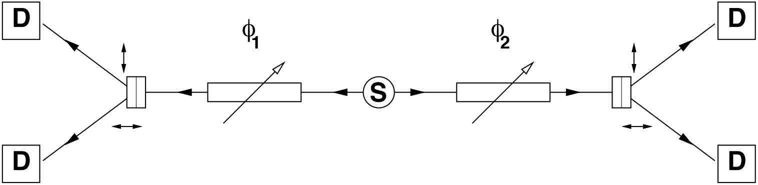
A study of entanglement in $e^+e^- \to B\overline{B}$ events at Belle

Bruce Yabsley

University of Sydney

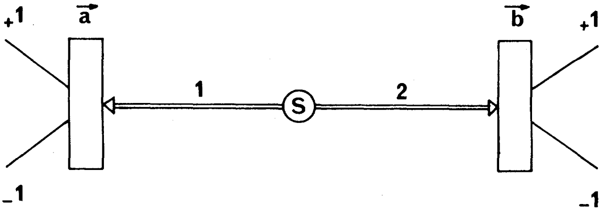
Top Quark Physics at the Precision Frontier, Purdue, 2nd October 2023



Outline

Einstein, Podolsky, and Rosen, via Bohm

spin-singlet state of photons or particles: $\frac{1}{\sqrt{2}}\left[|\Uparrow\rangle_1\,|\Downarrow\rangle_2 - |\Downarrow\rangle_1\,|\Uparrow\rangle_2\right]$



- measurements on 1 (2) indeterminate, but $\Longrightarrow$ full knowledge of 2 (1)
- Bell's Theorem (via Clauser, Horne, Shimony, and Holt):
  - correlation coeff: $E(\vec{a},\vec{b}) = \frac{R_{++}(\vec{a},\vec{b})+R_{--}(\vec{a},\vec{b})-R_{+-}(\vec{a},\vec{b})-R_{-+}(\vec{a},\vec{b})}{R_{++}(\vec{a},\vec{b})+R_{--}(\vec{a},\vec{b})-R_{+-}(\vec{a},\vec{b})+R_{-+}(\vec{a},\vec{b})}$
  - $S = E(\vec{a},\vec{b}) - E(\vec{a},\vec{b}') + E(\vec{a}',\vec{b}) + E(\vec{a}',\vec{b}')$
  - $|S| \leq 2$ for any local realistic model; $S_{QM} = \pm 2\sqrt{2}$ for optimal settings
- QM-like results rule out LR, even if we eventually "get behind" QM

Aspect et al., Phys. Rev. Lett. 92, 91 (1982)

source: 2-photon cascade decay

ν_1, ν_2 polarizations are correlated

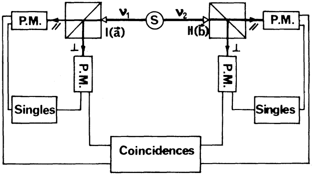


FIG. 2. Experimental setup. Two polarimeters I and II, in orientations $\vec{a}$ and $\vec{b}$, perform true dichotomic measurements of linear polarization on photons ν_1 and ν_2. Each polarimeter is rotatable around the axis of the incident beam. The counting electronics monitors the singles and the coincidences.

[two-channel polarimeters used]

correlation coeffs in data *vs* QM

optimum relative angles 22.5° and 67.5°

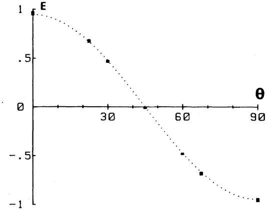


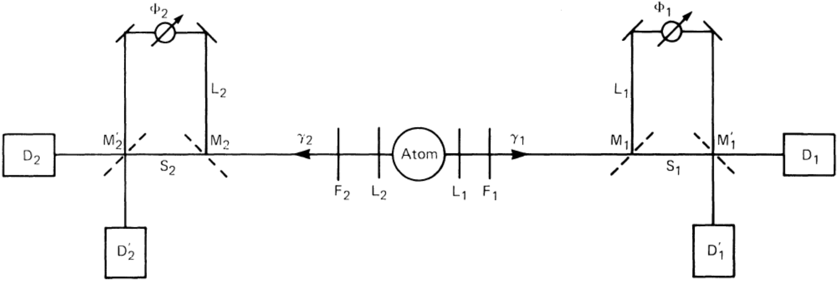
FIG. 3. Correlation of polarizations as a function of the relative angle of the polarimeters. The indicated errors are ±2 standard deviations. The dotted curve is not a fit to the data, but quantum mechanical predictions for the actual experiment. For ideal polarizers, the curve would reach the values ±1.

$$S = 2.697 \pm 0.015; \ cf.\ S_{QM} = 2.70 \pm 0.05$$

Einstein, Podolsky, and Rosen, via Bohm: Franson

J.D. Franson, Phys. Rev. Lett. 62, 2205–2208 (1989)

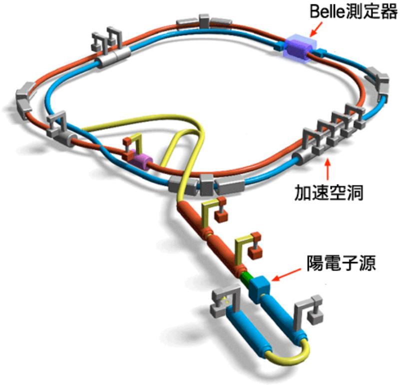
some more recent experiments are based on a different design with alternative paths setting up a *position-time* correlation:



here the polarizer orientations are fixed, and variable phase delays $\Phi_{1,2}$ (*Pockels cells* or similar) are introduced

the KEKB/Belle facility

the KEKB collider

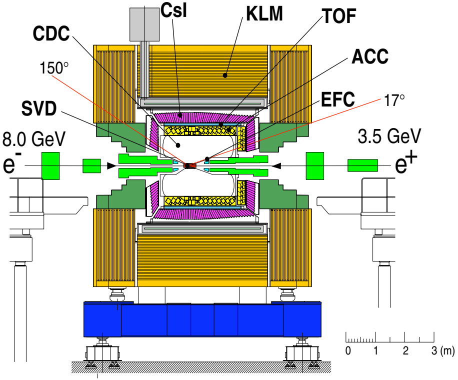


e^+ and e^- storage rings

[asymmetric energies]

$\mathcal{L}$ record: $21\,\mathrm{nb}^{-1}/\mathrm{s}$ at peak

the Belle detector



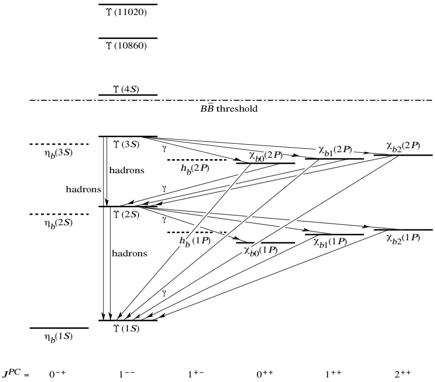
superconducting solenoid (1.5 T)

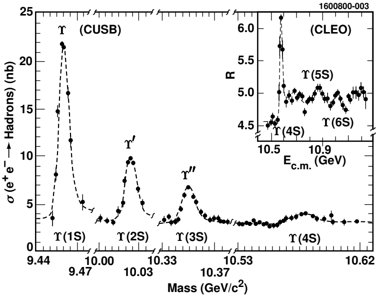
[tracking; calorimetry; K/π, e^-, μ ID]

772 million $B\overline{B}$ pairs on tape

CP: violated in the neutral B-meson system?

instead of $K^0 \equiv \bar{s}d$, try $B^0 \equiv \bar{b}d$, using $b\bar{b}$ resonance as a source . . .



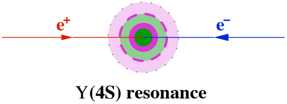


$$\Upsilon(nS) \longrightarrow B\overline{B} \text{ for } n \geq 4$$

$e^+e^- \to \Upsilon(4S) \to$ [flavor singlet state of] $B^0\overline{B}^0$

the B-pair has the same property, substituting flavor for spin/polarization:

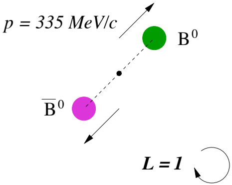
- the $\Upsilon(4S)$ is C-odd



$e^+e^- \to \Upsilon(4S) \to$ [flavor singlet state of] $B^0\overline{B}^0$

the B-pair has the same property, substituting flavor for spin/polarization:

- the $\Upsilon(4S)$ is C-odd
- an entangled B-pair is produced:

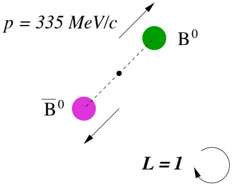


$$|\Psi(t)\rangle = \frac{e^{-t/\tau_{B^0}}}{\sqrt{2}} \left[|B^0(\vec{p})\overline{B}^0(-\vec{p})\rangle - |\overline{B}^0(\vec{p})B^0(-\vec{p})\rangle \right]$$

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow$ [flavor singlet state of] $B^0\overline{B}^0$

the B-pair has the same property, substituting flavor for spin/polarization:

- the $\Upsilon(4S)$ is C-odd
- an entangled B-pair is produced:
    - individual flavors indeterminate

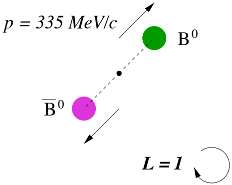


$$|\Psi(t)\rangle = \frac{e^{-t/\tau_{B^0}}}{\sqrt{2}} \left[|B^0(\vec{p})\overline{B}^0(-\vec{p})\rangle - |\overline{B}^0(\vec{p})B^0(-\vec{p})\rangle \right]$$

$e^+e^- \to \Upsilon(4S) \to$ [flavor singlet state of] $B^0\overline{B}^0$

the B-pair has the same property, substituting flavor for spin/polarization:

- the $\Upsilon(4S)$ is C-odd
- an entangled B-pair is produced:
  - individual flavors indeterminate
  - at fixed t, the pair is always $B^0\overline{B}^0$



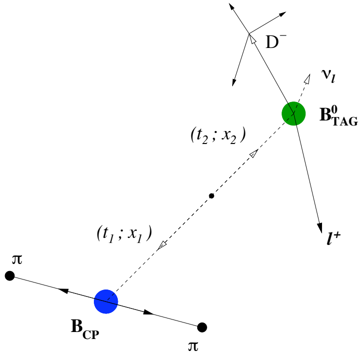
$$|\Psi(t)\rangle = \frac{e^{-t/\tau_{B^0}}}{\sqrt{2}}\left[|B^0(\vec{p})\overline{B}^0(-\vec{p})\rangle - |\overline{B}^0(\vec{p})B^0(-\vec{p})\rangle\right]$$

$e^+e^- \to \Upsilon(4S) \to$ [flavor singlet state of] $B^0\overline{B}^0$

the B-pair has the same property, substituting flavor for spin/polarization:

- the $\Upsilon(4S)$ is C-odd
- an entangled B-pair is produced:
  - individual flavors indeterminate
  - at fixed t, the pair is always $B^0\overline{B}^0$
- flagship B-factory measurements:

$$\begin{cases} B^0_{TAG} & \text{definite flavor state} \\ B^0_{CP} & \text{definite CP state} \end{cases}$$



$$\Gamma_{CP}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 \pm \{S_{CP}\sin(\Delta m \Delta t) + A_{CP}\cos(\Delta m \Delta t)\}\right]$$

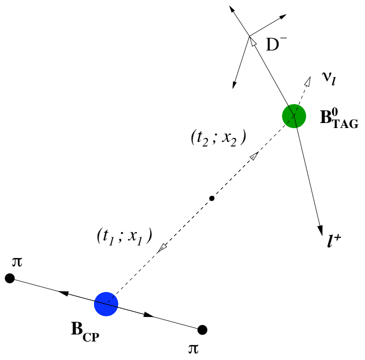
$e^+e^- \to \Upsilon(4S) \to$ [flavor singlet state of] $B^0\overline{B}^0$

the B-pair has the same property, substituting flavor for spin/polarization:

- the $\Upsilon(4S)$ is C-odd
- an entangled B-pair is produced:
  - individual flavors indeterminate
  - at fixed t, the pair is always $B^0\overline{B}^0$
- flagship B-factory measurements:

$$\begin{cases} B^0_{TAG} & \text{definite flavor state} \\ B^0_{CP} & \text{definite CP state} \end{cases}$$

  - decay rate modulated in $\Delta t \equiv t_1 - t_2$



$$\Gamma_{CP}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[1 \pm \{S_{CP} \sin(\Delta m \Delta t) + A_{CP} \cos(\Delta m \Delta t)\}\right]$$

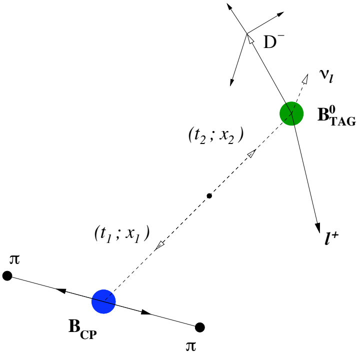
$e^+e^- \to \Upsilon(4S) \to$ [flavor singlet state of] $B^0\overline{B}^0$

the B-pair has the same property, substituting flavor for spin/polarization:

- the $\Upsilon(4S)$ is C-odd
- an entangled B-pair is produced:
  - individual flavors indeterminate
  - at fixed t, the pair is always $B^0\overline{B}^0$
- flagship B-factory measurements:

$$\begin{cases} B^0_{TAG} & \text{definite flavor state} \\ B^0_{CP} & \text{definite CP state} \end{cases}$$

  - decay rate modulated in $\Delta t \equiv t_1 - t_2$
  - with one rate for B^0_{TAG} . . .



$$\Gamma_{CP}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[1 + \left\{S_{CP} \sin(\Delta m \Delta t) + A_{CP} \cos(\Delta m \Delta t)\right\}\right]$$

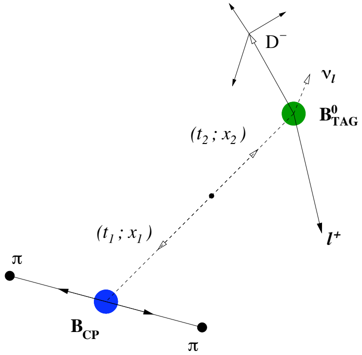
$e^+e^- \to \Upsilon(4S) \to$ [flavor singlet state of] $B^0\overline{B}^0$

the B-pair has the same property, substituting flavor for spin/polarization:

- the $\Upsilon(4S)$ is C-odd
- an entangled B-pair is produced:
  - individual flavors indeterminate
  - at fixed t, the pair is always $B^0\overline{B}^0$
- flagship B-factory measurements:

$$\begin{cases} B^0_{TAG} & \text{definite flavor state} \\ B^0_{CP} & \text{definite CP state} \end{cases}$$

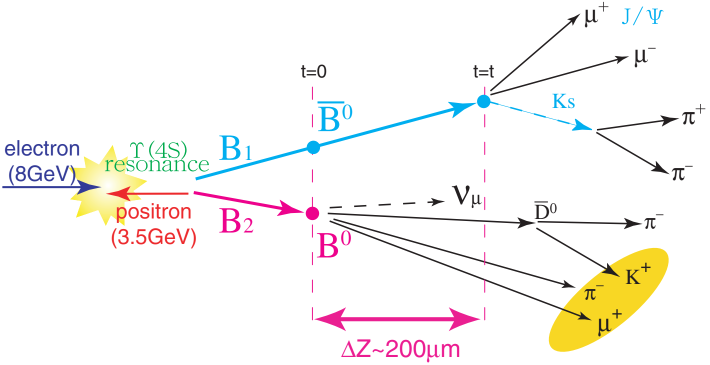
  - decay rate modulated in $\Delta t \equiv t_1 - t_2$
  - with one rate for B^0_{TAG} ...
  - and another rate for $\overline{B}^0_{TAG}$: CPV



$$\Gamma_{CP}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 - \{S_{CP}\sin(\Delta m \Delta t) + A_{CP}\cos(\Delta m \Delta t)\}\right]$$

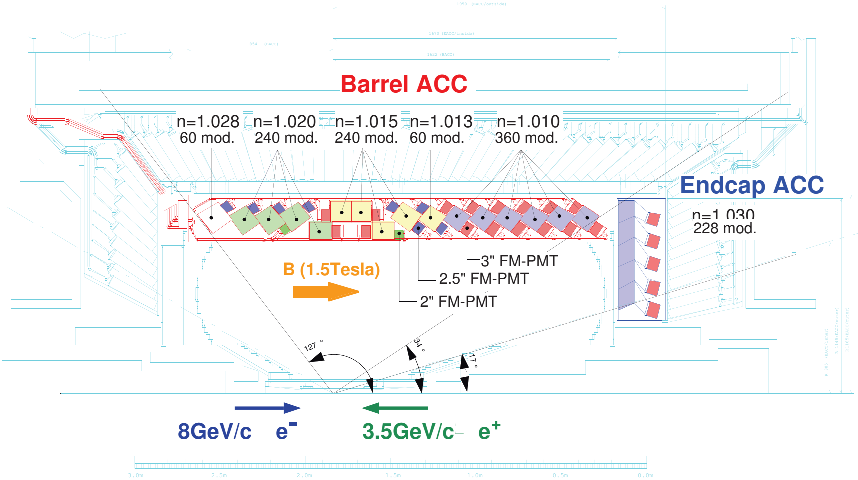
Measuring a time-dependent CPV asymmetry

$\Delta t \sim 10^{-12}\,\mathrm{s}$ unmeasurable, so use $\Delta z \overset{\sim}{\propto} \Delta t$



Measuring a time-dependent CPV asymmetry

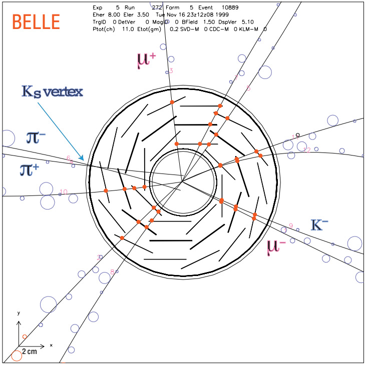
asymmetric c.m. system $\longrightarrow$ an asymmetric detector



What one of those events actually “looks” like . . .

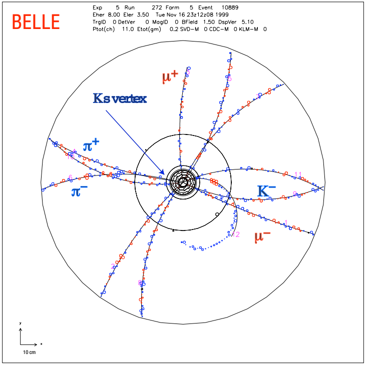
vertexing: SVD

silicon vertex detector



tracking: CDC

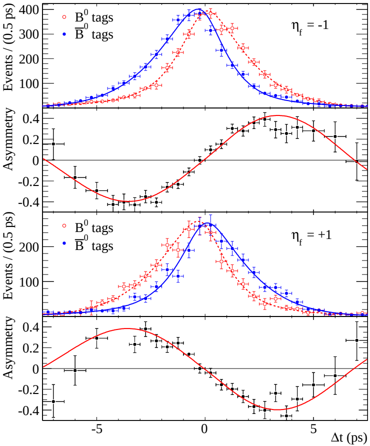
central drift chamber



CP: violated in the neutral B-meson system!!

Belle: I. Adachi et al., Phys. Rev. Lett. 108, 171802 (2012)

- measured by 2000, observed by 2001; 2012 final measurement shown $\longrightarrow$
- clear offset of $\overline{B}^0$ and B^0 tags
- decent fit to the expected *sinusoidal modulation* in Δt in the rate asymmetry
- opposite shift (with poorer precision) seen for $B^0 \to J/\psi K^0_L$
  - opposite η_{CP} to other modes
  - Δt measurement is $\approx$ the same
  - (for validation, not extra precision)
- huge project at Belle & BaBar:
  - confirm expected SM results
  - find deviations — NP signals [*cf.* top quark first "seen" in loops]



$K^0\overline{K}^0$ & $B^0\overline{B}^0$ systems: what can be measured

there is a beautiful optical analogy called *quasi-spin*
due to Lee and Wu (1966) and Lipkin (1968):

K meson	spin-$\frac{1}{2}$	photon
$\lvert K^0\rangle$	$\lvert\Uparrow\rangle_z$	$\lvert V\rangle$
$\lvert\overline{K}^0\rangle$	$\lvert\Downarrow\rangle_z$	$\lvert H\rangle$
$\lvert K^0_S\rangle$	$\lvert\Rightarrow\rangle_z$	$\lvert L\rangle = \frac{1}{\sqrt{2}}(\lvert V\rangle - i\lvert H\rangle)$
$\lvert K^0_L\rangle$	$\lvert\Leftarrow\rangle_z$	$\lvert R\rangle = \frac{1}{\sqrt{2}}(\lvert V\rangle + i\lvert H\rangle)$

- we are limited in the "polarization axes" we can choose:
  - can't measure along arbitrary $\alpha|K^0\rangle + \beta|\overline{K}^0\rangle = \alpha|\Uparrow\rangle + \beta|\Downarrow\rangle$
  - even more restricted for B-mesons: only B^0, $\overline{B}^0$ are practical
- but $|B^0\rangle \xrightarrow{t} \frac{1}{2}\left[\{1+\cos(\Delta m_d t)\}|B^0\rangle + \{1-\cos(\Delta m_d t)\}|\overline{B}^0\rangle\right]$, so *time difference $\Delta m_d \Delta t$ plays the role of phase difference $\Delta\phi$*

$K^0\overline{K}^0$ & $B^0\overline{B}^0$ systems: what can be measured

there is a beautiful optical analogy called *quasi-spin*
due to Lee and Wu (1966) and Lipkin (1968):

B meson	spin-$\frac{1}{2}$	photon
$\lvert B^0\rangle$	$\lvert\Uparrow\rangle_z$	$\lvert V\rangle$
$\lvert\overline{B}^0\rangle$	$\lvert\Downarrow\rangle_z$	$\lvert H\rangle$
	$\lvert\Rightarrow\rangle_z$	$\lvert L\rangle = \frac{1}{\sqrt{2}}(\lvert V\rangle - i\lvert H\rangle)$
	$\lvert\Leftarrow\rangle_z$	$\lvert R\rangle = \frac{1}{\sqrt{2}}(\lvert V\rangle + i\lvert H\rangle)$

- we are limited in the "polarization axes" we can choose:
  - can't measure along arbitrary $\alpha\lvert K^0\rangle + \beta\lvert\overline{K}^0\rangle = \alpha\lvert\Uparrow\rangle + \beta\lvert\Downarrow\rangle$
  - even more restricted for B-mesons: only B^0, $\overline{B}^0$ are practical
- but $\lvert B^0\rangle \xrightarrow{t} \frac{1}{2}\left[\{1+\cos(\Delta m_d t)\}\lvert B^0\rangle + \{1-\cos(\Delta m_d t)\}\lvert\overline{B}^0\rangle\right]$, so
  time difference $\Delta m_d \Delta t$ plays the role of phase difference $\Delta\phi$

the $B^0\overline{B}^0$ system: an optical analogy

an EPR experiment on $\Upsilon(4S) \to B^0\overline{B}^0$ is analagous to:

the $B^0\overline{B}^0$ system: an optical analogy

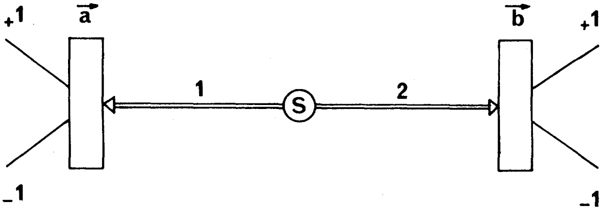
an EPR experiment on $\Upsilon(4S) \to B^0\overline{B}^0$ is analagous to:

- a photon pair in a singlet state

the $B^0\overline{B}^0$ system: an optical analogy

an EPR experiment on $\Upsilon(4S) \to B^0\overline{B}^0$ is analagous to:

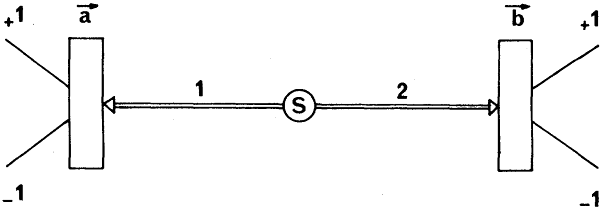
- a photon pair in a singlet state
- in the Aspect experiment, with two-channel polarimeters



the $B^0\overline{B}^0$ system: an optical analogy

an EPR experiment on $\Upsilon(4S) \to B^0\overline{B}^0$ is analagous to:

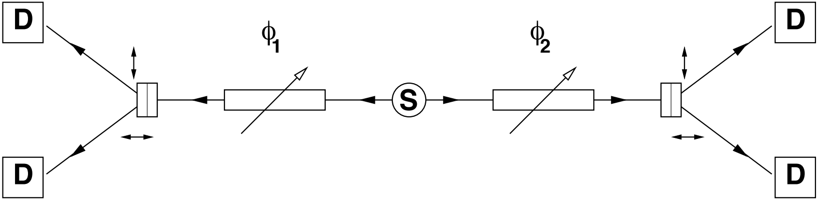
- a photon pair in a singlet state
- in the Aspect experiment, with two-channel polarimeters
- which are *fixed* in orientation, rather than rotating,



the $B^0\overline{B}^0$ system: an optical analogy

an EPR experiment on $\Upsilon(4S) \to B^0\overline{B}^0$ is analagous to:

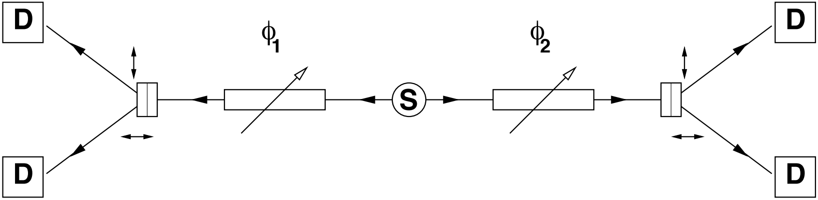
- a photon pair in a singlet state
- in the Aspect experiment, with two-channel polarimeters
- which are *fixed* in orientation, rather than rotating,
- *with a variable phase rotation* à la Franson *on the arms instead*



the $B^0\overline{B}^0$ system: an optical analogy

an EPR experiment on $\Upsilon(4S) \to B^0\overline{B}^0$ is analagous to:

- a photon pair in a singlet state
- in the Aspect experiment, with two-channel polarimeters
- which are *fixed* in orientation, rather than rotating,
- *with a variable phase rotation* à la Franson *on the arms instead*



- however, there is a catch ...

The Green Baize Table Conspiracy Model (1)

Bramon/Escribano/Garbarino, J. Mod. Opt. 52, 1681 (2005) via Chris Carter

- somewhere, there is a wood-panelled room with a green baize table

The Green Baize Table Conspiracy Model (1)

Bramon/Escribano/Garbarino, J. Mod. Opt. 52, 1681 (2005) via Chris Carter

- somewhere, there is a wood-panelled room with a green baize table
- men meet there together, smoke, and make conspiracy ...
  and decide *everything* that happens *in detail*: including $\Upsilon(4S) \to B\overline{B}$

The Green Baize Table Conspiracy Model (1)

Bramon/Escribano/Garbarino, J. Mod. Opt. 52, 1681 (2005) via Chris Carter

- somewhere, there is a wood-panelled room with a green baize table
- men meet there together, smoke, and make conspiracy . . .
  and decide *everything* that happens *in detail*: including $\Upsilon(4S) \to B\overline{B}$
- at $t = 0$, hidden variables are set:

The Green Baize Table Conspiracy Model (1)

Bramon/Escribano/Garbarino, J. Mod. Opt. 52, 1681 (2005) via Chris Carter

- somewhere, there is a wood-panelled room with a green baize table
- men meet there together, smoke, and make conspiracy . . .
  and decide *everything* that happens *in detail*: including $\Upsilon(4S) \to B\overline{B}$
- at $t = 0$, hidden variables are set:
  - mesons 1 & 2 are assigned variables (t_1, f_1) & (t_2, f_2)

The Green Baize Table Conspiracy Model (1)

Bramon/Escribano/Garbarino, J. Mod. Opt. 52, 1681 (2005) via Chris Carter

- somewhere, there is a wood-panelled room with a green baize table
- men meet there together, smoke, and make conspiracy ...
  and decide *everything* that happens *in detail*: including $\Upsilon(4S) \to B\overline{B}$
- at $t = 0$, hidden variables are set:
  - mesons 1 & 2 are assigned variables (t_1, f_1) & (t_2, f_2)
  - these act locally: meson i

The Green Baize Table Conspiracy Model (1)

Bramon/Escribano/Garbarino, J. Mod. Opt. 52, 1681 (2005) via Chris Carter

- somewhere, there is a wood-panelled room with a green baize table
- men meet there together, smoke, and make conspiracy ...
  and decide *everything* that happens *in detail*: including $\Upsilon(4S) \to B\overline{B}$
- at $t = 0$, hidden variables are set:
  - mesons 1 & 2 are assigned variables (t_1, f_1) & (t_2, f_2)
  - these act locally: meson i decays at time $t = t_i$

The Green Baize Table Conspiracy Model (1)

Bramon/Escribano/Garbarino, J. Mod. Opt. 52, 1681 (2005) via Chris Carter

- somewhere, there is a wood-panelled room with a green baize table
- men meet there together, smoke, and make conspiracy . . .
  and decide *everything* that happens *in detail*: including $\Upsilon(4S) \rightarrow B\overline{B}$
- at $t = 0$, hidden variables are set:
  - mesons 1 & 2 are assigned variables (t_1, f_1) & (t_2, f_2)
  - these act locally: meson i decays at time $t = t_i$ into final state $f = f_i$

The Green Baize Table Conspiracy Model (1)

Bramon/Escribano/Garbarino, J. Mod. Opt. 52, 1681 (2005) via Chris Carter

- somewhere, there is a wood-panelled room with a green baize table
- men meet there together, smoke, and make conspiracy ...
  and decide *everything* that happens *in detail*: including $\Upsilon(4S) \to B\overline{B}$
- at $t = 0$, hidden variables are set:
  - mesons 1 & 2 are assigned variables (t_1, f_1) & (t_2, f_2)
  - these act locally: meson i decays at time $t = t_i$ into final state $f = f_i$
- if (t_1, f_1, t_2, f_2) are chosen randomly according to QM ...
  the phenomena look like QM!

The Green Baize Table Conspiracy Model (1)

Bramon/Escribano/Garbarino, J. Mod. Opt. 52, 1681 (2005) via Chris Carter

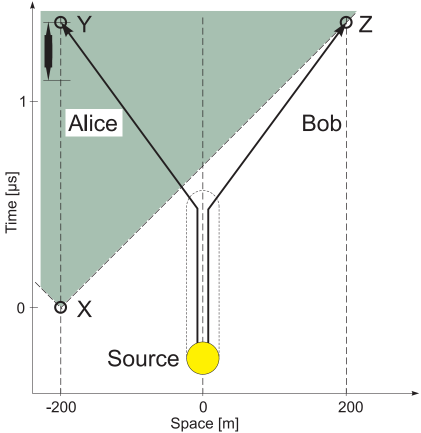
- somewhere, there is a wood-panelled room with a green baize table
- men meet there together, smoke, and make conspiracy . . .
  and decide *everything* that happens *in detail*: including $\Upsilon(4S) \to B\overline{B}$
- at $t = 0$, hidden variables are set:
  - mesons 1 & 2 are assigned variables (t_1, f_1) & (t_2, f_2)
  - these act locally: meson i decays at time $t = t_i$ into final state $f = f_i$

- if (t_1, f_1, t_2, f_2) are chosen randomly according to QM . . . the phenomena look like QM!
- because $\Delta m_d \Delta t$ plays the role of phase difference $\Delta\phi$, and the decays set Δt, **we cannot choose $\Delta\phi$ to defeat the conspiracy**

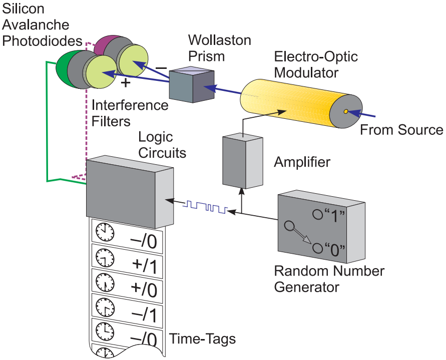
The Green Baize Table Conspiracy Model (2)

G. Weihs et al., Phys. Rev. Lett. 81, 5039–5043 (1998): "Aspect++"

changing $\Delta\phi$ in flight . . .



. . . based on random numbers



Here $\Delta\phi$ is *actively* chosen: not subject to the same sorts of conspiracy.

Beyond The Green Baize Table Conspiracy

Bertlmann, Bramon, Garbarino, Hiesmayr, Phys. Lett. A 332, 355–360 (2004)

With hypothetical active flavor measurement, could a Bell test be performed?

Beyond The Green Baize Table Conspiracy

Bertlmann, Bramon, Garbarino, Hiesmayr, Phys. Lett. A 332, 355–360 (2004)

With hypothetical active flavor measurement, could a Bell test be performed?

- B-meson sample decreases with Δt

Beyond The Green Baize Table Conspiracy

Bertlmann, Bramon, Garbarino, Hiesmayr, Phys. Lett. A 332, 355–360 (2004)

With hypothetical active flavor measurement, could a Bell test be performed?

- B-meson sample decreases with Δt
- crucial parameter $x_d = \Delta m_d / \Gamma_d$:
  rate of oscillation relative to decay

Beyond The Green Baize Table Conspiracy

Bertlmann, Bramon, Garbarino, Hiesmayr, Phys. Lett. A 332, 355–360 (2004)

With hypothetical active flavor measurement, could a Bell test be performed?

- B-meson sample decreases with Δt
- crucial parameter $x_d = \Delta m_d / \Gamma_d$:
  rate of oscillation relative to decay
- Bell test impossible if $x < 2.0$:

system	x
$B^0/\overline{B}^0$	0.77
$K^0/\overline{K}^0$	0.95
$D^0/\overline{D}^0$	< 0.03
$B_s^0/\overline{B}_s^0$	~ 26

Beyond The Green Baize Table Conspiracy

Bertlmann, Bramon, Garbarino, Hiesmayr, Phys. Lett. A 332, 355–360 (2004)

With hypothetical active flavor measurement, could a Bell test be performed?

- B-meson sample decreases with Δt
- crucial parameter $x_d = \Delta m_d / \Gamma_d$:
  rate of oscillation relative to decay
- Bell test impossible if $x < 2.0$:

system	x
$B^0/\overline{B}^0$	0.77
$K^0/\overline{K}^0$	0.95
$D^0/\overline{D}^0$	< 0.03
$B^0_s/\overline{B}^0_s$	~ 26

cf. Aspect: free to choose $\Delta\phi$

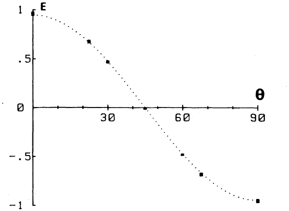


FIG. 3. Correlation of polarizations as a function of the relative angle of the polarimeters. The indicated errors are ±2 standard deviations. The dotted curve is not a fit to the data, but quantum mechanical predictions for the actual experiment. For ideal polarizers, the curve would reach the values ±1.

Beyond The Green Baize Table Conspiracy

Bertlmann, Bramon, Garbarino, Hiesmayr, Phys. Lett. A 332, 355–360 (2004)

With hypothetical active flavor measurement, could a Bell test be performed?

- B-meson sample decreases with Δt
- crucial parameter $x_d = \Delta m_d / \Gamma_d$: rate of oscillation relative to decay
- Bell test impossible if $x < 2.0$:

system	x
$B^0/\overline{B}^0$	0.77
$K^0/\overline{K}^0$	0.95
$D^0/\overline{D}^0$	< 0.03
$B_s^0/\overline{B}_s^0$	~ 26

cf. Aspect: free to choose $\Delta\phi$

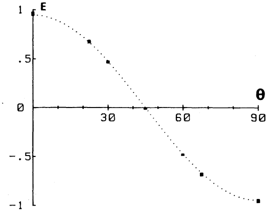


FIG. 3. Correlation of polarizations as a function of the relative angle of the polarimeters. The indicated errors are ±2 standard deviations. The dotted curve is not a fit to the data, but quantum mechanical predictions for the actual experiment. For ideal polarizers, the curve would reach the values ±1.

- so we are limited to comparing QM and *specific LR models*:

Beyond The Green Baize Table Conspiracy

Bertlmann, Bramon, Garbarino, Hiesmayr, Phys. Lett. A 332, 355–360 (2004)

With hypothetical active flavor measurement, could a Bell test be performed?

- B-meson sample decreases with Δt
- crucial parameter $x_d = \Delta m_d / \Gamma_d$: rate of oscillation relative to decay
- Bell test impossible if $x < 2.0$:

system	x
$B^0/\overline{B}^0$	0.77
$K^0/\overline{K}^0$	0.95
$D^0/\overline{D}^0$	< 0.03
$B_s^0/\overline{B}_s^0$	~ 26

cf. Aspect: free to choose $\Delta\phi$

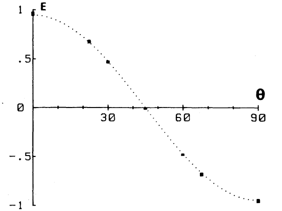


FIG. 3. Correlation of polarizations as a function of the relative angle of the polarimeters. The indicated errors are ±2 standard deviations. The dotted curve is not a fit to the data, but quantum mechanical predictions for the actual experiment. For ideal polarizers, the curve would reach the values ±1.

- so we are limited to comparing QM and *specific LR models*:
  - let mesons decay at various (t_1, t_2)

Beyond The Green Baize Table Conspiracy

Bertlmann, Bramon, Garbarino, Hiesmayr, Phys. Lett. A 332, 355–360 (2004)

With hypothetical active flavor measurement, could a Bell test be performed?

- B-meson sample decreases with Δt

cf. Aspect: free to choose $\Delta\phi$

- crucial parameter $x_d = \Delta m_d / \Gamma_d$: rate of oscillation relative to decay
- Bell test impossible if $x < 2.0$:

system	x
$B^0/\overline{B}^0$	0.77
$K^0/\overline{K}^0$	0.95
$D^0/\overline{D}^0$	< 0.03
$B^0_s/\overline{B}^0_s$	~ 26

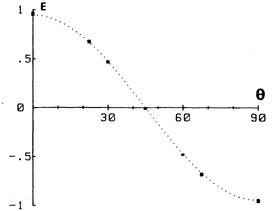


FIG. 3. Correlation of polarizations as a function of the relative angle of the polarimeters. The indicated errors are ±2 standard deviations. The dotted curve is not a fit to the data, but quantum mechanical predictions for the actual experiment. For ideal polarizers, the curve would reach the values ±1.

- so we are limited to comparing QM and *specific LR models*:
  - let mesons decay at various (t_1, t_2)
  - use final states (f_1, f_2) to determine flavours at (t_1, t_2)

Beyond The Green Baize Table Conspiracy

Bertlmann, Bramon, Garbarino, Hiesmayr, Phys. Lett. A 332, 355–360 (2004)

With hypothetical active flavor measurement, could a Bell test be performed?

- B-meson sample decreases with Δt
- crucial parameter $x_d = \Delta m_d / \Gamma_d$: rate of oscillation relative to decay
- Bell test impossible if $x < 2.0$:

system	x
$B^0/\overline{B}^0$	0.77
$K^0/\overline{K}^0$	0.95
$D^0/\overline{D}^0$	< 0.03
$B_s^0/\overline{B}_s^0$	~ 26

cf. Aspect: free to choose $\Delta\phi$

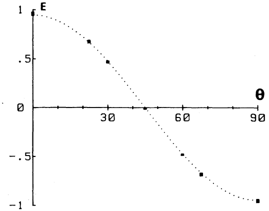


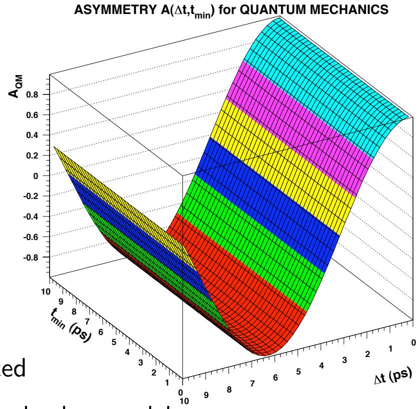
FIG. 3. Correlation of polarizations as a function of the relative angle of the polarimeters. The indicated errors are ±2 standard deviations. The dotted curve is not a fit to the data, but quantum mechanical predictions for the actual experiment. For ideal polarizers, the curve would reach the values ±1.

- so we are limited to comparing QM and *specific LR models*:
  - let mesons decay at various (t_1, t_2)
  - use final states (f_1, f_2) to determine flavours at (t_1, t_2)
  - check if this is consistent with a given model

QM versus specific local realistic models

The QM "model" has distinctive predictions for how B-meson flavours change:

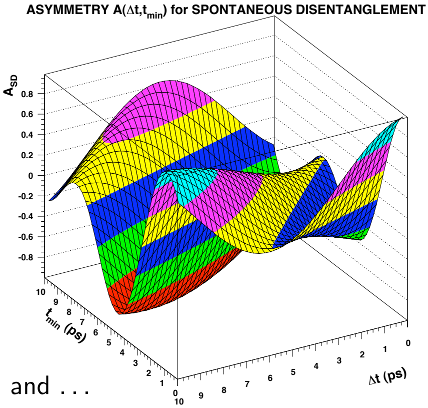
- after $\Upsilon(4S)$ decay, the two B-mesons operate as a unit
- when B_1 decays (50/50% $B^0/\overline{B}^0$), B_2 is in the opposite flavour state; as (proper) time passes, it oscillates opposite (OF) $\longleftrightarrow$ same flavour (SF)
- find *asymmetry* in pair decays:
  $$A(t_1, t_2) = \frac{R_{OF} - R_{SF}}{R_{OF} + R_{SF}} = \cos(\Delta m_d (t_2 - t_1))$$
- depends only on Δt $\longrightarrow$ (this is an entanglement thing)
- *cf.* a (t_1, t_2) plot would look complicated
- easy (in principle) to distinguish QM and other models: apart from Δt, *any* dependence on individual t_i is non-QM



QM versus specific local realistic models

LR model #1: spontaneous disentanglement

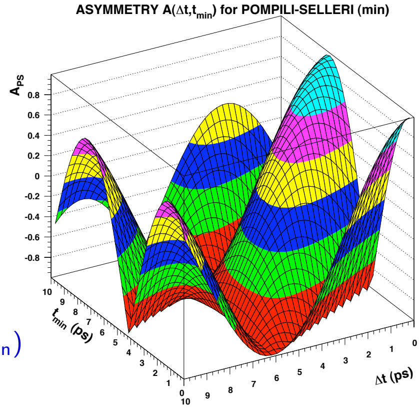
- after $\Upsilon(4S)$ decay, B's immediately separate into B^0 and $\overline{B}^0$
- $A_{SD} = \cos(\Delta m_d t_1)\cos(\Delta m_d t_2)$
  $= \frac{1}{2}[\cos(\Delta m_d \Sigma t) + \cos(\Delta m_d \Delta t)]$
- start with well-defined flavour
- oscillate *independently*
- A_{SD} depends on *both* t_1, t_2
- the variables shown are prejudicial: (t_1, t_2) would have looked simpler
- $(\Delta t, \Sigma t = [t_1 + t_2])$ likewise
- $(\Delta t, t_{min})$ chosen to compare with QM and ...



QM versus specific local realistic models

LR model #2: phenomenological model-family of Pompili & Selleri

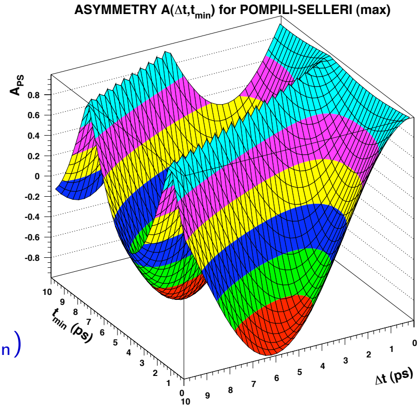
- QM-like states, including Δm
- individual meson masses are stable
- flavours of the pair are correlated: subject to instantaneous jumps
- require that QM predictions for *single B-mesons* are preserved
- asymmetry for any such model must fall within a *range*:
- $A_{PS}^{min} = 1 - \min(2+\Psi, 2-\Psi)$,
  $\Psi = \{1+\cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{\min}) - \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{\min})$
- $A_{PS}^{max} = 1 - |\{1-\cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{\min}) + \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{\min})|$



QM versus specific local realistic models

LR model #2: phenomenological model-family of Pompili & Selleri

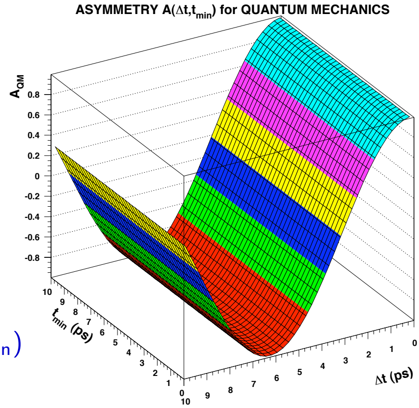
- QM-like states, including Δm
- individual meson masses are stable
- flavours of the pair are correlated: subject to instantaneous jumps
- require that QM predictions for *single B-mesons* are preserved
- asymmetry for any such model must fall within a *range*:
- $A_{PS}^{min} = 1 - \min(2+\Psi, 2-\Psi),$
  $\Psi = \{1+\cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{\min}) - \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{\min})$
- $A_{PS}^{max} = 1 - |\{1-\cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{\min}) + \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{\min})|$



QM versus specific local realistic models

LR model #2: phenomenological model-family of Pompili & Selleri

- QM-like states, including Δm
- individual meson masses are stable
- flavours of the pair are correlated: subject to instantaneous jumps
- require that QM predictions for *single B-mesons* are preserved
- asymmetry for any such model must fall within a *range*:
- $A_{PS}^{min} = 1 - \min(2+\Psi, 2-\Psi)$,
  $$\Psi = \{1+\cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{\mathrm{min}}) - \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{\mathrm{min}})$$
- $$A_{PS}^{max} = 1 - |\{1-\cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{\mathrm{min}}) + \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{\mathrm{min}})|$$

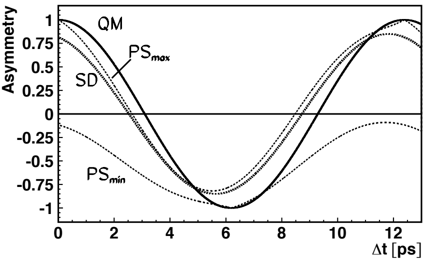


$A(\Delta t)$ for QM, SD, and Pompili-Selleri

- at Belle *we cannot measure individual decay times*
  [knowledge of the interaction point is poor compared to needed resolution]
- measuring Δt is fine for $A_{QM}(\Delta t) \equiv \frac{R_{OF} - R_{SF}}{R_{OF} + R_{SF}} = \cos(\Delta m_d \Delta t)$
- we must *integrate* over remaining variable for SD, PS:

SD: $\int_{\Delta t}^{\infty} \mathrm{d}(\Sigma t) R_{OF,SF}(\Sigma t, \Delta t) \longrightarrow$

PS: $\int_{0}^{\infty} \mathrm{d}t_{\mathrm{min}} R_{OF,SF}(t_{\mathrm{min}}, \Delta t) \longrightarrow$



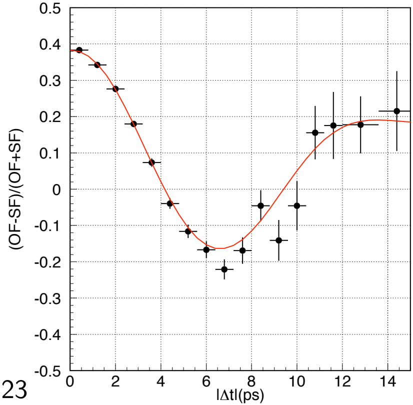
- these resemble the Δt evolution for QM, but differ in the detail: resolve the difference!!
- avoid assuming quantum mechanics along the way (which can be difficult)
- *N.B.* event rate at $\Delta t = 10\,\mathrm{ps}$ is $\sim \frac{1}{700} \times (\Delta t = 0)$

Adapt an existing analysis measuring Δm_d (1)

Belle: K. Abe et al., Phys. Rev. D 71, 072003 & 079903 (2005)

Belle's most current $\sin 2\phi_1$, $|\lambda|$, τ_B, Δm_d measurement at the time:

- 152×10^6 $B\overline{B}$ pairs
  - $5\times$ the discovery dataset
  - $\frac{1}{5}\times$ the eventual dataset
- 5417 CP- and 177368 flavour-eigenstate B-decay candidates
- sample purities vary 63–98% depending on the decay mode
- multivariate flavour-tagging of the other B decay; $\epsilon_{eff} = 28.7\%$
- $\Delta m_d = (0.511 \pm 0.005 \pm 0.006)\,\mathrm{ps}^{-1}$
  cf. $(0.5065 \pm 0.0019)\,\mathrm{ps}^{-1}$ PDG23

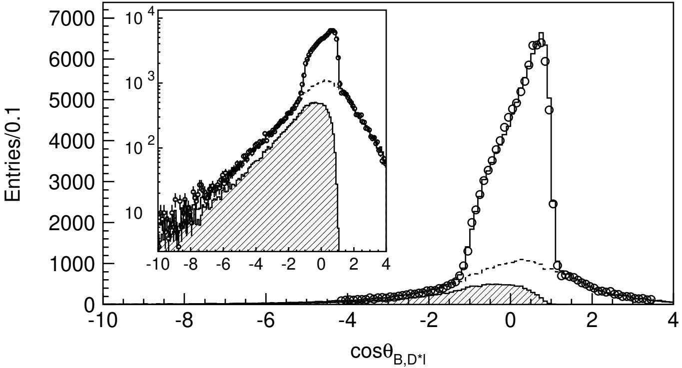


We then adapted this in various ways . . .

Adapt an existing analysis measuring Δm_d (2)

Belle: A. Go, A. Bay et al., Phys. Rev. Lett. 99, 131802 (2007)

- restrict 177368 $\rightarrow$ 84823 flavour eigenstates, choosing only $B^0 \rightarrow D^{*-}\ell^+\nu$ where the lepton explicitly determines the B-flavour

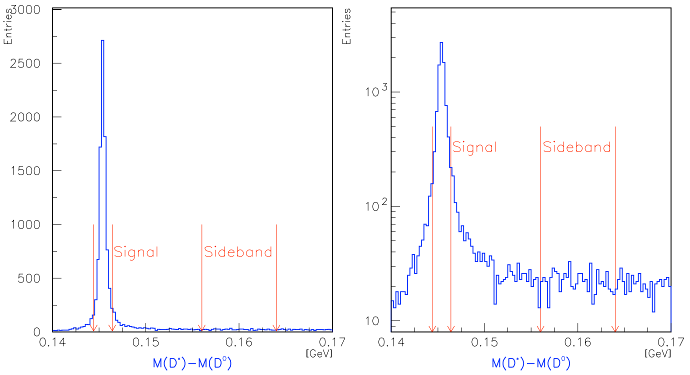


- restrict 84823 $\rightarrow$ 8565 by choosing only the best flavour tags of the other B: highest of 7 purity categories; leptons only

Then: background subtraction (1) fake D^*

Belle: A. Go, A. Bay et al., Phys. Rev. Lett. 99, 131802 (2007)

- signal relies on $D^{*-} \to \overline{D}^0\pi^-$ tag: energy release $Q \ll m_\pi \ll m_D$
- estimate background under peak using sideband region:



- affects samples differently: we subtract $\begin{cases} 126 \pm 6 & \text{OF events} \\ 54 \pm 4 & \text{SF events} \end{cases}$

Then: background subtraction (2) bad D^*-ℓ

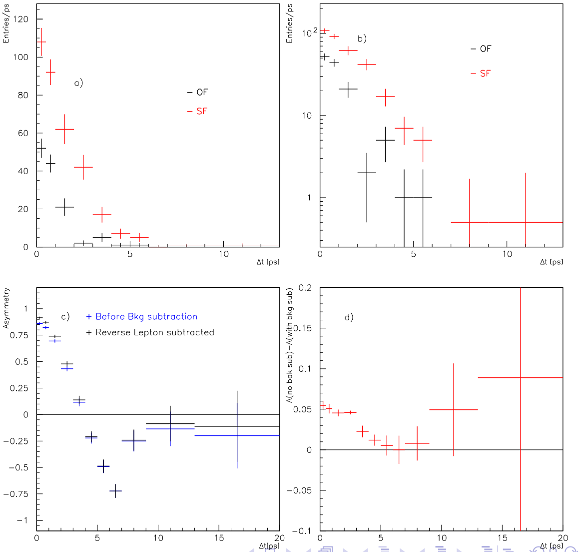
Belle: A. Go, A. Bay et al., Phys. Rev. Lett. 99, 131802 (2007)

- true D^* mesons; mostly, true leptons, D^*, ℓ produced by different B-decays
- estimated from data using a reversed momentum trick; Monte-Carlo validated

(a,b) here, unlike the last case, more SF bkgd

(c) $A(\Delta t)$ before & after correction

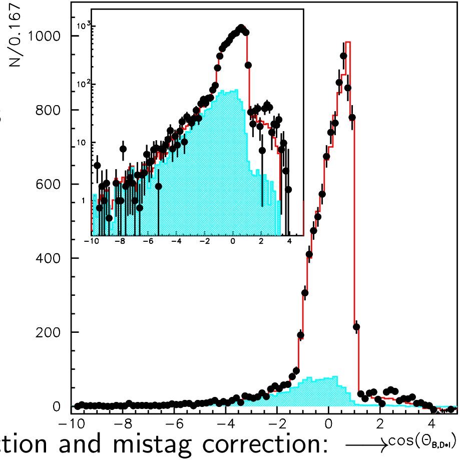
(d) residuals: note Δt structure



Then: background subtraction (3) $B^+ \to \overline{D}^{**0} \ell \nu$

Belle: A. Go, A. Bay et al., Phys. Rev. Lett. 99, 131802 (2007)

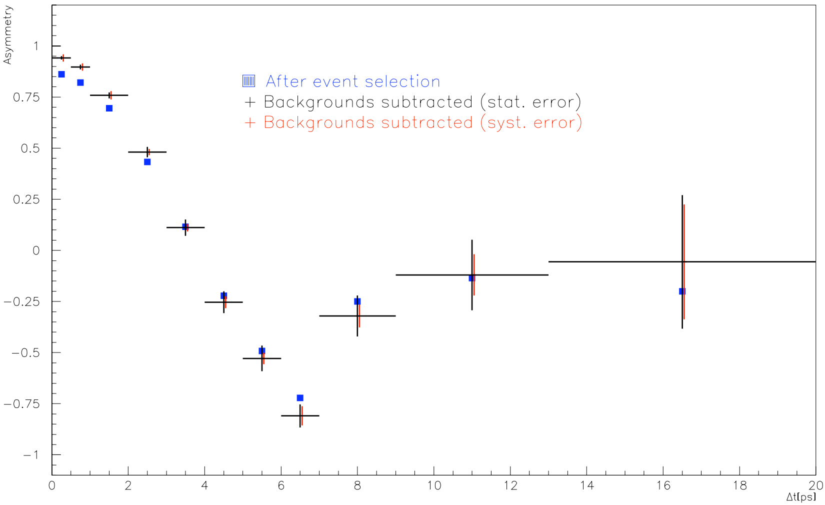
- the remaining background is from related decays of *charged B*
- we rely on the different distributions for D^{**} decays and D^* decays
- fit data to get fractions
- rely on MC for details:
  - — 254 OF *vs.* 1.5 SF events
  - — structured in Δt
  - — generous systematics



- $(1.5 \pm 0.1)\%$ mistag rate of other B corrected using OF and SF distributions; 0.5% systematic assigned
- effect of background subtraction and mistag correction: ⟶

Then: background subtraction (3) $B^+ \to \overline{D}^{**0}\ell\nu$

Belle: A. Go, A. Bay et al., Phys. Rev. Lett. 99, 131802 (2007)



Further adaptation: deconvolution and bias removal

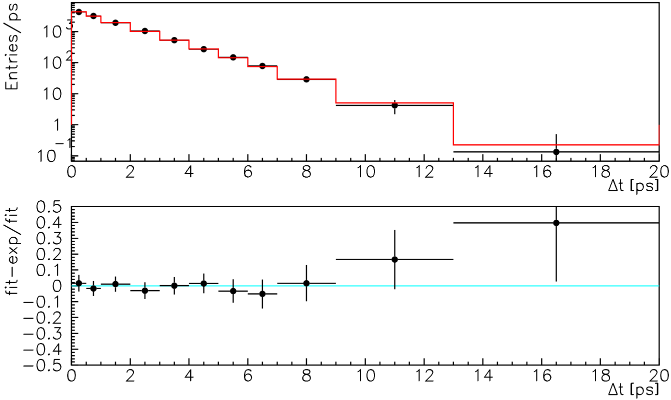
Belle: A. Go, A. Bay et al., Phys. Rev. Lett. 99, 131802 (2007)

- remaining effects are vertex resolution, efficiency losses ...
  these *blur out* the distribution in Δt
- use a deconvolution procedure (DSVD) to remove them:
  - due to falling rate with Δt, events assigned to 11 variable-width bins
  - build 11×11 response matrices in Δt using MC
  - optimise using toy MC study
  - regularisation (rank $11 \longrightarrow 5, 6$)
- MC events themselves produce a bias:
  e.g. SM has no SF events at $\Delta t = 0$
  - replace SF sample with $\mathrm{SF} + 0.2 \times \mathrm{OF}$
  - replace OF sample with $\mathrm{OF} + 0.2 \times \mathrm{SF}$
- measure remaining bias for 3 models: average it & subtract
- any bias still remaining $\longrightarrow$ systematic error
- check resulting OF & SF distributions by adding them ...

Further adaptation: deconvolution and bias removal

Belle: A. Go, A. Bay et al., Phys. Rev. Lett. 99, 131802 (2007)

. . . and fitting for the B^0 lifetime:



finds lifetime $\tau_B^0 = \quad (1.532 \pm 0.017)\,\mathrm{ps}$, with $\chi^2/n_{dof} = 3/11$

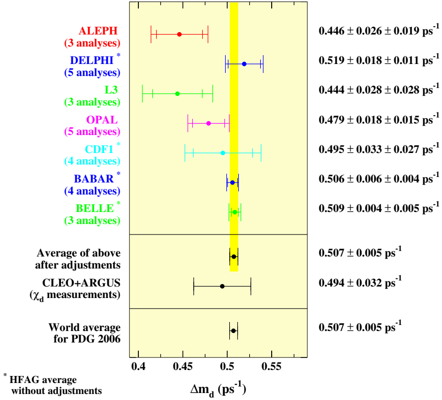
cf. world average $\quad (1.530 \pm 0.009)\,\mathrm{ps}$ from PDG2006

fitting to the QM, PS, and SD models (1)

Belle: A. Go, A. Bay et al., Phys. Rev. Lett. 99, 131802 (2007)

world average Δm_d is dominated by measurements that assume QM!!

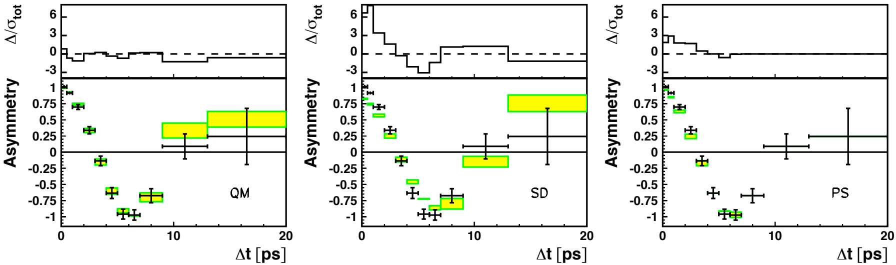
- $\langle \Delta m_d \rangle = (0.507 \pm 0.005)\mathrm{ps}^{-1}$
- so we remove Belle
- . . . and remove BaBar
- the resulting $\langle \Delta m_d \rangle_{\text{NO-QM}}$
  $= (0.496 \pm 0.014)\mathrm{ps}^{-1}$
- we add this to the fit as a new datapoint-with-uncertainty
- "Gaussian constraint", in current jargon
- the Δm_d parameter is then floated in the fits: each model chooses its value



fitting to the QM, PS, and SD models (2)

Belle: A. Go, A. Bay et al., Phys. Rev. Lett. 99, 131802 (2007)

fit: float Δm_d subject to WA-*sans*-(Belle+BaBar): $(0.496 \pm 0.014)\,\mathrm{ps}^{-1}$



QM fits well	SD disfavoured: 13σ	PS disfavoured: 5.1σ
$\chi^2/n_{dof} = 5/11$	$\chi^2/n_{dof} = 174/11$	$\chi^2/n_{dof} = 31/11$

- "SD fraction": $(1-\zeta_{B^0\overline{B}^0})A_{QM} + \zeta_{B^0\overline{B}^0}A_{SD}$, $\zeta_{B^0\overline{B}^0} = 0.029 \pm 0.057$
- Pompili-Selleri class: QM-like states, stable mass, flavor correlations; QM predictions for *single B-mesons* preserved

Summary and reflections

- entanglement at $\Upsilon(4S)$, used many times/second, was tested at Belle
  - test of specific models, not a Bell Inequality test ...
  - "decoherent fraction" $\zeta_{B^0\overline{B}^0} = 0.029 \pm 0.057$ [modified interf. term]
  - Pompili-Selleri class of LR models is ruled out at 5.1σ
- existing time-dependent $B\overline{B}$ analysis methods were adapted
  - this made the measurement feasible
  - the adaptation itself was a lot of work
  - care was needed to avoid surreptitiously assuming QM at various points
- we benefited enormously from an existing QM foundations study
  - excluding decoherence would have been familiar, but uninteresting
  - the Pompili-Selleri family was specific to $\Upsilon(4S) \to B\overline{B}$, and was something worth ruling out
  - importance depends on point of view ...
- future developments?

BACKUP SLIDES

The final data for posterity

Belle: A. Go, A. Bay et al., Phys. Rev. Lett. 99, 131802 (2007)

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