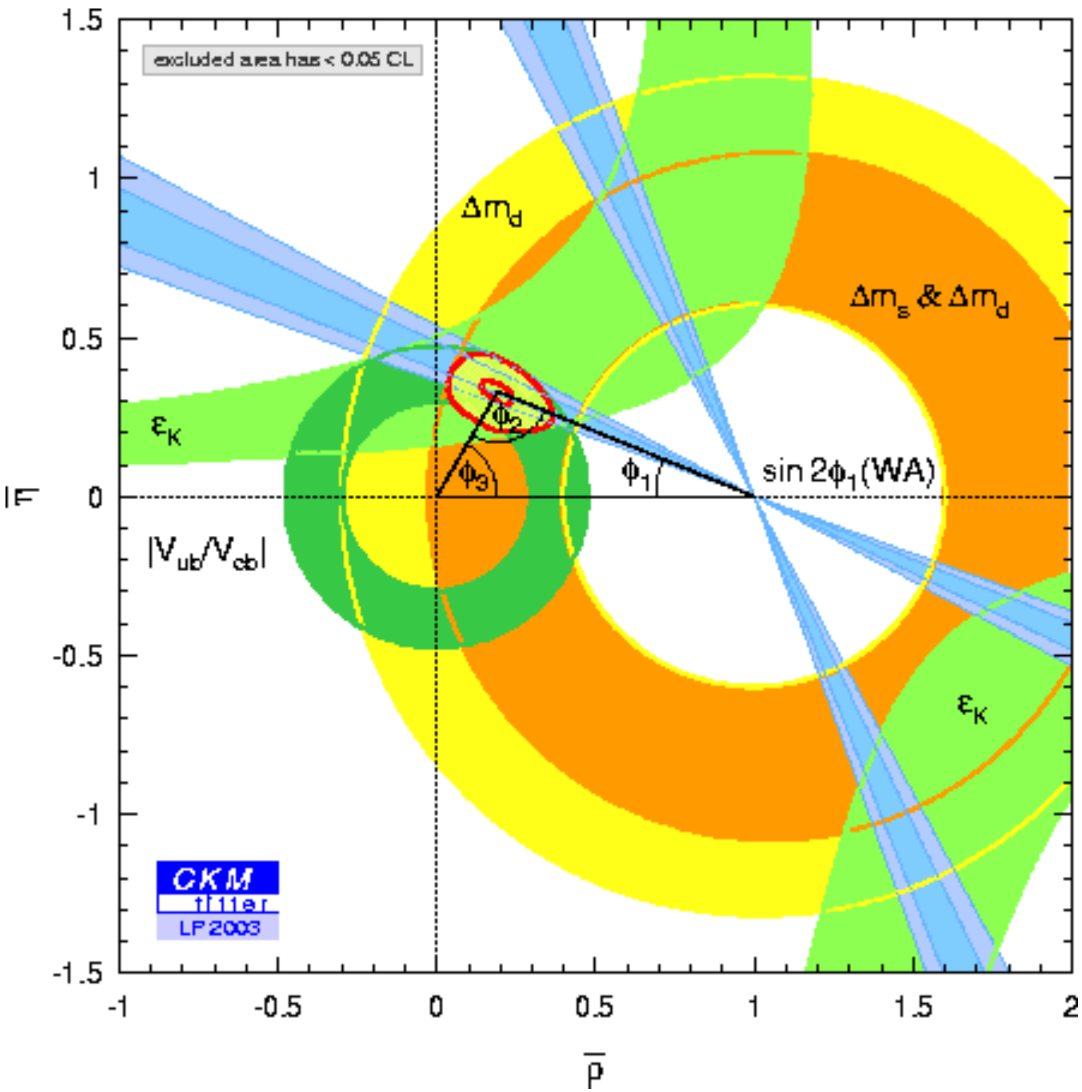
PRELIMINARY

$\sin(2\phi_1) = 0.733 \pm 0.057 \pm 0.028$





Current Belle and BaBar Results for sin(2φ_1)



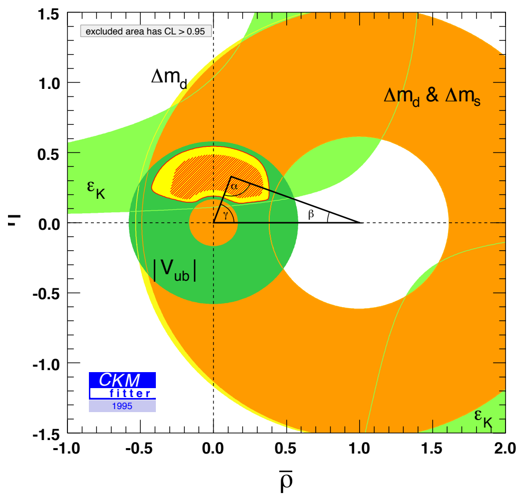
sin2ϕ_1 (Belle 2003,140 fb^1)
=0.733±0.057±0.028

sin2ϕ_1 (BaBar 2002, 81 fb^{-1})
=0.741±0.067±0.033

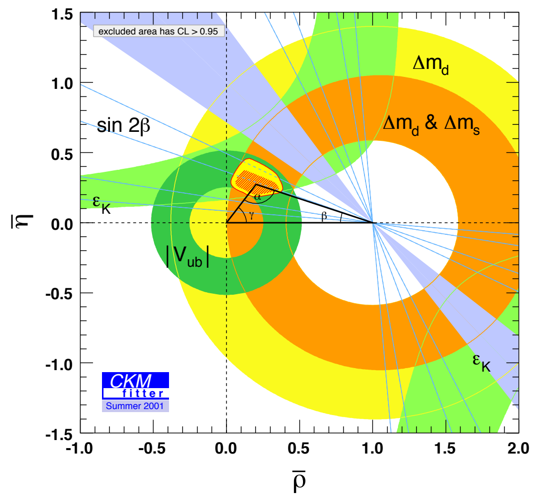
Precision Measurement

sin2ϕ_1 (New 2003 World Av.)
=0.736±0.049

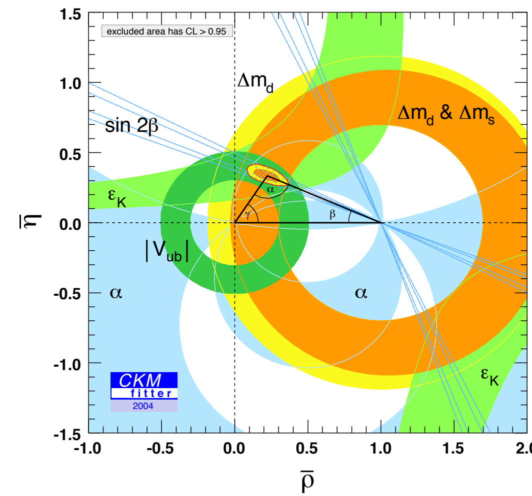
[LEP, KTeV, NA48, Babar, Belle, CDF, DØ, LHCb, CMS]



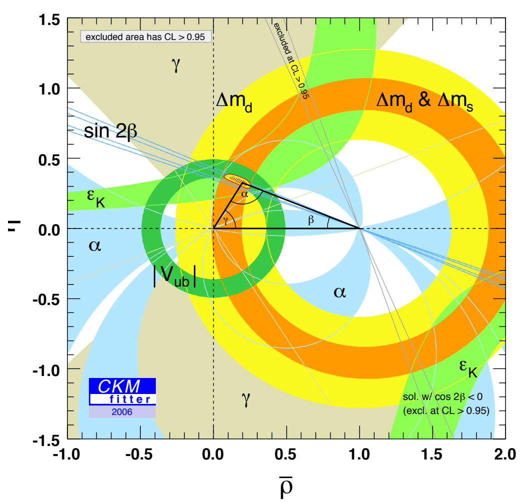
1995



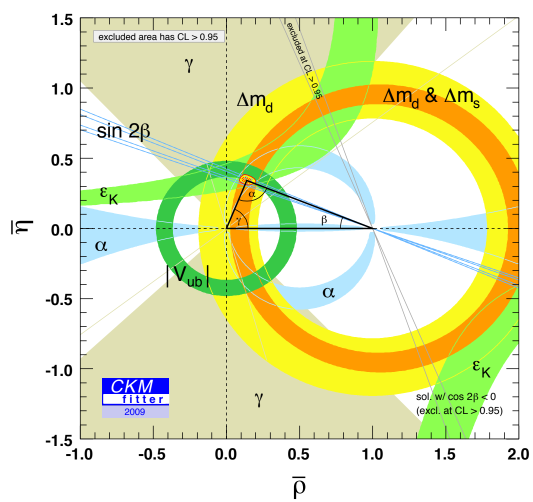
2001



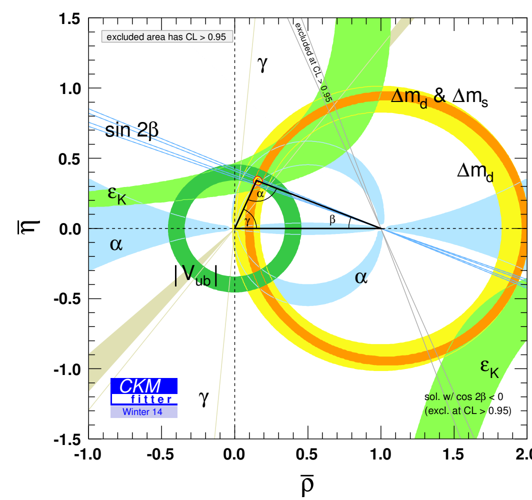
2004



2006

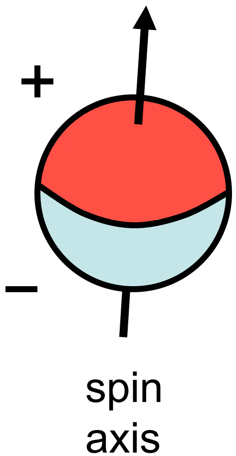


2009

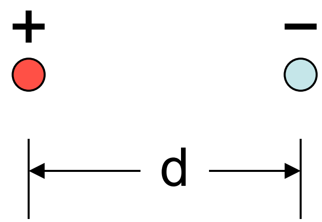


2014

EDM?

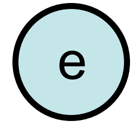


The size is given by two standard charges times their separation.



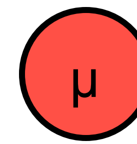
units of e•cm

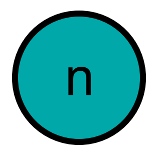
What do we know so far?



electron:
< 1.6 × 10^{-27} e•cm
(from Tl atom)

muon:
< 10^{-18} e•cm
(from g-2 exp.)



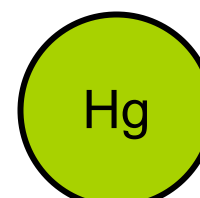


history of the neutron and electron (atom) searches

neutron:
< 6 × 10^{-26} e•cm

“size” of neutron ~ 10^{-13} cm,
EDM’s down another 10^{-12} !

mercury atom:
< 2 × 10^{-28} e•cm



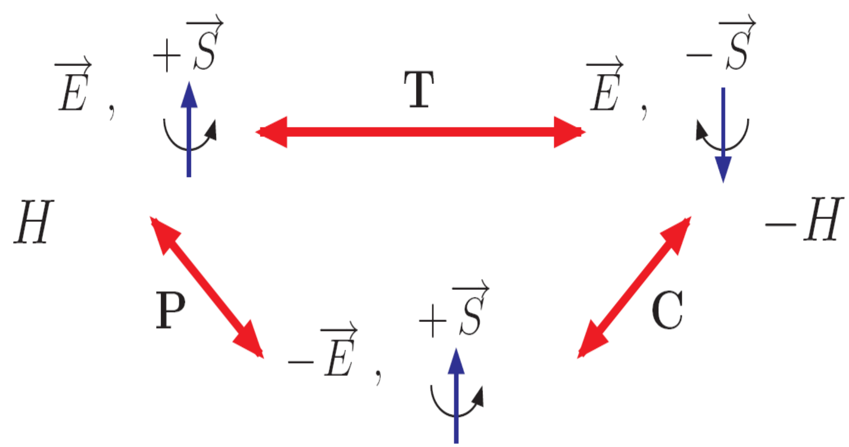
$$i\frac{d_f}{2}\bar{f}\sigma^{\mu\nu}\gamma_5 f F_{\mu\nu}$$

$$\mathcal{H} = d(\psi^\dagger \boldsymbol{\sigma}\psi - \psi^{c\dagger}\boldsymbol{\sigma}\psi^c)\cdot \mathbf{E}$$

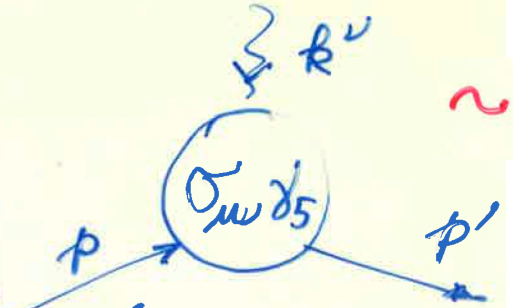
$P:\quad \mathbf{E} \overset{P}{\longleftrightarrow} -\mathbf{E}$, $\mathcal{H}$ sign flipped.

$\psi \overset{C}{\longleftrightarrow} \psi^c$, $\mathbf{E} \overset{C}{\longleftrightarrow} -\mathbf{E}$, $\psi^\dagger\boldsymbol{\sigma}\psi \overset{C}{\longleftrightarrow} \psi^{c\dagger}\boldsymbol{\sigma}\psi^c$, $\mathcal{H}$ unchanged.

$\psi \overset{T}{\longleftrightarrow} \psi^\dagger$, $\mathbf{E} \overset{T}{\longleftrightarrow} \mathbf{E}$, $\psi^\dagger\boldsymbol{\sigma}\psi \overset{T}{\longleftrightarrow} -\psi^\dagger\boldsymbol{\sigma}\psi$, $\mathcal{H}$ sign flipped.

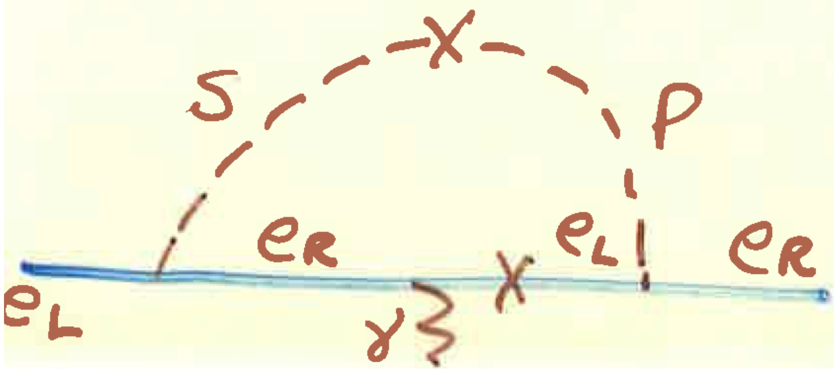


- chirality flip
- mixing between scalar and pseudoscalar
- smallness in 1-loop contribution



$$\sim d\, \bar{u}(p')\, \sigma_{\mu\nu} k^\nu \gamma_5\, u(p)$$

$$\frac{e}{2M_W}\left(\frac{m_e}{m}\right)^3$$



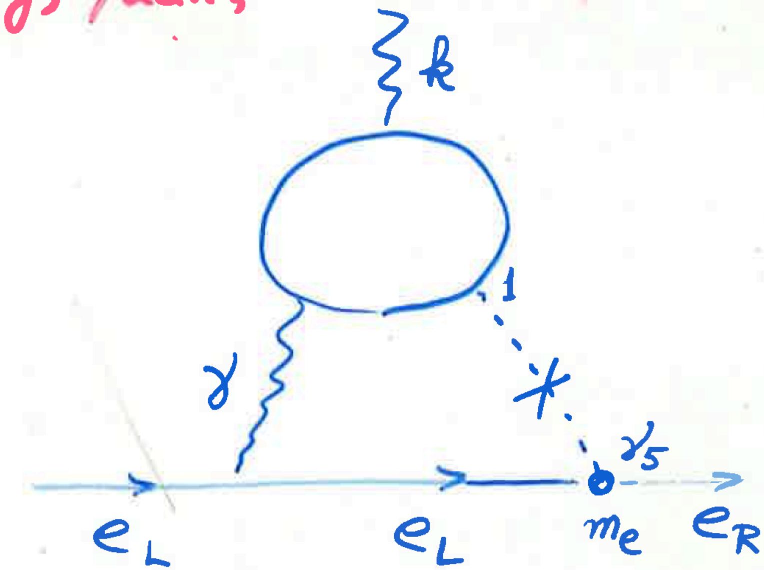
$$\frac{e}{2M_W} \sim 10^{-16}\ e\cdot cm$$

$$\frac{m_e}{M_W} \sim 10^{-5}$$

Barr & Zee; Chang, Keung, Yuan; Leigh et al.

$$\frac{2\ \text{loop}}{1\ \text{loop}} = \frac{\frac{e^2}{16\pi^2}\,\frac{m_e}{M_W^2}}{m_e^3/M_W^4}$$

$$\sim \frac{\alpha}{4\pi}\,\frac{M_W^2}{m_e^2}$$



$$A(H\gamma\gamma) \sim A(q^2)\left[q_\mu k_\nu - q\cdot k\, g_{\mu\nu}\right] \qquad \mathcal{M} \sim \int \frac{d^4q}{(2\pi)^4}\,\frac{A(q^2)\left[q_\mu \not{k} - q\cdot k\,\gamma_\mu\right]\not{q}\,\gamma_5}{q^2\,(q^2-m_H^2)\quad q^2}$$

$$\sim \int \frac{d^4q}{(2\pi)^4}\,\frac{A(q^2)\,(\not{k}\gamma_\mu - \gamma_\mu\not{k})\,\frac{1}{4}q^2}{q^2\,(q^2-m_H^2)\quad q^2}\,\gamma_5 = \frac{1}{16\pi^2}\int dQ^2\ \frac{i}{2}\sigma_{\mu\nu}\gamma_5 k^\nu\,\frac{Q^2 A(Q^2)}{Q^2(Q^2+m_H^2)}$$

New Two-Loop Contribution to Electric Dipole Moments in Supersymmetric Theories

Darwin Chang,[1,2] Wai-Yee Keung,[3,2] and Apostolos Pilaftsis[4,2]

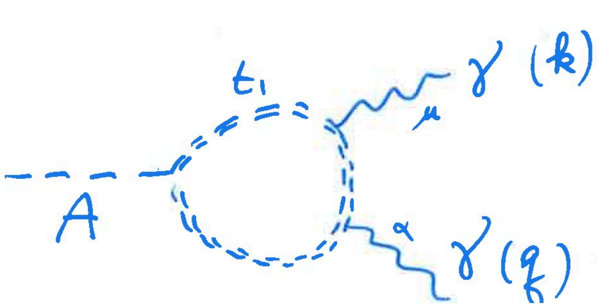
$$\mathcal{L}_{\tilde f} = -\xi_t\, v\, a\, (\tilde t_1^{\dagger} \tilde t_1 - \tilde t_2^{\dagger} \tilde t_2) + \frac{i g m_t}{2 m_W}\, \bar t \gamma_5 t\, a$$

CP even

in compatible CP parity.

CP odd

Analogous to $K_L \to \pi\pi$

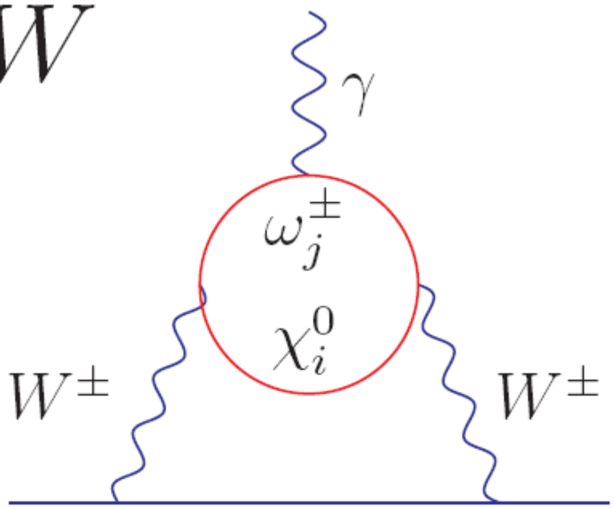


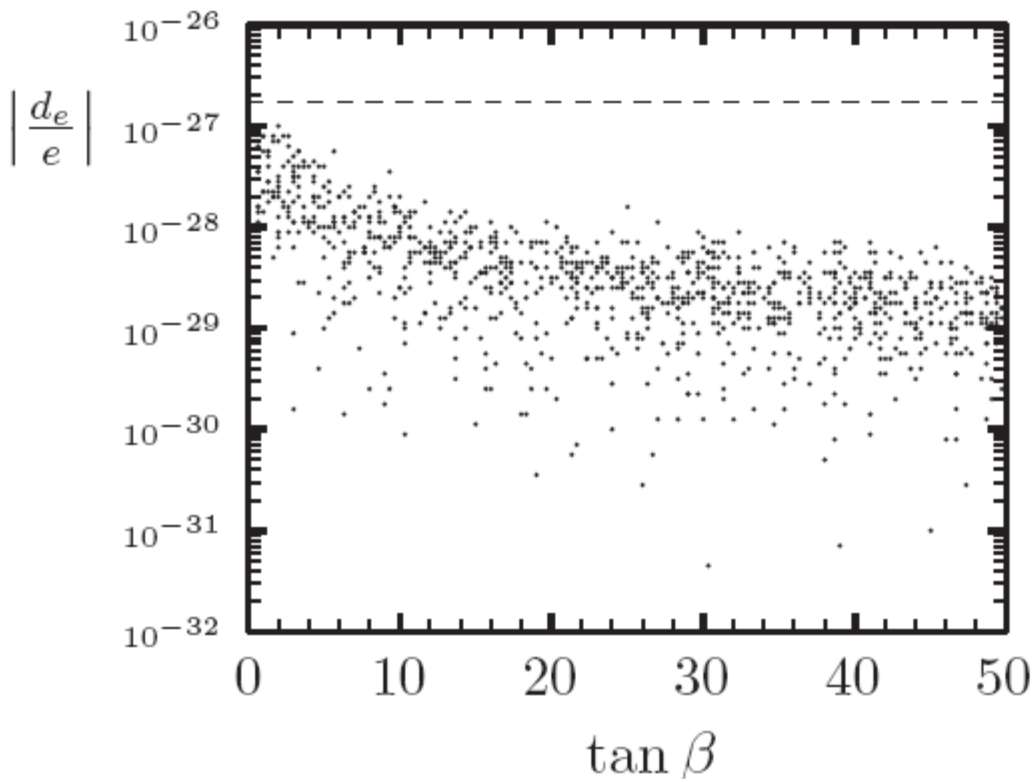
$$k^\alpha q^\mu - k\cdot q\, g^{\mu\alpha}$$

form factor without ε symbol.

Chang, Chang, Keung
Phys.Rev. D71 (2005) 076006

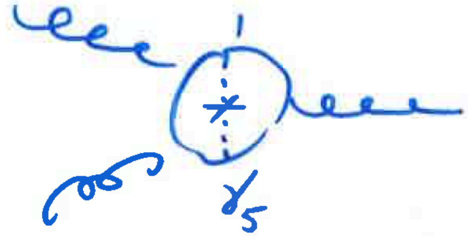
d^W





Remark : gluon CEDM $f^{abc}\tilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^{c\,\mu\rho}$

Weinberg (89)

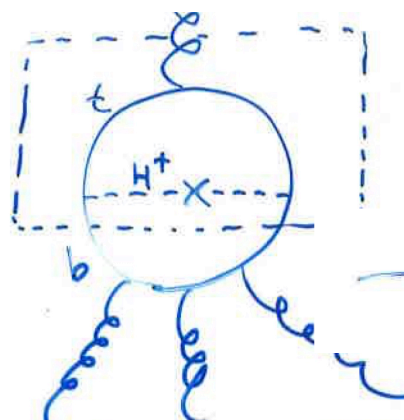


Braaten et al (90)

← QCD suppression.

$1/m_t^2$

b color electric dipole moment



$\rightarrow \frac{1}{m_t} \frac{1}{m_b^3}$

QCD enhancement

dimensional 8

Phys.Rev. D46 (1992) 2270-2271

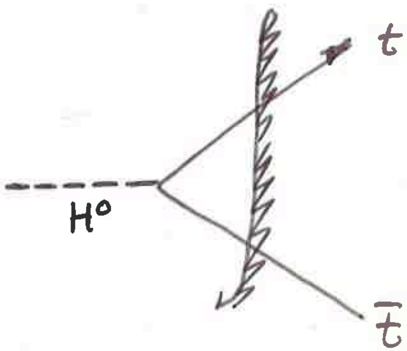
With Chang, Kephert, and Yuen

2 HDM and Beyond ✓

$$\mathcal{L} = -(\sqrt{2}G_F)^{\frac{1}{2}}\, \bar{t}\left(A\frac{1-\gamma_5}{2} + A^*\frac{1+\gamma_5}{2}\right) t H^0$$

phase cannot be rotated away because of the mass term $m\bar{t}t$.

$\sigma(t_L\bar{t}_L) \stackrel{?}{=} \sigma(t_R\bar{t}_R)$



$$\text{Amp}\,(H^0 \to t_L\bar{t}_L) \sim A_R\beta + i A_I$$

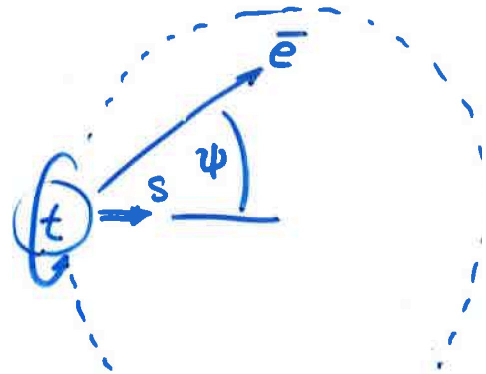
$$\text{Amp}\,(H^0 \to t_R\bar{t}_R) \sim A_R\beta - i A_I$$

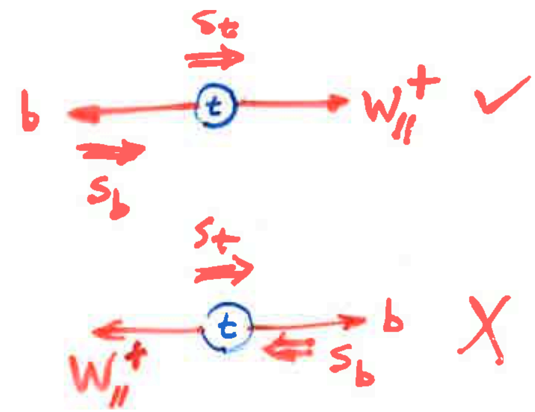
$$\rightarrow \quad \text{Amp}\,(t_L\bar{t}_L) \sim A_R\beta + i A_I(1+ia)$$

$$\text{Amp}\,(t_R\bar{t}_R) \sim A_R\beta - i A_I(1+ia)$$

$$P(t_L\bar{t}_L) - P(t_R\bar{t}_R) \sim 4\, a A_I A_R\beta$$

$$t \to b\, \bar{e}\, \nu$$





$$\frac{dN}{d\cos\psi} = 1 + \cos\psi$$

when t is moving

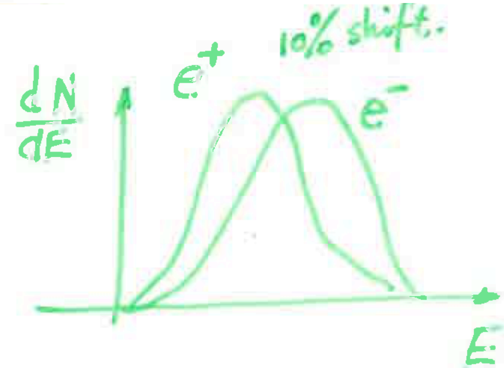
$\bar{e}$ has higher energy profile from t_R than t_L.

In parallel,

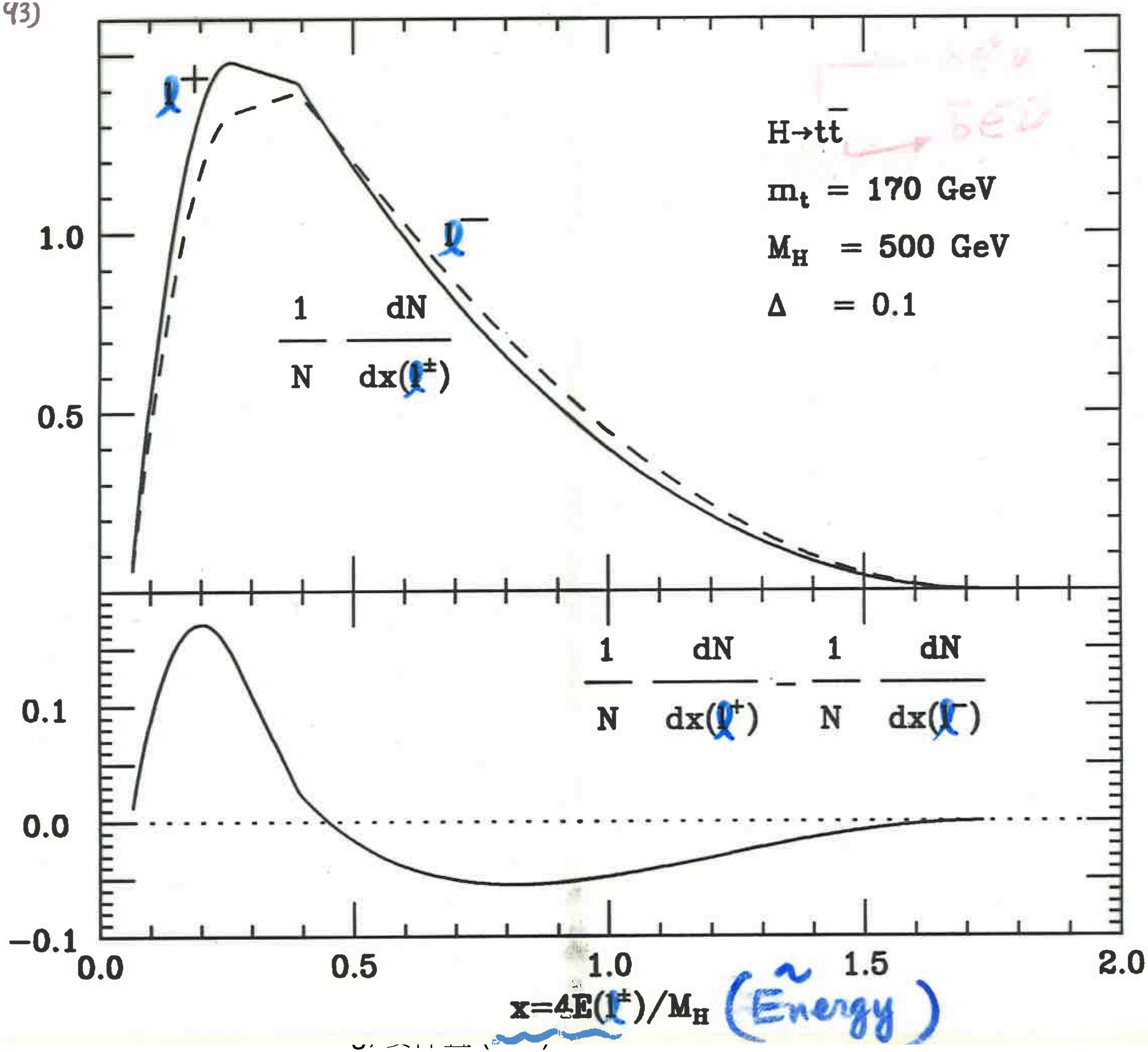
e has higher energy profile from $\bar{t}_L$ than $\bar{t}_R$.

If $t_L \bar{t}_L$ and $t_R \bar{t}_R$ are produced equally, difference is even out. But $N(t_L \bar{t}_L) \neq N(t_R \bar{t}_R)$;

$\Rightarrow$ Asymmetry in the energy of the secondary leptons.



PL, B305, 261(93)



Angular correlation in Z’ to ZZ

With Low and Shu, arXiv:0806.2864

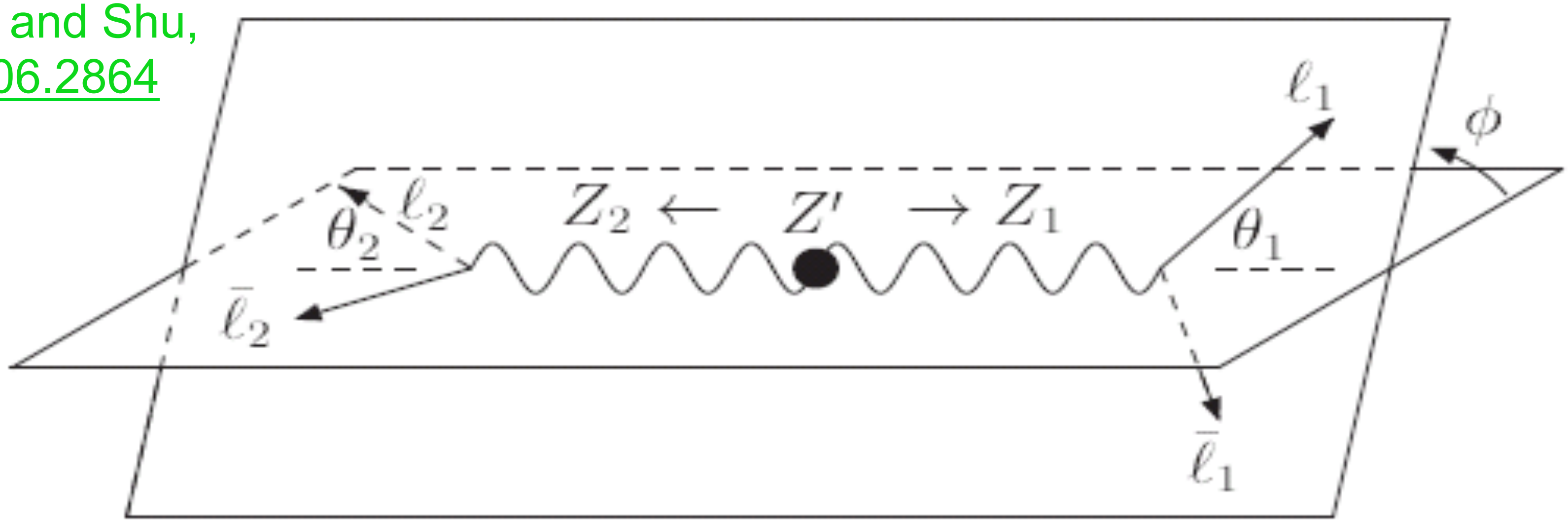


FIG. 1: *Two decay planes of $Z_1 \to \ell_1\bar{\ell}_1$ and $Z_2 \to \ell_2\bar{\ell}_2$ define the azimuthal angle $\phi \in [0, 2\pi]$ which rotates ℓ_2 to ℓ_1 in the transverse view. The polar angles θ_1 and θ_2 shown are defined in the rest frame of Z_1 and Z_2, respectively.*

$$O_{CPV} = f_4 Z'_\mu(\partial_\nu Z^\mu)Z^\nu, O_A = f_5 \epsilon^{\mu\nu\rho\sigma} Z'_\mu Z_\nu(\partial_\rho Z_\sigma)$$

Amplitudes $Z'(q_1+q_2,\mu) \to Z(q_1,\alpha)Z(q_2,\beta)$

$$\Gamma^{\mu\alpha\beta}_{Z'\to Z_1Z_2} = if_4(q_2^\alpha g^{\mu\beta} + q_1^\beta g^{\mu\alpha}) + if_5\epsilon^{\mu\alpha\beta\rho}(q_1-q_2)_\rho.$$

$$\beta^2 = 1 - 4m_Z^2/m_{Z'}^2$$

$$\begin{aligned}\mathcal{M}_{+,+0} &= -\mathcal{M}_{-,0+} = R(-f_5\beta + if_4)\\ \mathcal{M}_{+,0-} &= -\mathcal{M}_{-,-0} = R(-f_5\beta - if_4)\end{aligned}$$

$$R = \frac{\beta m_{Z'}^2}{2m_Z}$$

$$\sum_{\kappa,h_1,h_2}\left|\sum_{\lambda_1,\lambda_2}\mathcal{M}_{\kappa,\lambda_1\lambda_2}\, g_{h_1} f^{h_1}_{\lambda_1}(\theta_1,\phi)\, g_{h_2} f^{h_2}_{\lambda_2}(\theta_2,0)\right|^2$$

$$f^h_m(\bar\theta,\bar\phi) = (1+mh\cos\bar\theta)\frac{e^{im\bar\phi}}{2},\ f^h_0(\bar\theta,\bar\phi) = \frac{h}{\sqrt{2}}\sin\bar\theta.$$

Universal Angular dependence

$$\frac{8\pi dN}{N\, d\cos\theta_1 d\cos\theta_2 d\phi} = \frac{9}{8}\Big[1 - \cos^2\theta_1\cos^2\theta_2$$

$$-\cos\theta_1\cos\theta_2\sin\theta_2\sin\theta_1\cos(\phi+2\delta)$$

$$+\frac{(g_L^2-g_R^2)^2}{(g_L^2+g_R^2)^2}\sin\theta_1\sin\theta_2\cos(\phi+2\delta)\Big]$$

Amp. Squared sum

$$\mathcal{M}[+ \to (+,0) \text{ or } (0,-)]_{RR} = +g_R^2[(1+\cos\theta)e^{i\phi}\sin\theta' + (1-\cos\theta')\sin\theta]$$

$$\mathcal{M}[+ \to (+,0) \text{ or } (0,-)]_{LL} = -g_L^2[(1-\cos\theta)e^{i\phi}\sin\theta' + (1+\cos\theta')\sin\theta]$$

$$\mathcal{M}[- \to (-,0) \text{ or } (0,+)]_{RR} = +g_R^2[(1-\cos\theta)e^{-i\phi}\sin\theta' + (1+\cos\theta')\sin\theta]$$

$$\mathcal{M}[- \to (-,0) \text{ or } (0,+)]_{LL} = -g_L^2[(1+\cos\theta)e^{-i\phi}\sin\theta' + (1-\cos\theta')\sin\theta]$$

$$\mathcal{M}[+ \to (+,0) \text{ or } (0,-)]_{RL} = -g_R g_L[(1+\cos\theta)e^{i\phi}\sin\theta' - \sin\theta(1+\cos\theta')]$$

$$\mathcal{M}[+ \to (+,0) \text{ or } (0,-)]_{LR} = +g_L g_R[(1-\cos\theta)e^{i\phi}\sin\theta' - \sin\theta(1-\cos\theta')]$$

$$\mathcal{M}[- \to (-,0) \text{ or } (0,+)]_{RL} = -g_R g_L[(1-\cos\theta)e^{-i\phi}\sin\theta' - \sin\theta(1-\cos\theta')]$$

$$\mathcal{M}[- \to (-,0) \text{ or } (0,+)]_{LR} = +g_L g_R[(1+\cos\theta)e^{-i\phi}\sin\theta' - \sin\theta(1+\cos\theta')]$$

$$4(g_L^2+g_R^2)^2[1-\cos^2\theta\cos^2\theta' - \cos\theta\cos\theta'\sin\theta'\sin\theta\cos\phi] + 4(g_L^2-g_R^2)^2\sin\theta\sin\theta'\cos\phi$$

Ang. Integrated Oscillation

$$\frac{2\pi dN_\pm}{Nd\phi} = \frac{1}{2}\left[1 \mp \frac{1}{8}\cos(\phi+2\delta) + \frac{9\pi^2}{128}\frac{(g_L^2-g_R^2)^2}{(g_L^2+g_R^2)^2}\cos(\phi+2\delta)\right]$$

$$\frac{(g_L^2-g_R^2)^2}{(g_L^2+g_R^2)^2} \to \frac{(g_L^2-g_R^2)(g'^2_L-g'^2_R)}{(g_L^2+g_R^2)(g'^2_L+g'^2_R)}$$

SM ZZ background 79 fb

For 100 fb^{-1} luminosity at the LHC, if we require the ratio of the signal S to the statistical error in the background $\sqrt{B}$ to be 5 we need a σ(ZZ) about 70 fb for a 240 GeV Z'.

In the Littlest Higgs Model with T-parity, the predicted total cross section for T-odd particles, will be 1.3 pb.

Conclusion