Effective Action in Supergeometric QFTs

Viola Gattus

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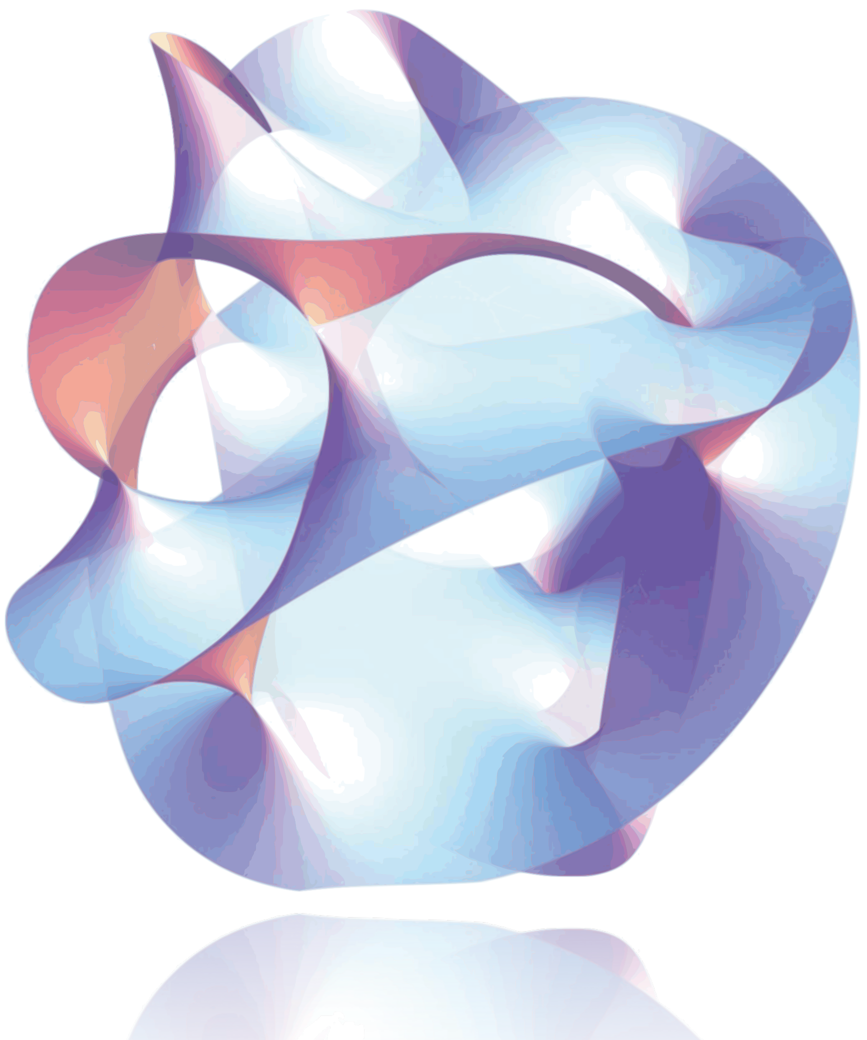
Based on hep-th/2406.13594 with
Prof Apostolos Pilaftsis



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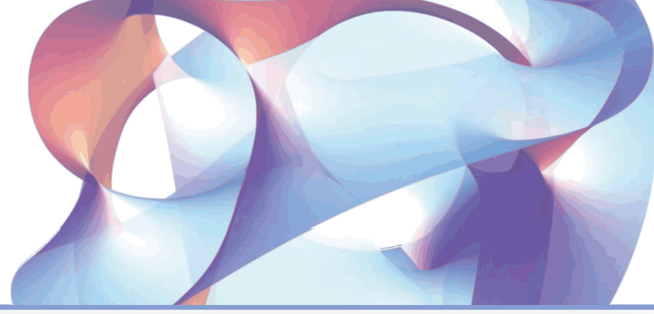


1. Supergeometry in QFT
2. Covariant Interactions
3. Covariant Effective Action
4. Effective Action with Curvature
5. Fermionic One-Loop Effective Action
6. Summary and Outlook

Supergeometry in QFT

Motivation

- Off-shell calculations sensitive to choice of parametrisation
- Gauge-fixing in gauge theory and quantum gravity
  [Barvinsky, Vilkovisky (1985), Ellicott, Toms (1989), Burgess, Kunstatter (1987), Odintsov (1990)]
- Potential solution to quantum frame problem
  [Burns, Karamitsos, Pilaftsis (2016), Falls, Herrero-Valea (2019), Finn, Karamitsos, Pilaftsis (2020) ..]
- New physics phenomena in SMEFT
  [Alonso, Jenkins, Manohar (2016), Cohen, Craig, Sutherland (2021), Talbert (2023), Assi, Helset, Manohar, Pagès, Shen (2023) ...]

Disclaimer: Supergeometry $\neq$ Supersymmetry

Theory with bosons and fermions and no extra symmetry

Supergeometry in QFT

Supermanifolds

Field-space supermanifold of dimension (N|8M) in 4d spacetime

Now fermions in the chart

[DeWitt (2012)]

$$\mathbf{\Phi} \;\equiv\; \{\Phi^a\} \;=\; \begin{pmatrix} \phi^A \\ \psi^X \\ \overline{\psi}^{Y\,\mathsf{T}} \end{pmatrix}$$

Field reparameterization = diffeomorphism

$$\Phi^a \;\to\; \widetilde{\Phi}^a \;=\; \widetilde{\Phi}^a(\mathbf{\Phi})$$

Diffeormophically - or frame invariant Lagrangian

[Finn, Karamitsos, Pilaftsis (2021), VG, Finn, Karamitsos, Pilaftsis (2022)]

$$\mathcal{L} \;=\; \frac{1}{2} g^{\mu\nu}\partial_\mu \Phi^A \;{}_A k_B(\mathbf{\Phi})\,\partial_\nu \Phi^B \;+\; \frac{i}{2}\,\zeta^\mu_A(\mathbf{\Phi})\,\partial_\mu \Phi^A \;-\; U(\mathbf{\Phi})$$

Supermanifolds

Supermanifold metric

$$ {}_A G_B = ({}_A G_B)^{\mathsf{sT}} $$

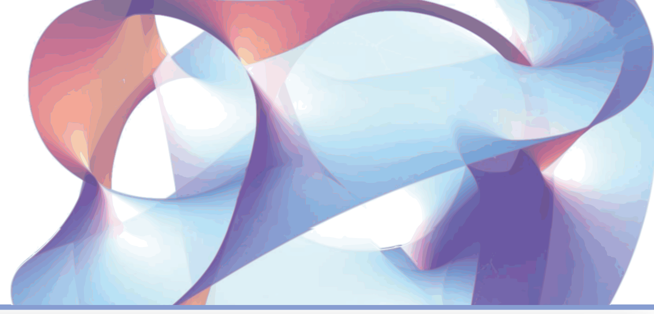
- supersymmetric rank-2 FS tensor
- ultralocal
- determined from action

Global metric found from vielbeins and local metric

[Finn, Karamitsos, Pilaftsis (2021), VG, Finn, Karamitsos, Pilaftsis (2022)]

$$ {}_A G_B = {}_A e^{\widehat{M}} \; {}_{\widehat{M}} H_{\widehat{N}} \; {}^{\widehat{N}} e_B^{\mathsf{sT}} $$

$$ {}_{\widehat{A}} H_{\widehat{B}} \equiv \begin{pmatrix} \mathbf{1}_N & 0 & 0 \\ 0 & 0 & \mathbf{1}_{dM} \\ 0 & -\mathbf{1}_{dM} & 0 \end{pmatrix} $$



Covariant Interactions

Scalar-Fermion Theories

D operator

[Ecker, Honerkamp, (1972)]

$$(\partial_\mu \Phi^a)_{;b} \;=\; \left(\delta^A{}_B\,\partial_\mu^{(A)} + \Gamma^A{}_{BM}\,\partial_\mu \Phi^M\right)\delta(x_A - x_B) \;\equiv\; (D_\mu)^a{}_b$$

Important supergeometric identity

$$(D_\mu)_{ab;c} \;=\; R_{abcm}\,\partial_\mu \Phi^m$$

Complete covariant inverse superpropagator

[VG, Pilaftsis (2024)]

$$\begin{aligned} S_{ab} =\;& (-1)^{am}(D_\mu)^m{}_a\;{}_m k_n\,(D^\mu)^n{}_b \;+\; \partial_\mu \Phi^m \Big({}_m k_n\, R^n{}_{abp}\,\partial^\mu \Phi^p \\ &+ (-1)^{an}\;{}_m k_{n;[a}\,(D^\mu)^n{}_{b]} + \frac{1}{2}(-1)^{n(a+b)}\;{}_m k_{n;ab}\,\partial^\mu \Phi^n \Big) \\ &+ i(-1)^a \Big({}_a\lambda^\mu_m (D_\mu)^m{}_b + (-1)^{bm}\;{}_a\lambda^\mu_{m;b}\,\partial_\mu \Phi^m \Big) - U_{ab} \end{aligned}$$

$${}_a\lambda^\mu_b \;\equiv\; \frac{1}{2}\left({}_{a,}\zeta^\mu_b \;-\; (-1)^{a+b+ab}\;{}_{b,}\zeta^\mu_a \right)$$

Covariant Effective Action

Implicit equation

Implicit equation for effective action using VDW

[Vilkovisky (1984), DeWitt (1985), Finn, Karamitsos, Pilaftsis (2022)]

$$\exp\left(\frac{i}{\hbar}\Gamma[\mathbf{\Phi}]\right) = \int \sqrt{|\,\mathrm{sdet}\,G|}\,[\mathcal{D}\mathbf{\Phi}_q]\exp\left(\frac{i}{\hbar}S\left[\mathbf{\Phi}_q\right] + \frac{i}{\hbar}\int \delta^4 x\sqrt{-g}\,\Gamma[\mathbf{\Phi}]_{,a}\,\Sigma^a\left[\mathbf{\Phi},\mathbf{\Phi}_q\right]\right)$$

Master functional differential equation for 1PI QEA at all orders [Kim (2006)]

$$2i\left(\Gamma^{(n)}\frac{\overleftarrow{\delta}}{\delta\Delta^{ab}}\right)\delta\Delta^{ba} = \mathrm{str}\left[\Delta^{-1}\sum_{k=1}^{n-1}(-1)^k\,\Delta\,\Pi^{(l_1)}\Delta\,\Pi^{(l_2)}\Delta\,\ldots\Pi^{(l_k)}\left(\delta\Delta\right)\right]$$

One and two loops expressions

$${}_aS_b \equiv {}_a\overrightarrow{\nabla}S\overleftarrow{\nabla}_b \equiv {}_a\Delta_b^{-1}$$

$$\Gamma^{(1)}[\mathbf{\Phi}] = \frac{i}{2}\ln\mathrm{sdet}\left({}^aS_b\right) = \frac{i}{2}\mathrm{str}\left(\ln{}^aS_b\right)$$

$$\Gamma^{(2)}[\mathbf{\Phi}] = -\frac{1}{8}S_{\{abcd\}}\,\Delta^{dc}\Delta^{ba} + \frac{1}{12}(-1)^{bc+m(b+d)}\,S_{\{mca\}}\,\Delta^{ab}\Delta^{cd}\Delta^{mn}\,{}_{\{ndb\}}S$$

$$\Delta^{ac}\,{}_cS_b = {}^a\delta_b$$

Covariant Effective Action

Schwinger-DeWitt Heat Kernel Method

Use HK to compute one-loop effective action in x-space

1. Represent $\ln \Delta$ as integral over t
2. Obtain UV divergences as $1/\varepsilon$-poles in $t \to 0^+$ limit
3. Solve iteratively a diffusion-type equation in powers of t

Covariant Effective Action

Schwinger-DeWitt Heat Kernel Method

Use HK to compute one-loop effective action in x-space

1. Represent $\ln \Delta$ as integral over t
2. Obtain UV divergences as $1/\varepsilon$-poles in $t \to 0^+$ limit
3. Use Zassenhaus formula to derive HK coefficients

$$\exp\left[t(X+Y)\right] = \exp(tX)\,\exp(tY)\,\exp\left(-\frac{t^2}{2}[X,Y]\right)\,\exp\left[\frac{t^3}{6}\Big(2[Y,[X,Y]]+[X,[X,Y]]\Big)\right]\dots$$

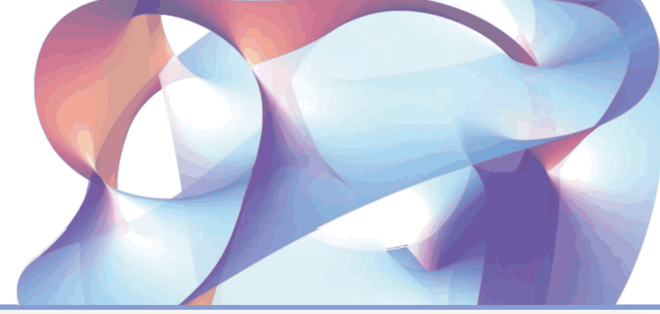
E.g. for $\widehat{X} = -\partial^2 - m^2$ and $\widehat{Y} = -V$

$$\langle x|e^{-t(-\partial^2-m^2)}|y\rangle = \frac{e^{-\frac{1}{4t}(x-y)^2+m^2 t}}{(4\pi t)^{d/2}}$$

$$\langle x|e^{-t(-\partial^2-m^2-V)}|x'\rangle = \int d^d y\,\langle x|e^{t(\partial^2+m^2)}|y\rangle$$

$$\times\,\langle y|e^{tV}e^{-\frac{t^2}{2}[\partial^2,V]}e^{\frac{t^3}{6}\left(2[V,[\partial^2,V]]+[\partial^2,[\partial^2,V]]\right)}e^{\mathcal{O}(t^4)}|x'\rangle$$

QEA with Curvature



Pure scalar theory

Diffeormophically - or frame invariant Lagrangian

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \Phi^A \, {}_A k_B(\mathbf{\Phi}) \, \partial_\nu \Phi^B + \frac{i}{2} \zeta^\mu_A(\mathbf{\Phi}) \, \partial_\mu \Phi^A - U(\mathbf{\Phi})$$

$${}_a G_b \equiv {}_A k_B \, \delta(x_A - x_B)$$

QEA with Curvature

Pure scalar theory

Scalar frame invariant Lagrangian

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi^A \, {}_A G_B(\phi) \, \partial_\nu \phi^B$$

Mixed-rank covariant inverse propagator

$${}^a S_b = -(D_\mu)^a{}_m \, (D^\mu)^m{}_b - R^a{}_{mbp} (\partial_\mu \phi^m)(\partial^\mu \phi^p) - U^a{}_b$$

Project D^2 operator with vielbeins

$$(D^2)^A{}_B \equiv (D_\mu)^A{}_M \, (D^\mu)^M{}_B = {}^A e_{\widehat{A}} \, (\widehat{D}^2)^{\widehat{A}}{}_{\widehat{B}} \, {}^{\widehat{B}} e^{\mathsf{sT}}_B$$

Extract covariant heat kernel

$$\langle x_A | e^{tD^2} | x_B \rangle = K^A{}_B \frac{e^{-(x_A - x_B)^2/4t}}{(4\pi t)^{d/2}} + W^A{}_B$$

$$K^A{}_B \equiv {}^A e_{\widehat{A}}(x_A) \, {}^{\widehat{A}} e^{\mathsf{sT}}_B(x_B) \to \delta^A{}_B$$

$$W^A{}_B \to 0$$

QEA with Curvature

Pure scalar theory

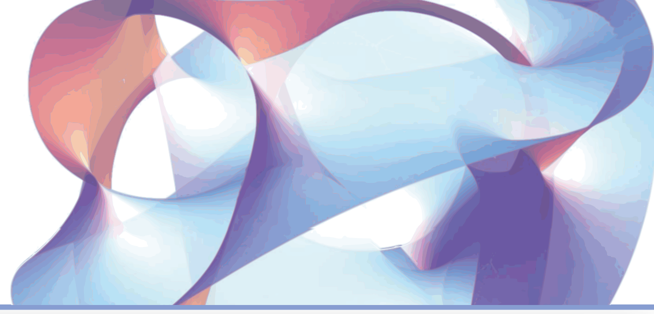
Covariant heat diffusion equation

$$\frac{\partial}{\partial t}\langle x_A|e^{tD^2}|x_B\rangle \;=\; \langle x_A|\,D^2\,e^{tD^2}|x_B\rangle \;=\; \langle x_A|\,e^{tD^2}\,D^2|x_B\rangle$$

Series expansion in t

$$\begin{aligned}\Gamma^{(1)} \;=\; & -\frac{i}{2}\int_{x_A,x_B}\int_0^\infty \frac{dt}{t}\frac{e^{-(x_A-x_B)^2/4t}}{(4\pi t)^{d/2}}\Big[t\left(R_{MN}\,\partial_\nu\phi^M\,\partial^\nu\phi^N + U^A{}_A\right) + \frac{t^2}{2}U^A{}_M U^M{}_A \\ & +\frac{t^2}{2}\left(R^A{}_{MPN}\,\partial_\nu\phi^M\,\partial^\nu\phi^N\,U^P{}_A + U^A{}_P R^P{}_{MAN}\,\partial_\nu\phi^M\,\partial^\nu\phi^N\right) \\ & +\frac{t^2}{2}R^A{}_{MPN}\,\partial_\mu\phi^M\,\partial^\mu\phi^N\,R^P{}_{SAT}\,\partial_\nu\phi^S\,\partial^\nu\phi^T\Big]\,\delta(x_B-x_A) \;+\; \Delta\Gamma^{(1)}\end{aligned}$$

QEA with Curvature



Pure scalar theory

Covariant heat diffusion equation

$$\frac{\partial}{\partial t} \langle x_A | e^{tD^2} | x_B \rangle \; = \; \langle x_A | \, D^2 \, e^{tD^2} | x_B \rangle \; = \; \langle x_A | \, e^{tD^2} \, D^2 | x_B \rangle$$

Integrate over t

$$\begin{aligned}
\Gamma^{(1)}_{\rm UV} = & - \frac{i}{16\pi^2} \int_{x_A, x_B} \left[(x_A - x_B)^2 \right]^{-1+\epsilon} \left(R_{MN} \, \partial_\nu \phi^M \, \partial^\nu \phi^N + U^A_{\ A} \right) \delta(x_B - x_A) \\
& + \frac{i}{64\pi^2 \epsilon} \int_{x_A, x_B} \left[(x_A - x_B)^2 \right]^{\epsilon} \Big\{ U^A_{\ M} U^M_{\ A} + R^A_{\ MPN} \, \partial_\mu \phi^M \, \partial^\mu \phi^N \, R^P_{\ SAT} \, \partial_\nu \phi^S \, \partial^\nu \phi^T \\
& \qquad + R^A_{\ MPN} \, \partial_\nu \phi^M \, \partial^\nu \phi^N \, U^P_{\ A} + U^A_{\ P} R^P_{\ MAN} \, \partial_\nu \phi^M \, \partial^\nu \phi^N \Big\} \, \delta(x_B - x_A) \, . \\
& + \; \Delta\Gamma^{(1)}
\end{aligned}$$

QEA with Curvature

Pure scalar theory

Covariant heat diffusion equation

$$\frac{\partial}{\partial t}\langle x_A|e^{tD^2}|x_B\rangle \;=\; \langle x_A|\,D^2\,e^{tD^2}|x_B\rangle \;=\; \langle x_A|\,e^{tD^2}\,D^2|x_B\rangle$$

Integrate over t

$$0$$

$$\Gamma^{(1)}_{\mathrm{UV}} = -\frac{i}{16\pi^2}\int_{x_A,x_B}\boxed{\left[(x_A-x_B)^2\right]^{-1+\epsilon}\left(R_{MN}\,\partial_\nu\phi^M\,\partial^\nu\phi^N + U^A{}_A\right)\delta(x_B-x_A)}$$
$$+\frac{i}{64\pi^2\epsilon}\int_{x_A,x_B}\left[(x_A-x_B)^2\right]^{\epsilon}\Big\{U^A{}_M U^M{}_A + R^A{}_{MPN}\,\partial_\mu\phi^M\,\partial^\mu\phi^N\,R^P{}_{SAT}\,\partial_\nu\phi^S\,\partial^\nu\phi^T$$
$$+R^A{}_{MPN}\,\partial_\nu\phi^M\,\partial^\nu\phi^N\,U^P{}_A + U^A{}_P R^P{}_{MAN}\,\partial_\nu\phi^M\,\partial^\nu\phi^N\Big\}\,\delta(x_B-x_A)\,.$$
$$+\boxed{\Delta\Gamma^{(1)}}$$

$$\Delta\Gamma^{(1)} = -\frac{i}{2}\int_{x_A,x_B}\int_0^\infty\frac{dt}{t}\frac{e^{-(x_A-x_B)^2/4t}}{(4\pi t)^{d/2}}\,\frac{t^2}{2}\,\langle x_B|\left(R^A{}_{MPN}\,\partial_\nu\phi^M\,\partial^\nu\phi^N + U^A{}_P\right)(D_\mu)^P{}_C(D^\mu)^C{}_A$$
$$-(D_\mu)^A{}_C(D^\mu)^C{}_P\left(R^P{}_{MAN}\,\partial_\nu\phi^M\,\partial^\nu\phi^N + U^P{}_A\right)|x_A\rangle$$

QEA with Curvature

Pure scalar theory

Covariant heat diffusion equation

$$\frac{\partial}{\partial t} \langle x_A | e^{tD^2} | x_B \rangle \;=\; \langle x_A | \, D^2 \, e^{tD^2} | x_B \rangle \;=\; \langle x_A | \, e^{tD^2} \, D^2 | x_B \rangle$$

Integrate over t

$$\Gamma^{(1)}_{\text{UV}} = -\frac{i}{16\pi^2} \int_{x_A, x_B} \left[(x_A - x_B)^2 \right]^{-1+\epsilon} \left(R_{MN} \, \partial_\nu \phi^M \, \partial^\nu \phi^N + U^A{}_A \right) \delta(x_B - x_A)$$

$$+ \frac{i}{64\pi^2 \epsilon} \int_{x_A, x_B} \left[(x_A - x_B)^2 \right]^{\epsilon} \Big\{ U^A{}_M U^M{}_A + R^A{}_{MPN} \, \partial_\mu \phi^M \, \partial^\mu \phi^N \, R^P{}_{SAT} \, \partial_\nu \phi^S \, \partial^\nu \phi^T$$
$$+ R^A{}_{MPN} \, \partial_\nu \phi^M \, \partial^\nu \phi^N \, U^P{}_A + U^A{}_P R^P{}_{MAN} \, \partial_\nu \phi^M \, \partial^\nu \phi^N \Big\} \, \delta(x_B - x_A) \, .$$

$$+ \;\; \Delta\Gamma^{(1)}$$

terms with $1/\epsilon$- poles

[Alonso, Jenkins, Manohar (2016), Jenkins, Manohar, Naterop, Pagès (2024)...]

UV contributing terms

$$\Gamma^{(1)}_{\text{UV}} \;=\; -\frac{1}{64\pi^2 \epsilon} \int_{x_A} \Big(U^A{}_M U^M{}_A + R^A{}_{MBN} \, \partial_\mu \phi^M \, \partial^\mu \phi^N \, U^B{}_A + U^A{}_B R^B{}_{MAN} \, \partial_\mu \phi^M \, \partial^\mu \phi^N$$
$$+ R^A{}_{MBN} \, \partial_\mu \phi^M \, \partial^\mu \phi^N \, R^B{}_{SAT} \, \partial_\nu \phi^S \, \partial^\nu \phi^T \Big) \, .$$

Fermionic One-loop QEA

New Clifford Algebra and Bosonization

Diffeormophically - or frame invariant Lagrangian

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \Phi^A \, {}_A k_B(\mathbf{\Phi}) \, \partial_\nu \Phi^B + \frac{i}{2} \zeta^\mu_A(\mathbf{\Phi}) \, \partial_\mu \Phi^A - U(\mathbf{\Phi})$$

use to get fermion metric

Fermionic One-loop QEA

Extracting divergent terms

Fermionic one-loop effective action

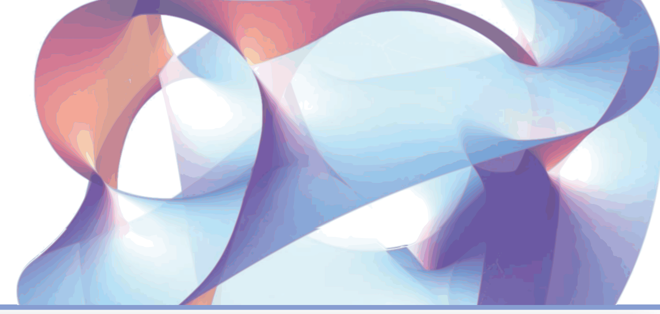
$$\Gamma^{(1)} = -\frac{i}{4}\,\mathrm{tr}\ln\left(-D^2 - A\right) - \frac{i}{2}\,\mathrm{tr}\ln\left[\mathbf{1} + i\bar{\lambda}^{\mu} D_{\mu}\left(-D^2 - A\right)^{-1} V\right]$$

Series expansion in t

$$\Gamma^{(1)} = \frac{i}{4}\,\mathrm{tr}\left(I_1 - 2I_2 - I_3 + \ldots\right) \qquad B \equiv A^2 - [D^2, A]$$

$$I_1 = \int_{x_A, x_B} \langle x_B| \left(\frac{1}{\pi^2}|x_A - x_B|^{-4+2\epsilon} + \frac{1}{4\pi^2}|x_A - x_B|^{-2+2\epsilon} A - \frac{1}{2}\frac{1}{16\pi^2\epsilon}|x_A - x_B|^{2\epsilon} B\right) |x_A\rangle$$

Fermionic One-loop QEA



Extracting divergent terms

Fermionic one-loop effective action

$$\Gamma^{(1)} = -\frac{i}{4}\,\mathrm{tr}\ln\left(-D^2 - A\right) - \frac{i}{2}\,\mathrm{tr}\ln\left[\mathbf{1} + i\bar{\lambda}^\mu D_\mu \left(-D^2 - A\right)^{-1} V\right]$$

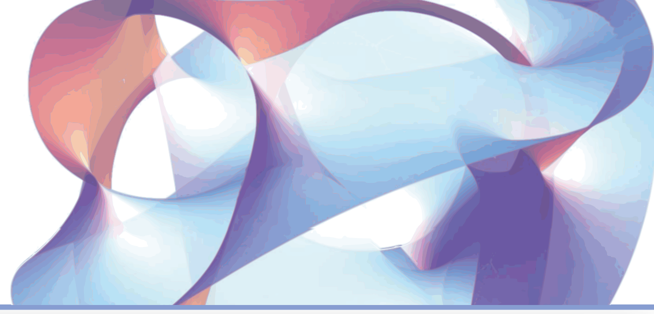
Series expansion in t

$$\Gamma^{(1)} = \frac{i}{4}\,\mathrm{tr}(I_1 - 2I_2 - I_3 + \ldots)$$

$$I_1 = \int_{x_A, x_B} \langle x_B| \left(\frac{1}{\pi^2}|x_A - x_B|^{-4+2\epsilon} + \frac{1}{4\pi^2}|x_A - x_B|^{-2+2\epsilon} A - \frac{1}{2}\frac{1}{16\pi^2\epsilon}|x_A - x_B|^{2\epsilon} B\right)|x_A\rangle$$

$$I_2 = \int_{x_A, x_B, x_C} \langle x_A| i\bar{\lambda}^\mu D_\mu |x_B\rangle \langle x_C| \left(\frac{1}{4\pi^2}|x_B - x_C|^{-2+2\epsilon} - \frac{1}{16\pi^2\epsilon}|x_B - x_C|^{2\epsilon} A + \frac{1}{2}\frac{1}{64\pi^2\epsilon}|x_B - x_C|^{2+2\epsilon} B\right) V |x_A\rangle$$

Fermionic One-loop QEA



Extracting divergent terms

Only terms with scaling factor $|x_A - x_B|^{2\epsilon}$ are non zero

$$I_1 = \int_{x_A, x_B} \langle x_B| \left(\frac{1}{\pi^2}|x_A - x_B|^{-4+2\epsilon} + \frac{1}{4\pi^2}|x_A - x_B|^{-2+2\epsilon} A - \frac{1}{2}\frac{1}{16\pi^2\epsilon}|x_A - x_B|^{2\epsilon} B \right) |x_A\rangle$$

$$I_2 = \int_{x_A, x_B, x_C} \langle x_A| i\bar{\lambda}^\mu D_\mu |x_B\rangle \langle x_C| \left(\frac{1}{4\pi^2}|x_B - x_C|^{-2+2\epsilon} - \frac{1}{16\pi^2\epsilon}|x_B - x_C|^{2\epsilon} A + \frac{1}{2}\frac{1}{64\pi^2\epsilon}|x_B - x_C|^{2+2\epsilon} B \right) V |x_A\rangle$$

No leftover δ- function integration ⟶ keep $\mathcal{O}(D^2)$ terms

$$I_3 = \int_{\substack{x_A, x_B, x_C \\ x_D, x_E, x_F}} \langle x_A| i\bar{\lambda}^\mu D_\mu |x_B\rangle \langle x_C| \left(\frac{1}{4\pi^2}|x_B - x_C|^{-2+2\epsilon} - \frac{1}{16\pi^2\epsilon}|x_B - x_C|^{2\epsilon} A + \frac{1}{2}\frac{1}{64\pi^2\epsilon}|x_B - x_C|^{2+2\epsilon} B \right) V |x_D\rangle$$

$$\langle x_D| i\bar{\lambda}^\nu D_\nu |x_E\rangle \langle x_F| \left(\frac{1}{4\pi^2}|x_E - x_F|^{-2+2\epsilon} - \frac{1}{16\pi^2\epsilon}|x_E - x_F|^{2\epsilon} A + \frac{1}{2}\frac{1}{64\pi^2\epsilon}|x_E - x_F|^{2+2\epsilon} B \right) V |x_A\rangle$$

Fermionic One-loop QEA

Divergent terms

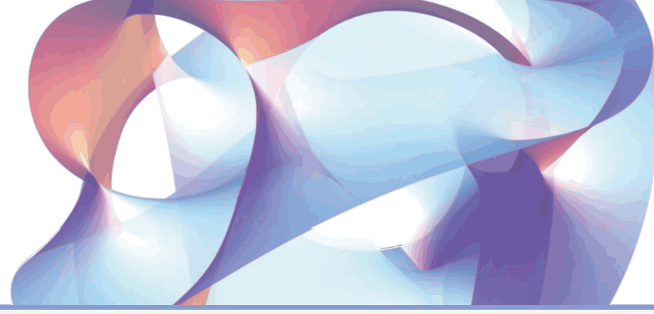
New fermionic operators in the UV

$$(I_1)_{\text{UV}} = \frac{1}{32\pi^2\epsilon}\int_{x_A} {}^A\Big[D_\nu(\lambda^\mu D_\mu\bar{\lambda}^\nu)D_\beta(\lambda^\alpha D_\alpha\bar{\lambda}^\beta) - D^2 D_\nu(\lambda^\mu D_\mu\bar{\lambda}^\nu) + D_\beta D_\nu(\lambda^\mu D_\mu\bar{\lambda}^\nu)\lambda^\alpha D_\alpha\bar{\lambda}^\beta\Big]_A$$

$$\begin{aligned}(I_2)_{\text{UV}} = -\frac{1}{64\pi^2\epsilon}\int_{x_A} {}^A\Big[&\bar{\lambda}_\alpha\, D_\beta(\lambda^\mu D_\mu\bar{\lambda}^\alpha)\lambda^\nu\, D_\nu\bar{\lambda}^\beta + \bar{\lambda}_\alpha\, D_\nu(\lambda^\mu D_\mu\bar{\lambda}^\nu)\, \lambda^\beta\, D_\beta\bar{\lambda}^\alpha - \bar{\lambda}_\nu D^2(\lambda^\mu D_\mu\bar{\lambda}^\nu) \\ &+ \bar{\lambda}_\alpha\lambda^\mu D_\mu\bar{\lambda}^\alpha D_\beta(\lambda^\nu D_\nu\bar{\lambda}^\beta) - 2\,\bar{\lambda}^\alpha D_\alpha D_\nu(\lambda^\mu D_\mu\bar{\lambda}^\nu)\Big]_M (-1)^{NA}\,{}^M\lambda^\mu_{N;A}\,\partial_\mu\Phi^N\end{aligned}$$

$$(I_3)_{\text{UV}} = -\frac{1}{32\pi^2\epsilon}\int_{x_A} {}^A\Big[\bar{\lambda}^\mu V\bar{\lambda}_\mu(D^2V) + (D^2\bar{\lambda}^\mu)V\bar{\lambda}_\mu V + 2(D_\nu\bar{\lambda}^\mu)V\bar{\lambda}_\mu(D^\nu V)\Big]_A$$

Conclusions



Summary

- New approach to Schwinger-DeWitt HK technique
- Systematically identify covariant EFT operators
- Computation of the covariant one-loop EA with fermions

Next up

- Include gauge and gravitational interactions
- Include global or local symmetries
- Phenomenology: dark-sector fermions & SM neutrinos/axions

Thank you!