New Trends in First Quantisation: Field Theory, Gravity and Quantum Computing

831. WE-Heraeus-Seminar

13 – 17 April 2025

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 831. WE-Heraeus-Seminar:

Welcome to this WE-Heraeus seminar which aims to provide a forum for discussing first-quantised and worldline approaches to field theory and gravity.

Our current best understanding of nature at its fundamental level is based on field theories:

Einstein's theory of gravity on cosmological scales, or quantum field theory describing interactions between elementary particles on sub-microscopic scales. Complementary to long-established conventional methods, several theoretical branches of fundamental physics based on the framework of first quantisation have blossomed during recent years, driven either by technological, observational or experimental advances. It is these non-standard approaches which are the focus of this WE-Heraeus seminar.

The aim of this workshop is to cultivate a common set of strategies among research communities using first quantised and worldline techniques, identifying shared challenges, exchanging cutting edge theoretical tools, and fostering new interdisciplinary collaborations.

The workshop will bring together researchers from around the world primarily working on the following list of themes:

- Foundations of the first quantised worldline approach to quantum field theory, with applications in elementary particle physics.
- Gravity in the first quantised approach, applied to binary mergers and gravitational wave phenomena.
- Non-perturbative techniques in first quantisation, applied to physics at the high amplitude frontier.
- Quantum computing and Hamitonian formalisms in first quantised frameworks.

Invited talks will present up-to-date results while keeping them accessible to nonexperts.
These talks will lead regular discussion sessions, which will have a prominent role to enhance cross-community knowledge exchange.

Introduction

Scientific Organizers:

Dr. James Edwards	University of Plymouth, UK E-mail: james.p.edwards@plymouth.ac.uk
Dr. Sebastián Franchino-Viñas	HZDR Dresden-Rossendorf, Germany E-mail: s.franchino-vinas@hzdr.de
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Administrative Organization:

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Registration:

Elisabeth Nowotka (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday
morning

Program

Program

Sunday, 13 April 2025

17:00 – 21:00	Registration	
18:00	*BUFFET SUPPER and informal get-together*	

Monday, 14 April 2025

08:00	*BREAKFAST*	
08:50	Scientific organizers	**Welcome words**
09:00 – 09:45	Christian Schubert	**History and state-of-the-art of the worldline formalism**
09:45 – 10:30	Olindo Corradini	**One-particle reducible contributions to Heisenberg-Euler effective Lagrangians**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:30	**Discussion I**	
11:30 – 11:50	Patrick Copinger	**Strong field QED in-in worldline formalism**
11:50 – 12:35	Anton Ilderton	**QFT in strong fields: applications of first-quantised methods**
12:45	*LUNCH*	

Program

Monday, 14 April 2025

14:30 – 15:15	Naser Ahmadiniaz	**Off-shell gluon amplitudes from the worldline formalism**
15:15 – 15:35	Karthik Rajeev	**Tunnelling in Lorentzian worldline path integrals**
15:35 – 16:00	**Discussion II**	
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 16:50	Rashid Shaisultanov	**The worldline approach to strong-field QED and N-photon amplitudes**
16:50 – 17:10	Roberto Bonezzi	**Worldline approach to Yang-Mills theory**
17:10 – 17:30	Azadeh Maleknejad *(online)*	**Weyl fermion creation by cosmological gravitational wave background at 1-loop**
17:30 – 17:40	Scientific organizers	**About the WE-Heraeus-Foundation**
17:40 – 18:30	**Networking**	
18:30	*DINNER*	

Program

Tuesday, 15 April 2025

08:00	*BREAKFAST*	
09:00 – 09:45	Rafael Porto	**Bootstrapping the two-body problem**
09:45 – 10:05	Paolo Di Vecchia	**The soft part of the gravitational waveform from scattering amplitudes**
10:05 – 10:25	Tianheng Wang	**Kerr black hole dynamics from an extended Polyakov action**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:30	**Discussion III**	
11:30 – 11:50	Ginevra Braga	**Proper time path integrals for gravitational waves**
11:50 – 12:35	Jan Steinhoff	**1st quantization of worldline EFT for black holes and neutron stars**
12:45	*LUNCH*	
14:30 – 15:15	Fiorenzo Bastianelli	**First quantisation and one-loop divergences in quantum gravity**
15:15 – 15:35	Domenico Bonocore	**Generalized Wilson lines, from QCD to gravity**
15:35 – 16:00	**Discussion IV**	
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 16:50	Jan Willem Van Holten	**Classical dynamics of particles with non-abelian charges**
16:50 – 17:20	**Flash talks I**	
17:20 – 18:30	**Posters I**	
18:30	*DINNER*	

Program

Wednesday, 16 April 2025

08:00	*BREAKFAST*	
09:00 – 09:45	Jose M Muñoz-Castañeda	**High temperature quantum fluctuations**
09:45 – 10:30	Greger Torgrimsson	**Worldline instantons for the momentum spectrum of strong-field-QED processes in space-time dependent fields**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:30	**Discussion V**	
11:30 – 11:50	Stefano Lionetti	**Anomalies and parity-odd interactions: Insights from CFT and beyond**
11:50 – 12:35	Silvia Pla Garcia	**Instantons in finite volume, quantum tunnelling, and cosmic bounce**
12:45	*LUNCH*	
14:30 – 15:15	Renata Ferrero *(online)*	**Background independent renormalization techniques**
15:15 – 15:35	Predag Cvitanovic	**Is QED finite?**
15:35 – 16:00	**Discussion VI**	
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 16:50	Viola Gattus	**A geometric perspective on heat Kernel techniques in field space**
16:50 – 17:20	**Flash talks II**	
17:20 – 18:30	**Posters II**	
18:30	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program

Thursday, 17 April 2025

08:00	*BREAKFAST*	
09:00 – 09:45	Jan Plefka	**High-precision gravitational wave physics from worldline quantum field theory**
09:45 – 10:05	Michael Florian Wondrak	**Particle production in electric and gravitational fields**
10:05 – 10:25	Lucas Manzo	**Worldline formalism in manifolds with boundaries**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:30	**Discussion VII**	
11:30 – 11:50	Olaf Lechtenfeld	**The Nicolai map in supersymmetric quantum mechanics**
11:50 – 12:35	Gerald Dunne	**Resurgence and high-intensity QFT**
12:35 – 12:45	Scientific organizers	**Closing words**
12:45	*LUNCH*	

End of the seminar

Departure

NO DINNER for participants leaving on Friday; however, a self-service breakfast will be provided on Friday morning

Posters

Posters

Rubén Omar Acuña-Cárdenas	**Wave propagation in a spacetime with thin concentric shells of matter**
Ivan Ahumada Hernandez	**Low-energy photon scattering amplitudes on the loop and line in a homogeneous electromagnetic field**
Tim Luis Borck	**Vacuum dependences of renormalization group flows in de sitter backgrounds**
Jesús Clemente-Gallardo	**Hybrid quantum-classical field theory: geometrodynamics with quantum sources.**
Matthias Diez	**Time ccales in the Sauter-Schwinger effect**
Siyouri Fatima-Zahra	**Effect of weak measurements on exciton-exciton interactions**
Filippo Fecit	**A worldline approach to resummations and (assisted) pair production**
César García-Pérez	**Heat kernel resummations: spinors on a constant axial vector field background**
Idrish Huet Hernández	**The n-hit function approach to quantum amplitudes; exploring asymptotic applications**
Rachel Kane	**Rejection-free monte carlo sampling for worldline numerics**
Amaury Marchon	**Entanglement in the Schwinger effect**
Cesar Mata	**Worldline methods for 4-photon amplitudes in scalar and spinor QED**
Arseny Mironov	**The Ritus-Narozhy conjecture: current status and outlook**

Posters

Carlos Pastor Marcos	**Functional renormalization group as a non-perturbative tool for gravity: Asymptotic safety of generalized proca theories**
Diego Saviot	**Examining the anomalous nature of the chiral vortical effect**
Carlos Javier Servin Tomas	**Worldline approach to the dressed scalar propagator with N photons**
Lorenzo Tamburino Ventimiglia Di Monteforte	**Nonlinear Thomson scattering in a strong gravitational wave**
Lea Van Dellen	**Spectral compatibility and analytical constraints in quantum marginal problems**

Abstracts of Talks

(in alphabetical order)

Off-shell gluon amplitudes from the worldline formalism

N. Ahmadiniaz

Institute For Theoretical Physics,
Helmholtz-Zentrum-Dresden-Rossendorf, Dresden, Germany

In this talk, I will begin with a brief introduction to the Worldline formalism and its application in deriving one-loop off-shell N-gluon amplitudes using the Bern-Kosower master formula. After a concise overview of the historical development of gluon amplitudes, I will explore two distinct integration-by-parts techniques—yielding the Q- and S-representations—and apply them to specialize the amplitudes for N=3 and N=4, corresponding to the fully off-shell three- and four-gluon vertices.
Off-shell gluon amplitudes, carry physical information, particularly on the infrared properties of QCD . They are also essential for the matching of perturbative information with lattice data, and constitute an essential ingredient for the Schwinger-Dyson equations.
The N=3 vertex is well-established, with its form factor decomposition known as the Ball-Chiu decomposition. In contrast, the N=4 case is a novel and highly nontrivial amplitude, rendered complex off-shell by its rich tonsorial structure. This four-gluon vertex has only recently been studied. I will present the one-loop, fully off-shell four-gluon amplitude and discuss its form factor decomposition.

References

[1] N. Ahmadiniaz and C. Schubert, Nucl. Phys. B 869 (2013) 417.
[2] N. Ahmadiniaz and C. Schubert, JHEP 1301 (2013) 132.
[3] N. Ahmadiniaz and C. Schubert, JIMPE 25 (2016) 1642004.
[4] N. Ahmadiniaz and C. Schubert, EPL 130 (2020) 41001.

First Quantisation and One-Loop Divergences in Quantum Gravity

Fiorenzo Bastianelli

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We discuss perturbative quantum gravity at the one-loop level using a first-quantized approach. Reviewing the N=4 spinning particle action, which describes graviton propagation on Einstein spaces, we analyze its path integral on the circle to derive a worldline representation of the one-loop effective action. This formalism allows us to compute UV divergences, revisiting established results while presenting new findings.

Worldline approach to Yang-Mills theory

Roberto Bonezzi

Institute for Physics, Humboldt University Berlin, Germany

The worldline formalism has proven advantageous, compared to standard Feynman diagrammatic techniques, to provide compact expressions for a variety of quantum field theory processes. In its typical applications, it is used to describe matter particles coupled to background gauge fields or gravity. Recently, it has been extended to account for self-interacting field theories, such as pure Yang-Mills theory and Einstein gravity. In this talk, based on [1,2,3], I will focus on a bosonic spinning particle model that yields a first-quantized description of the gluon. This theory can be coupled to a background Yang-Mills field, allowing one to define vertex operators that reproduce the gluon self-interactions. In particular, I will show how to compute gauge theory amplitudes in this framework, as worldline correlators of vertex operators. Due to its similarity to string theory, this first-quantized approach might give useful insights to investigate color-kinematics duality.

References

[1] R. Bonezzi, *Phys.Rev.D* 110 (2024) 6, 065022
[2] R. Bonezzi, M.F. Kallimani, arXiv:2502.18030
[3] F. Bastianelli, R. Bonezzi, O. Corradini, F. Fecit, work in progress

Generalized Wilson lines, from QCD to gravity

D.Bonocore[1]

[1]*TUM School of Natural Sciences*
Technische Universität München
Physics Department
Garching, Germany

Worldline techniques have been exploited in QCD phenomenology to derive generalized Wilson lines operators, which provide a powerful tool to extend the traditional soft gluon resummation program to subleading powers in the soft-collinear factorization. In this talk I discuss how these QCD-inspired techniques can be useful for the gravitational wave program, and how they compare with similar methods in the literature.

References

[1] D. Bonocore, JHEP **02** (2021) 007
[2] D. Bonocore, A. Kulesza, J. Pirsch, JHEP **03** (2022) 147
[3] D. Bonocore, A. Kulesza, J. Pirsch, 2412.16049

Proper Time Path Integrals for Gravitational Waves

Ginevra Braga,[a,b], Alice Garoffolo[c], Angelo Ricciardone[d,e,f], Nicola Bartolo[f,g,h], and Sabino Matarrese[f,g,h,a]

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[c]Center for Particle Cosmology, Department of Physics and Astronomy, University of Pennsylvania 209 S. 33rd St., Philadelphia, PA 19104, USA
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[g]INFN, Sezione di Padova, via Marzolo 8, I-35131 Padova, Italy
[h]INAF-Osservatorio Astronomico di Padova, Vicolo dell' Osservatorio 5, I-35122 Padova, Italy

As gravitational waves travel from their source to an observer, they interact with matter structures along their path, imprinting distinct deformations on their waveforms. In [1], we introduced a novel theoretical framework to describe wave optics effects in gravitational lensing, addressing the limitations of existing approaches. Our key innovation is the incorporation of the proper time technique, commonly used in field theory, into gravitational lensing. This method introduces an additional time-like variable, allowing us to recast the wave equation exactly into a Schrödinger-like form with an initial-value constraint, without requiring any approximations.

The primary advantage of this approach is its ability to describe fully relativistic wave dynamics in terms of associated particles, their trajectories, and momenta. The additional temporal parameter is ultimately eliminated through integration. This enables us to extend the standard formalism beyond the conventional eikonal and paraxial approximations, which are typically assumed in gravitational lensing studies.

One of the key results of this work is the worldline representation of the gravitational wave propagator, which characterizes wave dynamics during lensing events. This propagator is expressed as a sum over all possible values of the proper time in particle-like path integrals, effectively generalizing the diffraction integral. Furthermore, we demonstrate that our method not only encompasses conventional approaches as limiting cases but also provides a systematic way to incorporate polarization effects, an aspect often overlooked in the literature.

Our findings refine the theoretical foundation of gravitational wave propagation, enhancing our ability to extract unbiased information about the lensing structures from gravitational wave observations.

References

[1] Ginevra Braga, Alice Garoffolo, Angelo Ricciardone, Nicola Bartolo, and Sabino Matarrese. Proper time path integrals for gravitational waves: an improved wave optics framework. *JCAP*, 11:031, 2024.

Strong field QED in-in worldline formalism

P. Copinger[1] **and S. Pu**[2]

[1] *Centre for Mathematical Sciences, University of Plymouth, Plymouth, PL4 8AA, UK*
[2] *Department of Modern Physics, University of Science and Technology of China, Anhui 230026, China*

An in-in formalism is constructed in a first-quantised or worldline approach in strong field QED. This is derived from both a Bolgoliubov matrix and a Schwinger-Keldysh closed-time path approach. The gauge coupling is treated a classical background field. In-in augmentations to the in-out generating functional amount to the insertion of a non-local interaction term sandwiched by a propagator enclosing singularities in complex Schwinger propertime. A first-quantised/worldline definition is further shown for the probability of creating exactly N pairs.

One-particle reducible contributions to Heisenberg-Euler effective Lagrangians

N. Ahmadiniaz[1], O. Corradini[2] and C. Schubert[3]

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[2] Dipartimento di Scienze Fisiche, Informatiche e Matematiche,
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and I.N.F.N., Sezione di Bologna, Via Irnerio 46, 40126 Bologna, Italy

[3] Facultad de Ciencias Físico-Matemáticas, Universidad Michoacana de San Nicolás de Hidalgo,
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We discuss some results on the one-particle reducible (1PR) contributions to Heisenberg-Euler Lagrangians, i.e. non-perturbative effective Lagrangians in the electromagnetic field, generated by loops of charged virtual particles. The relevance of 1PR contributions, was first found by Gies and Karbstein [1], and later re-derived and extended, using first-quantized approaches, in Refs. [2] and [3]. Here we consider further extensions to the previous results, which involve the inclusion of virtual scalars and gravitons in the computation of the two-loop 1PR Lagrangians. In particular, we will concentrate on the features of the graviton contributions.

References

[1] H. Gies and F. Karbstein, “An Addendum to the Heisenberg-Euler effective action beyond one loop,” JHEP **03** (2017) 108 [arXiv:1612.07251 [hep-th]].

[2] J. P. Edwards and C. Schubert, “One-particle reducible contribution to the one-loop scalar propagator in a constant field,” Nucl. Phys. B **923** (2017), 339-349 [arXiv:1704.00482 [hep-th]].

[3] N. Ahmadiniaz, F. Bastianelli, O. Corradini, J. P. Edwards and C. Schubert, “One-particle reducible contribution to the one-loop spinor propagator in a constant field,” Nucl. Phys. B **924** (2017), 377-386 [arXiv:1704.05040 [hep-th]].

Is QED finite?

Predrag Cvitanović

Center for Nonlinear Science, School of Physics
Georgia Institute of Technology
Atlanta, GA USA

In 2017 Laporta completed the twenty-year project of computing analytically the individual contributions of 891 4-loop vertex diagrams contributing to the electron magnetic moment. Vertex diagrams separate in 25 gauge-invariant sets. The quenched QED sets are all of order +/- ½ (alpha/pi)^4. Why are these numbers so small? Can you prove that they remain small to all orders, i.e., that perturbative QED is not an asymptotic series, but a finite theory?

References

[1] birdtracks.eu/courses/QCD19/finiteQED.pdf ~ slides
[2] ChaosBook.org/~predrag/papers/finiteQED.pdf ~ a blog
[3] ChaosBook.org/~predrag/papers/finitness.html ~ a story
[4] ChaosBook.org/~predrag/papers/DFS_pris.pdf ~ an oration
[5] ChaosBook.org/~predrag/papers/g-2.html ~ the truth

The soft part of the gravitational waveform from scattering amplitudes

Paolo Di Vecchia[a,c]

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[c] *The Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen, Denmark*

Using the infrared divergences computed at one loop by Weinberg in 1965 we compute of universal part of the soft behaviour of the gravitational waveform.

Resurgence and High-Intensity QFT

Gerald Dunne

University of Connecticut, Storrs CT, USA

Resurgence unifies perturbative and non-perturbative physics, and enables more accurate interpolations between weak and strong coupling, and high and low intensity. I describe some natural applications to the physics of quantum field theory in intense fields.

Background independent renormalization techniques

R. Ferrero[1,2]

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[2] *Perimeter Institute, 31 Caroline Street North, Waterloo, ON, N2L 2Y5, Canada*

The main challenge in developing a quantum theory of gravity is the necessity of background independence. Physical (curved) metrics have to be determined by the dynamics of quantum gravity and backreacting matter. Surprisingly, background independent approaches to quantum gravity come with the possibility to solve "problematic infinities" [1]. In my talk I will present a background independent QFT computation: the method is based on the heat kernel (or Schwinger proper time) [2, 3] expansion and can be applied in a perturbative and a non-perturbative fashion.

References

[1] K. Falls and R. Ferrero, "Asymptotic Safety within on-shell perturbation theory," [arXiv:2411.00938 [hep-th]].

[2] R. Ferrero, S. A. Franchino-Vinas, M. B.Fröb and W. C. C. Lima, "Universal Definition of the Nonconformal Trace Anomaly," *Phys. Rev. Lett*. 132 (2024) no.7, 071601 doi:10.1103/PhysRevLett.132.071601 [arXiv:2312.07666 [hep-th]].

[3] R. Ferrero, M. B. Fröb and W. C. C. Lima, "Heat kernel coefficients for massive gravity," *J. Math. Phys*. 65 (2024) no.8, 082301 doi:10.1063/5.0196609 [arXiv:2312.10816 [hep-th]].

A Geometric Perspective on Heat Kernel Techniques in Field Space

V. Gattus[1] **and A. Pilaftsis**[1]

[1]*Department of Physics and Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom*

After reviewing the standard Heat Kernel (HK) formalism, we introduce a more intuitive approach that does not reply on the iterative solution of a Schrödinger-type equation. Instead, our method employs the Zassenhaus formula to handle exponentials of non-commutative operators more effectively. Additionally, we develop a direct procedure for extracting ultraviolet (UV) divergences in position space. Extending the HK techniques, we explore a formulation within a field-space supermanifold incorporating both scalar and fermionic coordinates, along with a non-zero field-space curvature. To illustrate the power of this framework, we compute the one-loop effective action for a scalar-fermion system and extract its UV behavior in terms of covariant operators. This talk is based on the article [1].

References

[1] V. Gattus, A. Pilaftsis, Supergeometric Quantum Effective Action, Phys. Rev. D 110, 105006 (2024)

QFT in strong fields: applications of first-quantised methods

Anton Ilderton
Higgs Centre, University of Edinburgh, Edinburgh, United Kingdom

Strong background fields are relevant in astrophysical scenarios, in modern intense laser-matter interactions, and in strongly curved gravitational settings. The calculation of observables in the presence of strong backgrounds, be it in gauge theory or gravity, is however significantly more challenging than in vacuum. This is because (i) a strong background is characterised by a coupling larger than unity, thus demanding non-perturbative methods and (ii) backgrounds can carry arbitrary (functional) spacetime dependence, meaning that even tree-level amplitudes are no longer simple rational functions of kinematic data.

QFT in strong fields therefore demands new, efficient methods.

In this talk I will discuss how worldline approaches can lead to original results in this area, in particular results which apply at all multiplicities [1] or which are far from apparent at the level of the action or Feynman rules [2]. I will also discuss non-perturbative contributions to pair production in strong fields [3]; expressing these in, crucially, their worldline form allows their resummation [4] and then the isolation and resolution of ambiguities at what are, essentially, electromagnetic event horizons [5].

References

[1] P.Copinger, J. P. Edwards, A. Ilderton and K. Rajeev,
"*Master formulas for N-photon tree level amplitudes in plane wave backgrounds*"
Phys. Rev. D **109** (2024) 065003
arXiv:2311.14638 [hep-th].

[2] P.Copinger, J. P. Edwards, A. Ilderton and K. Rajeev,
"*All-multiplicity amplitudes in impulsive PP-waves from the worldline formalism*"
JHEP **09** (2024), 148
arXiv:2405.07385 [hep-th].

[3] P. Copinger, J. P. Edwards, A. Ilderton and K. Rajeev,
"*Pair creation, backreaction, and resummation in strong fields*"
arXiv:2411.06203 [hep-ph] (to appear in PRD).

[4] A. Ilderton and K. Rajeev, *to appear.*

[5] A. Ilderton and W. Lindved,
"*Scattering amplitudes and electromagnetic horizons*"
JHEP **12** (2023), 118
arXiv:2306.15475 [hep-th].

Prof. Olaf Lechtenfeld

Institute of Theoretical Physics, Leibniz University Hannover
Appelstrasse 2, 30167 Hannover, Germany

I review the existence of a Nicolai map in supersymmetric quantum mechanics. This map relates quantum correlation functions at different values of couplings (including the free-field limit). I extend the discussion to sigma models with a Kähler target, relating different geometries.

Weyl Fermion Creation by Cosmological Gravitational Wave Background at 1-loop

Azadeh Maleknejad[a] **Joachim Kopp**[b,c]

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[b] *Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland*

[c] *PRISMA Cluster of Excellence & Mainz Institute for Theoretical Physics, Johannes Gutenberg University, Staudingerweg 7, 55099 Mainz, Germany*

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Abstract: Weyl fermions of spin $\frac{1}{2}$ minimally coupled to Einstein's gravity in 4 dimensions cannot be produced purely gravitationally in an expanding Universe at tree level. Surprisingly, as we showed in a recent letter [1], this changes at gravitational 1-loop when cosmic perturbations, like a gravitational wave background, are present. Such a background introduces a new scale, thereby breaking the fermions' conformal invariance. This leads to a non-vanishing gravitational self-energy for Weyl fermions at 1-loop and induces their production. In this paper, we present an extended study of this new mechanism, explicitly computing this effect using the in–in formalism. We work in an expanding Universe in the radiation-dominated era as a fixed background. Gravitational wave-induced fermion production has rich phenomenological consequences. Notably, if Weyl fermions eventually acquire mass, and assuming realistic – and potentially detectable – gravitational wave backgrounds, the mechanism can explain the abundance of dark matter in the Universe. More generally, gravitational-wave induced freeze-in is a new purely gravitational mechanism for generating other feebly interacting fermions, e.g. right-handed neutrinos. We show that this loop level effect can dominate over the conventional – tree-level – gravitational production of superheavy fermions in a sizable part of the parameter space.

arXiv:2406.01534v2 [hep-th] 3 Dec 2024

Worldline Formalism in Manifolds with Boundaries

L. Manzo[1]

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The Worldline Formalism (WLF) is a useful scheme in Quantum Field Theory (QFT) which has also become a powerful tool for numerical computations. It is based on the first quantisation of a point-particle whose transition amplitudes correspond to the heat-kernel of the operator of quantum fluctuations of the field theory. However, to study a QFT in a bounded manifold one needs to restrict the path integration domain of the point-particle to a specific subset of worldlines enclosed by those boundaries. In the present talk it is shown how to implement this restriction for the case of scalar, spinor and vector fields in a D-dimensional curved half-space $\mathbb{R}^{D-1} \times \mathbb{R}^{+}$ under mixed boundary conditions, following an approach based on the method of images for path integrals. This procedure is based on, but not limited to, articles [1-5].

References

[1] F. Bastianelli, O. Corradini and P. Pisani, "Worldline approach to quantum field theories on flat manifolds with boundaries", JHEP **0702**, 59 (2007).

[2] F. Bastianelli, O. Corradini and P. Pisani, "Scalar field with Robin boundary conditions in the worldline formalism", J. Phys. A **41**, 164010 (2008).

[3] O. Corradini, J. P. Edwards, I. Huet, L. Manzo and P. Pisani, "Worldline formalism for a confined scalar field", JHEP **1908**, 37 (2019).

[4] L. Manzo, "Worldline approach for spinor fields in manifolds with boundaries", JHEP **2406**, 144 (2024).

[5] S. Christiansen Murguizur, L. Manzo and P. Pisani, *work in progress*, (2025).

High temperature quantum fluctuations

Jose. M. Muñoz Castañeda and Gonzalo Sancho Garrido
(Valladolid University, Valladolid, SPAIN)

We will show recent results for the quantum vacuum physics magnitudes for scalar fields under the influence of general boundary conditions. We provide analytical results that do not require any numerical computations.

Instantons in finite volume, quantum tunnelling, and cosmic bounce

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Tunnelling between two degenerate vacua is allowed in finite-volume Quantum Field Theory. This effect induces a non-trivial vacuum energy, which results from the competition of different saddle point configurations in the partition function. In this talk, I will describe this mechanism and discuss its relevance to induce a cosmological bounce in light of singularity theorems in General Relativity. I will briefly discuss the role of anisotropies in such a model.

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Title: Bootstrapping the two-body problem

Author: Rafael A. Porto, DESY.

Abstract: I will review the worldline EFT approach to binary dynamics and recent results within the post-Minkowskian/post-Newtonian expansion.

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[1] Bootstrapping the relativistic two-body problem, Dlapa et al. *JHEP* 08 (2023) 109.

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Tunnelling in Lorentzian Worldline Path Integrals

Anton Ilderton[1] and Karthik Rajeev[1]

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We revisit the tunnelling-type mode functions in Schwinger effect and Hawking radiation using the Lorentzian worldline formalism to shed light on some common and distinct features. The positive frequency solutions of the Klein-Gordon equation -- in a constant electromagnetic case for the Schwinger effect and a dynamical black hole spacetime for the Hawking radiation -- encode useful details of the pair creation process. The solutions, in turn, admit Lorentzian worldline path integral representations with mixed boundary conditions. We explore how tunnelling and pair-creation effects manifest in an explicitly real-time-based path integral. While we confirm the generally held notion that complex worldlines play a crucial role in the semi-classical interpretation of the pair-creation process in both the Schwinger and Hawking effects, how they arise is found to be interestingly different.

History and state-of-the-art of the worldline formalism

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Simultaneously with his invention of modern quantum electrodynamics, Feynman in 1950 developed also an alternative approach based on relativistic path-integrals, nowadays usually called "worldline formalism"'. However, only in the nineties it was found through work relating this formalism to the path-integral formulation of string theory that it offers some distinct advantages over the Feynman diagram approach for certain types of calculations in perturbative quantum field theory. After a short historical review, I will give an overview of the present range of applications of the worldline formalism to the calculation of amplitudes, effective actions and pair-creation rates in gauge theory, gravity and the standard model.

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The worldline approach to strong-field QED and N-photon amplitudes

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The worldline formalism has been previously used to derive compact master formulas for QED N-photon amplitudes in vacuum, in a constant field and in a plane-wave field. In this work, we extend this approach by deriving master formulas for the scalar and spinor QED one-loop N-photon amplitudes in the background of the “parallel” special case of a combined constant and plane-wave field.

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1st quantization of worldline EFT for black holes and neutron stars

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This talk discusses how quantum-field-theory methods can be applied to model (classical) gravitational waves from binaries of compact objects (black holes or neutron stars). A compact object can be modeled by a worldline effective theory, incorporating spin effects, tidal effects, and strong-field effects beyond general relativity. A 1st quantization of the worldline theory provides an elegant way to compute observables for the scattering of compact objects, which provide gauge-invariant input for gravitational waveform models.

Worldline instantons for the momentum spectrum of strong-field-QED processes in space-time dependent fields

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Affleck et al used worldline instantons to obtain an all-orders-in-α result for Schwinger pair production by a constant electric field. Dunne and Schubert et al showed how to use instantons to obtain the probability for non-constant fields. In both cases, and in most subsequent papers, the instantons are closed loops, which give probabilities integrated over particle momenta (and summed over spins). We have developed an instanton formalism with open worldlines to obtain the momentum spectrum for Schwinger pair production in realistic 4D fields. We have also shown how to use open worldlines for other strong-field processes such as nonlinear Compton emission of hard photons ($e^- \to e^-\gamma$), nonlinear Breit-Wheeler ($\gamma \to e^+e^-$) and trident ($e^- \to e^-e^-e^+$).

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The classical dynamics of particles with (non-)abelian charges and spin moving on curved manifolds is established in the Poisson-Hamilton framework. Equations of motion are derived for the minimal quadratic Hamiltonian and some extensions involving spin-dependent interactions. The classical equations of motion imply current and energy-momentum conservation; however, they cannot be derived from an action principle without extending the model. One way to overcome this problem is the introduction of anticommuting Grassmann co-ordinates. The derivation of constants of motion based on symmetries of the background fields is discussed.

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Kerr Black Hole Dynamics from an Extended Polyakov Action

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We examine a hypersurface model for the classical dynamics of spinning black holes. Under specific geometric constraints, it reveals an intriguing solution resembling the Kerr Black three-point amplitude expectations. We explore various generalizations of this formalism and outline potential avenues for analyzing spinning black hole mergers.

Particle production in electric and gravitational fields

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This talk discusses a new avenue to unify the description of particle production in electric fields and curved spacetimes. It is based on a heat-kernel expansion in the context of effective field theory analogously to deriving the Schwinger effect. Using the Schwinger parametrization, it is possible to relate gravitational particle production to local field excitations.

Applying this method to an uncharged massless scalar field in a Schwarzschild spacetime, we show that tidal forces induced by spacetime curvature take a similar role as the electric field in the Schwinger effect. We interpret our results as local pair production in a gravitational field. The predictions for the particle number and energy flux are comparable with the ones from Hawking radiation. However, we question the relevance of the presence of a black hole event horizon.

This talk puts the underlying technical assumptions and physical results into context with recent literature and discusses further generalizations.

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Abstracts of Posters

(in alphabetical order)

Wave Propagation in a Spacetime with Thin Concentric Shells of Matter

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This work investigates the transmission of scalar, electromagnetic, and linearized odd-parity gravitational waves in a static spacetime characterized by a spherical distribution of matter in the form of thin, concentric, and equidistant shells, each with equal mass [1]. These shells connect Schwarzschild spacetimes of different masses [2,3,4], satisfying the Israel junction conditions [5,6] with a polytropic-type equation of state for the surface energy-momentum tensor. The central region is assumed to have zero mass, and it is verified that the resulting spacetime is stable against small perturbations of the shell radii, provided the gravitational field is sufficiently weak.

The study focuses on the transmission of monochromatic waves emitted from the center and propagating through a succession of N shells. For this purpose, the self-gravity of the waves is neglected, and the Regge-Wheeler equation [7,8,9] is solved in the weak-field limit of the background spacetime [10]. Analytical expressions for the transmission and reflection coefficients are derived, and their dependence on the frequency, the number of shells, and their separation is analyzed. In particular, in the high-frequency limit, the reflection coefficient is observed to decay with the fourth power of the frequency. As the number of shells increases, the transmission coefficient initially exhibits oscillations; however, as N grows, this coefficient rapidly stabilizes at a constant positive value. This behavior is attributed to the fact that reflections are primarily determined by the surface density of the shells, which decreases as the inverse square of their radii.

This spacetime model also permits the exploration of scenarios in which the masses of the shells and their separations exhibit random fluctuations. In such cases, it would be of interest to investigate whether these irregularities affect the transmission properties of outgoing waves and whether they could lead to localization effects, analogous to Anderson localization [11] in condensed matter systems.

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Low-energy photon scattering amplitudes on the loop and line in a homogeneous electromagnetic field

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The nonperturbative nature of quantum electrodynamics in the presence of strong background electromagnetic fields requires summing an infinite sequence of diagrams, which is difficult to capture in the standard QFT formalism. We present the worldline formalism as a tool for the construction of tree-level N-photon processes (all-multiplicity) for scalar and spinor particles under the influence of a homogeneous field with low-energy external photons. We show how the propagator expansion with respect to a homogeneous component of a background electromagnetic field contains the complete information about the amplitudes of low-energy photons in the complementary background and mention how an analogous calculation leads to one loop-level scattering processes.

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Vacuum Dependences of Renormalization Group Flows in de Sitter Backgrounds

Tim Luis Borck[1,2], **Frank Saueressig**[2]

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[2] *Radboud University, Nijmegen, Netherlands*

We combine the techniques of the functional renormalization group with semiclassical approaches from quantum field theory in curved spacetime (QFTCS). A key advantage of QFTCS is that, unlike flat space, there is no unique vacuum state initially selected. This flexibility allows for a broad exploration of all possible Hilbert space representations. In de Sitter spacetime, this family of invariant states corresponds to the α -vacua [1,2]. We investigate how these vacua influence correlation functions, renormalization group flow equations, and spontaneous symmetry breaking for a scalar field with a quartic interaction.

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Hybrid quantum-classical field theory: geometrodynamics with quantum sources.

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We summarize our recent work [1,2,3] offering a hybrid quantum-classical description of field theory which allows a mathematically consistent Hamiltonian description of QFT on curved space-times using bundles of dynamical Hilbert spaces and even its coupling with a dynamical gravitational field. In this way, we build a hybrid geometrodynamics, with quantum scalar fields as sources for the classical gravitational field.

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[2] J. L . Alonso, C. Bouthelier-Madre, J. Clemente-Gallardo and D. Martínez-Crespo, **Geometric flavours of Quantum Field theory on a Cauchy hypersurface. Part I: Gaussian analysis and other mathematical aspects** , J. Geom. Phys, **203** 105264 , 2024

[3]J. L . Alonso, C. Bouthelier-Madre, J. Clemente-Gallardo and D. Martínez-Crespo,**Geometric flavours of Quantum Field theory on a Cauchy hypersurface. Part II: Methods of quantization and evolution** , J. Geom. Phys, **203** 105265 , 2024

Time scales in the Sauter-Schwinger effect

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Pair creation in ultra-strong background fields, particularly the Sauter-Schwinger effect, has been a long-standing theoretical prediction. Despite extensive studies, one aspect, the formation times of particles, has remained elusive. In this poster, I present our recent work on time scales in Sauter-Schwinger pair production. To this end, we study the time evolution of observables in spatially and temporally structured electric fields within a (1+1)-dimensional Dirac-Heisenberg-Wigner approach. In order to interpret these extracted observables at intermediate times we use a hypothetical shutoff procedure [1]. The switching off of the field at intermediate times allows us to study pair and charge densities at non-asymptotic times. From this, we are able to identify different time scales in both, the spatial and momentum domains. We perform a detailed analysis of multiple parameters to obtain power laws for the parameter dependence of the time scales for pair production in the case of a single Sauter pulse [2,3]. This work therefore allows us interesting insights into non-equilibrium quantum systems.

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A worldline approach to resummations and (assisted) pair production

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Abstract

I will show how the Worldline Formalism can be adapted to explore non-perturbative phenomena that originate from the interaction of quantum fields with classical backgrounds. As a functional approach, it naturally lends itself to non-perturbative analyses, where obtaining suitably resummed expressions for effective actions and heat kernels plays a crucial role. Focusing on the specific case of a quantum scalar field coupled to a Yukawa background, I will present a systematic resummation of all the invariants constructed from powers, first derivatives, and second derivatives of the background field. These results allow for the computation of vacuum instability by evaluating the vacuum persistence amplitude and the associated Schwinger pair production probability. Furthermore, I will illustrate how the presence of an additional, rapidly varying background can significantly enhance pair production.

Heat kernel resummations: spinors on a constant axial vector field background

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This poster will present the latest results on currently ongoing research regarding a new heat kernel resummation formula for a system consisting of a quantum spinor field and a classical constant axial vector field background. These results throw some insight into some nonperturbative aspects of torsion-like background systems in a flat spacetime, and may serve as a stepping stone for further developing the techniques utilized into more general systems.

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The n-hit function approach to quantum amplitudes; exploring asymptotic applications

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The introduction of the n-hit function [1], a multi-point total proper-time propagator, has introduced a novel approach for calculating quantum amplitudes within the framework of the Worldline Formalism of Quantum Field Theory. The method provides an alternative to the numerical generation of worldlines. While this approach has demonstrated promising computational efficiency, its potential applications to various physical phenomena, such as the calculation of Casimir interaction energies and particle scattering, remain largely unexplored. This work outlines the theoretical foundation of this approach and presents new insights on its future improvement using methods from asymptotic analysis.

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Rejection-Free Monte Carlo Sampling for Worldline Numerics

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It is possible to map the propagator of the worldline formalism to that of a partition function in statistical mechanics via a Wick rotation $it \to \tau$. This allows us to estimate certain quantum expectations using Monte Carlo (MC) methods, but the traditional approach of Metropolis MC breaks down as the continuum-time limit is approached. Indeed, the thermalisation time of the simulation grows as $\sim \mathcal{O}(N^2)$, and the thermalised state fails to mix on timescales of any useful length. This is analogous to the well known statistical physics phenomenon of critical slowing-down at a phase transition. This work proposes that a different type of MC algorithm, Event Chain Monte Carlo (ECMC) can be used to overcome these limitations. ECMC has been studied extensively in statistical physics contexts, but never in the worldline case. Under ECMC, the system is driven through its state-space with ballistic dynamics, as opposed to the diffusive dynamics that result from Metropolis MC. We present simulations of a one-dimensional quantum harmonic oscillator using Metropolis and ECMC.

Our preliminary results demonstrate significant improvement over Metropolis MC. ECMC appears to thermalise in $\mathcal{O}(1)$ iterations and also exhibit improved scaling of the integrated autocorrelation time of thermalised configurations. Further testing is required to fully understand the failure behaviour of Metropolis MC in this limit and how ECMC is able to overcome this, but it is clear that ECMC will be a powerful tool for worldline numerics, which could allow access to the continuum-time limit of many expected observables of a broad range of quantum systems.

Entanglement in the Schwinger Effect

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We wish to quantify entanglement in the Schwinger effect, that is, the creation of pairs of particles-antiparticles in an electric field. The Schwinger effect can be simply computed in the gaussian formalism as a Bogolyubov transformation and the gaussian formalism gives powerfull tools to quantify entanglement, such as the von Neumann entropy and the log-negativity. We thus first derive the formulas that we will need in the gaussian formalism for bosons and fermions. Then we compute the Schwinger effect in the scalar (or bosonic) and spinor (or fermionic) cases as a Bogolyubov transformation. Finally, we compute the entropy and log-negativity both from a vacuum state and from a thermal state, both for scalars and for spinors. We see that there exists a temperature above which entanglement vanishes even for arbitrarily high values of the electric field.

Worldline Methods for 4-Photon Amplitudes in Scalar and Spinor QED

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Quantum effects introduce nonlinear corrections to Maxwell's equations, leading to phenomena crucial for understanding the quantum behavior of charged particles and electromagnetic fields. Among them, vacuum photon-photon scattering is particularly relevant, first computed in the low-energy limit [1,2] and later extended to arbitrary energies via second quantization [3]. The exploration of such problems using first quantization methods was initially outlined in [4], but a systematic framework for constructing one-loop N-gluon/photon amplitudes was later introduced by [5]. Shortly therafter, [6] demonstrated that a first quantization approach without relying on Feynman diagrams was feasible.

We employ the one-loop N-photon master formula to compute the four-photon amplitude. For its integral representation in terms of the Green's function and derivatives, see [7]. These master formulas were later optimized via integration by parts [6], leading to the off-shell four-photon amplitude computation in the worldline formalism [8].

Here, we revisit the computation of the box integral within the worldline formalism for arbitrary masses, unifying the scalar and spinor cases. We emphasize the importance of a method that streamlines such integrals without sector decomposition and analyze its effectiveness, advantages, and limitations in the context of 4-photon amplitudes.

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Ritus-Narozhy conjecture: current status and outlook

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A strong background field can significantly modify or induce new effects in interactions with quantum fields, with the brightest known examples of the Schwinger vacuum pair production induced by a critical field E_S in strong-field QED. Because of screening by pairs, the maximum reachable static electric field is limited. In contrast, magnetic and constant crossed ($E=H$, $\mathbf{E}\perp\mathbf{H}$) fields, which do not generate pairs from vacuum, are not limited in their strength. This naturally raises a question, what kind of non-perturbative physics arises as they exceed E_S by orders of magnitude.

In this presentation, we will focus on scattering processes in the special case of a constant crossed field $>10^3 E_S$. The symmetry of this field allows for treating its coupling to charged particles exactly in (some) scattering amplitudes. In 70-80-s, Ritus and Narozhny observed that loop corrections are enhanced in this field and grow surprisingly fast with its strength, namely, as a power in the amplitude pre-factor [2,3]. According to their conjecture, this leads to a breakdown of the perturbative expansion in the high-field limit (though below the electroweak scale). We will recap this conjecture and a resummation for curing the expansion breakdown [4,5], and outlook the possible implications of this novel fully non-perturbative regime of strong-field QED.

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Functional Renormalization Group as a Non-Perturbative Tool for Gravity: Asymptotic Safety of Generalized Proca Theories

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The Functional Renormalization Group (FRG) has emerged as a powerful non-perturbative framework to investigate the fundamental properties of quantum field theories. Initially developed in the context of critical phenomena, it has been successfully applied to gauge theories, statistical physics, and gravity, offering deep insights into renormalization group flows, fixed points, and the structure of effective actions. In quantum gravity, FRG plays a central role in exploring asymptotically safe (AS) scenarios, where ultraviolet fixed points can lead to a well-defined high-energy completion of the theory.

In this work, we illustrate the versatility of FRG by applying it to Generalized Proca theories—vector-tensor modifications of gravity that incorporate self-interacting vector fields and naturally extend General Relativity. These theories provide a rich testing ground for AS due to their broad implications in gravitational wave physics, strong-field regimes, and cosmology. We investigate their fixed-point structure within the AS paradigm, providing new insights into their non-perturbative behavior and potential ultraviolet consistency. By demonstrating how FRG techniques can systematically probe modified gravity scenarios, our results underscore the power of this approach in addressing key challenges in gravitational physics and effective field theory descriptions.

Examining the Anomalous Nature of the Chiral Vortical Effect

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The Chiral Vortical Effect (CVE) is a transport phenomenon appearing in relativistic fluids due to the presence of vorticity. It is one term in a derivative expansion which has enriched the hydrodynamic description. Yet, some of these novel transport operators have been related to the chiral anomaly.

To check this link in the case of the CVE, I will present a direct computation within the path integral formalism. This computation recovers the known connection between the chemical potential contribution and the chiral anomaly. However, by taking into account temperature in curved spacetime, it also shows that the temperature contribution to the CVE is not linked to the mixed gravitational anomaly.

Worldline Approach to the Dressed Scalar Propagator with N Photons

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The worldline formalism offers an alternative and efficient approach to computing scattering amplitudes in quantum field theory. In this work, we illustrate its application to the dressed propagator of a charged scalar particle interacting with N external photons in vacuum. Using path integral techniques, we express the amplitude in terms of a worldline representation, highlighting the advantages of this method over standard Feynman diagram calculations, particularly in handling multi-photon interactions. Our presentation aims to provide insight into the structure of worldline integrals and their potential applications in quantum electrodynamics. Moreover, the extension to the loop level is also discussed.

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EFFECT OF WEAK MEASUREMENTS ON EXCITON-EXCITON INTERACTIOS

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In our study of super quantum discord between two excitonic qubits inside a coupled semiconductor quantum dots system, our primary focus is to uncover the impact of weak measurement on its quantum characteristics. To achieve this, we analyze how varying the measurement strength x, affects this super quantum correlation in the presence of thermal effects. Additionally, we assess the effect of this variation on the system's evolution against its associated quantum parameters; external electric fields, exciton-exciton dipole interaction energy and Förster interaction. Our findings indicate that adjusting x to smaller values effectively enhances super quantum correlation, making weak measurements act as a catalyst. This adjustment ensures its robustness against thermal effects while preserving the non-classical attributes of system. Furthermore, our study unveils that the effect of weak measurements on this latter surpasses the quantum effects associated with the system. Indeed, manipulating the parameter x allows weak measurement to function as a versatile tool for modulating quantum characteristics and controlling exciton-exciton interactions within the coupled semiconductor quantum dots system.

Nonlinear Thomson scattering in a strong gravitational wave

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We investigate the nature of the classical emission spectrum via nonlinear Thomson scattering of a charge moving in a gravitational plane wave. This background is treated exactly and non-perturbatively. The classical approach allows us to explicitly reveal how memory effects, an intrinsic property of plane wave curved spacetimes, shape the electromagnetic spectrum, particularly demonstrating the roles of both position and velocity memory effects in the process. We compute the nonlinear Thomson spectrum with and without memory effects, highlighting the key features and differences between the two cases. Special attention is given to obtaining properly regularized expressions for the spectra. Finally, we explore the feasibility of applying a gravitational analogue of the locally constant field approximation, usually employed in electromagnetic backgrounds, to our results.

Spectral Compatibility and Analytical Constraints in Quantum Marginal Problems

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The compatibility of quantum marginals, or reduced density matrices, is a cornerstone of quantum mechanics, underlying phenomena like entanglement and non-locality. A fundamental variant of this problem concerns the compatibility of spectra, rather than the reduced density matrices themselves. Specifically, given eigenvalues $\vec{\lambda}_{AB}$ and $\vec{\lambda}_{BC}$ for subsystems AB and BC, the task is to determine whether there exists a joint quantum state ρ_{ABC} such that its reduced density matrices $\rho_{AB} = tr_C(\rho_{ABC})$ and $\rho_{BC} = tr_A(\rho_{ABC})$ exhibit these spectra. If such a state exists, the spectra are deemed compatible; otherwise, they are incompatible.
Recently, a hierarchy of semidefinite programs (SDP) was developed to address this challenge [1]. This hierarchy is complete and provides dimension-free certificates of incompatibility for all local dimensions. The poster introduces a new constraint on incompatibility by solving the second hierarchy level for multipartite qudit systems and highlights key incompatibility cases across different hierarchy levels.

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