CPLEAR
Results in Kaon Interferometry

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Overview of CPLEAR

- CPLEAR was design to measure CP and T violation parameters at CERN Low Energy Antiproton Ring (LEAR).
- It uses a particular channel of the pp annihilation at rest:

$$p\bar{p} \rightarrow K^0 K^- \pi+$$

$$p\bar{p} \rightarrow \bar{K}^0 K^+ \pi-$$

By measuring the charged tracks $K^+\pi^-$ or $K^-\pi^+$ and their vertex, one can know

1. Strangeness of the neutral kaon
2. Momentum of the neutral kaon
3. $p\bar{p}$ interation point (neutral kaon production point)

CPLEAR Method

- Combining with the decay vertex of the neutral K, one knows the length that neutral K lived, therefore its lifetime.

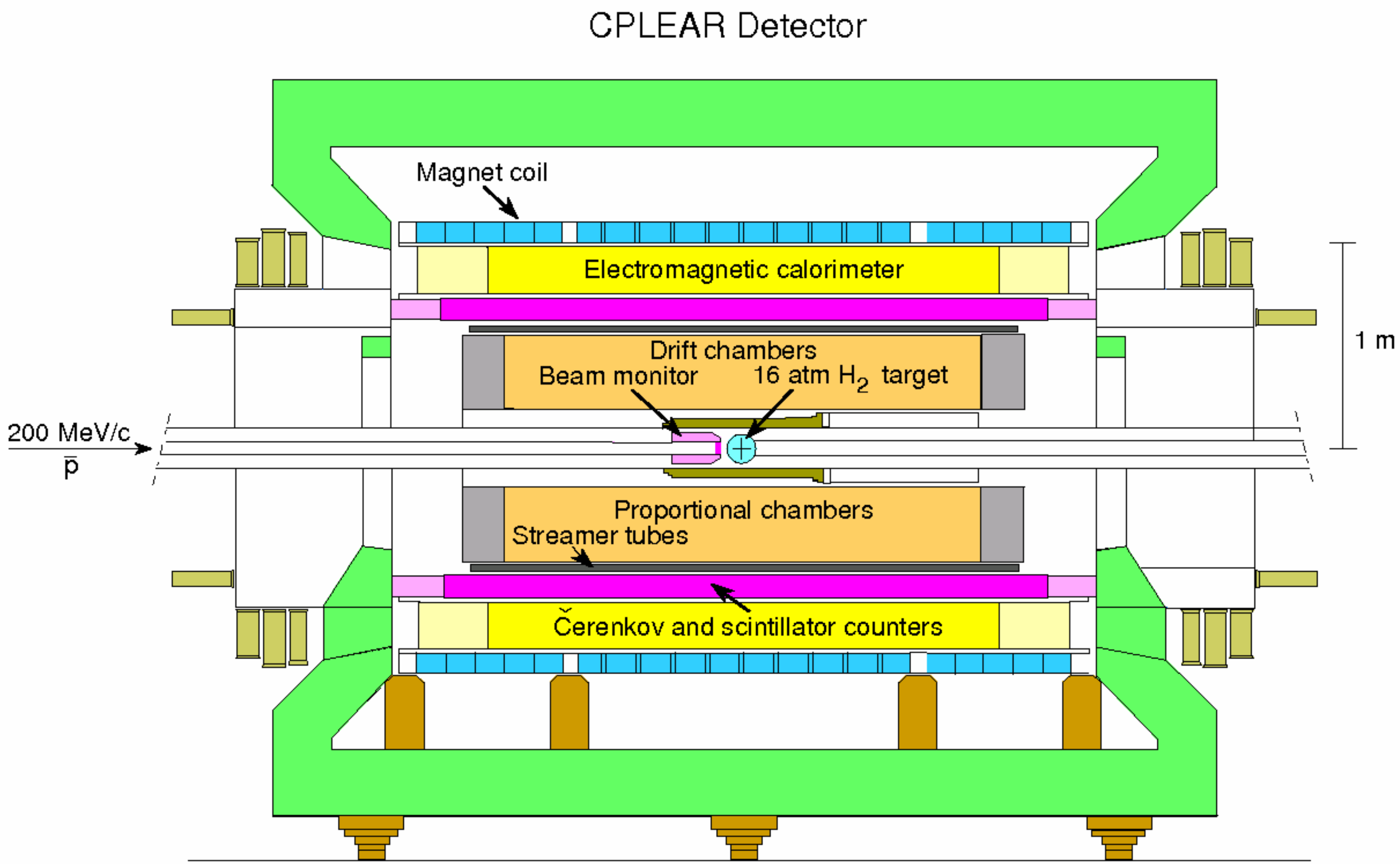
- With these in mind, CPLEAR was optimized to identify the charged kaon, to reconstruct the charged track.

- Since the production fraction is small (~10^{-3}), a sofisticated trigger was designed to quickly identify the charged kaon, reconstruct Kpi pair in order to reject all other backgrounds at fairly fast so that deadtime is reduced.

CPLEAR Collaboration

- University of Athens, Greece
- University of Basel, Switzerland
- Boston University, USA
- CERN, Switzerland
- 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

The CPLEAR detector consists of:

- 27 bar hydrogen target to stop the incoming antiproton beam (10^6 p/s) from the Low Energy Antoproton Ring (LEAR) at CERN => pp annihilation at rest.

- A multiwire proportional chamber at r=1.5cm(PC0) to tag/reject outgoing charged particle from the annihilation point.

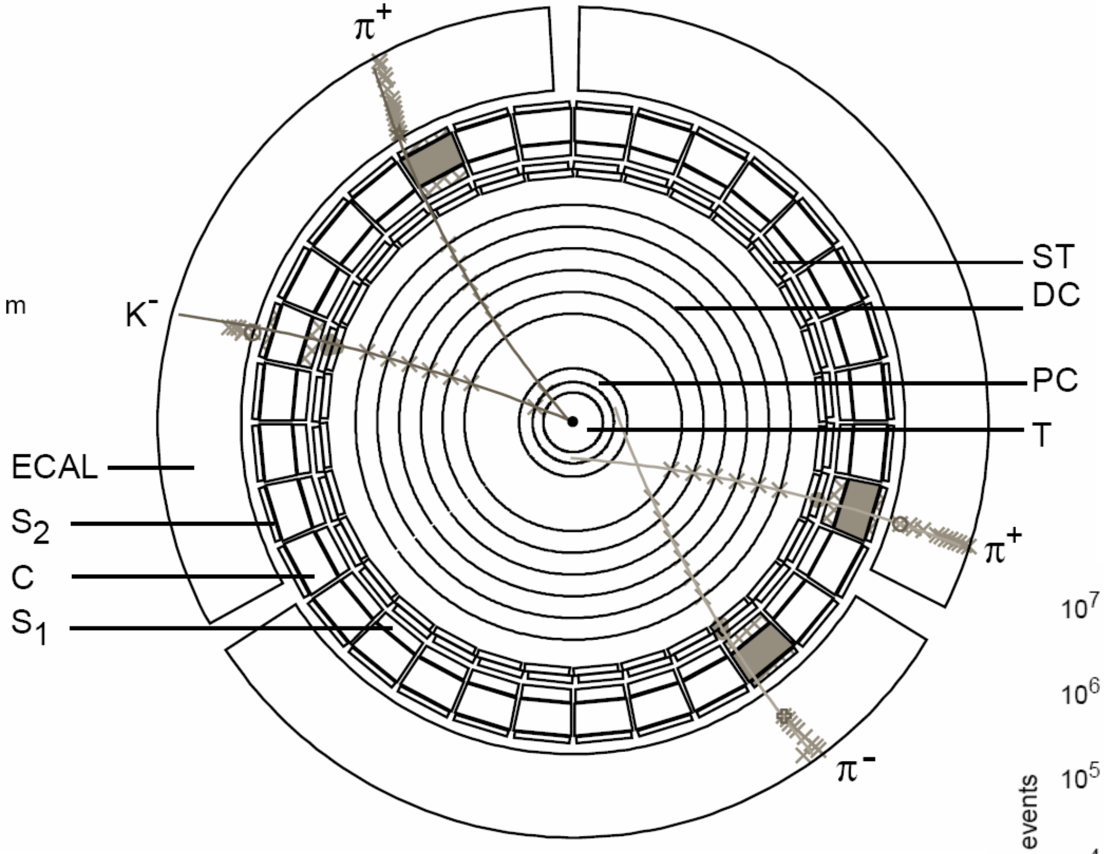
- Two layers of proportional chamber at r=9.4cm and r=12cm (PC1, PC2) and six layers of drift chambers (DC1-DC6) to track charged particles.

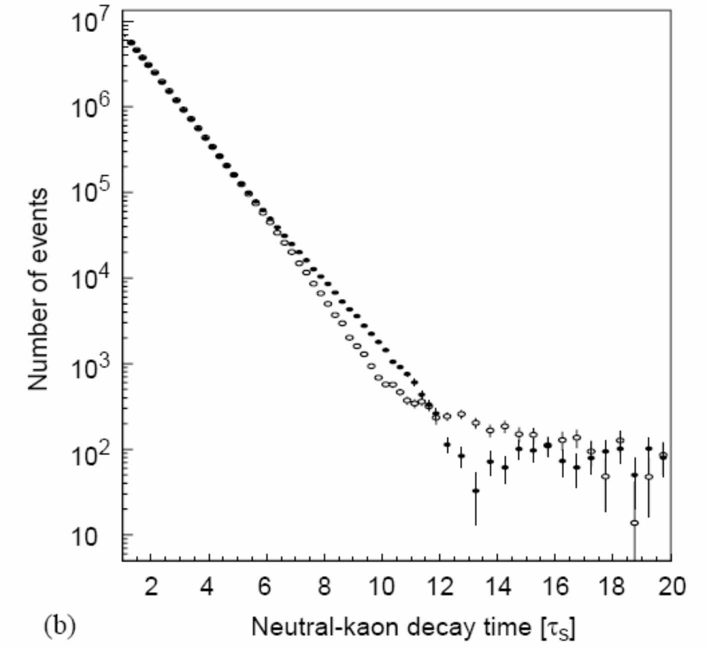
- A liquid Cherenkov counter sandwiched between two plastic scintillators (S1, S2) for particle identification by Cherenkov light emission, energy loss (dE/dx) and time of flight (TOF) of the traversing charged particle.

- All enclosed within a magnet providing 0.44T field parallel to antiproton beam.

Besides CP & T symmetry, CPLEAR can also be used for other measurements!

CPLEAR detector (sideview)





Loss of Quantum coherence

Since we have such high precision $K^0 \rightarrow \pi\pi$ and $K^0 \rightarrow e\pi\nu$ data, one can probe the loss of quantum coherence i.e. transition from pure state to mixed state due to topologically non-trivial space-time fluctuation.

Define $K^0\bar{K}^0$ system's 2x2 density matrix ρ

Loss of coherence

$$\dot{\rho} = -i[\Lambda\rho - \rho\Lambda^{\dagger}] + \delta\Lambda\rho$$

$$\Lambda = M - \frac{i}{2}\Gamma$$

Out of the 9 parameters, 3 can be measured at CPLEAR: α,β,γ

A fit was done on the $K^0 \rightarrow \pi\pi$ and $K^0 \rightarrow e\pi\nu$ to extra these parameter:

$$\alpha \leq 4.0\text{x}10^{-17}\ \text{GeV},$$

$$\beta \leq 2.3\text{x}10^{-19}\ \text{GeV}$$

$$\gamma \leq 3.7\text{x}10^{-21}\ \text{GeV}$$

90% CL

To be compare with $O(m_K/m_{PLANK}) \sim 2\text{x}10^{-20}$ GeV

Phys. Lett. B 364 (1995) 239

EPR Entanglement in Particle Physics

At CPLEAR we can have the state:

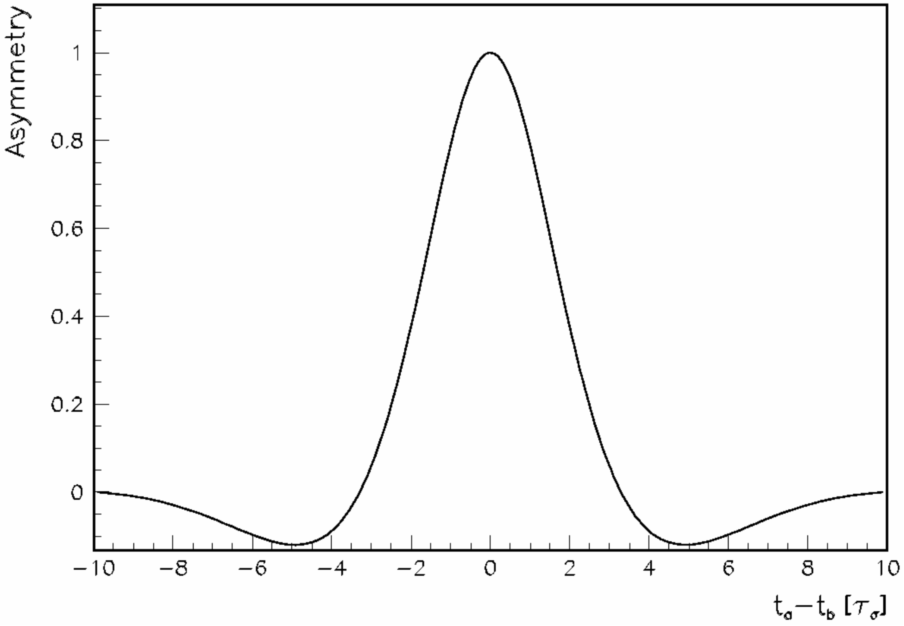
$$p\bar{p} \rightarrow K^0\bar{K}^0:$$

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

i.e. the strangeness of the neutral kaons are entangled, despite possible spacial separation.

Similar to the spin ½ system of Bohm.

Knowing the strangeness of the one K^0 will give us the information of the other K^0 at the same proper



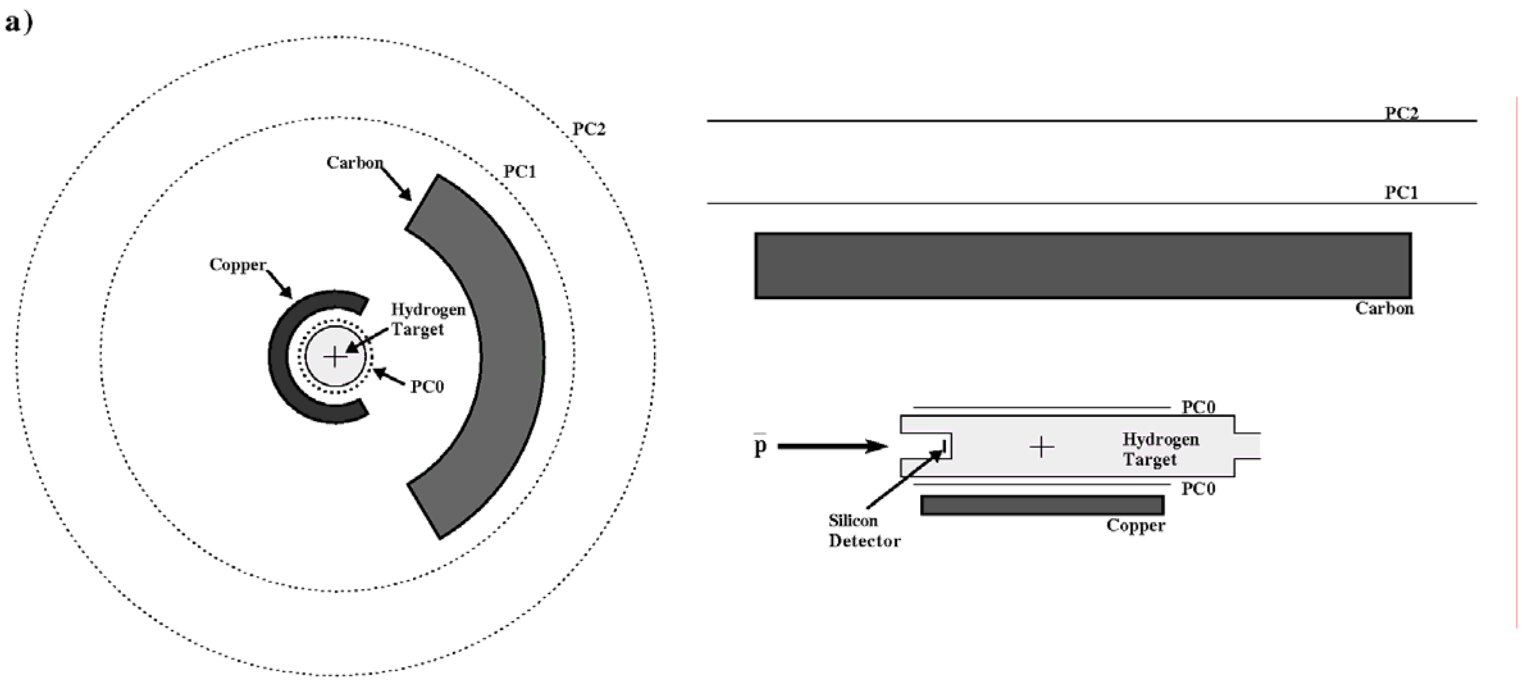
Asymmetry:

$$A(\Delta t) \equiv \frac{I_{OF} - I_{SF}}{I_{OF} + I_{SF}} = \frac{2e^{-(\gamma_L+\gamma_S)\Delta t/2}\cos(\Delta m \Delta t)}{e^{-\gamma_S \Delta t} + e^{-\gamma_L \Delta t}}$$

Experimental Configuration

A special set-up with two converters:

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



pp → K^0K^0 can have two configurations:

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

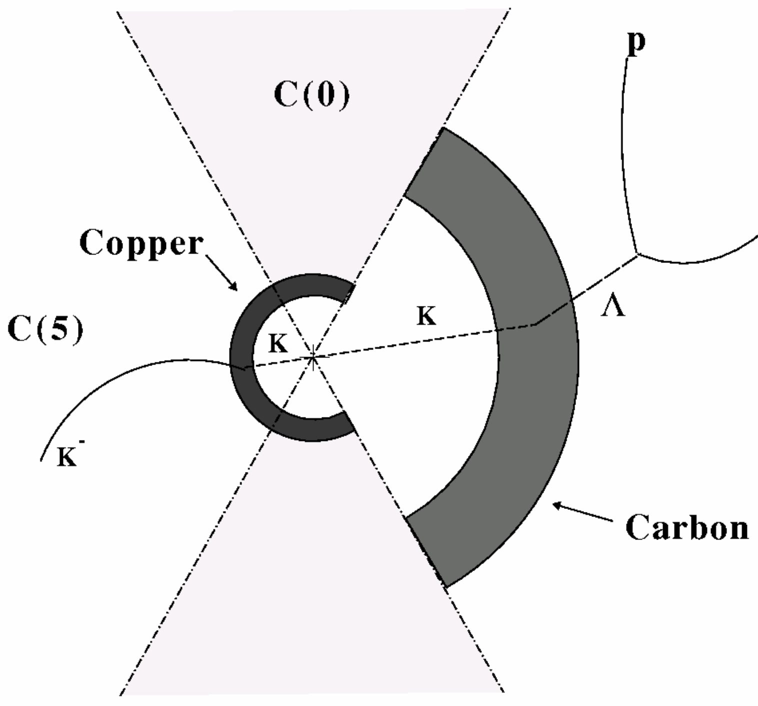
Special trigger with no hits in PC0

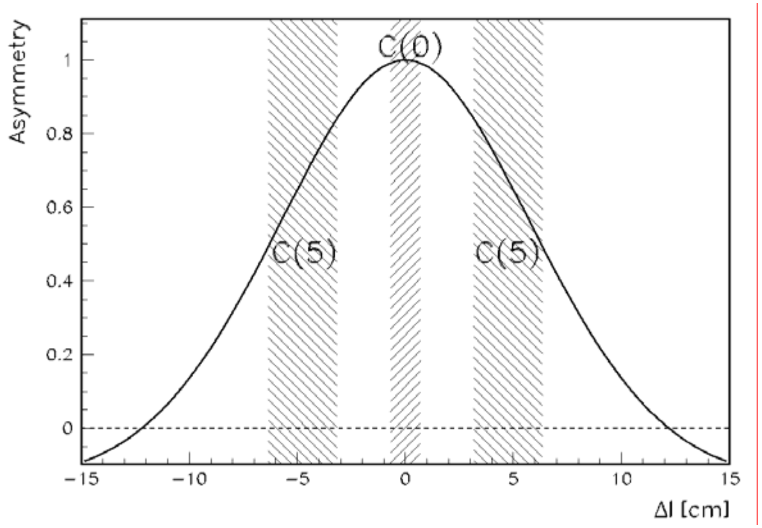
Experimental Configuration (2)

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

example:
($K^-\Lambda$)

Asymmetry:





Determine the strangeness/flavor of the two K^0 by their strong interaction products with two converters ($\bar{K}0 \rightarrow K^-,\Lambda$; $K0 \rightarrow K^+$)

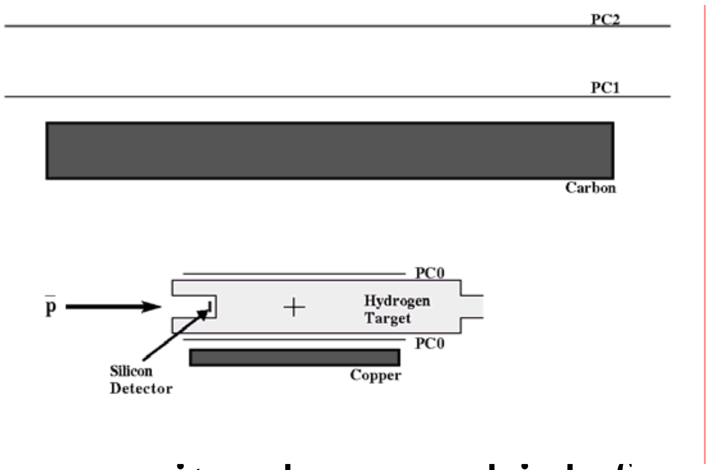
- Same Flavor: $K^-\Lambda$, $\Lambda\Lambda$
- Opposite Flavor: $K^+\Lambda$, $K^+ K^-$

Event Selection

8×10^7 events taken in a two 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



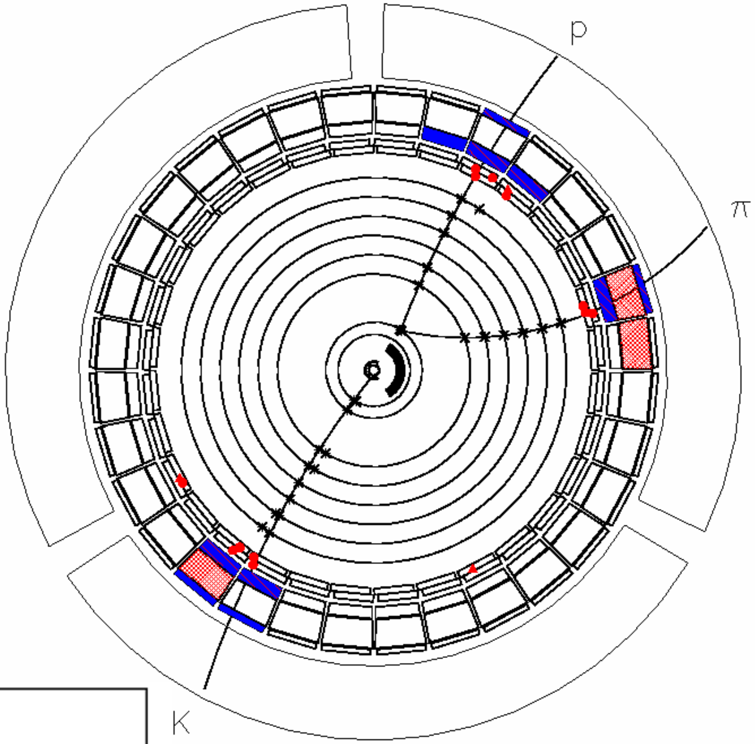
Event Selection:

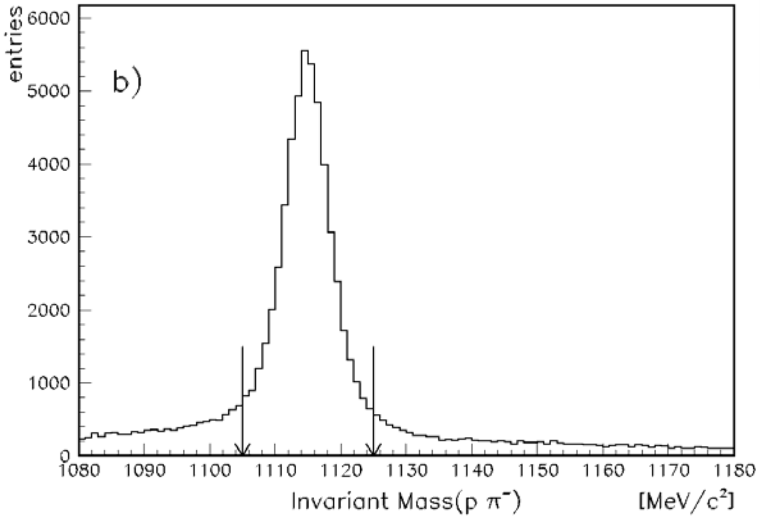
- At least one pair of track with opposite charge which forms vertex outside PC0
- Opening angle cut to reject gamma conversion e^+e^- pair

  ⇒ 20% accepted

Λ Selection

- $\Lambda(\rightarrow p\pi^{-})$ selection:
- a + charged track with Cherenkov 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
- Cut on the $p\pi^{-}$ invariant mass:

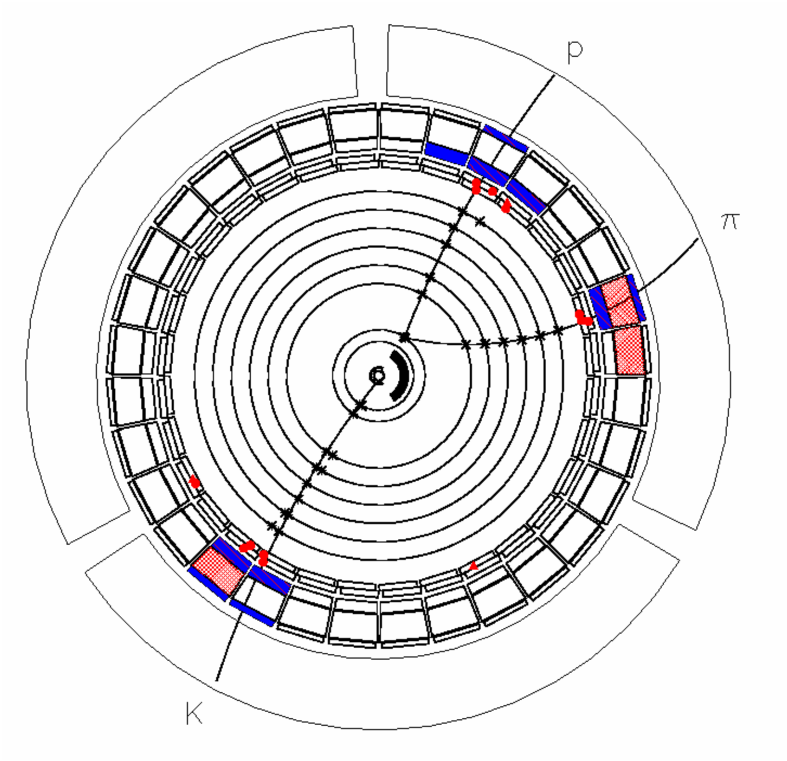




Charged Kaon Selection

A single charged track with:

- $P > 350$MeV/c
- Cherenkov threshold veto
- S1 & S2 hits
- Extrapolate back to absorbers



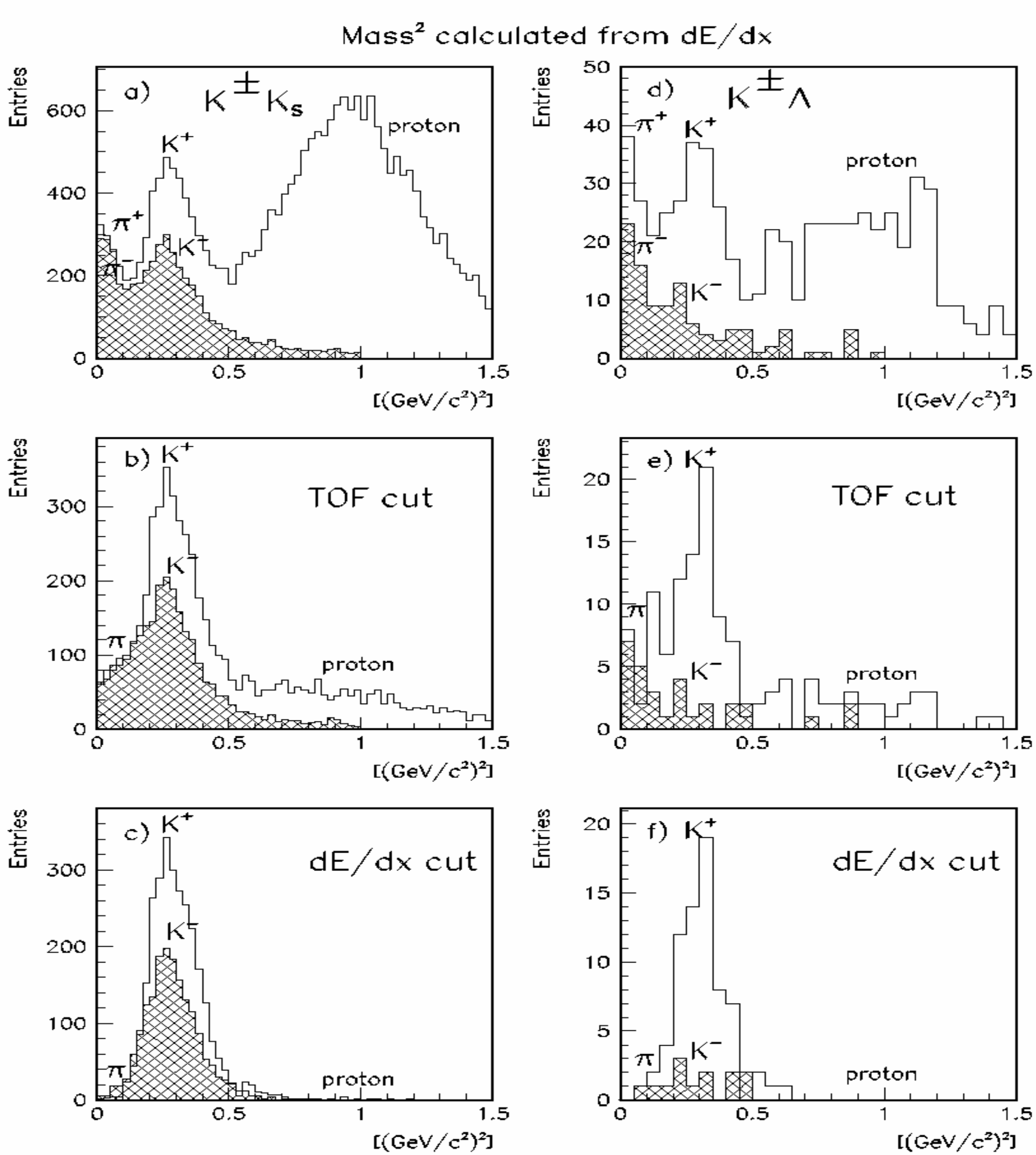
Plot M^2 from dE/dx and P

- ♦ dE/dx $\Rightarrow \beta^2$;
- ♦ β^2 & P $\Rightarrow M^2$

Further cuts:

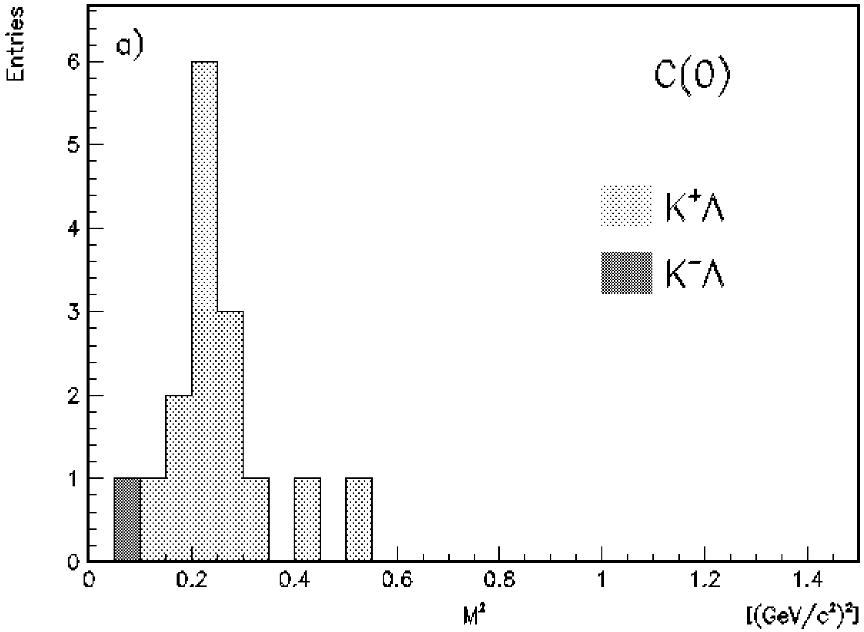
- ♦ Cut on TOF against the other charged particles
- ♦ Cut on χ^2 of dE/dx

K± selection

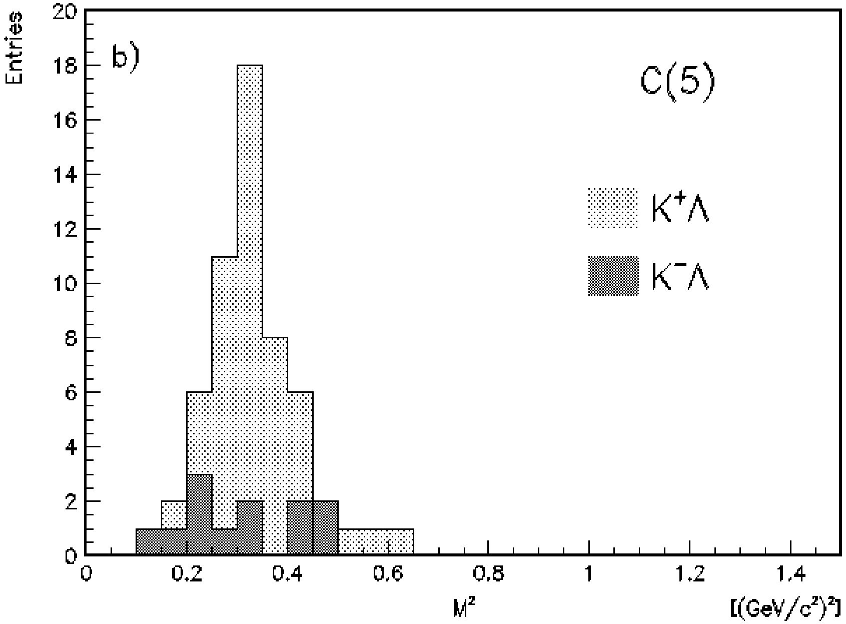

Mass² calculated from dE/dx
a) K± Ks
d) K± Λ
b) K+ TOF cut
e) K+ TOF cut
c) K+ dE/dx cut
f) K+ dE/dx cut
Entries
π+
π−
π
K+
K−
proton
[(GeV/c²)²]
0
0.5
1
1.5
200
400
600
100
300
10
20
30
40
50
5
15

$K^{\pm}\Lambda$ Results

Copper-Copper



Copper-Carbon



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

Number of events after $K^{\pm}$ and Λ Selection:

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

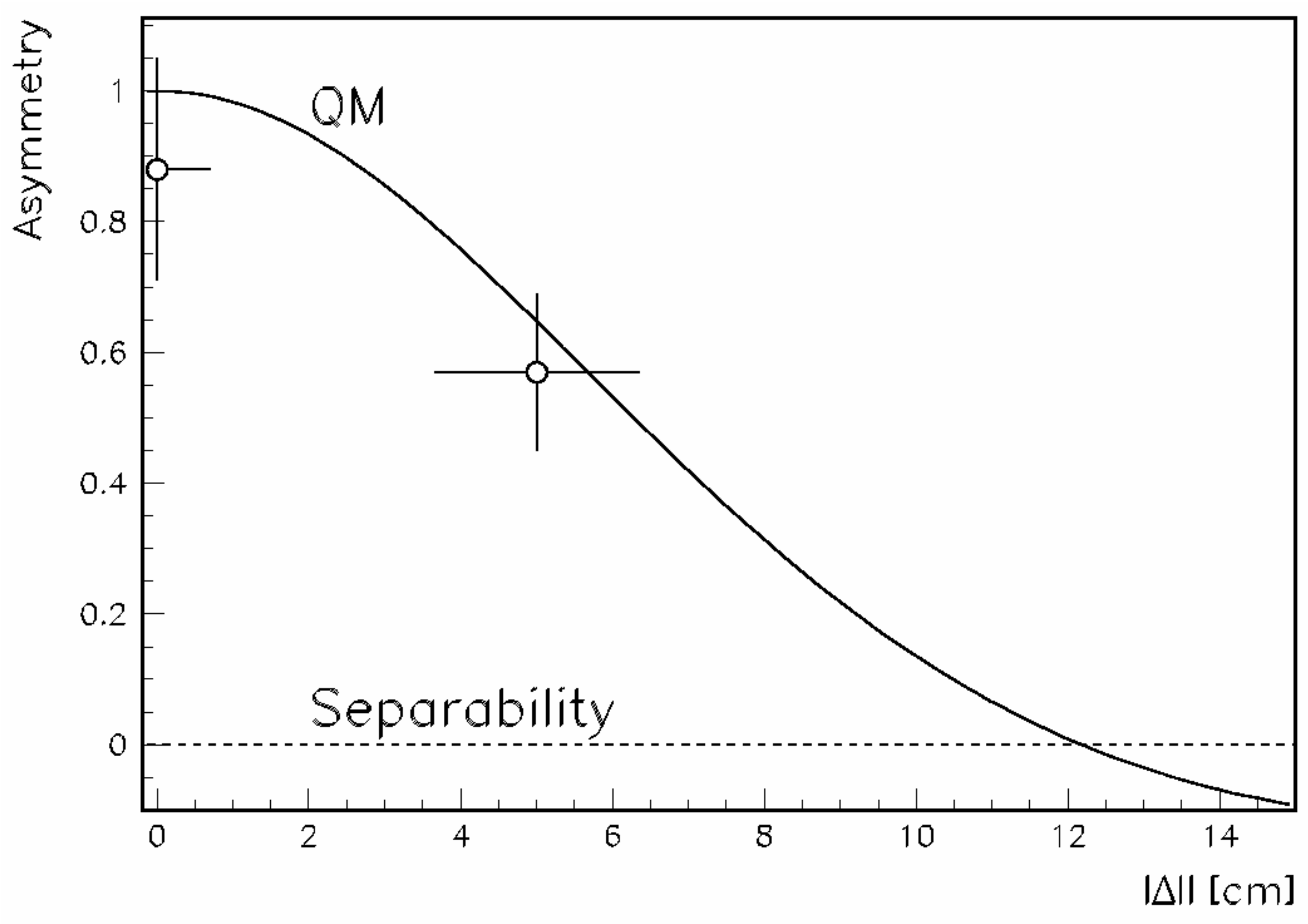
The asymmetry $A(t_a,t_b)$ after correcting for detection efficiency due to $K^{\pm}$ interaction differences and comparing with QM and Separability:

	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:



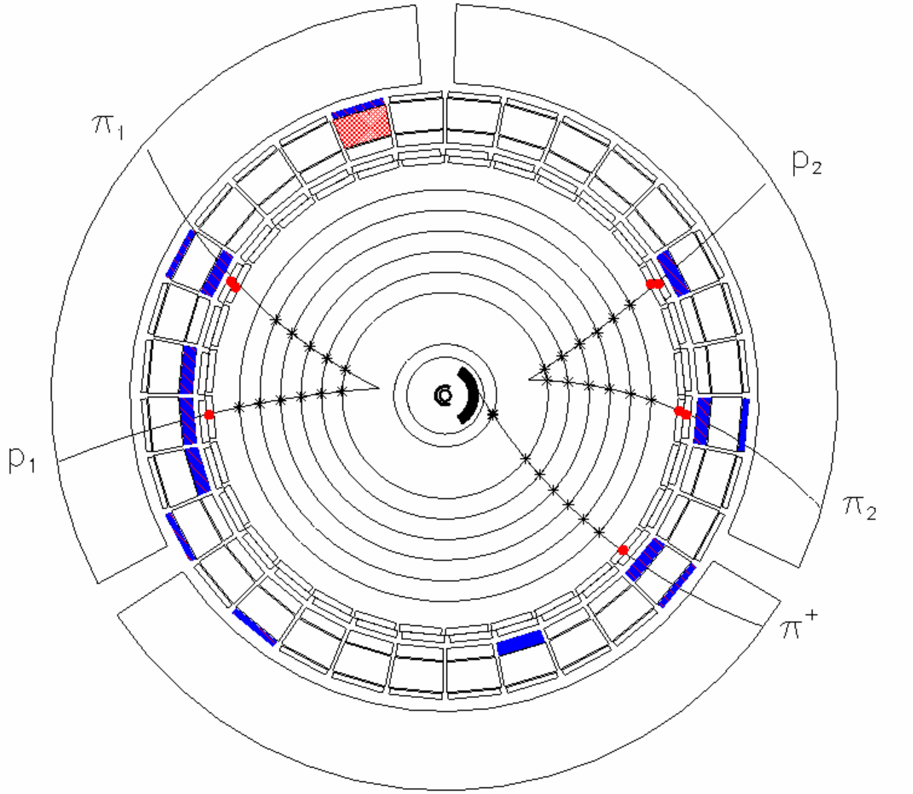
ΛΛ Selection

Another method, ΛΛ, is used as a cross check

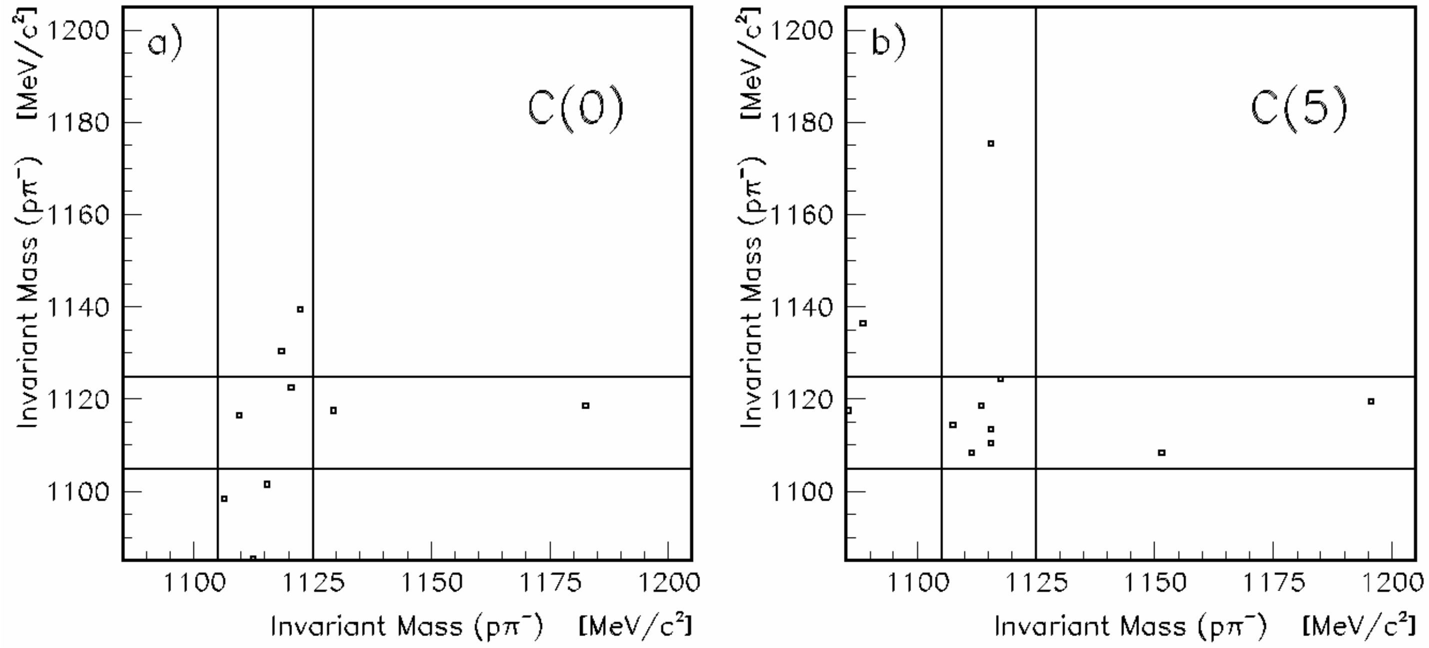
$N_{\Lambda\Lambda} \propto I_{\mathbf{like}}$

$\Lambda(\to p\pi^-)$ selection as before

Cut on the opening angle between the two Λ's ⇒ reduce $pp \to K^0K^0X$ background



ΛΛ Results



	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

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

Results are consistent with QM!

Decoherence Fit

Instead of Furry's hypothesis (100% separation), one can take only a part of the QM wavefunction undergo separation (decoherence).

Bertlmann et. al. (PRD 60, 114032) made the fit to our CPLEAR data:

The decoherence can happen either in K^0K^0 basis or in K_LK_S basis:

K_LK_S basis: $A=(1-\zeta)A_{QM}$ → $\zeta=0.13^{+0.16}_{-0.15}$

$K^0\bar{K}^0$ basis:

$$A_{\zeta}^{K^0\overline{K^0}}(t_r,t_l)=\frac{\cos(\Delta m\Delta t)-(1/2)\zeta\{\cos(\Delta m\Delta t)-\cos[\Delta m(t_r+t_l)]\}}{\cosh[(1/2)\Delta\Gamma\Delta t]-(1/2)\zeta\{\cosh[(1/2)\Delta\Gamma\Delta t]-\cosh[(1/2)\Delta\Gamma(t_r+t_l)]\}}$$

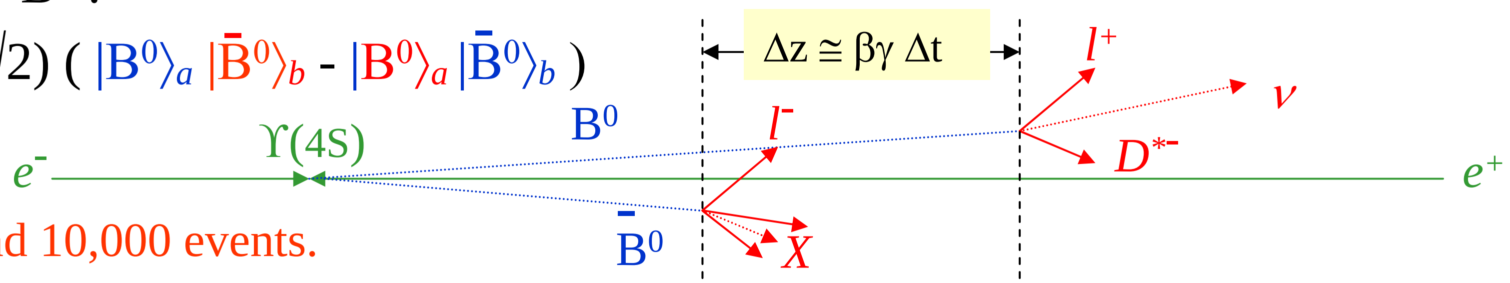
→ $\zeta=0.4\pm0.7$

Flavor correlation in $Y(4S) \rightarrow B^0\bar{B}^0$

I am measuring flavor correlation in $B^0\bar{B}^0$ at Belle Experiment in KEK Japan:

$\Upsilon(4S) \rightarrow B^0\bar{B}^0$:

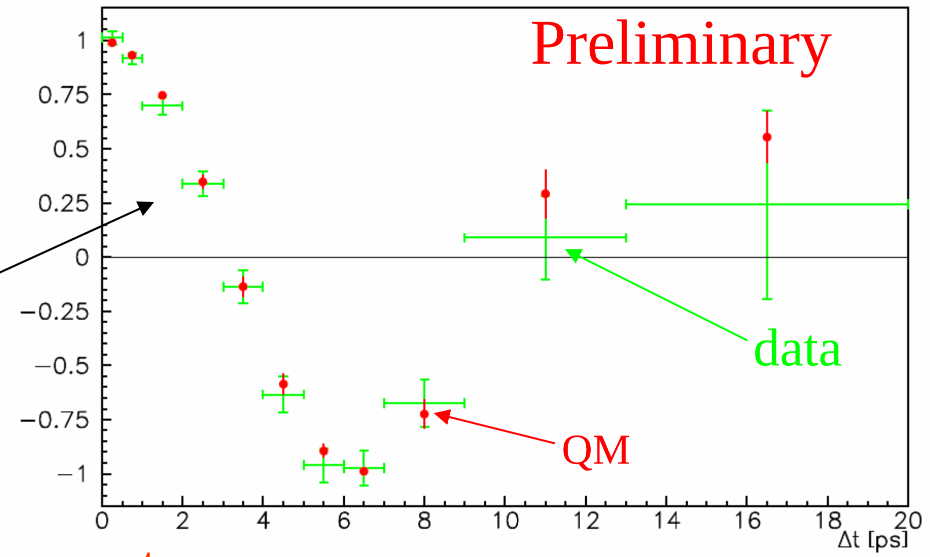
$|\Psi\rangle = (1/\sqrt{2})\ (\ |B^0\rangle_a\ |\bar{B}^0\rangle_b - |B^0\rangle_a\ |\bar{B}^0\rangle_b\ )$



stat: around 10,000 events.

Because $\tau_{B_L} \approx \tau_{B_H}$:

$A_{QM} = \cos(\Delta m_d \Delta t)$



Consistent with QM

Can also fit the decoherence parameter:

$B_L B_H$ basis: $A = (1-\zeta) A_{QM}$ → $\zeta = 0.004 \pm 0.020$

$B^0\bar{B}^0$ basis: $A = (1-\zeta)\cos(\Delta m_d \Delta t) + \zeta \cos(\Delta m_d t_1)\cos(\Delta m_d t_2)$

→ $\zeta = 0.028 \pm 0.063$

Testing Bell Inequality in K^0 system

Note:

- Best to use inequality with comparison of probabilities → use Wigner's form (4 angles):

$$P(A,B) \leq P(A,C) + P(C,B) + P(C,C)$$

- Hard to be convincing with interactions $K^0 \rightarrow K^+, \Lambda$ (only few % interaction probability!).
- Only control of where but not which interaction ($K^{\pm}$ or Λ) will occur (same as decay channel!).
- Inclusive detection of K_L in a calorimeter seems to be the best (high efficiency, no problem of decay channel).

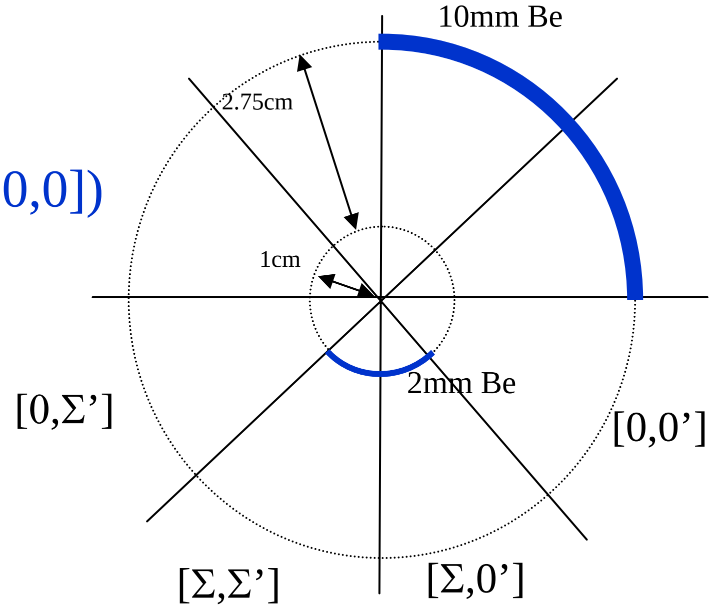
Testing Bell Inequality in K0 system

Following the idea of Eberhard (Nucl.Phys.B398(1993)155):

4 set-ups: [0,0’] [Σ,0’] [0,Σ’] [Σ,Σ’]

BI in Wigner’s form:

$$P([\Sigma,\Sigma']) \leq P([\Sigma,0']) + P([0,\Sigma']) + P([0,0])$$



Advantage: measure all 4 type of interation at the same time!

Back of envelop calculation (with Antonio´s regeneration parameters):

[Σ,0’]: ~114 events/fb^{-1}

[0,Σ’]: ~100 events/fb^{-1}

→Need only about 1-2 fb^{-1}

Feasible at KLOE2 !!

BI with measuring K_S

Alternatively, instead measuring K_L in the calorimeter, one can measure K_S pair by their decays to $\pi\pi$.

This has advantage of K_L living to interact with regenerator which is much higher than K_S. So the back-of-envelop calculation gives:

$[\Sigma, 0']$: ~218 events/fb^{-1}

$[0, \Sigma']$: ~346 events/fb^{-1}

Definitely feasible at KLOE2 !!

Same set-up might be used for quantum eraser/marking experiment.

Conclusion

- CPLEAR experiment not only provides precision measurements on the CP, T violation parameter and Kaon physics, it also can be used to study the fundamental QM issues.
- The non-separability of the $K^0\bar{K}^0$ wavefunction is well stablished.
- KLOE2 might be able to do better and measure the Bell Inequality.

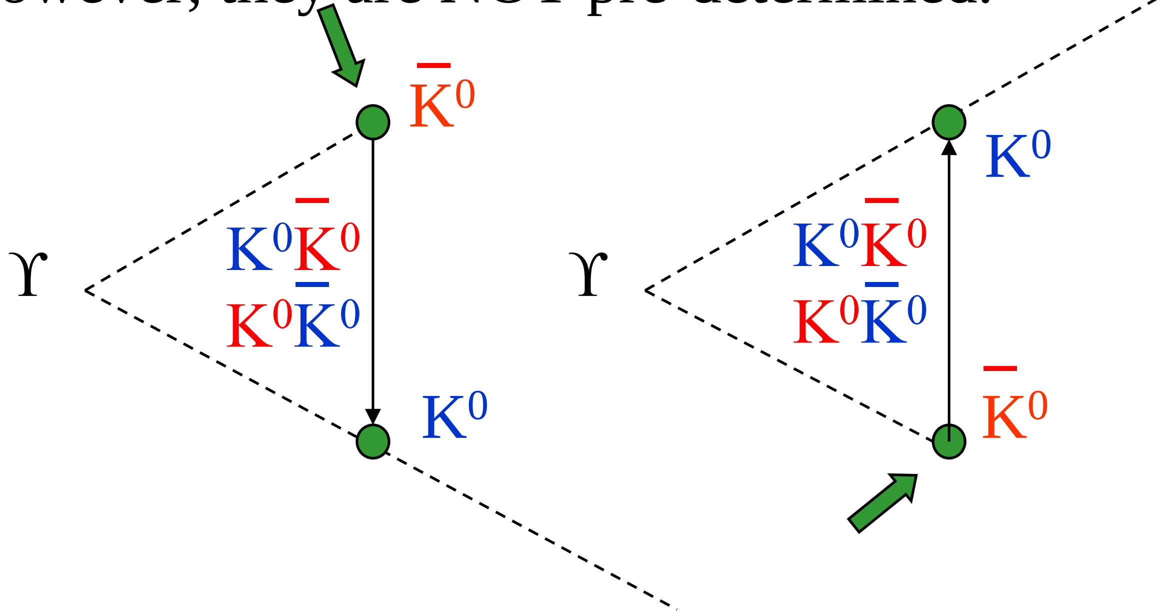
Entanglement in Particle Physics

A similar entangled system can be found in the decay of massive particle $\phi(1020) \rightarrow \bar{K}^0 K^0$:

The wavefunction (at t=0) has the same form as the two photon system.

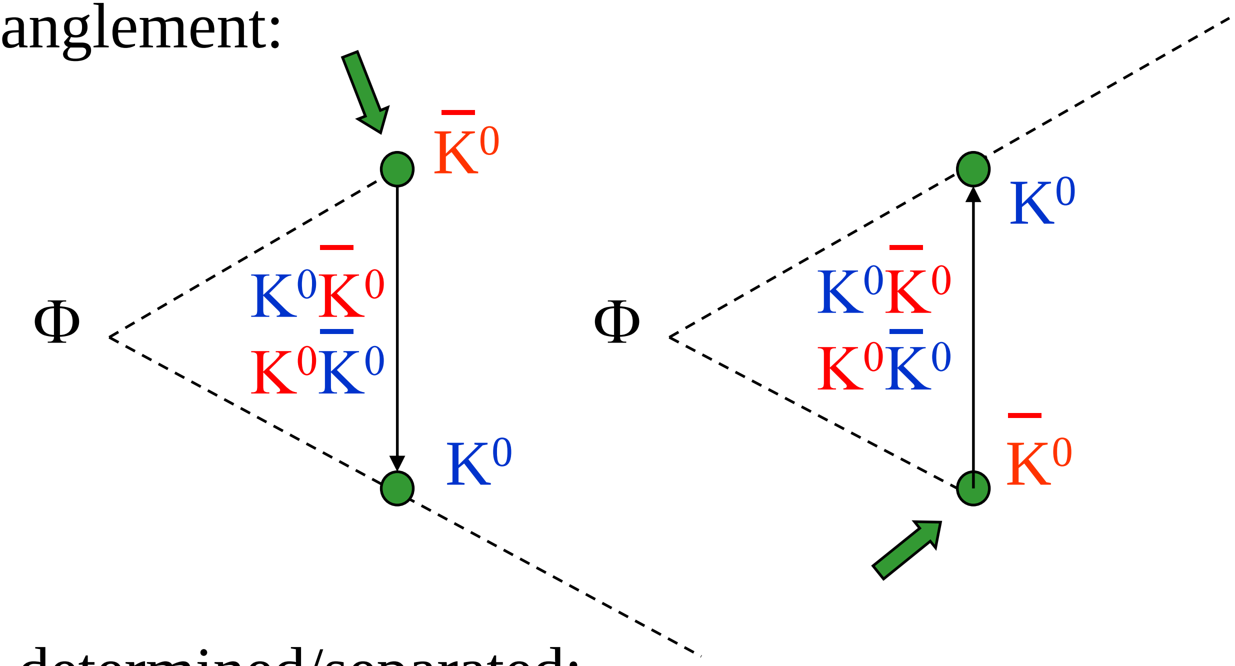
$$|\Psi\rangle = (1/\sqrt{2}) \left(|K^0\rangle_a |\bar{K}^0\rangle_b - |\bar{K}^0\rangle_a |K^0\rangle_b \right)$$

If one of them is measured to be $\bar{K}^0 \Rightarrow$ the other becomes K^0, However, they are NOT pre-determined.

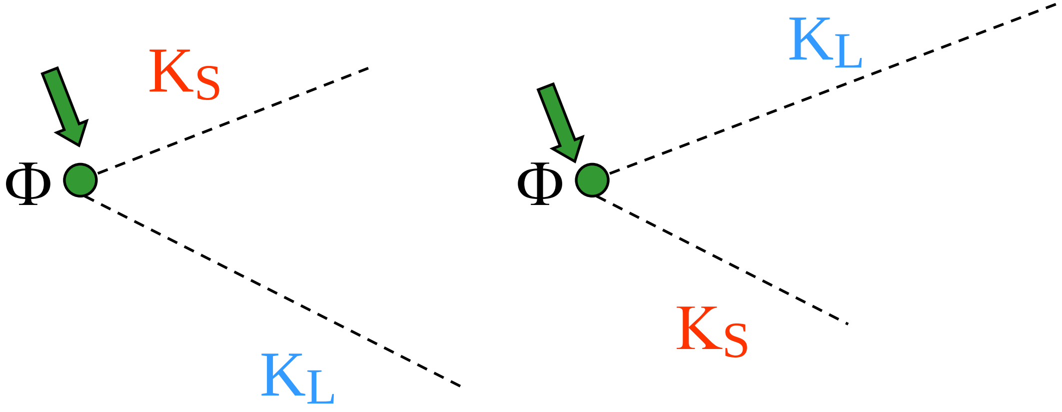


Entanglement vs separability

Entanglement:



Pre-determined/separated:

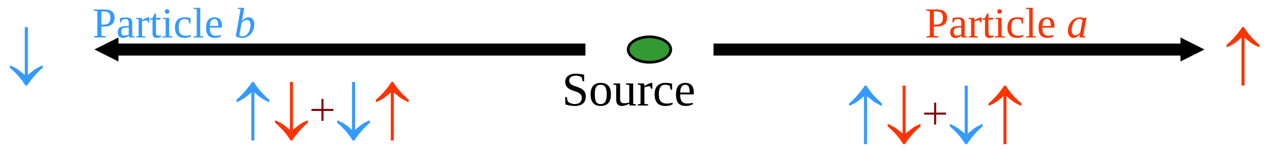


EPR Paradox

In 1935, Einstein. Podolsky and Rosen (EPR) published a paper based on entangled pair of particles, challenging the completeness of QM.

Their argument are based on three premises:

1. Experimental prediction of QM is correct: “agreement between the conclusion of the theory and human experience” (correctness vs. completeness)
2. Locality Principle: No action-at-a-distance in Nature. Never state explicitly, only implicit in “There is no longer any interaction”; “which does not disturb the second system in any way”
3. Reality Principle: “If, without in any way disturbing a system, we can predict with certainty the value of a physical quantity. Then there exists an element of physical reality corresponding to this physical quantity”



EPR Paradox

Argument (Bohm's version):

- By measuring particle a's spin on x-axis, S_x, one knows with certainty particle b's S_x without disturbing particle b.
- By measuring particle a's spin on y-axis, S_y, one knows with certainty particle b's S_y without disturbing particle b.

Therefore:

- Both S_x and S_y of particle b must both have definite value, "element of reality".

Conclusion:

- Since QM does not allow S_x both S_y and to have definite value (S_x, S_y are non-commuting) => Contradiction with above argument => QM incomplete.
- Since QM does not describe such "element" of reality, therefore, it must be incomplete. QM cannot be the most fundamental description of nature.

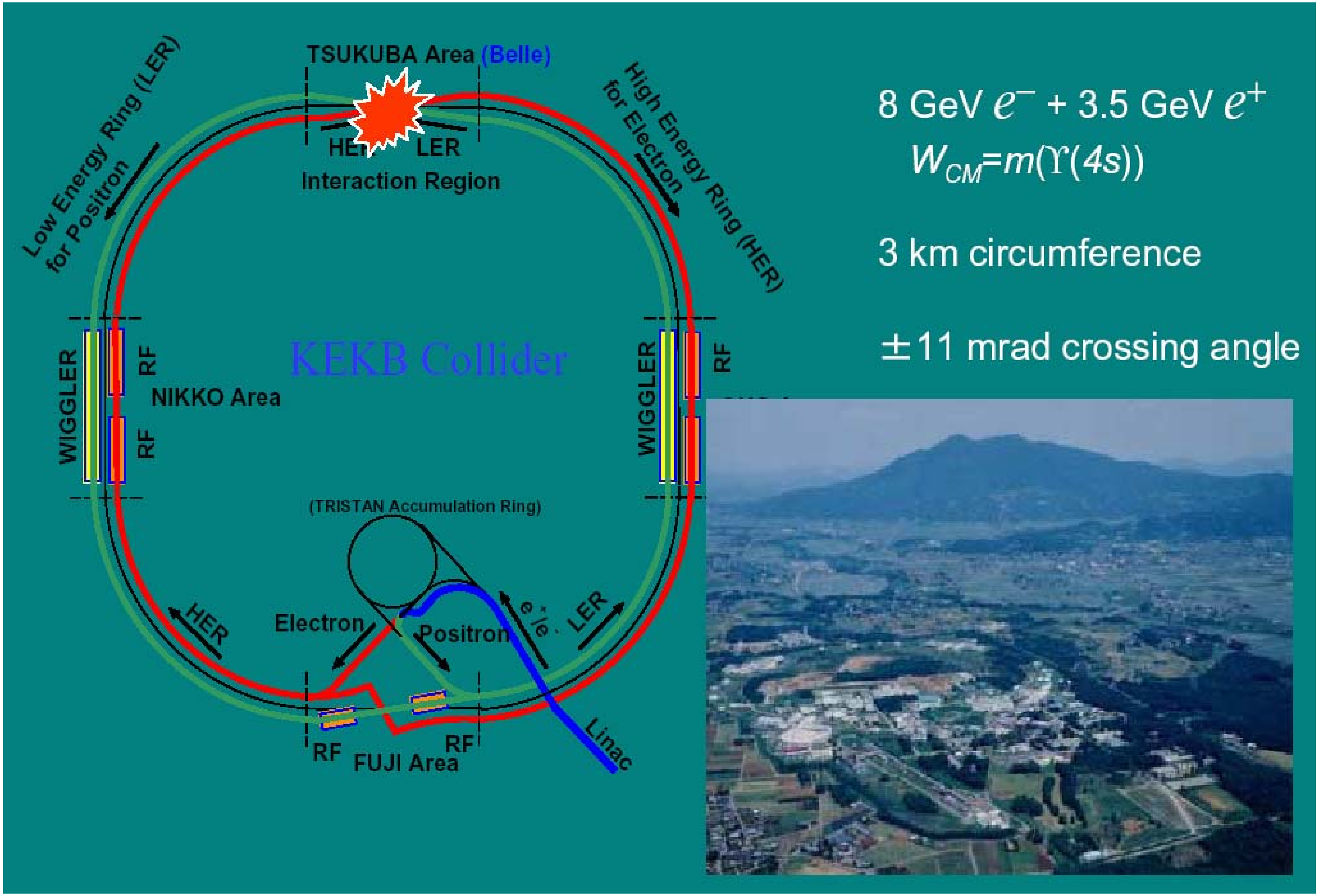
Need additional information?

Hidden Variable??

For 30 years, this remains as an "philosophical" question with no possibility of experimental verification, until…..

Experimental Tests: BELLE

At KEK B collider at Tsukuba, Japan: CP violation in B^0 system



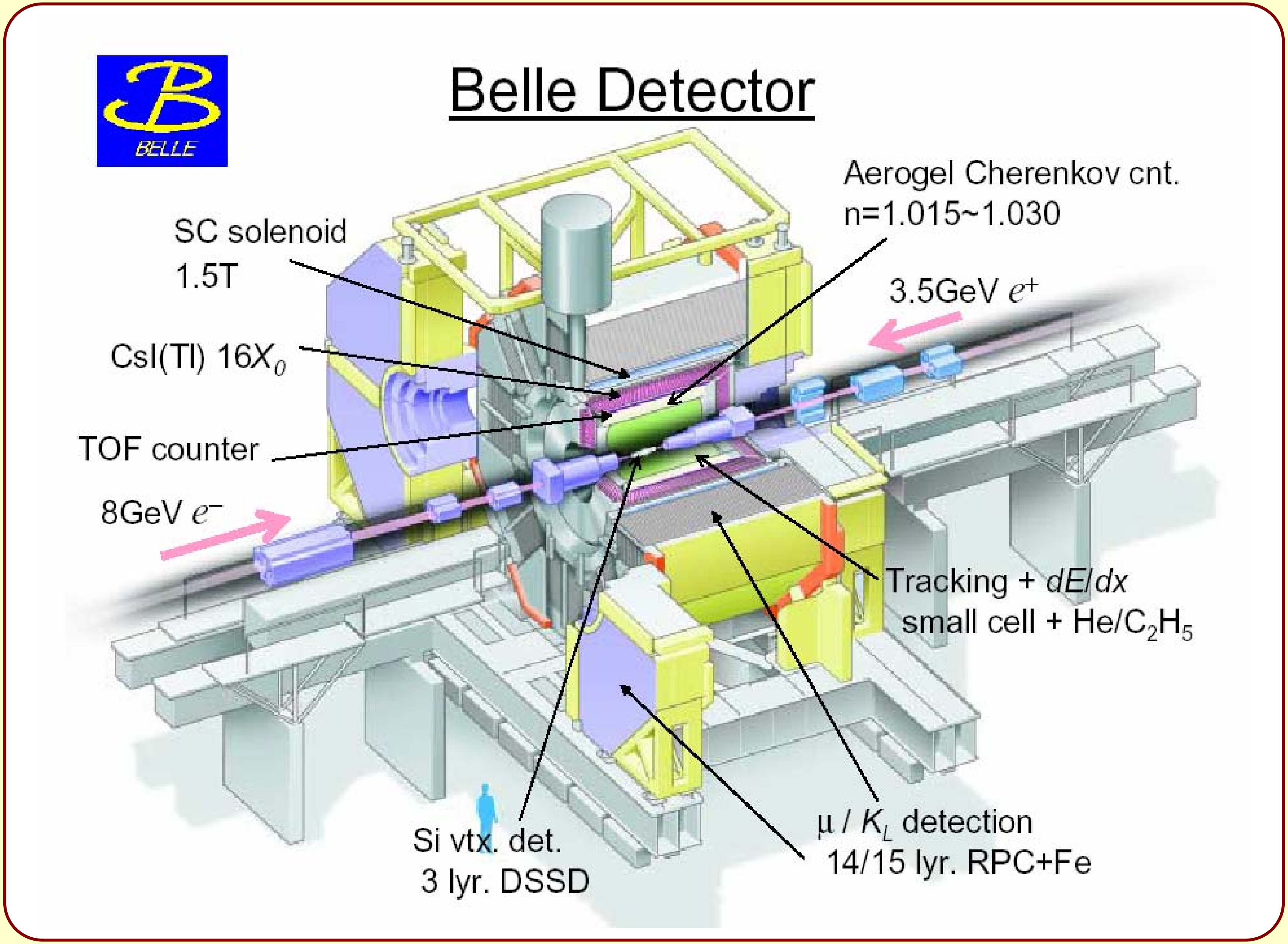
8 GeV e^- + 3.5 GeV e^+

$W_{CM}=m(\Upsilon(4s))$

3 km circumference

±11 mrad crossing angle

BELLE detector



BELLE experiment

KEKB:

CMS energy @ $\Upsilon(4S)$

$\beta\gamma = 0.425$

SVD:

$\sigma_z \approx 55\mu m$

for 1 GeV/c at 90°

CDC:

$\sigma_p/p \approx 0.35\%$

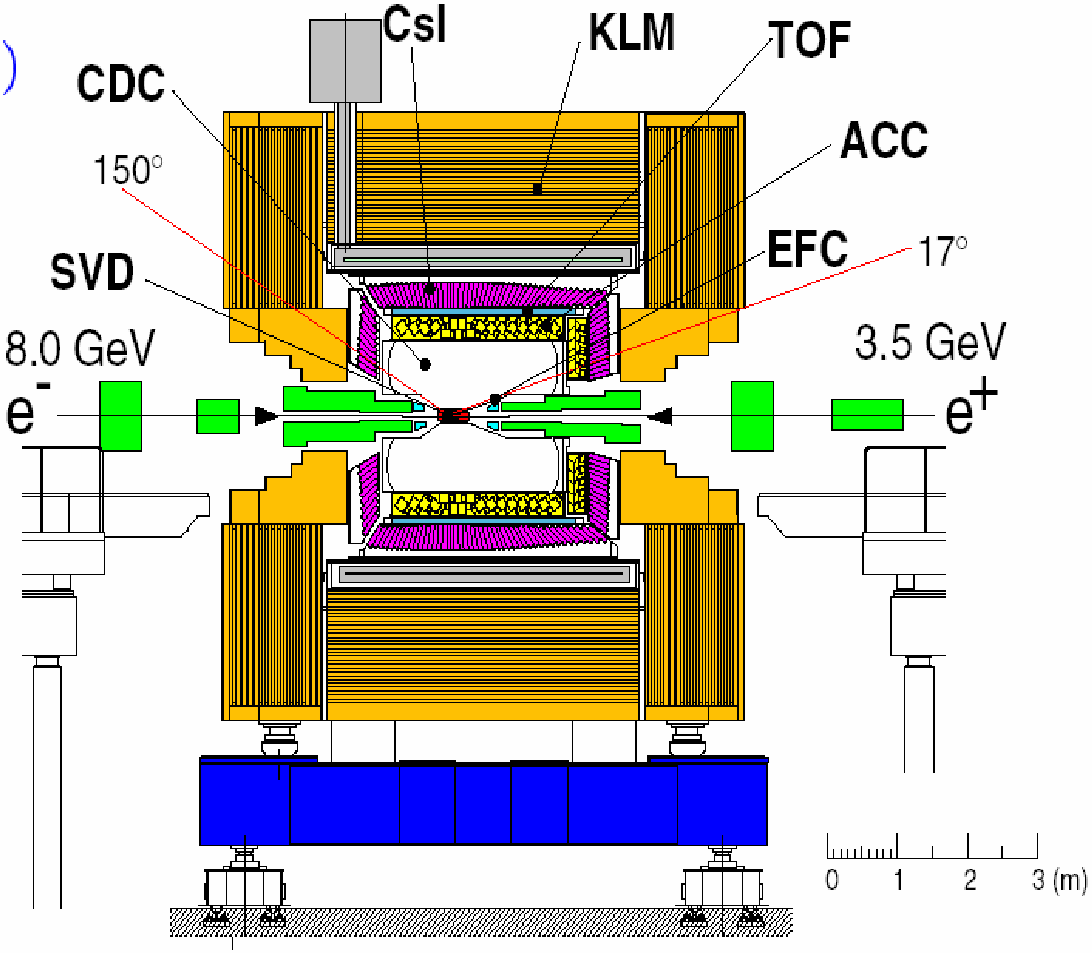
at 1 GeV/c

KLM:

$\epsilon_\mu > 90\%, \sim 2\%$ fakes

Magnet: 1.5 T

Superconducting solenoid



Ingetral luminosity of 78 fb^{-1} (corresponding to $80*10^6$ produced Bs) were used in this analysis (data from 99-2002).

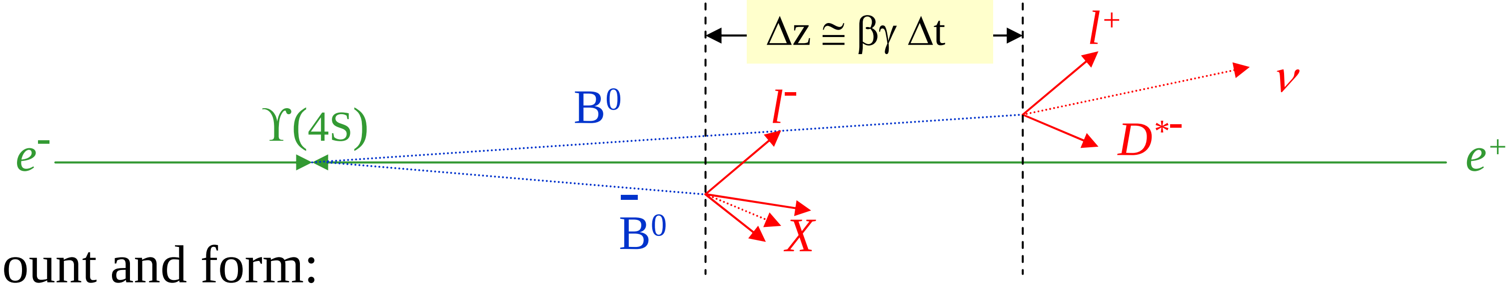
Experimental method at BELLE

Look for particle/antiparticle correlation in $\Upsilon(4S)\to B^0\bar{B}^0$:

1. Identify the flavor of the two B^0s by the charge of the decayed lepton:
   $l^+ \Leftrightarrow B^0$ $\quad$ $l^- \Leftrightarrow \bar{B}^0$

- First B^0: Fully reconstructed semileptonic decay
  $B^0\to D^{*-} l^+ \nu$, $\quad (l^+ = e^+, \mu^+)$ $\quad$ Branching Ratio=4.6%
  $\quad\hookrightarrow D^0\pi^-$
  $\quad\quad\hookrightarrow K^+\pi^-, K^+\pi^-\pi^0, K^+\pi^-\pi^+\pi^-$
- Second B^0: only identify lepton to tag the flavor
  $\bar{B}^0\to l^- X$ where X is any (one or more) particles. $\quad$ Branching ratio=10.5%

2. Find decay time difference Δt:



3. Count and form:

$$A(\Delta t) = \frac{N_{+-}(\Delta t)+N_{-+}(\Delta t)-N_{++}(\Delta t)-N_{--}(\Delta t)}{N_{++}(\Delta t)+N_{--}(\Delta t)+N_{+-}(\Delta t)+N_{-+}(\Delta t)} = \frac{N_{OF}(\Delta t)-N_{SF}(\Delta t)}{N_{OF}(\Delta t)+N_{SF}(\Delta t)}$$