CP violation

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Some authoritative literature about the lecture :

- BaBar physics book: http://www.slac.stanford.edu/pubs/slacreports/slac-r-504.html
- LHCb performance TDR: http://cdsweb.cern.ch/record/630827?ln=en
- A. Höcker and Z. Ligeti: CP Violation and the CKM Matrix. hep-ph/0605217
- To come next: the Belle II Physics TDR.

World Averages and Global Fits:

- Heavy Flavour Averaging Group: http://www.slac.stanford.edu/xorg/hfag/
- CKMfitter: http://ckmfitter.in2p3.fr/
- UTFit: http://www.utfit.org/

Disclaimers

- This is an experimentalist point of view on a subject which is all about intrications between experiment and theory.

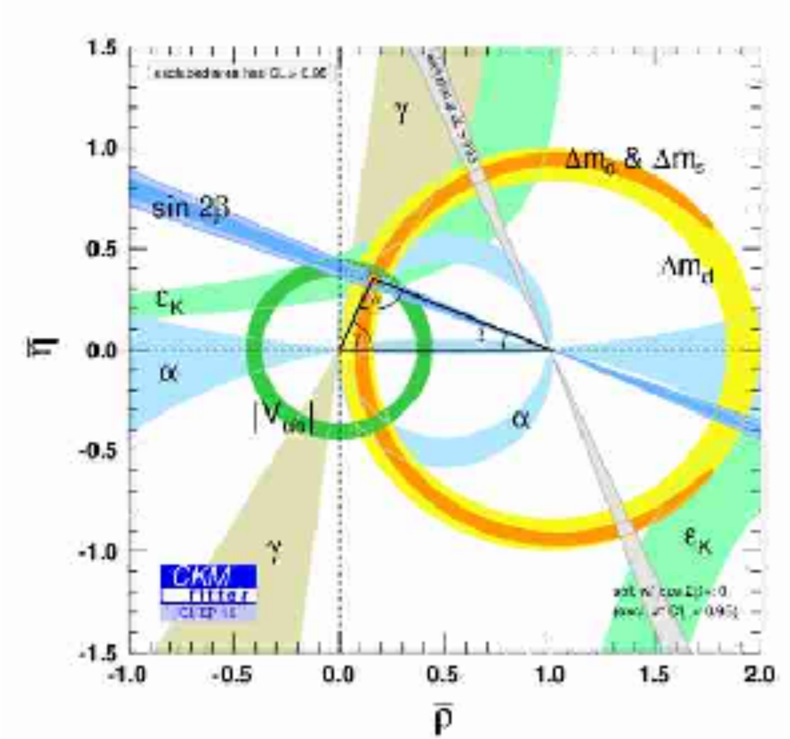
- I won't discuss (at all) CP violation in the lepton sector.

- The main machines in question here are the TeVatron (Fermilab, US), PEPII (SLAC, US), KEKB (KEK, Japan) and LHC (CERN, EU). Former experiments played a pioneering role: LEP (CERN, EU) and CLEO (CESR, US).

- Most of the material concerning global tests of the SM and above is taken from the CKMfitter group results (assumed bias) and Heavy Flavour Averaging Group (and hence the experiments themselves). I borrowed materials in presentations from colleagues which I tried to cite correctly.

Motivation

• In any HEP physics conference summary talk, you will find this plot, stating that (heavy) flavours and CP violation physics is a pillar of the Standard Model.



• One objective of these series of lectures is to undress this plot.

A more detailed outline

1. Introduction: setting the scene. History and recent past of the parity violation experiments. The discovery of the *CP* violation.
2. Few elements about CKM. Machine and experiments. Main observables and measurements relevant to study *CP* violation.
3. The global fit of the SM: CKM profile.
4. New Physics exploration with current data: two examples.

Parity symmetry breaking

Some authoritative literature about the lecture :

- ✓ Lee, T.D. and Yang, C.N. (1956) *Question of parity conservation in weak interactions*, Phys. Rev. 104(1): 254-258 (1956).
- ✓ The ^{60}Co experiment: Phys. Rev. 105, 1413-1414 (1957)
- ✓ The ^{152}Eu experiment: Phys. Rev. 109, 1015 (1958).

Parity symmetry breaking

The foundations

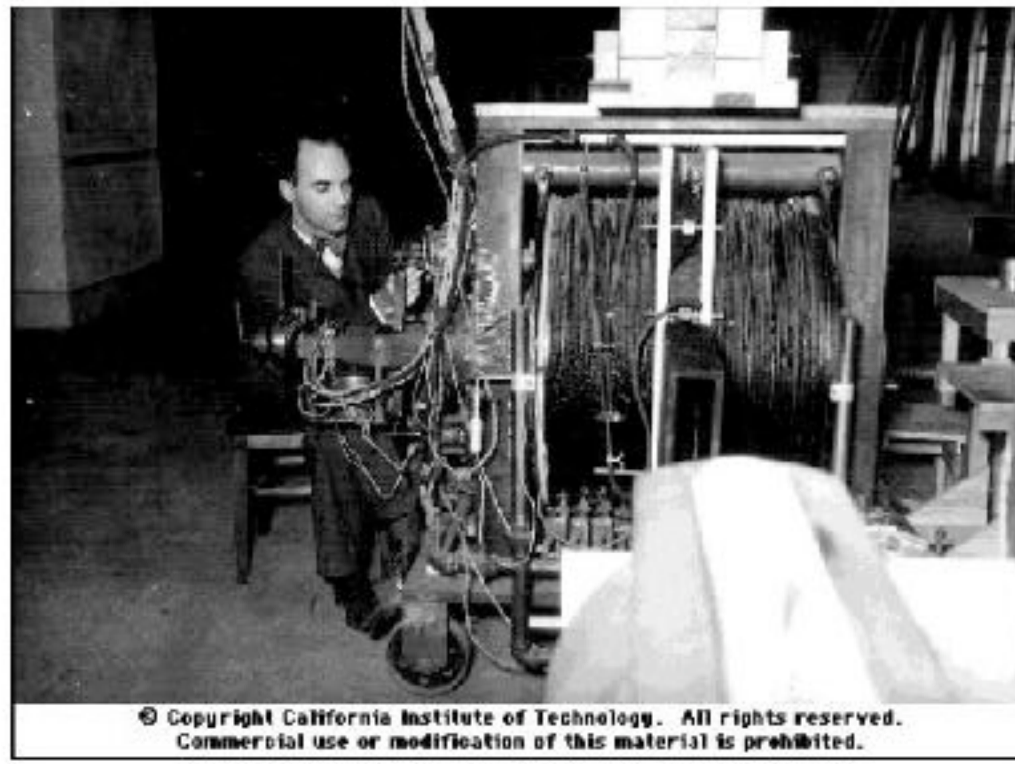
1. Antimatter discovery – C. Anderson.
2. The parity violation measurement – C.S. Wu.
3. The parity violation measurement – Goldhaber et al.
4. The emergence of the V-A theory. Premises of SU(2)L.
5. Recent parity violation measurements at LEP/SLD.
6. Selection of *CP* violation phenomena.

Parity symmetry breaking

Antimatter exists.

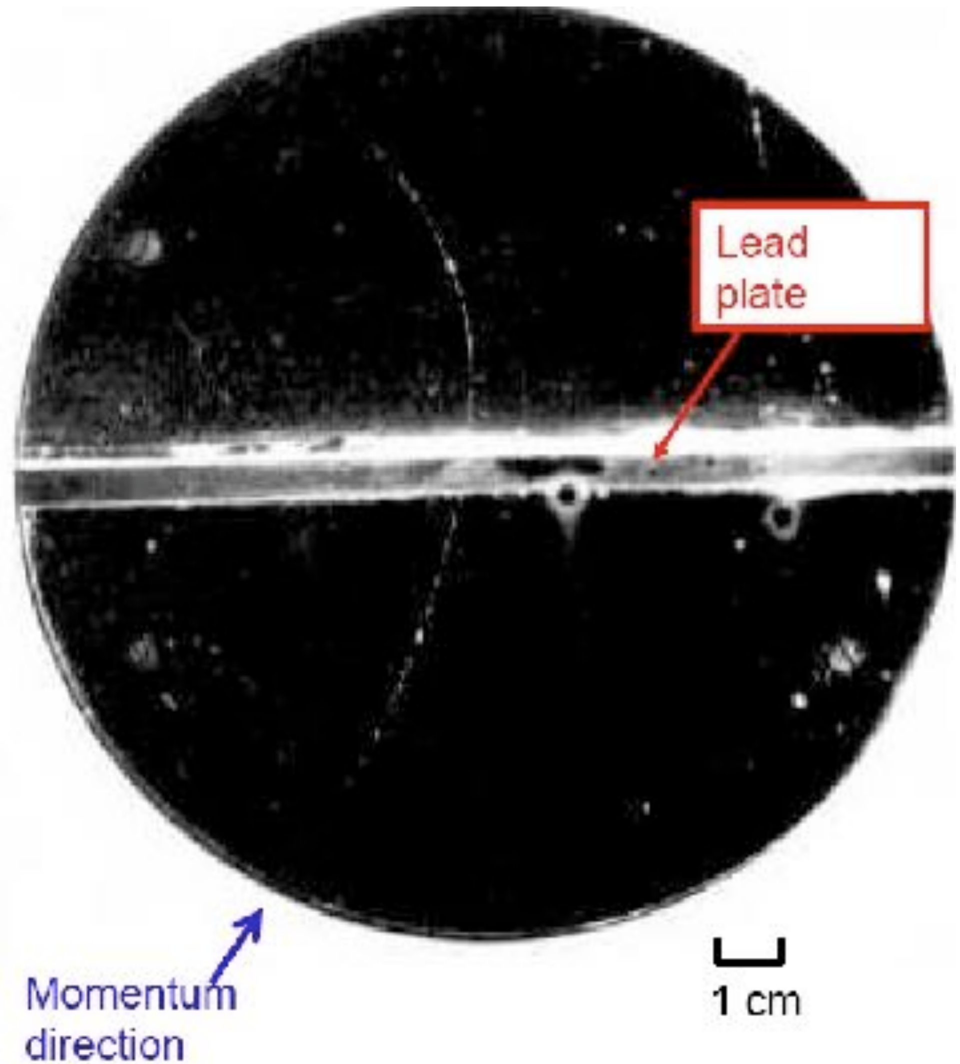
In 1929, P.A.M. Dirac solves the free motion of a relativistic spin 1/2 particle (electron or proton). It happened that there should exist a solution of negative energy, which he interpreted as an antiparticle.

$$\text{Dirac spin } 1/2 : \ (i\gamma^\mu\partial_\mu - m)\psi = 0$$



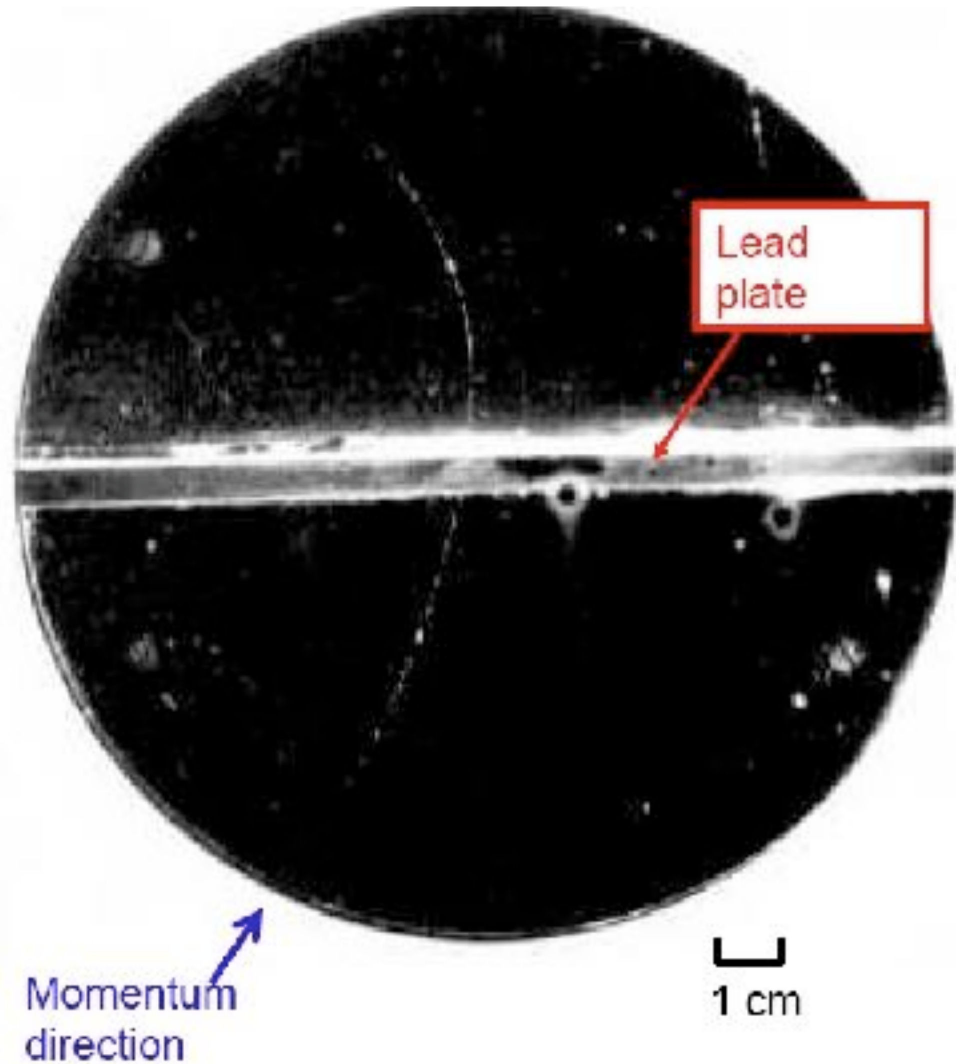
Anderson at work: discovery of the positron in 1932.

Parity symmetry breaking



Parity symmetry breaking

- The radius of curvature is smaller above the plate. The particle is slowed down in the lead → the particle is incoming from the bottom.



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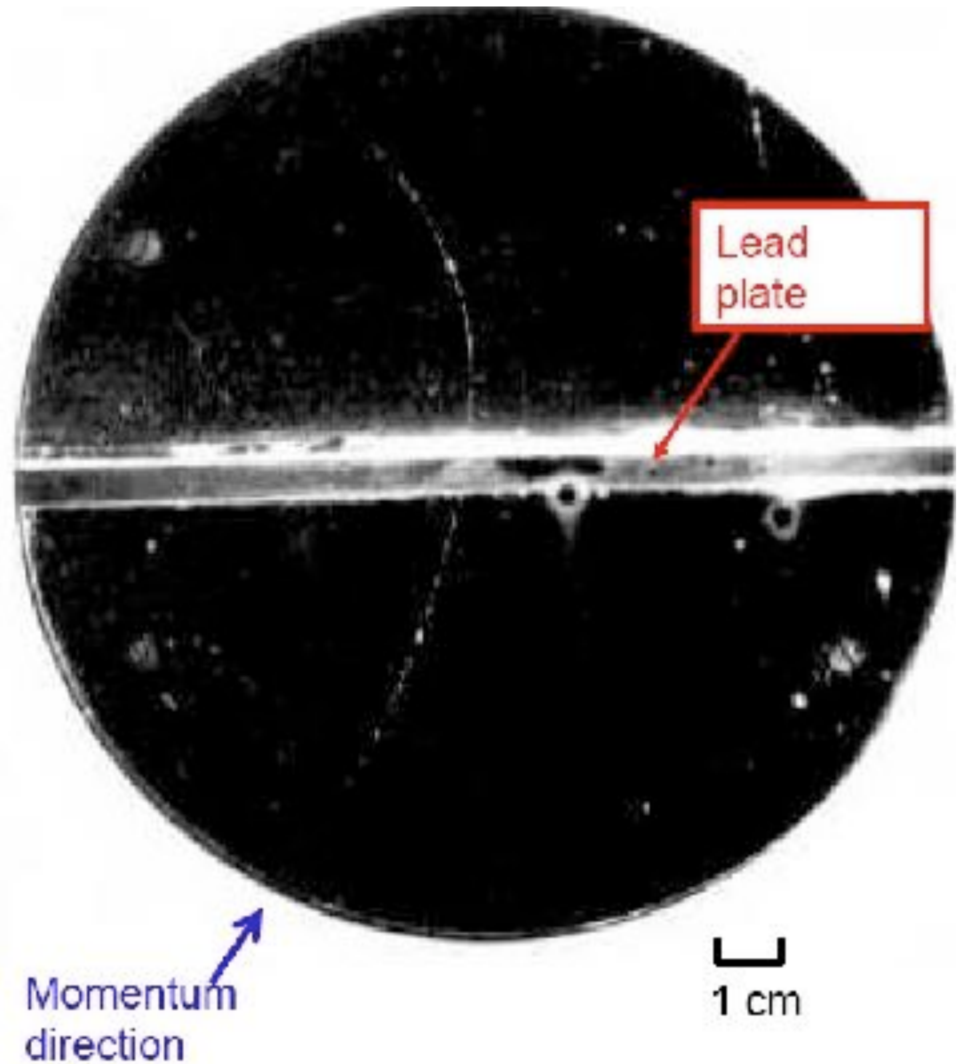

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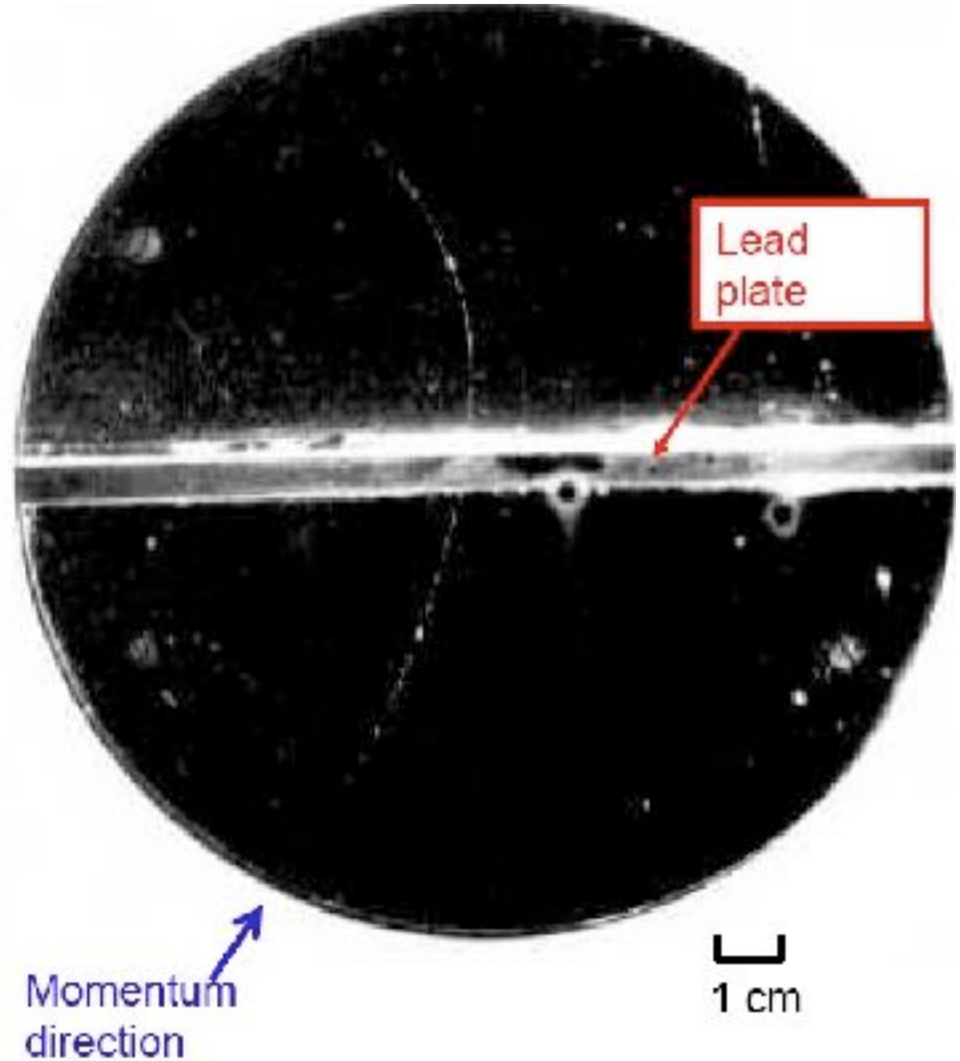

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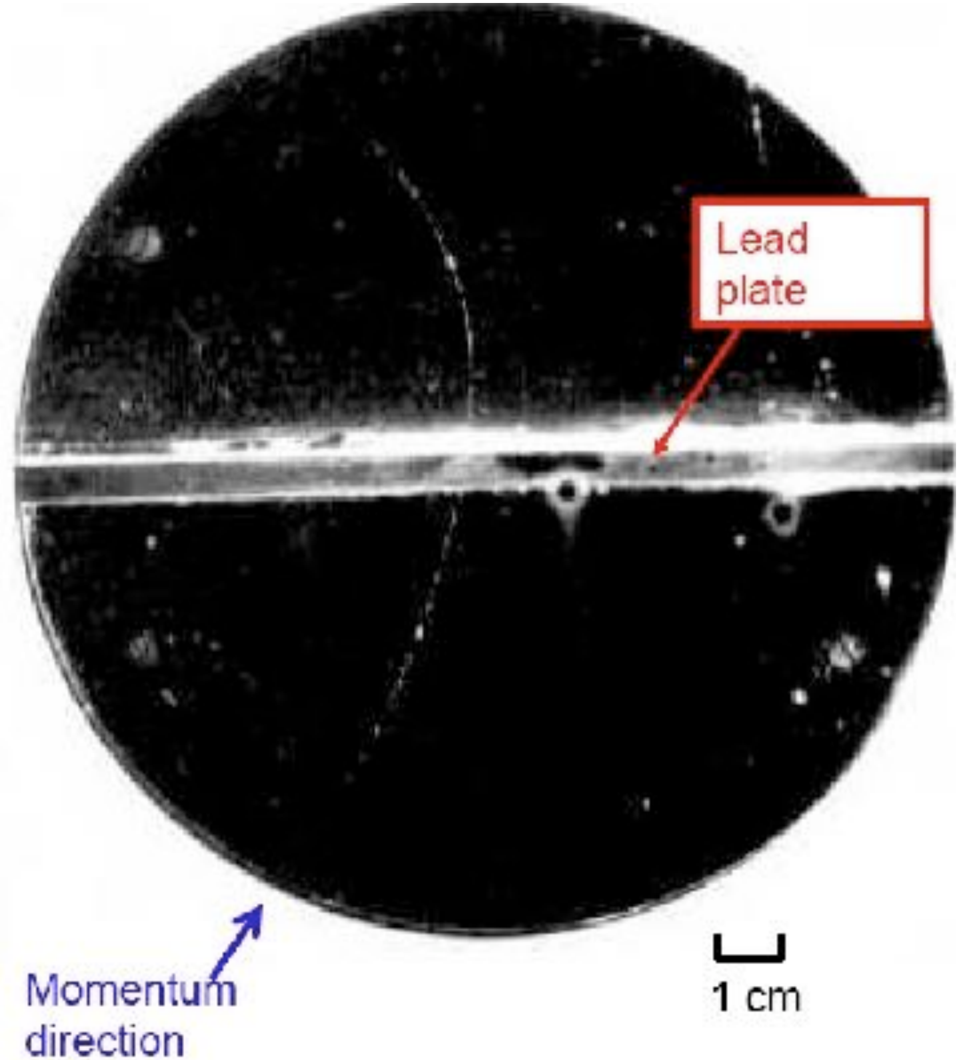

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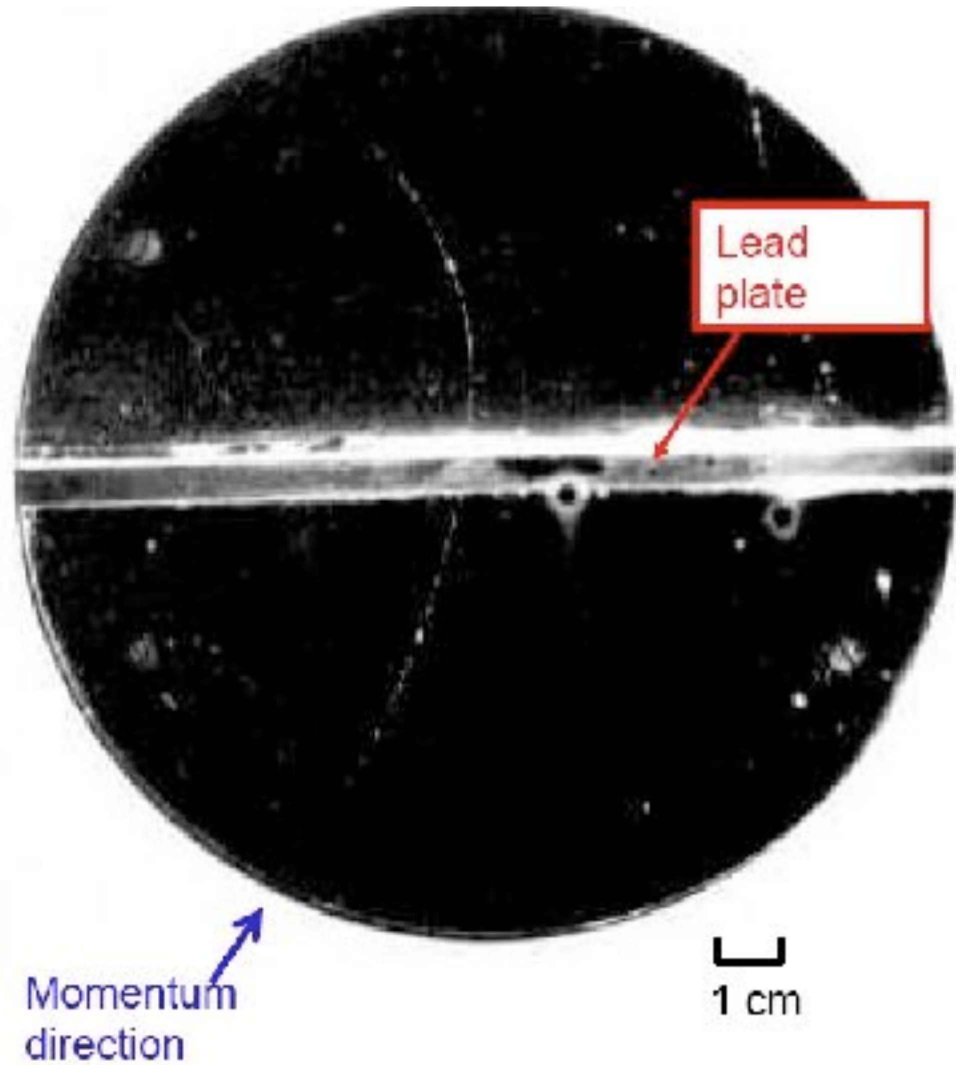
- From the density of the drops one can measure the ionizing power of the particle→ minimum ionizing particle.
- Similar ionizing power before and after the plate → same particle on the 2 sides.
- Curvature measurement after the lead: particle of ~23MeV → it is not a non-relativistic proton because it would have lost all its energy after ~5mm (a track of ~5 cm is observed).



Parity symmetry breaking

Why *P* must be a good symmetry

A variable describing a physical system is not an observable.

One can always find a mathematical transformation which lets the physical system invariant.

An observable is conserved.

Parity symmetry breaking

Why *P* must be a good symmetry

Non-observable	Mathematical transf.	Conserved quantity
Absolute spatial position	Space translation	Momentum
Absolute time	Time translation	Energy
Absolute space direction	Rotation	Angular momentum
Absolute right	Space reflexion (mirror)	Parity
Electric charge sign	$e \to -e$	Charge conjugation
Absolute time sign	$t \to -t$	Time reversal
Relative phase between electric charges	Gauge transformation	The electric charge

Evidence for *P* violation

- ✓ Before 1956 : all interactions were thought to be invariant under parity operation
- ✓ It was (quite comprehensively) tested for strong and electromagnetic interactions.
- ✓ Lee and Yang proposed an experiment to test it for weak interaction after the theta / tau puzzle.
- ✓ Designed and performed in 1956 by C.S. Wu and collaborators
- ✓ The Co^{60} experiment : Phys. Rev. 105, 1413-1414 (1957)

Evidence for *P* violation

The magnetic field is directed to the right. The spins are aligned along to it.

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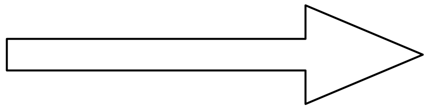

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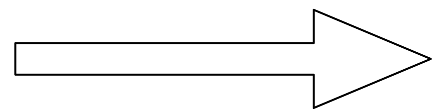

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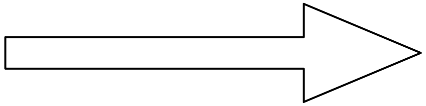
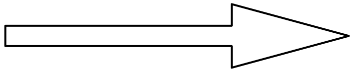
$^{60}\mathrm{Co}\ (J = 5)$ 

$^{60}\mathrm{Ni}\ (J = 4)$ 

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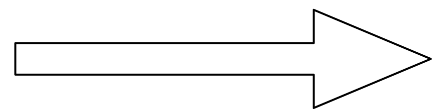
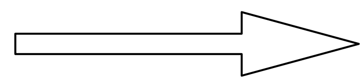
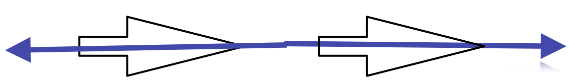
$^{60}\mathrm{Co}\ (J = 5)$ 

$^{60}\mathrm{Ni}\ (J = 4)$ 



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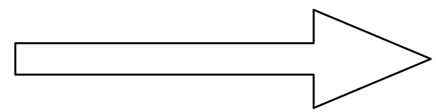

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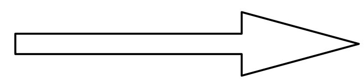
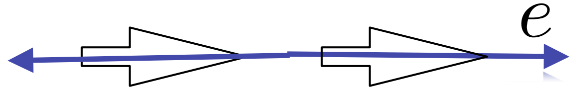


e^-



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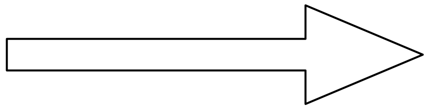

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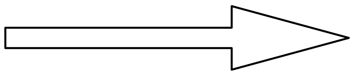

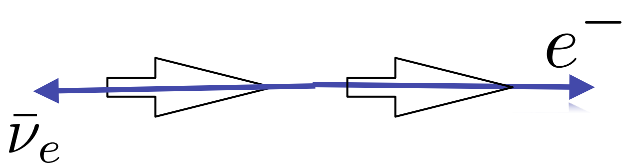

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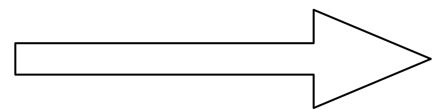

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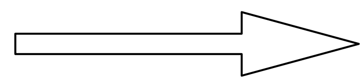

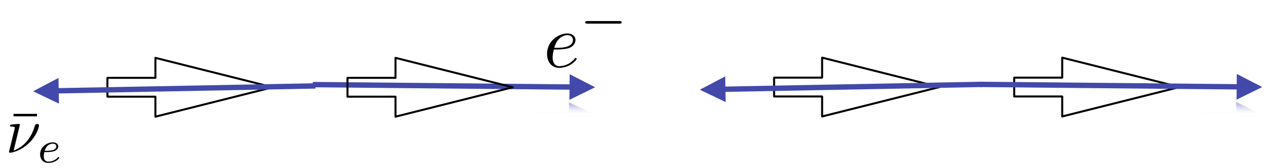

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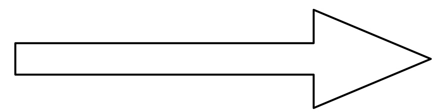

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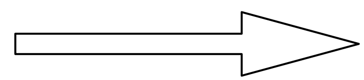

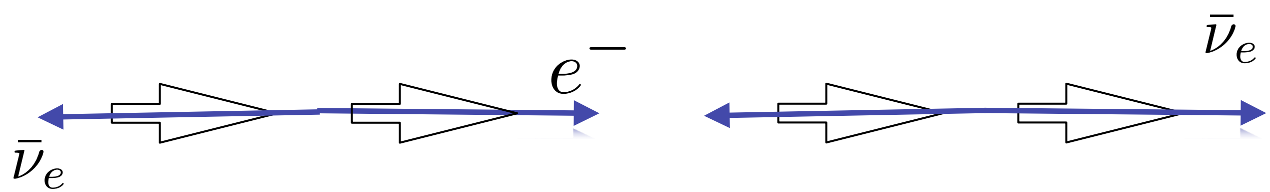

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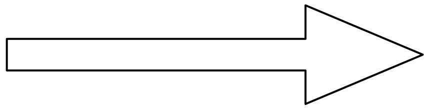

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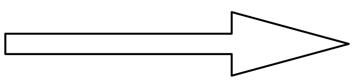

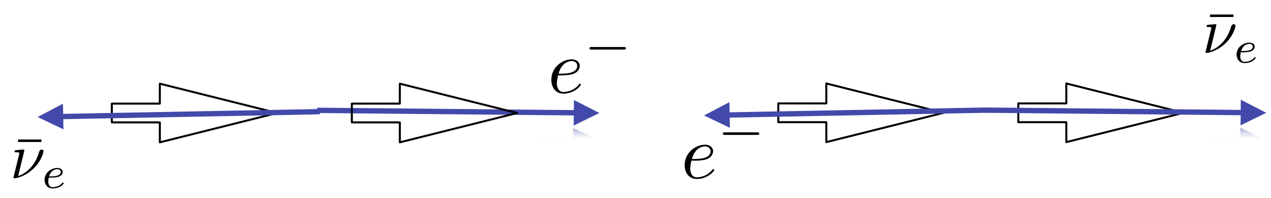

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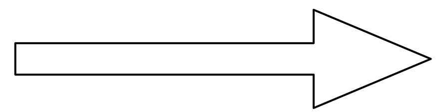

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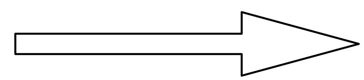

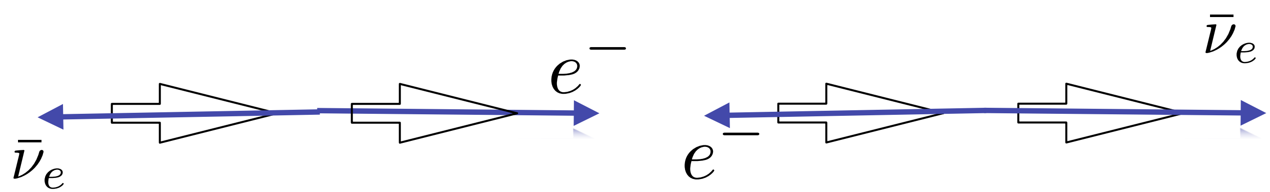

If the Nature can't distinguish left from right, then both decays are possible.

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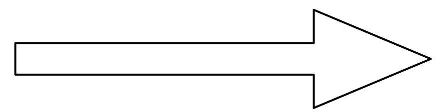
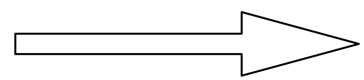
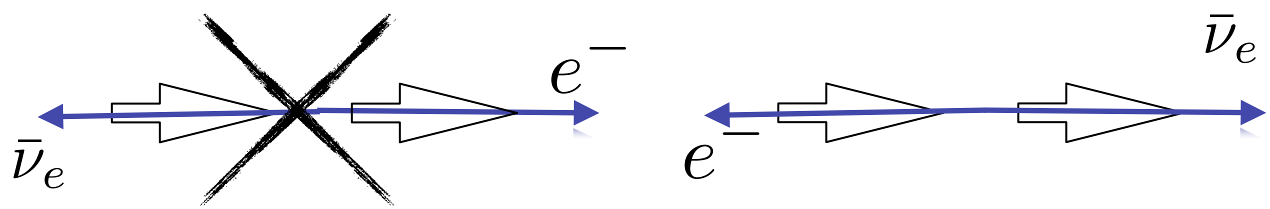
$^{60}\mathrm{Co}\ (J = 5)$ 

$^{60}\mathrm{Ni}\ (J = 4)$ 



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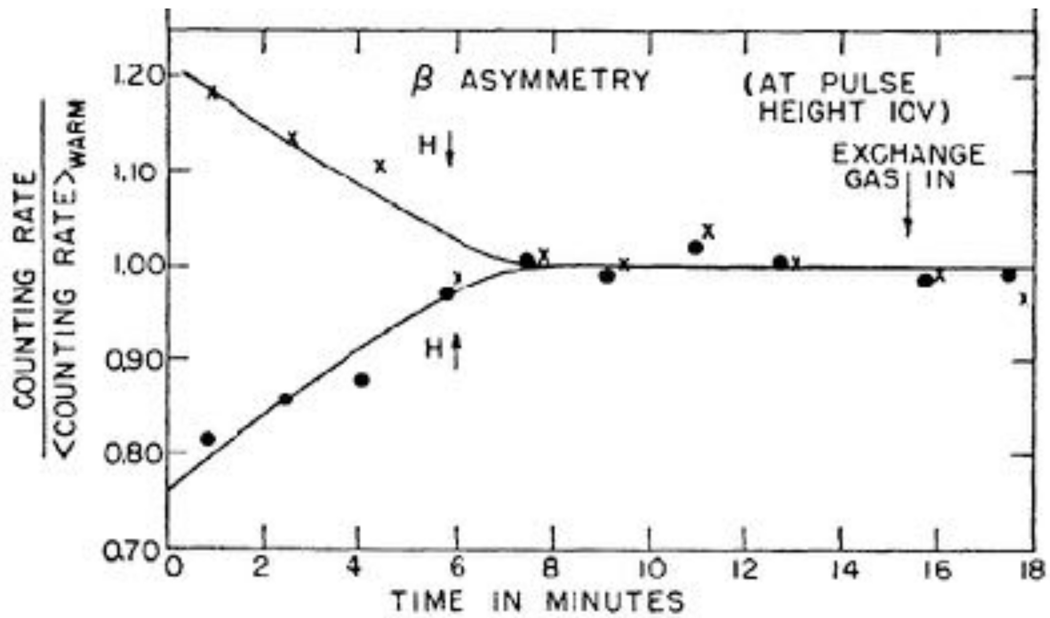
Evidence for *P* violation

- The magnetic field direction is changed and the rate for the electrons emission is measured in the two configurations. The asymmetry is reversed.



- The preferred chiral state is a right-handed anti-neutrino (left-handed electron).

Evidence for *P* violation

- The experiment was conducted during Christmas holidays 1956.
- The paper is published rightafter (2.5 pages).
- Lee and Yang receives the Nobel Prize in 1957 (sounds like this evidence was not overlooked).

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

In a recent paper[1] on the question of parity in weak interactions, Lee and Yang critically surveyed the experimental information concerning this question and reached the conclusion that there is no existing evidence either to support or to refute parity conservation in weak interactions. They proposed a number of experiments on beta decays and hyperon and meson decays which would ...cessary evidence for parity conservation ...tion. In beta decay, one could measure ...stribution of the electrons coming from polarized nuclei. If an asymmetry in the ...tween θ and $180°-\theta$ (where θ is the angle ...rientation of the parent nuclei and the ... the electrons) is observed, it provides ...oof that parity is not conserved in beta ...mmetry effect has been observed in the ... Co^{60}.
...nown for some time that Co^{60} nuclei can ...y the Rose-Gorter method in cerium ...balt) nitrate, and the degree of polari... ...d by measuring the anisotropy of the ...ma rays.[2] To apply this technique to the ...n, two major difficulties had to be over-

The Nobel Prize in Physics 1957

Chen Ning Yang
Prize share: 1/2

Tsung-Dao (T.D.) Lee
Prize share: 1/2

The Nobel Prize in Physics 1957 was awarded jointly to Chen Ning Yang and Tsung-Dao (T.D.) Lee *"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"*

Parity symmetry breaking

Neutrinos are left-handed

The Goldhaber experiment:

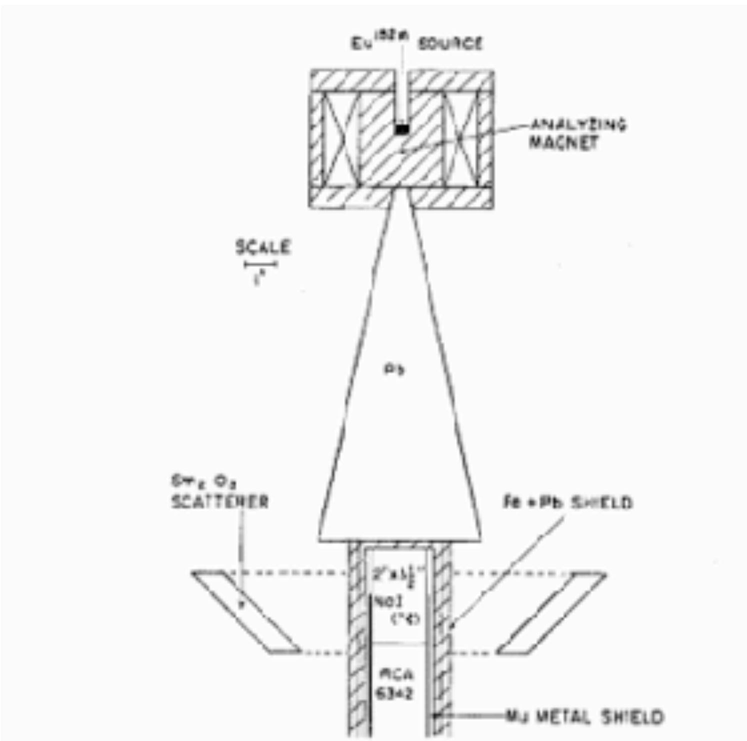
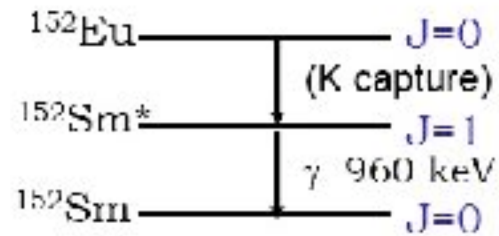


FIG. 1. Experimental arrangement for analyzing circular polarization of resonant scattered γ-rays. Weight of Sm_2O_3 scatterer: 1850 grams.

$$^{152}Eu(J=0) + e \;(\text{K capture}) \to {}^{152}Sm^*(J=1) + \nu$$
$$\hookrightarrow {}^{152}Sm(J=0) + \gamma$$



The spins of all final states particles are constrained. The gammas aligned with the ^{152}Sm are selected and their polarization is measured.

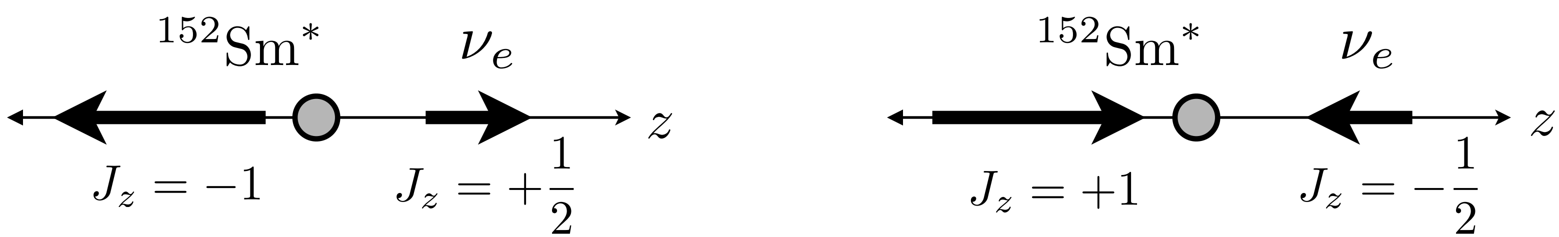
Neutrinos are left-handed

The Goldhaber experiment:

We write down the spin constraints: the spin of the electron defines the initial and the final states. We shall end up with a one-half spin projection.

$$^{152}\mathrm{Eu}(J=0) + e^- \rightarrow {}^{152}\mathrm{Sm}^*(J=1) + \nu_e$$

Two configurations are possible:



Parity symmetry breaking

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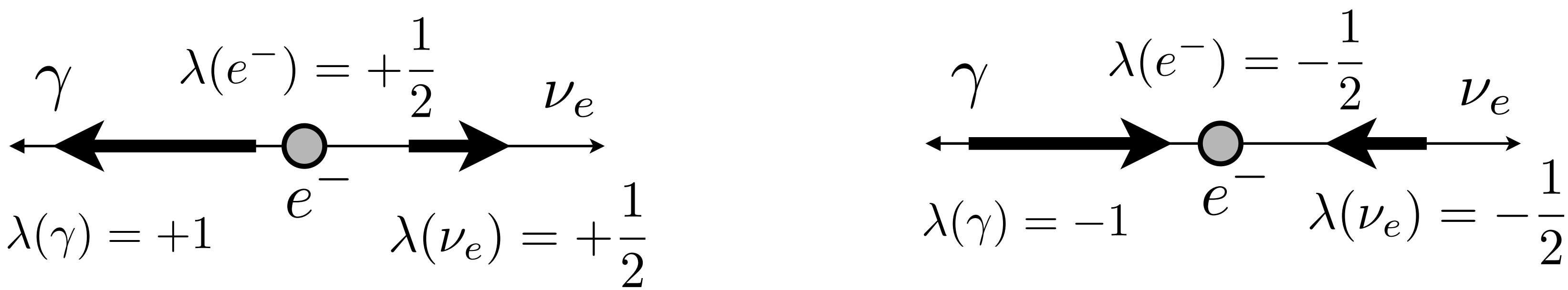
The Goldhaber experiment: $^{152}\mathrm{Eu}(J=0) + e^- \rightarrow {}^{152}\mathrm{Sm}^*(J=1) + \nu_e$

The above *K*-capture is followed by the excited Samarium decay:

$$^{152}\mathrm{Sm}^*(J=1) \rightarrow {}^{152}\mathrm{Sm}(J=0) + \gamma$$

The gamma (as a massless vector boson) has two possible polarisations, which manifest in the two and only two possible configurations of helicities:



From the gamma polarization measurement, Goldhaber et al. show that only left-handed neutrinos are found (i.e, the second configuration) in β decays. Goldhaber, Grodzins, Sunyar, Phys. Rev. 109, 1015 (1958).

Neutrinos are left-handed

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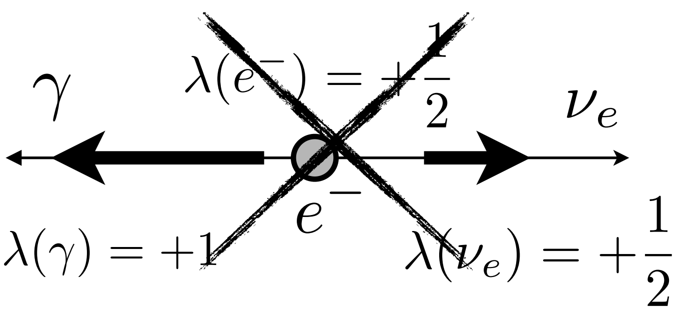
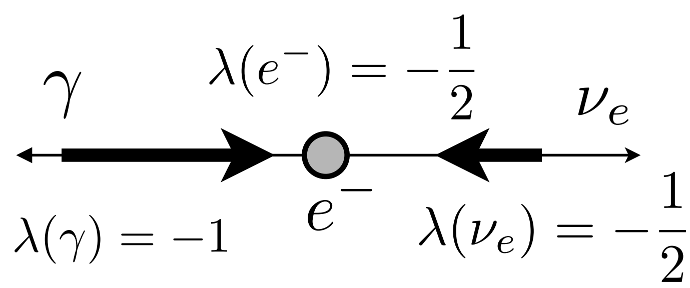
The gamma (as a massless vector boson) has two possible polarisations, which manifest in the two and only two possible configurations of helicities:





From the gamma polarization measurement, Goldhaber et al. show that only left-handed neutrinos are found (i.e, the second configuration) in β decays. Goldhaber, Grodzins, Sunyar, Phys. Rev. 109, 1015 (1958).

Parity symmetry breaking

Aparté: what is helicity? What is chirality?

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Parity symmetry breaking

Aparté: what is helicity? What is chirality?

Let's have a look first to the solutions (E>0) of Dirac equation written in the Pauli-Dirac basis:

$$\gamma^0 = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix} \qquad \gamma^k = \begin{pmatrix} 0 & \sigma_k \\ -\sigma_k & 0 \end{pmatrix} \qquad \gamma^5 = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$$

For the sake of the simplicity of the notation, I consider the momentum along the *z* coordinate only.

$$u_1 = \sqrt{E+m} \begin{pmatrix} 1 \\ 0 \\ \frac{p}{E+m} \\ 0 \end{pmatrix} \qquad u_2 = \sqrt{E+m} \begin{pmatrix} 0 \\ 1 \\ 0 \\ -\frac{p}{E+m} \end{pmatrix}$$

Parity symmetry breaking

Aparté: what is helicity? What is chirality?

$$\hat{h} = \frac{1}{2}\vec{p}\cdot\vec{\sigma} = \frac{1}{2}p\cdot\begin{pmatrix} \sigma_3 & 0 \\ 0 & \sigma_3 \end{pmatrix} \qquad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\hat{h} = \frac{p}{2}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \qquad u_1 = \sqrt{E+m}\begin{pmatrix} 1 \\ 0 \\ \frac{p}{E+m} \\ 0 \end{pmatrix}$$

$$u_2 = \sqrt{E+m}\begin{pmatrix} 0 \\ 1 \\ 0 \\ -\frac{p}{E+m} \end{pmatrix}$$

$$\hat{h}\cdot u_1 = \frac{1}{2}u_1 \ ,$$

$$\hat{h}\cdot u_2 = -\frac{1}{2}u_2 \ .$$

u_1 and *u_2* are helicity eigenstates

Parity symmetry breaking

Aparté: what is helicity? What is chirality?

$$u_1 = \sqrt{E+m}\begin{pmatrix} 1 \\ 0 \\ \frac{p}{E+m} \\ 0 \end{pmatrix}$$

Let's project those states with the chirality projectors:

$$u_2 = \sqrt{E+m}\begin{pmatrix} 0 \\ 1 \\ 0 \\ -\frac{p}{E+m} \end{pmatrix}$$

$$P_L = \frac{1}{2}(1-\gamma^5) = \begin{pmatrix} 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \\ -1 & 0 & 1 & 0 \\ 0 & -1 & 0 & 1 \end{pmatrix} \quad P_R = \frac{1}{2}(1+\gamma^5) = \begin{pmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{pmatrix}$$

$$P_L u_1 = \frac{1}{2}\sqrt{E+m}\begin{pmatrix} 1-\frac{p}{E+m} \\ 0 \\ -1+\frac{p}{E+m} \\ 0 \end{pmatrix} \qquad P_R u_1 = \frac{1}{2}\sqrt{E+m}\begin{pmatrix} 1+\frac{p}{E+m} \\ 0 \\ 1+\frac{p}{E+m} \\ 0 \end{pmatrix}$$

$$u_1 = P_L u_1 + P_R u_1 = \frac{1}{2}(1-\frac{p}{E+m})\sqrt{E+m}\begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix} + \frac{1}{2}(1+\frac{p}{E+m})\sqrt{E+m}\begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}$$

Parity symmetry breaking

Aparté: what is the helicity? What is the chirality?

$$u_L = \sqrt{E+m}\begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix} \qquad u_R = \sqrt{E+m}\begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}$$

$$u_1 = P_L u_1 + P_R u_1 = \frac{1}{2}(1 - \frac{p}{E+m})\sqrt{E+m}\begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix} + \frac{1}{2}(1 + \frac{p}{E+m})\sqrt{E+m}\begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}$$

$$u_1 = P_L u_1 + P_R u_1 = \frac{1}{2}(1 - \frac{p}{E+m})u_L + \frac{1}{2}(1 + \frac{p}{E+m})u_R$$

Parity symmetry breaking

Aparté: what is helicity? What is chirality?

$$u_1 = P_L u_1 + P_R u_1 = \frac{1}{2}(1 - \frac{p}{E+m})u_L + \frac{1}{2}(1 + \frac{p}{E+m})u_R$$

- For a massless particle, helicity IS chirality.

- For ultra-relativistic particles (*E*>>*m*), helicity IS chirality.

- The heavier is a particle, the larger is the mixing of chiral states for a given helicity.

Parity symmetry breaking

Aparté: what is helicity? What is chirality?

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Neutrinos are left-handed. Implications: the decay of the pion as an illustration

✓Quantum Field Theory: requirement of Lorentz Invariance (LI) of the matrix elements strongly constrains the form of the interaction vertices. We learnt QED and QCD to have vector currents. In general, 5 and only 5 combinations of 2 spinors and γ-matrices complies with Lorentz Invariance. They are called covariant bilinears:

Type	Expression	Components	Mediating Boson
Scalar	$\bar{\Psi}\Phi$	1	Spin 0
PseudoScalar	$\bar{\Psi}\gamma^5\Phi$	1	Spin 0
Vector	$\bar{\Psi}\gamma^\mu\Phi$	4	Spin 1
Axial Vector	$\bar{\Psi}\gamma^\mu\gamma^5\Phi$	4	Spin 1
Tensor	$\bar{\Psi}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)\Phi$	6	Spin 2

Parity symmetry breaking

Neutrinos are left-handed. Implications: the decay of the pion as an illustration

✓WE, have to find which form or combination of forms would fit the experimental observation that parity symmetry is maximally violated in weak interaction and that left-handed helicity (=chirality) neutrinos seem to be the only authorized state in that scope.

✓ First a reminder on chirality states. Let's consider a half-spin particle:

$$(i\gamma^\mu \partial_\mu - m)\Psi = 0.$$

$$\Psi = \Psi_L + \Psi_R, \Psi_L = P_L\Psi, \Psi_R = P_R\Psi,$$

$$P_{L,R} = \frac{(1 \pm \gamma^5)}{2},$$

$$\gamma^5 = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}.$$

Neutrinos are left-handed. Implications: the decay of the pion as an illustration

✓There are two vertex interaction forms complient with our objectives: these are the Vector-AxialVector interaction:

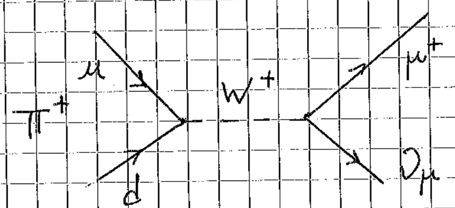
$$
\begin{aligned}
\bar{\Psi}\gamma^{\mu}(1-\gamma^{5})\Psi &= \bar{\Psi}(P_L+P_R)\gamma^{\mu}(1-\gamma^{5})(P_L+P_R)\Psi \\
\bar{\Psi}\gamma^{\mu}(1-\gamma^{5})\Psi &= 2\bar{\Psi}(P_L+P_R)\gamma^{\mu}(P_L^2+P_LP_R)\Psi \\
\bar{\Psi}\gamma^{\mu}(1-\gamma^{5})\Psi &= 2\bar{\Psi}_L\gamma^{\mu}\Psi_L
\end{aligned}
$$

✓Selection of chirality states. Only LL couplings allowed for particles. Maximal violation of the parity symmetry. A natural candidate for the weak interaction.

✓*Homework 1: show that vectorial interactions selects democratically LL and RR interaction vertices. Show as well that [V+A] does the same as [V-A].*

Neutrinos are left-handed. Implications: the decay of the pion as an illustration

π Decay - Decay width and related matter. Handsout.



$$d\Gamma = \frac{1}{2E}\,\frac{1}{(2s_{\pi^+}+1)} \sum_{spins} |\mathcal{M}|^2 \, dQ.$$

① HADRONIC MATRIX ELEMENT $j_q^\mu = \bar{u}(u)\,\gamma^\mu(1-\gamma^5)\,v(\bar{d})$

Since quarks, cannot be calculated perturbatively for the strong interaction $\longrightarrow j_q^\mu = f_\pi p^\mu$. p = momentum of π.

② LEPTONIC MATRIX ELEMENT AND $\mathcal{M}$.

$j_{l\mu} = \bar{u}(\mu^+)\gamma_\mu(1-\gamma^5)\,u(\nu_\mu)$ and $\mathcal{M} = \frac{G_F}{\sqrt{2}}\left[j^\mu_q\right]\left[j_{l\mu}\right]$.

$\longrightarrow \mathcal{M} = \frac{G_F}{\sqrt{2}} f_\pi m_\mu \left[\bar{u}(\mu^+)(1-\gamma^5)\,u(\nu_\mu)\right]$

Neutrinos are left-handed. Implications: the decay of the pion as an illustration

(3) SUM OVER FINAL STATES SPINS

$$|\bar{\mathcal{M}}|^2 = \sum_{spins} \mathcal{M}\mathcal{M}^* = 4 G_F^2 f_\pi^2 m_\mu^2 \, P(\mu)\cdot P(\nu_\mu)$$

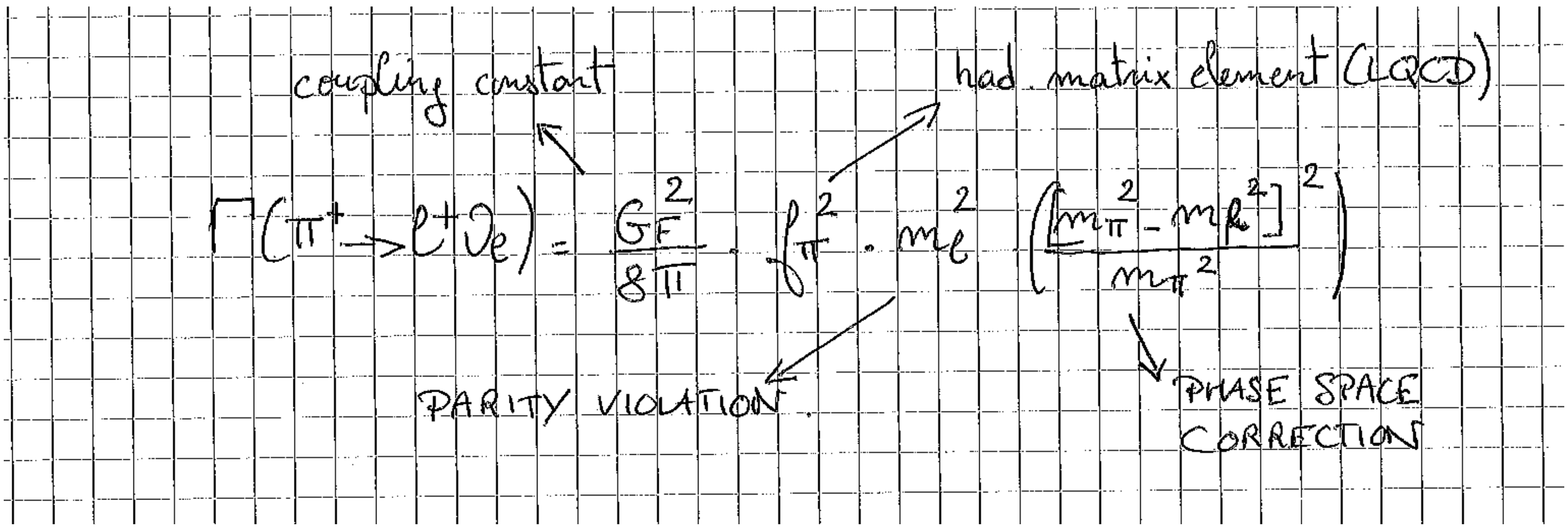
(4) PHASE SPACE INTEGRATION

$$dQ = \frac{d^3p(\mu)}{(2\pi)^3 \cdot 2E(\mu)} \cdot \frac{d^3p(\nu_\mu)}{(2\pi)^3 \cdot 2E(\nu_\mu)} (2\pi)^4 \delta^{(4)}\left(P - p(\mu) - p(\nu_\mu)\right)$$

(5) BOTTOMLINE

$$\Gamma = \frac{G_F^2}{8\pi} f_\pi^2 \cdot \frac{m_\mu^2}{m_\pi^2}\left(m_\pi^2 - m_\mu^2\right)^2$$

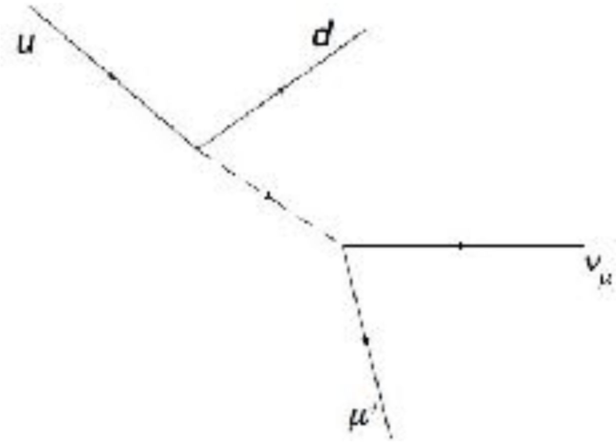
Neutrinos are left-handed. Implications: the decay of the pion as an illustration



✓Interpretation: you force the antilepton to be in its wrong helicity state (chirality is definitely right-handed). Electrons must hate you more than muons do (at least in the ratio of the squared masses).

Parity symmetry breaking

Neutrinos are left-handed. Implications: the decay of the pion as an illustration



To remove the QCD part of the decay width which is badly determined, it is relevant to consider a ratio of decay widths in leptons.

Again, we can compare the predictions with the different allowed Lorentz Invariant structures of the interaction to the measurement.

$$\frac{\Gamma(\pi^+ \to \mu^+ \nu_\mu)}{\Gamma(\pi^+ \to e^+ \nu_e)} = (0.813 \pm 0.004).10^4,$$

$$\frac{\Gamma(\pi^+ \to \mu^+ \nu_\mu)}{\Gamma(\pi^+ \to e^+ \nu_e)} = 0.2 \quad (\text{S or P prediction}),$$

$$\frac{\Gamma(\pi^+ \to \mu^+ \nu_\mu)}{\Gamma(\pi^+ \to e^+ \nu_e)} = 0.78\ 10^4 \quad (\text{V} - \text{A prediction}).$$

Neutrinos are left-handed. Implications:
the decay of the pion as an illustration

✓Final notes on the subject:

- If the electron and muon decay widths differ a lot, lepton and antilepton decay widths are the same within experimental uncertainties, making *CP* a good symmetry of the weak interaction.
- In the actual calculation (which I strongly encourage you to perform), you will observe a slight tension between the prediction and the measurement. Anticipating a bit the following elements of this lecture, this disagreement is related to the probability of the $d \rightarrow u$ transition which is not amounting to unity.

Modern parity violation experiments:LEP/SLD

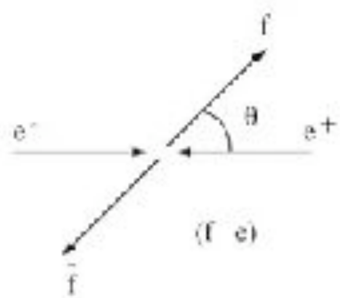
The Standard Model Tests (Part II)

3.3 The Parity-Violating forward-backward asymmetries in e+e-.

- Parity is maximally violated in weak interactions. This induces the fermion particle in the final state to be produced preferentially in the direction of the initial electron.

$$\frac{\mathrm{d}\sigma^f}{\mathrm{d}\cos\theta} = \sigma^f_{\mathrm{tot}} \cdot [\frac{3}{8}(1+\cos^2\theta) + A^{f\bar{f}}_{\mathrm{FB}}\cos\theta]$$

- The experimentalist's job is to identify the nature of the fermion and count how many times it is find forward (i.e in the electron direction)



$$A^{f\bar{f}}_{\mathrm{FB}} = \frac{N_F - N_B}{N_F + N_B} \text{ with } N_F = \int_0^1 \frac{\mathrm{d}\sigma_{f\bar{f}}}{\mathrm{d}\cos\theta} \cdot \mathrm{d}\cos\theta$$

$$A^{f\bar{f}}_{\mathrm{FB}} \propto A_e \cdot A_f \propto \frac{g_V^e g_A^e}{(g_V^e)^2 + (g_A^e)^2} \cdot \frac{g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2}$$

Hence depends primarily to $\sin^2\theta_{eff}$

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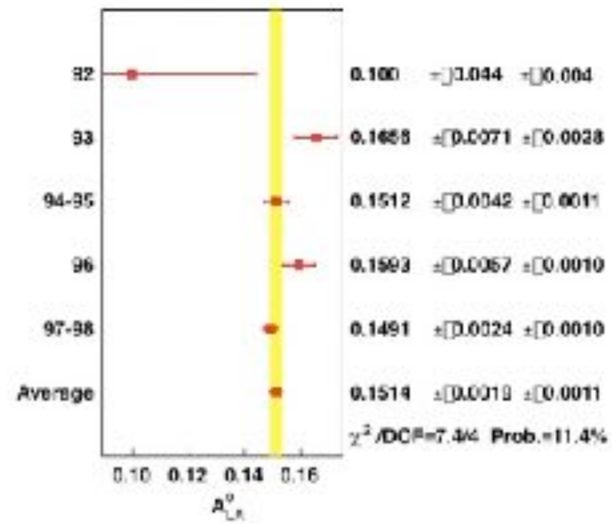
Parity symmetry breaking

Modern parity violation experiments: SLD

The Standard Model Tests (Part II)

3.4 The Parity-Violating Left-Right asymmetry from SLD

- We have seen in 3.3 that A_c was an excellent laboratory.
- SLC machine polarized the electron beam.
- Hence, knowing the polarization and just measuring the LL and RR production of Z boson yields A_e :



$$A_{\rm LR} = \frac{N_L - N_R}{N_L + N_R} \cdot \frac{1}{\langle P_e \rangle}$$

$$\langle P_e \rangle_{1998} = 0.7292 \pm 0.0038$$

$$A^0_{\rm LR} = 0.1514 \pm 0.0022$$

$$\sin^2\theta_{\rm eff} = 0.23097 \pm 0.00027$$

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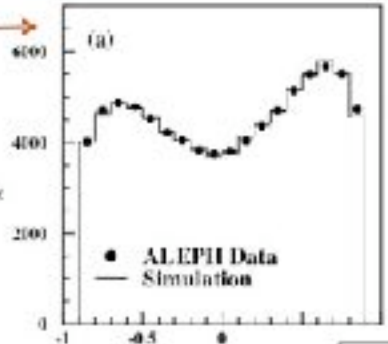
Modern parity violation experiments: LEP

The Standard Model Tests (Part II)

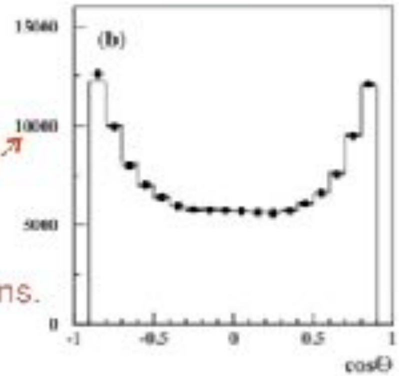
3.3 The Parity-Violating forward-backward asymmetries in e+e-.

- Then we fit the asymmetries to these data:

$$
\begin{aligned}
f_{ijkl} = & (F^{b}_{\ell,s})_{ijkl} \int_I [1 + x^2 + \tfrac{8}{3} A^{b}_{FB}(1 - 2\bar{\chi}_{ijkl})\, x]\, dx \\
& + (F^{mix}_{\ell,s})_{ijkl} \int_I [1 + x^2 - \tfrac{8}{3} A^{b}_{FB}(1 - 2\bar{\chi}_{ijkl})\, x]\, dx \\
& + (F^{asym}_{bkg,s})_{ijkl} \int_I [1 + x^2 + \tfrac{8}{3} A^{b}_{FB}(1 - 2\bar{\chi}_{ijkl})(2\eta^{b}_{ijk} - 1)\, x]\, dx \\
& + (F_{\ell,c})_{ijkl} \int_I [1 + x^2 - \tfrac{8}{3} A^{c}_{FB}\, x]\, dx \\
& + (F^{asym}_{c\to bkg})_{ijkl} \int_I [1 + x^2 - \tfrac{8}{3} A^{c}_{FB}(2\eta^{c}_{ijk} - 1)\, x]\, dx \\
& + (F^{asym}_{s\to bkg})_{ijkl} \int_I [1 + x^2 + \tfrac{8}{3} A^{s}_{FB}(2\eta^{s}_{ijk} - 1)\, x]\, dx \\
& + (F^{asym}_{d\to bkg})_{ijkl} \int_I [1 + x^2 + \tfrac{8}{3} A^{d}_{FB}(2\eta^{d}_{ijk} - 1)\, x]\, dx \\
& + (F^{asym}_{u\to bkg})_{ijkl} \int_I [1 + x^2 - \tfrac{8}{3} A^{u}_{FB}(2\eta^{u}_{ijk} - 1)\, x]\, dx \\
& + (F^{sym}_{bkg})_{ijkl} \int_I (1 + x^2)\, dx,
\end{aligned}
$$



Parity violation even seen for charm.



Includes QED and QCD effects.

Measuring simultaneously the mixing parameter w/ leptons.

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An intermediate conclusion

- ✓ Parity is violated in weak interaction.
- ✓ One gets from experimental results so far the following picture:

✓ Any theory of the weak interaction shall include these properties.

C and *P* breaking and *CP* symmetry

An intermediate conclusion

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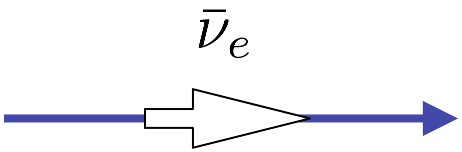

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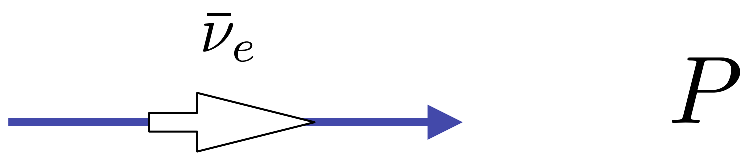

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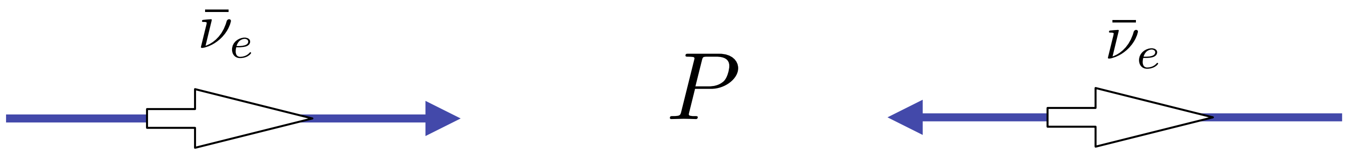

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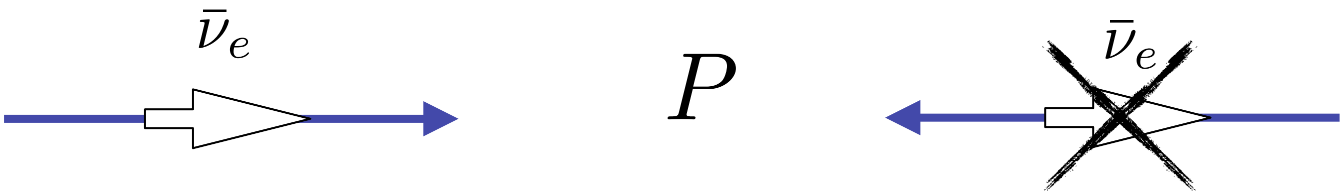

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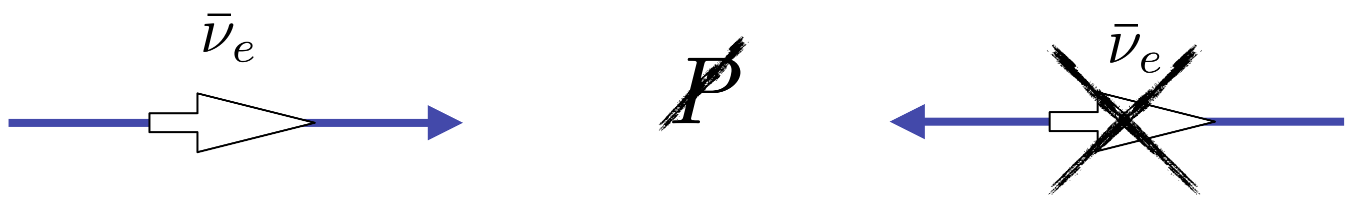

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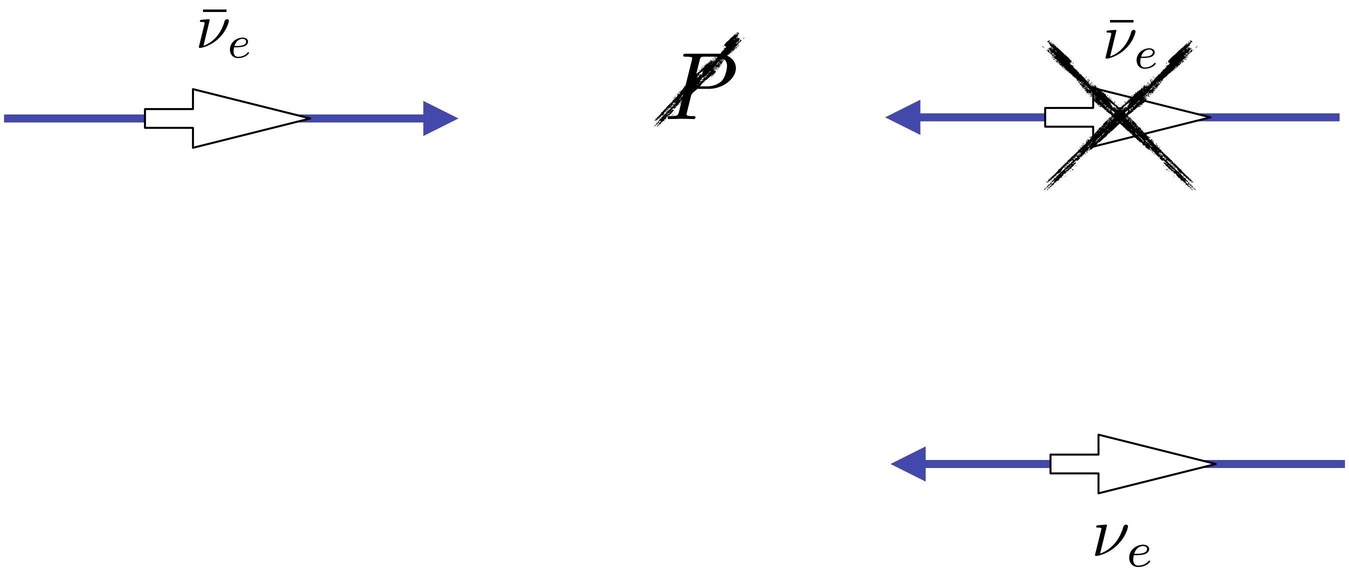

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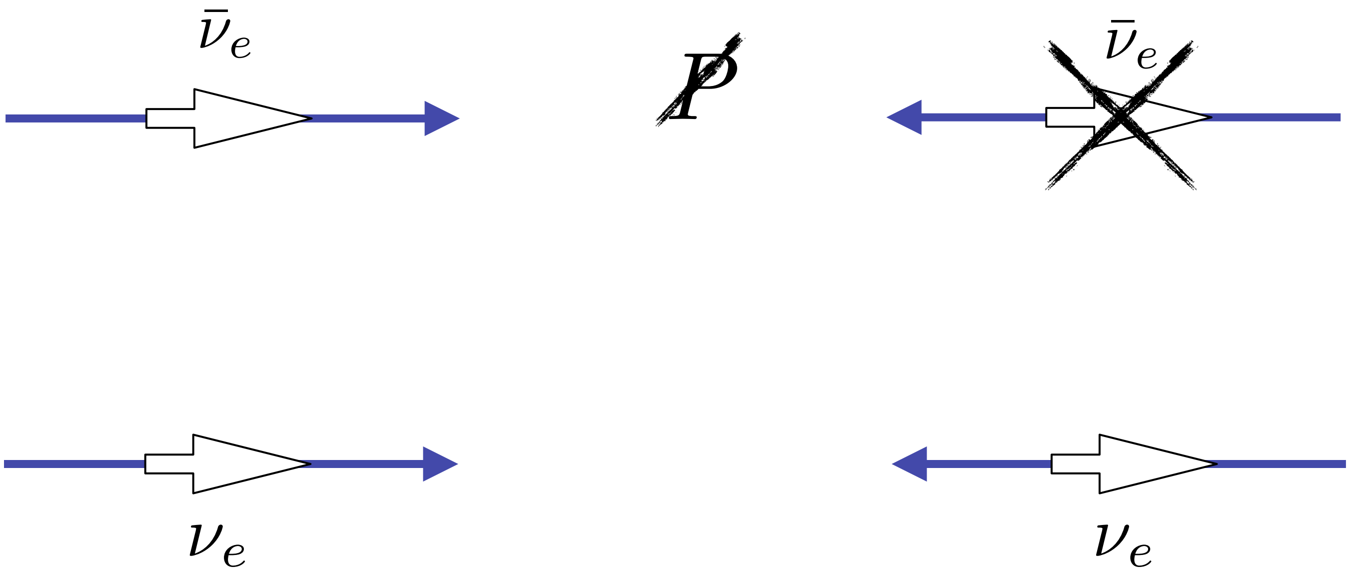

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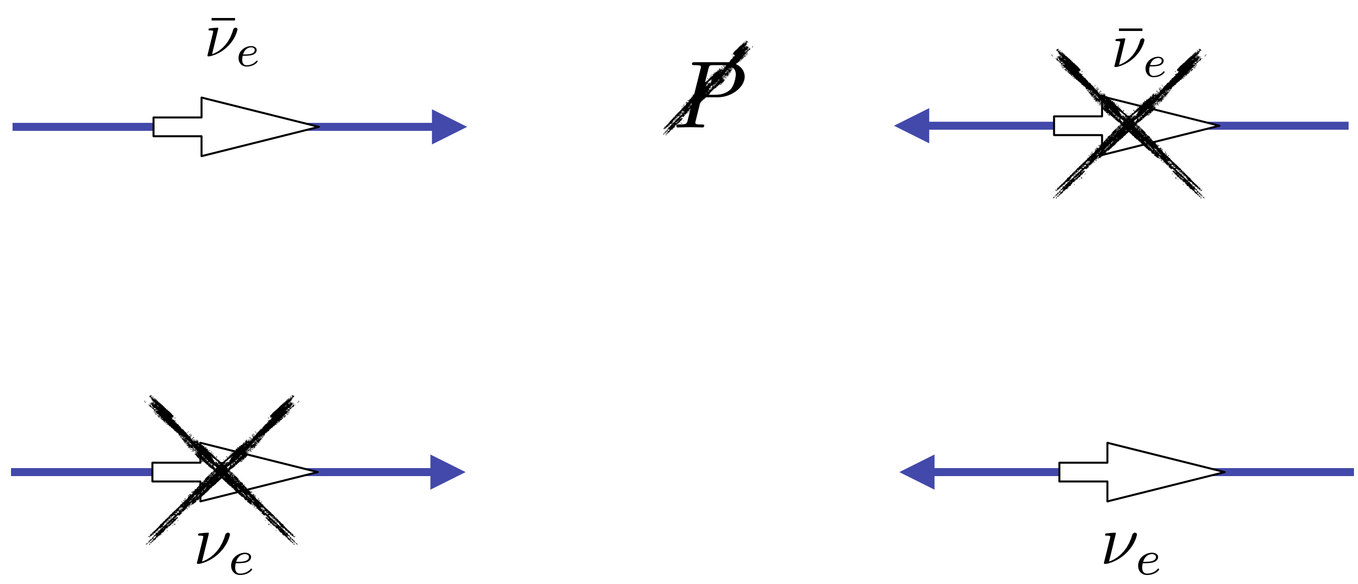

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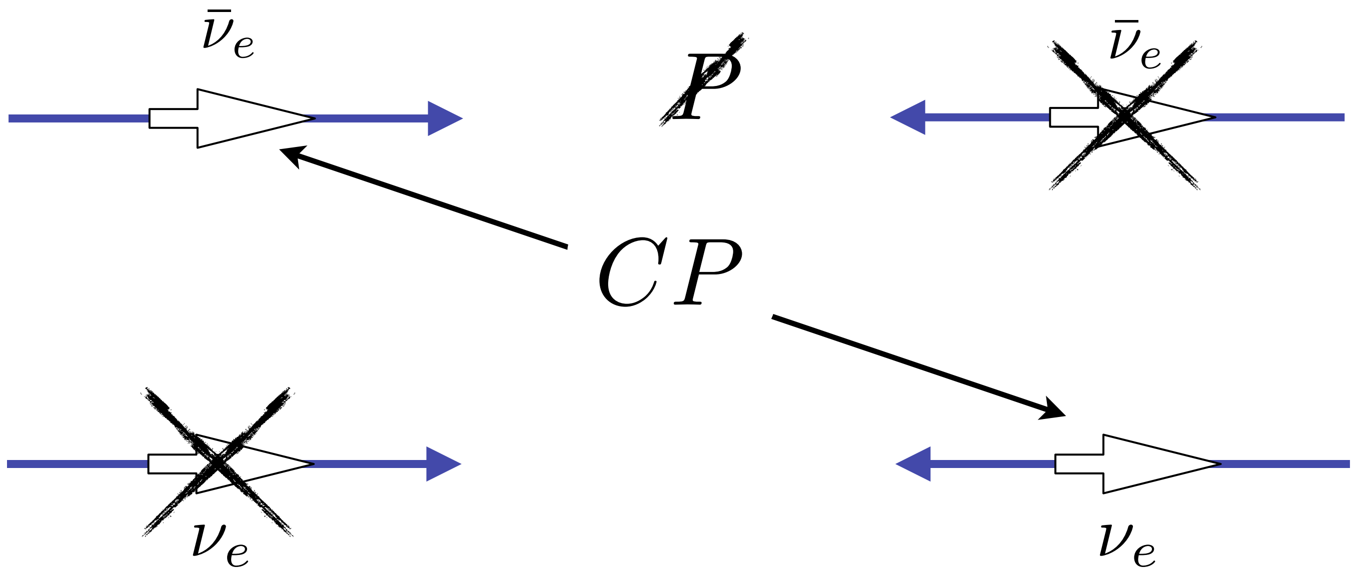


✓ Any theory of the weak interaction shall include these properties.

C and *P* breaking and *CP* symmetry

An intermediate conclusion

✓ Parity violation do occur elsewhere

✓But those are not of fundamental nature. The DNA molecule for instance can be synthesised.

Question: OK, parity is violated in the weak interaction. But can't we restore the left-right symmetry by considering the product *C* x *P*? Seems a good symmetry at least in the pion decay.

$$\Gamma(\pi^+ \to \ell^+ \nu_\ell) = \Gamma(\pi^- \to \ell^- \bar{\nu}_\ell)$$

Discovery of *CP* violation.

- With simple quantum mechanics, one can show that in absence of *CP* violation:

$$
\begin{aligned}
CP|K_1\rangle &= \frac{1}{\sqrt{2}}(CP|K^0\rangle + CP|\bar{K}^0\rangle) = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle) = +|K_1\rangle \\
CP|K_2\rangle &= \frac{1}{\sqrt{2}}(CP|K^0\rangle - CP|\bar{K}^0\rangle) = \frac{1}{\sqrt{2}}(|\bar{K}^0\rangle - |K^0\rangle) = -|K_2\rangle
\end{aligned}
$$

- Final states *CP* eigenvalues are +1 ($\pi\pi$) and -1 ($\pi\pi\pi$). If *CP* is a conserved quantity, one then should have:

$$
\begin{aligned}
K_1 &\rightarrow \pi\pi \\
K_2 &\rightarrow \pi\pi\pi.
\end{aligned}
$$

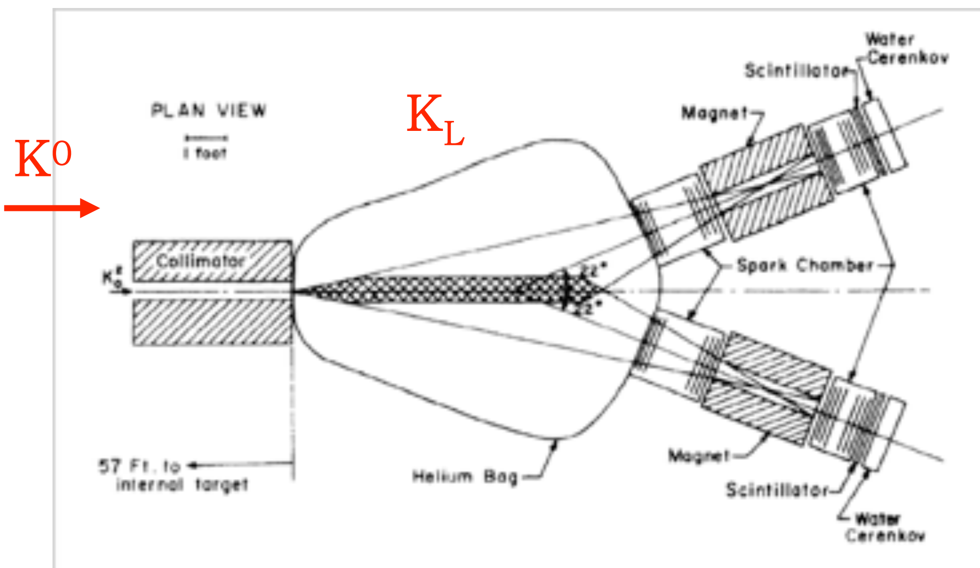
Which we'll identify as K^0_S and K^0_L respectively.

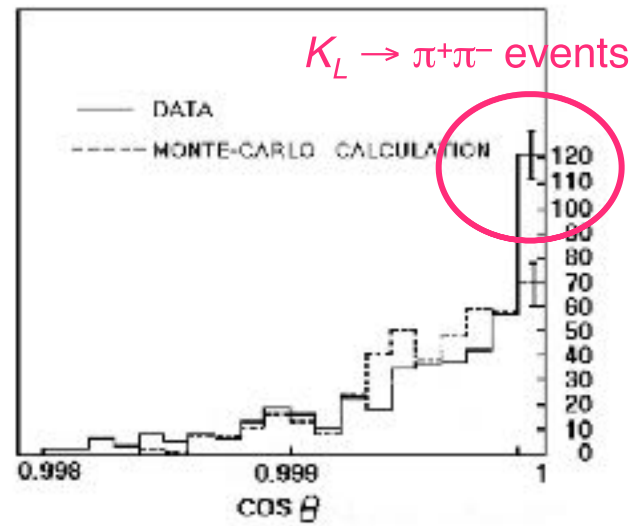
- measuring K^0_L decays into two pions ? Proof that *CP* symmetry is violated in weak interaction.

Discovery of *CP* violation.

- The CP violation in kaon system: Christenson, Cronin, Fitch , Turlay. Phys. Rev. Lett. 13 (1964) 138.

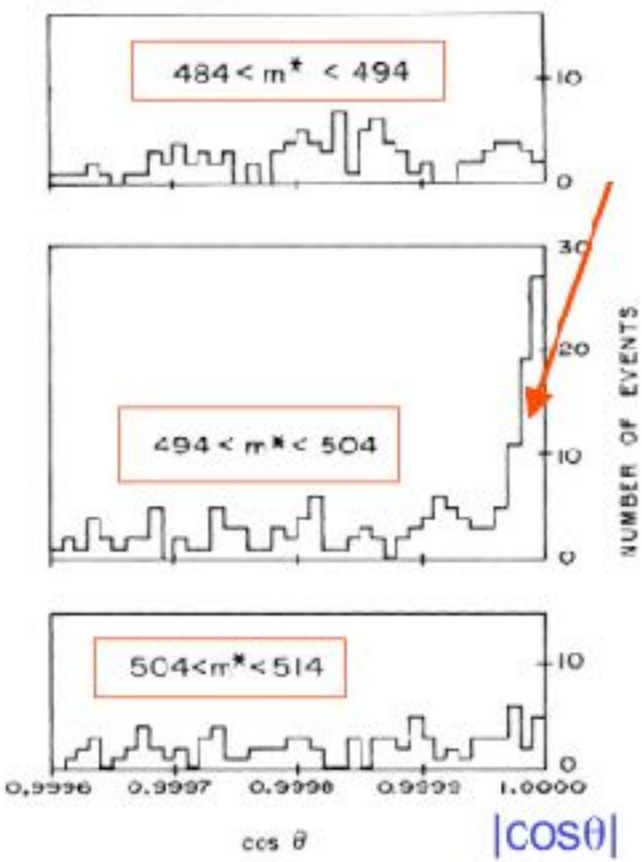
- Far after the target, only the long species of K^0 survive. They measured:





$$|\eta_{+-}| = \frac{A(K_L^0 \to \pi\pi)}{A(K_S^0 \to \pi\pi)}$$

Discovery of *CP* violation.



• Two-body decay : in the K^0 center of mass system the two π are back to back : |cosθ|=1.

• Today's more precise measurement for the ratio of amplitudes:

$$|\eta_{+-}| = \frac{A(K_L^0 \to \pi\pi)}{A(K_S^0 \to \pi\pi)} = (2.271 \pm 0.017)10^{-3}.$$

Discovery of *CP* violation.

Message Number 1:

The *CP* symmetry is violated in the mixing of neutral mesons, a pure electroweak phenomenon, *e.g.*

$$K^0 \longrightarrow \bar{K}^0 \neq \bar{K}^0 \longrightarrow K^0$$

Discoveries of *CP* violation

- At LHC, compare the decay rates of $B^0_{d,s}$ and *anti*$B^0_{d,s}$ into self-tagged final states $K\pi$

$$A_{CP}(B^0 \to K\pi) = \frac{\Gamma(\bar{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\bar{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)}$$

$$A_{CP}(B^0_s \to \pi K) = \frac{\Gamma(\bar{B}^0_s \to \pi^- K^+) - \Gamma(B^0_s \to \pi^+ K^-)}{\Gamma(\bar{B}^0_s \to \pi^- K^+) + \Gamma(B^0_s \to \pi^+ K^-)}.$$

- These raw asymmetries must be corrected from detection asymmetry and *B* production asymmetry:

$$A_\Delta(B^0_{(s)} \to K\pi) = \zeta_{d(s)} A_D(K\pi) + \kappa_{d(s)} A_P(B^0_{(s)} \to K\pi)$$

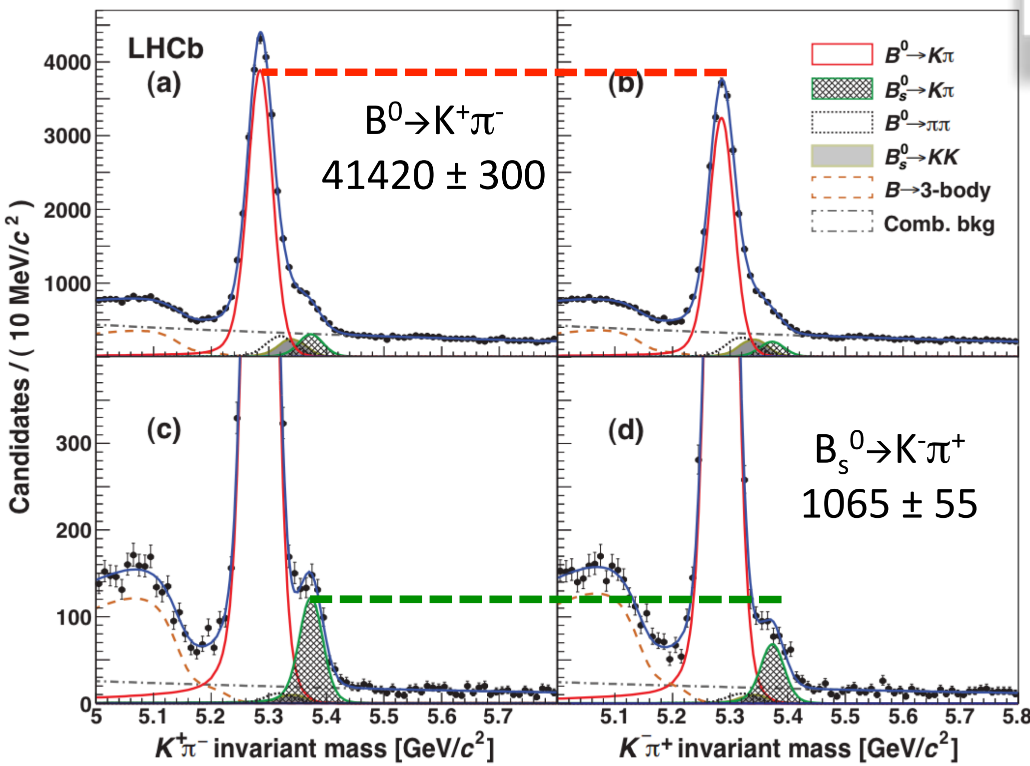
- Ingredients: these analyses are heavily relying on Particle Identification performance. It is also necessary to master the *B* production asymmetry and the differences of charged particle detection efficiencies (data-driven estimates).

Other discoveries of *CP* violation.

- Compare the decay rates of self-tagged modes $K\pi$

$$A_{\text{raw}}(B^0 \to K^-\pi^+) = -0.091 \pm 0.006,$$
$$A_{\text{raw}}(B_s \to K^+\pi^-) = 0.28 \pm 0.04,$$

$\mathcal{L}$ = (1/fb @ √s = 7 TeV)



- Data-driven control of PID efficiencies thanks to the self-tagged mode $D^{*+} \to D^0 (K^-\pi^+)\, \pi^+$
- Raw asymmetries corrected from detection asymmetry (also D^{*+} control sample.
- *B* production asymmetry simultaneously measured from decay time distribution.

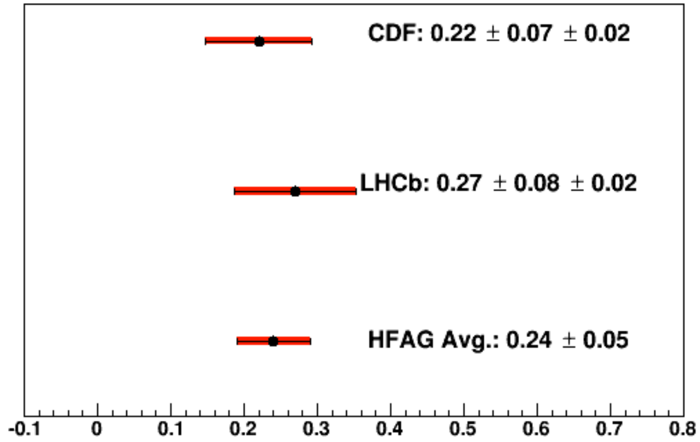
Other discoveries of *CP* violation.

$$A_{\rm CP}(B^0 \to K^-\pi^+) = -0.080 \pm 0.007\ ({\rm stat.})\ \pm 0.003\ ({\rm syst.}),$$
$$A_{\rm CP}(B_s \to K^+\pi^-) = 0.27 \pm 0.04\ ({\rm stat.})\ \pm 0.01\ ({\rm syst.}).$$

- World best measurement for the B^0

LHCB-PAPER-2013-018

- Former results for B_s



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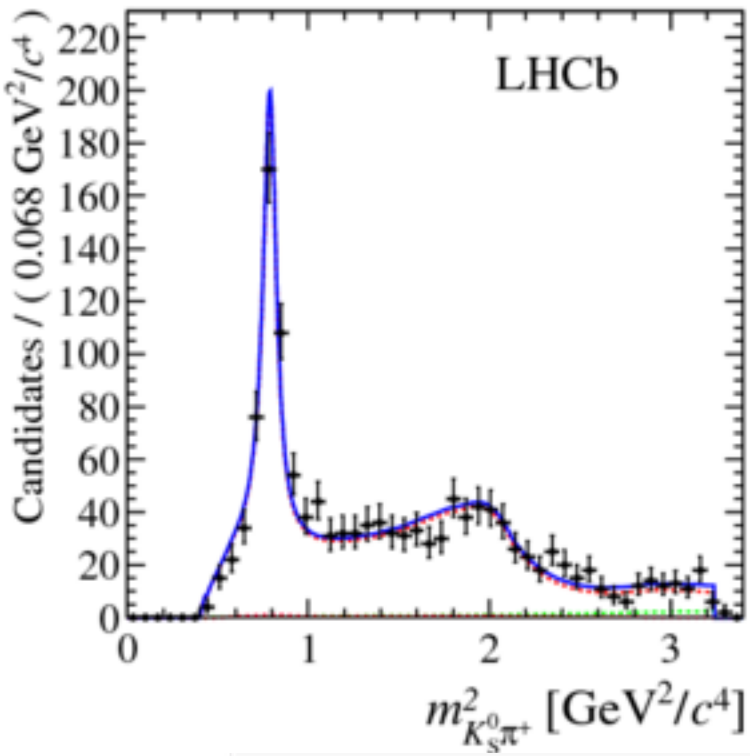
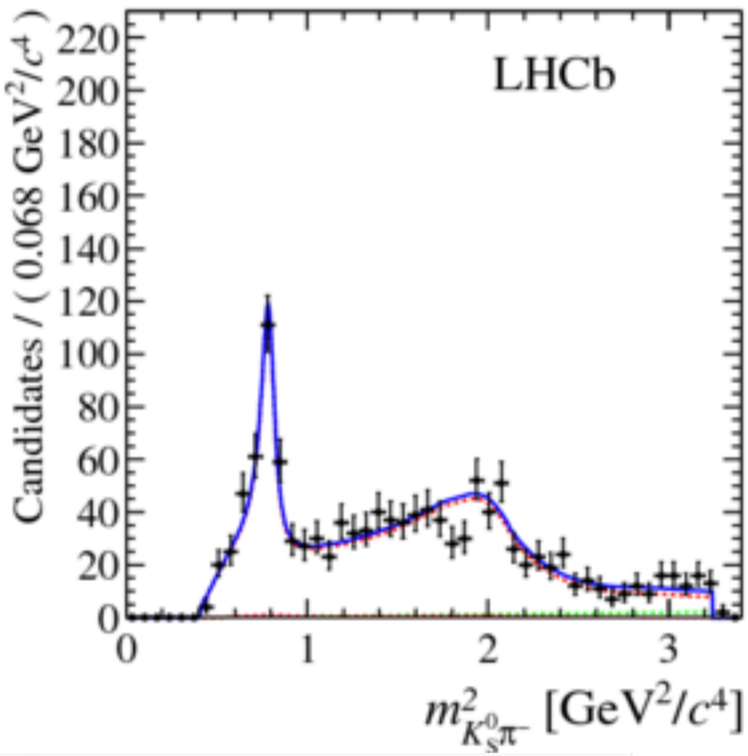
Phys. Rev. Lett. 108 (2012)

- **First observation of *CPV* in the B_s system.**

Other discoveries of *CP* violation.





Phys. Rev. Lett. 120, 261801 (2018)

$$A_{CP}(\overline{B}^0 \to K^*(892)^- \pi^+) = -0.30 \pm 0.06$$

Other discoveries of *CP* violation.

Message Number 2:

The *CP* symmetry is violated in the decay of beautiful particles, pure electroweak phenomenon, *e.g.*

$$B^0 \longrightarrow K^+\pi^- \neq \bar{B}^0 \longrightarrow K^-\pi^+$$

Other discoveries of *CP* violation.

Message Number 3:

The *CP* symmetry can be violated in the interplay (interference) of the two previous sources of *CP* violation, *e.g.*

$$\left(B^0 \longrightarrow f_{CP}, \quad B^0 \searrow \overline{B}^0 \nearrow f_{CP} \right) \neq \left(\overline{B}^0 \longrightarrow f_{CP}, \quad \overline{B}^0 \searrow B^0 \nearrow f_{CP} \right)$$

Concluding this introduction

- *C*, *P* and *CP* are (so far) conserved in electromagnetic and strong interactions.
- *C* and *P* symmetries are maximally violated by the weak interaction.
- *CP* symmetry is slightly violated in the electroweak interaction.

- There are three ways of *CP* violation to manifest in the Nature so far:

  1) In the mixing of neutral particles (observed solely in neutral kaon mixing - 1964).

  2) In the decay of the beautiful and strange mesons (*K* and $B_{d,s}$, 2001 and 2004,2013 resp.).

  3) In the interference between decay and mixing of the beautiful particles (2001, see next chapters) .

  And that's all.

A personal comment before going to Chapter II

- We do not have yet a (satisfactory) dynamical mechanism to explain these discrete symmetry breakings. And to my knowledge, no mathematical Physics way to do so.

- Still, what comes next is elegant.

- We'll try to make sense of the *CP* symmetry breaking phenomena.

2.4 Introduction: which measurements and where?

- B factories: all ! As far as UT is concerned.