Entanglement at Colliders

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Measurement of the degree of spin correlation and polarization at particle colliders has been studied for a long time and remains central to precision physics: The angular and spin distributions of the final state particles are sensitive to the chirality of the couplings and allow determination of parity and CP properties of the decaying particles. Recently, the study of quantum entanglement has received growing interest in high-energy physics as well, which goes beyond classical correlation - it is a defining feature of quantum mechanics and an important concept in quantum information theory.

Since particles are intrinsically quantum systems, we employ the density matrix, a fundamental tool in quantum mechanics, as the central framework. The density matrix fully characterizes a system and encodes all accessible information. Depending on the colliding particles, different density matrices are used to describe the respective quantum system. The simplest case is the collision of two spin 1/2 particles, such as fermions. They are characterized by a bipartite qubit system, where each fermion corresponds to a qubit. If one considers spin-1 particles such as massive gauge bosons, the underlying quantum system is described by qutrits. A useful parametrization for the bipartite qubit system is the so-called Fano- Bloch decomposition [1], given by the 4×4 density matrix as follows:

$$\rho = \frac{1}{4}\left(\mathbb{1}_4 + \sum_i B_i^+ \sigma^i \otimes \mathbb{1} + \sum_j B_j^- \mathbb{1}_2 \otimes \sigma^j + \sum_{ij} C_{ij} \sigma^i \otimes \sigma^j\right)$$

Here, $B^{\pm}$ represents the polarization of the two qubits and C_{ij} is the spin correlation matrix.

Experimentally, reconstructing the density matrix from angular decay distributions is known as quantum state tomography. If particles decay quickly enough, their spin information is transferred to their decay products, allowing the original correlations to be inferred. Theoretically, the density matrix can be computed from initial-state polarization and helicity amplitudes. Comparing Standard Model predictions with reconstructed matrices, or with Beyond Standard Model scenarios, offers a novel probe of new physics.

To quantify entanglement for a high-energy process, different measures can be explored. In general we will deal with mixed instead of pure quantum states, which are entangled in large regions of the phase space. One quite practical measure for entanglement at colliders is the so-called concurrence, which tells you not only if a system is entangled or not, but also to what degree. For a bipartite system, the concurrence can be easily computed from the density matrix. For higher-dimensional systems, the situation is more challenging. However, lower bounds on the concurrence can still be estimated.

In this talk, we will discuss different parameterizations of the density matrix for a general bipartite system and go through the explicit derivation for a simple QED scattering process. Here, the spin density matrix can be constructed analytically and used to evaluate entanglement witnesses such as the PPT criterion and the concurrence. We address the current experimental status and highlight perspectives at future colliderm which offer a clean environment to explore entanglement in a wide range of processes.

References

[1] Fano, U. Pairs of two-level systems. *Rev. Mod. Phys. 55* (Oct 1983), 855–874.