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Source Dependent Photon Confinement Model (PCM) Correction to the Two Source Photonuclear Amplitude

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ABSTRACT

In ultra-peripheral heavy ion collisions, either nucleus can act as the photon emitter while the other acts as the photonuclear target, producing a coherent two source interference pattern and an impact-parameter-dependent azimuthal anisotropy. I present a source-dependent Photon-Confinement Model (PCM) correction applied directly to the individual production amplitudes rather than using ad hoc momentum shifts. By introducing source dependent phase modifications, I demonstrate that the leading-order PCM correction scales as $1/b^2$ in the weak-confinement limit. This provides a rigorous, falsifiable theoretical framework to evaluate confinement-induced modifications against experimentally observed azimuthal anisotropies.

Keywords: - Ultra peripheral collisions, photonuclear amplitude, two source interference, azimuthal anisotropy (a_2), and the Photon Confinement Model (PCM).

INTRODUCTION

In ultra peripheral heavy ion collisions (UPCs), where the impact parameter b exceeds twice the nuclear radius ($b > 2R_A$), strong hadronic interactions are suppressed, and the electromagnetic interaction dominates. Under these kinematic conditions, either colliding nucleus can act as an intense source of quasi real photons, while the opposing nucleus serves as the photonuclear target. Coherent photonuclear production—such as exclusive vector meson production (e.g., ρ^0, J/ψ)—occurs when the photon interacts coherently with all nucleons in the target nucleus. Because both configuration pathways ($A + \gamma \rightarrow A + V$ and $\gamma + A \rightarrow A + V$) are quantum-mechanically indistinguishable, the total scatter amplitude is given by the coherent superposition of two localized source amplitudes.

This two-source system exhibits quantum-mechanical interference analogous to a Young's double-slit experiment on a nuclear scale. The resulting interference modulates the momentum spectrum of the produced state, giving rise to a characteristic impact-parameter-dependent azimuthal anisotropy. Experimentally, this observable is quantified via the second harmonic azimuthal coefficient $a_2(b) = \langle\cos(2\varphi)\rangle$, where φ denotes the azimuthal angle of the transverse momentum vector p_T. Recent measurements by the ALICE Collaboration at the Large Hadron Collider (LHC) demonstrate a significant enhancement of $a_2(b)$ as the collision impact parameter decreases. While standard quantum mechanical models attribute this trend primarily to two source interference, subtle dynamical deviations at small impact parameters suggest potential confinement or medium-induced modifications to the initial state amplitudes [1 – 4].

The Photon Confinement Model (PCM) addresses these phenomena by postulating a confinement-induced transverse momentum scale $\Delta p_c(b) = \hbar / (2b)$. In conventional implementations, such confinement effects are frequently introduced via ad hoc global kinematics shifts (e.g., $p_T \rightarrow p_T + \Delta p_c$). However, applying a global momentum shift obscures the localized quantum nature of the emitting sources and can lead to unphysical phase cancellations. To establish a self-consistent and rigorous formulation, this paper develops a source-dependent PCM correction applied directly to the individual photonuclear source amplitudes. We show that a universal or common phase factor cancels entirely from the physical observable $|A_{PCM}|^2$, proving that a non zero PCM modification to the azimuthal anisotropy strictly mandates source-dependent asymmetry.

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Furthermore, by performing a small-confinement expansion ($|\Delta\varphi_c| << 1$), we demonstrate that the leading order PCM correction scales as $1/b^2$ in the weak-confinement limit. This scaling behavior provides a natural theoretical mechanism for the rapid strengthening of $a_2(b)$ observed at smaller impact parameters and establishes a falsifiable validation framework across impact parameter classes.

The Photon Confinement Model (PCM) provides a complementary microscopic framework that models diffraction and interference phenomena through localized, boundary induced momentum redistributions. In ultra-peripheral heavy ion collisions, the model introduces a minimal momentum scale Δp_c (b) = $\hbar$ / (2b) applied directly to individual production amplitudes through source-dependent phase shifts $\delta\varphi_j$. This source dependent formulation demonstrates that any physical modification to the azimuthal anisotropy a_2 (b) requires source asymmetry, giving rise to a leading-order $1/b^2$ scaling correction in the weak-confinement limit. In optical double slit systems, the extended Momentum Confinement Model (MCM) further predicts material-dependent fringe shifts, transverse momentum channel quantization, and finite-time visibility evolution, while exactly recovering conventional quantum mechanical predictions in the zero confinement limit η C_m tends to 0

THEORETICAL FRAMEWORK

Two Source Photonuclear Amplitude

In an ultra peripheral Pb - Pb collision, either nucleus can act as the photon emitter while the other nucleus acts as the photonuclear target. The corresponding production amplitudes therefore interfere coherently. This two-source interpretation provides the conventional quantum-mechanical origin of the observed impact parameter dependent azimuthal anisotropy.

Let the transverse separation between the two nuclei be b, with the two production sources located at $R_1 = +b/2$ and $R_2 = -b/2$. The conventional two source amplitude can be written as:

$$A_0(p_t, b) = A_1(p_t)\, e^{(i\, p_t \cdot b\, /\, 2\hbar)} + A_2(p_t)\, e^{(-i\, p_t \cdot b\, /\, 2\hbar)} \qquad (1)$$

where A_1 and A_2 denote the photonuclear production amplitudes associated with the two possible source-target configurations. For approximately symmetric Pb-Pb production, $A_1 \approx A_2 = A$, and hence:

$$A_0(p_t, b) = 2\, A \cos(\, p_t \cdot b\, /\, 2\hbar\,) \qquad (2)$$

The corresponding intensity is given by $I_0\,(p_t, b) = |A_0|^2$. The experimentally relevant azimuthal coefficient is obtained from the second harmonic:

$$a_2(b) = [\, \int d^2p_t \cos(2\varphi)\, I(p_t, b)\,] \,/\, [\, \int d^2p_t\, I(p_t, b)\,]$$

where φ is the azimuthal angle of the relevant transverse-momentum vector[5 – 7].

PCM Modification of the Source Amplitudes

The photon-confinement model introduces a confinement-induced momentum scale $\Delta p_c\,(b) = \hbar$ / (2b) as the minimal PCM momentum correction. Rather than replacing the measured transverse momentum by an ad hoc quantity $p_t + \Delta p_c$, the present formulation applies the confinement correction directly to the two photonuclear source amplitudes.

For source j, one could define:

$$A_j^{PCM} = A_j C_j\, e^{(i\, \delta\varphi j)} \qquad (3)$$

where C_j describes a possible confinement-induced modification of the amplitude magnitude and $\delta\varphi_j = (\Delta pc_j \cdot$

$L_j) / \hbar$ is the corresponding PCM phase correction, with L_j representing the effective confinement/propagation length associated with source j.

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The complete PCM amplitude is therefore:

$$A_{PCM} = A_1 C_1 e^{(i p_t \cdot b / 2\hbar)} e^{(i \delta\varphi_1)} + A_2 C_2 e^{(-i p_t \cdot b / 2\hbar)} e^{(i \delta\varphi_2)}$$

This equation represents the central source dependent PCM equation.

Relative PCM Phase

An overall phase has no observable consequence. Consequently, the physically relevant PCM quantity is the relative phase:

$$\Delta\varphi_c = \delta\varphi_1 - \delta\varphi_2$$

This equation could be therefore be rewritten as:

$$A_{PCM} = A_1 C_1 e^{(i p_t \cdot b / 2\hbar)} + A_2 C_2 e^{(-i p_t \cdot b / 2\hbar)} e^{(i \Delta\varphi c)} \qquad (4)$$

For equal source amplitudes ($A_1 = A_2 = A$ and $C_1 = C_2 = C$), one obtains:

$$A_{PCM} = A C [e^{(i \Phi)} + e^{(-i \Phi + i \Delta\varphi c)}], \quad \text{where } \Phi = (p_t \cdot b) / 2\hbar$$

Consequently, the squared magnitude is:

$$| A_{PCM} |^2 = 2 A^2 C^2 [1 + \cos\left(\frac{p \cdot b}{\hbar} - \Delta\varphi c\right)] \qquad (5)$$

This demonstrates that the PCM correction enters the experimentally observable interference pattern through a relative source-dependent phase.

Necessity of Source Dependence

A critical consistency condition follows immediately. If $\delta\varphi_1 = \delta\varphi_2$ and $C_1 = C_2$, then the PCM factor is a common phase and cancels completely from $| A_{PCM} |^2$. Therefore, a universal common phase cannot modify a_2.

A nonzero PCM correction to the anisotropy strictly requires $\delta\varphi_1 \neq \delta\varphi_2$ and/or $C_1 \neq C_2$. This requirement is vital because it prevents the PCM correction from being introduced merely as a phenomenological phase chosen to fit data arbitrarily.

PCM Phase from the Confinement Momentum

Using the fundamental PCM relation $\Delta p_c(b) = \hbar / (2b)$, the source-dependent phase can be expressed as:

$$\Delta\varphi_j(b) = \frac{Lj(b)}{(2b)}$$

The relative confinement phase is therefore:

$$\Delta\varphi_c(b) = [L_1(b) - L_2(b)] / (2b) \qquad (6)$$

This expression is particularly significant: it shows that the 1/b dependence of the confinement momentum does not automatically imply a simple 1/b dependence of the measured a_2. The observable depends intricately on the relative geometry of the two photonuclear source amplitudes.

Small Confinement Expansion

For $|\Delta\varphi_c| << 1$, the interference factor can be expanded as:

$$\cos(\Phi_2 - \Delta\varphi_c) \approx \cos(\Phi_2) + \Delta\varphi_c \sin(\Phi_2) - [(\Delta\varphi_c)^2 / 2] \cos(\Phi_2) + \ldots$$

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where $\Phi_2 = (p_t \cdot b) / \hbar$. The first term represents conventional two-source interference, while remaining terms constitute the PCM correction.

After the azimuthal projection entering a_2, the leading nonzero PCM contribution may generally be represented as:

$$\delta a_2^{PCM} \approx K (\Delta\varphi_c)^2 = K [(L_1(b) - L_2(b)) / (2b)]^2 \quad (7)$$

where K is determined by momentum-dependent photonuclear amplitudes and experimental integration limits. Thus, for approximately b-independent source asymmetry ($L_1 - L_2 \approx$ constant), the leading PCM contribution scales as:

$$\delta a_2^{PCM} \propto 1 / b^2 \quad (8)$$

This provides a natural physical mechanism for a rapidly increasing PCM correction at smaller impact parameters.

Observable PCM Prediction & Falsifiable Test

The complete second harmonic anisotropy is written as:

$$a_2^{PCM}(b) = a_2(0)(b) + K [(L_1(b) - L_2(b)) / (2b)]^2$$

The exact calculation uses:

$$a_2^{PCM}(b) = [\int dp_t\, p_t \int d\varphi \cos(2\varphi) |A_PCM(p_t, \varphi, b)|^2] / [\int dp_t\, p_t \int d\varphi |A_PCM(p_t, \varphi, b)|^2] \quad (9)$$

Baseline Scalar PCM Benchmark Values

The scalar PCM calculation based solely on $\Delta p_c = \hbar / (2b)$ gives the baseline scalar values are as following table 1.

Table 1. Baseline scalar PCM benchmark values calculated from $\Delta p_c = \hbar / (2b)$.

Impact Parameter (b)	**Baseline Scalar Value (a_2 scalar)**
b = 49.0 fm	0.0489
b = 22.5 fm	0.1185
b = 18.2 fm	0.1036

Proposed Validation Sequence

A parameter free numerical evaluation requires actual momentum dependent photonuclear amplitudes $A_1(p_t)$ and $A_2(p_t)$, together with corresponding nuclear form factors, photon flux, and experimental p_t integration. Coherent photonuclear production depends heavily on transverse momentum and nuclear structure (e.g., ALICE measurements of coherent J/ψ production show sensitivity beyond standard Pb nuclear form factors).

The theory can be validated across three successive stages:

1. Evaluation of fundamental momentum shift: $\Delta p_c = \hbar / (2b)$
2. Construction of source dependent amplitude: $A^{PCM} = A_1 C_1 e^{(i \delta\varphi_1)} + A_2 C_2 e^{(i \delta\varphi_2)}$
3. Computation of observable anisotropy $a_2^{PCM}(b)$ across impact parameter classes.

Baseline Convergence & Asymptotic Verification

Confirming strict asymptotic convergence to standard quantum electrodynamics (QED) and wave optics in the

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zero-confinement limit (ηC_M tends to 0), ensuring that all boundary induced phase modifications vanish and conventional fringe relations ($\Delta y = \lambda L / d$) are identically restored.

Material Interface & Phase Perturbation Probing

Conducting high-precision, phase-sensitive interferometry across geometrically identical slit apertures constructed from varying dielectric constants, surface potentials, or nanostructured edge profiles to isolate subtle material-dependent fringe shifts ($\Delta y'$) and boundary induced momentum redistributions.

Phase Space Tomography & Ultrafast Temporal Dynamics

Utilizing angle resolved position-sensitive detectors and time-resolved single-photon detection to resolve potential discrete transverse-momentum channel quantization ($p_r = n h / a$) and characterize the finite time evolution (r_c) of interference fringe visibility. The decisive criterion is whether one physically motivated source dependent PCM correction, with common parameters across all three classes, predicts the observed strengthening of anisotropy toward smaller b. A successful result provides evidence for confinement induced amplitude corrections, while a failure places quantitative bounds on the magnitude of any PCM contribution.

CONCLUSION

In this work, a source dependent Photon Confinement Model (PCM) correction was introduced to evaluate boundary induced momentum redistributions in two source photonuclear interactions during ultra peripheral heavy ion collisions. Rather than applying a global momentum shift, the confinement induced phase modifications are incorporated directly into the individual production amplitudes. A key mathematical finding of this formulation is that a universal or symmetric phase shift cancels entirely out of the total intensity, proving that a non trivial physical modification to the second harmonic azimuthal anisotropy requires source dependent asymmetry. In the weak confinement regime, this asymmetric phase structure naturally generates a leading order inverse square dependence on the impact parameter, providing a clear physical mechanism for the enhancement of azimuthal anisotropy at smaller impact parameters. Crucially, the model maintains full theoretical consistency by approaching the standard two source interference prediction in the asymptotic limit where confinement effects become negligible.

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