

Quantum Information at Colliders

Sunday, 2 November 2025 11:20 (30 minutes)

We investigate whether collider experiments can reach the quantum limit of precision, defined by the quantum Fisher information (QFI), using only classical observables such as particle momenta. As a case study, we focus on the $\tau^+\tau^-$ system and the decay channel $\tau \rightarrow \pi\nu$, which offers maximal spin-analyzing power and renders the decay a projective measurement. We develop a general framework to determine when collider measurements can, in principle, saturate the QFI in an entangled biparticle system, and this framework extends naturally to other such systems. Within this framework, QFI saturation occurs if and only if the symmetric logarithmic derivative (SLD) commutes with a complete set of orthonormal separable projectors associated with collider-accessible measurements. This separability condition, reflecting the independence of decay amplitudes, is highly nontrivial. To meet this condition, a key requirement is that the spin density matrix be rank-deficient, allowing the SLD sufficient freedom. We show that the classical Fisher information asymptotically saturates the QFI for magnetic dipole moments and CP-violating Higgs interactions in selected phase-space regions, but not for electric dipole moments. These results bridge quantum metrology and collider physics, providing a systematic method to identify quantum-optimal sensitivity in collider experiments.

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Session Classification: Plenary

Track Classification: Theory