The weak interaction
Part II

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

- The CKM mechanism

- Measurements of the unitarity triangle parameters : some examples

- Neutrinos

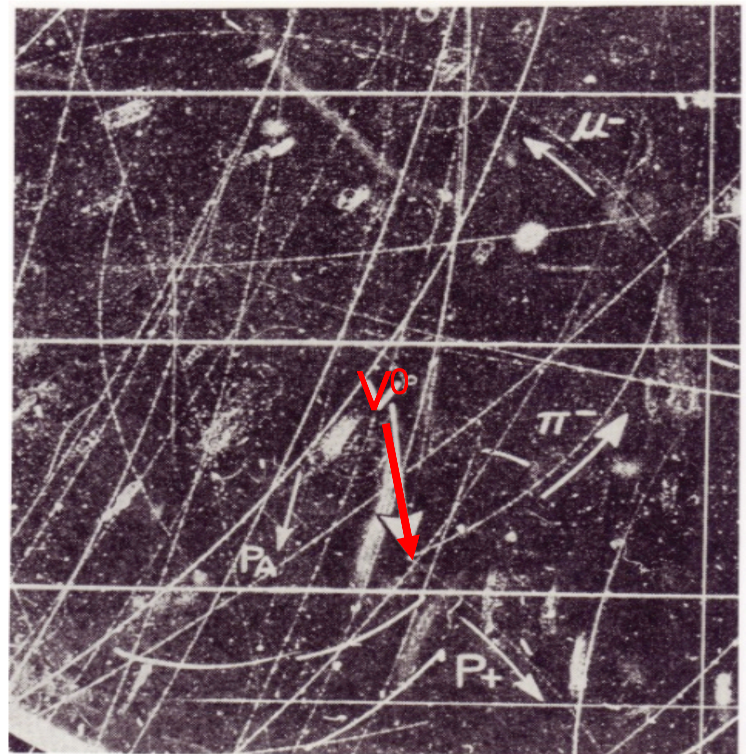
The K^0-$\bar{K}^0$ system

Remember the strange particles ?

Observation of Long-Lived Neutral *V* Particles*

K. Lande, E. T. Booth, J. Impeduglia, and L. M. Lederman,
Columbia University, New York, New York
and
W. Chinowsky, *Brookhaven National Laboratory, Upton, New York*

(Received July 30, 1956)



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Brookhaven, 1956

Two states :

$|K_1\rangle \rightarrow \pi\pi$

$|K_2\rangle \rightarrow \pi\pi\pi$

Same mass (~ 500 MeV)

M(π) ~ 140 MeV
M(K) ~ 500 MeV

Very different lifetimes

K_2 lifetime ~ 10000 K_1 lifetime due to phase space

CP violation in the K^0 system

NB : $K_1 = K_S$ and $K_2 = K_L$

$|K^0\rangle = |s\bar{d}\rangle$

$|\bar{K}^0\rangle = |\bar{d}s\rangle$

$CP|K^0\rangle = |\bar{K}^0\rangle \Rightarrow$ $|K^0\rangle = |s\bar{d}\rangle$, $|\bar{K}^0\rangle = |\bar{d}s\rangle$ — not CP eigenstates

One can build :

$$|K_1\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right)$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right)$$

CP eigenstates

$|K_1\rangle \to \pi\pi$ $\quad$ $|K_2\rangle \to \pi\pi\pi$ $\quad$ CP(ππ) = +1 and CP(πππ) = -1

if CP is a good symmetry for the weak interaction : $|K_2\rangle \not\to \pi\pi$

$$|K_1\rangle \rightarrow \pi\pi$$

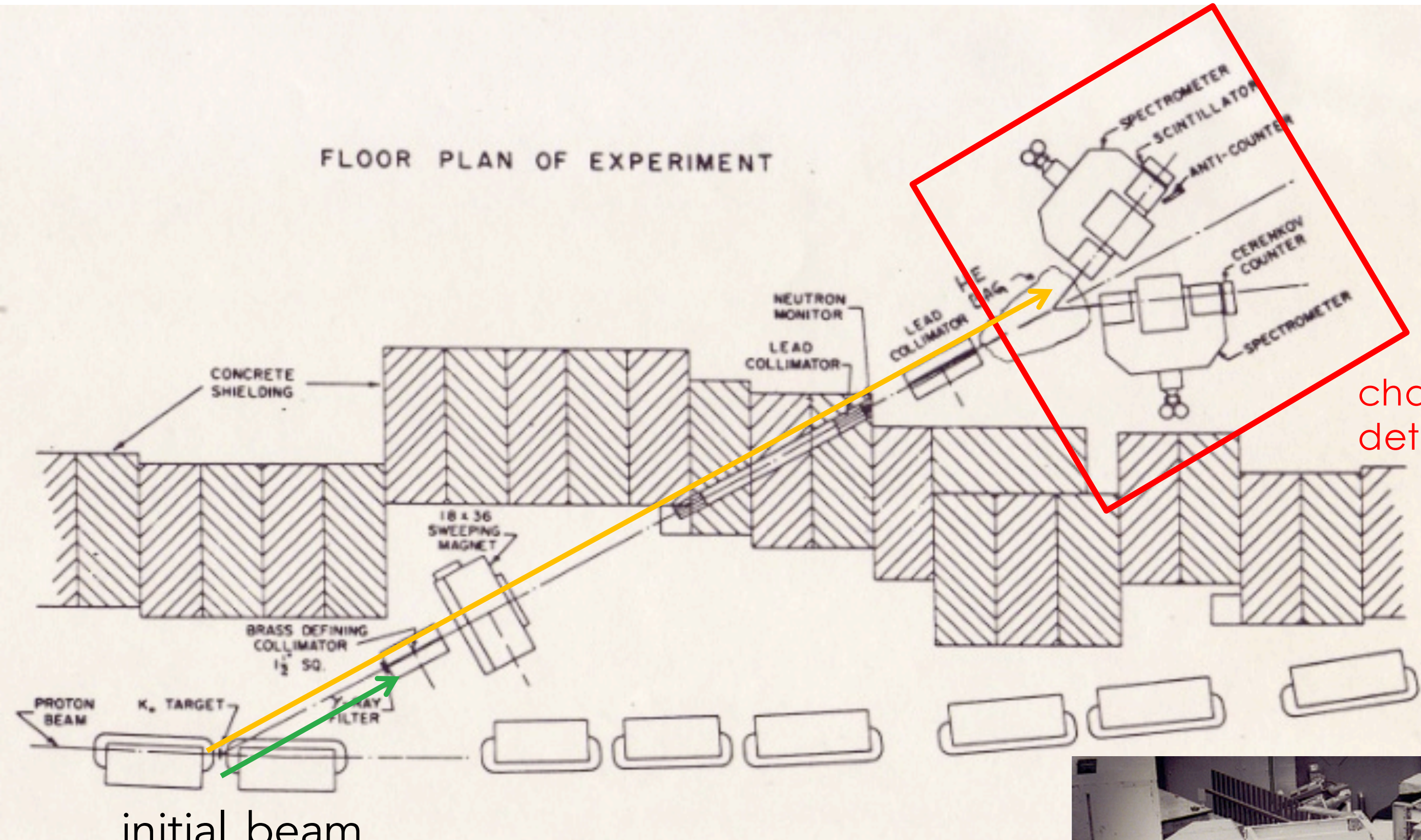
After some time, pure K_2 beam

initial beam
K_1 and K_2

Search for the signal of the decay $|K_2\rangle \rightarrow \pi\pi$ far (20 meters) from the production point of the K_1 and K_2

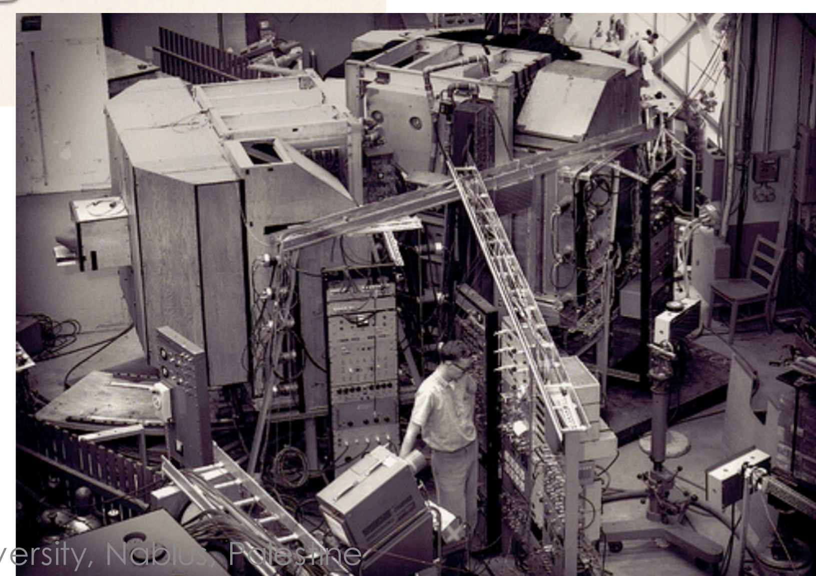
?

Cronin& Fitch experiment 1964



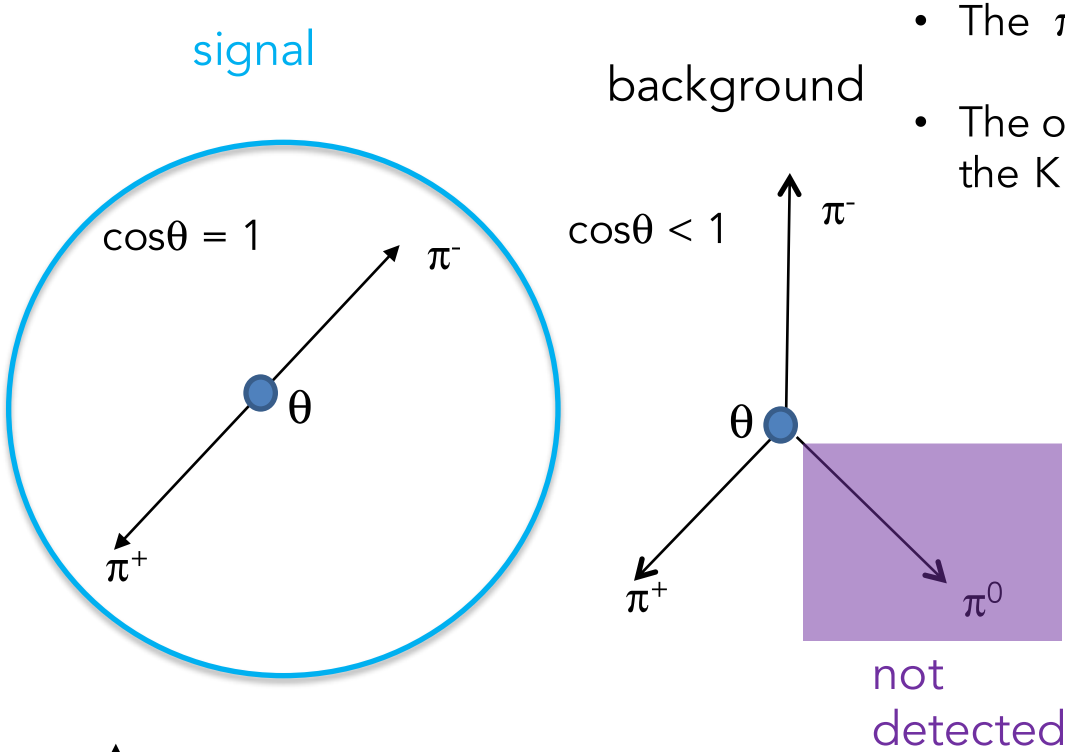
charged tracks detector

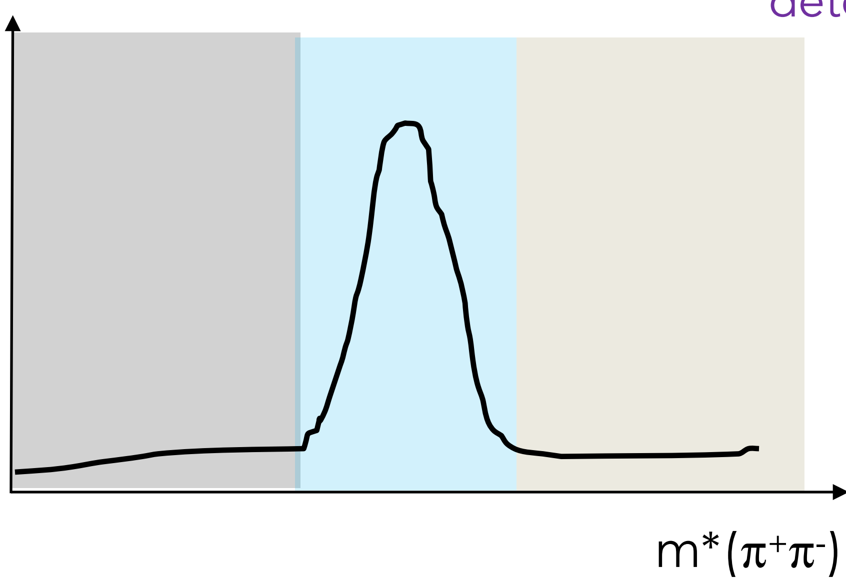
initial beam
K_1 and K_2

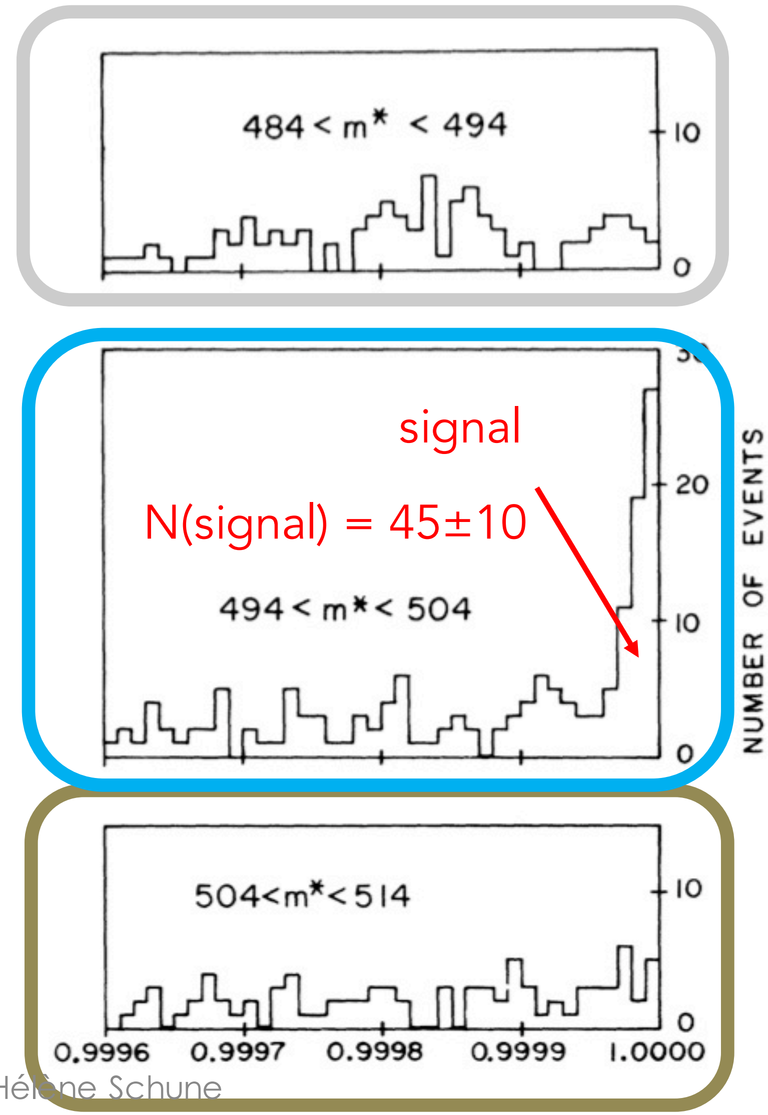


Two informations :

- The $\pi^+\pi^-$ invariant mass (m*)
- The opening angle between the two pions in the K center of mass frame







Volume 13, Number 4 PHYSICAL REVIEW LETTERS 27 July 1964

1964

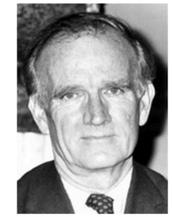
EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2 \to \pi^+ + \pi^-)/(K_2^0 \to \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ where the error is the standard deviation. As emphasized above, any alternate explanation of the effect requires highly nonphysical behavior of the three-body decays of the K_2^0. The presence of a two-pion decay mode implies that the K_2^0 meson is not a pure eigenstate of CP. Expressed as

The Nobel Prize in Physics 1980

James Watson Cronin
Prize share: 1/2



Val Logsdon Fitch
Prize share: 1/2

The Nobel Prize in Physics 1980 was awarded jointly to James Watson Cronin and Val Logsdon Fitch *"for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"*

R. Turlay was a PhD student
J Christenson was a graduate student

« The discovery emphasizes, once again, that even almost self evident principles in science cannot be regarded fully valid until they have been critically examined in precise experiments. »

Today :

$$\frac{A\left(|K_2\rangle \to \pi\pi\right)}{A\left(|K_1\rangle \to \pi\pi\right)} = \left(2.271 \pm 0.017\right)10^{-3}$$

0.7 % precision !

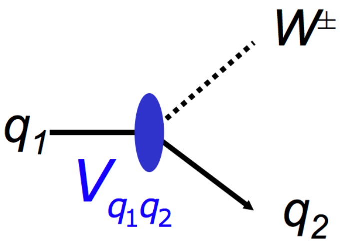
Experimental observation of CP violation in K decays

+ Cabibbo angle

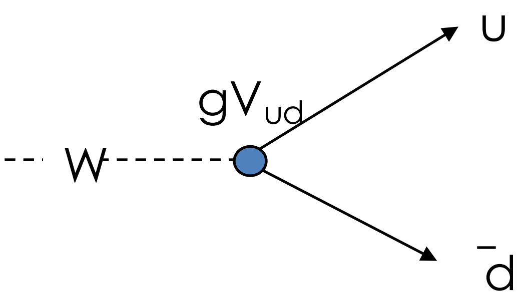
→ V_{CKM} Cabibbo-Kobayashi-Maskawa matrix

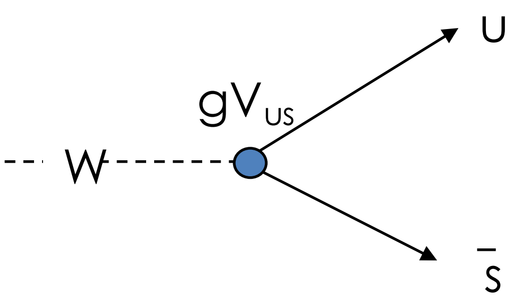
V_{CKM} Cabibbo-Kobayashi-Maskawa matrix

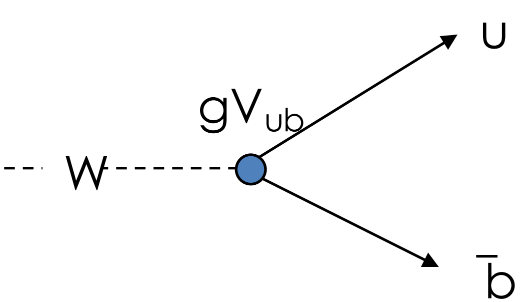
Two different way of seeing the charged interactions among quarks



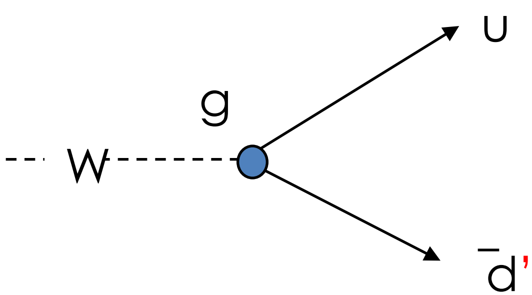
In the basis dealing
with mass eigenstates :







In the basis where :
charged interactions are just
between members of the same family
and « CKM » is diagonal



Weak interaction eigenstates ≠ Mass eigenstates (flavour or strong interaction eigenstates)

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

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

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

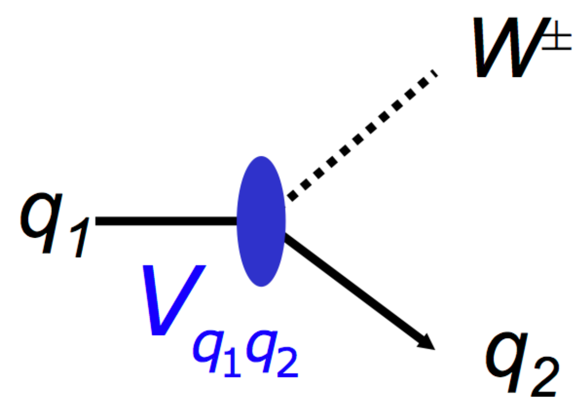
Department of Physics, Kyoto University, Kyoto

1973
Before the discovery of the 4^{th} quark

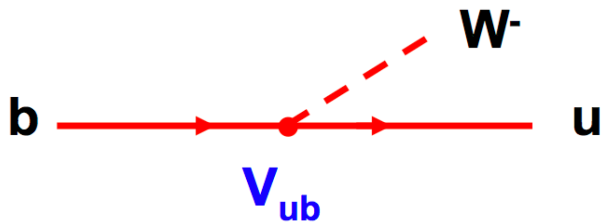
Prediction of the 3^{rd} family

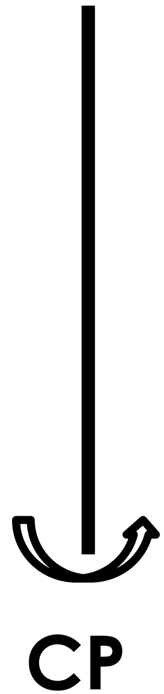
# families	# angles	# reducible phases	# irreducible phases
n	n(n-1)/2	2n-1	n(n+1)/2 –(2n-1)=(n-1)(n-2)/2
2	1		0
3	3		1
4	6		3

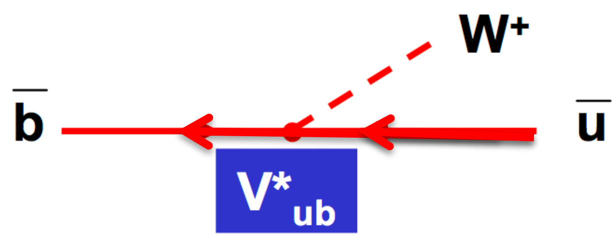
$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



V_{CKM} Cabibbo-Kobayashi-Maskawa matrix

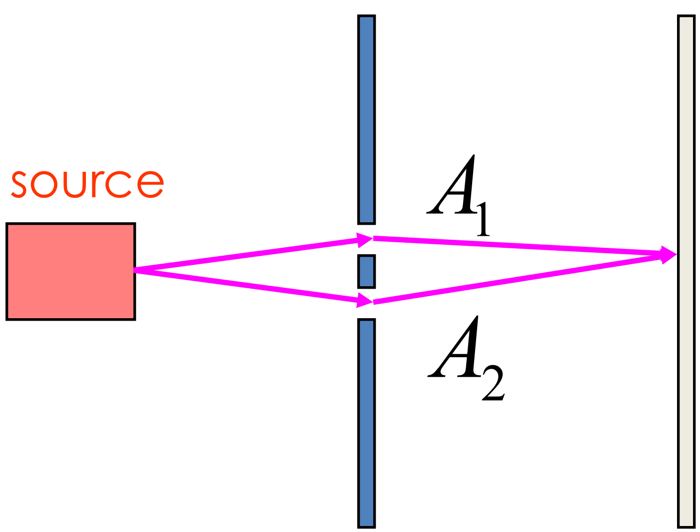


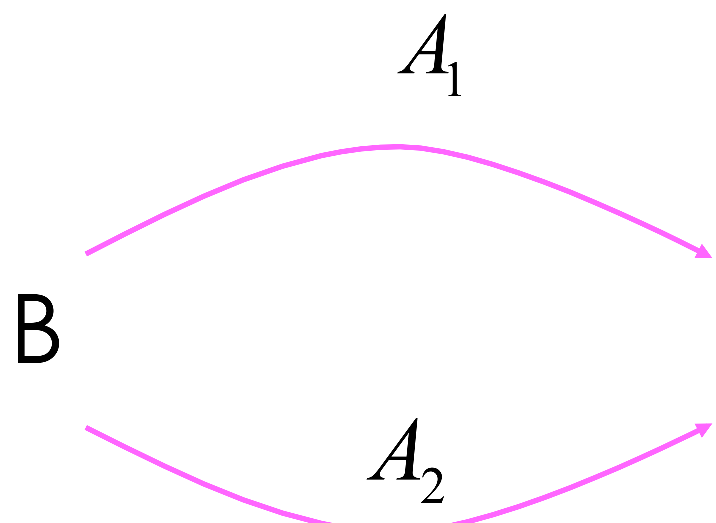




$V^*_{ub} \neq V_{ub} \rightarrow$ CP violation

One amplitude : no sensitivity on phase ($|V_{ij}|^2 = |V^*_{ij}|^2$)

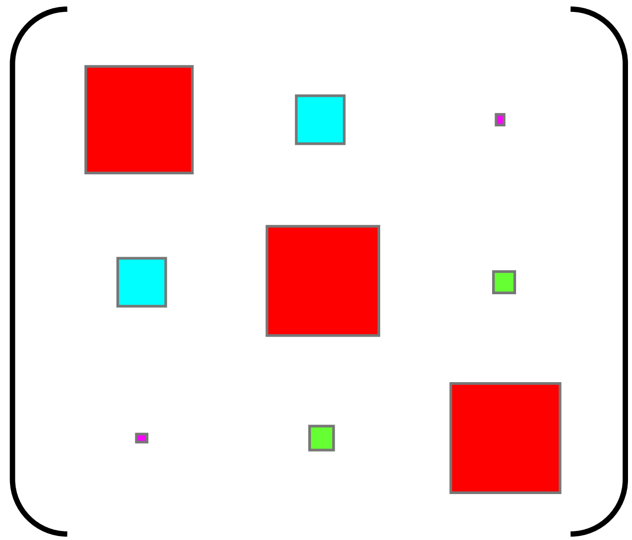


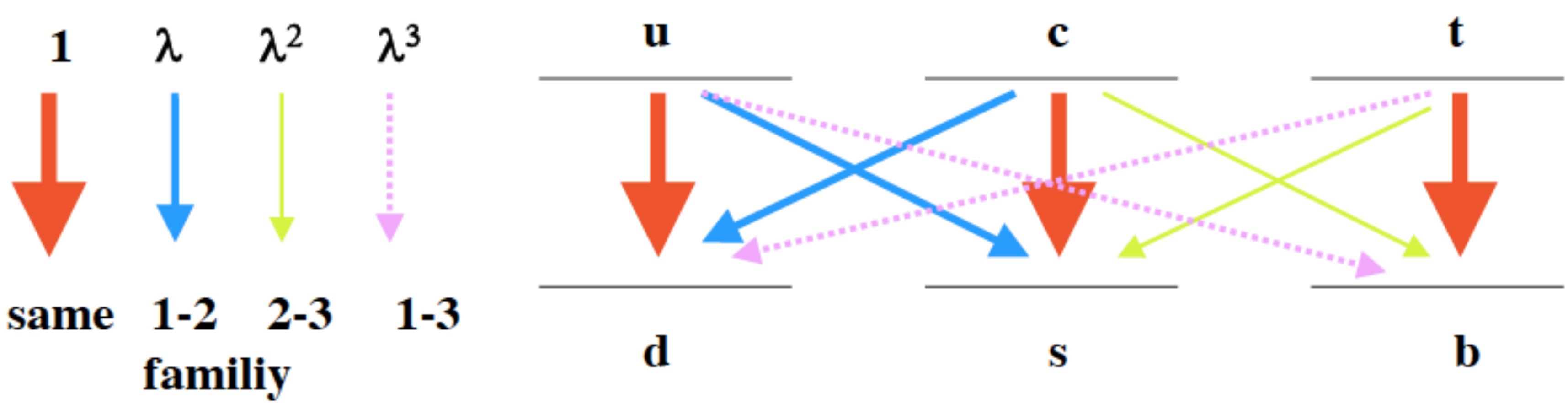


No prediction on the V_{ij} → they need to be measured

→ Experimental observations :

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





Measuring triangles

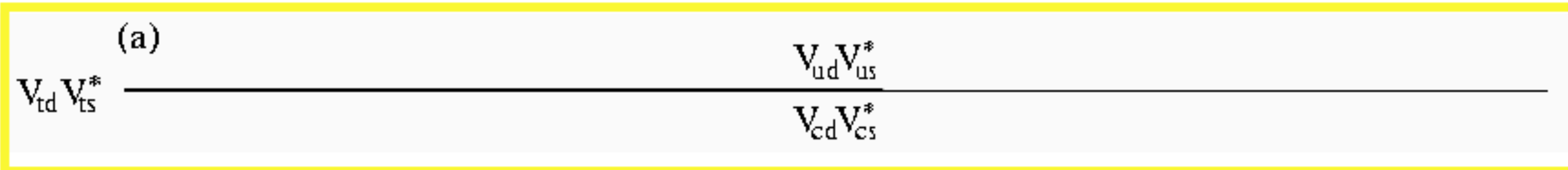
Stay within the 3 families

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

Unitarity of V_{CKM} $\quad VV^{\dagger} = V^{\dagger}V = 1$

→9 relations $\quad \sum_{k=1}^{n} V_{ik} V_{jk}^{*} = \delta_{ij},$

The non-diagonal elements of the matrix products correspond to 6 triangle equations



$$V_{ud}^* V_{us} + V_{cd}^* V_{cs} + V_{td}^* V_{ts} = 0 \qquad \lambda \;\; \lambda \;\; \lambda^5$$

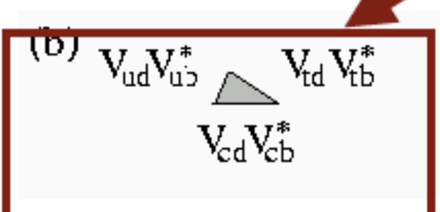
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0 \qquad \lambda^3 \;\; \lambda^3 \;\; \lambda^3$$

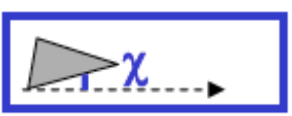
$$V_{us}^* V_{ub} + V_{cs}^* V_{cb} + V_{ts}^* V_{tb} = 0 \qquad \lambda^4 \;\; \lambda^2 \;\; \lambda^2$$

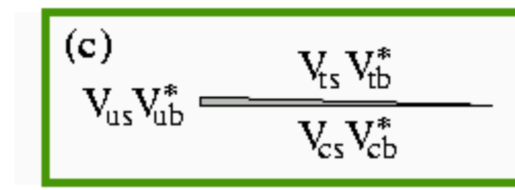
$$V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb} = 0 \qquad \lambda^3 \;\; \lambda^3 \;\; \lambda^3$$

$$V_{td}^* V_{cd} + V_{ts}^* V_{cs} + V_{tb}^* V_{cb} = 0 \qquad \lambda^4 \;\; \lambda^2 \;\; \lambda^2$$

$$V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} = 0 \qquad \lambda \;\; \lambda \;\; \lambda^5$$

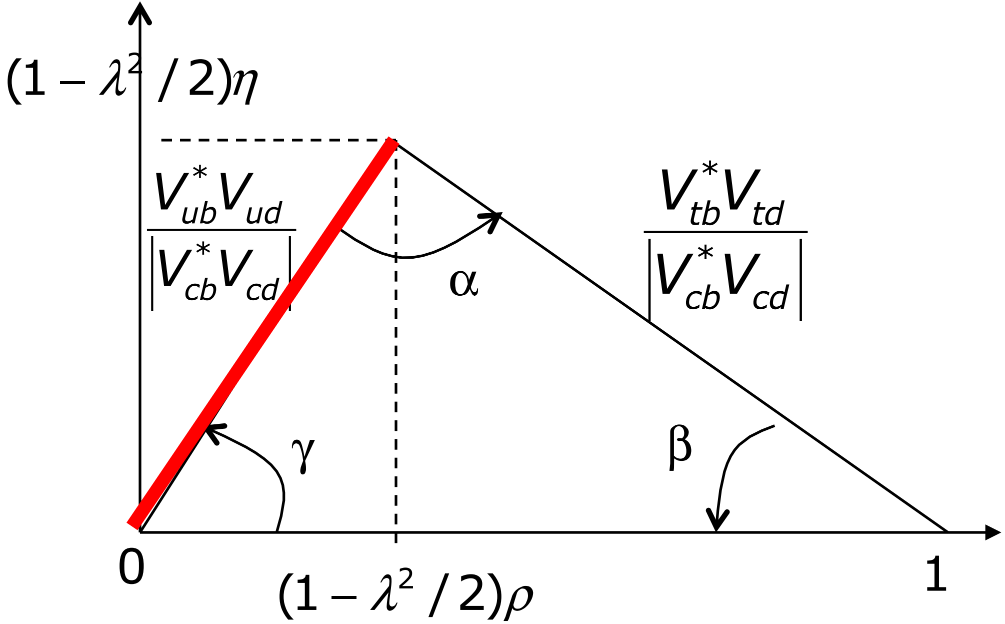


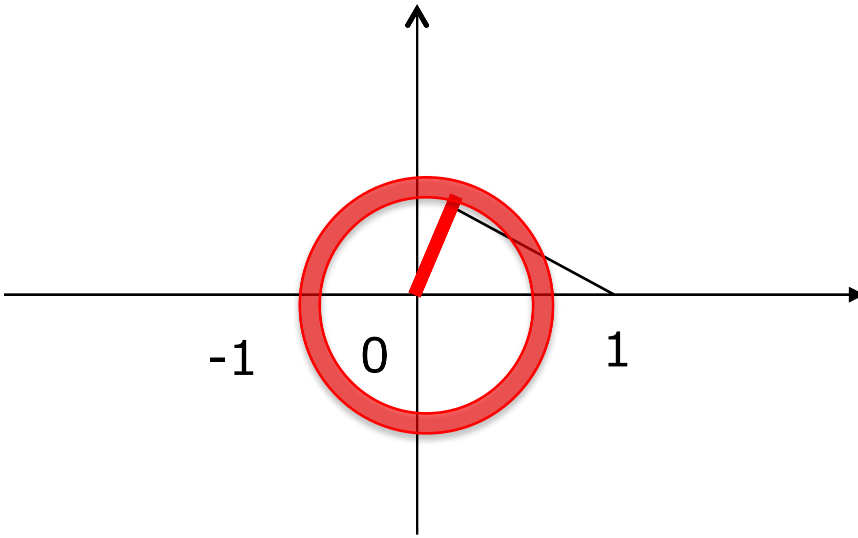




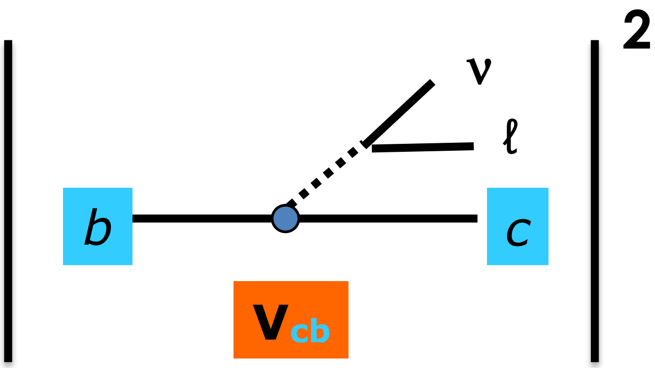
They all have the same area, proportionnal to the amount of CP violation in the SM

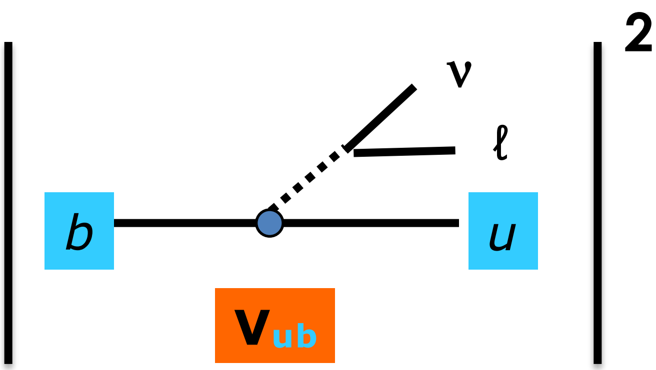
Measurements of the unitarity triangle parameters : some examples





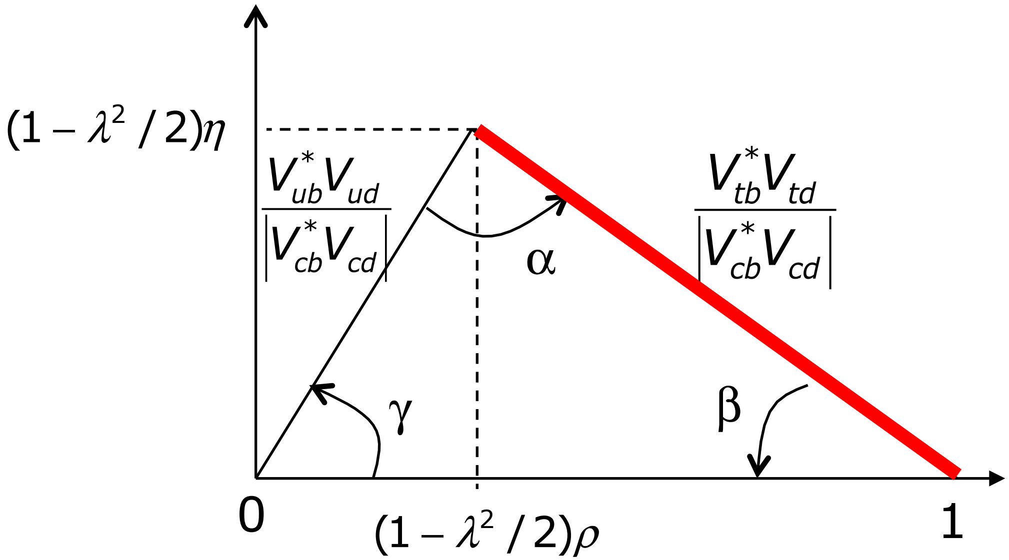
Rates of semileptonic B decays

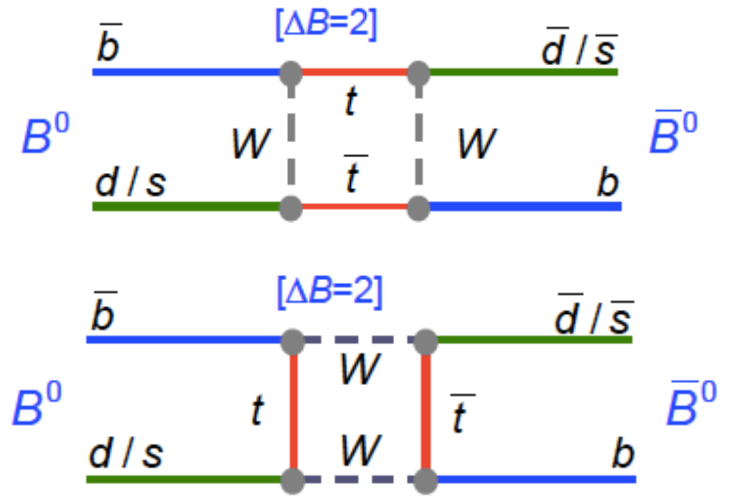




Conceptually simple, complicated by QCD

The other side : B^0-$\overline{B}^0$ oscillations





Diagrams involving V_{td} or V_{ts}

(

The mixing phenomenon

Pairs of self-conjugate mesons that can be transformed to each other via flavour changing weak interaction transitions are:

$$|K^0\rangle = |\bar{s}d\rangle \qquad |D^0\rangle = |c\bar{u}\rangle \qquad |B_d^0\rangle = |\bar{b}d\rangle \qquad |B_s^0\rangle = |\bar{b}s\rangle$$

They are **flavour eigenstates** with definite quark content

- useful to understand particle production and decay

$$|B^0\rangle, \ |\bar{B}^0\rangle$$

Apart from the flavour eigenstates there are **mass eigenstates**:

$$|B_L\rangle, \ |B_H\rangle$$

- eigenstates of the Hamiltonian
- states of definite mass and lifetime
- They are propagating through space-time

$$|B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$$

$$|B_H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$$

Since flavour eigenstates are not mass eigenstates, the flavour eigenstates are mixed with one another as they propagate through space and time

$$\left|B_{H,L}(t)\right\rangle = e^{-i\left(M_{H,L}-i\frac{\Gamma_{H,L}}{2}\right)t}\left|B_{H,L}(t=0)\right\rangle \quad +$$

$$\left|B_L\right\rangle = p\left|B^0\right\rangle + q\left|\overline{B}^0\right\rangle$$

$$\left|B_H\right\rangle = p\left|B^0\right\rangle - q\left|\overline{B}^0\right\rangle$$

Time evolution

The probability to observe a B^0 at time t if a B^0 was produced at time t=0 is :

$$\left|\left\langle B^0 \middle| H \middle| B^0(t)\right\rangle\right|^2 = \frac{e^{-\Gamma t}}{2}(1+\cos\Delta m t)$$

The probability to observe a B^0 at time t if a $\overline{B^0}$ was produced at time t=0 is :

$$\left|\left\langle \overline{B}^0 \middle| H \middle| B^0(t)\right\rangle\right|^2 = \frac{e^{-\Gamma t}}{2}(1-\cos\Delta m t)$$

This is the mixing phenomenon !

$$\frac{N_{Unmixed} - N_{Mixed}}{N_{Unmixed} + N_{Mixed}} \sim \cos\Delta m t$$

Simplified formulae assuming that the two mass eigenstates have the same lifetime and neglecting CP violation (q/p=1)

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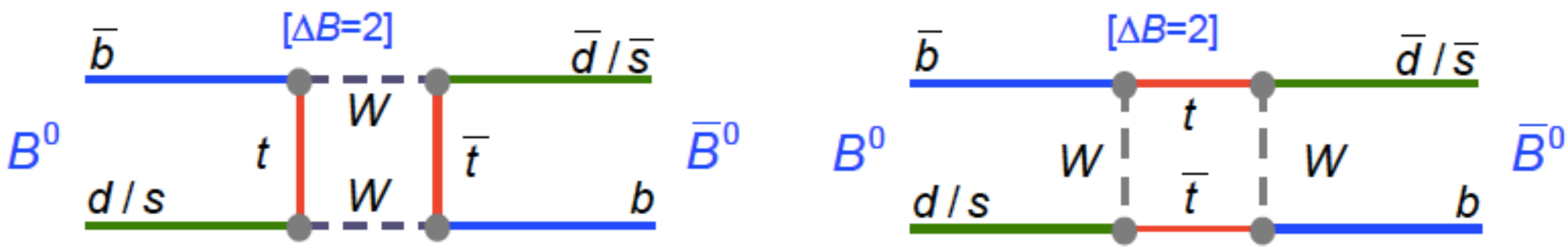
Let’s come back to the unitarity triangle

Δm can be computed in the Standard Model

Effective FCNC Processes (*CP* conserving — top loop dominates in box diagram):



Perturbative QCD

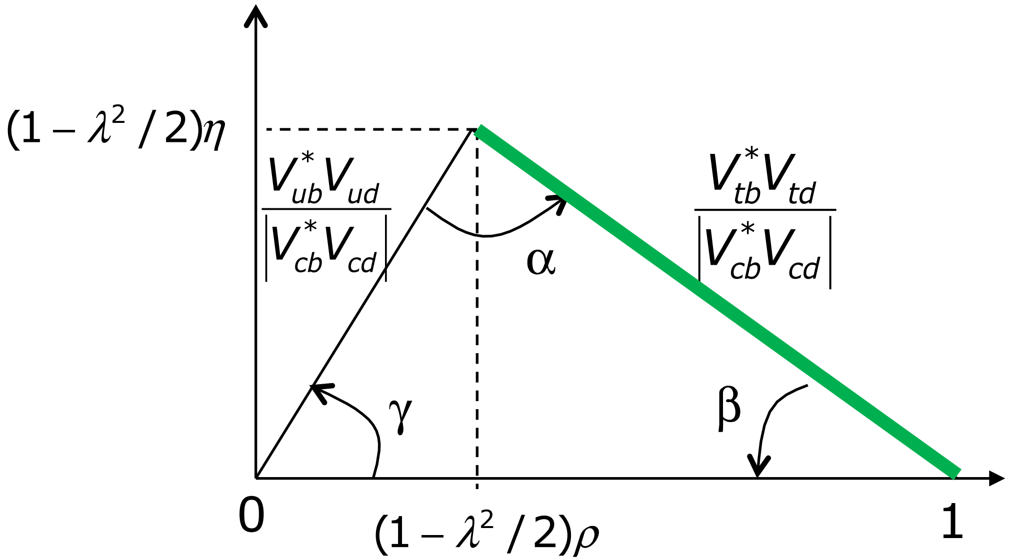
CKM Matrix Elements

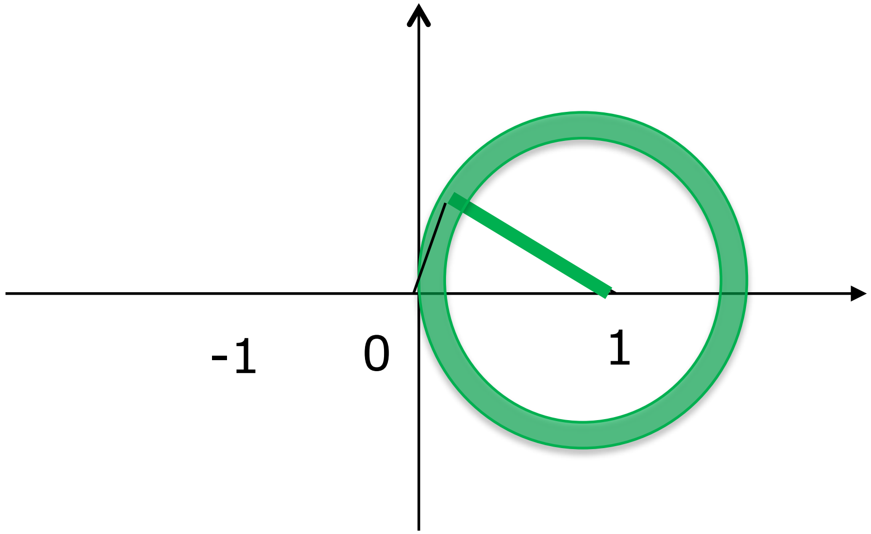
$$\Delta m_q = \frac{G_F^2}{6\pi^2} m_{B_q} m_W^2 \, \eta_B \, S(x_t) \, f_{B_q}^2 B_q \left| V_{tq} V_{tb}^* \right|^2 \quad (\text{for } q = d, s)$$

Loop integral (top loop dominates)

Non-perturbative QCD : dominant theoretical uncertainty

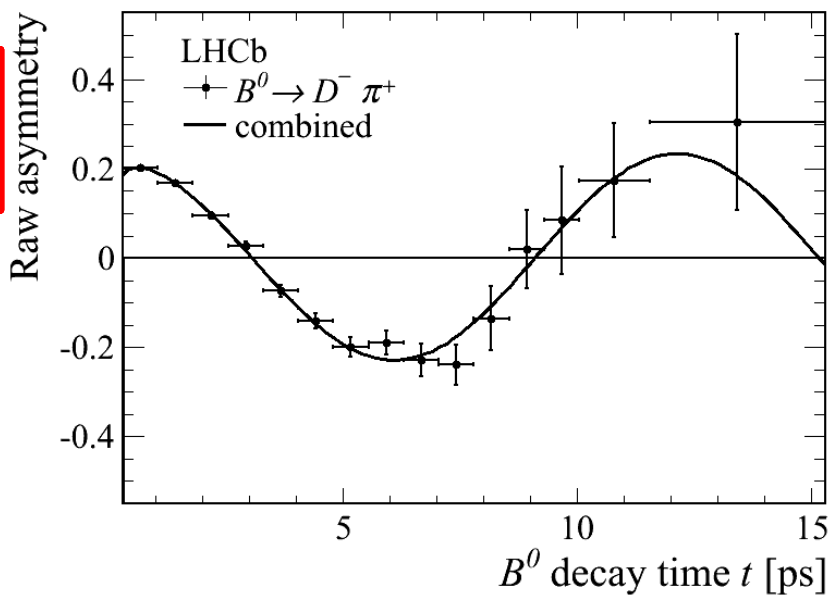
The other side : B^0-$\bar{B}^0$ oscillations

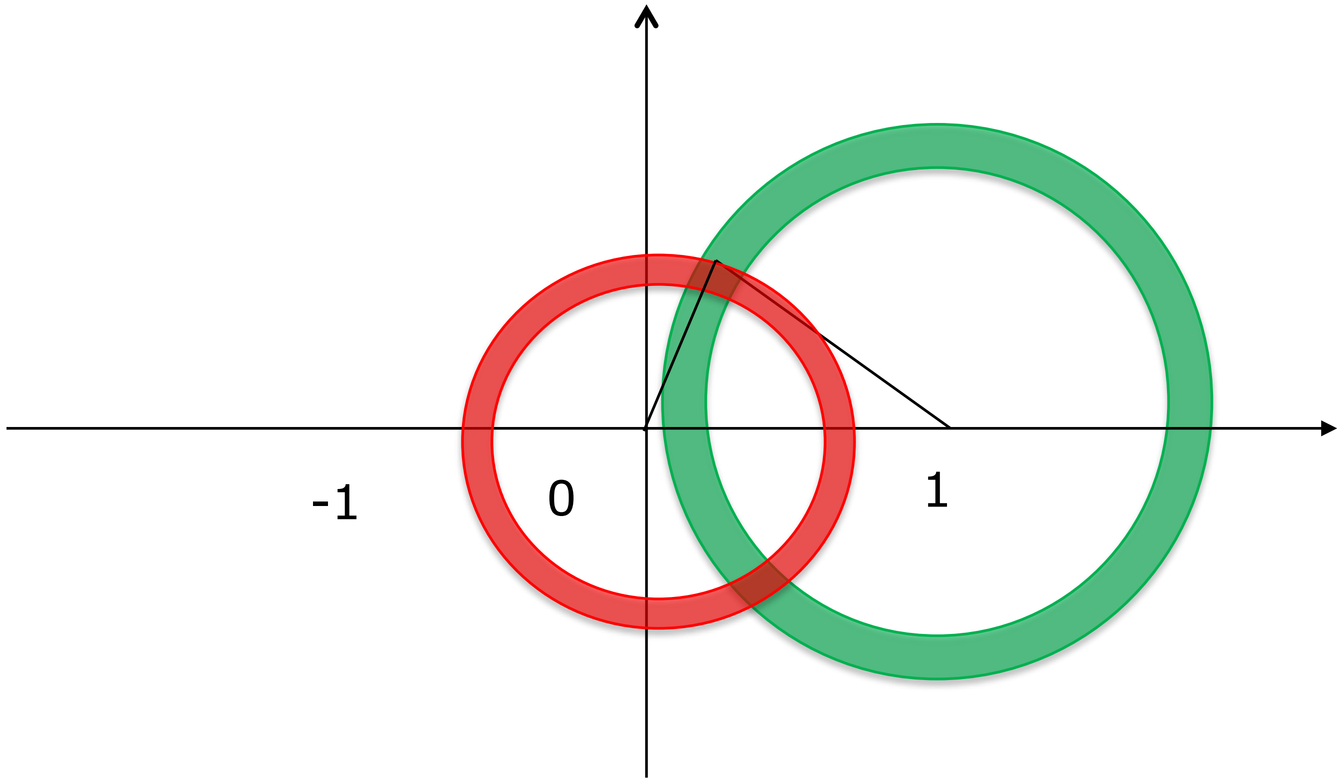




$$\frac{N_{Unmixed} - N_{Mixed}}{N_{Unmixed} + N_{Mixed}} \sim \cos \Delta m t$$

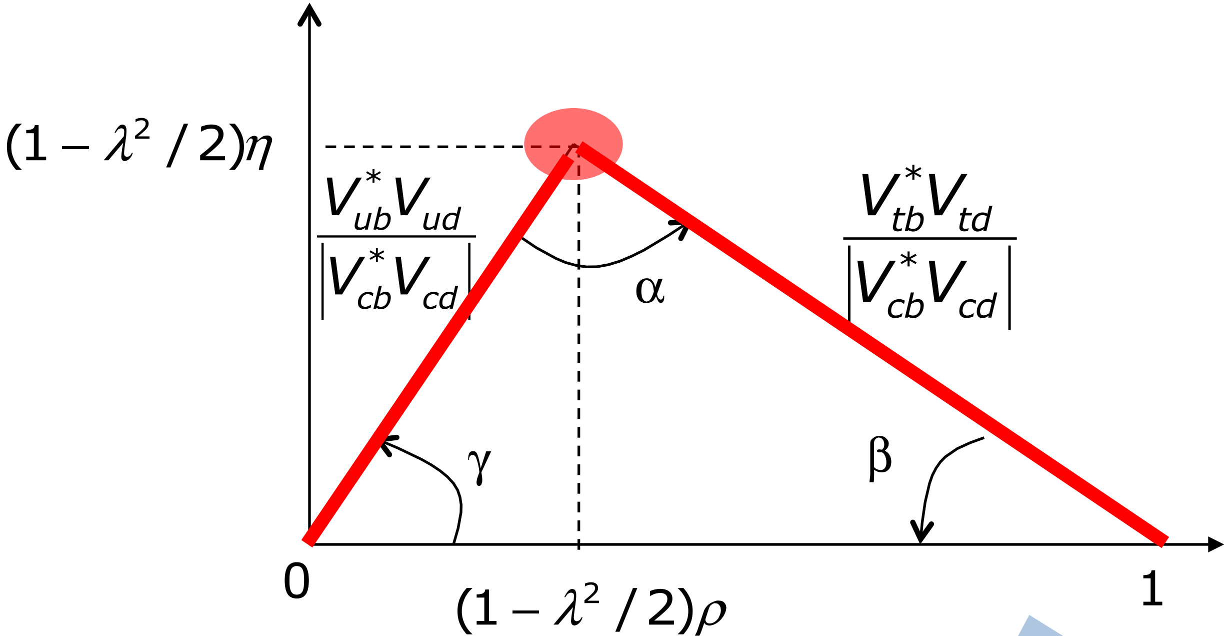
$\Delta m_d \propto |V_{td} V^*_{tb}|^2$



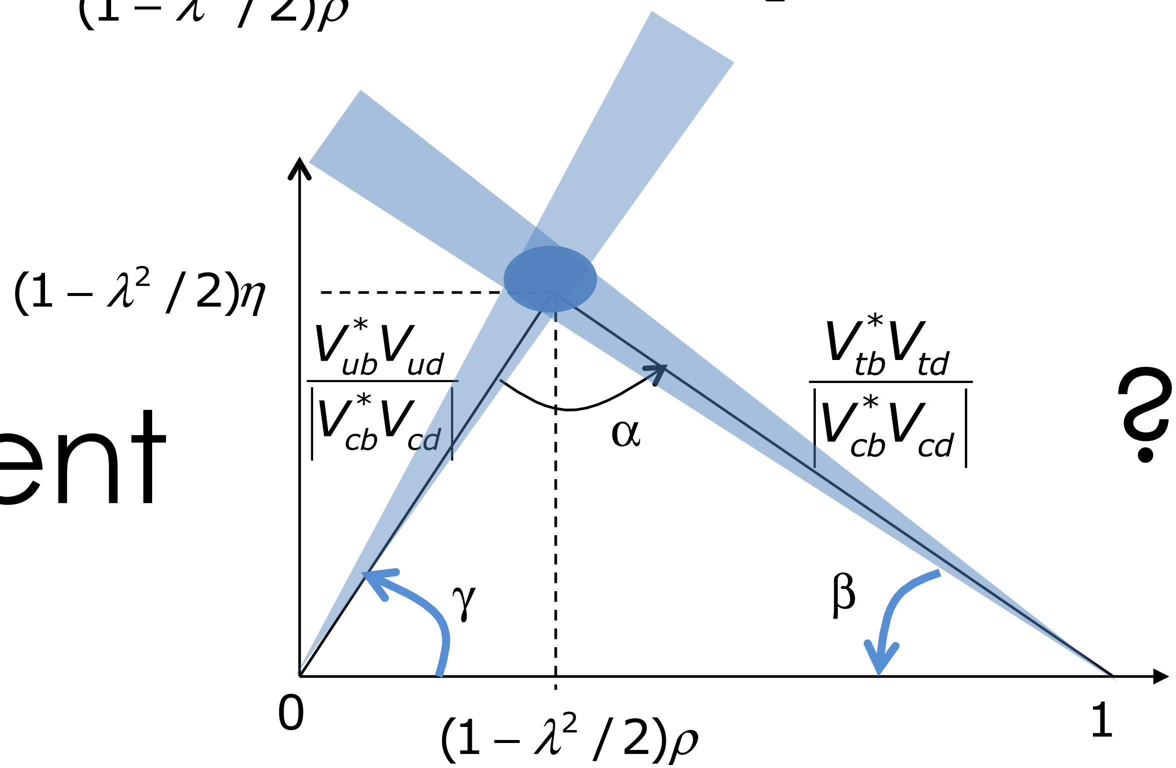


Are the two types of measurements compatible ?

Is



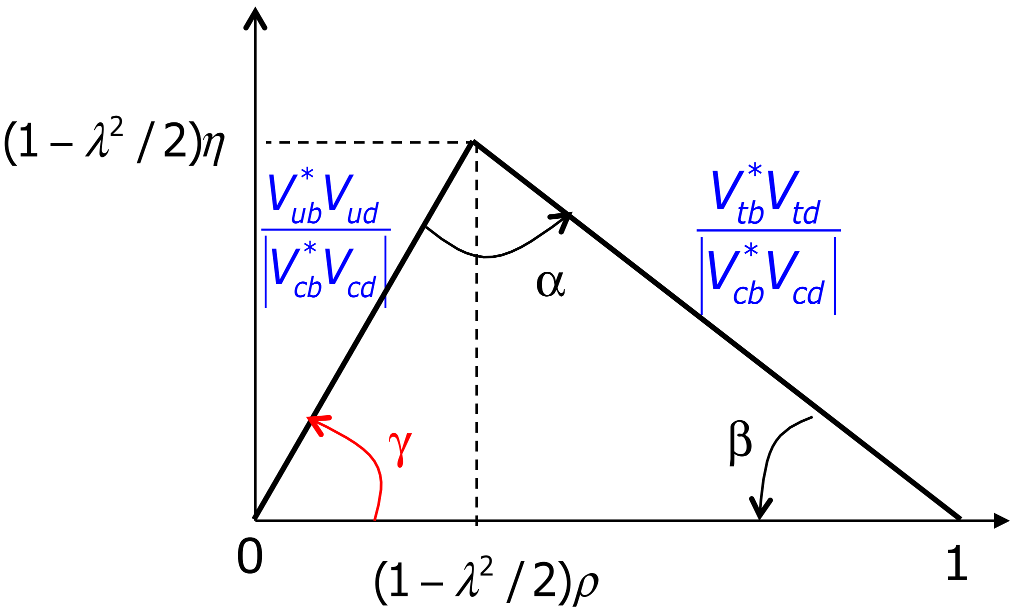
in agreement with



?

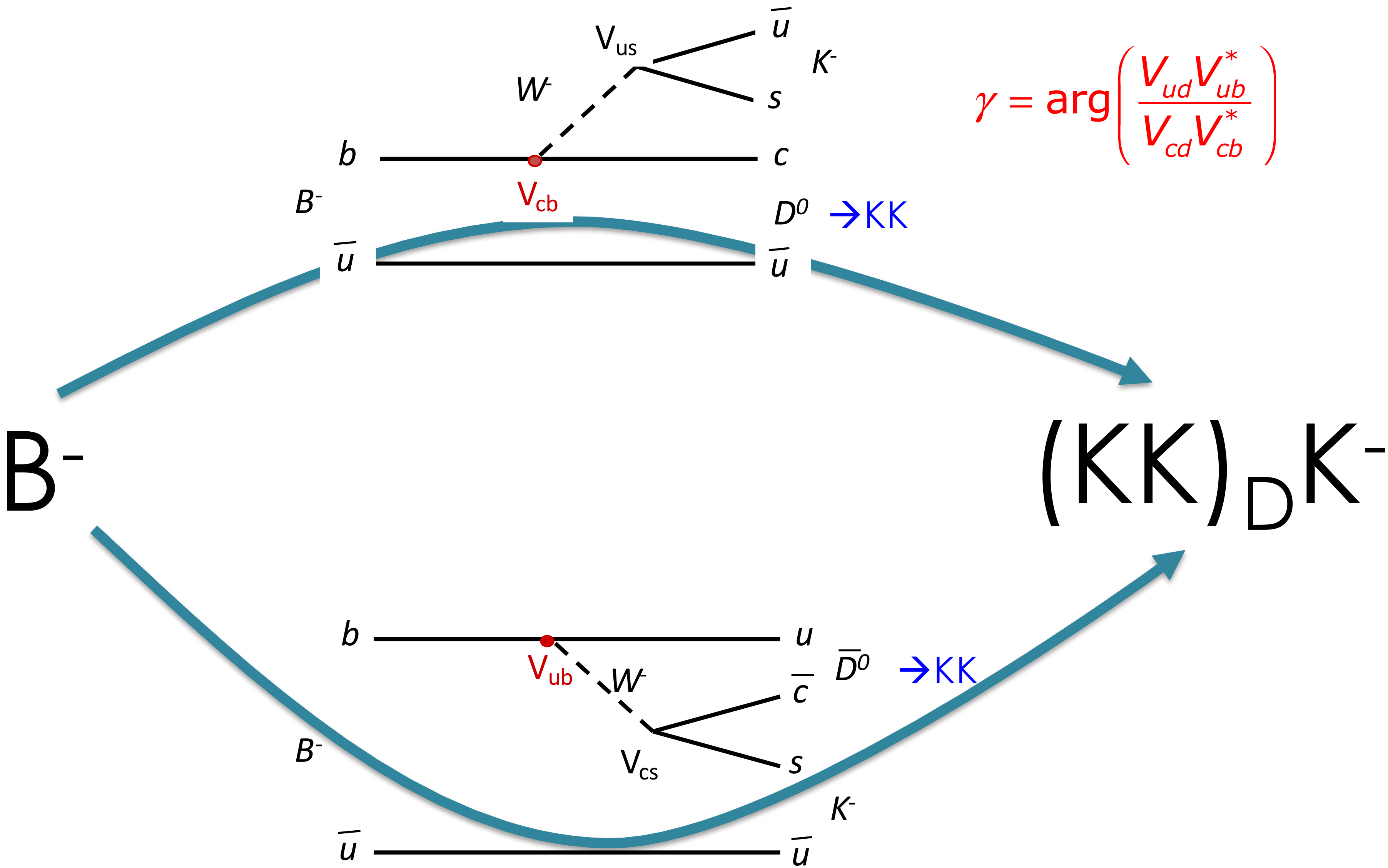
"the" unitarity triangle : $V_{ub}^*V_{ud} + V_{cb}^*V_{cd} + V_{tb}^*V_{td} = 0$

CP violation measurement



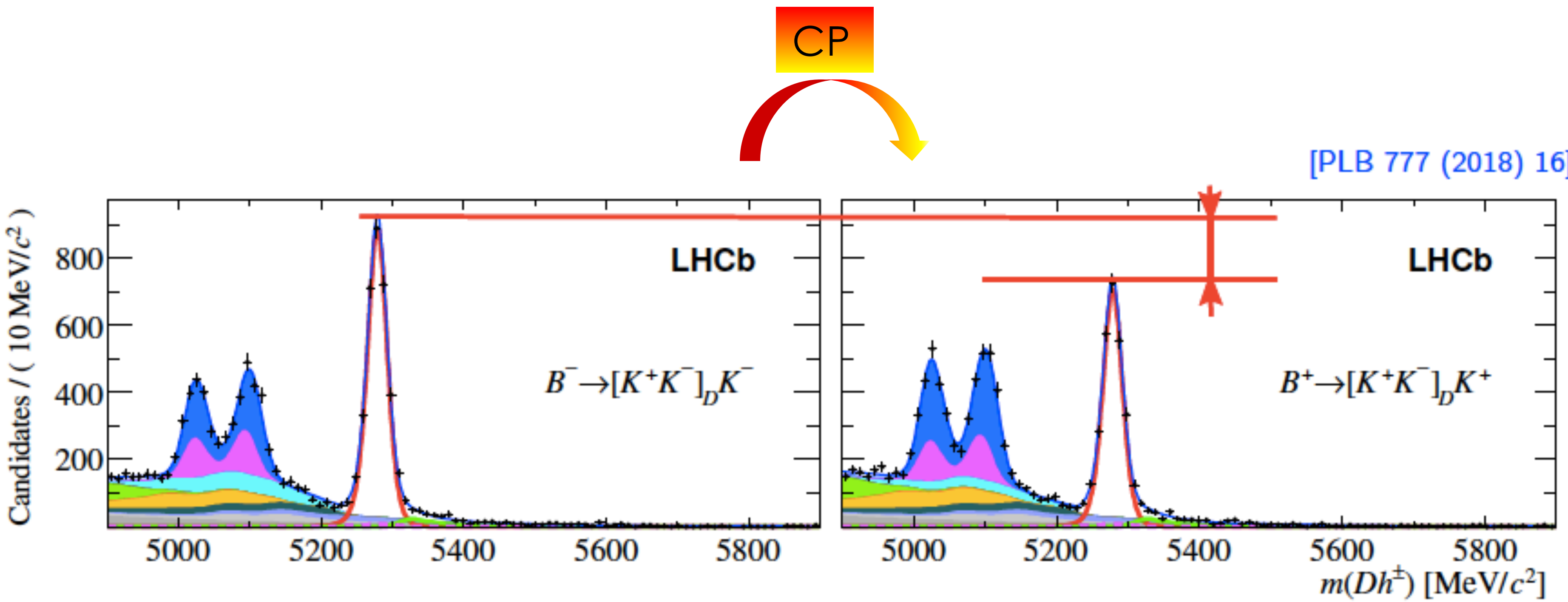
$$\gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

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



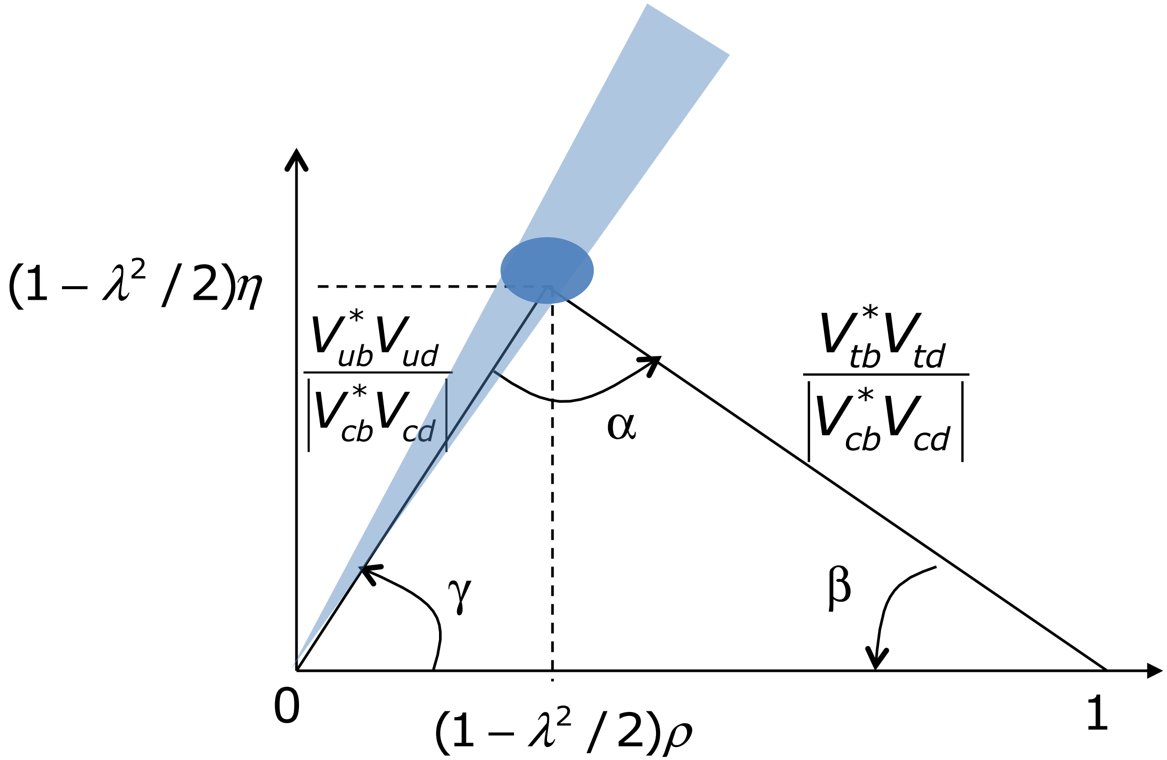
$(KK)_D K^{\pm}$

Start with the same amount of B^+ and B^-
Count $N(B^+ \rightarrow (KK)_D K^+)$ and $N(B^- \rightarrow (KK)_D K^-)$

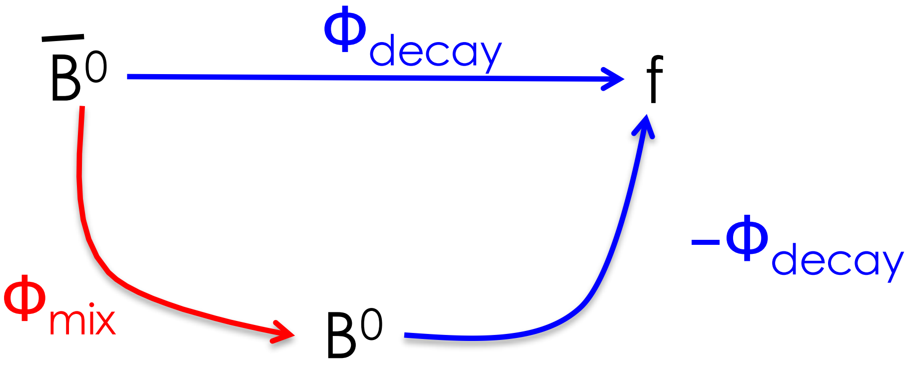


$$A_K^{KK} = +0.126 \pm 0.014 \text{ (stat)} \pm 0.002 \text{ (syst)}$$

significantly different from 0 !

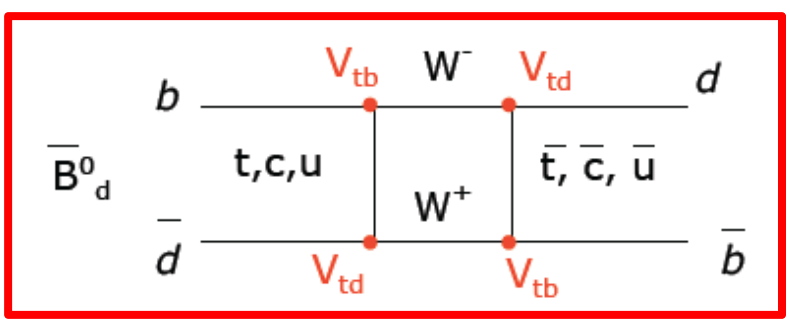

$(1-\lambda^2/2)\eta$
$\frac{V_{ub}^* V_{ud}}{|V_{cb}^* V_{cd}|}$
$\frac{V_{tb}^* V_{td}}{|V_{cb}^* V_{cd}|}$
α
γ
β
0
$(1-\lambda^2/2)\rho$
1

An example of CP induced by the interference between mixing and decay : the β angle

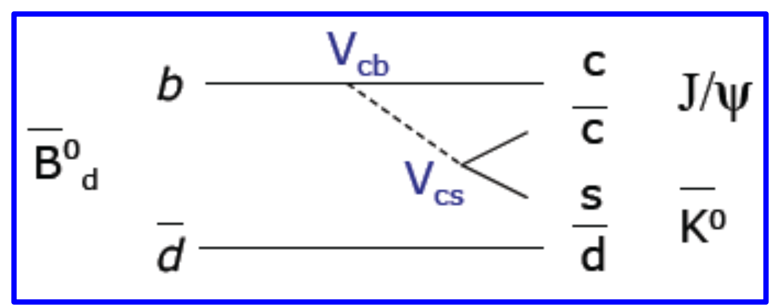


$$\Phi_d = \Phi_{mix} - 2\,\Phi_{decay}$$

Mixing



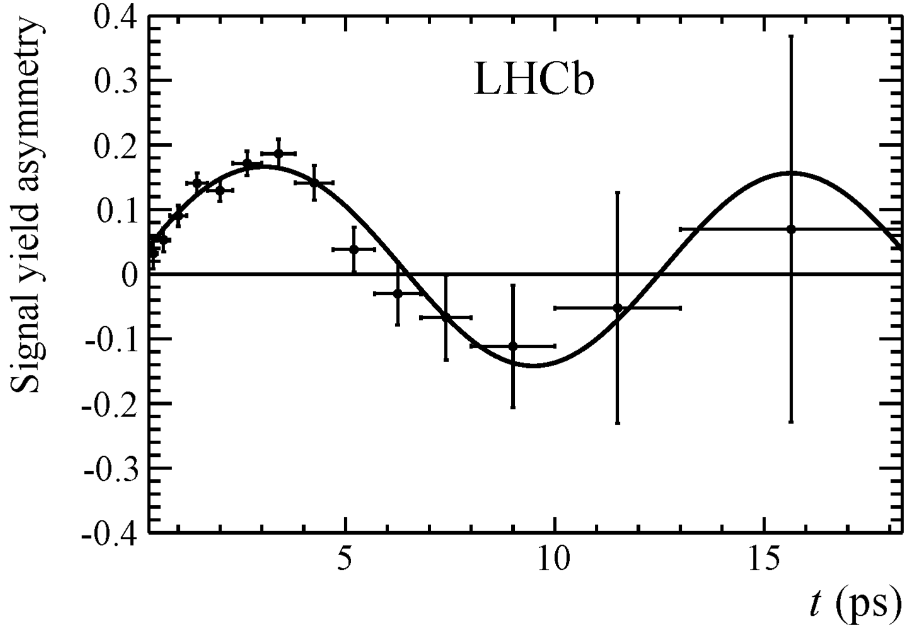
Decay



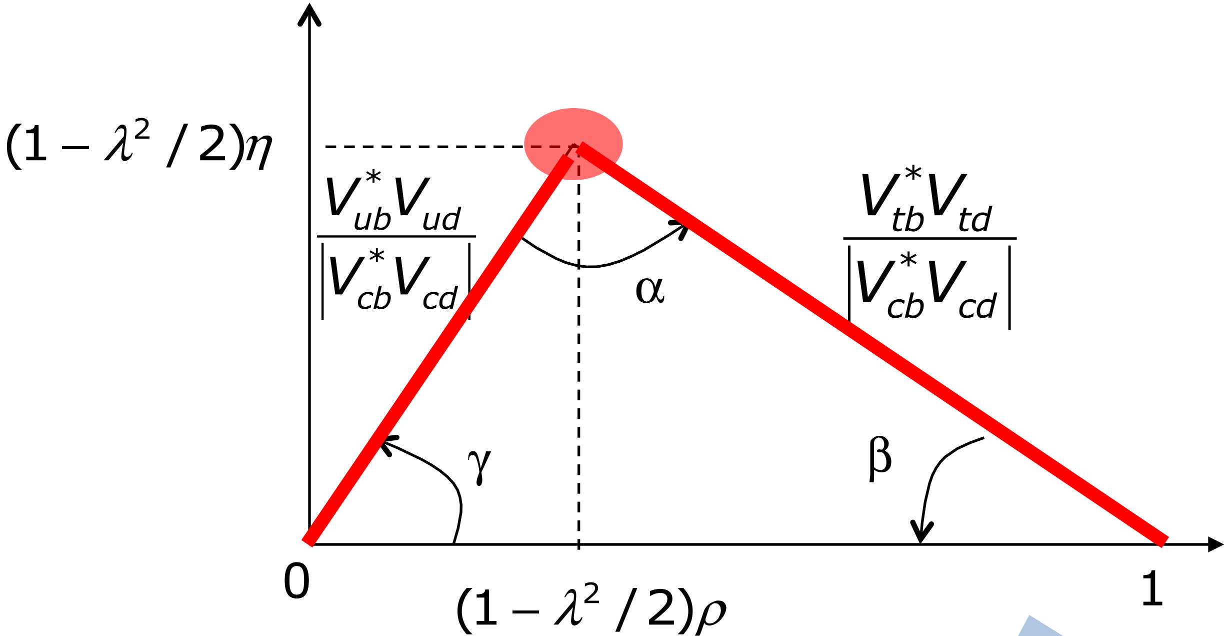
$$a_{f_{CP}}(t) = \frac{\text{Prob}(B^0(t) \to f_{CP}) - \text{Prob}(\overline{B^0}(t) \to f_{CP})}{\text{Prob}(\overline{B^0}(t) \to f_{CP}) + \text{Prob}(B^0(t) \to f_{CP})} =$$

$$= \sin(2\beta)\ \sin(\Delta m t)$$

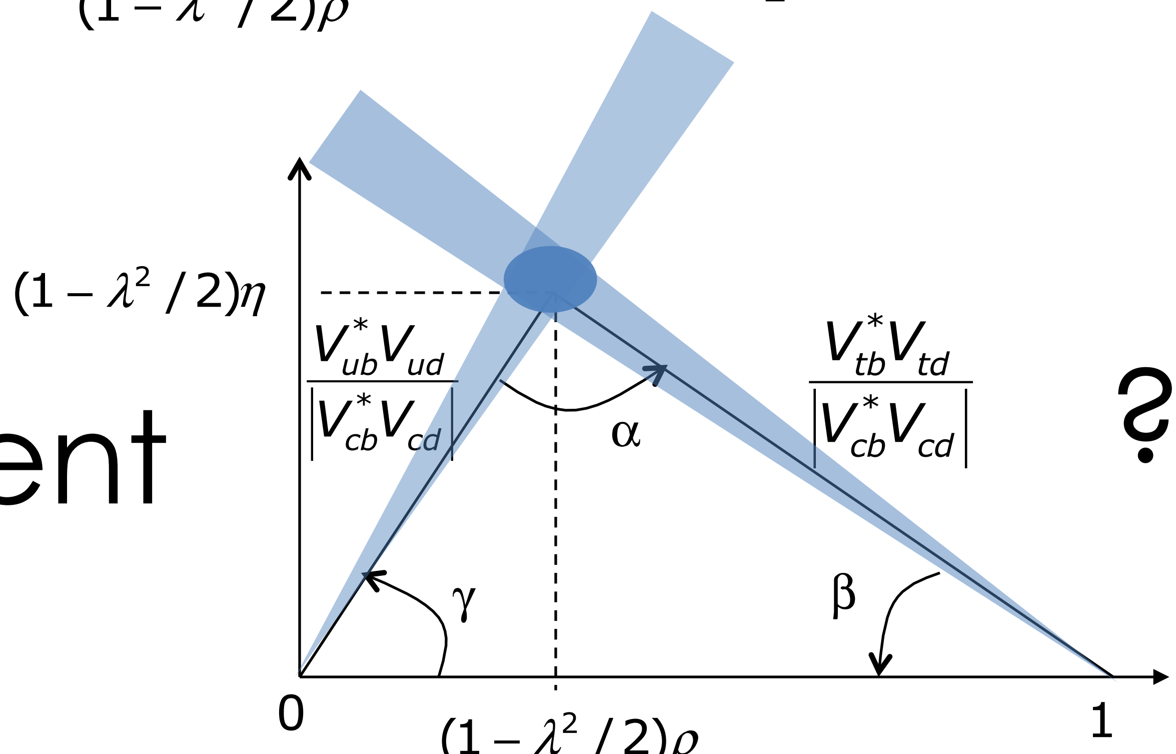
Pionnered by the B-factories



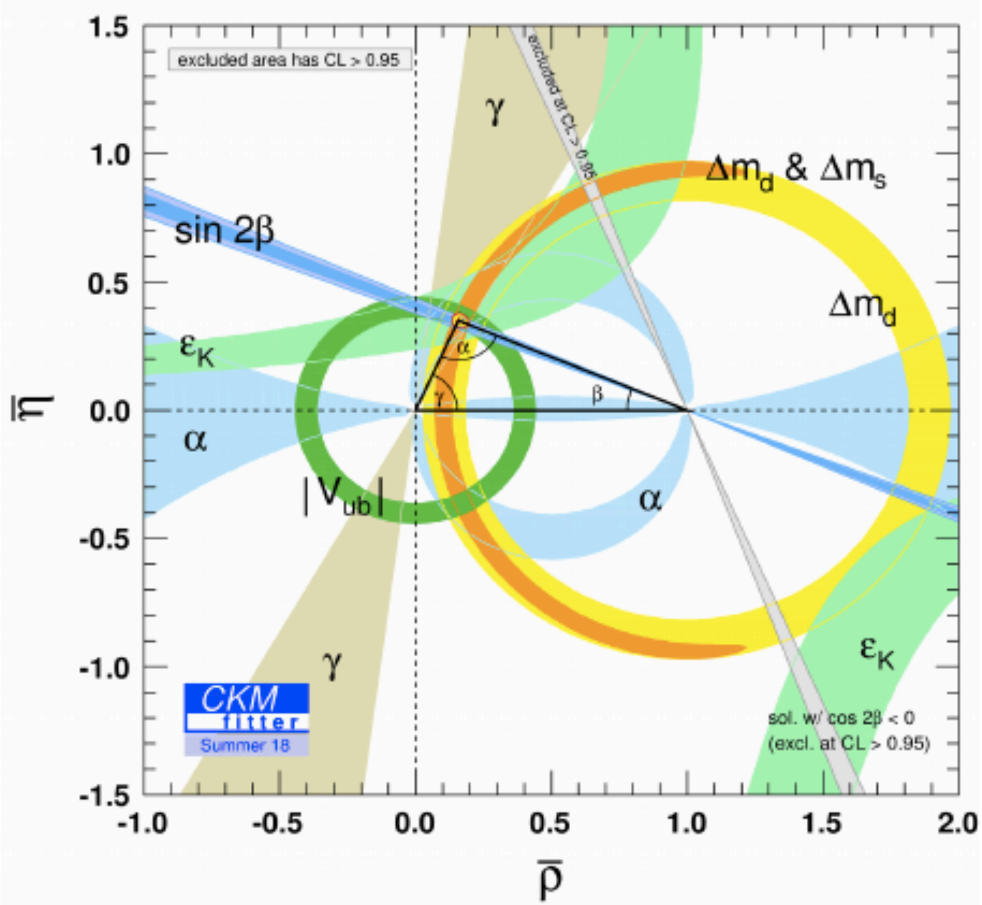
Is



in agreement with



?

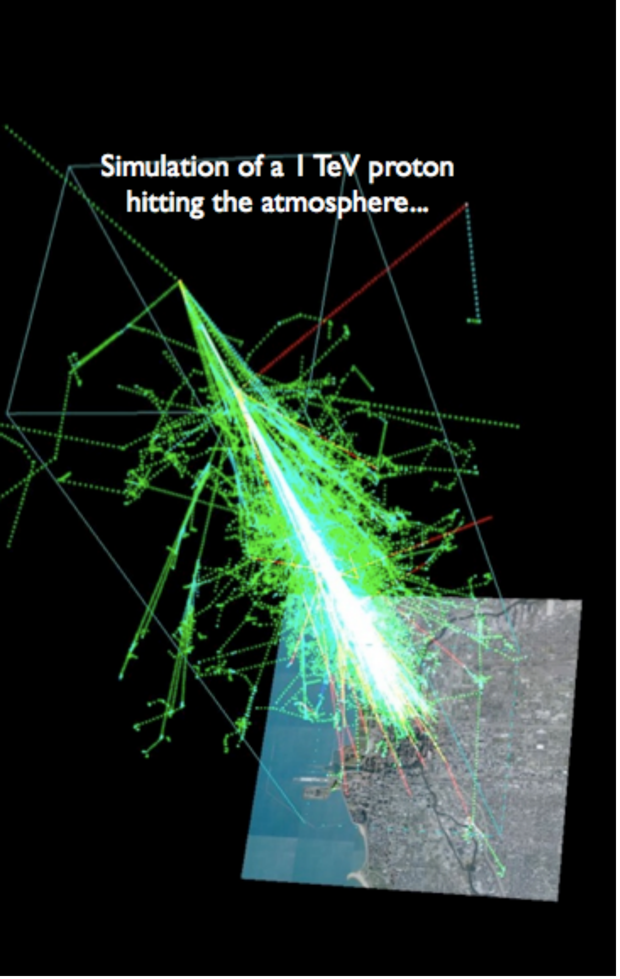


$$\bar{\rho} = 0.1577\,^{+0.0096}_{-0.0074}\ (5\%\ \text{unc.})$$
$$\bar{\eta} = 0.3493\,^{+0.0095}_{-0.0071}\ (2\%\ \text{unc.})$$

Sides and angles measurements in good agreement

The CKM model of CP violation has been confirmed

At the electroweak scale, the CKM mechanism dominates CP Violation

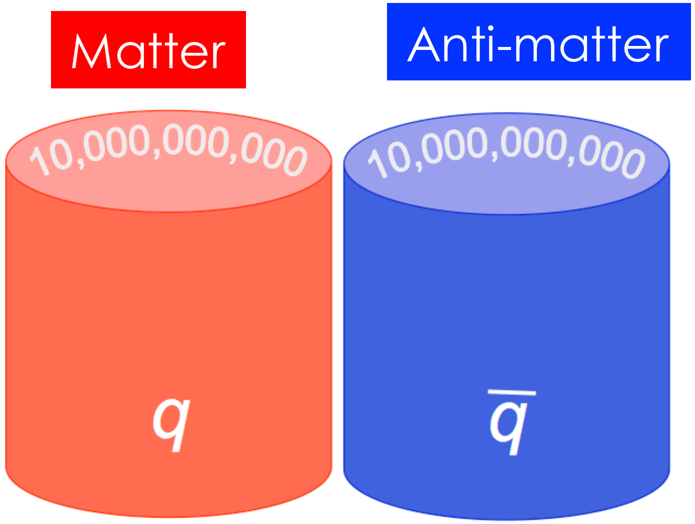


- Anti-matter in cosmic rays

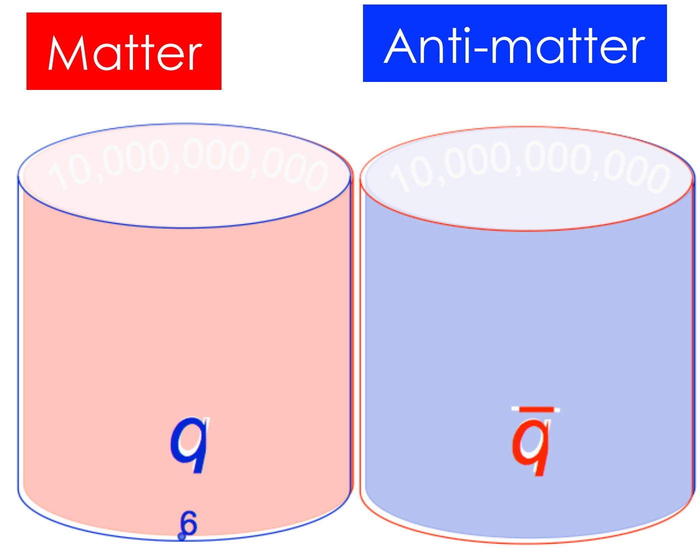
- No sign of light emission (anti-galaxy …)

- No significant sign of anti-nuclei (anti-He^4 …)
Searches on-going

Anti-matter in the Universe and Big Bang



Primordial Universe



Today

$$\frac{n(baryon) - n(antibaryon)}{n_\gamma} \sim 6\ 10^{-10}$$

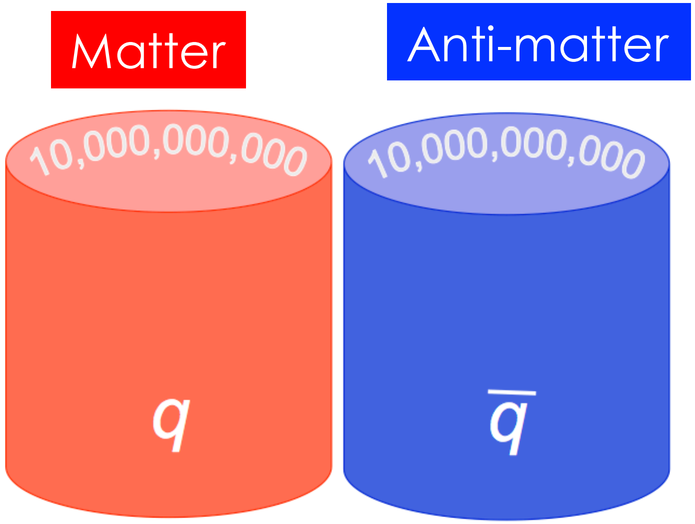
The 3 Sakharov conditions(1967)

1. Baryonic number violation: $X \rightarrow p\, e^-$

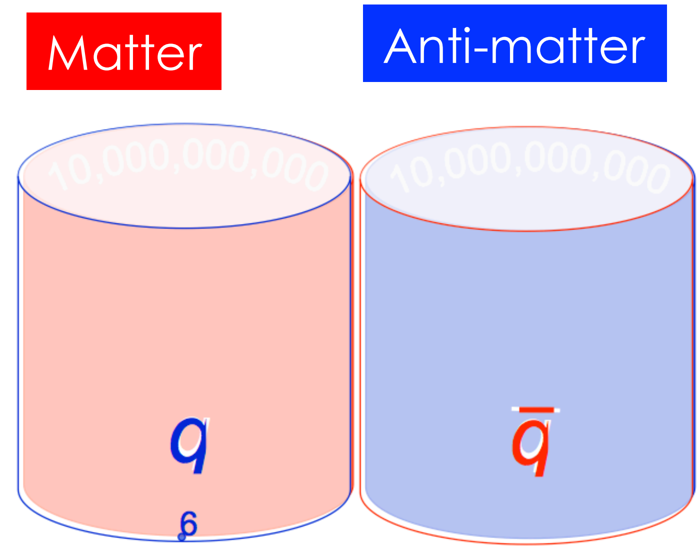
2. C and CP symmetries violation: $\Gamma(X \rightarrow p\, e^-) \neq \Gamma(\overline{X} \rightarrow \overline{p}\, e^+)$

3. To be out of equilibrium: $\Gamma(X \rightarrow p\, e^-) \neq \Gamma(p\, e^- \rightarrow X)$

Anti-matter in the Universe and Big Bang



Primordial Universe



Today

$$\frac{n(baryon) - n(antibaryon)}{n_\gamma} \sim 6\ 10^{-10}$$

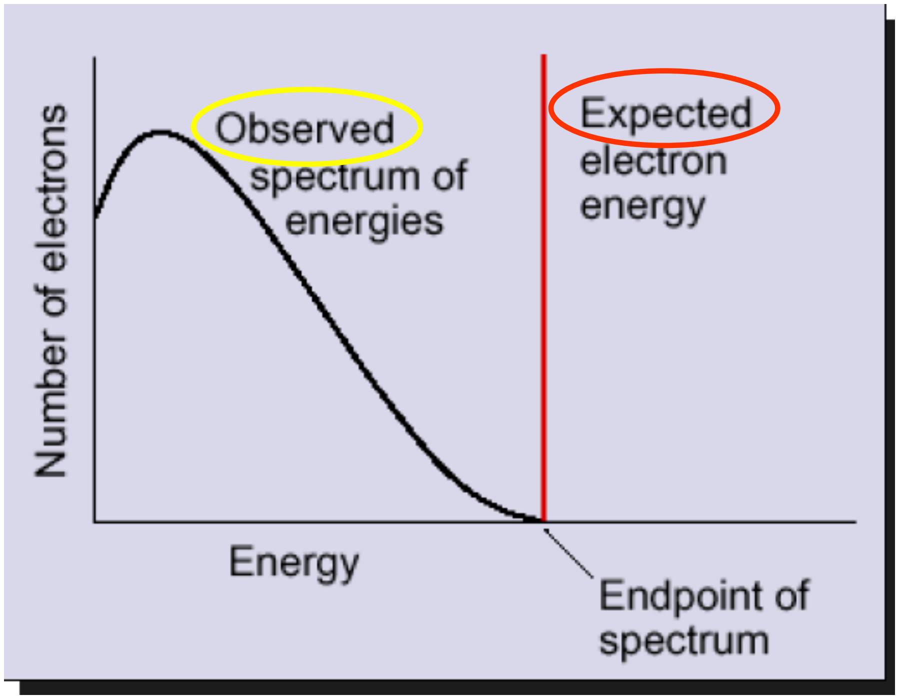
The 3 Sakharov conditions(1967)

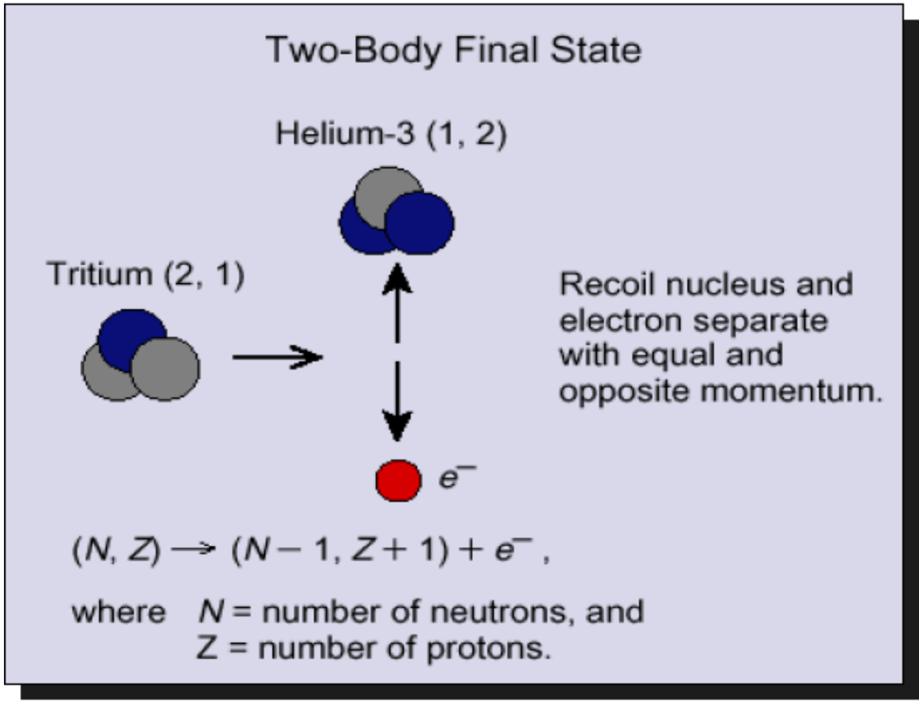
1. Baryonic n
2. C and CP
3. To be out of equilibrium:

But the CP violation phase of the SM is orders of magnitude too small

Neutrinos

The β decay





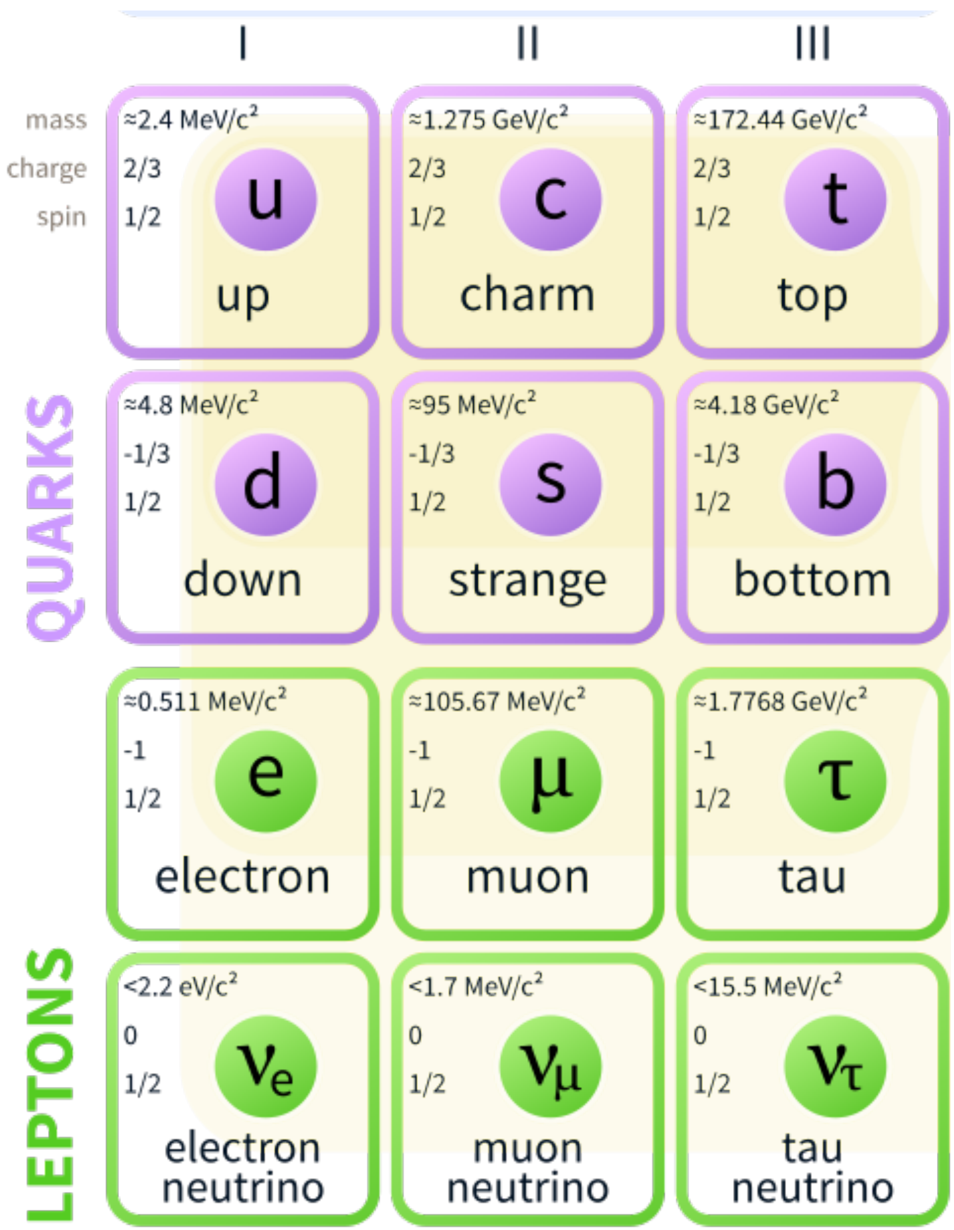
If β decay proceeds through n→p e^- the energy conservation predicts a monochromatic spectrum

1914 Chadwick observes a continuous spectrum …

→ Energy conservation is violated (Bohr) or an other particle is in the game (Pauli) :

β decay : n→p $e^- \bar{\nu}_e$

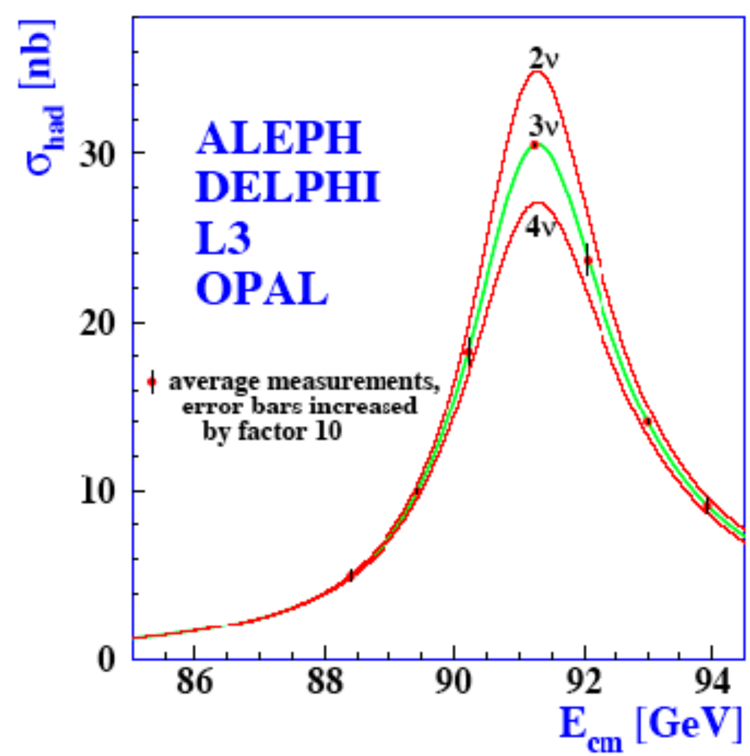
Fermionic sector of the SM :



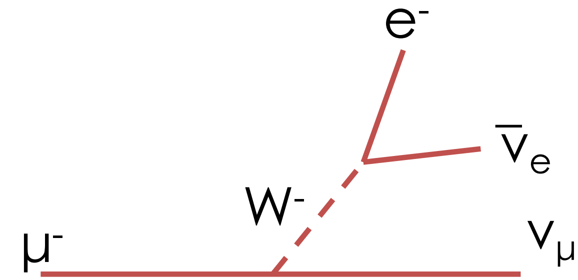
Lepton number conservation

3 types of neutrinos with m = 0

$N_\nu = 2.9840 \pm 0.0082$

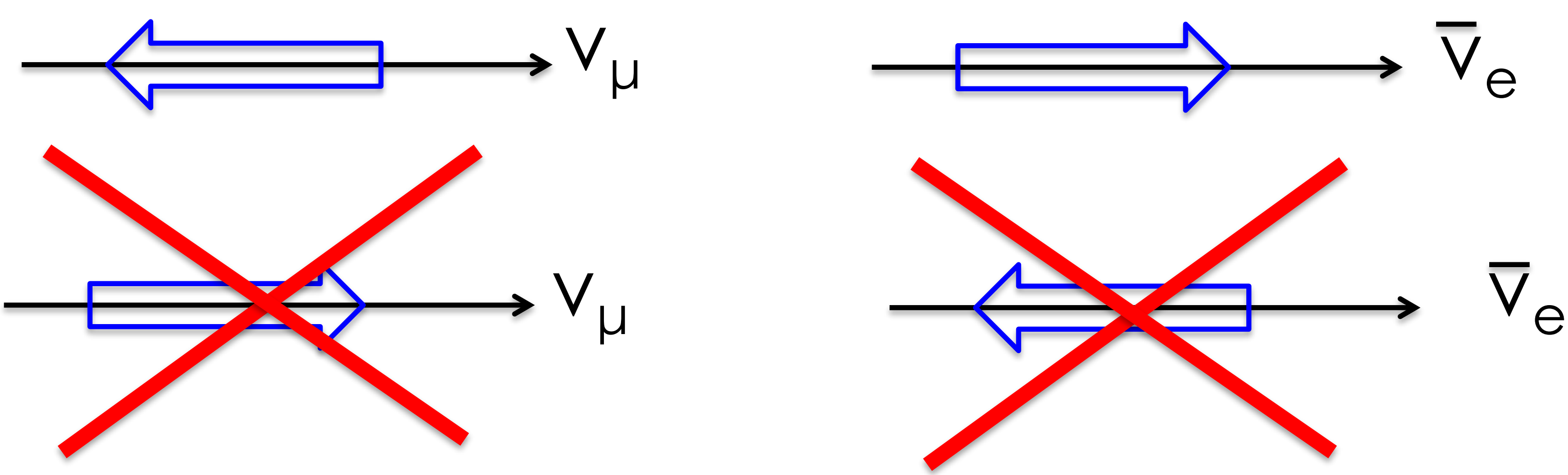


matrix element for the Feynman graph:



$$M = \left(\frac{g}{\sqrt{2}}\bar{u}_{\nu_\mu}\gamma^\mu \frac{1}{2}(1-\gamma_5)u_\mu\right)\frac{1}{M_W^2 - q^2}\left(\frac{g}{\sqrt{2}}\bar{u}_e\gamma_\mu \frac{1}{2}(1-\gamma_5)u_{\nu_e}\right)$$

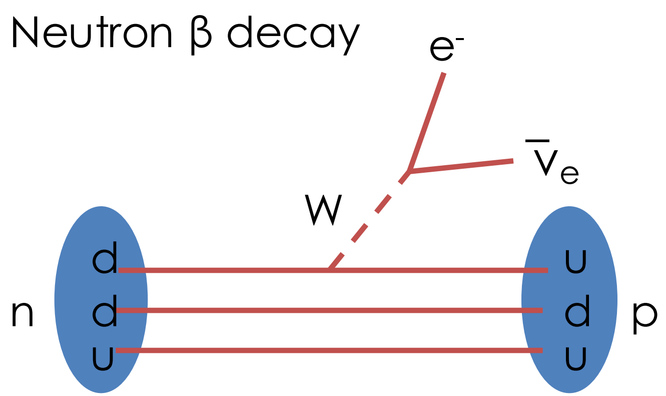
$$G_F = \frac{\sqrt{2}}{8}\frac{g^2}{M_W^2}$$

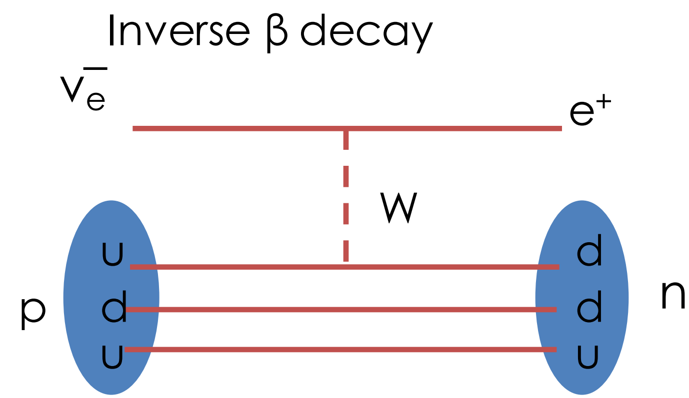


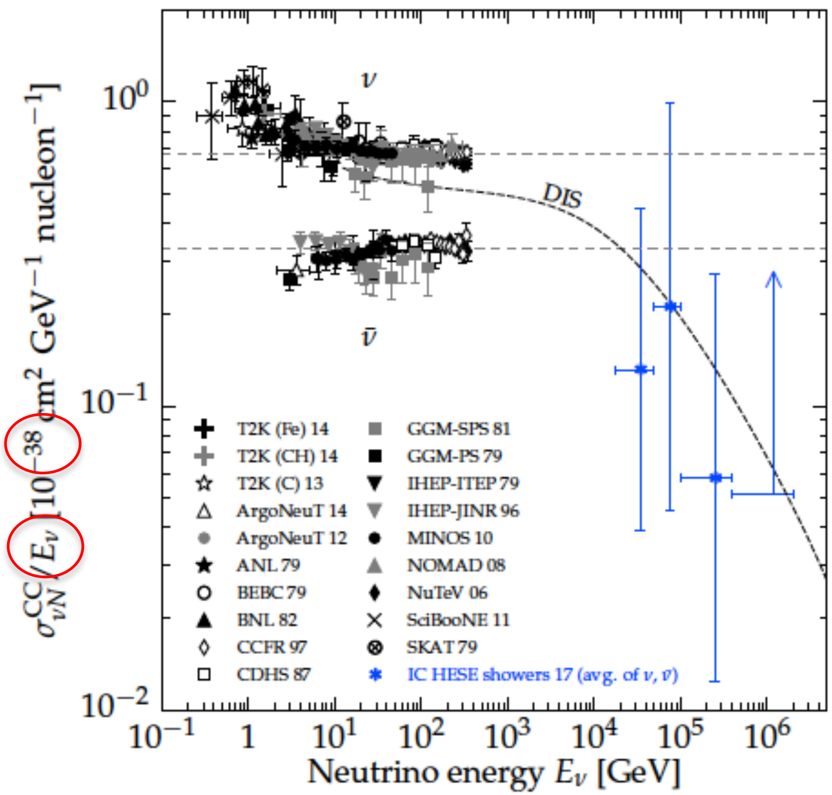
The ν is left handed (the anti-neutrino is right handed)

How to detect a neutrino

If ν are produced by β decay, they can be detected using the inverse reaction.







$\sigma(\nu\, p) \sim 10^{-43}\ cm^2$ for $E_\nu = 3$ MeV

So one needs :

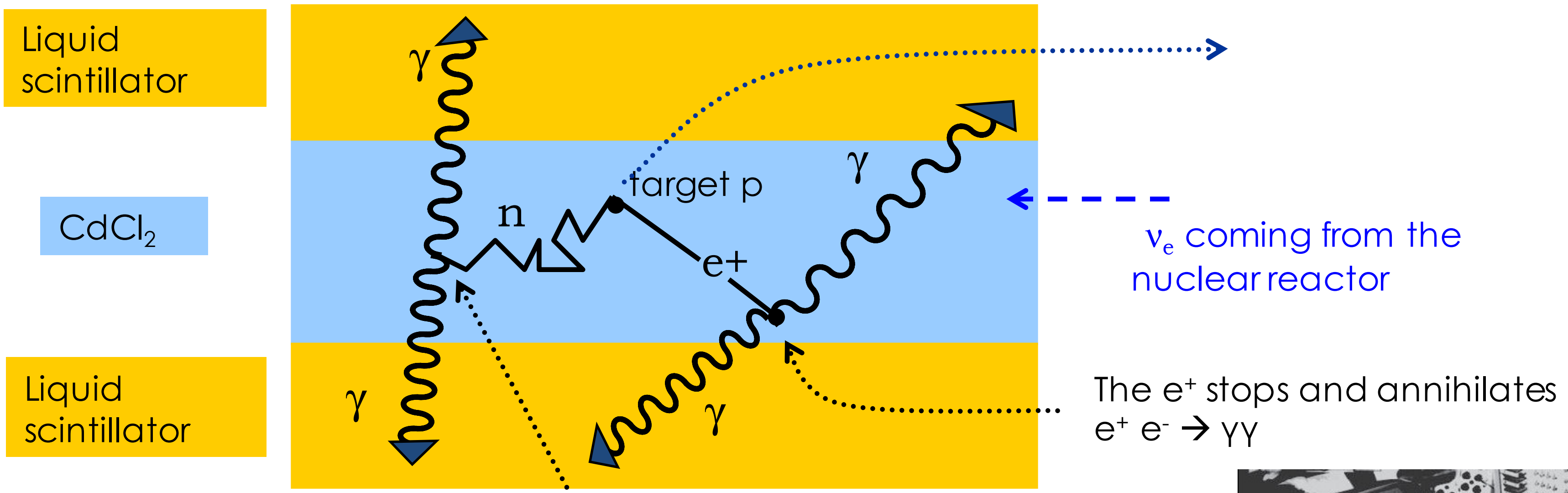
- Intense neutrino sources
- Large mass detectors

Sun
Cosmic rays interactions
Reactors
Accelerators

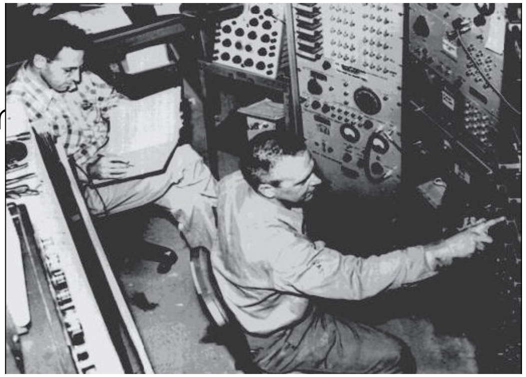
Direct experimental evidence of ν_e

- Reminder: around 1930, Pauli and Fermi made the hypothesis of the ν_e
- In 1956, Reines-Cowan experiment : experimental evidence using a nuclear reactor : search for the $\bar{\nu}_e\, p \rightarrow n\, e^+$ reaction

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



The neutron undergoes sequential collisions and after ~1 ms is captured by the Cadmium → γ emission

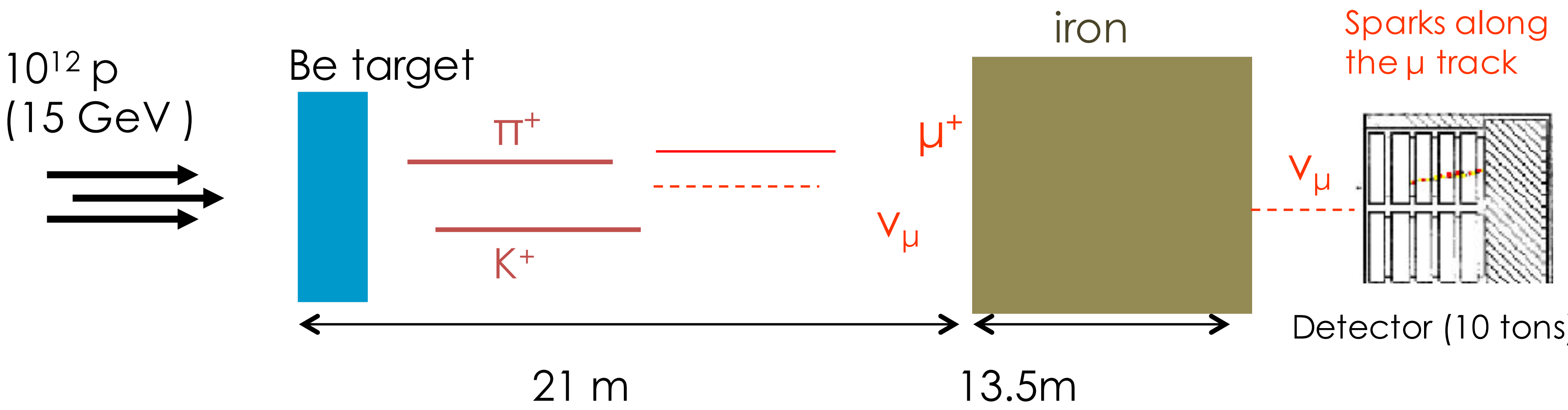


- Checks :
  - Target without cadmium
  - data taking with nuclear reactor OFF

→ 3.0 ±0.2 signal events/hour

Two other types de neutrinos

- In 1962 : Schwartz, Lederman et Steinberger experiment at BNL : $\nu_\mu \neq \nu_e$



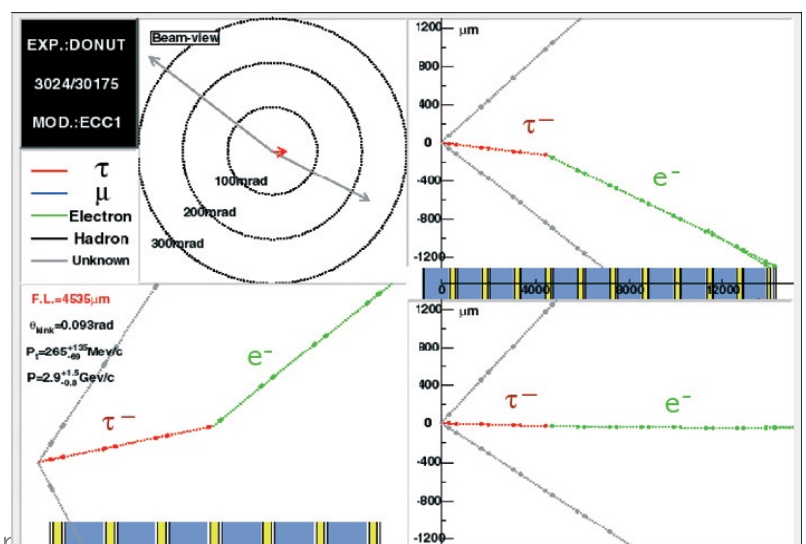
- in 2000 the third neutrino ν_τ (DONUT) at Fermilab :

$$D_s \to \tau \nu_\tau$$

ν_τ beam

$$\nu_\tau + N \to \tau + X$$

3 years of data taking : 4 unambiguous ν_τ signal events



BUT :

End of the 60's

In a deep mine the Davis Chlorine experiment

Inverse beta decay $Cl^{37}+\nu \rightarrow Ar^{37}+e^-$ → Searching for ν_e

Ar is chemically very different from Chlorine → can be separated

It is radioactive and reverts to Cl^{37} emitting an Auger electron (lifetime 35 days)

Count a few atoms in a tank of few hundred tons !

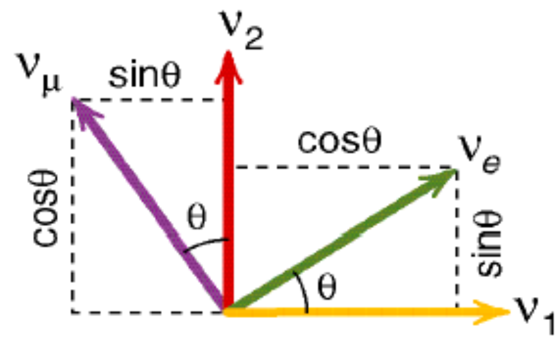
The observed rate was about 3 times smaller than the predicted one …

Which one is wrong ? The experiment or the Solar Model ?

Neutrinos mixing

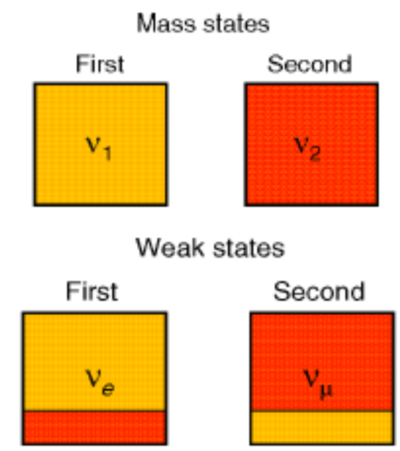
If neutrinos have masses : Mass eigenstates ≠ weak (flavour) eigenstates

→ 3x3 matrix (CKM-style)



Assume for simplicity two families : the 2 basis are connected through a simple rotation :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



In the case of 3 families :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Weak interaction eigenstates (n_α)

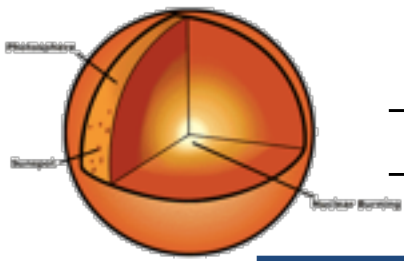
PMNS matrix (Pontecorvo, Maki, Nakagawa, Sakata)

Mass eigenstates (n_i)

$$\nu_\alpha = \sum_i^N U_{\alpha i} \nu_i$$

Neutrinos oscillations : the case for 2 families

source

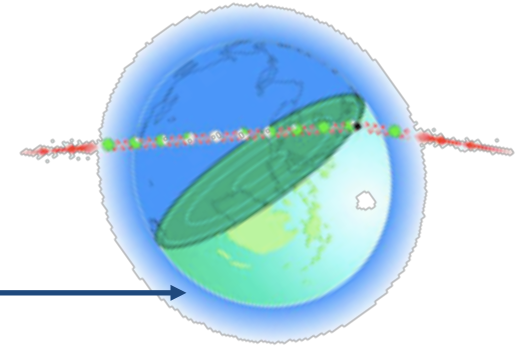


ν_e

propagation

L

detection



The weak interaction produces neutrinos of a given flavor

$$|\nu(x=0)\rangle = |\nu_e\rangle$$
$$= \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

Evolution with time in the mass eigenstates basis follows Schrödinger equation (lab frame):

$$|\nu(L)\rangle =$$
$$e^{-i(E_1 t - p_1 L)}\cos\theta|\nu_1\rangle + e^{-i(E_2 t - p_2 L)}\sin\theta|\nu_2\rangle$$

Ultra relativistic neutrinos of momentum p

$$p >> M \quad \Rightarrow E_i = \sqrt{p^2 + M_i^2} \approx p + \frac{M_i^2}{2p}$$

$$|\nu(L)\rangle = e^{-i\frac{M_1^2}{2p}L}\cos\theta|\nu_1\rangle + e^{-i\frac{M_2^2}{2p}L}\sin\theta|\nu_2\rangle$$

Detection again via weak interaction :

$$\nu_\mu N \rightarrow \mu^- X$$
$$\nu_e N \rightarrow e^- X$$

$$P(\nu_e \rightarrow \nu_\mu) = |< \nu_\mu \,|\, \nu(L) >|^2$$
$$\approx \sin^2 2\theta \sin^2 \frac{\Delta m_{12}^2 L}{4E}$$
$$\Delta m_{12}^2 = M_1^2 - M_2^2$$

E is the average energy of the mass eigenstates

The **probability** for a ν_μ to **transform** into a ν_e at a **distance L** from the source is:

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\frac{(m_2^2 - m_1^2)L}{4E}$$

Mixing angle between flavor and mass states

Neutrino masses

$$P_{\alpha\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

appearance

2 parameters
1 measurement

$$P_{\alpha\alpha} = 1 - P_{\alpha\beta} < 1$$

disappearance

The other flavour eigenstates (not present at t=0) appear during the propagation

The total flux is conserved.

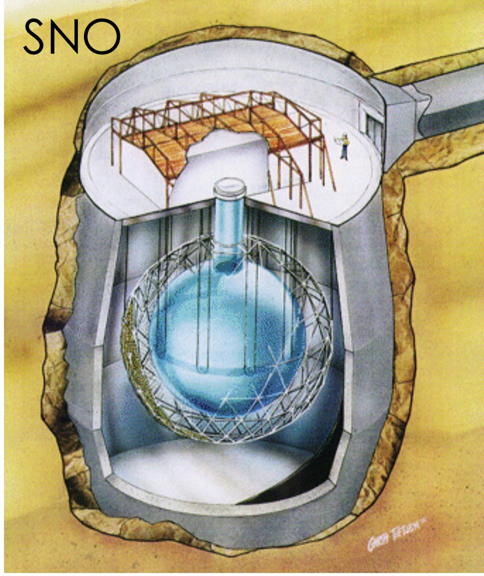
Neutrinos oscillations are only sensitive to the difference of the masses squared (NOT to the absolute value)

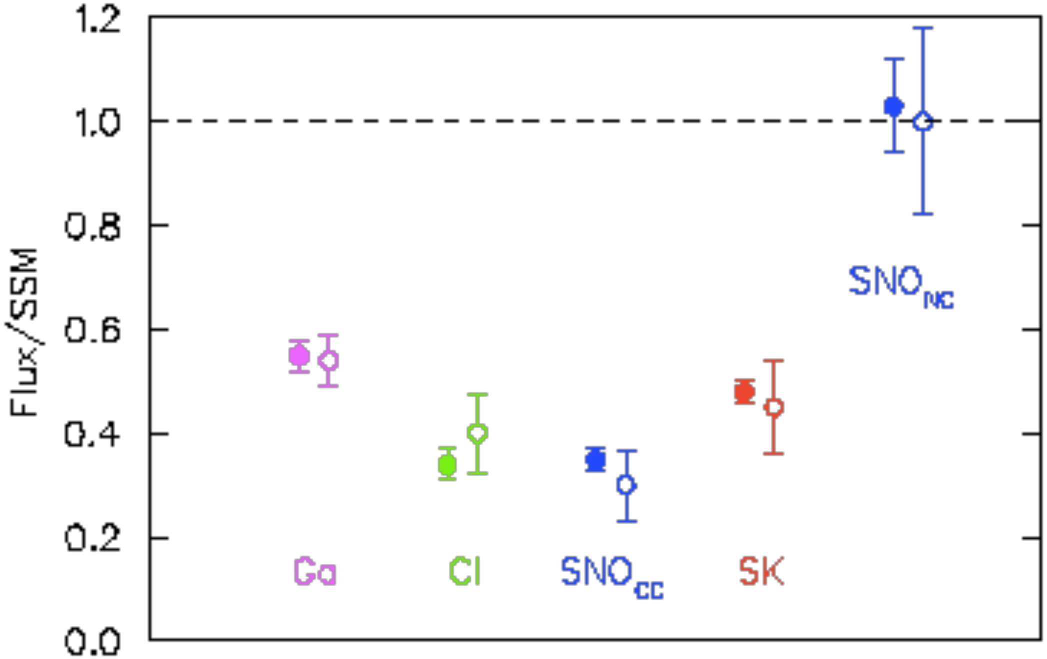
The mixing phenomenom can be tested using :

- Neutrinos from the sun
- Neutrinos from reactors
- Neutrinos from accelerators

If neutrinos oscillation is observed it implies that neutrinos have masses …

Neutrinos from the sun !





the neutral current reaction (NC) measures the ($\nu_e + \nu_\mu + \nu_{\tau,}$) flux

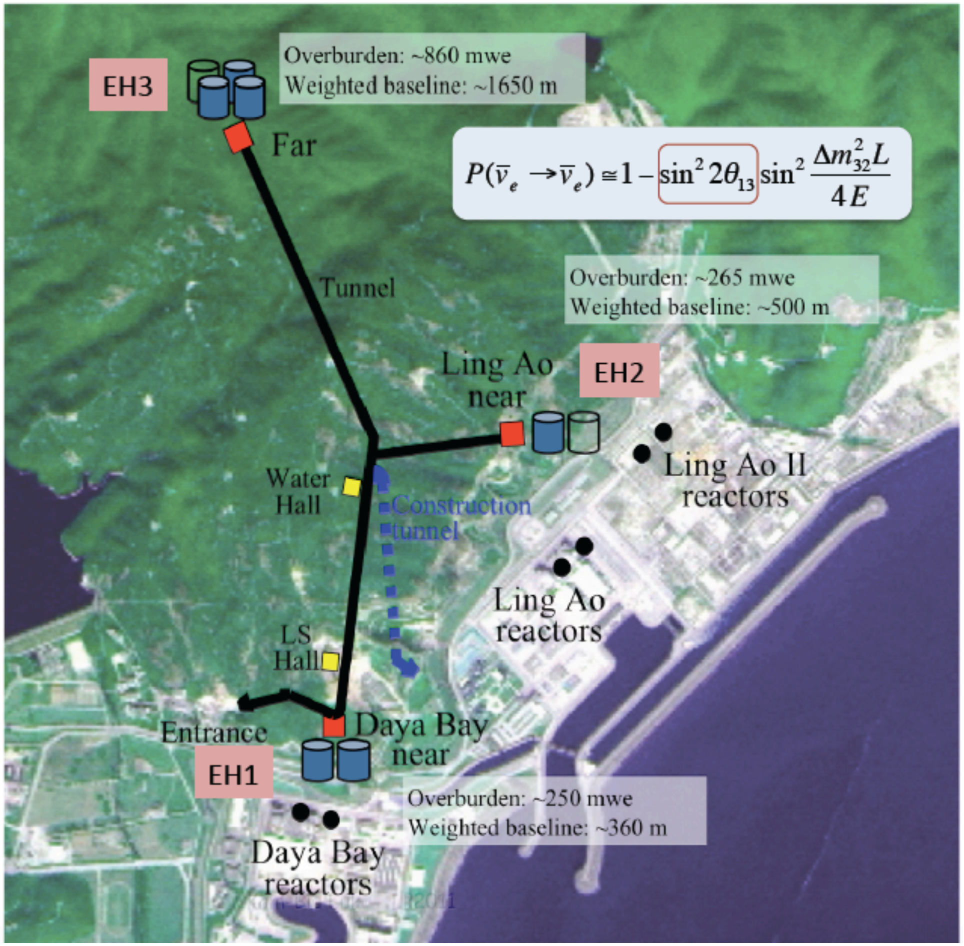
The charged current (CC) one the ν_e flux

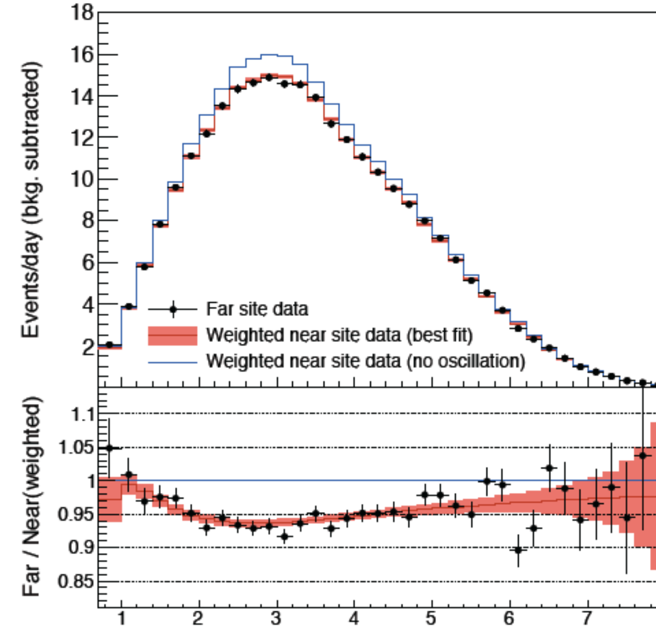
The combination of all solar neutrino experiments (before SNO) implied that solar neutrinos were disappearing between production (in the sun core) and detection in the earth.

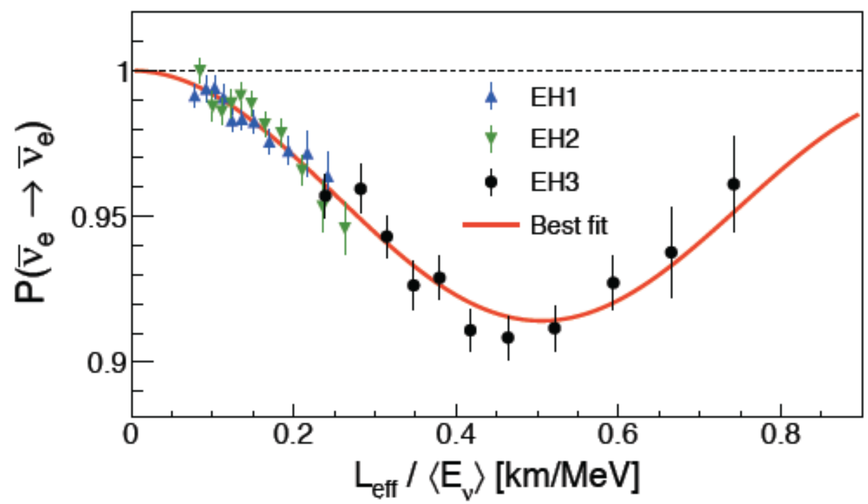
So the sun is shining the expected number of neutrinos but many of them are detected as and ν_μ and/or $\nu_{\tau,}$!

Neutrinos from the reactors : $\bar{\nu}_e$

PRL 115 111802 DayaBay

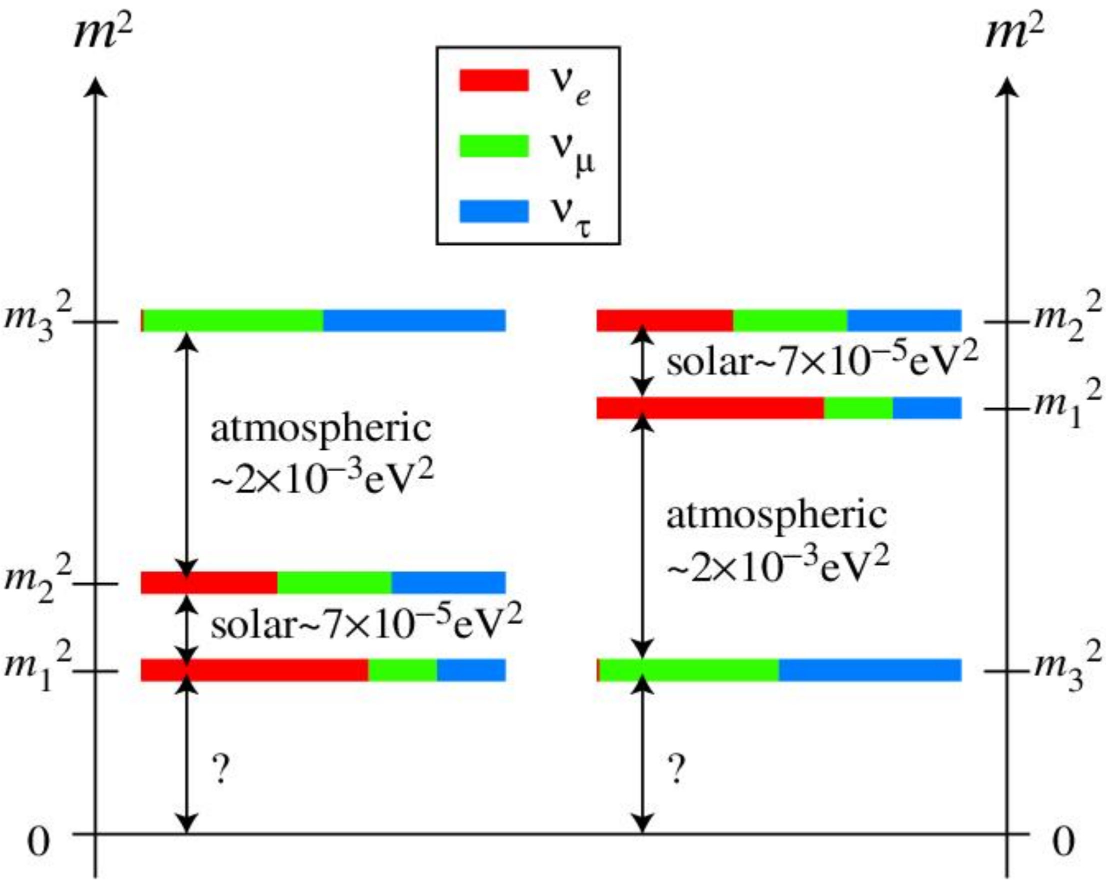






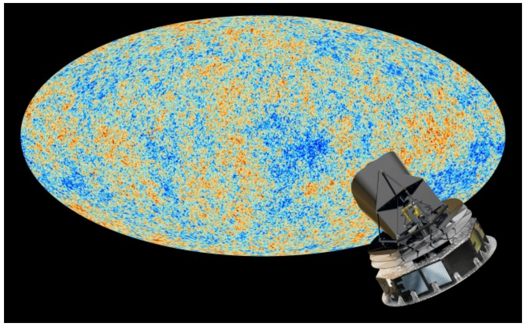
What is measured : $m_2^2 - m_1^2$ and $m_3^2 - m_2^2$

➔ the neutrinos have masses but two scenarii are possible :



Which is the correct hierarchy ?

Cosmological constraints on Σm(ν)



- The neutrinos mass would modify the (delicate) balance between gravity and the Hubble expansion

- They would also have also effect on the structure formation …

- Small modifications in the Cosmological Microwave Background which is the fingerprint of what happended at the very beginning of the Universe

→ $\Sigma m(\nu) < \sim 0.2$ eV

Weak interaction in summary

- All quarks and leptons are sensitive to the weak interaction
- M_W~M_Z~100 GeV
  - → short range
  - → Extremely weak : (~ 10^{-8} smaller intensity than the strong interaction at a distance of 1 fm)
- The weak interaction
  - violates maximally C and P
  - does not conserve the flavour
  - Exhibits a tiny CP violation
- The weak and mass eigenstates of quarks are not the same, they are related via V_{CKM} which is a natural source of CP violation
- Neutrinos are only sensitive to the weak interaction
  - They have masses ! (but we do not know the values)
  - They may be an open window to physics beyond the Standard Model

3 families ⎝ 3 angles (θ_{ij}) and one phase (δ)

V_{ub}

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

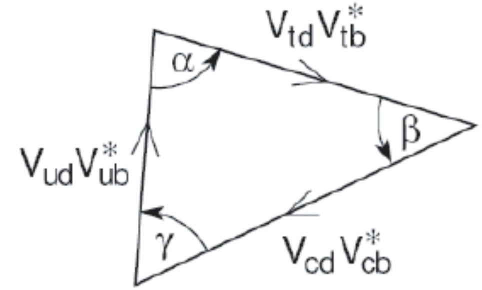
$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

→ Parametrization in power of λ ($=\sin\vartheta_C$) $= s_{12} = |V_{us}| \sim 0.22$

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \vartheta(\lambda^4)$$

$$\lambda = \sin\theta_c \sim 0.22$$
$$A \sim 0.80$$
$$\rho \sim 0.20$$
$$\eta \sim 0.35$$

“the” unitarity triangle : $V_{ub}^{*}V_{ud} + V_{cb}^{*}V_{cd} + V_{tb}^{*}V_{td} = 0$



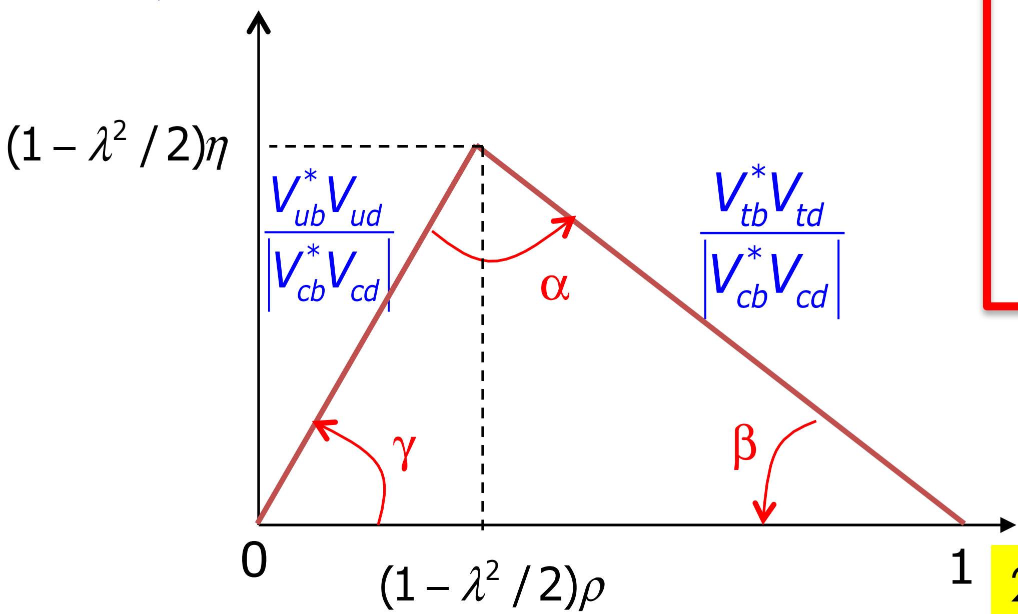
$$V_{td}\,V_{tb}^{*} = A\lambda^{3}(1-\rho-i\eta) + A\lambda^{5}(\rho+i\eta)$$

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

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

at order λ^5

Basis of the triangle aligned on the real axis, normalized to 1



$$\beta = \arg\left(\frac{V_{td}V_{tb}^{*}}{|V_{cd}V_{cb}^{*}|}\right) = \text{atan}\left(\frac{(1-\lambda^{2}/2)\eta}{1-(1-\lambda^{2}/2)\rho}\right)$$

$$\gamma = \arg\left(\frac{V_{ud}V_{ub}^{*}}{|V_{cd}V_{cb}^{*}|}\right) = \text{atan}\left(\frac{\eta}{\rho}\right)$$

$$\alpha+\beta+\gamma = \pi$$

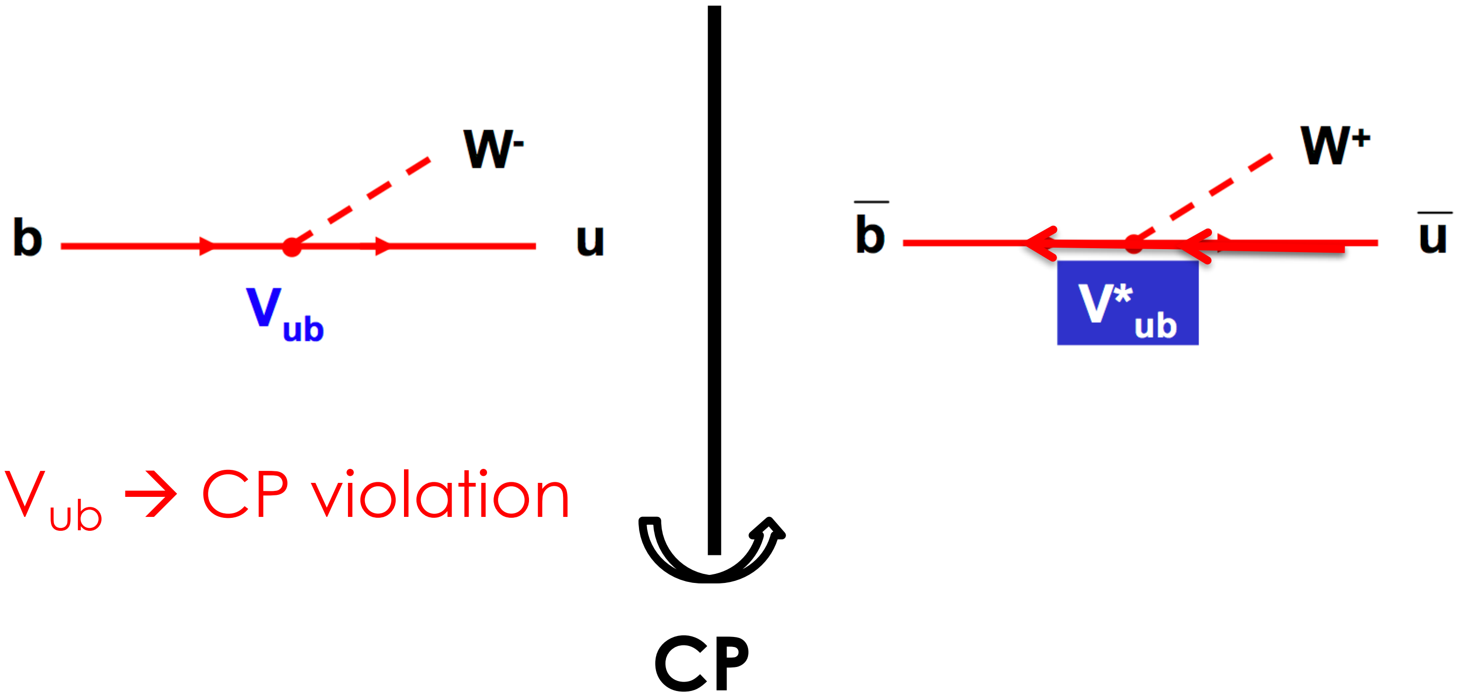
2 sides ; 3 angles

⇒ aim : to overconstrain this unitarity triangle

precision test of the Standard **Model**

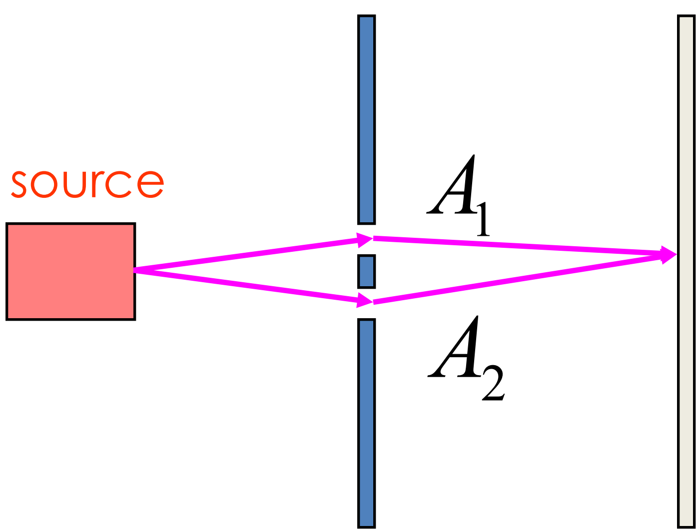
(

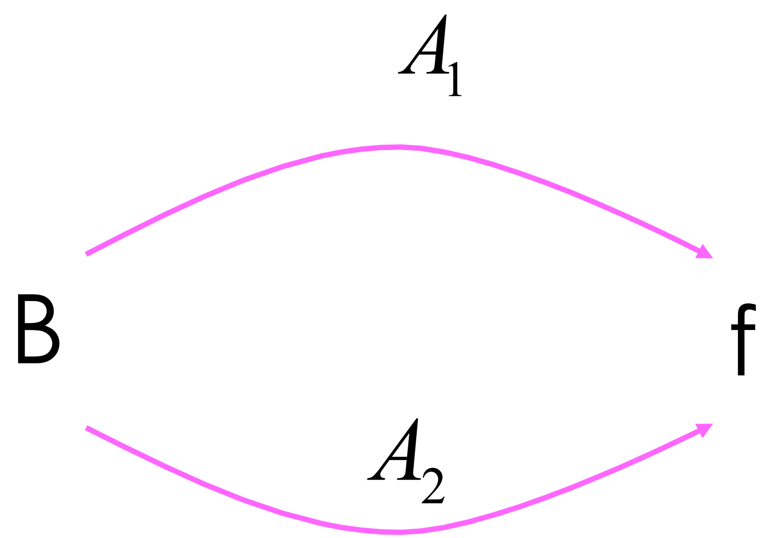
CP violation



$V^*_{ub} \neq V_{ub}$ → CP violation

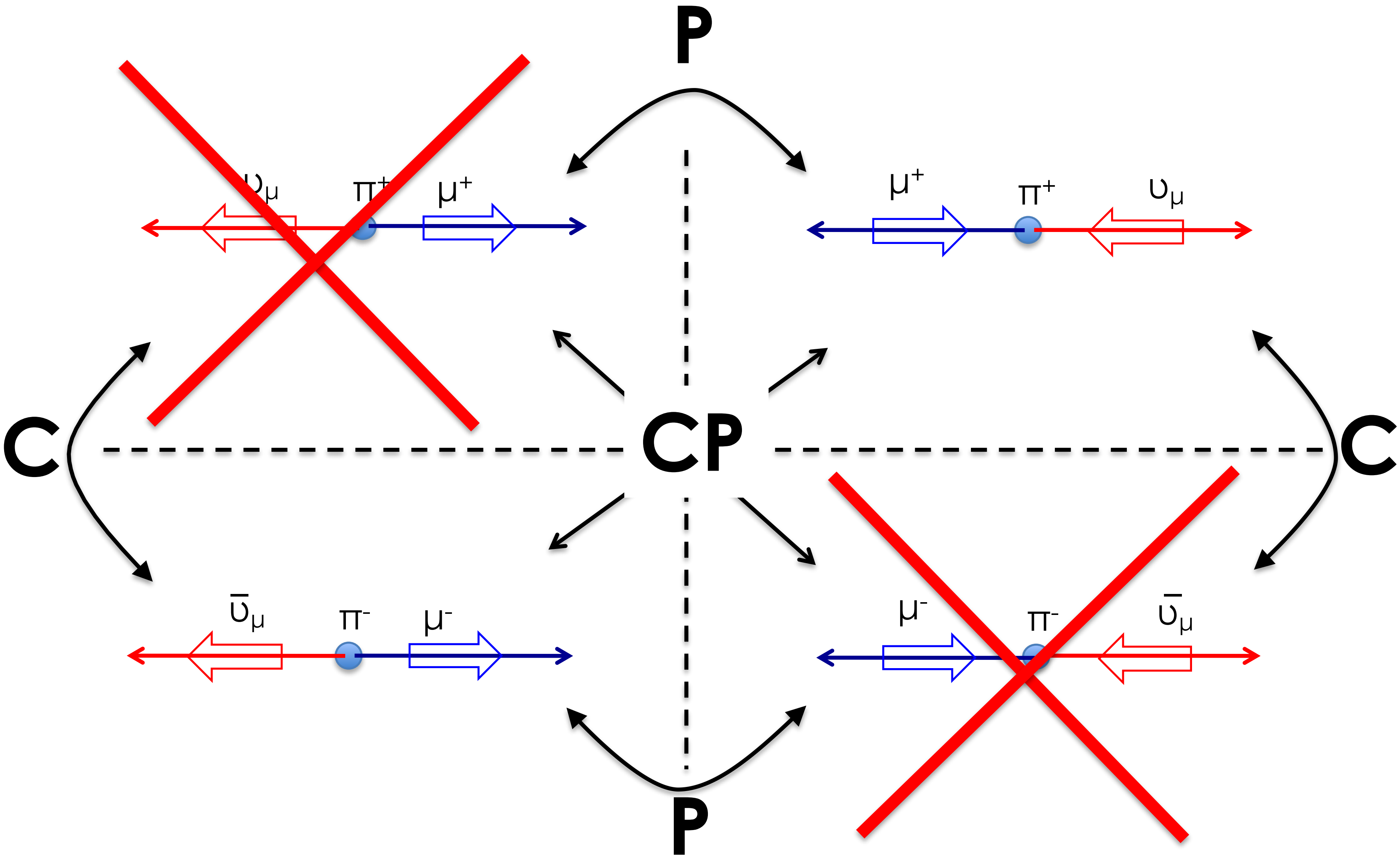
If you just have one amplitude : no sensitivity on phase ($|V_{ij}|^2 = |V^*_{ij}|^2$)





)

Let’s come back to the unitarity triangle



P
υ_μ
π^+
μ^+
μ^+
π^+
υ_μ
C
CP
C
$\bar{\upsilon}_\mu$
π^-
μ^-
μ^-
π^-
$\bar{\upsilon}_\mu$
P