B中間子による量子もつれの検証

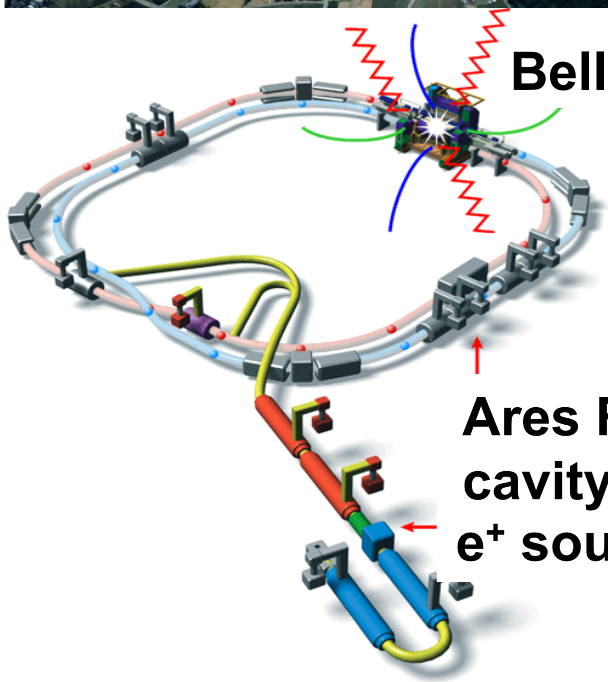
(submitted to PRL
quant-ph/0702267)

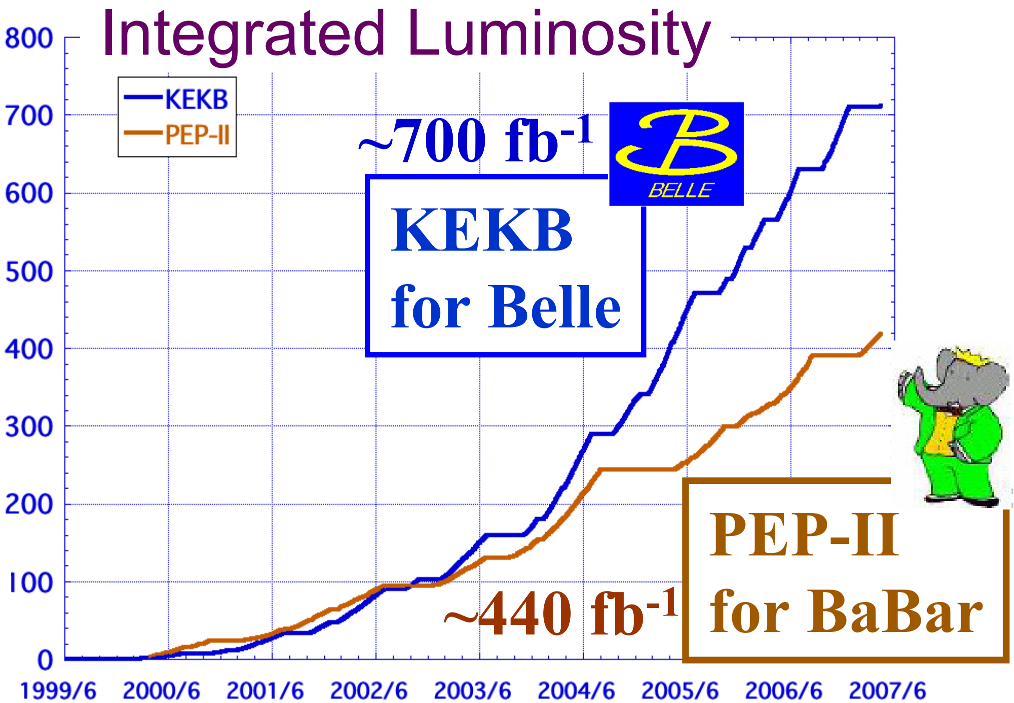
物理的背景と解析・結果

One of "Exotic" topics of Belle Results

Y.Sakai KEK 金茶会 6-July-2007

KEKB





8 GeV e^- x 3.5 GeV e^+

$L_{peak} = 1.71\times10^{34}$

Integ. Lum. ~700 fb^{-1}

Belle Detector

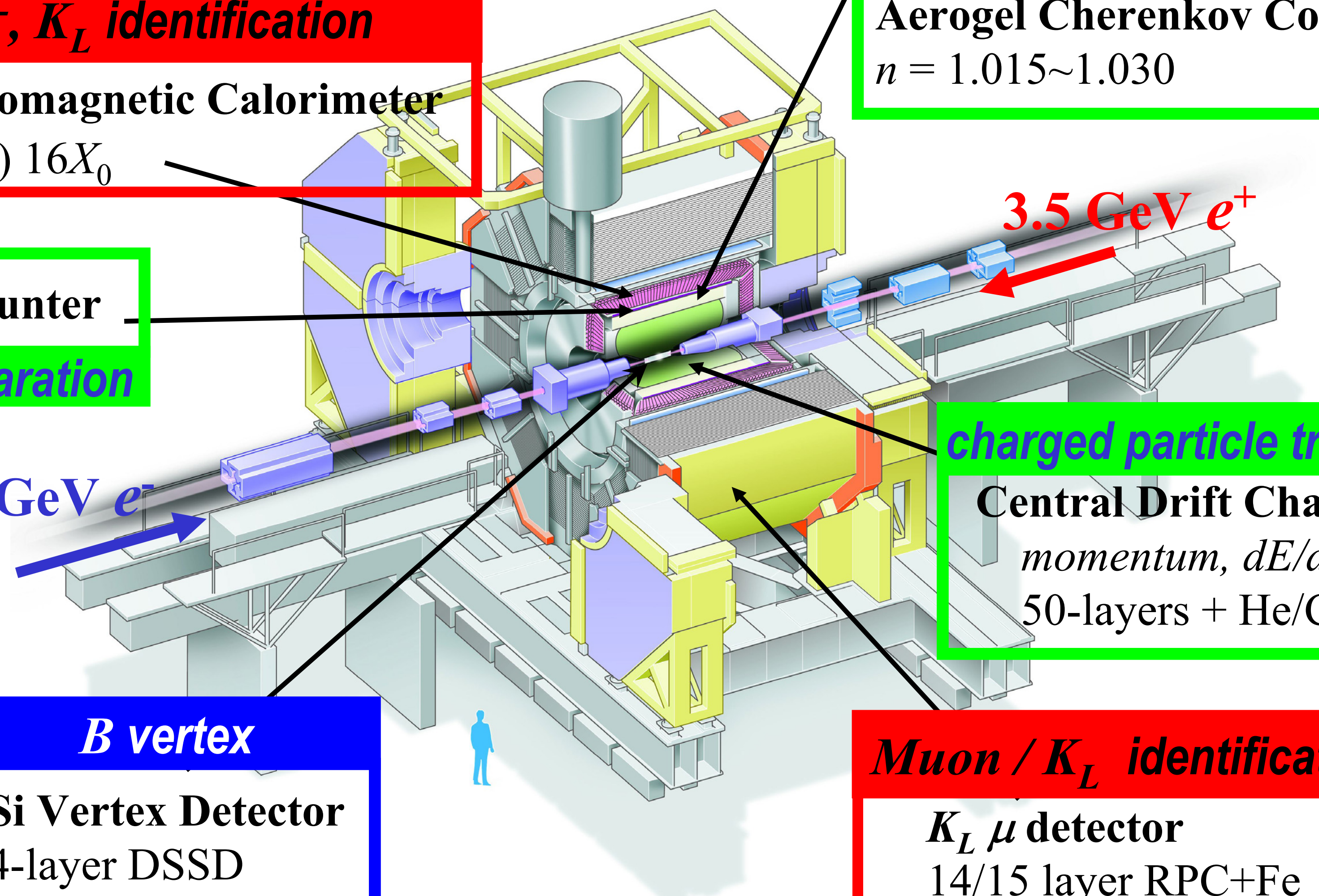
γ, π^0 reconstruction
e^{+-}, K_L identification

Electromagnetic Calorimeter
CsI(Tl) $16X_0$

TOF counter
K/π separation

K/π separation

Aerogel Cherenkov Counter
$n = 1.015\sim1.030$



charged particle tracking

Central Drift Chamber
momentum, dE/dx
50-layers + He/C_2H_6

B vertex

Si Vertex Detector
4-layer DSSD

Muon / K_L identification

K_L μ detector
14/15 layer RPC+Fe

13 countries, 55 institutes, ~400 collaborators

EPR Entanglement

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

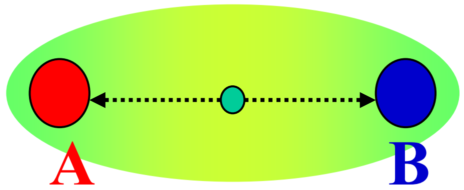
A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

EPR Paradox:

Quantum Mechanics:

Entangled state → non-separable wave function even for far apart particles



can not be a "complete" theory

Local realistic theory with "hidden" parameters

"an element corresponding to each element of reality"

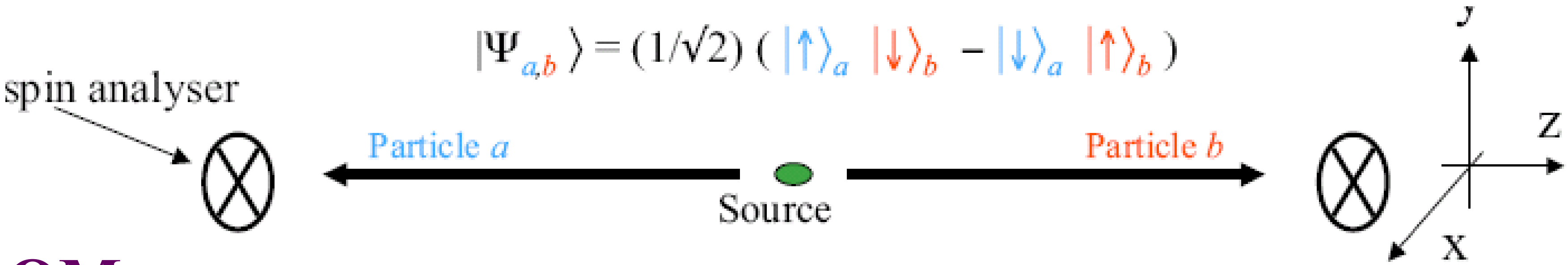
Bohm: Entangled states

[Gedanken experiment]

[D.Bohm., Quantum Theory, p614(1951)]

two spin ½ particles from singlet state

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



QM

Measurement: S_x=+1/2 for a → predict S_x = –1/2 for b

Decision of orientation of polarizer at very last moment
→ still above happen → No causal connection

Instantaneous communication ? (→ Quantum communication)

Hidden parameters (Local Realistic Theory) ?

Bell Inequality

Key for experimental check !

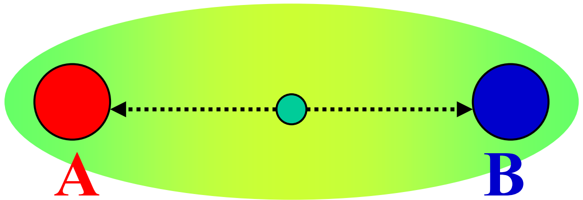
J.S.Bell, Physics 1, 195(1964);
Clauser,Horene, Shimony, Holt, PRL 23, 880(1969)

Any Local realistic theory with "hidden" parameters

$$S = |E(a,b) - E(a',b)| + |E(a,b') + E(a',b')| \leq 2$$

(Bell-CHSH Inequality)

E(a,b): correlation function between measurements a and b



Violation → Reject LRT, Confirm QM

Many experiments performed: loopholes

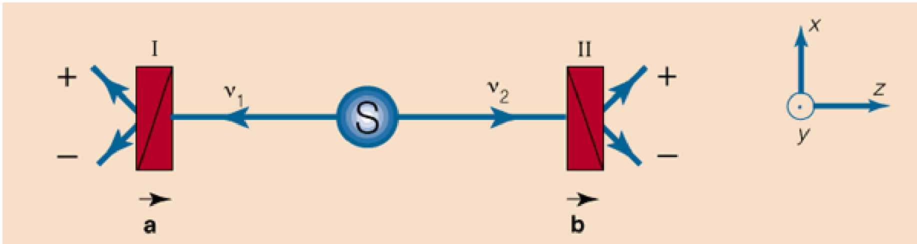
- **Locality: need space-like measurements of A and B**
- **Detection efficiency: sub-sample ↔ all**

⇨ Bell Inequality Violation = QM: ~established

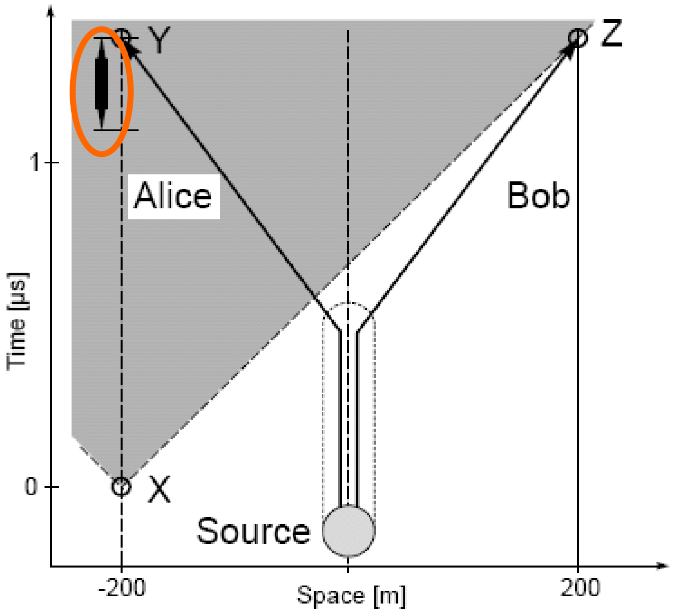
Bell Inequality: exp. (1)

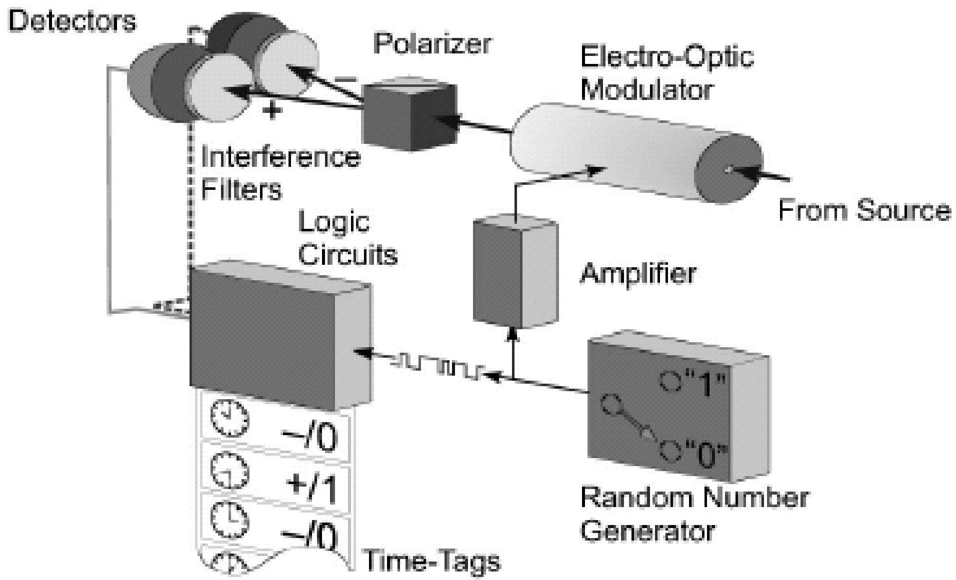
- **Entangled photons** [e.g. G.Weihs et al., PRL 81, 5039(1998)]

(Locality loophole)

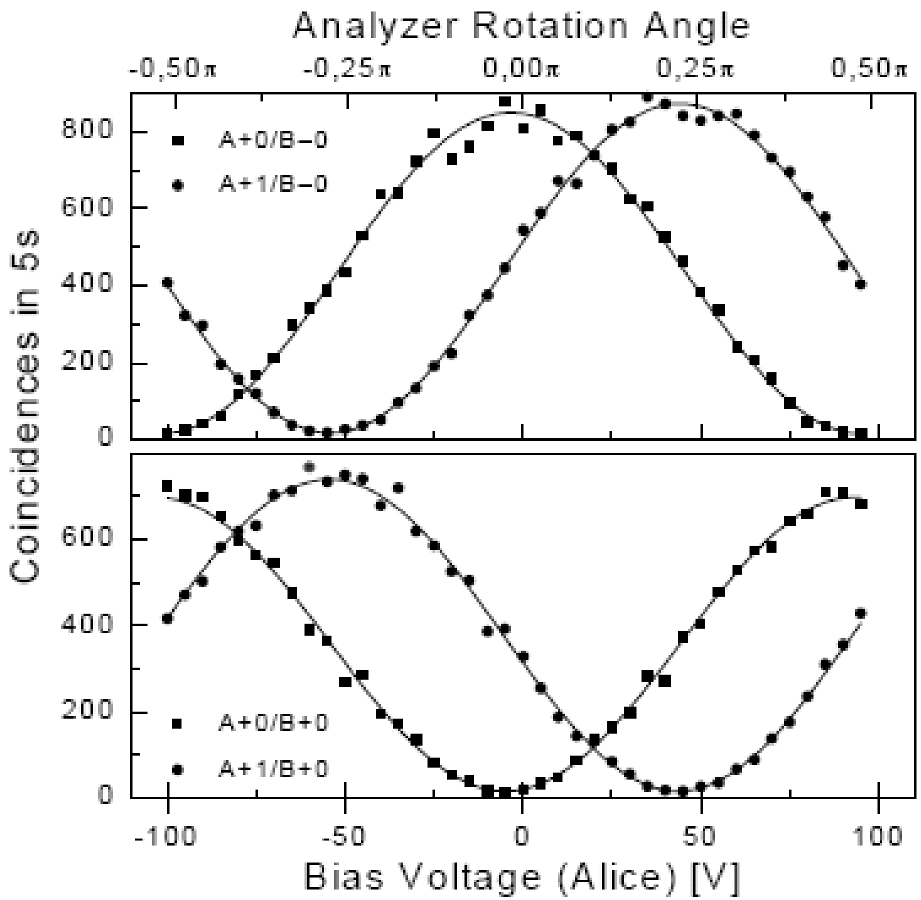


A,B: 400m away, measurements <<1.3μs





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



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

C_{xx}: # of coincidence

$S_{QM:max}$

A: α,α'= 0, 45 deg

B: β,β'= 22.5, 67.5 deg

S = 2.73 ± 0.02

14700 coincidence

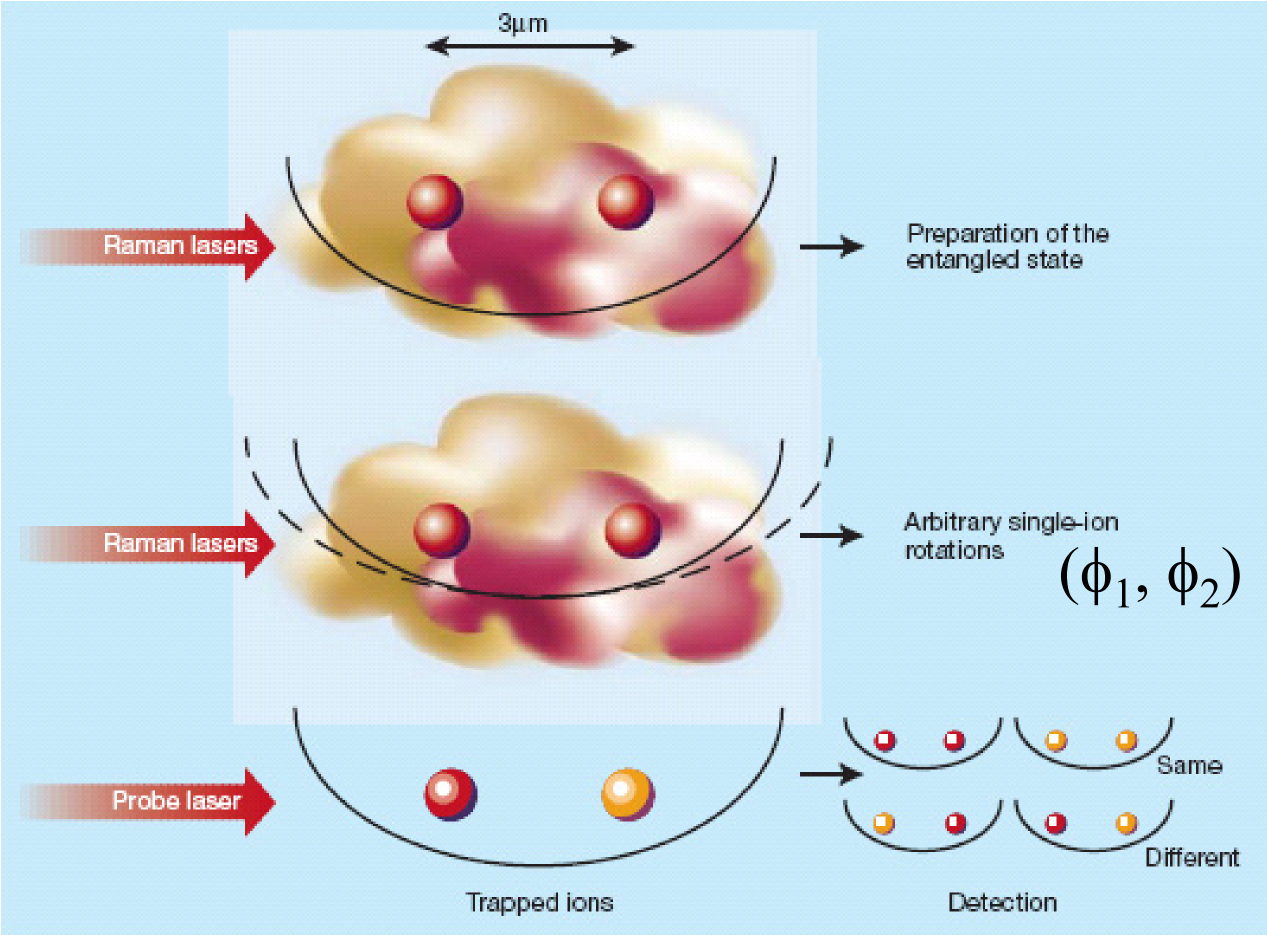
Bell Ineq. is violated !

Efficiency ~5%

Bell Inequality: exp. (2)

- **Entangled $^9Be^+$ ions** [e.g. M.A.Rowe et al., Nature 409, 791(2001)]

(Detection efficiency loophole) → ~98%

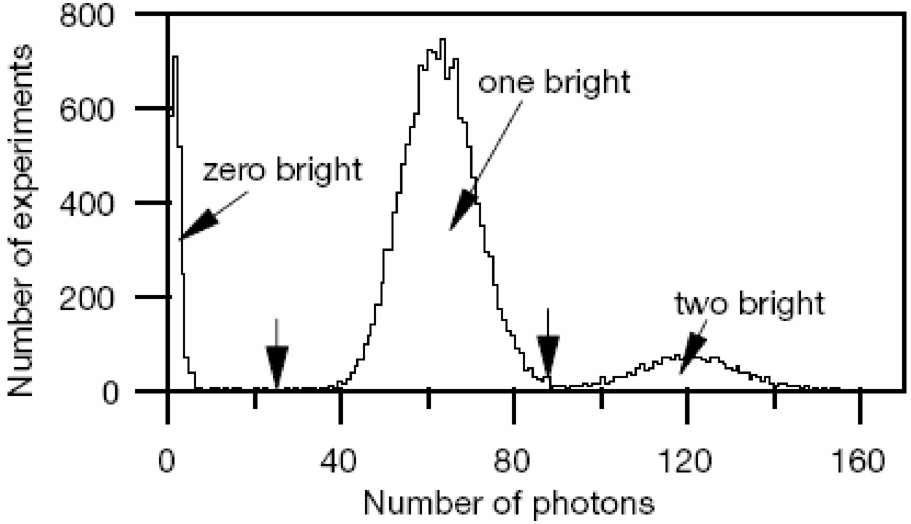


(ϕ_1, ϕ_2)

$$|\psi_2\rangle = \frac{1}{\sqrt{2}}(|\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle)$$

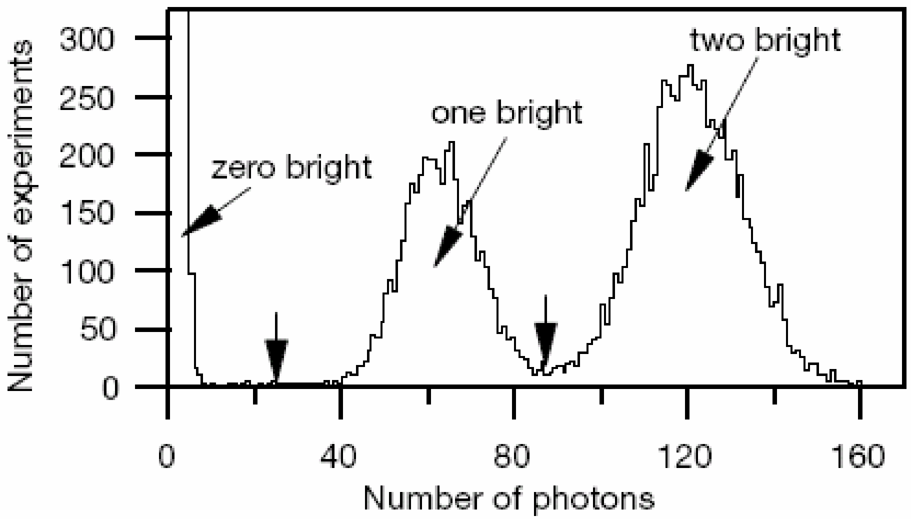
$$|\uparrow_j\rangle \rightarrow \frac{1}{\sqrt{2}}(|\uparrow_j\rangle - ie^{-i\phi_j}|\downarrow_j\rangle)$$

$$E(\phi_1,\phi_2) = \frac{N_{sam}-N_{dif}}{N_{sam}+N_{dif}}$$



Detect photons by PMT

$\phi_1 = 3\pi/8$, $\phi_2 = 3\pi/8$
E = –0.55



$\phi_1 = 3\pi/8$, $\phi_2 = -\pi/8$
E = 0.56

$$S\left(-\frac{\pi}{8},\frac{3\pi}{8},-\frac{\pi}{8},\frac{3\pi}{8}\right)$$

$$= 2.25 \pm 0.03$$

Bell Ineq. is violated !

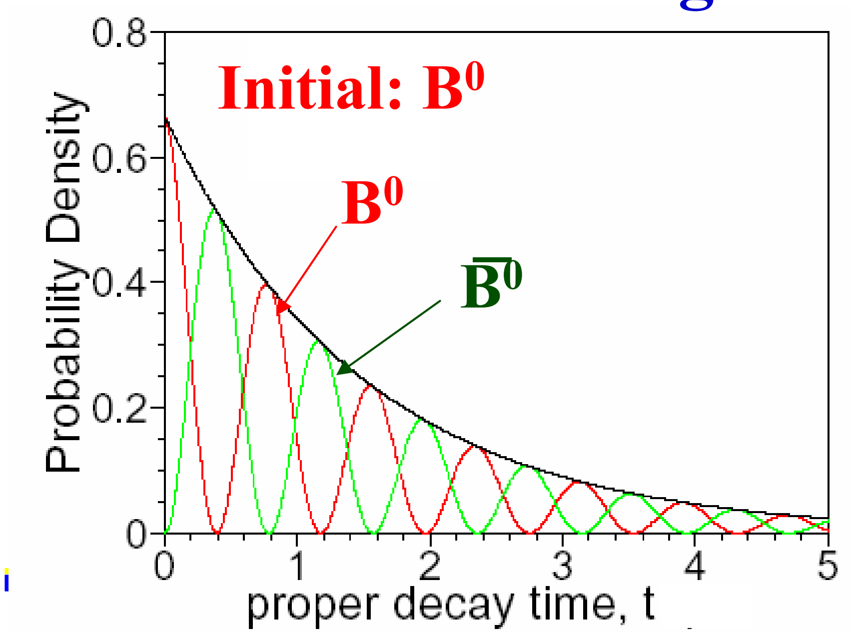
Why Υ(4S) → $B^0\bar{B}^0$ System

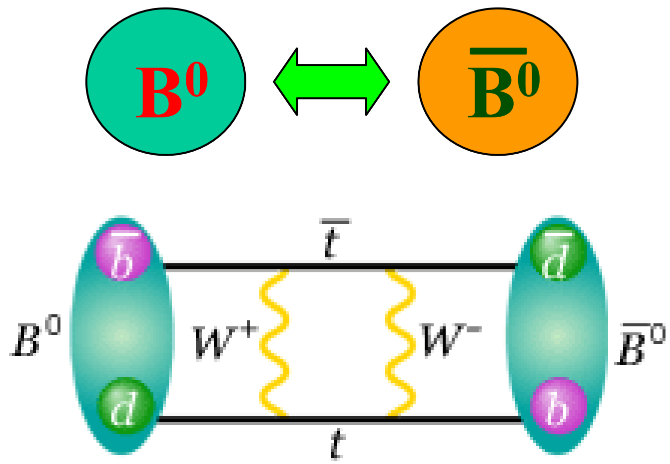
- **One of few entangled systems in HEP**
- **Highest energy scale (~10 GeV)**

  breakdown of QM at high energy ?

QM: $|\Psi_{\Upsilon(4s)}\rangle = (1/\sqrt{2})\,(\,|B^0\rangle_a\,|\bar{B}^0\rangle_b - |\bar{B}^0\rangle_a\,|B^0\rangle_b\,)$ [C= −1]

+ $B^0\bar{B}^0$ mixing





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

QM: $|\Psi_{\Upsilon(4s)}\rangle = (1/\sqrt{2})\,(\,|B^0\rangle_a\,|\bar{B}^0\rangle_b - |\bar{B}^0\rangle_a\,|B^0\rangle_b\,)$

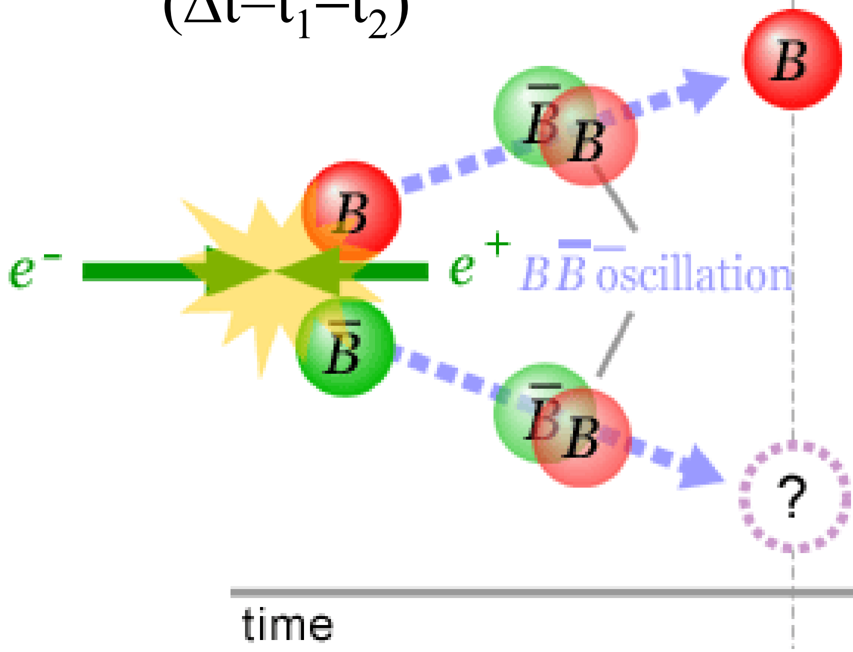
Joint Probability **at $t_1=t_2$, $B^0\bar{B}^0$ or $\bar{B}^0B^0$ only**

Same Flavor (B^0B^0, $\bar{B}^0\bar{B}^0$): $\propto e^{-\Gamma|\Delta t|}\,[1 + \cos(\Delta m \Delta t)]$

Opposite Flavor ($B^0\bar{B}^0$) **:** $\propto e^{-\Gamma|\Delta t|}\,[1 - \cos(\Delta m \Delta t)]$

$(\Delta t = t_1 - t_2)$

$$A_{QM}(\Delta t) = \frac{OF - SF}{OF + SF} = \cos(\Delta m \Delta t)$$



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

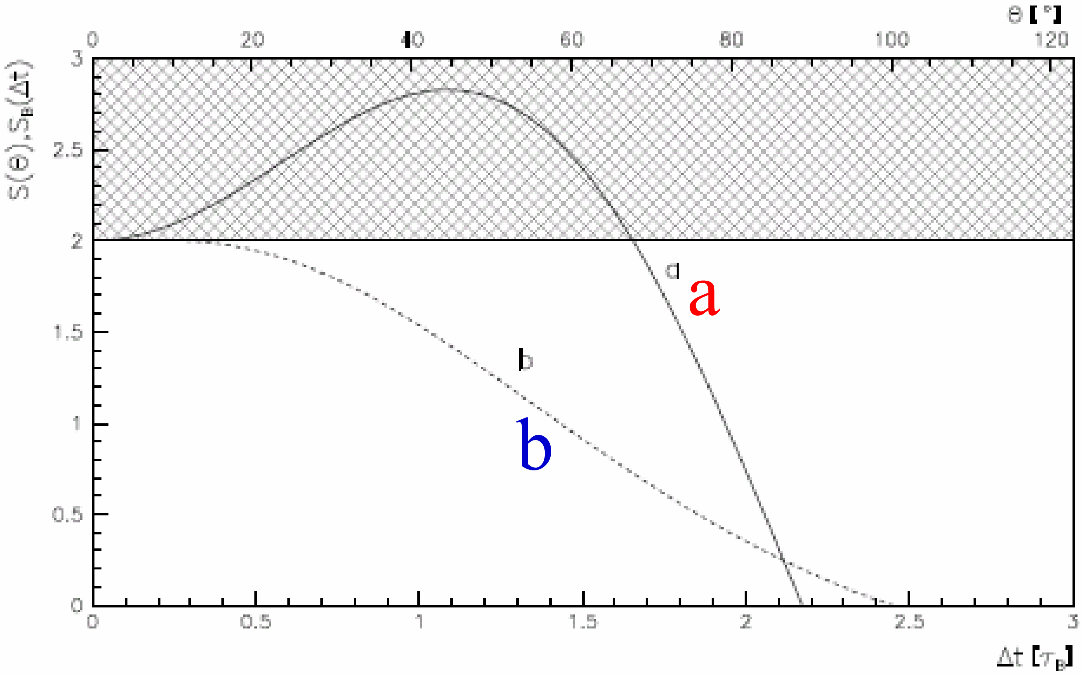
Bell Inequality Test ?

$$A_{QM}(\Delta t) = \cos(\Delta m \Delta t) \quad \Rightarrow \quad E(a,b) = \cos(\Delta m \Delta t) \ ?$$

curve a: same as "Entangled photons"

$$\text{or } E(a,b) = -\, e^{-2\Gamma t'}\, e^{-\Gamma \Delta t} \cos(\Delta m \Delta t) \ ?$$ [includes decay rate]

($t' = \mathrm{Min}(t_a - t_b)$) curve b



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

[A.Bertlmann et al., PL A332, 355(2004)]

Curve b should be taken

Bell Inequality Test : intrinsically impossible

- **QM to violate Bell Inequality ;**

  $x = \Delta m/\Gamma > 2.6 \quad \leftrightarrow x_d = 0.78$

- **Active measurement needed**

  ↔ Flavor measurement via decay reconstruction = passive

[some arguments may exist against above]

Any way to test QM at Υ(4S) ?

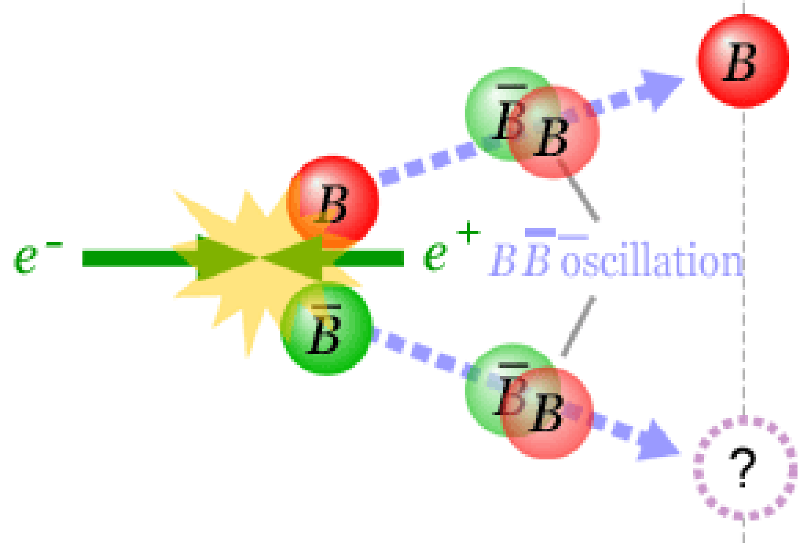
Belle's Approach

Precise measurement of Time-dependent Flavor Correlation

- **Quantitative proof of QM Entanglement**
- **Quantitative Comparison with Non-QM model**
- **Fully corrected (= true) A(Δt)**
  → Direct comparison with (any) theories

QM:

$$A_{QM}(\Delta t) = \frac{OF-SF}{OF+SF} = \cos(\Delta m \Delta t)$$



Non-QM models (example 1)

- **Local Realism: Pompili & Selleri (PS)**

[EPJ C14,469(2004)]

"elements of reality" (hidden variables)
= Flavor & mass (B_H, B_L, $\bar{B}_H$, $\bar{B}_L$)

Mass states: stable
random jump of Flavor within pair
Single B^0: oscillation ~ 1 ± cos(Δmt)

only determine upper/lower limits of $A(t_1,t_2)$

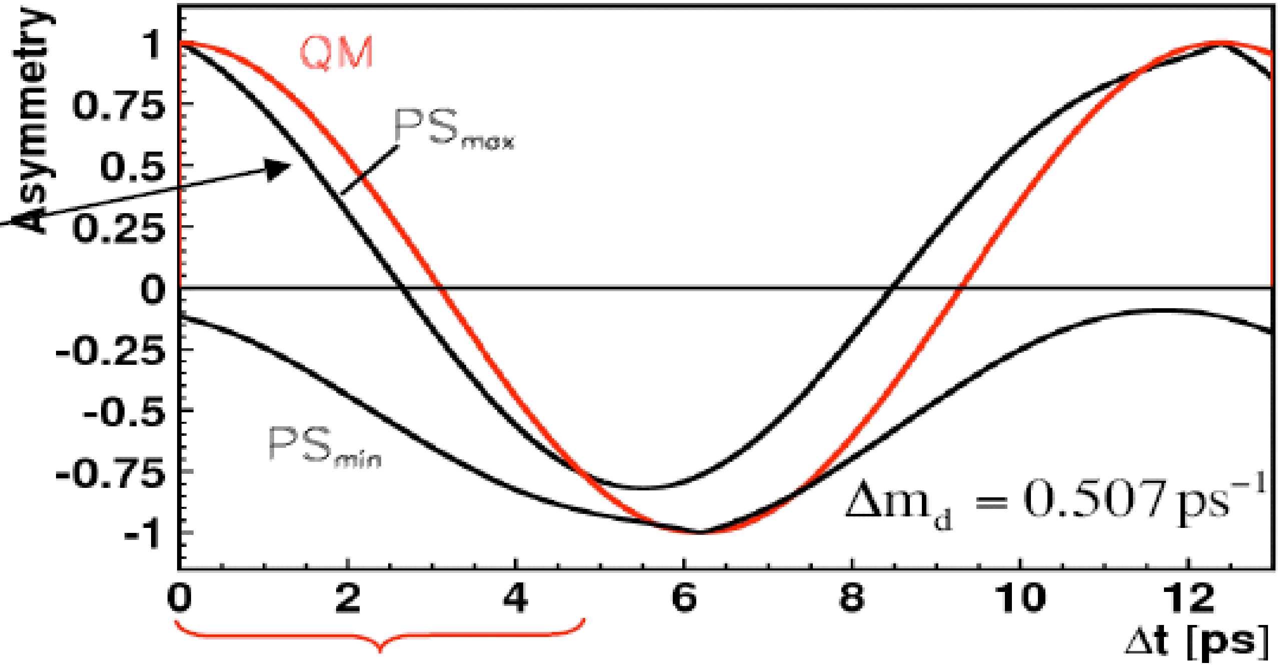
$$A_{PS}^{max}(t_1,t_2) = 1 - |\{1-\cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{min}) + \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{min})|, \text{ and} \quad (3)$$

$$A_{PS}^{min}(t_1,t_2) = 1 - \min(2+\Psi,\ 2-\Psi), \text{ where} \quad (4)$$

$$\Psi = \{1+\cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{min}) - \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{min}). \quad (5)$$

A(Δt): PS model

Integrated over t_{min}



$A_{QM} > A_{PS}$ in the Δt region below ~5 ps

Note) Local realistic model with same A(Δt) as QM is possible [quant-ph/0703206]

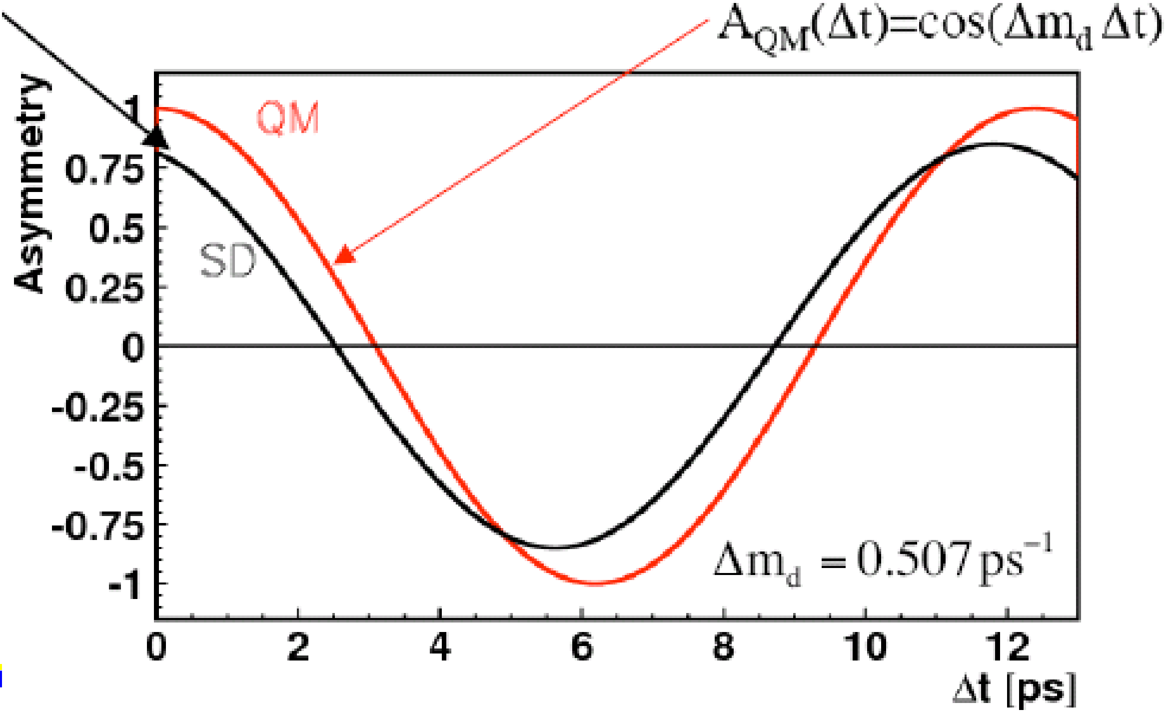
Non-QM models (example 2)

- **Spontaneous immediate Disentanglement (SD)**

  separates into B^0 & $\bar{B}^0$ evolve independently [e.g. PR 49,393(1936)]

$$A_{SD}(t_1, t_2) = \cos(\Delta m_d t_1)\cos(\Delta m_d t_2)$$
$$= \frac{1}{2}[\cos(\Delta m_d(t_1+t_2)) + \cos(\Delta m_d \Delta t)]$$

Integrated over t_1+t_2



Analysis Method

$B^0 \to D^{*-} l^+ \nu$ + Lepton-tag

~Same as Δm measurement
[PRL,89,251,803(02),PRD 71,972003(05)]

(high quality lepton-tag only)

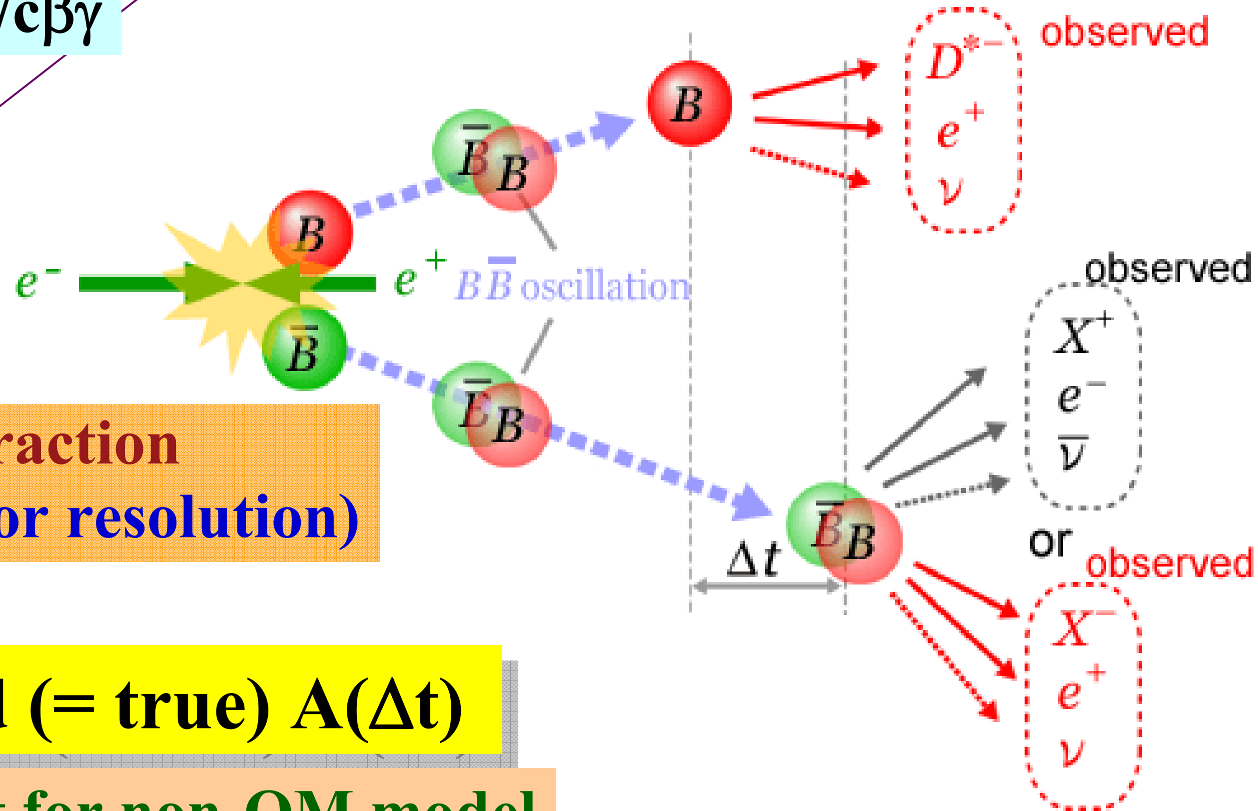
Reconstruction
Vertexing: $\Delta t = \Delta z / c\beta\gamma$

OF & SF
Δt distribution

- **Background subtraction**
- **Unfolding (detector resolution)**

Fully corrected (= true) A(Δt)

➤ **Quantitative Test for non-QM model**



Signal Reconstruction

$B^0 \to D^{*-} \ell^+ \nu$

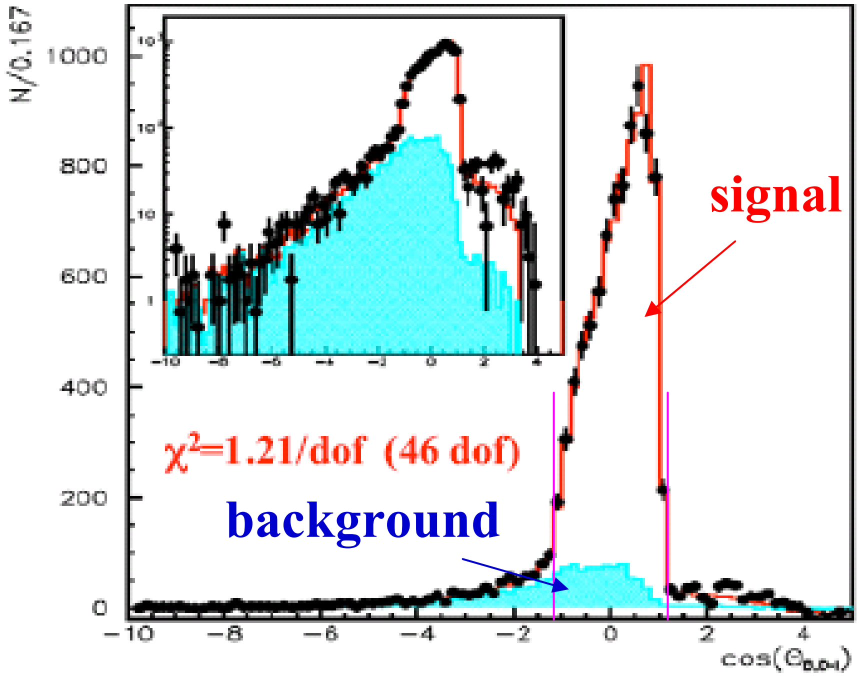
$\to \overline{D}^0 \pi^-_{slow}$

$\to K^+\pi^-$

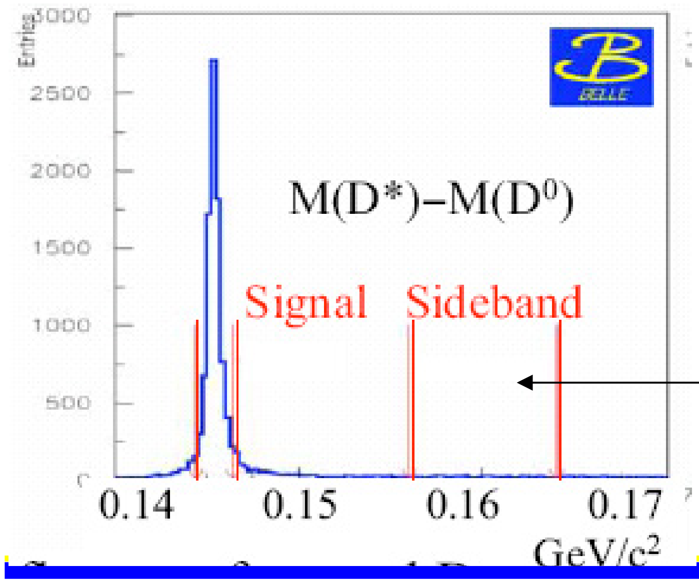
$\to K^+\pi^-\pi^0$

$\to K^+\pi^-\pi^+\pi^-$

152M $B\overline{B}$



$$(E_B^* - E_{D^*l}^*)^2 - |p_B^*|^2 - |p_{D^*l}^*|^2 + 2|p_B^*||p_{D^*l}^*|\cos(\theta_{B,D^*l}) = M_\nu^2 \approx 0$$



Background subtraction of fake D*

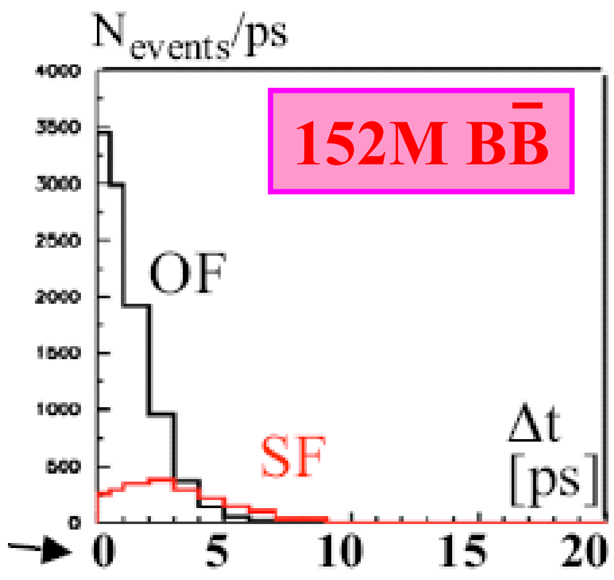
6718 OF
1847 SF

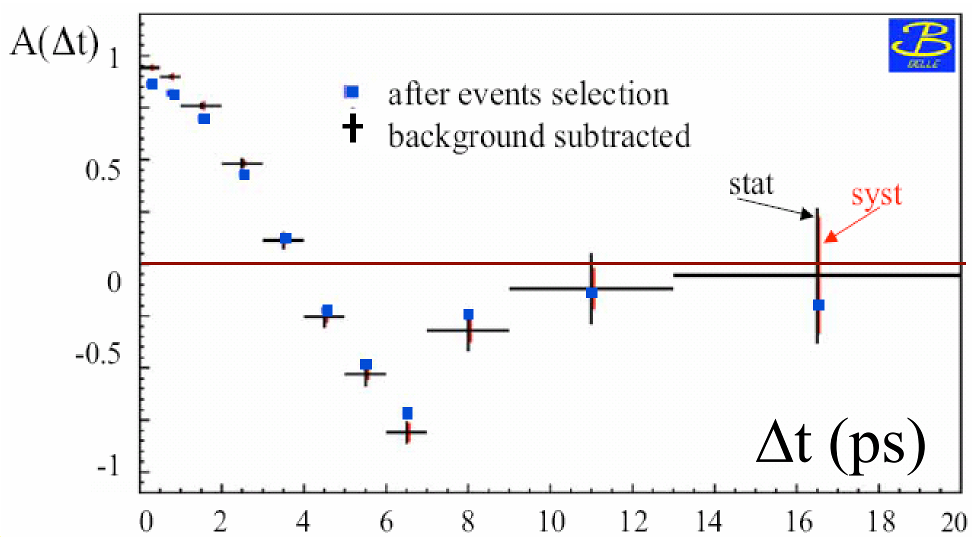
Background Subtraction

Bin-by-bin (Δt) for OF & SF

- **Continuum:** use off-Res. (negligible)
- **Fake D*:** M(D*)–M(D^0) sideband
- **Combinatoric D^*l :** "reversed *l*" method
- $B^+ \to D^{**0} l \nu$: MC
- **Wrong-tag correction : 1.5 ±0.5% (MC,data)**

	OF	SF
Continuum	-	-
Fake D*	126	54
Combinatoric D*l	78	237
$B^+ \to D^{**0} l \nu$	254	2
Wrong-tag correction	22 ↔86	
Total	6324	1490





Unfolding (Deconvolution)

Singular Value Decomposition (SVD) method

[A.Hoecker, V.KKartvelishvile NIM A372, 469(1996)]

Measured Δt distribution → **True Δt distribution**

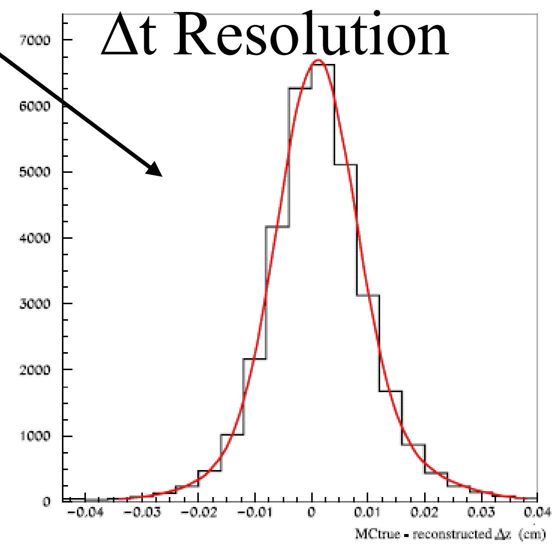
Detector effect

OF, SF separately

11 Δt bins: 11 x 11 Response Matrix

(measured) = R x (true) (using MC)

⇒ **Matrix inversion**

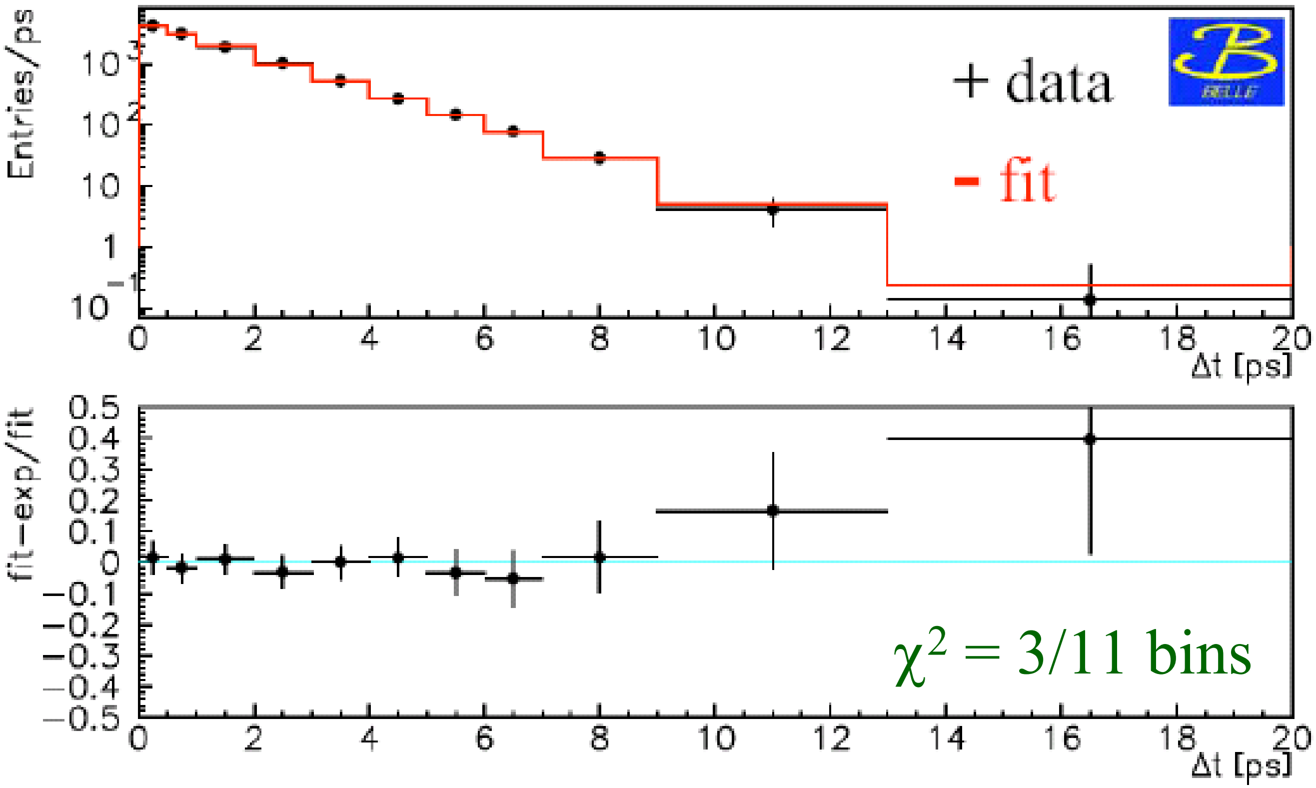


Data/MC difference included

- Robustness against input:
  checked by Toy MC → Sys. error

Cross Check: Lifetime

Fully corrected OF+SF: fit with $e^{-\Delta t/\tau}$



$\tau = 1.532 \pm 0.017$(stat) ps $\rightarrow$ consistent with PDG

(1.530 ±0.009 ps)

Results & Sys. errors

Fully corrected A(Δt)

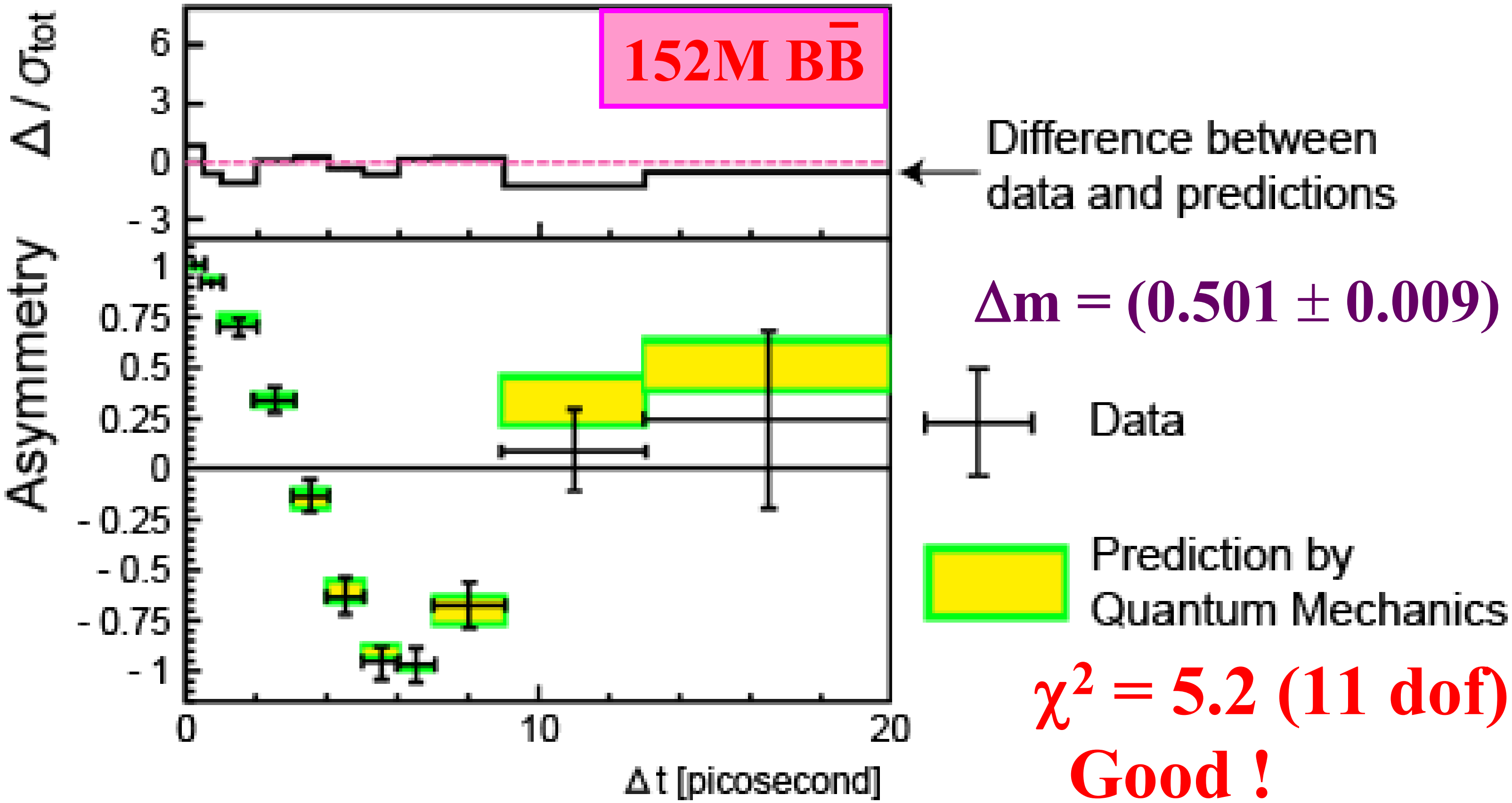
	Window	Asymmetry		Systematic Errors				
Δt bin	window [ps]	A and total error	stat. error	total	event sel.	bkgd sub.	wrong tags	deconvol.
1	0.0 – 0.5	1.013 ± 0.028	0.020	0.019	0.005	0.006	0.010	0.014
2	0.5 – 1.0	0.916 ± 0.022	0.015	0.016	0.006	0.007	0.010	0.009
3	1.0 – 2.0	0.699 ± 0.038	0.029	0.024	0.013	0.005	0.009	0.017
4	2.0 – 3.0	0.339 ± 0.056	0.047	0.031	0.008	0.005	0.007	0.029
5	3.0 – 4.0	-0.136 ± 0.075	0.060	0.045	0.009	0.009	0.007	0.042
6	4.0 – 5.0	-0.634 ± 0.084	0.062	0.057	0.021	0.014	0.013	0.049
7	5.0 – 6.0	-0.961 ± 0.077	0.060	0.048	0.020	0.017	0.012	0.038
8	6.0 – 7.0	-0.974 ± 0.080	0.060	0.053	0.034	0.025	0.020	0.025
9	7.0 – 9.0	-0.675 ± 0.109	0.092	0.058	0.041	0.027	0.022	0.022
10	9.0 – 13.0	0.089 ± 0.193	0.161	0.107	0.067	0.063	0.038	0.039
11	13.0 – 20.0	0.243 ± 0.435	0.240	0.363	0.145	0.226	0.080	0.231

stat. ~ sys.

Results & fit with QM

Fully corrected A(Δt): fit with QM

[quant-ph/0702267, submitted to PRL]



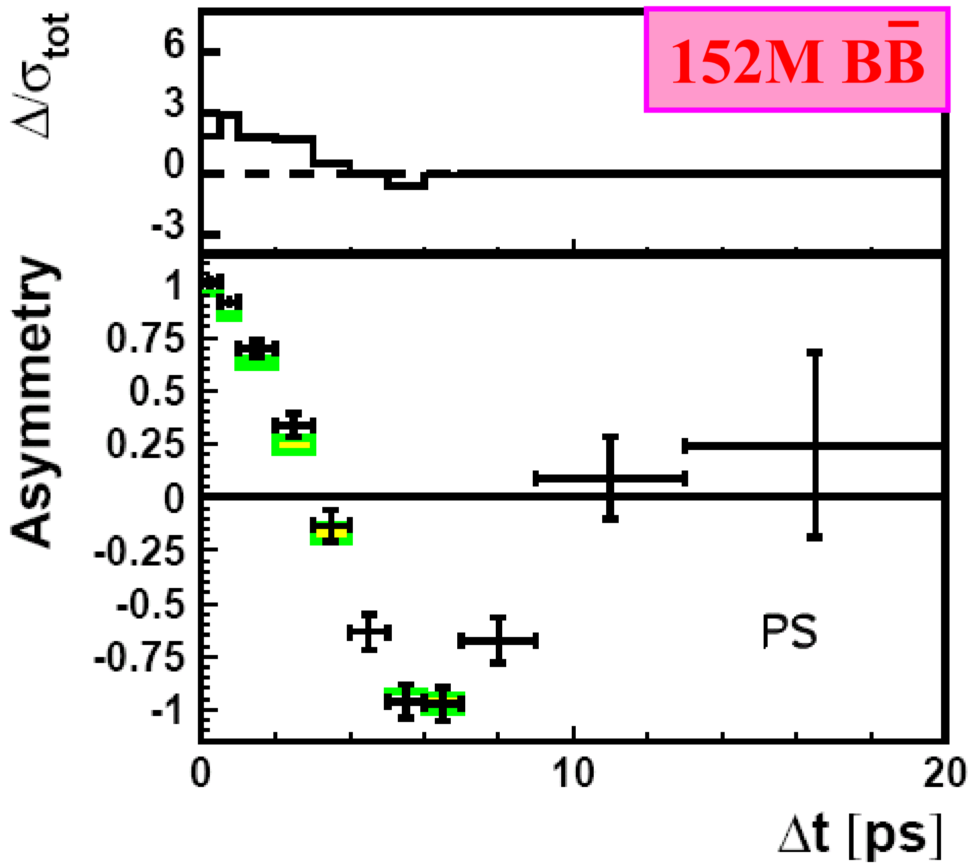
$\Delta m = (0.501 \pm 0.009)\ ps^{-1}$

$\chi^2 = 5.2$ (11 dof)

Good !

[fit including WA $\Delta m = (0.496 \pm 0.014)\ ps^{-1}$ (excl. Belle/BaBar)]

Result: PS model



difference btw. Data/Fit
(points not used if
$PS_{min} < Data < PS_{max}$)

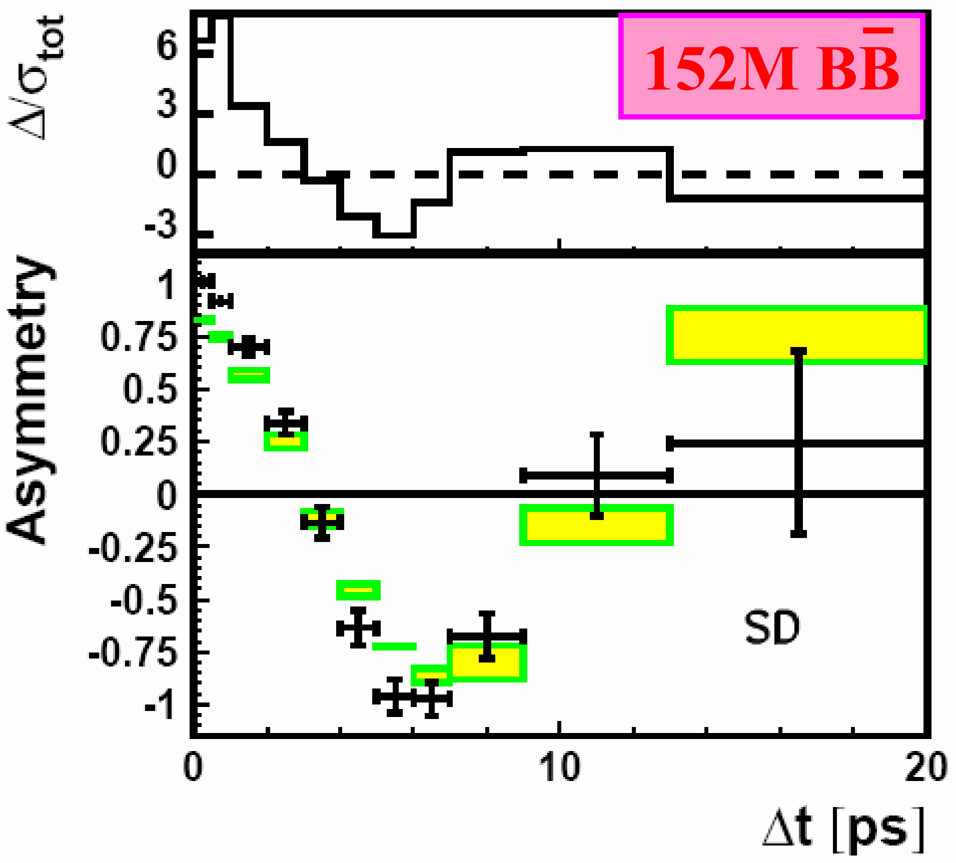
PS Best Fit
(error from Δm)

$\Delta m = (0.447 \pm 0.010)\ ps^{-1}$

$\chi^2 = 31.3$

disfavored 5.1σ over QM

Result: SD model



difference btw. Data/Fit

SD Best Fit (error from Δm)

$\Delta m = (0.419 \pm 0.008)\ ps^{-1}$

$\chi^2 = 174$

disfavored 13σ over QM

Decoherence fraction:

Fit $(1-\zeta)A_{QM} + \zeta A_{SD}$: $\zeta = 0.029 \pm 0.057$

cf) $K^0\bar{K}^0$ system

[CPLEAR, PLB 422, 339(1998)
KLOE, PLB 642, 315 (2006)]

Summary

Quantitative study of EPR-type Flavor entanglement in $\Upsilon(4S) \rightarrow B^0\bar{B}^0$ decays has been performed

- **Fully corrected $A(\Delta t)$ measurement**
  $\rightarrow$ allow Direct comparison with any theory

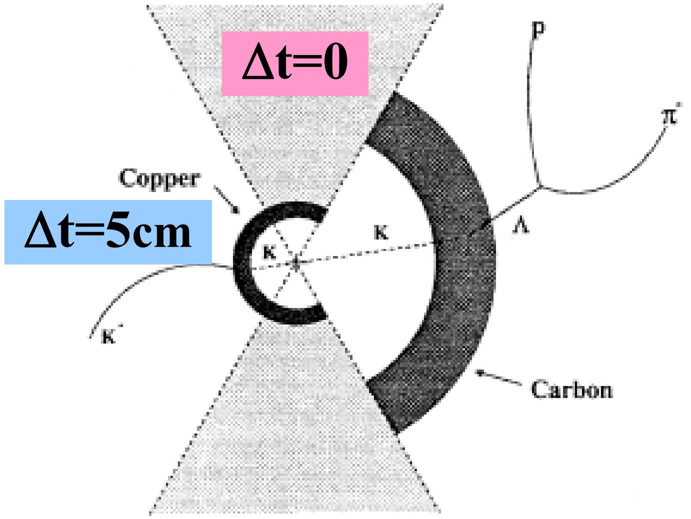
- **QM Entanglement : confirmed**
- **Pompili-Selleri type (Local Realism) model : disfavored by 5.1σ**
- **Spontaneous Disentanglement: rejected by 13σ**

Bell Inequality Test might be reconsidered ?

K^0 system EPR: CPLEAR

[PLB 422,339 (1998)]

$p\,\bar{p} \rightarrow K^0\bar{K}^0$ at rest (J^{PC}~1^{--})

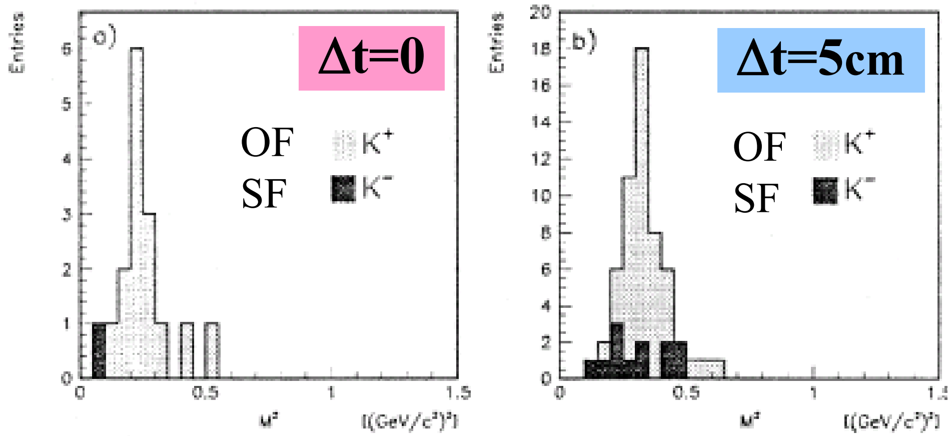


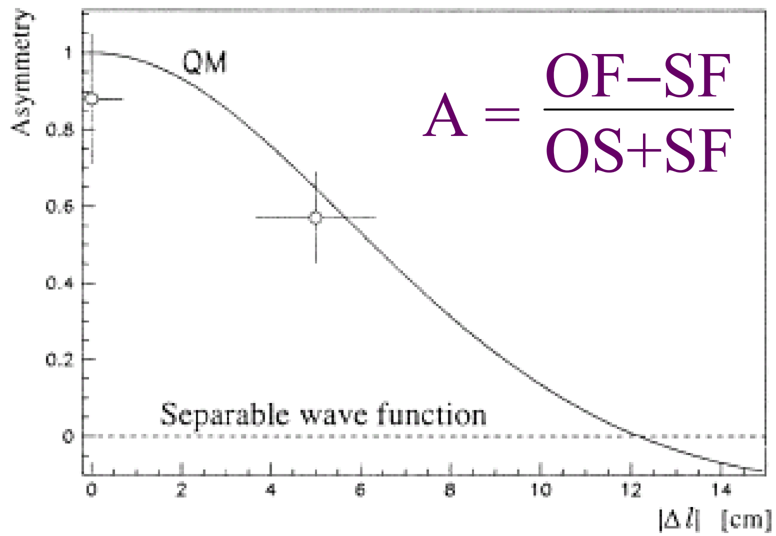
Decoherence fraction in
$K^0\bar{K}^0$ basis

$\zeta = 0.40 \pm 0.7$

[PRD 60,114032 (1999)]

$\Lambda + K^{\pm}$ (K-id by dE/dx)



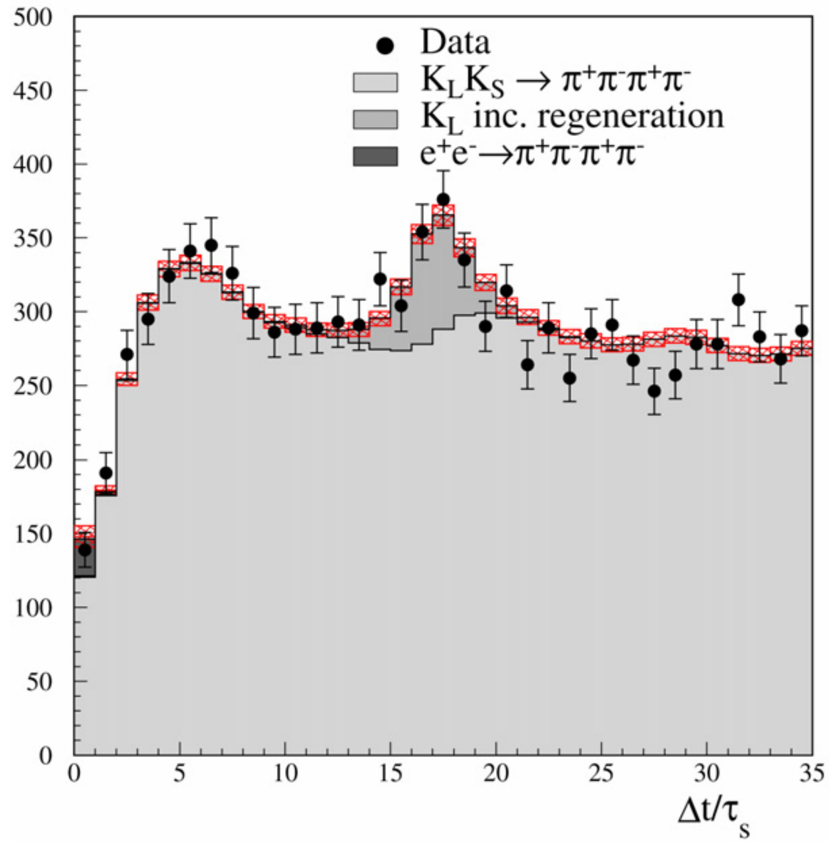


$$A = \frac{OF-SF}{OS+SF}$$

K^0 system EPR: KLOE

KLOE at DAPHNE (ϕ Factory) [PLB 642,315(2006)]

$\phi \to K_S K_L \to (\pi^+\pi^-)(\pi^+\pi^-)$ **CPV decay** **$380 pb^{-1}$**



Fit to Δt distribution including regeneration

Decoherence fraction in $K^0\bar{K}^0$ basis

$\zeta = (0.10 \pm 0.21 \pm 0.04) \times 10^{-5}$

(Decoherence: CP allowed decay $\phi \to K_S K_S$)

Time-dependent Asymmetry