



improved quantum treatment, which smooths the discussion  
to a more complete picture. I find myself looking  
at the original idea - that of using  $n$  and  $V$  as  
independent variables - with great appreciation, and  
I no longer see special merit in the boundary  
condition  $\phi(y_0) = 0$ , while  $\sqrt{\phi(y_0)} = \frac{1}{3}$  looks more app

## Julian Schwinger Centennial Conference

7-12 February 2018

Held at the Guild House and the Alumni House  
on the campus of the National University of Singapore

### Programme

(updated 31 January 2018)

Jointly organized by  
Julian Schwinger Foundation for Physics Research (JSF)  
Institute of Advanced Studies, Singapore (IAS, NTU)  
Centre for Quantum Technologies (CQT, NUS)

**JSF** Julian Schwinger  
Foundation



Institute of Advanced Studies



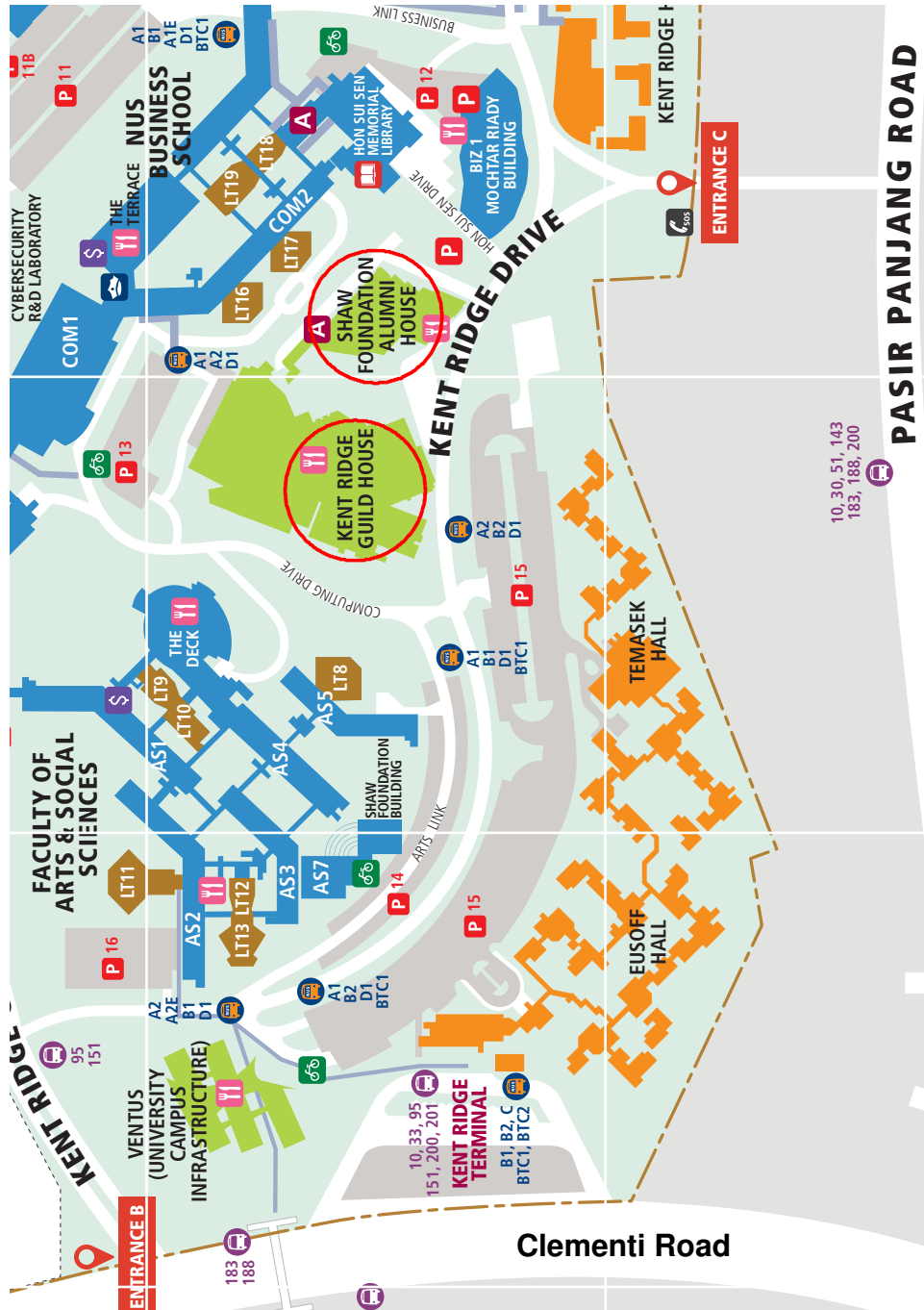
Julian Schwinger (12 February 1918 – 16 July 1994) is best known for his work on the theory of quantum electrodynamics (QED), in particular for developing a relativistically invariant perturbation theory, and for renormalizing QED to one loop order. For his substantial contributions to many areas, he is widely recognized as one of the greatest physicists of the twentieth century. Along with Richard Feynman and Sin-Itiro Tomonaga, he won the 1965 Nobel Prize in Physics for his work on quantum electrodynamics.

Starting as a leader in nuclear physics, the discoverer of tensor forces, Schwinger pioneered powerful variational methods in classical electrodynamics and was the American developer of the theory of synchrotron radiation. He was responsible for much of modern quantum field theory, including a quantum version of the action principle, and the equations for the Green's functions that define the content of such theories. He laid the foundations for non-equilibrium quantum statistical mechanics and for quantum gravity. He developed the first electroweak model, an  $SU(2)$  gauge group spontaneously broken to electromagnetic  $U(1)$  at long distances. He also explored the first example of confinement in the Schwinger model, quantum electrodynamics in 1+1 dimensions. He was responsible for the theory of multiple neutrinos, Schwinger terms, the theory of the spin-3/2 field, and discovered anomalies in quantized fields. He advanced the theory of magnetic charge, monopoles and dyons. As Schwinger contributed to many more areas in classical and quantum physics, the above is just a selection of topics.

## Venues on NUS Kent Ridge Campus

7–9 February  
 Kent Ridge Guild House  
 9 Kent Ridge Drive  
 Singapore 119244

12 February  
 Shaw Foundation Alumni House  
 11 Kent Ridge Drive  
 Singapore 119244



## List of Speakers

Dmitry ABANIN

*University of Geneva*

Stephen ADLER

*Institute of Advanced Studies, Princeton*

Gordon BAYM

*University of Illinois*

Zvi BERN

*Department of Physics and Astronomy, University of California at Los Angeles*

Klaus BLAUM

*Max-Planck-Institut für Kernphysik, Heidelberg*

Iver BREVIK

*Norwegian University of Science and Technology*

Lai Him CHAN

*Louisiana State University, Baton Rouge*

Shau-Jin CHANG

*Emeritus Professor of University of Illinois*

Steven CHRISTENSEN

*Department of Physics and Astronomy, University of North Carolina at Chapel Hill*

Andrzej CZARNECKI

*University of Alberta*

Stanley DESER

*Brandeis University; California Institute of Technology*

Gerald DUNNE

*University of Connecticut*

Berge ENGLERT

*Centre for Quantum Technologies and Department of Physics*

*National University of Singapore*

Robert J. FINKELSTEIN

*Department of Physics and Astronomy, University of California at Los Angeles*

Herbert M. FRIED

*Brown University*

Gerald GABRIELSE

*Leverett Professor of Physics, Harvard University*

*Director of the Center for Fundamental Physics at Northwestern*

Thomas GASENZER  
*University of Heidelberg*

Doron GAZIT  
*Hebrew University of Jerusalem*

Edward GERJUOY  
*Department of Physics and Astronomy, University of Pittsburgh*

Daniel GREENBERGER  
*City College, City University of New York*

Song HE  
*Chinese Academy of Sciences and Perimeter Institute*

Yu-tin HUANG  
*National Taiwan University*

Paul INDELICATO  
*Laboratoire Kastler Brossel (CNRS, ENS, Sorbonne University)*

Margaret KIVELSON  
*Earth, Planetary and Space Sciences, UCLA, Los Angeles*  
*Climate and Atmospheres and Space Physics, University of Michigan, Ann Arbor*

Michael LIEBER  
*University of Arkansas*

Kimball MILTON  
*University of Oklahoma*

Djordje MINIC  
*Virginia Tech*

Krzysztof PACHUCKI  
*Faculty of Physics, University of Warsaw*

Jonathan SAPIRSTEIN  
*University of Notre Dame*

Marlan O. SCULLY  
*Texas A&M University; Princeton University; Baylor University*

Gordon W. SEMENOFF  
*University of British Columbia*

Charles SOMMERFIELD  
*Yale University*

Daniel STERNHEIMER  
*Rikkyo University, Tokyo, and Université de Bourgogne*

Luis F. URRUTIA RIOS

*Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México*

Kris VAN HOUCKE

*Ecole Normale Supérieure de Paris*

Walter WILCOX

*Baylor University*

Tung-Mow YAN

*Cornell University, Ithaca*

York-Peng YAO

*Leinweber Center for Theoretical Physics, University of Michigan, Ann Arbor*

*Kavli Institute for Theoretical Physics, University of California, Santa Barbara*

**Wednesday, 7 February 2018 — First Science Session**  
(Kent Ridge Guild House)

- 9:15am Opening address
- 9:30am Jonathan Sapirstein  
*The g factor of an electron in hydrogenlike carbon  
and the precision determination of the electron mass*
- 10:00am Krzysztof Pachucki  
*Quantum electrodynamics of atomic and molecular systems*
- 10:30am Coffee break
- 11:00am Gerald Gabrielse  
*Greatest Triumph of the Standard Model*
- 11:30am Klaus Blaum  
*Precision tests of QED with stored and cooled highly charged ions*
- 12:00nn Lunch break
- 1:30pm Andrzej Czarnecki  
*Precise Quantum Electrodynamics of Bound States*
- 2:00pm Gerald Dunne  
*The Search for the Schwinger Effect:  
Non-perturbative Pair Production from Vacuum*
- 2:30pm Coffee break
- 3:00pm Lai Him Chan  
*Baryon Isospin Mass Splittings*
- 3:30pm Robert J. Finkelstein  
*Are Dyons the Preons of the Knot Model?*
- 4:00pm Luis F. Urrutia Rios  
*The magneto-electric effect in axion-electrodynamics*
- 4.30pm End of session

## Thursday, 8 February 2018 — Second Science Session

(Kent Ridge Guild House)

- 9:00am Marlan O. Scully  
*Black hole acceleration radiation from quantum optical perspective*
- 9:30am Iver Brevik  
*Remarks on the Abraham-Minkowski problem*
- 10:00am Coffee break
- 10:30am Doron Gazit  
*Plasma microscopic phenomena in extreme conditions:  
New approach to the solar abundance problem*
- 11:00am Walter Wilcox  
*Multiquark States in the Thomas–Fermi Quark Model*
- 11:30am Berge Englert  
*Julian Schwinger and the Semiclassical Atom*
- 12:00nn Lunch break
- 1:30pm Herbert M. Fried  
*Non-Abelian QCD: No longer in the Shadow of Abelian QED*
- 2:00pm York-Peng Yao  
*Some Comments on Solving the Scattering Equations*
- 2:30pm Coffee break
- 3:00pm Daniel Greenberger  
*Schwinger homework problems as the source of research projects*
- 3:30pm Thomas Gasenzer  
*Universal dynamics and non-thermal fixed points*
- 4:00pm Kris Van Houcke  
*Summation of diagrammatic series for a strongly correlated  
fermionic theory with zero convergence radius*
- 4:30pm End of session

## Friday, 9 February 2018 — Third Science Session

(Kent Ridge Guild House)

- 9:00am Gordon Baym  
*With Julian looking over my shoulder through the years:  
From Martin–Schwinger many-particle theory  
to transport theory in strongly interacting systems*
- 9:30am Paul Indelicato  
*The Seven Year Itch: The proton size puzzle 7 years later*
- 10:00am Coffee break
- 10:30am Song He  
*Scattering from Geometries*
- 11:00am Zvi Bern  
*The methodological unification of gravitons and gluons*
- 11:30am Yu-tin Huang  
*Geometric unification of symmetries and unitarity*
- 12:00nn Lunch break
- 1:30pm Stephen Adler  
*Investigations on gauged Rarita–Schwinger theory*
- 2:00pm Tung-Mow Yan  
*Drell–Yan mechanism and Its Implications*
- 2:30pm Coffee break
- 3:00pm Dmitry Abanin  
*Ergodicity, entanglement, and many-body localization*
- 3:30pm Djordje Minic  
*Manifest quantum non-locality in quantum mechanics,  
quantum field theory and quantum gravity*
- 4:00pm Gordon W. Semenoff  
*Entanglement and the Infrared*
- 4:30pm End of session

**Saturday, 10 February 2018: No talks**

**Sunday, 11 February 2018: No talks**

**Monday, 12 February 2018 — History Session**

(Shaw Foundation Alumni House)

- 9:00am Kimball Milton  
*Reminiscences of Julian Schwinger — Late Harvard, Early UCLA Years*
- 9:30am Steven Christensen  
*The Schwinger–DeWitt Proper Time Technique: A History*
- 10:00am Coffee break
- 10:30am Stanley Deser  
*Julian Schwinger — Recollections from many decades*
- 11:00am Shau-Jin Chang  
*Working with Professor Schwinger*
- 11:30am Michael Lieber  
*Off on a Tangent*
- 12:00nn Lunch break and Poster session (Guild House)
- 2:00pm Edward Gerjuoy  
*Memories of Julian Schwinger*
- 2:30pm Margaret Kivelson  
*From Julian to Jupiter: Unanticipated Outcomes*
- 3:00pm Coffee break
- 3:30pm Charles Sommerfield  
*Schwingerians*
- 3:50pm Daniel Sternheimer  
*Fond memories of Julian and Clarice, especially involving Moshe Flato and Noriko Sakurai*
- 4:10pm Closing remarks

## Overview

### Wednesday, 7th

Time	Speaker
9:15am	Opening address
9:30am	Sapirstein
10:00am	Pachucki
10:30am	Coffee break
11:00am	Gabrielse*
11:30am	Blaum
12 noon	Lunch break
1:30pm	Czarnecki
2:00pm	Dunne
2:30pm	Coffee break
3:00pm	Chan
3:30pm	Finkelstein*
4:00pm	Urrutia Rios
4:30pm	End of session

### Thursday, 8th

Time	Speaker
9:00am	Scully
9:30am	Brevik
10:00am	Coffee break
10:30am	Gazit
11:00am	Wilcox
11:30am	Englert
12 noon	Lunch break
1:30pm	Fried
2:00pm	Yao
2:30pm	Coffee break
3:00pm	Greenberger
3:30pm	Gasenzer
4:00pm	Van Houcke
4:30pm	End of session

### Friday, 9th

Time	Speaker
9:00am	Baym
9:30am	Indelicato
10:00am	Coffee break
10:30am	He
11:00am	Bern
11:30am	Huang
12 noon	Lunch break
1:30pm	Adler
2:00pm	Yan
2:30pm	Coffee break
3:00pm	Abanin
3:30pm	Minic
4:00pm	Semenoff
4:30pm	End of session

### Monday, 12th

Time	Speaker
9:00am	Milton
9:30am	Christensen
10:00am	Coffee break
10:30am	Deser*
11:00am	Chang
11:30am	Lieber
12 noon	Lunch break and Poster Session
2:00pm	Gerjuoy*
2:30pm	Kivelson*
3:00pm	Coffee break
3:30pm	Sommerfield*
3:50pm	Sternheimer
4:10pm	Closing remarks

\* Presentation by video

## **Ergodicity, entanglement, and many-body localization**

Dmitry ABANIN

*University of Geneva*

Dmitry.Abanin@unige.ch

We are used to describing systems of many particles by statistical mechanics. However, recently it was realized that the basic postulate of statistical mechanics — ergodicity — breaks down in so-called many-body localized systems, where disorder prevents particle transport and thermalization. In this talk, I will describe the theory of the many-body localized (MBL) phase, based on new insights from quantum entanglement. I will argue that, in contrast to ergodic systems, MBL eigenstates are not highly entangled, but rather obey so-called area law, typical of ground states in gapped systems. I will use this fact to show that MBL phase is characterized by a new kind of integrability and universal dynamics. Turning to the experimental implications, I will show that MBL systems exhibit a universal response to quantum quenches: surprisingly, entanglement shows logarithmic in time growth, reminiscent of glasses, while local observables exhibit power-law approach to “equilibrium” values. Ergodicity breaking in MBL systems enables new phases of matter, some of which I will describe. I will close by discussing other recent theoretical and experimental developments in exploring ergodicity and its breakdown in quantum many-body systems.

## **Investigations on gauged Rarita–Schwinger theory**

Stephen ADLER

*Institute of Advanced Studies, Princeton*

adler@ias.edu

For a number of years I have been studying gauged Rarita–Schwinger theory, to assess whether in formulating grand-unified models, the gauge anomalies can be cancelled between a spin-3/2 sector and a spin-1/2 sector, instead of requiring that anomalies cancel entirely within the spin-1/2 sector as usually assumed. This study grew out of a specific unification model that I proposed based on the gauge group  $SU(8)$ , which has interesting properties. In my initial paper on gauged Rarita–Schwinger theory, I showed that by adding a dimension-1/2 spin-1/2 auxiliary field the model can be extended to have an exact off-shell gauge invariance. In the first part of the conference talk, based on work with Henneaux and Pais, I show that the extended version, like the original massless Rarita–Schwinger theory, is pathological at weak fields, with the singularity (in radiation gauge) transferred from the Rarita–Schwinger field to the auxiliary field. In the second part of the conference talk, based on my most recent work, I examine a model with the Rarita–Schwinger field coupled to a dimension-3/2 spin-1/2 field in a way suggested by the  $SU(8)$  unification model. In this coupled model there is no weak field singularity, permitting calculation of the fermion loop contribution to the gauge anomaly. Further work is underway to clarify the ghost contribution to the anomaly, by extending the coupled model through inclusion of an auxiliary field.

**With Julian looking over my shoulder through the years:  
From Martin–Schwinger many-particle theory  
to transport theory in strongly interacting systems**

Gordon BAYM

*University of Illinois*  
gbaym@illinois.edu

Over half a century ago Leo Kadanoff (Paul Martin’s student and Julian Schwinger’s grandstudent) and I generalized the Martin–Schwinger approach to many-particle theory [1] using Schwinger’s formulation in real, rather than imaginary time [2]. After developing self-consistent approximations in interacting systems in equilibrium, we went on to construct generalized Boltzmann (or Kadanoff–Baym) equations to describe transport in strongly interacting systems [3]. In recent years theoretical, computational, and experimental advances have pushed the development of the technique, generalized Boltzmann equations have found application in a wide range of physical systems, from the very small (e.g., single molecule conduction) to the very large (e.g., leptogenesis in the early universe). This talk will review the basic concepts of the formalism, and its applications in a variety of systems.

- [1] P. C. Martin and J. Schwinger, *Theory of Many-Particle Systems. I*, Phys. Rev. **115**, 1342 (1959).
- [2] J. Schwinger, *Brownian Motion of a Quantum Oscillator*, J. Math. Phys. **2**, 407 (1961).
- [3] L. P. Kadanoff and G. Baym, *Quantum Statistical Mechanics* (W.A. Benjamin, NY, 1962).

## **The methodological unification of gravitons and gluons**

Zvi BERN

*Department of Physics and Astronomy, University of California at Los Angeles*  
bern@physics.ucla.edu

In 1976 Julian Schwinger wrote an essay entitled “Gravitons and Photons: The Methodological Unification of Source Theory” where he emphasized the close relationship of Einstein’s theory of General Relativity to that of gauge theory. His purpose was to demystify gravity. In this talk I will give an overview of the modern perspective linking these two theories, showing that in a rather precise sense perturbative gravity can be thought of as two copies of gauge theory. Applications to quantum gravity and classical gravitational radiation problems will be described.

## Precision tests of QED with stored and cooled highly charged ions

Klaus BLAUM

*Max-Planck-Institut für Kernphysik, Heidelberg*  
sekretariat.blaum@mpi-hd.mpg.de

Bound electron  $g$ -factors of highly charged ions take on a key role in the fundamental exploration of the atomic structure of nature. The combination of high-precision bound electron  $g$ -factor measurements and state-of-the-art bound-state quantum electrodynamics (BS-QED) calculations provide firstly most stringent tests of QED in strongest fields and secondly a unique access to fundamental constants, e.g. the atomic mass of the electron and the fine-structure constant  $\alpha$ . We have performed in recent years several high-precision  $g$ -factor measurements in Penning traps on highly charged hydrogen-like and lithium-like systems, as e.g.  $^{12}\text{C}^{5+}$ ,  $^{28}\text{Si}^{11+}$ , and  $^{28}\text{Si}^{13+}$  as well as  $^{40}\text{Ca}^{17+}$  and  $^{48}\text{Ca}^{17+}$ , which allowed among others to provide the most stringent test of BS-QED predictions [1,2], the most stringent test of the pure relativistic recoil effect [3], as well as the most precise determination of the atomic mass of the electron [4]. In the presentation I will discuss the experimental setup, the measurement procedure, and the results obtained and will provide an outlook on bound electron  $g$ -factor measurements up to hydrogen-like  $^{208}\text{Pb}^{81+}$ .

- [1] S. Sturm *et al.*, Phys. Rev. Lett. **107** (2011) 023002.
- [2] A. Wagner *et al.*, Phys. Rev. Lett. **110** (2013) 033003.
- [3] F. Köhler *et al.*, Nature Commun. **7** (2016) 10246.
- [4] S. Sturm *et al.*, Nature **506** (2014) 467.

## **Remarks on the Abraham-Minkowski problem**

Iver BREVIK

*Norwegian University of Science and Technology*

iver.h.brevik@ntnu.no

The electromagnetic energy-momentum problem in media has been under discussion for more than 100 years, at varying intensity, since the proposals of Abraham and Minkowski were put forward around 1910. The interest in the topic has become quite large in recent years, largely related to the advent of very accurate experimental techniques in optics. We intend to highlight some issues of this problem complex, discussing first from the theoretical side how natural the Minkowski tensor fits into the canonical formalism, and then discuss from the practical side the real importance of some of the recent experiments in radiation optics. Some criticism is here called for, as one will notice that some experimenters tend to overestimate the fundamental importance of their work.

## **Baryon Isospin Mass Splittings**

Lai Him CHAN

*Louisiana State University, Baton Rouge*  
chan@phys.lsu.edu

Soon after the discovery of charm hadrons, I have proposed that if the strong quark-quark magnetic moment interaction is so important for the explanation of the hadron mass spectrum according to the DGG model, it must also contribute to the Hadron isospin splittings because of the up and down quark mass difference. When such a term is included in the analysis, the D and the D\* isospin mass splitting was predicted extremely successfully. However, the accurate measurements of the relatively small charm baryon isospin mass splittings have taken 30–40 years to improve such that the comparison with the predictions can become meaningful.

In this talk I review the analysis of the calculation of the isospin splittings from two independent sources, the electromagnetic contribution and the strong interaction contribution. The electromagnetic Hamiltonian operator consists of the Coulomb part transformed like  $Q \otimes Q$  and the spin dependent magnetic moment interaction transformed like  $\mu \otimes \mu$ . The strong interaction contribution includes the up and down mass difference and more importantly the strong quark-quark magnetic moment interaction.

The agreements between the predicted values and the latest experimental values for all seven charm baryon isospin mass splittings are excellent within the order of one tenth of 1 MeV, well beyond expectation. A few results of the bottom baryons will also be presented.

**Working with Professor Schwinger**

Shau-Jin CHANG

*Emeritus Professor of University of Illinois*

shaujinchang@yahoo.com

General description of my thesis work with Professor Schwinger in the years of 1963–1967 at Harvard University.

## **The Schwinger–DeWitt Proper Time Technique: A History**

Steven CHRISTENSEN

*Department of Physics and Astronomy, University of North Carolina at Chapel Hill*  
stevec49@email.unc.edu

Much of my career in physics (as well as those of my colleagues) has been related to the study of the so-called Schwinger–DeWitt proper time technique for studying renormalization in quantum field theory in curved spacetimes. As a student of Bryce DeWitt, I was soon introduced to Schwinger’s classic 1951 paper, *On Gauge Invariance and Vacuum Polarization*, Phys. Rev. **82**, 664–679. I became aware of this through DeWitt’s detailed presentation in his book *Dynamical Theory of Groups and Fields* (Gordon and Breach, 1965), based on his Les Houches lectures. Since then we have used this technique and extensions of it to understand things like black hole radiation and back reaction, trace and other anomalies, index theorems, and more. In my talk, I will present some of this history as well as how the method has shown its value in physics and led to interesting developments in mathematics and computer software.

## Precise Quantum Electrodynamics of Bound States

Andrzej CZARNECKI

*University of Alberta*  
andrzejc@ualberta.ca

One of the goals Julian Schwinger had in mind in developing the Source Theory was to achieve greater flexibility in describing bound states and unstable particles. I will review recent progress in these areas. Special emphasis will be on the decay of a bound muon, soon to be studied in COMET and Mu2e experiments, and on the gyromagnetic factor ( $g$ ) of a bound electron, used to determine the electron mass.

**Julian Schwinger — Recollections from many decades**  
(pre-recorded video)

Stanley DESER

*Brandeis University; California Institute of Technology*  
deser@brandeis.edu

I present some reminiscences, both personal and scientific, over a lifetime of admiration and friendship with one of the grandmasters of our subject.

**The Search for the Schwinger Effect:  
Non-perturbative Pair Production from Vacuum**

Gerald DUNNE

*University of Connecticut*  
gerald.dunne@uconn.edu

The quantum vacuum is not empty: in fact it is inherently unstable, and the application of an external electric field can lead to the production of electron-positron pairs. This “Schwinger effect” was in fact one of the first non-trivial predictions of quantum electrodynamics (QED), but the effect is so weak that it has not yet been directly observed. However, new developments in ultra-high intensity lasers come tantalizingly close to opening a new window on this unexplored extreme ultra-relativistic regime. This has prompted a fresh look at both experimental and theoretical aspects of this and other nonlinear QED effects. I review the basic physics of the problem and describe some recent theoretical ideas aimed at making the elusive Schwinger effect observable, by careful shaping of laser pulses. This is an example of an emerging new field using ultra-intense lasers to probe fundamental problems in particle physics, gravity and quantum field theory.

## Julian Schwinger and the Semiclassical Atom

Berge ENGLERT

*Centre for Quantum Technologies and Department of Physics*  
*National University of Singapore*  
cqtebg@nus.edu.sg

In the early 1980s, Schwinger made seminal contributions to the semiclassical theory of atoms. There had, of course, been earlier attempts of improving upon the Thomas–Fermi model of the 1920s. Yet, a consistent derivation of the leading and next-to-leading corrections to the formula for the total binding energy of neutral atoms,

$$-\frac{E}{e^2/a_0} = 0.768745Z^{7/3} + \frac{1}{2}Z^2 - 0.269900Z^{5/3} + \dots,$$

had not been accomplished before Schwinger got interested in the matter [1,2]; here,  $Z$  is the atomic number and  $e^2/a_0$  is the Rydberg unit of energy. His work not only triggered extensive investigations by mathematicians, who eventually convinced themselves that Schwinger got it right, but also laid the ground, in passing, for later refinements — some of them very recent.

- [1] J. Schwinger, *Thomas–Fermi model: The leading correction*, Phys. Rev. A **22**, 1827 (1980).
- [2] J. Schwinger, *Thomas–Fermi model: The second correction*, Phys. Rev. A **24**, 2353 (1981).

## **Are Dyons the Preons of the Knot Model?**

(pre-recorded video)

Robert J. FINKELSTEIN

*Department of Physics and Astronomy, University of California at Los Angeles*

finkel@physics.ucla.edu

We consider the possibility that the preons defined by the  $SL_q(2)$  extension of the Standard Model may be identified with Schwinger dyons. The  $SL_q(2)$  extension is here presented as a model that may exist in either a currently observable electric phase or in a magnetic phase that is predicted but currently unobservable.

## **Non-Abelian QCD: No longer in the Shadow of Abelian QED**

Herbert M. FRIED

*Brown University*

fried@het.brown.edu

Starting from the Schwinger Generating Functional, and the added realization that a “source term” for the generation of added, external gluons of well-defined 4-momentum has no place in a theory where such gluons can never be measured; and taking into account the Gaussian nature of the well-known functional formulations of Fradkin and Halpern, manifest gauge-invariance becomes an immediate feature of Functional QCD. In addition, there automatically appear “Gluon Bundles”, each GB representing the sum of an infinite number of internal gluons exchanged between interacting quarks. Further, a new property of the theory appears, called “Effective Locality”, which reduces remaining functional integrations to sets of ordinary integrals, such that lattice gauge analyses can be replaced by far simpler approximations. Finally, since all gluons have been summed over, and their sums appear as GBs, a new, relevant form of Renormalization need be defined, both for the GBs and closed-quark-loop virtual interactions that are connected to “external” quarks. The definition of that Renormalization which we have chosen is surely the simplest one possible, and as shown in the striking fits of P. Tsang (this Conference) to the High-Energy, elastic proton-proton scattering data at the ISR (20-60 GeV) and LHC (7 TeV), our choices would seem to be quite correct.

## **Greatest Triumph of the Standard Model**

(pre-recorded video)

Gerald GABRIELSE

*Leverett Professor of Physics, Harvard University*

*Director of the Center for Fundamental Physics at Northwestern*

*gabrielse@physics.harvard.edu*

Schwinger made the first correction to the Dirac equation's prediction for the size of the electron magnetic moment. Thousands of additional corrections have been made, including harmonic and weak contributions, to make what is now the Standard Model's most precise prediction. With a single trapped electron, we determined this moment to 3 parts in  $10^{13}$ . Remarkably, this most accurately measured property of an elementary particle confirms the Standard Model prediction to 12 significant figures — arguably the greatest triumph of the Standard Model.

## Universal dynamics and non-thermal fixed points

Thomas GASENZER

*University of Heidelberg*

t.gasenzer@uni-heidelberg.de

Quantum many-body systems far from equilibrium show much richer characteristics than those in equilibrium. There is the possibility for universal dynamics, showing up with the same properties in very different systems irrespective of their concrete building blocks. Examples which are being studied intensely at present are the phenomenon of prethermalisation [1] and of superfluid turbulence [2]. Non-thermal fixed points have been proposed on the grounds of the Schwinger–Keldysh approach to non-equilibrium quantum field theory. These lead beyond standard equilibrium universality and are characterized by different anomalous scaling dimensions for statistical and spectral functions [3]. Turbulent dynamics in Bose systems will be discussed which are characterized by universal scaling behavior in space and time, with strong anomalous effects caused by conservation laws and non-dissipative dynamics [4]. This exhibits a close relation between quantum turbulence, the dynamics of topological defects, as well as magnetic and charge ordering phenomena.

- [1] T. Langen, T. Gasenzer, and J. Schmiedmayer, JSTAT 064009, 2016; arXiv:1603.09385 [cond-mat.quant-gas].
- [2] B. Nowak, S. Erne, M. Karl, J. Schole, D. Sexty, and T. Gasenzer, arXiv:1302.1448 [cond-mat.quant-gas], in *Strongly Interacting Quantum Systems out of Equilibrium*, edited by T. Giamarchi, *et al.* (Oxford University Press, 2016).
- [3] I. Chantesana, A. Pineiro Orioli, T. Gasenzer, *Kinetic theory of non-thermal fixed points in a Bose gas*, arXiv: to appear (2018).
- [4] M. Karl and T. Gasenzer, New J. Phys. **19**, 093014, 2017; arXiv:1611.01163 (2016).

**Plasma microscopic phenomena in extreme conditions:  
New approach to the solar abundance problem**

Doron GAZIT

*Hebrew University of Jerusalem*

doron.gazit@mail.huji.ac.il

Over the past decade, an outstanding open problem in solar physics has emerged, as solar photospheric abundances of metallic elements have been significantly revised downward. Standard solar models cannot reproduce helioseismic measurements, such as the convection zone radius, the surface helium abundance and the sound speed profile, when using these revised abundances. This gave rise to the solar composition problem, motivating a rapid growth of research efforts in the field.

With this problem of in mind, I study two main microscopic phenomena occurring in the extreme conditions of the Solar interior, and discuss their theoretical uncertainties and ways to reduce them. The theoretical methods go back to different milestones in J. Schwinger's career.

First, a novel diagrammatic quantum effective field theory approach to the fusion rate of two protons into a deuteron, which is too rare to measure terrestrially in the solar conditions, is developed. It is shown that new measurements of the neutron half-life have enormous effect on this reaction.

Second, I study the effects of plasma phenomena on the structure of atoms in the solar interior, in particular ionic correlations and line broadening. Both microscopic phenomena have a significant effect on the solar problem. Moreover, it is argued that the solar opacity problem is hindered due to the large uncertainties. In the case of the atomic effects, we propose a method to measure opacities at solar temperatures and densities that were never reached in the past via laboratory radiation flow.

**Memories of Julian Schwinger**  
(pre-recorded video)

Edward GERJUOY

*Department of Physics and Astronomy, University of Pittsburgh*  
gerjuoy@pitt.edu

The career and accomplishments of Julian Schwinger, who shared the Nobel Prize for physics in 1965, have been reviewed in numerous books and articles. For this reason these Memories, which seek to convey a sense of Schwinger's remarkable talents as a physicist, concentrate primarily (though not entirely) on pertinent recollections of the youthful Schwinger by this speaker, who first encountered Schwinger in 1934 when they both were undergraduates at the City College of New York.

## **Schwinger homework problems as the source of research projects**

Daniel GREENBERGER

*City College, City University of New York*

greenbgr@sci.ccny.cuny.edu

Schwinger gave few homework problems. But many of them led to deep thoughts and if followed through, could yield new insights about Physics. I will give two examples, one concerning why orbital angular momentum yields only integral values of  $\hbar$  for  $L$ , and the other concerning the Galilean transformation as the non-relativistic limit of the Lorentz transformation.

## **Scattering from Geometries**

Song HE

*Chinese Academy of Sciences and Perimeter Institute*  
songhe@itp.ac.cn

Scattering amplitudes are among the most basic calculations in Quantum Field Theory (QFT) and most important objects in high energy physics. It has been known for decades that they possess remarkable simplicity and structures, which are obscured in conventional formulation of QFT. I will review some recent progress in the search of new formulations that manifest such structures. Surprisingly these formulations are related to certain geometries, including those of Riemann surfaces, Grassmannian and “polytopes” in kinematic spaces.

## **Geometric unification of symmetries and unitarity**

Yu-tin HUANG

*National Taiwan University*

yutin@phys.ntu.edu.tw

While in the usual approach to QFT, Lorentz invariance and unitarity are implemented separately and in a very different fashion, a consistent theory requires both. For the past few years it has been realized that in the context of S-matrix, the two principles can be restated geometrically. In this talk I will show that in the context of effective field theory and conformal field theories, the symmetry principle and the principle of quantum mechanics, are unified into a simply geometric property in the space of physical observables.

## The Seven Year Itch: The proton size puzzle 7 years later

Paul INDELICATO

*Laboratoire Kastler Brossel (CNRS, ENS, Sorbonne University)*  
paul.indelicato@lkb.upmc.fr

In 2010, a measurement of the  $n = 2$  Lamb shift in muonic hydrogen lead to a very accurate measurement of the proton charge radius [1]. Yet this new value was 5 standard deviations away from the value deduced from normal hydrogen. Since then a second transition was measured that lead to a 7 standard deviation difference [2]. Then muonic deuterium was measured, leading to an isotopic shift in agreement with normal hydrogen and deuterium, and to a 3 standard deviation discrepancy for the deuteron charge radius [3]. Analysis of a new measurement performed on muonic  $^3\text{He}$  and  $^4\text{He}$  is underway. The situation on hydrogen has also changed with the publication of a new measurement of the  $2s-4p$  transition, leading to a value in agreement with muonic hydrogen [4]. Improved measurements of the  $1s-3s$  transition in hydrogen are on the way. I will give a review of all results and a detailed comparison of the charge radii measured in muonic and normal light atoms. I will explore possible explanations for this long-lasting puzzle.

- [1] R. Pohl, A. Antognini, F. Nez, *et al.*, *Nature* **466**, 213 (2010).
- [2] A. Antognini, F. Nez, K. Schuhmann, *et al.*, *Science* **339**, 417 (2013).
- [3] R. Pohl, F. Nez, L. M. P. Fernandes, *et al.*, *Science* **353**, 669 (2016).
- [4] A. Beyer, L. Maisenbacher, A. Matveev, *et al.*, *Science* **358**, 79 (2017).

**From Julian to Jupiter: Unanticipated Outcomes**  
(pre-recorded video)

Margaret KIVELSON

*Earth, Planetary and Space Sciences, UCLA, Los Angeles*  
*Climate and Atmospheres and Space Physics, University of Michigan, Ann Arbor*  
mkivelson@igpp.ucla.edu

I never expected that my Ph.D. work on quantum electrodynamics, completed under the tutelage of that superstar of Physics, Julian Schwinger, would serve as a foundation for a life in research that focused on problems that rarely include an  $\hbar$ . I shall talk about my path from QED to the exploration of magnetized plasmas in the solar system and mention some areas of interest to me, including theoretical studies of the interactions of particles with magnetohydrodynamic waves, analysis of magnetic reconnection in the Earth's magnetosphere, studies of the structure and dynamics of planetary magnetospheres, and inferences regarding properties of the moons of Jupiter and Saturn from their interactions with the flowing plasma in which they are embedded. This celebration of the 100th anniversary of Julian's birth gives me an opportunity to celebrate his influence on diverse studies by describing some of my contributions to plasma- and planetary-science.

## **Off on a Tangent**

Michael LIEBER

*University of Arkansas*  
mikeliieber1@yahoo.com

When I completed my dissertation under Schwinger's direction, he recommended that I pursue a post-doc with Larry Spruch at NYU because Larry was "doing some nice work on variational methods." At NYU, I indeed worked on developing a Kohn-type variational method for the breakup problem:  $A + (BC) \rightarrow A + B + C$ . This work, which resulted in two Phys. Rev. papers, was restricted to short-range potentials, but it introduced me to the difficulties of the quantum three-body problem, especially scattering. After my post-doc ended, I moved to the University of Arkansas where I found a group, experimentalists and theorists working on atomic physics, including collisions. Three-body collisions, combined with the marvels of the Coulomb potential, has been a theme of much of my later career. I will describe one or two contributions.

**Reminiscences of Julian Schwinger — Late Harvard, Early UCLA Years**

Kimball MILTON

*University of Oklahoma*

kmilton@ou.edu

I will discuss my interactions with Julian Schwinger as a student and postdoc, and subsequently. This will include his work on source theory, his interactions with the high-energy physics community, and his work on magnetic charge and the Casimir effect. His legacy in education and public outreach will also be highlighted.

**Manifest quantum non-locality in quantum mechanics,  
quantum field theory and quantum gravity**

Djordje MINIC

*Virginia Tech*  
dminic@vt.edu

I will report on my recent work with Laurent Freidel (Perimeter) and Rob Leigh (Urbana) on manifest quantum non-locality in quantum mechanics, quantum field theory and string theory/quantum gravity [1-4]. In this context, I will emphasize the prescient work of Julian Schwinger on the foundational topics in quantum mechanics and quantum field theory, as well as his pioneering attempts in quantum gravity.

- [1] <https://arxiv.org/abs/1707.00312>.
- [2] <https://arxiv.org/abs/1706.03305>.
- [3] <https://arxiv.org/abs/1606.01829>.
- [4] <https://arxiv.org/abs/1502.08005>.

## Quantum electrodynamics of atomic and molecular systems

Krzysztof PACHUCKI

*Faculty of Physics, University of Warsaw*

krp@fuw.edu.pl

I will present very recent results from high precision spectroscopy of the helium atom [1] and the hydrogen molecule [2–4] with the aim to find discrepancies with predictions of the Quantum Electrodynamics Theory and the possible discovery of new interactions.

- [1] X. Zheng *et al.*, *Phys. Rev. Lett.* **119**, 263002 (2017).
- [2] *Toward a determination of the proton-electron mass ratio from the Lamb-dip measurement of HD*, L.G. Tao *et al.* (submitted to PRL).
- [3] *Sub-Doppler frequency metrology in HD for test of fundamental physics*, F.M.J. Cozijn *et al.* (submitted to PRL).
- [4] *Nuclear spin-spin coupling in HD, HT, and DT*, M. Puchalski *et al.* (submitted to PRL).

**The g factor of an electron in hydrogenlike carbon  
and the precision determination of the electron mass**

Jonathan SAPIRSTEIN

*University of Notre Dame*

jsapirst@nd.edu

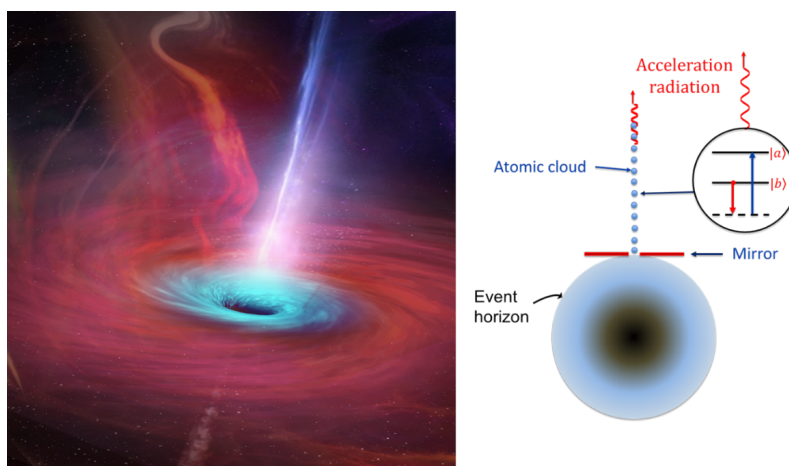
Recent advances in determining the electron mass with very high precision require a detailed understanding of the g factor of a bound electron. Schwinger's contributions to the theory of the free g factor and the theory of binding corrections for the related case of hyperfine splitting will be described. Emphasis will be placed on how the latter one-loop correction can now be treated to all orders of binding corrections for both hyperfine splitting and the g factor.

## Black hole acceleration radiation from quantum optical perspective

Marlan O. SCULLY

*Texas A&M University; Princeton University; Baylor University*  
scully@tamu.edu

General relativity as originally developed by Einstein is based on the union of geometry and gravity. Half a century later the union of general relativity and thermodynamics was found to yield surprising results such as Bekenstein–Hawking black hole entropy and Hawking radiation. In their seminal works, Hawking, Unruh and others showed how quantum effects in curved space yield a blend of thermodynamics, quantum field theory and gravity which continues to intrigue and stimulate. It has been shown [1] that virtual processes in which atoms jump to an excited state while emitting a photon is an alternative way to view Unruh acceleration radiation. The present work [2] is an extension of that logic by considering what happens when atoms fall into a black hole (BH) as shown in the figure below. Specifically, we analyze the problem of atoms outside the event horizon emitting acceleration radiation as they fall into the BH. We find that the quantum master equation technique, as developed in the quantum theory of the laser, provides a useful tool for the analysis of BH acceleration radiation and the associated entropy [2]. The emitted radiation is essentially, but not precisely, thermal and has an entropy analogous to that obtained by Bekenstein and Hawking. However, the physics is very different. Here we have radiation coming from the atoms, whereas Hawking radiation requires no extra matter (e.g. atoms).



**Left:** Artist's concept illustrating a supermassive BH surrounded by matter flowing onto the BH in an accretion disk. Also shown is an outflowing jet of energetic particles powered by the BH's spin. **Right:** BH is bombarded by a pencil-like cloud of two level atoms falling radially from infinity. The relative acceleration between the atoms and the field yields generation of acceleration radiation.

- [1] M.O. Scully, V.V. Kocharovskiy, A. Belyanin, E. Fry, and F. Capasso, *Phys. Rev. Lett.* **91**, 243004 (2003).
- [2] M.O. Scully, S. Fulling, D. Lee, D. Page, W. Schleich, and A.A. Svidzinsky, arXiv:1709.00481 [quant-ph].

## **Entanglement and the Infrared**

Gordon W. SEMENOFF

*University of British Columbia*

gordonws@phas.ubc.ca

I will discuss the subtle interplay of infrared singularities in quantum electrodynamics and perturbative quantum gravity and information theoretic issues such as quantum entanglement between soft and hard degrees of freedom.

**Schwingerians**  
(pre-recorded video)

Charles SOMMERFIELD

*Yale University*

charles.sommerfield@yale.edu

Schwinger influenced many physicists during his productive lifetime. I will talk about my interactions with him and others in this group as I look back over my career. I will include both the professional and the personal.

**Fond memories of Julian and Clarice, especially involving  
Moshe Flato and Noriko Sakurai**

Daniel STERNHEIMER

*Rikkyo University, Tokyo, and Université de Bourgogne*  
Daniel.Sternheimer@u-bourgogne.fr

We start with some general remarks related to Julian's works in, and attitude to, physics, in particular in relation with Moshe and me. Then we recall some notable events with Moshe (70s to 90s) and (since the 80s) with Noriko, and also with Clarice and me this millennium. A few photos illustrate the talk.

## **The magneto-electric effect in axion-electrodynamics**

Luis F. URRUTIA RIOS

*Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México*  
urrutia@nucleares.unam.mx

We consider an external piecewise constant axion field which divides space in two regions separated by a domain wall where the modifications to the standard Maxwell dynamics are localized. This model provides an effective theory for the electromagnetic response of a topological insulator. The static Green's functions are obtained for the cases of plane, cylindrical and spherical symmetries by exploiting the delta-like axionic contributions at the domain wall. For a plane symmetric domain wall some consequences of the magneto-electric effect are discussed in the case of Casimir forces and in the shifting of the energy spectra of hydrogen-like ions.

## **Summation of diagrammatic series for a strongly correlated fermionic theory with zero convergence radius**

Kris VAN HOUCKE

*Ecole Normale Supérieure de Paris*

`kvhoucke@toursol.lps.ens.fr`

We consider the unitary Fermi gas (spin 1/2 fermions with contact interactions in 3D, which describes cold atomic gases at a Feshbach resonance) in the normal phase. For this system we have developed a diagrammatic Monte Carlo algorithm, which evaluates the Feynman diagrammatic series in a stochastic way. Thanks to this method we can accurately calculate the sum of all skeleton diagrams (built on dressed single-particle and pair propagators) up to order 9. The diagrammatic series turns out to be divergent and there is no small parameter so that a resummation method is needed. Previously we used Abelian resummation methods, which are applicable under the assumption that the diagrammatic series has a non-zero radius of convergence; this led to good agreement with experimental data for the equation of state and Tan's contact coefficient. Computation of the large-order asymptotics of the diagrammatic series, based on a functional integral representation of the skeleton series and the saddle-point method, reveals however that the radius of convergence is actually zero. Our new numerical results and analytical arguments show that the series is resumable by a generalised conformal-Borel transformation that incorporates the large-order asymptotics. This demonstrates that one can obtain controlled results for a strongly correlated fermionic field theory based on diagrammatic series with zero convergence radius.

## **Multiquark States in the Thomas–Fermi Quark Model**

Walter WILCOX

*Baylor University*

walter\_wilcox@baylor.edu

One of the long-standing issues which has challenged particle physicists is the existence and properties of exotic states of baryons of more than three quarks, or mesons of two or more quark/antiquark pairs, or mixed combinations. There is a need for realistic models that can extend beyond present day lattice calculations and lead in the right direction. We will build these states for baryons and mesons in a Thomas–Fermi inspired model and examine the energy slopes to determine family stability.

## **Drell–Yan mechanism and Its Implications**

Tung-Mow YAN

*Cornell University, Ithaca*

ty18@cornell.edu

The Drell–Yan Mechanism was proposed in 1970 as an application of the parton model to describe the massive muon pair production at BNL. It is still a very active area for research after almost 50 years both theoretically and experimentally. Theoretically, after QCD has been accepted as the correct theory of strong interactions, this mechanism provides an arena to investigate the factorization theorem for hard processes involving two initial hadrons. Experimentally, it has emerged as an important tool for discoveries of new physics, including the discovery of the Higgs Boson in 2012. In this talk we will briefly discuss the history and developments of the mechanism.

## Some Comments on Solving the Scattering Equations

York-Peng YAO

*Leinweber Center for Theoretical Physics, University of Michigan, Ann Arbor*

*Kavli Institute for Theoretical Physics, University of California, Santa Barbara*

yyao@umich.edu

The CHY formulation for gauge and gravitational interactions sums all ‘color ordered’ Feynman diagrams for the tree-level  $n$ -particle scattering amplitude into a single compact expression, which involves Mobius parameter  $\sigma_i$ ,  $i = 1 \dots n$ . To convert it into kinematical invariants only requires knowing all the solutions of  $\sigma_i$  to the scattering equations:

$$\sum_{j=0}^n \frac{s_{ij}}{\sigma_i - \sigma_j} = 0,$$

in which  $s_{ij} = -(p_i + p_j)^2$ . These solutions in explicit analytical forms are not known in general and are likely to be complicated. We use  $n \leq 6$  to show that the complexity can be reduced by (1) using non-linear relations for each solution due to Mobius and permutation invariance of the scattering equation and/or (2) making an insightful ansatz on the structure of the sum over  $j$ .