FOM-evaluation

Programme FP31: Fundamental Interactions
and
Programme FP52: Theoretical Subatomic Physics

Results 1998-2002 and plans 2002-2006

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1.1 Brief aan Uitvoerend Bestuur van de Stichting FOM

Aan de leden van het
Uitvoerend Bestuur van FOM

Geachte bestuursleden,

Zoals afgesproken bij de totstandkoming en goedkeuring van de FOM programma's FP31 (Fundamental Interactions) en FP52 (Theoretical High Energy Physics) zullen deze programma's in 2002 midtijds geevalueerd worden. Om redenen van efficiency alsmede complementariteit en verwovenheid van het onderzoek in beide programma's is besloten deze evaluaties tegelijkertijd te laten plaatsvinden.

Als vorm voor deze evaluatie stellen wij als programmaleiders voor een panel van drie of vier buitenlandse experts uit te nodigen, die middels rechtstreekse consultatie van de programmaleiders en een aantal onderzoekers kennis kunnen nemen van het werk dat in de programma's is uitgevoerd en van de plannen en nieuwe ontwikkelingen die worden voorgesteld. Ter voorbereiding van dit bezoek hebben wij voor de programma's in samenspraak met FOM een aantal relevante gegevens in een zelf-evaluatie document gebundeld.

Op basis van dit bezoek kan het panel adviseren over de voortgang van de programma's, en eventueel suggesties doen over accentverschuivingen.

Wij zouden een dergelijke evaluatie graag nog in juni of juli gerealiseerd zien worden, bij voorbeeld in de periode voorafgaand aan de grote internationale hoge-energie fysica conferentie ICHEP 2002 in Amsterdam, eind juli. Nieuwe post-docs en promovendi kunnen dan zonder vertraging na de zomer weer aan de slag.

Met vriendelijke groeten,

Jan-Willem van Holten (programmaleider FP52)
Piet Mulders (programmaleider FP31)

1.2 Information for review panel

In 1998 the FOM programme FP31 'Fundamental Interactions' was approved. Its three branches 'Phenomenology', 'Quantum Field Theory' and 'Quantum gravity/string theory' cover most of the activities of the former FOM *Werkgemeenschap Theoretische Hoge-Energie Fysica* (Hth), which financed part of the research of the university groups in the field of theoretical high-energy physics. The programme runs from 1998-2006 with a midterm-evaluation planned in 2002.

The FOM programme FP52 'Theoretical Subatomic Physics' was approved in 2000 to accomodate the theoretical physics group of NIKHEF, the FOM institute for subatomic physics. Its research programme fits together with that of FP31, the programmes being complementary in range and choice of topics. The programme FP52 runs from 2000-2007, and it is to be evaluated together with its sister programme FP31 because of the close connections on the thematic, personal and organisational level. Co-operation between the two programmes exists in the form of joint publications, joint local and national seminars and the participation of FOM-staff in university research and education through special professorships.

As a result of the dynamics in the field, a new FOM programme FP57 'String theory and quantum gravity' has recently been approved. This programme grew out of the research projects in this area in both FP31 and FP52, having taken on an independent status. The three theoretical high-energy physics programmes FP31, FP52 and FP57 constitute a national network of research groups in close contact and joint activities in the areas of research and education.

In this evaluation document we summarise the results and performance of the two initial programmes FP31 and FP52 so far (till January 1, 2002), and present the outlook for the continuation of the programmes for the remaining period.

2 Past performance of FP31 and FP52

The objectives of the programme Fundamental Interactions and the programme Theoretical Subatomic Physics were stated to be:

- Study of theoretical models incorporating the known electromagnetic, weak and strong interactions, aimed at predicting and describing new and existing experimental results.
- Development of mathematical and computational tools necessary for the analysis of such models.
- Understanding the conceptual basis of quantum field theory, in particular in connection with its symmetry properties.
- Study of the quantum mechanical description of gravity and the nature of space and time.

The programmes were set up to assure the maintenance of the existing diversity in expertise, enabling a swift reaction to new developments in theoretical high-energy physics. In FP31, three themes were selected, 'Phenomenology', 'Quantum field theory' and 'Quantum gravity and strings', although these are not strictly separable. Generally the research proposals were flexible and open to change. This is necessary as in theoretical physics progress cannot be enforced, developments are difficult to predict and directions change rapidly. Furthermore, large parts of the programme are carried out in international co-operations such as EU or INTAS networks and the choice of research lines also depends on the feasibility of attracting postdocs and visitors. The programme FP31, however, in the same way as the former 'werkgemeenschap' plays an important role, because it contributes in a significant way to the infrastructure of the university theory groups. The material budget in the programmes contributes to the possibilities to disseminate knowledge via conferences and workshops. It also allows the groups to invite visitors.

The programme FP52 is a theoretical physics programme complementing the experimental programmes at NIKHEF. Within the Netherlands, NIKHEF encompasses all activities in the area of experimental high-energy physics, including university groups and the institute. The institute is the focus point of the experimental activities and the presence of a theory group covering a broad spectrum of topics is essential. The presence of the group turns out to be attractive for foreign graduate students, postdocs and senior physicists. The programme includes provisions for inviting guest scientists.

The narrow ties between the various groups working on high-energy physics shows itself among others in the following:

- The organization of a series of national seminars (5 times per year) held at the NIKHEF institute, in which new developments are presented to the community. The morning talk usually features a visitor presenting new theoretical developments to the community of theoretical *and* experimental high-energy physicists, while in the afternoon the various projects of graduate student and postdoc are discussed by the theoretical community.
- In close co-operation with the national research schools for theoretical physics (DRSTP) and Subatomic Physics (SAF/NIKHEF), the network participates in the organization of academic training programmes in theoretical high-energy physics for PhD students in theoretical physics as well as in experimental physics. These schools offer a balanced programme of lectures to Ph.D. students in their first and second year.
- The semi-annual meetings of the former FOM werkgemeenschap (facilitated by FOM), which included a representative of the NIKHEF group, in which scientific, organizational and financial issues were discussed. As of January 1, 2002 due to the restructuring of FOM the werkgemeenschap no longer exists as such. Instead, a 'Network Theoretical High-energy Physics' has been created chaired by the programme coordinators of the (presently three) relevant programmes FP31, FP52 and FP57.
- Staff members of various groups hold special professorships at other locations. In the past J. Smit (UVA) was appointed as an extraordinary professor in Utrecht (UU), J.W. van Holten (NIKHEF) is associated with the VUA in Amsterdam, J. Koch (NIKHEF) with the University of Amsterdam

(UvA), E. Laenen (NIKHEF) with Utrecht (UU) and B. Schellekens (NIKHEF) with Nijmegen (KUN). These appointments stimulate collaborations between the various groups.

- Ph.D. students and post-docs at different locations work on joint projects and write joint publications. The beforementioned organization of schools and seminars at a national level also has led to a large mobility of graduate students, Ph.D. students and postdocs between the groups.

- Several workshops and conferences have been organized, e.g. string conferences in Amsterdam in July .... . In 2000 an international workshop on QCD and deep inelastic scattering was organized at the Lorentz center in Leiden (van Neerven and Mulders).

Because of the overlap between the FOM programmes and the other research projects at the various locations, we review in this section the *full* spectrum of research in theoretical high-energy physics centered around the themes mentioned above, but only in a global way; the contributions of each of the groups involved are made more specific in sections 3 and 4, and further in the lists of publications attached.

The possibility to react swiftly to new developments has been demonstrated by the way the research field of 'Quantum gravity and strings' grew into a new independent programme, FP57.

2.1 Quantum gravity and string theory

A quantum theory of gravity does not yet exist, but many valuable ideas have been developed in the context of canonical gravity, supergravity and string theory. Canonical gravity in 2, 3 or 4 dimensions, quantum black holes and Hawking radiation provide concrete models of gravitational physics incorporating essential quantum aspects. Supergravity has been studied as an effective theory of particle physics close to the Planck scale and/or an effective long-range field theory for strings.

In recent years important progress in string theory and supergravity has been made thanks to the discovery of new and powerful symmetries, called dualities, which relate strongly coupled theories (difficult to handle) to well-understood weakly coupled theories. It was realized that different formulations of string theory are in fact all related, being particular limits of a single underlying theory called M-theory. Although the precise formulation of this M-theory is not yet known, the study of its properties has provided a wealth of new information about a vast range of systems. Essential in these developments has been the so-called D-brane description of the extended solitons of string theory; it has also stimulated renewed interest in the theory of open strings.

Research has focused on three important and closely related aspects: the first is to try to find the formulation of M-theory that underlies all of string theory, and to investigate its consequences for the structure of space and time. It is hoped that the recent breakthroughs in black hole physics will lead to a concrete synthesis with other ideas in particular the holographis principle of 't Hooft. The second is to use the newly discovered techniques to tackle important and unresolved questions concerning the physics of elementary particles, in particular those related to the strong interactions and the question of supersymmetry breaking. Finally, the D-brane scenario has been picked up by cosmologists to formulate new models for the evolution of the universe.

It should be stressed that the study of string theory is not an isolated endeavour into Planck-scale physics and cosmology. There have been various developments in the context of string theory which have become independent fields of research, where a fruitful exchange of ideas and research results with other parts of theoretical physics takes place. For example, conformal field theory has many interesting applications in statistical mechanics and condensed matter physics, such as in the description of critical phenomena, turbulence and impurity problems.

Contributions to canonical and supergravity and/or the theory of strings and M- theory, D-branes and conformal field theory have been made by the groups in Amsterdam (UvA), Groningen (RUG), Leiden (UL), NIKHEF and Utrecht (UU). In view of the broad spectrum of activities in this research field, it was decided that a new nationally coordinated research programme *String Theory and Quantum Gravity* would be formulated and submitted to the FOM. In the meantime the Executive Board of FOM has approved this as one of its programmes (FP57), which will run for 8 years. Dijkgraaf is programme

manager. We will not further expand on the plans described in this programme as it has now acquired an independent status.

2.2 Quantum field theory

Quantum field theory (QFT) is the universal framework to describe nature at the atomic and subatomic level; as such it provides the basis of theoretical high-energy physics and a considerable part of astrophysics; it is also indispensable in the physics of condensed matter. Studies of field theories of gravity, and topological and conformal field theories are also part of quantum gravity and string theory.

Work in QFT includes research on exact results and classical solutions, quantization, general aspects of perturbative methods, and non-perturbative and numerical studies. Exact results have been obtained in recent years for supersymmetric Yang-Mills theories by exploiting duality properties relating weak and strong coupling regimes. This can shed light on properties like confinement. In the non-supersymmetric context the analysis is much more difficult. Classical solutions, like solitons and instantons, are known to play an important role, and their study is an active field of research. Studies center around their properties and classification and the interplay with topology. Other aspects concern their role in the quantized theories, and the generalization to fields at finite temperature.

Apart from confinement, the study of the dynamics of bound states in relativistic quantum field theory is a long-standing problem; some progress has been made in recent years by using light-front methods. Some aspects of bound states and long-range correlations in QFT can also be approached through all-order perturbative methods, based on a resummation of perturbative expansions.

The perturbative quantization of gauge theories requires the introduction of additional ghost degrees of freedom. Their decoupling from physical matrix elements is guaranteed by the existence of BRST symmetry. Physical states can be characterized in terms of the cohomology of the BRST operator, which can have a quite non-trivial structure. Incorporating fermions in QFT poses consistency problems when there are chiral symmetries. In certain cases these are resolved by the inclusion of Wess-Zumino type effective actions. In recent years it has become clear, that there exists an interesting map between the Wess-Zumino consistency conditions and BRST-cohomoloy.

Many divergence problems of QFTs can be avoided by formulating them in a finite volume and/or on a space-time lattice. Such studies give insight into the non-perturbative dynamics, allowing simulations to provide numerical answers to dynamical questions. These studies can also be done at finite temperature, and are now widely used to study phase transitions, including the one between a hadron gas and the quark gluon plasma.

Investigations into quantum field theory are carried out in all groups participating in the programme (KUN, NIKHEF, RUG, UL, UvA, UU and VUA).

2.3 Phenomenology

Work in particle phenomenology has strong roots in, and is closely interwoven with, quantum field theory. This is particularly evident for the strong and electroweak interactions in the standard model of particle physics.

In strong interaction physics perturbative calculations have proven to be indispensable for interpreting high-energy scattering experiments. High-order diagrammatic calculations have been undertaken in QCD, up to order α_s^4, and Born level calculations hav been performed for processes in which many (up to 9) jets are produced in hadron collisions. For such calculations tools have been developed, such as the FORM programme which is able to handle very large algebraic calculations on the computer. Knowing the corrections, one is able to extract distribution and fragmentation functions, which are key quantities for our understanding of the quark and gluon dynamics in hadrons. Polarization and detection of specific final state hadrons have led to new and more detailed insight into the quark and gluon sturcture of the proton, in turn stimulating developments to understand the results via effective field theories in QCD, lattice calculations, or models incorparating essential symmetries, such as chiral symmetry. Significant progress has also been made in all-order resummations of Sudakov logarithms in the calculation of QCD cross sections, where e.g., new developments in factorization theorems enable resummation of both threshold

and recoil logarithms, thus reconciling QCD with certain fixed-target prompt photon data.

In electroweak field theory new concepts and methods have been developed. These include e.g. an improved understanding of the Sudakov logarithms in broken gauge theories (which will be very important for future high-energy linear colliders) and the treatment of the effects of instability of either outgoing particles (e.g., W-bosons), or incoming particles (as in muon colliders). Advances have been made in the related field of numerical methods, both theoretically in the study of discrepancy distributions and applied in the construction of novel MC algorithms.

Other research projects in phenomenology include studies of heavy-quark production, in particular single-top production to measure the top-W coupling; Higgs production in hadron colliders; and furthermore the development of new ways to use polarization and particle production to map out the quark and gluon spin structure in a nucleon. The study of finite temperature field theories finds direct applications in heavy-ion collisions looking for the quark-gluon plasma. As concerns studies of particle phenomenology beyond the standard model, we mention studies of supersymmetric particle production at hadron colliders.

Research in particle phenomenology is carried out in Amsterdam (VUA and NIKHEF), in Leiden (UL) and Nijmegen (KUN).

2.4 The projects in FP31

A summary of projects financed in the programme FP31 is given in the table below. We note that actually only 40 % of the positions has ended. Others are running projects.

group	position	person	field	supervisor	remarks
FOM-A-01	staff	J. Smit	QFT		
	oio	M. Sallé	QFT	Smit	running
	oio	J. Striet	QFT	Smit	running
	oio	R.H. Boels	Strings	de Boer	running
	postdoc	M. Alishahiha	Strings		
	postdoc	S. Bilke	Gravity		
	postdoc	J.I. Skullerud	QFT		running
FOM-G-01	oio	E.A. Eyras	Strings	Bergshoeff	
	oio	J.P. van der Schaar	Strings	Bergshoeff	
	oio	T.C. de Wit	Strings	de Roo/Bergshoeff?	running
	postdoc	U.G.V. Gran	Strings		running
FOM-L-01	oio	A.P. Chapovsky	Phenomenology	Berends	
	oio	J. Schweizer	Phenomenology	van Neerven	changed job
	postdoc	T.G. Kovács	QFT		
FOM-N-01	oio	A. van Hameren	Phenomenology	Kleiss	
	oio	C. Dams	Phenomenology	Kleiss	
FOM-U-01	oio	G.A.P.T. Aarts	QFT	Smit	
	oio	J. Weda	Phenomenology	Tjon	running
	oio	J. Käppeli	QFT	de Wit?	running
	postdoc	S. Stanciu	Strings		
	postdoc	V. Shevchenko	?		running
FOM-V-01	oio	M. van Iersel	QFT	Bakker/Mulders	running
	postdoc	R. Kundu	Phenomenology		
	postdoc	A. Metz	Phenomenology		running

Of all these projects descriptions can be found in the FOM year reports. These have been included in the material for the committee.

In the next section, we have included the projects in full lists of the various FOM working groups, because only in that context one is able to judge te programme FP31 and its impact.

3 Embedding of FOM programme FP31 at the universities

3.1 University of Amsterdam (UVA): FOM-A-01

staff	dates	employer	
prof.dr.ir. F.A. Bais		UvA	
drs. G.G.A. Bäuerle		UvA	
prof.dr. J. de Boer	from 1/9/2000	UvA	
prof.dr. R.H. Dijkgraaf		UvA	
prof.dr. K.J.F. Gaemers		UvA	
dr. L.J. van den Horn		UvA (CHEAF)	
prof.dr. J.H. Koch		NIKHEF/UvA	
dr. K. Skenderis	from 1/1/2003	UvA/NWO	
prof.dr. J. Smit		FOM-FP31	
prof.dr. H.L. Verlinde	till 1/1/2000	UvA	
dr. J.C. Vink	1/10/1999-1/1/2002	UvA/FOM	
prof.dr. Ch.G. van Weert		UvA	

postdocs	dates	employer	project
dr. M. Alishahiha	1/12/2000-1/8/2001	FOM-FP31 FOM-99HT02	String field theory and tachyon condensation
dr. S. Bilke	8/12/1997-8/12/1999	FOM-FP31	Fluctuating geometries and quantum gravity
dr. J.I. Skullerud	1/10/2001-1/10/2003	FOM-FP31	Non-equilibrium field theories
dr. M. Serone	1/9/1998-1/9/2000	FOM-97PR1688	Anomaly cancelation for extended objects
dr. S. Terashima	1/9/2001-1/9/2003	FOM-97PR1688	Strings and K-theory
dr. M.A. Vazquez-Mozo	1/10/1998-1/1/2001	FOM-97PR1688	Nonperturbative string theory
dr. L. Cornalba	1/10/2001-1/10/2004	FOM-00PR1889	The physics of D-branes
dr. B.J. Schroers	1/9/1995-1/9/1998 1/9/1998-1/9/1999	NWO Pionier UvA	Non-abelian dualities

Ph.D. students	dates	employer	project
drs. W.H. Tang	1/2/1993-1/2/1997	FOM-Hth-A	Baryon number violation
drs. J.M. Smit	1/10/1991-1/10/1995	FOM-Hth-A	Neutrinos in supernovae
drs. N.M. Muller	1/2/1994-1/2/1998	FOM-Hth-A	Topology/quantum symmetries
drs. M. Sallé	1/2/1998-1/2/2002	FOM-FP31	Non-equilibrium quantum fields
drs. J. Striet	1/5/1999-1/5/2003	FOM-FP31	Alice electrodynamics
drs. R.H. Boels	1/8/2001-1/8/2005	FOM-FP31 FOM-99HT02	String theory in time dependent backgrounds
drs. A.X. Arrizabalaga	1/9/1999-1/9/2003	FOM-SF-A-b/3	Non-equilibrium dynamics of symmetry breaking
drs. J.A.E.F. van Dongen	1/2/1998-1/2/2002	NWO/Zeeman St./CHEAF	Einstein and unification
drs. R.J. Duivenvoorden	18/9/2000-18/9/2004	FOM-00PR1889	Strings/holography
drs. F. Hacquebord	1/1/1995-1/1/1999	NWO Pionier	Matrix string theory
drs. B.J. Nauta	1/7/1996-1/7/2000	UvA	High-T field theory
drs. J.S. Park	1/10/1995-1/10/1999	NWO Pionier	Cohomological field theories
drs. J.K. Slingerland	1/6/1998-1/6/2002	UvA	Hopf symmetries
drs. M. Temürhan	1/9/2001-1/9/2005	FOM-97PR1688	Holography
drs. A. Tranberg	1/10/2000-1/10/2004	UvA	Non-equilibrium QFT and early universe
drs. M.L. Vonk	1/10/1998-1/10/2002	FOM-MF-A-a	Quantum gravity/strings/ gauge theories
drs. J.S. Wijnhout	15/4/2001-15/4/2005	FOM-97PR1688	Black holes/noncommutative geometry

Ph.D. degrees awarded in Amsterdam (UVA), 1998-2001.

1. N.M. Muller, *"Topological Interactions and Quantum Double Symmetries"*, promotor: prof. dr ir F.A. Bais, University of Amsterdam, Amsterdam, 2 October 1998, ISBN 90-5776-008-8.

2. J.M. Smit, *Neutrino Transport in Core-collapse Supernovae*, promotor: prof. dr E.P.J. van den Heuvel and prof. dr Ch.G. van Weert, copromotor dr L.J. van den Horn, University of Amsterdam, 20 May 1998, Universal Press, Veenendaal.

3. W-H. Tang, *Numerical Calculation of the Baryon Number Violation Rate in Hot Electroweak Theory*, promotor: prof.dr. J. Smit, University of Amsterdam, 1 September 1998, ISBN 90-5776-006-1.

4. F.H. Hacquebord, *Symmetries and Interactions in Matrix String Theory*, promotor prof.dr. H.L. Verlinde, Universiteit van Amsterdam, Amsterdam, September 22, 1999, 120p.

5. J.-S. Park, *Cohomological Field Theories on Complex Manifolds*, promotor prof.dr. H.L. Verlinde, Universiteit van Amsterdam, Amsterdam, November 23, 1999, 165p.

6. B.J. Nauta, *Dynamics of Gauge Fields at High Temperature*, promotor: prof.dr. Ch.G. van Weert, Universiteit van Amsterdam, Amsterdam, November 8, 2000, UvA, 128 pages, proefschrift.

Relevant developments at the university

The research in High Energy Theory at the UvA is mainly part of the Institute for Theoretical Physics (ITFA).

The String Theory group at the University of Amsterdam is a common initative of the institute for Theoretical Physics (ITFA) and the Korteweg-de Vries Institute for Mathematics (KdVI). It receives additional funds from the University Board through the Center of Mathematical Physics Amsterdam (CMPA, Dijkgraaf director), and external funding by FOM and NWO (GBE-Mathematics). The group

is at this moment located at the ITFA, but will be given a more integrated housing once the move to the Watergraafsmeer campus is completed.

Amsterdam has from the beginning continuously supported this field, both from the mathematics and physics side. It was the first place in the Netherlands to offer permanent positions in this field (Dijkgraaf 1992, H. Verlinde 1994). With the aid of a NWO Pionier grant a number of infrastructure investments have been made. String theory is a main research theme in the research programme of both the ITFA and the KdV Institute and acts furthermore as a backbone of the CMPA.

String theory has a strong impact on and interaction with mathematics. This has been particularly encouraged in Amsterdam, and is reflected in the research profile at the KdV Institute. The recent appointments of Opdam and Landsman (with FOM support, also NWO pionier)) have strengthened this relation.

Dijkgraaf and J. de Boer are now heading the active research group in this field (H. Verlinde left per 1-1- 2000 to take upo a full professorship at Princeton University, but is still associated to the UvA as visiting professor). A succesful application was put in for a NWO Vernieuwingsimpuls grant for Kostas Skenderis. Skenderis is presently an Assistant Professor in the High Energy Theory group at Princeton University and will become Associate Professor at the UvA. Skenderis' project will start September 2002. His grant will partly used to finance postdocs and graduate students.

The University has awarded a *honorary professorship* to Nobel laureate Prof. Martinus Veltman in 2001.

Another development was the appointment of Dr J.C. Vink to work in the group of Prof. J. Smit to strengthen the efforts in computational field theory. His presence was highly productive but unfortunately he left the Institute because of a very attractive offer from industry.

We mention major responsibilities taken up by some of the senior staff taking up other tasks at the University in the period starting in 1998: Bais has been scientific director of the ITFA from 1997 on, Gaemers has been dean of the department and Van Weert is director of the Teaching Institute of Physics Astronomy and Mathematics.

Specific research topics, 1998-2001.

The research is roughly divided in two parts. One part is concerned with

- String Theory and Quantum Gravity. This research is now part of the FOM programme of the same title.

The other part concerns the investigation and application of non-perturbative aspects of QFT and covers the following topics.

- Electroweak baryogenesis
- High temperature field theory and heavy ion collisions
- Computational Field Theory
- Topological defects and topological interactions
- Quantum group symmetries and their breaking

3.2 Rijksuniversiteit Groningen: FOM-G-01

Staff	appointment dates	employed by	
Prof.dr. D. Atkinson	until May 2000	RUG	
Dr. M. de Roo		RUG	
Prof.dr. E.A. Bergshoeff		RUG	
Postdocs	**appointment dates**	**employed by**	**topic**
Dr. J.C.R. Bloch	1/9/96-1/9/98	FOM Hth-G	Dyson-Schwinger equations
Dr. U.G.V. Gran	1/10/01-1/10/03	FOM FP31	domain walls
Dr. P. Sundell	1/9/99-1/9/01	FOM 98PR1751	noncommutative geometry
Dr. D. Berman	1/9/99-1/9/00	TMR	noncommutative geometry
Ph.D. students	**appointment dates**	**employed by**	**topic**
B. Janssen	1/9/94-1/9/98	FOM Hth-G	properties of branes
A.H. Hams	1/9/96-1/9/98	FOM Hth-G	Dyson-Schwinger equations, computational physics
E.A. Eyras	1/9/95-1/12/99	FOM FP31	Kaluza-Klein monopoles
J.P. van der Schaar	1/9/96-1/9/00	FOM FP31	domain wall/QFT correspondence
T.C. de Wit	1/10/99-1/10/03	FOM FP31	Susy Randall-Sundrum scenario
R.S. Halbersma	1/7/98-1/7/02	FOM 98PR1751	Susy Randall-Sundrum scenario
M.G.C. Eenink	1/9/01-1/9/05	FOM FP57	non-Abelian Born-Infeld
D. Roest	1/9/00-1/9/04	RUG	massive dualities
A. Collinucci	1/9/01-1/9/05	RUG	non-Abelian Born-Infeld

PhD degrees awarded in Groningen (RUG), 1998-2001

1. B. Janssen, *Dualities of Strings and Branes*, University of Groningen, 12 june 1998 (Promotor: Prof.dr. D. Atkinson, referenten Dr. E.A. Bergshoeff, Dr. M. de Roo)
2. E.A. Eyras, *Brane Dynamics in Diverse Backgrounds*, University of Groningen, 11 june 1999 (Promotor: Prof.dr. D. Atkinson, referenten Dr. E.A. Bergshoeff, Dr. M. de Roo)
3. J.P. van der Schaar, *String Theory Limits and Duality*, University of Groningen, 30 june 2000 (Promotor: Prof.dr. D. Atkinson, referenten Dr. E.A. Bergshoeff, Dr. M. de Roo)

Relevant developments at the university

Prof.dr D. Atkinson retired in May 2000. In 2001 Dr. E.A. Bergshoeff was appointed as his successor. In 2000 our European TMR network *Quantum aspects of Gauge Theories, Supersymmetry and Unification* ended, and was continued as the RTN programme *The Quantum Structure of Spacetime and the Geometric Nature of Fundamental Interactions.* In the TMR network David Berman (Durham) joined our group as a postdoc for one year, in the RTN network Mikkel Nielsen (Goteborg) will come to Groningen for two years, starting in 2002. Contacts with Goteborg and other Scandinavian universities have been strengthened by our participation in the Nordisk Forskerutdanningsakademi (NORFA) programme *SupersymmetriskaFält- och Strängteorier* (1999-present).

Specific research topics, 1998-2001

In the period 1998-2001 our research programme centered on the following topics:

- Branes, and in particular domain walls (branes which D-2 spatial extensions in a D-dimensional spacetime) have played an important role in our research programme and have become a recurrent theme in our field. For instance, in the Randall-Sundrum scenario our universe is a domain wall

in a five-dimensional spacetime. The AdS/CFT correspondence can be extended to domain walls, and our group contributed to this Domain Wall/Quantum Field Theory correspondence.

- The dynamics of D-branes have been investigated. This resulted in a complete action for D-branes. Recently we have attempted to extend this work to the case where the fields on the branes include Yang-Mills fields, as in the Standard Model. Work along these lines is being continued at present.
- There is observational evidence for a small positive cosmological constant (de Sitter spacetime). The Randall-Sundrum scenario is hard to reconcile with supersymmetry, which is an essential part of string theory. We have made a specific proposal how to circumvent no-go theorems in this context.
- A intriguing aspect of branes is that, in a particular limit, the geometry on the brane becomes a so-called noncommutative geometry, in which coordinate functions no longer commute. The coordinates involved are the points where strings are attached to the brane. In the case of rolled-up membranes ending on higher branes the intersection is a circle, and we have shown that this gives rise to a noncommutative geometry of loops. This work has an interesting interface with mathematics, since not much is known about such geometries.

3.3 Universiteit Leiden (UL): FOM-L-01

Staff	appointment dates	employed by	topic
Prof. Dr. P.J. van Baal		UL	QFT
Prof. Dr. F.A. Berends		UL	Phenomenology
Dr. W.L.G.A.M. van Neerven		UL	Phenomenology
Dr. W.J.P. Beenakker	03/1995 - 09/1998	KNAW-fellow	Phenomenology
Prof. Dr. J. de Boer	01/1999 - 09/2000	FOM Springplank	Strings
Prof. Dr. A. Achúcarro	*from 04/2002*	*UL/FOM*	*Astro-Particle*
Postdocs	**appointment dates**	**employed by**	**topic**
Dr. T.G. Kovács	09/1998 - 09/2000	FOM FP31	QFT
Dr. F. Bruckmann	since 10/2001	FOM 99PR1797	QFT
Dr. A. Vogt	09/1998 - 09/2001	EU(TMR[1])	Phenomenology
Dr. C. Ford	since 07/2001	EU(Marie-Curie)	QFT
Ph.D. students	**appointment dates**	**employed by**	**topic**
Dr. A.P. Chapovsky	02/1996 - 11/1999	FOM FP31	Phenomenology
J. Schweizer[4]	09/2000 - 05/2001	FOM FP31	Phenomenology
Dr. T.C. Kraan	01/1996 - 04/2000	FOM 94MF14	QFT
Dr. J.A.H. Keurentjes	09/1996 - 09/2000)	UL	QFT/Strings
Dr. R.C.W. van Gulik[2]	05/1997 - 09/2001	UL/NIKHEF	Phenomenology/Exp
D. Nogradi[3]	since 12/2000	UL	QFT/Strings

[1)] FMRX-CT98-0194 (DG12-MIHT), TMR Research Network (EC), Quantum Chromodynamics and the Deep Structure of Elementary Particles. Coordinator W.J. Stirling, Durham, UK. Responsible scientist: W.L. van Neerven.

[2)] R. van Gulik, first and last year in Leiden, otherwise at NIKHEF and CERN. His output is not reported here, except for date and title of thesis.

[3)] D. Nogradi, is on unpaid leave from Oct 2001 for 9 months, to follow the Tripos III course at DAMTP, Cambridge, UK.

[4)] J. Schweizer, returned to home-University, Bern, Schwitzerland.

Ph.D. degrees awarded in Leiden 1998-2001.

1. A.P. Chapovsky, *Instability and radiative corrections in pair production of W-bosons*, 23 september 1999, Univ. Leiden, promotor: Prof. Dr. F.A. Berends, co-promotor: Dr. W.J.P. Beenakker.
2. T.C. Kraan, *Periodic Instantons and Monopoles*, Univ. Leiden, 30 March 2000. Promotor: Prof. Dr. P.J. van Baal.

3. J.A.H. Keurentjes, *New Vacua for Yang-Mills Theory on a 3-torus*, Univ. Leiden, 29 June 2000. Promotor Prof. Dr. P.J. van Baal, co-promotor Prof. Dr. J. de Boer.

4. R.C.W. van Gulik, *Resonance Production in Two-Photon Collisions*, Univ. Leiden, 22 November 2001. Promotores: Prof. Dr. F. A. Berends and Prof. Dr. F.L. Linde.

Relevant developments at the university

In Leiden some important changes in the staff will occur. Prof. F.A. Berends will retire at the end of 2003 and an important shift of research interests will be made with the appointment of Prof. A. Achúcarro to include active research in the field of theoretical cosmology and astroparticle physics. A few of her publications over the last 5 years are included under items 92-97 (see A.4) at the end of the Leiden publication list (but are of course **not** part of the Leiden output). She will start 1 May 2002 and will be an active member of this FOM programme.

Specific research topics, 1998-2001.

The research topics in the Ht-L working group for this period fall under the themes 'Phenomenology' and 'Quantum field theory'. It also included 'Quantum gravity and string theory', in particular in the period that Jan de Boer was in Leiden on a FOM-springplank position.

3.4 University Nijmegen (KUN): FOM-N-01

staff	date	emplyed by	topic
Dr. W. Beenakker	from 1/2001	FOM FP31/KUN	Field theory, rad. corr.
Prof. Dr. R. Kleiss		KUN	field theory, MC, multijets
Dr. Th. Rijken		KUN	Baryon-Baryon interactions
Prof. Dr. C. Dullemond		emeritus	Field theory, quantum mechanics
Prof. Dr. J. de Swart		emeritus	Nucleon-Nucleon interactions
visitors			
J. Nagata	up to 07/1998	Min. of Educ., Japan	phase-shift analysis
C. Makamoto	04/1999 - 03/2000	Min. of Educ., Japan	hybrid quark models
R. Bryan	06/2000-07/2000 and 10/2001-12/2001	Texas A&M	scalar mesons
Ph.D. students			
A. van Hameren	up to 01/2001	FOM FP31	numerical methods
C. Dams	from 10/2000	FOM FP31	Unstable particle collisions
H. Polinder	from 04/1999	KUN	Kaon-Nucleon models
P. Draggiotis	from 08/1998	KUN	QCD multijet production

Ph.D. degrees awarded in Nijmegen (KUN), 1998-2001.

1. A.F.W. van Hameren, *Loaded dice in Monte Carlo: importance sampling in phase space integration and probability distributions for discrepancies.*, Jan 2001. 160pp. Advisor: Prof. dr. R.H.P. Kleiss. e-Print Archive: hep-ph/0101094

2. M.C.M. rentmeester, *Applied Nucleon-Nucleon Partial-wave Analyses*, 21 May 2001. Advisor: Prof. dr. ir. J.J. de Swart

3. P. den Haan, *Aspects of QED renormalization in anti-de Sitter space*, 3 June 2001. Advisor: Prof. dr. C. Dullemond

Relevant developments at the university

In 2000, the EU program *Particle Physics Phenomenology at High Energy Colliders* was awarded, starting in August 2000 with a duration of 48 months. In 2001, Dr. W. Beenakker joined the group as UD with support from FOM.

Specific research topics, 1998-2001.

The research topics in the Hth-N working group fall under the themes 'Phenomenology' and 'Quantum field theory'. Specifically we mention

- Discrepancy distributions: in numerical (Monte-Varlo or quasi-Monte Carlo) integration the *discrepancy, i.e.* the nonuniformity of the point set used governs the accuracy of the method. We have applied techniques from quantum field theory to compute the distribution of discrepancies for random point sets. This will enable a valid assessment of the quality of quasi-random point sets to be used in integration.

- Phase-space Monte Carlo algorithms: a set of MC algorithms (`SARGE`) was developed to model accurately the phase-space distribution of QCD antennae, thereby allowing the MC calculation of multijet production at high-energy colliders to be speeded up by a large factor.

- Multijet QCD: a program was developed that allows the computation of multijet production (up to at least 8 jets) in hadron collisions. This will be used for QCD studies and background studies at the LHC.

- Zero-dimensional field theories: these serve as both a pedagogical paradigm and as an approximation (static ultralocal limit) to realistic field theories. We have studied the validity of perturbation theory as a function of the complex values of the coupling constants, explicit solutoins, and *recursive models* in which, for instance, higher-order corrections to certain amplitudes vanish beyond the one-loop order.

3.5 Universiteit Utrecht (UU): FOM-U-01

Staff	appointment dates	employed by	topic
prof. Dr. B. de Wit		UU	
prof. dr. G. 't Hooft		UU	
prof. dr. J.A. Tjon		UU	
prof.dr. E.P. Verlinde	till 2000	UU	
dr. S. Vandoren		UU	
dr. R. Loll		UU	
dr. N. Obers	1/7/2000 - 1/4/2002	FOM springplank	
Postdocs/visitors	**appointment dates**	**employed by**	**topic**
dr. V. Shevchenko	1/07/2001-1/7/2003	FOM FP31	
dr. S. Stanciu	1/10/1999-1/10/2001	FOM FP31	D-branes
dr. J. Barbon	1998	Pionier	
dr. D. Berman	1998	TMR	M-theory 5-brane
dr. G. Cardoso	1998-2000	TMR/Spinoza	supergravity/string theory
dr. M. O'Loughlin	1998-2000	Pionier	
dr. Y. Lozano	1998-1999	Spinoza	
dr. S. Massar	1998	Spinoza	quantum information theory
dr. H.J. Matschull	1998	UU/HCM/Spinoza	3-dim gravity
dr. M.K. Parikh	1998-2000	Pionier/Spinoza	
dr. K. Skenderis	1998-1999	Pionier	
dr. S.N. Solodukhin	1998-2000	Spinoza	
dr. A.E.M. v.d. Ven	1998-2000	Spinoza	
dr. H. Anastopoulos	?? - ??	Marie Curie	Quantum gravity?
dr. A. Sinkovics	2000	Spinoza	
dr. G. Arcioni		UU	
dr. G. Bonelli	1999-2001	Pionier	branes/gravity
dr. A.M. Boyarsky	1999-2001	Spinoza	branes/gravity
dr. B. Körs	2001-2003	NWO	
dr. J.F. Morales Morera	2000-2002	TMR[2)]	
dr. M.K. Parikh	2001-2003	Pionier/Spinoza	branes/gravity
dr. H. Samtleben	2001-2003	UU	
dr. M.M. Taylor-Robinson	2001-2003	NWO	
dr. U. Theis	2001-2003	DFG	
dr. M. Trigiante	2000-2002	RTN/Marie Curie	D-branes
dr. S. de Haro	2001-2003	Spinoza	
Ph.D. students	**appointment dates**	**employed by**	**topic**
drs. B.J.K. Kleijn	1/9/1994 - 1/9/1998	FOM Hth-U	supergravity
drs. V. Pascalutsa	1/9/1994 - 1/9/1998	FOM Hth-U	πN interaction
drs. G.A.P.T. Aarts	1/10/1995 - 1/10/1999	FOM FP31	baryogenesis
drs. J. Weda (oio)	1/9/1999 - 1/9/2003	FOM FP31	confinement in mesons
drs. J. Käppeli	1/4/1999 - 1/4/2003	FOM FP31	supersymmetry
drs. M. Holman	1/11/1999 - 1/11/2003	FOM PR/IGGN	
drs. G.T.J. Zwart	1/11/1995 - 1/11/1999	FOM	
drs. I. Herger	1998-2001	FOM	supergravity and AdS/CFT
drs. C.M. Hofman	1996-2000	oio	duality
drs. I.L. Savonije	1998-2002	NWO	holography/cosmology
drs. B.J.W. van Tent	1998-2002	aio	cosmology
drs. G.T.J. Zwart	1998	oio	extended objects in string th.
drs S. de Haro	1997-2001	UU	Black holes
drs. Z. Kadar		UU	
drs. S. Nobbenhuis		UU	

[1)] ERBCHBGCT940690, Physics at every scale. Coordinator: Universiteit Utrecht (J.E. van Himbergen).

Responsible scientist: G. 't Hooft. Duration: 1-12-94/1-3-98
[2)] ERBCHRXCT940621, Gauge theories in elementary particle physics and gravitation. Coordinator: Foundation for Research and Technology-Hellas, Crete (E.N. Economou). Responsible scientist: G. 't Hooft. Duration: 1-1-95/31-12-98
[3)] INTAS-contract: 96-0308, Quantum structure of gauge theories and extended supersymmetry. Coordinator: Univ. of London, King's College (P. Howe). Responsible scientist: B. de Wit. Duration: 1-10-97/1-10-99
[4)] ERBFMRX-CT96-0045, Quantum aspects of gauge theories, supersymmetry and unification. Coordinator: Katholieke Universiteit Leuven, België (A. Van Proeyen). Responsible scientist: B. de Wit. Duration: 1-9-96/1-9-00

Ph.D. degrees awarded in Utrecht (UU), 1998-2001.

1. Kleijn, B.J.K.: New couplings in $N = 2$ supergravity. Promotor: B. de Wit. Utrecht, May 25, 1998.

2. Pascalutsa, V.: Covariant description of pion-nucleon dynamics. Promotor: prof.dr. J.A. Tjon. Utrecht, October 19, 1998.

3. Peeters, K.: Geometrical aspects of supersymmetry. Spinning particles, string dualities and the eleven-dimensional supermembrane. Promotor: B. de Wit. Utrecht, June 3, 1998.

4. Welling, M.: Classical and quantum gravity in 2+1 Dimensions. Promotor: G. 't Hooft. Utrecht, January 19,1998.

5. Aarts, G.A.P.T.: *Dynamics in equilibrium and nonequilibrium quantum field theory*, Promotor: prof.dr. J. Smit. Utrecht, October 4, 1999.

6. Zwart, G.T.J.: *String perspectives on gauge theories.* Promotor: prof.dr. E.P. Verlinde, Utrecht, November 29, 1999.

7. Hofman, C.M.: *Strings, Matrices, and Noncommutative Gauge Theory.* Promotor: prof. dr. E.P. Verlinde, Utrecht, September 19. 2000.

8. Haro Ole, S. de: *Quantum gravity and the holographic principle (type I).* Advisor: prof. dr. G. 't Hooft, Utrecht, Juni 18. 2001.

Relevant developments at the university

The theoretical high-energy physics activities are carried out in the context of the program *Quantum Gravity, Strings and Supersymmetry* of the Spinoza Institute and the program *Quantum Gravity, Strings and Elementary Particles* of the Institute for Theoretical Physics. Both Institutes belong to the Department of Physics and Astronomy of Utrecht University.

Specific research topics, 1998-2001.

The research topics in the FOM program Fundamental Interactions cover all three themes 'Quantum gravity and string theory', 'Quantum field theory' and 'Phenomenology'.

3.6 Vrije Universiteit Amsterdam (VUA): FOM-V-01

Staff	dates	employer	topic
Prof. Dr. P.J. Mulders	since 01/01/1998	VUA	
Dr. B.L.G. Bakker		VUA	
Dr. D. Boer	since 01/07/2001	KNAW	
Postdocs/visitors	**dates**	**employer**	**topic**
Dr. A. Metz	01/09/2000-01/12/2001	EU-IHP[2)]	Chiral symmetry and
	01/12/2001-01/07/2002	FOM-FP31	fragmentation functions
Dr. R. Kundu	01/10/2000-01/12/2001	FOM-FP31	Lightcone field theory
Dr. M. Boglione	15/10/1997-15/02/1999	EU-TMR[1)]	Deep inelastic scattering
	16/02/1999-01/07/2000	FOM-98PR1714	and azimuthal asymmetries
Prof. Dr. E. Leader	1998 - 2002	FOM-98PR1714	Deep inelastic scattering
Dr. B. Krippa	01/03/1999-31/05/2001	FOM-98PR1714	Chiral symmetry
		Russian Academy	
Dr. J.G. Milhano	01/10/2001-01/10/2003	VUA	Low x/Phases of QCD
Ph.D. students	**dates**	**employer**	**topic**
Drs. N. Schoonderwoerd	15/12/1995-01/03/1999	FOM-Hth	Lightcone field theory
Drs. M. van Iersel	01/08/1999-01/08/2003	FOM-FP31	Lightcone field theory
Drs. A. Bacchetta	01/11/1998-01/11/2002	FOM-98PR1714	Transverse spin polarization
Drs. A. Henneman	01/10/1996-01/08/2001	VUA	Evolution and transverse momentum
Drs. J. Rodrigues	1994 - 1998	external[3)]	Gluon correlations in DIS
Drs. F. Pijlman	01/11/2001-01/11/2005	VUA	DIS/intrinsic transverse momentum
Drs. H. Warringa	01/12/2001-01/12/2005	VUA/USF	Phases of QCD

[1)] EU-TMR HAPHEEP: ERBFMRX-CT-96-0008, TMR Research Network (EU), Hadronic Physics with High Energy Electromagnetic Probes. Coordinator J.-M. Laget, Saclay, France. Responsible physicist: P.J. Mulders

[2)] EU-IHP ESOP: HPRN-CT-2000-00130, IHP Research Network (EU), Electromagnetic Scattering off Confined Partons. Coordinator J.-M. Laget, Saclay, France. Responsible physicist: P.J. Mulders

[3)] supported by the University of Lisbon and PRAXIS programme.

Ph.D. degrees awarded in Amsterdam (VUA), 1998-2001.

1. D. Boer, *Azimuthal asymmetries in hard scattering processes*, 15 Sep 1998, Vrije Universiteit. Promotor: Prof. dr. P.J.G. Mulders.

2. N.C. Schoonderwoerd, *Light front hamiltonian field theory; towards a relativistic description of bound states*, 14 Jan. 1999, Vrije Universiteit. Promotor: Prof. dr. P.J.G. Mulders; copromotor: Dr. B.L.G. Bakker.

3. J. Rodrigues, *Modelling quark and gluon correlation functions*, 16 Oct. 2001, Vrije Universiteit. Promotor: Prof. dr. P.J.G. Mulders.

Relevant developments at the university

The theoretical high-energy physics activities at the VU are part of the Theoretical Physics department within the Division of Physics and Astronomy. In 1999 the university has approved a proposal of Prof. Mulders to initiate studies on *Phases of QCD*. This program has started recently and is performed in collaboration with Dr. D. Boer, who has been appointed as a KNAW fellow in 2001.

Specific research topics, 1998-2001.

In VU theory group working in particle physics, a number of topics are addressed belonging to themes 'Quantum field theory' and 'Phenomenology'.

- Deep inelastic scattering processes. The emphasis of the group is on the inclusion of effects of parton intrinsic transverse momentum. This gives rise to azimuthal asymmetries, in particular in polarized processes. For this a detailed analysis of quark distribution and fragmentation functions in polarized hadrons has been made.

- Lightcone quantization. Quantization in the front form is in principle equivalent to instant form quantization. In practice many details remain to be studied. For QCD front form quantization may be a promising route, because the wave functions in the hamiltonian formulation can be directly connected to the quark distribution functions in deep inelastic scattering.

- The study of phases in QCD, that may have played a role in early-universe physics, is a research line that has just started in 2001.

4 FOM programme 52 at NIKHEF[1)]

Staff	dates	employer	
Prof. Dr. J.W. van Holten		NIKHEF/FP52	
Prof. Dr. J. Koch		NIKHEF/FP52	
Prof. Dr. E. Laenen		NIKHEF/FP52	
Prof. Dr. A.N. Schellekens		NIKHEF/FP52	
Dr. J.A.M. Vermaseren		NIKHEF/FP52	
Postdocs	**dates**	**employer**	**topic**
dr. J. Plefka	1996-1998	NIKHEF/FOM	String th. & supergravity
dr. A. Waldron	1997-1999	NIKHEF/FOM	String th. & supergravity
dr. S. Moch	1997-2000	NIKHEF/FOM	Phen. & QCD
dr. S. Weinzierl	1998-2000	NIKHEF/FOM	Phen. & QCD
dr. V. Pascalutsa	1998-1999	NIKHEF/FOM	Phen. & hadron physics
dr. K. Schalm	1999-2001	NIKHEF/FOM	String th. & supergravity
dr. M. Zhou	2000-2002	NIKHEF/FP52	Phen. & QCD
dr. A. Vogt	2001-2003	NIKHEF/FP52 and FP7	Phen. & QCD
dr. F. Riccioni	2001-2003	NIKHEF/FP52	Supersymmetry & supergravity
Ph.D. students	**dates**	**employer**	**topic**
L. Haakman	1994-1998	NIKHEF/FOM	Phen. & QCD
S. Groot Nibbelink	1997-2000	NIKHEF/FOM	Supersymmetry & supergravity
T.O. Eynck	1998-2002	NIKHEF/FOM	Phen. & QCD
T.S. Nyawelo	2000-2004	NIKHEF/FP52	Supersymmetry & supergravity
J. van der Heide	2000-2004	NIKHEF/FP52	Finite temp. QCD & Phen.
K. Peeters	1994-1998	FOM 94BR1253	String th. & supergravity
D. Boer	1994-1998	FOM 94BR1217	Phen. & QCD
L. Huiszoon	1998-2002	FOM 97MF02/03	String th.
N. Sousa	1998-2002	Min. Science Portugal[2)]	String th.
L. Phaf	1999-2003	NIKHEF/FP7	Exp. & QCD
M. Lutterot	1999-2001	NIKHEF/FP21	Finite temp. QCD & Phen.
A. Fuster	2001-2005	Basque Min. Educ.[3)]	Supersymmetry & supergravity
Visitors	**year**	**financial support**	
J. Smith (SUNY)	2000	NIKHEF/FOM	
A. Mueller (Columbia)	2000	NIKHEF/FOM	
E. Laermann (Bielefeld)	2000, 2001	NIKHEF/FP52 and FP21	
P. Yndurain (Madrid)	2001	NIKHEF/FP52	
P. Horvathy (Tours)	2001	NIKHEF/FP52	
P. Jarvis (Tasmania)	2001	NIKHEF/FP52	
M. Veltman	(perm.)	NIKHEF/FP52	

[1)] The programme provides the complete support for staff, research and infrastructure of the NIKHEF Theory Group.

[2)] Fundação para a Ciência e Technologia

[3)] Depart. de Educación. Universidades e Investigación

Ph.D. degrees awarded in NIKHEF Theory Group 1998-2001.

1. K. Peeters, *Geometrical Aspects of Supersymmetry*, June 1998, Univ. Utrecht; promotor: Prof. Dr. B. de Wit, co-promotor: Dr. J.W. van Holten.

2. L.P.A. Haakman, *QCD Aspects of the Pomeron: from soft to hard scales*, June 1998, Univ. of Amsterdam; Promotor: Prof. Dr. J. Koch.

3. D. Boer, *Azimuthal Asymmetries in hard Scattering Processes*, Free Univ. Amsterdam, September 1998; Promotor Prof. Dr. P.J. Mulders.

4. S. Groot Nibbelink, *Supersymmetric non-linear Unification in Particle Physics*, Free Univ. Amsterdam, November 2000; Promotor: Prof. Dr. J.W. van Holten.

Relevant developments at the NIKHEF institute

Several NIKHEF scientists hold special chairs at one of the universities, where they contribute to teaching and research. In theoretical physics van Holten is associated with the Free University (VUA), Koch with the university of Amsterdam (UvA), Laenen with the university of Utrecht (UU), and Schellekens with the university of Nijmegen (KUN).

NIKHEF Research Programme 1998-2001

The research of the NIKHEF Theory Group covers a broad range of subjects from hadron structure, QCD and supersymmetry to string theory, with an emphasis on particle physics phenomenology. The main topics are summarized here.

- *QCD: physics of the standard model and beyond*
  Work in QCD centers around high-order perturbation theory and its applications to phenomenology. We mention three projects in particular:
  a. The precision of present day collider experiments requires NNLO calculations in QCD to match theory with experiments. To carry out accurate tests of the standard model and search for signals of new physics at the Tevatron and LHC, a precise knowledge of the running coupling $\alpha_s(\mu^2)$ and the parton densities inside the nucleon is mandatory. The calculations necessary to determine the nucleon structure functions to the required level of precision involve huge numbers (thousands) of Feynman diagrams, and can only be performed using the most sophisticated computer algebra techniques available. The programme FORM developed by Vermaseren represents the state of the art, and is the de facto world standard for calculations in high-energy physics. In collaboration with S. Moch, A. Vogt and M. Botje he is involved in a project to develop a complete new set of parton distribution functions in NNLO meeting the highest standards for the LHC.
  b. Resummation techniques allow to go one step beyond perturbation theory, or to improve perturbation theory when large radiative corrections are present which do not become negligeable at any order of perturbations theory. In particular, the effect of soft gluons and long-range correlations are taken into account by Sudakhov-resummation of large logarithms factorizing in cross sections and decay rates. Laenen and co-workers have developed such techniques for various processes, including $\bar{t}t$ production at NLO in proton collisions, and the electroproduction of charm to NNLO. They lead to markably improved results, such as strongly reduced scale-dependence of cross sections and better control over tranverse momentum effects.
  c. To relate theoretical calculations with experimental data, it is important to develop Monte Carlo programs for the calculation of event distributions of various types. At NIKHEF NLO Monte Carlo generators have been developed for heavy quark production in photon and ep collisions, as well as for single top production in pp-scattering. The latter one is presently being integrated in the D0-experiment and will allow the determination of top couplings in the CKM matrix.

- *Hadrons at finite temperature*
  The transition between the confined and unconfined phases of QCD is preceded by a transition

region in which the structure of hadrons changes: a 'melting' process in which the size increases and partons can move more freely at large distances. To investigate these processes, Koch has initiated a programme to study hadron form factors at finite temperature. The lattice calculations on which these studies are based are carried out in collaboration the university of Bielefeld (E. Laermann).

- *Supersymmetry*
  a. Supersymmetry appears in many guises; in field theory it can be used as a Bose-Fermi symmetry to extend the standard model, directly or in a gauge unification scenario. In supergravity it is elevated to the status of a local symmetry. As the unification scale is supposedly close to the Planck scale, both linear and non-linear gauge-unification scenarios can be incorporated in a supergravity frame work. Consistency of such scenarios depends on the cancellation of anomalies; van Holten and co-authors have found a way to circumvent previous no-go theorems in this context allowing anomaly matching in non-linear unification schemes based on Kaehler coset spaces like $SO(10)/SU(5)\times U(1)$ or $E_6/SO(10)\times U(1)$.
  b. Supersymmetries also arise in the context of the quantum mechanics of spinning particles and strings; in certain non-trivial background fields, associated with monopoles, instantons or black holes, non-standard supersymmetries can be realised, first discovered jointly by Gibbons, Rietdijk and van Holten. This work has been extended and applied to various systems; it has also inspired work to find an expression for anomalies in space-times with torsion and non-trivial boundaries (Peeters and Waldron).

- *Open string theory*
  String theory is the main candidate for a theory of quantum gravity. As no string-field theory exists, perturbation theory for closed strings is formulated in terms of conformal field theories on Riemann-surfaces. For open strings, such a formulation is more difficult. Schellekens and his students study the conformal field theory formulation of open strings, studying in particular the role of structures known as D-branes and O-planes. This work will be continued in the context of the FOM-programme *Strings and Quantum Gravity* (FP57).

- *Classical gravity*
  Classical gravity and cosmology are sidelines of theoretical research at NIKHEF. Van Holten has studied exact gravitational-wave solutions and perturbative expansions for geodesic motion in gravitational background space-times. Groot-Nibbelink and van Tent (UU) have developed a theory of cosmological scalar fields and fluctuations in the CMBR in the context of supersymmetry.

5 Future of the programmes

5.1 Change and continuity in programme and network

The programmes under review, FP31 based at the universities and FP52 based at NIKHEF, have strong thematic links. In addition, a programme *String theory and quantum gravity* (FP57) co-ordinating all research in these fields, has recently been approved. Together these three programmes constitute since January 1, 2002 a Research Network for Theoretical High-Energy Physics in the Netherlands. Programmes and network have an important impact on research and training in this branch of theoretical physics. All active theoretical high-energy physicists in the Netherlands participate in one or several of the programmes.

The programmes will continue to jointly organize the national seminar on theoretical high-energy physics, an annual series of five one-day meetings of all researchers in the field, at the NIKHEF institute, where ongoing research projects are presented by staff, post-docs and PhD students. Already since the spring of 2000 the two universities in Amsterdam and NIKHEF alternatingly organize a seminar on astroparticle physics and cosmology, attended by colleagues from other research groups (Leiden, Utrecht) as well. The string theory programme organizes widely announced weekly research seminars, alternating between Utrecht and Amsterdam.

The group in Groningen is preparing an international workshop on strings, branes and cosmology to be held in Leiden in November 2002. In August 2003 an Advanced Study Institute on Astro-particle physics will be organized together with experimental subatomic physicists and astronomers.

As mentioned in section 2, staff members of various groups hold special professorships at other locations. The Network and in particular the proposed future research projects around selected themes in the different programmes will stimulate these joint appointments as well as the very important possibilities for Ph.D. students and post-docs at different locations to work on joint projects.

Like in other branches of physics, developments in theoretical high-energy physics are fast and sometimes unexpected. To stay in the forefront of research the programme of the Dutch research community must be flexible and innovative. Compared to the originally approved programmes FP31 and FP52, for the next few years we propose the continuation of succesful projects as well as the exploration of new areas of research. Projects will center around topics in quantum field theory, particle phenomenology and astroparticle physics. It is to be stressed that these three topics are closely interwoven, and researchers often work in more than one field. We provide a brief overview of active developments in each area in turn.

5.2 Quantum field theory

After many years of development quantum field theory (QFT) is still a field full of new ideas and surpises. Fundamental problems in quantum field theory can be identified both in the perturbative and non-perturbative regime.

1. In perturbatively renormalizable QFT an important objective is to find analytic expressions for Feynman diagrams with an arbitrary number of loops. In recent times considerable progress in this direction has resulted from the study of the properties of Mellin transforms and harmonic polylogarithms. The structure of multi-loop diagrams will be further investigated by van Neerven (UL) and Vermaseren (NIKHEF) under the programmes FP31 and FP52.

2. At the interface of perturbative and non-perturbative quantum field theory, resummation techniques are an important tool to analyse all-order perturbative behaviour of field theoretical expressions. Such resummation techniques are closely linked to the factorization properties of the observables in a field theory. Quantum corrections at high orders can become large, e.g. as a result of long-distance correlations. Laenen (NIKHEF/UU) will study extensions and applications of these techniques, in particular in the context of QCD.

3. The presently ongoing project in lightcone field theory by Bakker (VU) is the study of front form quantization as a possible nonperturbative approach to study bound states in field theories. The

developments are aimed at applications in QCD to study quark and gluon distribution and fragmentation functions.

4. On the non-perturbative level, non-trivial topological configurations of gauge theories imply the existence of stable objects or well-defined excitations such as monopoles, vortices and instantons. The study of the spectrum and properties of these topological excitations has revealed rich underlying branches of mathematics involving intricate geometrical and group-theoretical structures. Quantum groups and Hopf algebras have been found to play a rôle. Dualities between electric and magnetic charges and phases, as well as between strong- and weak-coupling regimes shed light on the various realizations of symmetries and the phase structure of these theories. Bais and coworkers (UvA) plan specific investigations of such topological properties of quantum field theories, especially in 2 and 3 dimensions. New developments in the classification of the phases of non-abelian (topological) field theories and the related breaking of quantum symmetries have exciting consequences and will be studied in the programme FP31.

5. The quest for understanding of QFT in the perturbative and non-perturbative regimes has stimulated studies of QFT at finite temperature, volume and/or density. Van Baal (UL) investigates non-perturbative aspects of field theories at finite temperature and in finite volume with the aim of increasing the understanding of the relations between different types of topological excitations. An effort to clarify the rôle of self-dual solutions known as calorons will be made. Furthermore, he intends to extend these studies to supersymmetric field theories in finite volume. Because of the sensitivity of such field theories to the global topology of the configuration space, it is expected that topological effects will have a large impact on non-perturbative dynamics.

6. Other studies of finite-temperature QFT address the construction of effective classical actions, the subject of studies by van Weert (UvA), and the dynamics of phase transitions in gauge theories, which may be relevant to heavy ion collisions as well as to the physics of the early universe. Smit (UvA/UU) investigates in particular the non-equilibrium aspects of the dynamics, and the rôle of topological defects. In the context of the programme FP31 he intends to develop methods for real-time simulations, and to address applications to the problem of baryogenesis in the early universe. Prof. Koch (NIKHEF/UvA) and coworkers address the finite temperature properties of QCD by studying the temperature dependence of hadron form factors using a lattice approach. Boer (VUA) has recently started to investigate topological (instanton) aspects of the phase diagram of QCD, in particular regarding the color superconducting phase and the possibility of spontaneous CP violation in QCD, including the relation to heavy ion collisions and the physics of neutron stars.

7. Symmetries determine many properties of quantum field theories. They determine e.g. the spectrum of states, the nature of interactions and the analytical properties of the S-matrix. Space-time symmetries also determine the Planck-scale aspects of QFT, in particular the coupling to gravity. A symmetry of particular interest is supersymmetry, which can be used to construct extensions of the standard model of particle physics at the TeV scale, models of unified gauge interactions (GUTs) as well as supergravity theories. The interplay of supersymmetry and internal symmetries, including the cancellation of anomalies in 4-D non-linear supersymmetric field theories, is studied by van Holten (NIKHEF/VUA). He also investigates supersymmetries and generalizations of supersymmetry in the quantum mechanics of point particles, such as found in the background of monopoles and black holes. As an extension of these studies he has started a project to study supersymmetric generalizations of fluid dynamics (spinning fluids).

5.3 Phenomenology

The applications of quantum field theory to the realm of particle physics provide a rich source of research problems, of importance both to the analysis of existing and the planning of future experiments. Particular topics to be studied are found in the area of the standard model, as well as in possible physics beyond the standard model.

1. The single most important topic in electroweak interactions at present is the mechanism of symmetry breaking and the properties of the Higgs particle(s). The experiments planned at the Tevatron, LHC and future linear electron-positron colliders all aim to establish the existence of the Higgs particle and measure its mass and couplings to quarks and leptons. These studies will reveal the nature of spontaneous symmetry breaking in the electroweak interactions. Signals for the production of a Higgs boson, and the separation of signal and background, require the computation of radiative corrections due to strong interactions (QCD) in next-to-next-to-leading order (NNLO). Such high-order corrections in QCD involve multi-loop diagrams as computed by van Neerven (UL) and Vermaseren (NIKHEF), who has developed the widely used computer algebra programme FORM for such purposes.

2. A quantity of particular importance is the NNLO total cross section for hadron-hadron scattering, which is required to improve our understanding of Higgs-boson production at hadron colliders like Tevatron and LHC. Van Neerven (UL) has undertaken a computation of this total cross section, valid also in the domain of large Higgs boson mass ($m_{Higgs} \sim m_{top}$), which is to be completed under the present programme.

3. Another important development in electroweak physics is the recent strong evidence for neutrino masses and oscillations. Apart from its intrinsic interest and the opening up of new channels for CP-violation in the context of the standard model, it has profound implications for the production and spectrum of neutrinos from astrophysical sources. Gaemers (UvA/NIKHEF) and van den Horn (UvA) study the physics of neutrinos and the astrophysical processes in which they are produced. Also Mulders (VUA) plans studies on neutrinos not only from astrophysical but also from terrestrial sources such as a possible future neutrino factory.

4. The study of heavy quarks bridges the domain of both the strong and the electroweak interactions. The production of top-quarks and b-quarks will enable the determination of their coupling to the Higgs field by measuring the fundamental parameters of the standard model encoded in the CKM matrix. In particular the physics of B-mesons provides an important window on CP-violation, the only one —apart from the neutral kaon system— we can presently study. Laenen (NIKHEF/UU) and coworkers study single-top production, contributing directly to the analysis of Tevratron data. Charm and B-production at colliders are being investigated as well.

5. Application of field theoretical techniques to QCD require dedicated effort. In order to arrive at a reliable prediction of multijet QCD processes, as well as processes involving both QCD and electroweak interactions, it is necessary to understand the colour structure of the cross section. Kleiss (KUN) intends to study colour flow in multijet processes. For accurate MC simulation of complicated processes with many external particles, adequate phase-space algorithms need to be developed. This is a continuing field of research at the KUN (Kleiss). Also, for processes with many external legs, described by extremely large numbers of Feynman diagrams, explicit diagram-by-diagram evaluation quickly becomes impractical. The succesful Caravaglios-Moretti algorithm to compute large tree-level amplitudes needs, if at all possible, to be extended to include loop corrections without invoking the effective action. The feasibility of such an approach will be investigated.

6. Not only in QCD, also in electroweak theory resummation improves the behaviour of perturbative expressions for physical quantities. High-order corrections will be of particular importance at future (linear) colliders. Beenakker (KUN) is involved in such calculations, with special emphasis on large doubly-logarithmic (Sudakov) effects.

7. The structure of hadrons, in particular the proton, is quite complicated. In fact the density of partons (quarks and gluons) inside a proton depends on the energy scale at which it is probed, as described by the parton distribution functions. A precise comparison of the theory with present experiments is possible only if NNLO quantum corrections from QCD are taken into account. The knowledge of proton structure to this accuracy is indispensable for the analysis of data from Tevatron

and LHC. Vermaseren and Vogt (NIKHEF) have recently begun a project under the programme FP52 to develop a set of NNLO parton distribution functions meeting the highest standards of precision presently within reach.

8. The study of the quark spin and flavour structure of the nucleon has uncovered an intriguing role for the intrinsic transverse momenta of partons. These are found in azimuthal asymmetries in high-energy semi-inclusive processes, which actually have been observed in LEP (CERN) and HERMES (DESY) experiments. This makes the study of the factorization properties within the framework of QCD necessary. This will become the focus of new theoretical studies of Mulders and Boer (VUA).

9. The study of the baryon (meson) - baryon interactions will remain the main subject of Rijken (KUN). With the coming of the Japan-Hadron-Facility (JHF) in 2006, the study of baryon-baryon interactions will enter a new era. The detailed description and understanding of these interactions will be basic for the analysis of the new experiments and the possibility for progress in the theory of nuclear- and stellar- structure. In particular strange matter will be an important topic.

10. New physics beyond the standard model, such as supersymmetry, implies the existence of a more complicated Higgs sector, involving also new pseudoscalar particles. The computation of their coupling through radiative corrections requires a proper treatment of γ_5 and the ϵ-tensor in regularized perturbation theory, in particular in the presence of IR and collinear divergences. This problem will be addressed by van Neerven (UL).

11. Supersymmetric unification close to the Planck scale in an effective supergravity scenario may involve non-renormalizable couplings, not only in the gravitational but also in the gauge sector. Consistent (anomaly-free) models with a standard-model fermion generation spectrum are studied by van Holten and coworkers (NIKHEF/VUA).

5.4 Astroparticle physics

Increasing amounts of precise and exciting data on astrophysics and cosmology have opened up the study of applications of field theory and particle physics to the dynamics and evolution of the universe at large. Studies of the proper motion of stars in galaxies, and of galaxies in clusters point to the existence of large amounts of non-baryonic dark matter, the nature of which is presently completely unknown. Speculations run from black holes to weakly interacting heavy neutral particles, such as are predicted e.g. by supersymmetric extensions of the standard model.

New states of ordinary baryonic matter can arise under extreme pressure and density, as in neutron stars, or at extreme density and temperature, as in the early universe. Phase transitions can occur, driven for example by electroweak symmetry breaking, chiral symmetry breaking in QCD, or GUT-scale symmetry breaking close to the Planck scale. In such processes localizable or quasi-localizable extended objects can be formed, like monopoles and strings. All such processes can be modeled in analytical and numerical studies of field theories at finite density and temperature. Laboratory experiments in condensed matter systems can provide experimental tests of such calculations.

A special and important problem in this relation is the origin of baryonic matter, and the domination of matter over anti-matter. Its explanation must involve unusual but real field-theory and particle-physics effects, like CP-violation and non-equilibrium thermodynamics.

Research efforts in these directions in the context of the present programmes (FP31 and FP52) are to be stepped up.

1. We already mentioned the involvement of Smit (UvA) in numerical simulations of phase transitions in the standard model with an eye to the problem of baryogenesis. Also the plans of Koch (NIKHEF/UvA) to study cosmological applications of his work on the phase transition between a hadron gas and a quark-gluon plasma as well as the work of Boer (VUA) on QCD phases have astrophysical impact

2. Prof. Achúcarro (UL) has recently been appointed in Leiden to study the cosmological phase transitions and the formation of topological excitations in such processes. The simulation of such

processes in condensed matter systems has her special interest[1]. Prof. van Weert (UvA) is also involved in studies of phase transitions in condensed matter systems.

3. The observed expansion and flatness of the universe, deduced from the recent measurements of the redshift of distant supernovae and the fluctuation spectrum of the cosmic microwave background, provide evidence for an epoch of inflation and the existence of dark matter and energy, including a cosmological constant. Cosmic scalar fields can provide a mechanism to drive inflation and/or provide the dark energy necessary to explain the observed flatness of space. The origin and dynamics of such cosmic scalar fields may open up an observational window on Planck scale physics. Other windows on the universe at very early times are expected from the study of relic neutrinos and gravitational waves. In recent years Prof. van Holten (NIKHEF/VUA) has been involved in the study of the properties, the sources and the detection of gravitational waves. He is advisor to the DFG (Germany) in setting up a theory programme linked to the GEO 600 gravitational wave observatory. Under his supervision and that of prof. 't Hooft (UU), Groot Nibbelink (NIKHEF) and van Tent (UU) have begun to investigate cosmological scalar fields and their rôle in driving inflation. Such studies will be extended in the near future.

4. We already mentioned the interest in neutrinos from astrophysical sources and their production mechanisms by Gaemers (UvA/NIKHEF) and van den Horn (UvA). The participation of NIKHEF in the ANTARES experiment to develop a high-energy neutrino telescope in the Mediterranean has stimulated interest in the astrophysics and cosmology involved. It is intended to initiate a new line of research in this direction by appointment of a junior researcher (post-doc/tenure track level) under the programme FP52.

5. At the intersection with string theory, scenarios for cosmology based on brane worlds have been developed recently and are presently under intense investigation. Supersymmetry, which is a desirable property from the phenomenological point of view, is hard to reconcile with these models. In a similar vein, supersymmetry and a positive cosmological constant, which is indicated by recent observations, do not go well together. Bergshoeff and de Roo plan to investigate these problems. The groups in Leiden, Amsterdam and Groningen will organize the International Workshop Branes and Cosmology at the Lorentz Center in Leiden in november 2002. One of the purposes of this Workshop is to stimulate interactions between the theoretical physics and astronomy communities in the Netherlands.

[1] Prof. Achúcarro is presently secretary of COSLAB, an ESF programme to support studies of cosmology in the laboratory.

6 Programme summary and requested support

6.1 FP31: Fundamental interactions

The summary of the status at present is given in the following table, containing the actual number of postdoc and graduate student months spent in the years 1999, 2000 and 2001, the number of months committed because of currently employed postdocs and graduate students and the remaining number of months that according to the plans in section 5 will be spent in the years 2002 up to end of 2006 in the programme FP31.

location	total in proposal	actually used in 1999-2002	already committed 2002-2007	remaining request 2002-2007
Staff (months)	84	36	48	0
FOM-A-01	84	36	48	0
FOM-L-01				
Postdocs (months)	240	103	78	96
FOM-A-01		23	21	24
FOM-G-01		3	21	0
FOM-L-01		20	0	24
FOM-N-01		12	12	24
FOM-U-01		30	18	0
FOM-V-01		15	6	24
OIOs (months)	816	291	143	336
FOM-A-01		72	35	96
FOM-G-01		58	21	0
FOM-L-01		20	0	96
FOM-N-01		39	33	48
FOM-U-01		70	35	48
FOM-V-01		32	19	48

Table 6.1: Employment of post-docs and PhDs in FP31

The remaining positions are intended to support the following research projects (the numbers refer to the items listed in section 5):

group	position	supervisor	field	topic
FOM-A-01	oio	Smit	Astro-particle	5.2.6; 5.4.1
	oio	Bais	QFT	5.2.4
	pd		QFT/Astro-particle	5.2.4/5/6; 5.4.1
FOM-G-01	pm		Astro-particle	5.4.5
FOM-L-01	oio/pd	Achúcarro	Astro-particle	5.4.2
	oio	van Neerven	Phenomenology	5.3.1/2/10
	pd	van Baal	QFT	5.2.5
FOM-U-01	oio	't Hooft	QFT	5.2.x
FOM-N-01	oio	Kleiss	Phenomenology	5.3.5
	pd		Phenomenology	5.3.6
FOM-V-01	oio	Mulders	Phenomenology	5.3.8
	pd		Astro-particle	5.2.6

Table 6.2: Requested support in FP31

6.2 FP52: Theoretical subatomic physics

The NIKHEF Theory Group being based at a FOM research institute, not only its research grants but basically all its financial support comes through FOM, including staff salaries, infrastucture and overhead. As its budget is part of the NIKHEF budget, and separate from the university support programme FP31, the NIKHEF programme FP52 receives independend funding. For the remaining period of the programme FP52, the years 2003-2007, we request the following *annual support*:

	Amount p.a. (kEuro)
Personnel:	
- 5 senior staff	410
- 1 visitor position	40
- 2 junior staff (post-doc)	90
- 3 Ph D positions	105
Material and travel support	40
Indirect costs	180
Total	865

Table 6.3: Total annual budget request for FP52

The research programme to be supported by these positions is summarized below.

senior staff	research fields
J. Koch	QCD and hadron structure at finite temperature
E. Laenen	perturbative QCD, heavy quark physics and Sudakov effects
A.N. Schellekens	open string theory and D-branes
J.W. van Holten	supersymmetry, gravity and cosmology
J.A.M. Vermaseren	multiloop QCD, structure functions and computer algebra

Table 6.4a: Permanent staff FP52

post-docs	research field	topic	# months
2	high-order perturb. QCD/structure functions	5.3.1/4/7	48
1	astroparticle/neutrino physics	5.4.4/1/3	24
1	QCD/hadrons at finite temperature	5.2.6	24
1	supersymmetry/cosmology	5.2.7/5.4.3	12

Table 6.4b: Requested post-doc positions FP52

PhD (oio)	research field	topic	# months
1	high-order perturb. QCD/heavy quark physics	5.3.1/4/7	48
1	QCD/hadrons at finite temperature	5.2.6	48
1	supersymmetry/astroparticle physics	5.2.7/5.4.3/4	48

Table 6.4c: Requested PhD positions FP52

The visitor position is used to support international collaborations of the various research projects, and to invite guests contributing to the information and education of the members of the theory group and their colleagues in theoretical or experimental subatomic physics on new developments in high-energy physics, by giving seminars or lectures. A small part of the budget is used to provide material support for emeritus prof. M. Veltman, who is a permanent guest of the NIKHEF theory group.

A Publications

A.1 Publications Hth-A

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COH: Dit zijn de stukjes in de jaarboeken van FOM