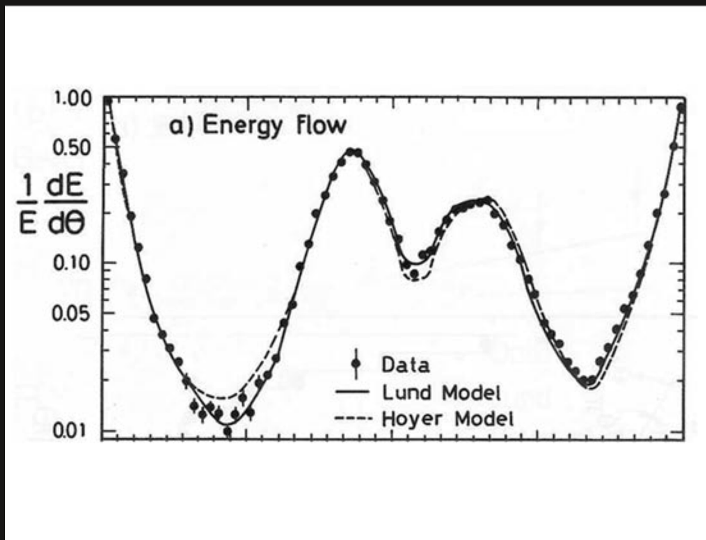


The Lund model for high energy collisions

The famous Lund model – theoretical ideas meet experimental reality.

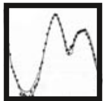
Historical background

M Gell-Mann

Yoishiro Nambu

During the 1930s it was known that matter consists of atomic nuclei (protons and neutrons) with electrons orbiting around them. During the 1940s and 50s many other particles were discovered, called hadrons, that appeared to be as elementary as protons and neutrons. These hadrons interact with each other via the strong nuclear force.

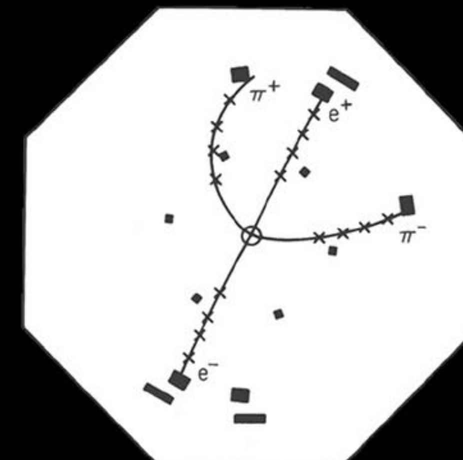
In 1964, M Gell-Mann and G Zweig independently introduced the hypothesis that hadrons are made up of even smaller particles, called quarks. Y Nambu suggested that quarks come in three variaties, colours, which interact via the exchange of gauge bosons, called gluons.



The observation of quarks

In 1968, an experiment was carried out at the linear accelerator center in Stanford USA (SLAC) in which 20 GeV electrons were scattered off protons. The results were similar to those obtained in Rutherford's experiment where a gold target was bombarded with alpha particles, showing the existence of a dense nucleus. The results of the SLAC experiment were interpreted as showing that the electrons had been scattered by smaller constituents in the protons.

In 1974 a particle was discovered that contained a new quark, the charm quark, which had been predicted by the quark theory. Thereafter, a majority of physicists considered that the quark hypothesis was probably correct.



Tracks from a J/psi meson, which decays to two pions (pi$^+$, pi$^-$), an electron (e$^-$) and a positron (e$^+$). The J/psi meson consists of a charm quark and its antiquark.

The linear accelerator at Stanford, USA, where experiments showed that a proton is made up of quarks.

Quantum chromodynamics – QCD

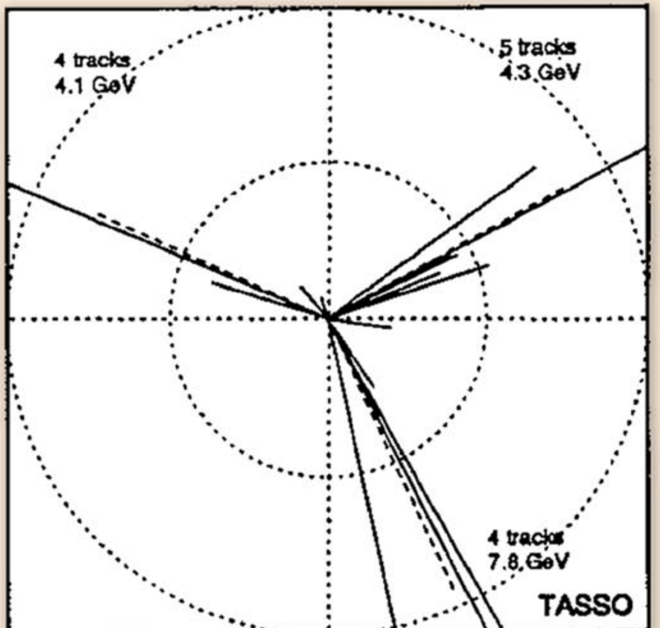


Figure from the TASSO experiment at DESY in Hamburg, which demonstrated the existence of gluons, thereby confirming the theory of QCD. The figure shows three particle showers from a quark, an antiquark and a gluon created by the collision between an electron and a positron.

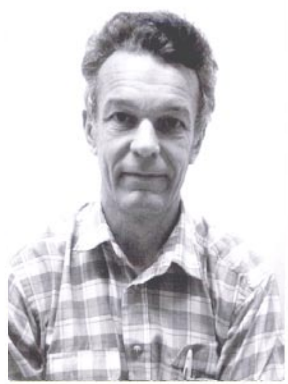
In 1972, a consistent hypothetical theory for strong interactions, quantum chromodynamics (QCD), was formulated based on Gell-Mann's och Nambu's ideas of coloured quarks and massless gluons.

The theory was confirmed in 1979 when the existence of gluons was demonstrated in electron–positron collisions.

The equations governing QCD can, however only be solved when the quarks or gluons are very close to each other. In other cases, QCD-inspired models are required.

The beginning

Bo Andersson



Gösta Gustafson

When Gunnar Källén came to Lund in 1958 he assembled a lively group of postgraduate students who studied field theoretical problems. When Källén died in 1968, his students were dispersed all over the world.

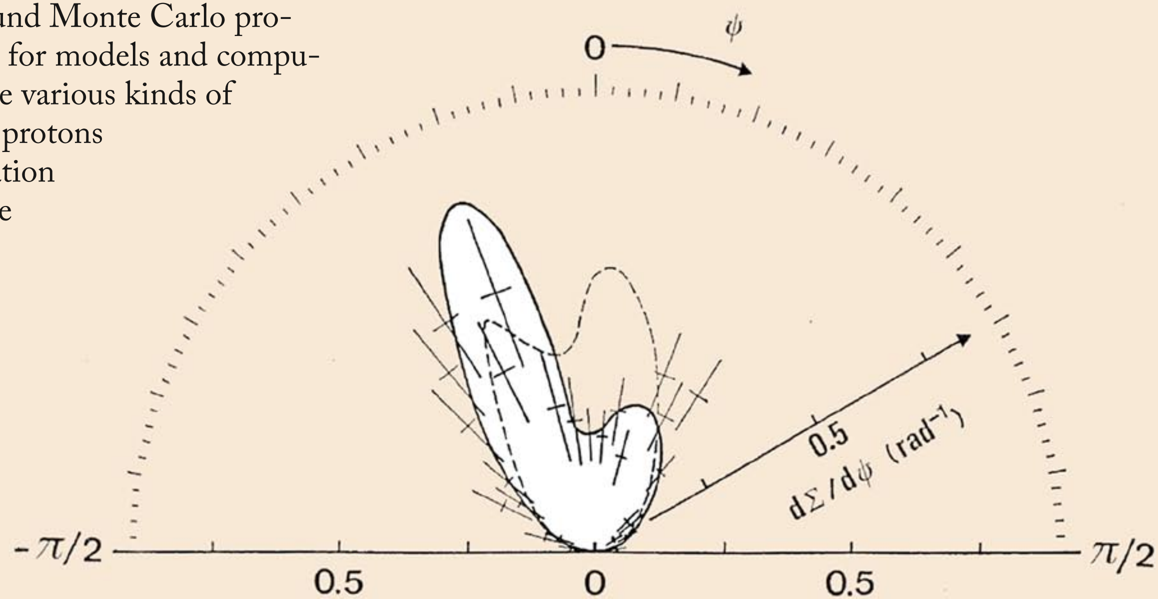
In the mid 1970s, there was increasing evidence that quarks formed the basis of all matter. Bo Andersson and Gösta Gustafson, who had then returned to Lund, togehter with the PhD student Carsten Peterson decided to study what was for them a new area. This was the start of what was later to become the Lund Model.

Early development

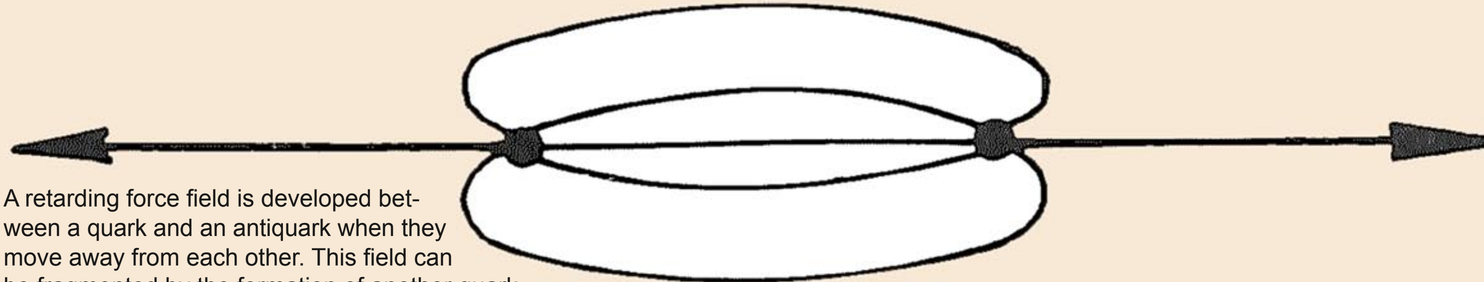
Carsten Peterson obtained his doctorate in 1977, and left Lund soon after. He was replaced by several other talented PhD students. Torbjörn Sjöstrand, Bo Söderberg, Gunnar Ingelman and, somewhat later, Hans-Uno Bengtsson, made especially important contributions to the quark project. Efforts were directed to understanding and describing high-energy collisions.

The Lund Model and the Lund Monte Carlo program became the terms used for models and computer programs used to simulate various kinds of collisions between electrons, protons and nuclei. String fragmentation and quark–gluon cascades are important components in these models and programs.

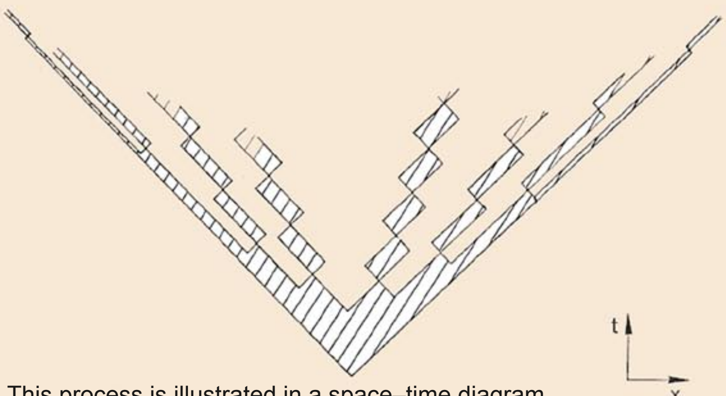
Results from a study by Andersson, Gustafson, Ingelman & Sjöstrand, showing the angular distribution of energy of gluon emission in electron–proton collisions. The solid line shows the Lund Model prediction.



Quark fragmentation



A retarding force field is developed between a quark and an antiquark when they move away from each other. This field can be fragmented by the formation of another quark–antiquark pair. Repeated fragmentation leads to several bound quark–antiquark systems. These are the observable particles in the showers, or jets, in the direction of the quark and the antiquark.



This process is illustrated in a space–time diagram, in which time extends upwards. The extension of the force field is shown by the hatched area.

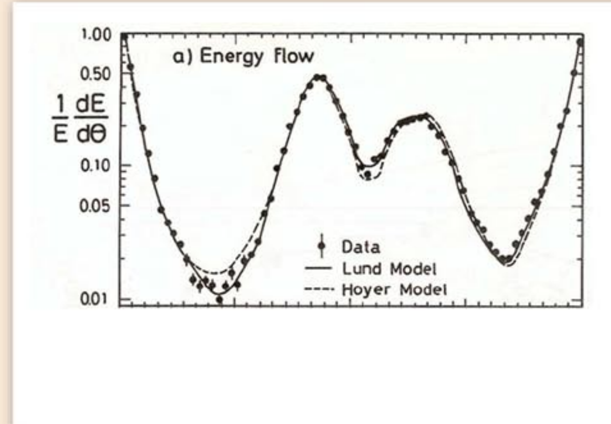
In high-energy collisions between, for example, an electron and a proton, a quark can be ejected from the proton. However, as it cannot be isolated, it materializes as a shower or jet of hadrons (bound states in a quark–antiquark pair, or three quarks).

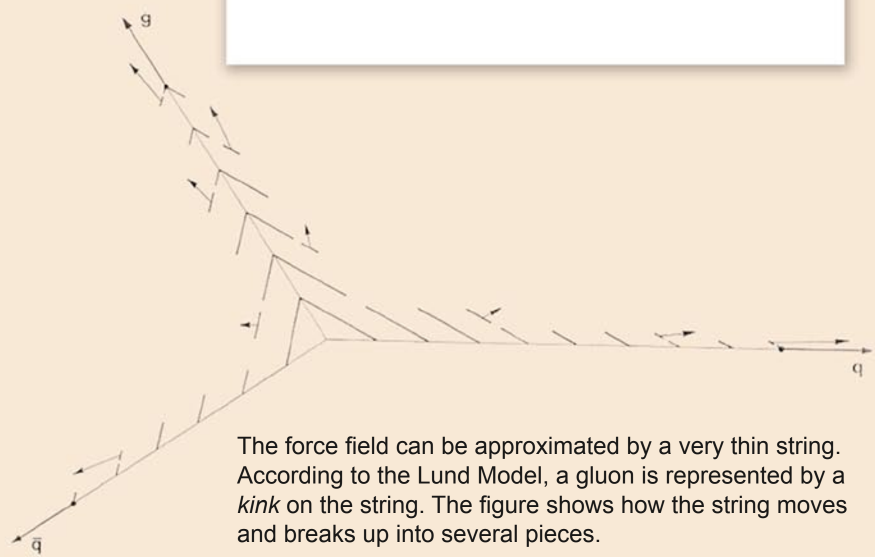
Similar jets arise from reactions where the electron–positron pair is transformed into a quark–antiquark pair. In 1977, an important step was taken with a model describing how the energy of a high-energy quark is transformed into such a jet.

Gluon fragmentation

The jet fragmentation model was refined and developed, and in 1979 was also able to describe gluon jet fragmentation (as a gluon with high energy also cannot be isolated, it similarly gives rise to a jet of hadrons). The force field that holds the particles together is assumed to be similar to a massless relativistic string, and the model is thus called the Lund String Fragmentation Model.

This model predicted a specific asymmetry in the particles produced in electron–positron collisions, and was widely acclaimed when this was observed experimentally in 1980.





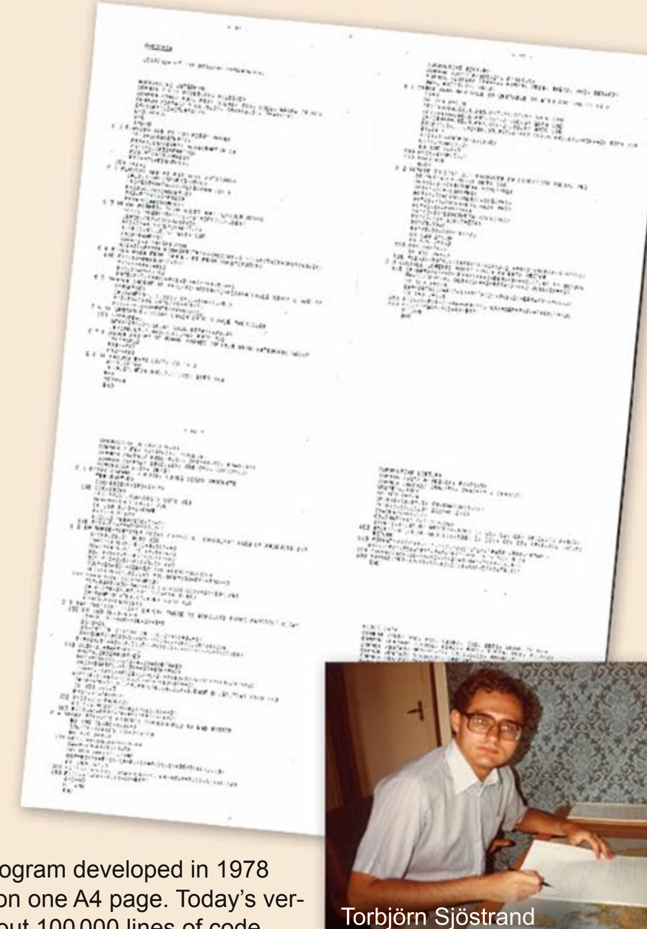
The force field can be approximated by a very thin string. According to the Lund Model, a gluon is represented by a *kink* on the string. The figure shows how the string moves and breaks up into several pieces.

Monte Carlo

A high-energy collision is so complex that it cannot be treated analytically. It was thus necessary to complement the models with simulation programs, generally called Monte Carlo programs.

The Lund MC program was developed to simulate collisions between all conceivable elementary particles and also atomic nuclei. Such simulations are used in both the planning of experiments and the analysis of the results.

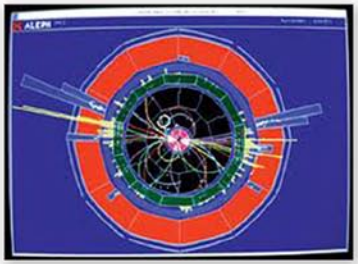
The program PYTHIA, developed mainly by Torbjörn Sjöstrand, is particularly important, and is now the world's most commonly used program for high-energy collisions.



The first Monte Carlo program developed in 1978 was short enough to fit on one A4 page. Today's version (2014) contains about 100 000 lines of code.

Torbjörn Sjöstrand

Quark–gluon cascades



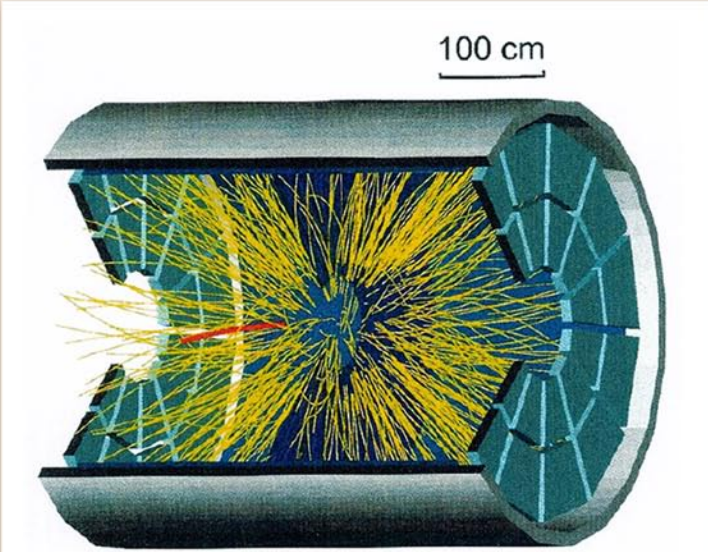
Electrons and positrons of high energy are collided in the Large Electron–Positron collider (LEP) at CERN. This leads to the formation of a quark, an antiquark and a large number of gluons. The production of these multigluon states is well described by the dipole formulation, which is simulated in the Monte Carlo program ARIADNE.

Leif Lönnblad

When quarks collide, gluons are produced. These gluons can in turn emit more gluons, forming a cascade. At very high energies, these cascades have an important effect on the results. Models of the cascades constitute important components in the description of high-energy collisions. A dipole formulation of such cascades was developed by Gösta Gustafson and Ulf Pettersson.

The simulation program ARIADNE, developed mainly by Leif Lönnblad, has been especially successful in describing electron–positron collisions. The dipole formalism is now generally used for the description of quark–gluon cascades.

Nuclear collisions



When atomic nuclei collide, a large number of particles are produced. The figure shows a collision at the Relativistic Heavy Ion Collider at Brookhaven, outside New York.

Working together with experimentalists has been very valuable. A collaboration between Bo Andersson and the experimentalist Ingvar Otterlund on nuclear collisions took place already in 1974, before the start of the Lund Model.

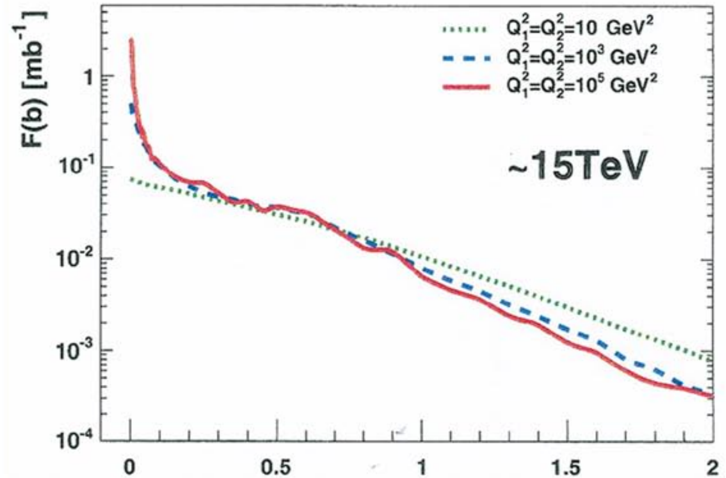
The collaboration resumed in the 1980s, leading to the development of the FRITIOF model, were the theoretician Bo Nilsson-Almqvist and the experimentalist Evert Stenlund together wrote the simulation program.

Studies on nuclear collisions have recently been resumed in connection with the development of the DIPSY model.

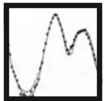
High gluon density

At high collision energies, the density of low-energy gluons can be very high. Beyond a certain value, the gluons can no longer be regarded as individual particles, but interact coherently. These effects can be expected earlier in nuclear collisions, and are therefore important in the analysis of a possible phase transition to a quark–gluon plasma.

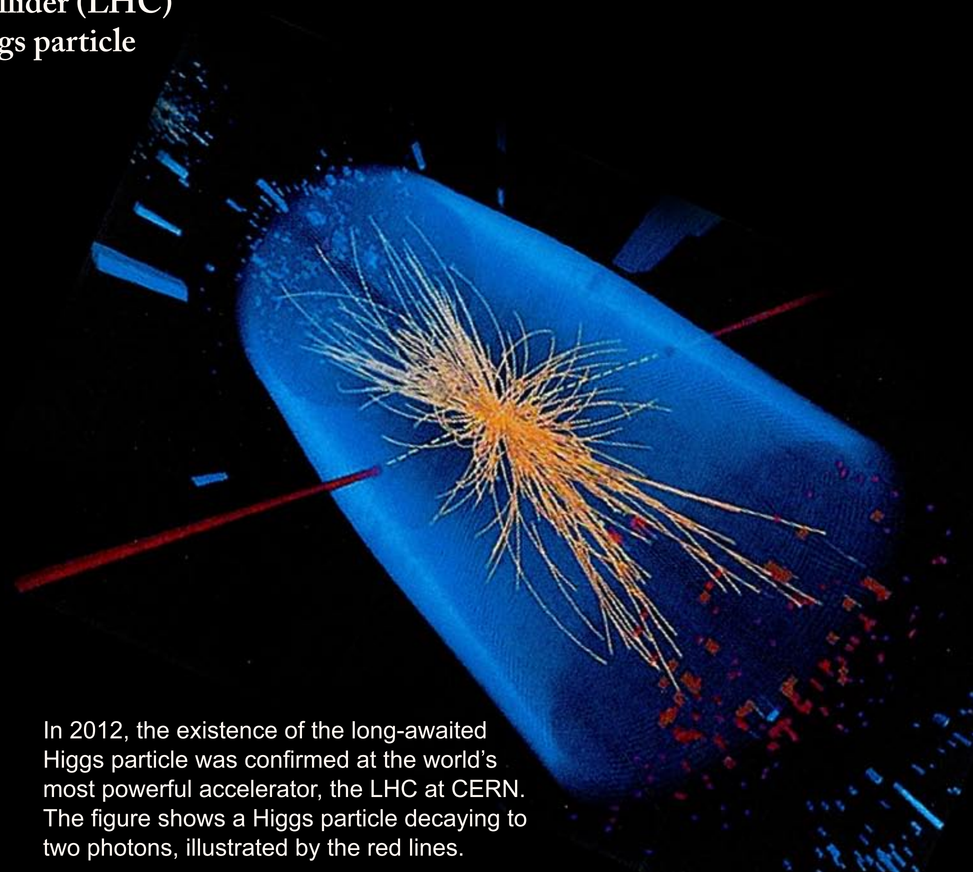
The effects of high gluon density have been included in the DIPSY model. This model is especially suited to the study of the effects of fluctuations and correlations, and finds applications in collisions between electrons, protons and nuclei.



Correlation between two gluons in a proton at high energy, where b denotes the distance between the gluons in the transverse direction. The peak at b=0 indicates that many gluons are found close together. This is important for the possibility for two gluons to scatter simultaneously in a proton–proton collision.



Physics beyond the standard model



Efforts are now being concentrated on analysing the results obtained at the Large Hadron Collider (LHC) at CERN, where the presence of the Higgs particle was confirmed in 2012.

The Higgs particle constitutes the last component in the standard model of the microcosmos. A Higgs particle is produced in only one in 10 billion collisions, and it is therefore important to have good descriptions of both normal events and the expected Higgs signal. The PYTHIA Monte Carlo model had an important role in this context.

Work is now continuing with more detailed studies of the Higgs particle, and the search for signals that can be associated with the so-called dark matter in the universe.

In 2012, the existence of the long-awaited Higgs particle was confirmed at the world's most powerful accelerator, the LHC at CERN. The figure shows a Higgs particle decaying to two photons, illustrated by the red lines.

Teaching and collaboration

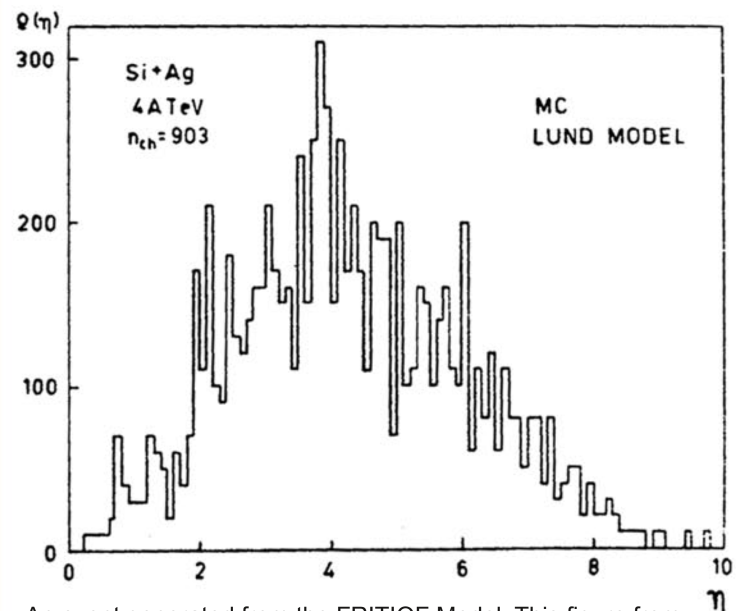
Over 30 PhD students have got their training working on the Lund Model. Among these, Torbjörn Sjöstrand and Leif Lönnblad are now professors still working at Lund University. Gunnar Ingelman has established an affiliate in Uppsala, and some are now working in the theoretical biophysics group started by Carsten Peterson in Lund.

Contact with the experimental high-energy physics group at Lund has been extremely fruitful, leading, amongst other things, to the development of the FRITIOF model. During recent years, the two groups have together supervised seven EU-financed PhD students.

Hans-Uno Bengtsson (1953-2007), Bo Andersson and Gösta Gustafson. After obtaining his doctorate, Hans-Uno Bengtsson spent some time as a post-doc at UCLA. He was an accomplished and popular lecturer and speaker, and was director of studies at the department. He also wrote and translated a number of books.

Important milestones

- A model for quark jet fragmentation (1977)
- A model for electron–hadron and hadron–hadron collisions, called the fragmentation model (1977)
- The first Monte Carlo program (1978)
- The Lund string fragmentation model (1979)
- Model for proton collisions based on multiple quark–gluon collisions.
  The beginning of PYTHIA(1986)
- FRITIOF, a model for collisions between hadrons and/or nuclei (1986)
- Dipole formulation of gluon cascades, ARIADNE (1988)
- PYTHIA is developed into a standard program that also includes hypothetical reactions, like the Higgs and supersymmetric particles (gradual development over many years)
- Saturation and small x, DIPSY (2005)



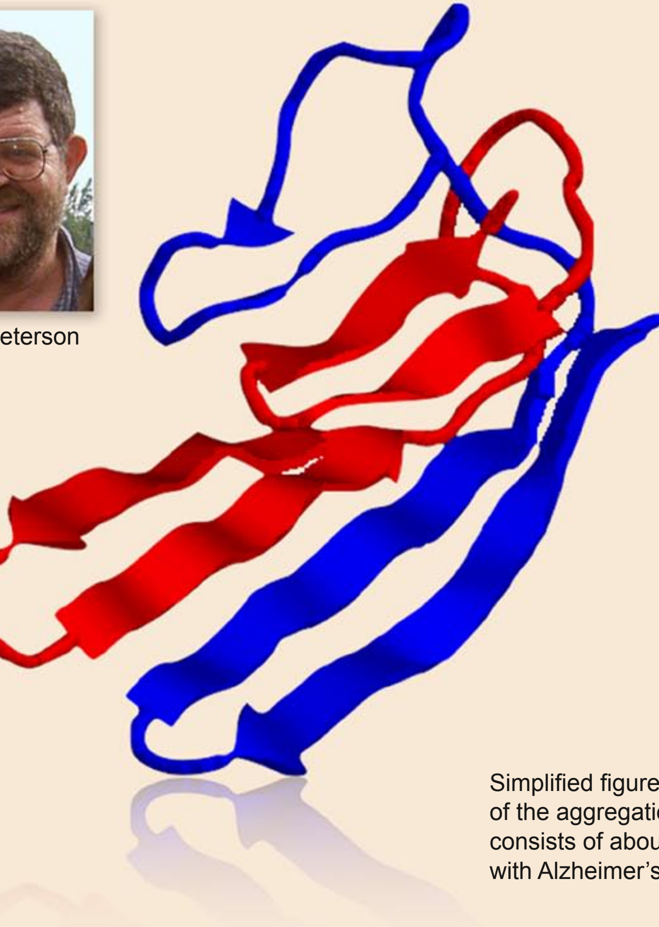
An event generated from the FRITIOF Model. This figure from 1986 shows the distribution of particles in a high energy collision between a silicon and a gold nucleus.

Theoretical biophysics

Carsten Peterson

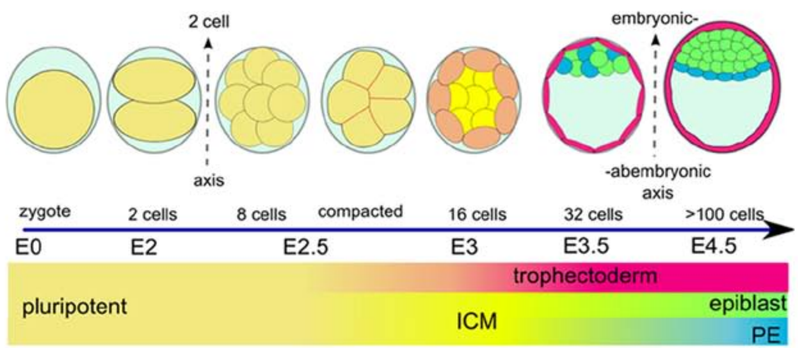
Carsten Peterson started his career with what was later to be the Lund Model, but he changed the direction of his work and started to study lattice QCD, where the usual continuous space-time is approximated by a discrete lattice, using statistical mechanical methods.

This approximation later served as the foundation for another step forward in 1988, which led to a number of new multidisciplinary subjects: Pattern recognition, complicated optimization problems, protein folding and the identification of biomarkers in cancer diagnosis.



Simplified figure showing the results of modelling of the aggregation of Aβ peptides. This peptide consists of about 600 atoms, and is associated with Alzheimer's disease.

Stem cells differentiate



Schematic illustration of the early development of an embryo (4-5 days) from one to about 100 cells. The outer (trophectoderm) and inner (endoderm) layers are responsible for the supply of nutrients and delineation between the organs that will develop later.

Considerable effort is currently being devoted to the modelling of the dynamics of genes and stem cells in an attempt to direct the development of the stem cells.

Studies are being carried out on how millions of blood cells can be produced each day from relatively few blood stem cells in the bone marrow, and the first stages of embryonic development.

Anders Irbäck and Mattias Ohlsson have developed their own areas of specialization in protein dynamics and clinical issues.