Letter of Intent: The Feasibility of Bell-type Tests at Future Lepton Colliders in $Z \to \tau\tau$ Events

Lawrence Lee
Harvard University[*]

Karri Folan Di Petrillo
Fermi National Accelerator Laboratory
(Dated: August 31, 2020)

I. INTRODUCTION

The standard model (SM), as a *quantum* field theory, should exhibit the behaviors that characterize quantum theory as a radical departure from classical dynamics. In particular, the effects of quantum nonlocality should be present within the realm of the SM. The spin correlation experiment setup due to Bell, Bohm, and EPR [1–3], represents a way to test the nonlocal nature of quantum mechanics. Most past experiments on this effect have been on polarization-correlated pairs of photons in a singlet state from a common atomic source measured at space-like separation [4, 5]. Such quantum entanglement should be present in two-particle states exhibiting specific correlations as a result of a common origin. The SM describes many such processes where a particle with definite spin decays to particles with correlated, but indeterminate, spin. We aim to study the feasibility of measuring this effect and its spacetime dependence at a future collider, especially in $Z \to \tau\tau$ events, probing a new corner of physics and testing not just the SM, but more importantly, the foundational core of quantum mechanics.

Definite quantum correlations with indefinite measurement outcomes like this are present in various corners of physics and often arise in the SM used to describe interactions at very high energies. At modern colliders, such correlations are often present, if often not measurable. Some particles, however, decay through the weak interaction such that parity violation allows for observable kinematic properties in some way correlated with spin states. This information obtained at the decay of such particles can be considered a self-measurement of the particle's spin state as described by the SM. Inferring spin states in this way has been widely studied both theoretically and experimentally. Spin-correlated pairs of such particles can act as a self-measuring Bell system. These ideas have been widely explored and measured experimentally at LEP showing expected correlations assuming prompt decays of these particles, confirming the quantum mechanical predictions while leaving the nonlocal nature unprobed. [6, 7] Much of the focus at LEP was on measuring such a correlation in the Z boson system. This is accessible through the decay to two τ leptons where kinematic information about the τ decay products stores τ spin information.

Since the τ has a well-understood macroscopic lifetime $c\tau \sim O(100\mu s)$, there exists an inherit space-time separation between the two τ decay events.

This work hopes to expand on these ideas in such a way that statements about the nonlocal nature of quantum mechanics can be made, instead of simply measuring SM spin correlations. The goal here is to probe the nature of quantum mechanics itself, rather than simply to measure SM couplings. The feasibility of this measurement for various collider and detector assumptions will be studied in $Z \to \tau\tau$ events.

Previous studies involving space-time locations of 'measurement' events, while more concrete in their conclusions because the choice of spin measurements is made by the experimenter rather than the particle, have been at atomic length scales and established through electromagnetic means. Such a confirmation of SM correlations at the LHC that is invariant across space-time separation of the 'measurement' events would be the strongest confirmation of this quantum mechanical effect at such small length scales to date. [8] In addition, this measurement would probe this nonlocal effect when established via the weak interaction in a way that has not been done.

Proposed future lepton collider facilities (ILC, FCC-ee, CLIC, etc) all have the ability to obtain very large samples of Z boson events. The FCC-ee facility has the impressive goal of being a "tera-Z" instrument providing a unique high-statistics view into the decays of the Z, making it a prime candidate for such a study, producing on the order of 10 billion $Z \to \tau\tau$ in which both τs decay hadronically.

II. OBSERVABLES

Two key observables are required to perform this test. One must establish the transverse spin correlation of the τs, and another must provide some handle on the space-time separation of the two decay events. The presence of the τ neutrino at every τ decay immediately makes this a challenge as the ditau system is not completely reconstructable as neutrinos escape such experiments undetected. Much work has been done to find viable correlation observables for Z spin studies, as well as for measurements of the CP nature of the Higgs boson in ditau

[*] Lawrence.Lee.Jr@cern.ch

final states. Most of these studies involve measuring the azimuthal angle between the planes spanned by each τ's decay products in the ditau rest frame or some suitable proxy, since the system is not reconstructable. [9–13]

Performing τ polarimetry as desired requires hadronic decays of the taus. The simplest correlation observable requires τ decays with exactly one charged hadron – *one prong* τ decays – and may even require a specific decay mode $\tau \to \rho\nu \to \pi^+\pi^0\nu$. Fortunately, the one-prong hadronic τ branching fraction is the single largest of possible modes, and within that, the ρ channel holds a large fraction of the decay width.

A prescription has been outlined in [9–11] where a proxy frame can be created using the directions of the reconstructed ρ mesons. While the difference between this proxy frame and the true $\tau\tau$ frame will bias the final spin correlation measurements, in principle, this should have not affect the existence of non-isotropic effects in the final distributions.

The second observable needed to help make statements about the spacetime separation between the decay of each τ involves trying to infer the lifetime of individual τs. Again, for simplicity, it is desirable to work only with one prong τs where measured impact parameters give a handle on the particle's lifetime. In τ decays to three charged particles, modern and future charged particle trackers have the sensitivity to resolve a secondary vertex, the location of the τ decay, and measure its distance from the initial collision point, providing a direct measurement of the *tau* decay time. Unfortunately, there is no existing transverse polarization observable for three-prong τs and the branching fraction for such decays may be too small to be a viable decay chain for study.

III. SENSITIVITY TO ALTERNATE MODELS

The unintuitive prediction from quantum theory begs one to compare the distributions obtained in such a measurement with the prediction of nonquantum models. For example, a local hidden variable could define the precise τ-system spin state throughout the decay chain, though such a theory has been ruled out at lower energy scales. Alternatively, one could construct a theory in which the quantum state represents the complete picture but only local effects are allowed. This should lead to a decay pattern that is isotropic when the τ decays are space-like separated. Therefore, the spin correlations should depend strongly on the decay locations. In the absence of experimental effects, the spin correlation and its dependence on the separation of the two τ decays should allow one to probe this difference in models.

IV. PLANS

The estimated sensitivity to deviations from the SM will be explored for the various proposed Z factories, especially the FCC-ee. The required statistics at the Z pole and detector resolutions will be determined. The sensitivity to this effect in Higgs decays may also be explored.

[1] D. Bohm, *Quantum Theory*, Prentice-Hall physics series (Dover Publ., 1951).

[2] A. Einstein, B. Podolsky, and N. Rosen, Can quantum-mechanical description of physical reality be considered complete?, Phys. Rev. **47**, 777 (1935).

[3] J. S. Bell *et al.*, On the einstein-podolsky-rosen paradox, Physics **1**, 195 (1964).

[4] A. Aspect, Bell's inequality test: more ideal than ever, Nature **398**, 189 (1999).

[5] D. Salart, A. Baas, C. Branciard, N. Gisin, and H. Zbinden, Testing the speed of 'spooky action at a distance', Nature **454**, 861 (2008).

[6] Measurement of the transverse spin correlations in the decay $Z \to \tau^+\tau^-$, Phys. Lett. B **405**, 191 (1997).

[7] F. Sánchez, The effect of the masses of the τ decay products on the transverse spin correlation in $\tau^+\tau^-$ production at the Z pole, Phys. Lett. B **384**, 277. 7 p (1996).

[8] Bohm suggested that quantum nonlocality may break down at higher energies and may give hints to new physics as a result [14]. The energy range in question here at the Z peak of 91 GeV is much higher than previous tests performed in the eV range.

[9] K. Desch, Z. Was, and M. Worek, Measuring the Higgs boson parity at a linear collider using the tau impact parameter and tau → rho nu decay, Eur.Phys.J. **C29**, 491 (2003), arXiv:hep-ph/0302046 [hep-ph].

[10] G. Bower, T. Pierzchala, Z. Was, and M. Worek, Measuring the Higgs boson's parity using tau → rho nu, Phys.Lett. **B543**, 227 (2002), arXiv:hep-ph/0204292 [hep-ph].

[11] T. Pierzchala, E. Richter-Was, Z. Was, and M. Worek, Spin effects in tau lepton pair production at LHC, Acta Phys.Polon. **B32**, 1277 (2001), arXiv:hep-ph/0101311 [hep-ph].

[12] S. Berge, W. Bernreuther, and S. Kirchner, Prospects of constraining the higgs boson's *cp* nature in the tau decay channel at the lhc, Phys. Rev. D **92**, 096012 (2015).

[13] S. Berge, W. Bernreuther, and H. Spiesberger, Higgs CP properties using the τ decay modes at the ILC, Phys. Lett. B **727**, 488 (2013), arXiv:1308.2674 [hep-ph].

[14] D. Bohm, A suggested interpretation of the quantum theory in terms of "hidden" variables. ii, Phys. Rev. **85**, 180 (1952).