(Super)KEKB and Belle (II)
Entanglement of B-Mesons in $\Upsilon(4s)$ decays
$B^0$ Oscillations and CP Violation
Can Bell’s Inequality be checked?

Effects of decoherence on time dependent measurements
Indirect indicators
Measurement at Belle
Plans at Belle II
Conclusions
Accelerator: KEKB and superKEKB

KEKB: 1999-2010

- $\beta_\gamma = 0.42$
  (8 GeV, 3.5 GeV)

SuperKEKB/Belle II

<table>
<thead>
<tr>
<th>$\mathcal{L}_{\text{peak}}$ [$\text{cm}^{-2}\text{s}^{-1}$]</th>
<th>KEKB/Belle</th>
<th>SuperKEKB/Belle II</th>
</tr>
</thead>
<tbody>
<tr>
<td>achieved</td>
<td>target</td>
<td></td>
</tr>
<tr>
<td>$L_{\text{peak}}$</td>
<td>$2.1 \times 10^{34}$</td>
<td>$4.7 \times 10^{34}$</td>
</tr>
<tr>
<td>$L_{\text{int}}$ [fb$^{-1}$]</td>
<td>$1,004$ (711$_{Y(4S)}^\gamma$)</td>
<td>$424$ (362$_{Y(4S)}^\gamma$)</td>
</tr>
<tr>
<td>$N(B\bar{B})_{Y(4S)}$</td>
<td>$772 \times 10^6$</td>
<td>$387 \times 10^6$</td>
</tr>
</tbody>
</table>

superKEKB: 2019 - .....
Belle (II)

SVD: 4 lyr → VXD=(PXD 2 lyr + SVD 4 lyr)
CDC: small cell, long lever arm
ACC+TOF → ARICH + TOP
ECL: waveform sampling read-out electronics
KLM: RPC → Scintillator + RPC
\( \Upsilon(4s) \)

\[ e^+ e^- \rightarrow \Upsilon(4s) \rightarrow B^0 \bar{B}^0 \]

\[
m(\Upsilon(4s)) = 10.579 \ (\Gamma=0.0205) \text{ GeV} \\
2 \times m(B^0) = 10.558 \text{ GeV} \\
\Delta E = 21 \text{ MeV} \\
m(B^*) - m(B) = 45.2 \text{ MeV}
\]
Entanglement in $\Upsilon(4s)$ decays

$B^0/\bar{B}^0$ from a $\Upsilon(4s)$ decay are supposed to be in an entangled state

$$\Psi = \frac{1}{\sqrt{2}} \left[ |B^0(p)\rangle |\bar{B}^0(-p)\rangle - |\bar{B}^0(p)\rangle |B^0(-p)\rangle \right]$$

If one $B$ decays, the common wave function collapses and the $B^0/\bar{B}^0$ are in a defined state.

$$\gamma \beta c \tau/r(B^0) \sim 5 \times 10^{10} \Rightarrow \text{well separated spatially}$$

Measurements of $\Delta m_d$ and CP violation are based on entanglement (B-tag).

1) Can we demonstrate the entanglement (e.g. checking Bell’s inequality)?

2) How certain are we that the entanglement is always 100%?

$\Upsilon(4s) \rightarrow B^0 \bar{B}^0 \gamma$

Decoherence due to interaction with (BSM) background fields

Such effects could lead to systematic errors of our CP violation measurements
Due to weak interaction a $B^0$ can transform into its antiparticle. Formally this is described by a new (weak) base of $B^0_L$ and $B^0_H$:

$$|B_{L,H}\rangle = p|B^0_q\rangle \pm q|\overline{B}^0_q\rangle$$

$|p/q| = 1$ (CP conserved)

These two states interfere and resulting in time dependent oscillations:

$$P(B^0 \rightarrow \overline{B}^0) = \frac{1}{2} \Gamma \exp(-\Gamma t) (1-\cos(\Delta m \, t))$$

$$P(B^0 \rightarrow B^0) = \frac{1}{2} \Gamma \exp(-\Gamma t) (1+\cos(\Delta m \, t))$$

$\Delta m$: mass difference of $B^0_H$ and $B^0_L$

+ diagrams with $u, c$ exchange
CP violation

Weak interaction is also a source for CP violation

CP violation is a consequence of the complex phase of the CKM matrix

It happens if two (or more) amplitudes interfere

\[ A_f(B^0 \rightarrow f) = A_1 \exp(i\phi_w) + A_2 \exp(i\phi_s) \]
\[ A_b(\bar{B}^0 \rightarrow \bar{f}) = A_1 \exp(-i\phi_w) + A_2 \exp(i\phi_s) \]

\[ \Rightarrow |A_f|^2 \neq |A_b|^2 \]

In decays this happens either by interference of different decay amplitudes (tree and higher order)
or (more important) by interference of mixing and decay

Precise measurements of CP violation are the primary goals of the Belle and Belle II experiments
Y(4s) created at t=0 and decays in $B^0/\bar{B}^0$

**Tag:** one $B^0$ decays at $t_1$ in a way that we know whether it is $B^0$ or $\bar{B}^0$ (e.g. $\mu^+\nu D^-$) (in practice: use a BDT or NN to determine the decay state)

The other $B^0$ (always in the opposite state because of entanglement) starts oscillating

**Sig:** the other $B^0$ decays at $t_2$ in the signal mode we are interested in

- oscillation ($\Delta m$) measurement: $\mu^+\nu D^-$
- CP violation ($\sin(2\beta)$): $J/\psi K_s$

From the spatial separation and the known boost we determine $\Delta t = t_2 - t_1$
Phenomenology

Oscillations:

\[ P(B^0 \rightarrow \bar{B}^0) = \frac{1}{2} \Gamma \exp(-\Gamma \Delta t) (1 - \cos(\Delta m \Delta t)) \]

\[ A_{osc} = \frac{N(B^0 \rightarrow B^0) - N(B^0 \rightarrow \bar{B}^0)}{N(B^0 \rightarrow B^0) + N(B^0 \rightarrow \bar{B}^0)} = \cos(\Delta m \Delta t) \]

In reality: take into account mistag, resolution, background

Mixing induced (or time dependent) CP violation (TDCPV):

'Golden mode' \( \bar{B}^0(q=+1); B^0(q=-1) \rightarrow J/\psi K_s \)

\[ P(\Delta t, q) = \frac{1}{4} \Gamma \exp(-\Gamma \Delta t) \{ 1 + q [S \sin(\Delta m \Delta t) - C \cos(\Delta m \Delta t)] \} \]

For \( J/\psi K_s \) \( S = \sin(2\beta) \) \( C \sim 0 \)

\[ a_{CP} = \frac{N(B^0 \rightarrow f_{CP}) - N(\bar{B}^0 \rightarrow f_{CP})}{N(B^0 \rightarrow f_{CP}) + N(\bar{B}^0 \rightarrow f_{CP})} = S \sin(\Delta m \Delta t) \]
Can we check Bell’s inequality?

Classical Aspect type correlation experiment

spin-singlet state of photons or particles: \[
\frac{1}{\sqrt{2}} [ |\uparrow\rangle_1 |\downarrow\rangle_2 - |\downarrow\rangle_1 |\uparrow\rangle_2 ]
\]

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

\[
S = 2.697 \pm 0.015; \quad \text{cf.} \quad S_{QM} = 2.70 \pm 0.05
\]

Replace \( \uparrow \) by \( B^0 \) and \( \downarrow \) by \( \bar{B}^0 \)
Bell’s inequality with $B^0\bar{B}^0$

\[ \frac{1}{\sqrt{2}} \left[ |B^0(p)|\overline{B^0(-p)} - |\overline{B^0}(p)|B^0(-p) \right] \]

Replace the angle between the polarizers by $\alpha_{\text{eff}} = \Delta m \Delta t$

$S = 2.8$ (for $\alpha_{\text{eff}} = 45^\circ$, $90^\circ$ and $135^\circ$)

(A. Go & Chung Li, quant-ph/0310192v1 (2003): $S = 2.725 \pm 0.167 \pm 0.092$ (Belle data) )

Non QM test: Assume complete decoherence (both $B$ oscillate independently from $t=0$)

$S = 2.3$ \( S(\text{decoherent}) > 2 \) for $\Delta m/\Gamma < 2$

What’s wrong? => high correlation due to short lifetime
No way for Bell at Belle (II)


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

<table>
<thead>
<tr>
<th>system</th>
<th>( x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^0 ) / ( \bar{B}^0 )</td>
<td>0.77</td>
</tr>
<tr>
<td>( K^0 ) / ( \bar{K}^0 )</td>
<td>0.95</td>
</tr>
<tr>
<td>( D^0 ) / ( \bar{D}^0 )</td>
<td>&lt; 0.03</td>
</tr>
<tr>
<td>( B_s^0 ) / ( \bar{B}_s^0 )</td>
<td>( \sim 26 )</td>
</tr>
</tbody>
</table>

Furthermore:

We rely on the random decays of both \( B_s \).
No (reasonable) way to actively determine \( \Delta \mathcal{A}_{a,b} \rightarrow \Delta m \Delta t \).

A kind of Laplace demon could tune hidden parameters \( (t_1, t_2, \text{decay type}) \)
so that QM and Bell’s inequality is emulated, despite it’s not QM and local.
No practical way to close this loophole.
We can still calculate effects of special decoherent or non local models
Fit (modified) time dependence to data

• Spontaneous decoherence (SD):
  entanglement is lost at t=0 for a certain fraction of events
decoherence fraction $\zeta$

  local realism, which reproduces oscillation phenomenology

• Lindblad type decoherence (Comm. Math. Phys. 48(2) 119)
  Loss of coherence due to interaction with environment.
  coherence is gradually lost within a decoherence time $\tau_{\text{dec}}$
  a) $\tau_{\text{dec}} \ll \tau_B$: equivalent to SD
  b) $\tau_{\text{dec}} \gg \tau_B$: can be ignored
Time dependence if decoherent

Entangled

\[ \Psi = \frac{1}{\sqrt{2}} \left[ |B^0(p)|B^0(-p) - |\bar{B}^0(p)|B^0(-p) \right] \]

Decohered (Spontaneous, SD)

\[ \frac{1}{2} \left[ \{1 + \cos(\Delta m_d t)\}|B^0\rangle + \{1 - \cos(\Delta m_d t)\}|ar{B}^0\rangle \right] \]

\[ \frac{1}{2} \left[ \{1 + \cos(\Delta m_d t)\}|ar{B}^0\rangle + \{1 - \cos(\Delta m_d t)\}|B^0\rangle \right] \]

\[ \frac{1}{2} \left[ \{1 + \cos(\Delta m_d t)\}|\bar{B}^0\rangle + \{1 - \cos(\Delta m_d t)\}|B^0\rangle \right] \]

\[ t_1 \text{ cannot be measured: Integrate over } t_1 \]

\[ t_1 \text{ to } t_2 \]
Spontaneous Decoherence

$B^0/\bar{B}^0$ Oscillations: Probability to measure a same sign (SS) event:

a) Full coherence:

$$P(B^0 \bar{B}^0, \bar{B}^0 B^0) = \frac{1}{2} \Gamma \exp(-\Gamma t_2)(1 - \cos \Delta m t_2)$$

b) Full decoherence (Spontaneous decoherence, SD)

$$P(B^0 \bar{B}^0, \bar{B}^0 B^0) = \frac{1}{2} \Gamma \exp(-\Gamma t_2)(1 - \frac{1}{2} \frac{\Delta m + 2\Gamma^2}{\Gamma^2 + \Delta m^2} \cos \Delta m t_2 + \frac{\Gamma \Delta m}{2 \Gamma^2 + \Delta m^2} \sin \Delta m t_2)$$

Damping by \(~0.81\)

Additional SIN-term: \(~0.24\)

(using PDG averages: $\Delta m = 0.505 \pm 0.002$ ps$^{-1}$, $\Gamma = 0.658 \pm 0.002$ ps$^{-1}$)
The damping is probably difficult to measure, as it could be interpreted as mistag.

The SIN term (or phase shift) should be measurable.

Similar damping and phase shifts in measurements of time dependent CP violation

The damping could lead to a wrong measurement of $\sin(2\beta)$. This might be compensated if the mistag is calibrated using oscillation measurements.

The phase shift leads to a cross talk between S and C.
**Indirect Indicator: \( \chi \)**

### Time integrated oscillations: measure \( \chi = \frac{1}{2} \Delta m^2/(\Delta m^2 + \Gamma^2) \) using dilepton events

- Use \( \Delta m \) from LHCb as reference (no entanglement at LHCb!)

- Coherence: \( R = \frac{N^{++} + N^{-}}{N^{++} + N^{-} + N^{++}} = \chi \)

- SD: \( R = \frac{N^{++} + N^{-}}{N^{++} + N^{-} + N^{++}} = 2(\chi - \chi^2) \)

Use \( \chi \) calculated from LHCb’s \( \Delta m \) measurement (always decoherent)

![Graph](image.png)

- Old CLEO/ARGUS measurement of \( R = 0.182 \pm 0.015 \) (PDG) compatible with \( \sim 10\% \) decoherence

- Should be able to do much better at Belle II
Indirect Indicators: TDCPV

Compare $S_{\text{CP}}$ and $C_{\text{CP}}$ measurements at LHCb (always decoherent) and at $Y(4s)$

Same damping (0.81) and x-talk factors (0.24) as on slide 3

Compatible with up to 5-20% decoherence, preferred: 10% (1.7$\sigma$)

My averages, no correlations!

mistag calibration could cancel damping partially!
Belle’s most current \( \sin 2\phi_1, |\lambda|, \tau_B, \Delta m_d \) measurement at the time:

- \( 152 \times 10^6 B\bar{B} \) 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; \( \epsilon_{\text{eff}} = 28.7\% \)
- \( \Delta m_d = (0.511 \pm 0.005 \pm 0.006) \text{ps}^{-1} \)
  - cf. \( (0.5065 \pm 0.0019) \text{ps}^{-1} \) PDG23

We then adapted this in various ways...
Event Selection

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

- Background subtraction, deconvolution of $\Delta t$ resolution, mistag.....

- Fit for the $B^0$ lifetime:

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

\[
cf. \text{ world average } \tau_B^0 = (1.530 \pm 0.009) \text{ ps from PDG2006}
\]
Fit functions

QM: standard quantum mechanical entanglement
SD: spontaneous decoherence
Results

- **QM fits well**
  \[ \frac{\chi^2}{n_{dof}} = 5/11 \]

- **SD disfavoured**: \( 13\sigma \)
  \[ \frac{\chi^2}{n_{dof}} = 174/11 \]

- **PS disfavoured**: \( 5.1\sigma \)
  \[ \frac{\chi^2}{n_{dof}} = 31/11 \]

- "SD fraction": \( (1 - \zeta_{B^0\bar{B}^0})A_{QM} + \zeta_{B^0\bar{B}^0}A_{SD} \), \[ \zeta_{B^0\bar{B}^0} = 0.029 \pm 0.057 \]

- Pompili-Selleri class: QM-like states, stable mass, flavor correlations; QM predictions for single \( B \)-mesons preserved
What do we learn?

SD excluded by 13σ, but more relevant is the fraction of decoherent events

\[ f = (1 - \zeta) A_{QM} + \zeta A_{SD} \]
\[ \zeta = 0.029 \pm 0.057 \]

A fraction of ~10% is still possible!

This could lead to a shift of our \( S_{cp} \) measurements by \( \Delta S_{cp} \approx 0.012 \) (@ \( \Upsilon(4s) \))

The total systematic errors of the Belle II J/\( \psi \) \( K_s \) analysis is 0.014!

<table>
<thead>
<tr>
<th>Source</th>
<th>( \sigma(\varepsilon_{tag}) ) [%]</th>
<th>( \sigma(S_{cp}) )</th>
<th>( \sigma(C_{cp}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^0 \rightarrow D^{(*)-}\pi^+ ) sample size</td>
<td>0.43</td>
<td>0.004</td>
<td>0.007</td>
</tr>
<tr>
<td>( B^0 \rightarrow J/\psi K^0_s ) sample size</td>
<td>0.035</td>
<td>0.026</td>
<td></td>
</tr>
<tr>
<td>Fit model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analysis bias</td>
<td>0.02</td>
<td>0.002</td>
<td>0.005</td>
</tr>
<tr>
<td>Fixed resolution parameters</td>
<td>0.07</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>( \tau &amp; \Delta m_d )</td>
<td>0.06</td>
<td>0.001</td>
<td>0.000</td>
</tr>
<tr>
<td>( \sigma_{\Delta t} ) binning</td>
<td>0.04</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>( \Delta t ) measurement</td>
<td></td>
<td></td>
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<tr>
<td>Alignment</td>
<td>0.06</td>
<td>0.005</td>
<td>0.003</td>
</tr>
<tr>
<td>Beam spot</td>
<td>0.16</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>CMS Energy</td>
<td>0.03</td>
<td>0.000</td>
<td>0.001</td>
</tr>
<tr>
<td>Backgrounds</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>( B^0 \rightarrow D^{(*)-}\pi^+ S ) weight bias</td>
<td>0.24</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>( B^0 \rightarrow D^{(*)-}\pi^+ \Delta E ) backgrounds</td>
<td>0.11</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Signal ( \Delta E ) shape</td>
<td>0.08</td>
<td>0.002</td>
<td>0.000</td>
</tr>
<tr>
<td>Tag-side interference</td>
<td>—</td>
<td>0.010</td>
<td>0.007</td>
</tr>
<tr>
<td>Total systematic</td>
<td>0.34</td>
<td>0.014</td>
<td>0.012</td>
</tr>
</tbody>
</table>

Belle II 362 fb\(^{-1}\), preliminary
Plans @ Belle II

Repeat Belle analysis with higher statistics, more channels, better resolution

\[ B^0 \rightarrow D^- \pi^+, D^{*-} \pi^+, D^{*-} \rho^+ \]

Make use of better vertex resolution and smaller interaction region:

<table>
<thead>
<tr>
<th></th>
<th>KEKB</th>
<th>superKEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_x )</td>
<td>150 µm</td>
<td>10 µm</td>
</tr>
<tr>
<td>( \sigma_y )</td>
<td>940 nm</td>
<td>50 nm</td>
</tr>
<tr>
<td>( \sigma_z, \text{ eff} )</td>
<td>7 mm</td>
<td>0.25 mm</td>
</tr>
</tbody>
</table>

\( \gamma \beta c = 0.125 \text{ mm} \)

Not perfect yet, but some chance to limit \( t_1 \)

Transverse separation \( \sim 50 \mu m \)

Vertex resolution \( \sigma_{\text{res}} \sim 20 \mu m \)
Access to $t_1$ adds a new dimension and should result in higher sensitivity.

**Asymmetry for QM**

Entanglement: depends only on $\Delta t$

**Asymmetry for SD**

Decoherence: depends on $t_1$ and $\Delta t$

Setting a lower limit on $t_1$ could also make a check of Bell’s inequality possible (randomize).

Bruce Yabsley
Conclusions

• ‘Aspect’ style experiments to check Bell’s inequality are not possible with $\Upsilon(4s) \rightarrow B^0 \bar{B}^0$
  
  – no active measurement (random decay of the $B^0$): conspiracy loophole!
  
  – short $B^0$ lifetime induces correlations which violate Bell’s inequality even for a local realistic scenario.

• QM and alternative models can be tested fitting the time dependence of $B^0$ oscillations. Belle analysis: alternative scenarios excluded by $13\sigma$ (SD) and $5.1\sigma$ (PS).

• A fraction of ~10% of decoherent events is still compatible with the data.

• Possible systematic error of our time dependent CP violation measurements (so far not taken into account!).

• Belle II has the potential to improve on this.

• Questions to theory: what mechanisms (SM or BSM) could lead to a loss of coherence?

  With contributions from Sven Vahsen & team (Hawaii), Bruce Yabsley (Sidney), Fumiaki Otani, Takeo Higuchi (IPMU)
Any entanglement destroyed by fragmentation and hadronization

$B^0/B$(any) system created with many other hadrons: mixed state

Primary Vertex detectable: each $B^0$ timed independently