Queen Mary
University of London

Particle Physics Research Centre
DETECTOR
DEVELOPMENT GROUP

Subatomic qbit pairs.

What can we learn?

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Overview

- **QMUL's detector development group and facilities**
- **Preparing pairs of qbits at a B Factory**
- **Discrete symmetries**
- **Sidereal time variations**
- **Questions**
- **Summary**

Note that entanglement in top quark pairs has recently been observed by the ATLAS Collaboration at CERN [ATLAS-CONF-2023-069], which is not covered here.

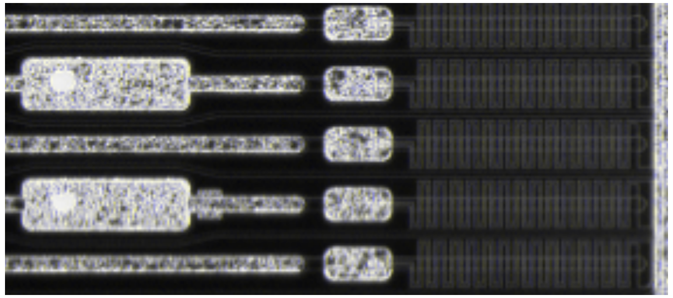
QMUL’s detector development group and facilities

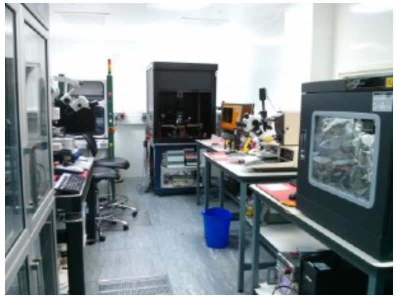
- Our mission is to develop novel technologies for fundamental science and apply our skills to solving real world problems
- Currently working on:
  - Silicon detectors for future colliders: High Luminosity Large Hadron Collider at CERN in Switzerland; and an upgrade of the Belle 2 vertex detector for KEK in Japan.
  - Novel radiation detector and forensics solutions for the nuclear sector
  - Novel neutron detectors for medical physics
- See Nicola’s talk for some new work we are starting to get involved with

QMUL's detector development group and facilities

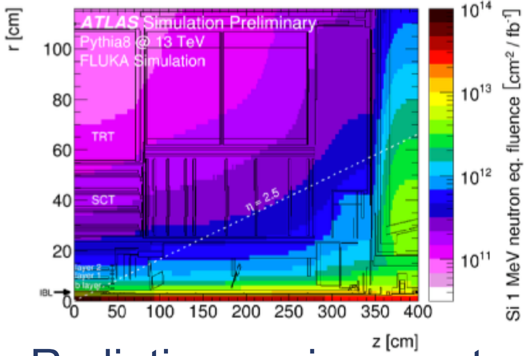
- Our nano and micro fabrication expertise spans a wide range of capabilities
  - Quantum device fabrication and testing - see Jan Mol's presentation
  - Decades of contributing to silicon detector builds for particle physics
  - OPAL at LEP through to the High Luminosity LHC (ATLAS) and Belle 2 upgrades - microelectronics and systems engineering expertise e.g.

Examples from the ATLAS (CERN, Switzerland) and Belle 2 (KEK, Japan) upgrade projects

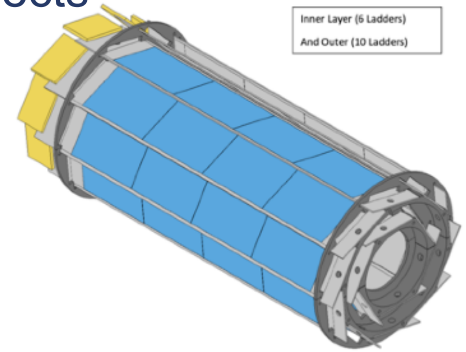




Micron resolution image capture, testing and quality control for silicon sensors



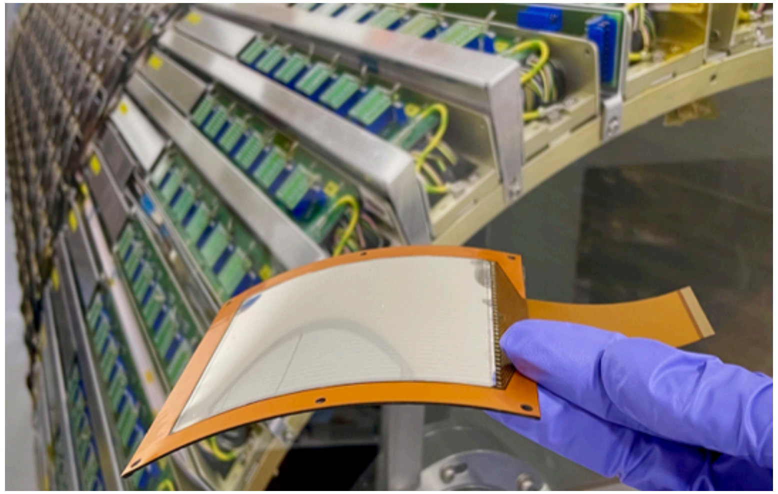
Radiation environment simulation

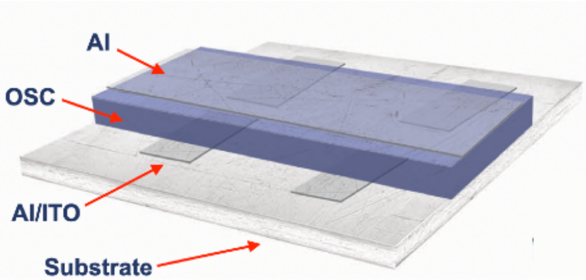


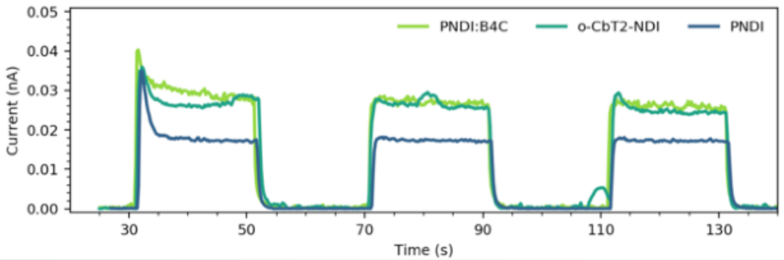
System engineering design and realisation

QMUL’s detector development group and facilities

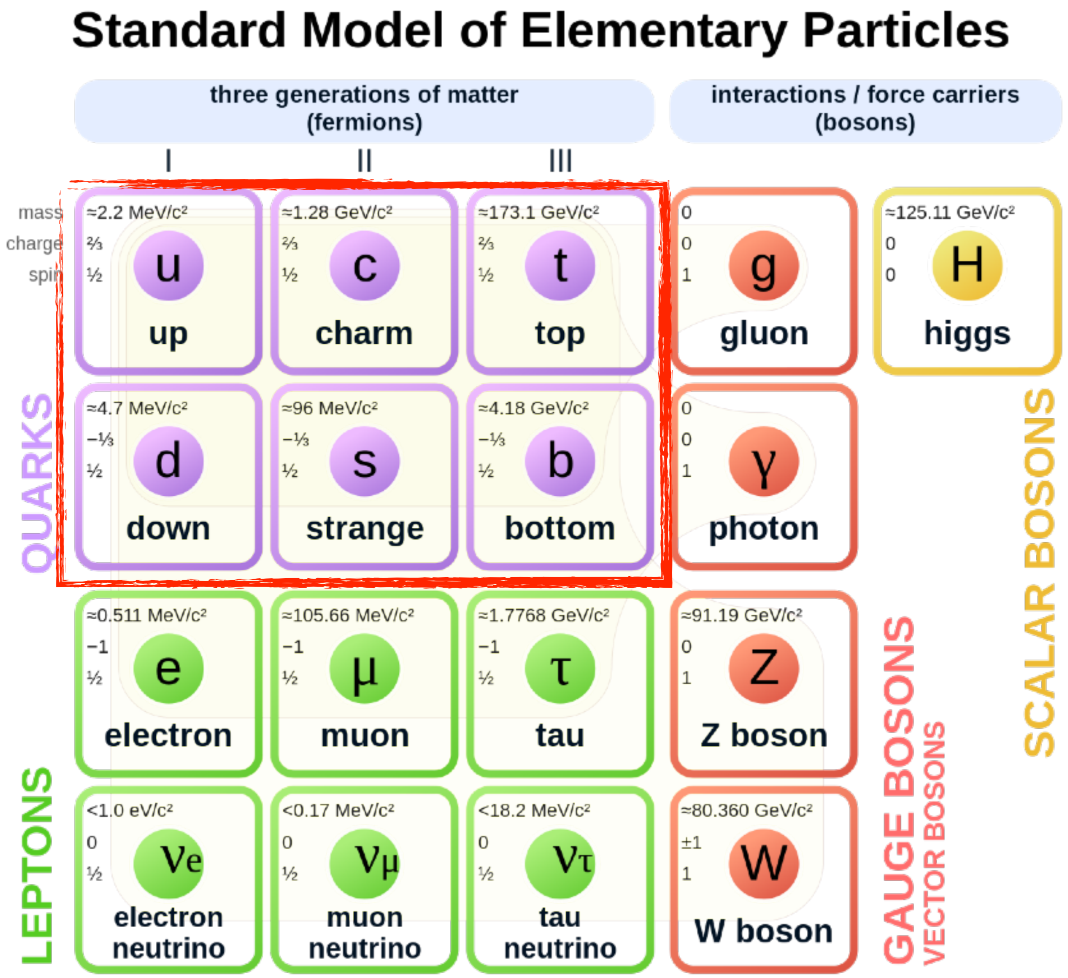
- **Work on novel and conventional technologies:**
  - **Silicon for particle physics**
  - **Curved ultra thin silicon**
  - **Solution processed electronics and materials for novel hadron and neutron detection capabilities**
    - **Looking to deploy neutron beam background monitors using this**
  - **Long range α detection for civil nuclear applications**
  - **Product development for SME’s**

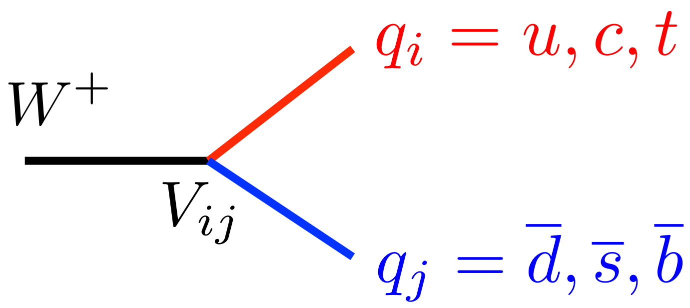






Subatomic building blocks





$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\phi_1 = \beta \equiv \arg\left[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right]$$
$$\phi_2 = \alpha \equiv \arg\left[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right]$$
$$\phi_3 = \gamma \equiv \arg\left[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right]$$

Pairs of qbits at a B Factory

- Entanglement from collisions at the $\Upsilon(4S)$ resonance: 10.58 GeV centre of mass

$$e^+e^- \to B^0\overline{B}^0$$

- Antisymmetric wave function of an entangled system

$$\psi = \frac{1}{\sqrt{2}}(|B^0\rangle|\overline{B}^0\rangle - |\overline{B}^0\rangle|B^0\rangle)$$

- Different ways to analyse the states:
  - CP filters
  - Flavour filters

Decays are filters to analyse the quantum state of the B when it decays.

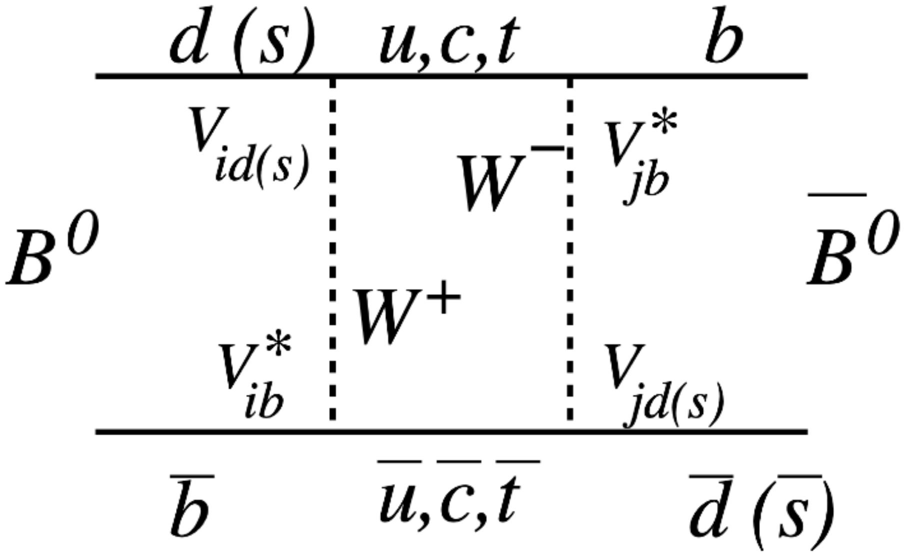
Like B field selection for the Stern Gerlach experiment; but with some important differences

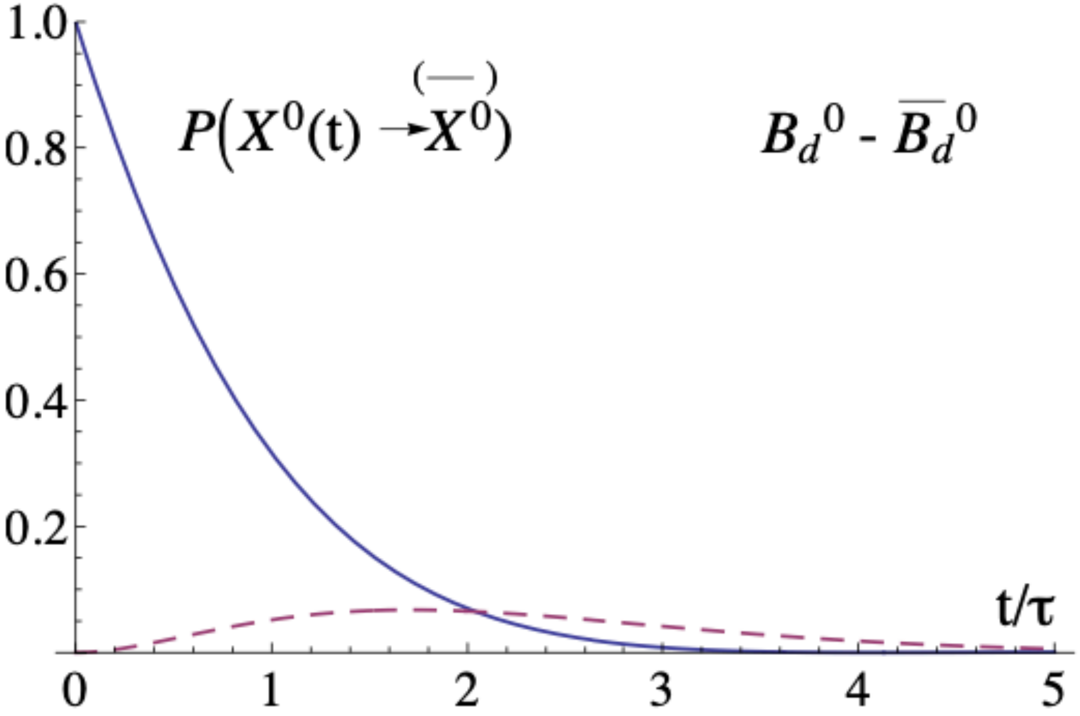
- 16 combinations to use discrete symmetries to examine this qbit pair analogue (see later)

e.g. see A. Bevan et. al Eur. Phys. J. C74 (2014) 3026 and references therein.

Pairs of qbits at a B Factory

- B mesons have a finite lifetime and oscillate between particle and antiparticle
- Oscillation frequency is the mass difference: $\Delta m_d = 0.5065\,\mathrm{ps}^{-1}$





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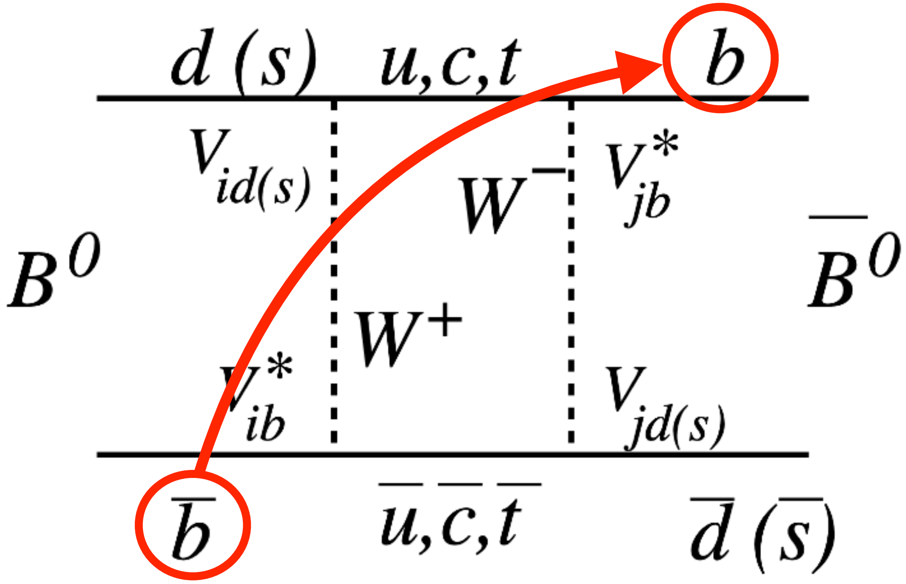

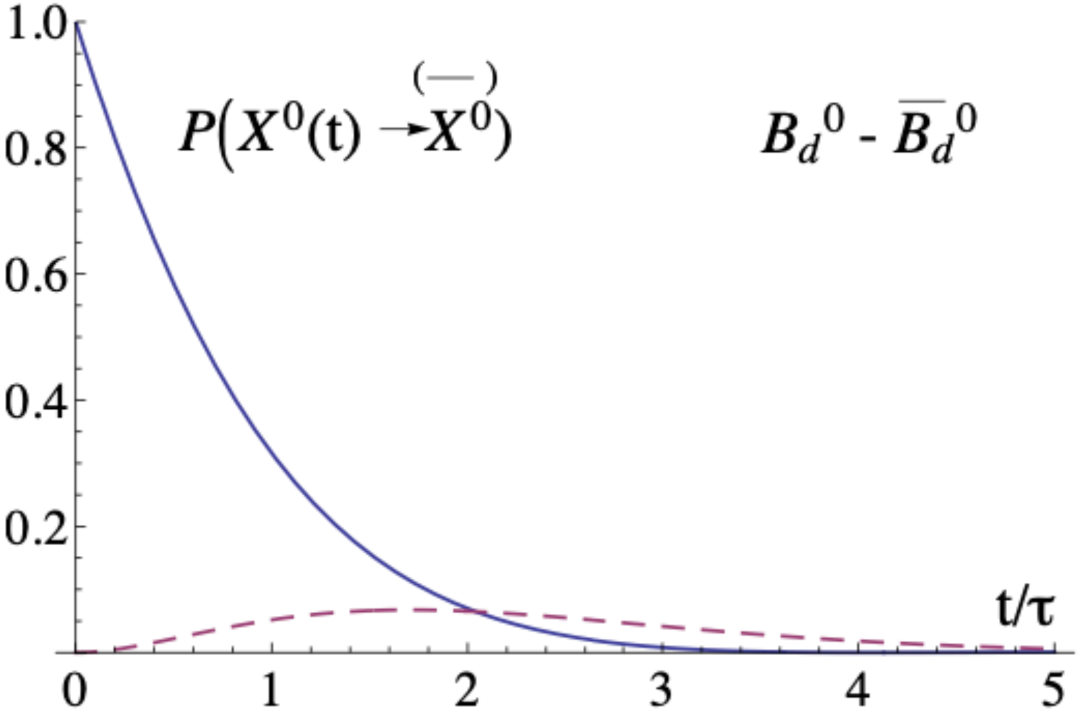

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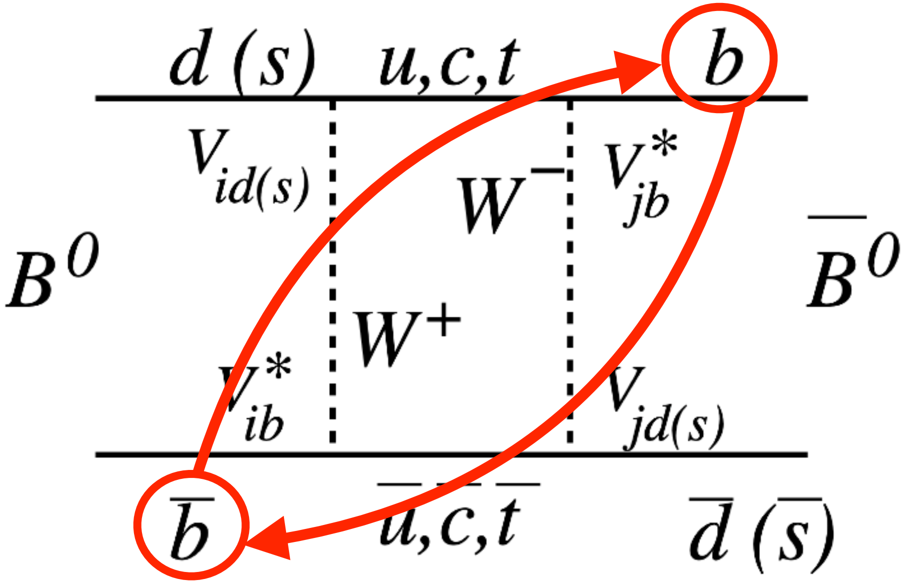

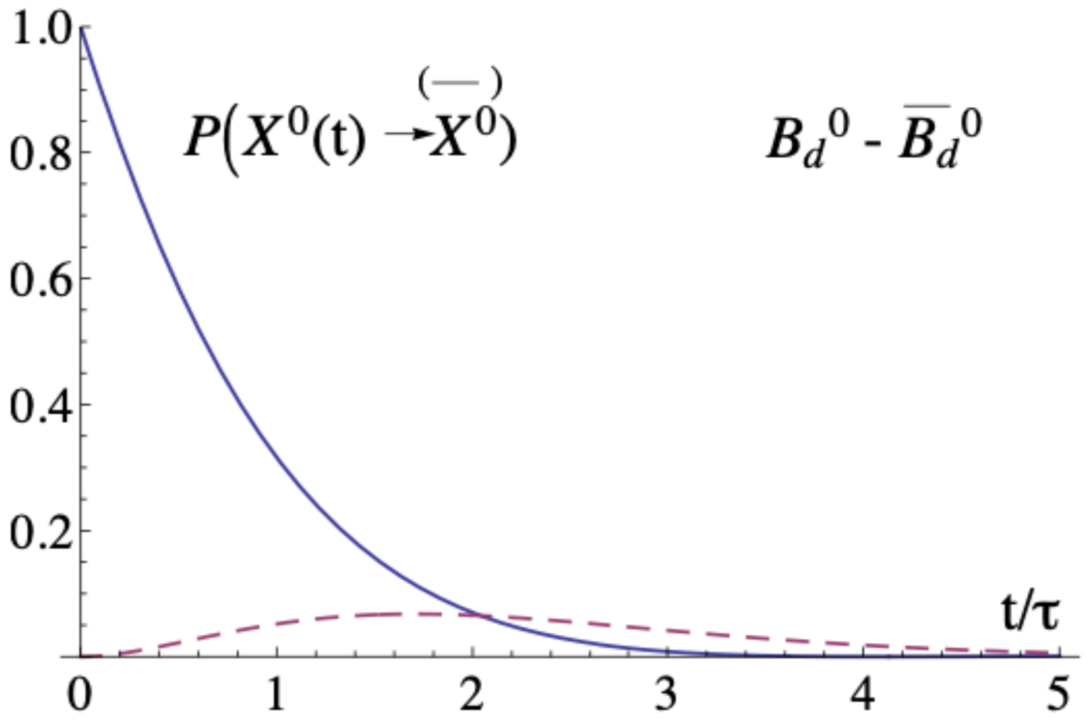

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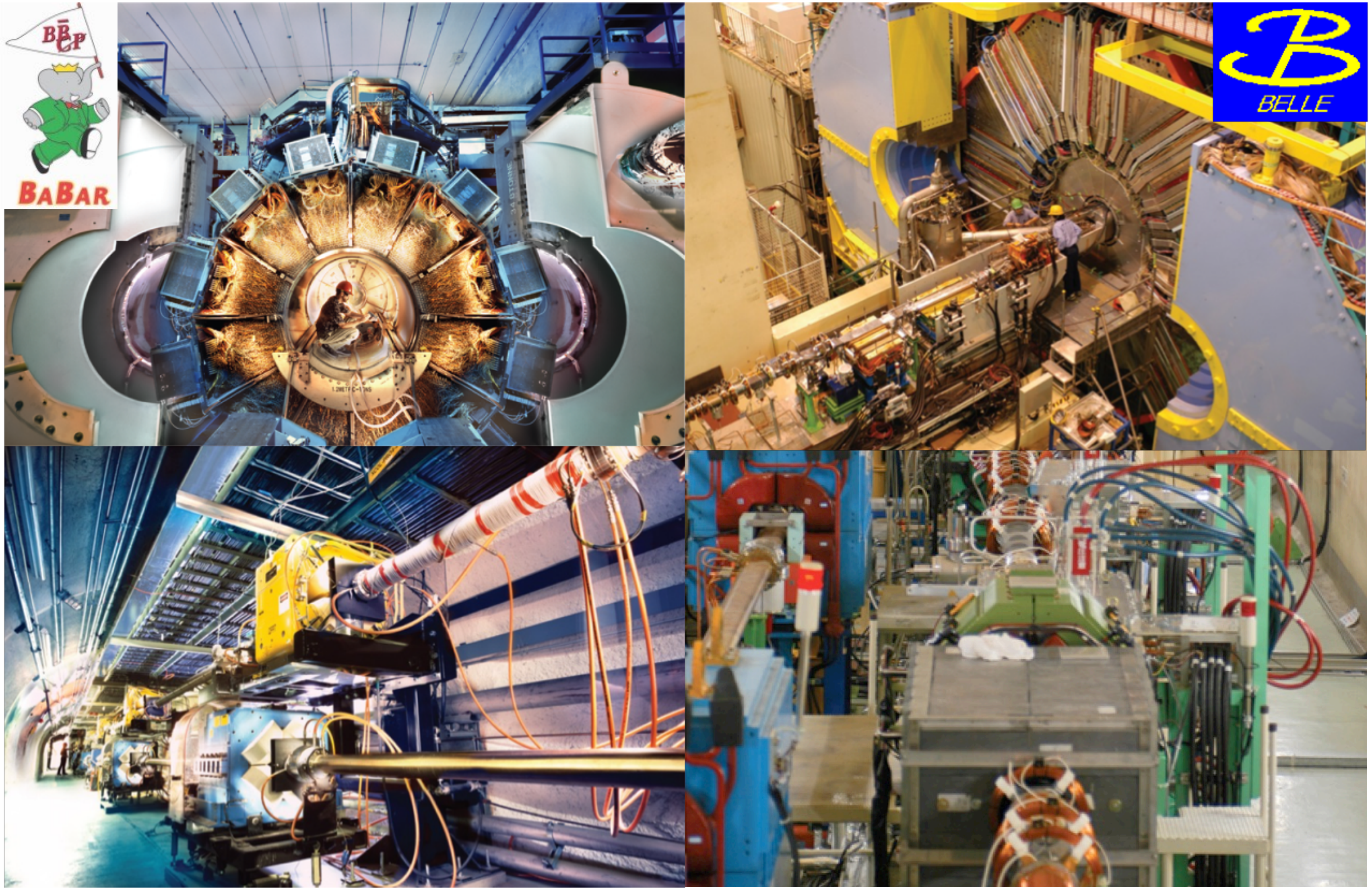
Facilities: BaBar @ SLAC, Belle (2) @ KEK



Pairs of qbits at a B Factory

- qbit pairs are initially in

$$\psi = \frac{1}{\sqrt{2}}(|B^0\rangle|\overline{B}^0\rangle - |\overline{B}^0\rangle|B^0\rangle)$$

- which is equivalent to

$$\psi = \frac{1}{\sqrt{2}}(|0\rangle|1\rangle - |1\rangle|0\rangle)$$

- At some later time after one of the B mesons decays the data evolves into the four available outcomes, with different probabilities of the states existing at any point in time

$$\psi(t) = \alpha(t)|0\rangle|1\rangle + \beta(t)|1\rangle|0\rangle) + \gamma(t)|0\rangle|0\rangle + \delta(t)|1\rangle|1\rangle$$

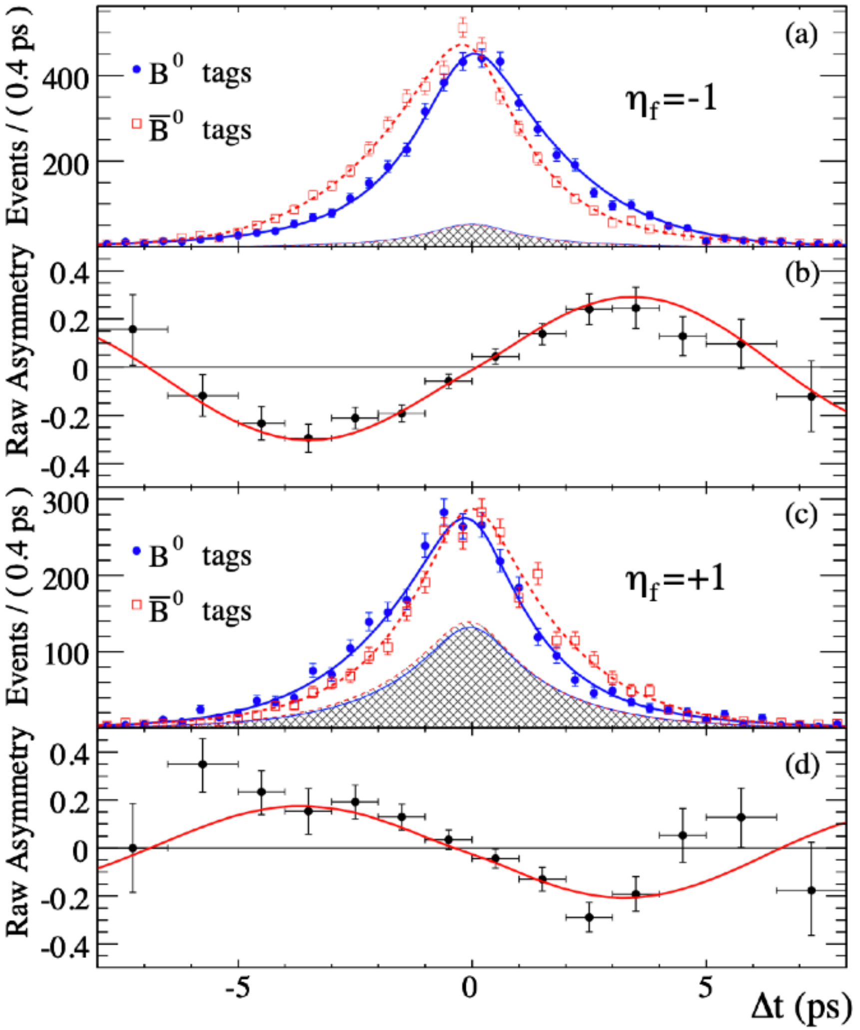
Pairs of qbits at a B Factory

- **Analyse B mesons via flavour specific final states (B_{tag}, direct link between the strong force/ quark composition of the B and the final state), or via the CP nature of the final state (even/odd, $\eta_{CP} = \pm 1$), B_{CP}.**

- **Examples of B_{tag} include**
  - $B^0 \rightarrow D^{(*)-}(\pi^+, \rho^+, a_1^+)$
  - $\overline{B}^0 \rightarrow D^{(*)+}(\pi^-, \rho^-, a_1^-)$

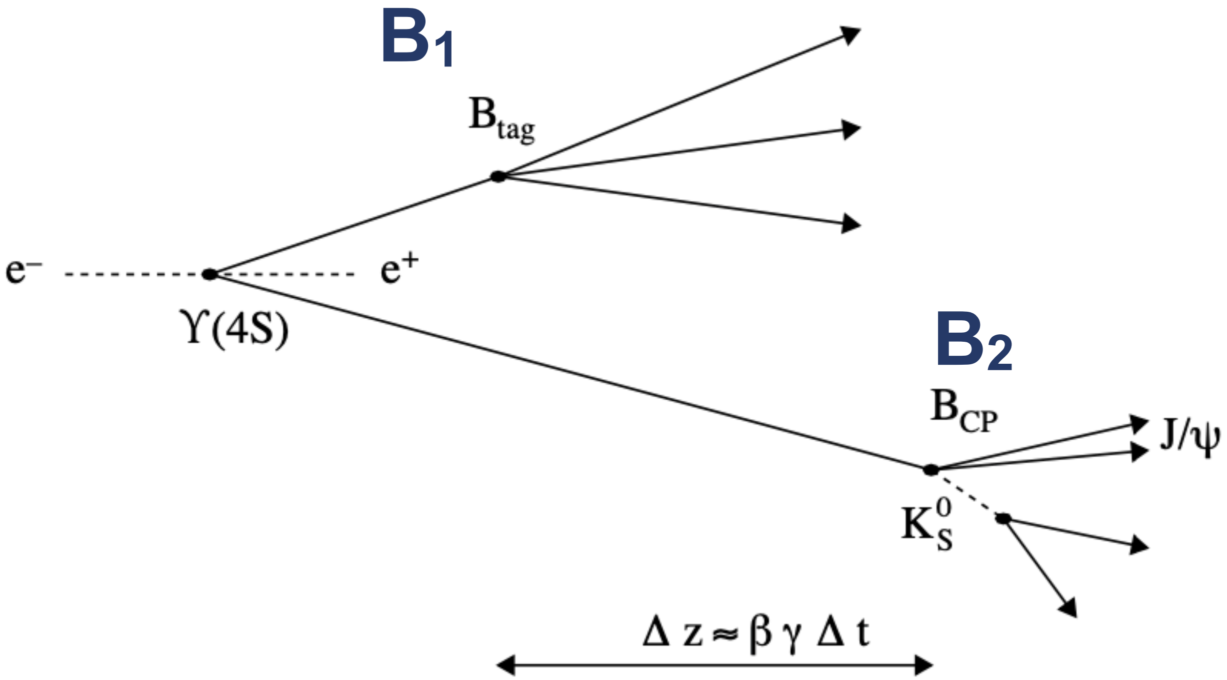
- **Examples of B_{CP} include:**
  - $B^0 \rightarrow J/\psi K^0_S, \eta_{CP} = -1$
  - $B^0 \rightarrow J/\psi K^0_L, \eta_{CP} = +1$

+ other $\eta_{CP} = -1$ modes



Pairs of qbits at a B Factory

- Analyse the B meson states by their decay products



- Four ways to group the data to enable tests for different fundamental phenomena:

States / B meson	B_1	B_2
di-lepton final state	B_{tag}	B_{tag}
Flavour and CP states	B_{tag}	B_{CP}
Flavour and CP states	B_{CP}	B_{tag}
CP states only	B_{CP}	B_{CP}

- The qbit changes happen in the vacuum of a beam pipe (so these are isolated quantum systems) and we detect the decay products in our detectors.

Discrete symmetries

- Fundamental transformations:
  - C: charge conjugation
  - P: parity - spatial inversion
  - T: time-reversal

- Combinations:
  - CP: matter-antimatter asymmetry (CP equivalent to T if CPT is conserved)
  - CPT: balance of CP and time-reversal; conserves Lorentz symmetry

- Interesting tests:
  - T, CP, CPT symmetries: CP and T violated by weak decays, CPT conserved

Discrete symmetries

- We can apply these discrete symmetries to our data to understand what physical measurements we can make to test the behaviour

S

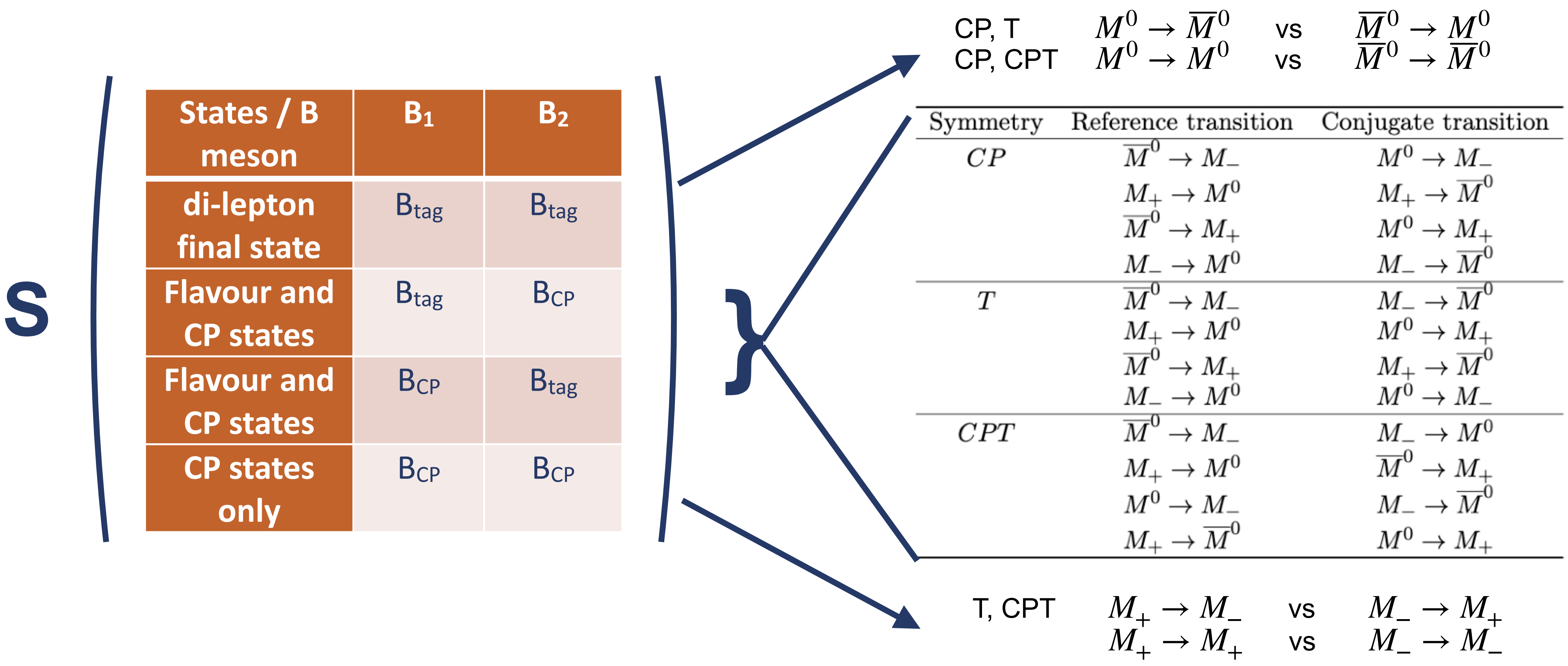
States / B meson	B_1	B_2
di-lepton final state	B_{tag}	B_{tag}
Flavour and CP states	B_{tag}	B_{CP}
Flavour and CP states	B_{CP}	B_{tag}
CP states only	B_{CP}	B_{CP}

= ?

- Typically construct asymmetries that are time dependent or time integrated to look for any interesting patterns
- 16 different asymmetries we can construct

CP, T and CPT asymmetries

- **Full set of 16 comparisons listed for B_{CP} and B_{tag} combinations**



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Flavour and CP states	B_{CP}	B_{tag}
CP states only	B_{CP}	B_{CP}

CP, T $M^0 \to \overline{M}^0$ vs $\overline{M}^0 \to M^0$

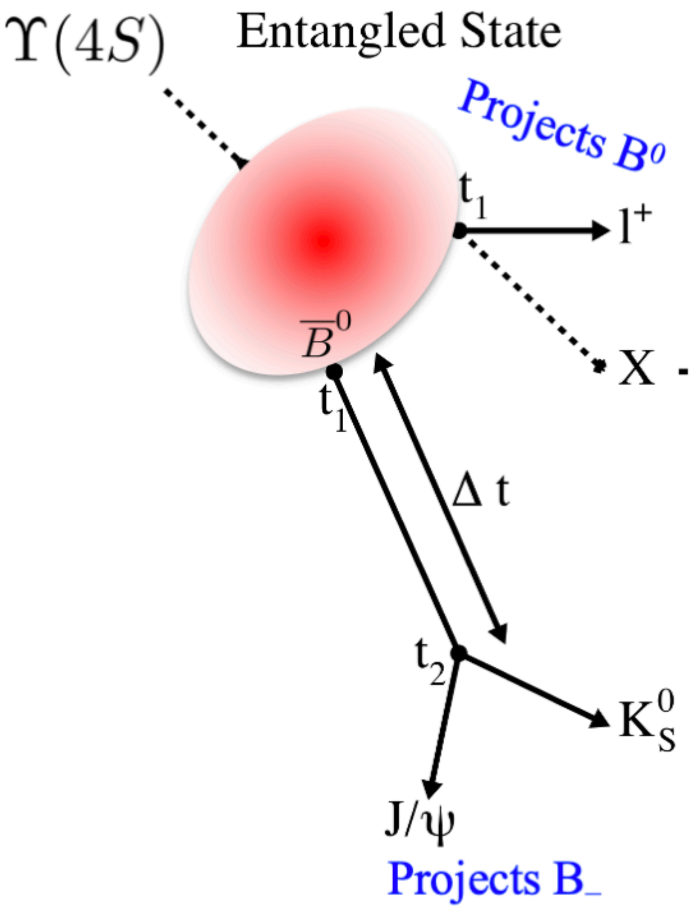
CP, CPT $M^0 \to M^0$ vs $\overline{M}^0 \to \overline{M}^0$

Symmetry	Reference transition	Conjugate transition
CP	$\overline{M}^0 \to M_-$	$M^0 \to M_-$
	$M_+ \to M^0$	$M_+ \to \overline{M}^0$
	$\overline{M}^0 \to M_+$	$M^0 \to M_+$
	$M_- \to M^0$	$M_- \to \overline{M}^0$
T	$\overline{M}^0 \to M_-$	$M_- \to \overline{M}^0$
	$M_+ \to M^0$	$M^0 \to M_+$
	$\overline{M}^0 \to M_+$	$M_+ \to \overline{M}^0$
	$M_- \to M^0$	$M^0 \to M_-$
CPT	$\overline{M}^0 \to M_-$	$M_- \to M^0$
	$M_+ \to M^0$	$\overline{M}^0 \to M_+$
	$M^0 \to M_-$	$M_- \to \overline{M}^0$
	$M_+ \to \overline{M}^0$	$M^0 \to M_+$

T, CPT $M_+ \to M_-$ vs $M_- \to M_+$

$M_+ \to M_+$ vs $M_- \to M_-$

T conjugate B mesons: $\overline{B}^0 \rightarrow B\_$



1) At time t_1 the wave function collapses into the state:

$$B^0\overline{B}^0$$

2) The B^0 promptly decays to a flavor state via: l^+X.

3) The second B evolves naturally thereafter until it too decays.

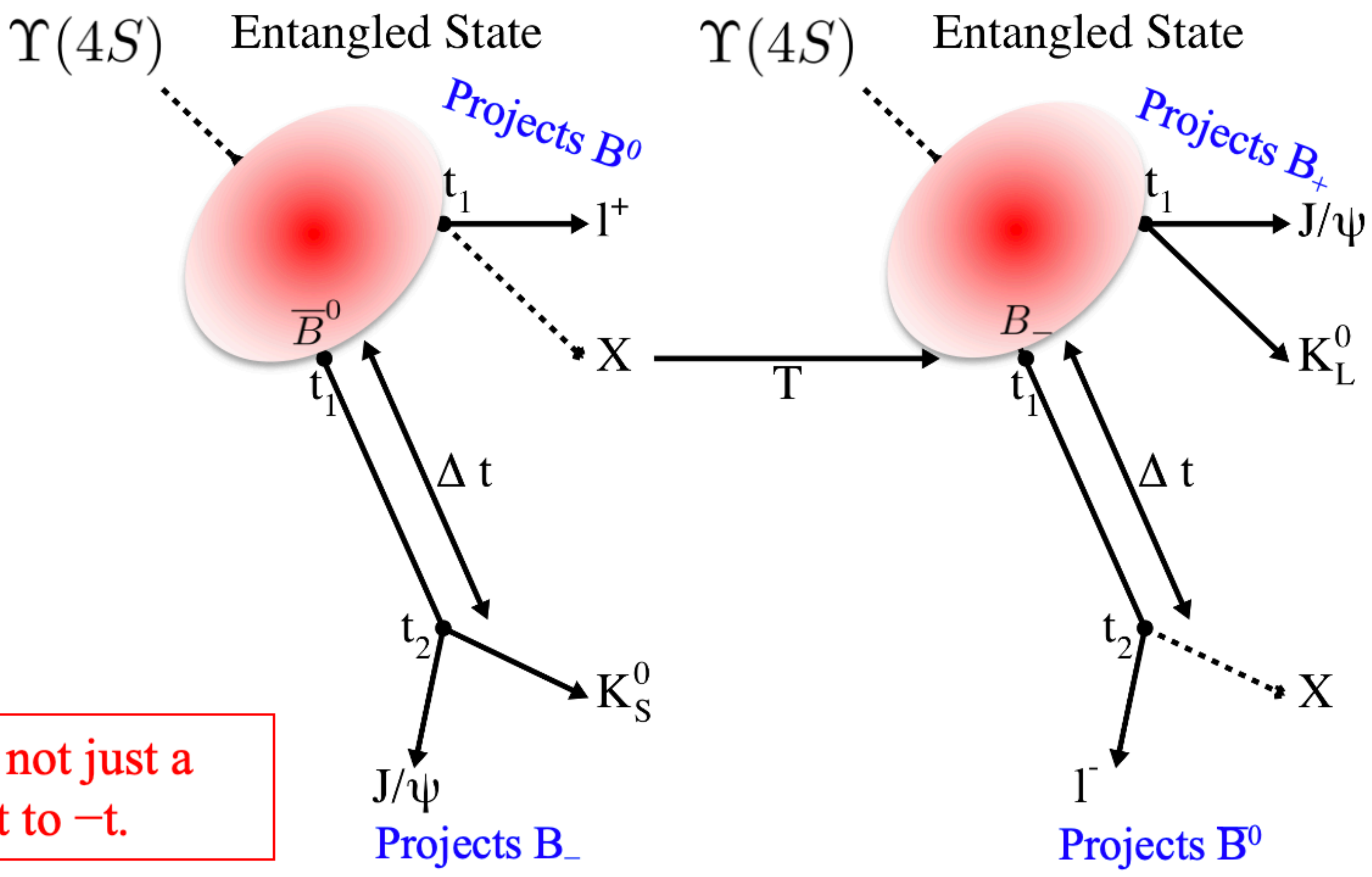
4) At some later time t_2 the second B decays as a B_-.

$$\Delta t = t_2 - t_1$$

T conjugate B mesons: $T(\overline{B}^0 \to B\_) = B\_ \to \overline{B}^0$

$K_S \to K_L$ is a subtle but important effect on analysing the T-conjugate process.

Same logic required for all 12 asymmetries involving flavour and CP filter pairings.



This is not just a flip of t to −t.

$$\Delta t = t_2 - t_1$$

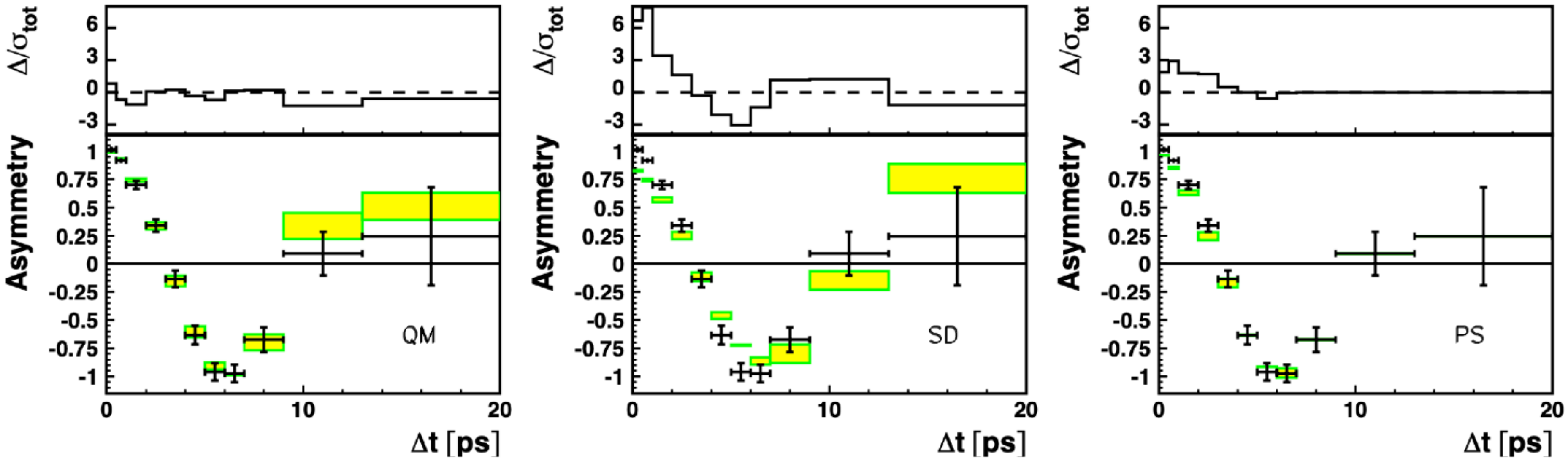
Interesting tests

- CP → matter antimatter asymmetries
- T → time reversal symmetry
- CPT → combination of the above, conserved in locally invariant gauge theory (e.g. the Standard Model of Particle Physics), and linked to Lorentz symmetry
- Wave function decoherence, linked to Lorentz symmetry violation and quantum gravity
- Can measure via:
  - Time integrated
  - Time-dependent
  - Sidereal time dependent

analyses

Wave function decoherence

- The Belle experiment, Tsukuba, Japan tested for decoherence
- Measure decays as a function of the proper time difference



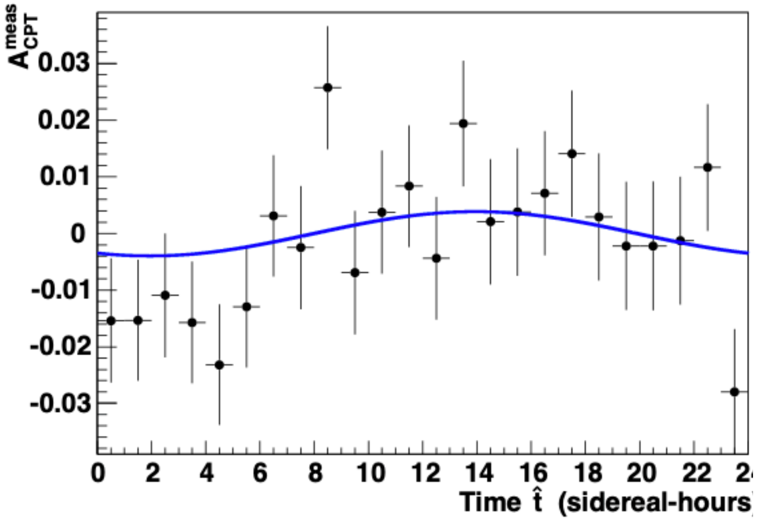
- Results consistent with Quantum Mechanics (QM) and inconsistent with two other local realistic models (Pompili-Selleri [PS] and Spontaneous Disentanglement [SD])
- No decoherence evident in data

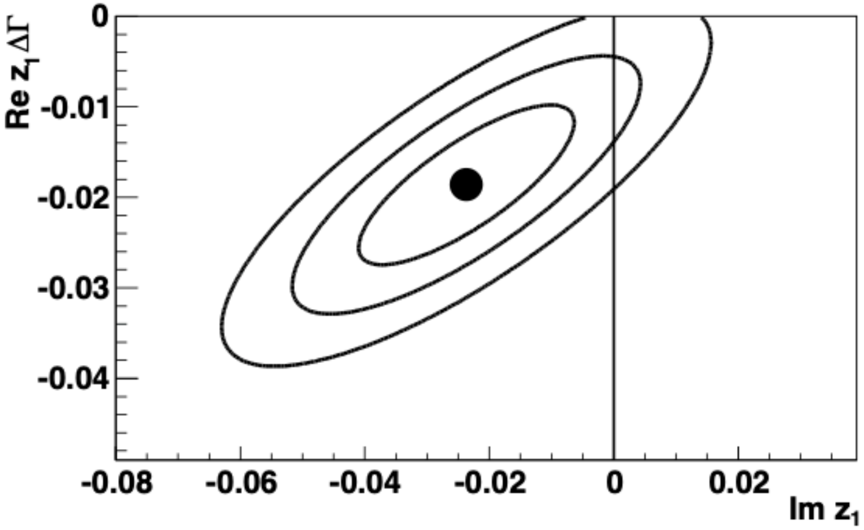
Go. et al., PRL 99 131802 (2007). quant-ph/0702267.

Sidereal time-dependent measurement

- **The BaBar experiment, SLAC, California tested Lorentz symmetry**
- **Measure decays as a function of the sidereal time dependence**
- **Look for wave function decoherence:** $z \neq 0$

$$|B_L\rangle = p\sqrt{1-z}\,|B^0\rangle + q\sqrt{1+z}\,|\overline{B}^0\rangle$$
$$|B_H\rangle = p\sqrt{1+z}\,|B^0\rangle - q\sqrt{1-z}\,|\overline{B}^0\rangle$$





z found to be consistent with zero; consistent with CPT (and Lorentz symmetry) being conserved: BaBar Phys.Rev.Lett.100:131802 (2008)

Subsequent suggestions have been made on possible better ways to analyse the data e.g. Tilburg and Veghel Phys. Lett. B742 (2015) 236

Known limitations

- The entangled B meson pairs passively decay into final states that allow measurements to be made:
  - No control over mixing phase or filter decay for a given data point.
  - Not possible to perform a test of Bell's inequalities using these systems.
  - B mixing is too slow for the B$_d$ meson to make a viable test. The critical parameter is $x_q\,(>2)$:

$$x_q = \frac{\Delta m_q}{\Delta \Gamma_q}, x_d = (0.775 \pm 0.007)$$

  - It is plausible to make a test of Bell's inequalities for B$_s$ mesons at some point in the future if data permits $(x_s = 26.82)$, but not with B$_d$ mesons.

Bertlmann, Bramon, Garbarino, and Hiesmayr, PRL A332 355–360 (2004). quant-ph/0409051.

Questions

- What can we learn from these tests of qbit pairs about fundamental science?
  - Tests of: CP, T, CPT, Lorentz Symmety & wave function decoherence, + … ?
- Can we learn anything useful from these systems that may help us understand macroscopic quantum devices?
- Can we get a deeper understanding of fundamental physics by understanding how macroscopic devices work and reflecting on that in this subatomic system?

Summary

- Entanglement for pairs of qbits has been studied extensively for decades at B Factories
- Used quantum mechanics to test fundamental symmetries
  - e.g. led to the discovery of CP violation in B mesons, and subsequently the Nobel Prize for Kobayashi and Maskawa in 2008
- Some tests noted today have yet to be performed
- Questions arise as to what we can learn from this work to inspire macroscopic tests using ensembles of qbits and vice versa