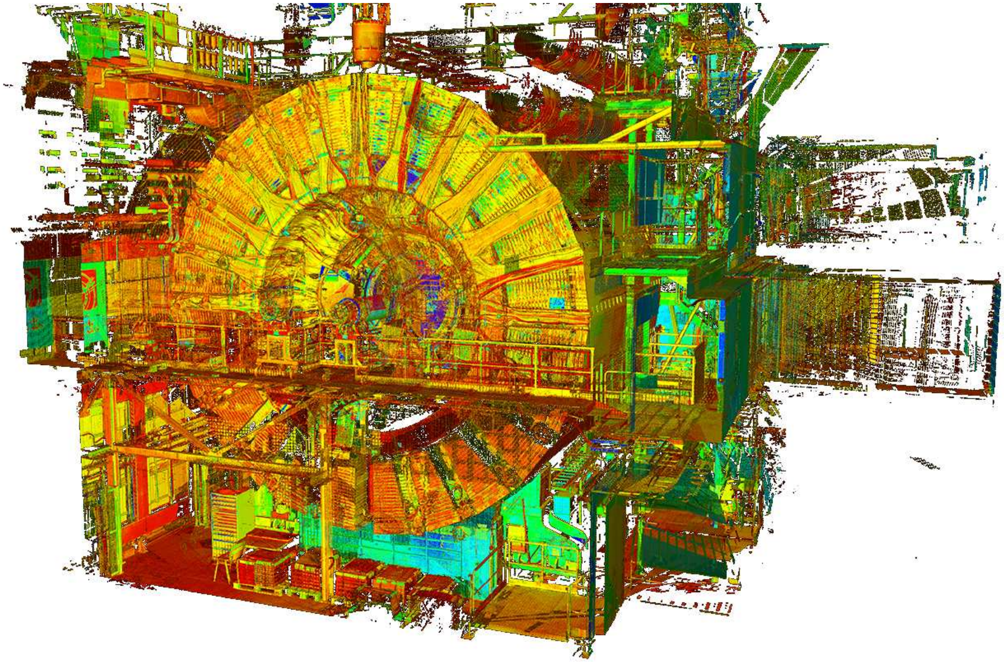
Physics of Fundamental Interactions and Particles



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 origin of fermion masses

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 (or, more precisely, in their interaction with the Higgs field). Surprisingly enough, a series of precision measurements performed recently by the LHCb experiment at CERN seem to challenge this prediction: these measurements hint to a different behaviour of leptons belonging to different families that is not related to their mass.

These results have stimulated a lot of theoretical investigations. A first natural question to be addressed is the consistency of these “anomalous” results, so far observed only in the decays of B mesons (containing quarks of the 3rd generation), with the tight bounds on possible extensions of the SM derived by many past experiments. A theoretical study of our group has clarified that there is no inconsistency between

the recent B-physics anomalies and the past tight bounds, provided the hypothetical "new force" responsible for the anomalies is not universal not only in the lepton sector, but also when acting on quarks. More precisely, the strength of the new interaction should be maximal for quarks and leptons of the third generation, should become weaker for particles of the second generation, and must be super-weak for those of the first generation (this is why we do not experience it on ordinary matter). Interestingly enough, this hypothesis also explains the hierarchy of the different anomalies so far observed, and provides a hint that this new interaction may be the key towards a deeper understanding about the origin of particle masses. Encouraged by these observations, we have started a systematic investigation of realistic extensions of the SM aimed at this twofold goal: a phenomenological explanation of the recent anomalies, linked to a solution of the long-standing puzzle of quark and lepton masses. A promising line in this direction has lead us to an extended gauge group that unifies the interactions of quarks and lepton at high energies, i.e. a class of models where quarks and leptons are different states of the same fundamental particle, and where new force mediators called leptoquarks do appear. We are not yet in a position to draw definite conclusions about such models, but our studies have identified a series of precise predictions that could allow us to confirm or disproof them in the near future with the help of more experimental data.

Highlighted Publications:

1. A three-site gauge model for flavor hierarchies and flavor anomalies, M. Bordone, C. Cornella, J. Fuentes-Martin, G. Isidori, Phys. Lett. B **779** (2018) 317
2. Low-energy signatures of the PS^3 model: from B-physics anomalies to LFV, M. Bordone, C. Cornella, J. Fuentes-Martín, G. Isidori, JHEP **1810** (2018) 148
3. Leptonic WIMP coannihilation and the current dark matter search strategy, M.J. Baker and A. Thamm, JHEP **1810** (2018) 187

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.

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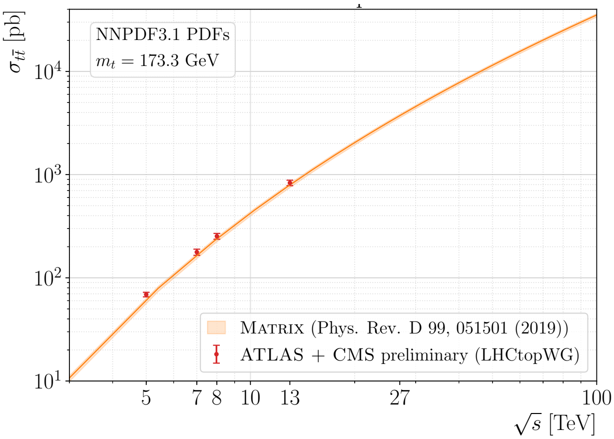
Precise predictions for top quark production

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. Therefore, accurate theoretical predictions for this process are needed, which 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 generated with OpenLoops, an automated tool also developed



NNLO calculation of the top pair cross section as a function of the centre of mass energy [1].

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. Top-quark production is a more complicated process due to the additional soft radiation from the top-quark pair. To address this problem we have developed an extension of our methods to this process, and computed the missing soft contributions at NNLO. 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 result, which is the first independent confirmation of a landmark result obtained in 2013, is implemented in a fully differential parton level event generator that is able to compute fiducial cross sections and distributions for stable top quarks. The 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. 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. D99 (2019) no.5, 051501
2. ZZ production at the LHC: NLO QCD corrections to the loop-induced gluon fusion channel,
   M. Grazzini *et al*, JHEP **1903** (2019) 070
3. Higgs boson production at large transverse momentum within the SMEFT: analytical results,
   M. Grazzini *et al*, Eur.Phys.J. C**78** (2018) no.10, 808

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.

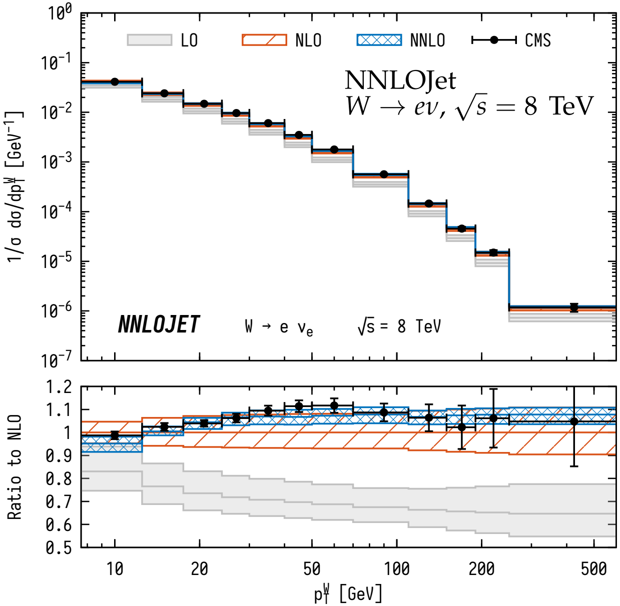
https://www.physik.uzh.ch/g/gehrmann

Theory of electroweak boson production

The production of electroweak gauge bosons is one of the most prominent processes at hadron–hadron colliders such as the LHC. The gauge bosons are produced in abundance and their clean leptonic signature allows this class of processes to be measured with great precision. As a consequence, the production of $V = (W, Z)$ bosons is among the most important benchmark processes at hadron colliders and has a wide range of applications.

The transverse-momentum (p_T^V) spectrum of the gauge bosons plays a particularly important role: this observable probes multiple aspects of the theory predictions and enables precision measurements of electroweak parameters. In particular, the ratio of the transverse momentum spectra in W and Z boson production is the key ingredient to the determination of the W-mass at hadron colliders.

To confront LHC precision data with theory predictions of matching accuracy requires the computation of higher order corrections in QCD. In the past years, 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 for the first time the NNLO corrections to the p_T^W distribution. Our theory predictions are at the level of fiducial cross sections, taking full account of the experimental cuts on the lepton momentum and on missing transverse energy from the unobserved neutrino.



Normalized p_T^W distribution in the electron-neutrino channel. Theory predictions (NNLOJet) at leading order (grey), next-to-leading order (orange) and next-to-next-to-leading order (blue) in perturbative QCD are compared to CMS data. The bands on the theory predictions estimate their uncertainty through the variation of renormalization and factorization scales. The lower frame displays the ratio to the previously available NLO theory.

Comparing the newly computed NNLO predictions with experimental data from the CMS experiment (figure on the left), we observe a considerably improved description of the kinematical shape of the distribution, and a decrease in theory uncertainty, now comparable in magnitude to the experimental errors.

We performed similar studies for Z and Higgs boson production, combining fixed-order calculations with all-order resummations of large logarithmic corrections at low p_T^V.

Further recent calculations obtained in the NNLOJET framework include jet production observables in hadron-hadron and lepton-hadron collisions, which are of direct impact to the precise determination of the proton structure.

Highlighted Publications:

1. NNLO QCD Corrections to the transverse momentum distribution of weak gauge bosons,
   A. Gehrmann-De Ridder *et al*, Phys. Rev. Lett. **120** (2018) 122001
2. Fiducial distributions in Higgs and Drell-Yan production at N^{3}LL+NNLO,
   W. Bizon *et al*, JHEP **1812** (2018) 132
3. N^{3}LO corrections to jet production in deep inelastic scattering using the Projection-to-Born method,
   J. Currie *et al*, JHEP **1805** (2018) 209

Particle Physics Theory: Automated Simulations for Collider Physics

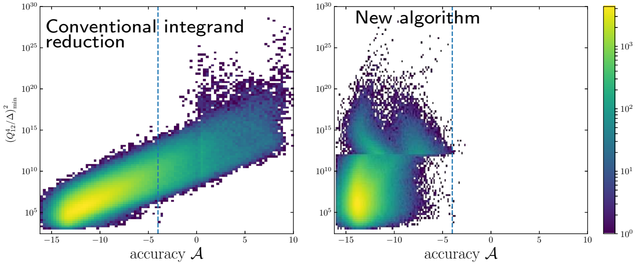
Prof. Stefano Pozzorini

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. It is applicable to arbitrary collider processes and can account for the full spectrum of first-order quantum effects induced by strong and electroweak interactions. Its reach in terms of process complexity outperforms traditional algorithms by more than two orders of magnitude. 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

A new way of constructing scattering amplitudes

Recently we have proposed and implemented in OpenLoops a novel method for the calculation of scattering amplitudes with first-order quantum effects. Such effects are described in terms of Feynman diagrams with one loop. Each Feynman diagram represents one of the possible intermediate states in a given scattering processes, and one-loop diagrams correspond to quantum fluctuations where extra intermediate particles and anti-particles are created and annihilated in a closed loop.

The number and complexity of one-loop diagrams grow 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 or simply unaffordable. This is due also to the occurrence of severe numerical instabilities that require to carry out certain parts of the calculations in quadruple precision, slowing down the codes in a dramatic way. Such instabilities



Correlation of the one-loop accuracy $\mathcal{A}$ of a $2 \to 4$ scattering amplitude with a critical kinematic variable Q_{12}. At small Q_{12} conventional algorithms (left) suffer from huge instabilities that can generate output several orders of magnitude away from the correct result, while the new OpenLoops algorithm (right) provides stable results in the whole phase space.

are related to the fact that loop amplitudes are typically constructed in terms of complex (high-rank) integrals, which are subsequently reduced to a relatively small set of well-know and simple (rank-zero) integrals.

In order to avoid the explosion of complexity at intermediate stages of the calculations, in [1] we have developed a new type of algorithm where fundamental operations associated with the construction and the reduction of loop amplitudes are interleaved in a way that minimises the complexity (rank) at all stages of the calculation.

The new algorithm, which is publicly available in the latest release of OpenLoops, features an unprecedented level of numerical stability and is amenable to one-loop calculations with up to 10^5 one-loop diagrams. This will benefit theoretical simulations based on a variety of multipurpose simulations programs that are interfaced to OpenLoops, such as Sherpa, Powheg and Matrix. As a first phenomenological application we have presented a study of $pp \to t\bar{t}b\bar{b}j$, a multi-particle process that plays a key role in measurements of the recently discovered process of Higgs-boson production in association with top-quark pairs. The new OpenLoops algorithm is also an optimal basis for the extension of automated methods beyond first order in perturbation theory.

Highlighted Publications:

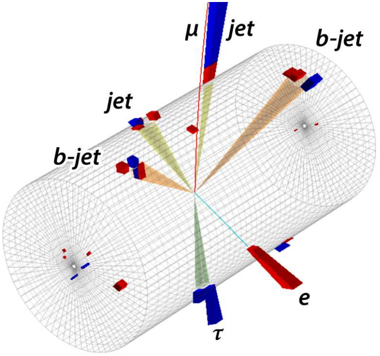
1. On-the-fly reduction of open loops,
   F. Buccioni, S. Pozzorini and M. Zoller,
   Eur. Phys. J. C**78** (2018) no.1, 70
2. New NLOPS predictions for $\boldsymbol{t\bar{t}} + \boldsymbol{b}$-jet production at the LHC, T. Ježo, J. M. Lindert, N. Moretti and S. Pozzorini, Eur.Phys.J. C**78** (2018) no.6, 502
3. A theoretical study of top-mass measurements at the LHC using NLO+PS generators of increasing accuracy, S. Ferrario Ravasio, T. Ježo, P. Nason and C. Oleari, Eur. Phys. J. C **78** (2018) no.6, 458

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, as well as differences between data and theory calculations that could mean discoveries of 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. The detector is used to determine the energy and direction of emerging particles. By reconstructing these particles, the forces and particles producing the interactions can be deciphered. In 2012, the CMS collaboration discovered the Higgs boson, and was thereby able to prove the mechanism for how particles acquire mass. CMS finished the Run 2 data taking period in 2018, achieving a record dataset of 150 fb^{-1} that allows more precise measurements and searches for new physics.
https://www.physik.uzh.ch/r/cms

The CMS group at UZH has strong analysis groups, 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 2018, we observed the simultaneous production of a Higgs boson with top quarks [1] and demonstrated for the first time that the Higgs boson couples to leptons [2]. Dark matter can be produced in LHC collisions, and would manifest itself as a momentum imbalance. In 2018, we explored the potential interaction of dark matter with heavy quarks [3]. To explain why the Higgs boson has an unnaturally light mass, we performed a search for the production of a new heavy particle decaying to a Higgs boson and a b quark [4]. Recent measurements point to certain anomalies which might indicate the existence of leptoquarks, new particles carrying quark and lepton properties that would cause a violation of lepton flavor universality. During 2018, we initiated new searches to directly detect such



An event candidate for the production of a top quark and antiquark in conjunction with a Higgs Boson in the CMS detector.

a leptoquark decay [5]. Finally, we also looked for heavy versions of gravitons decaying into standard model bosons [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 2018, we designed a prototype of the detector with lightweight mechanical, cooling, and powering, 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 about 40 picoseconds (40E-12 s) in our lab. Such a technology could greatly improve the physics potential of CMS in later upgrades.

Highlighted Publications:

1. Observation of $t\bar{t}H$ production,
   CMS Collab., Phys. Rev. Lett. **120** 231801;
2. Observation of the Higgs boson decay to a pair of τ leptons with the CMS detector,
   CMS Collab., Phys. Lett. B **779**, 283 (2018)
3. Search for dark matter particles produced in association with a top quark pair at $\sqrt{s} = 13$ TeV,
   CMS Collab., Phys. Rev. Lett. **122** 011803
4. Search for single production of vector-like quarks decaying to a b quark and a Higgs boson,
   CMS Collab., JHEP **06** (2018) 031
5. Search for a singly produced third-generation scalar leptoquark decaying to a τ lepton and a bottom quark in proton-proton collisions at $\sqrt{s} = 13$ TeV,
   CMS Collab., JHEP **1807**, 115 (2018)
6. Search for massive resonances decaying into WW, WZ, ZZ, qW, and qZ with dijet final states at $\sqrt{s} = 13$ TeV,
   CMS Collab., Phys. Rev. D **97**, no. 7, 072006 (2018)

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

LHCb Experiment

Prof. Nicola Serra, PD Dr. Olaf Steinkamp

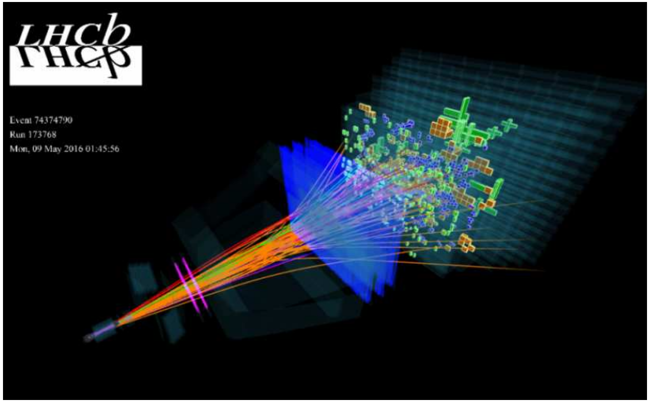
LHCb is an experiment for **precision measurements** of observables in the decays of B mesons at the Large Hadron Collider (LHC) at CERN.
We play a leading role in measurements with B meson decays and in measurements of electroweak gauge boson production, and have made important contributions to the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

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

Tests of Lepton Flavour Universality

In the Standard Model (SM) of particle physics, each fermion is replicated three times into different flavours. For charged leptons, these three flavours are identical copies of each other, apart from different masses. For example, the muon is simply a heavier copy of the electron in the SM. This prediction is called lepton flavour universality (LFU), any violation of which would be a clear sign of physics beyond the Standard Model. Lepton universality has been well-tested in the decays of many different SM particles such as pions, kaons and gauge bosons and the measurements are consistent with the SM. The LHCb experiment has been testing LFU in decays of beauty quarks. These measurements are highly sensitive to New Physics particles which preferentially couple to the 2nd and 3rd lepton flavours.

The ratio R_K describes how often a B^+ meson decays to a charged kaon and either a muon and anti-muon pair or an electron and anti-electron pair. The decays involve the transformation of a beauty quark into a strange quark ($b \to s$), a process that is highly suppressed in the Standard Model and can be affected by the existence of new particles, which could have masses too high to be produced directly at the Large Hadron Collider. These decays are extremely rare, occurring at a rate of only one in two million B^+ meson decays.



Display of an event with in the LHCb detector.

The challenge in the experimental analysis is to control for the fact that electrons and muons interact very differently with the detector. Electrons are absorbed by the electromagnetic calorimeter and muons traverse through the calorimeter into the muon stations.

To minimise the influence of detector and other experimental effects, LHCb physicists used a "double ratio" method: what they measure is R_K divided by another ratio, $r_{J/\psi}$, the true value of which is known to be very close to 1 but which has similar sensitivity to detector effects to R_K. The double ratio method greatly reduces systematic uncertainties related to the different experimental treatment of muons and electrons, which largely cancel in the double ratio.

The result of the measurement is

$$R_K = 0.846^{+0.060}_{-0.054}(\text{stat})^{+0.016}_{-0.014}(\text{syst})[2],$$

which is consistent with the SM at the level of 2.5 standard deviations. The measurement does not confirm nor refute previous hints of lepton universality violation. The measurement is statistically limited and so will be improved with the full run-II dataset and the upcoming LHCb upgrade.

Highlighted Publications:

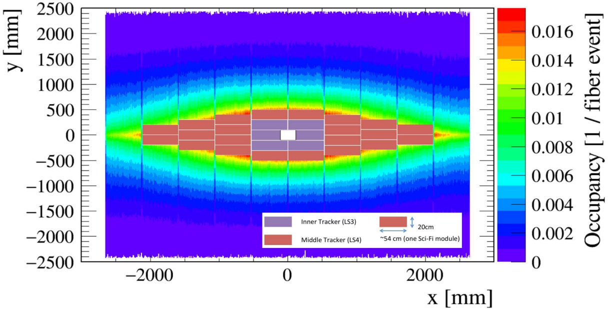
1. All LHCb publications:
   http://lhcb.web.cern.ch/lhcb/
2. Search for lepton-universality violation in
   $B^+ \to K^+\ell^+\ell^-$ decays,
   LHCb collab., Phys. Rev. Lett. **122** (2019) no.19, 191801
3. Measurement of antiproton production in pHe
   collisions at $\sqrt{s_{NN}} = 110$ GeV,
   LHCb collab., Phys. Rev. Lett. **121** (2018) no.22, 222001
4. Measurement of the lifetime of the doubly charmed
   baryon Ξ_{cc}^{++},
   LHCb collab., Phys. Rev. Lett. **121** (2018) no.5, 052002
5. γ combination, LHCb collab.,
   https://cds.cern.ch/record/2319289

LHCb Experiment – Upgrades

Prof. Nicola Serra, PD Dr. Olaf Steinkamp

At the end of 2018, the LHCb experiment has collected a data sample corresponding to about 10/fb in proton-proton collisions. Even after analysing the full available data sample, most measurements will be limited by statistical uncertainties. To be able to further reduce uncertainties on a reasonable time scale will require to collect data at higher instantaneous luminosity and with higher efficiency. The LHCb collaboration has therefore decided to perform a comprehensive upgrade I of the experiment in 2019/2020 and to study an upgrade II around 2030.

Upgrade I of the LHCb experiment in 2019/2020 necessitates the replacement of the entire tracking system. Our group is involved in the replacement of the tracking station that was located upstream of the LHCb dipole magnet. The new Upstream Tracker is going to employ silicon microstrip detectors with finer granularity and better radiation hardness, and a new readout chip that is compatible with triggerless readout. Our group is involved in the testing of the readout chip and in the development of hardware and firmware for the detector control and readout. We also contribute to feasibility studies for upgrade II of the tracking system. We study algorithms for efficient and fast track reconstruction and we work towards the development of a new silicon pixel detector for the inner part of the tracking stations downstream of the LHCb magnet. A first version of this new detector could be installed in 2025.



Occupancy in the downstream tracking stations and possible layout of a new pixel detector for upgrade II of the LHCb detector.

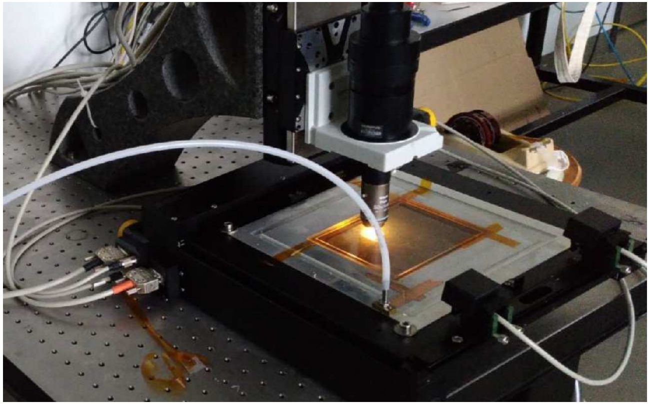
SHiP - Search for Hidden Particles

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, featuring two new members, 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 which is critical for the SHiP experiment since hidden particles are mostly produced in the decay of charmed hadrons. A test run was conducted in July 2018 using nuclear emulsions films, alternated with layers of passive materials. Emulsion films have micrometric resolution, allowing us to resolve the proton interaction point and the vertex-decay location of the charmed hadron, a few hundred micrometers away. Our group is involved in the analysis of the data recorded in the emulsion films using an automated microscope for the emulsion scanning.



Microscope setup for the scanning of the emulsion films.