달팽이 강연 : B 물리학의 이상현상

일정: 2017년 6월 30일 (금요일)

- 1:30 – 3:30 실험리뷰 권영준 교수 (연세대)
- 4:00 – 6:00 이론리뷰 K. Nishiwaki 박사 (KIAS)
- 6:10 – 8:00 저녁식사

장소: 연세대학교 물리학과 과학관 B104호

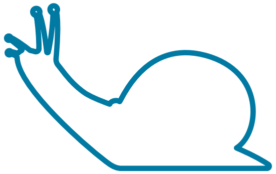
달팽이 강연 조직 위원

박성찬 (연세대), 이현민 (중앙대), 송정현 (건국대)

협찬: 아시아태평양이론물리센터

APCTP
Asia Pacific Center for Theoretical Physics

https://www.apctp.org/plan.php/rxanomaly



Outline

- Basic stuffs for high-school kids
  - Lepton Universality in the Standard Model
  - CKM matrix for quarks
- Contents for grown-ups* ("R_X anomalies of *B*")
  - $R(D^{(*)})$
  - $R(K^{(*)})$ and related stuffs
- Prospects

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* with snail-pace intro for kids on each subject

THE STANDARD MODEL OF
FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$) where 1 GeV = 10^9 eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

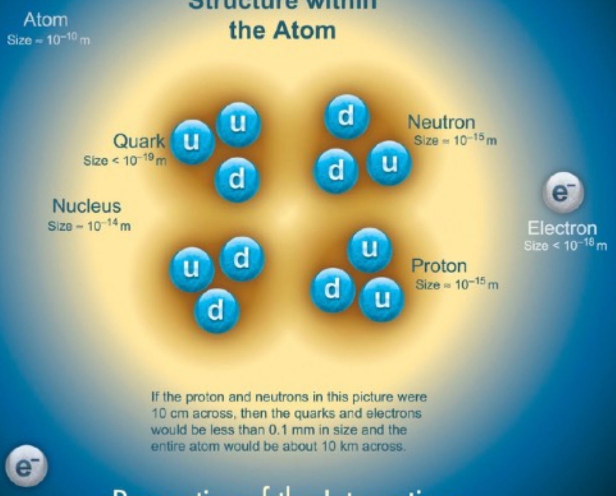
Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite-mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

Structure within the Atom



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Higgs Boson spin = 0

Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

Higgs Boson

The Higgs boson is a critical component of the Standard Model. Its discovery helps confirm the mechanism by which fundamental particles get mass.

Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), and neutron (udd). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), and B^0 ($d\bar{b}$).

Learn more at ParticleAdventure.org

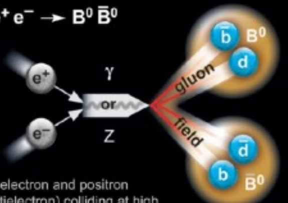
Particle Processes

These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.

$n \rightarrow p\, e^-\, \bar{\nu}_e$

A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

$e^+ e^- \rightarrow B^0 \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.

Why is the Universe Accelerating?

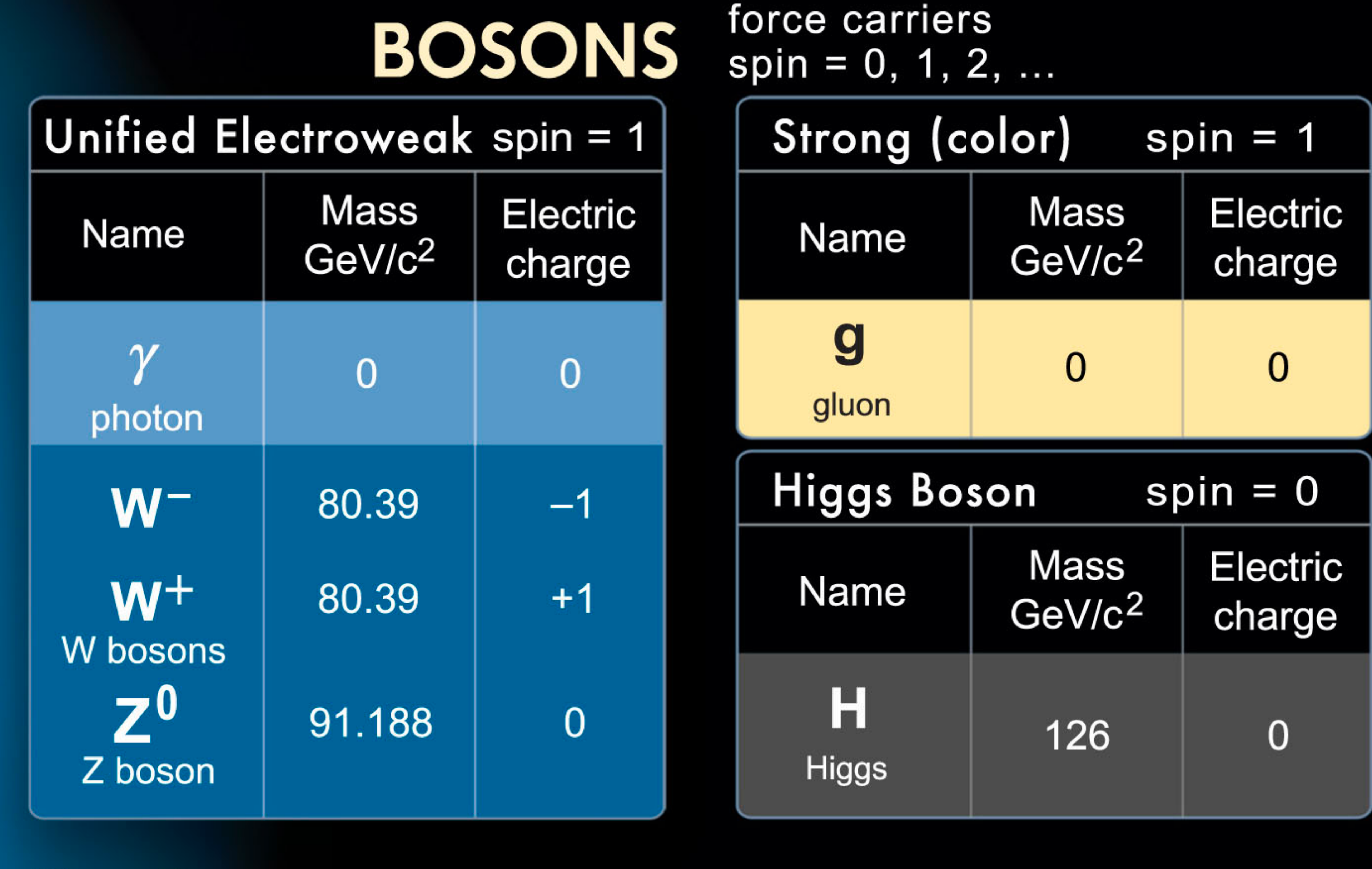
Why No Antimatter?

What is Dark Matter?

Are there Extra Dimensions?

Learn more at ParticleAdventure.org

Bosons of the Standard Model



BOSONS

force carriers
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W⁺ W bosons	80.39	+1
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Strong (color) spin = 1

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g gluon	0	0

Higgs Boson spin = 0

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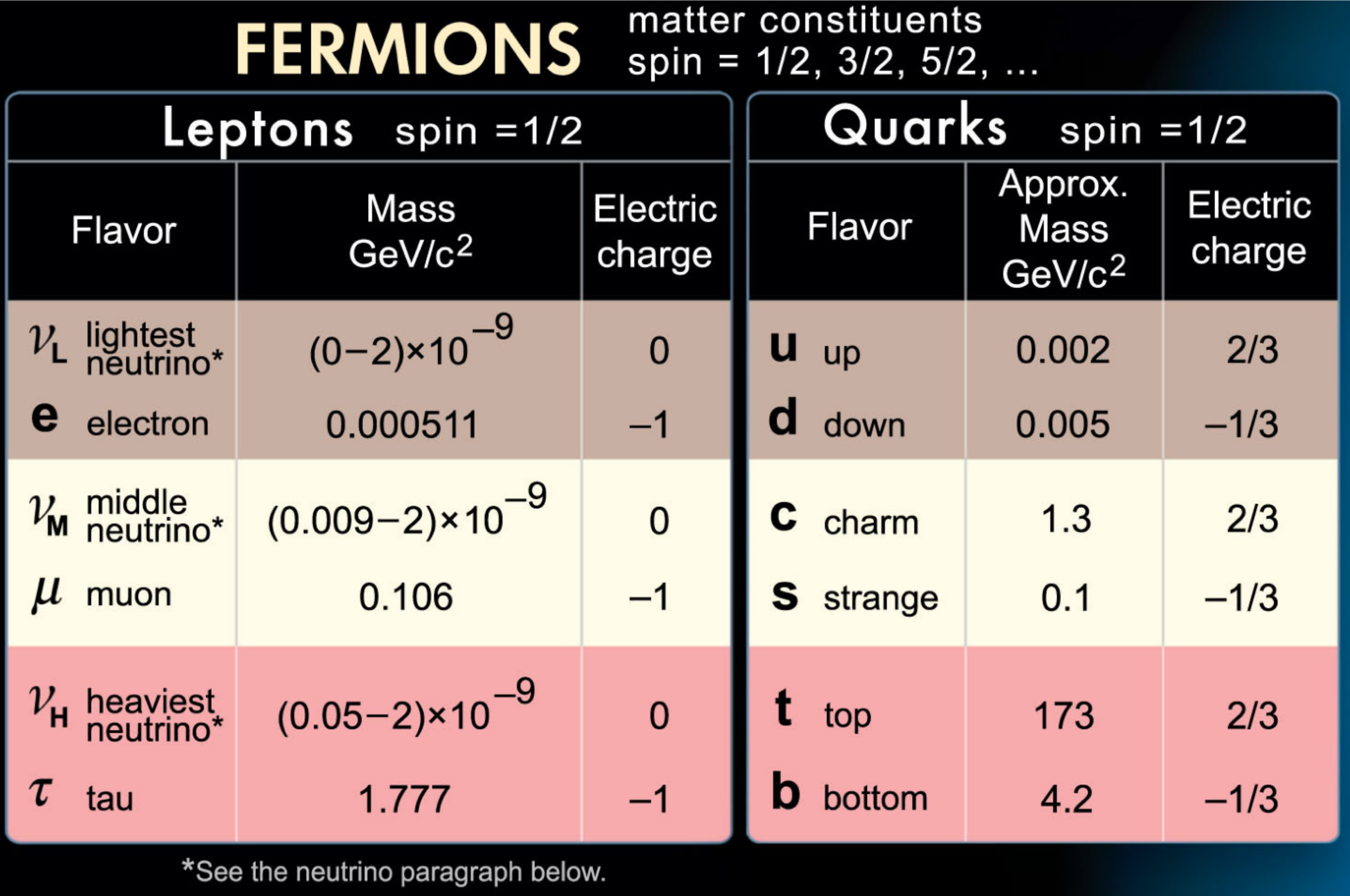
H Higgs	126	0

Fermions of the Standard Model



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*See the neutrino paragraph below.

Lepton universality

- Do all leptons and quarks carry the same unit of weak charge?
  - **YES**, for leptons and **NO** for quarks
- First, let's consider a **muon decay**
  - low energy process ($q^2 \sim m_\mu \ll m_W$)
  - specified by the Fermi constant: G_F ($\sim g^2/m_W{}^2 \sim [\text{energy}]^{-2}$)
  - dimensional analysis

$$\Gamma(\mu^- \to e^- \bar{\nu}_e \nu_\mu) = \frac{\hbar}{\tau_\mu} \propto G_F^2 m_\mu^5$$

$$= \frac{G_F^2 m_\mu^5}{192\pi^3}$$

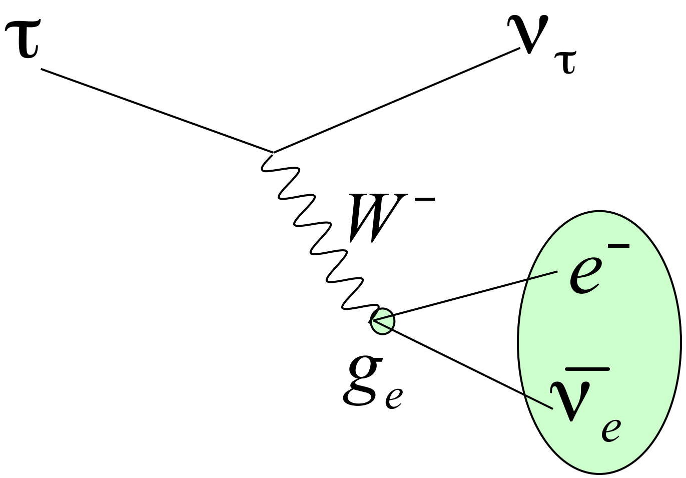
from full calculation (V–A)

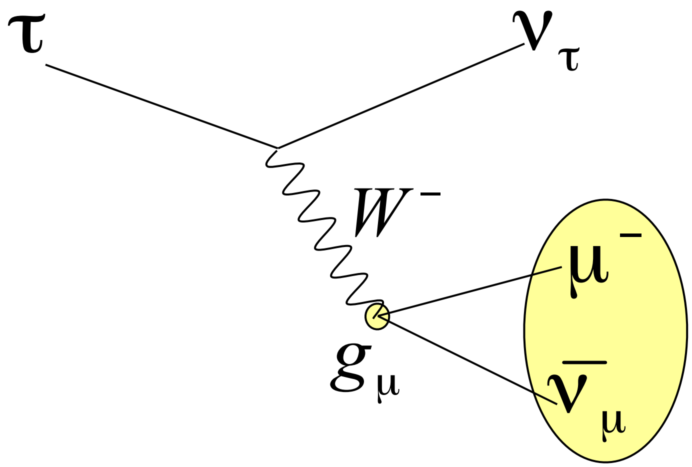
Lepton universality

- Now consider the tau (τ) lepton decay

$$B(\tau^- \to e^- \bar{\nu}_e \nu_\tau) = (17.83 \pm 0.06)\%$$

$$B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) = (17.37 \pm 0.07)\%$$





$$g_\mu / g_e = 1.001 \pm 0.004$$

Lepton universality

- Again, from the τ decay

$$B(\tau^- \to e^-\bar{\nu}_e\nu_\tau) = \frac{\Gamma(\tau^- \to e^-\bar{\nu}_e\nu_\tau)}{\Gamma(\tau^- \to \text{all})} = (17.83 \pm 0.06)\%$$

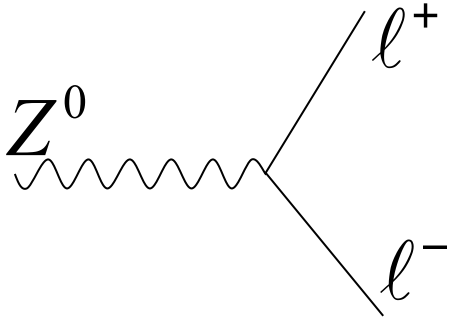
$$\Gamma(\tau^- \to e^-\bar{\nu}_e\nu_\tau) = \frac{B(\tau^- \to e^-\bar{\nu}_e\nu_\tau)}{\tau_\tau} \propto G_F^2 m_\tau^5$$

Since $\Gamma \propto G_F^2 \propto g^4$

$$\Rightarrow \left(\frac{g_\tau}{g_\mu}\right)^4 = B(\tau^- \to e^-\bar{\nu}_e\nu_\tau)\left(\frac{m_\mu}{m_\tau}\right)^5\left(\frac{\tau_\mu}{\tau_\tau}\right)$$

$$g_\tau / g_\mu = 0.999 \pm 0.003$$

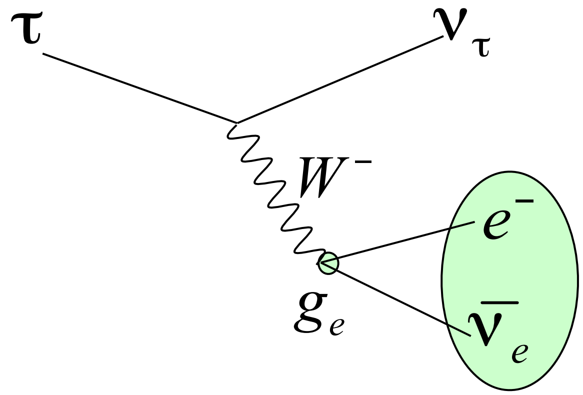
Lepton universality: example for Z^0



$$Z^0 \to e^+e^- : \mu^+\mu^- : \tau^+\tau^-$$
$$= 1 : 1.000 \pm 0.004 : 0.999 \pm 0.005$$

Universality of weak interactions?

- Do all leptons and quarks carry the same unit of weak charge?
  - **YES**, for leptons, but **NO** for quarks



- ☐ for quarks, the couplings to the weak gauge bosons depend on the quark flavors, due to "quark-mixing"
  → **CKM mechanism**

Universality of W.I. for quarks?

- Consider the (semileptonic) weak decay

$\Delta S = 1$

$$\Sigma^- \to n + e^- + \bar{\nu}_e$$
$$\left(s \to u + e^- + \bar{\nu}_e\right)$$

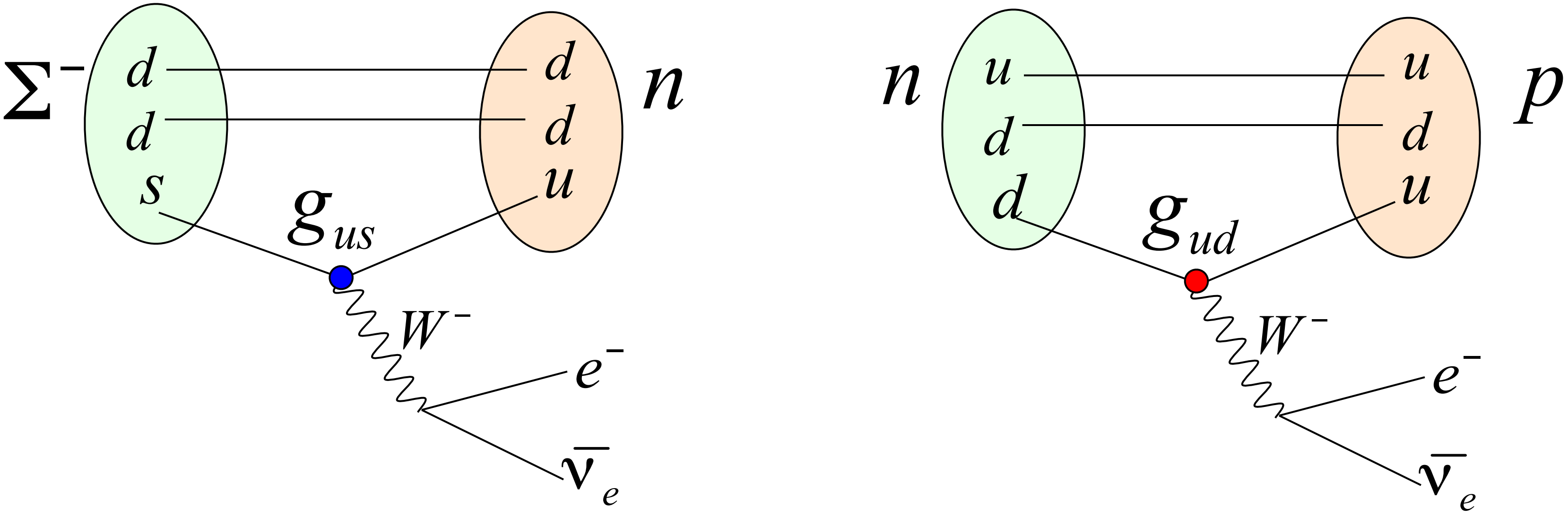
$$n \to p + e^- + \bar{\nu}_e$$
$$d \to u + e^- + \bar{\nu}_e$$

$\Delta S = 0$

- Assuming universality of weak decays of quarks, we expect both decays would happen in similar rate, but...

$$\frac{\Gamma(\Sigma^- \to n e^- \bar{\nu}_e)}{\Gamma(n \to p e^- \bar{\nu}_e)} \cong \frac{1}{20}$$

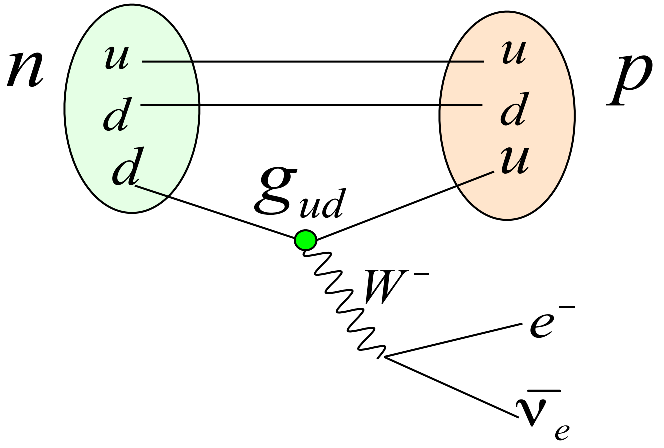
Universality of W.I. for quarks?

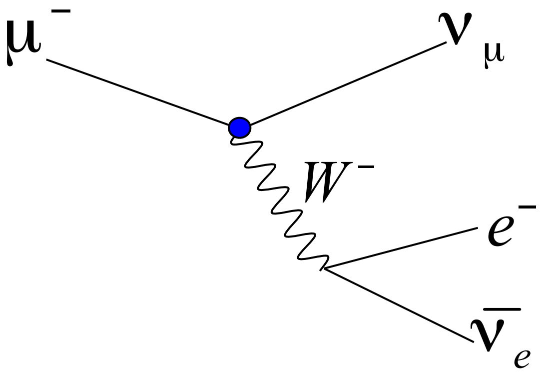


$$\frac{\Gamma(s \to u e^- \bar{\nu}_e)}{\Gamma(d \to u e^- \bar{\nu}_e)} \cong \left|\frac{g_{us}}{g_{ud}}\right|^2 \approx \frac{1}{20} \neq O(1)$$

Universality of W.I. for quarks?

It was also noticed that the value of the Fermi constant G_F deduced from nuclear β-decay was slightly less than that obtained from muon decay.





So, what are we going to do?
No universality for weak interaction?

Cabibbo theory

- Try to keep the universality, by modifying the quark doublet structure…
- Assume that the charged current ($W^{\pm}$) couples the "rotated" quark states

$$\begin{pmatrix} u \\ d' \end{pmatrix} \qquad \begin{pmatrix} c \\ s' \end{pmatrix}$$

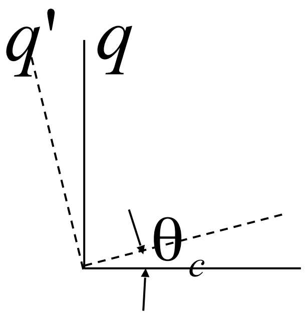
- where d', s' (**weak interaction eigenstates**) are linear combinations of **mass eigenstates** d, s

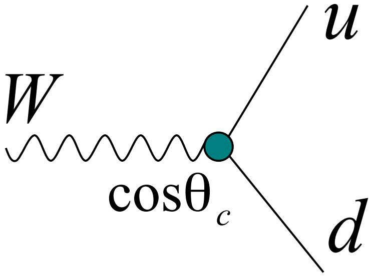
$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

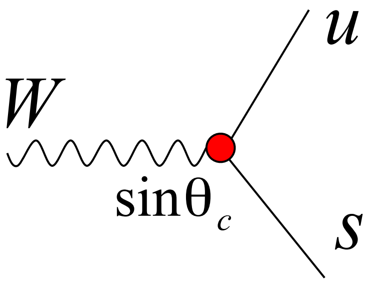
θ_c : the quark mixing angle
"Cabibbo" angle

Cabibbo theory

- "**Cabibbo-favored**" vs. "-**suppressed**"





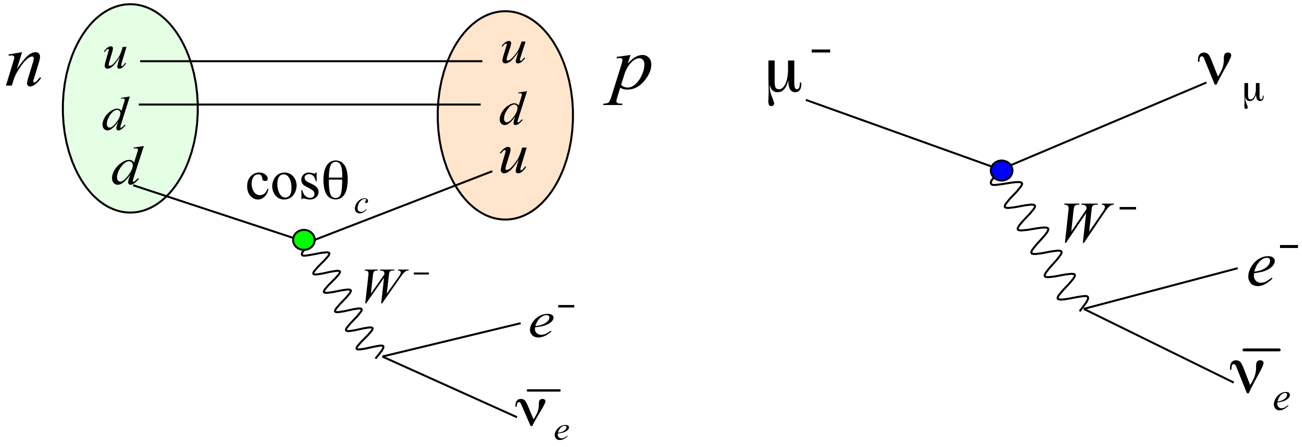


- effective weak coupling for ΔS=0 (d→uW) is **cos θ_c**
- effective weak coupling for ΔS=1 (s→uW) is **sin θ_c**

$$\frac{\Gamma(s \to ue\bar{\nu}_e)}{\Gamma(d \to ue\bar{\nu}_e)} \cong \left|\frac{g_{us}}{g_{ud}}\right|^2 \approx \left|\frac{\sin\theta_c}{\cos\theta_c}\right|^2 \approx \frac{1}{20} \neq O(1) \quad \Rightarrow \theta_c \approx 12^{o}$$

Cabibbo theory

(Ex) What is the relationship between the weak couplings for muon decay ($G_\mu=G_F$) and nuclear β-decay (G_β) ?



$$\boldsymbol{G_\beta = G_\mu \cos\theta_c}$$

$$G_\mu = (1.16639 \pm 0.00001) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

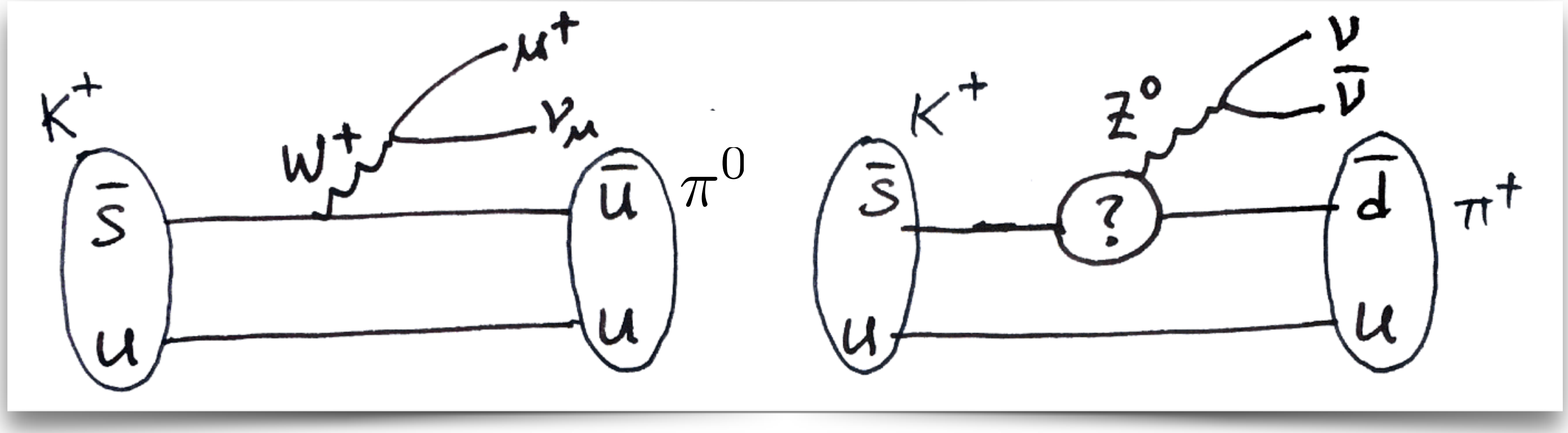
$$G_\beta = (1.136 \pm 0.003) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

Flavor-Changing Neutral Currents (FCNC)

- a very stringent suppression of flavor-changing neutral current reactions

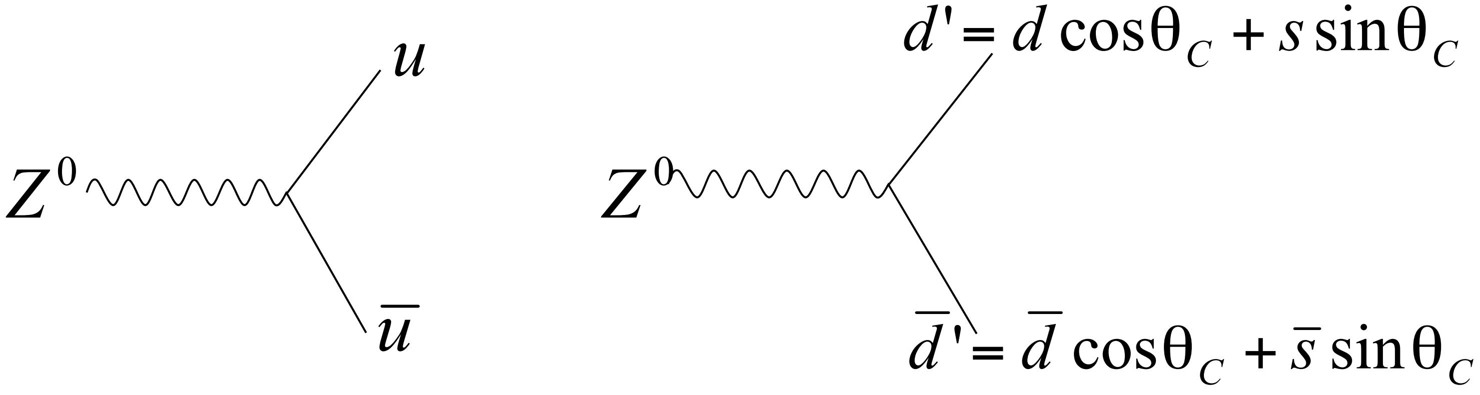
$$BF(K^+ \to \pi^+ \nu\bar{\nu}) = (1.5^{+3.4}_{-1.2}) \times 10^{-10}$$

$$BF(K^+ \to \pi^0 \mu^+ \nu_\mu) = (3.17 \pm 0.08)\%$$



FCNC

Neutral-current reactions for (*u*,*d'*) quarks



$$d' = d\cos\theta_C + s\sin\theta_C$$

$$\bar{d}' = \bar{d}\cos\theta_C + \bar{s}\sin\theta_C$$

$$\underbrace{u\bar{u} + (d\bar{d}\cos^2\theta_c + s\bar{s}\sin^2\theta_c)}_{\Delta S = 0} + \underbrace{(s\bar{d} + d\bar{s})\sin\theta_c\cos\theta_c}_{\Delta S = 1}$$

In this picture, FCNC is perfectly allowed by theory.
Then, why such a severe suppression ???

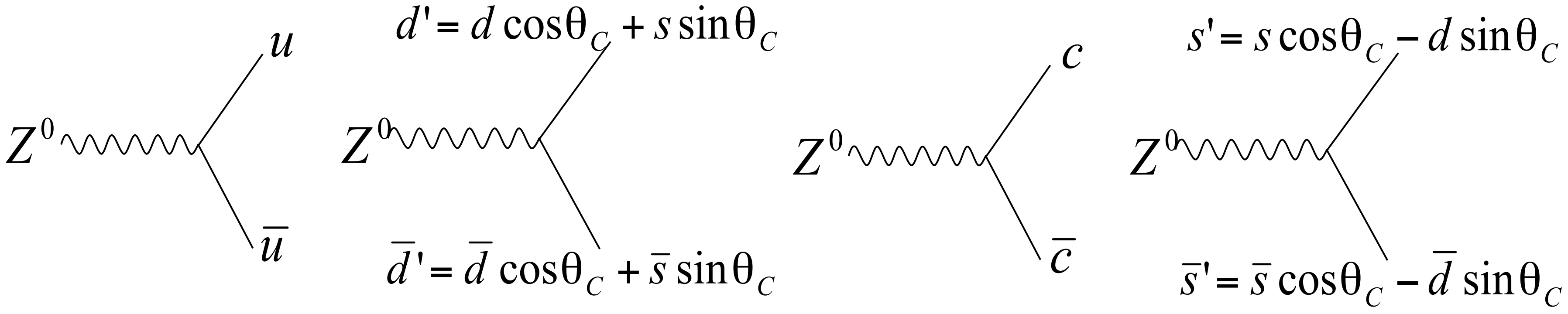
GIM mechanism for FCNC suppression

- In 1970, Glashow, Iliopoulos & Maiani (GIM) proposed the introduction of a new quark of Q=+2/3, with label c for ‘charm’.
- With this new quark, a second quark doublet is also introduced.

$$\begin{pmatrix} u \\ d' \end{pmatrix} = \begin{pmatrix} u \\ d\cos\theta_c + s\sin\theta_c \end{pmatrix}, \quad \begin{pmatrix} c \\ s' \end{pmatrix} = \begin{pmatrix} c \\ s\cos\theta_c - d\sin\theta_c \end{pmatrix}$$

- Then we have additional terms for the neutral current reactions

GIM mechanism



$d' = d\cos\theta_C + s\sin\theta_C$

$\bar{d}' = \bar{d}\cos\theta_C + \bar{s}\sin\theta_C$

$s' = s\cos\theta_C - d\sin\theta_C$

$\bar{s}' = \bar{s}\cos\theta_C - \bar{d}\sin\theta_C$

$$u\bar{u} + (d\bar{d}\cos^2\theta_c + s\bar{s}\sin^2\theta_c) + (s\bar{d} + d\bar{s})\sin\theta_c\cos\theta_c$$

$$+ c\bar{c} + (d\bar{d}\sin^2\theta_c + s\bar{s}\cos^2\theta_c) - (s\bar{d} + d\bar{s})\sin\theta_c\cos\theta_c$$

$$= u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c}$$

FCNC has disappeared!

GIM mechanism

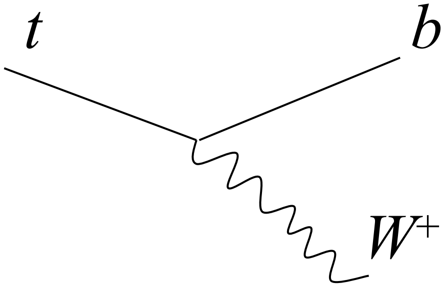
- At the price of a new quark ‘charm’ and another quark doublet, the (experimentally) unwanted FCNC has been removed!
- Later, in 1974, the bound state of charm–anti-charm was discovered: J/ψ
- Indeed, just before this discovery, it was possible to estimate the mass of this new quark!!

$\leftarrow$ by considering $K^0\overline{K}^0$ mixing

Features of SM interactions

- Leptons do not undergo strong interactions
- Quarks & Leptons do not change its flavor when interacting with neutral gauge bosons
  - quarks do not change flavor under strong int.
  - leptons & quarks do not change flavor when interacting with γ or Z^0
  - leptons & quarks **change** flavor only when interacting with $W^{\pm}$, and **only within its family**

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L \quad \updownarrow W^{\pm}$$



Cabibbo theory for 3 generations

- Then how does b decay at all?

  Note: $\mathrm{b} \rightarrow \mathrm{W}^{-}\mathrm{t}$ but $\mathrm{m(t)} \gg \mathrm{m(b)}$

- For quarks,
  - mass eigenstates ≠ weak interaction eigenstates
  - flavor mixing through **CKM** matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} \mathrm{V}_{ud} & \mathrm{V}_{us} & \mathrm{V}_{ub} \\ \mathrm{V}_{cd} & \mathrm{V}_{cs} & \mathrm{V}_{cb} \\ \mathrm{V}_{td} & \mathrm{V}_{ts} & \mathrm{V}_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

weak interaction
eigenstates

mass
eigenstates

CKM matrix

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

- CKM is 3x3 and unitary
  - – only 3 generations in the SM
- CKM is almost 1, but not exactly

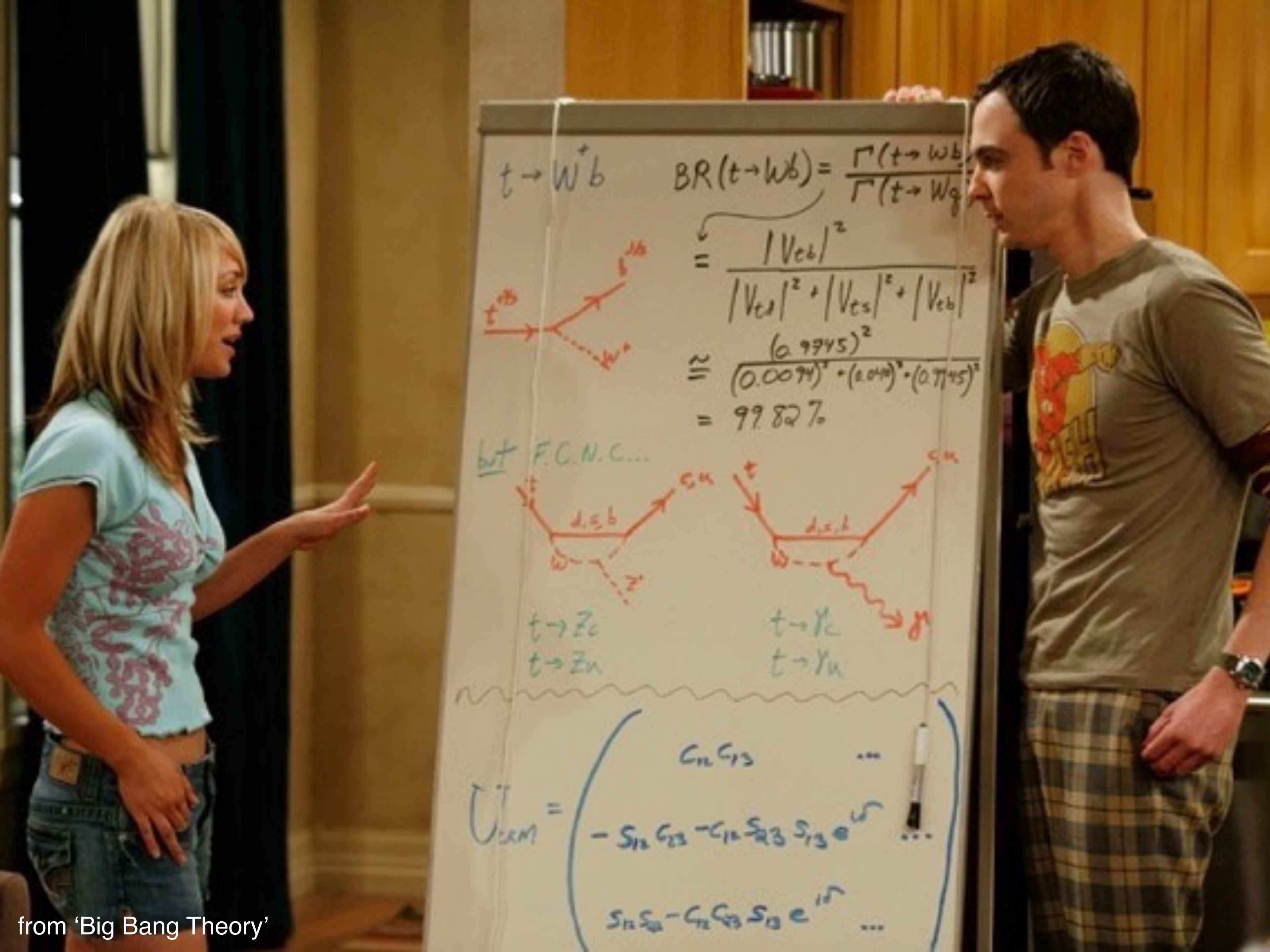
$$V_{ii} \approx 1, \; V_{ij} \approx 0 \;\; \text{for} \;\; i \neq j$$

$$\mathbf{V}_{\mathrm{CKM}} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$|\lambda| \approx O(0.1)$$

$$3 \;\; \text{real parameters} \;\; (\lambda, A, \rho) \;\; \text{and} \;\; 1 \;\; \text{phase} \;\; (\eta)$$

- *How do we determine the CKM matrix elements?*

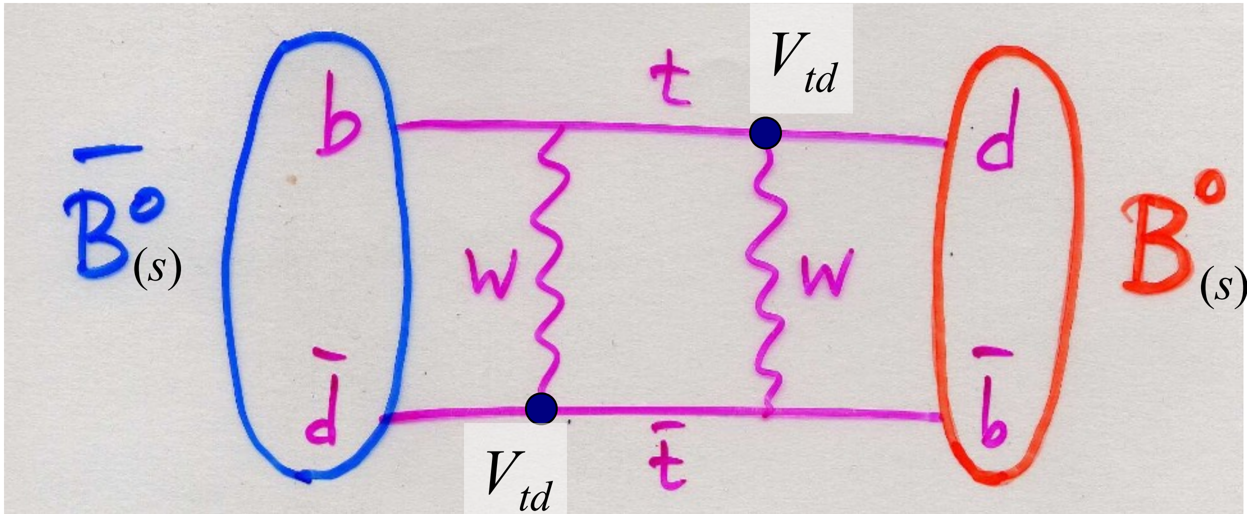


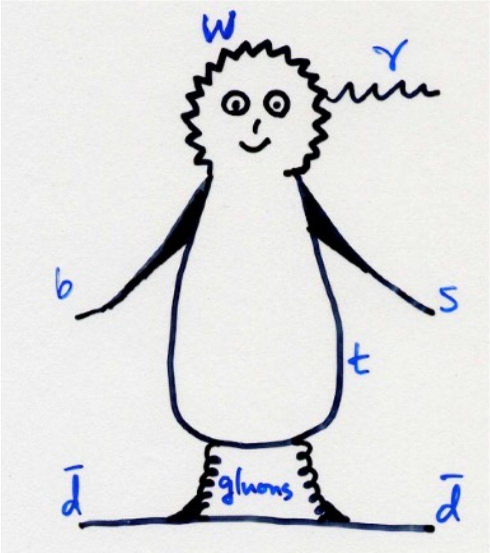
from ‘Big Bang Theory’

Expt’l determination of CKM elements

- V_{td} and V_{ts}

(1)





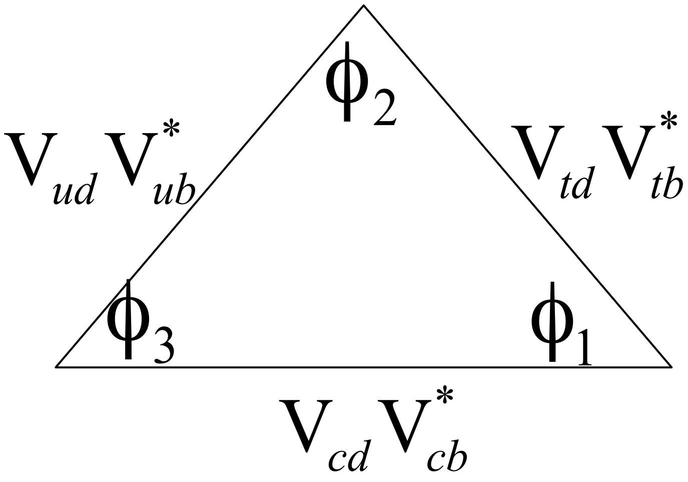
(2)

$$R_{K^*/\rho} \equiv \frac{BR\left(B \to \rho\gamma\right)}{BR\left(B \to K^*\gamma\right)} \propto \left|\frac{V_{td}}{V_{ts}}\right|^2$$

CKM Unitarity Triangle

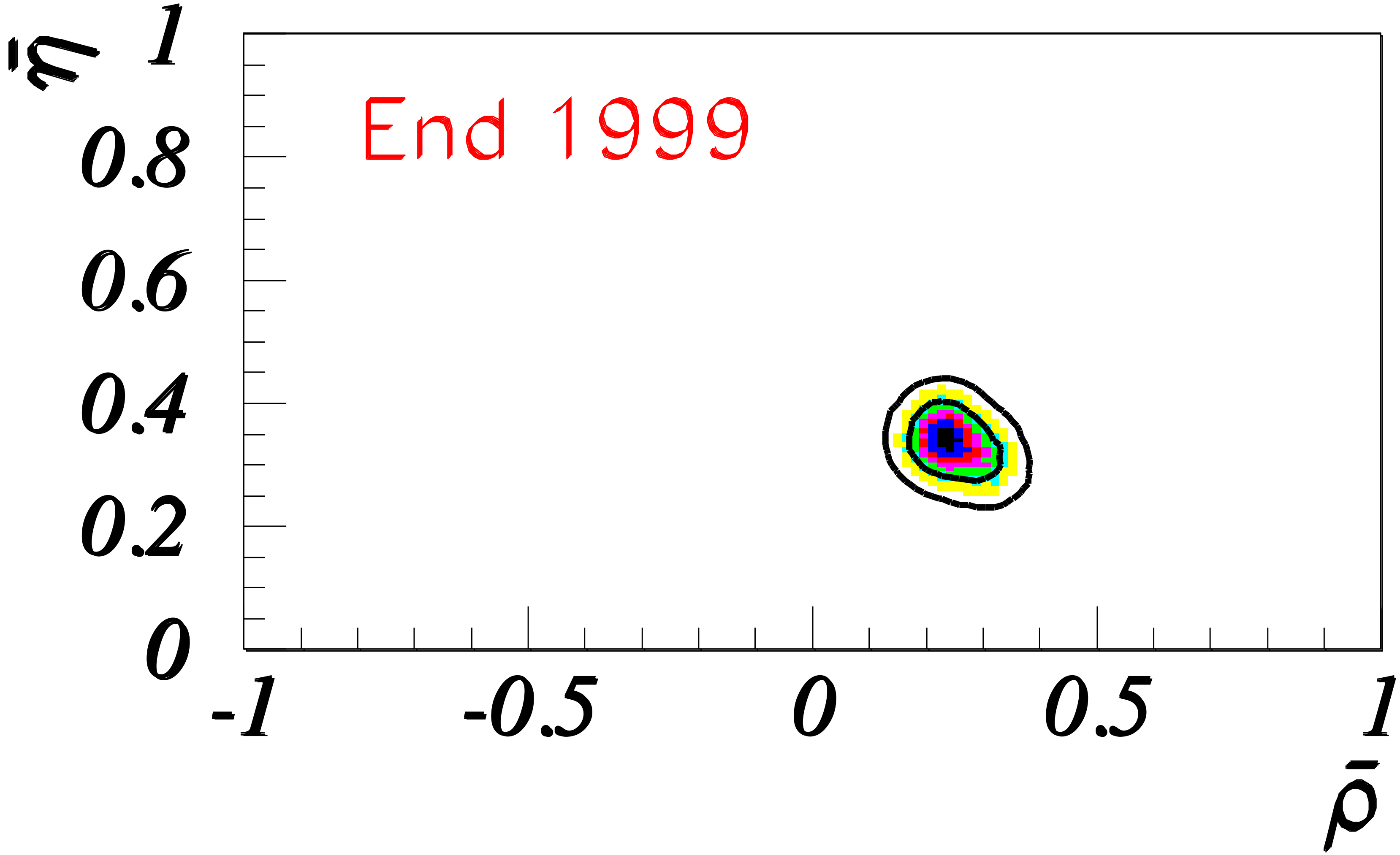
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

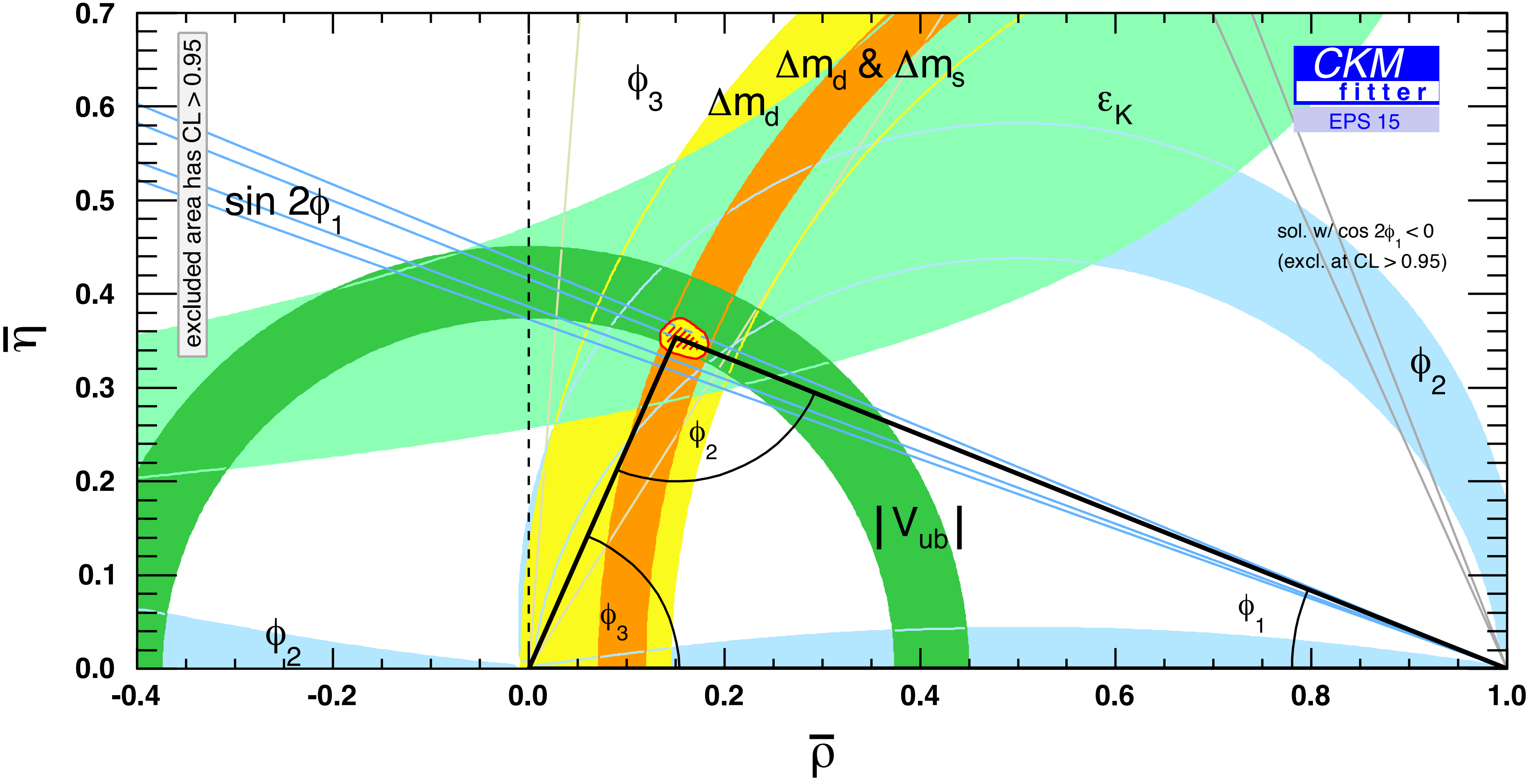


Unitarity triangle angles			
BABAR:	β	α	γ
BELLE:	ϕ_1	ϕ_2	ϕ_3
This talk:	易	難	魔

Z. Ligeti, from plenary talk @ ICHEP 2004

End 1999
$\bar{\eta}$
1
0.8
0.6
0.4
0.2
0
-1
-0.5
0
0.5
1
$\bar{\rho}$

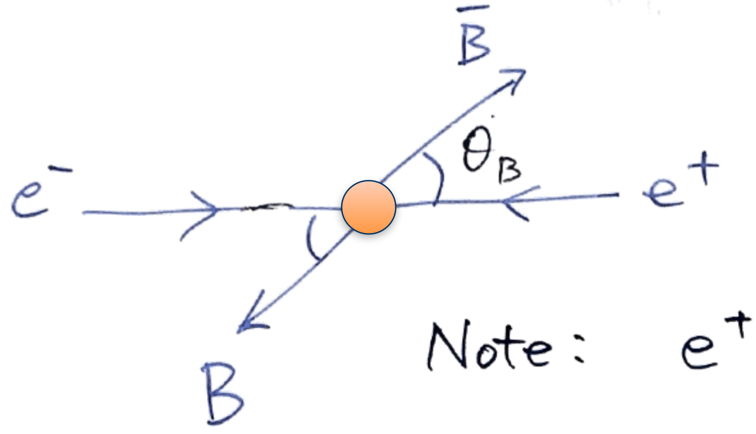
CKM UT as of 2015



Appendix

Angular Distribution 101

① Consider $e^+e^- \to B\bar{B}$



$|\psi|^2 \propto f(\theta) = ?$

Note: $e^+e^- \to \underbrace{\Upsilon(4S)}_{J^P=1^-\ \text{state of}\ (b\bar{b})} \to B\bar{B}$

$|J\,m\rangle_{\gamma^*} = |1\,\pm1\rangle$ $\qquad$ B (or $\bar{B}$) : $J^P = 0^-$

$|J\,m\rangle_B = |0\,0\rangle$

To conserve angular momentum, we need

$$|\psi_{\text{orbital}}\rangle \propto \underbrace{Y_{1\pm1}}_{\propto\,\sin\theta} \Rightarrow \therefore f(\theta) \propto \sin^2\theta$$

② $B \to K^* \gamma$

$|0\,0\rangle$ $\uparrow$ $|1\,\pm1\rangle$

$J^P = 1^-$ ∴ $|J\,m\rangle = |1\,\mp1\rangle$

What about subsequent $K^* \to K\,\pi$?

$\uparrow\,\uparrow$ each $J=0$

$\Rightarrow$ ∴ We need $|\ell\,m\rangle = |1\,\mp1\rangle$

and $f(\theta) \propto \sin^2\theta$

The end of the kids' stuffs.
Any questions?