Particle Physics Theory and Phenomenology

Working Group Ita

Physics Aims

Quantum field theories are the key for understanding particles and their interactions at the highest energy scales.

Significant cross stimulation occurs between seemingly very different research directions: formal theory and particle theory. Newly developed mathematical methods help us to address questions important for New Physics searches at the Large Hadron Collider (LHC) and for interpreting gravity-wave measurements (LIGO):

- Do collider data show traces of new particles at high energies beyond the Standard Model (SM)?
- What are the characteristics of multi-particle processes?
- How can we extract blackhole characteristics from emitted gravity waves.

Role of Quantum Field Theory (QFT)

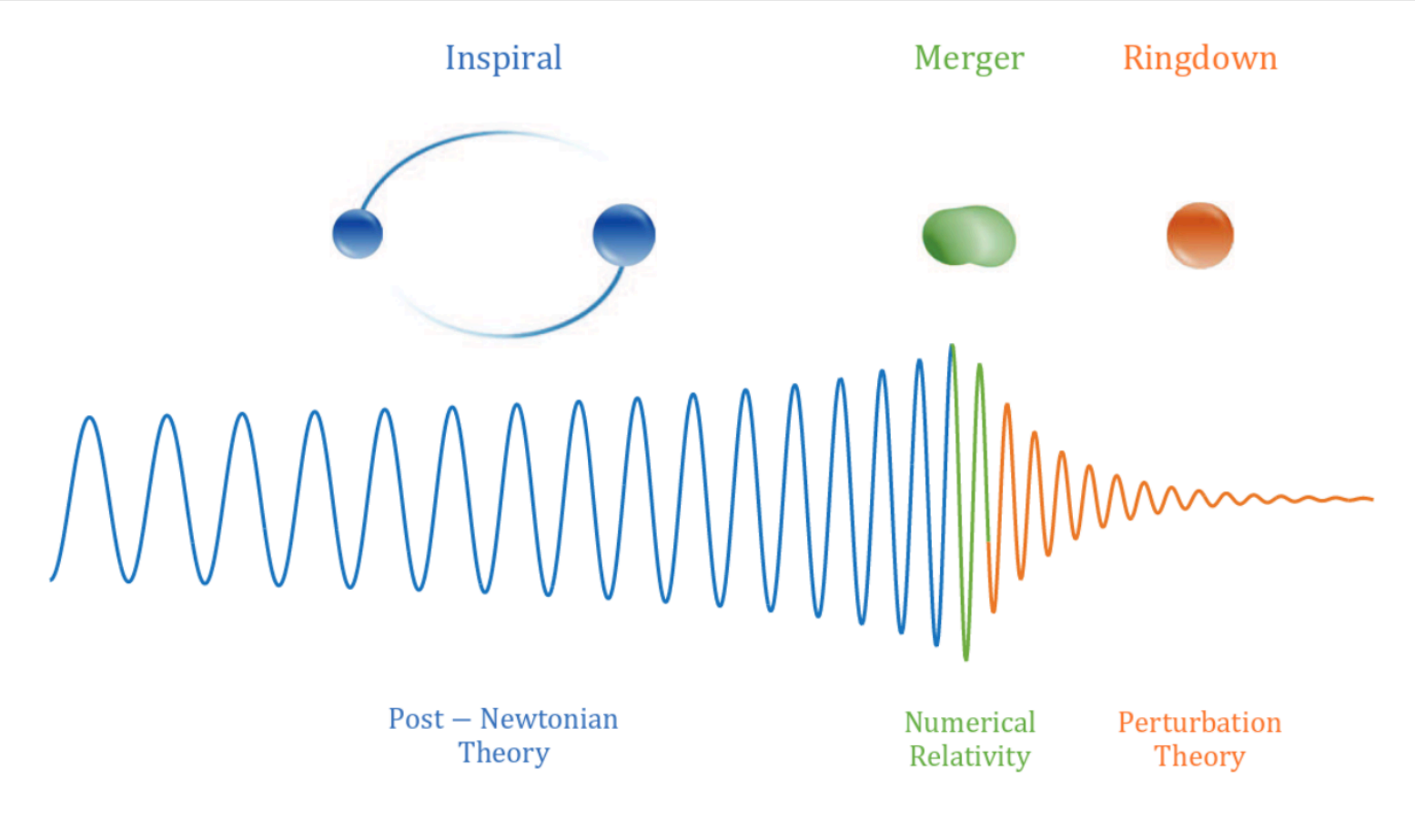
Experimentalists measure the scattering matrix (of particles) and theorists analyse the implications of Lagrangians (written in terms of fields). It takes some expertise and ingenuity to move from one perspective to the other. Similarly orbit data of black holes can be related to the classical scattering problem.

Perturbative computations in QFT are needed to obtain first-principle predictions from the SM or from Einstein's theory of relativity.

Signatures @ LIGO

Theory predictions based on Feynman diagrams in general relativity explain frequency change of inspired in Post-Newtonian approximation.

Blackhole merger:

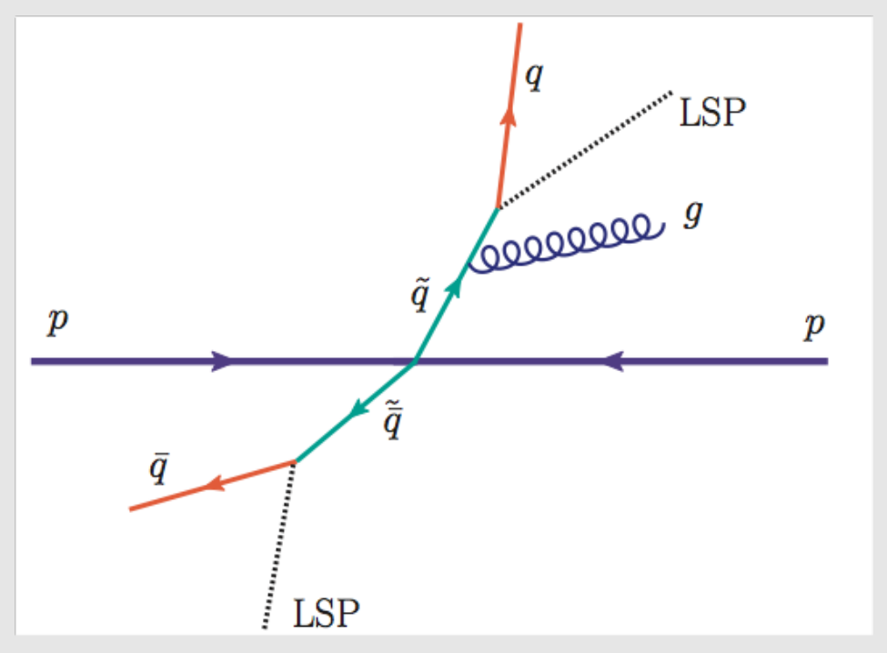


Signatures @ LHC

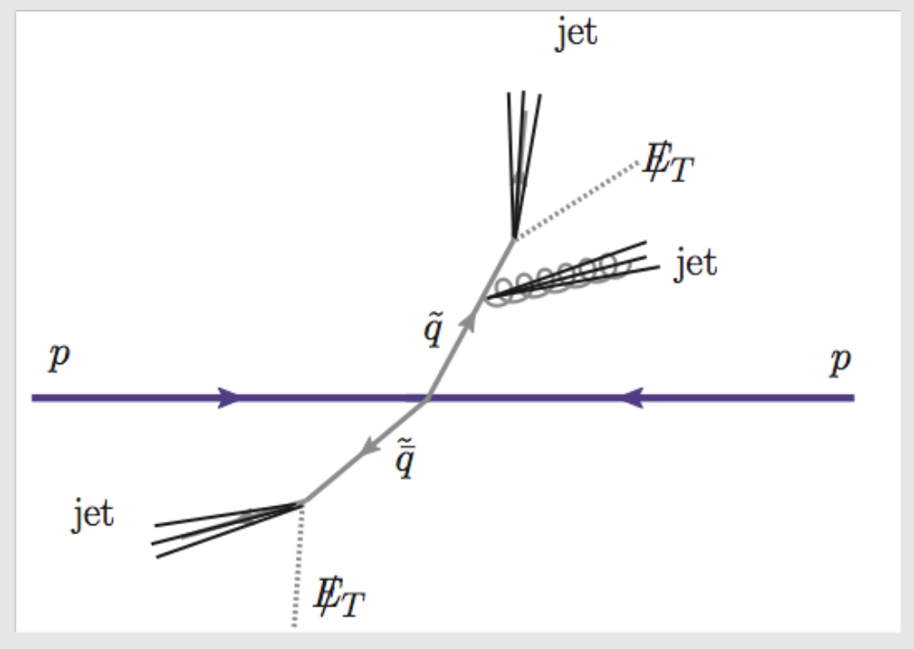
Most interesting (new) particles are heavy and decay into a spray of light ones. Thus high-multiplicity events are common and important in many New Physics searches at the LHC:

- Importance of high-multiplicity signals:
  - Standard candles at colliders (weak bosons in association with many jets)
  - Backgrounds to Supersymmetry, Top Physics, Higgs Physics
- Theory challenge:
  - Precise theory predictions ⇒ need quantum corrections in QCD

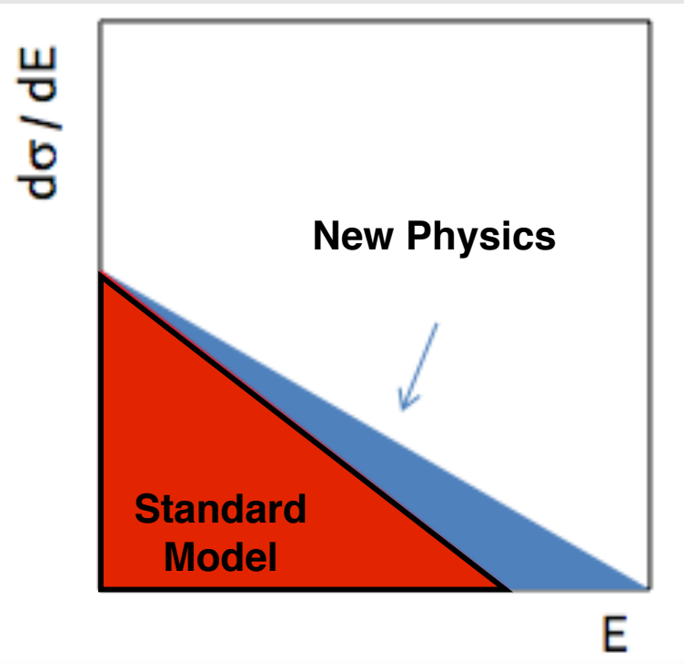
Supersymmetry process:



Supersymmetry signature:



Schematic measurement:

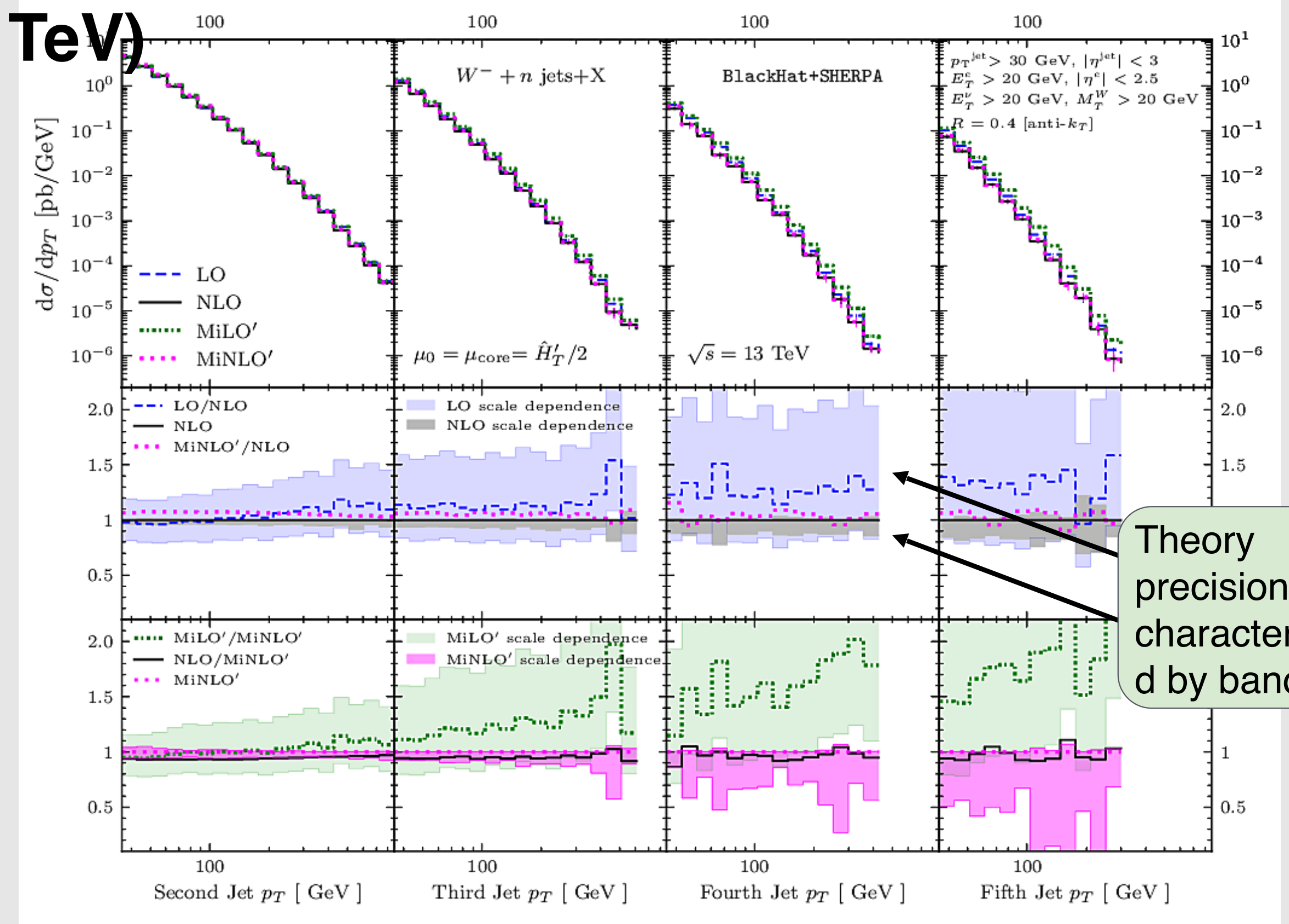


Impact of Quantum Corrections

The inclusion of quantum corrections increases the precision of the observables predictions.

- Impact on normalizations & shapes of distributions
- Multiplicity sets the powers of strong coupling
- Dependence on the unphysical factorization and renormalization scales stabilized at higher orders
- Inclusion of QCD effects: multiple partons merged into jets, initial/final state radiation included

W+2,3,4,5 Jet Production at the LHC (13 TeV)

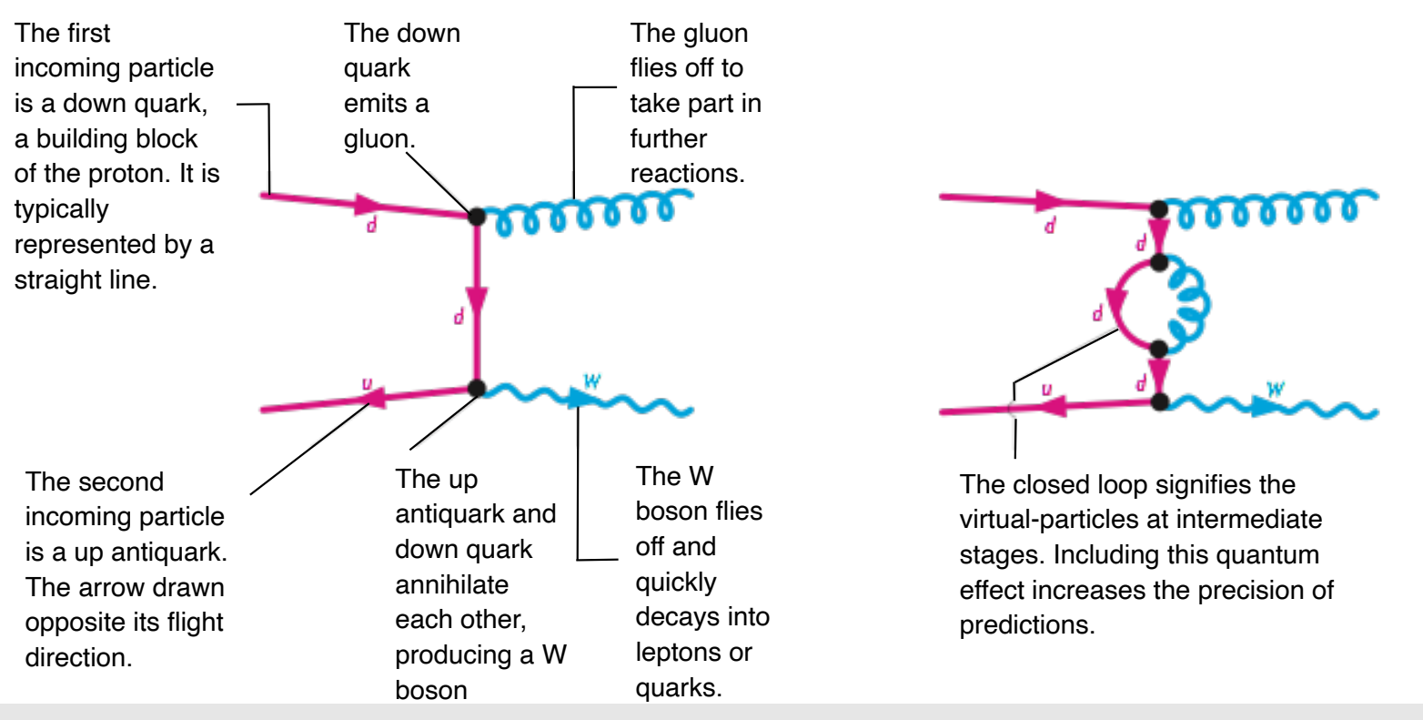


Theory precision is characterized by bands.

Challenges

A given Feynman diagram visualizes one possible way particles may scatter. A clear mathematical prescription allows to quantify each diagram's contribution to the total scattering probability as a function of the particles' quantum numbers. However, keeping track of spins and particle momenta quickly leads to very demanding computations. Surprisingly the results of such computations often look much simpler than one would have anticipated.

Typical **Feynman diagrams** that have to be evaluated in order to obtain quantitative predictions for SM physics.



The first incoming particle is a down quark, a building block of the proton. It is typically represented by a straight line.

The down quark emits a gluon.

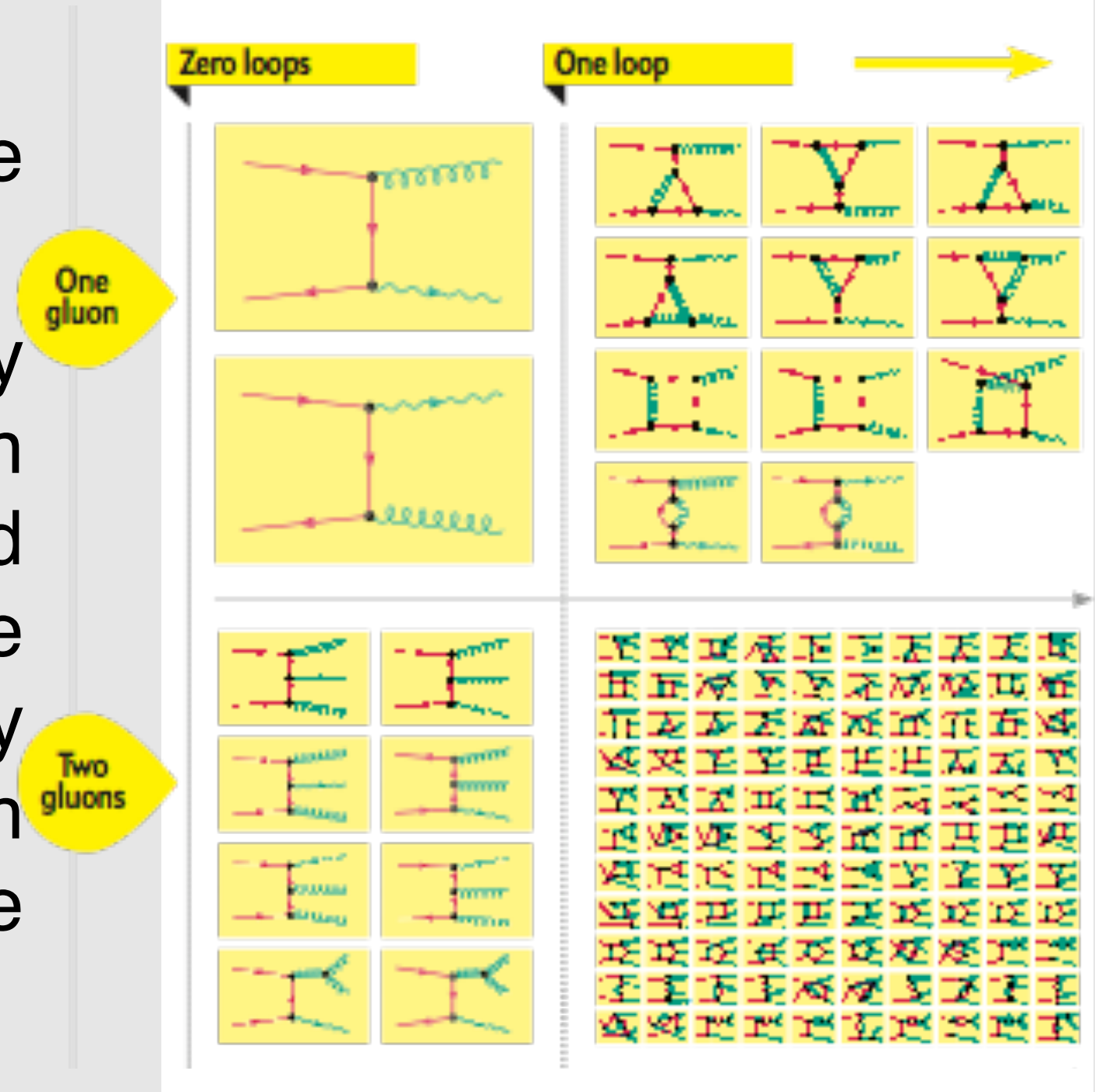
The gluon flies off to take part in further reactions.

The second incoming particle is a up antiquark. The arrow drawn opposite its flight direction.

The up antiquark and down quark annihilate each other, producing a W boson

The W boson flies off and quickly decays into leptons or quarks.

The closed loop signifies the virtual-particles at intermediate stages. Including this quantum effect increases the precision of predictions.



For further details see article by Bern, Dixon, Kosower, **Sci.Am. 306N5 (2012)20-27**

Over the years many clever ideas (often from students) helped theorists to beat the growth in complexity and keep up with demands at particle colliders.

Unitarity and On-Shell Methods

The scattering matrix obeys probability conservation (unitarity) and factorization properties. When viewed as an analytic function of the particles' momenta these physical properties get translated into the analytic behavior such as branch cuts and poles.

The discontinuities of branch cuts as well as the residues of the poles are themselves given in terms of scattering amplitudes leading to sets of consistency equations among the amplitudes:

- Unitarity conditions (optical theorem) relate different orders in the perturbation expansion.
- Factorization conditions relate n-particle scattering amplitudes to m-particle ones (m<n).

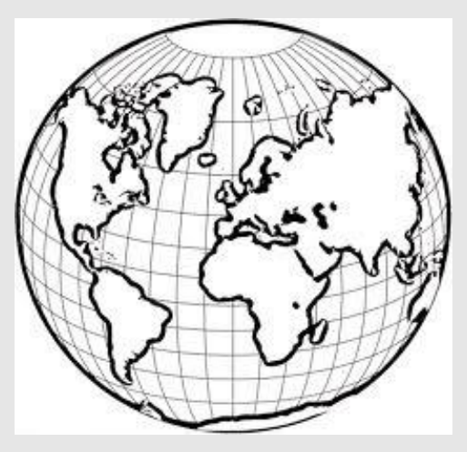
In turn the consistency relations can be exploited for a bootstrap program giving:

- quantum corrections (loops) from semi-classical results, and
- multi-particle amplitudes from low-multiplicity ones.

These bootstrap techniques lead to efficient algorithms for numerical computations.

The Research Collaboration

Our research groups consists of Harald Ita, Giuseppe De Laurentis, and the PhD students Maximilian Klinkert, Evgenij Pascual, Michael Rui and Wladimir Tschernow.



Collaboration: Our collaboration includes S. Abreu (CERN), Z. Bern (UCLA), L.J. Dixon (SLAC), S. Höche (SLAC), D.A. Kosower (Saclay), D. Maître (Durham), B. Page (CERN), V. Sotnikov (MPI Munich) and M. Zeng (Oxford).

BlackHat and Caravel Libraries

The BlackHat C++ library is a matrix element generator which provides high-multiplicity one-loop matrix elements for LHC phenomenology. The Caravel C++ library is a tool for computing multi-loop amplitudes in QFT. Both programs use field theory methods such as the unitarity approach and recursive techniques. Developing advanced numerical approaches based on field-theory properties has been an important and interesting recipe to obtain challenging physics predictions.