# Introduction of heavy flavor physics

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# Outline

I. Introduction of heavy flavor physics

GIM, CKM, leptonic/semi-leptonic decays

II. Theory of non-leptonic B/D decays

effective Hamiltonian, factorization, QCD factorization, perturbative QCD

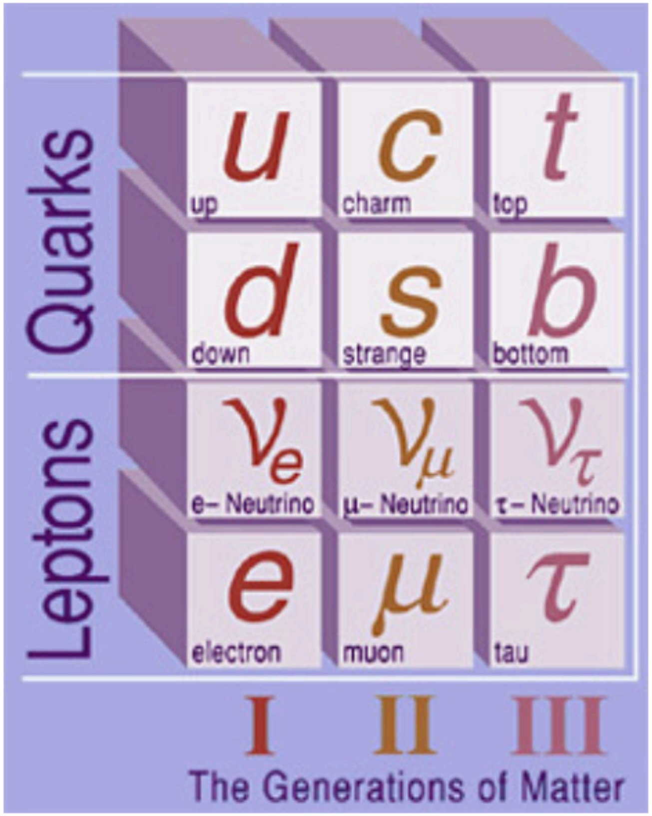
III. Recent progress/Rare B decays

Various anomalies, puzzles

# A quantum number is needed to identify each particle state

- For fermions:

$f =$



| | I | II | III |
|---|---|---|---|
| Quarks | $u$ up | $c$ charm | $t$ top |
| | $d$ down | $s$ strange | $b$ bottom |
| Leptons | $\nu_e$ e– Neutrino | $\nu_\mu$ μ– Neutrino | $\nu_\tau$ τ– Neutrino |
| | $e$ electron | $\mu$ muon | $\tau$ tau |

The Generations of Matter

$=$ Flavor

# Two directions of particle physics experiments

- **Higher Energy**： **Tevatron, LHC, FCC** — **Direct detection of new particle**, **new physics**

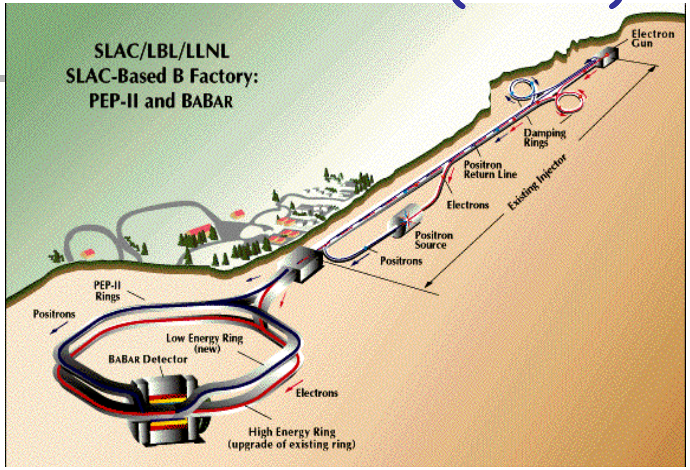
Need a big money

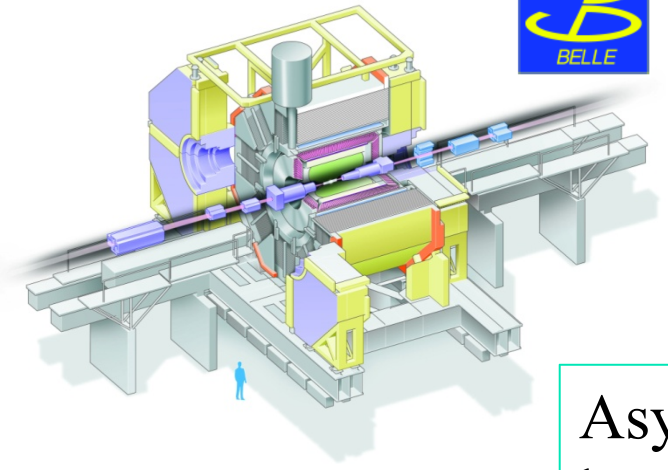
- **High Intensity**： **B factories**， **tau－charm factory, Higgs factory — precision test**， **Indirect search of new physics**，**more economic**
- **Many of the new discoveries are predicted by intensive precision experiments before their direct discovery**

# The Duel of the B Factories

KEK (Japan)

SLAC (USA)

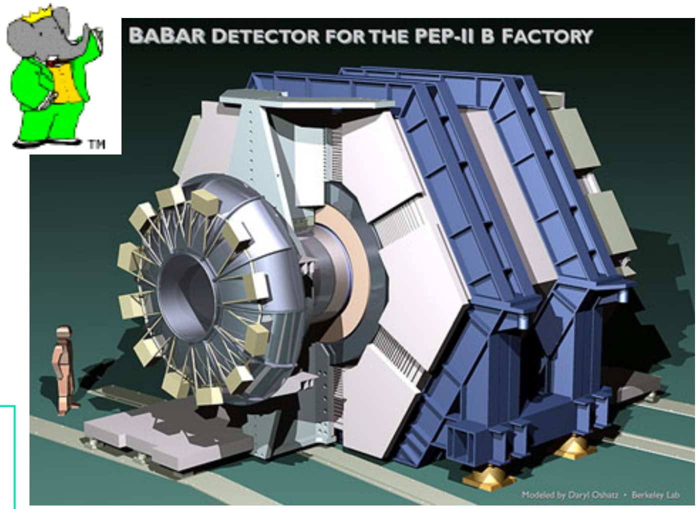




BELLE

Belle

Asymmetric beam energy



BaBar

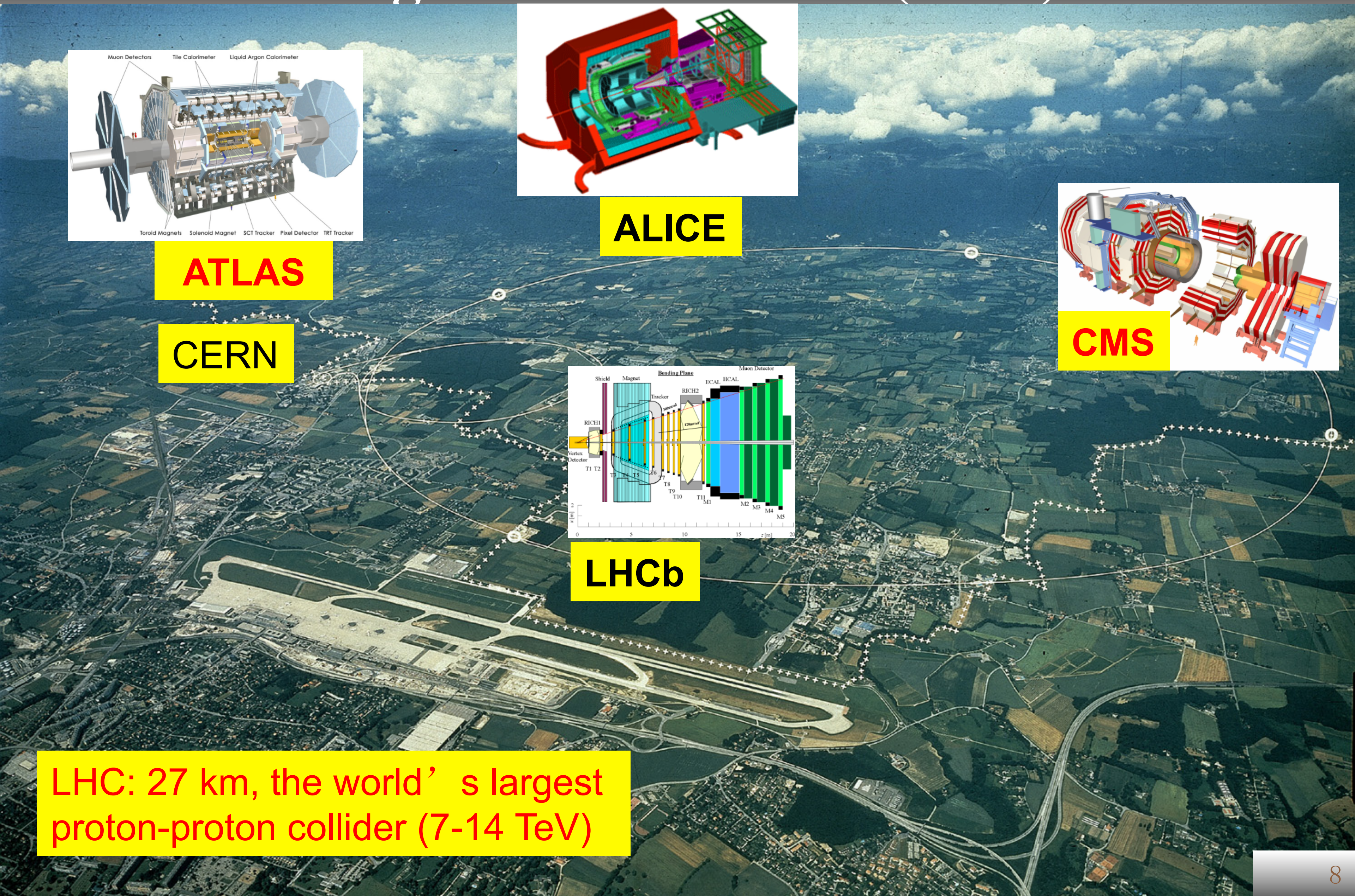
# B factory


Mt. Tsukuba
KEKB ring (HER+LER)
3km circumference
Belle detector
Linac
KEK Tsukuba site

Super B factory
Belle II

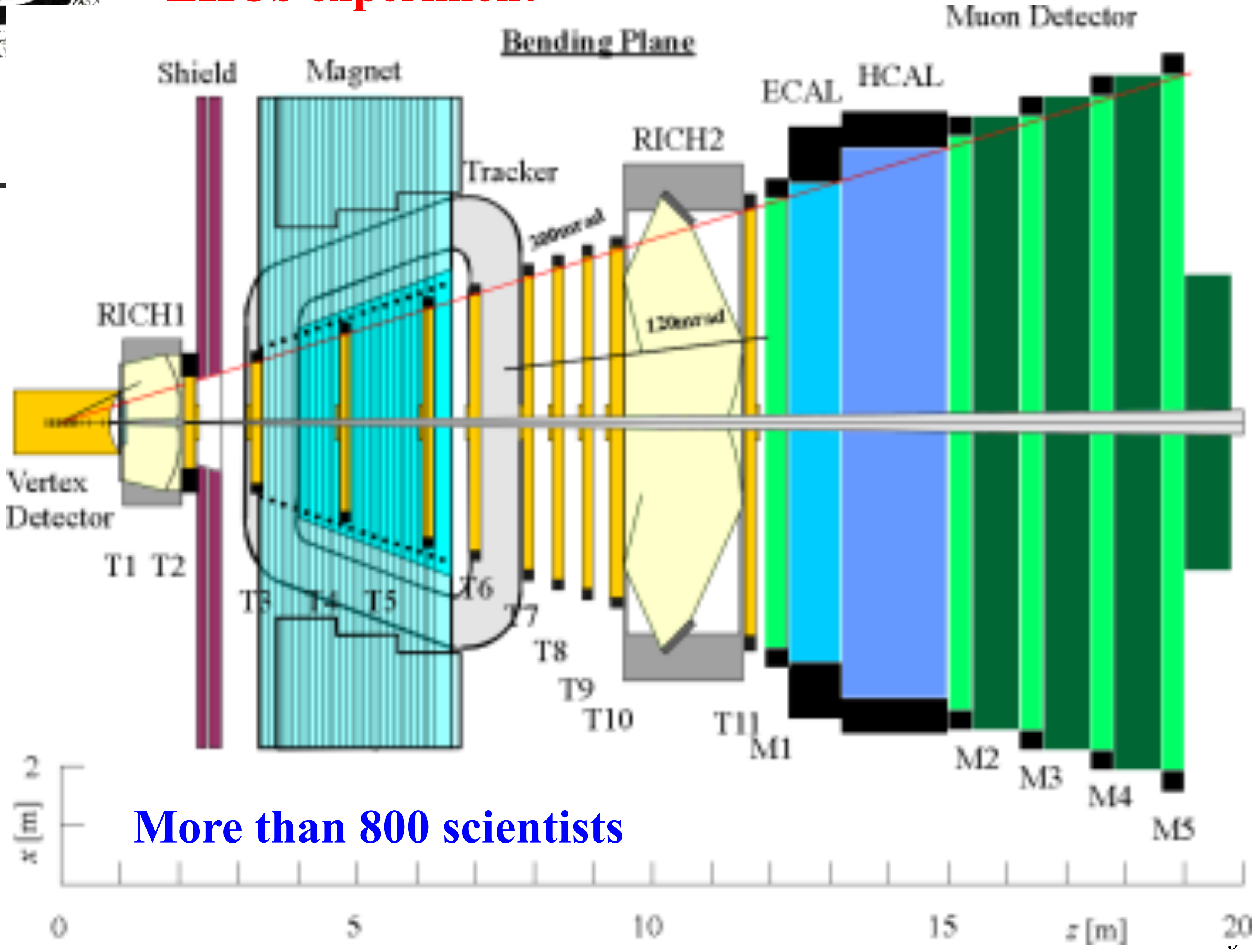
**The discovery of direct CP violation leads to 2008 Nobel Prize**

# Large Hadron Collider(LHC)



LHC: 27 km, the world’s largest proton-proton collider (7-14 TeV)

# LHCb experiment



**More than 800 scientists**

# The mixing of quark flavor

- In the SM, the lepton flavor eigenstates are the same as the weak eigenstates

The weak coupling is universal for different generation of leptons

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

However, the story is different for quarks:

The weak decay of $\Sigma^- \longrightarrow n e^- \overline{\nu}_e$ is suppressed 20 times comparing with $n \longrightarrow p e^- \overline{\nu}_e$

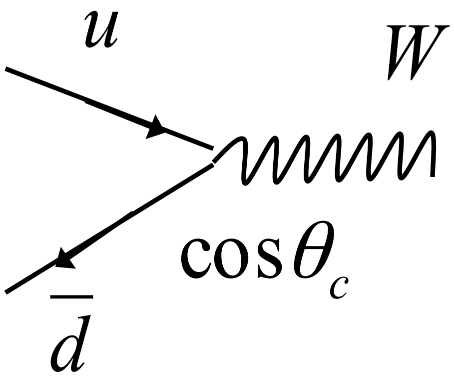
d and s quark mix to a new state d’ in weak interaction

# Cabibbo angle (1963)

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

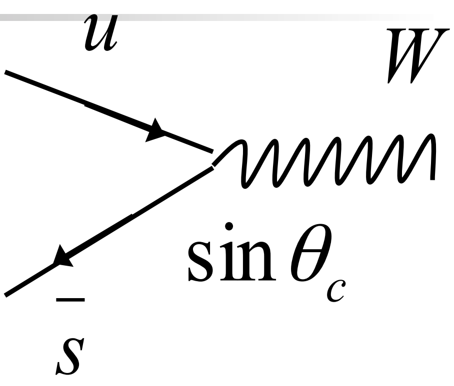
**u and d'quark make a weak isospin doublet**

**The Fermi weak couplings $G_F$ should be universal for quarks and leptons. The difference comes from the small Cabibbo angle $\theta_c$**



**The weak beta decay involves u and d quark, thus it is Cabibbo Favored, the effective coupling is $G_F \cos\theta_c$**

# For ΔS=1 process，



such as kaon decay, it involves u and s quark， which is Cabbibo suppressed，

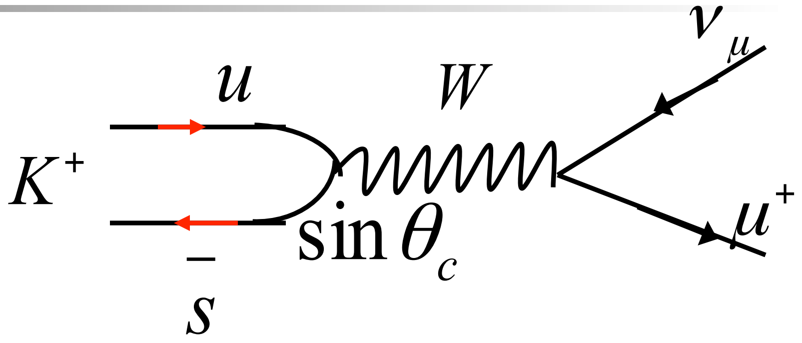
the effective coupling is $G_f \sin\theta_c$

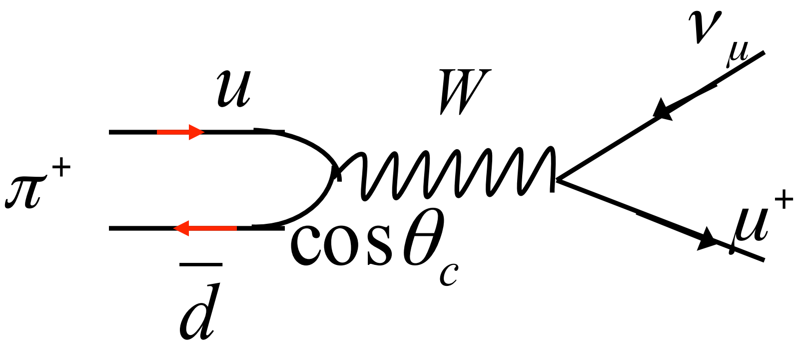
$\sin\theta_c \sim 0.22$, $\sin^2\theta_c \sim 0.05$, $\cos^2\theta_c \sim 0.95$

That is the reason why $\Sigma^- \rightarrow n e^- \bar{\nu}_e$ decay is suppressed 20 times comparing with $n \rightarrow p e^- \bar{\nu}_e$

# Cabbibo suppressed and favored decays

$$\frac{\Gamma(K^+ \rightarrow \mu^+\nu_\mu)}{\Gamma(\pi^+ \rightarrow \mu^+\nu_\mu)} \sim \sin^2\theta_c / \cos^2\theta_c$$

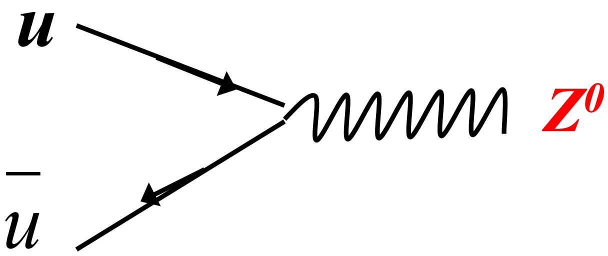


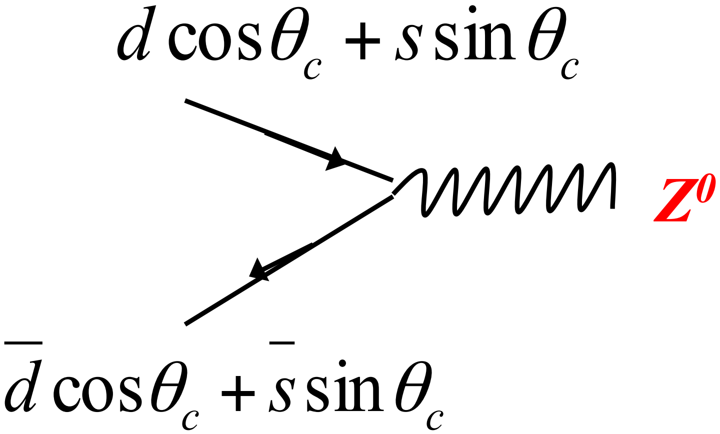


$$\frac{\Gamma(K^+ \rightarrow \pi^0 e^+\nu_e)}{\Gamma(\pi^+ \rightarrow \pi^0 e^+\nu_e)} \sim \sin^2\theta_c / \cos^2\theta_c$$

# Flavor changing neutral current

- **Although Cabibbo's theory is successful in explaining the** **charged current**
- **It is difficult for** **neutral current**
- **Similar to $Z^0$ coupling with $e^+e^-$, $\mu^+\mu^-$, $\nu_e\overline{\nu_e}$, $\nu_\mu\overline{\nu_\mu}$**
- **We should also have $Z^0$ coupling with** $u\overline{u}$, $d'\overline{d'}$





# $Z^0$ coupling

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

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

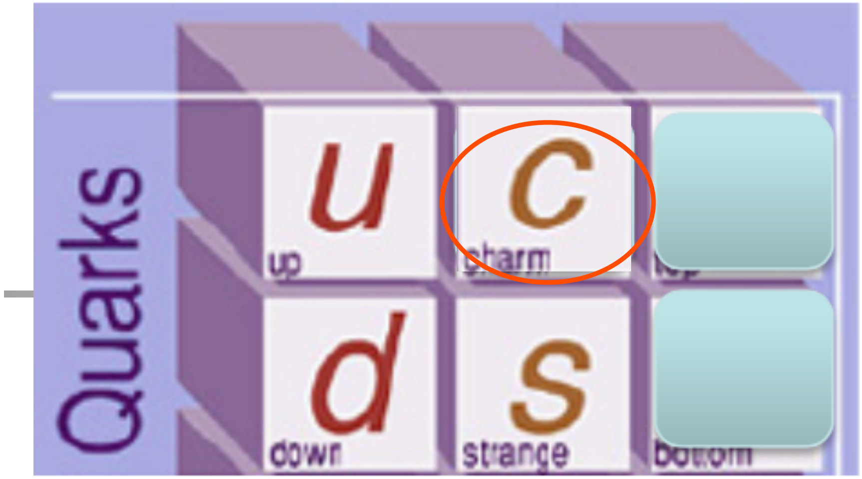
$$+ (s\bar{d} + d\bar{s})\cos\theta_c \sin\theta_c \qquad \Delta S = 1 \text{ process}$$

- So there is flavor changing neutral current decay

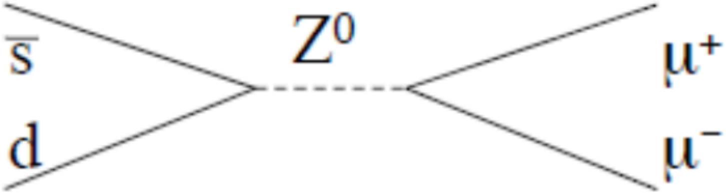
Long time ago, we had only 3 flavors of quarks: u,d,s.

Experimentally we found that

$$K^0 \not\to \mu^+\mu^-$$



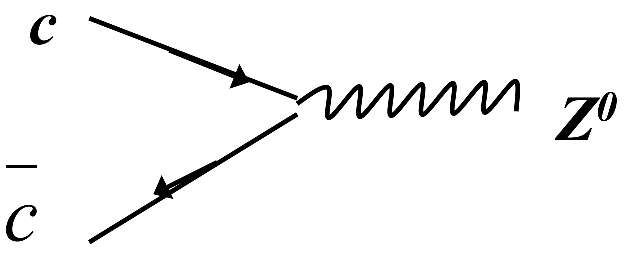
**But theoretically, we had**

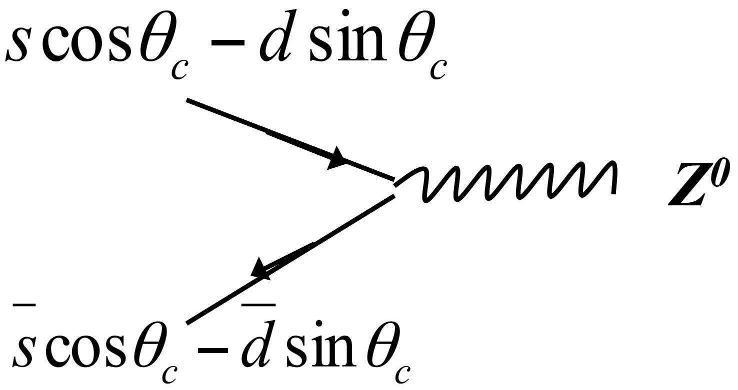


**The GIM mechanism gives prediction of Charm quark**

# GIM mechanism

- 1970，**Glashow, Iliopoulos and Maiani introduce a new quark, named “charm”**
- **There will be a new weak doublet，c quark and s’ (orthogonal to d’)**





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

# With the new flavor doublet, the flavor changing neutral current canceled

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

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

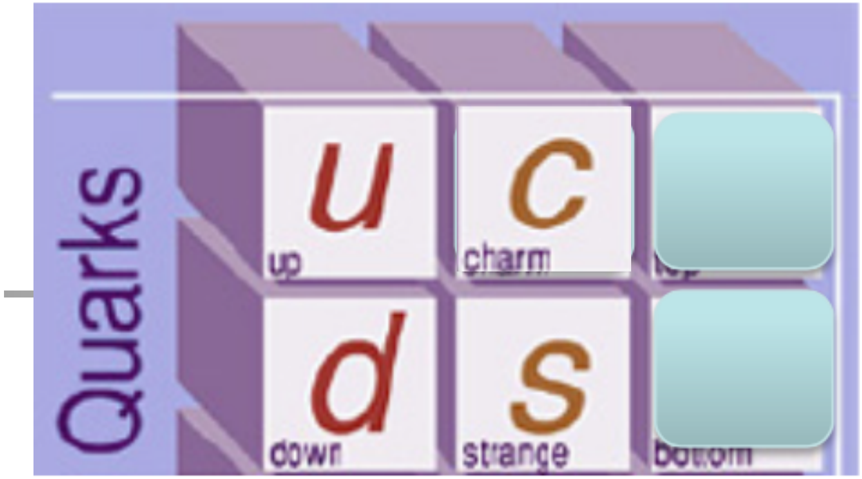
$$\left.\begin{aligned} &= u\bar{u} + (d\bar{d}\cos^2\theta_c + s\bar{s}\sin^2\theta_c) \\ &\quad + c\bar{c} + (s\bar{s}\cos^2\theta_c + d\bar{d}\sin^2\theta_c) \end{aligned}\right\} \quad \boxed{\Delta S = 0}$$

$$+ (s\bar{d} + d\bar{s} - s\bar{d} - d\bar{s})\cos\theta_c\sin\theta_c \qquad \boxed{\Delta S = 1}$$

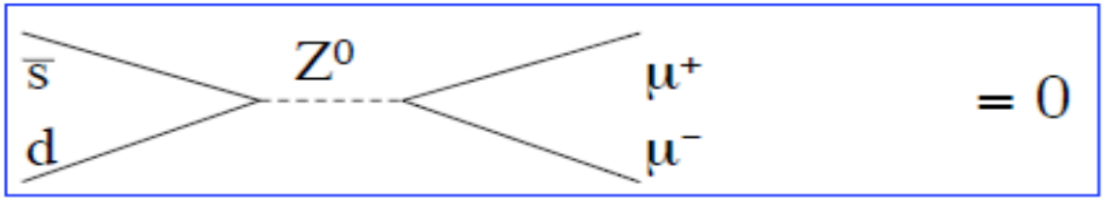
$$= u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c}$$

Long time ago, we had only 3 flavors of quarks: u,d,s.

Experimentally we found that

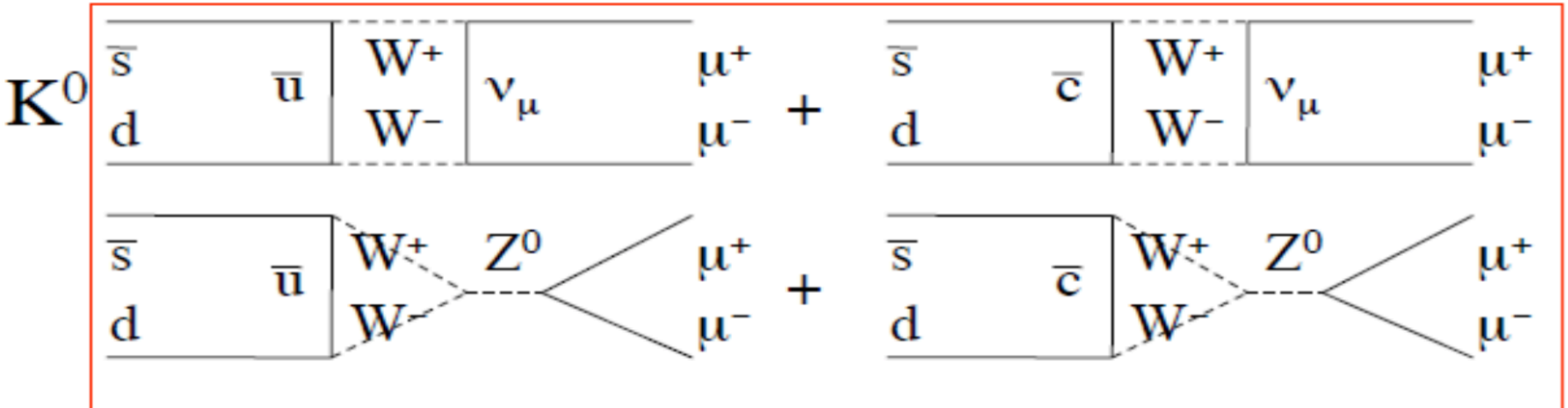


$$K^0 \not\to \mu^+\mu^-$$



$= 0$

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



$= 0$ if $m_u = m_c$

# For a complete two generation of quarks, the weak Lagrangian is then

$$J^{+} = W_{\mu}\begin{pmatrix} \bar{u} & \bar{c} \end{pmatrix}\gamma^{\mu}(1-\gamma^{5})\begin{pmatrix} \cos\theta_{c} & \sin\theta_{c} \\ -\sin\theta_{c} & \cos\theta_{c} \end{pmatrix}\begin{pmatrix} d \\ s \end{pmatrix}$$

$$= W_{\mu}\begin{pmatrix} \bar{u} & \bar{c} \end{pmatrix}\gamma^{\mu}(1-\gamma^{5})\begin{pmatrix} d' \\ s' \end{pmatrix}$$

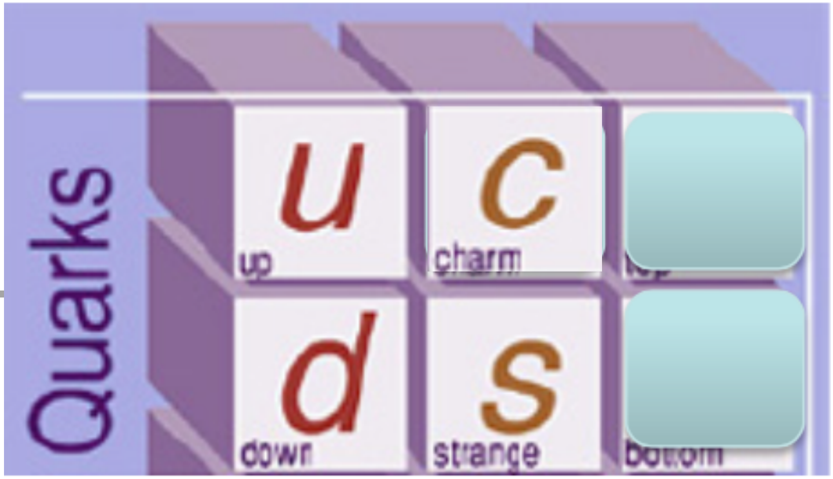
Charged current

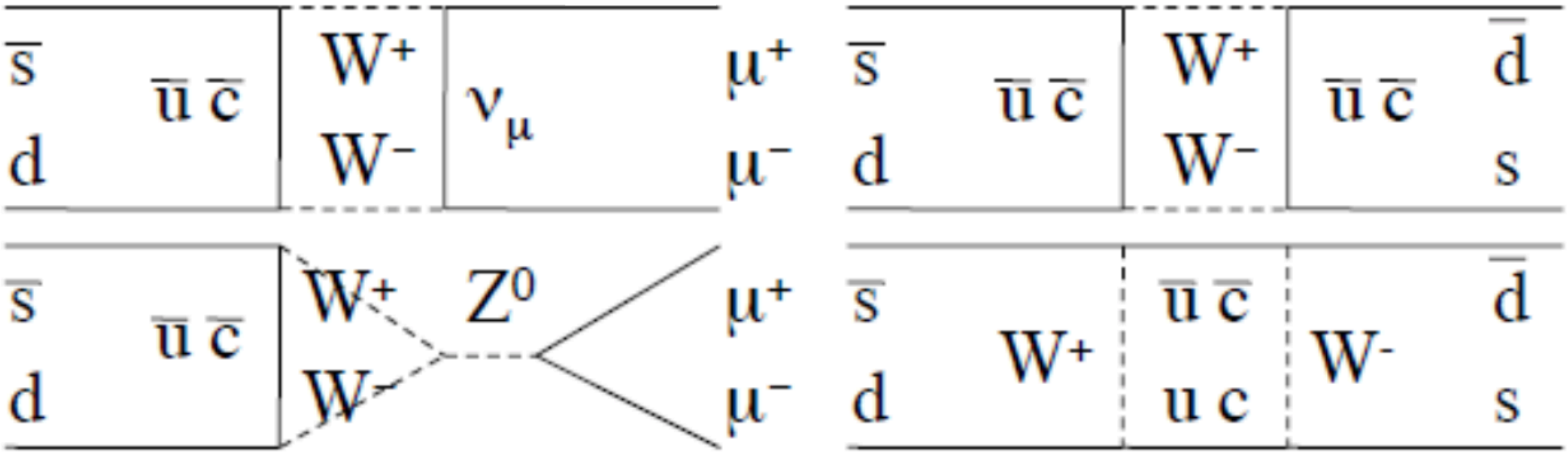
Simlarly,

$$J^{-} = W_{\mu}\begin{pmatrix} \bar{d} & \bar{s} \end{pmatrix}\begin{pmatrix} \cos\theta_{c} & -\sin\theta_{c} \\ \sin\theta_{c} & \cos\theta_{c} \end{pmatrix}\gamma^{\mu}(1-\gamma^{5})\begin{pmatrix} u \\ c \end{pmatrix}$$

Later, more precise experiments found that

$$Br(K^0 \to \mu^+\mu^-) \sim 10^{-9}$$





$Br(K^0 \to \mu^+\mu^-) = F(m_c, \ldots)$ $\Delta m_K = G(m_c, \ldots)$

$$\to m_c \approx 1.5\text{GeV}$$

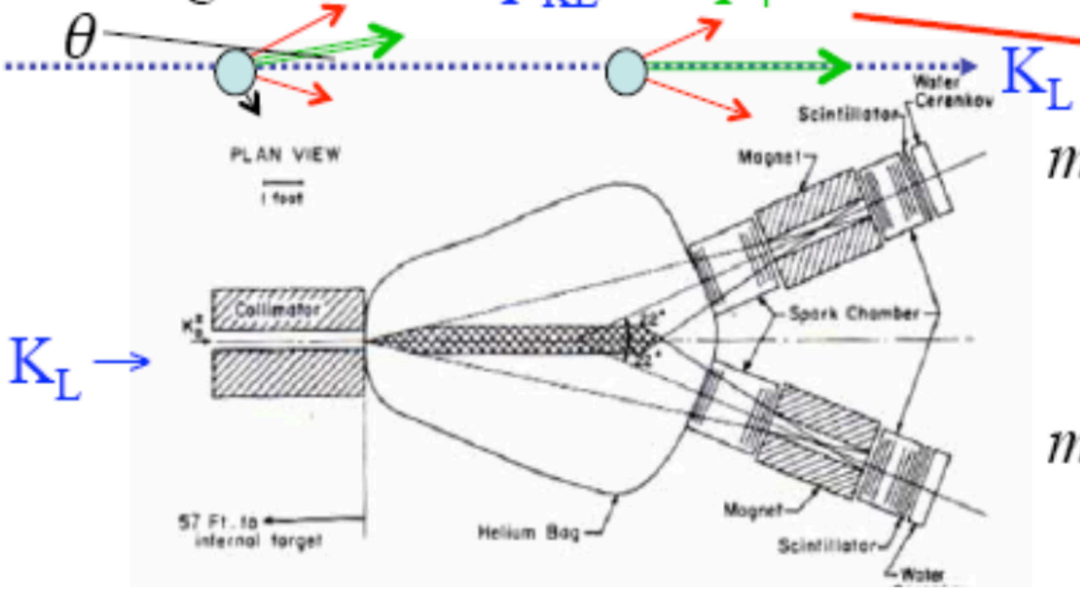
# In 1964, CP violation is found in K decays, this is long before the fourth quark/charm is discovered

CPV

1964, J.H. Christenson et al., $\mathrm{Br}(K^0_L \to \pi^+\pi^-) \neq 0$

$p_{+-} = p_{\pi+} + p_{\pi-}$

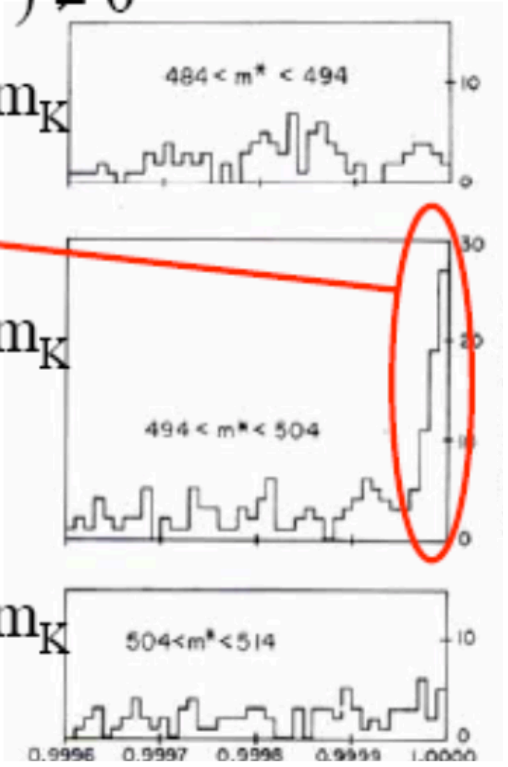
$\theta$ = angle between $p_{KL}$ and $p_{+-}$



$m(\pi^+\pi^-) < m_K$

$m(\pi^+\pi^-) = m_K$

$m(\pi^+\pi^-) > m_K$



Fitch Turlay Cronin Christenson

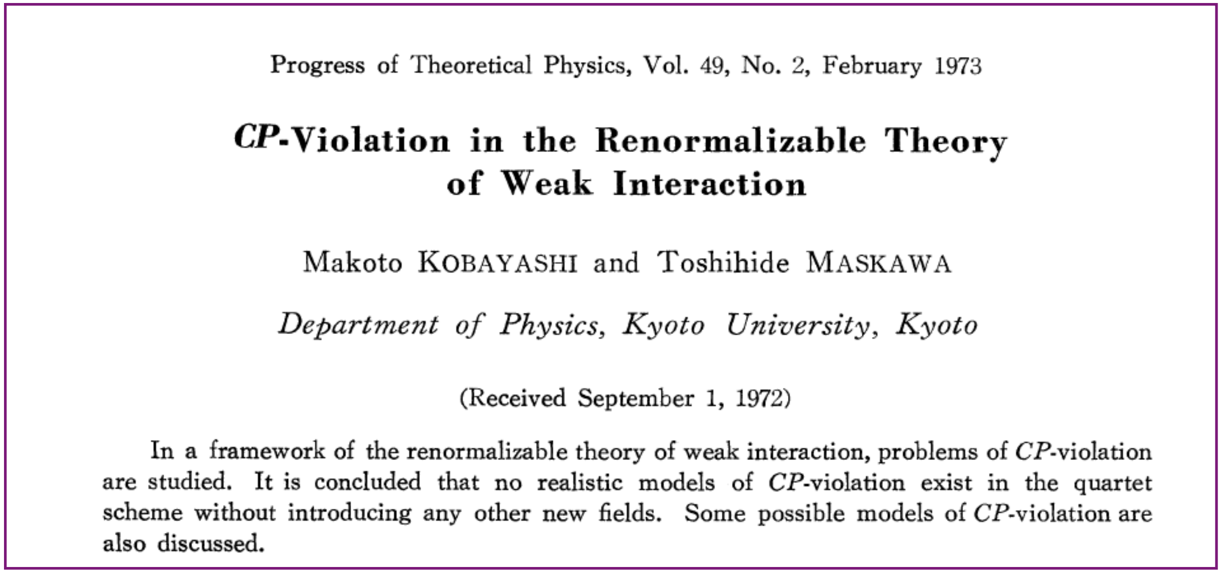
Nobel prize ('80) for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons

A lot of models have been proposed to explain the CP violation phenomena

In 1973, Kobayashi (b, 1944) & Maskawa (b, 1940) give a new explanition

Both received Ph.D. from Nagoya ('72 & '67) and both joined Kyoto as an assistant ('72 & '70).

Started collaboration in May of 1972, completed the work in August and submitted it to Progress of Theoretical Physics. Published in Feb, 1973 [Prog. Theor. Phys. 49, 652-657 (1973)]



Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

**$CP$-Violation in the Renormalizable Theory of Weak Interaction**

Makoto KOBAYASHI and Toshihide MASKAWA

*Department of Physics, Kyoto University, Kyoto*

(Received September 1, 1972)

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

We accepted the Glashow-Weinberg-Salam theory of the weak interaction’s extension to the hadron…, because the fourth quark already existed for us in a sense. Sometimes it is said that our *CP* paper was written before the discovery of charm. In this sense, however, our paper came after the charm.

-- Kobayashi (1992)

# M. Kobayashi and K. Maskawa found that if we extend the 3 quark flavors to 6, we will need a 3x3 matrix, describing the mixing

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

$[c_i = \cos\theta_i$ and $s_i = \sin\theta_i]$

**2008Nobel prize**

$$\begin{pmatrix} c_1 & -s_1c_3 & -s_1s_3 \\ s_1c_2 & c_1c_2c_3 - s_2s_3e^{i\delta} & c_1c_2s_3 + s_2c_3e^{i\delta} \\ s_1s_2 & c_1s_2c_3 + c_2s_3e^{i\delta} & c_1s_2s_3 - c_2c_3e^{i\delta} \end{pmatrix}$$

Prog. Theor. Phys. 49, 652 (1973)

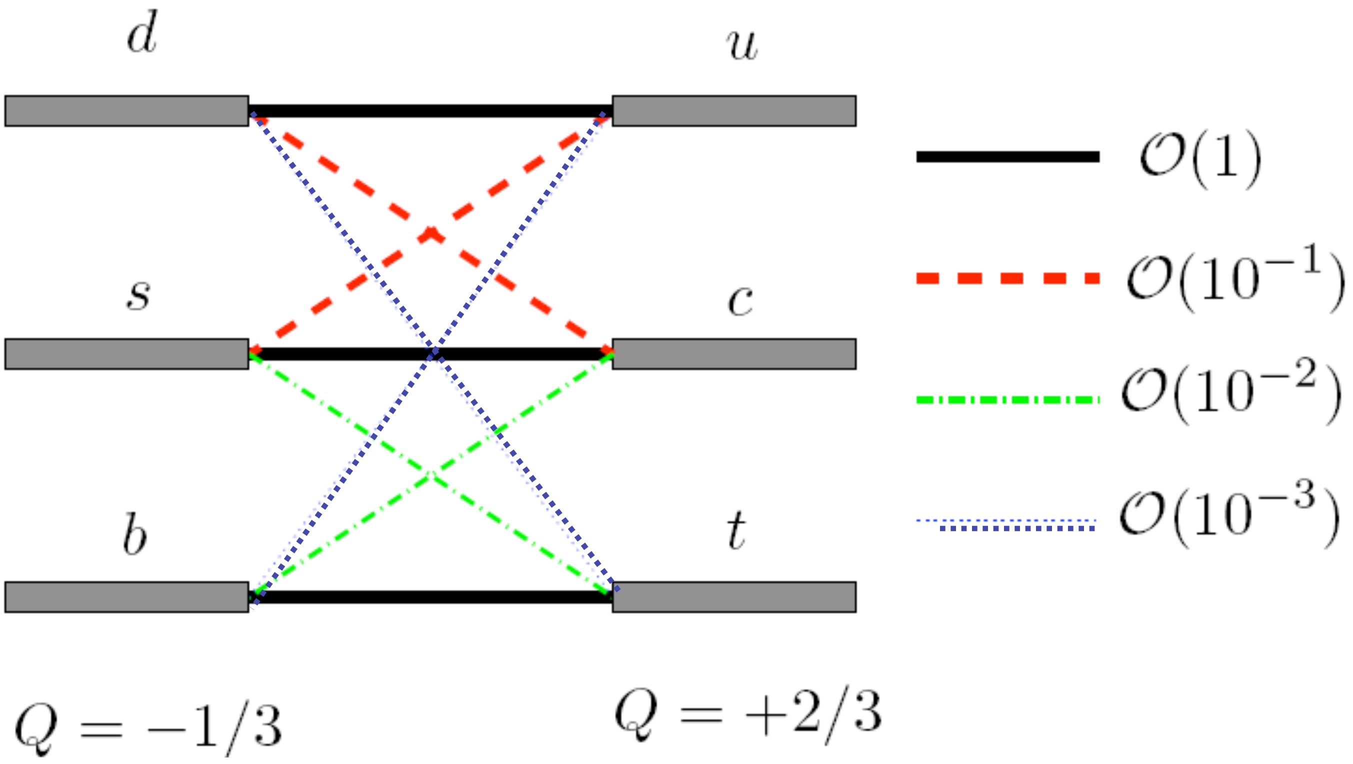
# The weak Lagrangian

- **left handed current** $W_\mu \bar{u}\gamma^\mu(1-\gamma^5)\enclose{circle}{d'}$
- **Mass term：** $m_u^2\bar{u}u + m_d^2\bar{d}d + \ldots$
- **Mass eigenstate** ≠ **weak eigenstate**
- **The mixing need a 3x3 matrix（CKM）**

$$W_\mu \bar{u}_i\gamma^\mu(1-\gamma^5)(V_{CKM})_{ij}d_j$$

# Wolfenstein parameterization1983

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\boxed{\rho-i\eta}) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho\boxed{-i\eta}) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$



# Standard parameterization in PDG

$$V=\begin{pmatrix}1 & 0 & 0\\ 0 & c_2 & s_2\\ 0 & -s_2 & c_2\end{pmatrix}\begin{pmatrix}c_1 & s_1 & 0\\ -s_1 & c_1 & 0\\ 0 & 0 & e^{i\delta}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & c_3 & s_3\\ 0 & -s_3 & c_3\end{pmatrix}$$

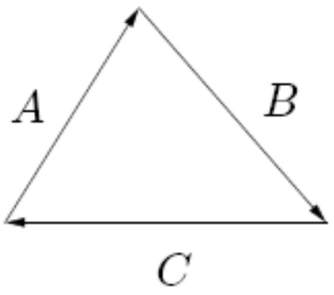
$$=\begin{pmatrix}c_1 & s_1c_3 & s_1s_3\\ -s_1c_2 & c_1c_2c_3-s_2s_3e^{i\delta} & c_1c_2s_3+s_2c_3e^{i\delta}\\ s_1s_2 & -c_1s_2c_3-c_2s_3e^{i\delta} & -c_1s_2s_3+c_2c_3e^{i\delta}\end{pmatrix}$$

- **Unitary condition**

$$V^+V=VV^+=1$$

# Unitarity Triangle(s) of the CKM Matrix

- Unitarity of the CKM matrix: $\boxed{\hat{V}^{\dagger}_{\mathsf{CKM}} \cdot \hat{V}_{\mathsf{CKM}} = \hat{1} = \hat{V}_{\mathsf{CKM}} \cdot \hat{V}^{\dagger}_{\mathsf{CKM}}}$ $\Rightarrow$
  - 6 normalization relations (columns and rows)
  - 6 orthogonality relations (columns and rows): $\boxed{A + B + C = 0}$
- The orthogonality relations can be represented as 6 triangles:



$\longrightarrow$ $\boxed{\text{unitarity triangles!}}$

- These triangles have all the same area $A_{\Delta}$:

$$\boxed{2A_{\Delta} \equiv |J_{\mathrm{CP}}| = \lambda^6 A^2 \eta = \mathcal{O}(10^{-5})}$$

- Columns:

$$\begin{aligned}
\underbrace{V_{ud}V_{us}^*}_{\mathcal{O}(\lambda)} + \underbrace{V_{cd}V_{cs}^*}_{\mathcal{O}(\lambda)} + \underbrace{V_{td}V_{ts}^*}_{\mathcal{O}(\lambda^5)} &= 0 \\
\underbrace{V_{us}V_{ub}^*}_{\mathcal{O}(\lambda^4)} + \underbrace{V_{cs}V_{cb}^*}_{\mathcal{O}(\lambda^2)} + \underbrace{V_{ts}V_{tb}^*}_{\mathcal{O}(\lambda^2)} &= 0 \\
\underbrace{V_{ud}V_{ub}^*}_{(\rho+i\eta)A\lambda^3} + \underbrace{V_{cd}V_{cb}^*}_{-A\lambda^3} + \underbrace{V_{td}V_{tb}^*}_{(1-\rho-i\eta)A\lambda^3} &= 0
\end{aligned}$$

- Rows:

$$\begin{aligned}
\underbrace{V_{ud}^*V_{cd}}_{\mathcal{O}(\lambda)} + \underbrace{V_{us}^*V_{cs}}_{\mathcal{O}(\lambda)} + \underbrace{V_{ub}^*V_{cb}}_{\mathcal{O}(\lambda^5)} &= 0 \\
\underbrace{V_{cd}^*V_{td}}_{\mathcal{O}(\lambda^4)} + \underbrace{V_{cs}^*V_{ts}}_{\mathcal{O}(\lambda^2)} + \underbrace{V_{cb}^*V_{tb}}_{\mathcal{O}(\lambda^2)} &= 0 \\
\underbrace{V_{ud}^*V_{td}}_{(1-\rho-i\eta)A\lambda^3} + \underbrace{V_{us}^*V_{ts}}_{-A\lambda^3} + \underbrace{V_{ub}^*V_{tb}}_{(\rho+i\eta)A\lambda^3} &= 0
\end{aligned}$$

- Only in two relations, all terms are of $\mathcal{O}(\lambda^3)$, and *agree* with one another

# CKM Unitary triangle

$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$$

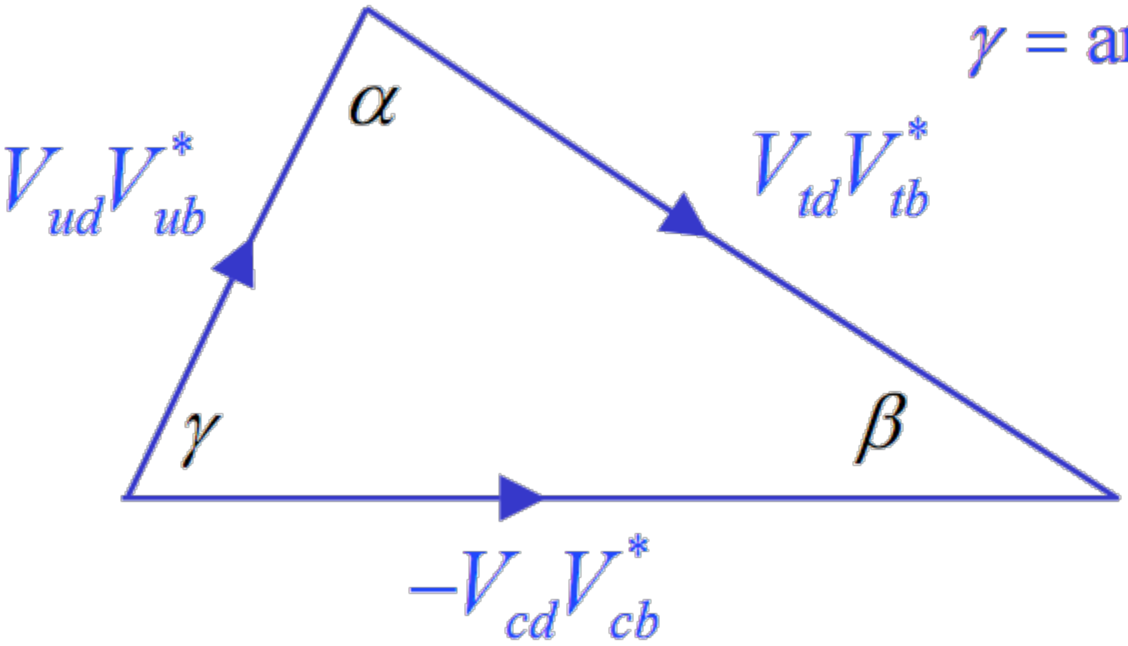
$$\boxed{V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0}$$

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

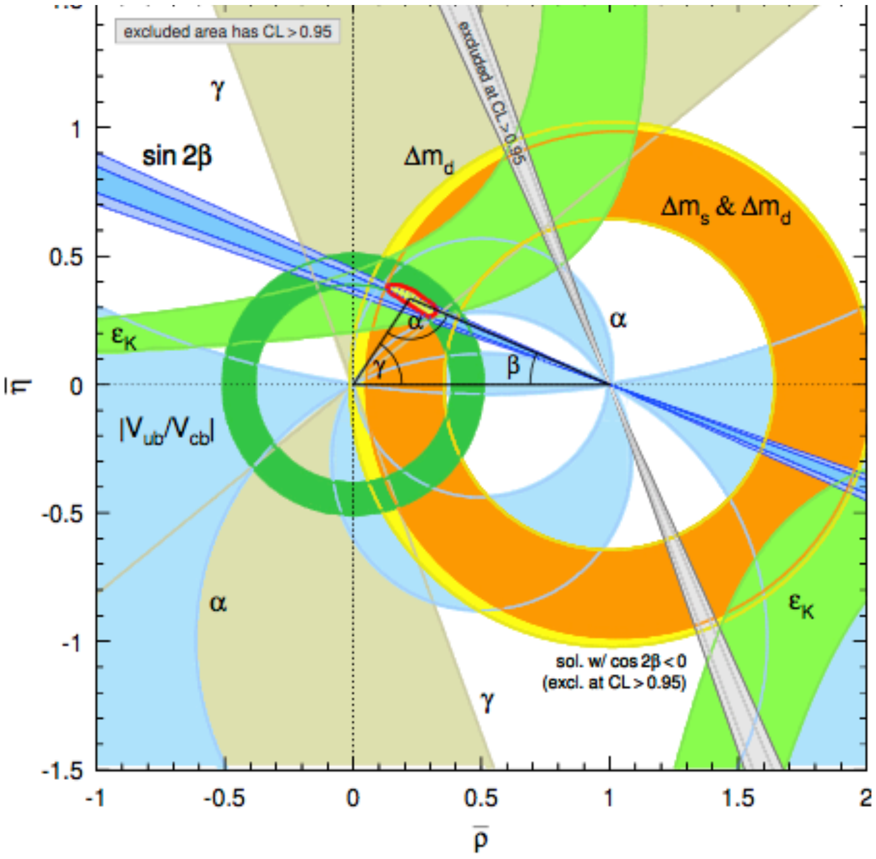
$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

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

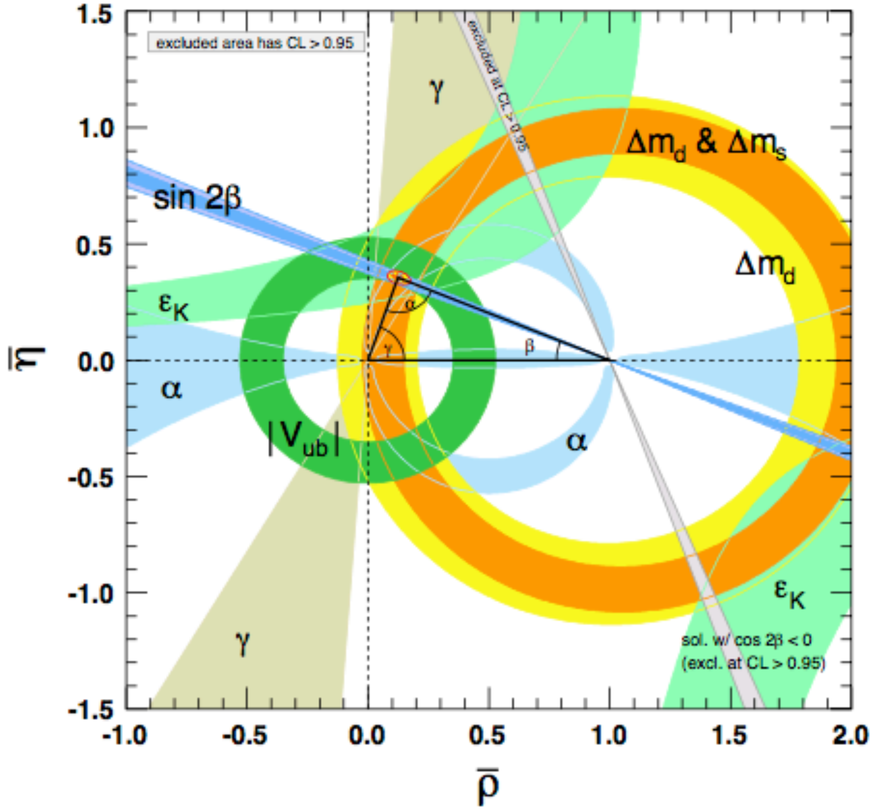
$$\gamma = \arg\left(\frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



# PDG2006 & 2016 Unitarity Triangle Comparison



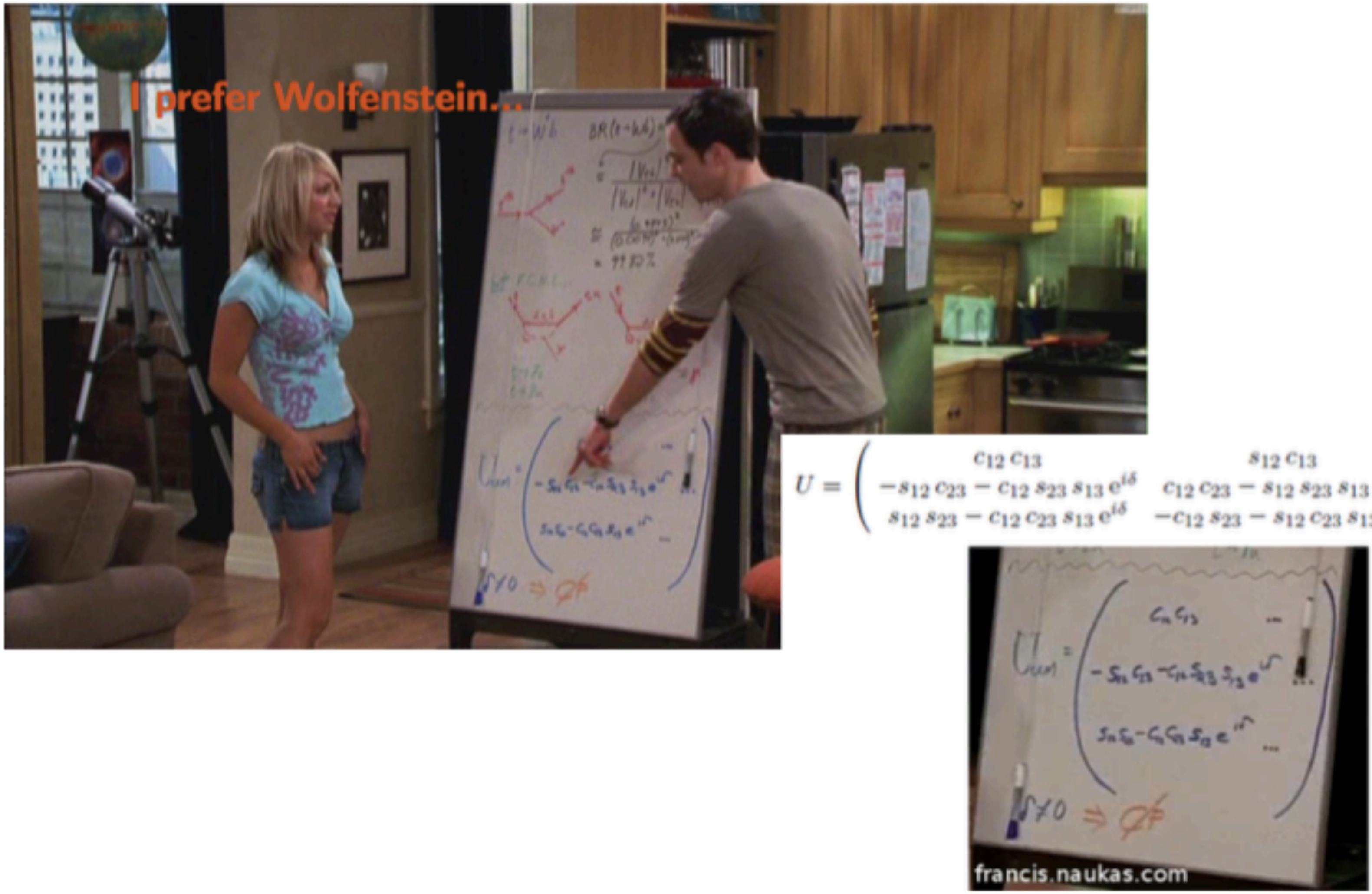
2006



2016

# The CKM (Cabibbo·Kobayashi·Maskawa) matrix

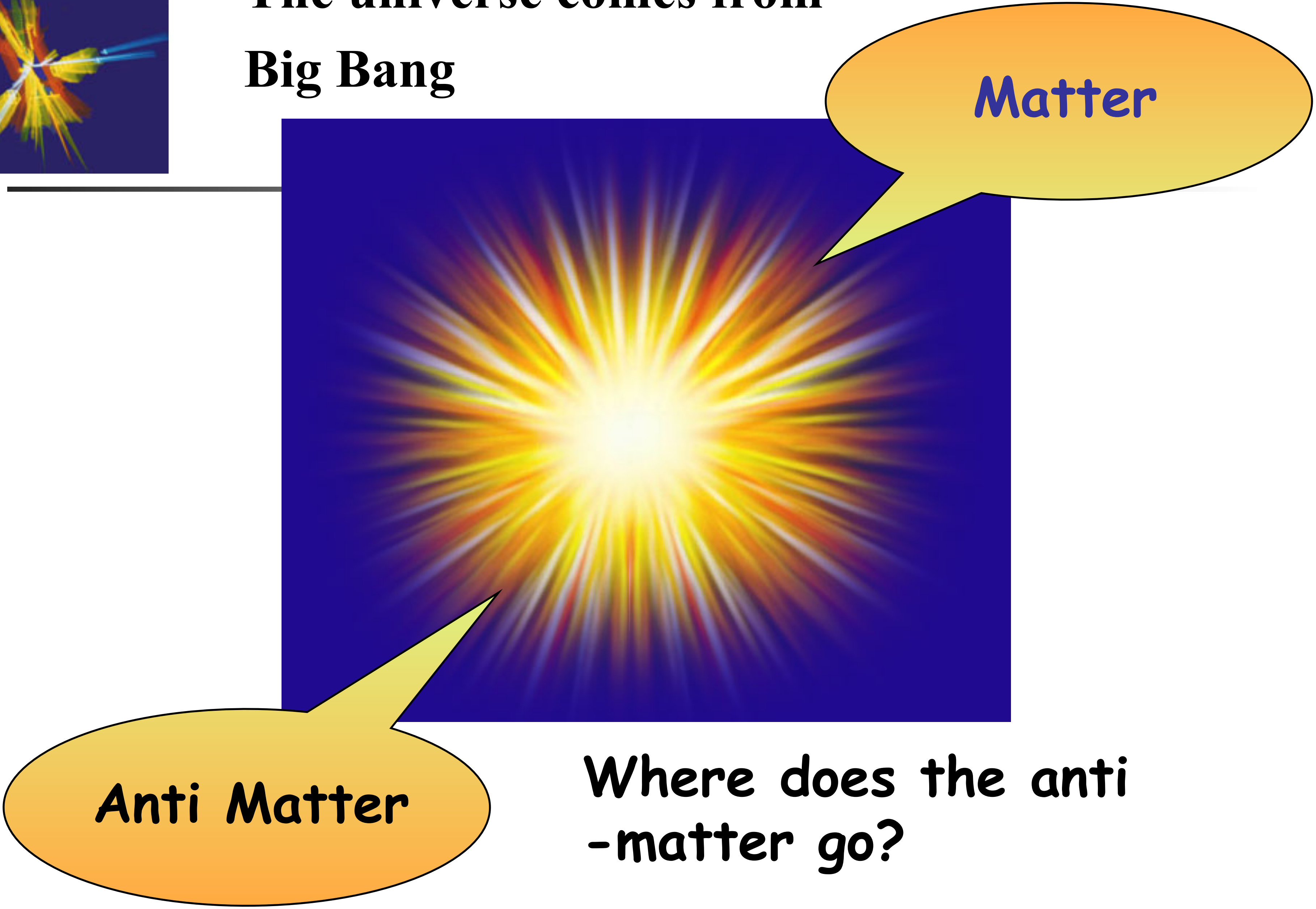
Another possible parametrisations (Chau and Keung parametrisation, adopted by PDG):



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

francis.naukas.com

# The universe comes from Big Bang



Where does the anti-matter go?

# Well motivated:

Baryon asymmetry of the Universe: $\left.\frac{n_{\mathcal{B}}}{n_{\gamma}}\right|_{\mathrm{WMAP}} = (5.1^{+0.3}_{-0.2}) \times 10^{-10}$ WMAP

SM expectation (KM CPV phase): $\left.\frac{n_{\mathcal{B}}}{n_{\gamma}}\right|_{SM} \approx 10^{-20}$

too small by
10 orders-of-mag.

Additional source of CPV is required:

lepton-sector ($\nu$'s)?
4th generation quarks)?
(SUSY has ~40 CPV phases)

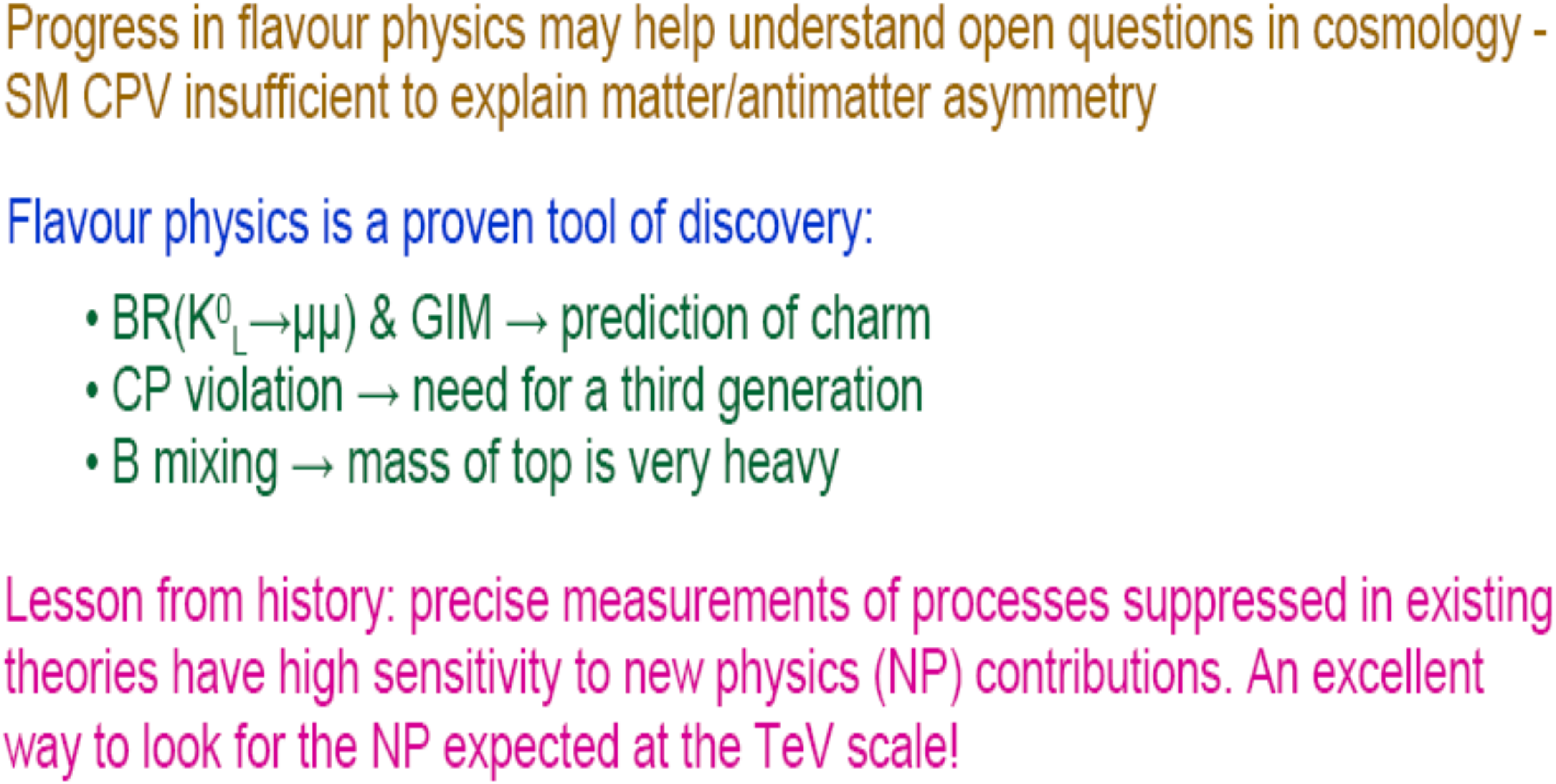
New Physics CPV searches are ~QCD-uncertainty-free!

# The importance of CP violation

- **IF we find aliens in the far universe**
- **Before we visit each us, it is essentials to make sure that they are not made of anti-matters— "Important"**
- **The definition of matter-anti-matter and left-right is arbitrarily**
- **They can be defined only through CP violation：**

$$\frac{\Gamma(K_L \to \pi^- \mu^+ \nu) - \Gamma(K_L \to \pi^+ \mu^- \overline{\nu})}{\Gamma(K_L \to \pi^- \mu^+ \nu) + \Gamma(K_L \to \pi^+ \mu^- \overline{\nu})} = (0.64 \pm 0.08)\%$$

# Flavor physics is important



Progress in flavour physics may help understand open questions in cosmology - SM CPV insufficient to explain matter/antimatter asymmetry

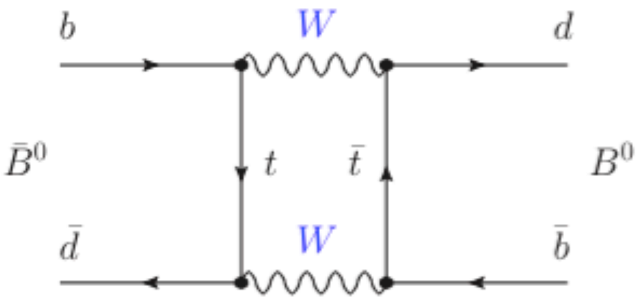
Flavour physics is a proven tool of discovery:

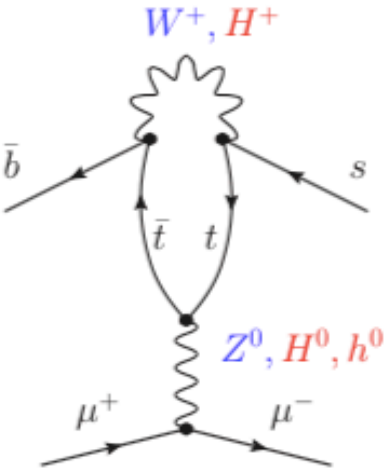
- BR($K^0_L \to \mu\mu$) & GIM → prediction of charm
- CP violation → need for a third generation
- B mixing → mass of top is very heavy

Lesson from history: precise measurements of processes suppressed in existing theories have high sensitivity to new physics (NP) contributions. An excellent way to look for the NP expected at the TeV scale!

# New physics probes

**Search for deviations from SM predictions from virtual contributions of new heavy particles in loop processes**

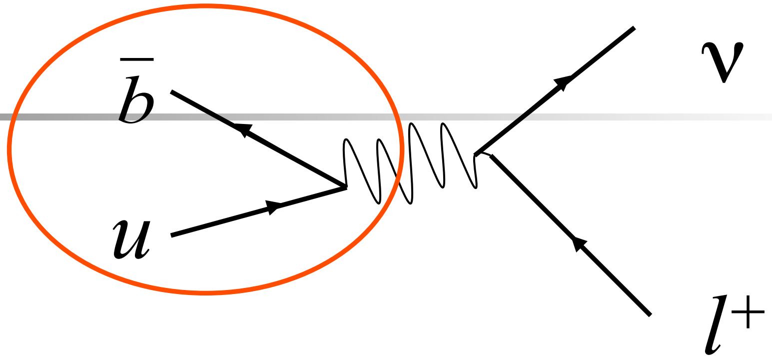




- Measure CP violating phases and study rare decays of heavy quarks
- Compare to very precise predictions of the SM
  - Uncertainties from QCD is main problem
- Most interesting processes those where SM contribution is suppressed (e.g FCNC)
  - Effects of New Physics (NP) are large
- Discovery potential for NP extends to mass scales >> centre-of-mass energy of collision

Prof. John Ellis @ SymmetryMagazine.org

# B meson decays, similarly b baryon decays



- Pure leptonic decays
- Semileptonic decays
- Non-leptonic decays

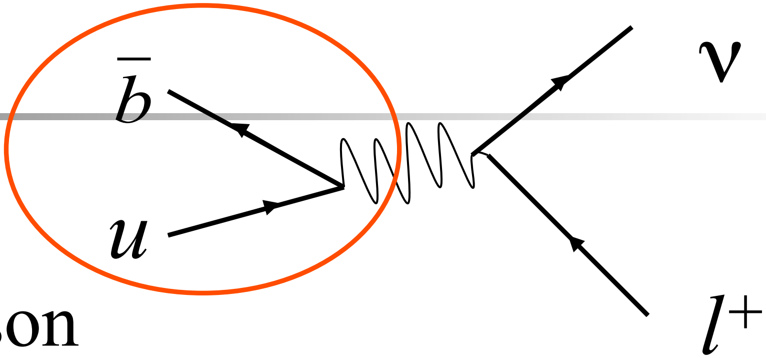
Pure leptonic is the simplest:

The hadronic part of the calculation is just the definition of the meson decay constant, for example, a pseudo-scalar meson:

$$\langle P(p)|\bar{q}\gamma^{\mu}Lq'|0\rangle = if_{P}p^{\mu}.$$

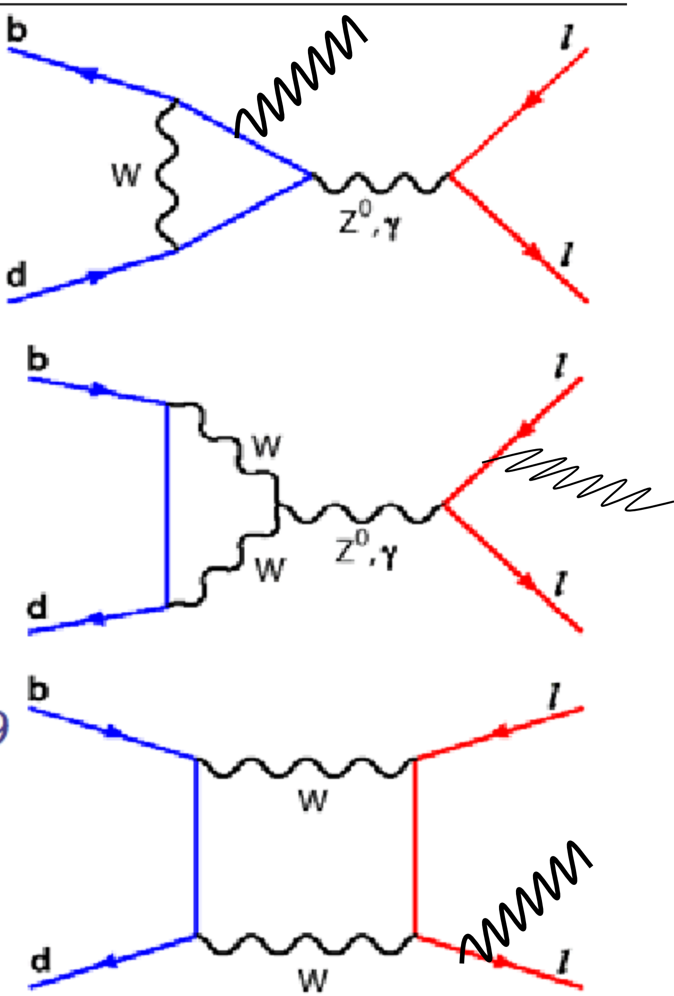
# Pure leptonic decays

$$\langle P(p)|\bar{q}\gamma^{\mu}Lq'|0\rangle = if_P p^{\mu}.$$



- The decay constant is the normalization of the meson wave function i.e. the zero point of wave function
- The experimental measurement of pure leptonic decay can provide the product of decay constant and CKM matrix element.
- Theoretically decay constant can be calculated by QCD sum rule or Lattice QCD

# Rare decays, which are sensitive to new physics signals



- $B_{s,d} \to \nu\bar{\nu}$ is helicity forbidden decay mode，（only by Z boson）
- $B_{s,d} \to l^+ l^-$ is helicity suppressed，similar to $B^+ \to l^+ \nu$, $\Gamma \propto m_l^2$
- But further suppressed by loop
- Theory:

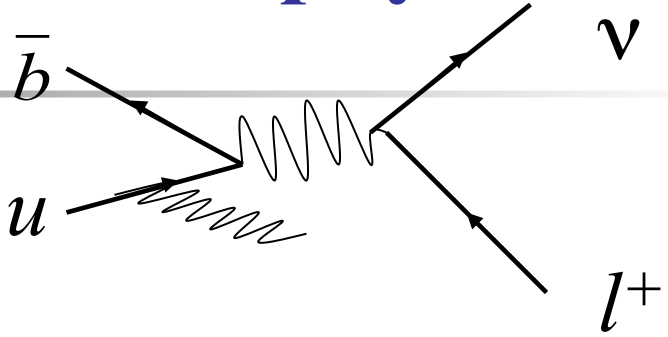
$$\mathcal{B}\left(\bar{B}_s \to \mu^+\mu^-\right) = (3.65 \pm 0.06) \times 10^{-9}$$

Exp.

$$\mathcal{B}\left[B_s^0 \to \mu^+\mu^-\right] = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

**LHCb, CMS, ATLAS**

# Radiative leptonic decays, which are also sensitive to new physics



- $B^+ \to l\bar{\nu}\gamma$ is not helicity suppressed， but $\alpha_{QED}$ suppressed with Brs: $10^{-6}$
- Similarly, we have $B_c \to l\bar{\nu}\gamma$, also not helicity suppressed（$10^{-5}$).
- With one more photon in the final states, easier for exp.
- But more difficult for theoretical study with long distance contribution

- **$B_{s,d} \to \nu \nu \gamma$ can also decay， but $\alpha_{QED}$ suppressed**

  **Theory： Br($B^0 \to \nu \nu \gamma$)~$10^{-9}$,**

  **Exp.:** 〈 1. 7 **x $10^{-5}$**

  **Theory Br($B_s \to \nu \bar{\nu} \gamma$)~$10^{-8}$**

- **Similarly $B_{s,d} \to l^+ l^- \gamma$ （$l$=e,μ） also not helicity suppressed**

- **Theory: Br($B_s \to l^+ l^- \gamma$)~$10^{-9}$**

  **Br($B_d^0 \to l^+ l^- \gamma$)~$10^{-10}$ Exp. $< 10^{--7}$**

# Pure leptonic decays with lepton number violation

- **Can only occur in new physics beyond SM**
- **We have only experimental upper limits:**
- $\mathrm{Br}(B^0 \to e^+ \mu^-) < 2.8 \times 10^{-9}$
- $\mathrm{Br}(B^0 \to e^+ \tau^-) < 2.8 \times 10^{-5}$
- $\mathrm{Br}(B^0 \to \mu^+ \tau^-) < 2.2 \times 10^{-5}$
- $\mathrm{Br}(B_s^0 \to e^+ \mu^-) < 1.1 \times 10^{-8}$

# We have two hadrons in semi-leptonic decays. It is described by form factors

Scalar

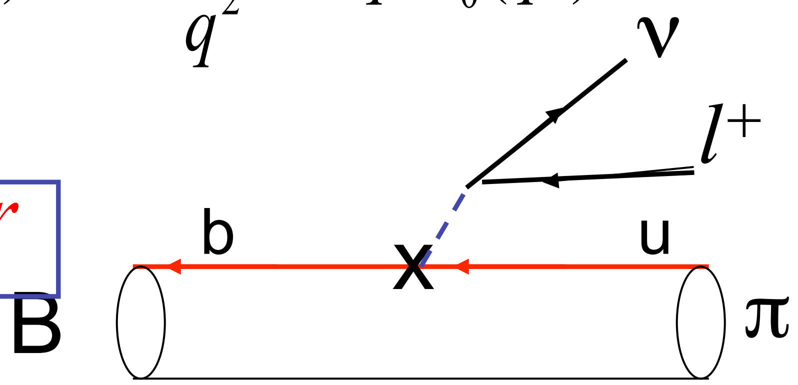
$$\langle \pi | \bar{u} \gamma^{\mu} b | B \rangle = p_B{}^{\mu} f_1 + p_{\pi}{}^{\mu} f_2$$

$$= \left[ (p_B + p_{\pi})^{\mu} - \frac{m_B{}^2 - m_{\pi}{}^2}{q^2} q^{\mu} \right] F_1(q^2) + \frac{m_B{}^2 - m_{\pi}{}^2}{q^2} q^{\mu} F_0(q^2)$$

$$q = p_B - p_{\pi}$$

Vector

$$F_1(0) = F_0(0)$$



**If form factors known, the experimental measurement can give the size of CKM matrix element Vub**

# Form factors(B→Vector transition)

- **Vector Current**

$$\langle \rho | \bar{u}\gamma_{\mu} b | B \rangle = \varepsilon_{\mu\nu\alpha\beta}\varepsilon^{\nu} p_B{}^{\alpha} p_{\rho}{}^{\beta} \frac{2V(q^2)}{m_B + m_{\rho}}$$

- **Form factors can be calculated by lattice QCD, QCD sum rules, light cone sum rules etc.**
- **In the quark model, it is calculated by the overlap of two meson wave functions.**

# Form factors(B→Vector transition)

- **Axial Vector Current**

$$\langle \rho | \bar{u}\gamma^{\mu}\gamma^{5} b | B\rangle = i\left[\varepsilon^{\mu} - \frac{\varepsilon\cdot q}{q^{2}} q^{\mu}\right](m_B + m_\rho)A_1(q^2)$$

$$- i\left[(p_B + p_\rho)^{\mu} - \frac{m_B{}^{2} - m_\rho{}^{2}}{q^{2}} q^{\mu}\right](\varepsilon\cdot q)\frac{A_2(q^2)}{m_B + m_\rho}$$

Vector

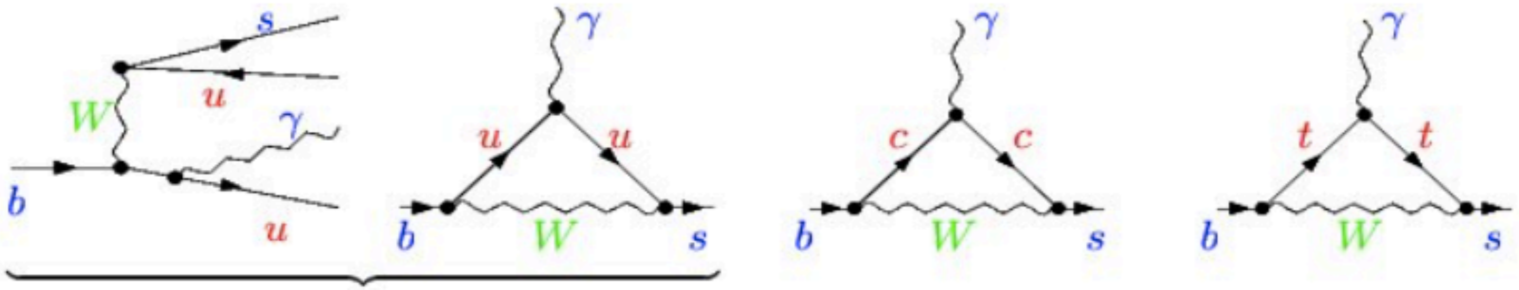
$$+ i\frac{2m_\rho(\varepsilon\cdot q)}{q^{2}} q^{\mu} A_0(q^2)$$

Scalar

Tensor

$$2m_\rho A_0(0) = (m_B + m_\rho)A_1(0) - (m_B - m_\rho)A_2(0)$$

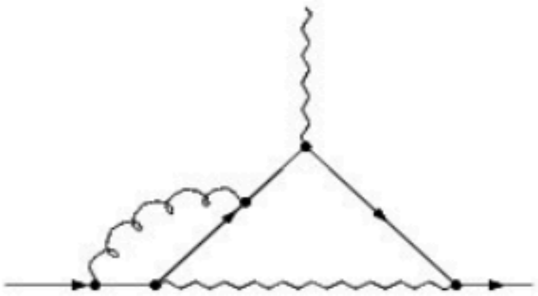
# Examples of leading electroweak diagrams for $B \to X_s\,\gamma$



$$\left|\frac{V_{ub}V_{us}}{V_{cb}}\right| \simeq \left|\frac{V_{ub}V_{us}}{V_{ts}}\right| \simeq 2\%$$

$$\underbrace{\sim +200\% \qquad\qquad \sim -100\%}$$

**In the amplitude, after including LO QCD effects.**

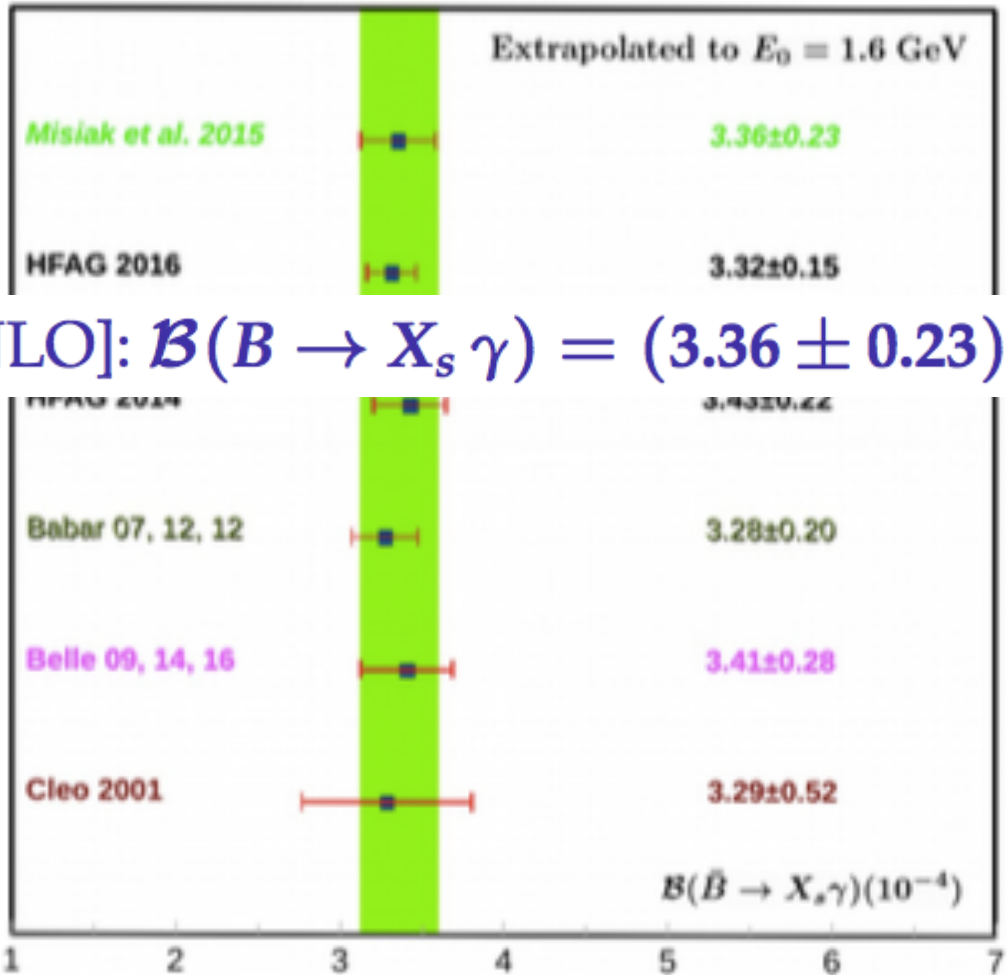


- QCD logarithms $\alpha_s \ln \frac{M_W^2}{m_b^2}$ enhance BR($B \to X_s\gamma$) more than twice

# **Branching fraction**; HFAG [arXiv:1612.07233]

uncertainty 4.5%

$$\mathcal{B}(\bar{B} \to X_s\gamma)^{Exp}_{E_\gamma > 1.6\mathrm{GeV}} = (3.32 \pm 0.15) \cdot 10^{-4}$$

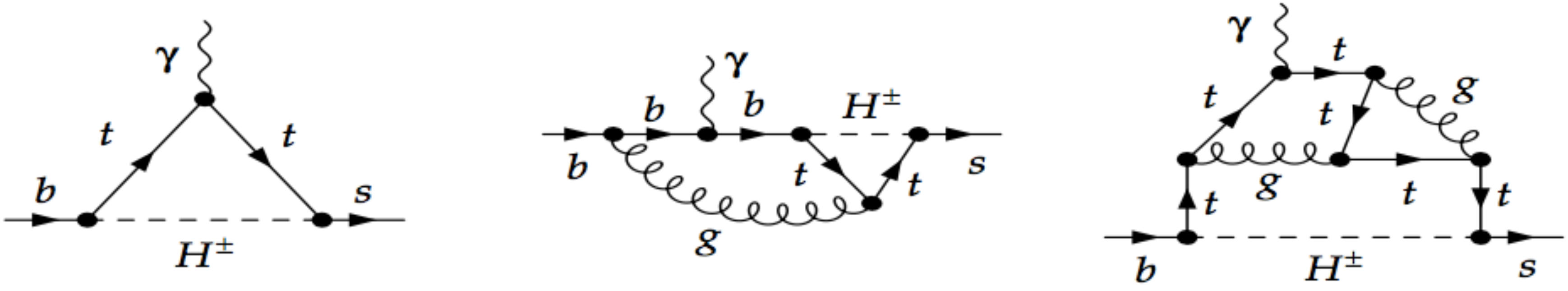


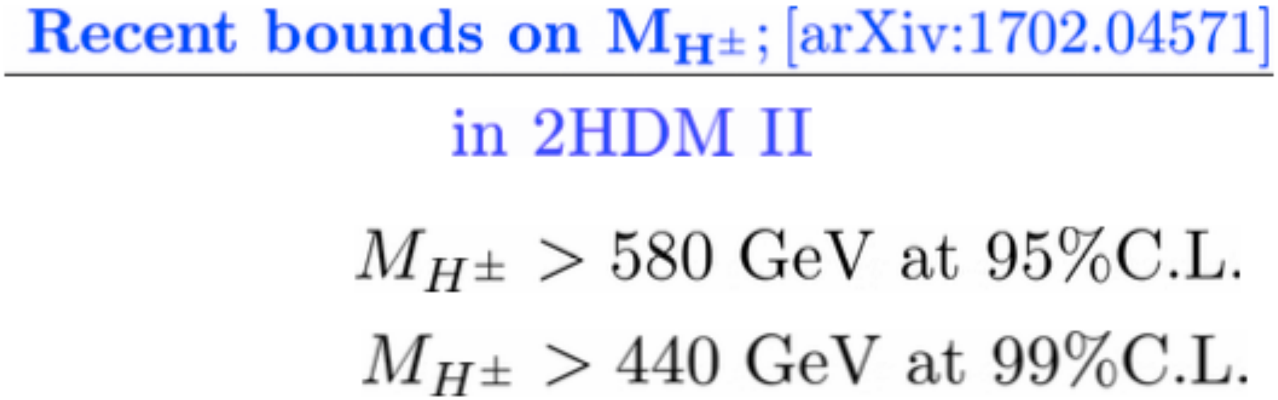
SM [NNLO]: $\mathcal{B}(B \to X_s\gamma) = (3.36 \pm 0.23) \times 10^{-4}$

**Belle-II** Better accuracy is expected, ~ 3%.

# Many new physics models contribute to b→s γ decay

**For example, the charged Higgs contribute to b→s γ decay**




Recent bounds on $M_{H^{\pm}}$; [arXiv:1702.04571]

in 2HDM II

$$M_{H^{\pm}} > 580 \text{ GeV at } 95\% \text{C.L.}$$

$$M_{H^{\pm}} > 440 \text{ GeV at } 99\% \text{C.L.}$$

*Thanks !*