Mass Generation without a Higgs

Strongly Coupled Systems.

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Outline

The Higgs Mechanism.

Putting Mass back into the Lagrangian.

- Consequence of EW interactions: explicit fermion mass terms break GI.
- The particles corresponding to these fields indeed have mass - introduce this without breaking GI.
- Employ the Higgs to give these mass through spontaneous symmetry breaking.
- Other mechanisms (technicolour, little higgs, $t\bar{t}$ condensate etc) have been proposed to achieve similar effects. Not without their own problems.
- While a necessary part of the theory, doesn't answer all questions regarding particle masses - notably the connection between the quark picture and the hadrons we observe.

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Quantum Chromodynamics.

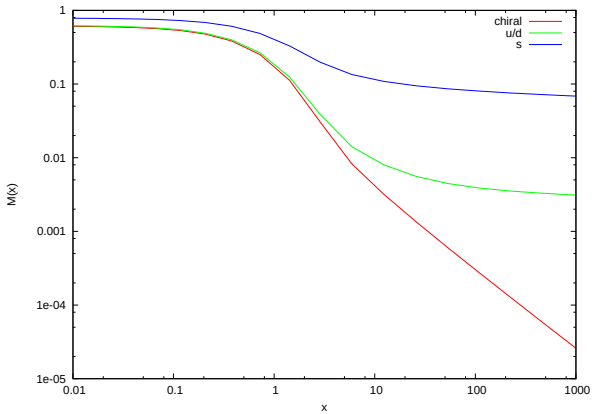
- Quarks and Gluons Described by QCD with small number of basic interactions.
- Hadrons much more difficult to describe, yet arise from the same theory.
- (p, n), $(\pi^{\pm}, \pi^0)$ have same strong interactions and similar masses. Isospin symmetry.
- From this $m_p \sim m_n$ so expect $m_u \sim m_d$ - QCD indeed has approximate SU(2) symmetry.

Current and Constituent Masses

For QCD with two flavours $\psi = \begin{pmatrix} u \\ d \end{pmatrix}$, $M = \begin{pmatrix} m_u \\ m_d \end{pmatrix}$:

$$\mathcal{L} = \bar{\psi}\left(i\gamma^\mu D_\mu - M\right)\psi - \frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu}$$

- Mass entering $\mathcal{L}$ the *current* mass, of order *MeV*.
- Compares with constituent mass of order $\sim$ 300 *MeV*.



- Light quark current masses $\ll \Lambda_{QCD} \longrightarrow m_u = m_d = 0$ to good approximation.
- Opens up larger chiral symmetry, which is NOT seen in Hadron world.
  i.e. $\exists$ no simple relation between masses of scalars and pseudoscalars etc.
- Due to complicated nature of the "vacuum".
  QED: Dirac sea of e^+ e^- pairs.
  QCD: $q\bar{q}$ pairs, glue and **condensates**.
- Over short distances quarks travel quickly - asymptotic freedom. Over larger distances move slowly - corresponds to the dynamical generation of mass.

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Dynamical Mass Generation.

Current masses ~ 0 *MeV*, Constituent masses ~ 300 *MeV*.
Experiment indicates non-trivial vacuum.

- Can this be seen from theoretical calculations of QCD?

Perturbation Theory

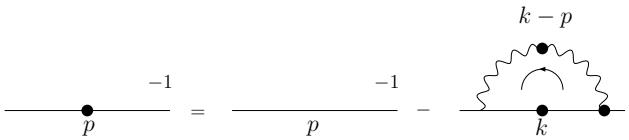
$$\mathcal{M}(p) = m_0 \left(1 + c_1 \alpha_\mu \log\left(p^2/\mu^2\right) + c_2 \alpha_\mu^2 \log^2\left(p^2/\mu^2\right) + \cdots\right)$$

- Cannot attain non-zero dressed mass if bare mass is zero with PT.
- Require non-perturbative methods

Schwinger Dyson Equations

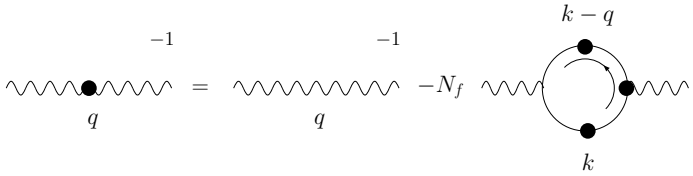
QED in Four Dimensions.

- We can depict the equations diagrammatically.



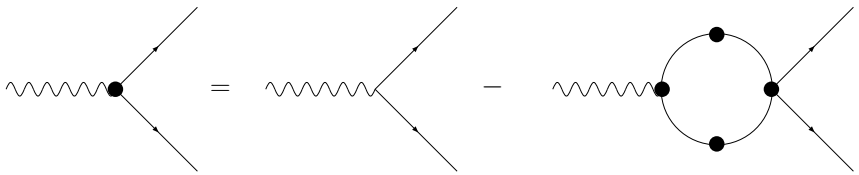
$$\frac{1}{\mathcal{F}} = 1 - \int d\tilde{k}\, Tr\left[\not{p}\gamma^{\mu} S(k)\Gamma^{\nu}\right] D_{\nu\mu}$$

$$\frac{\mathcal{M}}{\mathcal{F}} = m_0 + \int d\tilde{k}\, Tr\left[\gamma^{\mu} S(k)\Gamma^{\nu}\right] D_{\nu\mu}$$



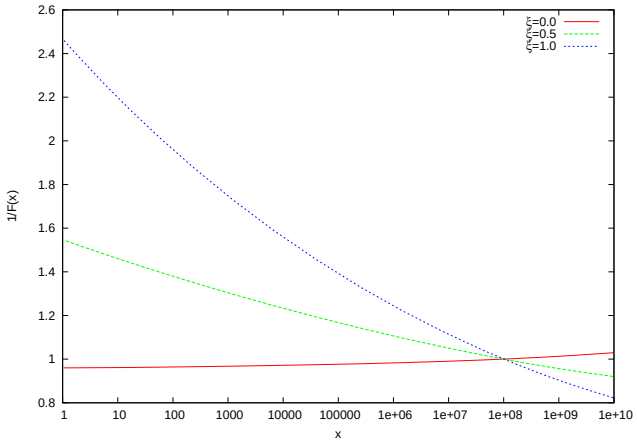
$$\frac{1}{\mathcal{G}} = 1 - \mathcal{P}_{\mu\nu} \int d\tilde{k}\, Tr\left[\gamma^{\mu} S(k)\Gamma^{\nu} S(p)\right]$$

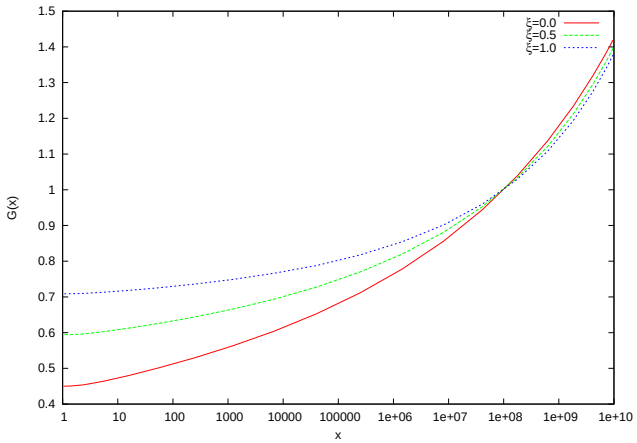
- These in turn depend upon higher order green's functions:



ξ Dependence of Physical Observables.

Rainbow-Vertex





Solutions for a vertex violating GI and MR. Photon wavefunction renormalisation is gauge dependent.

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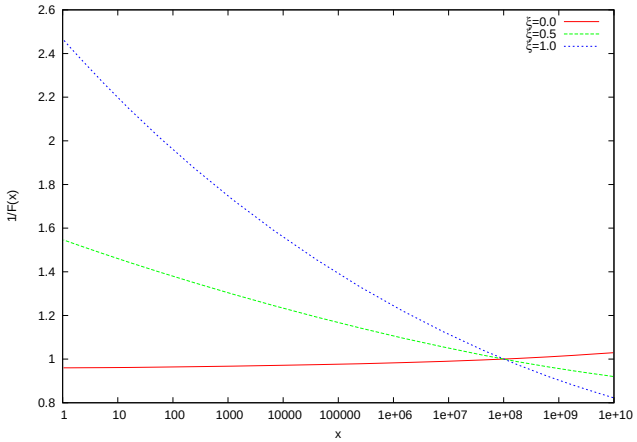
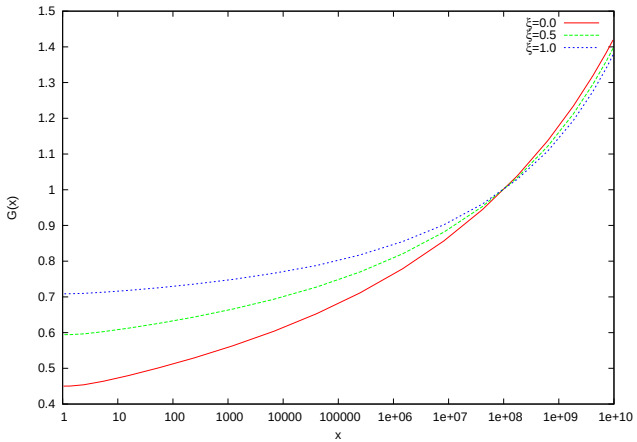
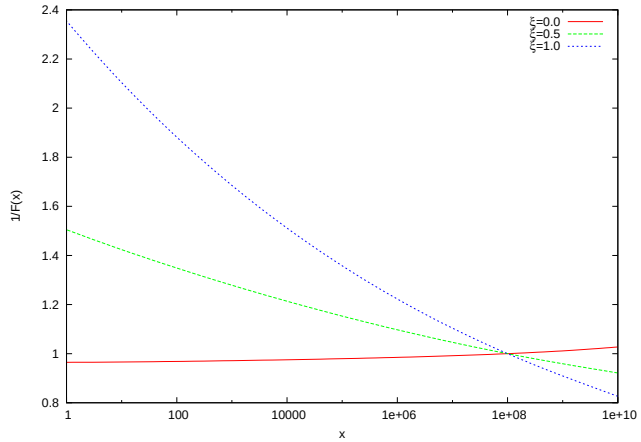
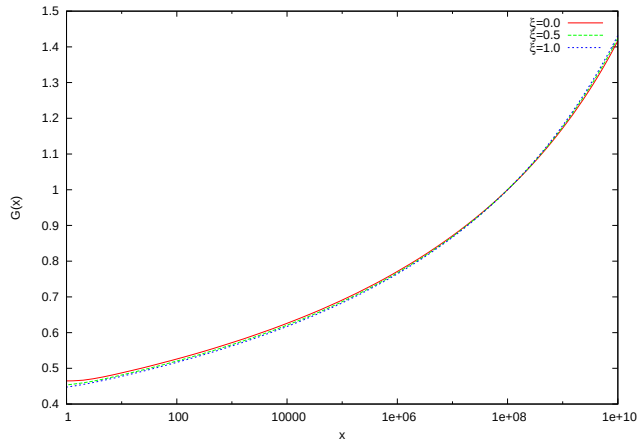




KP-Vertex





Critical couplings and mass generation in QED4.

QED in Three Dimensions.

A Toy Model with Confi nement

- Very different to QED4:
  - Super-renormalisable.
  - Dimensionful coupling - naturally sets scale for dynamics.
  - Exhibits a confi ning phase.
- Thus QED3 is a good toy model to develop NP techniques.
- DMG occurs $\forall$ values e^2. May exist a critical number of flavours above which no DMG occurs.

[Review: Appelquist & Wijewardhana, hep-ph/0403250]

- LKFT applied directly in momentum space - fourier transforms performed analytically. Tool for refining model.

[Bashir, Raya, hep-ph/0511291]

Criticality

- Studies generally conclude DMG $\leftrightarrow \chi$SB if number of four-component fermions $< N_{F,crit}$.
- Theory is UV-complete. $N_{F,crit}$ governed by IR-fixed point.
- $1/N_F$ expansion unreliable due to presence of large logarithms.
- Lattice studies severely hampered by finite-size effects. Cannot determine whether QED is in symmetric or broken phase for given N(=2).
- Determination of this critical value may be useful for condensed matter systems.

Gauge Dependence in unquenched QED3.

Chiral Condensate for QED3 (units $10^{-5}e^4$)
for different N_F and gauges. Computed via hybrid CP/BC vertex.

ξ	$N_f = 0$	$N_f = 1$	$N_f = 2$	$N_f = 3$	$N_f = 4$	$N_f = 5$	$N_f = 6$
0	333	121	13	0.026	??	0	0
0.5	340	165	79	39	23	15	11
1	351	202	108	74	55	37	29
2	356	259	189	143	107	92	77

[Fischer, Alkofer, Dahm, Maris, hep-ph/0407104]

- Gauge dependence clearly worse for increasing flavours.
- No evidence for critical value except in Landau gauge.
- Clearly gauge transformation inconsistent with LKFT.

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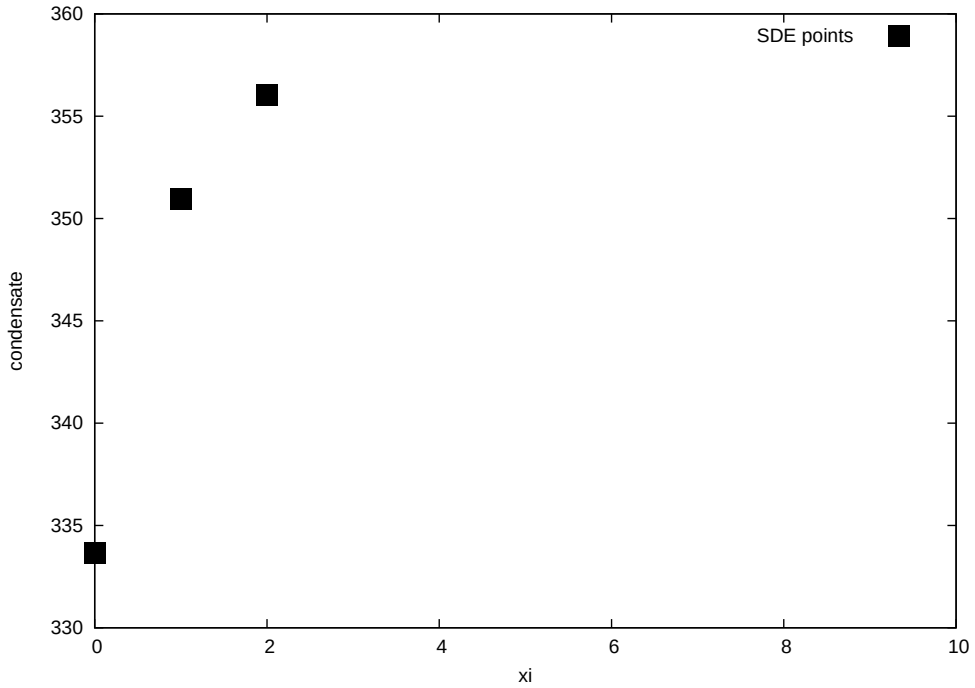
Landau-Khalatnikov-Fradkin Transformation

Application to SDE results.



- SDE solutions show some gauge dependence on condensate.
- LKF transforms condensate consistent with gauge invariance.
- LKF transforms correctly for all SDE solutions.
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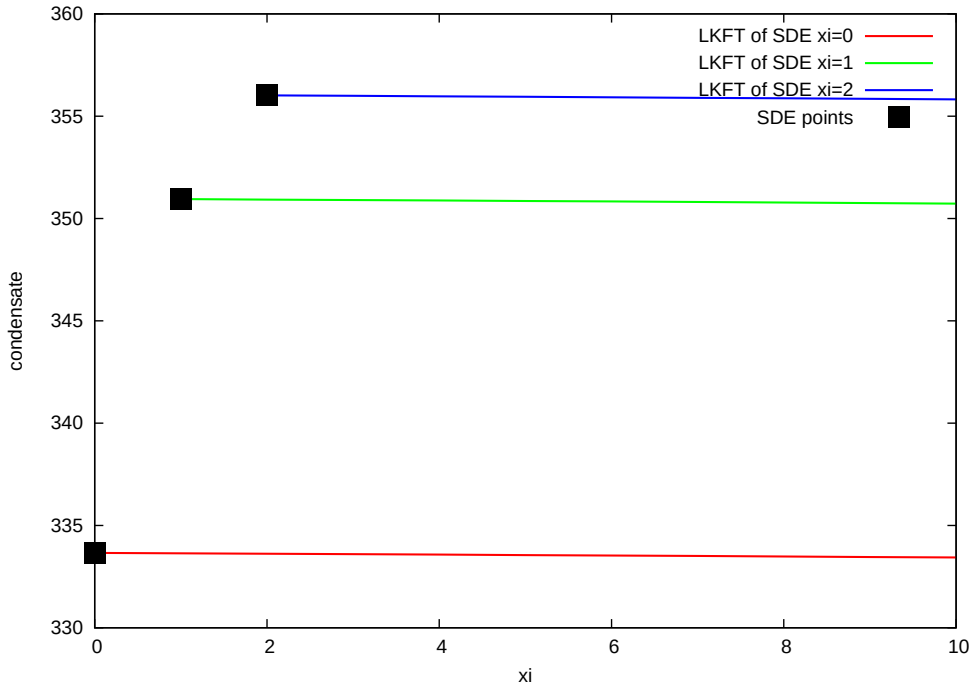

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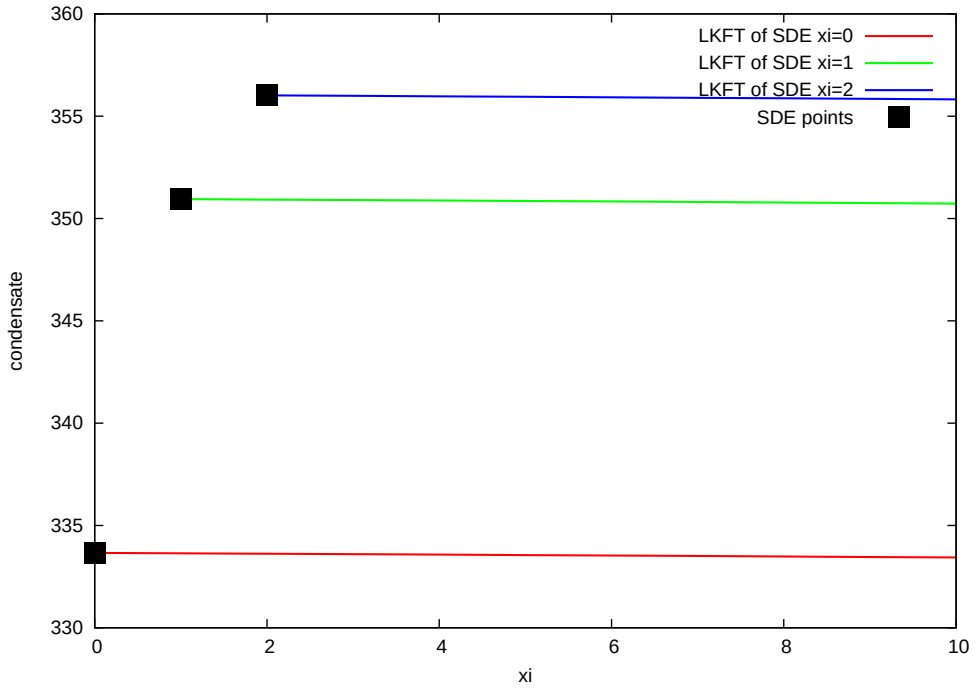

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Summary

- Putting masses in Lagrangian is insufficient. An understanding of dynamical effects is required.
- $D\chi SM$ in QED3 is an IR continuum effect. Lattice is not well suited.
- Ensuring symmetries are not broken by ansatz is key to developing models.

- Outlook
  - Adapt our best QED4 vertex for QED3. Investigate criticality.
  - Apply developments to QCD for the study of bound states.