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One-loop Amplitudes in QED:
A Worldline Formalism Approach

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One-loop Amplitudes in QED:
A Worldline Formalism Approach

Outline:

- QED History & Path Integrals
- The Master Formula
- Integration problem
- Low energy limit
- Conclusions

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A Snapshot of QED History

QED History & Path Integrals

The Birth of Positron Theory

- The quantum theory of the electron. — Dirac, P. A. M. (1928).
- Experimental discovery of the positron. — Anderson, C. D. (1933).
- Solvay Conference (1933): Dirac identifies negative energy solutions with positrons.
- Heisenberg: Formalizes quantum fluctuations in the Dirac Sea picture. — Heisenberg, W. (1934).

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QED History & Path Integrals

The Birth of QED

- Computation of the light-by-light scattering cross-section in the low energy limit — Euler, H., & Kockel, B. (1935)

  The Euler-Kockel paper established the conceptual framework of the quantum vacuum as a polarizable medium

- Heisenberg and Euler obtained the full nonlinear correction to the Maxwell Lagrangian

  Heisenberg, W., & Euler, H. (1936)

$$\mathcal{L} = \frac{e^2}{hc}\int_0^\infty \frac{d\eta}{\eta^3} e^{-\eta}\left\{ i\eta^2(\vec{E}.\vec{B})\frac{\left[\cos\left(\frac{\eta}{\mathcal{E}_c}\sqrt{\vec{E}^2-\vec{B}^2+2i(\vec{E}.\vec{B})}\right)+\text{c.c.}\right]}{\left[\cos\left(\frac{\eta}{\mathcal{E}_c}\sqrt{\vec{E}^2-\vec{B}^2+2i(\vec{E}.\vec{B})}\right)-\text{c.c.}\right]} + \mathcal{E}_c^2 + \frac{\eta^2}{3}(\vec{B}^2-\vec{E}^2)\right\}$$

- Soon after, Weisskopf derived the equivalent effective action for scalar QED — Weisskopf, V. (1936)

QED History & Path Integrals

The Birth of QED

- Heisenberg and Euler expressed their Lagrangian in terms of a critical field strength

$$\mathcal{E}_c = \frac{m^2c^3}{e\hbar} \approx 10^{16}\mathbf{V}/\mathrm{cm}$$

- Effective Lagrangian in Spinor and Scalar QED

$$\mathcal{L}^{EH}_{spin} = -\frac{1}{8\pi^2}\int_0^\infty \frac{dT}{T}e^{-m^2T}\left(\frac{e^2ab}{\tanh(eaT)\tan(ebT)} - \frac{e^2}{3}(a^2-b^2) - \frac{1}{T^2}\right)$$

$$\mathcal{L}^{EH}_{scalar} = \frac{1}{16\pi^2}\int_0^\infty \frac{dT}{T}e^{-m^2T}\left(\frac{e^2abT}{\sinh(eaT)\sin(ebT)} + \frac{e^2}{6}(a^2-b^2) - \frac{1}{T^2}\right).$$

- Where

$$ab = \vec{E}\cdot\vec{B}. \qquad a^2 - b^2 = \vec{E}^2 - \vec{B}^2.$$

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QED History & Path Integrals

Although QED vacuum effects are extraordinarily small, they have been confirmed with unprecedented precision:

- **Electron Anomalous Magnetic Moment (g−2):** The most precisely tested prediction in the history of physics.
- **Delbrück Scattering:** The deflection of high-energy photons in the Coulomb field of heavy nuclei.
- **Light-by-Light Scattering:** Recently observed in lead-ion collisions at the **LHC (ATLAS/CMS).**
- **Vacuum Birefringence:** Detected in the extreme magnetic environments of neutron stars.
- **Lamb Shift:** Confirming the interaction between the electron and vacuum fluctuation

Path Integrals in Quantum Mechanics

QED History & Path Integrals

- Alternative to Operator Methods.
- Generalization of Least Action
- The transition amplitude is a "sum" over all trajectories connecting x´ to x

$$K(x, x'; t) \sim \sum_{\{x(\tau)\}} e^{iS[x(\tau)]}$$

Key Publications in the Worldline Formalism

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From strings to particles Feynman 1950 "Mathematical formulation of the quantum theory of electromagnetic interaction"

Bern and Kosower 1991 "Efficient calculation of the one-loop QCD amplitudes"

M. J.Strassler 1992 "Field Theory without Feynman Diagrams: One-Loop Effective Actions"

QED History & Path Integrals

Advantages over the Feynman Diagrammatic Approach

- **Holistic Representation:**
  - Treats scalar/spinor lines and loops as a single global object.
  - Eliminates the need to decompose processes into individual propagators.
- **Permutation Invariance:**
  - Does not require external photon legs to be ordered along the loop from the start.
  - All N! permutations are captured by a single expression.
- **Computational Efficiency:**
  - **No Dirac Algebra:** Avoids tedious trace technology for closed-loop processes.
  - **No Momentum Integrals:** At the one-loop level, the algebraic complexity is significantly reduced.

QED History & Path Integrals

Advantages over the Feynman Diagrammatic Approach.

- **Symmetry & Gauge Invariance:**
  - Integration by parts (IBP) allows for the homogenization of integrands.
  - Keeps gauge invariance manifest throughout the calculation, making underlying symmetries transparent.

One-loop N-point amplitude

One-loop effective action

Scalar case:

$$\Gamma_{\text{scalar}}[A] = \int_0^\infty \frac{dT}{T} e^{-Tm^2} \int_{x(0)=x(T)} \mathscr{D}x e^{-\int_0^T d\tau(\frac{1}{4}\dot{x}^2 + ieA_\mu \dot{x}^\mu)}$$

Spinor case:

$$\Gamma_{\text{spin}}[A] = -\frac{1}{2}\int_0^\infty \frac{dT}{T} e^{-Tm^2} \int_{x(0)=x(T)} \mathscr{D}x e^{-\int_0^T d\tau(\frac{1}{4}\dot{x}^2 + ieA_\mu \dot{x}^\mu)} \text{Spin}[x, A]$$

Where:

$$\text{Spin}[x, A] \rightarrow \int \mathscr{D}\psi(\tau) \exp\left[-\int_0^T d\tau \left(\frac{1}{2}\psi \cdot \dot{\psi} - ie\psi^\mu F_{\mu\nu}\psi^\nu\right)\right]$$

$$\psi(\tau_1)\psi(\tau_2) = -\psi(\tau_2)\psi(\tau_1) \qquad \psi(T) = -\psi(0)$$

One-loop N-photon amplitude

$$\Gamma_{\rm scalar}[A] = \int_0^\infty \frac{dT}{T} e^{-Tm^2} \int_{x(0)=x(T)} \mathscr{D}x e^{-\int_0^T d\tau(\frac{1}{4}\dot{x}^2 + ieA_\mu \dot{x}^\mu)}$$

Polyakov 1987 (in "Gauge Fields and Strings")

Strassler 1992

In the presence of an N-photon background $\quad A_\mu(x) = \sum_{i=1}^{N} \varepsilon_{i\mu} e^{ik_i \cdot x}$

$$\Gamma_{\rm scal}[\{k_i, \varepsilon_i\}] = (-ie)^N \int \frac{dT}{T} {\rm e}^{-m^2 T} \int_{x(0)=x(T)} \mathscr{D}x {\rm e}^{-\int_0^T d\tau \frac{1}{4}\dot{x}^2} V_{scal}[k_1, \varepsilon_1] V_{scal}[k_2, \varepsilon_2] \cdots V_{scal}[k_N, \varepsilon_N]$$

Photon Vertex Operator: $\quad V_{scal}[k_i, \varepsilon_i] = \int_0^T d\tau_i \varepsilon_i \cdot \dot{x}(\tau_i) e^{ik_i \cdot x(\tau_i)}$

One-loop N-photon amplitude

Master Formula:

$$\Gamma_{\rm scal}(k_i,\varepsilon_i) = (-ie)^N \int_0^\infty \frac{dT}{T}(4\pi T)^{-D/2} e^{-m^2 T} \prod_{i=1}^{N} \int_0^T d\tau_i \exp\left\{ \sum_{i,j=1}^{N} \left(\frac{1}{2} G_{Bij} k_i \cdot k_j - i\dot{G}_{Bij}\varepsilon_i \cdot k_j + \frac{1}{2}\ddot{G}_{Bij}\varepsilon_i \cdot \varepsilon_j \right) \right\} \Bigg|_{\varepsilon_1 \ldots \varepsilon_N}$$

Where:

$$G(\tau_1,\tau_2) = |\tau_1 - \tau_2| - \frac{(\tau_1-\tau_2)^2}{T}$$

$$\dot{G}(\tau_1,\tau_2) = \mathrm{sgn}(\tau_1 - \tau_2) - \frac{2(\tau_1-\tau_2)}{T}$$

$$\ddot{G}(\tau_1,\tau_2) = 2\delta(\tau_1 - \tau_2) - \frac{2}{T}$$

One-loop N-photon amplitude

Q-Representation

$$\Gamma_{\rm scal}(k_i,\varepsilon_i) = (-ie)^N \int_0^\infty \frac{dT}{T}(4\pi T)^{-D/2} e^{-m^2T} \prod_{i=1}^N \int_0^T d\tau_i \exp\left\{\sum_{i,j=1}^N \left(\frac{1}{2}G_{Bij}k_i\cdot k_j - i\dot{G}_{Bij}\varepsilon_i\cdot k_j + \frac{1}{2}\ddot{G}_{Bij}\varepsilon_i\cdot\varepsilon_j\right)\right\}\Bigg|_{\varepsilon_1\ldots\varepsilon_N}$$

IBP:

$$\exp\left\{\sum_{i,j=1}^N \left(\frac{1}{2}G_{Bij}k_i\cdot k_j - i\dot{G}_{Bij}\varepsilon_i\cdot k_j + \frac{1}{2}\ddot{G}_{Bij}\varepsilon_i\cdot\varepsilon_j\right)\right\}\Bigg|_{\varepsilon_1\ldots\varepsilon_N} \longrightarrow Q_N(\dot{G}_{Bij})\exp\left\{\frac{1}{2}\sum_{i,j=1}^N G_{Bij}k_i\cdot k_j\right\}$$

- **The polynomial Q:**
  - Homogeneous of degree N in the photon momenta
  - Natural decomposition into cycles: It is defind as products of $\dot{G}_{ij}$´s with indices that form a closed cycle
  - And certain left-overs called tails

One-loop N-photon amplitude

Q-Representation

$$\Gamma_{\text{scal}}(k_i,\varepsilon_i) = (-ie)^N \int_0^\infty \frac{dT}{T}(4\pi T)^{-D/2} e^{-m^2 T} \prod_{i=1}^N \int_0^T d\tau_i Q_N(\dot{G}_{Bij}) \exp\left\{\frac{1}{2}\sum_{i,j=1}^N G_{Bij} k_i \cdot k_j\right\}$$

τ-cycle $\quad \dot{G}(i_1 i_2 \cdots i_N) = \dot{G}_{i_1 i_2}\dot{G}_{i_2 i_3}\cdots\dot{G}_{i_N i_1}$

"Lorentz-cycle"

$$Z_2(ij) \equiv \frac{1}{2}\mathrm{tr}(f_i f_j) = (\varepsilon_i \cdot k_j)(\varepsilon_j \cdot k_i) - (\varepsilon_i \cdot \varepsilon_j)(k_i \cdot k_j)$$

$$Z_n(i_1 i_2 \ldots i_n) \equiv \mathrm{tr}\left(\prod_{j=1}^n f_{i_j}\right) \quad (n \geq 3)$$

$$f_i^{\mu\nu} = k_i^\mu \varepsilon_i^\nu - \varepsilon_i^\mu k_i^\nu$$

One-loop N-photon amplitude

Q-Representation Spinor result

Replacement Rule $\dot{G}_{i_1i_2}\dot{G}_{i_2i_3}\cdots\dot{G}_{i_ki_1} \to \dot{G}_{i_1i_2}\dot{G}_{i_2i_3}\cdots\dot{G}_{i_ki_1} - G_{Fi_1i_2}G_{Fi_2i_3}\cdots G_{Fi_ki_1}$

Where $G_F(\tau_1, \tau_2) = \mathrm{sgn}(\tau_1 - \tau_2)$

Integration Problem

$$\int_0^1 du_i \dot{G}_{i1}\dot{G}_{i2}\dot{G}_{i3} = \int_0^1 du_i(\mathrm{sgn}(u_i - u_1) - 2(u_i - u_1))\cdots(\mathrm{sgn}(u_i - u_3) - 2(u_i - u_3))$$

Six sectors
$$\begin{cases} 1 > u_1 > u_2 > u_3 > 0 \\ 1 > u_1 > u_3 > u_2 > 0 \\ \vdots \end{cases}$$

One-loop N-photon amplitude

Integration Problem

Fixing $1 > u_1 > u_2 > u_3 > 0$

$$\int_0^1 du_i \dot{G}_{i1}\dot{G}_{i2}\dot{G}_{i3} = \int_0^{u_3} du_i(-1-2u_i+2u_1)(1+2u_i-2u_2)(1+2u_i-2u_3) + \int_{u_3}^{u_2} du_i(-1-2u_i+2u_1)(-1-2u_i+2u_2)(1-2u_i+2u_3)$$
$$+\int_{u_2}^{u_1} du_i(-1-2u_i+2u_1)(1-2u_i+2u_2)(1-2u_i+2u_3) + \int_{u_1}^{1} du_i(1-2u_i+2u_1)(1-2u_i+2u_2)(1-2u_i+2u_3)$$

After integration

$$\int_0^1 du_i \dot{G}_{i1}\dot{G}_{i2}\dot{G}_{i3} = -\frac{1}{6}(\dot{G}_{12}-\dot{G}_{23})(\dot{G}_{23}-\dot{G}_{31})(\dot{G}_{31}-\dot{G}_{12})$$

One-loop N-photon amplitude

Integration Problem

- The inverse operator ∂_P^n is related with the Bernoulli polynomials $B_n(x)$

$$\langle u_i | \partial_P^{-n} | u_j \rangle = -\frac{1}{n!} B_n(|u_i - u_j|)\mathrm{sign}^n(u_i - u_j)$$

$$\langle u_i | \partial_P^{0} | u_j \rangle = \delta(u_i - u_j) - 1$$

- In this representation the Green function looks like

$$\frac{1}{2} G_{ij} = \langle u_i | \partial_P^{-2} | u_j \rangle + \frac{1}{12}$$

$$\frac{1}{2} \dot{G}_{ij} = \langle u_i | \partial_P^{-1} | u_j \rangle$$

$$\frac{1}{2} \ddot{G}_{ij} = \langle u_i | \partial_P^{0} | u_j \rangle = \delta(u_i - u_j) - 1$$

One-loop N-photon amplitude

Integration Problem

- Integration properties

$$\int |u\rangle\langle u|\, du = 1$$

$$\int du_i du_j \,\langle u_i | \partial_P^{-n} | u_j\rangle = 0$$

$$\langle u | \partial_P^{-2n} | u\rangle = -\frac{B_{2n}}{(2n)!} = -\hat{B}_n$$

$$\langle u | \partial_P^{-(2n-1)} | u\rangle = 0$$

$$\langle u_i | \partial_P^{-n} | u_j\rangle = (-1)^n \langle u_j | \partial_P^{-n} | u_i\rangle$$

One-loop N-photon amplitude

Integration Problem

Scalar cycle $$\int_0^1 du_2 \int_0^1 du_3 \cdots \int_0^1 du_n \dot{G}_{12}\dot{G}_{23}\cdots\dot{G}_{n(n+1)}$$

Two ingredients $\dot{G}_{ij} = 2\langle u_i | \partial_P^{-1} | u_j \rangle$ & $\int_0^1 du_j \langle u_i | \partial_P^{-1} | u_j \rangle \langle u_j | \partial_P^{-1} | u_k \rangle = \langle u_i | \partial_P^{-2} | u_k \rangle$

$$\int_0^1 du_2 \cdots \int_0^1 du_n \dot{G}_{12}\dot{G}_{23}\cdots\dot{G}_{n(n+1)} = 2^n \int_0^1 du_2 \cdots \int_0^1 du_n \langle u_1 | \partial_P^{-1} | u_2 \rangle \langle u_2 | \partial_P^{-1} | u_3 \rangle \cdots \langle u_n | \partial_P^{-1} | u_{n+1} \rangle$$

$$= 2^n \int_0^1 du_3 \cdots \int_0^1 du_n \langle u_1 | \partial_P^{-2} | u_3 \rangle \langle u_3 | \partial_P^{-1} | u_4 \rangle \cdots \langle u_n | \partial_P^{-1} | u_{n+1} \rangle$$

$$\vdots$$

$$= 2^n \langle u_1 | \partial_P^{-n} | u_{n+1} \rangle = -\frac{2^n}{n!} B_n(|u_1 - u_{n+1}|)\mathrm{sgn}^n(u_1 - u_{n+1})$$

One-loop N-photon amplitude

Low-energy limit

$$\omega_i \ll m, \quad i = 1, \ldots N .$$

$$V_{scal}[k_i, \varepsilon_i] = \int_0^T d\tau_i \varepsilon_i \cdot \dot{x}(\tau_i) e^{ik_i \cdot x(\tau_i)} \rightarrow \quad V_{scal}^{(\mathrm{LE})}[k, \varepsilon] = \int_0^T d\tau \, \varepsilon \cdot \dot{x}(\tau) ik \cdot x(\tau) .$$

Low-energy Photon vertex

$$V_{scal}^{(\mathrm{LE})}[f] = V_{scal}^{(\mathrm{LE})}[k, \varepsilon] - \frac{i}{2} \int_0^T d\tau \frac{d}{d\tau} (\varepsilon \cdot x(\tau) k \cdot x(\tau)) = \frac{i}{2} \int_0^T d\tau x(\tau) \cdot f \cdot \dot{x}(\tau)$$

$$f^{\mu\nu} \equiv k^\mu \varepsilon^\nu - \varepsilon^\mu k^\nu$$

One-loop N-photon amplitude

The scalar QED N-photon amplitudes in terms of Wick contractions of vertex operators

$$\Gamma_{\text{scal}}[k_1,\varepsilon_1;\dots;k_N,\varepsilon_N] = (-ie)^N \int_0^\infty \frac{dT}{T} \mathrm{e}^{-m^2T}(4\pi T)^{-\frac{D}{2}} \left\langle V^A_{\text{scal},1}\cdots V^A_{\text{scal},N}\right\rangle$$

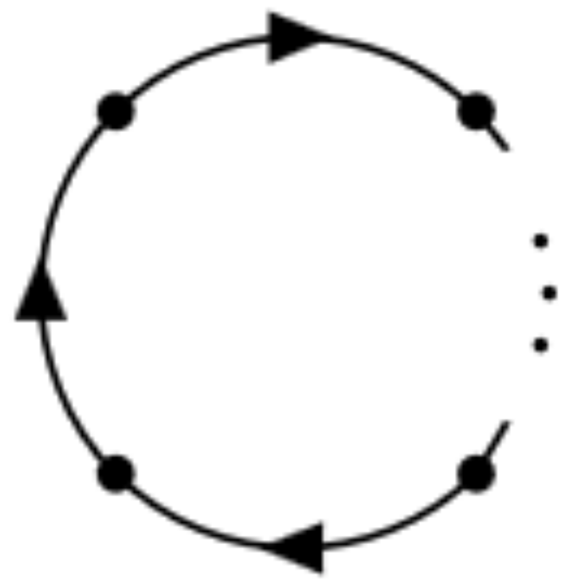
Low-energy limit

$$\left\langle V^{\gamma(\text{LE})}_{\text{scal}}[f_1]\dots V^{\gamma(\text{LE})}_{\text{scal}}[f_n]\right\rangle = i^n T^n \exp\left\{\sum_{r=1}^{\infty}\frac{b_{2r}}{4r}\text{tr}(f_{tot}^{2r})\right\}\Bigg|_{f_1\dots f_n}$$

Where $\quad f_{\text{tot}} \equiv \sum_{i=1}^{N} f_i$

$$b_n \equiv \int_0^T d\tau_{i_1}\dots\int_0^T d\tau_{i_n}\dot{G}_{i_1i_2}\dot{G}_{i_2i_3}\cdots\dot{G}_{i_ni_1} = -2^n\frac{B_n}{n!}$$

Identified with the one-loop N-point



One-loop N-photon amplitude

Low-energy limit

$$\Gamma^{(\mathrm{LE})}_{\mathrm{scal}}[\{k_i,\varepsilon_i\}] = (-ie)^N \int_0^\infty \frac{dT}{T} \mathrm{e}^{-m^2T}(4\pi T)^{-D/2} i^N T^N \exp\left\{ \sum_{r=1}^{\infty} \frac{b_{2r}}{4r} \mathrm{tr}(f_{tot}^{2r}) \right\}\Bigg|_{f_1\ldots f_n}$$

$$= \frac{e^N \Gamma(N-2)}{(4\pi)^2 m^{2N-4}} \exp\left\{ \sum_{r=1}^{\infty} \frac{b_{2r}}{4r} \mathrm{tr}(f_{tot}^{2r}) \right\}\Bigg|_{f_1\ldots f_n}$$

4-Photons

$$\exp\left(\sum_{m=1}^{\infty} \frac{b_{2m}}{4m} \mathrm{tr}(f_{tot}^{2m}) \right)\Bigg|_{f_1\ldots f_n} = \frac{b_4}{8}\mathrm{tr}(f_{tot}^4) + \frac{1}{2!}\left(\frac{b_2}{4}\mathrm{tr}(f_{tot}^2) \right)^2$$

$$\Gamma^{(\mathrm{LE})}_{\mathrm{scal}}[\{k_i,\varepsilon_i\}] = = \frac{e^4\Gamma(2)}{(4\pi)^2 m^4}\left(\frac{b_4}{8}\mathrm{tr}(f_{tot}^4) + \frac{1}{2!}\frac{b_2^2}{4^2}\mathrm{tr}(f_{tot}^2)^2 \right)$$

One-loop N-photon amplitude

Low-energy limit

$$\Gamma^{(\mathrm{LE})}_{\mathrm{scal}}[\{k_i,\varepsilon_i\}] = (-ie)^N \int_0^\infty \frac{dT}{T} \mathrm{e}^{-m^2T}(4\pi T)^{-D/2} i^N T^N \exp\left\{\sum_{r=1}^{\infty} \frac{b_{2r}}{4r} \mathrm{tr}(f_{tot}^{2r})\right\}\Bigg|_{f_1\ldots f_n}$$

$$= \frac{e^N \Gamma(N-2)}{(4\pi)^2 m^{2N-4}} \exp\left\{\sum_{r=1}^{\infty} \frac{b_{2r}}{4r} \mathrm{tr}(f_{tot}^{2r})\right\}\Bigg|_{f_1\ldots f_n}$$

All helicities ´+´

$f_{\mathrm{tot}}^2 = -\chi_+ \mathbb{1}$ Whith $\chi_+ \equiv \frac{1}{2} \sum_{1\le i<j\le N} [k_i k_j]^2$

$$\mathrm{tr}(f_{\mathrm{tot}}^{2m}) = 4(-1)^m \big(\chi_+\big)^m$$

$$\exp\Big\{\sum_{m=1}^{\infty} \frac{b_{2m}}{4m} \mathrm{tr}(f_{\mathrm{tot}}^{2m})\Big\}\Big|_{f_1\ldots f_N} = \exp\Big\{\sum_{m=1}^{\infty} (-1)^m \frac{b_{2m}}{m} \chi_+^m\Big\}\Big|_{\text{all different}}$$

$$-2\ln \frac{\sin\sqrt{\chi_+}}{\sqrt{\chi_+}}$$

One-loop N-photon amplitude

Low-energy limit

All helicities ´+´

$$\Gamma^{(\mathrm{LE})}_{\mathrm{scal}}(k_1,\varepsilon_1;\ldots;k_N,\varepsilon_N) = -\frac{m^4}{(4\pi)^2}\left(\frac{2ie}{m^2}\right)^N \frac{\mathcal{B}_N}{N(N-2)}\chi_N^+$$

Where

$$\chi_N^+ \equiv \chi_+^{\frac{N}{2}}\Big|_{\text{all different}} = \frac{\left(\frac{N}{2}\right)!}{2^{\frac{N}{2}}}\Big\{[k_1k_2]^2[k_3k_4]^2\cdots[k_{N-1}k_N]^2 + \text{ all distinct permutations}\Big\}$$

For example N=4

$$\chi_4^+ = \frac{1}{2}\Big\{[k_1k_2]^2[k_3k_4]^2 + [k_1k_3]^2[k_2k_4]^2 + [k_1k_4]^2[k_2k_3]^2\Big\}$$

$$\chi_4^+ = \frac{1}{2}(s^2+t^2+u^2)$$

Conclusions

The Power of the Worldline Formalism

- The worldline approach has proven to be highly efficient for calculating N-photon amplitudes, significantly reducing the complexity compared to traditional Feynman diagrams.

Persistent Mathematical Challenges

- Despite its elegance, significant challenges remain, particularly in handling higher-loop corrections and extending these techniques to more complex non-Abelian gauge theories.

Conclusions

No "Single Superior Path"

- Since its inception, Quantum Mechanics has provided us with diverse frameworks (from Matrix Mechanics to Path Integrals). History shows that there is no "absolute superior" method; rather, different formalisms offer unique insights.

The Importance of Community

- Meetings like this are essential. Discussing diverse methodologies allows us to cross-pollinate ideas and find the most robust tools for the next generation of problems in Quantum Field Theory.

Thanks!