Letter of intent

ACRONYM, **PROJECT TITLE**: **HARMONY:** ***HAdron physics Research into Models of Nonunitary Dynamics and quantum gravity;***

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1. Research objectives

a) Physics Motivation:

At the crossroad of high-precision hadron physics and quantum theory lies a new frontier for probing quantum foundations, in particular quantum gravity (QG) and quantum collapse models. Despite decades of theoretical effort, a unified framework reconciling quantum mechanics and general relativity remains elusive. Recent advances highlight the potential of hadronic systems—due to their intrinsic complexity and sensitivity—to test universal features of QG such as gravitational decoherence, minimal length effects, and violations of fundamental symmetries. Emerging approaches to unifying quantum mechanics and gravity increasingly draw on innovative mathematical tools, including complexity theory and stochastic processes. Stochastic methods developed in hadron and statistical physics provide a natural framework for modeling quantum collapse and QG effects, linking them to observable phenomena—especially in out-of-equilibrium and critical regimes. Furthermore, entangled meson experiments may reveal CPT violations arising from QG-induced quantum decoherence in matter.

HARMONY aims to establish a research network focused on leveraging hadron physics to investigate quantum foundations, bridging high-sensitivity experiments with advanced stochastic modeling. The project will integrate this approach with past, ongoing and future experiments such as LHCb, ATLAS, CMS, BESIII, FOCUS, KLOE, VIP, CUORE, LEGEND, JUNO, XENON, and other upcoming collider and underground facilities.

Key questions include: How can experiments in hadron, nuclear, and atomic physics shed light on quantum gravity and the nature of quantum collapse? What role does the underlying physics of wave-function collapse play in relaxation phenomena?

b) Networking activities, tasks and vision: A promising modern approach to QG focuses on identifying universal features across different QG theories to enable robust, testable outcomes. Two prominent examples are the existence of a minimal length at the Planck scale and potential violations of CPT symmetry. While traditional phenomenological searches have struggled to reach Planck-scale sensitivity, recent breakthroughs are particularly noteworthy: 1 - the prediction that a minimal length induces a universal quantum-gravitational decoherence mechanism. 2 - The potential violation of the spin-statistics connection—verified in effective QG models such as θ-Poincaré. 3 - The possibility that the CPT operator becomes ill-defined in the presence of QG fluctuations—commonly referred to as space-time foam.

HARMONY seeks to foster strong synergies between theory and experiment to both model novel physical phenomena and design next-generation underground and accelerator-based experiments capable of probing these effects with unprecedented sensitivity using hadron physics tools. The overarching goal is to bring current experimental constraints significantly closer to the Planck scale. Specifically:

- Underground Nuclear and Atomic Experiments: These are now capable of testing key predictions related to spontaneous decoherence and spin-statistics violations. In the former case, space-time uncertainty leads to Brownian-like motion of electrically charged quantum systems, potentially producing a faint spontaneous electromagnetic signal. In the latter case, violations of the Pauli Exclusion Principle (PEP) would give rise to anomalous atomic or nuclear transitions—detectable with high-resolution silicon and germanium detectors. A novel experimental proposal aims to simultaneously detect both the characteristic radiation from PEP-violating transitions and spontaneous radiation induced by combined nuclear and electronic effects. This approach could extend QG sensitivity to the Planck scale, potentially improving current time-of-flight bounds by up to 16 orders of magnitude.

- CPT Violation in Entangled Systems: If CPT symmetry is violated due to entanglement with unobserved QG degrees of freedom, then Einstein-Podolsky-Rosen correlations may be altered. Specifically, QG-induced fluctuations can deform the standard form of entangled meson states by acting on the CPT-symmetry generator. This deformation can be parametrized by a complex variable, which HARMONY will investigate through experiments involving entangled particle (mesons and baryons) pairs. Upgraded experimental facilities are expected to reach sensitivities better than 10^{-4}.
- Links Between QG and QCD Phase Transitions: HARMONY will also explore emerging connections between QG and phase transitions in Quantum Chromodynamics (QCD) under extreme conditions, as well as the insights offered by AdS/QCD (holographic) approaches to hadron spectroscopy. Key areas of inquiry include: phase transitions in hadronic systems and their relation to collapse dynamics; critical phenomena and symmetry-breaking in QCD as analogues for stochastic gradient flows modeling quantum decoherence; holographic (AdS/QCD) approaches to spectroscopy, offering dual descriptions relevant to spacetime emergence.

The project will support theory–experiment feedback loops, encourage joint analysis efforts, and promote standardized simulation platforms. Dedicated workshops will identify emergent opportunities and accelerate cross-disciplinary collaborations.

2. Connection to Transnational Access infrastructures (TAs) and / or Virtual Access projects (VAs): HARMONY will strategically engage with key TA infrastructures to promote probing quantum gravity effects using hadronic systems: **CERN (ATLAS, CMS, LHCb)**: precision measurements of hadrons and entangled mesons to test CPT violation and QG-induced decoherence; **GSI/FAIR**: studies of QCD phase transitions and exotic nuclear states relevant to collapse dynamics and symmetry breaking; **MAMI/MESA and ELSA (Germany)**: provide high-precision electron/photon beams ideal for possible rare transition searches and tests of spin-statistics violations; **INFN-LNF (Italy)**: past/existing experiments (VIP, KLOE) and detector R&D support searches for symmetries breaking (QG) and spontaneous radiation; **ECT***: could host focused theory–experiment workshops and support modeling efforts linking hadron physics with quantum gravity; **JLAB and BNL (USA)**: Complementary access to precision hadronic structure studies relevant for CPT and fundamental symmetry tests.

HARMONY will foster coordinated use of these facilities, enabling cross-site analysis, detector synergies, and optimized experimental design to push sensitivity toward the Planck scale.

3. Estimated budget request: For a 4-year duration, the total estimated cost is **€300,000**, allocated as: Outreach and administration: €20,000/year, Annual workshops and travel: €40,000/year, Indirect costs: €15,000/year. These funds will ensure smooth coordination, stakeholder engagement, and broad dissemination.

4. Participating and partner institutions: Enrico Fermi Research Center, Italian National Institute of Nuclear Physics (INFN), Salerno Univ., Italian National Research Council (CNR), Fudan Univ., Regensburg Uni., Lund Univ., Antofagasta Univ., Jagiellonian Univ., Zurich Univ., National Institute of Physics and Nuclear Engineering (Bucharest-Magurele), King's

Coll. London, Natl. Tech. Univ. Athens, Mines Paris, Wigner Research Centre for Physics, Eötvös Loránd Univ., Univ. of Zagreb.