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.

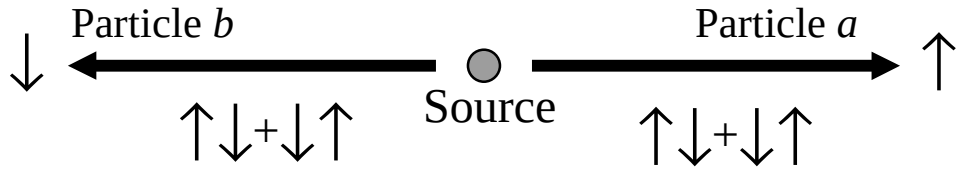
Entanglement

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.

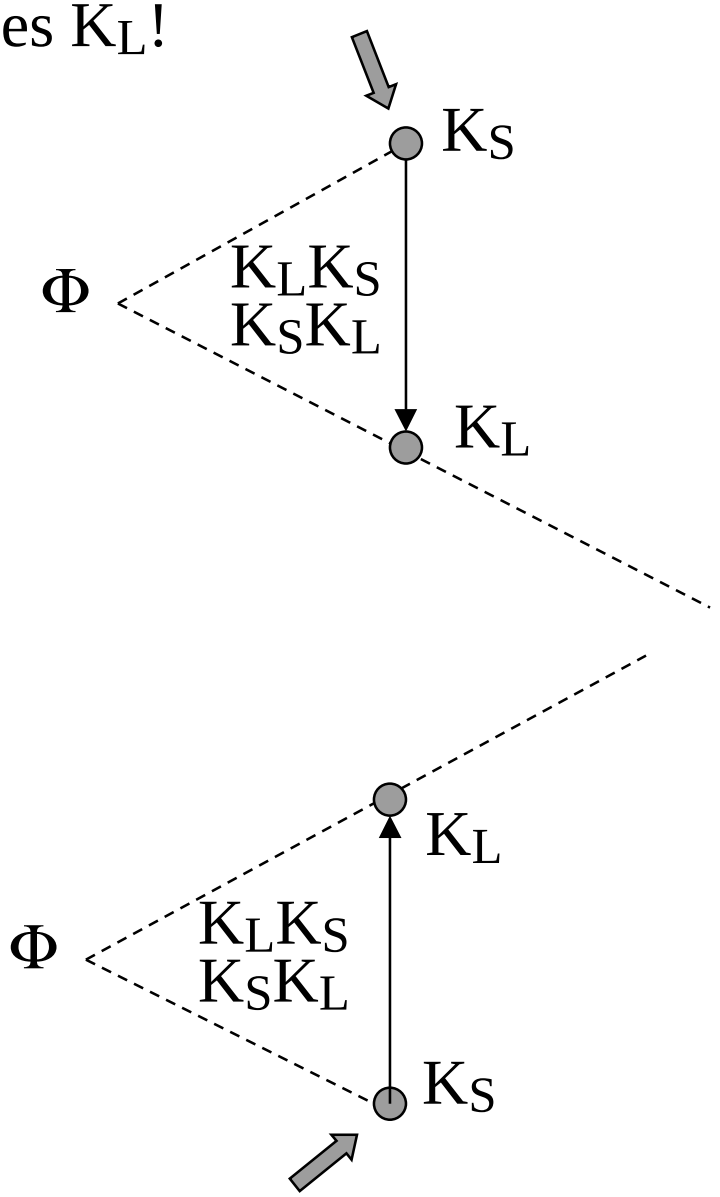
Examples

- Two photo singlet state: one spin up $\Rightarrow$ the other spin down



$\Phi \rightarrow K_L\ K_S$

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

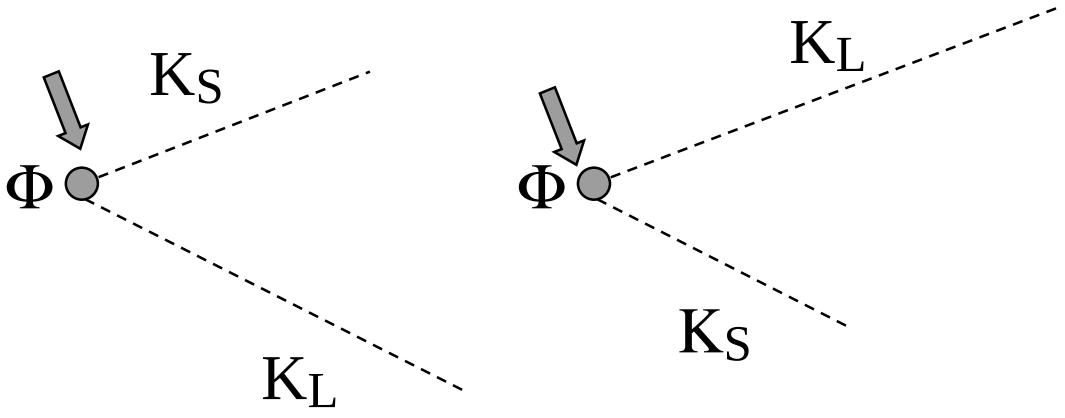


EPR Paradox

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), $K_S \equiv K_1$ $K_L \equiv K_2$

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

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

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

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

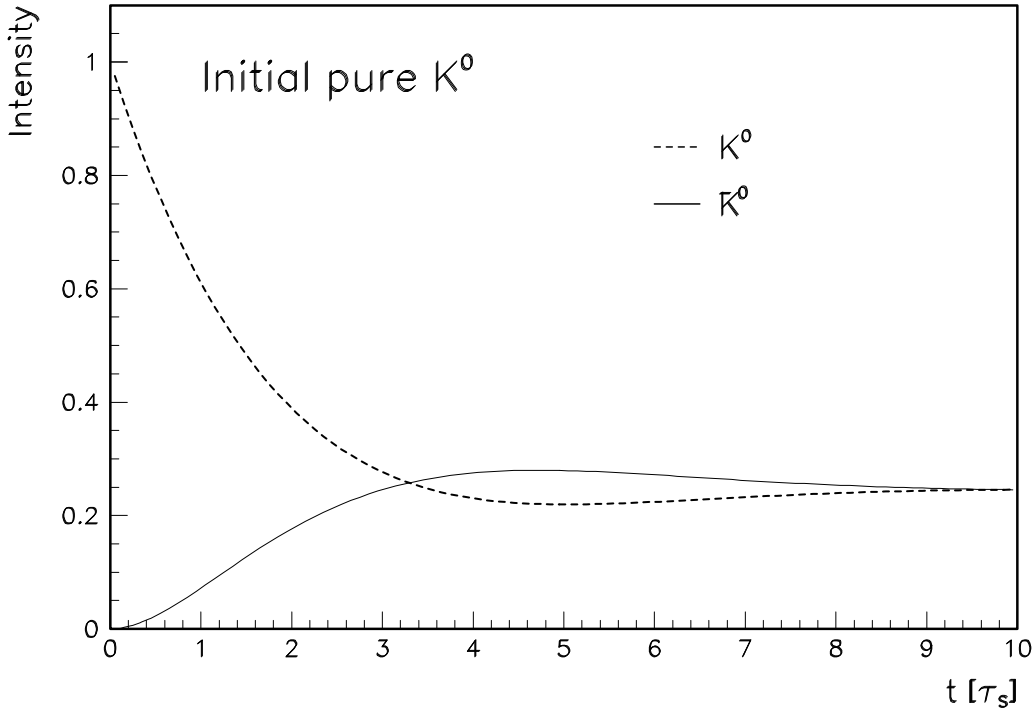
m_S, $m_L \Rightarrow$ mass of K_S, K_L

$\gamma_S = 1/\tau_S$, $\gamma_L = 1/\tau_L \Rightarrow$ 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 ($t_a= t_b=0$):

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

Time Evolution:

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

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!!

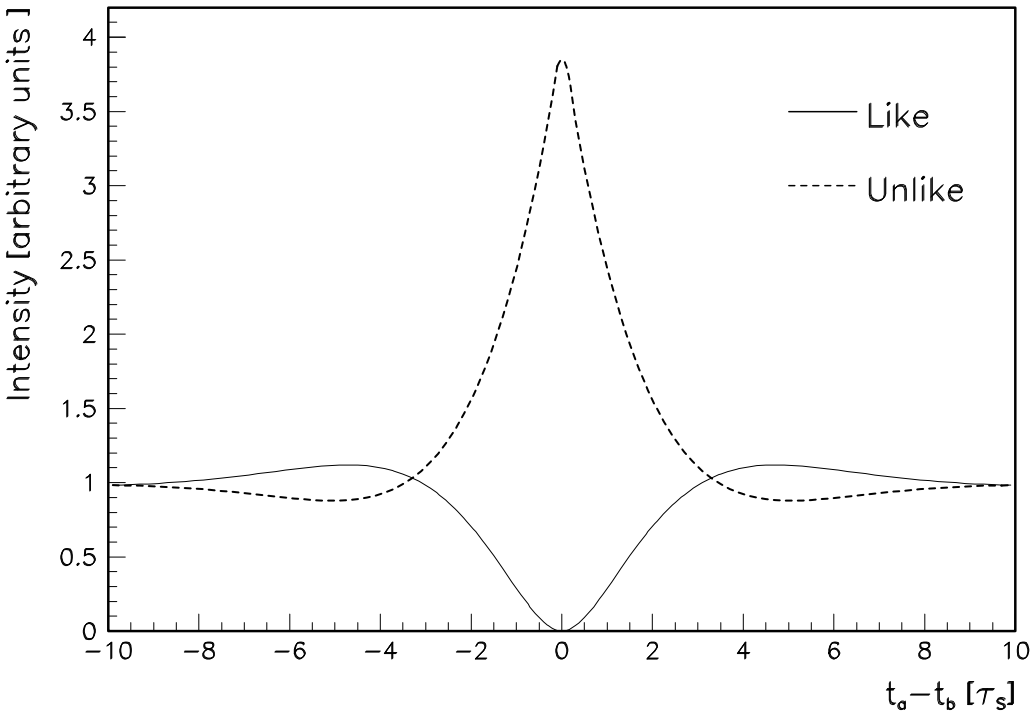
• Unlike Strangeness ($K^0\bar{K}^0$)

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

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

Constructive interference!!

Strangeness Correlation



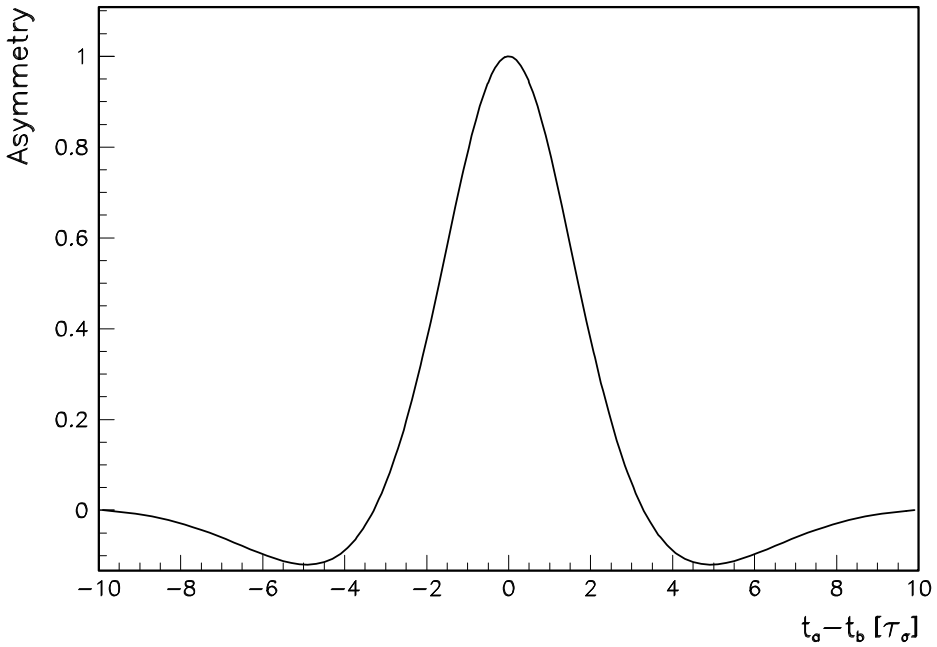
Measurement of the strangeness state of first neutral K defines the strangeness state of the second second K which evolves as if it was created with definite strangeness at that instant.

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 $\Delta t = t_a - t_b$



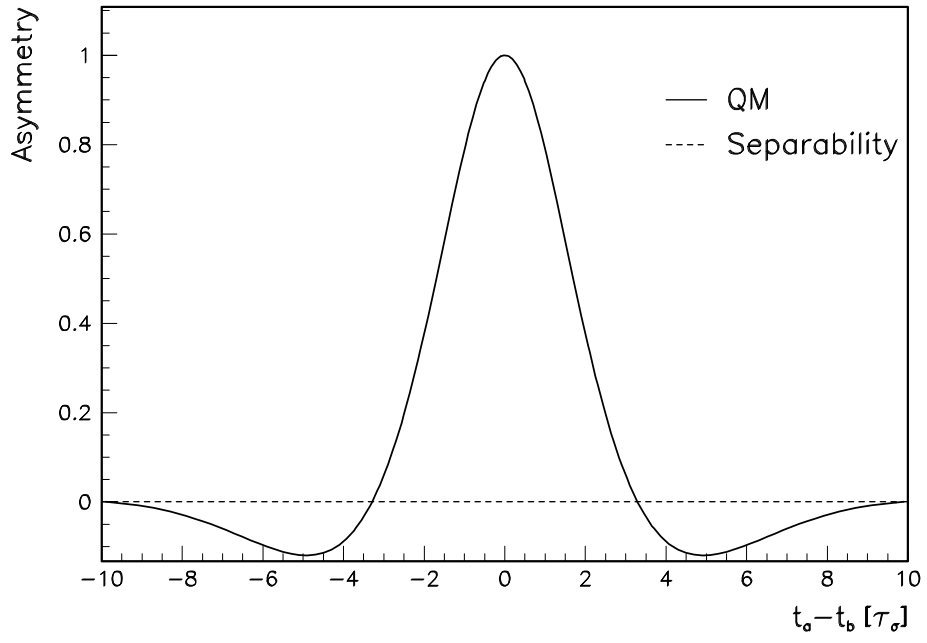
Separability Hypothesis

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:

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

Intensities become:

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

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

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

$p\bar{p} \rightarrow K^0\ \bar{K}^0$ 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 $\rightarrow K_SK_L$ anti-symmetric state
P wave $\rightarrow K_SK_S$, K_LK_L symmetric state

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

$K_SK_S/K_SK_L=0.037\pm0.002$

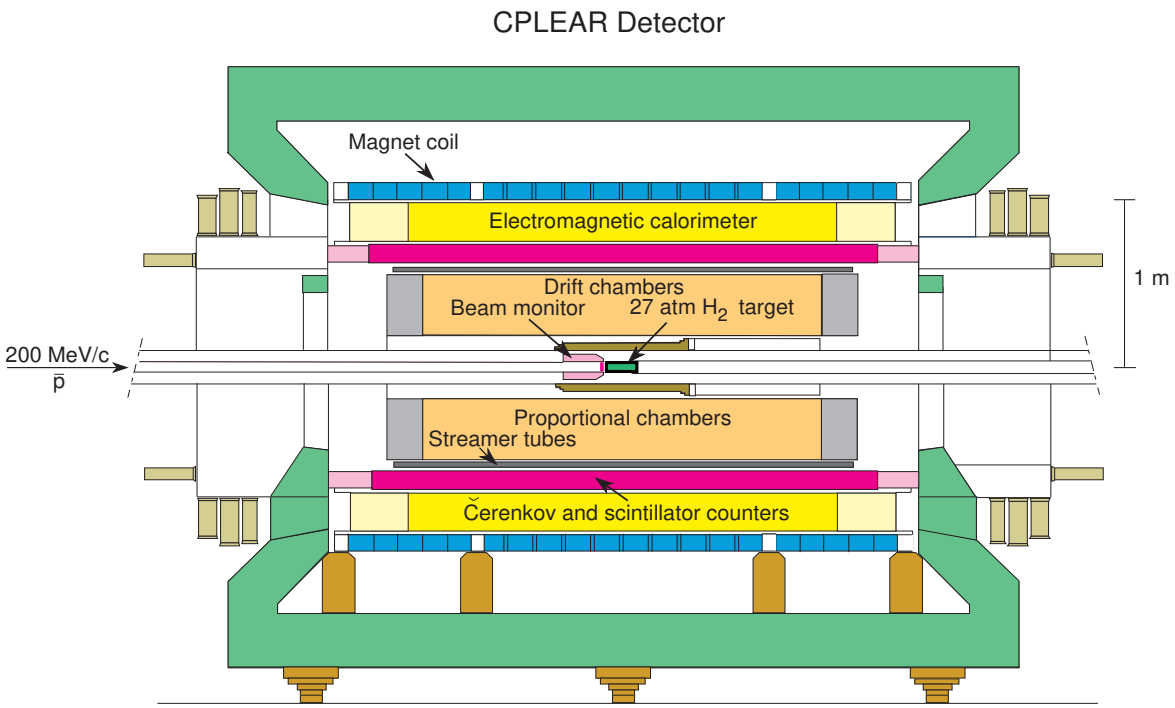
(Phys. Let. B 403 (1997) 383)

$\Rightarrow$ The symmetric state is small and can be considered as background correction

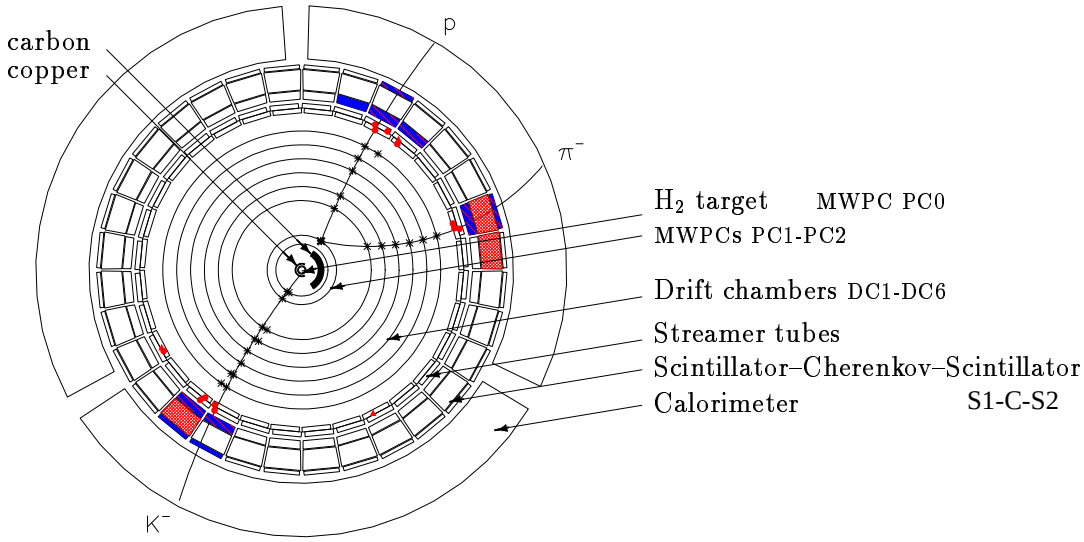
CPLEAR Collaboration

- 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



Side View



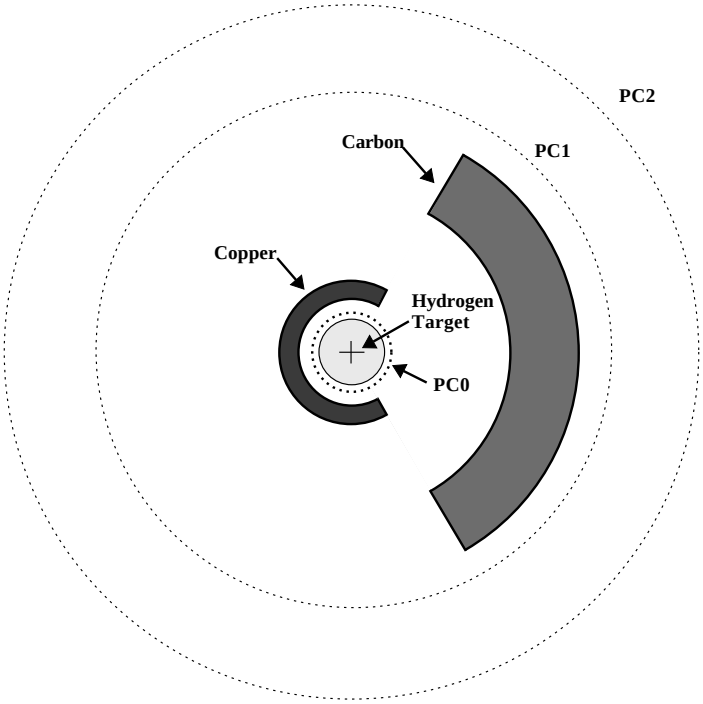
Cross sectional View

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°

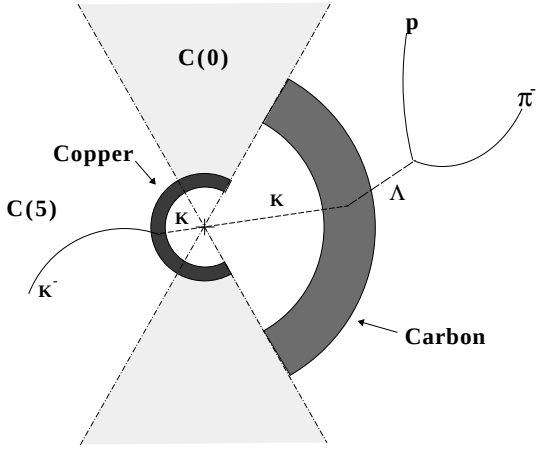


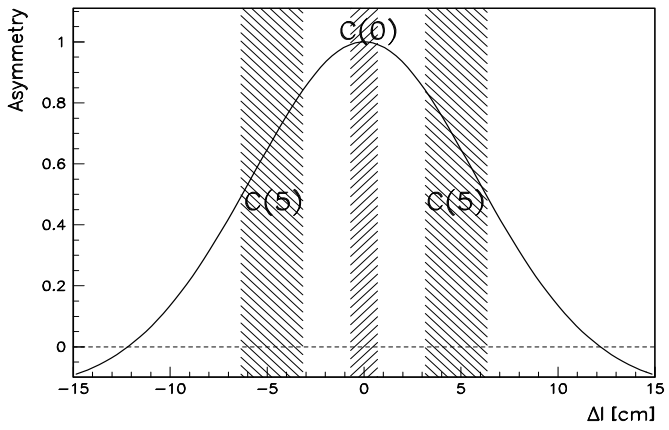
Experimental Method (2)

Two configurations:

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

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





Strangeness Measurement & Correlation

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

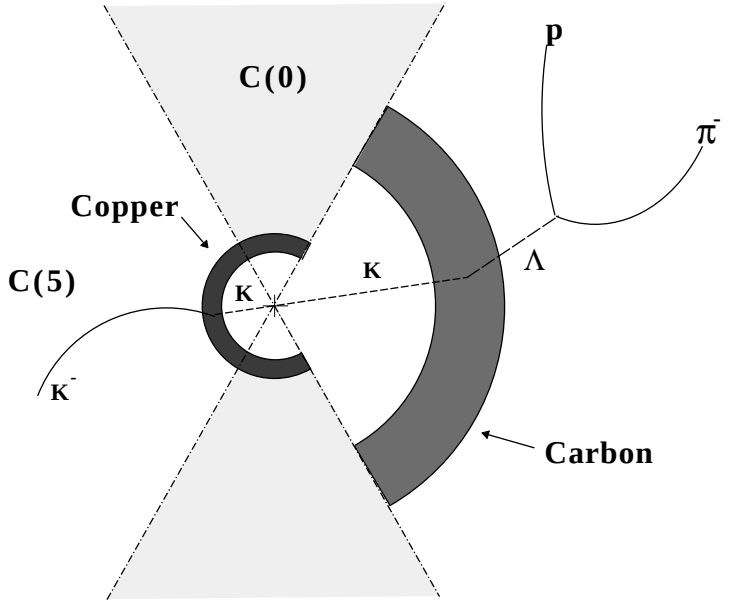
- S=1: $\underline{K}^0 + \text{matter} \rightarrow K^+ X$
- S=-1: $\bar{K}^0 + \text{matter} \rightarrow K^- X$

$$\rightarrow \Lambda(\rightarrow p\pi^-) X$$

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

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

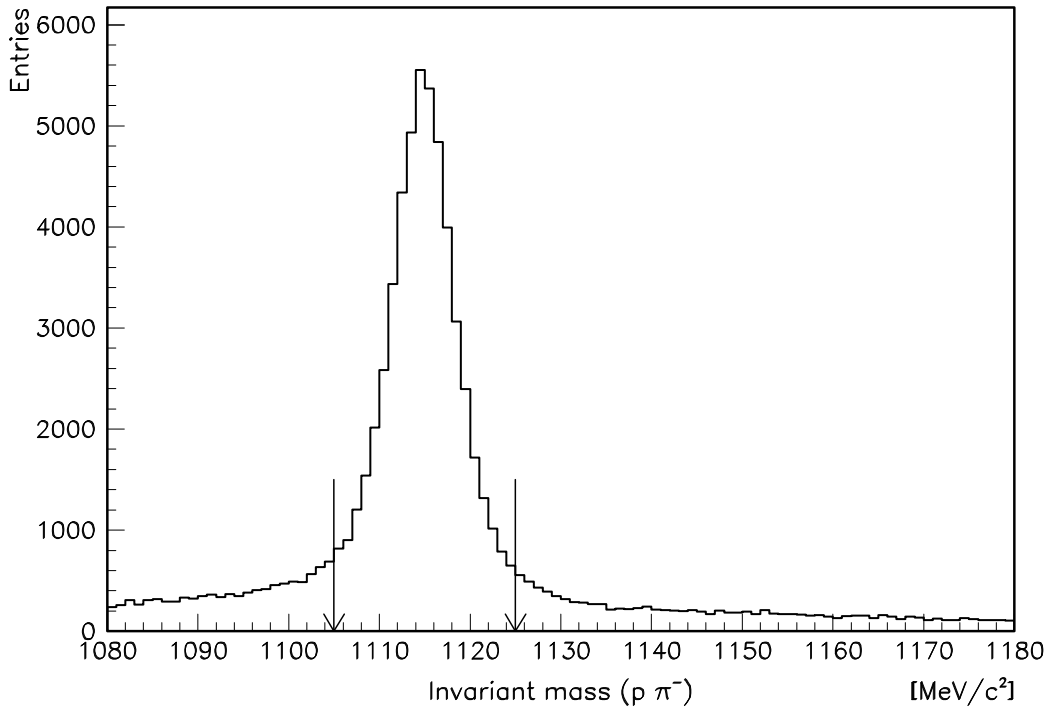
- At least one pair of track with opposite charge form vertex outside PC0
- Photon conversion e^+e^- pair rejected by opening angle cut

$\Rightarrow$ 20% accepted

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

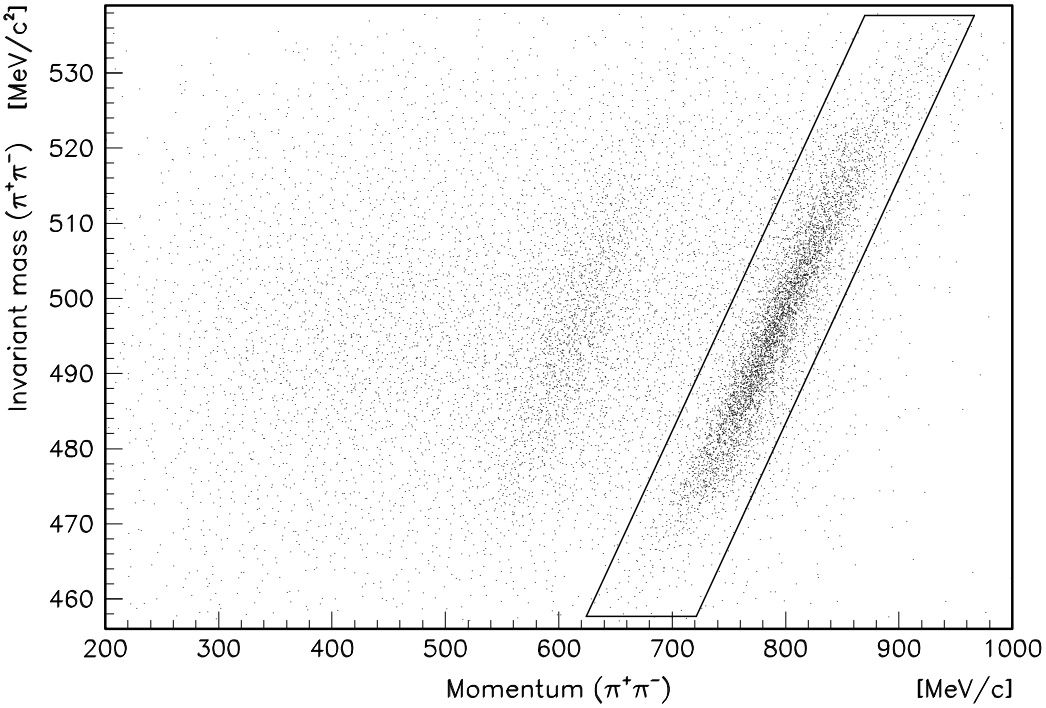
Λ Selection

- Λ($\rightarrow p\pi^-$) 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

$\Rightarrow$ Need to be normalized

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

$pp \rightarrow K_S K_L$:

- $K_S \rightarrow \pi^+\pi^-$ (P=800 MeV/c)
- K_L interact with absorber $\rightarrow K^\pm$ (50% K^0, 50% $\bar{K}^0$)

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

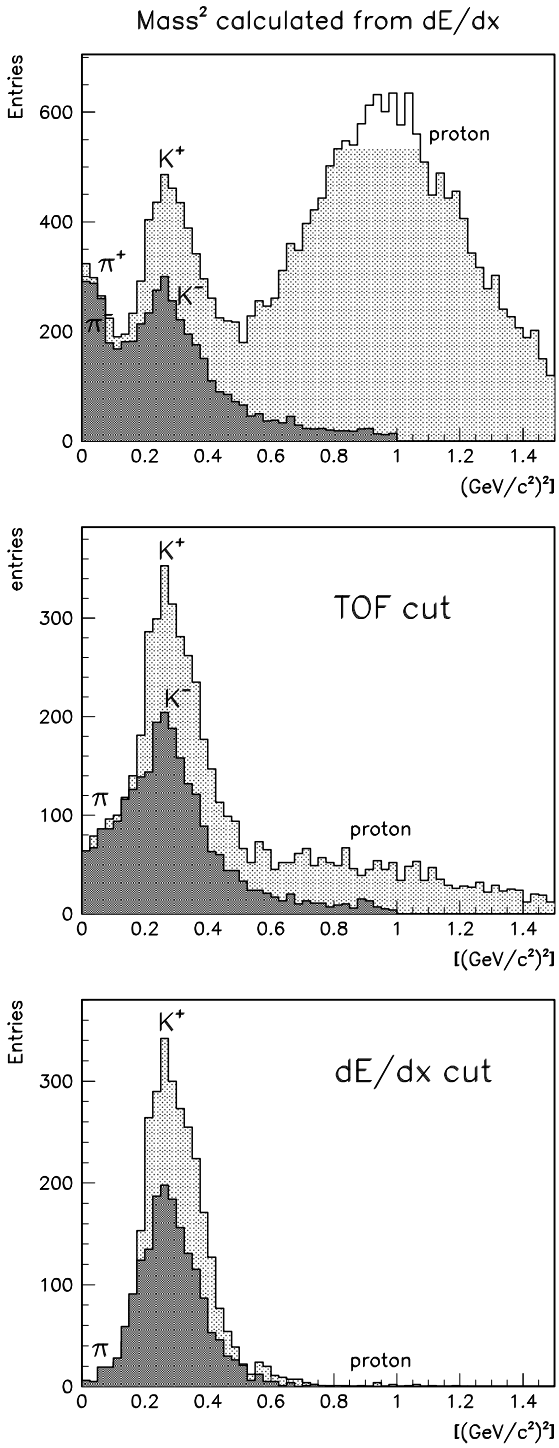
$\Rightarrow$ $K^\pm$ selected as before.

Result:

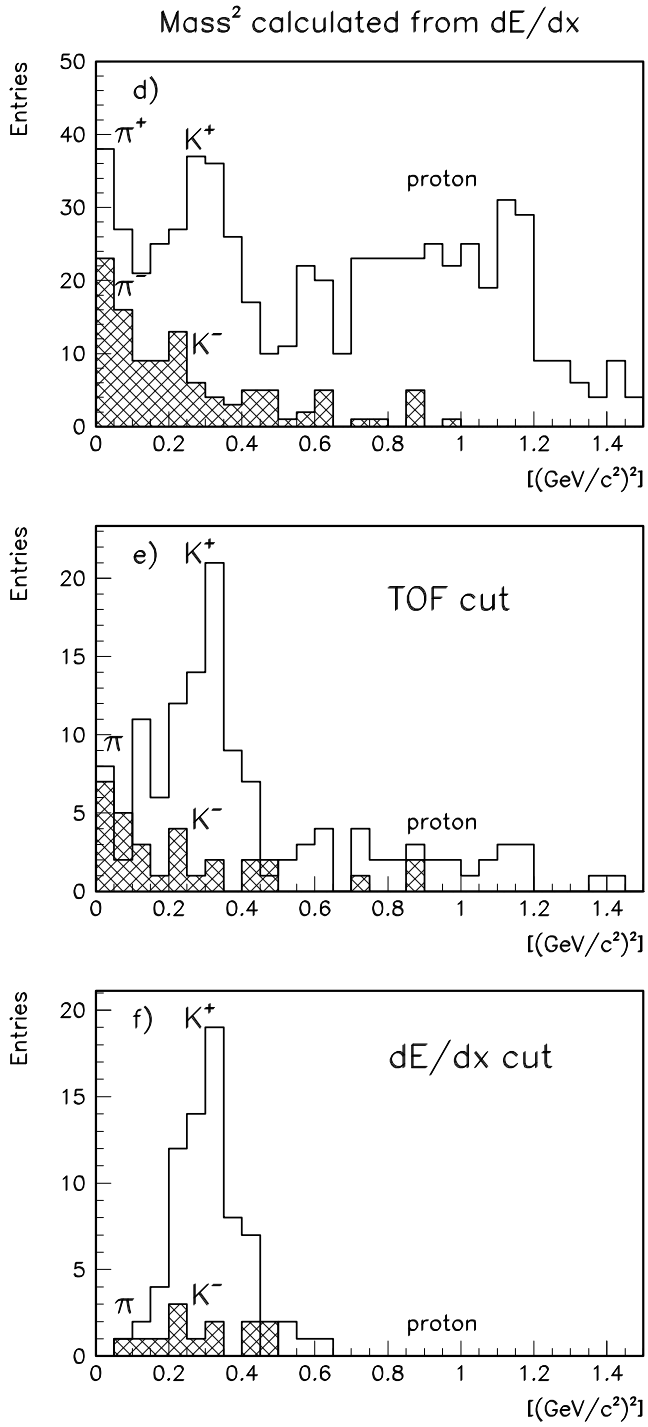
- Copper: $K^+/K^- = 1.64 \pm 0.06$
- Carbon: $K^+/K^- = 1.60 \pm 0.08$

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

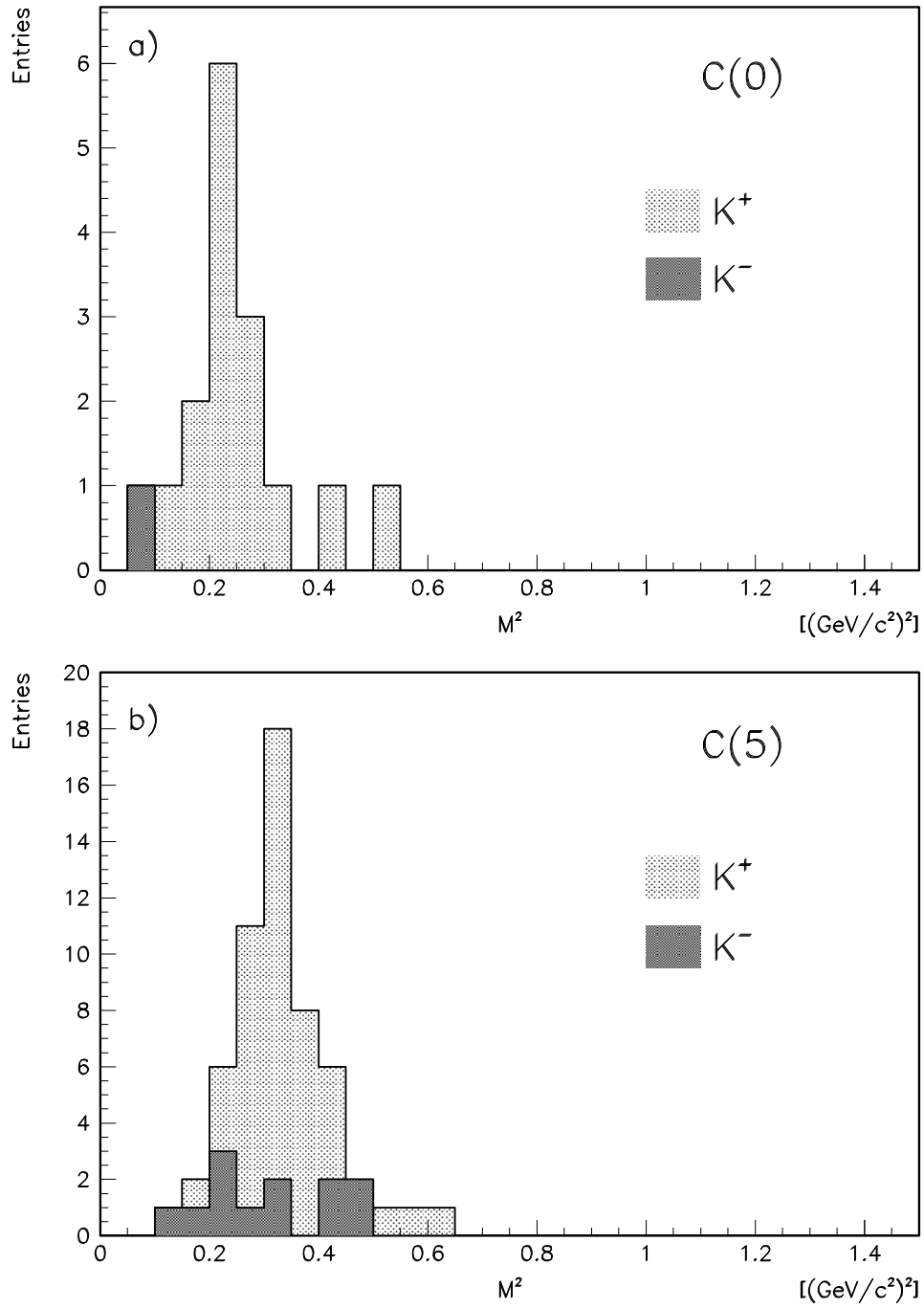
$K^{\pm}K_S$ selection



$K^{\pm}\Lambda$ 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

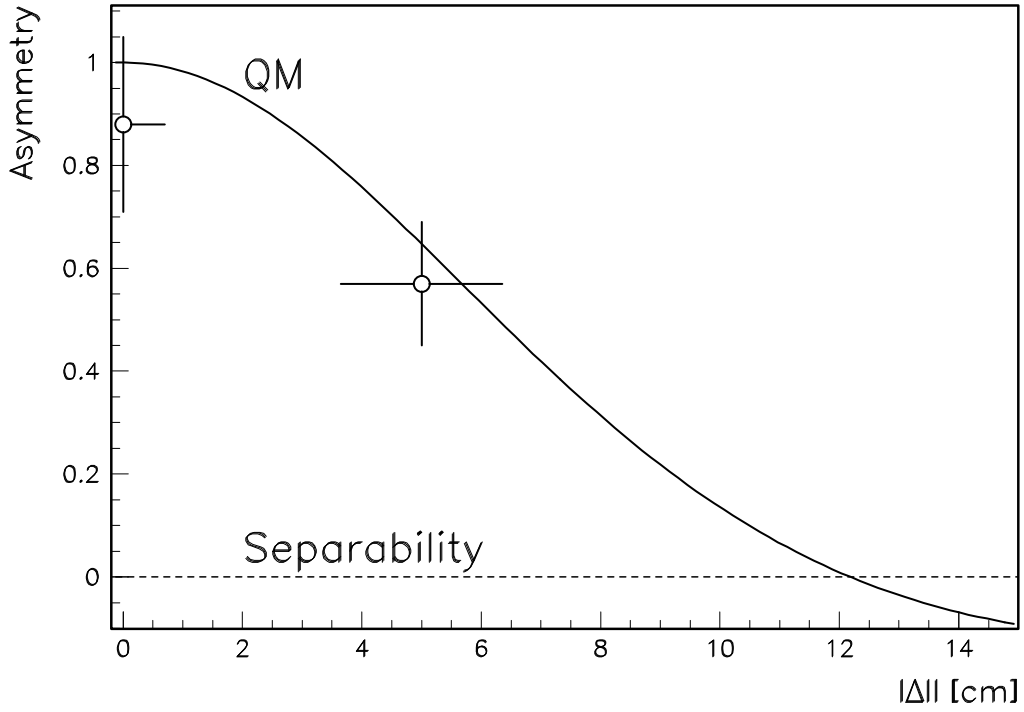
The asymmetry $A(t_a,t_b)$ after correcting for $K^{\pm}$ normalization, comparing with QM and Separability:

	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)

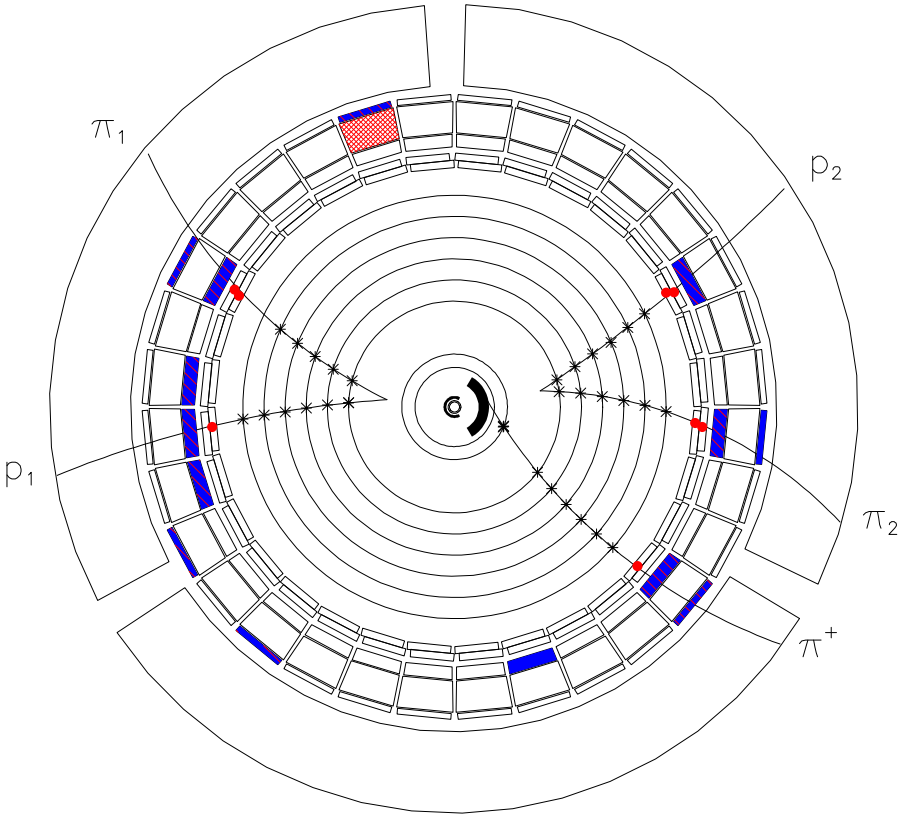
One can compare with QM correlation curve by subtracting background from data:



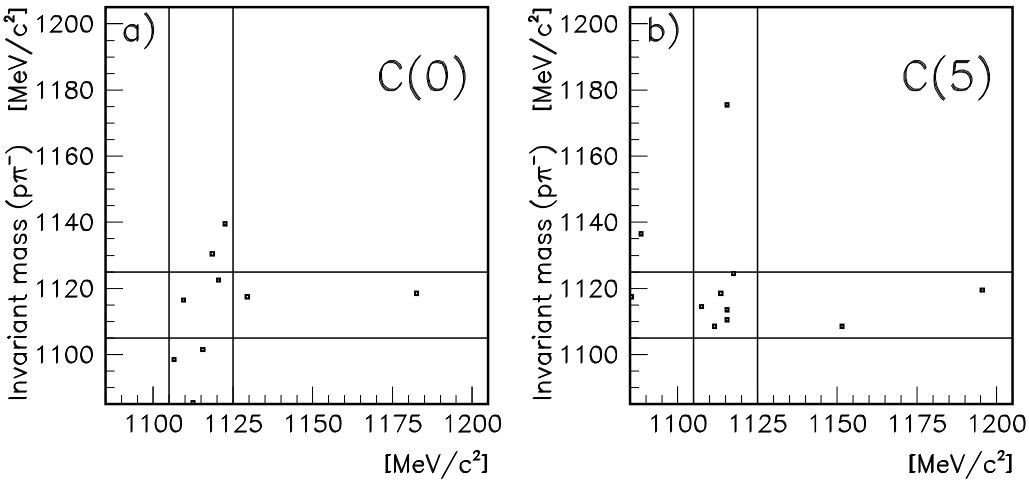
$\Lambda\Lambda$ Selection

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

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

Conclusion

- Two methods have been used to measure EPR type correlation and compare with QM prediction and with separability hypothesis.
- The results are totally compatible with the predictions of Quantum Mechanics
- The separability of the wavefunction after the creation into two particles are excluded with CL>99.99%

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