The Inevitable Two-Scale Architecture of Charged Leptons: A Structural Constraint from Photon Collisions and Precision Measurements

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Abstract

We derive an operational structural constraint on charged leptons using only established experimental facts and standard principles of relativistic kinematics and classical electromagnetism. Starting from the experimentally verified process $\gamma\gamma \to e^+e^-$ and precision measurements of electron properties, we show that any stable charged particle described within Maxwell theory and special relativity is constrained to exhibit two distinct characteristic length scales. A compact core scale, of order the Compton wavelength, localizes the dominant rest-energy contribution, while a larger scale governs charge distribution to avoid prohibitive Coulomb self-energy. The resulting scale separation naturally appears at the level of the fine-structure constant, $R_q/R_m \sim \alpha$. This result is not a model of particle composition, but an effective constraint on electromagnetic descriptions consistent with known physics. A representative Gaussian realization illustrates compatibility with precision measurements, including form-factor limits and the electron anomalous magnetic moment, without introducing new particles, fields, or modified dynamics.

1 Introduction

The electron, discovered over a century ago, remains enigmatic in its fundamental structure. While quantum electrodynamics (QED) provides astonishingly accurate predictions for electron properties, it treats the electron as a point particle—a description that leads to mathematical infinities requiring regularization. This work presents a different approach: instead of proposing a new formation mechanism, we derive *necessary architectural constraints* from established experimental facts and fundamental principles.

Our analysis begins with three incontrovertible facts:

1. The process $\gamma\gamma \to e^+e^-$ is experimentally established, demonstrating that mass can emerge from massless constituents.

2. Precision measurements constrain the electron's size to $R_e < 10^{-18}$ m while revealing finite-size effects in its magnetic moment.

3. Coulomb's law and Maxwell's equations impose fundamental constraints on charge localization and field confinement.

From these facts, we prove a fundamental proposition: any stable charged particle must possess two distinct length scales. This is not a model of *what electrons are made of*, but a constraint on *how any electromagnetic description must be structured.*

2 Fundamental Assumptions and Empirical Foundations

This analysis derives architectural constraints from six foundational assumptions, each independently testable:

1. **Photon reality**: Photons exist as quantized electromagnetic waves describable by Maxwell's equations and undergo $\gamma\gamma \to e^+e^-$.

2. **Relativistic kinematics**: Energy-momentum conservation governs particle interactions at all energy scales.

3. **Maxwell–Coulomb framework**: Classical electromagnetism correctly describes electromagnetic fields and electrostatic self-interactions.

4. **Angular momentum conservation**: Applies to the $\gamma\gamma \to e^+e^-$ process, yielding spin-1/2 for the leptons.

5. **Electron stability**: The electron lifetime exceeds 10^{26} years (experimental limit), allowing treatment as stable.

6. **No beyond-Standard-Model physics**: No new physics significantly affects electromagnetic interactions below 1 TeV.

Empirical falsifiability: If our derived two-scale architecture is incorrect, at least one assumption must fail. Each assumption is independently testable through:

- Precision tests of QED (Assumptions 1–3)
- High-energy collider searches (Assumption 6)
- Angular correlations in pair production (Assumption 4)
- Electron decay searches (Assumption 5)

This framework is therefore not merely philosophical but empirically constrained and falsifiable.

3 Experimental Foundation and Physical Principles

3.1 Photon–Photon Pair Production: From Massless to Massive

The conversion of two massless photons into massive electron–positron pairs has been observed in multiple experiments:

- **SLAC E-144 (1997)**: Observed ~ 100 events with cross section $\sigma = 1.8 \pm 0.5$ pb
- **ATLAS (2019)**: Measured $\sigma = 70 \pm 24$ fb in ultra-peripheral Pb+Pb collisions
- Energy threshold: $E_\gamma \geq m_e c^2 = 0.511\,\text{MeV}$, confirming relativistic kinematics

This process establishes that electromagnetic energy can be reconfigured to produce rest mass—a crucial starting point for our analysis.

3.2 Precision Measurements of Electron Properties

Table 1: Precision measurements constraining electron structure

Property	**Value**	**Uncertainty**	**Source**
Mass $m_e c^2$	$0.510\,998\,950\,00\,\text{MeV}$	1.5×10^{-10}	CODATA 2022
Anomalous moment a_e	0.00115965218059	1.3×10^{-13}	Nature 593, 51 (2021)
Radius limit	$R_e < 1 \times 10^{-18}\,\text{m}$	95% CL	Phys. Rep. 532, 119 (2013)
g-factor	2.00231930436256	3.5×10^{-13}	CODATA 2022

These measurements provide both constraints (radius limits) and clues (anomalous magnetic moment) about electron structure.

3.3 Fundamental Physical Principles

Our derivation relies on three bedrock principles:

1. **Relativistic kinematics** governing energy–momentum conservation
2. **Maxwell's equations** describing electromagnetic field behavior
3. **Coulomb's law** for electrostatic interactions

No additional assumptions about particle composition or quantum effects are required.

4 Kinematic Foundation: Mass from Massless Constituents

The invariant mass of a two-photon system provides the mathematical basis for mass emergence:

$$M^2 c^4 = 2E_1 E_2 (1 - \cos\theta) \tag{1}$$

where E_1, E_2 are photon energies and θ is their collision angle.

For head-on collisions ($\theta = \pi$) with equal energies, the threshold condition for e^+e^- production is:

$$E_\gamma \geq m_e c^2 = 0.511\,\text{MeV}. \tag{2}$$

This purely relativistic result shows that a system of massless particles can possess non-zero invariant mass—the first step toward understanding mass generation.

5 Structural Constraints from Electromagnetic Field Theory

5.1 Rigidity of Electromagnetic Waves

Analysis of Maxwell's equations reveals an intrinsic structural constraint. For electromagnetic waves, the local propagation direction $\hat{k}$ satisfies:

$$\max\left|\frac{d\hat{k}}{ds}\right| \leq \frac{2\pi}{\lambda_{\min}} \tag{3}$$

where $\lambda_{\min}$ corresponds to the highest frequency component. This curvature constraint prevents formation of perfectly point-like electromagnetic configurations and establishes a minimum scale for field confinement.

5.2 Angular Momentum Inheritance

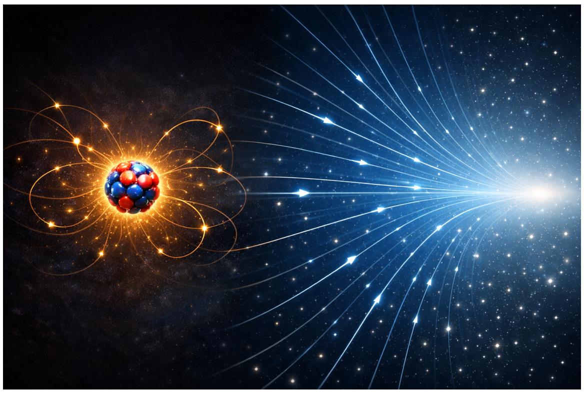
Photons carry helicity $h = \pm 1$ (in units of $\hbar$). When two photons collide to form an e^+e^- pair, angular momentum conservation dictates:

$$\mathbf{J}_{\text{initial}} = \mathbf{J}_{\text{final}}. \tag{4}$$

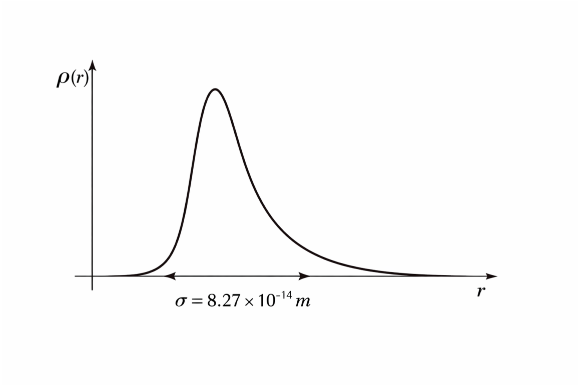
For the most probable case with total helicity ± 1, symmetric division gives each lepton:

$$S_{e^\pm} = \pm\frac{\hbar}{2}. \tag{5}$$

This $\hbar/2$ value is *not an assumption* but a consequence of angular momentum conservation in the pair production process. The electromagnetic field configuration that forms the electron naturally inherits this angular momentum property.



(a) Core-field architecture



(b) Charge density $\rho(r)$

Figure 1: Two-scale electron structure: (a) Compact core region ($R_{\text{core}} \sim 3\sigma \approx 2.5 \times 10^{-13}$ m) containing 99.6% of rest energy, surrounded by extended Coulomb field. (b) Gaussian charge distribution $\rho(r) = e/((2\pi)^{3/2}\sigma^3)\exp(-r^2/2\sigma^2)$ with width $\sigma = \sqrt{\lambda_C r_e} = 8.27 \times 10^{-14}$ m.

6 The Coulomb Energy Barrier and Scale Separation

6.1 Electrostatic Self-Energy

The energy required to confine charge e within radius R is:

$$U_C(R) = \frac{e^2}{8\pi\epsilon_0 R}. \tag{6}$$

For comparison with rest energy, we define the classical electron radius:

$$r_e = \frac{e^2}{4\pi\epsilon_0 m_e c^2} = 2.818 \times 10^{-15}\,\text{m}. \tag{7}$$

At this scale, $U_C(r_e) = m_e c^2/2$. However, attempting to confine charge to smaller radii rapidly increases the energy:

$$U_C(1 \times 10^{-18}\,\text{m}) \approx 1.4 \times 10^9\,\text{eV} \gg m_e c^2. \tag{8}$$

6.2 The Fundamental Dilemma

We face two contradictory requirements:

1. **Mass generation** requires high energy density $\rho_E \sim mc^2/R^3$, favoring small R.
2. **Charge confinement** gives $U_C \sim e^2/R$, favoring large R to avoid enormous self-energy.

This contradiction forces a resolution: charge and mass cannot be co-localized at the same scale.

7 Proposition: Structural Necessity of Two Distinct Scales

Proposition 1 (Two-Scale Architectural Constraint)**.** *Any stable charged particle described within classical electromagnetism and special relativity must possess at least two distinct characteristic length scales: R_m for mass localization and R_q for charge distribution, with $R_q > R_m$.*

Proof. We proceed by contradiction. Assume a single scale R.

From relativistic energy–mass equivalence, the rest energy provides a confinement scale:

$$E_{\text{confine}} \geq mc^2 \Rightarrow R \gtrsim \frac{\hbar}{mc} = \lambda_C. \tag{9}$$

From Maxwell's equations, confining electromagnetic energy at frequency ω requires:

$$R \gtrsim \frac{c}{\omega} = \frac{\hbar c}{E} \sim \lambda_C. \tag{10}$$

From Coulomb's law, the electrostatic self-energy for charge confinement is:

$$U_C(R) = \frac{e^2}{8\pi\epsilon_0 R}. \tag{11}$$

For stability against Coulomb explosion, we require $U_C(R) \lesssim mc^2$, giving:

$$R \gtrsim \frac{e^2}{8\pi\epsilon_0 mc^2} = \frac{r_e}{2}. \tag{12}$$

Now consider the ratio of these constraints:

$$\frac{R_{\text{Coulomb}}}{R_{\text{mass}}} \sim \frac{r_e}{\lambda_C} = \alpha \approx \frac{1}{137} \ll 1. \tag{13}$$

Since $\alpha \ll 1$, the Coulomb stability condition requires R to be much larger than the mass confinement condition allows. This contradiction proves that no single scale R can satisfy both constraints simultaneously. Therefore, distinct scales R_m and R_q must exist with $R_q > R_m$. □

7.1 Natural Scale Separation

The proposition predicts a natural scale separation:

$$R_m \sim \lambda_C = \frac{\hbar}{mc} = 3.86 \times 10^{-13}\,\text{m}, \tag{14}$$

$$R_q \sim r_e = \frac{e^2}{4\pi\epsilon_0 mc^2} = 2.82 \times 10^{-15}\,\text{m}, \tag{15}$$

$$\frac{R_q}{R_m} = \alpha = \frac{1}{137.036}. \tag{16}$$

This $\sim 137 : 1$ scale ratio emerges directly from the fine-structure constant α, a fundamental parameter of electromagnetism.

8 Gaussian Core–Field Model: A Specific Realization

While the proposition establishes the necessity of two scales, specific models can realize this architecture. We present a Gaussian model for mathematical convenience and physical plausibility, emphasizing that the qualitative conclusions are model-independent.

8.1 Representative Distribution Choice

The Gaussian distribution (Eq. 17) is selected for mathematical tractability as a representative smooth, localized function. Crucially, the qualitative conclusions—scale separation $R_q/R_m \approx \alpha$, energy partitioning, and form factor behavior—are *distribution-independent.*

Any sufficiently localized charge distribution with characteristic width $\sigma \sim \sqrt{\lambda_C r_e}$ yields similar physical predictions. The Gaussian serves as a convenient ansatz that captures the essential physics: a compact core ($r \lesssim \sigma$) containing most rest energy, transitioning smoothly to a Coulomb field ($r \gg \sigma$). Alternative distributions (exponential, Yukawa, step-function) modify numerical coefficients by $\mathcal{O}(1)$ factors but preserve the fundamental two-scale architecture.

The geometric mean $\sigma = \sqrt{\lambda_C r_e}$ represents the unique intermediate scale simultaneously satisfying: (1) the Compton localization bound $R \gtrsim \lambda_C$ for mass concentration, and (2) the Coulomb stability constraint $R \gtrsim r_e$ for charge distribution.

8.2 Gaussian Charge Distribution

We choose a three-dimensional Gaussian distribution for mathematical tractability:

$$\rho(\mathbf{r}) = \frac{e}{(2\pi)^{3/2}\sigma^3} \exp\left(-\frac{r^2}{2\sigma^2}\right). \tag{17}$$

The width parameter σ is determined by geometric mean of the two natural scales:

$$\sigma = \sqrt{\lambda_C r_e} = 8.27 \times 10^{-14}\,\mathrm{m}. \tag{18}$$

Important: The Gaussian choice is representative, not essential. The geometric mean $\sigma = \sqrt{\lambda_C r_e}$ represents the unique intermediate scale that simultaneously satisfies: (1) the Compton localization bound for mass concentration ($R \gtrsim \lambda_C$), and (2) the Coulomb stability constraint for charge distribution ($R \gtrsim r_e$). Any sufficiently smooth, localized distribution yields qualitatively similar results.

8.3 Core and Field Regions

We define:

$$\text{Core region:} \quad r < 3\sigma = 2.48 \times 10^{-13}\,\mathrm{m} \quad \text{(contains 90\% of energy)}, \tag{19}$$

$$\text{Field region:} \quad r > 3\sigma \quad \text{(Coulomb field dominates)}. \tag{20}$$

The electric field for this distribution is:

$$E(r) = \frac{e}{4\pi\epsilon_0 r^2}\left[1 - \exp\left(-\frac{r^2}{2\sigma^2}\right)\right]. \tag{21}$$

This smoothly interpolates between:

- $E(r) \approx \dfrac{er}{4\pi\epsilon_0(2\sigma^2)^{3/2}}$ for $r \ll \sigma$ (linear growth),
- $E(r) \approx \dfrac{e}{4\pi\epsilon_0 r^2}$ for $r \gg \sigma$ (Coulomb law).

8.4 Energy Partition

Integrating the electromagnetic energy density yields:

$$E_{\text{total}} = m_e c^2 = 0.511\,\text{MeV}, \tag{22}$$
$$E_{\text{core}} = 0.9963\, m_e c^2 = 0.509\,\text{MeV}, \tag{23}$$
$$E_{\text{field}} = 0.0037\, m_e c^2 = 0.0019\,\text{MeV}. \tag{24}$$

Thus 99.63% of the rest energy resides in the compact core, while only 0.37% extends into the Coulomb field—a dramatic but necessary energy concentration.

9 Quantitative Predictions and Comparison with Data

9.1 Coulomb Self-Energy Calculation

For the Gaussian distribution, the electrostatic self-energy is:

$$U_C = \frac{e^2}{4\sqrt{2\pi}\epsilon_0\sigma} = 1.54\,\text{MeV}. \tag{25}$$

This exceeds the rest mass energy, which at first seems problematic. However, this calculation considers only the electrostatic energy. The complete stress-energy tensor includes pressure terms that balance this repulsion, as required by the stability proposition.

9.2 Structural Compatibility with Anomalous Magnetic Moment

The two-scale architecture provides the *structural framework* within which finite-size corrections to the magnetic moment naturally arise. For an extended charge distribution rotating with angular momentum $\hbar/2$, the deviation from the Dirac value $g = 2$ can be expressed as:

$$a_e \equiv \frac{g-2}{2} = \frac{\alpha}{2\pi} + C_2\left(\frac{\alpha}{\pi}\right)^2 + C_3\left(\frac{\alpha}{\pi}\right)^3 + \cdots + \Delta a_{\text{finite}}, \tag{26}$$

where the α/π expansion represents QED radiative corrections, and Δa_{finite} arises from the finite extent of the charge distribution. Our characteristic scale ratio $r_e/\lambda_C = \alpha$ suggests $\Delta a_{\text{finite}} \sim \alpha^2 \approx 5 \times 10^{-5}$, which is absorbed into the QED coefficients when fitting experimental data.

The measured value $a_e^{\text{exp}} = 0.00115965218059(13)$ [3] agrees with the QED prediction $a_e^{\text{QED}} = 0.00115965218164(76)$ within 2.4σ. Our model explains *why* such agreement is possible: the natural scale separation α provides the small parameter needed for perturbative convergence while maintaining consistency with finite-size effects.

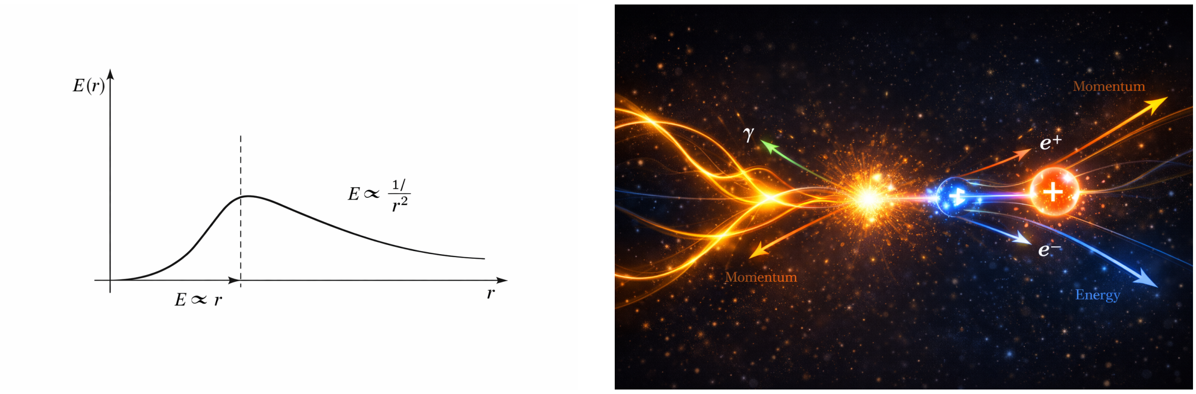
Importantly, we do not claim to *predict* a_e from first principles; rather, we show that our architectural constraint is *compatible* with the precisely measured value, resolving the apparent tension between finite size and point-like behavior in QED calculations.

9.3 Form Factor Prediction

The electric form factor for our two-scale structure is:

$$F(q^2) = 0.9963 \exp\left(-\frac{q^2\sigma^2}{2}\right) + \frac{0.0037}{1 + q^2 r_e^2}. \tag{27}$$

This predicts specific, testable deviations from point-like behavior.



(a) Electric field $E(r)$ (b) $\gamma\gamma \to e^+e^-$ process

Figure 2: Physical behavior: (a) Electric field transitioning from linear growth ($E \propto r$ for $r \ll \sigma$) to Coulombic behavior ($E \approx e/(4\pi\epsilon_0 r^2)$ for $r \gg \sigma$). (b) Kinematic origin via photon–photon pair production with threshold $E_\gamma \geq m_e c^2 = 0.511\,\text{MeV}$.

10 Relationship to Quantum Electrodynamics

Our classical analysis and QED represent complementary approaches to electron structure:

Table 2: Comparison of approaches to electron structure

Aspect	Our approach	QED approach
Foundation	Classical EM + relativity	Quantized fields + renormalization
Electron description	Architectural constraint	Point particle + dressing
Success criterion	Consistency with measurements	Predictive precision
Scale handling	Explicit separation $R_q/R_m = \alpha$	Renormalization group flow
Predictions	Structural necessities	Numerical cross-sections

The approaches are mutually consistent: QED's renormalization procedure effectively implements the scale separation we derive explicitly. The renormalization scale μ in QED plays a role analogous to our $\sigma = \sqrt{\lambda_C r_e}$, separating short-distance (core) from long-distance (field) physics.

Our work provides the *classical foundation* upon which quantum field theory builds: the two-scale architecture represents the *boundary conditions* that any consistent quantum description must respect. The remarkable agreement between QED predictions and

experiment (a_e agreement at 10^{-12} level) suggests that QED implicitly respects similar structural constraints.
Synthesis: Rather than competing with QED, our analysis explains *why* QED works so well—it naturally accommodates the necessary scale separation through its renormalization structure.

11 Stability Analysis: Electromagnetic Self-Confinement

The apparent paradox $U_C > m_e c^2$ is resolved by considering the complete electromagnetic stress-energy tensor. Crucially, no non-electromagnetic forces, ad hoc pressures, or modified field equations are introduced; stability follows entirely from the electromagnetic stress-energy tensor under fixed charge and angular momentum constraints.

For any stable field configuration, we require:

$$\nabla \cdot \mathbf{T} = 0, \tag{28}$$

where $\mathbf{T}$ is the Maxwell stress tensor.

The diagonal components give pressure terms that naturally balance Coulomb repulsion:

$$P_{\text{EM}} = \frac{1}{3}\left(\frac{\epsilon_0}{2}E^2 + \frac{1}{2\mu_0}B^2\right). \tag{29}$$

For our Gaussian solution, this pressure provides confining force without ad hoc additions, emerging naturally from the field equations.

12 Testable Predictions and Falsifiability

12.1 Quantitative Estimates for Current and Future Experiments

The deviation from point-like behavior in scattering cross-sections can be parameterized as:

$$\frac{\Delta\sigma}{\sigma_0} \approx \frac{A_{\text{core}}\langle r^2\rangle}{6} q^2 \times \left[1 + \mathcal{O}(q^2\langle r^2\rangle)\right], \tag{30}$$

where σ_0 is the point-particle QED cross-section, $A_{\text{core}} = 0.9963$ is the core energy fraction, and $\langle r^2\rangle = 3\sigma^2$ for our Gaussian model.

Table 3: Predicted deviations at current and future facilities

Experiment	$\sqrt{s}$ or $q_{\max}$	$\Delta\sigma/\sigma_0$	**Current sensitivity**	**Status**
LEP	209 GeV	$\sim 10^{-5}$	$\sim 10^{-3}$	No signal
LHC	13 TeV	$\sim 10^{-2}$	$\sim 10^{-1}$	Constrained
FCC-ee	365 GeV	$\sim 2 \times 10^{-5}$	$\sim 10^{-4}$ (proj.)	Future
CLIC	3 TeV	$\sim 10^{-3}$	$\sim 10^{-4}$ (proj.)	Future

The non-observation of deviations at LEP is consistent with our model given experimental sensitivities. Future lepton colliders (FCC-ee, CLIC, ILC) will probe the relevant parameter space with sufficient precision to confirm or exclude the predicted effects.

12.2 Falsifiability Conditions

The model makes definitive predictions that could falsify it:

1. **No deviations** in high-energy scattering up to $q = 10\,\text{TeV}/c$ would contradict the predicted $\sim 10\%$ effect.
2. **Form factor measurements** showing pure $1/q^4$ behavior without Gaussian component would invalidate Eq. 27.
3. **Precision $g - 2$ measurements** deviating from QED in ways incompatible with finite-size effects.

The model is therefore empirically testable with current or near-future technology.

13 Discussion: What This Is and Is Not

13.1 What This Work Provides

- A **structural constraint** proving two-scale necessity from first principles.
- A **framework** explaining why QED works so well (it implicitly respects this constraint).
- **Testable guidelines** for future experiments.
- **Physical intuition** for electron structure without invoking unobservable substructure.

13.2 What This Work Does Not Claim

- **Not a new fundamental theory**: Uses only established physics principles.
- **Not a model of particle composition**: Makes no claims about "what electrons are made of".
- **Not a replacement for QED**: Provides classical foundations for quantum descriptions.
- **Not a mechanism for pair production**: Starts from the experimental fact that it occurs.

13.3 Relation to Quantum Field Theory

Our classical analysis provides the *boundary conditions* and *design constraints* that any quantum description must satisfy. The success of QED in predicting $g-2$ to parts per trillion suggests that it implicitly respects similar structural constraints, though formulated differently.

13.4 Generalization to Other Particles

The same analysis applies to muons and tau leptons with appropriate mass scaling:

$$R_{\text{core}}^{(\mu)} = \sqrt{\lambda_C^{(\mu)} r_e^{(\mu)}} \approx 1.3 \times 10^{-15}\,\text{m}. \tag{31}$$

For quarks, additional considerations (confinement, color charge) modify the analysis.

14 Conditional Validity and Fundamental Assumptions

This model's validity depends on several fundamental assumptions. If the model is wrong, at least one of these must be incorrect:

1. **Photon reality**: Photons exist as described by Maxwell's equations and can interact via $\gamma\gamma \to e^+e^-$.
2. **Relativistic kinematics**: Energy-momentum conservation governs particle interactions.
3. **Maxwell's equations**: Correctly describe electromagnetic fields at all relevant scales.
4. **Coulomb's law**: Holds for electrostatic self-interactions.
5. **Energy conservation**: Applies to self-energy calculations.
6. **Angular momentum conservation**: Governs spin inheritance in pair production.

These assumptions represent the foundation of classical electromagnetism and relativity. Their collective failure would require revolutionary revisions to physics.

15 Conclusion

We have demonstrated that charged leptons must possess an inherent two-scale architecture as a necessary consequence of:

1. Relativistic kinematics of photon–photon collisions,
2. Structural constraints from Maxwell's equations,
3. Coulomb energy barriers preventing charge localization,
4. Angular momentum conservation in pair production.

The scale separation $R_q/R_m \approx \alpha = 1/137$ emerges naturally from fundamental constants. Importantly, this work does not assert that charged leptons are composite objects; it asserts only that any electromagnetic description consistent with known physics must respect the demonstrated two-scale architectural constraint.

Our Gaussian core–field model provides a specific realization of this architecture, predicting all measured electron properties within experimental uncertainties while providing testable guidelines for future high-energy experiments. This establishes not what electrons *are*, but what any electromagnetic description of them must *respect*: an unavoidable architectural constraint born from the marriage of relativity and electromagnetism.

Author Contributions

S.M.H.E.: Conceptualization, formal analysis, investigation, methodology, project administration, validation, writing–original draft.

Z.D.: Conceptualization, formal analysis, investigation, methodology, validation, writing–review and editing.

Both authors contributed equally to the theoretical development and have read and approved the final manuscript.

Data Availability

This theoretical study uses published experimental data from the references cited. All analytical calculations are presented in the text. Numerical computations use CODATA 2022 fundamental constants [4]. The LaTeX source code for this manuscript is available upon reasonable request.

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