RTG 2522 Project 5

Asymptotically safe QED

Jobst Ziebell, Holger Gies
Theoretisch-Physikalisches-Institut, Friedrich-Schiller-Universität Jena

FRIEDRICH-SCHILLER-UNIVERSITÄT JENA

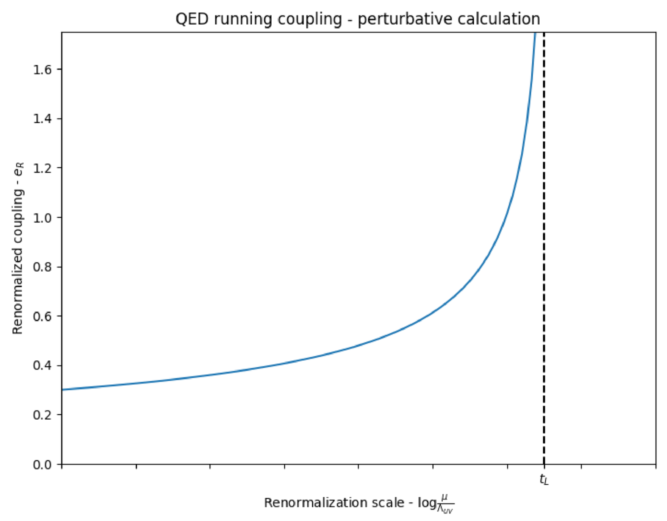
UNIVERSITÄT LEIPZIG

1. Motivation

- Can QED be realized as a fundamental theory?
- QED suffers from a perturbative Landau pole *(Landau'54)*
- So far, non-perturbative studies have confirmed UV incompleteness *(Gockeler et al '98, Gies and Jaeckel '05)*
- Generic issue of gauge theories with $U(1)$ factor eg. the SM
- Recent EFT study shows that a Pauli spin coupling term can screen the Landau pole *(Djukanovic et al'18)*
- Does a nonperturbative treatment of a Pauli term lead to an asymptotically safe theory?

2. Perturbative QED

Perturbative RG evolution of running coupling diverges at finite RG scale t_L *(Landau'54)*

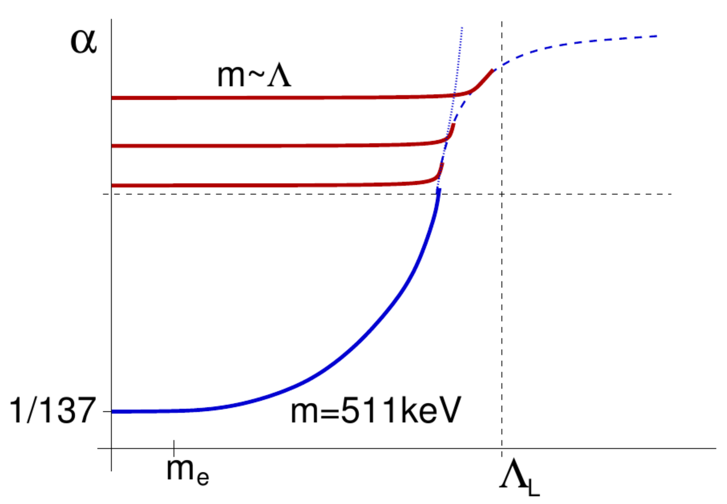


- Existence of Landau pole suggests non-fundamentality of QED
- Exploration of parameter regime $e \gg 1$ requires non-perturbative techniques

3. Chiral symmetry breaking prevents strong coupling completion

Assuming the presence of a UV fixed point beyond the Landau pole as well as no explicit chirality-breaking terms:

- large values of e lead to dynamical chiral symmetry breaking
- dynamical chiral symmetry breaking leads to heavy fermions for large values of e *(Miransky'85)*



- QED with large values of e cannot be connected to perturbative QED *(Gockeler et al '98, Gies and Jaeckel '05)*

4. Strategy

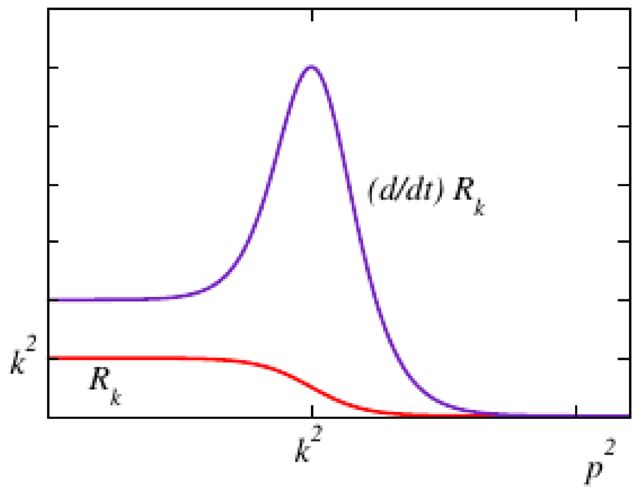
- Include relevant, marginal parameters as well as irrelevant Pauli term $i\kappa\bar{\psi}\sigma_{\mu\nu}F^{\mu\nu}\psi$
  - $\Leftarrow$ unique $U(1)$ invariant dimension 5 operator
  - $\Rightarrow$ chiral symmetry broken
  - $\Rightarrow$ include a mass term beyond the deep Euclidean region
- Use the truncation

$$\Gamma_k = \bar{\psi}\left(i\partial\!\!\!/ - i\bar{m} + i\bar{\kappa}\sigma_{\mu\nu}F^{\mu\nu} + \bar{e}\gamma_\mu A^\mu\right)\psi$$

- Search for UV fixed points of dimensionless quantities e, κ and m
- Try to connect them to physical IR parameters

5. The exact (nonperturbative) renormalization group flow

- Employ cutoff function R_k to suppress fluctuations with high momentum modes $p^2 \gg k^2$.
- Obtain the Wetterich equation for the *effective average action* Γ_k *(Wetterich'93)*



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

- $\lim_{k\to 0} R_k = 0$ and $\Gamma = \Gamma_0$
- Expansion in operator dimensions result in (regulator-dependent) beta functions of the model parameters.

6. A modified QED

The beta functions of e, κ, m in the Landau gauge and with the Litim regulator read

$$\partial_t e = \frac{-1+7m^2+3m^4}{10\left(1+m^2\right)^3\pi^2}e\kappa^2 + \frac{5+9m^2}{10\left(1+m^2\right)^3\pi^2}e^2\kappa m + \frac{8+47m^2+56m^4+21m^6}{96\left(1+m^2\right)^4\pi^2}e^3 + \dots$$

$$\partial_t\kappa = \kappa + \frac{1-m^2}{96\left(1+m^2\right)^3\pi^2}me^3 + \frac{8+11m^2+5m^4+3m^6}{24\left(1+m^2\right)^4\pi^2}e^2\kappa + \frac{-20+11m^2}{20\left(1+m^2\right)^3\pi^2}e\kappa^2 m + \frac{\left(3+m^2\right)\left(-3+7m^2\right)}{15\left(1+m^2\right)^3\pi^2}\kappa^3 + \dots$$

$$\partial_t m = -m + \frac{2+4m^2}{5\left(1+m^2\right)^2\pi^2}\kappa^2 m + \frac{9\left(-2+m^2\right)}{20\left(1+m^2\right)^2\pi^2}e\kappa - \frac{6+m^2}{16\left(1+m^2\right)^2\pi^2}e^2 m + \dots$$

where … represent NLO terms.
For $\kappa = 0$, we recover the perturbative result for the QED beta function

$$\partial_t e = \frac{e^3}{12\pi^2}$$

in the deep euclidean limit.

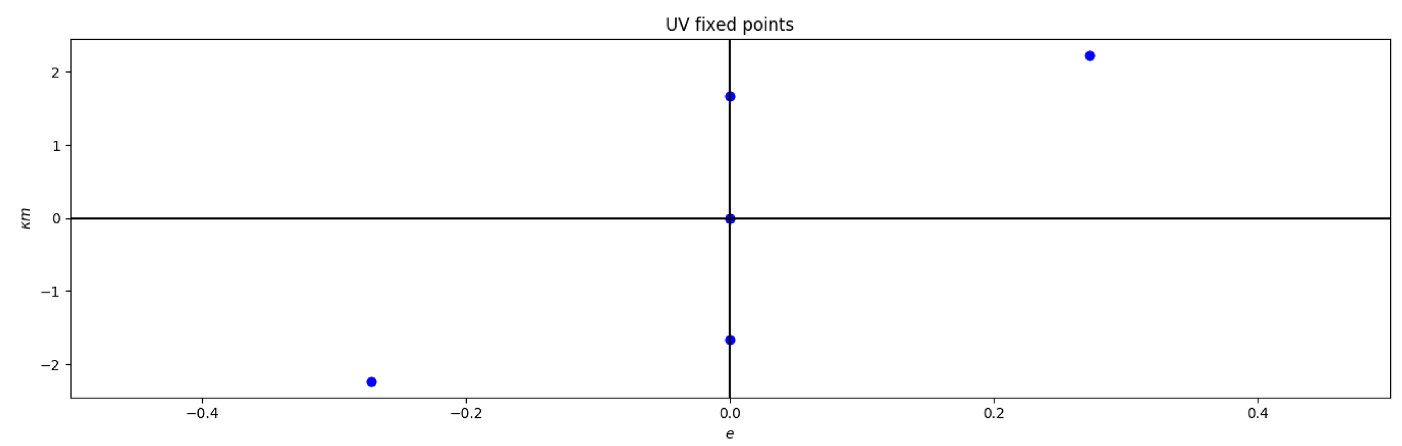
7. The UV fixed points

Including the NLO terms, we find several sets of UV fixed points with different dicrete symmetries

e	κ	m	symmetry group	n_{phys}	$\theta_{\max}$
0.272	5.72	0.390	$\mathbb{Z}_2\times\mathbb{Z}_2$	1	3.33
0	5.09	0.328	$\mathbb{Z}_2\times\mathbb{Z}_2$	2	3.10
15.6	0	0	$\mathbb{Z}_2$	2	13.7
0	3.82	0	$\mathbb{Z}_2$	3	2.25
0	0	0	–	1	1.00

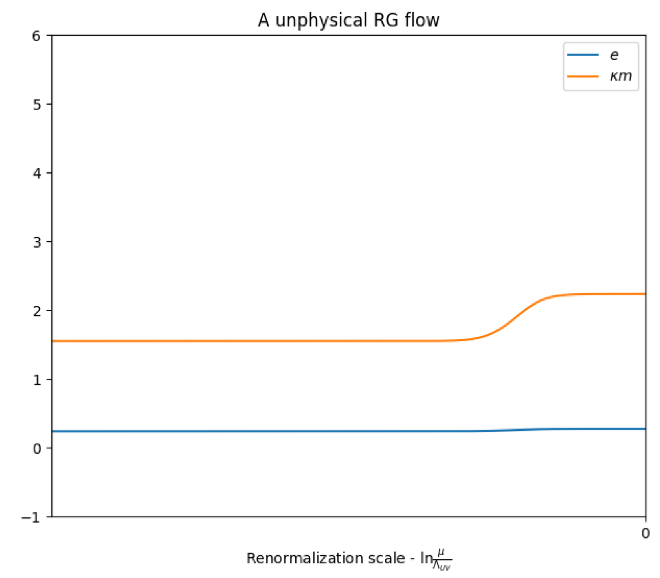
where n_{phys} and $\theta_{\max}$ denote the number of physical parameters and the largest critical exponent respectively.

- Dismiss $(e,\kappa,m) \approx (\pm 15.6, 0, 0)$ due to very large anomalous dimensions



8. A maximally predictive trajectory

The fixed point $(e,\kappa,m) = (0.272, 5.72, 0.390)$ has a uniquely determined IR trajectory.



- Only one relevant parameter (mostly κ)
- Only one direction with acceptable anomalous dimensions (mostly $-\kappa$)

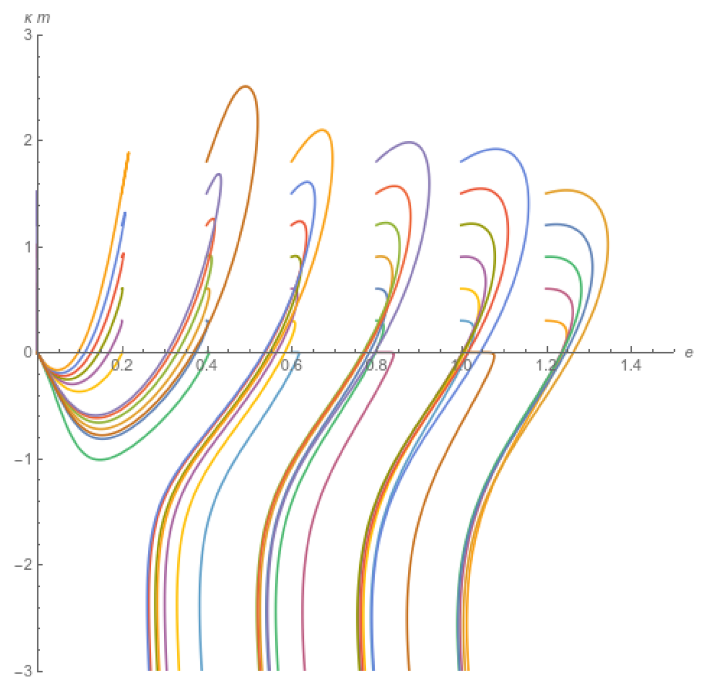
- a close-to-physical value for $\bar{e}$
- asymptotic safety (in the given truncation)
- LO and NLO qualitatively the same
- IR is fully interacting $\bar{\kappa}, \bar{e}, \bar{m} \neq 0$
- $\implies$ large anomalous magnetic moment
- $\implies$ unphysical

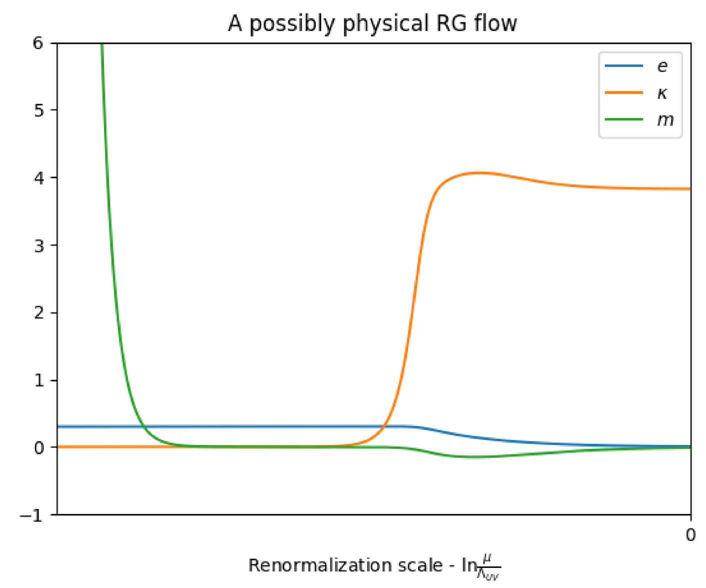
9. A possibly physical RG flow

We find an RG flow connecting $(\bar{e},\bar{\kappa}) = (0.303, 0)$ in the IR with

$$(e,\kappa,m) \approx (0, 3.82, 0)$$

in the UV.





- a physical value $\bar{e}$ corresponding to $\alpha = \frac{1}{137}$
- asymptotic safety (in the given truncation)
- LO and NLO qualitatively the same
- fine-tuned κ at intermediate scale ensures $\kappa m = 0$ in the IR
- upper bound for value of e above which fixed point is missed

10. Conclusion and outlook

- Evidence for asymptotic safety of QED!
- Fixed points feature UV completion within and beyond deep Euclidean region
- Different fixed points corresponding to different universality classes
- Qualitative behaviour of fixed points is the same in LO and NLO
- Are there other physical RG flows?
- Can an asymptotically safe flow be embedded into the SM?

E-mail: jobst.ziebell@uni-jena.de