Eric D'Hoker and Per Kraus are investigating thermodynamic and transport properties of fermions in strongly interacting gauge theories using string theory ideas and techniques. Specifically, Maldacena's gauge/gravity duality maps a strongly coupled Yang-Mills gauge theory in 4 space-time dimensions onto an effective Einstein-Maxwell gravity theory in 5 dimensions. The extra dimension essentially plays the role of a varying length scale. Quantum states in gauge theory are mapped to solutions of the gravity theory. If a gravity solution contains a black hole, then the corresponding gauge theory state is thermal. Its temperature coincides with the Hawking temperature of the black hole. A finite charge density (or equivalently a chemical potential) and/or an external magnetic field may be introduced on both gauge and gravity sides, thereby providing an exciting semi-realistic theoretical laboratory for the study of strongly correlated fermions.

Using a combination of analytical methods and high-precision numerical analysis to study the existence and behavior of gravity solutions with black holes, D'Hoker and Kraus have shown that 4-dimensional gauge theory undergoes a quantum phase transition as the external magnetic field $B$ approaches a critical value $B_c$. Near this quantum critical point, the specific heat coefficient diverges as $1/(B-B_c)$ at zero temperature (signaling the onset of non-Fermi liquid behavior), and a simple universal cubic polynomial governs the scaling in both temperature and magnetic field. The corresponding dynamical scaling exponent is found to be $1/3$. These results, originally inferred from numerical study, were later derived analytically from the existence and regularity properties of new electrically charged magnetic black hole solutions.

Actually, the story is more complicated and also more interesting. In the effective 5-dimensional gravity description, the gauge theory strong coupling dynamics is characterized by a single free dimensionless parameter $k$. In fact, $k$ governs the strength of the chiral anomaly and gives a measure of the number of chiral fermion species in the gauge theory. In ongoing work, it is becoming clear that the strong coupling gauge dynamics exhibits a remarkably rich structure as a function of $k$. For example, the quantum critical point only exists for $k > 1/2$; all supersymmetric gauge theories must have $k^2=4/3$; the dynamical critical exponent takes the value of $1/3$ (described in the preceding paragraph) only when $k > 3/4$; but takes on the continuously varying value $1/k - 1$ when $k < 3/4$; and so on.

These quantum phase transitions involve non-analytic behavior of the specific heat and magnetization as the magnetic field crosses a non-zero value, but no change in symmetry. They are often referred to as \{\textit{meta-magnetic}\} transitions. One physical application is to certain magnetic solid state materials, where the strongly coupled fermions are electrons. Indeed, above the critical magnetic field, the scaling behavior found from string theory is consistent with the predictions of the Hertz/Millis theory applied to meta-magnetic quantum phase transitions, such as have been observed experimentally in compounds like Strontium Ruthenates. Another physical application, which remains to be explored, may be to quark-gluon plasmas, in the presence of external magnetic fields. Here, the strongly coupled fermions are now quarks.

The theoretical particle physics group's research will be the highlight article in this year's annual report. Look for the report in early December 2011.