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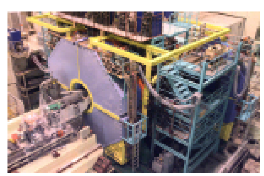
Mesons violate Bell's inequality

6 November 2003

The famous Bell's inequality of quantum mechanics has been tested in a high-energy particle physics experiment for the first time. The inequality was violated by three standard deviations in experiments with B mesons at the KEK laboratory in Japan - yet again confirming the predictions of quantum theory (arxiv.org/abs/quant-ph/0310192; *J. Mod. Optics* to be published). Previously most Bell's inequality experiments have been performed with photons or ions.

Experiments to test Bell's inequality involve measuring the properties of pairs of particles that are space-like separated in the sense of special relativity: in other words, there is no time for a light signal to travel between them within the duration of the experiment. In a typical Bell's inequality experiment the polarizations of a pair of photons are measured as the relative angle between the axes of polarizers making the measurements is varied.

Quantum mechanics predicts that "non-local" correlations can exist between the particles. This means that if one photon is polarized in, say, the vertical direction, the other will always be polarized in the horizontal direction, no matter how far away it is. However, some physicists argue that this cannot be true and that quantum particles must have local values - known as "hidden variables" - that we cannot measure.



Belle experiment

Bell and others showed that it was possible to distinguish between quantum mechanics and these hidden-variable theories in a certain type of experiment that measure a parameter known as S. Put simply, the local theories predict that S will always be less than two, whereas the quantum prediction is $S = 2\sqrt{2}$. When S is greater than two, Bell's inequality is said to be violated.

Apollo Go of the National Central University in Taiwan and co-workers in the Belle collaboration performed the experiment at the KEK B-factory. At this accelerator beams of electrons and positrons are collided to produce pairs of B mesons and their antiparticles, which then decay into lighter particles. The meson pairs behave like photon pairs, but instead of analyzing correlations between directions of polarization, the Belle team study particle-antiparticle correlations using a technique known as "flavour tagging". Go and colleagues calculated that S = 2.725, with error bars that mean that the inequality is violated by three standard deviations.

"If quantum mechanics is the fundamental description of nature, then non-local correlations should be found with any quantum number," Go told *PhysicsWeb*. "In this experiment we are testing a quantum number that has never been tested before. Moreover, the particle-antiparticle quantum number is a very fundamental quantity in particle physics and the results might have implications in this area - I am waiting for comments from other particle theorists!"

The team now plans to study particle-antiparticle correlations in more detail and probe the boundary between classical and quantum mechanics.

Author

Peter Rodgers is Editor of *Physics World*

Bell @ Belle

Testing Bell Inequality at Belle experiment

Apollo Go
National Central University, Taiwan

John S. Bell (1928-1990)

CERN Physicist, 1960-1990

Introduction

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

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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.*

Quantum 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 -- Multi-particle wavefunction implies correlation even at a large distance.

Uncertainty Principle

QM puts an ultimate limit on how precise can we know about two physical quantities at the same time:

$$\Delta x \, \Delta p \geq \hbar$$

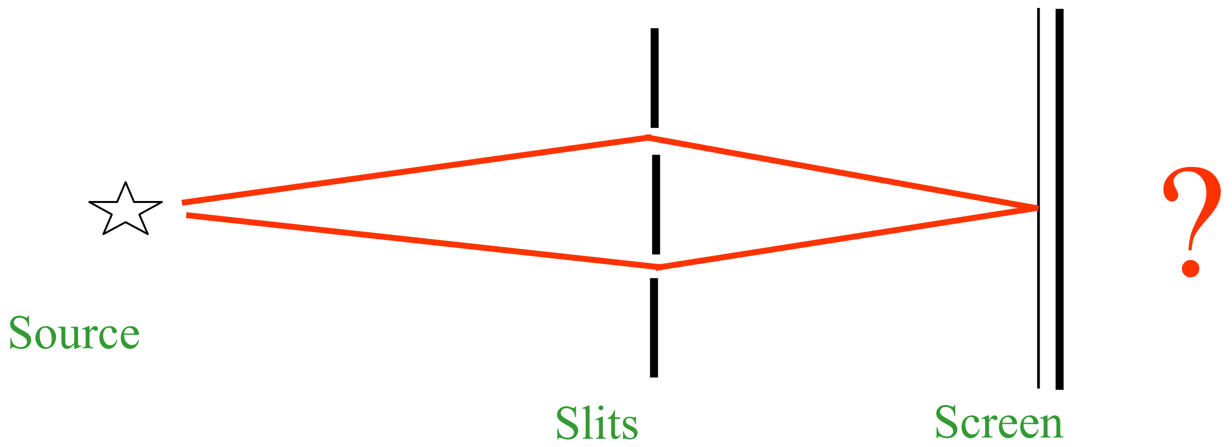
$$\Delta E \, \Delta t \geq \hbar$$

In fact, ANY non-commuting operators.

QUESTION: Is this limit built into the nature, i.e. fundamental? Or is it just because of the limitation of the theory itself?

Wave-Particle Duality

- Is photon a particle or wave?
- Double slit experiment seems to indicate both! Depends on what we look for.



In fact, electron also behaves both as wave and as particle.

QUESTION: How can photon be both particle and wave? How can we reconcile wave (non-localized) concept with particle (localized)? Or we need a completely new description?

Superposition

- A QM wavefunction consists of linear superposition of eigenstates $|\alpha\rangle$, $|\beta\rangle$,….

$$|\varphi\rangle = a\,|\alpha\rangle + b\,|\beta\rangle + \ldots..$$

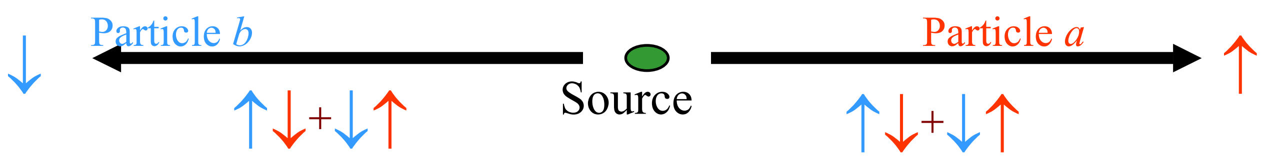
a, b are the square root of the probability of each eigenstate.

- Reduction of wavefuction: In a measurement, the wavefunction is reduced to ONE of its eigenstates with probability described by the coefficients a^2, b^2 ….
- QUESTION: How is wavefuction reduced? What determines which eigenstate it reduced to? Is it inherently random? Is it due to some unknown factor?

Entanglement

Peculiar two-particle QM system

Two particles created in a single QM state are spatially separated yet belong to the same wavefunction: a single wavefunction $\Psi_{a,b}$ describing particles *a* and *b*.



$$|\Psi_{a,b}\rangle = (1/\sqrt{2})\,(\,|\uparrow\rangle_a\,|\downarrow\rangle_b + |\downarrow\rangle_a\,|\uparrow\rangle_b\,)$$

The outcome is not defined until measurement!

Measurement on *a* will define the state of *b* *instantaneously* even without measuring it.

QUESTION: This seems to contradict Special Relativity! How can two separate particles knows about each other immediately? Does this violate locality? Or it was pre-determined by some factor, just we do not know?

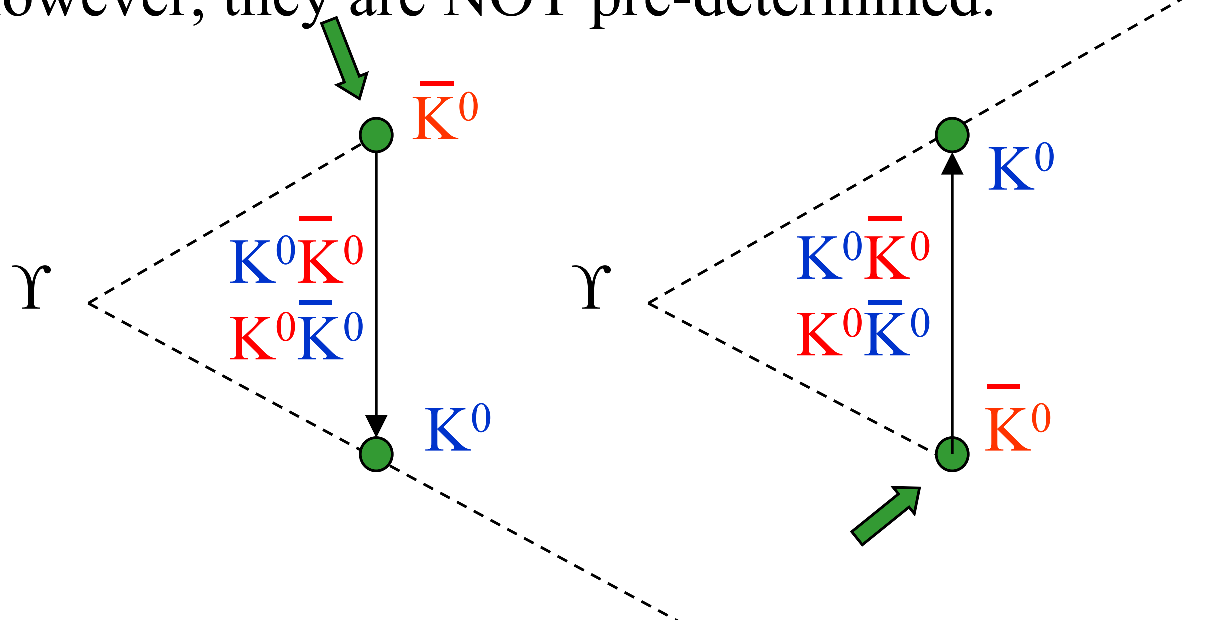
Entanglement in Particle Physics

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.

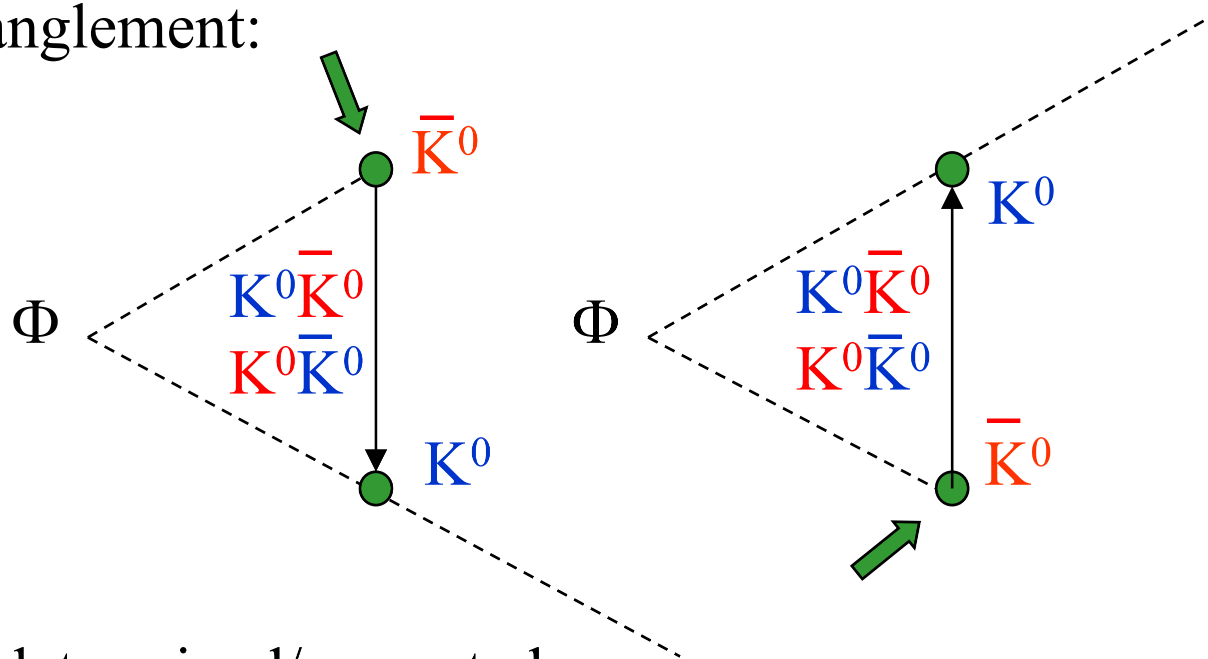
$$|\Psi\rangle = (1/\sqrt{2})\,(\,|K^0\rangle_a\,|\bar{K}^0\rangle_b - |\bar{K}^0\rangle_a\,|K^0\rangle_b\,)$$

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

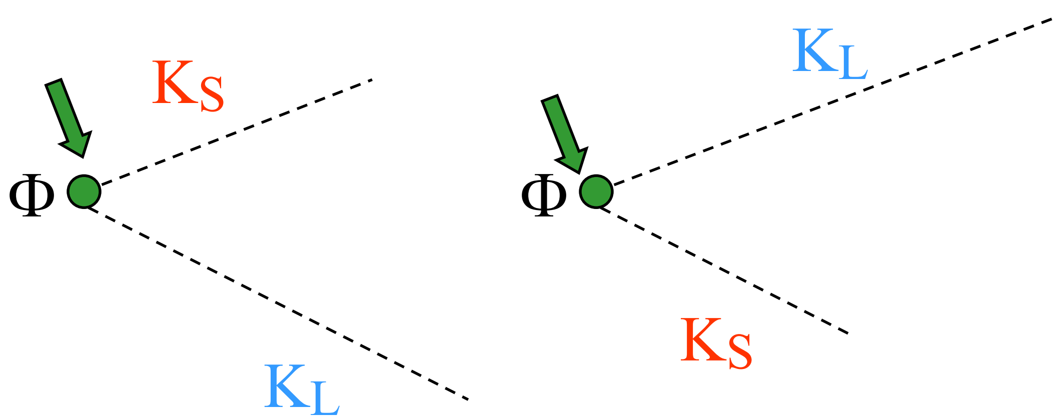


Entanglement vs separability

Entanglement:

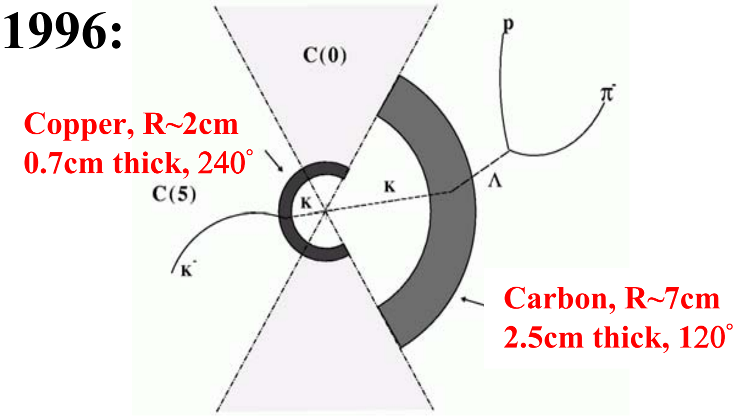


Pre-determined/separated:



EPR Test in Particle Physics

We did such experiment at CPLEAR in 1996:



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

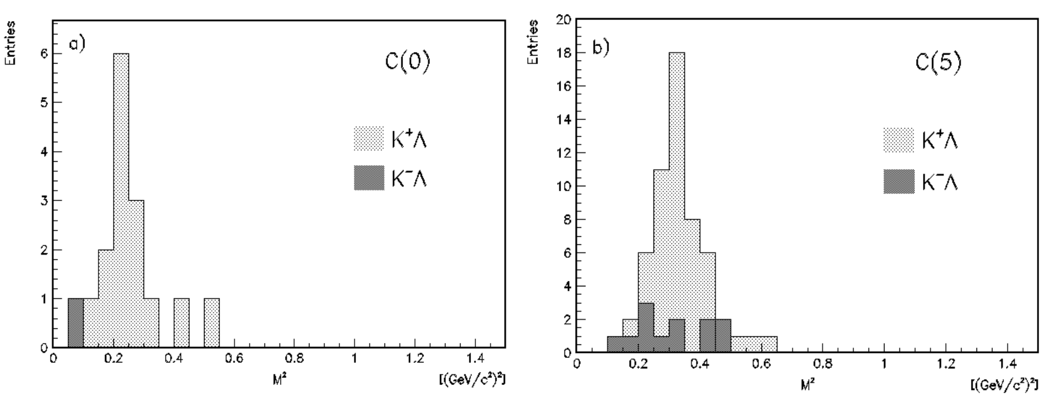
$$|\Psi\rangle = (1/\sqrt{2})\ (\ |K^0\rangle_a\ |\bar{K}^0\rangle_b\ -\ |K^0\rangle_a\ |\bar{K}^0\rangle_b\ )$$

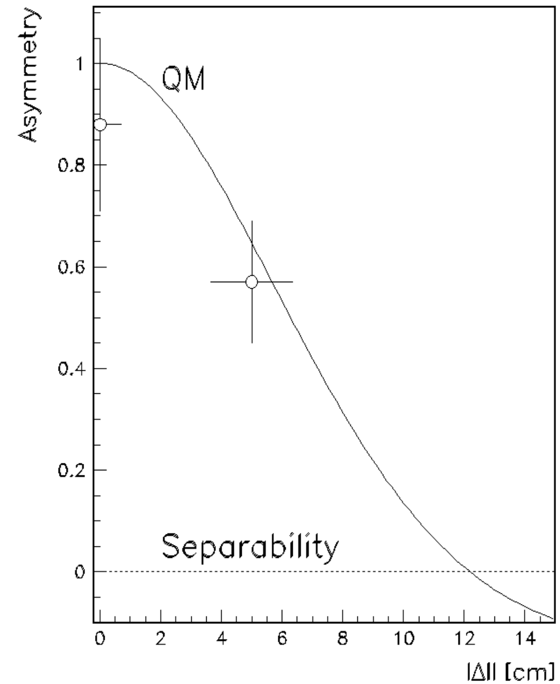
Determine the strangeness/flavor of the two K^0 by their strong interaction products with two converters.

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

Asymmetry:

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





Physics Letters B 422 (1998) 339-348

EPR Paradox

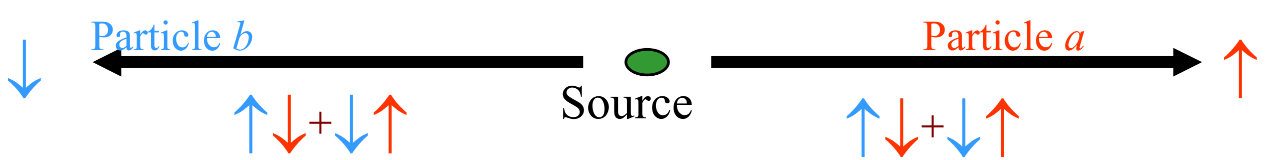
In 1935, Einstein. Podolsky and Rosen (EPR) published a paper based on entangled pair of particles, challenging the completeness of QM.

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?

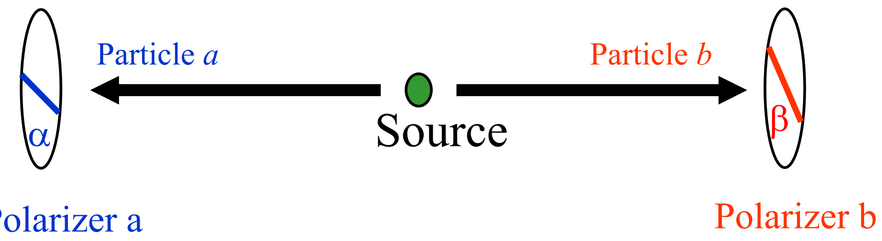
Hidden Variable??

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

Bell's Inequality

In 1964, J.S. Bell, a CERN Theorist, put the locality principle in EPR into testable form with a reasonable assumption on locality (in simplified CHSH form):

Take the photon polarization case:



α, β: angles of the polarizer

Define expectation value E(α,β) of the join outcome of both sides:

$$E(\alpha,\beta) = \int \rho(\lambda)\, \mu(\alpha,\beta,\lambda)\, d\lambda$$

- $\mu(\alpha,\beta,\lambda)=\pm 1$ is the join measurement outcomes on polarizer a and polarizer b.
- λ is the hidden variable,
- $\rho(\lambda)$: probability distribution of the hidden variable λ .

EPR's locality: $\mu(\alpha,\beta,\lambda)= \mu(\alpha,\lambda)\, \mu(\beta,\lambda)$ ← Outcome on one side does not depend on the polarizer setting of the other side

$$E(\alpha,\beta) = \int \rho(\lambda)\, \mu(\alpha,\lambda)\, \mu(\beta,\lambda)\, d\lambda$$

- $\mu(\alpha,\lambda)=\pm 1$ is the measurement outcome on polarizer a with polarizer angle α.
- $\mu(\beta,\lambda)=\pm 1$ is the measurement outcome on polarizer b with polarizer angle β

Bell's Inequality

Now let's construct a trivial inequality with 4 polarization angles ($\alpha,\alpha',\beta,\beta'$):

$$D(\alpha,\beta,\alpha',\beta',\lambda) = \mu(\alpha,\lambda)\mu(\beta,\lambda) - \mu(\alpha,\lambda)\mu(\beta',\lambda) + \mu(\alpha',\lambda)\mu(\beta,\lambda) + \mu(\alpha',\lambda)\mu(\beta',\lambda)$$

$$= \mu(\alpha,\lambda)[\mu(\beta,\lambda)-\mu(\beta',\lambda)] + \mu(\alpha',\lambda)[\mu(\beta,\lambda)+\mu(\beta',\lambda)] \leq 2$$

Note: either $\mu(\beta,\lambda)=\mu(\beta',\lambda)$ or $\mu(\beta,\lambda)=-\mu(\beta',\lambda)$

Let $S=\int\rho(\lambda)\, D(\alpha,\beta,\alpha',\beta',\lambda)\, d\lambda$

So the trivial inequality becomes:

$$S=E(\alpha,\beta)-E(\alpha,\beta')+E(\alpha',\beta)+E(\alpha',\beta') \leq 2$$

Any model with a local hidden variable λ will have $S \leq 2$!!

Bell's Inequality

In the case of photo polarization, E is the correlation function:

$$E(\alpha,\beta) = P_{+-}(\alpha,\beta)+P_{-+}(\alpha,\beta)-P_{++}(\alpha,\beta)-P_{--}(\alpha,\beta)$$

where α, β are the polarizer's angles, +,- are up, down

In real experiment:

$$E(\alpha,\beta) = \frac{N_{+-}(\alpha,\beta)+N_{-+}(\alpha,\beta)-N_{++}(\alpha,\beta)-N_{--}(\alpha,\beta)}{N_{++}(\alpha,\beta)+N_{--}(\alpha,\beta)+N_{+-}(\alpha,\beta)+N_{-+}(\alpha,\beta)}$$

Take a particular case:

$\alpha=0$, $\alpha'=2\theta$, $\beta=\theta$, $\beta'=3\theta$,

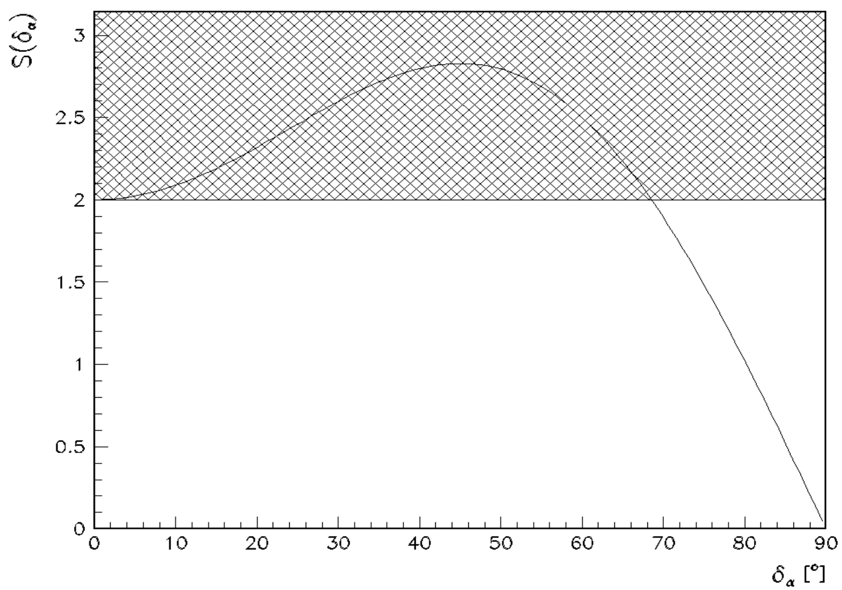
$$S(\theta)=3E(\theta)-E(3\theta) \leq 2$$

However, according to QM:

$$E(\alpha,\beta)=\alpha\bullet\beta=\cos(\theta)$$

=> violate Bell Inequality for $\theta<70^{o}$.

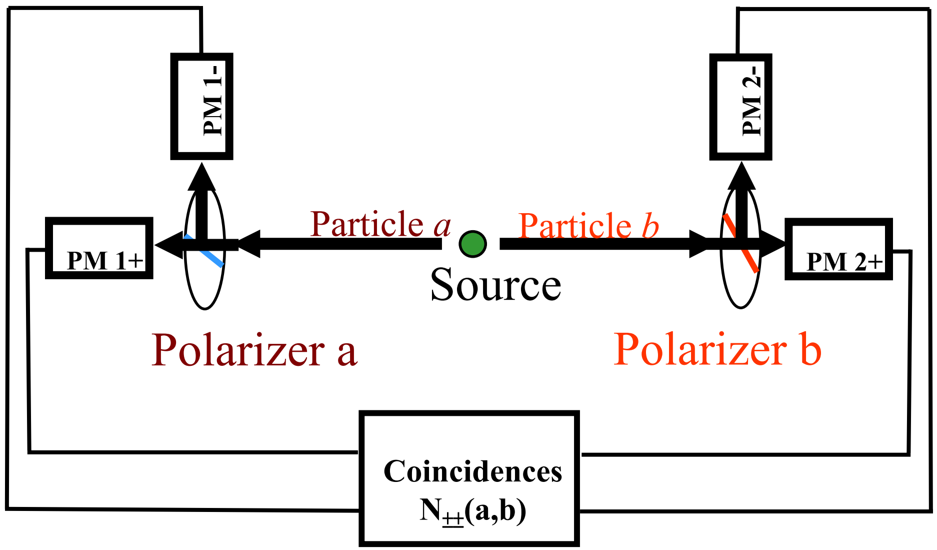
with $S_{max}(45^{o})=2\sqrt{(2)}$



The beauty and power of Bell Inequality is in its simple locality assumption. Therefore, a violation (S>2) excludes ALL local hidden variables models, not just a certain prediction of a given model.

Aspect's Experiment

In 1982, Alan Aspect of Orsay realized the spin correlation experiment using Ca-40 radiative cascade photons:



experimentally, E is defined as:

$$E(a,b) = \frac{R_{+-}(a,b)+R_{-+}(a,b)-R_{++}(a,b)-R_{--}(a,b)}{R_{++}(a,b)+R_{--}(a,b)+R_{+-}(a,b)+R_{-+}(a,b)}$$

(R: detection rate
i.e. normalized to the detection efficiency)

The result confirms QM prediction and violate Bell's Inequality by >5σ

Since then, there has been many experiment, mostly with photons, some with atoms, has been done.

B^0 wavefunction

$\Upsilon(4S) \rightarrow B^0\bar{B}^0$ has same wavefunction: $|\Psi\rangle = (1/\sqrt{2})\,(\,|B^0\rangle_a\,|\bar{B}^0\rangle_b - |\bar{B}^0\rangle_a\,|B^0\rangle_b\,)$

Single B^0 wavefunction:

- Two eigenstates, just like the spin 1/2 particle: spin up and spin down.
- Can be written in 2 basis:
  - B^0, $\bar{B}^0$: Flavor eigenstates (particle/anti-particle)
  - B_L, B_H : mass eigenstates (with small mass split: $m_d = 0.489*10^{-12}\hbar s^{-1}$)
- Transform from one basis to the other:

$|B_H\rangle = (1/\sqrt{2})\,(\,|\bar{B}^0\rangle + |B^0\rangle\,)$

$|B_L\rangle = (1/\sqrt{2})\,(\,|\bar{B}^0\rangle - |B^0\rangle\,)$

$|B^0\rangle = (1/\sqrt{2})\,(\,|B_H\rangle + |B_L\rangle\,)$

$|\bar{B}^0\rangle = (1/\sqrt{2})\,(\,|B_H\rangle - |B_L\rangle\,)$

=> *Spin along S_x or S_y axis*

- Unstable particle with a decay lifetime of $1/\gamma$=1.542ps: $|B_H(t)\rangle = e^{-i\alpha_H t}\,|B_H\rangle$

=> *Loss in fiber, detector inefficiency*

- Due to the B_H, B_L mass difference (Δm_d), a B^0 can oscillate into $\bar{B}^0$ and vice versa (flavor mixing).

A B^0 at t=0 evolves as:

$|\Psi(t)\rangle = (1/\sqrt{2})\,(e^{-i\alpha_H t}\,|B_H\rangle + e^{-i\alpha_L t}\,|B_L\rangle\,)$

Probability of finding $\bar{B}^0$ at time t:

$P(\bar{B}^0(t) / B^0(t=0)) = 1/2\; e^{-\gamma t}\,(1 - \cos(\Delta m_d t))$ none-zero prob. for t>0!

=> *Spin rotation in the magnetic field, birefringence…*

BUT this magnetic field has a fix strength and cannot be turn off!

$\Upsilon(4S)\to B^0B^0$

$\Upsilon(4S)\to B^0\bar{B}^0$: $|\Psi\rangle = (1/\sqrt{2})\,(\,|B^0\rangle_a\,|\bar{B}^0\rangle_b - |\bar{B}^0\rangle_a\,|B^0\rangle_b\,)$ is formally the same as the spin ½ system BUT…

Differences compared to spin ½ system:

- Instead of spin or polarization, the correlation is in the flavor (particle-antiparticle quantum number), experiments are done by looking at the flavor specific interaction or decays.
- Instead of rotating the polarizer, we look for flavor at different time Δt (similar to the spin rotation under magnetic field or birefringence in fibers), this is due to flavor mixing ($B^0 \leftrightarrow \bar{B}^0$).
- Since B^0 are unstable particles, one need to deal with the loss of correlation due to decays (similar to PDL in fibers). More later.

Gisin and I wrote a paper making detail comparisons between kaon and photon in fiber: Am. J. Phys. 69 (3), Mar. 2001, 264-270

EPR test with photons and kaons: Analogies

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(Received 15 May 2000; accepted 30 August 2000)

Testing Bell with B mesons?

Can Bell's Inequality be tested with B mesons?

Quick answer: **NO**, because B^0s are unstable. Decay means rapid decrease of the wavefunction and of the correlation function:

$$E(a,b) = P_{+-}(a,b)+P_{-+}(a,b)-P_{++}(a,b)-P_{--}(a,b)$$ where

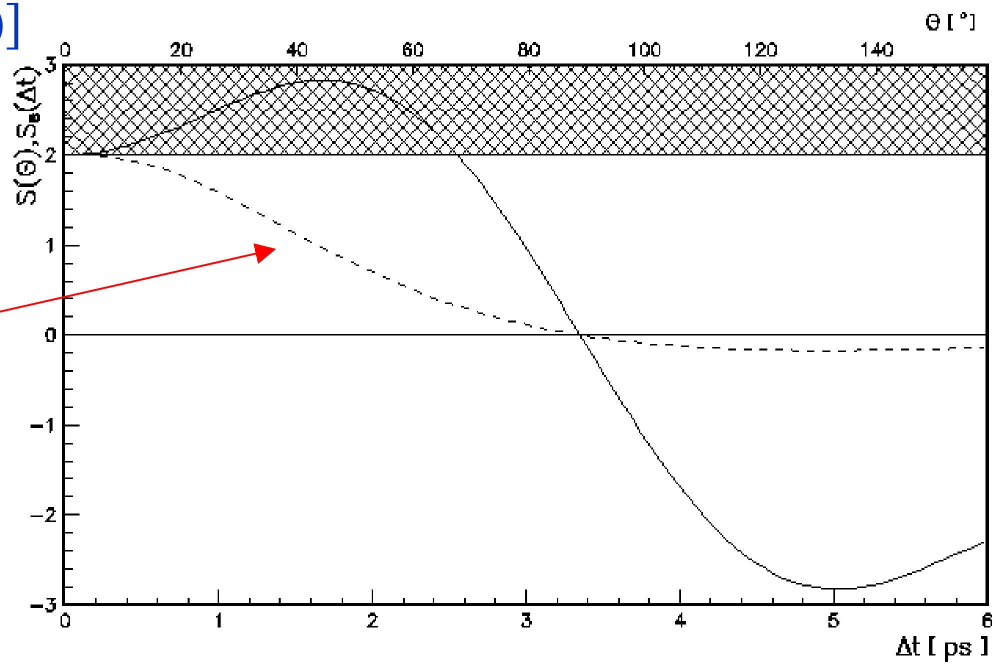
$$P_{++}(t_a,t_b) = P_{--}(t_a,t_b) = e^{-2\gamma t'}e^{-\gamma\Delta t}[1-e^{-\gamma\Delta t}\cos(\Delta m_d\Delta t)]/4$$

$$P_{+-}(t_a,t_b) = P_{-+}(t_a,t_b) = e^{-2\gamma t'}e^{-\gamma\Delta t}[1+e^{-\gamma\Delta t}\cos(\Delta m_d\Delta t)]/4$$

P_{+-}: + denotes B^0 and - denotes B^0

$\Delta t = |t_a - t_b|$ and $t' = \min(t_a,t_b)$

□$E(t_a,t_b) = e^{-2\gamma t'}e^{-\gamma\Delta t}\cos(\Delta m_d\Delta t)]$



=> S is never >2

□Bell Inequality not violated.

Testing Bell with B mesons?

But… **YES**, just like in the photon experiments, where one normalizes to the detected photons due to detection efficiencies, here we normalize the intrinsic losses due to decay:

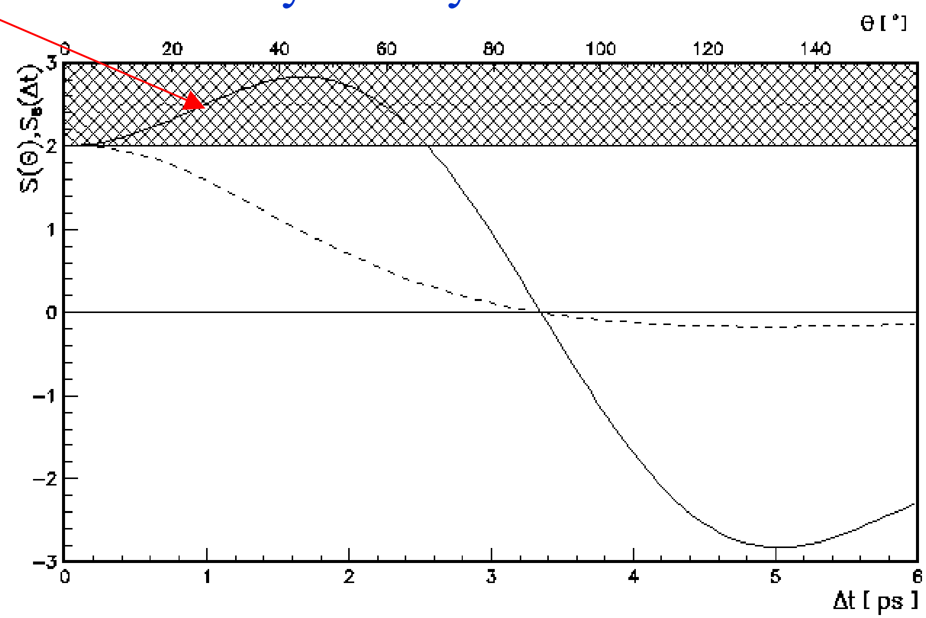
$$E(t_a,t_b) = \frac{N_{+-}(t_a,t_b)+N_{-+}(t_a,t_b)-N_{++}(t_a,t_b)-N_{--}(t_a,t_b)}{N_{++}(t_a,t_b)+N_{--}(t_a,t_b)+N_{+-}(t_a,t_b)+N_{-+}(t_a,t_b)} = A(\Delta t)$$

In such case, $E(t_a,t_b)$ is same as in the photons:

$E(t_a,t_b) = \cos(\Delta m_d \Delta t) = A(\Delta t)$ → flavor assymmetry

=> Bell Inequality is violated

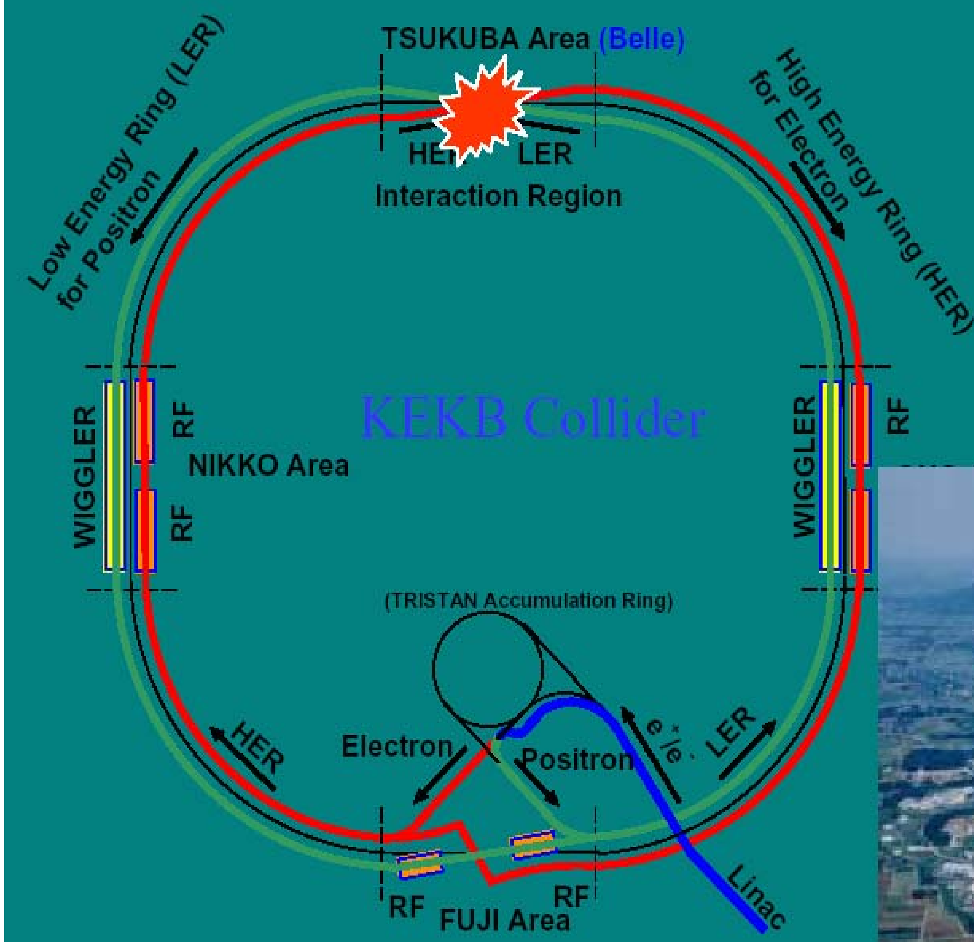
for $\Delta t<2.6$ps



I proposed this test in Am. J. Phys. 69 (3), Mar. 2001, 264-270

Experimental Tests: BELLE

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



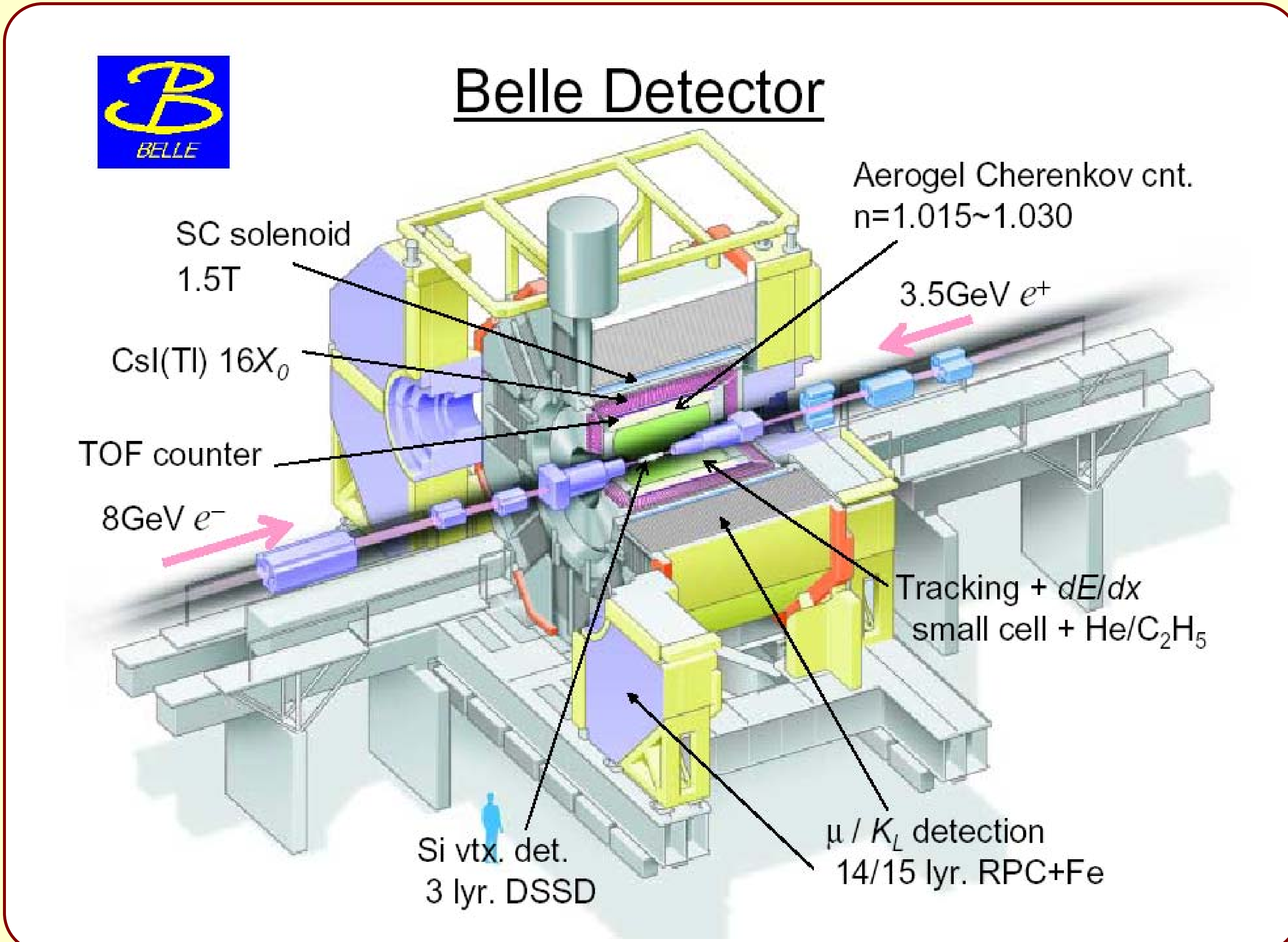
8 GeV e^- + 3.5 GeV e^+

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

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:

$\sigma_p/p \approx 0.35\%$

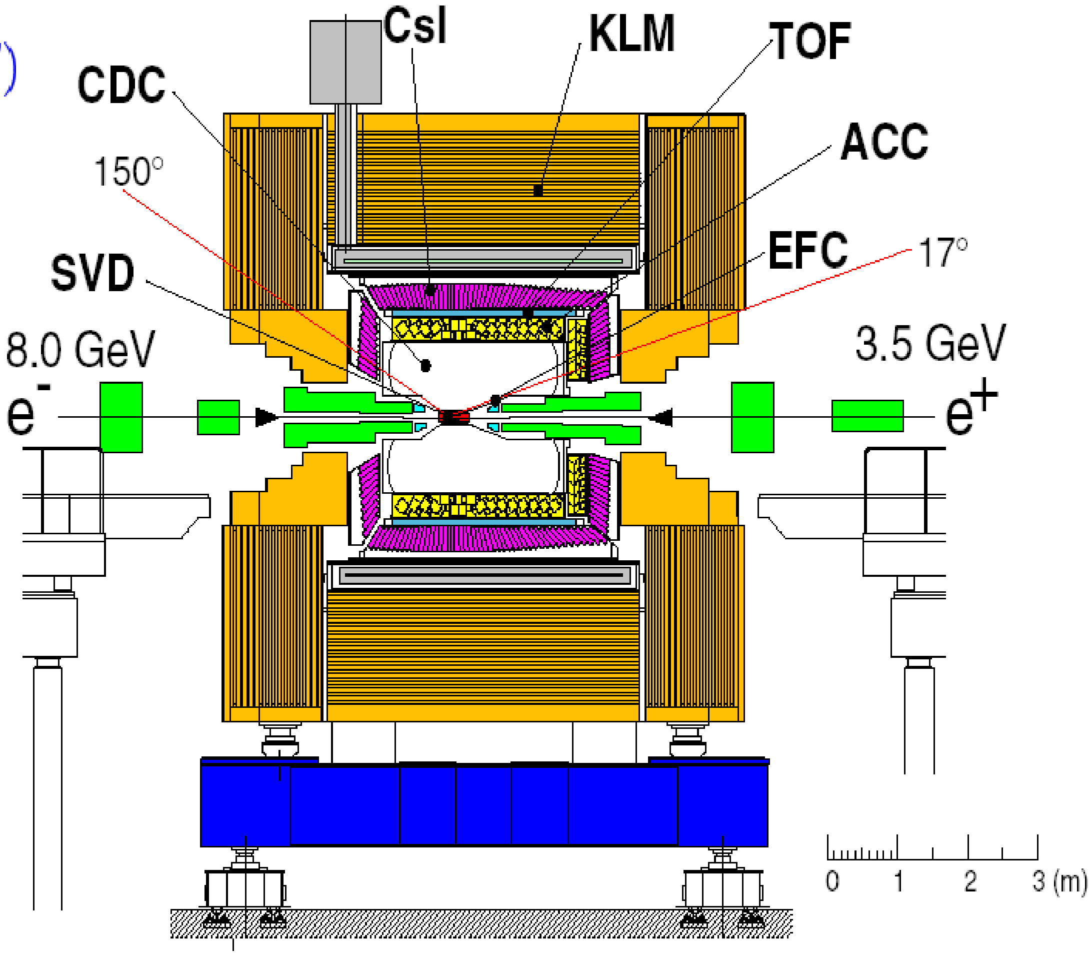
at 1 GeV/c

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).

Testing Bell @ 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:
   $l^+ \Leftrightarrow B^0 \qquad l^- \Leftrightarrow \bar{B}^0$

- First B^0: Fully reconstructed semileptonic decay

  $B^0 \to D^{*-} l^+ \nu, \quad (l^+ = e^+, \mu^+)$ Branching Ratio=4.6%

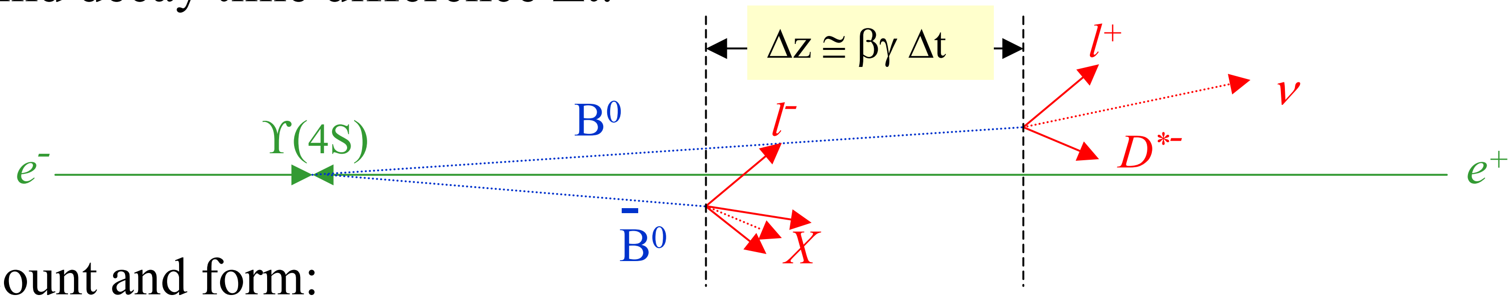
  $\quad \hookrightarrow D^0 \pi^-$

  $\quad\quad \hookrightarrow K^+\pi^-, K^+\pi^-\pi^0, K^+\pi^-\pi^+\pi^-$

- Second B^0: only identify lepton to tag the flavor

  $\bar{B}^0 \to l^- X$ where X is any (one or more) particles. Branching ratio=10.5%

2. Find decay time difference Δt:



3. Count and form:

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

$S(\Delta t)=3E(\Delta t)-E(3\Delta t) \le 2$ compare to $E(\Delta t) = \cos(\Delta m_d \Delta t)$

Event selection

Event Selection:

- Charge tracks: at least one 2D SVD hits. Impact parameter |dr|<0.2cm.
- $D^0 \rightarrow K^+\pi^-\pi^0$ mode: tracks has p>0.2GeV in lab frame.

- Kaon candidate: K/π likelihood ($P_{K/\pi}$) >0.5
- Pion candidate: $P_{K/\pi}$<0.5 (except slow π_s)

- $p_{\pi 0}$ >0.2GeV, mass within 11MeV/c² of $M_{\pi 0}$
- D^0 selection:
  - $|M_{K^+\pi^-, K^+\pi^-\pi^+\pi^-} - M_{D^0}| < 13$ MeV/c².
  - -37 MeV/c² $< (M_{K^+\pi^-\pi^0} - M_{D^0}) <$ 23 MeV/c², π^0 with Dalitz weight > 10.

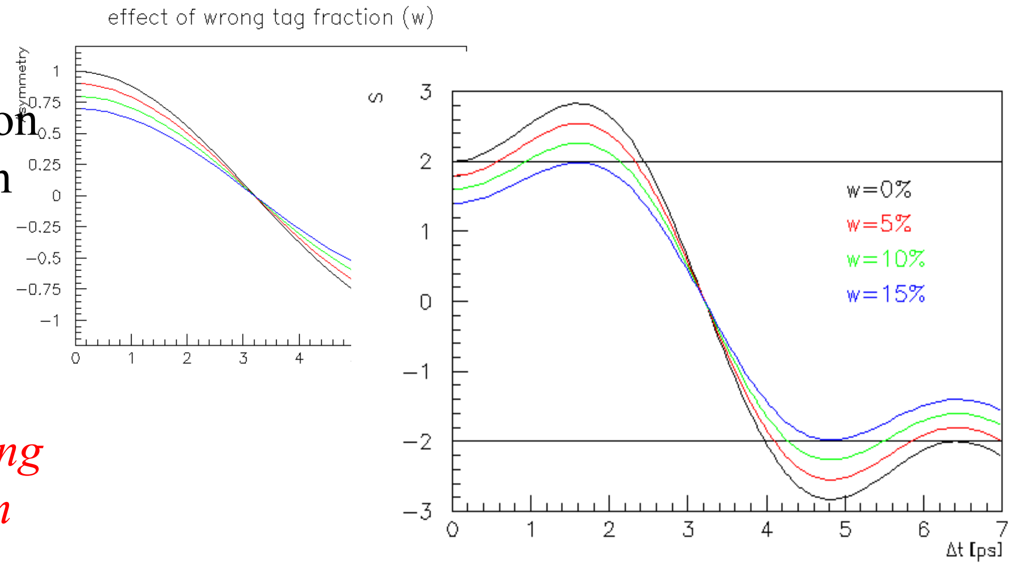
Event selection (2)

- D^* selection:
  - Combine D^0 candidate and slow π (refitted to the B^0 vertex)
  - D^* momentum < 2.6 GeV/c in lab frame (kinematical limit)
  - $0.1444\ \text{GeV}/c^2 < M_{D^*} - M_{D^0} < 0.1464\ \text{GeV}/c^2$
- $D^{*-} l^+ \nu$ selection:
  - **Lepton (e,μ) momentum: 1.4 GeV/c < P^*_l < 2.4 GeV/c**
  - **Angle between D* and lepton > 90° Cos(θ_{B,D^*l}) < 1.1**
  - **Reversing p_l: Cos($\theta_{B,D^*l'}$) > 1.1 (later used for background subtraction)**
  - **Vertex fit χ^2/df < 100**
- Once the B^0 is selected, all other tracks are used to identify the flavor of the accompanying B.

Flavor Tagging

A high purity flavor tagging is essential because wrong tag fraction (w) dilutes the correlation function (flavor asymmetry) and S:

$$A(\Delta t) = (1-2w)\cos(\Delta m \Delta t)$$



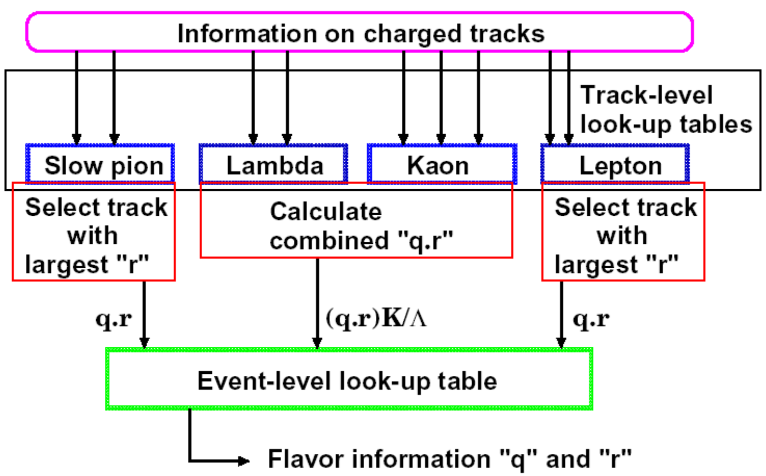
Use lepton tag only (highest tagging purity comes from high momentum leptons)

For each track, q (flavor) and r (tagging dilution factor) is assigned using:

- $|dr|<2cm, |dz|<10cm$
- Electron: $P_1^{cms}>1.4$, $P(e)/P(K)>0.8$
- Muon: $P_1^{cms}>0.8GeV$, $P(\mu)/P(K)>0.95$
- Discriminants: track charge, P_1^{cms}, θ_{lab}, M_{recoil}, P_{miss}^{cms}, Lepton ID quality.

Track with highest r is assign as the event flavor.

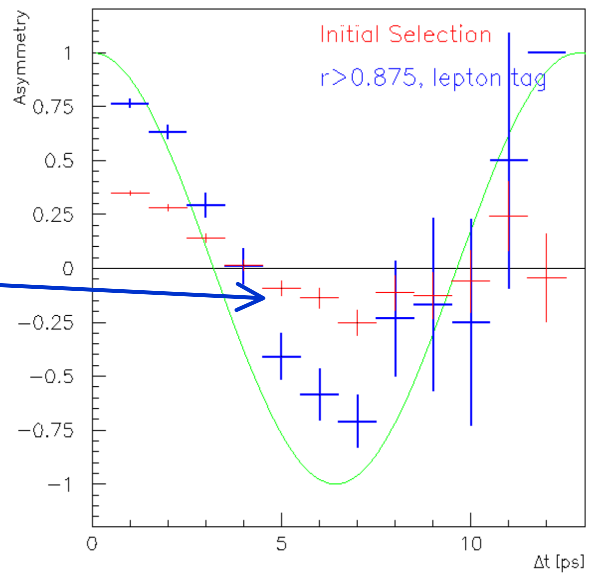
Multidimensional Likelihood Method



Reducing Mistag: r>0.875 and Lepton Tag

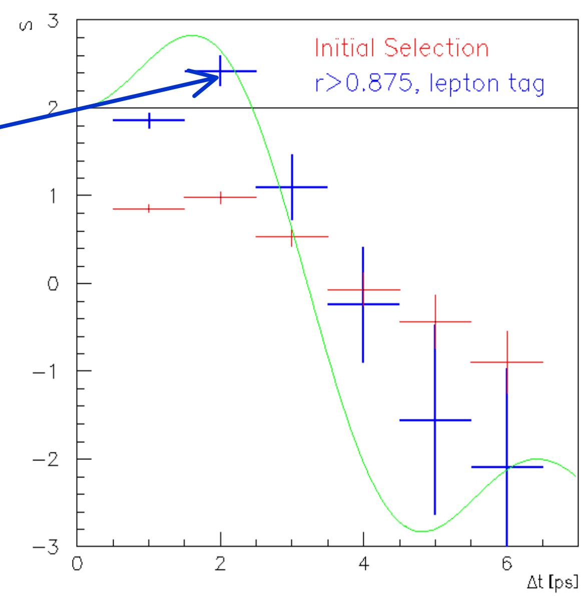
Select events with high flavor purity:

r > 0.875



This greatly reduces the dilution on A and S:

Measure S close to the maximum violation (for Δt=2 ± 0.5 ps interval):



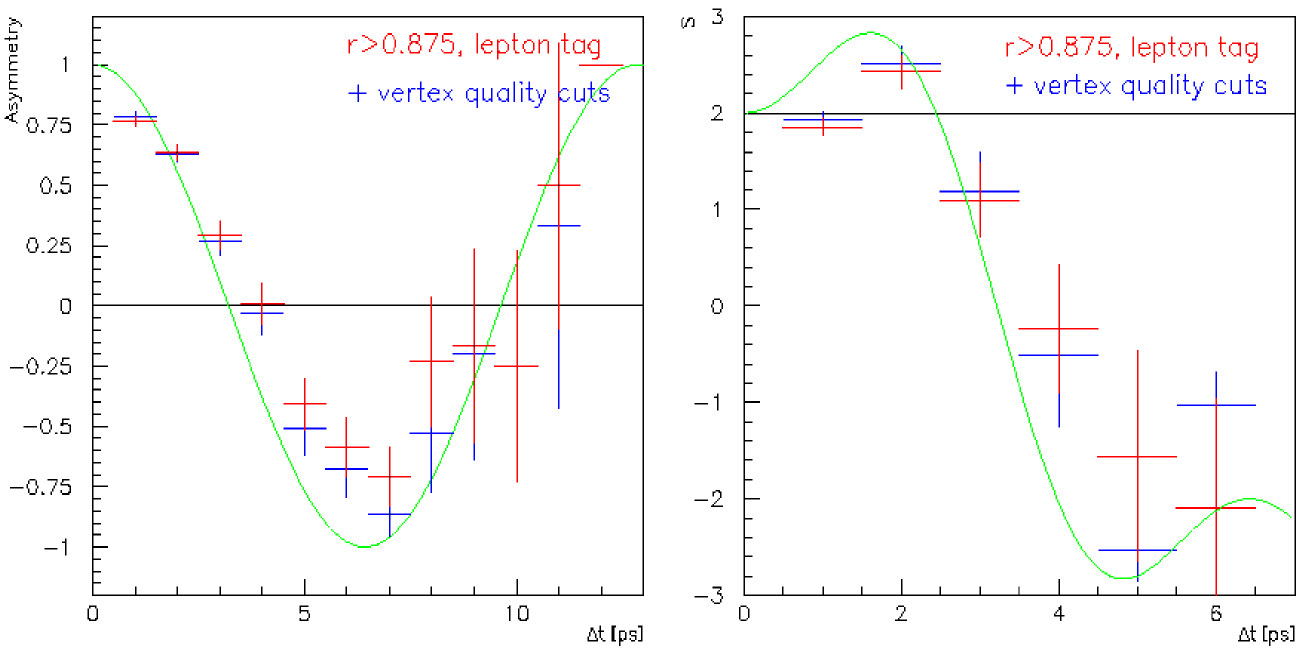
S(2ps) = 2.426 ± 0.168   (3782 events)

Already violate Bell Inequality!

B^0 decay vertex resolution

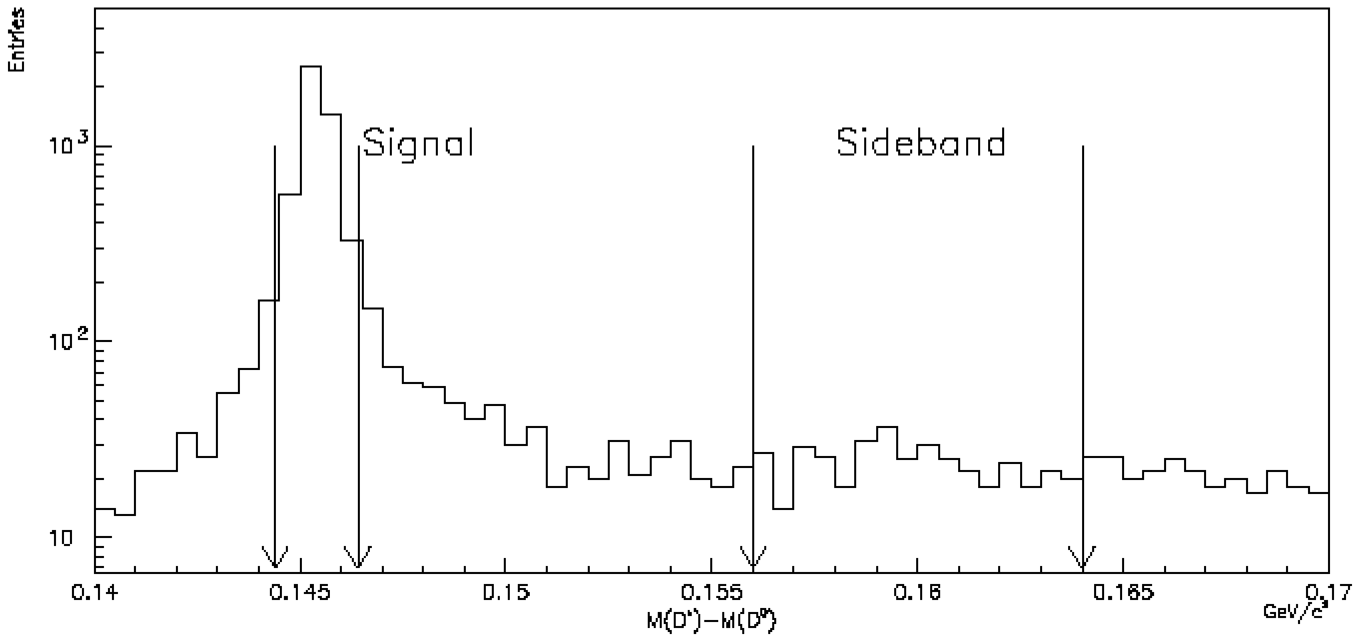
The dilution on Asymmetry and S can be further reduced by stringent cut on the z-vertex error (after the vertex re-fit) and the χ^2 of the vertex fit: *(to make Δt measurement more accurate)*

- *B^0 vertex: $\delta v_z < 100\mu m$, $\chi^2/df < 50$*
- *Tag vertex: $\delta v_z < 140\mu m$, $\chi^2/df < 50$*



Background subtractions

•Fake D* due to K,π combinatorial
Can be estimated from data using the sideband (0.156-0.164GeV/c^2) on the mass difference between D* and D^0

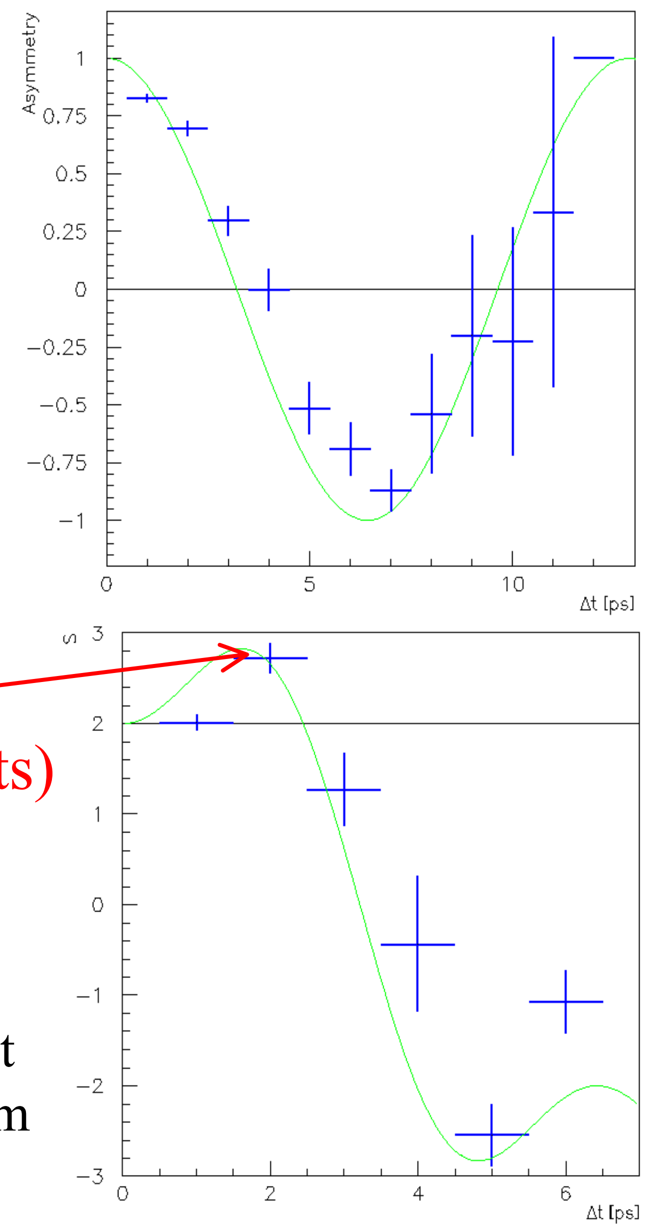


•Continuum background are estimated from off-resonance data (4.6 fb^{-1}). No event pass the cuts → negligible

Background subtractions

•Uncorrelated, random combinations of lepton & D*, mainly due to lepton & D* coming from different B^0.

•To estimate and subtract it, reverse lepton momentum (l') and select events which passes $\text{Cos}(\theta_{B,D^*l'})<1.1$ cut.



S(2ps) = 2.725 ± 0.167 (3186 events)

No MC used!! (MC has built-in QM entanglement.) Bell Inequality is to rule out models with locality, not so much to confirm QM.

Systematic Error

Systematic error estimation:

•Fake D* sideband correction is statistical dependent: 386 events => use twice the statistical error: 10%, we estimate $\Delta S<0.005$

•Uncorrelated D* and lepton correction is from 183 events: 7.5% error. We estimate $\Delta S<0.030$

•Other cuts are changed by ~20% and see the effect on S.

Source	error
Fake D*	0.005
Uncor. D*l	0.030
Lepton momentum	0.060
Mistag cut	0.030
Particle ID	0.028
Vertices Quality	0.023
Remaining cuts	0.042
Total	0.092

Final Result:

$$S(2ps) = 2.725 \pm 0.167_{stat} \pm 0.092_{syst}$$

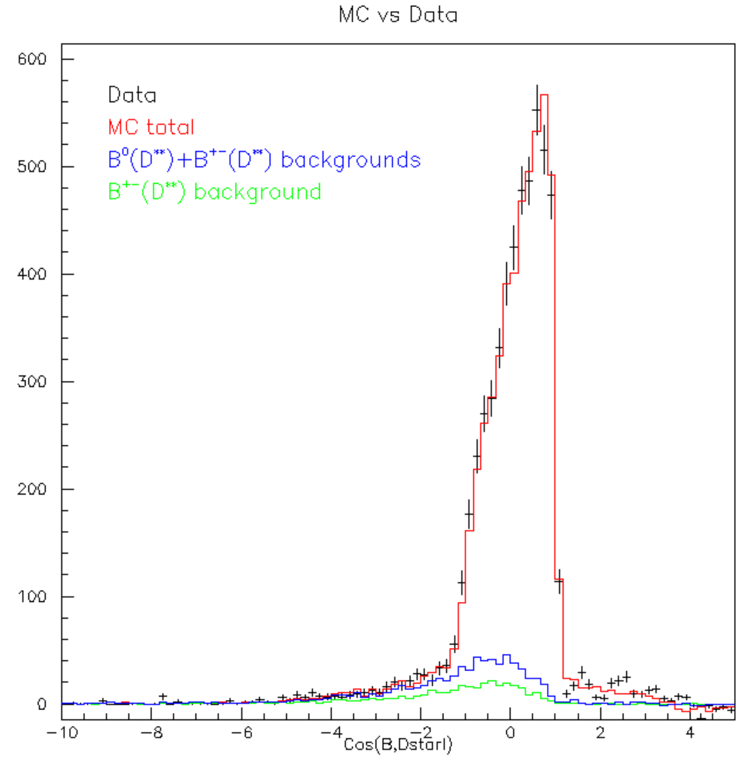
A clear violation of Bell Inequality by over 3σ

Preprint: quant-ph/0310192

Comparison with QM Prediction

To compare this result with QM prediction, we use Monte Carlo simulation events generated according to QM with all the detector resolution and efficiencies folded in. Three types of events were generated:

- $B^0 \to D^{*-} l^+ \nu$ (Signal)
  $\quad \lfloor\!\to D^0\pi^-$
- $B^0 \to D^{**-} l^+ \nu$ (Has mixing, taken as signal)
  $\quad \lfloor\!\to D^{*-}\pi^0$
  $\quad\quad \lfloor\!\to D^0\pi^-$
- $B^+ \to D^{**0} l^+ \nu$ (No mixing, background)
  $\quad \lfloor\!\to D^{*-}\pi^+$
  $\quad\quad \lfloor\!\to D^0\pi^-$

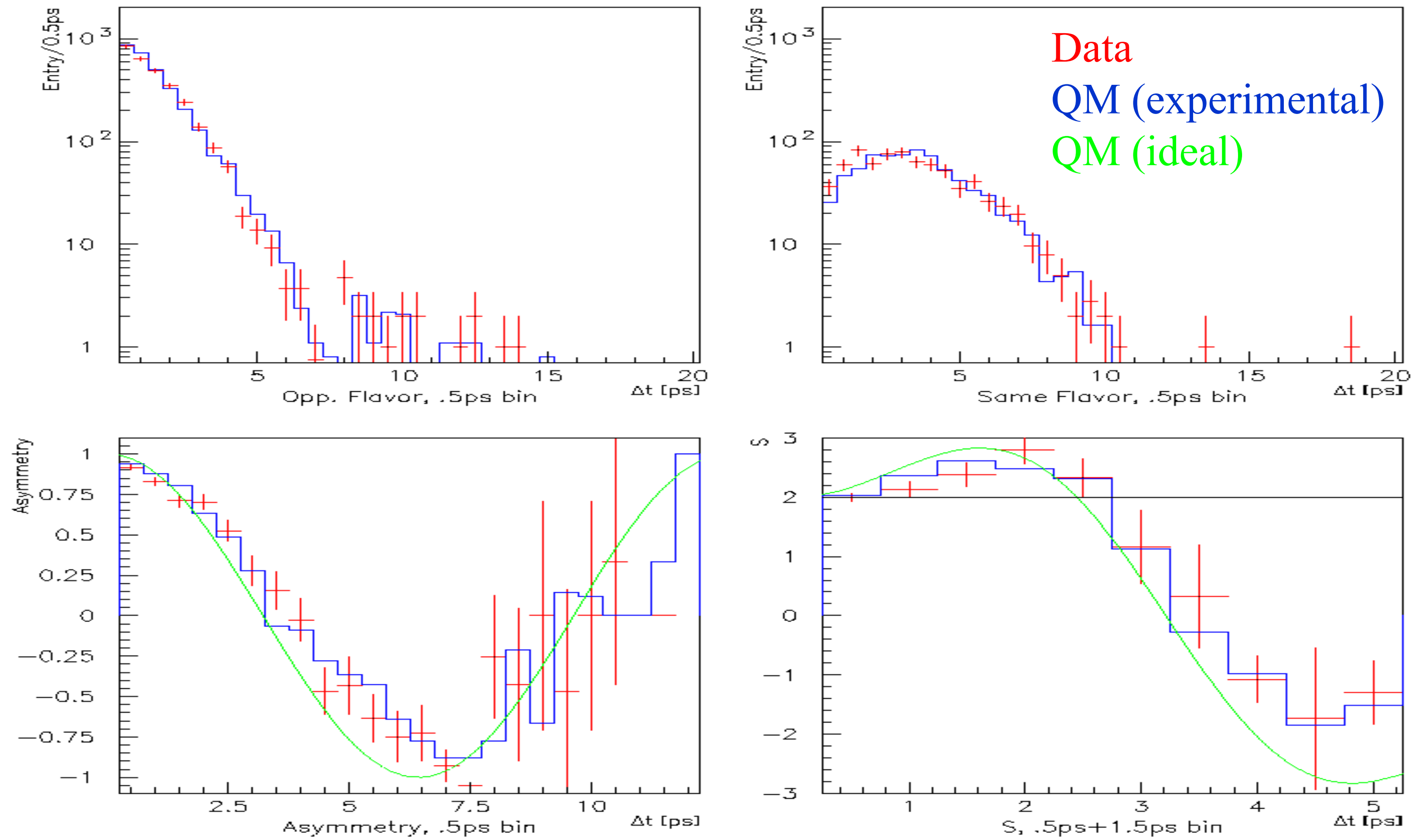


To determine the amount of background, we fit the above MC with the data:

$B^0 \to D^{**-} l^+ \nu$ has mixing and the Δt distribution is similar to $B^0 \to D^{*-} l^+ \nu$, so we consider it as signal (4.5%).

$B^+ \to D^{**0} l^+ \nu$ has no mixing, it is a background (3.8%)

Data vs QM Prediction



QM (exp.): Simulation with detector resolution, efficiencies and backgrounds.

QM (theory): Ideal, theoretical prediction by QM; $E(\Delta t)=\cos(\Delta m_d \Delta t)$

Data are consistent with QM prediction!

Conclusion

- Entanglement in particle/antiparticle Hilbert space exists for $\Upsilon(4S) \rightarrow B^0 B^0$.
- With correction to the intrinsic loss (decays) , one can form the Bell-CHSH Inequality.
- Experiment was carried out by looking at semileptonic decays for the B^0s at BELLE experiment in KEK, Japan
- A violation of Bell Inequality of $>3\sigma$ is observed:

$$S(\Delta t = 2ps) = 2.725 \pm 0.167_{stat} \pm 0.092_{syst}$$

First ever Bell Inequality measurement with particle/antiparticle quantum number.

- The result is consistent with QM prediction (with detector resolution, efficiency, and background folded in).

Outlook:

- Study decoherence using inclusive dilepton data:

both $B^0 \rightarrow l^+ X$ where X is any (one or more) particles.

Testing Decoherence

Strong believe in the community that the transition from QM to Classical world is not the size (microscopic vs. macroscopic) but the decoherence (loss of quantum correlation)

In the correlated pair of B^0s, decoherence can happen during the time evolution of the pair, before they decay…

Decoherence can be introduced into the SF and OF intensities as a parameter $0 \leq \zeta \leq 1$:

$$\mathbf{I}_{\mathbf{SF}} \propto e^{-\gamma\Delta t}\,[1-(1-\zeta(t))\cos(\Delta m\,\Delta t)]$$

$$\mathbf{I}_{\mathbf{OF}} \propto e^{-\gamma\Delta t}\,[1+(1-\zeta(t))\cos(\Delta m\,\Delta t)]$$

$\zeta=0$: no decoherence (i.e. QM)

$\zeta=1$: total decoherence (i.e. Separability)

$$\mathbf{A(\zeta,\Delta t=0)=(1-\zeta(t))}$$

By measuring at different t (absolute decay time), A is constant if no decoherence, decreasing if there is decoherence.