Monday EP seminars

An EPR Experiment Testing the Non-separability of the K^0-$\bar{K}^0$ wavefunction

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Outline

- Introduction
- Entanglement and EPR paradox
- Neutral Kaon pair and strangeness correlation
- Testing EPR type correlation in CPLEAR
- Conclusion

Introduction

If a tree falls in the forest and nobody is there to listen, does it make sound?

- Realist world view: Things exist out there *independent* of our observation
- Tacit assumption: We talk about scientific *discovery* rather than *invention*

QM Innovations

But QM forces us to modify our view on the reality of a physical system by new conceptual innovations:

- Uncertainty Principle -- less precise knowledge of the physical system
- Wave-Particle duality -- How can an electron be both a particle (local) and a wave (non-local)?
- Superposition -- several possible outcomes exist (or at least potentially) until the measurement
- Probability -- reduction of wavefunction to a single outcome is purely by chance.
- Entanglement -- A multi-particle wavefunction imply correlation even at a large distance.

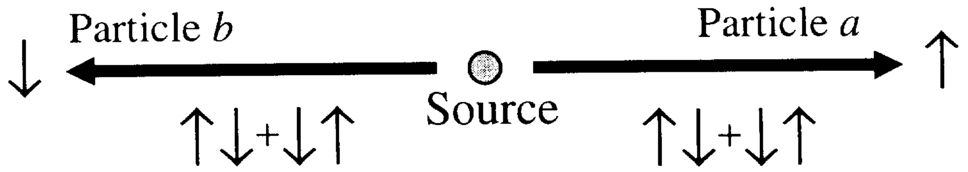
Entanglement

Peculiar two-particle QM system

- Two particle created in a single QM state are spatially separated but nevertheless belong to the same wavefunction: one single wavefunction $\Psi_{a,b}$ describing particles *a* and *b*.
- Outcome was not defined until measurement!
- Measurement on *a* will define the state of *b* *instantaneously* even without measuring it.

Examples

- Two photo singlet state: one spin up ⇒ the other spin down



↓ Particle *b*

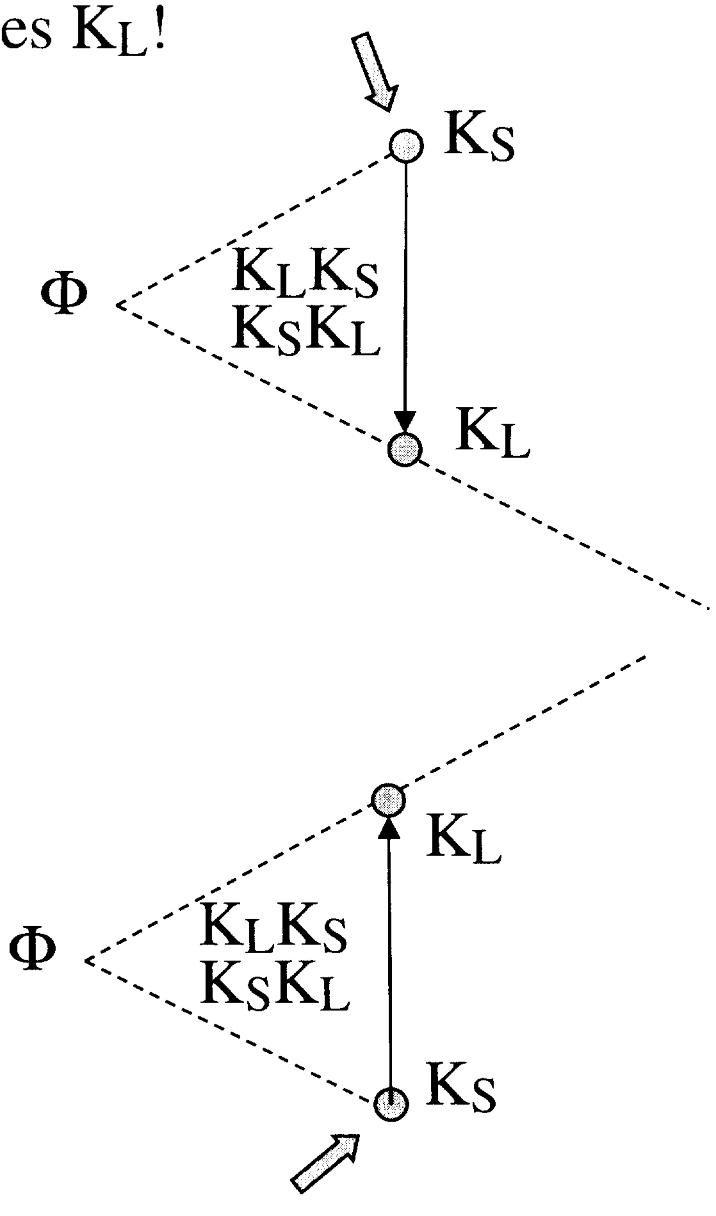
Particle *a* ↑

Source

$\uparrow\downarrow+\downarrow\uparrow$ $\uparrow\downarrow+\downarrow\uparrow$

$\Phi \rightarrow K_L\, K_S$

- $\phi \rightarrow K_L\, K_S$: measure $K_S \Rightarrow$ the other becomes K_L!



EPR Paradox

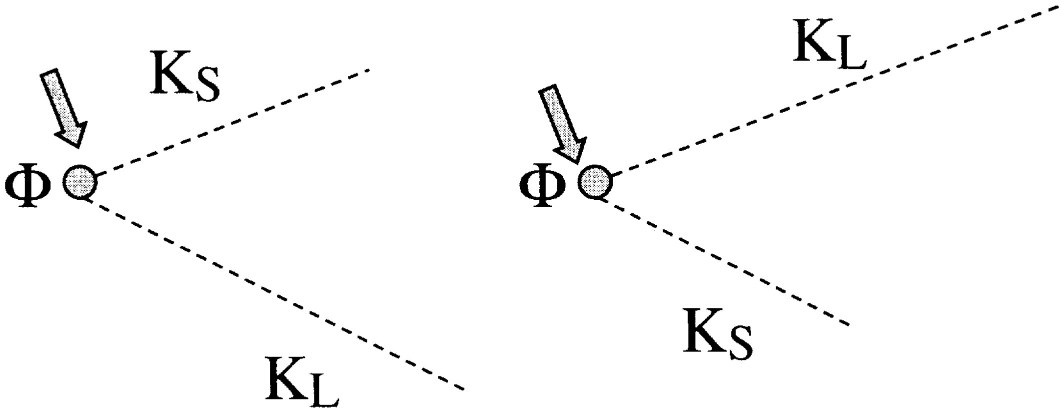
Einstein, Podolsky and Rosen was the first to point out this peculiar system in 1935.

When two particles are far away, how can *b* know instantaneously about the result of measurement done on *a*?

•Transfer of signal faster than light?

•Are the states predetermined, or randomly defined, at the creation?

•Are the wavefunction separated (factorization) right after the creation?



Up to now, these two cases cannot be distinguished!

Neutral Kaon Formalism

Three basis:

- K^0, $\bar{K}^0$: strangeness eigenstate
- K_1, K_2 : CP eigenstate
- K_L, K_S : mass eigenstate

Neglecting CP (10^{-3} effect), $K_S \equiv K_1$ $K_L \equiv K_2$

- $|K_S\rangle = (1/\sqrt{2})\ (\ |K^0\rangle + |\bar{K}^0\rangle\ )$
- $|K_L\rangle = (1/\sqrt{2})\ (\ |K^0\rangle - |\bar{K}^0\rangle\ )$
- $|K^0\rangle = (1/\sqrt{2})\ (\ |K_S\rangle + |K_L\rangle\ )$
- $|\bar{K}^0\rangle = (1/\sqrt{2})\ (\ |K_S\rangle - |K_L\rangle\ )$

Time evolution:

$|K_S(t)\rangle = e^{-i\alpha_s t}\ |K_S(0)\rangle$

$|K_L(t)\rangle = e^{-i\alpha_L t}\ |K_S(0)\rangle$

where

$\alpha_S = m_S - i\,\gamma_S/2$,

$\alpha_L = m_L - i\,\gamma_L/2$

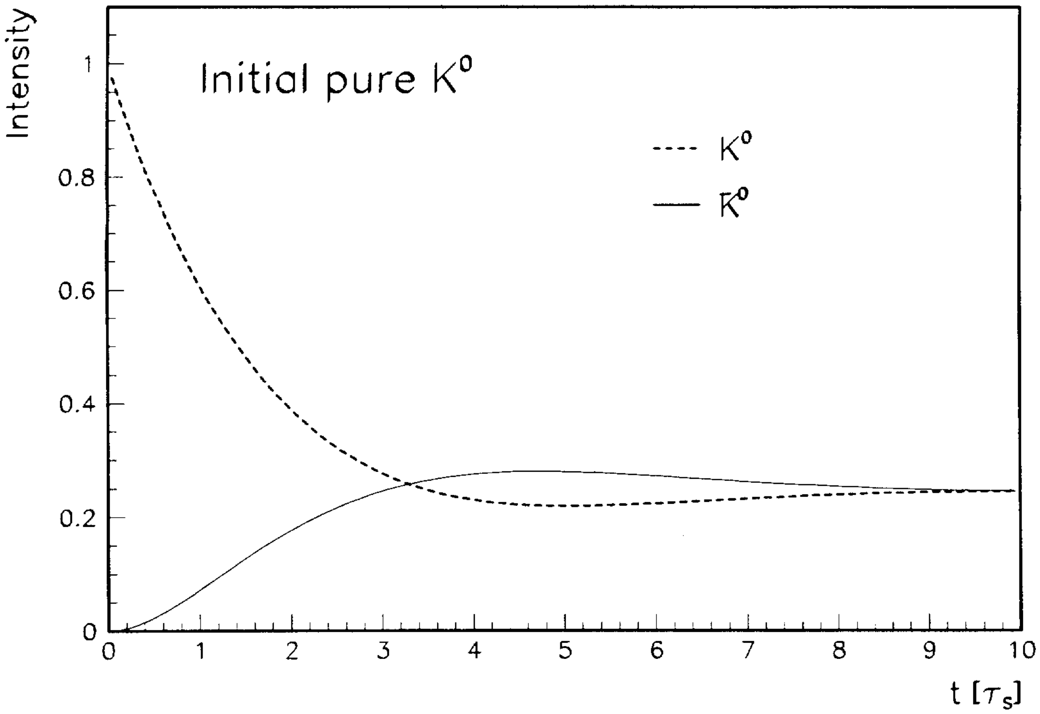
m_S, m_L ⇒ mass of K_S, K_L

$\gamma_S = 1/\tau_S$, $\gamma_L = 1/\tau_L$ ⇒ decay rate of K_S, K_L

Strangeness Oscillation

Due to the mass difference between the K_S and K_L, A $\bar{K}^0$ can oscillate into K^0 and viceversa:

For example, for a initially pure K^0 sample:



Neutral Kaon Anti-symmetric Pair

A pair of neutral kaon can created in two possible QM states: anti-symmetric state ($J^{PC}=1^{--}$) and symmetric state ($J^{PC}=0^{++}$)

The anti-symmetric state ($J^{PC}= 1^{--}$) exhibits EPR type correlation

At the production ($t_a= t_b=0$):

$$|\Psi(0,0)\rangle = (1/\sqrt{2})\,(\,|K^0(0)\rangle_a\,|\overline{K}^0(0)\rangle_b - |\overline{K}^0(0)\rangle_a\,|K^0(0)\rangle_b\,)$$
$$= (1/\sqrt{2})\,(\,|K_S(0)\rangle_a\,|K_L(0)\rangle_b - |K_L(0)\rangle_a\,|K_S(0)\rangle_b\,)$$

Time Evolution:

$$|\Psi(t_a,t_b)\rangle = (1/\sqrt{2})\,(e^{-i\alpha_S t_a}\,|K_S(0)\rangle_a\,e^{-i\alpha_L t_b}\,|K_L(0)\rangle_b$$
$$- e^{-i\alpha_L t_a}\,|K_L(0)\rangle_a\,e^{-i\alpha_S t_b}\,|K_S(0)\rangle_b)$$

Anti-symmetric State

Express K_S, K_L as superposition of K^0, $\bar{K}^0$; two time-dependent intensities can be calculated from $|\Psi(t_a, t_b)\rangle$:

- Like Strangeness (K^0K^0, $\bar{K}^0\bar{K}^0$)

$$I_{\mathbf{like}} \propto e^{-\gamma_S(t_a-t_b)} + e^{-\gamma_L(t_a-t_b)} - 2e^{-(\gamma_L+\gamma_S)(t_a-t_b)/2}\cos(\Delta m \Delta t)$$

Note: $I_{\mathbf{like}}=0$ for $t_a=t_b$

Destructive interference!!

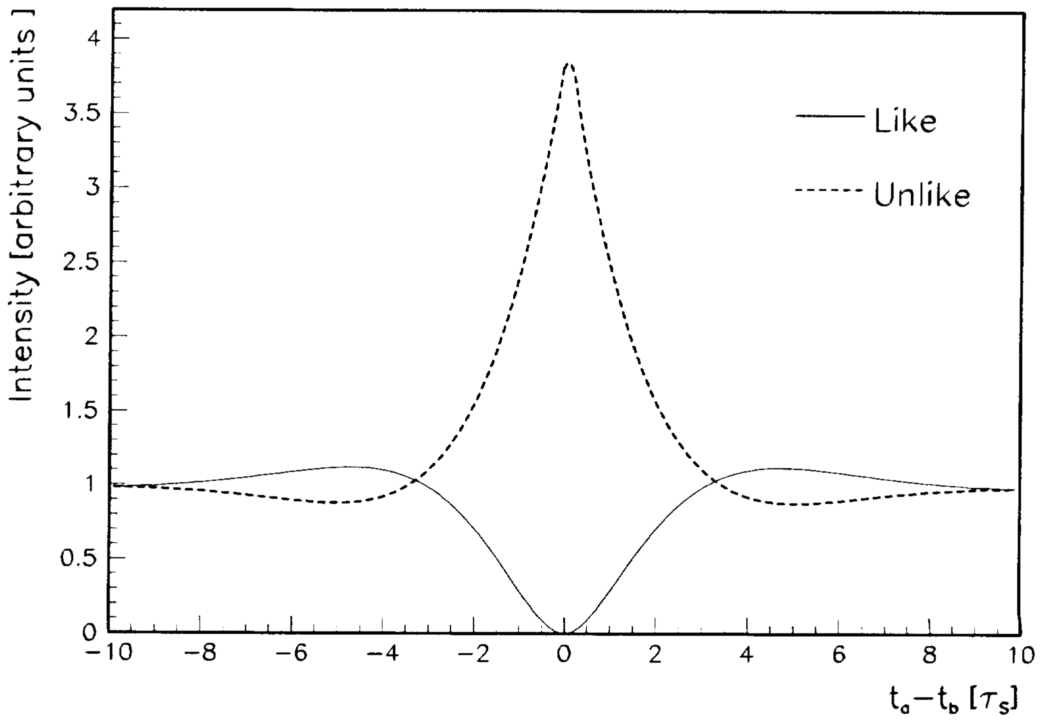
- Unlike Strangeness ($K^0\bar{K}^0$)

$$I_{\mathbf{unlike}} \propto e^{-\gamma_S(t_a-t_b)} + e^{-\gamma_L(t_a-t_b)} + 2e^{-(\gamma_L+\gamma_S)(t_a-t_b)/2}\cos(\Delta m \Delta t)$$

Note: $I_{\mathbf{unlike}}=1$ for $t_a=t_b$

Constructive interference!!

Strangeness Correlation



Measurement of the strangeness state of first neutral K defines the strangeness state of the second second K which evolves as if it was created with definite strangeness at that instant.

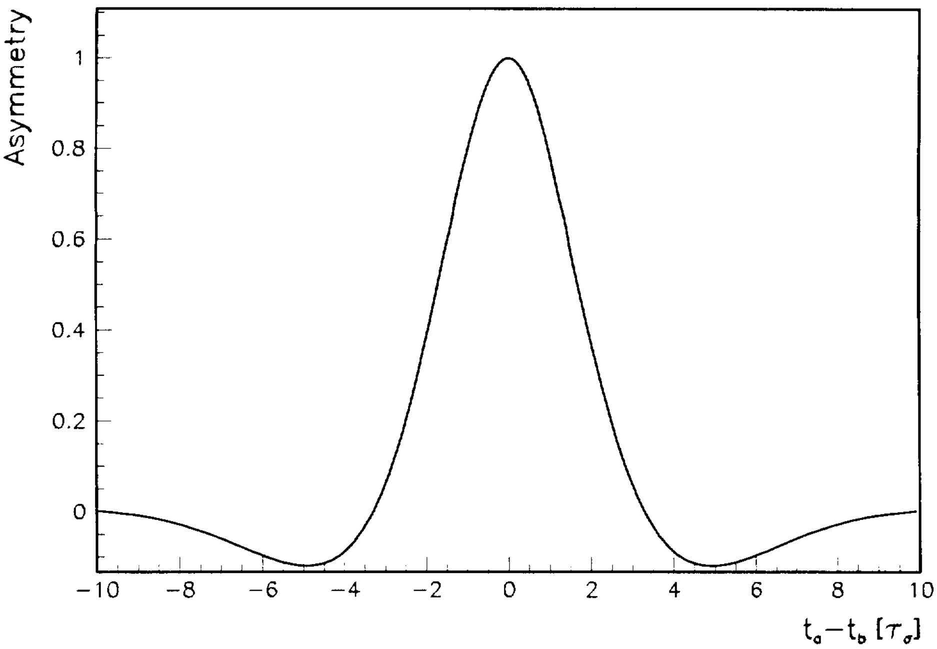
Asymmetry

Form asymmetries $A(t_{a}, t_{b})$:

$$A(t_{a}, t_{b}) \equiv (I_{\mathbf{unlike}} - I_{\mathbf{like}})/(I_{\mathbf{unlike}} + I_{\mathbf{like}})$$

$$= [2e^{-(\gamma_L+\gamma_S)\Delta t/2}\cos(\Delta m \Delta t)]/[e^{-\gamma_S \Delta t} + e^{-\gamma_L \Delta t}]$$

where $\Delta t = t_a - t_b$



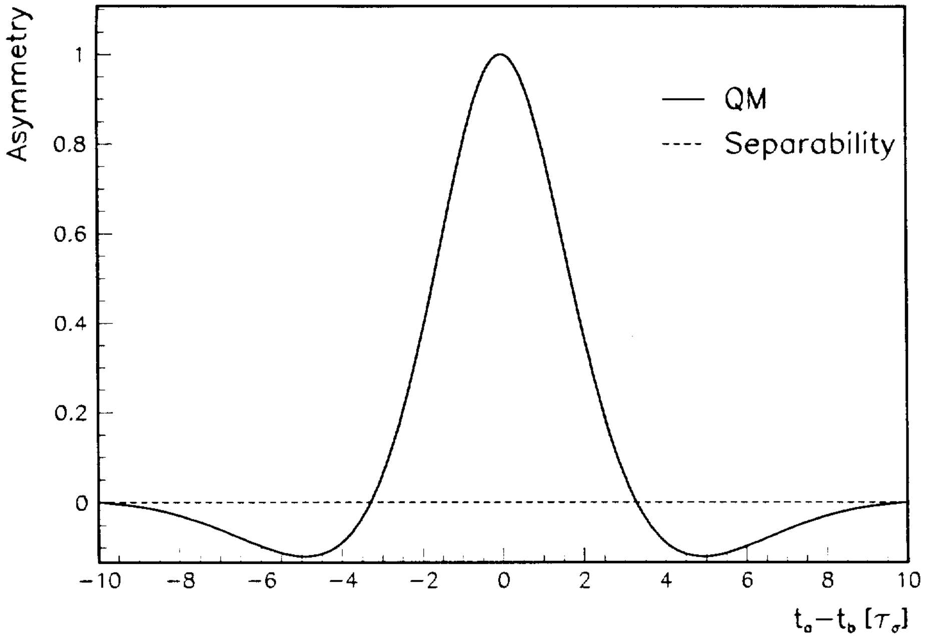
Separability Hypothesis

After creation, the wavefunction is separated into a $K_S K_L$ wavefunction and a $K_L K_S$ wavefunction (consistent with experimental result of $\phi \rightarrow K_S K_L$).

The intensities of the two wavefunctions have to be added quadratically.

- K_S : $I_{K^0} = I_{\overline{K}^0} = 50\%$
- K_L : $I_{K^0} = I_{\overline{K}^0} = 50\%$

$I_{\mathbf{like}} = I_{\mathbf{unlike}} = 50\% \Rightarrow A(t_a, t_b) = 0$



Allows tests of QM vs. Separability

Neutral Kaon Symmetric Pair

The symmetric $K^0\bar{K}^0$ state ($J^{PC}=0^{++}$) exhibits a different correlation:

$|\Psi\rangle = (1/\sqrt{2})\,(\,|K^0\rangle_a\,|\bar{K}^0\rangle_b + |\bar{K}^0\rangle_a\,|K^0\rangle_b\,)$

$\quad = (1/\sqrt{2})\,(\,|K_S\rangle_a\,|K_S\rangle_b - |K_L\rangle_a\,|K_L\rangle_b\,)$

Intensities become:

$I_{\mathbf{like}} \propto e^{-\gamma_S(ta+tb)} + e^{-\gamma_L(ta+tb)}$

$\qquad -2e^{-(\gamma_L+\gamma_S)(ta+tb)/2}\cos(\Delta m(t_a+t_b))$

$I_{\mathbf{unlike}} \propto e^{-\gamma_S(ta+tb)} + e^{-\gamma_L(ta+tb)}$

$\qquad +2e^{-(\gamma_L+\gamma_S)(ta+tb)/2}\cos(\Delta m(t_a+t_b))$

Interference oscillate with (t_a+t_b) rather than (t_a-t_b) ==> $I_{\mathbf{like}}$ never vanishes

Testing QM in CPLEAR

CPLEAR is designed to test fundamental symmetries. This is an subproduct of the experiment with minor modifications.

$K^0\ \bar{K}^0$ pair created in $p\bar{p}$ annihilation (10^6 $\bar{p}$/s) at rest in 27 bar hydrogen target

$p\bar{p} \to K^0\ \bar{K}^0$ with (700 pair/s)

- mono energetic K^0 (~800MeV/c)
- mean K_S decay length of 4cm

Two $p\bar{p}$ annihilation sates (S and P wave):
S wave → K_SK_L anti-symmetric state
P wave → K_SK_S, K_LK_L symmetric state

It has been measured with the same apparatus, the anti-symmetric state is favored:

$K_SK_S/K_SK_L=0.037\pm0.002$

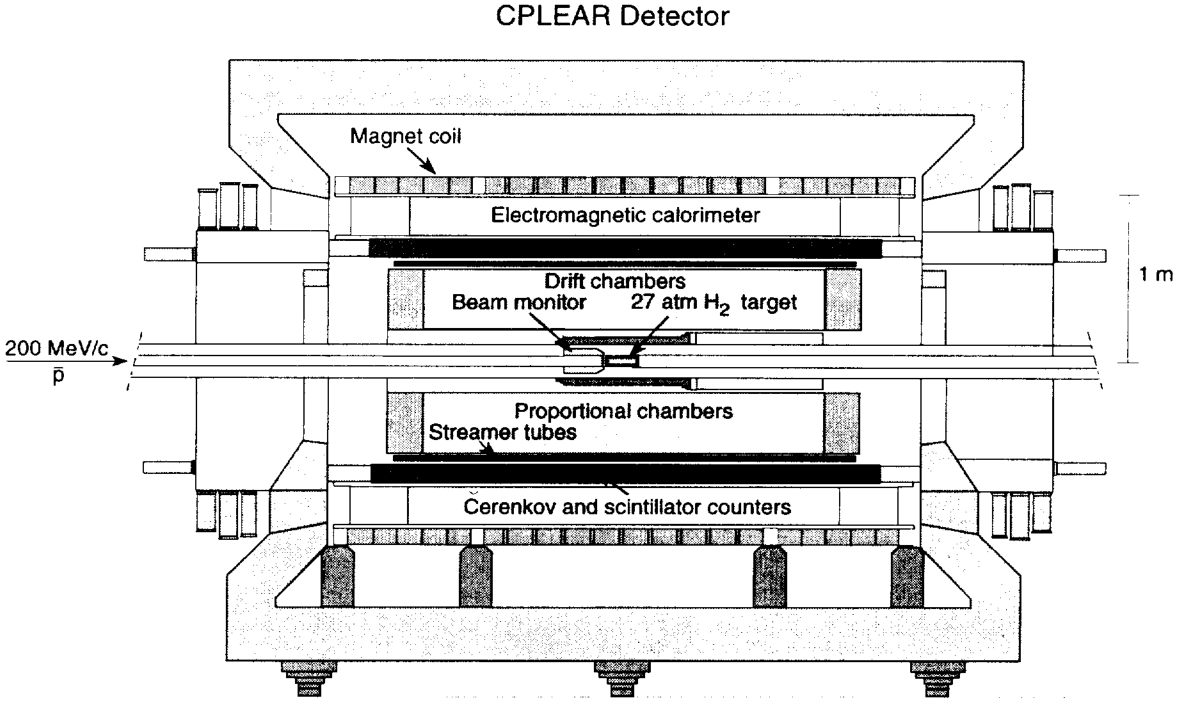
(Phys. Let. B 403 (1997) 383)

⇒ The symmetric state is small and can be considered as background correction

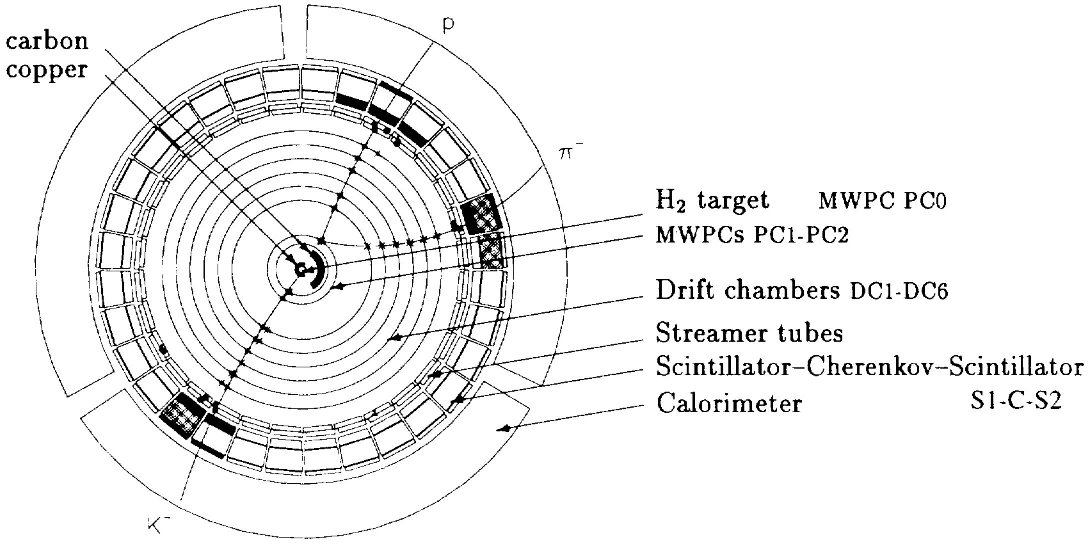
CPLEAR Collaboration

- University of Athens, Greece
- University of Basel, Switzerland
- Boston University, USA
- CERN
- LIP Coimbra, Portugal
- Delft University, Netherlands
- University of Fribourg, Switzerland
- University of Ioannina, Greece
- University of Liverpool, UK
- J. Stefan Institute, Slovenia
- CPPM Marseille, France
- CSNSM Orsay, France
- PSI, Switzerland
- CEA Saclay, France
- KTH Stockholm, Sweden
- University of Thessaloniki, Greece
- ETH Zurich, Switzerland

CPLEAR Detector


CPLEAR Detector

Side View



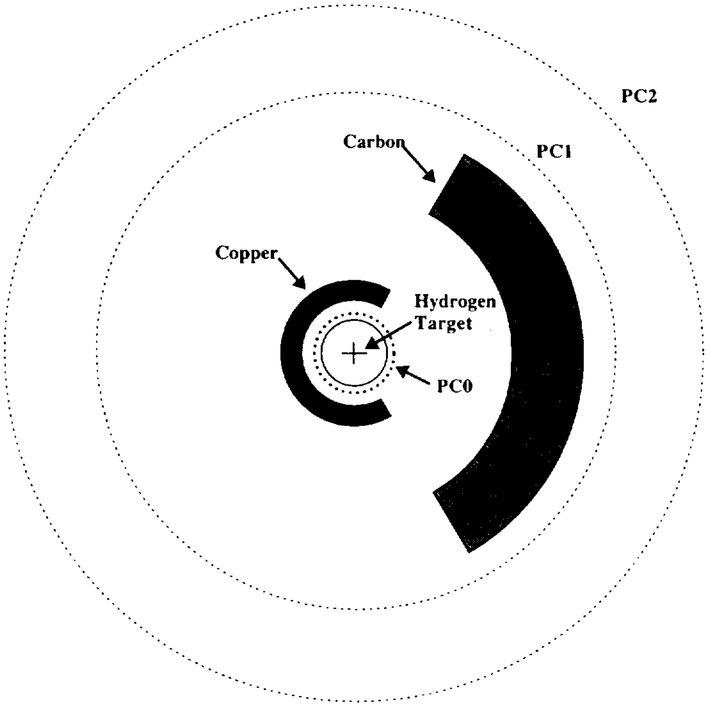
Cross sectional View

Experimental Method

AIM: To measure the like-unlike strangeness correlation of the neutral kaon pair.

Done by determine the strangeness of K^0s by their strong interaction products with two absorbers:

- Copper R~2cm, 0.7cm thick, 240°
- Carbon R~7cm, 2.5cm thick, 120°

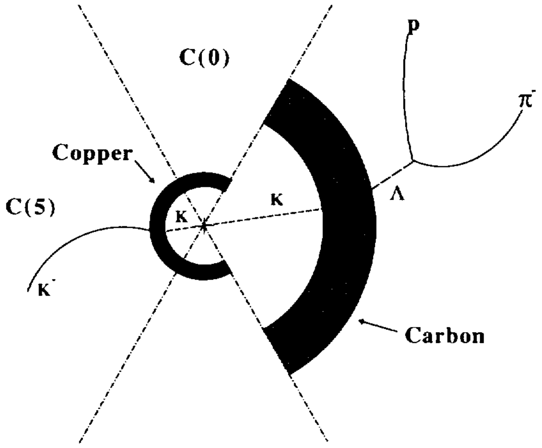


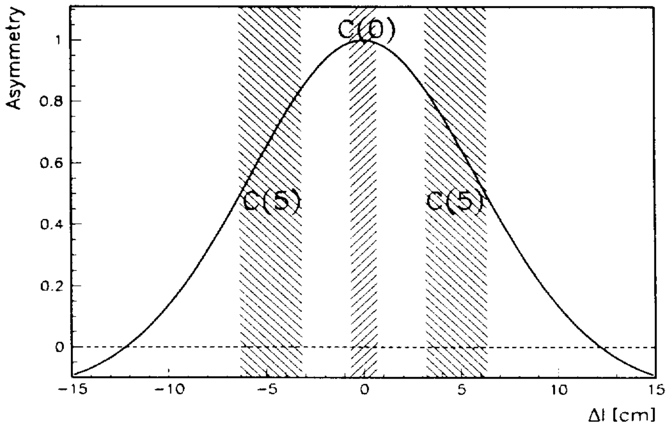
Experimental Method (2)

Two configurations:

- Copper-Copper: C(0)
- Copper-Carbon: C(5)

Config.	Δl	Δt	Asym.
Cu-Cu	~0cm	~ 0	~1
Cu-C	~5cm	$\sim 1.2\tau_S$	~0.6





Strangeness Measurement & Correlation

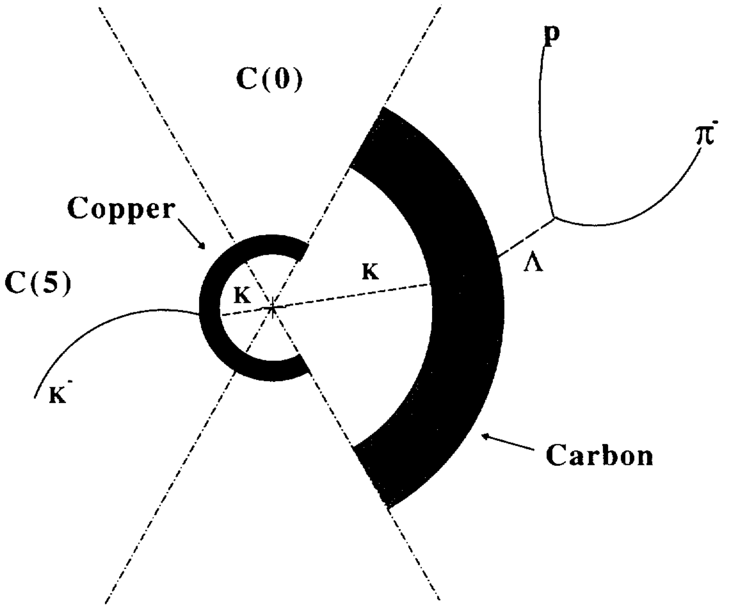
Measure strangeness of K^0 by the strangeness of the final state product:

- S=1: $\underline{K}^0 + \text{matter} \rightarrow K^+ X$
- S=-1: $\bar{K}^0 + \text{matter} \rightarrow K^- X$
  $\rightarrow \Lambda(\rightarrow p\pi^-)\ X$

$$K^0 \Rightarrow K^+;\ \bar{K}^0 \Rightarrow K^-, \Lambda$$

When both Kaon interact:

- Unlike strangeness: $K^+\Lambda$
- Like strangeness: $K^-\Lambda$, $\Lambda\Lambda$



Asymmetry from comparing $K^+\Lambda$ vs. $K^-\Lambda$

Event Selection

8×10^7 events taken in a one week run at the end of CPLEAR data taking period in July 1996

Trigger

- $\bar{p}$ entering target and fires silicon detector in front of the entrance window
- PC0 in veto
- At least 2 charged tracks

Event Selection

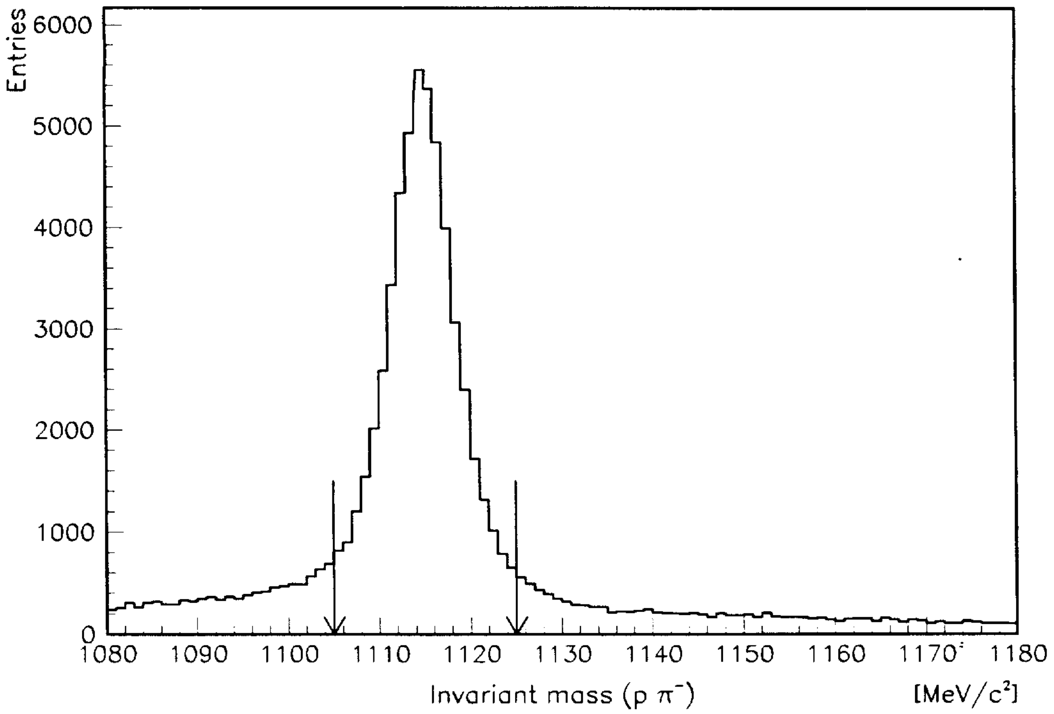
- At least one pair of track with opposite charge form vertex outside PC0
- Photon conversion e^+e^- pair rejected by opening angle cut

⇒ 20% accepted

Two samples: $\Lambda \rightarrow p\pi^-$ and $K_S \rightarrow \pi^+\pi^-$

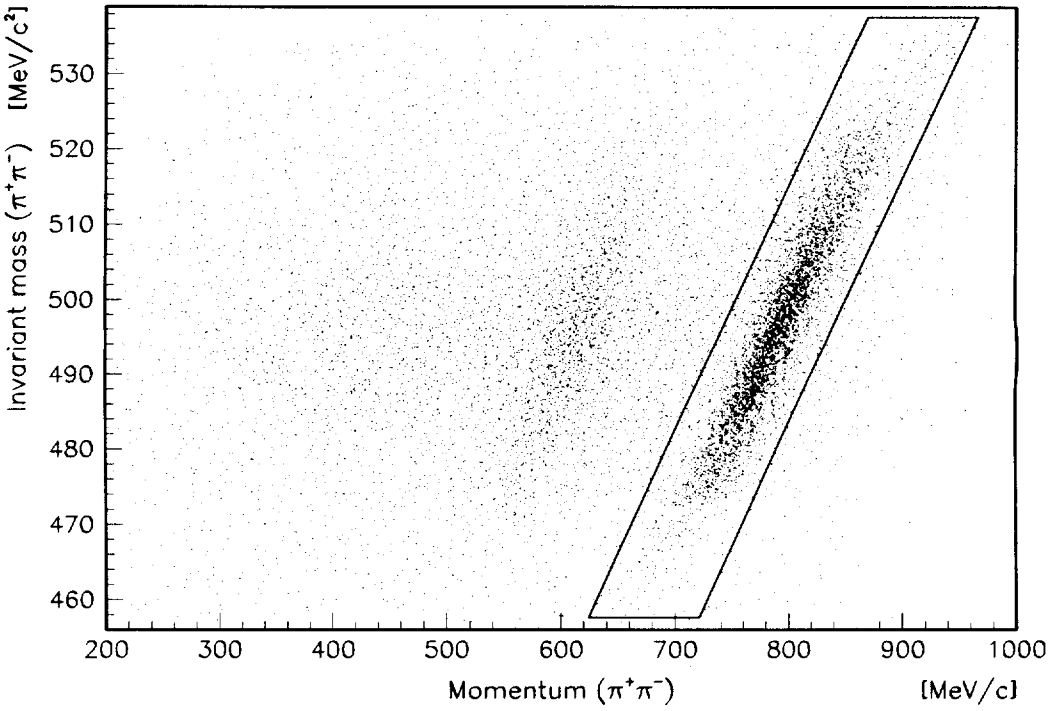
Λ Selection

- $\Lambda(\rightarrow p\pi^-)$ selection:
  - ¤ positive track: C veto, dE/dx in S1 consistent with proton.
  - ¤ Λ direction extrapolate back to the absorbers
  - ¤ $\pi^+\pi^-$ invariant mass anti-cut to reduce K_S background



K_S Selection

- Selecting 800 MeV/c K_S by cuts in momentum vs. invariant mass plane:



Charged Kaon Selection

Cherenkov threshold veto

- C in veto
- S1 & S2 hits
- P > 350MeV/c
- Extrapolate back to absorbers

Further cuts:

- ♦ Cut on TOF against the other charged particles
- ♦ Cut on χ^2 of dE/dx

Plot Mass^2 from dE/dx $\Rightarrow \beta^2$; β^2 & P $\Rightarrow$ Mass^2

K^+ vs K^- Normalization

K^+ & K^- have different strong interaction cross section and detection efficiencies

⇒ Need to be normalized

Using $K_S K^+$ and $K_S K^-$ sample from

$pp \to K_S K_L$:

- $K_S \to \pi^+\pi^-$ (P=800 MeV/c)
- K_L interact with absorber $\to K^\pm$

(50% K^0, 50% $\bar{K}^0$)

⇒ K_S selected with $P(\pi^+\pi^-)$ vs. Inv. Mass

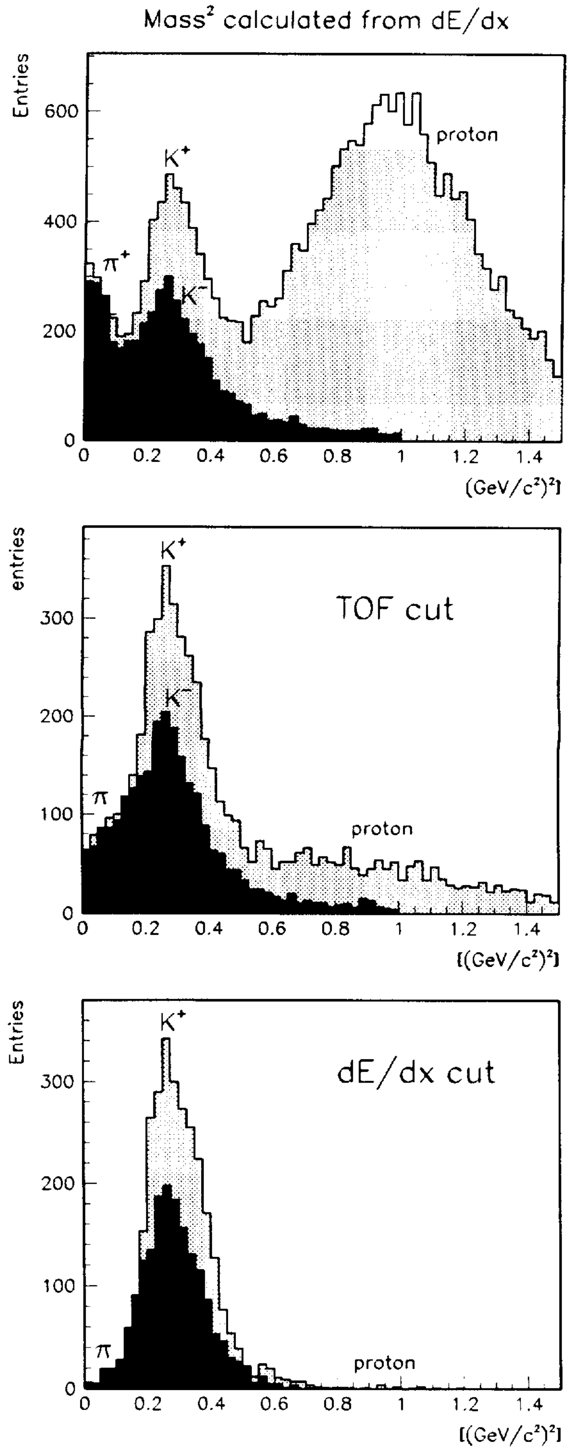
⇒ $K^\pm$ selected as before.

Result:

- Copper: $K^+/K^- = 1.64 \pm 0.06$
- Carbon: $K^+/K^- = 1.60 \pm 0.08$

These ratios correct for cross section and detection efficiency at P_{K^0}=800 MeV/c

$K^{\pm}K_S$ selection

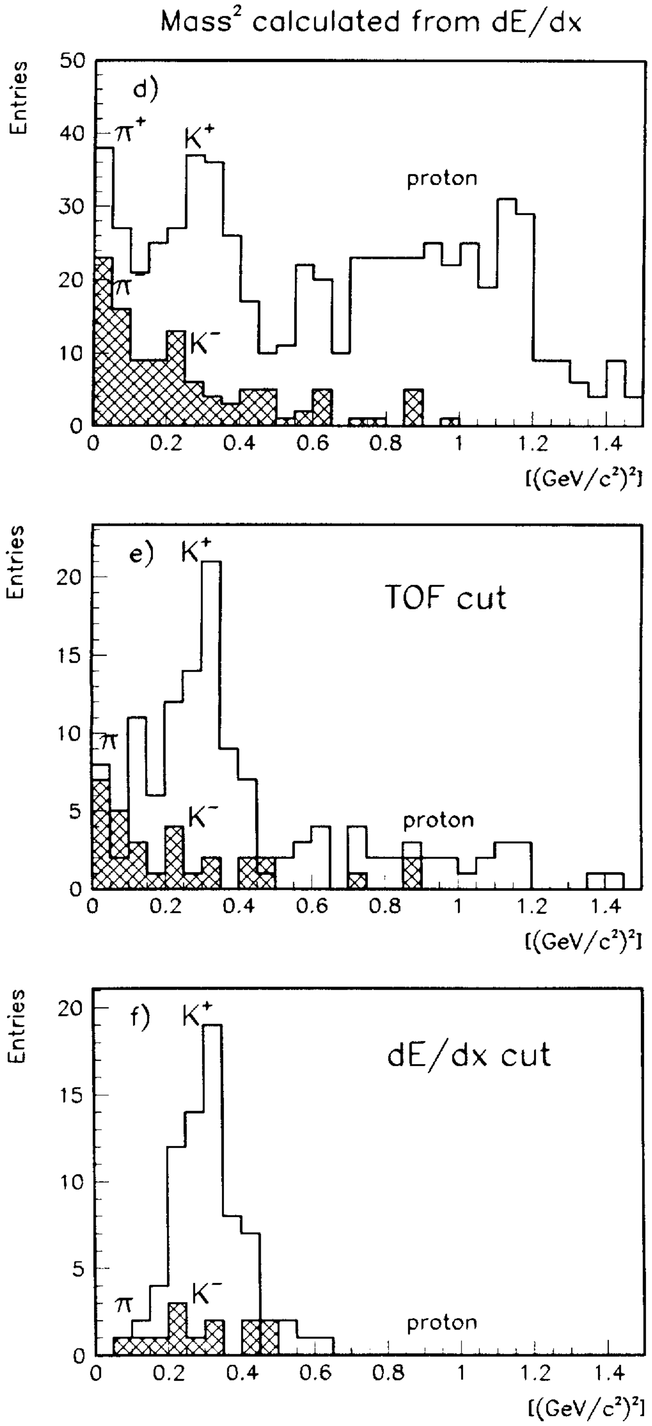


Mass^2 calculated from dE/dx

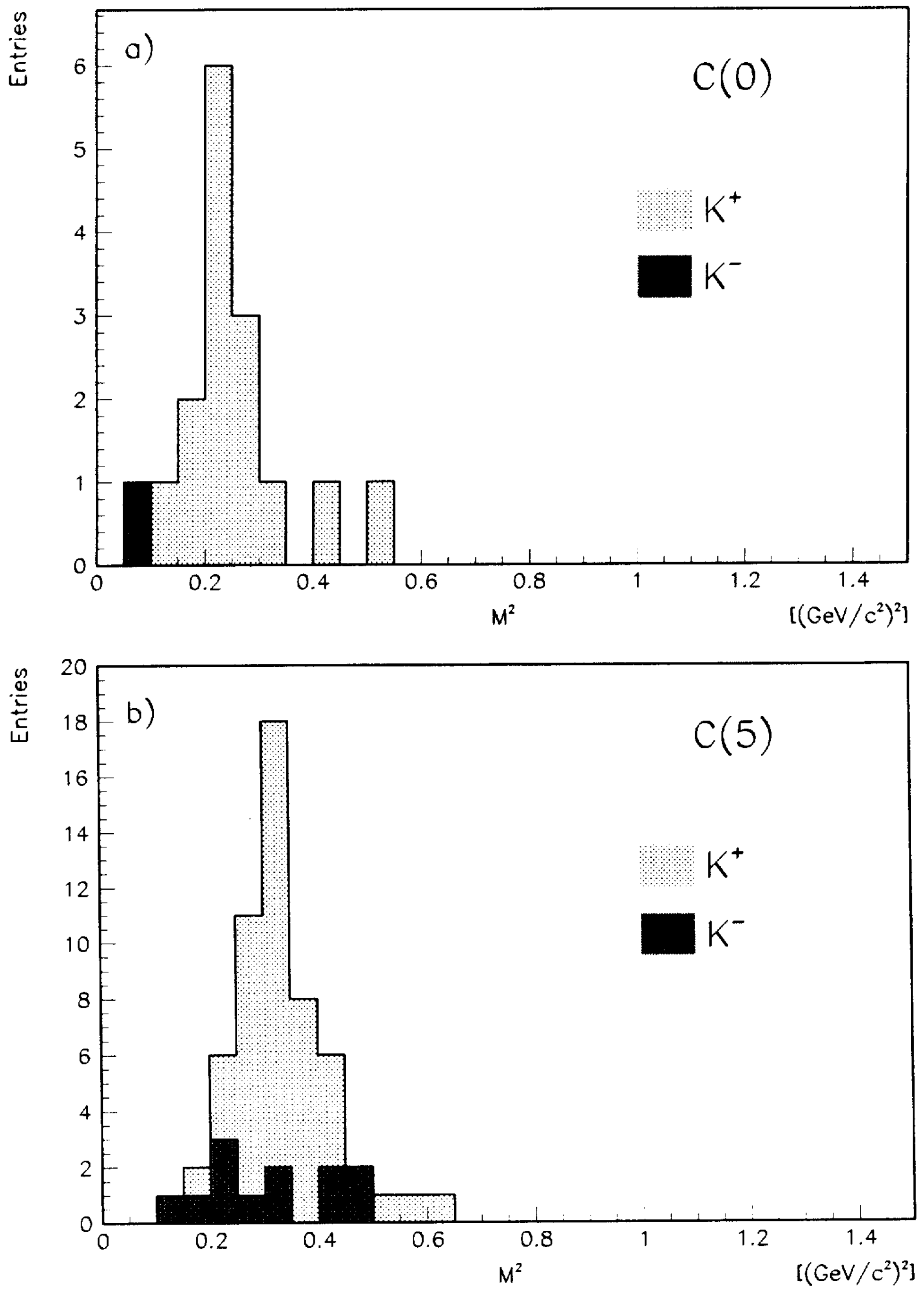
TOF cut

dE/dx cut

K±Λ selection



$K^{\pm}\Lambda$ Results



$K^{\pm}\Lambda$ Results (2)

After Applying $K^{\pm}$ and Λ Selection:

	$N_{K+\Lambda}$	$N_{K-\Lambda}$
Cu-Cu	1	16
Cu-C	12	54

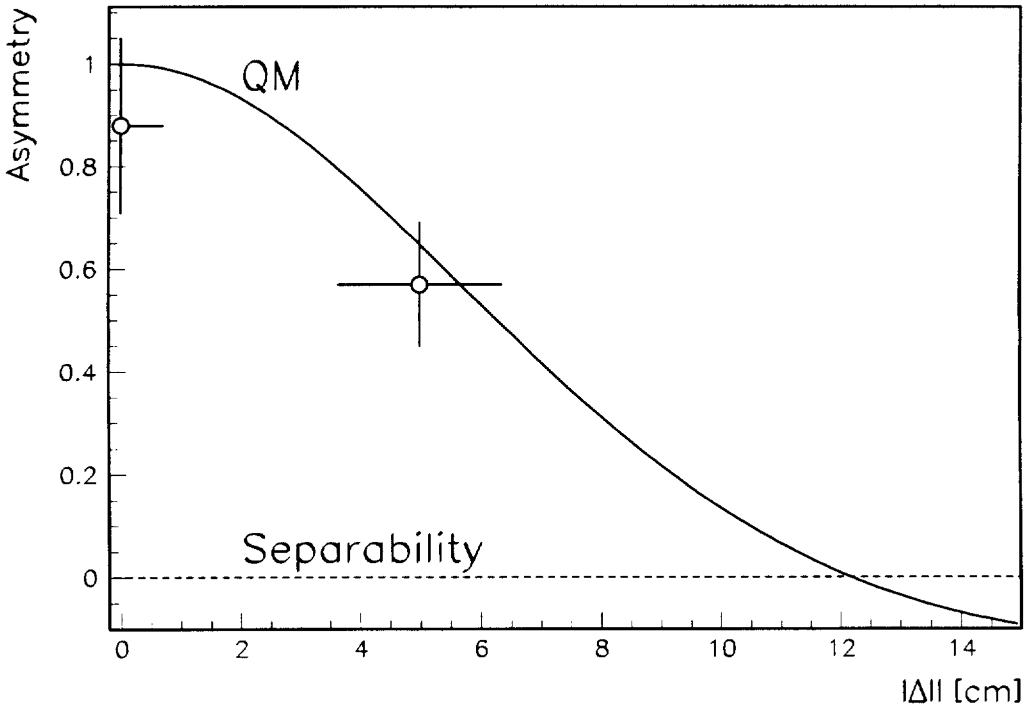
The asymmetry $A(t_{a},t_{b})$ after correcting for $K^{\pm}$ normalization, comparing with QM and Separability:

	Measurement	QM	Separability
Cu-Cu	0.81±0.17	0.93	0
Cu-C	0.48±0.12	0.56	0

Excludes Separability (A=0) with CL>99.99%

$K^{\pm}\Lambda$ Results (3)

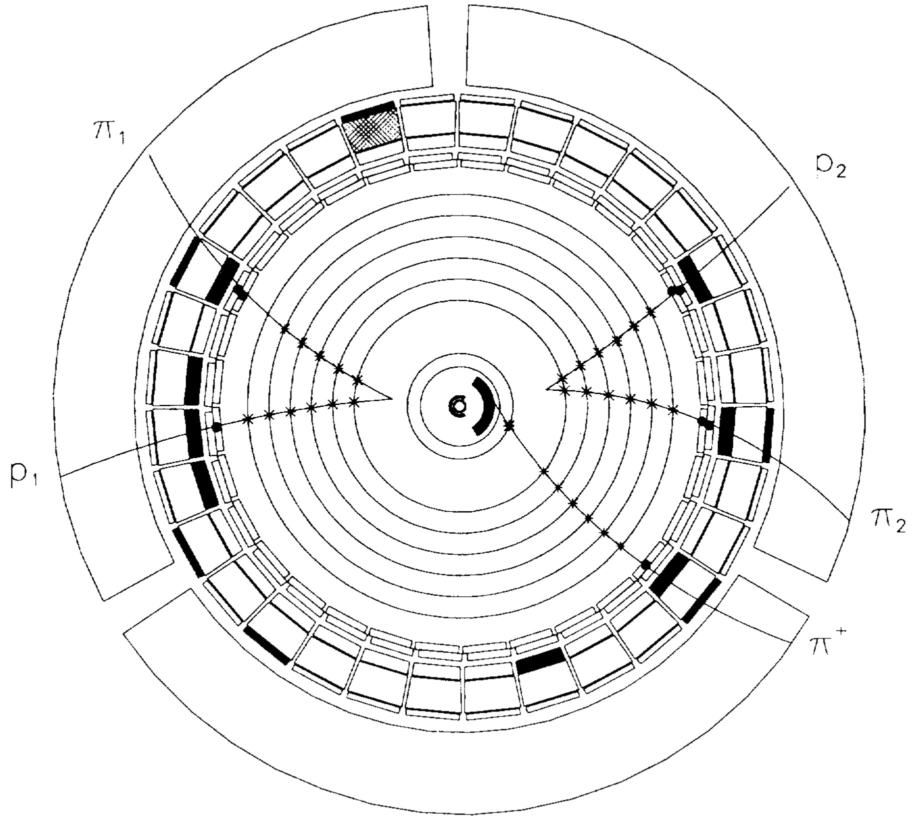
One can compare with QM correlation curve by subtracting background from data:



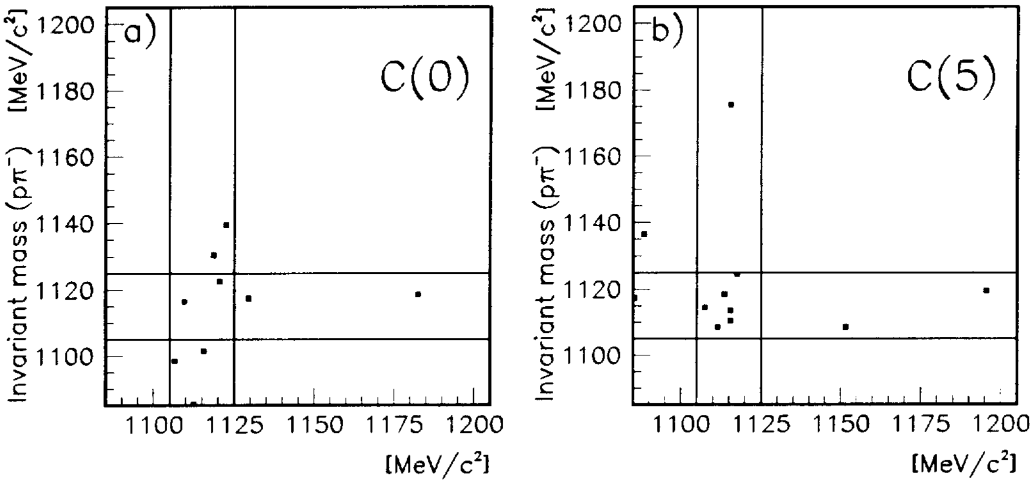
$\Lambda\Lambda$ Selection

Another method, $\Lambda\Lambda$, is used as a cross check

- $N_{\Lambda\Lambda} \propto I_{\mathbf{like}}$
- $\Lambda(\to p\pi^-)$ selection as before
- Cut on the opening angle between the two Λ's $\Rightarrow$ reduce $p\bar{p}\to K^0\bar{K}^0X$ background



ΛΛ Results



- Expected $N_{\Lambda\Lambda}$ can be calculated from measuring N_{Λ} and efficiency of K^0 production from Λ with and without QM correlation, including background corrections.

	Measured	QM	Separability
Cu-Cu	1±1	2.1±0.4	16.8±3.1
Cu-C	5±2	10.2±1.5	16.0±2.7

- Results are consistent with QM!