Particle Dimensions in Oscillation–Phase–Tilt / Spiral Wave Geometry

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Abstract

This paper develops a first-order interpretation of elementary particle dimensions within the **Oscillation–Phase–Tilt / Spiral Wave Geometry** framework, hereafter **OPT/SWG**. The central proposal is that an elementary massive particle is neither a hard sphere nor a mathematical point, but a **finite wrapped phase mode**: a localized standing-wave configuration whose internal phase advance produces rest energy and whose spatial closure produces a characteristic extent. The main body presents this argument descriptively, while the detailed mathematical derivations are collected in **Appendix A**. The resulting picture distinguishes two size scales. The first is the **phase-envelope dimension**, whose natural scale is set by the reduced Compton length. The second is the smaller **interaction/contact dimension**, which is not a rigid surface but the threshold at which phase-field overlap, phase-gradient curvature, or channel-specific phase matching becomes dynamically significant. A further implication is that the full Compton wavelength may be understood as the natural full-cycle complement to the reduced-Compton closure radius. If this interpretation is physically correct, then particle accelerators may be probing different layers of a phase-geometric object rather than merely testing whether particles possess hard classical radii.

1. Introduction

The question of elementary particle size has more than one physically meaningful answer. In the Standard Model, elementary leptons and quarks are treated as point-like field excitations at presently accessible experimental resolutions, while composite particles such as protons have measured form-factor and charge-distribution radii. At the same time, every massive particle carries a Compton length and a reduced Compton length, which enter quantum localization, wave phase, and relativistic rest-energy relations.[5] [6] [12] These scales are not identical to hard-sphere diameters, yet they are unavoidable consequences of combining mass, quantum phase, Planck's constant, and the speed of light.

OPT/SWG begins from this phase-based standpoint. In the uploaded OPT/SWG source corpus, a massive particle is modeled as a **wrapped mode**, namely a finite-energy, closed phase configuration whose internal oscillation supplies rest energy and whose phase winding or closure supplies identity, stability, and spatial extent.[1] [2] The mathematical formalization paper extends this language into a field-theoretic framework in which the primary entity is a phase field, with localized modes understood as structured solutions rather than assumed point masses.[4] The foundational combined papers further emphasize that interactions are not literal hard-body impacts, but phase-continuity adjustments in a shared field when wrapped modes overlap.[3]

The purpose of this paper is to convert those ideas into a specific interpretation of particle dimensions. The requested target is twofold. First, the paper explains the **diameter** or broad spatial extent of an elementary particle in OPT/SWG. Second, it explains the smaller scale at which particles effectively **interact**, **touch**, or **collide**. These two scales should not be collapsed into one number. A broad phase envelope may exist even when the hard high-momentum-transfer response is localized to a much smaller interaction core.

> ***Definition.*** *In this paper, the* ***phase-envelope radius*** *is the characteristic closure radius of a wrapped OPT/SWG mode, while the* ***interaction/contact radius*** *is the smaller operational radius at which overlap, phase-gradient curvature, or phase matching becomes dynamically significant. The explicit derivations of these two radii are provided in* ***Appendix A.1*** *and* ***Appendix A.4****.*

This distinction is necessary because experimental statements about “particle size” are probe-dependent. Elastic scattering of the proton measures charge distributions through form factors, whereas deep-inelastic scattering revealed point-like partons inside the proton.[13] Similarly, collider searches for quark and lepton compositeness constrain hard contact interactions and form-factor deviations at very short distances, not necessarily every possible non-hard phase-envelope interpretation of a particle.[15] [14]

2. Source-Theory Foundations

The OPT/SWG corpus uses several recurring principles that are directly relevant to particle dimension. The first is that rest energy is internal phase advance. The original annihilation paper and the internal/external phase advance paper both treat mass as inseparable from a persistent internal oscillation or clock-like phase advance.[1] [2] The second principle is phase closure. A wrapped mode is not merely an oscillation at a point; it is a closed configuration whose phase returns consistently after a complete winding. The third principle is that interactions arise through shared phase-field structure: when two wrapped modes overlap, the combined phase field must maintain continuity, compatible gradients, and dynamically allowed phase matching.[3]

The hard mathematical expressions for these principles are collected in **Appendix A.1**. In the main body, the important conceptual point is that a massive OPT/SWG particle is an organized phase geometry. Its size is therefore not the size of a material bead; it is the characteristic spatial scale required for the wrapped phase configuration to close on itself while preserving the internal phase rhythm associated with rest mass.

OPT/SWG concept	Descriptive meaning	Role in deriving size	Appendix reference
Internal phase advance	Rest mass corresponds to an internal oscillation rate	Links mass to a clock-like phase process	Appendix A.1
Phase closure	A wrapped mode must complete an allowed phase winding	Converts identity and stability into spatial structure	Appendix A.1
Spatial closure	The phase winding must fit around a finite mode extent	Produces a characteristic radius or diameter	Appendix A.2
Reduced Compton scale	The mass-dependent length paired with rest energy and phase	Supplies the natural closure scale	Appendix A.2
Shared phase field	Interacting modes jointly modify one phase environment	Defines collision by overlap rather than hard contact	Appendix A.4

These principles imply that an OPT/SWG particle has a **finite spatial phase structure**. However, this does not mean that it has a rigid material surface. The source annihilation paper is especially useful here because it frames particle-antiparticle annihilation as a phase-geometric process involving opposite winding and compatible phase cancellation, rather than as the collision of two tiny billiard balls.[1] The same logic should be applied to particle size. OPT/SWG dimensions are dimensions of a field configuration and its interaction kernel.

3. The Phase-Envelope Radius

The most direct interpretation begins with closure. A wrapped mode must fit its phase winding into a finite spatial extent. For the simplest fundamental mode, this closure condition produces a radius-like length equal to the reduced Compton scale. The full derivation is shown in **Appendix A.2**.

This result should be read as a statement about **phase-envelope size**, not about hard material size. The phase-envelope radius is the scale over which the mode's internal phase advance, spatial winding, and relativistic propagation speed are mutually synchronized. Under the simplest closure convention, the radius is the reduced Compton length, and the broad phase-envelope diameter is twice that value. More generally, the radius can include a profile factor and a winding number, because a realistic wrapped mode may not be a perfectly circular or uniform phase loop.

The source annihilation paper also identifies a particularly strong synchronization relation, described there as the **Frequency-to-Radius Pipeline**. Since OPT defines mass as internal oscillation frequency, and since the wrapped field's limiting propagation speed is the speed of light, one radian of internal phase advance maps naturally onto one reduced-Compton-radius light-travel distance. A full phase cycle then maps to the full Compton wavelength. This is the "too perfect to be a coincidence" feature: the temporal clock of rest mass and the spatial closure radius are not independent assumptions, but two expressions of the same phase geometry.[1]

Closure interpretation	Descriptive result	Physical caution
Fundamental phase-envelope radius	Reduced-Compton closure scale	Not a hard scattering radius
Fundamental phase-envelope diameter	Twice the reduced-Compton closure scale	Not a classical sphere diameter
Full Compton wavelength	One complete phase-cycle length	Complements, rather than replaces, the radius-like closure scale
Profile-corrected radius	Closure scale adjusted by geometry and winding	Requires a complete field solution to fix numerically

The value of this interpretation is that it turns the Compton scale from a merely familiar quantum length into an explicit geometric clue. If a massive particle is a wrapped phase mode, then its mass fixes the rhythm of its internal phase advance, and that rhythm fixes the scale on which the phase can close while propagating consistently at the relativistic limiting speed.

4. Energy-Minimization Interpretation

The original annihilation paper provides a complementary route to the same scale. It argues that a wrapped mode cannot collapse to zero radius because gradient, curvature, or tilt energy would become too large as the mode is compressed. At the same time, it cannot expand indefinitely because the internal oscillation energy associated with the active wrapped structure would grow. The stable mode is therefore expected to occur at a finite balance point.[1]

The raw variational model for this balance is moved to **Appendix A.3**. In descriptive terms, the energy-minimization argument says that an OPT/SWG particle must occupy a finite radius because both excessive compression and excessive expansion are energetically disfavored. If the microscopic problem is controlled only by the particle mass, quantum phase, and relativistic propagation, then the only natural first-order length available is the reduced Compton scale.

This second route is important because it avoids making closure appear like a purely kinematic assumption. Closure provides the phase-topological reason for a finite radius, while energy minimization provides the stability reason. Together, they suggest that the reduced Compton scale is not an arbitrary imported length, but the natural balance scale of a massive wrapped phase mode.

5. Representative Phase-Envelope Dimensions

Using the fundamental closed-loop convention, the phase-envelope dimensions for representative particles are as follows. The electron, muon, tau, and proton reduced Compton wavelengths are CODATA/NIST values.[6] [7] [8] [9] The table reports the descriptive first-order OPT/SWG interpretation: the reduced Compton value is treated as the phase-envelope radius, and twice that value as the broad phase-envelope diameter.

Particle	Reduced Compton wavelength (m)	OPT/SWG phase-envelope radius under fundamental convention (m)	OPT/SWG phase-envelope diameter under fundamental convention (m)
Electron	(3.8615926744\times10^{-13})	(3.8615926744\times10^{-13})	(7.7231853488\times10^{-13})
Muon	(1.867594306\times10^{-15})	(1.867594306\times10^{-15})	(3.735188612\times10^{-15})
Tau	(1.110538\times10^{-16})	(1.110538\times10^{-16})	(2.221076\times10^{-16})
Proton	(2.10308910051\times10^{-16})	(2.10308910051\times10^{-16})	(4.20617820102\times10^{-16})

This table illustrates a central prediction of the first-order OPT/SWG model: for particles described by the same closure convention, phase-envelope size varies inversely with rest mass. Heavier particles have tighter phase closure. However, composite particles require caution. The proton has a reduced Compton wavelength of approximately (2.10\times10^{-16},\mathrm{m}), while its measured rms charge radius is approximately (8.4075\times10^{-16},\mathrm{m}).[9] [11] This difference is not a contradiction because the proton is not an elementary wrapped mode in the same sense as a lepton; it has internal quark and gluon structure and scale-dependent form factors.[13]

6. The Compton Wavelength as a Natural Complementary Size Scale

In hindsight, the appearance of the Compton wavelength in a theory of massive-particle size is not merely convenient; it is structurally natural. The Compton scale is the unique length obtained by combining the constants that define quantum phase, relativistic propagation, and rest mass. It is therefore the natural bridge between the internal oscillation of a massive mode and the spatial closure required for that mode to exist as a localized object.[5] [6] [12]

The reduced Compton length functions in the present interpretation as the **radius-like closure scale**. The full Compton wavelength then functions as the **full phase-cycle scale**. This distinction is useful because OPT/SWG treats massive particles as wrapped phase structures rather than as literal solid bodies. A single radian of internal phase advance corresponds to a reduced-Compton light-travel distance, while a complete phase cycle corresponds to the full Compton wavelength. The reduced and unreduced Compton lengths are therefore not competing definitions of size; they are complementary descriptions of the same phase geometry. The explicit frequency-to-radius relationship is given in **Appendix A.2**.

Compton-related scale	OPT/SWG interpretation	Physical meaning
Internal frequency	Rest-mass clock	Temporal phase rate of the wrapped mode
Reduced Compton length	Radius-like closure scale	Distance associated with one radian of internal phase advance at the limiting propagation speed
Full Compton wavelength	Full phase-cycle scale	Distance associated with one complete internal phase cycle
Phase-envelope diameter	First-order wrapped-mode diameter	Characteristic broad extent of the closed phase envelope
Contact radius	Probe-dependent interaction scale	Threshold radius sampled by a specific interaction channel

This perspective clarifies why the Compton scale has often appeared more like a quantum-localization boundary than a conventional radius. In ordinary relativistic quantum theory, attempts to localize a particle below roughly its Compton wavelength encounter pair-production and field-theoretic effects, so the Compton scale marks the point at which single-particle localization ceases to be operationally simple.[12] In OPT/SWG, the same scale receives a geometric interpretation: below the closure scale, the mode cannot be treated as an independently localized wrapped structure without disturbing the phase relation that gives it mass and identity.

This reframing may open several useful lines of inquiry. First, it suggests that particle "size" should be separated into **phase closure**, **phase-cycle extent**, and **interaction kernel** rather than forced into a single radius. Second, it suggests that mass hierarchy is also a hierarchy of closure tightness: heavier particles are not simply more massive, but have more tightly wrapped internal phase geometry. Third, it offers a way to compare leptons, hadrons, and resonances without assuming that every measured radius is the same kind of radius. A lepton's Compton-derived envelope, a proton's charge radius, and a quark's hard form-factor limit may all be real scales, but they answer different physical questions.

The claim should be stated carefully. The Compton wavelength is not being redefined as a hard experimental diameter. Rather, OPT/SWG proposes that it is the natural **phase-size complement** to mass: the spatial expression of the same internal oscillation that produces rest energy. In this sense, the Compton scale may be less an incidental quantum length than a clue that massive particles are extended phase-closure phenomena whose hard collision response is only one operational aspect of their geometry.

7. Potential Implications for Particle Accelerator Research

If the Compton-scale interpretation of particle size is correct, it would not mean that accelerators should suddenly observe elementary particles as large classical spheres. It would instead mean that accelerator experiments may already be sampling only selected operational layers of a larger phase-geometric structure. High-energy scattering would be especially sensitive to the hard interaction core, while lower-energy, threshold, polarization, resonance, or coherence-sensitive measurements might reveal subtler evidence of the broader phase envelope.

This distinction could change how null results are interpreted. Present collider constraints on electron, quark, and lepton compositeness are usually framed as evidence that particles remain point-like down to very small distances.[14] [15] Within the OPT/SWG two-scale view, such results would still be essential, but they would primarily constrain the **hard contact radius** and the absence of conventional substructure. They would not automatically rule out a broader phase-envelope scale if that envelope couples weakly, coherently, or only through specific phase-gradient conditions.

Accelerator question	**Conventional interpretation**	**OPT/SWG-inspired reinterpretation**	**Possible future study**
Do high-energy collisions reveal a hard radius?	Look for form-factor deviations or contact interactions	Constrain the high-curvature interaction kernel	Extend compositeness searches with channel-dependent phase-overlap models
Do threshold processes show unexpected structure?	Attribute deviations to new particles, loops, or systematic effects	Examine whether closure or phase-cycle scales affect near-threshold behavior	Reanalyze precision threshold data for mass-scaled phase signatures
Do polarization or spin correlations contain hidden geometry?	Test Standard Model spin and helicity amplitudes	Search for signatures of winding, handedness, or phase orientation	Compare spin-correlation residuals across particle species
Do resonances encode closure conditions?	Fit resonance masses and widths phenomenologically	Interpret some resonance behavior as excited wrapped-mode structure	Seek mass-scaled patterns linked to Compton closure or higher winding
Can lepton universality tests reveal phase profile differences?	Compare coupling strengths across lepton generations	Ask whether different closure tightness changes effective overlap kernels	Study precision lepton scattering and decay data for generation-dependent residuals

The most immediate accelerator implication is methodological. Instead of asking only whether a particle has a hard radius, one could ask which experimental channels are sensitive to which part of the phase structure. Deep-inelastic and high-momentum-transfer events may continue to be the best probes of the smallest interaction radius. However, precision measurements near thresholds, bound-state formation, anomalous magnetic moments, spin correlations, and angular distributions may be better places to look for residual phase-envelope signatures.

If future studies found evidence that certain deviations scale with reduced Compton length, full Compton phase cycle, winding number, or channel-dependent overlap thresholds, that would represent a significant conceptual breakthrough. It would suggest that mass is not merely a parameter assigned to a point excitation, but a measurable signature of how phase closes in space. Conversely, if increasingly precise accelerator and precision experiments show no such mass-scaled or phase-correlated residuals, that would sharpen the limits on OPT/SWG and force the theory to specify why the broader phase envelope remains observationally hidden.

The research program suggested by this section is therefore not to replace the Standard Model's successful scattering formalism, but to add a layer of phase-geometric diagnostics. Accelerator data could be revisited with models that separate broad closure scale from hard contact scale, compare different interaction channels, and test whether any unexplained residuals organize around Compton-scale quantities. If the Compton scale truly reflects particle size in the OPT/SWG sense, the most important breakthroughs may come not from seeing a literal surface, but from discovering consistent phase-closure fingerprints across otherwise unrelated experiments.

8. The Interaction or Contact Radius

The second requested dimension is the smaller scale of interaction or touching when particles collide. In OPT/SWG, touching cannot mean hard-surface contact unless the theory first defines a hard surface. The more consistent definition is **phase-field contact**: two particles interact when their phase profiles overlap strongly enough that the combined field must adjust to preserve continuity, phase compatibility, and allowed gradient structure.

The explicit overlap and threshold formulas are given in **Appendix A.4**. Descriptively, the contact radius is the radius at which the combined phase field stops behaving like two independent wrapped modes and begins behaving like a coupled configuration. That threshold can depend on the interaction channel, the phase offset between modes, the spatial profile of each mode, the curvature or gradient needed to trigger the interaction, and the experimental resolution.

This is why the contact radius should be treated as a fraction of the broader phase-envelope radius rather than automatically identified with the full envelope. A soft electromagnetic overlap, a hard deep-inelastic scattering event, and a particle-antiparticle annihilation process may sample different effective radii even for the same underlying phase-envelope scale.

Symbol or term	Meaning	Expected behavior
Phase-envelope radius	Broad closure radius of the wrapped phase mode	Set primarily by closure and the reduced Compton scale
Phase-envelope diameter	Broad diameter of the closed phase structure	Twice the phase-envelope radius under the chosen convention
Interaction/contact radius	Threshold radius sampled by a specific process	Smaller than, or at most equal to, the phase-envelope radius

Symbol or term	Meaning	Expected behavior
Contact fraction	Ratio between contact radius and phase-envelope radius	Smaller for hard, high-curvature probes; larger for soft overlap
Effective interaction area	Geometric estimate of the sampled region	Useful only as a phase-overlap approximation

This should be interpreted as a phase-overlap estimate, not as a universal scattering cross-section. Actual cross-sections depend on energy, spin, charge, coupling constants, exchange channels, and available final states.

9. Relation to Experimental Size Limits

The distinction between phase-envelope radius and interaction/contact radius is essential for comparison with data. Collider experiments do not usually measure a literal particle diameter. They measure deviations from Standard Model scattering amplitudes, form-factor behavior, or effective contact interactions. The ZEUS/HERA analysis of inclusive electron-proton scattering reports a 95% confidence-level upper limit on the effective quark radius of $0.43\times10^{-16}\,\mathrm{cm}$, equal to $4.3\times10^{-19}\,\mathrm{m}$, within a quark form-factor model.[14]

The Particle Data Group review on quark and lepton compositeness describes how possible substructure would appear through high-energy contact terms. Recent LHC limits summarized there include quark contact-interaction lower limits ranging from approximately 9.2 to $29.5\,\mathrm{TeV}$, depending on the model, and lepton-quark contact-interaction limits extending into the 20–$30\,\mathrm{TeV}$ range or above.[15] The conversion between energy scale and length scale is shown in **Appendix A.5**. These inferred lengths are far smaller than the electron reduced Compton wavelength of approximately $3.86\times10^{-13}\,\mathrm{m}$.[6]

Scale type	Representative value	What it constrains	OPT/SWG interpretation
Electron reduced Compton scale	$3.8616\times10^{-13}\,\mathrm{m}$	Quantum phase/localization scale	Candidate phase-envelope radius for electron
Classical electron radius	$2.8179\times10^{-15}\,\mathrm{m}$	Electromagnetic coupling-derived length	Not a hard electron radius
HERA effective quark-radius limit	$<4.3\times10^{-19}\,\mathrm{m}$	Quark form-factor deviations	Constraint on hard interaction radius, not necessarily on soft phase envelope

Scale type	Representative value	What it constrains	OPT/SWG interpretation
(30,\mathrm{TeV}) compositeness length	Approximately (6.6\times10^{-21},\mathrm{m})	Contact-interaction scale	Constraint on point-like hard scattering response
Proton rms charge radius	(8.4075\times10^{-16},\mathrm{m})	Composite charge distribution	Composite-hadron size, not elementary closure radius

The implication is direct: an OPT/SWG paper should not claim that the full Compton-scale phase envelope is what collider experiments would see as a hard radius. Instead, it should claim that the full phase envelope governs the wrapped mode's closure and internal phase geometry, while hard scattering samples a much smaller interaction radius determined by profile overlap and channel thresholds.

10. Interpretation of "Touching" in Particle Collisions

The everyday word "touch" implies material surfaces. In a phase-field theory, the analogous event is not surface contact but the emergence of a non-negligible shared-field constraint. Two wrapped modes begin to interact when their phase gradients overlap enough that the total phase configuration is no longer separable into two independent modes. In this sense, particle contact is a **loss of independent phase closure** at the interaction threshold.

For identical modes, contact occurs when the center separation falls below the combined interaction reach of the two objects. For non-identical modes, the corresponding threshold is set by the sum of their respective interaction radii. The hard expressions are provided in **Appendix A.4**. The descriptive meaning is simple: lighter particles may have broader phase envelopes because their closure scale is larger, while the actual interaction region can remain small if the relevant channel samples only the high-curvature core.

Particle-antiparticle annihilation is a special case. The source annihilation paper associates antiparticles with opposite winding or phase orientation and describes annihilation as a geometric unwinding or cancellation process.[1] In the present two-scale language, annihilation occurs when the two phase envelopes overlap sufficiently for opposite-winding phase matching to activate. Its contact scale is therefore not simply the full radius of either particle, but the radius at which overlap and phase compatibility cross the annihilation threshold.

11. Limitations and Predictions

The interpretation presented here is intentionally first-order. It establishes the natural dimension scale of OPT/SWG wrapped modes, but it does not yet solve the complete nonlinear phase-field equations for every particle species. Several quantities remain to be computed by future work, including the profile factor, the channel-dependent threshold fraction, and the detailed relationship between OPT/SWG phase overlap and Standard Model coupling constants.

Nevertheless, the framework makes several clear claims. First, if a massive elementary particle is a wrapped phase mode, then its closure-scale radius should be proportional to the reduced Compton length. Second, the full phase-envelope diameter should not be identified with a hard radius. Third, experimentally constrained contact or form-factor radii correspond most closely to the interaction radius, not necessarily to the phase-envelope radius. Fourth, different experimental probes may infer different effective sizes because they activate different overlap thresholds and phase-gradient regions.

These claims produce a concrete research program. A later OPT/SWG paper should specify a normalized radial phase profile, compute energy density and curvature density, define an observable interaction kernel for each force channel, and derive the contact fraction from measurable thresholds rather than treating it phenomenologically. Such a calculation would turn the present dimensional interpretation into a quantitative scattering model.

12. Conclusion

Within OPT/SWG, elementary particle size is best understood as a two-scale concept. The first scale is the **phase-envelope dimension** of the wrapped mode. Phase closure, rest-energy phase advance, dimensional analysis, and the frequency-to-radius synchronization all converge on the reduced Compton scale as the natural radius-like closure length. For a fundamental mode under the simplest closure convention, the characteristic phase-envelope diameter is twice the reduced Compton length. This is the broad diameter of the closed phase structure, not a rigid material diameter.

The second scale is the **interaction/contact dimension**. In OPT/SWG, particles touch when their phase fields overlap enough to trigger continuity constraints, phase-gradient curvature, or channel-specific phase matching. The contact radius is therefore a threshold-dependent fraction of the broader phase-envelope radius. This two-scale structure is the key to making OPT/SWG particle dimensions physically coherent. It allows the theory to assert finite wrapped-mode extent while respecting the fact that high-energy scattering experiments constrain much smaller hard form-factor and contact-interaction radii.

The Compton wavelength then becomes a natural complementary scale rather than an arbitrary add-on: the full phase-cycle length paired with the reduced-Compton closure radius. The resulting picture is not a return to classical hard spheres, but a phase-geometric account in which mass sets closure scale, the full Compton wavelength marks phase-cycle extent, and interaction thresholds set the smaller observable contact scale. If true, this interpretation could motivate a new style of accelerator analysis: one that searches not for literal surfaces, but for consistent phase-closure fingerprints across scattering, threshold, resonance, polarization, and precision data.

Appendix A. Mathematical Derivations

Appendix A.1. Source-Theory Phase Relations

The OPT/SWG source corpus treats rest energy as internal phase advance. The basic relation is

$$E_0=\hbar\omega_0=mc^2.$$

A wrapped mode must also satisfy a phase-closure condition. In its simplest winding form,

$$\Delta\phi=2\pi n,$$

where (n) is an integer winding number. If the closure is represented along a spatial length (L), then

$$\phi(x+L)=\phi(x)+2\pi n.$$

For an approximately uniform spatial phase gradient (k), this becomes

$$kL=2\pi n.$$

Interactions between two wrapped modes are represented through a combined phase field,

$$\Phi=\phi_1+\phi_2,$$

with interaction strength determined by continuity, gradient compatibility, and phase matching in the combined field.

Appendix A.2. Closure Derivation of the Phase-Envelope Radius

For a wrapped mode with winding number (n), the phase advance around a closed path is

$$\oint \nabla\phi\cdot d\ell=2\pi n.$$

For a first-order circular closure with approximately uniform tangential phase gradient (k), this becomes

$$k(2\pi R_\phi)=2\pi n.$$

Solving gives

$$R_\phi=\frac{n}{k}.$$

The standard quantum phase relations are

$$E=\hbar\omega,\qquad p=\hbar k,$$

and the rest-energy relation is

$$E_0=mc^2=\hbar\omega_0.$$

A massive rest mode has the natural Compton angular-frequency scale

$$\omega_0=\frac{mc^2}{\hbar}.$$

The corresponding inverse length scale is

$$k_C=\frac{mc}{\hbar},$$

so that

$$\bar\lambda_C=\frac{1}{k_C}=\frac{\hbar}{mc}.$$

Substitution into the closure result gives the first-order closed-loop radius

$$R_\phi=n\bar\lambda_C=n\frac{\hbar}{mc}.$$

For a realistic wrapped mode, the radius convention may refer to an RMS energy-density radius, a phase-boundary radius, or a curvature-weighted radius. Introducing an order-unity geometric/profile factor (η) gives

$$\boxed{R_\phi=\eta n\frac{\hbar}{mc}.}$$

The corresponding phase-envelope diameter is

$$\boxed{D_\phi=2R_\phi=2\eta n\frac{\hbar}{mc}.}$$

For the fundamental mode ($n=1$) and the simplest closure convention ($\eta=1$), the derived OPT/SWG phase diameter is

$$\boxed{D_\phi=\frac{2\hbar}{mc}.}$$

The frequency-to-radius synchronization emphasized in the annihilation paper follows directly from

$$R\approx\frac{c}{\omega_0}=\frac{c}{mc^2/\hbar}=\frac{\hbar}{mc}.$$

Thus one radian of internal phase advance maps to one reduced-Compton-radius light-travel distance, while a full 2π phase cycle maps to the full Compton wavelength,

$$\lambda_C=2\pi\bar\lambda_C=\frac{h}{mc}.$$

Appendix A.3. Energy-Minimization Derivation

A schematic energy model for a finite wrapped mode may be written as

$$E(R)=\frac{D}{R}+BR^3,$$

where D summarizes gradient and curvature/tilt contributions, while B represents the volume-associated internal oscillation contribution. Minimizing this energy gives

$$\frac{dE}{dR}=-\frac{D}{R^2}+3BR^2=0,$$

and hence

$$R=\left(\frac{D}{3B}\right)^{1/4}.$$

This variational expression does not by itself fix the numerical radius until the coefficients are specified. However, if the non-gravitational microscopic problem is controlled only by m, $\hbar$, and c, then dimensional analysis allows only one fundamental length scale:

$$\frac{\hbar}{mc}.$$

Thus the energy-minimization argument converges with the phase-closure argument:

$$R_\phi=\eta\frac{\hbar}{mc}.$$

Appendix A.4. Interaction and Contact Radius Derivation

Let ϕ_1 and ϕ_2 be two wrapped-mode phase fields whose centers are separated by impact parameter or center separation b. A generic overlap functional may be written as

$$\mathcal{O}(b)=\int d^3x\,W(x)\,\nabla\phi_1\left(x+\frac{b}{2}\right)\cdot\nabla\phi_2\left(x-\frac{b}{2}\right),$$

where $W(x)$ is a channel-dependent weighting function. The contact scale can then be defined by a threshold condition,

$$\frac{\mathcal{O}(b_c)}{\mathcal{O}(0)}=\epsilon,$$

where $0<\epsilon<1$ is the minimum overlap fraction required for a detectable interaction. The corresponding interaction/contact radius is

$$R_{\mathrm{int}}=b_c.$$

Equivalently, if the interaction is governed by phase-gradient curvature, one may define

$$R_{\mathrm{int}}:\quad \left|\nabla^2\Phi(r)\right|\ge\kappa_c,$$

where $\Phi=\phi_1+\phi_2$ and κ_c is the critical curvature for the channel. If gradient magnitude rather than curvature is the relevant trigger, one may instead write

$$R_{\mathrm{int}}:\quad \left|\nabla\phi_1(r)+\nabla\phi_2(r)\right|\ge G_c.$$

Both forms express the same principle: the contact radius is a threshold radius inside the broader phase envelope. It is therefore natural to parameterize it as

$$\boxed{R_{\mathrm{int}}=\chi R_\phi,\qquad 0<\chi\le 1.}$$

Using the phase-envelope result gives

$$\boxed{R_{\mathrm{int}}=\chi\eta n\frac{\hbar}{mc},}$$

and the corresponding contact diameter is

$$\boxed{D_{\mathrm{int}}=2\chi\eta n\frac{\hbar}{mc}.}$$

Under the simplest geometric approximation, the effective interaction cross-section is

$$\sigma_{\mathrm{int}}\approx\pi R_{\mathrm{int}}^2=\pi\chi^2\eta^2n^2\left(\frac{\hbar}{mc}\right)^2.$$

For two identical fundamental modes with radius R_ϕ, one may define a center-separation contact condition as

$$b\le 2R_{\mathrm{int}}=2\chi R_\phi.$$

For non-identical modes, the corresponding condition is

$$b\le R_{\mathrm{int},1}+R_{\mathrm{int},2}=\chi_1R_{\phi,1}+\chi_2R_{\phi,2}.$$

Appendix A.5. Compositeness-Scale Length Conversion

Collider compositeness limits are often expressed as an energy scale (Λ). The associated length scale is estimated by

$$\ell_\Lambda\sim\frac{\hbar c}{\Lambda}.$$

Thus ($\Lambda=10\,\mathrm{TeV}$) corresponds to

$$\ell_\Lambda\approx1.97\times10^{-20}\,\mathrm{m},$$

while ($\Lambda=30\,\mathrm{TeV}$) corresponds to

$$\ell_\Lambda\approx6.58\times10^{-21}\,\mathrm{m}.$$

These lengths are many orders of magnitude smaller than the electron reduced Compton wavelength. In the OPT/SWG interpretation, such limits therefore constrain the hard interaction/contact scale more directly than the broad phase-envelope scale.

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