Title: Quantum Gravitational Corrections to Matter: A Running Controversy

Date: Nov 07, 2009 04:30 PM

URL: http://pirsa.org/09110125

Abstract:

Quantum Gravitational Corrections to Matter: A Running Controversy

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Gravitational Corrections to Matter

Focus on: gravity and particle physics.

Indeed *gravity* certainly has an effect on (and is affected by) the dynamics of ordinary quantum fields of the SM and beyond.

- Even if its quantum formulation is in general still not well established, it is very reasonable to apply at low energies an effective theory approach (Donoghue).
- Starting point: inside a *window* of scales we are confident to give a reasonable description of the quantum gravitational dynamics, related to Einstein gravity or some modifications of it.

  Tipically, corrections to particle physics dynamics are at energies and momenta such that $\boxed{E_{min} < E \ll M_{pl}}$. Corrections are functions of ratios like E/M_{pl}.
- Being more ambitious, as in taking the Asymptotic Safety paradigm, with gravity pushed to a fundamental QFT, one may also consider corrections to matter interactions beyond the Planck scale. In such a case both the gravitational and non gravitational quantum corrections become important in addressing the nature of the non trivial UV fixed point structure.
- The corrections are typically encoded in the running of couplings or anomalous dimensions. For a dimensionless coupling g involving massless fields the simpler correction to its beta function is expected to be of the form $\Delta\beta_g \sim a\, g \frac{E^2}{M_{pl}^2}$, since gravitons couple to momentum (generating the energy-momentum tensor current) with coupling $\frac{1}{M_{pl}}$.

Some calculations: contributions present or absent

- Griguolo, Percacci - The Beta functions of a scalar theory coupled to gravity, PRD52,5787-5798 (1995).
- Percacci, Perini - Asymptotic safety of gravity coupled to matter, PRD68, 044018 (2003).
- Robinson, Wiczek - Gravitational Correction to Running of Gauge Couplings, PRL96, 231601 (2006).
- Pietrykowski - Gauge Dependence of Gravitational Correction to Running of Gauge Couplings, PRL98,061801(2007).
- Toms - Quantum gravity and charge renormalization, PRD76, 045015 (2007).
- Ebert, Plefka, Rodigast - Absence of gravitational contributions to the running Yang-Mills coupling, PLB660.579-582 (2008).
- Tang, Wu - Gravitational Contributions to the Running of Gauge Couplings, arXiv:0807.0331 [hep-th].
- Toms - Cosmological constant and quantum gravitational corrections to the running fine structure constant, PRL101,131301(2008).
- Zanusso, Zambelli, Vacca , Percacci - Gravitational corrections to Yukawa systems, arXiv:0904.0938 [hep-th].
- Rodigast, Shuster - Gravitational Corrections to Yukawa and phi^4 Interactions, arXiv:0908.2422 [hep-th].
- Mackay, Toms - Quantum gravity and scalar fields, arXiv:0910.1703 [hep-th].
- Daum, Harst, Reuter - Running Gauge Coupling in Asymptotically Safe Quantum Gravity, arXiv:0910.4938 [hep-th].

Differences in the approaches

Let's try to cut this ensemble in slices from different points of view...

- Background field (BF) method (7.5+2.5) or traditional perturbative QFT (pQFT) method (1+2)
  One blue paper uses both BF and pQFT approaches.
- All calculations are offshell: with gauge fixing dependence (6+3) or independence (Vilkowisky-DeWitt,VDW) (1.5+1.5)
- Regularization and renormalization: Wilsonian-like (FRGE) approach (with an IR cutoff (C) preserving the degree of divergence but with some scheme and gauge fixing dependence) (4+0)
  or approaches which regularizes the infinities in one loop integrals using
  - dimensional regularization (DR)(degree of divergence lost) (1.5+3.5)
  - simple UV cutoff (C) (1+2)
  - loop regularized UV cutoff (LRC) (claimed compatible with gauge invariance) (1+0)
    One red paper uses both DR and SC regularizations.

A table

	YM (gauge)	Scalar	Scalar-Fermion
FRGE,C,BF	DHR	GP, PP	ZZVP
VDW,DR,BF	T, T†	MT*	
BF QFT, C	P , RW		
PQFT,DR	EPR		RS
PQFT,C	EPR		
PQFT,LRC	TW		
BF,LRC	TW		

† Gravitational corrections present only for a non zero cosmological constant!

* For a ϕ^4 scalar theory only the running mass is studied.

Gauge coupling:BF

The background field method implemented by Robinson and Wiczek and by Pietrykowski.

- Action

$$S = -\int d^4x\sqrt{-g}\Big[\frac{1}{\kappa^2}R(g) + \frac{1}{4g_{YM}^2}g^{\alpha\mu}g^{\beta\nu}F^c_{\alpha\beta}F^c_{\mu\nu}\Big]\quad,\quad \kappa = \sqrt{16\pi G}$$

- background decomposition: $g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$, $A^c_\mu = \bar{A}^c_\mu + a^c_\mu$
  (commonly employed flat space background $\bar{g}_{\mu\nu} = \delta_{\mu\nu}$ is generically offshell)
- gauge transformations:
  - diffeomorphism: $\delta_D(\xi)g_{\mu\nu} = \mathcal{L}_\xi g_{\mu\nu}$, $\delta_D(\xi)A^c_\mu = \mathcal{L}_\xi A^c_\mu$
  - local SU(N): $\delta_{YM}(\alpha)g_{\mu\nu} = 0$, $\delta_{YM}(\alpha)A^c_\mu = -\partial_\mu\alpha^c + f^{cab}\alpha^b A^c_\mu$
- Then one gives the definition of background gauge transformations and true gauge transformations
- and finally provides the gauge fixing of the true gauge transformations of the quantum fluctuations:

$$L_{GF} = \frac{1}{2\alpha}\delta^{\mu\nu}C_\mu C_\nu + \frac{1}{2\rho}(\bar{D}^\mu a^c_\mu)^2,\quad C_\mu(h,a) = (\delta^\beta_\mu\partial^\alpha - \frac{1}{2}\delta^{\alpha\beta}\partial_\mu)h_{\alpha\beta} - \zeta\frac{\kappa^2}{g_{YM}^2}\bar{F}^{c\mu\nu}a^c_\nu$$

Robinson,Wiczek: $(\alpha = 1, \zeta)$ find effects for any $\zeta \neq 0$, depending on ζ. Original paper for $\zeta = 1$. Pietrykowski: $(\alpha, \zeta = 0)$, no effects and result independent of α.

Gauge coupling:BF

- Using Fadeev-Popov method, also ghost terms are added. At one loop the diffeomorphim ghosts are not contributing.
- One loop contribution to the effective action is given by
  $\Delta S_{eff} = \frac{1}{2} Tr \log[S^{(2)}_{tot}]$, $\quad S_{tot} = S + S_{GF} + S_{gh}$
  where $S^{(2)}_{tot}$ is the second functional derivative obtained by an expansion in quantum fluctuations up to second order.
- The beta function of g_{YM} is obtained extracting the coefficient of $\bar{F}^{c}_{\mu\nu}\bar{F}^{c\mu\nu}$
- The computation of the trace requires a regularization.
  Here an UV cutoff Λ is introduced.
- For $\zeta = 1$ RW find $\beta(g, E) = -\frac{b_0}{(4\pi)^2} g^3 - 3g\frac{\kappa^2 E^2}{(4\pi)^2}$
  Comments: This result depends on the gauge fixing choice (since obtained for an offshell effective action) and may also depend on the cutoff regularization.

Gauge coupling:VDW

To cure off-shellness Toms uses a reparametrization invariant, gauge invariant and gauge fixing independent approach: the Vilkowisky-DeWitt off-shell effective action.
The main idea is to consider the space of fields as a manifold M and φ_i (in DeWitt condensed notation) as local coordinates.
The effective action is constructed to be a scalar under field reparameterizations.
A metric g and connection Γ on M are introduced.

- Gauge transformations (G): $\delta\varphi^i = K^i_\alpha[\varphi]\delta\epsilon^\alpha$. In this framework a change of gauge is a change of reparameterizations in the space of group orbits $\mathcal{M} = M/G$.
- Using the background field decomposition: $\varphi^i = \bar{\varphi}_i + \eta^i$
  a Landau-DeWitt gauge fixing is chosen. This leads to simpler Christoffel connection and the final result does not depend on this choice.
  $\chi_\alpha[\bar{\varphi}_i, \eta_i] = K_{\alpha i}[\bar{\varphi}]\eta^i = 0$
- The invariant off-shell effective action is defined by:

$$\Gamma[\bar{\varphi}] = S[\bar{\varphi}] + \frac{1}{2}\lim_{\rho\to 0}\log\det\left(\nabla^i\nabla_j S[\bar{\varphi}] + \frac{1}{2\rho}K^i_\alpha[\bar{\varphi}]K^\alpha_i[\bar{\varphi}]\right) - \log\det Q_{\alpha\beta}[\bar{\varphi}]$$

  with the reparameterization covariant laplacian $\nabla^i\nabla_j S[\bar{\varphi}] = S_{,ij}[\bar{\varphi}] - \Gamma^k_{ij}[\bar{\varphi}]S_{,k}[\bar{\varphi}]$
  and ghost related term $Q_{\alpha\beta}[\bar{\varphi}] = \frac{\delta\chi_\alpha}{\delta\epsilon^\beta}$

Computing the traces Toms employs Dimensional Regularization. Corrections in the beta functions appear only for a non zero Cosmological constant.

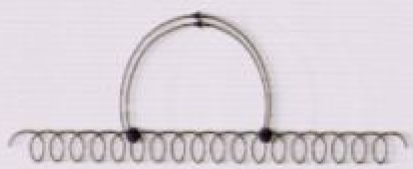
Comment: DR is not preserving the nature of quadratic divergences.

Gauge coupling: pQFT

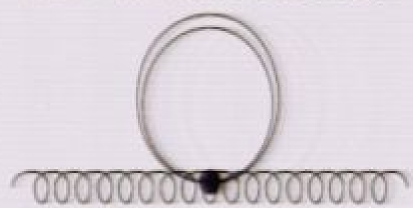
Ebert, Plefka, Rodigast compute the corrections to 2 and 3 point functions using standard Feynman diagram techniques.

- They start from the action on a flat background and rederive the expression for the graviton propagator and for all the necessary vertices involving graviton and gauge fields (in feynman gauge for gluons and harmonic (De donder) gauge for gravitons)
- Let us consider here just the gauge field 2-point function (It is enough for U(1)). They obtain two contributions:

$$(a) = \frac{i}{16\pi^2}\kappa^2(q^2\eta^{\mu\nu} - q^\mu q^\nu)\,\delta^{ab}\Big[-\frac{3}{2}\begin{Bmatrix}\Lambda^2\\ 0\end{Bmatrix} - \frac{q^2}{6}\begin{Bmatrix}\log\Lambda^2\\ \frac{2}{\epsilon}\end{Bmatrix} + \text{finite}\Big]\,,$$



$$(b) = \frac{i}{16\pi^2}\kappa^2(q^2\eta^{\mu\nu} - q^\mu q^\nu)\,\delta^{ab}\,\frac{3}{2}\begin{Bmatrix}\Lambda^2\\ 0\end{Bmatrix}$$



The column vectors indicate contributions for regularization with cutoff (C) or dimensional regularization (DR).

- DR: In each diagram separately no contributions to YM beta function.
  C: There is a cancellations among the two diagrams.

Comment: Some concern about the regularization, not compatible with gauge invariance. Again dependence on gauge fixing.

Gauge coupling: modified cutoff regularization

Tang and Wu compute the same corrections to 2 and 3 point functions using standard Feynman diagram techniques, as well as the background field method, but employing a different regularization based on cutoff (loop regularization).

- The regularization is based in the introduction of Irreducible loop integrals, tipically divergent, and to introduce a cutoff regularization which, it is claimed, is compatible with gauge invariance and at the same time able to maintain the divergent behavior of the original integral. For each integral they provide precise expressions.
- Essentially, defining

$$I_{-2\alpha}(M^2) = \int d^4k \frac{1}{(k^2 - M^2)^{2+\alpha}} \quad I_{-2\alpha\,\mu\nu}(M^2) = \int d^4k \frac{k_\mu k_\nu}{(k^2 - M^2)^{3+\alpha}}$$

  they are able to obtain within the regularization precise expressions such that $I_{0\,\mu\nu} = \frac{1}{4} g_{\mu\nu} I_0$ and $I_{2\,\mu\nu} = \frac{1}{2} g_{\mu\nu} I_2$
- These expressions are used to compute the gravitational corrections to the YM beta function.
  They find a non zero contribution!

Comment: This regularization should be better understood. Again dependence on gauge fixing.

Gauge coupling: Wilsonian approach

Lastly, in a work appeared few days ago, Daum, Harst and Reuter, give a new contribution to the list, in favour of the reality of the effect. They employ a Wilsonian approach to renormalization using some truncated functional renormalization group equation (FRGE) and the background field method to preserve gauge invariance.

- Starting point is the path integral for the generating functional $\mathcal{Z}$ which include gauge fixing, ghosts and source terms.
- Since the generators of *Diff* and $SU(N)_{loc}$ do not commute, a deformation of *Diff* is proposed which do not mix with the $SU(N)$ gauge transformations.
- The crucial point is the introduction of an IR cutoff term ΔS_k quadratic in the quantum fluctuations with kernel $R_k(\Delta)$ which depends on some generalized background covariant laplacian. It suppress the contribution of the infrared modes (below the k scale) in the path integral. A modified Legendre transform of $\log \mathcal{Z}_k$ w.r.t. the sources leads to the effective average action Γ_k, which depends on both the background fields and on the classical fields.
- It satisfies the RG equation $k\partial_k \Gamma_k = \frac{1}{2}\mathrm{STr}\left[\left(\Gamma_k^{(2)} + R_k(\Delta)\right)^{-1} k\partial_k R_k(\Delta)\right]$
- The computation of the trace in this approach leads always to perfectly UV finite quantities thanks to the properties of the operator $k\partial_k R_k$.
- After choosing a truncation of Γ_k the computation reveals the presence of gravitational contribution to the YM beta function.

Comment: The cutoff regularization is keeping quadratic divergencies. Results gauge fixing and scheme (cutoff choice) dependent. Possible truncation dependence?

Yukawa systems: wilsonian approach

Let us consider the following form of the euclidean effective action for a Yukawa system interacting with Einstein-Hilbert gravity:

$$\Gamma_k[g_{\mu\nu}, \phi, \psi, \bar{\psi}] = \int d^4x (L_0 + L_{1/2} + L_g + L_{GF} + L_{gh})$$

- scalar field with potential $V(\phi)$

$$L_0 = \sqrt{g}(\frac{1}{2} Z_\phi \nabla^\mu \phi \nabla_\mu \phi + V(\phi))$$

- N_f fermion fields interacting with the scalar via $H(\phi) = y\phi$ $(U(N_f)$ symmetric $)$

$$L_{1/2} = \sqrt{g} \left[\frac{Z_\psi}{2} \left(\bar{\psi}\gamma^\mu i D_\mu \psi - i D_\mu \bar{\psi}\gamma^\mu \psi \right) + i H(\phi) \bar{\psi}\psi \right] .$$

Starting from local inertial reference frames the vierbein fields e^a_μ are introduced so that $D_\mu = \partial_\mu + \frac{1}{2}\omega_{\mu cd} J^{cd}$ is the covariant derivative, $\omega_{\mu cd} = e^\nu{}_c \left(e_{\nu d,\mu} - \Gamma^\rho{}_{\mu\nu} e_{\rho d} \right)$ is the metric compatible $(e_{\beta b;\mu} = 0)$ spin connection and $J^{cd} = \frac{1}{4}[\gamma^c, \gamma^d]$ are the $O(4)$ generators.

- Einstein-Hilbert gravity

$$L_g = -Z\sqrt{g} R[g_{\mu\nu}] \quad , \quad Z = \frac{1}{16\pi G}$$

Quantization

Quantization is performed using the background field method

The analysis is restricted to flat space and we keep frozen corrections to gravitational dynamics.

Backgrounds $\bar{g}_{\mu\nu} = \delta_{\mu\nu}$, ϕ and ψ Fluctuations: $h_{\mu\nu}$, φ and χ
for metric, scalar and fermion fields.

- Invariance under reparameterization is fixed with the gauge fixing action term:

$$L_{GF} = \frac{Z}{2\alpha}\delta^{\mu\nu} F_\mu F_\nu \; ; \; F_\mu = (\delta^\beta_\mu \partial^\alpha - \frac{1+\beta}{4}\delta^{\alpha\beta}\partial_\mu) g_{\alpha\beta}$$

- the corresponding ghost term is:

$$L_{gh} = \bar{c}_\mu \left(-\delta^{\mu\nu}\partial^2 + \frac{\beta - 1}{2}\partial^\mu \partial^\nu \right) c_\nu$$

- for fermions the vierbeins contain and extra $O(4)$ gauge symmetry. We employ a symmetric gauge ($e_{a\mu} = e_{\mu a}$) so that vierbein fluctuations can be written in terms of metric fluctuations and no $O(4)$ ghosts are present. (van Nieuwenhuizen, Woodard)

Comments:
due to offshellness there is a gauge fixing depencence.
Question: is there an extra dependence due to the vierbein gauge fixing?
What happens if one is employing a deformation of *Diff* to make it commute with the $O(4)_{loc}$?

RG flow

- We extract RG flow equations from the "potentials" which can be seen as the generating function of the various beta functions.

$$\dot{\Gamma}_k \sim \int d^4x \left(\dot{V}_k + i\dot{H}_k \bar{\psi}\psi + \dot{Z}_\psi \bar{\psi}\gamma^\mu i\partial_\mu \psi + \frac{1}{2}\dot{Z}_\phi \partial^\mu \phi \partial_\mu \phi + \cdots \right)$$

- one can extract the running of the potentials and of the anomalous dimensions performing suitable functional derivatives on the FRGE equation

$$\partial_t \Gamma_k = \frac{1}{2} \mathrm{STr} \left[\left(\frac{\delta^2 \Gamma_k}{\delta\phi\delta\phi} + R_k \right)^{-1} \partial_t R_k \right]$$

and after setting $\phi =$ constant and $\psi = \bar{\psi} = 0$. For the anomalous dimensions it is also necessary to perform some derivatives with rispect to the momenta flowing in the corresponding 2-point functions.

beta function generators

We consider here the case without anomalous dimensions ($Z_\phi = Z_\psi = 1$).
It is convenient to introduce dimensionless quantities: $\tilde{G} = k^2 G$, $\tilde{\phi} = \phi/k$, $v(\tilde{\phi}) = V(k\tilde{\phi})/k^4$ and $h(\tilde{\phi}) = H(k\tilde{\phi})/k$.

- The RG flow for $v_k(\tilde{\phi})$ and $h_k(\tilde{\phi})$ can be computed exactly in G for general gauge fixing parameters α and β. Expanded to first order in G, setting $\beta = 1$, the flow equations are given by:

$$\dot{v} = -4v + \tilde{\phi} v' - \frac{N_f}{8\pi^2\left(1+h^2\right)} + \frac{3+2v''}{32\pi^2(1+v'')} - \tilde{G}\frac{(3-\alpha)v'^2\left(2+v''\right)}{2\pi(1+v'')^2} + \tilde{G}\frac{v(3+2\alpha)}{\pi} + O(\tilde{G}^2)\,.$$

$$\dot{h} = -h + \tilde{\phi} h' - \frac{h''}{32\pi^2(1+v'')^2} + \frac{hh'^2\left(2+h^2+v''\right)}{16\pi^2\left(1+h^2\right)^2(1+v'')^2} + \tilde{G}\frac{(3-\alpha)v'^2}{\pi(1+v'')^3}\left(\frac{1}{2}h''\left(3+v''\right) - \frac{hh'^2\left(4+3h^2+\left(2+h^2\right)v''\right)}{\left(1+h^2\right)^2}\right)$$
$$+\tilde{G}h\frac{27+\alpha\left(26+93h^2+48h^4\right)}{16\pi\left(1+h^2\right)^2} + \tilde{G}h' v'\frac{4\alpha-6-(3-2\alpha)v''+h^2(15-4\alpha)+2h^2(3-\alpha)\left(\left(2+h^2\right)v''+2h^2\right)}{2\pi\left(1+h^2\right)^2(1+v'')^2} + O(\tilde{G}^2)$$

$v' = v_{\tilde{\phi}}$ is the partial derivative w.r.t. the scalar field, and so on...

- One may consider a Z_2 symmetric potential for the scalar field.
- Extraction of the beta functions: there are two possible expansions, not equivalent for a broken phase, for the scalar field ϕ around 0 (which is the VEV in the symmetric phase only) or around the VEV $\langle\tilde{\phi}\rangle = \sqrt{\kappa} = \text{VEV}$.

- For example, considering the potentials $v(\tilde{\phi}) = \lambda_0 + \lambda_2\tilde{\phi}^2 + \lambda_4\tilde{\phi}^4$ and $h(\tilde{\phi}) = y\tilde{\phi}$ using the flow exact in G but setting on the r.h.s. $\lambda_0 = 0$ we get

$$
\begin{aligned}
\dot{\lambda}_0 &= -4\lambda_0 + \frac{3+4\lambda_2}{32\pi^2(1+2\lambda_2)} - \frac{N_f}{8\pi^2}, \\
\dot{\lambda}_2 &= -2\lambda_2 + \frac{N_f y^2}{8\pi^2} - \frac{3\lambda_4}{8\pi^2(1+2\lambda_2)^2} + \frac{3\tilde{G}\lambda_2}{\pi(1+2\lambda_2)^2} + 2\alpha\tilde{G}\lambda_2\frac{1+6\lambda_2(1+\lambda_2)}{\pi(1+2\lambda_2)^2}, \\
\dot{\lambda}_4 &= \frac{9\lambda_4^2}{2\pi^2(1+2\lambda_2)^3} - \frac{N_f y^4}{8\pi^2} + 3\tilde{G}\lambda_4\frac{1-10\lambda_2+36\lambda_2^2+24\lambda_2^3}{\pi(1+2\lambda_2)^3} + 2\alpha\tilde{G}\lambda_4\frac{1+14\lambda_2}{\pi(1+2\lambda_2)^3} + O(\tilde{G}^2), \\
\dot{y} &= \frac{y^3(1+\lambda_2)}{8\pi^2(1+2\lambda_2)^2} + \tilde{G}y\frac{9+12\lambda_2(1+\lambda_2)}{8\pi(1+2\lambda_2)^2} + \alpha\tilde{G}y\frac{13+84\lambda_2(1+\lambda_2)}{8\pi(1+2\lambda_2)^2}
\end{aligned}
$$

  where only λ_4 has also G^2 corrections.
- From the above results gravitational corrections are of order k^2/M_{Pl}^2 and beyond the Planck scale they may grow. In any case the gaussian fixed point $(\lambda_2, \lambda_4, y) = (0, 0, 0)$ is meaningful. Gravitational corrections make λ_4 and y relevant (eigenvalues are $(3+2\alpha)\tilde{G}/\pi$ and $(9+13\alpha)\tilde{G}/8\pi$, positive for any gauge parameter α.
- Gauge dependence of the results is due to offshellness of the calculation (in flat space).

Expansion around the VEV

- For a broken phase, as an improved approach, one can expand around the VEV. We analyze this possibility expanding the "potentials" v and h around $\tilde{\phi} = \sqrt{\kappa}$ such that $v'(\sqrt{\kappa}) = 0$.
- Let us start by looking for the flow of the VEV itself. Differentiating $v'(\sqrt{\kappa}) = 0$ one immediately gets
$$\dot{\kappa} = -2\sqrt{\kappa}\,\dot{v}'(\sqrt{\kappa})/v''(\sqrt{\kappa})$$
- Therefore, for a generic potential v, and keeping the full dependence in G of the RG flow equation, one finds

$$\dot{\kappa} = -2\kappa + \frac{\sqrt{\kappa}v'''}{16\pi^2 v''(1+v'')^2} - \frac{hh' N_f \sqrt{\kappa}}{2\left(1+h^2\right)^2 \pi^2 v''}\Bigg|_{\tilde{\phi}=\sqrt{\kappa}}$$

Remarkably, with this prescription,
the beta function of κ does not receive any gravitational correction!
(This is obviously true also in the symmetric phase).

Recently it appeared a perturbative calculation by Rodigast and Schuster, which compute perturbative one loop corrections in the harmonic gauge using dimensional regularization. They find gravitational correction to the Yukawa coupling and scalar self-coupling only proportional to the masses. This result is anyway in contradiction also with a very recent result of Toms for scalar fieds obtained withing the VDW approach.

Last remarks

- Essentially all disagreements encountered are tipically associated to the treatment of the quadratic divergences. One can see again that is seems that they are not considered also in earlier works, for example in the one loop analysis of higher derivative modified gravity together with matter (Fradkin, Tseytlin) (Buchbinder, Odintsov, Shapiro).
- Apart from the VDW approach, all offshell calculations are affected by gauge depencence. Anyway any computation of physical observables should lead to quantities perfectly well defined with such a dependence cancelled.
- It would be interesting to have a wilsonian approach defining a scale dependent offshell effective action, which is reparameterization invariant and then free of gauge dependences. There is a obstacle: tipically a cutoff is physically motivated, i.e. associated to some kind of physically relevant set of field coordinates for a certain range of scales. Then a coarse graining procedure is clearly not invariant under general field reparameterization.