Quantum Entanglement at the $\Upsilon(5S)$ at Belle II

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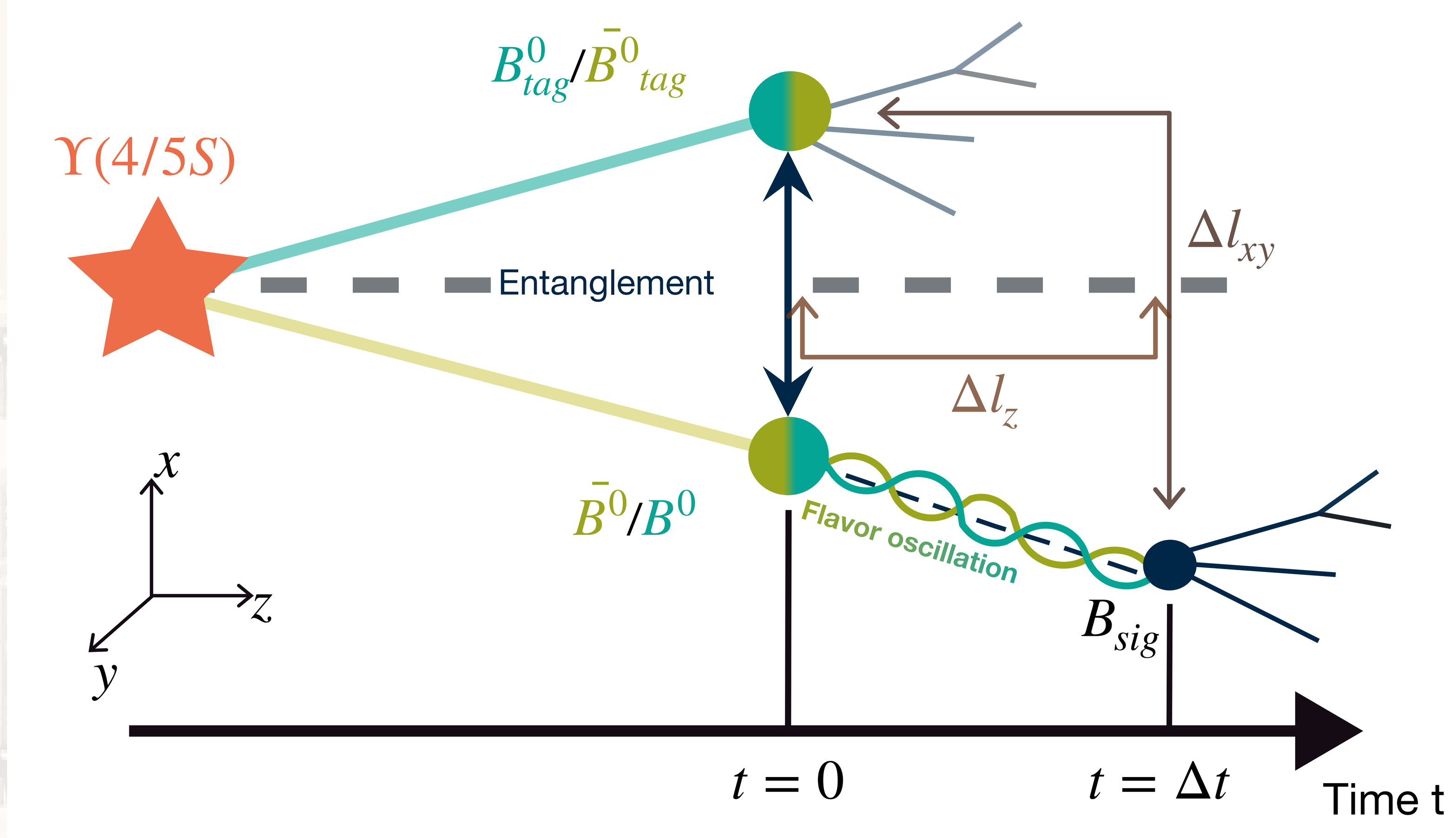
Belle II

What is Quantum Entanglement?

- Quantum entanglement is a fundamental property in quantum mechanics.
- It describes a phenomenon where two or more particles become correlated.
- The state of one particle cannot be described without the state of the other, even when separated by large distances.
- A typical example is the entangled Bell state for two particles with possible states up and down. The wave function for the Bell state is: $|\Psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$.

Entanglement and Particle Physics at Belle

- $\Upsilon(4S)$ decay to $B^0\bar{B}^0$ are supposed to be **entangled state**. This means their flavor state are supposed to **oscillate** in opposite phase with each other.
- How certain are we that entanglement is consistently 100 %?
- $\Upsilon(5S)$ offers even **richer quantum states**, leading to more scenarios of disentanglement and more measurements possible.
- Measurements of the **spatial separations** of the B-meson allow us to compute **time-dependent** parameters, which are directly correlated to the **quantum coherence** of the system.



Sketch of the decay of the resonance into the B-meson pair in the laboratory frame. Δl_{xy} is the spatial separation in the transverse plane, it is only accessible at the $\Upsilon(5S)$.

Comparing the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances

- The $\Upsilon(4S)$ decays almost exclusively into $B^0\bar{B}^0$ pairs in a **pure antisymmetric ($C=-1$) entangled state**:

$$|\Psi_{4S}\rangle = \frac{1}{\sqrt{2}}\left(\left|B_1^0\bar{B}_2^0\right\rangle - \left|\bar{B}_1^0 B_2^0\right\rangle\right)$$

- This means we expect the two B mesons to be **maximally entangled**.
- The time evolution observable is only $\Delta t = t_1 - t_2$.
- Previous results by Belle find that a **10 % fraction of decoherent events** is still possible: need for **precision measurement**,

- The $\Upsilon(5S)$ is more energetic, and can also decay into excited $B^{*0}\bar{B}^{*0}$ and $B^{*0}\bar{B}^0$ states.
- These states lead to both **symmetric ($C=+1$)** and **antisymmetric ($C=-1$)** configurations, which can **mix**.

$$|\Psi_{5S}\rangle = \frac{1}{\sqrt{2}}\left(\left|B_1^0\bar{B}_2^0\right\rangle \pm \left|\bar{B}_1^0 B_2^0\right\rangle\right)$$

- The mixed sample behaves like a **partially disentangled state**, allowing studies of **decoherence**.
- The higher momentum at the $\Upsilon(5S)$ allows independent reconstruction of t_1 and t_2 instead of only Δt.

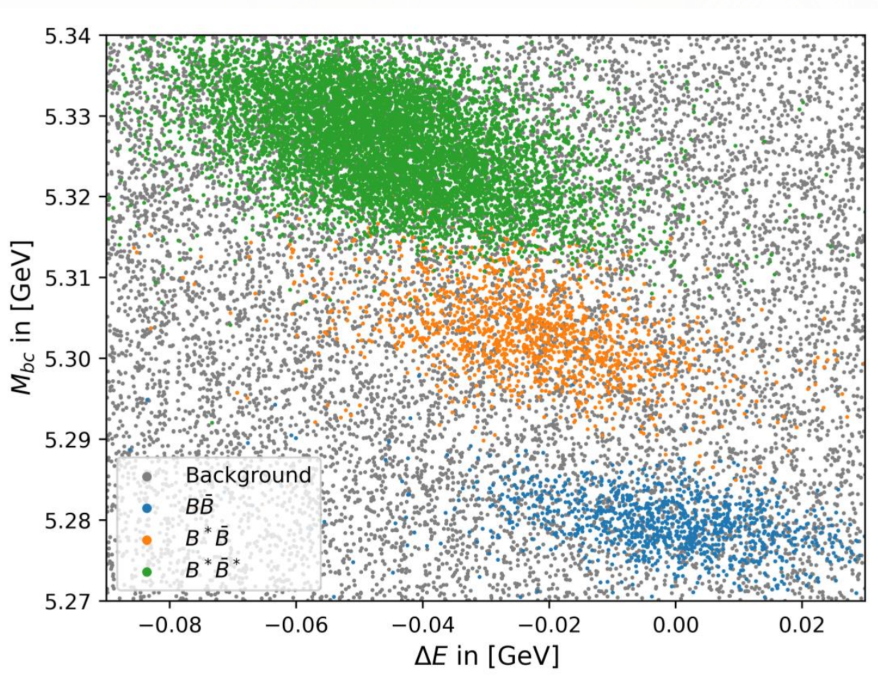
Analysis and theory at $\Upsilon(5S)$

State separation

- Decay channel reconstructed: $B^0 \to D^{(*)-}\pi^+$, $D^-\pi^+$. Integrated luminosity on on-resonance $\Upsilon(5S)$ $L = 121$ fb^{-1}.
- Need to separate between :

Decay type	C-state
$\Upsilon(5S) \to \bar{B}^0 B^0$	-1
$\Upsilon(5S) \to \bar{B}^0 B^{0*}$, $B^{0*} \to \gamma B^0$	**+1**
$\Upsilon(5S) \to \bar{B}^{0*} B^{0*}$, $B^{0*} \to \gamma B^0$	-1

- The energy of the photon (45 MeV) is too low to be reconstructed: differentiate the channels using M_{bc} and ΔE information.

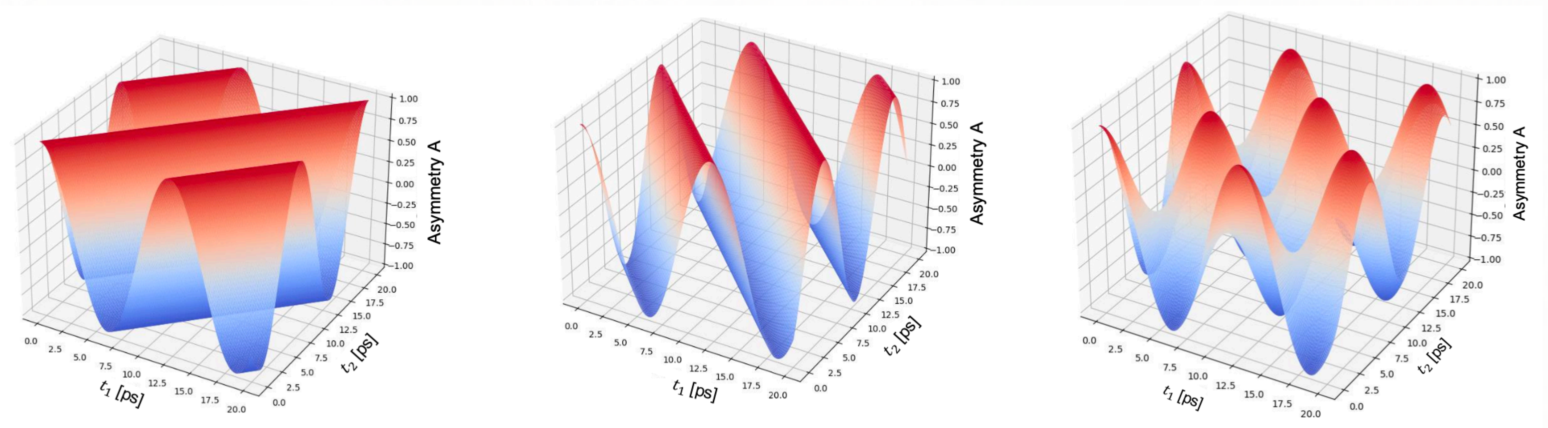


M_{bc} against ΔE plotted for different decay states and background (combinatorial and continuum).

Outlook

- Ongoing analysis of the decoherence fraction at the $\Upsilon(5S)$.
- Prospect of use of quantum state tomography to independently probe the $B^0\bar{B}^0$ entanglement.
- Current questioning on possible CHSH measurement at $\Upsilon(5S)$.

Asymmetry and disentanglement



Left: anti-symmetric, C=-1. *Center*: symmetric, C=+1. *Right*: disentangled

Antisymmetric wavefunction C=-1: $A = \cos\Delta m(t_1 - t_2)$

Symmetric wavefunction C=+1: $A = \cos\Delta m(t_1 + t_2)$

The **flavor asymmetry** is defined as: $A = \frac{P_{OF}-P_{SF}}{P_{SF}+P_{OF}}$ it quantifies the difference between observing **opposite-flavor** and **same-flavor** decays of the two B-mesons. P_{OF} and P_{SF} are the probabilities for opposite-flavor and same-flavor decays, respectively

Case of disentanglement, the wavefunctions become:
$|\Psi_1(t_1,t_2)\rangle = [|B^0(t_1)\rangle \otimes |\bar{B}^0(t_2)\rangle]$,
$|\Psi_2(t_1,t_2)\rangle = [|\bar{B}^0(t_1)\rangle \otimes |B^0(t_2)\rangle]$
with probability 1/2. The Asymmetry is:
$A(t_1,t_2) = \cos\Delta m t_1 \cos\Delta m t_2$

Entanglement of formation (EOF)

- Properly **disentangled states** can be created by selecting a **mixture** of $C = \pm 1$:

$$A_{mixed} = \cos\frac{\Delta m(t_1+t_2)}{2} + \cos\frac{\Delta m(t_1-t_2)}{2} = \cdots = \cos(\Delta m t_1)\cos(\Delta m t_2)$$

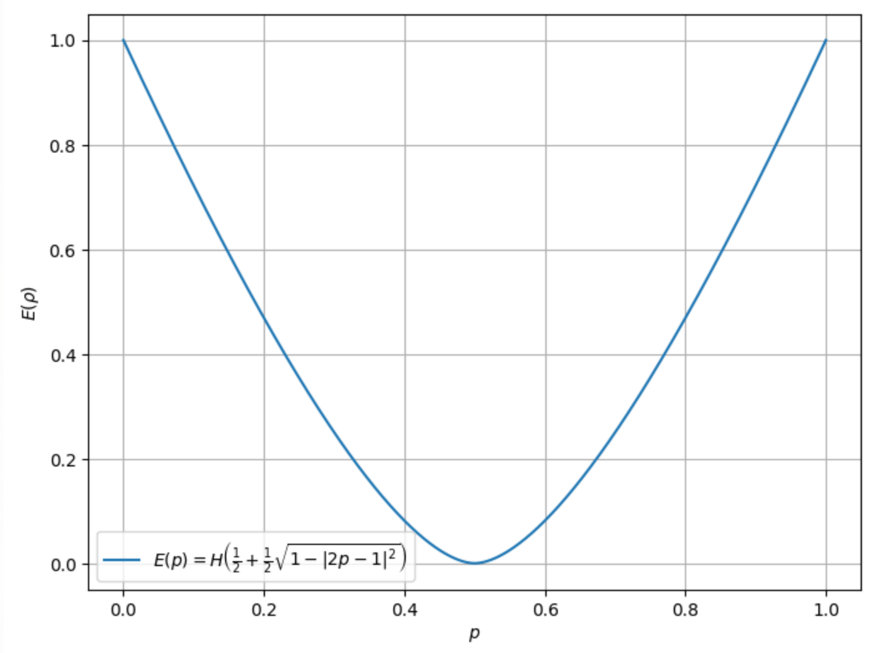
- These states are indistinguishable from a genuine disentangled independent state.

  - Suppose the mixed state density matrix:

$$\rho = p|C_{+1}\rangle\langle C_{+1}| + (1-p)|C_{-1}\rangle\langle C_{-1}|$$

  - One can compute the concurrence as a measure of entanglement, as a function of the mixture fraction p. For an equal mixture $p = \frac{1}{2}$, the system behaves as if completely disentangled.

p	Concurrence $C(p)$	EOF $E(p)$
0 (C=-1)	1	$H(\frac{1}{2}) = 1$
1 (C=+1)	1	$H(\frac{1}{2}) = 1$
$\frac{1}{2}$ (equal mixture)	0	$H(1) = 0$



Entanglement of the mixed state plotted against the mixing value p. $E=1$ is completely entangled, $E=0$ is completely disentangled.

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