Flavour oscillations and CP violation in neutral mesons (a.k.a. a biased introduction to heavy flavour physics) Park 2.2 Mirco Dorigo (EPFL)

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Roma — May 31<sup>st</sup> & Jun 1<sup>st</sup>, 201



I. Introduction

2. Mixing of neutral mesons

Part 1

3. CP violation phenomenology

4. Put everything in the SM...

5. ( and maybe a look beyond)

Part 2

# CP violation i.e. matter-antimatter asymmetry

#### Back in the '60s

- CP still a good symmetry
- Observed neutral kaon mixing
- Neutral kaons come into two states:
  - K<sub>1</sub> with  $\tau_1 = 0.89 \times 10^{-10}$  s (CP even)
  - + K<sub>2</sub> with  $\tau_2$  = 5.2 x 10<sup>-8</sup> s (CP odd)
- Can have a beam of pure  $K_2$
- If CP is conserved K<sub>2</sub> never decays into 2 pions





# Cronin & Fitch experiment



Val Fitch

Search for the CP violating  $K_2 \rightarrow \pi \pi$  decay.



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Data taken with a hydrogen target in the beam

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#### PHYSICAL REVIEW LETTERS

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#### EVIDENCE FOR THE $2\pi$ DECAY OF THE $K_2^{\circ}$ MESON\*<sup>†</sup>

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

This Letter reports the results of experimental studies designed to search for the  $2\pi$  decay of the  $K_2^0$  meson. Several previous experiments have served<sup>1,2</sup> to set an upper limit of 1/300 for the fraction of  $K_2^{0}$ 's which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit.

In this measurement,  $K_2^{0}$  mesons were produced at the Brookhaven AGS in an internal Be target bombarded by 30-BeV protons. A neutral beam was defined at 30 degrees relative to the circulating protons by a  $1\frac{1}{2}$ -in.× $1\frac{1}{2}$ -in.×48-in. collimator at an average distance of 14.5 ft. from the internal target. This collimator was followed by a sweeping magnet of 512 kG-in. at 20 ft and a 6-in.×6-in.×48-in. collimator at 55 ft. A  $1\frac{1}{2}$ -in. thickness of Pb was placed in front of the first collimator to attenuate the gamma rays in the beam.

The experimental layout is shown in relation to the beam in Fig. 1. The detector for the decay products consisted of two spectrometers each composed of two spark chambers for track delineation separated by a magnetic field of 178 kG-in. The axis of each spectrometer was in the horizontal plane and each subtended an average solid angle of 0.7×  $10^{-2}$  storadians. The spark chamThe analysis program computed the mentum of each charged particle observed decay and the invariant mass,  $m^*$ , as each charged particle had the mass of charged pion. In this detector the  $K_e$  leads to a distribution in  $m^*$  ranging MeV to ~536 MeV; the  $K_{\mu3}$ , from 280 to 363 MeV. We e that  $m^*$  equal to the  $K^0$  mass is not a result when the three-body decays ar in this way. In addition, the vector s two momenta and the angle,  $\theta$ , betwee direction of the  $K_2^0$  beam were determined angle should be zero for two-body decays decays ar in general, different from zero for the direction of the statements and the angle should be zero for two-body decays ar in general.

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An important calibration of the approximate approximate the decays of  $K_1^{0}$  mesons produced by regeneration in 43 gm/cm<sup>2</sup> of tungster  $K_1^{0}$  mesons produced by coherent regeneration in 43 gm/cm<sup>2</sup> of tungster  $K_2^{0}$  beam, produced by coherent regeneration in  $K_1^{0}$  decay simulates the cay of the  $K_2^{0}$  into two pions. The regeneration in the region of the beam sensed here the region of the beam sensed here the region of the beam sensed here the target of target of the target of the target of the target of tar

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$$g_{\pm}(t) = \frac{e^{-i\omega_{S}t} \pm e^{-i\omega_{L}t}}{2} \\ \begin{pmatrix} \kappa^{-}(\iota) \neq & (\bar{p}g_{-}(\iota) + g_{+}(\iota) + f_{-}) \end{pmatrix} \begin{pmatrix} K^{0}(0) \\ \overline{K^{0}}(0) \end{pmatrix} \qquad g_{\pm}(t) = \frac{e^{-i\omega_{S}t} \pm e^{-i\omega_{L}t}}{2}$$



Time evolution (again...) t = 0 t







#### $\mathbf{I} \pi^- e^+ \nu(\mathbf{U}) \mathbf{T} \mathbf{I} \pi^+ e^- \overline{\nu}(\mathbf{U})$

# $\begin{array}{l} \text{Matter and apply hatter are not arbitrary} \\ t = 0 \end{array} \stackrel{t}{=} \frac{1}{1 + \left| \frac{d}{q} / p \right|^4} = 4\mathcal{R}\epsilon \\ \left( \frac{K^0(t)}{V^0(t)} \right) = \left( \frac{g_+(t)}{q} \frac{p_{g-}(t)}{q} \right) \left( \frac{K^0(0)}{\overline{T}^0(t)} \right) \stackrel{g_{\pm}(t)}{g_{\pm}(t)} A_T(t) = \frac{\overline{I}_{\pi^-e^+\nu}(t) - I_{\pi^+e^-\overline{\nu}}(t)}{\overline{I}_{\pi^-e^+\nu}(t) + I_{\pi^+e^-\overline{\nu}}(t)} \end{array}$

$$\begin{pmatrix} \frac{K^{0}(t)}{K^{0}(t)} \end{pmatrix} = \begin{pmatrix} g_{+}(t) & \frac{p}{q}g_{-}(t) \\ \frac{q}{p}g_{-}(t) & g_{+}(t) \end{pmatrix} \begin{pmatrix} \frac{K^{0}(0)}{K^{0}(0)} \end{pmatrix}$$
$$K |q/p| = 0.9967 \pm 0.0008 \neq 1$$

 $K^0$ 

What are you made of ???

 $= \frac{1 - \left|q/p\right|^4}{1 + \left|q/p\right|^4} = 4\mathcal{R}\epsilon$ 

8

 $e [\tau_s]$ 

51

20

(The answer would be likely (hopefully?) straightforward...  $N(baryons)/N(photons) \approx 6 \times 10^{-10}$ )



#### CP violation in B mixing?

Use large samples of semileptonic  $B^0 \rightarrow D\mu\nu$  and  $B_s^0 \rightarrow D_s\mu\nu$  decays at LHCb to measure CP violation in mixing

$$a_{\rm sl} = \frac{\Gamma(\overline{B} \to B \to f) - \Gamma(B \to \overline{B} \to \overline{f})}{\Gamma(\overline{B} \to B \to f) + \Gamma(B \to \overline{B} \to \overline{f})} = \operatorname{Im}(M_{12}/\Gamma_{12})$$

$$a_{\rm sl} = \frac{\Gamma(\overline{B} \to B \to f) - \Gamma(B \to \overline{f}) + \Gamma(B \to \overline{f}) \to \overline{f}}{\Gamma(\overline{B}^{0}_{(s)} \to \ell^{+}X) + \Gamma(B^{0}_{(s)} \oplus \overline{f}) + \Gamma(B \to \overline{f}) - \overline{f}} = \operatorname{Im}(M_{12}/\Gamma_{12})$$

$$a_{P} = \frac{(g)(\overline{p}p\ell \to \overline{B}) - \overline{f}}{\sigma(pp \to \overline{B}) + \sigma(pp \to B)}$$
The "untagged" asymmetry:

$$\frac{N(B,t) - N(\bar{B},t)}{N(B,t) + N(\bar{B},t)} = \frac{a_{\rm sl}}{2} \cdot \left[1 - \frac{\cos \Delta M t}{\cosh \frac{\Delta \Gamma t}{2}}\right]$$

but there are other asymmetries to consider...





$$\frac{N(B,t) - N(B,t)}{N(B,t) + N(\bar{B},t)} = \frac{a_{\rm sl}}{2} \cdot \left[1 - \frac{\cos \Delta M t}{\cosh \frac{\Delta \Gamma t}{2}}\right]$$

$$\frac{N(B,t) - N(B,t)}{N(B,t) + N(\bar{B},t)} = \frac{a_{\rm sl}}{2} - \left[a_P + \frac{a_{\rm sl}}{2}\right] \cdot \frac{\cos\Delta M t}{\cosh\frac{\Delta\Gamma t}{2}}$$



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 $\begin{array}{c} \text{Integrate in time:} \\ \underline{N(B,t) - N(\bar{B},t)}_{N(eB,t) - \mu^+} & \underline{F[D^+\mu^-]}_{P} & \underline{a_{sl}}_{P} \\ \hline \underline{N(eB,t) - \mu^+}_{P} & \underline{F[D^+\mu^-]}_{P} & \underline{a_{sl}}_{P} \\ \hline \underline{A_{m(eB,t)}}_{P} & \underline{F[D^+\mu^+]}_{P} & \underline{F[D^+\mu^-]}_{P} & \underline{a_{sl}}_{P} \\ \hline \underline{A_{m(eB,t)}}_{P} & \underline{A_{m(eB,t)}}_$ 



$$\frac{N(B,t) - N(B,t)}{N(B,t) + N(\bar{B},t)} = \frac{a_{\rm sl}}{2} - \left[a_P + \frac{a_{\rm sl}}{2}\right] \cdot \frac{\cos \Delta M t}{\cosh \frac{\Delta \Gamma t}{2}}$$

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<10<sup>-4</sup> for  $\Delta m_s = 18 \text{ ps}^{-1}$ 



N(B,t) - N(B,t)	$a_{\rm sl}$	$a_{\rm sl}$	$\cos \Delta M t$
$\overline{N(B,t) + N(\bar{B},t)}$	$-\frac{1}{2}$	$\left\lfloor \frac{1}{2} \right\rfloor$	$\overline{\cosh \frac{\Delta \Gamma t}{2}}$



Expected sensitivity on a<sub>sl</sub>: 10<sup>-3</sup>

<10<sup>-4</sup> for  $\Delta m_s = 18 \text{ ps}^{-1}$ 

#### Signal Yields



Yet, other spurious asymmetry to cancel...

#### **Detection asymmetries**



#### **Detection asymmetries**



#### Muons



#### **Detection asymmetries**



#### **Detection asymmetries**



Effectiveness depends on high frequency (2 week) of changes.

Does not cancel asymmetries to 10<sup>-3</sup> level, but crucial systematic check of result.







# So far (so good?)

- ★ No primordial antimatter observed, universe matter dominated
- ★ Need breaking of CP symmetry to explain this
- ★ C and P are violated by weak interactions (CP looks still healthy...)
- ★ Matter-antimatter oscillations: K<sup>0</sup> can turn into anti-K<sup>0</sup>; the physical states are not the flavour eigenstates.
- ★ Using flavour-specific decays we can observe the flavour oscillations
- \* A very rich phenomenology of mixing of K, D, and B mesons
- ★ CP is broken!
- ★ Observed CP violation in K mixing; no evidence so far for B mesons (neither for D mesons).

#### If the final state is a CP eigenstate



$$g_{\pm}(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2}$$



















 $\bar{\pi}\pi^{-}_{\pi^{-}} \propto |A_{+-}[g_{+}(t) + \lambda_{+-}g_{-}(t)]|^{2}$ 



$$g_{\pm}(t) = \frac{e^{-i\omega_{S}t} \pm e^{-i\omega_{L}} \prod_{\substack{i=1 \ i=1 \ i$$

$$\Gamma \left( K^{0} \to \pi^{+} \pi^{-} \right) \propto |A_{+-}|^{2} \left[ |g_{+}(\underline{t})|^{2} + |\lambda_{+}|^{2} |g_{+}(\underline{t})|^{2} + 2\mathcal{R}_{+}(\underline{\lambda}_{+})|^{2} |g_{+}(\underline{t})|^{2} + 2\mathcal{R}_{+}(\underline{\lambda}_{+})|^{2} |g_{+}(\underline{t})|^{2} |g_{+}(\underline{t})|^{2} + 2\mathcal{R}_{+}(\underline{\lambda}_{+})|^{2} |g_{+}(\underline{t})|^{2} |g_{+}(\underline{t})$$

I. CP violation in **decay**:

$$\left|\frac{\overline{A}_{\overline{f}}}{A_f}\right| \neq 1$$

$$|B - \langle f |^2 \neq |\overline{B} - \langle \overline{f} |^2$$
  
both neutral and charged mesons

# $\Gamma\left(K^{0} \to \pi^{+}\pi^{-}\right) \propto \left|\overline{A_{+-}}\right|^{2} \left[|g_{+}(t)|^{2} + |\lambda_{+-}|^{2} |g_{-}(t)|^{2} + 2\mathcal{R}\left(\lambda_{+-}g_{+}^{*}(t)g_{-}(t)\right)\right]$ $\Gamma\left(\overline{K^{0}} \to \pi^{+}\pi^{-}\right) \propto \left|\overline{A_{+-}}\right|^{2} \left[|g_{+}(t)|^{2} + \frac{1}{|\lambda_{+-}|^{2}} |g_{-}(t)|^{2} + 2\mathcal{R}\left(\lambda_{+-}g_{+}^{*}(t)g_{-}(t)\right)\right]$

I. CP violation in **decay**:

$$\left|\frac{\overline{A}_{\overline{f}}}{A_f}\right| \neq 1$$

 $|\mathbb{B} - \mathbb{K} f|^2 \neq |\mathbb{B} - \mathbb{K} f|^2$ both neutral and charged mesons

2. CP violation in mixing:

$$\frac{q}{p} \neq 1 \qquad \begin{array}{c|c} \mathbb{B}_{s}^{\circ} - \mathbb{B}_{s}^{\circ} \mathbb{P}_{s}^{\circ} = \mathbb{B}_{s}^{\circ} \mathbb{P}_{s}^{\circ} \mathbb{P}$$

41  

$$D^{\circ} \rightarrow \overline{D}^{\circ} \rightarrow \overline{f}^{2} \neq |\overline{D}^{\circ} \rightarrow \overline{D}^{\circ} \rightarrow \overline{f}|^{2}$$

#### CP violation: 3 ways



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$$\begin{split} \eta_{+} &= \frac{1-\lambda}{1+\lambda} \quad \underbrace{pA-q\overline{A}}_{A \text{ Germanization of the CP violation between equations of the decay of krangeness-tagged neutral kaons } \\ \eta_{-} &= \frac{1-\lambda}{1+\lambda} \quad \underbrace{pA-q\overline{A}}_{DA+q\overline{A}} \stackrel{(\pi^+\pi^-)}{\subseteq [n]_{+} + q\overline{A}]} \stackrel{(\mu^+e^+)}{\subseteq [n]_{+} + q\overline{A}]} \stackrel{(\mu^+e^+)}{\underset{(\mu^+e$$

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where the errors are purely statistical and  $\chi^2/d.o.f. = 1.2$ . Table 1 shows the correlation coefficients

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- ★ CP is broken!
- \* Observed CP violation in K mixing; no evidence so far for B mesons (neither for D mesons).
- \* We can measure CP violation in 3 ways: decays, mixing, interference
- \* (time-dependent) CP in interference allows to measure phases (difference)