

Violation and Restoration of Probability Positivity in Perturbative Quantum Field Theory

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We address the long-standing problem of negative decay and production rates in perturbative QCD for exclusive processes by proposing amplitude-level NRQCD factorization as a systematic prescription. Building on this, we present the first complete next-to-next-to-leading-order (NNLO) QCD correction to the decay $J/\psi \rightarrow 3\gamma$. The resulting partial width, $\Gamma(J/\psi \rightarrow 3\gamma) = 0.96^{+4.32}_{-0.13}$ eV, combines this NNLO contribution with the known up to $\mathcal{O}(\alpha_s v^2)$ relativistic correction and shows markedly improved agreement with the high-precision BESIII measurement. In the same way, $\Gamma(\Upsilon \rightarrow 3\gamma) = 0.0086^{+0.0028}_{-0.0006}$ eV is obtained.

From a first-principles perspective, it is clear that for exclusive processes, taking the complete modulus squared of the full amplitude is precisely the proper definition of the probability distribution and guarantees its manifest positivity. This makes the amplitude-level prescription the natural and physically motivated scheme. For inclusive processes, however, one is forced to abandon the full modulus square due to the need to cancel infrared divergences at the level of the truncated squared amplitude.

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