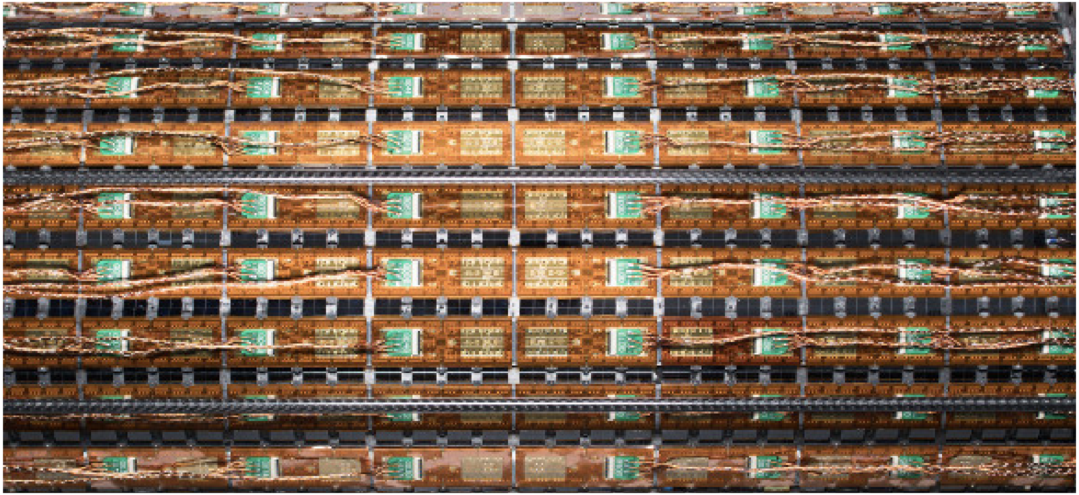
Physics of Fundamental Interactions and Particles



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

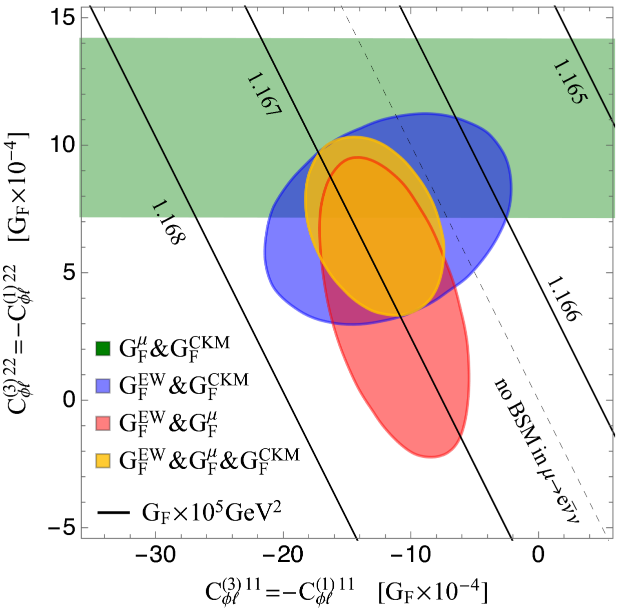
Hints for New Sources of Lepton Flavour Universality Violation

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. Furthermore, all SM gauge interactions treat leptons in the same way; i.e. they respect lepton flavour universality (LFU) and the only source of LFU violation are the couplings of the Higgs.

However, several experiments found hints for deviations from lepton flavour universality in different observables [1], causing considerable interest within the theoretical community.

One of these observables is a precision measurements of a property of the muon called “anomalous magnetic moment”. Here we studied possible explanations in detail [2].

Furthermore, there exist discrepancies between different ways of determining elements of the aforementioned CKM



Example of the complementarity between the Fermi constant G_F determinations from muon decay (G_F^{μ}), CKM unitarity (G_F^{CKM}), and the global EW fit (G_F^{EM}) in case of $C_{\Phi\ell}^{(3)ii} = C_{\Phi\ell}^{(1)ii}$, corresponding to modifications of neutrino couplings to gauge bosons. Here, we show the preferred 1σ regions obtained by requiring that two or all three G_F determinations agree. The contour lines show the value of the Fermi constant extracted from muon decay once BSM effects are taken into account (from [1]).

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, possibly also related to muons [3].

Highlighted Publications:

1. Hints of lepton flavor universality violations,
   A. Crivellin and M. Hoferichter,
   Science **374** (2021) no.6571, 1051
   arXiv:2111.12739 [hep-ph]
2. Consequences of chirally enhanced explanations of
   $(g-2)$ for $h \to \mu\mu$ and $Z \to \mu\mu$,
   A. Crivellin and M. Hoferichter,
   JHEP **07** (2021), 135
   arXiv:2104.03202 [hep-ph]
3. Fermi Constant from Muon Decay Versus Electroweak
   Fits and Cabibbo-Kobayashi-Maskawa Unitarity,
   A. Crivellin, M. Hoferichter and C. A. Manzari,
   Phys. Rev. Lett. **127** (2021) no.7, 071801
   arXiv:2102.02825 [hep-ph]

Particle Physics Theory: Beyond the Standard Model

Prof. Gino Isidori

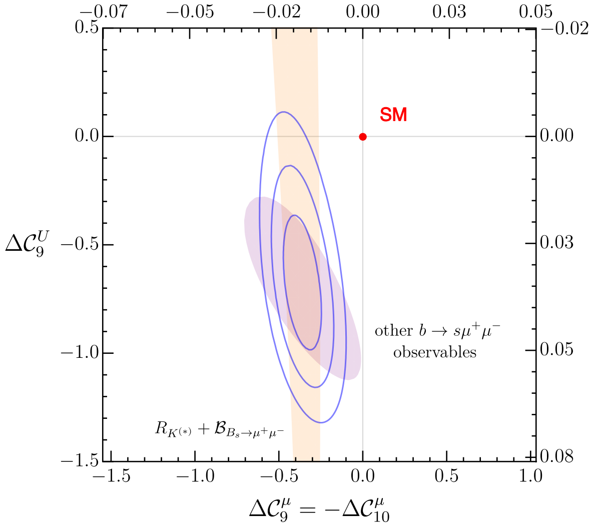
The Standard Model of fundamental interactions describes the nature of the basic constituents of matter, the so-called quarks and leptons, and the forces through which they interact. This Theory is very successful in laboratory experiments over a wide range of energies. However, it fails in explaining 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 five 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 2021 new experimental results by the LHCb experiment have strengthened the evidence of the anomalies. Motivated by these new results we have shown



Global fit of observables in $b \to s\ell^+\ell^-$ decays exhibiting deviations from the SM predictions.

how to obtain a conservative estimate of the overall significance of the anomalies irrespective of the hypotheses about the nature of physics beyond the SM. At the same time, we have refined the theoretical model developed in the last five years which provides a good description of all available data. This model is based on the hypothesis of a new force-mediator called "leptoquark", transforming quarks into leptons and vice versa. We also developed general theoretical tools for the interpretation of new type of data expected by the LHCb collaboration in the next few years, which could provide a decisive test of this hypothesis.

Highlighted Publications:

1. Reading the footprints of the B-meson flavor anomalies, C. Cornella, D. A. Faroughy, J. Fuentes-Martin, G. Isidori and M. Neubert,
   JHEP **08** (2021), 050, arXiv:2103.16558 [hep-ph]
2. On the significance of new physics in $b \to s\ell^+\ell^-$ decays, G. Isidori, D. Lancierini, P. Owen and N. Serra,
   Phys. Lett. B **822** (2021), 136644,
   arXiv:2104.05631 [hep-ph]
3. The LFU ratio R_π in the Standard Model and beyond,
   M. Bordone, C. Cornella, G. Isidori and M. König,
   Eur. Phys. J. C **81** (2021) no.9, 850,
   arXiv:2101.11626 [hep-ph]

Particle Physics Theory: Precision Calculations

Prof. Thomas Gehrmann

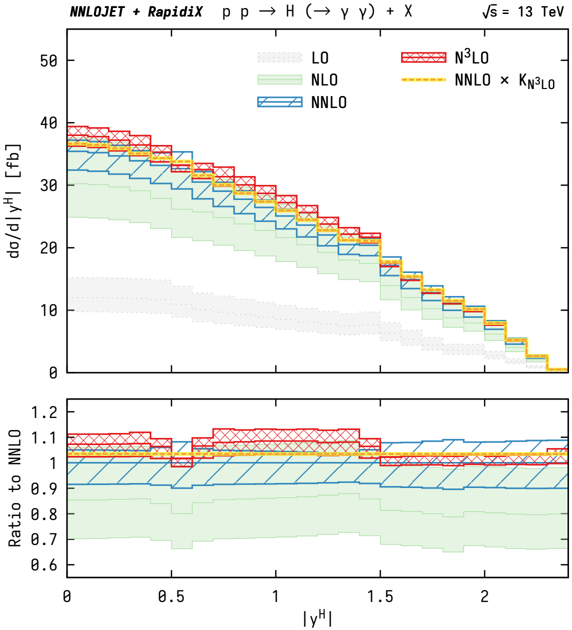
Our research group focuses on precision calculations for collider observables within the Standard Model and their application in the interpretation of experimental data. We develop novel techniques and computer algebra tools that enable analytical calculations in perturbative quantum field theory and 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

Ultimate precision for fiducial Higgs cross sections

To address the fundamental nature of the Higgs boson and to measure its properties, it is of paramount importance to understand theoretically the features of its production and decay to a degree that rivals or surpasses the precision achieved by the experimental measurements. Predictions for fiducial cross sections that include realistic selection cuts on the final-state decay products of the Higgs boson will allow to compare theoretical predictions directly to experimental observations. To prepare for Higgs boson studies at per-cent level precision with future HL-LHC data, our group is currently developing methods and tools to perform fully differential calculations of fiducial cross sections that QCD corrections expanded up to third order (N3LO) in perturbation theory.

Fully differential predictions at higher orders in perturbation theory require special treatment for the cancellation of infrared singularities that appear at the intermediate stages of the calculation. The Projection-to-Born method accomplishes this through a special projection operation that allows matching an inclusive calculation to a differential calculation at one order lower but with an additional real emission. As a first application of this method to Higgs boson production at the LHC, we have focused on the di-photon decay mode of the Higgs boson. Combining the second-order (next-to-next-to-leading order, NNLO) QCD calculation of fully differential



Higgs boson rapidity distribution from di-photon final states at LO, NLO, NNLO and N3LO (newly computed, red) in perturbation theory, compared to approximate N3LO prediction (orange).

Higgs-boson-plus-jet production with the inclusive N3LO Higgs boson rapidity distribution, we obtain fully differential N3LO Higgs production cross sections.

The fiducial cross section in the di-photon decay mode is defined through cuts on the photon transverse momenta and rapidities as well as by isolation requirements on the photons. This setup induces a highly non-trivial interplay between the final-state photons and QCD emissions leading to kinematical features in the resulting distributions, seen prominently in the Higgs boson rapidity distribution in the fiducial di-photon channel (figure). We observe for example that in the central region of the rapidity distribution N3LO corrections are larger than expected from the inclusive correction factor, and that the corrections are not uniform in rapidity. Similar features are also observed in other kinematical distributions. Our results will enable a new level of quantitative precision for the study of the di-photon decay mode of the Higgs boson, and can possibly be extended to other channels.

Computing more complex final states to N3LO in QCD will however require substantial advances in concepts, algorithms and techniques for perturbative calculations. The major challenges associated with this endeavour will be addressed by our group in the framework of a recently awarded ERC Advanced Grant 'Theory of Particle Collider Processes at Ultimate Precision (TOPUP)'.

Highlighted Publications:

1. Fully Differential Higgs Boson Production to Third Order in QCD, X. Chen *et al.*, Phys. Rev. Lett. 127 (2021) 072002.

Particle Physics Theory: Standard Model and Higgs Physics at Colliders

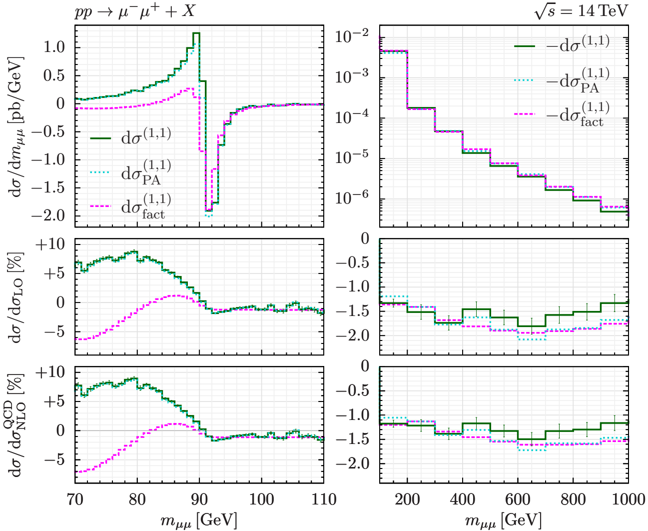
Prof. Massimiliano Grazzini

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 and jet production, to Higgs boson studies within and beyond the Standard Model.

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

Mixed strong-electroweak corrections to the Drell-Yan process

The Drell-Yan (DY) process is the most classic hard-scattering process at hadron colliders. It corresponds to the inclusive production of a lepton pair through an intermediate vector boson. It provides large production rates and clean experimental signatures, given the presence of at least one lepton with large transverse momentum in the final state. Historically, it offered the first application of parton model ideas beyond deep inelastic scattering and led to the discovery of the W and Z bosons at CERN SpS. The DY process was one of the first hadronic reactions for which radiative corrections in the strong and EW couplings α_S and α were computed. Radiative corrections for an on-shell vector boson are now known even at the third order in the strong coupling, at least for the inclusive cross section. Since the high-precision determination of EW parameters requires control over the kinematical distributions at very high accuracy, the attention has recently turned to the mixed QCD-EW corrections. The mixed corrections are exactly known for an on-shell vector boson. Beyond the on-shell limit, the most relevant results have been obtained in the *pole* approxi-



Complete $\mathcal{O}(\alpha_s\alpha)$ correction to the differential cross section $d\sigma^{(1,1)}$ in the dimuon invariant mass compared to the corresponding result in the pole approximation and to the factorised approximation $d\sigma^{(1,1)}_{\text{fact}}$. The top panels show the absolute predictions, while the central (bottom) panels display the $\mathcal{O}(\alpha_s\alpha)$ correction normalized to the LO (NLO QCD) result. For the full result the ratios also display our estimate of the numerical uncertainties.

mation, which is based on a systematic expansion of the cross section in the resonant region, so as to split the radiative corrections into well-defined gauge-invariant contributions.

Given the relevance of mixed QCD-EW corrections for precision studies of DY production and for an accurate measurement of the W mass, it is important to go beyond these approximations. Recently our group has presented the first complete computation of the mixed QCD-EW corrections for the neutral-current DY process [1].

The required tree-level and one-loop scattering amplitudes are computed with the Openloops and Recola generators, finding complete agreement. The two-loop virtual amplitude is computed by using semi-analytical techniques. Even when all the amplitudes have been computed, the completion of the calculation is highly non trivial. Indeed, double-real, real-virtual and purely virtual contributions are separately infrared divergent, and a method to handle and cancel infrared singularities has to be worked out. In our work we use a formulation of the q_T subtraction formalism derived from the second order QCD computation of heavy-quark production through an appropriate abelianisation procedure. The same method has been applied to the charged-current DY process [2].

1. Mixed Strong-Electroweak Corrections to the Drell-Yan Process, R. Bonciani *et al.*,
   Phys. Rev. Lett. **128** (2022) no. 1, 012002
2. Mixed Strong-Electroweak Corrections to the Drell-Yan Process, L. Buonocore *et al.*, Phys. Rev. D **103** (2021), 114012

Particle Physics Theory: Automated Simulations for high-energy colliders

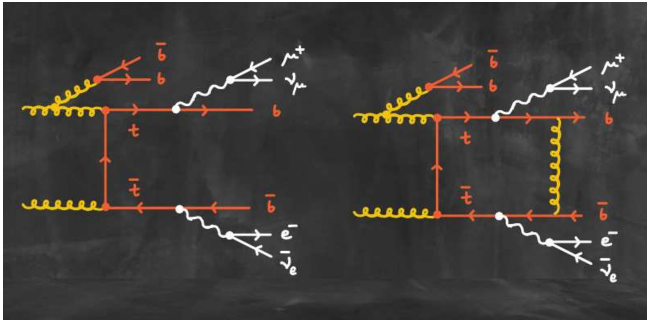
Prof. Stefano Pozzorini

Our research deals with the development of automated methods for precision simulations of scattering processes in quantum-field theory. The OpenLoops program, developed in our group, is one of the most widely used tools for the calculation of scattering amplitudes at the LHC. OpenLoops 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

New algorithm for challenging multi-particle calculations

Recently we have developed a new algorithm for the calculation of first-order quantum effects in non-trivial multi-particle processes. Scattering processes can be described in terms of so-called Feynman diagrams, which encode the different quantum states that occur in the transition between the initial and final states of particle collisions. In this picture, first-order quantum effects correspond to "one-loop" diagrams that involve the exchange of virtual quanta with one unconstrained momentum and require the calculation of so-called one-loop integrals. The number of one-loop diagrams and the complexity of the associated integrals grow very fast with the number of scattering particles. For this reason, the preparation of precise predictions for scattering processes with more than four final-state particles can be very challenging. In particular, the required computing time can become prohibitively large. Moreover, the evaluation of one-



Examples of lowest-order (left) and one-loop (right) Feynman diagrams contributing to $t\bar{t}b\bar{b}$ production at the LHC. This process can be initiated by various combinations of gluons, quarks and anti-quarks, and the depicted diagrams belong to the gluon–gluon channel, which involves more than 200'000 different one-loop diagrams. The orange curly lines represent gluons, the mediators of strong interactions, while red lines stand for top and bottom quarks or anti-quarks. White lines correspond to the weakly interacting particles that arise in top-quark decays: W-bosons, neutrinos and charged leptons.

loop integrals can be jeopardised by large numerical instabilities.

To address these challenges we have developed a new algorithm, dubbed OTTER, that makes it possible to evaluate arbitrary one-loop integrals with unprecedented speed and numerical stability. This new tool will be made publicly available as part of a forthcoming release of the OPENLOOPS program, while its first applications have already appeared. Recently, together with collaborators at Würzburg and Cambridge University, the OTTER algorithm has been employed for the first full calculation of the first-order corrections to $t\bar{t}b\bar{b}$ production and decay [1] at the LHC. The precise theoretical understanding of this process plays a key role to test Higgs-boson interactions with heavy quarks, and the calculation at hand provides the first full quantum description of the $2 \rightarrow 8$ process that involves the production and decay of the top-antitop quark system. The OTTER algorithm has played a key role in enabling this highly non-trivial calculation, which involves several quark/gluon-initiated subprocesses with up to 200'000 one-loop diagrams.

The technical features of OTTER render it ideally suited also for high-precision calculations at the second order in perturbation theory, and this new algorithm is going to be a key building block for the automation of second-order calculations within the OPENLOOPS framework.

Highlighted Publications:

1. Full NLO QCD corrections to off-shell ttbb production,
   A. Denner, J-N. Lang, M. Pellen,
   Phys. Rev. D **104** (2021) no.5, 056018

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. The Paul Scherrer Institut (PSI) has obtained numerous lasting results with pions, muons and neutrons in the past decades and an overview has been compiled as a SciPost proceedings.

Using the world's most intense muon beam at 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.

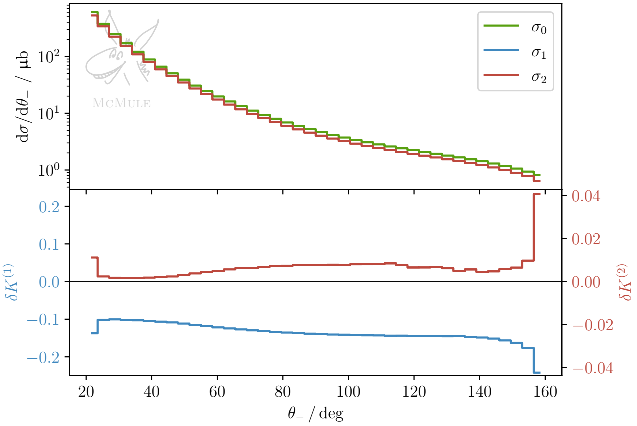
https://www.physik.uzh.ch/g/signer

Bhabha scattering at NNLO

Our group has set up McMule (Monte Carlo for MUons and other LEptons), a generic framework for higher-order QED calculations of scattering and decay processes involving leptons (`https://gitlab.com/mule-tools/mcmule`). 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 calculated the photonic NNLO corrections to Bhabha (electron-positron) scattering. Currently, we treat Bhabha scattering as a pure QED process, restricting application to the low-energy domain, where the effect of the Z boson is negligible.

In QED it is important to keep the fermion masses at their physical value, rather than setting them to zero. This



Differential cross section $d\sigma/d\theta_-$ for Bhabha scattering at $\sqrt{s} =$ 1020 MeV, where θ_- is the scattering angle in the centre-of-mass frame of the outgoing electron. The relative NLO and NNLO corrections $\delta K^{(1)}$ and $\delta K^{(2)}$ are shown in the lower panel.

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 these logarithms cancel.

Since the massive two-loop amplitudes for Bhabha scattering are not yet available, we had to apply 'massification'. This is a method that allows to obtain the dominant terms of the massive amplitudes from their massless counterpart. All terms that are not polynomially suppressed by the (small) mass are recovered. For the one-loop amplitudes we use OpenLoops. In addition we apply next-to-soft stabilisation, a method to use the analytic form of the soft limit to sufficient precision in order to guarantee a numerically reliable phase-space integration.

As a first application we have studied the impact of the full NNLO corrections for Bhabha scattering at $\sqrt{s} =$ 1020 MeV, compared to an earlier calculations with the code Babayaga, where the NNLO corrections are approximated through a parton-shower algorithm. The additional contributions of our calculation modify the NNLO coefficient by about 15%, in line with expectations. This amounts to a change of 0.07% for the total cross section. While this is a small correction, including corrections of this size is important when using Bhabha scattering as luminosity measurement for future electron-positron colliders.

Highlighted Publications:

1. Particle Physics at PSI, A. Signer, K. Kirch and C. Hoffman, SciPost Phys. Proc. **5** (2021)
2. Bhabha scattering at NNLO with next-to-soft stabilisation, P. Banerjee *et al.*, Phys. Lett. B **820** (2021) 136547

Effective Field Theories at the Precision Frontier

Prof. Peter Stoffer

The research of our group is focused on indirect searches for physics beyond the Standard Model and the theoretical challenges at the precision frontier: these concern the model-independent description of non-perturbative effects due to the strong interaction at low energies as well as higher-order perturbative effects that can be described within effective field theories.
Our current research activity is mainly motivated by experimental progress at the low-energy precision frontier, such as searches for CP- or lepton-flavor-violating observables and the improved measurement of the muon anomalous magnetic moment.

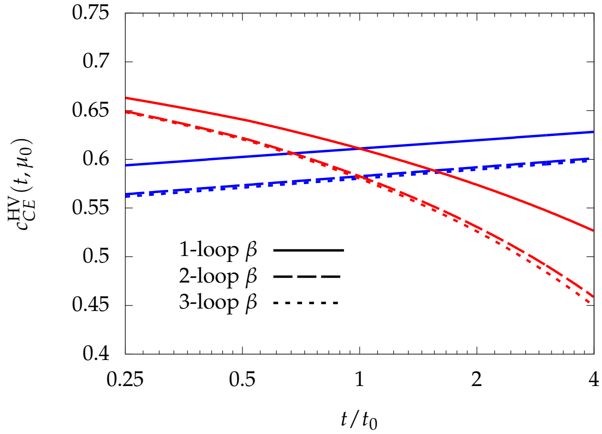
https://www.physik.uzh.ch/g/stoffer

Despite its success, the Standard Model (SM) of particle physics fails to explain certain observations, such as the baryon asymmetry in the universe, dark matter, or neutrino masses. Our group is interested in indirect searches for physics beyond the SM, conducted in low-energy experiments at very high precision. These observables pose interesting theoretical challenges concerning the model-independent description of effects beyond the SM, as well as non-perturbative effects due to the strong nuclear force.

CP and lepton-flavor violation

Beyond-the-SM sources of CP or lepton-flavor violation are probed up to very high scales by searches for electric dipole moments (EDMs) or lepton-flavor-violating decay processes, e.g., in the upcoming n2EDM and Mu3e experiments at PSI. We are interested in non-perturbative effects that affect these observables at low energies. Their description is based on effective field theories (EFTs) and usually requires input from lattice QCD.

We recently worked out the one-loop matching for the dimension-five quark-dipole operators between the MS scheme used in EFTs and a gradient-flow scheme that can be implemented with lattice QCD. This calculation will enable the use of future lattice-QCD input for an accurate determina-



Scale dependence of the matching coefficient for the dipole operator between the MS-HV and gradient-flow scheme at an $\overline{\mathit{MS}}$ *scale of 3 GeV. The calculated one-loop effect amounts to a correction of about* -40%.

tion of the dipole-operator contribution to the neutron EDM, which encodes effects beyond the SM.

Anomalous magnetic moment of the muon

The current SM prediction of the anomalous magnetic moment of the muon differs from the experimental value by 4.2σ. The theoretical uncertainty is dominated by hadronic contributions, i.e., effects due to the strong interaction, in particular hadronic vacuum polarization and hadronic light-by-light scattering. We are working on reducing these uncertainties using dispersion relations, which are based on the fundamental principles of unitarity and analyticity. In recent work, we analyzed the contribution of scalar resonances. On the other hand, within an EFT framework we worked out the potential contribution of heavy physics beyond the SM to one-loop accuracy, including renormalization-group and matching effects.

Highlighted Publications:

1. One-loop matching for quark dipole operators in a gradient-flow scheme, E. Mereghetti, C. J. Monahan, M. D. Rizik, A. Shindler, P. Stoffer, arXiv:2111.11449 [hep-lat], submitted to JHEP
2. A dispersive estimate of scalar contributions to hadronic light-by-light scattering, I. Danilkin, M. Hoferichter, P. Stoffer, Phys. Lett. B **820**, 136502 (2021), [arXiv:2105.01666 [hep-ph]]
3. Effective field theory interpretation of lepton magnetic and electric dipole moments, J. Aebischer, W. Dekens, E. E. Jenkins, A. V. Manohar, D. Sengupta, P. Stoffer, JHEP **07**, 107 (2021), [arXiv:2102.08954 [hep-ph]]

CMS Experiment

Prof. Cristina Botta, Prof. Lea Caminada, 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 when colliding protons produces an energy density comparable to that of the universe one ten- billionth of a second after it started. The CMS detector is used to determine the energy and direction of the energy and directions of the particles emerging from the LHC collisions of protons and heavy ions. In 2012, with 10 fb^{-1}, CMS discovered the Higgs boson, proving the mechanism on how particles acquire mass. The current dataset of 150 fb^{1} allows CMS to make precise measurements and searches for new physics. CMS is also focused on detector refurbishment for the data-taking period of 2022 to 2025, and upgrades needed for the high-luminosity run of the LHC from 2029 to 2038.

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 are searching for dark matter in unexplored phase space, and we are measuring standard model processes that can elucidate rare phenomena.

A leap forward in 2021 is the first observation of standard model triple J/Ψ production [1]. Most physics processes at the LHC occur when one parton, a quark or gluon, from each colliding proton interacts. Instead, in this new measurement, the dominant production mechanisms are when two (74% of the time) or three (20%) partons from each proton interact. This is the first time that the simultaneous production of three particles has been observed at the LHC. The process creates three J/Ψ mesons, each decaying to two muons, producing the spectacular signature of six muons (Fig. 1).

The discovery of the Higgs boson in 2012 has created more questions than answers, as its low mass is contradictory to theoretical expectations unless some new physics processes

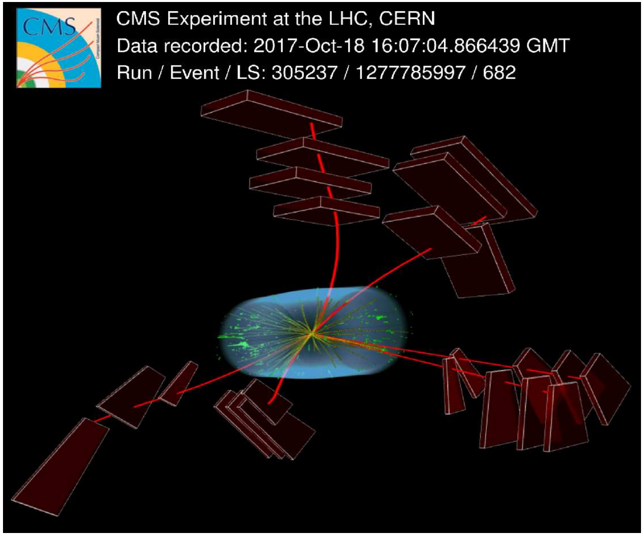


Fig. 1: In 2021, the UZH CMS group produced the first observation of the simultaneous production of three heavy particles. Shown is a Candidate event in which three J/Ψ particles are produced. Each J/Ψ decays to two muons (red lines), which are observed in the tracker and dedicated muon chambers (red blocks).

can stabilize it. A possible solution is a model where a new heavy particle couples strongly to the Higgs boson and other standard model bosons. In 2021, the CMS group searched for such a particle, and placed the most stringent bounds on its cross section as a function of its mass [2], up to 4.6 TeV, more than 25 times larger than the heaviest particle known.

Our group is performing searches for new particles that decay into weakly interacting massive particles (WIMPs) that could compose the dark matter of our universe. Our new search considers WIMPs produced in a compressed mass spectrum, meaning that the new particles have similar masses, such that when they decay into WIMPs and standard model particles, the detected particles have low momenta (Fig. 2). A compressed mass spectrum could be the reason why the LHC has not discovered dark matter yet. Searches for compressed particlesare experimentally challenging due to the very low momentum of the the observable particles, and therefore special reconstruction techniques are required. We make use of the identification of muons and electrons, with “soft" transverse momentum down to 3 and 5 GeV, respectively. In 2021, we used these techniques to produce new results extending the search for the supersymmetric partners of the Higgs boson [3]. The UZH CMS group also develops new tools for data analysis techniques inspired on modern methods of machine learning. In 2021, we created a pethod for point cloud information and applied it to jet-tagging of highly-boosted particles [4].

CMS will double its current dataset during the period of 2022 to 2025. UZH has played a major role in upgrading the pixel detector in 2017 to cope with the higher data rate and to provide better detector resolution [5]. The inner most pixel detector layer is subject to extremely high data rates and irradiation levels, and an improved inner layer was installed in June 2021 to mitigate these [6] (Fig. 3). Currently we are working on the testing and calibration of the detector to ensure a successful operation during the upcoming data-taking period.

CMS will collect more than 20 times the current data set during the period of 2029 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 2021, we carried out tests on prototype sensor modules integrated with the disk electronics and the pixel detector readout chain. 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 ($40 \cdot 10^{-12}$ s) in our lab, as well as demonstrate its high hit efficiency. Such a technology could greatly improve the physics potential of CMS in later upgrades.

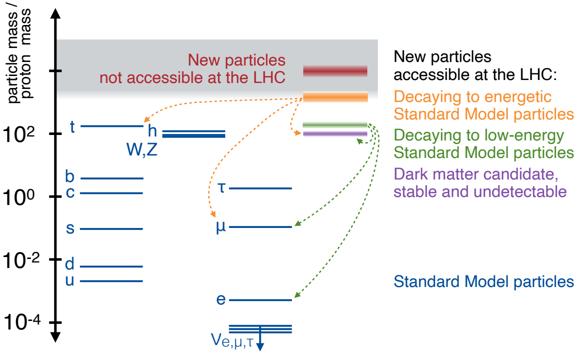


Fig. 2: A theory for dark matter in a compressed spectrum of new particles. New particles in yellow or green decay to standard model particles in blue and dark matter in purple. The mass difference between the new particle and its decay particles is small enough that the standard model particles are difficult to observe.

With the upcoming HL-LHC project, the CMS L1 Trigger, instrumented by custom hardware processor boards, needs to be redesigned to face the challenge of the high luminosity. The UZH group is involved in the design of a completely novel approach: the inclusion of tracking and high-granularity calorimeter information, together with a longer latency and a flexible and modular architecture, enables real-time state-of-the-art offline techniques, such as a global event reconstruction. The UZH group performed developments of new algorithms, implemented firmware, and emulated software to facilitate the performance studies of the proposed L1 trigger system. We have also played a major role in the Technical Design Report for the L1 trigger upgrade [7].

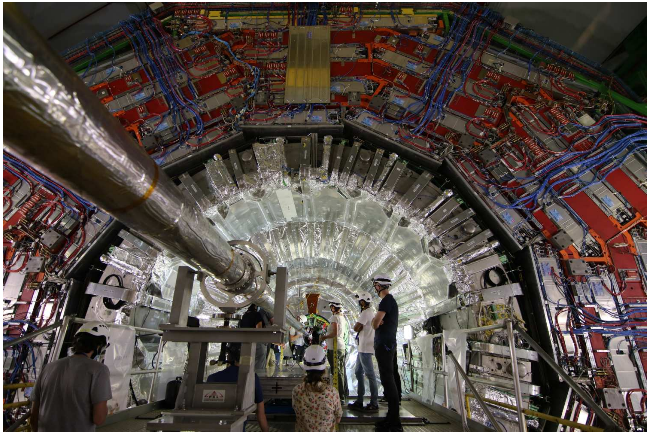


Fig. 3: After collecting data in 2017 and 2018, the CMS pixel detector inner layers were replaced in 2021 with new detectors designed to have better irradiation tolerance and higher rate capabilities for the data-taking period 2022 to 2025.

Highlighted Publications:

1. Observation of triple J/Ψ meson production in ...
   CMS Collab., https://cds.cern.ch/record/2790122
2. Search for a heavy vector resonance decaying to a Z ...
   CMS Collab., https://arxiv.org/abs/2102.08198
3. Search for supersymmetry in final states with two ...
   CMS Collab., https://arxiv.org/abs/2111.06296
4. Point cloud transformers ..., V. Mikuni and F. Canelli,
   https://iopscience.iop.org/article/10.1088/2632-2153/ac07f6
5. The CMS Phase-1 Pixel Detector Upgrade,
   CMS Tracker Group, https://inspirehep.net/literature/1838384
6. CMS Phase-1 pixel detector refurbishment ...
   L. Noethe, https://cds.cern.ch/record/2797711
7. The Phase-2 Upgrade of the CMS Level-1 Trigger,
   CMS Collab.,
   https://cds.cern.ch/record/2714892/files/CMS-TDR-021.pdf

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 contribute to an ongoing major uphgrade of the detector for 2023 and are involved in studies for future upgrades of the experiment.

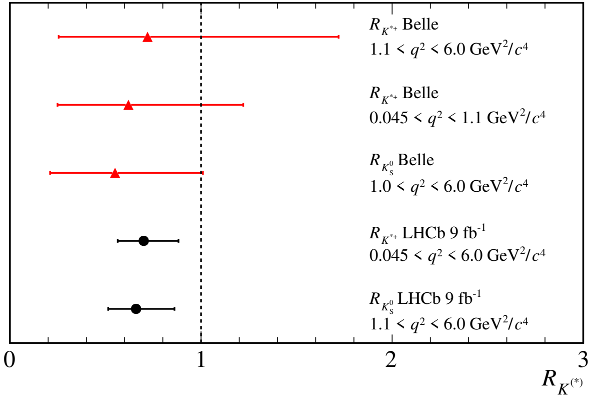
https://www.physik.uzh.ch/r/lhcb

New measurements strengthen hints of lepton universality violation

A distinctive feature of the Standard Model (SM) is the concept of lepton universality, whereby the charged leptons (electron, muon and tauon) have identical interaction strengths to the gauge bosons. This accidental symmetry does not necessarily hold in theories beyond the SM. The LHCb group at UZH has a strong focus on testing lepton universality with beauty quark decays, whereby the behaviour of beauty quark decays into different lepton flavours is compared.

Last year a high precision measurement of R_K was reported, for which the UZH group had a major role [2]. The measurement deviated from the SM prediction by 3.1 standard deviations (p-value $\sim$ 0.1%), constituting the first evidence of lepton universality violation from a single measurement. The discovery threshold in particle physics is 5.0 standard deviations and so more independent measurements, sensitive to the same physics are needed.

At the end of last year, LHCb reported two new lepton universality tests in the decays $B^+ \to K^{*+}K\ell^+\ell^-$ with $K^{*+} \to K_s^0\pi^+$ and $B^0 \to K_s^0\ell^+\ell^-$, where ℓ denotes either an electron or muon and K^{*+} and K^0 are mesons containing a strange quark [3]. These decays result in K_s^0 mesons,



Comparison of the measurements of R_{K_s} and $R_{K^{*+}}$. Although the measurements are compataible with the Standard Model, they have values in the same direction as previous deviations [2].

which have a large lifetime and typically travel 2 meters in the experiment before decaying. This results in a lower statistical sensitivity compared to the previous measurement of R_K, but nevertheless provides an independent test of the underlying physics.

As for other lepton universality analyses, one of the main challenges is to control for the different detector response of electrons and muons. Electrons radiate a significant number bremsstrahlung photons when traversing through the LHCb detector, which degrades the reconstruction efficiency and signal resolution compared to muons. The key to control this effect is to use the standard candle decays $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$, which are known have the same decay probability and can be used to calibrate and test electron reconstruction efficiencies. High precision tests with the J/ψ are compatible with lepton universality which provides a powerful cross-check on the experimental analysis.

The ratios R_{K_s} and $R_{K^{*+}}$ were measured with the full run1-run2 dataset and were both found to be consistent with the Standard Model at the level 1.5 standard deviations. The results are shown alongside previous measurements made by the Belle and BaBar experiments. Interestingly, the central values of both these measurements are below the Standard Model predictions, which is in the same direction as previous, more precise, results which show deviations from the SM.

Highlighted Publications:

1. All LHCb publications: lhcb.web.cern.ch/lhcb/
2. Test of lepton universality in beauty-quark decays, LHCb Collab., arXiv:2103.11769
3. Tests of lepton universality using $B^0 \to K^0_S\ell^+\ell^-$ and $B^+ \to K^{*+}\ell^+\ell^-$ decays, LHCb Collab., arXiv:2110.09501

LHCb Experiment – Upgrade

Prof. Nicola Serra, PD Dr. Olaf Steinkamp

Since the end of the data taking in 2018, the LHCb detector has been undergoing a major upgrade. The goal is to accumulate five times more data in the next running periods of the LHC in order to increase the precision of previous measurements and to further extend the rich physics programme of LHCb.

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

All the front-end electronics have been changed to read out the full detector at the collider collision rate of 40MHz. Also, the average number of pp collisions will be multiplied by five, which makes track reconstruction more challenging and increases radiation damage. This implied that the full tracking system of LHCb had to be replaced. Our group is involved in the installation of one of the three new sub-detectors, the Upstream Tracker, as part of a large international effort to make the LHCb Upgrade detector ready to start recording very exciting new data sets for physics analysis in 2023.

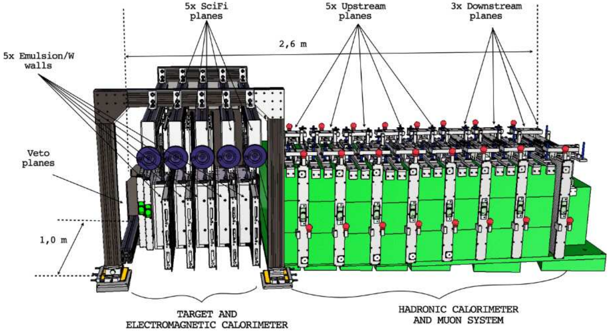
Lowering of part of the Scintillating Fibre detector into the LHCb cavern (Photo: Blake Leverington).

SND@LHC

Prof. Nicola Serra

SND@LHC is a compact experiment to exploit the high flux of energetic neutrinos of all three flavours from the LHC. It covers the pseudo-rapidity range of $7.2 < \eta < 8.4$, so far unexplored, in which a large fraction of neutrinos originate from charmed-hadron decays. Thus, neutrinos probe heavy-flavour production in a region that is not accessible to the other LHC experiments.

The UZH is a founding member of SND@LHC, and has spearheaded the design and construction of the veto and muon systems. The veto system aims at rejecting charged particles, mostly muons coming from ATLAS interaction point. It is located upstream of the target region and comprises two parallel planes of stacked scintillating bars read out on both ends by silicon photomultipliers. Downstream of the target region lies the hadronic calorimeter and muon system. Besides identifying muons it will serve together with the SciFi as a sampling hadronic calorimeter, enabling measurement of the energy of hadronic jets. The muon system comprises eight layers of scintillating planes interleaved between layers of iron slabs, which will act as passive material.



The experiment was approved in March 2021. Designs for the veto and muon systems were finalised in June, while construction was completed in the fall. Installation is nearly complete and the first physics runs will begin in June 2022.

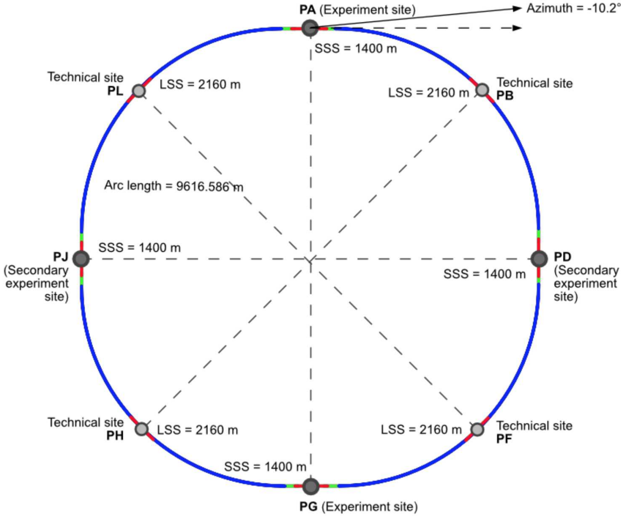
Future Circular Collider (FCC)

Prof. Florencia Canelli

The goal of the Future Circular Collider study (FCC) is to greatly push the energy and intensity frontiers of particle colliders and lay the foundations for a new research infrastructure that can succeed the LHC and serve the world-wide physics community for the rest of the 21st century. The FCC project envisions a staged approach, in which a new, 100-km tunnel is first used for electron-positron collisions (FCC-ee), after which the complex is upgraded to collide hadrons (FCC-hh), with the aim of reaching collision energies of 100 TeV, in the search for new physics [1].
https://www.physik.uzh.ch/r/fcc

In June 2021, the CERN Council endorsed the FCC feasibility study [2,3] with a budget of 100 MCHF to investigate the viability of the colliders and related infrastructure for the next Update of the European Strategy for Particle Physics in 2026. At the same time, our group started a collaboration with Vrije Universiteit Brussel (Belgium) to develop tracking detectors and algorithms for the FCC-ee.

A precise determination of the interaction vertices is crucial for the success of the FCC-ee physics program. Our group therefore develops state-of-the-art silicon sensors optimized for the Vertex detector at the FCC-ee. They feature a single point spatial resolution of a few microns while adding only a minimal amount of material to the detector. This enables a reliable determination of the jet flavour and to discriminate the decaying particles over a wide range of momentum, paving the way for flavour physics and precise Higgs coupling studies. In addition to this, our group implements modern analysis techniques, currently used at the LHC, into the FCC analysis framework and simulates the vertex detector perfor-



New FCC-ee baseline layout with four collision sites and circumference of 91.2 km. Source: J. Gutleber et al. https://indico.cern.ch/event/1065778

mance to evaluate the potential physics reach of the FCC-ee.

Highlighted Publications:

1. Future Circular Collider - European Strategy Update Documents,
   M. Benedikt et al., CERN-ACC-2019-0003 (2019)
2. Organisational structure of the FCC feasibility study,
   CERN, CERN/3566 (2021)
3. Main deliverables and timeline of the FCC feasibility study,
   CERN, CERN/3588 (2021)