LHCb Experiment

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Outline

- Part I
- Basics on Flavor Physics & CP violation

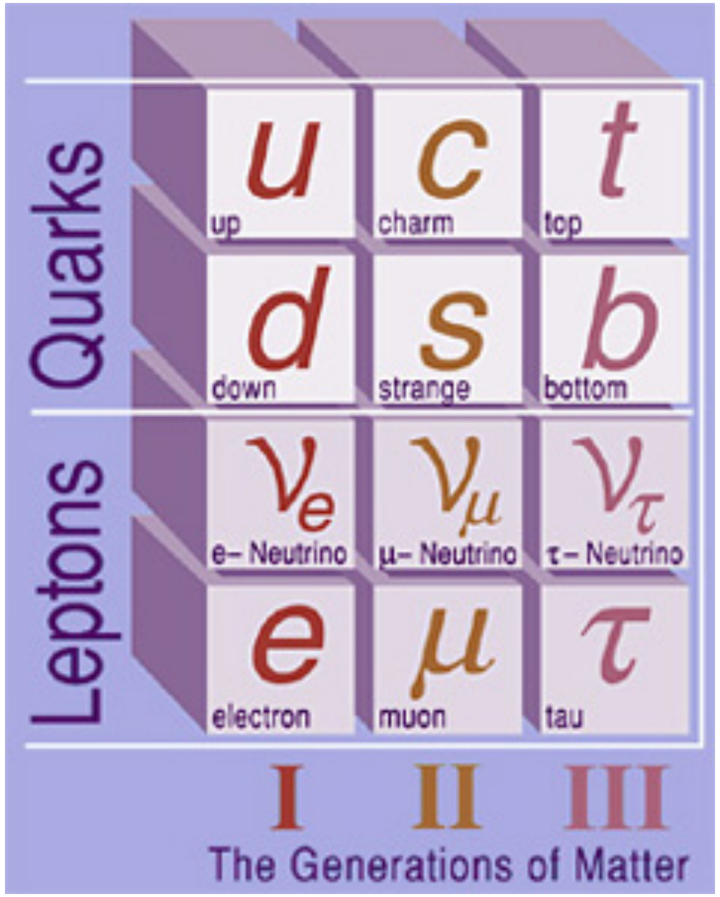
- Part II
- The LHCb Experiment
- Selected topics on physics at LHCb

Basics on
Flavor Physics & CP Violation

Part I

Flavor (particle physics)

- In particle physics, flavour or flavor refers to a species of an elementary particle. The Standard Model counts six flavours of quarks and six flavours of leptons. They are conventionally parameterized with flavour quantum numbers that are assigned to all subatomic particles, including composite ones. For hadrons, these quantum numbers depend on the numbers of constituent quarks of each particular flavour.



What is an electron (in quantum physics)?

- There is a quantum state $|\psi\rangle$
- Measurements (operations on the state)

$$\begin{aligned} \hat{H}\,|\psi\rangle &= E\,|\psi\rangle \\ \hat{\vec{P}}\,|\psi\rangle &= \vec{p}\,|\psi\rangle \\ \hat{Q}\,|\psi\rangle &= -e\,|\psi\rangle \end{aligned}$$

$$E^2 - \vec{p}^2 = m_e^2$$

$$\begin{aligned} \hat{J}^2 \left| \begin{matrix} \psi_+ \\ \psi_- \end{matrix} \right\rangle &= \frac{1}{2}(\frac{1}{2}+1) \left| \begin{matrix} \psi_+ \\ \psi_- \end{matrix} \right\rangle \\ \hat{J}_z \left| \begin{matrix} \psi_+ \\ 0 \end{matrix} \right\rangle &= +\frac{1}{2} \left| \begin{matrix} \psi_+ \\ 0 \end{matrix} \right\rangle \\ \hat{J}_z \left| \begin{matrix} 0 \\ \psi_- \end{matrix} \right\rangle &= -\frac{1}{2} \left| \begin{matrix} 0 \\ \psi_- \end{matrix} \right\rangle \end{aligned}$$

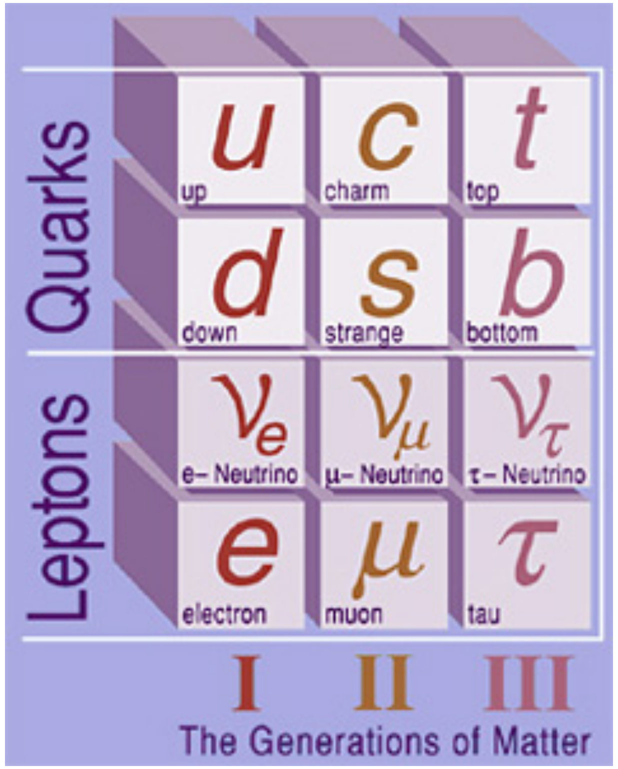
- The meanings of

$$\pi^0 : \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$$

Flavor is a quantum number ···

- $\hat{H}\,|\psi_f\rangle = E_f\,|\psi_f\rangle$

$f =$



= 味

Flavor & Color

Fermions ("matter")	Bosons ("forces")
$\left\{ \begin{array}{c} \text{Quarks} \\ uuu \quad ccc \quad ttt \\ ddd \quad sss \quad bbb \\ \\ \text{Leptons} \\ e \quad \mu \quad \tau \\ \nu_e \quad \nu_\mu \quad \nu_\tau \end{array} \right\} \times \left\{ \begin{array}{c} \text{MATTER} \\ \text{ANTIMATTER} \end{array} \right\}$	$gggggggg$ γ W^+ W^- Z H

The term *flavor* was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena. Just as ice cream has both color and flavor so do quarks (Fritzsch, 2008).

$$\hat{H} |\psi_{f_c}\rangle = E_{f_c} |\psi_{f_c}\rangle$$
$$c = R, G, B$$

3 degenerate states

The quark sector of The Standard Model

- Quark states

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L ,\ldots\ldots u_R, d_R, c_R, s_R, t_R, b_R$$

- The lagrangian

$$L_{cc} = -\frac{g}{\sqrt{2}} J^{\mu}_{cc} W^{*}_{\mu} + h.c.$$

- The current

$$J^{\mu}_{cc} = \left(\bar{u}, \bar{c}, \bar{t}\right)_L \gamma^{\mu} V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$

CKM Matrix

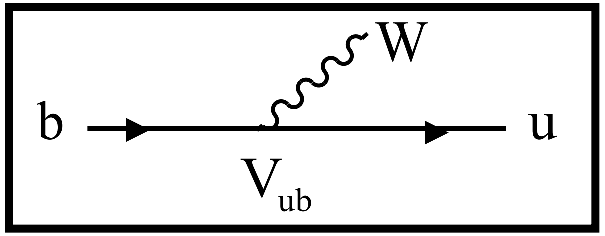
- V_{CKM} describes rotation between the weak eigenstates (d',s',b') and mass eigenstates (d,s,b)

weak states | CKM matrix | mass states

V_{ij} proportional to transition amplitude from quark j to quark i

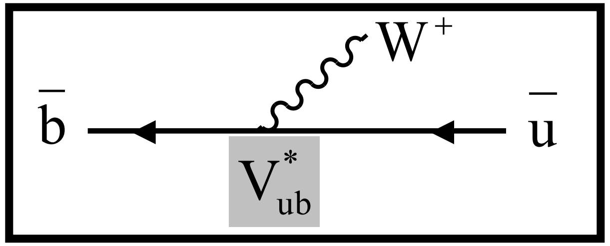
Quarks

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



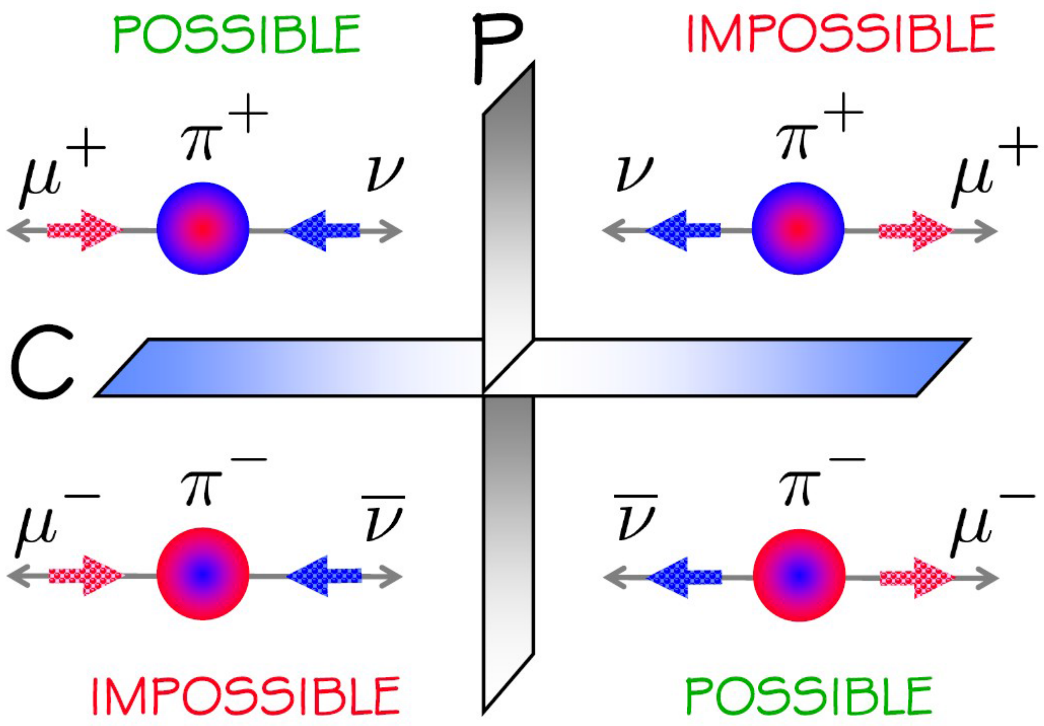
Antiquarks

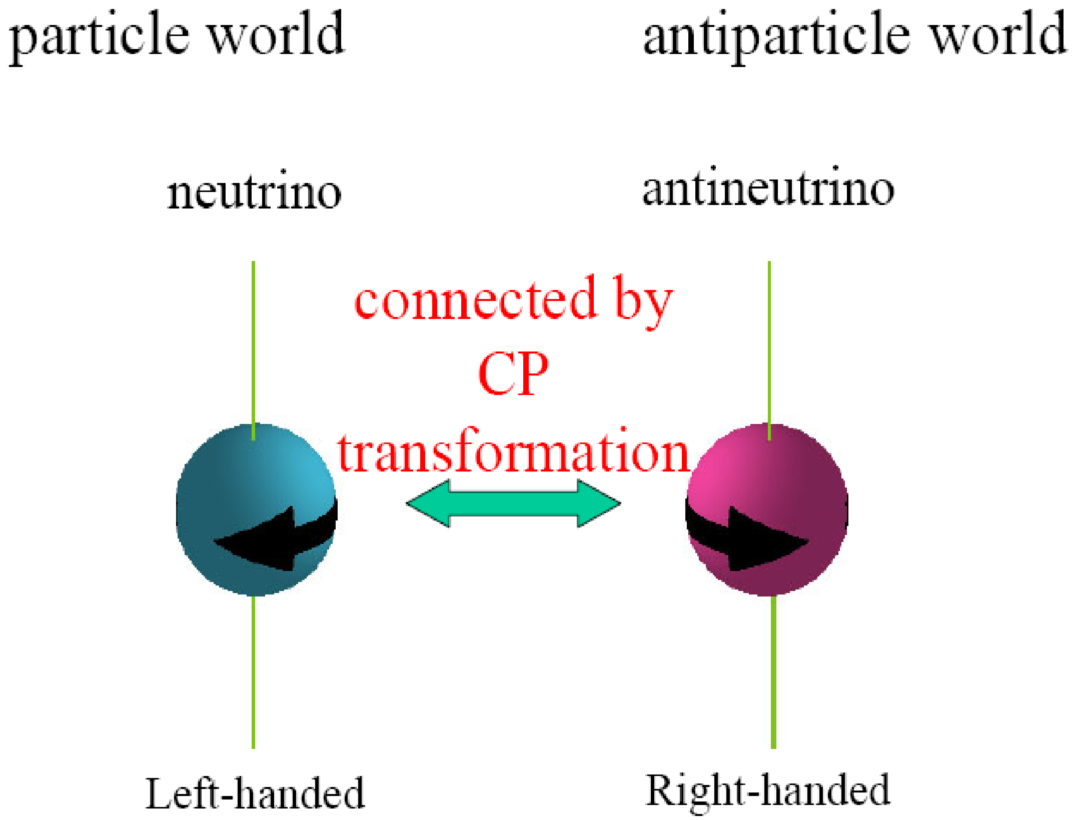
$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = \begin{pmatrix} V^*_{ud} & V^*_{us} & V^*_{ub} \\ V^*_{cd} & V^*_{cs} & V^*_{cb} \\ V^*_{td} & V^*_{ts} & V^*_{tb} \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$



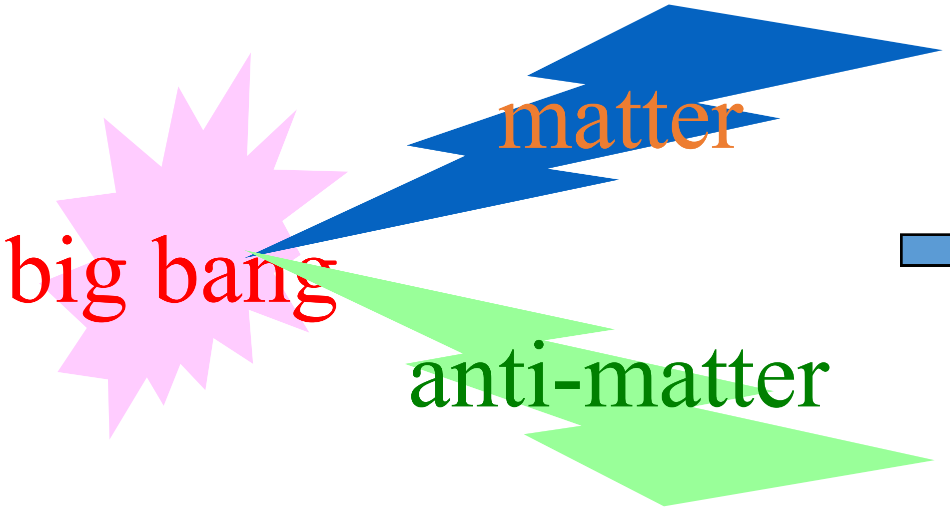
CP transformation

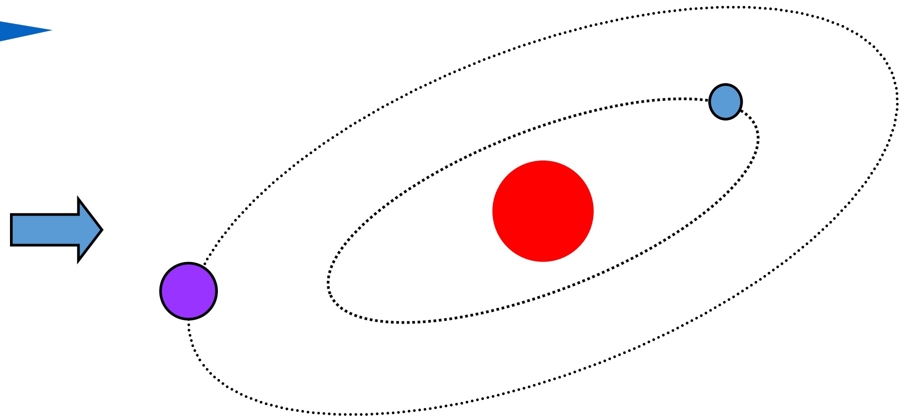
- CP: connect matter and anti-matter





Matter-Antimatter Asymmetry in universe





amount of matter
= amount of anti-matter

our universe
only with matter

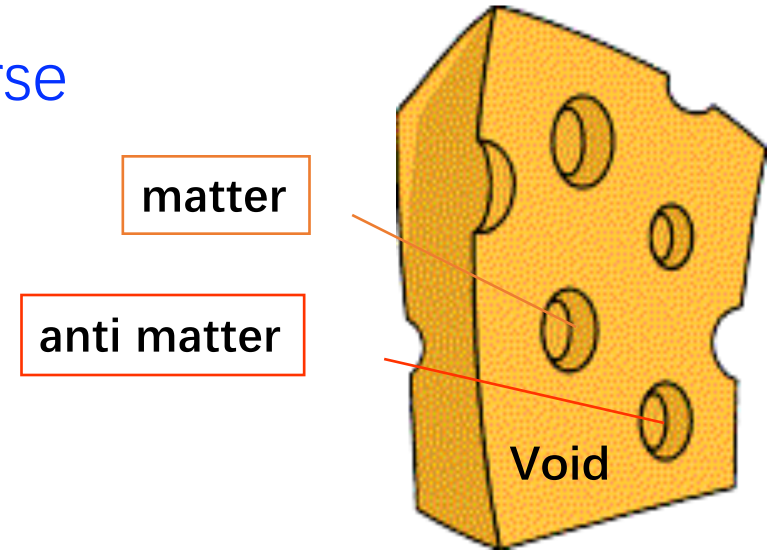
What do we know?

- Evidences

- no anti-nucleus in the cosmic ray
- no γ rays from $p\bar{p}$ annihilation in space

- Conclusions

- no evidence of anti-matter in our domain of universe
  (~ 20 Mps ≈ 10^8 light-years)
- "Inverse Emmental Cheese" ? Unlikely
- most likely, no anti-matter in our universe
  (~ 3000 Mps ≈ 10^{10} light-years)



Two key numbers:

stars, gas etc.

$$\frac{\text{Number of baryons } (N_B)}{\text{Number of photons } (N_\gamma)} = 10^{-9} \sim 10^{-10}$$

cosmic microwave background radiation

Number of baryons now ≈0 but ≠0

$$\Longrightarrow \quad \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} = 10^{-9} \sim 10^{-10}$$

1 baryon out of 10^{10} did not annihilate and survived.

How can we generate

$$\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} = 10^{-9} \sim 10^{-10}$$

from $N_B - N_{\bar{B}} = 0$ (initial condition for Big Bang at t =0)?

Necessary conditions:

1) Baryon number violations:
   initial and final baryon numbers are different.

2) **C and CP violation**:
   partial decay widths are different.

3) Out of equilibrium:
   no reversing reaction installing the initial state.

(A.Sakharov, 1967)

CP violations in Hamiltonian

- **P**arity is violated, **C**harge conjugation is violated
- **CPT** *must be* respected, ~~CP~~ is like ~~T~~
- **T** transformation is like making complex conjugation:

$$e^{-iEt} \rightarrow \mathrm{T} \rightarrow e^{iEt}$$

T transformation to the Hamiltonian operator H

$$H \rightarrow \mathrm{T} \rightarrow H^*$$

if $H \neq H^*$, $\mathrm{e}^{-iHt} \;\rightarrow\; \mathrm{e}^{iH^*t} \neq \mathrm{e}^{iHt}$ ~~T~~ i.e. ~~CP~~

CP violations in SM

- **Need a complex phase for ~~C~~P in SM ！**
  - **CKM is the only place**

$$L_{cc} = -\frac{g}{\sqrt{2}} J^{\mu}_{cc} W^{*}_{\mu} + h.c.$$

$$J^{\mu}_{cc} = (\bar{u}, \bar{c}, \bar{t})_L \gamma^{\mu} V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$

$$V^{+}_{CKM} V_{CKM} = I$$

Standard parametrization of CKM matrix

- 4 independent parameters: 3 angles $(\theta_{12}, \theta_{23}, \theta_{13})$ and 1 phase δ

$$V_{CKM} = R_{23} \times R_{13} \times R_{12}$$

$$R_{12} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad R_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \quad R_{13} = \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij} \quad c_{ij} = \cos\theta_{ij}$$

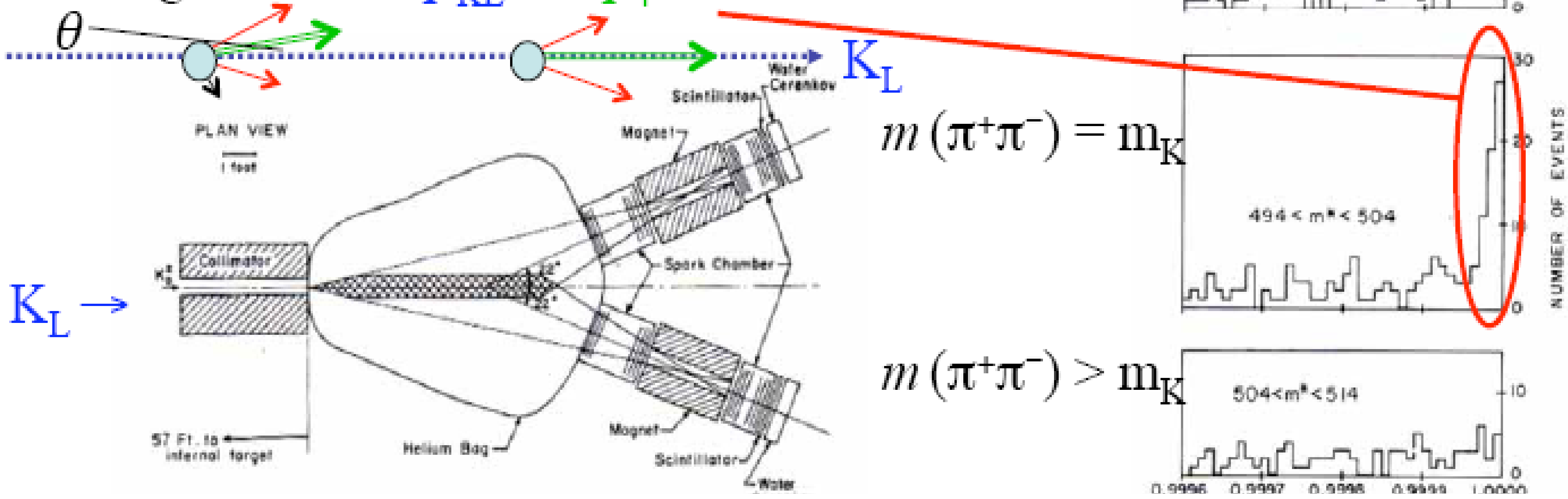
The discovery of CP violation

CPV

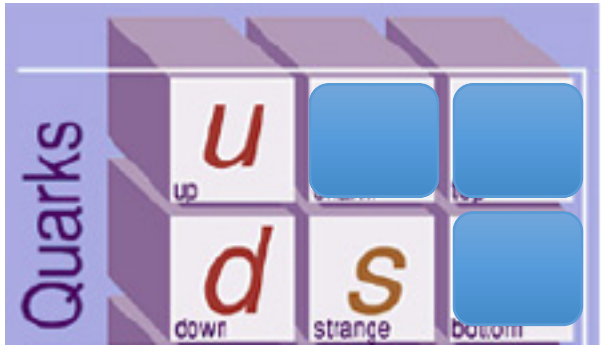
1964, J.H. Christenson et al., $Br(K^0_L \to \pi^+\pi^-) \neq 0$

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

θ = angle between p_{KL} and p_{+-}



The need of three families…



- Kabayashi & Maskawa (1973)
  - c quark discovered in 1974
  - b quark discovered in 1977
  - t quark discovered in 1995

Nobel prize 2008



"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Problem!!

CP violation in
the K and B meson decays
can
be explained by
the Standard Model.

CP violation in
the universe
cannot
be explained by
the Standard Model.

Universe: $$\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} = 10^{-9} \sim 10^{-10}$$

Standard Model: $$\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} = \sim 10^{-20}$$

New source for CP violation
beyond the Standard Model in the particle world?

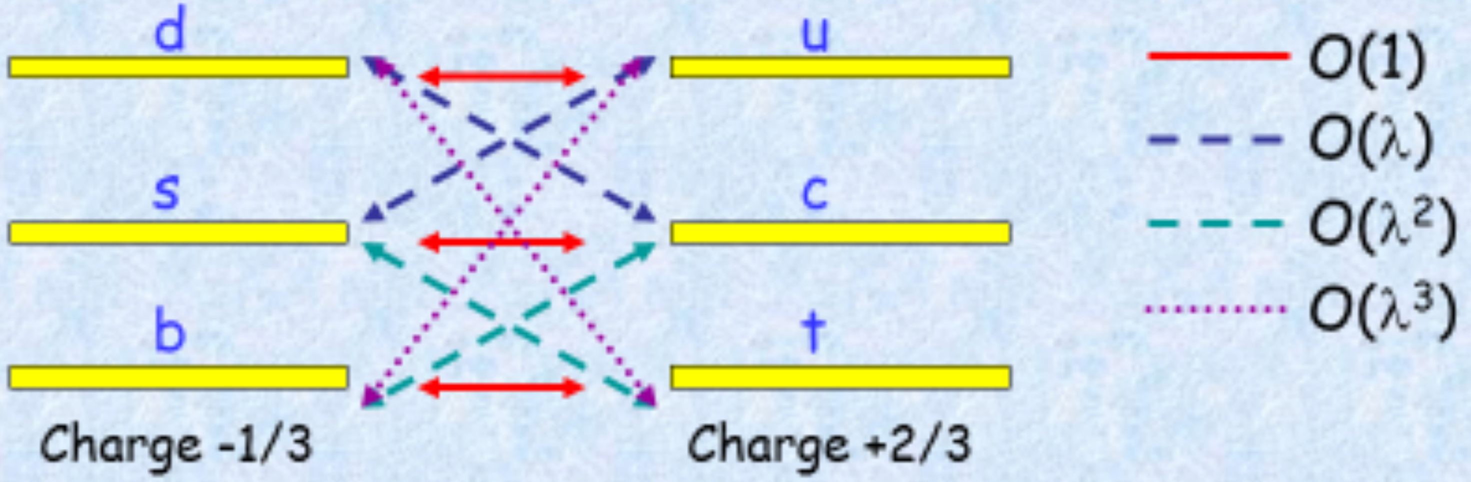
Wolfenstein Parameterization

Wolfenstein parameterization (perturbative form)

$$\lambda = s_{12} \qquad A = \frac{s_{23}}{s_{12}^2} \qquad \rho = \frac{s_{13}\cos\delta}{s_{12}s_{23}} \qquad \eta = \frac{s_{13}\sin\delta}{s_{12}s_{23}}$$

$$\lambda = \sin\theta_{12} \approx 0.23$$

Reflects hierarchy of strengths of quark transitions



Wolfenstein Parameterization

Wolfenstein parameterization to O(λ^3):

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Next-to leading order corrections in λ will be important in LHC era:

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + A^2\lambda^5(1/2-\rho-i\eta) & 1-\lambda^2/2-\lambda^4/8\,(1+4A^2) & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 + A\lambda^4(1/2-\rho-i\eta) & 1-A^2\lambda^4/2 \end{pmatrix} + O(\lambda^6)$$

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

CP Violation in the Standard Model

Requirements for CP violation

$$\left(m_t^2 - m_c^2\right)\left(m_t^2 - m_u^2\right)\left(m_c^2 - m_u^2\right)$$
$$\times\left(m_b^2 - m_s^2\right)\left(m_b^2 - m_d^2\right)\left(m_s^2 - m_d^2\right)\times J_{CP} \neq 0$$

J_{CP} Jarlskog determinant

where $$J_{CP} = \left|\mathrm{Im}\left\{V_{i\alpha}V_{j\beta}V_{i\beta}^{*}V_{j\alpha}^{*}\right\}\right| \quad (i \neq j, \alpha \neq \beta)$$

Using parameterizations

$$J_{CP} = s_{12}s_{13}s_{23}c_{12}c_{23}c_{13}\sin\delta = \lambda^6 A^2 \eta = O\left(10^{-5}\right)$$

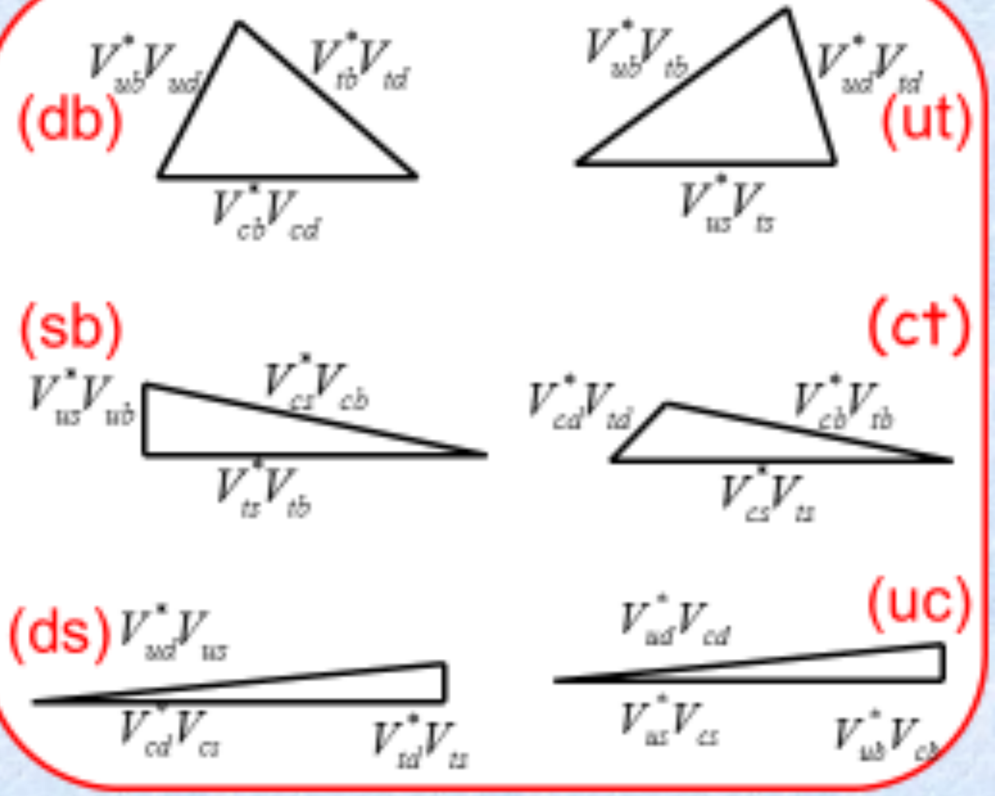
→ CP violation is small in the Standard Model

Unitarity Triangles

CKM matrix is unitary : 12 conditions (6 normalisation, 6 orthoganality)

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad \text{(db)}$$
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \quad \text{(sb)}$$
$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0 \quad \text{(ds)}$$

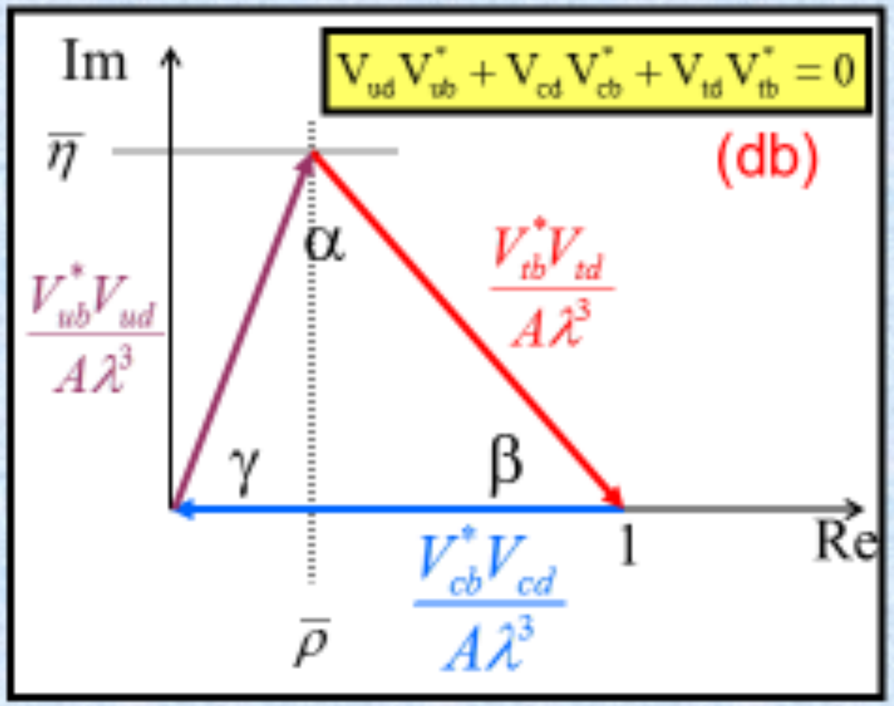
$$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0 \quad \text{(ut)}$$
$$V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0 \quad \text{(ct)}$$
$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0 \quad \text{(uc)}$$



All 6 Δ's have the same area (= $J_{CP}/2$), a measure of CPV in the Standard Model.

The Unitarity Triangle

Redraw "unsquashed" Δ's and take real divide by

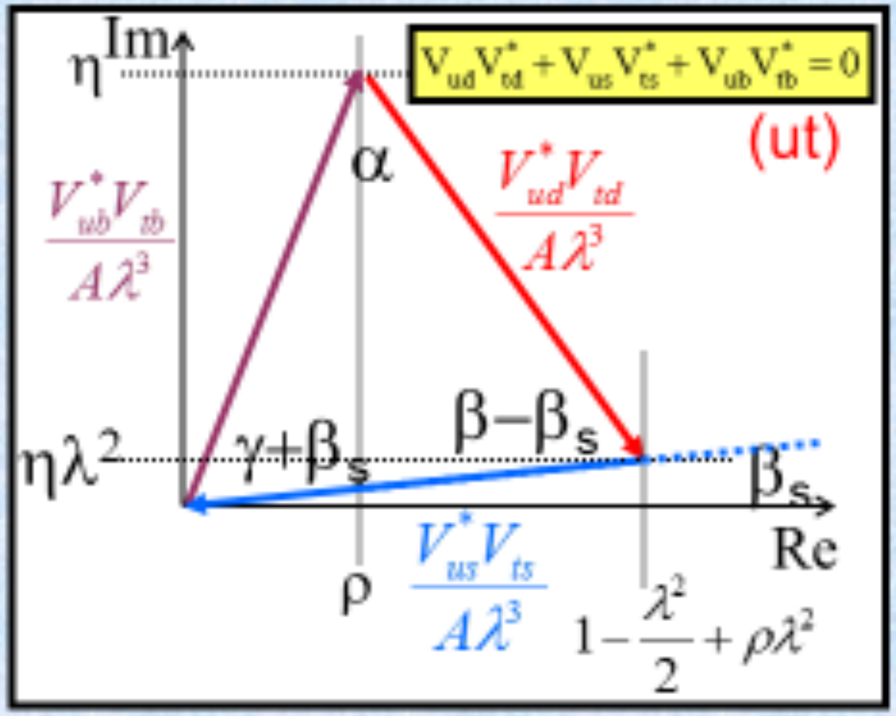


$$\alpha \equiv \pi - \beta - \gamma$$

$$\gamma \equiv \arg\left[-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right] = \tan^{-1}\frac{\eta}{\rho} \sim 70^\circ$$

$$\beta \equiv \arg\left[-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right] = \tan^{-1}\frac{\bar{\eta}}{1-\bar{\rho}} \sim 21^\circ$$

The ... other...Unitarity Triangle



$$\beta_s \equiv \arg\left[-\frac{V_{cb}^* V_{cs}}{V_{tb}^* V_{ts}}\right] \sim \eta\lambda^2 \sim 1^\circ$$

2 Δ's identical to O(λ^3)

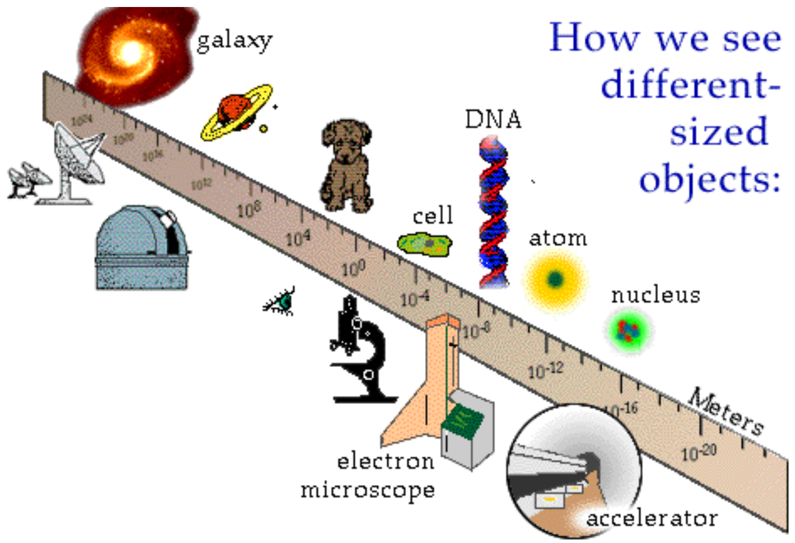
The role of flavor physics

- **Flavor Physics deal with transitions among particles (states) with different flavors**
  - **Flavor is conserved in Strong and EM interactions. Effects from new physics could be relatively large in flavor changing processes.**
  - **Some theoretical predictions are *reasonably* reliable**

- **Search for (small) deviations from SM predictions …**

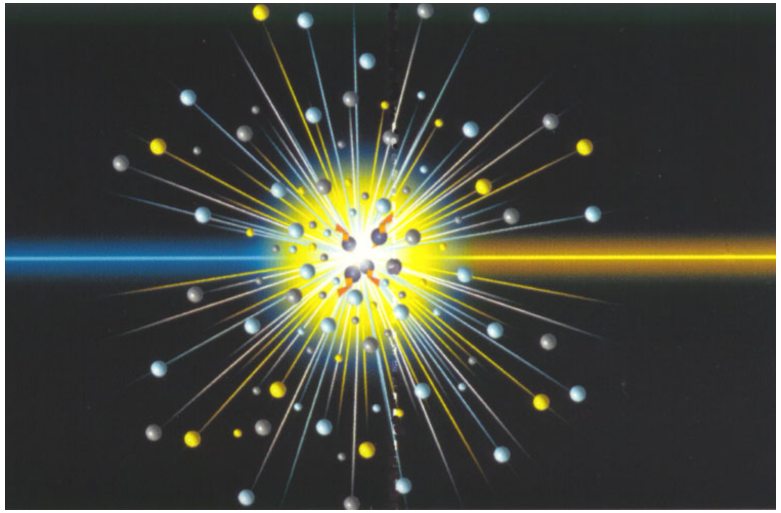
Searches for New Physics- Direct or Indirect

- New Physics could be found in smaller and smaller scale



$$\lambda = \frac{h}{p}$$

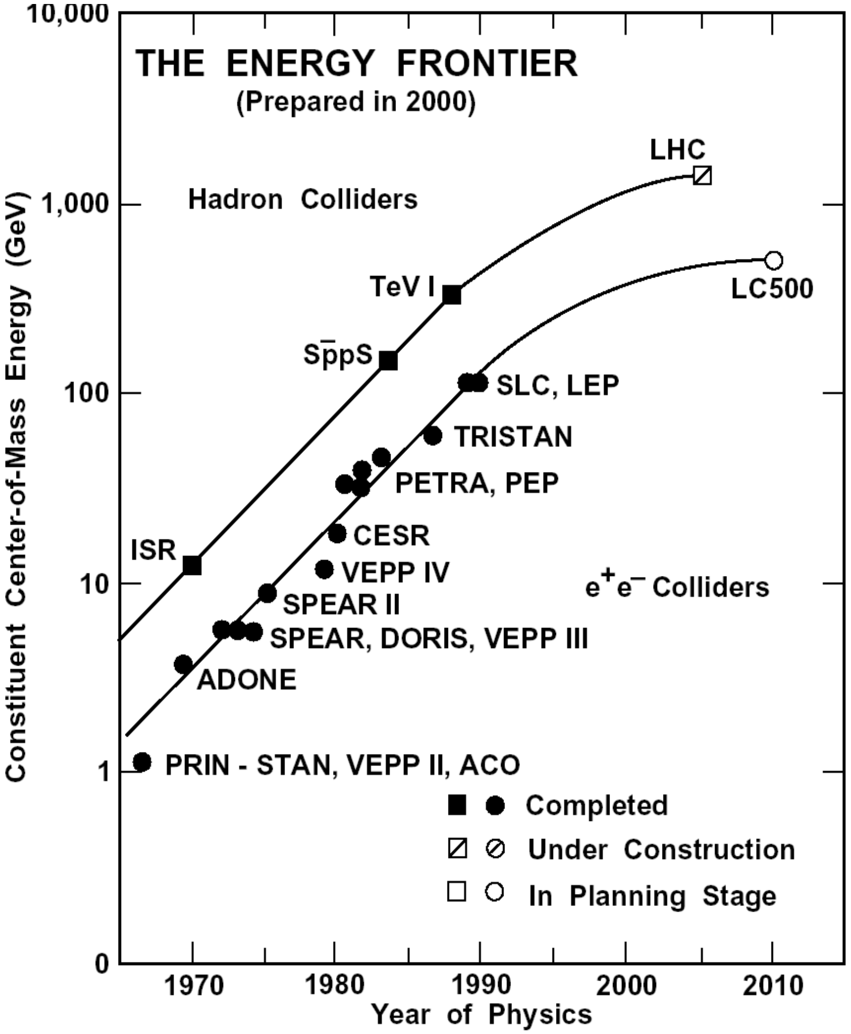
$$E = mc^2$$



- New Particles could be created by higher and higher energy collisions

Particle Physics ≈ High Energy Physics

Large Hadron Collider (LHC)



Searches for New Physics- Direct or Indirect

- However you might also heard some other projects

  - B Factories (~ 10 GeV)
  - Beijing Electron Positron Collider (BEPC, 2-5 GeV)
  - LHCb (at LHC but …)
  - …

-

$$\mu \to e\gamma$$

$$g_\mu - 2$$

-

- …

Searches for New Physics- Direct or Indirect

- "Indirect Search"

$$O_{obs} - O_{th} = \Delta O_{NP}$$

$$O : \text{an observable}$$

$$O_{obs} : \text{value from the measurement}$$

$$O_{th} : \text{value from the theory prediction}$$

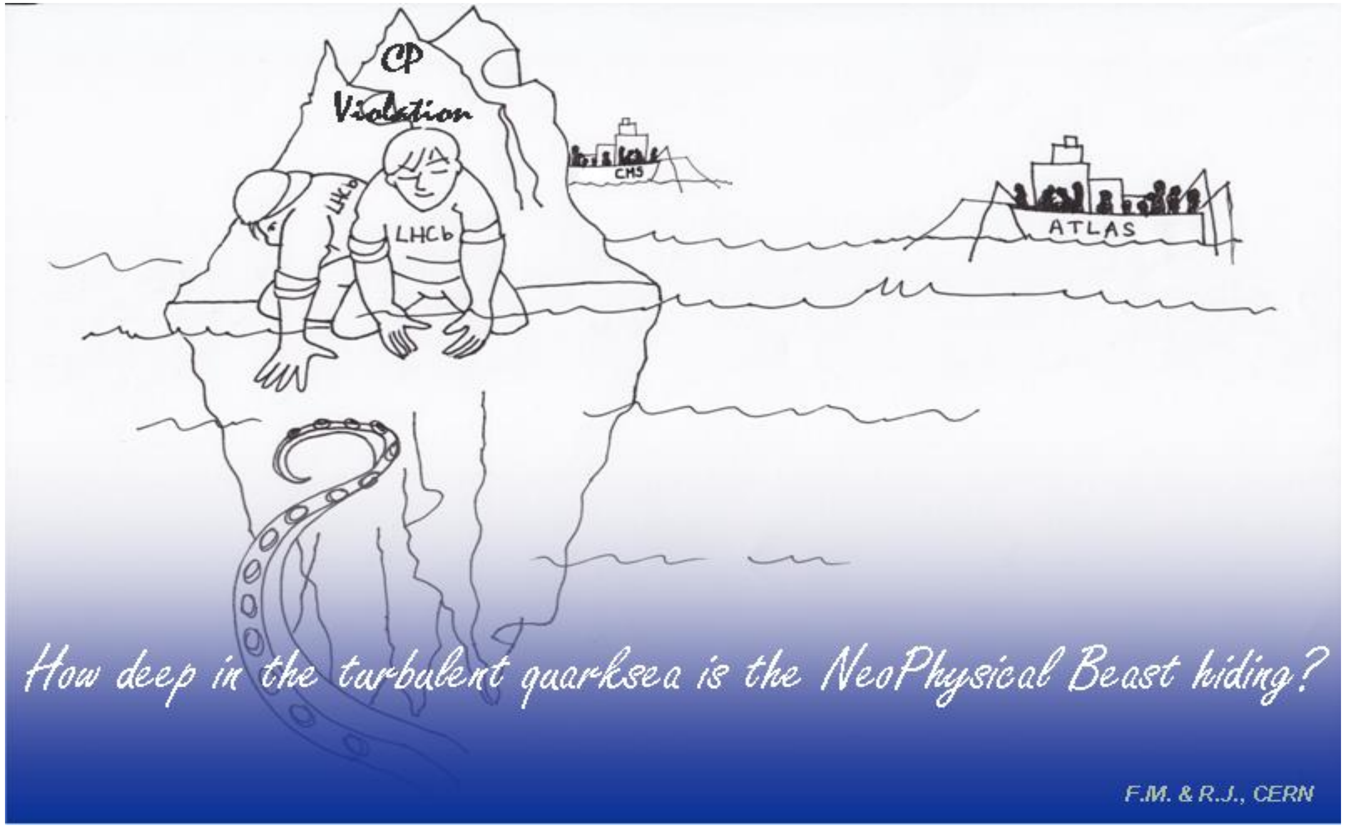
$$\Delta O_{NP} : \text{new physics effect}$$

- **Precision is the lord !**

$$\sqrt{\sigma^2_{O_{obs}} + \sigma^2_{O_{th}}} \ll \Delta O_{NP} : \text{an indirect discovery}$$

Searches for New Physics- Direct or Indirect

- **Two frontiers of modern particle physics: High Energy & High Precision**



What is on the moon?

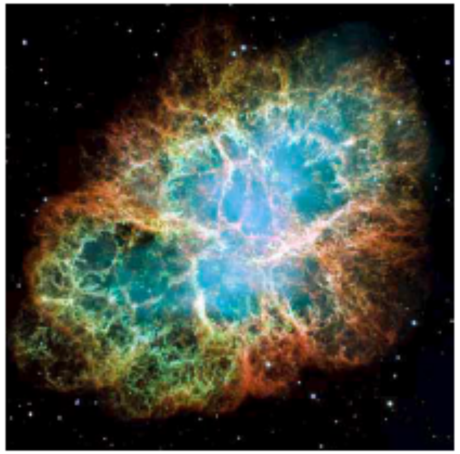
Of course going there...

- By T. Nakada

But you can study a
lot from here before

And may be finding
something new?

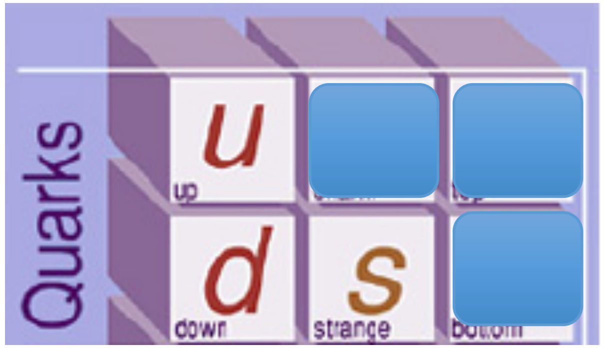
Instruments can be
improved and

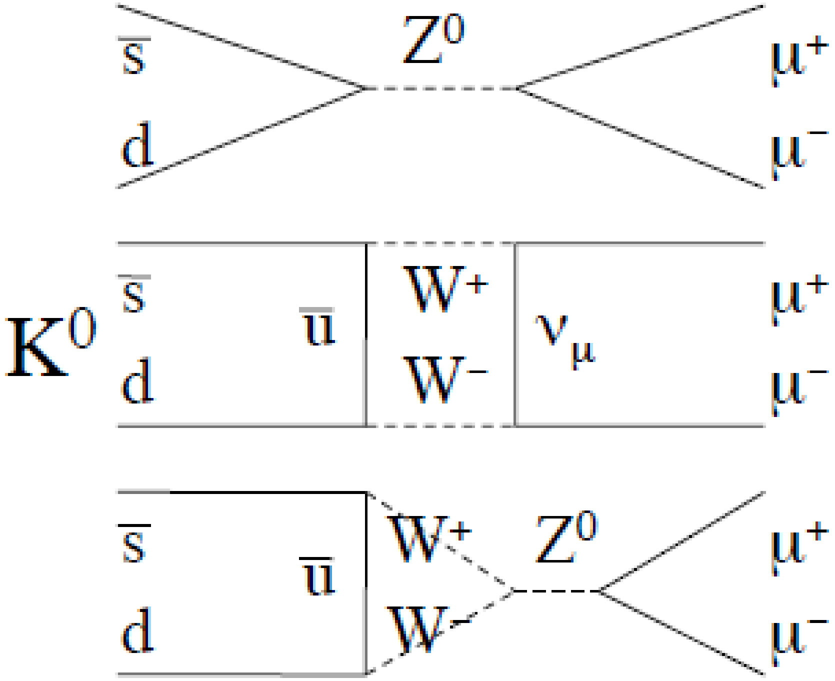


We see far beyond
the direct reach...

Long time ago···

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





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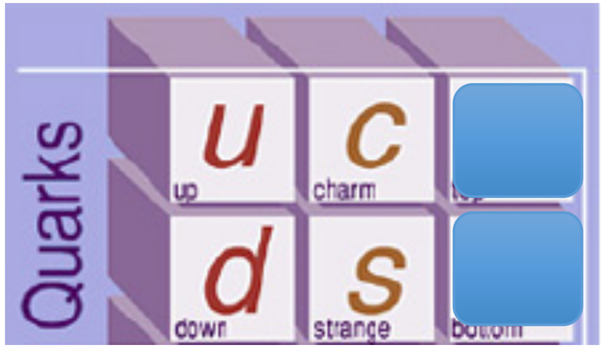
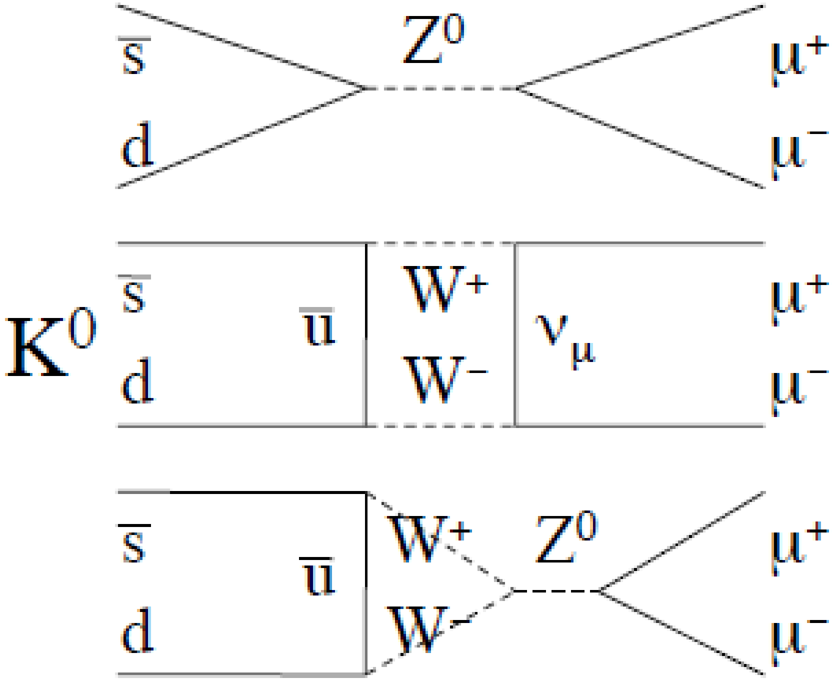
Long time ago···

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





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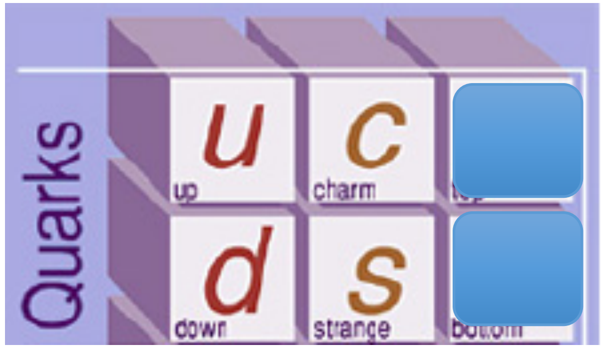
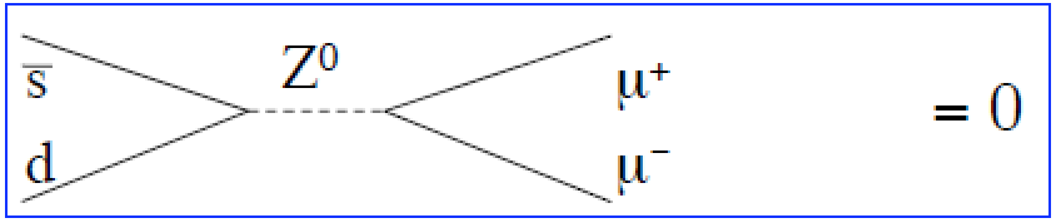
GIM mechanism: prediction of c-quark

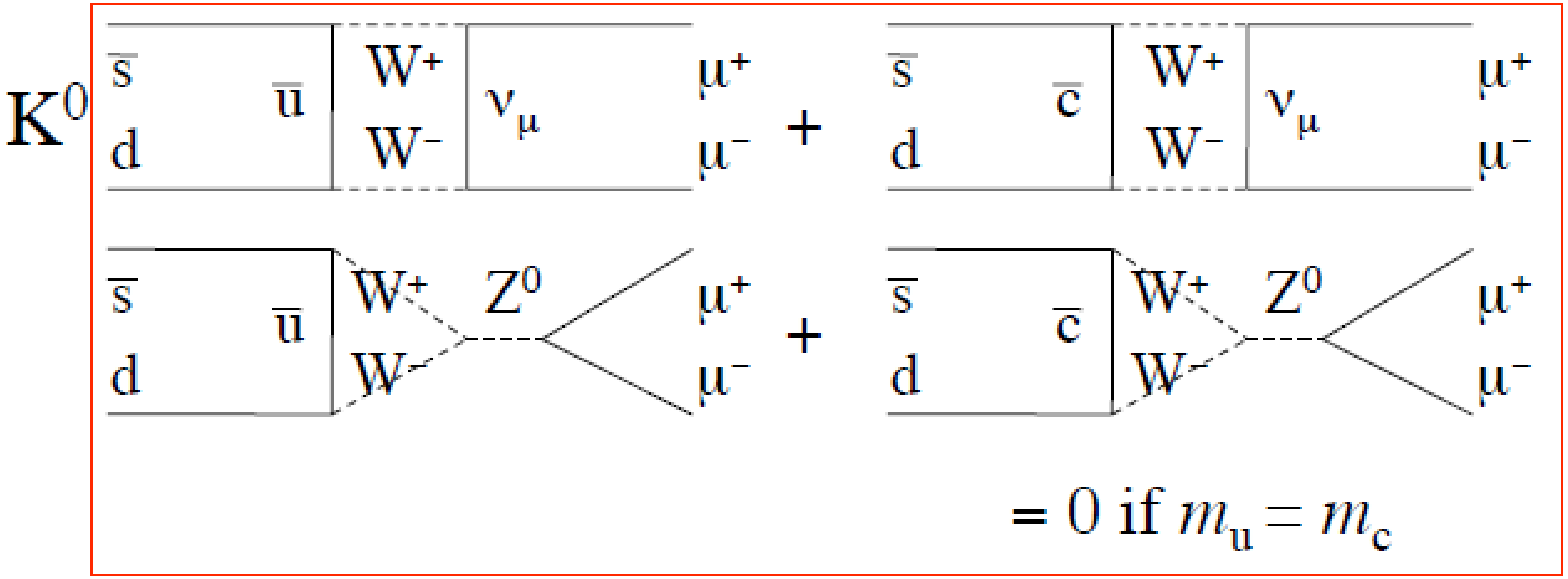
Long time ago…

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



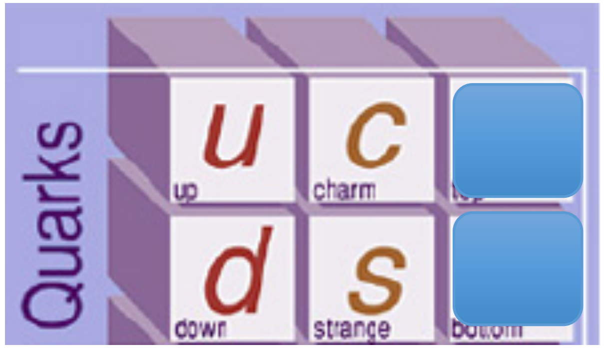


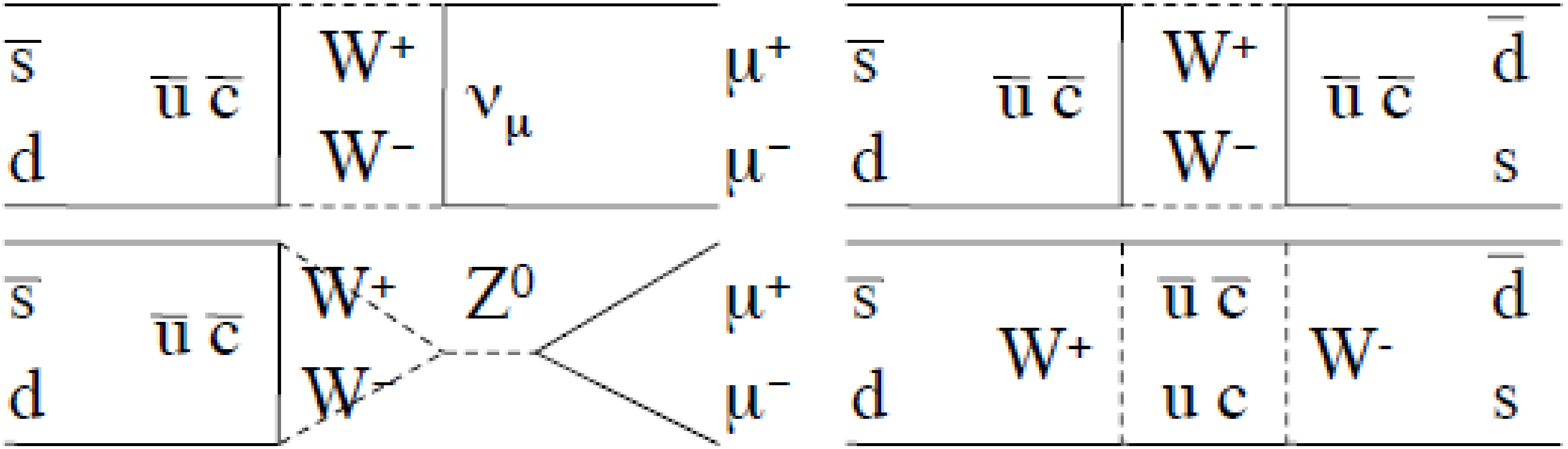
$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$$



Long time ago⋯

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





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

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

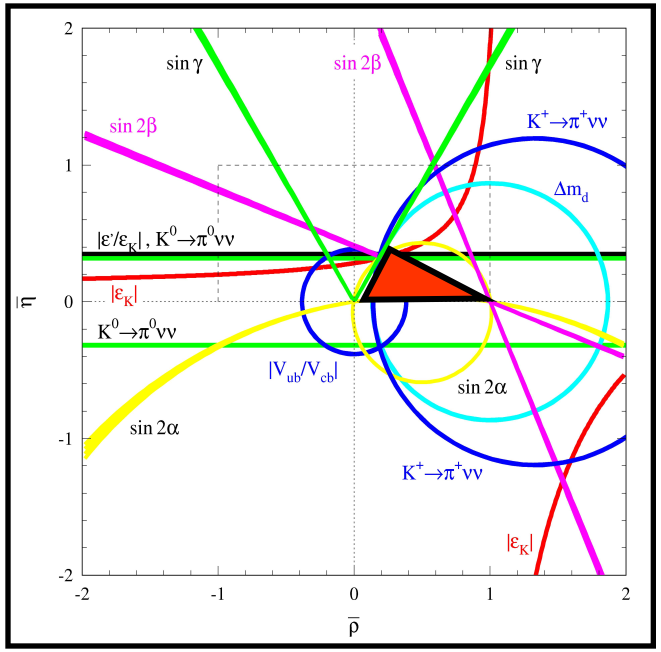
The Quest…

NP models introduce new particles which could

- be produced and discovered as real particles
- appear as virtual particles in loop processes → observable deviations from the SM expectations in flavour physics and CPV

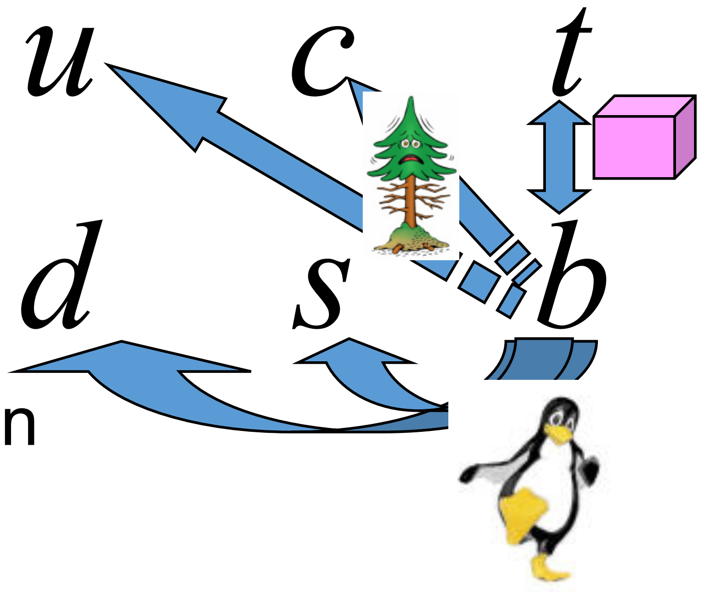
Heavy flavour programme

- Precision measurements of CKM elements
- Compare tree level processes with loop processes sensitive to NP
- Measure all angles and sides in many different ways and look for inconsistencies
- Measure processes very suppressed in SM



Why the b-quark ?

- Heaviest quark that forms hadronic bound s
- Must decay outside 3rd family
  - All decays are CKM suppressed
  - Long lifetime (~1.6 ps)
- High mass: many accessible final states



- Dominant decay process: “tree” b→c transition
- Very suppressed “tree” b→u transition
- FCNC: “penguin” b→s,d transition
- Flavour oscillations (b→t “box” diagram)
- CP violation – expect large CP asymmetries in some B decays

End of part I