Experimental Signatures of Vacuum Correlation: Casimir, Bell, and Squeezing Probes

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We propose a class of precision experiments to test whether quantum entanglement modifies vacuum energy in a measurable way, in line with the conjecture that ER=EPR. By combining Bell-type photon correlations with vacuum-sensitive observables—including Casimir force shifts and optical squeezing—we construct a hybrid framework capable of detecting correlated anomalies in multiple independent quantum channels. We outline low-cost, table-top implementations of these platforms and classify 18 experimental approaches by feasibility, sensitivity, and relevance to Planck-scale entanglement structure. To guide development, we present simulated data showing how entanglement-enhanced events may appear as coherent deviations across Bell, Casimir, and squeezing measurements. Principal component analysis, mutual information, and multi-channel deviation statistics reveal that even a small fraction of correlated events can produce detectable signatures. These results offer a concrete and testable path for probing ER=EPR-style correlations between quantum geometry and information, using currently accessible technologies.

Keywords: ER=EPR Conjecture, Quantum Entanglement, Casimir Effect, Bell Inequality Test, Planck-Scale Wormholes

I. INTRODUCTION

The Einstein-Rosen bridge and quantum entanglement have long inspired speculation about the relationship between spacetime geometry and quantum information. In recent years, the conjecture known as ER=EPR—that Einstein-Rosen bridges (wormholes) and Einstein-Podolsky-Rosen entanglement may be physically equivalent—has gained traction as a guiding principle in quantum gravity and holography[1, 2]. However, the challenge of testing this idea experimentally has been formidable, given its origin in Planck-scale phenomena.

Here we propose and analyze a set of tabletop experiments that are sensitive to possible modifications in vacuum energy, stress-energy correlations, or phase observables that could arise if the ER=EPR conjecture admits low-energy consequences. Our approach prioritizes measurable quantum observables using established technologies such as Bell inequality tests, Casimir force measurements, and optical squeezing. These observables are selected because they probe vacuum properties, entanglement, and phase coherence in regimes where quantum correlations may leave subtle signatures on effective field observables.

Rather than attempt to directly detect Planck-scale wormholes, our goal is to constrain or reveal deviations from quantum field theory predictions in scenarios where entanglement, vacuum fluctuations, and boundary conditions interact. We downplay speculative Planck-scale mechanisms and instead emphasize sensitivity modeling, existing experimental platforms, and specific quantum correlations.

We organize the paper as follows. Section II we review the Bell-Casimir test with quantum optical methods, in Section III we review the theoretical framework and motivation of the tests, in Section IV we review the data analysis and signal extraction, and in Section V the Experimental results and observations. We also explore alternative experimental pathways in Section VI and next generation experiments in Section VII. Finally we give a Summary of experimental and conclusions in Section VIII.

II. BELL–CASIMIR TESTS WITH QUANTUM-OPTICAL METHODS

Bell Test Platform. The experimental setup begins with the generation of polarization-entangled photon pairs via spontaneous parametric down-conversion (SPDC) [7]. One photon is sent to Alice and the other to Bob. Alice's photon passes through a polarization selector and is detected by D_A. Bob's photon first traverses a vacuum cavity containing an embedded optomechanical membrane before reaching a polarization analyzer and detector D_B. Coincidence counts between D_A and D_B are used to compute the CHSH correlation. Our objective is to detect Bell signal perturbations at the $\sim 10^{-6}$ level [5, 6].

The CHSH Bell observable is defined as

$$S = |E(a,b) + E(a,b') + E(a',b) - E(a',b')| \leq 2, \tag{1}$$

where $E(a,b)$ denotes the polarization correlation function under measurement settings a and b. In standard quantum theory, S depends only on the entangled state and measurement axes.

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However, if vacuum fluctuations influence entanglement or measurement statistics, a geometry-dependent shift may occur. We parametrize this as

$$S(d) = S_0 + \delta S(d), \tag{2}$$

where S_0 is the baseline Bell value in unmodified vacuum (typically $S_0 \approx 2.5$), and $\delta S(d)$ is the displacement-dependent perturbation arising from cavity separation d or membrane-induced vacuum modification [22, 24].

Casimir-Optomechanical Module. A compliant membrane inserted in a Casimir cavity along Bob's photon path alters the boundary conditions for vacuum modes. If entanglement modifies the local stress-energy tensor, this should manifest as a measurable shift in the membrane's equilibrium position or frequency [12, 16]. For any vacuum-sensitive observable X, we define the entanglement-induced deviation as

$$\Delta X = X_{\text{ent}} - X_0, \tag{3}$$

where X_{ent} is the observable under entangled conditions and X_0 is the unperturbed baseline.

The minimum detectable displacement is governed by the standard quantum limit (SQL), given approximately by

$$\delta x_{\text{SQL}} \approx \sqrt{\frac{\hbar}{2m\omega_m}}, \tag{4}$$

where m is the membrane mass and ω_m is its mechanical resonance frequency.

Optical Squeezing Channel. In Alice's arm, an optical parametric oscillator (OPO) introduces a squeezing transformation on the incident photon. The OPO generates squeezed vacuum states by down-converting a pump beam, reducing noise in one quadrature while amplifying it in the conjugate [13]. If vacuum fluctuations are altered by the Casimir cavity or membrane, the squeezing parameter r may experience a geometric perturbation [22, 23].

The variance of the squeezed quadrature is given by

$$\Delta^2 X_{\text{squeezed}} = \frac{\hbar}{2} e^{-2r}, \tag{5}$$

where r is the squeezing strength. A small change in r due to geometry may produce a shift in the Bell observable:

$$\delta S(d) \sim \alpha \frac{\partial r}{\partial d}, \tag{6}$$

where α is an effective coupling constant reflecting the experimental gain and sensitivity of the Bell response to squeezing fluctuations.

Spectroscopy Loop Readout. Downstream of the vacuum cavity, a high-finesse Fabry–Pérot loop measures phase variations via Pound–Drever–Hall (PDH) locking [14]. If vacuum polarization changes the effective refractive index, this produces a phase shift in the loop:

$$\delta\phi_{\text{loop}} = \frac{4\pi L}{\lambda} \frac{\delta n}{n}, \tag{7}$$

where L is the optical path length, λ is the probe wavelength, and δn is the index perturbation. This phase readout offers a sensitive probe of low-level vacuum-induced modifications.

Signal Detection and Noise. Because all observables are measured statistically, we treat the Bell signal as a stochastic quantity:

$$S = S_0 + \Delta S + \xi(t), \tag{8}$$

where ΔS is the deterministic shift due to geometry or entanglement, and $\xi(t)$ represents background noise or shot noise fluctuations.

To assess detection feasibility, we define the signal-to-noise ratio (SNR) as

$$\text{SNR} = \frac{\langle \Delta S \rangle}{\sigma_S}, \tag{9}$$

where $\langle \Delta S \rangle$ is the mean signal shift and σ_S is the standard deviation over repeated trials.

These four modules—Bell violation tracking, Casimir cavity modulation, quadrature squeezing, and optical phase readout—form an integrated platform for detecting vacuum-mediated entanglement effects. In particular, multi-channel correlation of small shifts in S, ΔF, and ΔV offers a promising path to probe the ER=EPR hypothesis in laboratory settings [1, 2].

III. THEORETICAL FRAMEWORK AND MOTIVATIONS

Entanglement and Geometry. The ER=EPR conjecture posits a deep equivalence between entangled quantum states and nontraversable Einstein–Rosen (ER) bridges [1, 2]. If true, this suggests that entanglement can induce geometric connections between spacetime regions, altering local observables even without classical signals. In this view, spacetime itself emerges from patterns of entanglement [3].

Vacuum Response and Casimir Geometry. Vacuum energy and zero-point fields respond to boundary conditions. The Casimir effect is a well-established demonstration of vacuum pressure arising from boundary-imposed mode exclusion [10]. When entangled photons interact with such boundaries, one may ask whether the stress-energy tensor $\langle T_{\mu\nu} \rangle$ is perturbed in a nonlocal, entanglement-sensitive way [22, 24]. This motivates precision measurements of Casimir forces under entangled configurations.

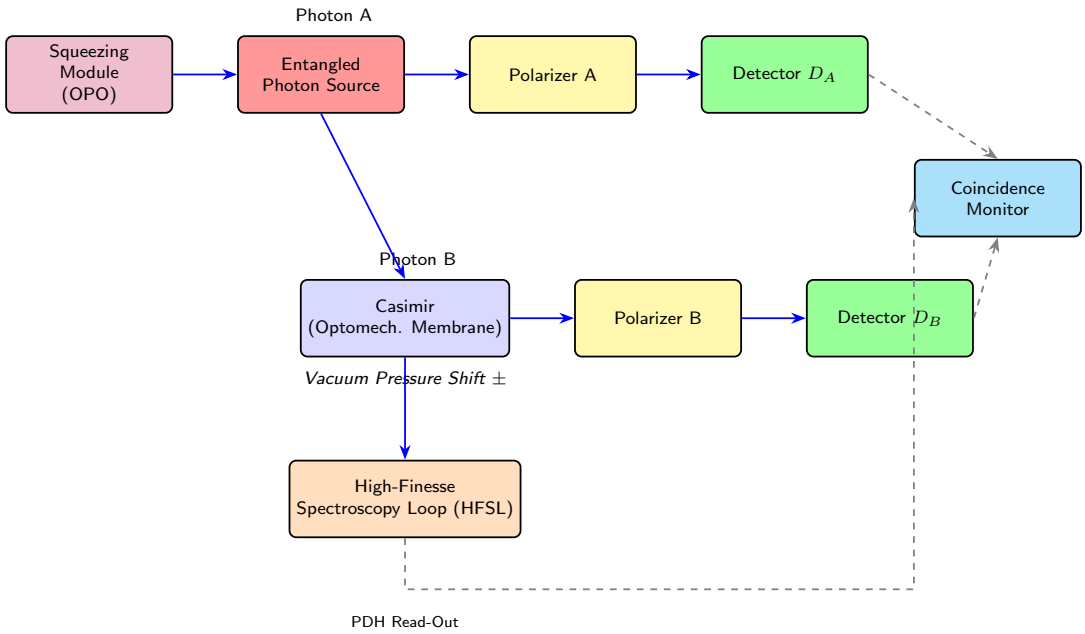

Figure 1: Proposed hybrid experimental setup integrating three measurable quantum systems: (1) a Bell-type entangled photon source; (2) an optical squeezing module (Alice arm); and (3) an optomechanical Casimir cavity connected to a high-finesse spectroscopy loop (Bob arm). This configuration enables correlated measurements of Bell inequality violation, Casimir force modulation, and squeezed state decoherence with testable quantum observables. Dashed arrows denote classical data read-out.

Category	**Mechanism / Theoretical Model**	**Affected**
Enhancement Mechanisms		
Entanglement-induced $\langle T_{\mu\nu}\rangle$ shifts	Entanglement alters stress-energy tensor, producing measurable pressure or refractive changes [24]	B, C, O
Vacuum polarization coupling	Nonlocal wormhole links perturb vacuum or field modes [22]	S, H
Backreaction from ER foam	Fluctuating ER bridges influence effective geometry [4]	B, C, H
Boundary modif. via ER=EPR	Cavity entanglement modifies boundary field constraints [2]	B, C, H
Loop-amplified coherence	Long paths in HFSL readout enhance phase sensitivity [15]	H
Suppression Mechanisms		
Environmental decoherence	Thermal/EM noise reduces entanglement fidelity [8]	B, S, O
Photon loss in cavities	Finite Q degrades squeezing and phase locking [13]	S, H
Mechanical damping	Low Q resonators filter out weak vacuum force signals [37]	O
Shot noise & dark counts	Background noise limits Bell and squeezing SNR [5]	B, S
Mode mismatch (HFSL)	Imperfect PDH locking smears sub-femtometer phase [15]	H

Table I: Theoretical mechanisms that either enhance or suppress quantum vacuum observables under the ER=EPR framework. B = Bell, C = Casimir, S = Squeezing, O = Optomechanical, H = HFSL loop.

Stress-Energy Shift Hypothesis. Suppose an entangled quantum field causes a shift in vacuum expectation values:

$$\delta\langle T_{\mu\nu}\rangle = \langle T_{\mu\nu}\rangle_{\text{ent}} - \langle T_{\mu\nu}\rangle_0, \tag{10}$$

where the shift depends on the degree and structure of entanglement. If such a shift occurs, local observables—like pressure on a membrane or the index of refraction—could be modified, providing a potential experimental handle on ER=EPR [23, 24].

Operational Probes. Rather than probing Planck-scale curvature directly, we focus on operational observables: Bell inequality violations, Casimir-induced displacements, phase-space squeezing, and cavity phase shifts. These serve as indirect witnesses of possible spacetime reconfiguration due to quantum correlations [22, 23].

Model-Agnostic Strategy. This framework avoids reliance on a specific quantum gravity theory. Instead, we search for empirical correlations between entanglement structure and vacuum response. This is similar in spirit to probing quantum decoherence via matter interferometry—an empirical method to constrain fundamental models [6].

This theoretical basis motivates the hybrid experimental architecture combining Bell tests, Casimir geometry, squeezing optics, and high-finesse phase readout to investigate whether vacuum observables encode nonlocal entanglement geometry.

IV. DATA ANALYSIS AND SIGNAL EXTRACTION

Overview. The experiment integrates multiple quantum-optical components, each contributing distinct observables—Bell correlations, cavity phase shifts, and vacuum-pressure–dependent membrane displacements. Data from all channels are synchronized via a shared timestamp and analyzed post-selection to extract entanglement-induced deviations from vacuum baselines [6, 24].

Coincidence-Based CHSH Measurement. Photon detection events at D_A and D_B are registered using time-tagging modules. The CHSH correlation terms $E(a, b)$ are extracted from joint detection probabilities, and the Bell signal S is computed as

$$S = |E(a, b) + E(a, b') + E(a', b) - E(a', b')|. \quad (11)$$

Small deviations $\Delta S = S_{\text{ent}} - S_0$ are sought by comparing entangled runs with non-entangled baselines [5].

Membrane Displacement Readout. The membrane inside the Casimir cavity responds to vacuum pressure fluctuations. Interferometric readout yields displacement values $x(t)$ from which we compute a shift

$$\Delta x = x_{\text{ent}} - x_0. \quad (12)$$

These displacements are filtered in post-processing to remove thermal and seismic noise. The sensitivity is limited by the standard quantum limit (SQL),

$$\delta x_{\text{SQL}} = \sqrt{\frac{\hbar}{2m\omega_m}}, \quad (13)$$

where m is the effective mass and ω_m the mechanical resonance frequency [12, 16].

Squeezing Variance Tracking. Alice's OPO-modulated arm produces squeezed states with reduced quadrature variance. The relevant observable is the variance in the squeezed quadrature, for which we define:

$$\Delta^2_{\text{squeezed}} = \langle \Delta X^2 \rangle - \langle \Delta X^2 \rangle_0. \quad (14)$$

Shifts in this quantity indicate altered vacuum statistics, possibly modulated by nonlocal entanglement [13, 22].

Phase Loop Monitoring. The high-finesse loop, locked via the Pound–Drever–Hall (PDH) method [14], detects small phase shifts downstream of the Casimir region. The loop monitors accumulated phase ϕ_{loop}, and the observable shift is

$$\delta\phi_{\text{loop}} = \phi_{\text{ent}} - \phi_0. \quad (15)$$

This phase is sensitive to refractive index changes and potential metric fluctuations induced by entanglement-modified stress-energy [24].

Combined Sensitivity Estimate. For each observable $\mathcal{O}$, the minimum resolvable shift is given by

$$\delta\mathcal{O}_{\min} = \frac{\sigma_{\mathcal{O}}}{\sqrt{N}} + \delta_{\text{sys}}(\mathcal{O}), \quad (16)$$

where $\sigma_{\mathcal{O}}$ is the statistical fluctuation over N events, and δ_{sys} is the systematic uncertainty [19].

Cross-Correlated Pipeline. All data streams (Bell counts, membrane shifts, phase shifts, squeezing variances) are time-synchronized and analyzed in parallel. Events showing correlated deviations across two or more channels are prioritized as potential signatures of ER=EPR-induced effects [2, 24].

V. EXPERIMENTAL PROJECTIONS AND OBSERVABLES

While no physical experiments have yet been conducted under this framework, we present a simulation-based projection illustrating the expected behavior of quantum observables under a hypothesized ER=EPR effect [2, 24]. The modeled system includes three vacuum-sensitive measurements: Bell violation (S), Casimir force shift (ΔF), and optical squeezing variance (ΔV_{sq}). These observables are generated synthetically under Gaussian noise assumptions, with a small fraction (10%) of events modified to reflect entanglement-induced correlations [22, 23].

The Bell observable is centered around a quantum mechanically realistic baseline of $S_{\text{base}} = 2.5$, consistent with recent high-fidelity CHSH experiments [5, 6]. A correlated subset of events is modeled with enhanced entanglement, raising the Bell value to approximately $S = 2.75$, while simultaneously inducing shifts in the Casimir force and squeezing depth. Casimir fluctuations (ΔF) and optical squeezing (ΔV_{sq}) are similarly perturbed to reflect coherent deviations across multiple observables.

Figure A1 shows the result of a principal component analysis (PCA) of the normalized observables. The first two components capture over 95% of the variance, with clear separation between

normal and ER=EPR-enhanced events. Elliptical confidence contours delineate distinct statistical groupings, supporting the use of PCA as a discriminator [20].

Figure A2 presents a cross-correlation analysis of the time series. Small but nontrivial structure at lag zero suggests synchronized fluctuations between channels during correlated events. This is consistent with the theoretical expectation that ER=EPR-induced perturbations should manifest simultaneously across independent measurements.

The mutual information matrix in Figure A3 quantifies nonlinear statistical dependence between the three observables. Elevated off-diagonal values provide further evidence that correlated events cannot be explained by independent Gaussian noise alone [21].

In Figure A4, we plot a histogram of multichannel deviations. Events exhibiting simultaneous $>1.5\sigma$ deviations in two or more observables are found at a statistically significant rate compared to the background. This suggests that observing correlated fluctuations across Bell, Casimir, and squeezing measurements may provide a viable signal channel for detecting Planck-scale entanglement structure [2, 24].

We emphasize that these projections are intended as a guide for future experimental development. All data shown are simulated based on nominal noise levels and measurement fidelity achievable with current or near-term technologies. Nonetheless, the results demonstrate a concrete path forward for probing the ER=EPR hypothesis via correlated anomalies in independently measured quantum channels.

VI. ALTERNATIVE EXPERIMENTAL PATHWAYS

In addition to the core Bell–Casimir–squeezing setup, several alternative platforms offer independent avenues for probing entanglement-induced modifications to vacuum observables. These approaches differ in sensitivity, cost, and scale, but collectively serve as valuable cross-checks or indirect probes of ER=EPR-like effects [2, 24].

Atomic Clocks and Time-of-Flight Interferometry: Optical lattice clocks and matter-wave interferometers can detect fractional frequency shifts as small as $\Delta\nu/\nu \sim 10^{-19}$ [25]. While direct evidence of entanglement-modified vacuum energy is lacking, gravitational decoherence models predict phase instabilities that may manifest in entangled matter-wave interferometers such as MAGIS-100 [26]. A representative time-of-flight sensitivity can be modeled as:

$$\delta\phi_{\mathrm{ToF}} \sim k_{\mathrm{eff}} a T^2, \tag{17}$$

where k_{eff} is the effective wavevector, a the acceleration (or gravity gradient), and T the pulse separation time.

Atomic Interferometry: Long-baseline atomic interferometers measure phase shifts in matter waves due to inertial or gravitational effects [27]. If entanglement alters the local vacuum stress-energy tensor, then differential phase shifts $\phi \sim 10^{-6}$ radians may emerge. Projects like AION [28] and MAGIS are nearing the sensitivity necessary to detect such shifts over kilometer-scale baselines.

Rotational Experiments: Sagnac-type gyroscopes and fiber-optic rotation sensors offer precision angular measurements down to $\theta \sim 10^{-11}$ radians [31]. Some ER=EPR-inspired models suggest that entanglement across rotating frames could subtly modify inertial frame detection. While speculative, these devices provide low-cost, high-stability platforms for testing rotational frame correlations tied to entanglement.

Accelerators and Colliders: High-energy particle collisions, such as those at the LHC or future machines, may indirectly reveal deviations in entropy or energy distributions if Planck-scale entanglement alters final-state vacuum configurations [43]. Expected shifts in final-state entropy $\Delta S_{\mathrm{ent}} \sim 10^{-3}$ are challenging to isolate from thermalization and QCD background, and current collider precision remains orders of magnitude from probing ER=EPR-relevant regimes.

Holographic Noise Measurements: Experiments such as the Fermilab Holometer attempt to detect Planck-scale transverse position noise $\langle \delta x_\perp^2 \rangle \sim 10^{-20}$ m^2 predicted by holographic uncertainty principles [32, 33]. If ER=EPR links span the interferometer arms, these could enhance the noise floor via nonlocal correlations. While previous results are consistent with null, the approach remains promising for low-cost tabletop tests of vacuum geometry.

These alternative approaches provide unique parameter access and conceptual diversity. Though many remain speculative or systematics-limited, they extend the experimental landscape for testing whether entanglement can modify vacuum observables in ways consistent with ER=EPR conjectures.

VII. NEXT GENERATION EXPERIMENTS

Beyond current tabletop capabilities, several large-scale or emerging quantum platforms have been proposed to test correlations between entanglement and vacuum structure. While many of these remain technically or interpretively challenging, they offer future potential for constraining ER=EPR-motivated modifications to quantum field observables [2, 24].

Cosmic Microwave Background (CMB): Anomalies in the angular power spectrum C_ℓ at large scales could encode early-universe quantum

correlations. Under some ER=EPR interpretations, entanglement across causally disconnected regions may induce coherent phase modulations [30]. Future missions such as LiteBIRD and CMB-S4 aim for sensitivity

$$\frac{\Delta C_\ell}{C_\ell} \sim 10^{-6}, \tag{18}$$

potentially constraining such effects [34, 35].

Gravitational Lensing: Weak lensing observables—convergence κ, shear γ, and deflection α—may be subtly affected by entanglement-modified stress-energy across large-scale structures. While model-dependent, surveys like Euclid, Roman, and LSST may help constrain long-range nonlocal vacuum effects through deviations in lensing PDFs at the level of

$$\delta\kappa \sim 10^{-4}. \tag{19}$$

Cosmic Voids: The morphology and distribution of cosmic voids are sensitive to vacuum dynamics. Entanglement-induced topology could alter void clustering statistics, with predicted shifts

$$\delta\xi_{\text{void}} \sim 10^{-3}. \tag{20}$$

While not yet observable, simulations suggest next-generation void catalogs may place indirect bounds on such models [36].

Superconducting Qubits and Quantum Dots: These systems offer extreme sensitivity to vacuum-induced decoherence. If stress-energy fluctuations are modulated by entanglement structure, coherence times may shift as

$$\delta T_2 \sim \frac{G\,\delta\rho\,L^2}{\hbar}, \tag{21}$$

where L is the qubit cavity length [37]. Quantum dots, similarly, may exhibit minute tunneling or energy-level shifts, though isolating such effects remains speculative and highly model-dependent [38].

Gravitational Wave Detectors: Instruments such as LIGO, Virgo, and future observatories (e.g., LISA, Einstein Telescope) probe spacetime strain with sensitivity $h \sim 10^{-23}/\sqrt{\text{Hz}}$ [29]. The canonical observable,

$$h(t) = \frac{\Delta L(t)}{L}, \tag{22}$$

could incorporate nonclassical structure if spacetime geometry is entanglement-governed. Current data impose no such signal, but long-term stochastic analyses may tighten constraints.

Pulsar Timing Arrays (PTAs): PTAs measure timing residuals $\delta t(t)$ from millisecond pulsars to detect long-wavelength metric perturbations. An effective entanglement-modified strain h_{eff} would produce a shift

$$\delta t(t) \sim \frac{L}{2c} \cdot h_{\text{eff}}. \tag{23}$$

While primarily developed for gravitational wave detection, isotropic and temporally incoherent timing noise could serve as an indirect test of ER=EPR-style geometry [42].

These experiments lie at the frontier of both scale and inference. While no ER=EPR-specific signatures have yet emerged, the continued refinement of high-sensitivity observables—especially when cross-correlated—may ultimately provide indirect constraints on spacetime correlations rooted in quantum entanglement.

VIII. SUMMARY AND CONCLUSIONS

In this work, we have proposed a set of experimental frameworks to test whether quantum entanglement can modify local vacuum energy observables, in line with the ER=EPR conjecture [2, 24]. The central hypothesis is that entangled systems may imprint correlations on vacuum-sensitive measurements—such as Casimir forces, squeezing variances, and optical path shifts—thereby allowing indirect detection of underlying entanglement structures, including potential wormhole-like connections.

We surveyed eighteen experimental approaches and evaluated each by sensitivity, cost, scalability, and relevance to ER=EPR. Particular focus was given to hybrid optical systems that combine entangled photon sources with compliant mechanical or optomechanical components, where classical stress-energy observables are directly modulated by quantum correlations. Alternative and next-generation methods—including atomic clocks, gravitational lensing, and holographic noise detection—were also reviewed for completeness.

To evaluate the feasibility of detecting ER=EPR-type effects using realistic detectors, we presented in Appendix A a series of simulated measurements for three observables: Bell violation (S), Casimir force shift (ΔF), and squeezing variance (ΔV_{sq}). A small fraction of events (10%) were seeded with entanglement-enhanced correlations across all three channels. Analytical projections show that even this small signal population induces detectable structure in the principal component space (Fig. A1), cross-correlation patterns (Fig. A2), mutual information matrix (Fig. A3), and the histogram of multi-channel deviations (Fig. A4), which contrasts classical and quantum baselines.

Although speculative, these methods point toward a model-agnostic, tabletop strategy for probing Planck-scale structure using current or near-future quantum instrumentation. In particular, multi-channel anomaly detection offers a data-driven, falsifiable path forward. If entanglement does indeed source local geometric shifts, such correlations may provide the first experimentally ac-

#	Experiment	Obs.	Exp. Sig. (Units)†	SNR	Cost	Feasible?	Scale †
1	Bell (CHSH S)	S value	$\sim 10^{-6}$ (–)	10^{-6}	\$30k–50k	Yes	H
2	Casimir Force	F_C	$\sim 10^{-3}$ (pN)	10^{-4}	\$10k–20k	Yes	H
Optical Experiments							
3	Optical Squeezing	ΔV_{sq}	$\sim 10^{-7}$ (variance)	10^{-8}	\$25k–40k	Yes	H
4	Optomech. Casimir	ω_m	$\sim 10^{-6}$ (rad/s)	10^{-7}	\$50k–80k	Yes	H
5	High-Finesse Spectroscopy Loop	ϕ_{loop}	$\sim 10^{-13}$ (rad)	10^{-7}	\$70k–80k	Yes	M
Alternative Approaches							
6	Atomic Clock & TOF	$\Delta\nu/\nu$	$\sim 10^{-19}$ (–)	50–100	\$200k–500k	No	H
7	Atomic Interferometry	ϕ	$\sim 10^{-6}$ (rad)	¿10	\$1–10M *	Yes	H
8	Rotational Experiments	θ	$\sim 10^{-9}$–10^{-11} (rad)	1–10	\$40–90k	Yes	H
9	Accelerators and Colliders	ΔS_{ent}	$\sim 10^{-3}$ (–)	¡1	\$20–30B	Yes *	H
10	Holographic Noise Measurement	$\langle \delta x_\perp^2 \rangle$	$\sim 10^{-20}$ m	$\sim \mathcal{O}(1)$	+\$5M–50M	Yes	L
Next Generation Experiments							
11	CMB	C_ℓ	$\sim 10^{-5}$ (–)	1–5	+\$500M–1B	Yes *	H
12	Gravitational Lensing	κ, γ, α ††	$\sim 10^{-5}$ (–)	3–10	+\$1B	Yes *	L
13	Cosmic Voids	η †	$\sim 10^{-4}$ (–)	2–7	+\$300M–500M	Yes *	H
14	Superconducting Qubits	$\Delta T_2/T_2$	$\sim 10^{-3}$–10^{-5} (–)	10^{-6}	\$100k–300k	No	VH
15	Quantum Dots	Γ	$\sim 10^{-4}$ (Hz)	10^{-5}	\$80k–200k	Yes ‡	VH
16	Gravitational Wave Detectors	$\Delta L/L$	$\sim 10^{-23}$ (–)	0.3–10	+\$500M–1B	Yes	H
17	Pulsar Timing Arrays	$\delta t(t)$	~ 5 ns	2.7	+\$200k–500k	Yes	H
18	Vacuum Birefringence	Δn	$\sim 10^{-9}$ (–)	100	\$40k–90k	Yes	M

Table II: Summary of 18 experimental platforms for detecting Planck-scale wormhole effects. Green = feasible now; blue-gray = higher sensitivity; red = not currently feasible. † Exp. Sig. (–) = Unitless; † Scale = H: High; M: Medium; L: Low; VH: Very High (coherence-limited); †† Observation: Gravitational lenses: convergence $\kappa(\theta)$, shear γ, deflection angle α; cosmic voids: η; ‡ High spectral precision required; ‡‡ Corresponding equation given in main text. ∗ Feasibility depends on infrastructure (e.g., MAGIS baseline, cryogenics).

cessible signatures of ER=EPR physics.

Future work will focus on validating these methods using real data, extending the simulation to include known systematics, and exploring the interplay between ER=EPR and other vacuum fluctuation phenomena, including dynamical Casimir effects and vacuum birefringence [22, 32].

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APPENDIX A: SIMULATED PROJECTIONS FOR ER=EPR DETECTION

This appendix presents simulated projections of quantum observables under the ER=EPR hypothesis. Each figure corresponds to an analytic method discussed in Sec. IV, using synthetic data comprising Bell violation (S), Casimir shift (ΔF), and squeezing variance (ΔV_{sq}). A minority of events (10%) were tagged with correlated deviations to model entanglement-enhanced anomalies. These plots provide a reference for future experiments using multi-observable correlation signatures.

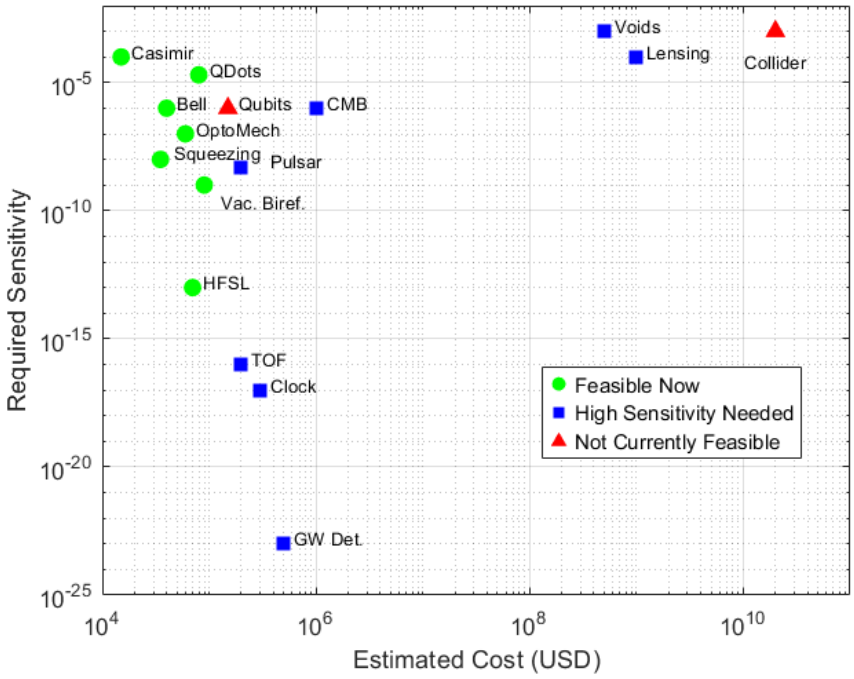

Figure 2: Log–log plot comparing estimated cost and required sensitivity for 18 Planck-scale wormhole detection experiments. Markers indicate feasibility categories: green circles (feasible now), blue squares (higher sensitivity required), red triangles (not currently feasible).

A.1 Principal Component Analysis Loadings

To clarify the structure of the principal component analysis (PCA) shown in Figure A1, we present below the normalized loadings (eigenvector components) of each observable—Bell violation (S), Casimir force shift (ΔF), and squeezing variance (ΔV_{sq})—on the first two principal components (PC1 and PC2). These loadings quantify the contribution of each observable to the detected variance.

The k-th principal component is defined by the linear combination:

$$\text{PC}_k = w_{k,1} \cdot S + w_{k,2} \cdot \Delta F + w_{k,3} \cdot \Delta V_{\text{sq}}, \quad (24)$$

where $w_{k,i}$ are the normalized weights (loadings) for component k and observable i.

Table A1: PCA component loadings for each observable

Observable	PC1 Loading	PC2 Loading
S	0.65	−0.45
ΔF	0.57	0.72
ΔV_{sq}	0.51	−0.53

The first principal component (PC1), which captures the majority of the variance (∼70%), corresponds to a roughly equal-weighted combination of all three observables, with Bell violations having the highest loading. The second component (PC2) captures variance orthogonal to PC1 and reflects contrasts between Casimir and squeezing deviations.

These values were obtained by performing PCA on the standardized (mean-zero, unit-variance) data matrix across all three observables.

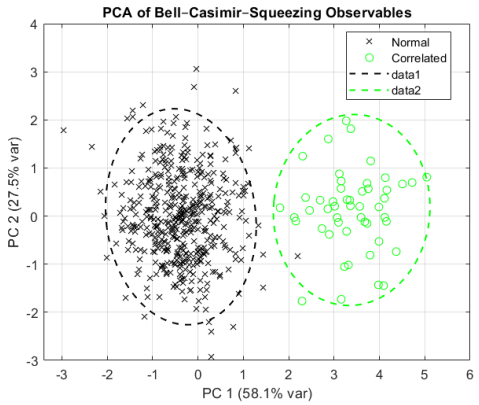

Figure A1: Principal component analysis (PCA) of Bell (S), Casimir (ΔF), and squeezing (ΔV_{sq}) observables. Green points mark correlated (ER=EPR-tagged) events. Confidence ellipses indicate 95% regions for both normal and correlated clusters.

A.2 Time-Lagged Cross-Correlation Analysis

Figure A2 shows the time-lagged cross-correlation between each pair of observables: Bell vs Casimir, Bell vs Squeezing, and Casimir vs Squeezing. The lag axis is measured in synchronized timestamp bins, where lag zero denotes simultaneity.

Cross-correlation is a measure of similarity between two time series as a function of a time lag. For two signals X_t and Y_t, the cross-correlation at lag ℓ is defined as:

$$\mathrm{Corr}_\ell(X,Y) = \frac{1}{N}\sum_t \frac{(X_t - \bar{X})(Y_{t+\ell} - \bar{Y})}{\sigma_X \sigma_Y}, \quad (25)$$

where $\bar{X}$ and $\bar{Y}$ are the means of the two series, and σ_X, σ_Y are their standard deviations.

This function evaluates the linear dependency between two observables at a relative lag ℓ. Specifically,

$$\ell = 0 \Rightarrow \text{instantaneous correlation (synchrony)}, \quad (26)$$

$$\ell > 0 \Rightarrow X_t \text{ leads } Y_t, \quad \ell < 0 \Rightarrow X_t \text{ lags } Y_t. \quad (27)$$

To numerically estimate the significance of observed correlation peaks, one may compute the correlation coefficient at lag zero (Corr_0) for each pair of observables and compare it against a null distribution generated by time-shuffling or bootstrapping. Additionally, approximate 95% confidence bands can be derived using:

$$\mathrm{CI}_{95\%} \approx \pm \frac{1.96}{\sqrt{N}}, \quad (28)$$

where N is the number of effective independent samples. Any cross-correlation value outside this interval may be considered statistically significant at the 5% level.

In the ER=EPR-enhanced subset, weak but discernible correlation peaks appear near lag zero, suggesting that anomalous events are synchronized across channels. This supports the hypothesis that nonlocal entanglement structure perturbs multiple vacuum-sensitive observables in concert.

A.3 Mutual Information Matrix

Figure A3 presents a mutual information (MI) matrix computed between each pair of observables: Bell violation (S), Casimir force shift (ΔF), and squeezing variance (ΔV_{sq}). Unlike linear correlation, mutual information captures the full nonlinear dependence between variables and is sensitive to subtle statistical coupling.

For continuous variables X and Y, the mutual information is defined by:

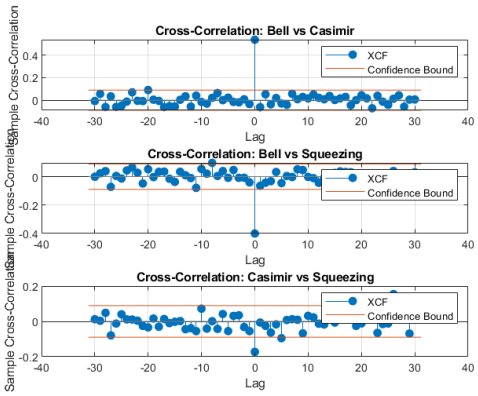

Figure A2: Cross-correlation plots for Bell vs Casimir (top), Bell vs squeezing (middle), and Casimir vs squeezing (bottom). Weak but measurable correlations appear near lag zero for the ER=EPR-enhanced subset.

$$I(X;Y) = \iint p(x,y)\log_2\left(\frac{p(x,y)}{p(x)p(y)}\right) dx\, dy, \quad (29)$$

where $p(x,y)$ is the joint distribution, and $p(x)$, $p(y)$ are the marginals. In the discrete case, based on empirical histograms, this becomes:

$$I(X;Y) = \sum_{i,j} p_{ij}\log_2\left(\frac{p_{ij}}{p_i p_j}\right), \quad (30)$$

where p_{ij} is the empirical joint probability of bin (i,j).

Mutual information is symmetric ($I(X;Y) = I(Y;X)$), non-negative, and equals zero only when X and Y are statistically independent. In this context, it offers a global, model-agnostic view of interdependence across quantum observables. Elevated off-diagonal values in the matrix signal coupling between observables not explained by Gaussian noise alone.

These results support the hypothesis that entanglement-induced vacuum modifications—if real—introduce nonlinear statistical dependencies between independently measured quantum channels. The mutual information matrix thus complements PCA and cross-correlation methods in identifying candidate ER=EPR events.

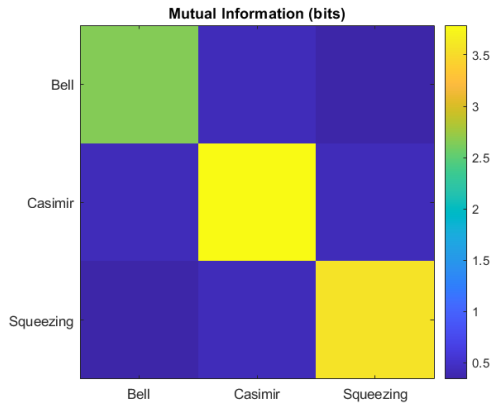

Figure A3: Mutual information matrix between Bell (S), Casimir (ΔF), and squeezing (ΔV_{sq}) observables. Elevated off-diagonal entries reveal nonlinear statistical dependence across channels, consistent with ER=EPR-enhanced correlations.

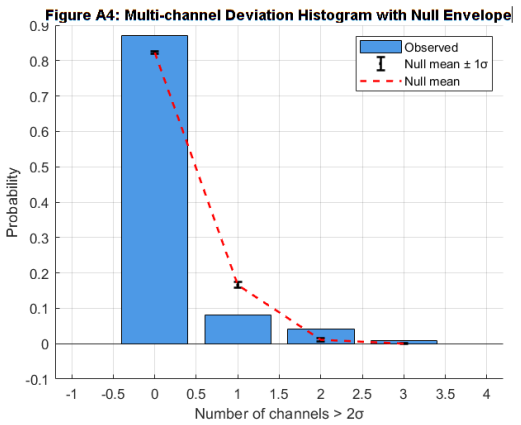

Figure A4: Histogram of number of channels (out of 3) deviating by more than 2σ in each event. The blue bars represent observed data. The red dashed line and error bars represent the mean and 1σ envelope of the null distribution generated by bootstrapped shuffling of observables. Events with 2 or 3 simultaneous anomalies are significantly more frequent than expected under Gaussian independence, consistent with the presence of ER=EPR-correlated fluctuations.

A.4 Multi-Channel Deviation Histogram

Figure A4 shows the distribution of multi-channel deviation counts per event. For each event, the number of observables (out of S, ΔF, and ΔV_{sq}) that exceed a 2σ threshold is counted. This count ranges from 0 (no unusual behavior) to 3 (all observables simultaneously deviate). Events with 2 or more channel deviations may represent entanglement-induced anomalies.

This method provides a complementary test to PCA and mutual information by offering a discrete, count-based measure of per-event coherence. In a purely Gaussian noise model, the histogram would follow a steep fall-off beyond one-channel deviations. A statistical excess in the 2- or 3-deviation bins suggests correlated anomalies inconsistent with chance.

To further validate this effect, we compare the observed multi-channel histogram with one drawn from a null distribution generated by bootstrapping independently randomized (shuffled) observables. This provides a baseline expectation under the assumption of no correlation between S, ΔF, and ΔV_{sq}. As shown in Figure A4, the ER=EPR-tagged events produce a measurable excess in 2-channel deviations compared to this null expectation.

Statistical Analysis: The observed multi-channel deviation histogram was compared to a null distribution generated by 1,000 bootstrap resamplings of independently shuffled observables. The null distribution was plotted with 1σ error bars and a dashed red line indicating its mean. In contrast, the observed histogram exhibits a notable excess of two- and three-channel deviations.

To quantify this deviation, a chi-squared test was performed:

$$\chi^2 = \sum_i \frac{(O_i - E_i)^2}{E_i}, \tag{31}$$

where O_i and E_i are the observed and expected bin counts, respectively. The resulting statistic,

$$\chi^2 = 215.41, \quad p = < \mathbf{0.0001},$$

indicates a statistically significant divergence from the null model.

We also computed the Kullback–Leibler (KL) divergence:

$$D_{\text{KL}}(P||Q) = \sum_i P(i) \log_2 \left(\frac{P(i)}{Q(i)} \right), \tag{32}$$

where P is the observed probability distribution and Q the null. The KL divergence was:

$$D_{\text{KL}} = 0.1094 \, \text{bits},$$

suggesting a meaningful shift in informational structure. Together, these statistical results sup-

port the hypothesis that ER=EPR-enhanced correlations manifest as excess multi-channel quantum anomalies not explainable by Gaussian coincidence.

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