ETTORE MAJORANA FOUNDATION AND
CENTRE FOR SCIENTIFIC CULTURE

TO PAY A PERMANENT TRIBUTE TO GALILEO GALILEI, FOUNDER OF MODERN SCIENCE
AND TO ENRICO FERMI, "THE ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES

A charming opportunity for T-violation

Testing Time Reversal Violation in neutral meson systems

arXiv:1302.4191v1

Michele Zoccali
mhzoccali@gmail.com

Queen Mary
University of London

Discrete symmetries: Charge conjugation and Parity

- Charge conjugation, *C*: exchange of particle with antiparticle

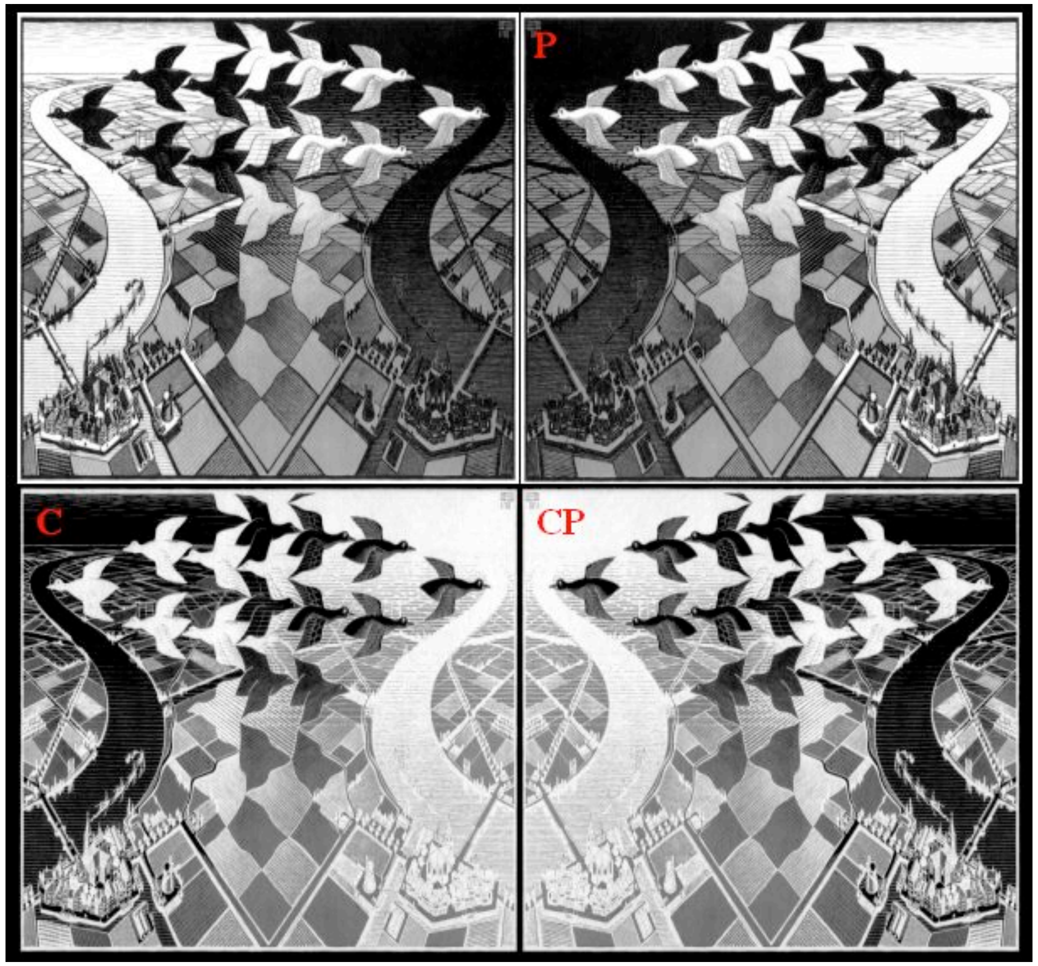
- Parity, *P*: spatial inversion (x ⟶ -x)

$$\mathcal{C}\,|\psi\rangle = e^{i\phi}\,|\overline{\psi}\rangle$$

$$\mathcal{C}\,|\overline{\psi}\rangle = e^{-i\phi}\,|\psi\rangle$$

$$\mathcal{P}\,|\psi\rangle = e^{i\delta}\,|-\psi\rangle$$

$$\mathcal{P}\,|-\psi\rangle = e^{-i\delta}\,|\psi\rangle$$



Escher: Migrating birds (revisited)

Discrete symmetries: Charge conjugation + Parity = CP

- The combined symmetry CP, as well as C and P individually, is violated in weak decays.

$$\mathcal{CP}\,|\psi\rangle = e^{i\xi}\,|\overline{\psi}\rangle$$
$$\mathcal{CP}\,|\overline{\psi}\rangle = e^{-i\xi}\,|\psi\rangle$$

- CP Violation accounts for (at least part of) the imbalance between matter and antimatter in the universe.

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

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\bar{\rho}-i\bar{\eta})(1+\lambda^2/2) \\ -\lambda+A^2\lambda^5[1-2(\bar{\rho}+i\bar{\eta})]/2 & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3[1-\bar{\rho}-i\bar{\eta}] & -A\lambda^2+A\lambda^4[1-2(\bar{\rho}+i\bar{\eta})]/2 & 1-A^2\lambda^4/2 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

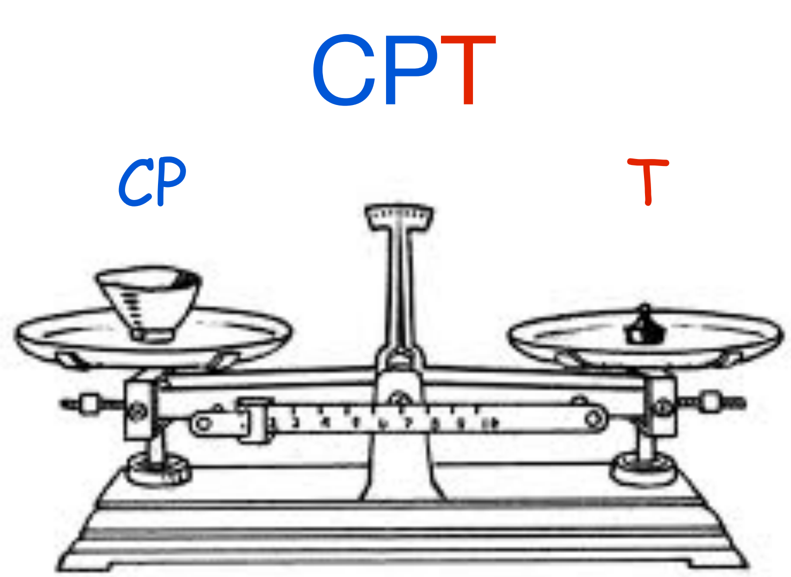
CKM extension for CPV in Charm sector

See: arXiv:1106.5075v4

- Weak decays are known to violate the set of discrete symmetries C (charge), P (parity), CP.

- More generally, CPT is thought to be conserved within the Standard Model, where T is time reversal symmetry ($t \longrightarrow -t$).

- So, within the SM, T-symmetry must be violated by the same amount as CP, in order to conserve CPT.



⟷ strong constraint on the amount of T-violation, exploiting the existing data for CPV from the *B* Factories

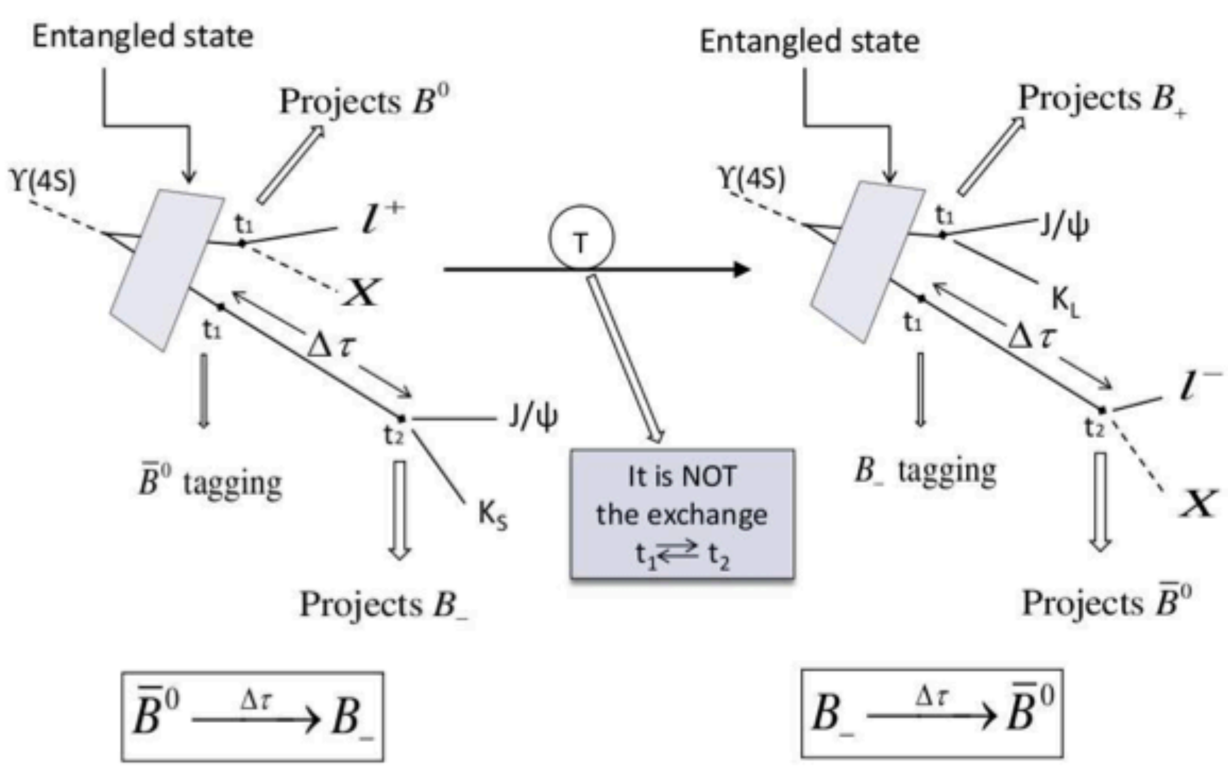
Time reversal violation

- In the same fashion as CP-violation, there exist different types of T-violation: in the decay, in mixing, and in the interference between decay with and without mixing.
- Low branching ratios of time-reversed processes make it difficult to test T-violation associated to CP violation.
- However, it is possible to construct a direct test of T-violation!

How do we test time reversal violation directly?

- Use inversion of *in* an *out* states, i.e. compare decay rates of T-conjugated pairs.

- Technique: choosing an appropriate set of decays, whereby one can exploit flavour as well as CP tagging on either side of a quantum entangled meson system.



flavour projected:

$$|i\rangle = \frac{1}{\sqrt{2}}[B^0(t_1)\bar{B}^0(t_2) - \bar{B}^0(t_1)B^0(t_2)]$$

CP projected:

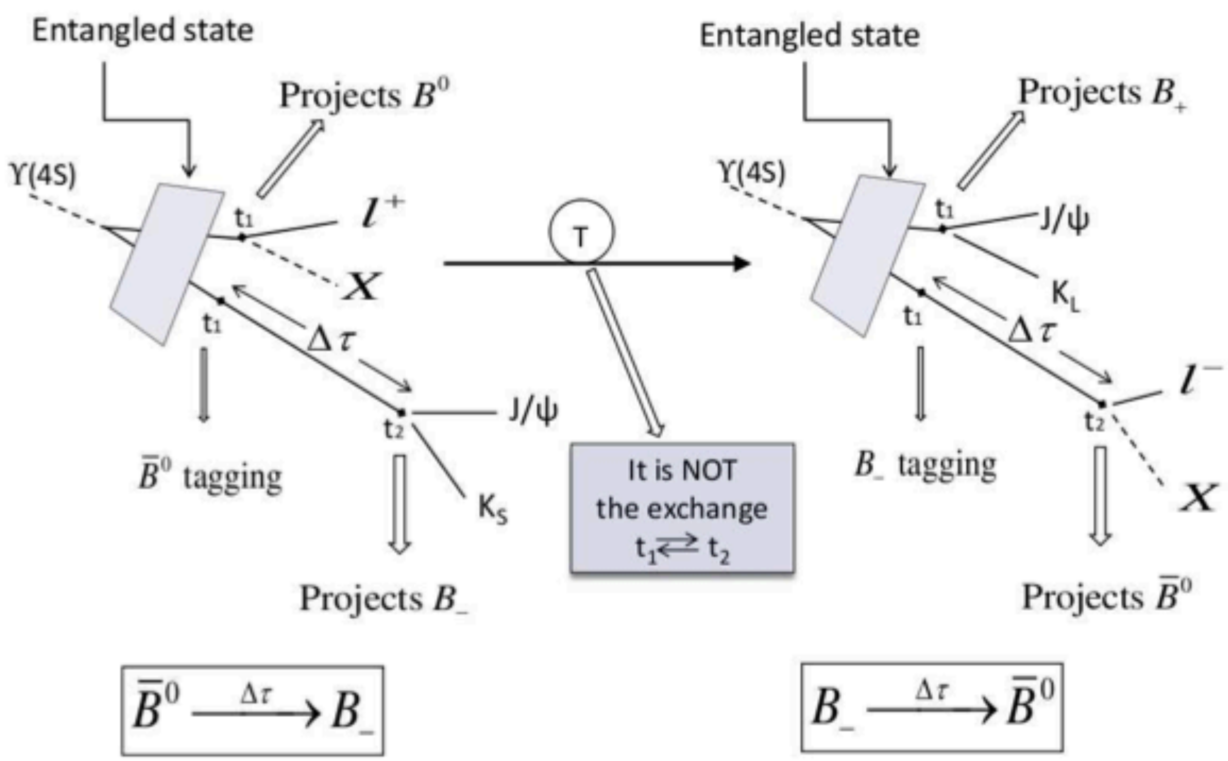
$$|i\rangle = \frac{1}{\sqrt{2}}[B_+(t_1)B_-(t_2) - B_-(t_1)B_+(t_2)]$$

See: arXiv:1203.0171v2

How do we test time reversal violation directly?

- Use inversion of *in* an *out* states, i.e. compare decay rates of T-conjugated pairs.

- Technique: choosing an appropriate set of decays, whereby one can exploit flavour as well as CP tagging on either side of a quantum entangled meson system.



Interesting T-conjugated decays:

$\overline{B}^0 \to B_- \, (\ell^+ X, J/\psi K^0_S)$ vs $B_- \to \overline{B}^0 \, (J/\psi K^0_L, \ell^- X)$

$B_+ \to B^0 \, (J/\psi K^0_S, \ell^+ X)$ vs $B^0 \to B_+ \, (\ell^- X, J/\psi K^0_L)$

$\overline{B}^0 \to B_+ \, (\ell^+ X, J/\psi K^0_L)$ vs $B_+ \to \overline{B}^0 \, (J/\psi K^0_S, \ell^- X)$

$B_- \to B^0 \, (J/\psi K^0_L, \ell^+ X)$ vs $B^0 \to B_- \, (\ell^- X, J/\psi K^0_S)$

See: arXiv:1203.0171v2

What parameters do we look at?

$$g^{\pm}_{\alpha,\beta}(\Delta\tau) \propto e^{-\Gamma\Delta\tau}\{1 + C^{\pm}_{\alpha,\beta}\cos(\Delta m\Delta\tau) + S^{\pm}_{\alpha,\beta}\sin(\Delta m\Delta\tau)\}$$

$$S = \frac{2Im\lambda_f}{1+|\lambda_f|^2}$$

$$C = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

- One studies the (possible) asymmetry between decay rates:

$$\mathcal{A}_T = \frac{g^{-}_{l^-,K_L} - g^{+}_{l^+,K_s}}{g^{-}_{l^-,K_L} + g^{+}_{l^+,K_s}} \approx \frac{\Delta C^{+}_{T}}{2}\cos(\Delta m\Delta t_+) + \frac{\Delta S^{+}_{T}}{2}\sin(\Delta m\Delta t_+)$$

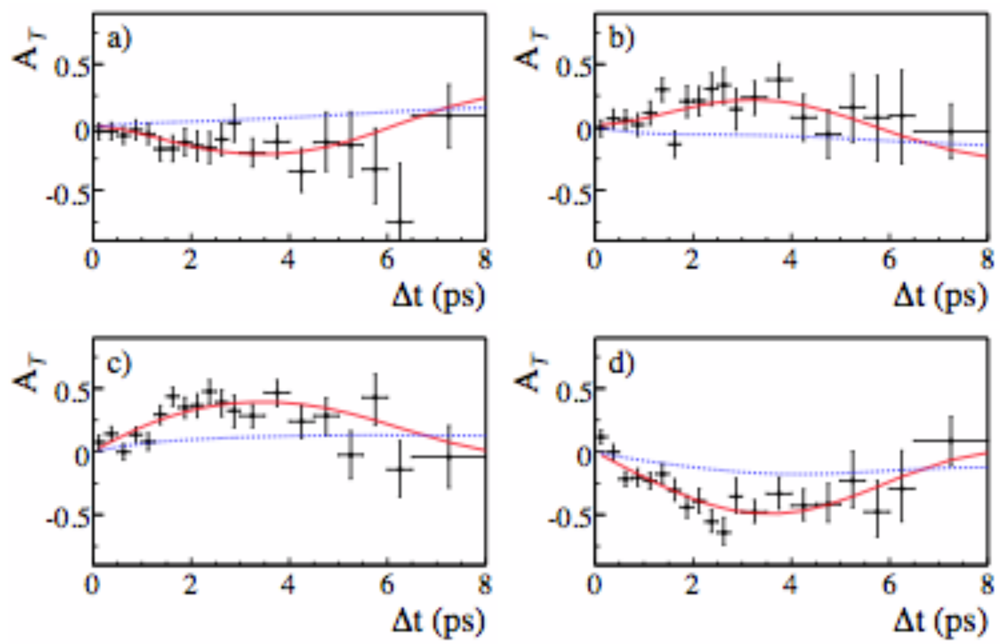
$$\Delta C^{+}_{T} = C^{-}_{l^-,K_L} - C^{+}_{l^+,K_s}$$
$$\Delta S^{+}_{T} = S^{-}_{l^-,K_L} - S^{+}_{l^+,K_s}$$

- A non-vanishing value of these parameters implies T-violation.

Tested in the B-sector

- BaBar has recently used this method to test T non-invariance directly, with a confidence of 14σ.

Parameter	Result
$\Delta S_T^+ = S^-_{\ell^-,K^0_L} - S^+_{\ell^+,K^0_S}$	$-1.37 \pm 0.14 \pm 0.06$
$\Delta S_T^- = S^+_{\ell^-,K^0_L} - S^-_{\ell^+,K^0_S}$	$1.17 \pm 0.18 \pm 0.11$
$\Delta C_T^+ = C^-_{\ell^-,K^0_L} - C^+_{\ell^+,K^0_S}$	$0.10 \pm 0.14 \pm 0.08$
$\Delta C_T^- = C^+_{\ell^-,K^0_L} - C^-_{\ell^+,K^0_S}$	$0.04 \pm 0.14 \pm 0.08$



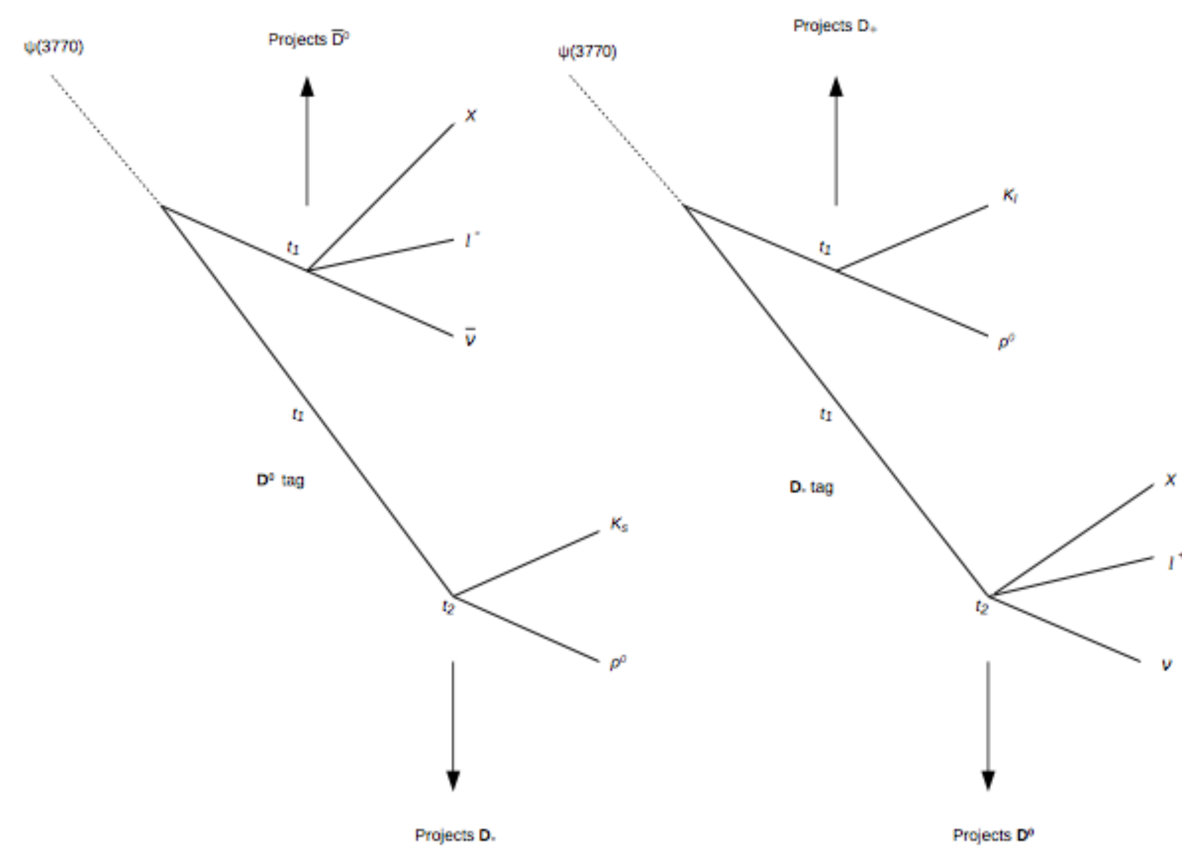
See: arXiv:1207.5832v4

What about the Charm sector?

- Recent studies at Psi(3770) show strong evidence for small (yet non-zero) CP Violation in D decays.

- It is indeed possible to construct T-conjugated pairs of decays with neutral D mesons, which can be compared by means of the asymmetry term.

Reference		$\mathcal{T}$-conjugate	
$D^0 \to D_-$	$(l^- X, K_s \rho^0)$	$D_- \to D^0$	$(K_L \rho^0, l^+ X)$
$D^0 \to D_+$	$(l^- X, K_s \pi^+ \pi^-)$	$D_+ \to D^0$	$(K_L \pi^+ \pi^-, l^+ X)$



Thank you

Backup

- The mass eigenstates as a superposition of strong eigenstates:

$$|P_{1,2}\rangle = p|P^0\rangle \pm q|\overline{P}^0\rangle$$

- Amplitudes of decays:

$$A = |T|e^{i\phi_T} + |CS|e^{i\phi_{CS}} + |W|e^{i\phi_W} + \sum_{q=d,s,b} |P_q|e^{i\phi_q}$$

$$\lambda_f = \frac{q}{p}\frac{\overline{A}}{A}$$