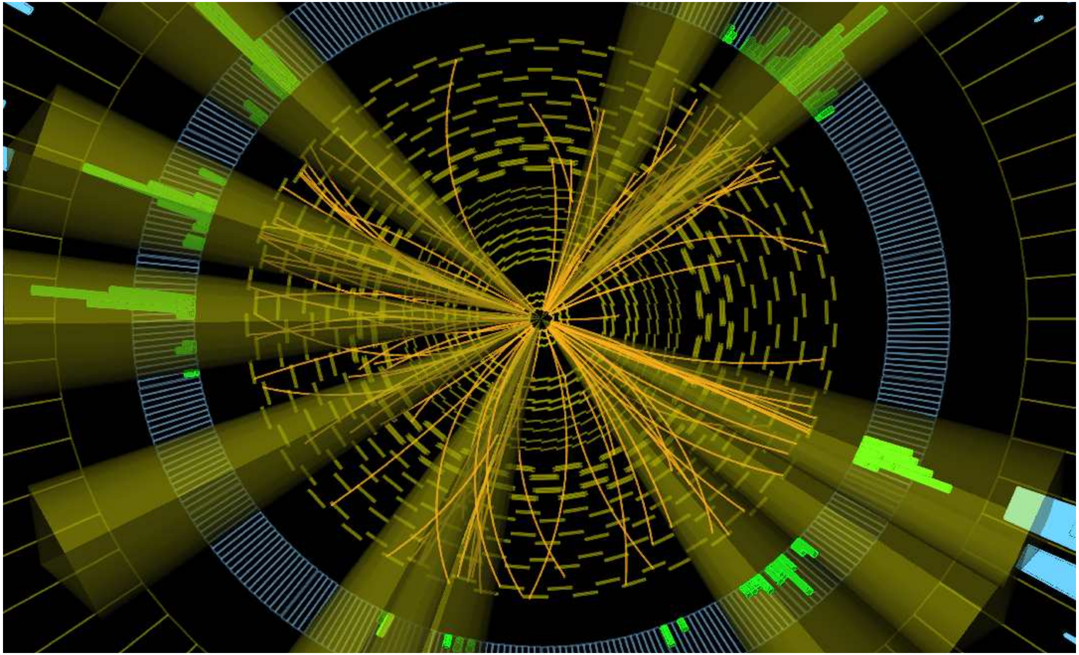
Physics of Fundamental Interactions and Particles



Particle Physics Theory: Flavour beyond the Standard Model

Prof. Andreas Crivellin

The Standard Model (SM) of particle physics describes the fundamental constituents and interactions of Nature. Matter consists of quarks and leptons (fermions) which interact via the exchange of force particles (gauge bosons). The SM has been tested to a very good accuracy, both in high-energy searches at the Large Hadron Collider (LHC) at CERN and in low energy precision experiments. However, it is well known that it cannot be the ultimate theory of nature since it fails to explain observations like Dark Matter, Dark Energy, neutrino masses or the presence of more matter than anti-matter in the Universe. The goal of our research is to construct and study models of physics beyond the SM.

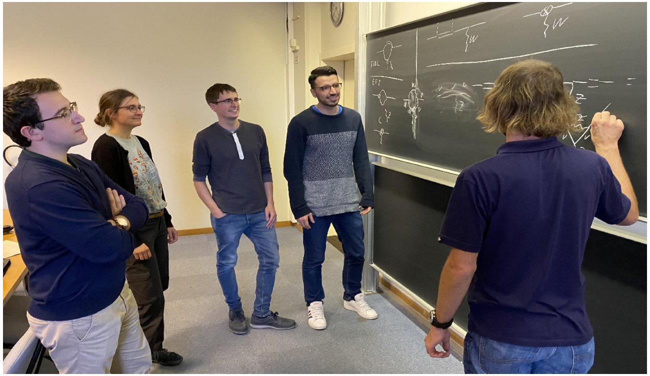
https://www.psi.ch/en/ltp-crivellin

Hints for New Sources of CP- and Lepton Flavour Universality Violation

One of the predictions of the SM is that quarks and leptons appear in three generations (or families), called flavours, which only differ in their couplings to the Higgs, leading to different masses for particles of different flavour.

All SM gauge interactions treat leptons in the same way; i.e. they respect lepton flavour universality and the only source of charge-parity (CP) violation – the violation of the symmetry between matter and antimatter – in the SM is the single phase in the CKM matrix, which describes the mixing between quarks of different flavours.

However, several experiments found hints for deviations from lepton flavour universality and also for CP violation beyond the SM. These experimental results caused considerable interest within the theoretical community. Concerning the violation of lepton flavour universality, we found that models with particles called “scalar leptoquarks” can explain



Members of Andreas Crivellins' group at a blackboard discussion.

these hints for new physics both in the decay of heavy B mesons and in precision measurements of a property of the muon lepton called "anomalous magnetic moment" [1].

Furthermore, there exist significant discrepancies between different ways of determining elements of the aforementioned CKM matrix. In particular, the CKM element determined from nuclear beta decay does not agree with the one from kaon decays. Here, we pointed out that this tension can also be explained in terms of lepton flavour universality violating physics beyond the SM since beta decays involve only electrons while the best data from kaon decays is related to muons [2].

Concerning CP violation, we pointed out the complementarity between low-energy precision experiments and high-energy searches at the LHC [3]. Furthermore, we showed that the hints for additional sources of CP violation in kaon and B decays can be explained within a consistent framework involving a flavour symmetry. In fact, a model involving a new gauge boson can explain CP violating data well and even lead at the same time to the lepton flavour universality violation as described above [4].

Highlighted Publications:

1. "Flavor Phenomenology of the Leptoquark Singlet-Triplet Model," A. Crivellin, D. Müller and F. Saturnino, arXiv:1912.04224 [hep-ph].
2. "Global Fit to Modified Neutrino Couplings and the Cabibbo-Angle Anomaly," A. M. Coutinho, A. Crivellin and C. A. Manzari, arXiv:1912.08823 [hep-ph].
3. "CP Violation in Higgs-Gauge Interactions: From Tabletop Experiments to the LHC," V. Cirigliano, A. Crivellin, W. Dekens, J. de Vries, M. Hoferichter and E. Mereghetti, Phys. Rev. Lett. **123** (2019) no.5, 051801
4. "Z' models with less-minimal flavour violation," L. Calibbi, A. Crivellin, F. Kirk, C. A. Manzari and L. Vernazza, arXiv:1910.00014 [hep-ph]

Particle Physics Theory: Beyond the Standard Model

Prof. Gino Isidori

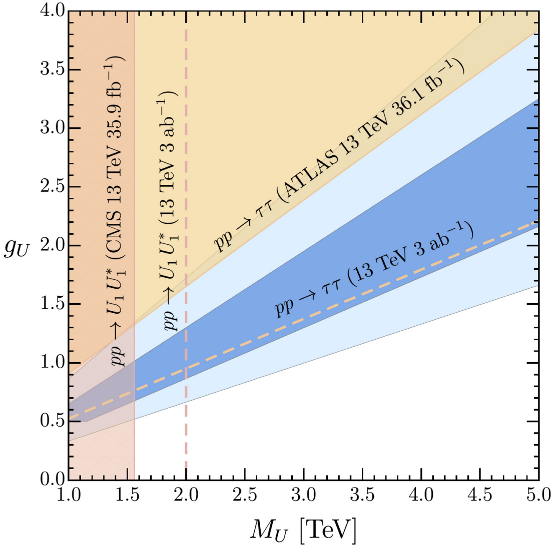
The Standard Model of fundamental interactions describes the nature of the basic constituents of matter, the so-called quarks and leptons, and the forces through which they interact. This Theory is very successful in laboratory experiments over a wide range of energies. However, it fails in explaining cosmological phenomena such as dark matter and dark energy. It also leaves unanswered basic questions, such as why we observe three almost identical replicas of quarks and leptons, which differ only in their mass. Finally, it gives rise to conceptual problems when extrapolated to very high energies, where quantum effects in gravitational interactions become relevant. The goal of our research activity is to formulate extensions of this Theory that can solve its open problems, identifying way to test the new hypotheses about fundamental interactions in future experiments.

https://www.physik.uzh.ch/g/isidori

Flavour Anomalies and the Leptoquark

One of the key predictions of the Standard Model (SM) is that quarks and leptons do appear in three replicas (denoted generations, or flavours) that behave exactly in the same manner under the known microscopic forces and differ only in their mass. Surprisingly enough, a series of precision measurements performed recently by the LHCb experiment at CERN seem to challenge this prediction.

The theoretical investigation of these surprising results has been the main research activity of our group in the last three years. This research comprises three main directions: 1) the investigation of the consistency of the "anomalous" results with other data; 2) the construction of models able to describe the new data in terms of new interactions; 3) the analysis of the predictions of these new interactions for future experiments. In the past years we showed that there is no inconsistency between the anomalies reported by LHCb experiment and other data, provided the hypothetical



Experimental constraints on leptoquark mass (horizontal axes) and coupling (vertical axes) from present and future searches at colliders. The blue and light-blue regions denotes the parameter region preferred by the B-physics anomalies at 1 and 2 sigma, respectively.

"new force" responsible for the anomalies has a peculiar strength on the different families of quarks and leptons: maximal for the third generation, weaker for particles of the second generation, and super-weak for those of the first generation. We also built an explicit model where such new force appears as a result of a unified description of quarks and leptons, i.e. in a model where quarks and leptons are two manifestations of the same fundamental field. In such model the new force, acting between quarks and leptons, is mediated by the exchange of a new hypothetical particle called "leptoquark". In 2019 we devoted quite a lot of attention to investigate the properties of this new particle: we clarified his properties, we explained why it has not been observed yet, and how it could possibly manifest itself in future experiments.

Highlighted Publications:

1. Revisiting the vector leptoquark explanation of B-physics anomalies,
   C. Cornella, J. Fuentes-Martín, G. Isidori,
   JHEP **1907** (2019) 168
2. High-p_T signatures in vector-leptoquark models,
   M.J. Baker, J. Fuentes-Martín, G. Isidori and M. König,
   Eur. Phys. J. C **79** (2019) 334
3. Vector Leptoquarks Beyond Tree Level,
   J. Fuentes-Martín, G. Isidori, M. König, N. Selimović,
   Phys. Rev. D **101** (2020) 035024

Particle Physics Theory: Precision Calculations

Prof. Thomas Gehrmann

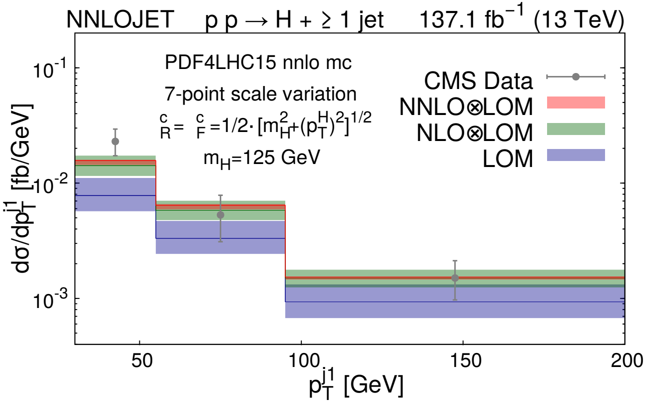
Our research group focuses on precision calculations for collider observables within the Standard Model and their application in the interpretation of experimental data. We develop novel techniques and computer algebra tools that enable analytical calculations in perturbative quantum field theory and help to unravel the underlying mathematical structures. We implement our results into numerical parton-level event generator programs, which are flexible tools that allow to take proper account of the details of experimental measurements, enabling precision theory to be directly confronted with the data.

https://www.physik.uzh.ch/g/gehrmann

Theory predictions for Higgs boson production and decay

With the increased statistics and excellent performance of the experiments at the Large Hadron Collider (LHC), precision studies of the production and decay of the Higgs boson are now becoming reality. A key observable is in particular the production of the Higgs boson in association with a hadronic jet, which is mediated at the quantum level through a top quark loop. It is probing the interaction of the Higgs boson with Standard Model particles and possible new states, reaching higher energy scales than in inclusive Higgs boson production. The measurement of Higgs-plus-jet production is performed in specific Higgs decay modes, each which different kinematical restrictions and background processes.

To confront these LHC precision data with theory predictions of commensurate accuracy requires the computation of higher order corrections in QCD, taking into account the kinematical definition of the final state under consideration. Our group has pioneered the antenna subtraction method for second-order (next-to-next-to-leading order, NNLO) QCD corrections, and is developing a numerical code, NNLOJET, for NNLO-accurate predictions of collider observables. Using this framework, we computed Higgs boson observables in the decay mode to four charged leptons. This mode offers a very clean experimental reconstruction of the Higgs boson; its theoretical description is however challenging due to the high dimensionality of the decay phase space, which com-



Transverse momentum distribution of the leading jet in events with a Higgs boson decaying into four leptons, computed with fiducial cuts for this final state as used in the CMS measurement, whose data are superimposed. Predictions at leading order (blue), next-to-leading order (green) and NNLO (red), all corrected for leading top quark mass effects, demonstrate the convergence of the perturbative series. Bands on the theory predictions estimate their uncertainty through the variation of renormalization and factorization scales.

bines with lepton identification and isolation cuts.

An example of our results is shown in the figure, displaying the transverse momentum distribution of the leading jet in events with a Higgs boson decaying into four leptons, compared to recent data from the CMS experiment. The newly computed corrections lead to residual uncertainties on the theory predictions at a level of below five per cent, which are ready to be confronted with future high-luminosity LHC data. Our study uncovered a subtle interplay between lepton isolation and event selection cuts, resulting in sizable QCD corrections to the acceptance factors that are used in the experimental extraction of the cross sections.

Our recent results on precision Higgs physics also include the transverse momentum spectrum of the Higgs boson, obtained by combining fixed-order predictions with resummation of large logarithmic corrections, and the third-order (N3LO) QCD corrections to the Higgs boson rapidity distribution.

Highlighted Publications:

1. Fiducial cross sections for the four-lepton decay mode in Higgs-plus-jet production up to NNLO QCD,
   X. Chen, T. Gehrmann, E.W.N. Glover, A. Huss,
   JHEP 1907 (2019) 052
2. Higgs boson production at the LHC using the q_T subtraction formalism at N3LO QCD, L. Cieri, X. Chen, T. Gehrmann, E.W.N. Glover, A. Huss,
   JHEP **1902** (2019) 096
3. Precise QCD description of the Higgs boson transverse momentum spectrum,
   X. Chen *et al.*, Phys. Lett. B**788** (2019) 425

Particle Physics Theory: Standard Model and Higgs Physics at Colliders

Prof. Massimiliano Grazzini

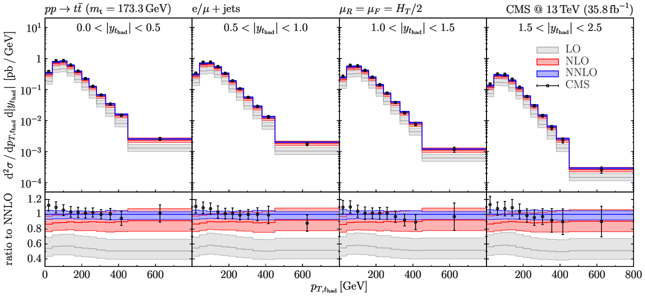
Our research activity is focused on the phenomenology of particle physics at high-energy colliders. We perform accurate theoretical calculations for benchmark processes at the Large Hadron Collider and we make their results fully available to the community. We strive to develop flexible numerical tools that can be used to perform these calculations with the specific selection cuts used in the experimental analyses. These tools can be exploited to carry out detailed comparisons with the data. Our projects span over a wide range of processes from vector-boson pair production to heavy-quark production, to Higgs boson studies within and beyond the Standard Model.

https://www.physik.uzh.ch/g/grazzini

Precise predictions for top quark production

The top quark is the heaviest known elementary particle and it is expected to play a special role in electroweak symmetry breaking. Studies of top-quark production and decay are central in the LHC physics programme, allowing us to precisely test the Standard Model and, at the same time, opening a window on possible physics beyond the Standard Model. At hadron colliders, the main source of top-quark events is top-quark pair production. The proton-proton collisions at the LHC supply a huge number of top-quark pairs, thereby offering an excellent environment for physics studies. At the same time, top-quark pair production is a crucial background to Higgs studies and new-physics searches. For the above reasons, accurate theoretical predictions for this process are needed, and this implies including higher-order radiative corrections.

We have completed a new computation of the top-pair production cross section that includes perturbative corrections at next-to-next-to-leading order (NNLO) in Quantum Chromo Dynamics (QCD). The calculation is obtained by combining tree level and one-loop scattering amplitudes gen-



Double-differential cross sections as a function of the transverse momentum ($p_{T,t_{\rm had}}$)of the hadronically decaying top quark in four rapidity ($y_{t_{\rm had}}$) intervals. The CMS data are compared to the QCD predictions at LO, NLO and NNLO. The central value of the renormalisation and factorisation scales is fixed to $H_T/2$, where H_T is the sum of the transverse masses of the top and anti-top quarks [2].

erated with OpenLoops, an automated tool also developed in Zurich, with two-loop amplitudes that are available in numerical form. The various contributions are separately divergent, and a method is required to handle and cancel infrared singularities appearing at intermediate stages of the computation. In our group we have carried out several NNLO calculations for final states involving Higgs and vector bosons, which do not carry colour charge, but top-quark production is a more complicated process due to the additional soft radiation from the top-quark pair. By using advanced numerical techniques to carry out the phase space integrations, we have assembled all the above ingredients to compute the NNLO cross section. Our calculation is implemented in the general purpose numerical program MATRIX, which can already produce analogous results for all the relevant diboson production processes, fully accounting for their leptonic decays. We have presented results for single and double differential distributions of the top quarks and compared them to available data from the CMS collaboration. The extension of MATRIX to top-quark production paves the way to new and more accurate Monte Carlo simulations for this process, as it happened for Higgs and vector boson production.

Highlighted Publications:

1. Top-quark pair hadroproduction at next-to-next-to-leading order in QCD,
   S. Catani *et al*, Phys.Rev. D**99** (2019) no.5, 051501
2. Top-quark pair production at the LHC: Fully differential QCD predictions at NNLO
   S. Catani *et al*, JHEP **1907** (2019) 100
3. NNLO QCD+NLO EW with MATRIX+OpenLoops: precise predictions for vector-boson pair production,
   S. Kallweit *et al*, JHEP **2002** (2020) 087

Particle Physics Theory: Automated Simulations for Collider Physics

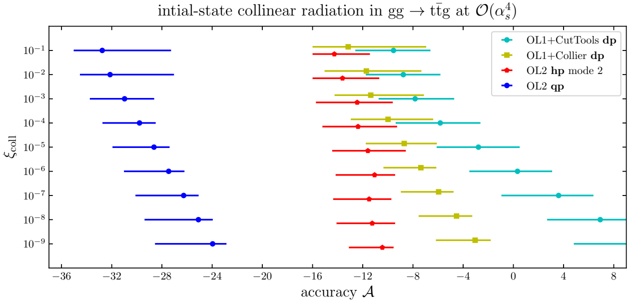
Prof. Stefano Pozzorini

Our research deals with the development of automated methods for the simulation of scattering processes in quantum-field theory. The OpenLoops algorithm, developed in our group, is one of the most widely used programs for the calculation of scattering amplitudes at the LHC. This tool is applicable to arbitrary collider processes up to high particle multiplicity and can account for the full spectrum of first-order quantum effects induced by strong and electroweak interactions.
Currently, new automated methods for second-order quantum effects are under development. Our phenomenological interests include topics like the strong and electroweak interactions of heavy particles at the TeV scale, or theoretical challenges related to the extraction of rare Higgs-boson and dark-matter signals in background-dominated environments.

https://www.physik.uzh.ch/g/pozzorini

OpenLoops 2

Recently we have released a new version of the OpenLoops program [1] that implements various new techniques and enables a broad spectrum of new applications. One of the main novelties is an entirely new method for the construction of scattering amplitudes at one loop and their reduction to a family of well known integrals. Such one-loop amplitudes belong to the most fundamental building blocks that are required for precision calculations of scattering processes at particle colliders. In particular, the theoretical interpretation of the measurements carried out at CERN's Large Hadron Collider (LHC) requires the calculation of one-loop scattering amplitudes for a large variety of scattering processes. The complexity of one-loop amplitudes grows extremely fast with the number of scattering particles, and for many of the nontrivial processes that are routinely probed at the LHC one-loop calculations can be still extremely CPU intensive. In



High-precision (NNLO) calculations require the evaluation of one-loop scattering amplitudes in regions where the final-state momenta become soft (small energy) of collinear (small angular separation). The plot illustrates the numerical stability of various one-loop tools for the process $gg \to t\bar{t}g$ *(see [1]). In the collinear limit,* $\xi_{\mathrm{coll}} \to 0$*, standard one-loop reduction algorithms feature severe instabilities that can reach the level of* 10^{-3} *in Collier (yellow) and even* 10^{8} *in CutTools (turquoise). In contrast, the new on-the-fly reduction techniques implemented in* OpenLoops 2 *(OL2, red curve) guarantee a level of numerical stability better than* 10^{-10} *even in the deeply collinear regime.*

OpenLoops 2 we have implemented a new method, dubbed on-the-fly reduction, that permits to tame the complexity of multi-particle calculations in a very efficient way. This algorithm implements new sophisticated techniques that guarantee a stable evaluation also in kinematic regions with soft and collinear particles. Such regions play a crucial role in high-precision (NNLO) calculations and are notoriously very challenging (see Figure). The other main novelty in OpenLoops 2 is the extension of one-loop calculations from QCD—the theory of strong interactions—to the full Standard Model of particle physics, including electroweak, Yukawa and Higgs interactions. Besides increasing the physics content of the predictions in a very significant way, the inclusion of electroweak effects is a key prerequisite for the theoretical description of high-precision measurements. Moreover it plays a very important role for a variety of measurements and searches at the high-energy frontier. In OpenLoops 2 the above mentioned features are implemented in the form of public libraries that cover more than two-thousand independent hard scattering processes. Such libraries can be easily exploited through various multipurpose simulation programs that are interfaced to OpenLoops, such as Matrix, Sherpa, Powheg and Herwig.

Highlighted Publications:

1. OpenLoops 2, F. Buccioni *et al.*,
   Eur. Phys. J. C **79** (2019) no.10, 866
2. NLO QCD predictions for $t\bar{t}b\bar{b}$ production in association with a light jet at the LHC,
   F. Buccioni *et al.*, JHEP **1912** (2019) 015
3. Extracting the Top-Quark Width from Nonresonant Production, C. Herwig, T. Ježo and B. Nachman,
   Phys. Rev. Lett. **122** (2019) no.23, 231803

High-intensity low-energy particle physics

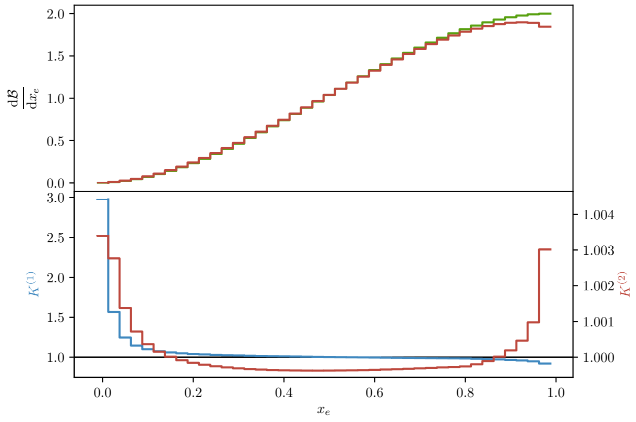
Prof. Adrian Signer

Particle physics at low energy but high intensity provides an alternative road towards a better understanding of the fundamental constituents of matter and their interactions. Using the world's most intense muon beam at the Paul Scherrer Institut (PSI) allows to look for tiny differences to the Standard Model or for extremely rare decays. Our group provides theory support for such experiments by computing higher-order corrections in Quantum Electrodynamics (QED) to scattering and decay processes and by systematically analysing the impact of experimental bounds on scenarios of physics beyond the Standard Model. These calculations are also adapted to experiments performed at other facilities with lepton beams.
https://www.physik.uzh.ch/g/signer

Fully differential muon decay including mass effects

Our group is in the process of setting up a generic framework for higher-order QED calculations of scattering and decay processes involving leptons. This framework properly treats infrared singularities when combining loop amplitudes and allows to obtain fully differential cross sections at any order in QED perturbation theory with massive fermions. The long-term goal is to provide a library of relevant processes with sufficient precision, typically at next-to-next-to leading order (NNLO) in the perturbative expansion.

After the implementation of several processes at next-to-leading order (NLO), recently we have implemented the muon decay $\mu \to e\nu\bar{\nu}$ at NNLO. In QED it is important to keep the fermion masses at their physical value, rather than setting them to zero. This allows to compute contributions with large mass logarithms, which often produce the dominant part of the corrections in QED. This is in contrast to similar calculations in the context of Quantum Chromodynamics, where observables are typically more inclusive such that



The normalised energy fraction x_e of the electron in the muon decay $\mu \to e\nu\bar{\nu}$, with experimental cuts adapted to the MEG experiment at PSI. In the upper panel the LO result (green) is compared to the NNLO result (red). In the lower panel, the NLO and NNLO correction factors are shown as $K^{(1)}$ (blue, left scale) and $K^{(2)}$ (red, right scale). The corrections are large at the end points, partly due to logarithms mentioned in the text.

these logarithms cancel.

Keeping finite fermion masses makes the analytic computation of two-loop amplitudes much more demanding, and in fact often impossible. In the case of the muon decay we were able to analytically compute the two-loop amplitude including all mass effects. For more complicated processes, we have developed a method called 'massification' that extracts the leading fermion-mass terms of two-loop amplitudes from the corresponding amplitudes with massless fermions. This method, as well as the treatment of infrared singularities, has been tested in the muon decay. To do so we compared the fully massive with the massified computation. We also compared to already available inclusive calculations.

The analytic results of two-loop amplitudes are often expressed in terms of so-called generalised polylogarithms (GPL). These GPL depend on the kinematic variables of the process and need to be evaluated numerically repeatedly in the Monte Carlo code. To facilitate this we have implemented a fast numerical evaluation of GPL in Fortran. This code is an intrinsic part of the Monte Carlo framework, and will be essential in the implementation of further processes.

Highlighted Publications:

1. Small-mass effects in heavy-to-light form factors,
   T. Engel, C. Gnendiger, A. Signer, and Y. Ulrich,
   JHEP **1902** (2019) 118
2. A subtraction scheme for massive QED, T. Engel, A. Signer, and Y. Ulrich, JHEP **2001** (2020) 085
3. *handyG* - rapid numerical evaluation of generalised polylogarithms in Fortran,
   L. Naterop, A. Signer and Y. Ulrich, arXiv:1909.01656

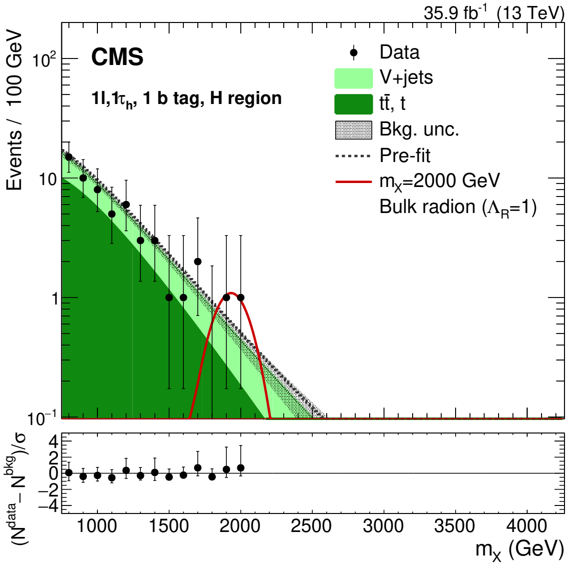
CMS Experiment

Prof. Florencia Canelli, Prof. Ben Kilminster

The CMS (Compact Muon Solenoid) experiment at CERN measures properties of the fundamental particles and their interactions, and can uncover new forces and particles. CMS surrounds one of the interaction points at the Large Hadron Collider (LHC), which produces an energy density comparable to that of the universe one ten-billionth of a second after it started. Detectors are used to determine the energy and direction of emerging particles. By reconstructing these particles, the particles and their interactions can be deciphered. In 2012, CMS discovered the Higgs boson, thus proving how particles acquire mass. By 2018, CMS recorded a record dataset of 150 fb^{-1}, allowing more precise measurements and searches for new physics. CMS is now focused on physics analyses, detector maintenance and upgrade activities, and pushing forward the Phase-2 upgrades and infrastructure needed for the high-luminosity run of the LHC envisioned to start in 2027.

https://www.physik.uzh.ch/r/cms

The CMS group at UZH is strong in data analysis, focusing on the fundamental mysteries remaining in particle physics. We are studying the Higgs boson, and also using it as a probe to look for new forces and particles. We undergo measurements of the heaviest fundamental particle known, the top quark, which is as heavy as a gold atom. In 2019, we have measured the simultaneous production of a pair of top quarks with a pair of b quarks in the challenging all-jets channel [1]. A good knowledge of this production is crucial in order to gain insight into other very rare processes containing top quarks. A new search for a massive particle that would decay to quarks in a region previously unaccessible was developed using a special data-taking technique, known as "data scouting" [2]. We continued our program of searching for new, heavy particles that would represent new forces. In three separate publications, we present searches that probe higher masses than previously achieved, in their decays to combinations of Higgs, W, and



A new search for heavy particles that decay to Higgs bosons. The new particles could be heavy excitations of the graviton that would be possible if our universe had extra dimensions [3].

Z bosons, as well as other standard model particles [3,4,5]. These searches probe models in which a new mass scale of physics is introduced to explain the theoretically anomalous observed Higgs boson mass. We have now a research program searching for new physics with tau leptons, and in 2019, we published a search for a low-mass $\tau\tau$ resonance [6].

CMS will collect more than 20 times the current data set during the period of 2026 to 2038. The UZH group will construct in Zurich an inner tracking detector for this period that will extend the tracking coverage. This Tracker Extended Pixel detector (TEPX) will be composed of a billion pixels, and is capable of making 40 million measurements per second. In 2019, we produced a prototype of the detector with lightweight mechanical and electrical components. We studied detector sensor options that could dramatically reduce the cost of the detector, and measured the signal quality of detector modules in particle beams. Using a new type of particle detector called an LGAD, we were able to measure a timing resolution of less than 40 picoseconds (40 10^{-12} s) in our lab. Such a technology could greatly improve the physics potential of CMS in later upgrades.

Highlighted Publications:

1. CMS Collab., arxiv.org:1909.05306, accepted by Phys. Lett. B
2. CMS Collab., arxiv.org:1911.03761, submitted to Phys. Lett. B
3. CMS Collab., JHEP **01** (2019) 051
4. CMS Collab., Phys. Lett. B **798** (2019) 134952
5. CMS Collab., Eur. Phys. J. C **79** (2019) 564
6. CMS Collab., JHEP **05** (2019) 210

More publications at: https://www.physik.uzh.ch/r/cms

LHCb Experiment

Prof. Nicola Serra, PD Dr. Olaf Steinkamp

LHCb is an experiment for **precision measurements** of observables in the decays of B mesons at the Large Hadron Collider (LHC) at CERN.
We play a leading role in measurements with B meson decays and in measurements of electroweak gauge boson production, and have made important contributions to the LHCb detector. We are also involved in the preparation of a major upgrade of the detector for 2019/2020.

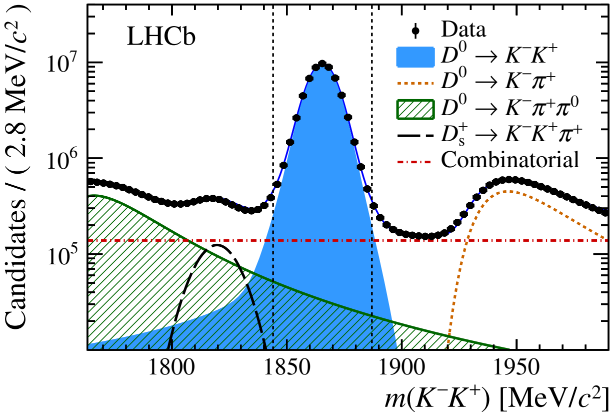
https://www.physik.uzh.ch/r/lhcb

Observation of CP violation in charm

Everything we see around us is the result of a triumph of matter over antimatter in the early stages of the universe. A necessary condition for this so-called baryon asymmetry is Charge-parity violation (CPV), whereby the laws of physics change under the reversal of particle electric charge and the inversion of spatial coordinates. The Standard Model of particle physics (SM) includes CPV through an irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. However, the size of CPV in the SM appears to be too small to account for the observed matter-antimatter asymmetry, suggesting the existence of sources of CPV beyond the SM.

While CPV with strange and beauty quarks is well established, the observation of CPV in the charm sector had not been achieved, despite decades of experimental searches. The size of CPV in charm decays is expected to be very small in the SM, with asymmetries typically of the order of $10^{-4} - 10^{-3}$. The uncertainties however are large due to the presence of low-energy strong-interaction effects.

At peak luminosity, the LHC produces approximately one million charm hadrons per second. This huge production rate allows for very precise searches for CPV. The LHCb collaboration performed a search for CPV in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays, using the full Run 2 dataset collected be-



Left: Invariant-mass distributions of $D^0 \to K^-K^+$ *candidates with the fit results overlaid. The various components included in the fit model are indicated in the legend (from [2]).*

tween 2015-2018 [2]. The idea is to compare the rate of D^0 decay with the corresponding $\bar{D}^0$ decay, and calculate the asymmetry, A_{CP} from these two.

Experimentally, it is easier to determine ΔA_{CP}, the difference in CP asymmetries between $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays, where many systematic uncertainties cancel.

The combination with the Run 1 analyses gives $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$. The significance of the deviation from zero corresponds to 5.3 standard deviations and is the first observation of CPV in the decay of charm hadrons. The result is consistent with, although at the upper end of the SM expectations. The upgraded LHCb detector will allow for each larger charm-hadron samples to be collected in order to study different decays which can shed light on the origin of the CPV. The figure shows the invariant-mass distribution of $D^0 \to K^-K^+$ candidates with fit results overlaid.

Highlighted Publications:

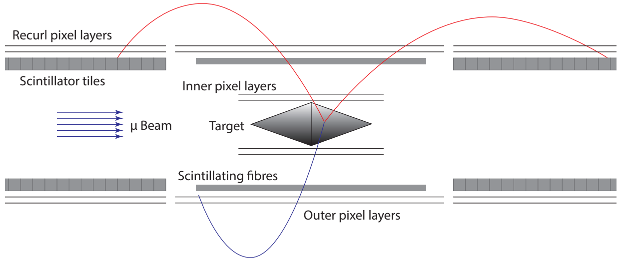
1. All LHCb publications:
   http://lhcb.web.cern.ch/lhcb/
2. Observation of CP Violation in Charm Decays,
   LHCb collab., Phys. Rev. Lett. **122** (2019) no.21, 211803
3. Search for lepton-universality violation in
   $B^+ \to K^+\ell^+\ell^-$ decays,
   LHCb collab., Phys. Rev. Lett. **122** (2019) no.19, 191801
4. Test of lepton universality with $\Lambda_b^0 \to pK^-\ell^+\ell^-$ decays, LHCb collab., arXiv:1912.08139
5. Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure of the $P_c(4450)^+$, LHCb collab., Phys. Rev. Lett. **122** (2019) no.22, 222001

The $\mu^+ \rightarrow e^+e^-e^+$ experiment

Prof. Nicola Serra, PD Dr. Olaf Steinkamp

The Mu3e experiment aims to search for the lepton flavour violating decay $\mu^+ \rightarrow e^+e^-e^+$. The experiment is currently finalising the design and is expected to start data taking in the next two years.

The conservation of lepton flavour, where the number of leptons in an interaction of a particular flavour is conserved, is a key symmetry in the Standard Model. Although lepton flavour violation has already been observed in neutrino oscillations, it has never been seen in charged leptons. The incredibly high intensity muon beam at PSI, Villigen offers a unique opportunity to probe lepton flavour violating decays such as $\mu^+ \rightarrow e^+e^-e^+$ and is expected to be sensitive to one $\mu^+ \rightarrow e^+e^-e^+$ decay in every 10^{16} muon decays, around 1000 times more sensitive than previous limits. The design is currently being finalised with data taking foreseen in the next two years.



Schematic of the Mu3e detector. Incoming muons are stopped in the target and decay. The resulting electrons are recorded in the pixel layers for spatial information and scintillating fibre detector for time information.

Highlighted Publication:

1. Research Proposal for an Experiment to Search for the Decay $\mu^+ \rightarrow e^+e^-e^+$,
   Mu3e Collaboration, arXiv:1301.6113

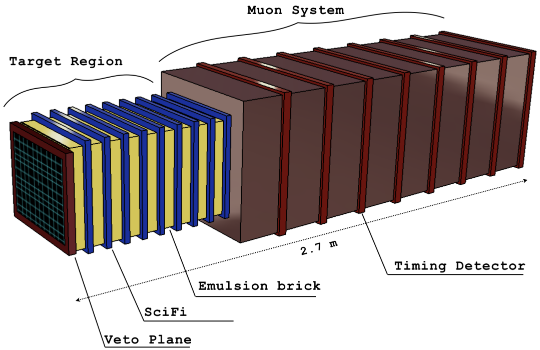
SHiP - Search for Hidden Particles

Prof. Nicola Serra

The **SHiP (Search for Hidden Particles)** experiment is a proposed beam dump target experiment at CERN. Its aim is to search for very weakly interacting long living particles, in particular for sterile neutrinos.

https://www.physik.uzh.ch/r/ship

Our group is involved in the development of the official simulation software, in the estimation of neutrino interactions which mimic the signal we are looking for and also has a leading role in the design of the SHiP veto timing detector. We are also involved in the measurement of charm production from 400 GeV protons and we are among the main proponents of a Letter of Interest [2] sent to the LHC committee to build and operate a detector that, for the first time, will measure the process $pp \to \nu X$ at the LHC and search for feebly interacting particles in an unexplored domain.



Schematic view of the neutrino detector for the SND@LHC project.

Highlighted Publications:

1. SHiP Experiment, Comprehensive Design Study, Report, SHiP Collaboration
   https://cds.cern.ch/record/2709550/files/LHCC-I-035.pdf
2. SND@LHC, SHiP Collaboration,
   https://cds.cern.ch/record/2704147/files/SPSC-SR-263.pdf