SWHEPPS 2016:

Summary of the
Strategic Workshop for High Energy Particle Physics
in Switzerland

Seminarhotel Aegerisee, 7-9 June 2016
https://indico.cern.ch/event/504502/

Swiss Institute of Particle Physics

FINAL VERSION
July 3, 2017

1 Overview of the Workshop

SWHEPPS [1], the Strategic Workshop on High Energy Particle Physics in Switzerland, was a 2.5 day workshop that took place from 8-10 June 2016 at Seminarhotel Aegerisee. It was modeled as a plenary session-only retreat of primarily senior CH researchers and PIs engaged in CHIPP [2] pillar 1 activities, i.e. research at the high energy and low energy frontier (an introduction to the pillar structure of CHIPP can be found in the CHIPP roadmap [3]). The aim of the workshop was to take stock of the present state of the field in order to identify key elements influencing the strategy of Swiss researchers active in pillar 1 research activities for the next 5-15 years or - failing that - define milestones when identifying those elements should become clearer. The workshop should furthermore serve as a kick-off meeting to start process of editing a CHIPP whitepaper on future pillar 1 activities in order to complement similar documents pertaining to the neutrino pillar [4] and the astroparticle pillar [5] in time for the Update of the European Strategy for Particle Physics of the CERN council [6].

The workshop consisted of 28 plenary talks of 25 minutes length and 5 minutes discussion and three 90-minute discussion sessions. 11 external speakers were invited to offer their perspective from outside Switzerland. Figure 1 shows the timetable.

Final Programme V4 11.May 2016

	Day 1	Day 2	Day 3
7:30-9:00		Breakfast	Breakfast
9:00-10:30		**Flavor Physics**	**New Accelerators: Facilities**
10:30-11:00		Coffee	Coffee
11:00-12:30	**Registration**	**Low Energy Physics**	**New Accelerators: Detectors**
12:30-13:45	Buffet Lunch	Buffet Lunch	Buffet Lunch
14:00-15:30	**Higgs Physics**	**Standard Model**	**Discussion: New Accelerators**
15:30-16:00	Coffee	Coffee	
16:00-18:00	**LHC Searches and perspectives**	**Theory including connections to other fields**	**Summary (16-17h)**
18:00-19:30	**Discussion:** Status Searches at High Energy Frontier	**Discussion: Connection to other fields**	
20:00-22:00	Apero & Dinner	Dinner	

25+5min plenary talks: summarize status, raise questions.
Discussion sessions 90min to 2 hrs max.

Figure 1: SWHEPPS Workshop Timetable.

The convenors (mentioned as section editors in the session summaries) were asked to select and invite speakers for their session primarily from the CH community with the possibility to invite an external keynote speaker (with paid expenses) that could help to shape and sharpen the discussion. A salient feature of the workshop structure was the "embedding" of phenomenological contributions by theorists to otherwise experimental sessions to highlight the theory-experiment interplay.

This summary write up (in its current preliminary form) should for the time being be considered as a CHIPP-internal document and as work in progress. The intention of the organizing committee (consisting of F. Canelli, G. Colangelo, G. Dissertori, B. Kilminster, G. Iacobucci, T. Nakada and R. Wallny) is that the document serves as a starting point for editing the pillar 1 whitepaper. The convenors have kindly agreed to act as editors for the pillar 1 whitepaper as well. The organizers wish to thank all speakers and convenors as well as the secretarial staff (G. Amstutz, C. Keufer-Platz of IPP ETHZ) and and CHIPP (M. Türler) for their support. The workshop was financially supported by the participants' registration fee as well as a grant of SCNAT and contributions by CHIPP, the Univ. of Geneva, the Univ. of Zurich and by ETH Zurich. This financial support is gratefully acknowledged.

2 Session on Higgs Boson Physics

editors: F. Canelli, M. Weber

The Higgs boson physics session consisted of the following two experimental and one experimental presentations:

- "SM Higgs properties", by Sinead Farrington (Univ. of Warwick, UK);
- "SM Higgs couplings and BSM Higgs", by Mauro Donega (ETH Zurich);
- "Theory tools for precise EW and Higgs physics", by Stefano Pozzorini (University of Zurich).

One of the primary goals of the LHC is to probe the nature of Electroweak Gauge Symmetry breaking. In the standard model (SM), electroweak symmetry breaking occurs as a result of the Higgs mechanism, which predicts an additional scalar field, accompanied by an associated scalar boson. A Higgs boson was discovered by the ATLAS and CMS experiments in the Summer of 2012, with properties consistent with SM predictions. Understanding the properties of this new state is of fundamental importance and requires further investigation in the form of a precision experimental program. Any deviation in the predicted properties of the Higgs boson is a strong, unambiguous signature for new physics.

Since its observation, measurements in all of the main production and decay channels of the Higgs boson have been completed with the full integrated luminosity available from LHC Run 1, which consists of 5 fb^{-1} at $\sqrt{s} = 7$ TeV from 2011, and 20 fb^{-1} at $\sqrt{s} = 8$ TeV from 2012. Measurements of the mass, total width, spin, couplings, CP mixtures, as well as searches for multiple Higgs bosons represents the main legacy of the LHC Run 1. Some of the primary results are:

- The total Higgs boson cross-section has been measured to be 1.09 ± 0.11 of the SM prediction.
- Production modes via gluon fusion and vector-boson fusion have been observed.
- Most decay modes have been observed: $\gamma\gamma$, ZZ, WW, and $\tau\tau$.
- The mass has been determined with 0.2% precision, m_H = 125.0 $\pm$ 0.21 (stat) $\pm$0.11 (syst).
- The spin and parity are consistent with spin 0 and even parity and exclude non-SM scenarios at 99.9% C.L.
- Constraints on the width have been set to $\sim 4\times$ SM Higgs boson width.
- Coupling properties to fermions and bosons are only established at the 10-20% level.

The picture of the minimal standard model may now appear complete, yet open questions remain on its stage, which will be addressed by the current and future LHC runs. The LHC Run 2 has successfully started in 2015, opening a new period of particle physics exploration, at higher energy and intensity. Higgs physics results shown at ICHEP 2016 based on up to 20 fb^{-1} of 13 TeV collisions now achieve similar sensitivity to that of the previous Run 1 data. These data are allowing an increase in precision and opening up new channels that will undoubtedly deliver more insight on the electroweak model, its symmetry-breaking mechanism. In particular, the fermionic Higgs sector is relatively unknown, and will be probed in detail. Future upgraded detectors and two orders of magnitude more statistics will allow for a precision picture of the symmetry-breaking mechanism and possible solutions to its conundrums.

The discovery of a Higgs boson opens up the question of whether the Higgs boson observed is the SM Higgs boson or one of several Higgs boson, predicted by extensions of the SM. There are strong theoretical arguments that suggest nature should have an extended Higgs sector with additional charged or neutral (CP-even or odd) Higgs bosons (2HDM theories), or that the Higgs boson is not an elementary particle, introducing a new strong interaction at energies beyond the TeV scale (little or composite Higgs theories). These theories are continually probed with the greater reach in Run 2 and HL-LHC. Complementary searches for anomalous or forbidden decays of the Higgs boson, including invisible decays, are also an important part of the physics program of the LHC. In many BSM scenarios, the couplings of the Higgs boson are expected to show discrepancies with respect to the prediction of the SM. During Run 1 the overall branching fraction of the Higgs boson into BSM decays was determined to be less than 34% at 95% C.L. leaving ample space for new physics. Significant improved precision and sensitivity is expected to be achieved in the future LHC analyses.

3 Session on Searches for BSM Physics at the LHC

editors: B. Kilminster, T. Golling

The session on searches for BSM physics at the LHC consisted of the following two experimental and one experimental presentations:

- "Implications of di-photon excess and future strategies for BSM searches at high-energies (theory/pheno)", by Riccardo Torre (EPFL);
- "BSM at the energy frontier", by Ashutosh Kotwal (Duke University);
- "Unconventional signatures", by John Paul Chou (Rutgers University).

The search for physics beyond the standard model is the primary objective of the LHC physics program, as well as particle physics in general, and therefore all avenues for discovery should be exploited in the future. The experimental necessity of a candidate particle to explain dark matter with a relic density being consistent with it having an electroweak interaction, and the theoretical need of new physics to stabilize the Higgs boson mass at the electroweak scale, both lead to the expectation of new particles to be discovered at the LHC. New physics can reveal itself as small deviations from parameters of the standard model, such as Higgs boson couplings, as mentioned in section 2, or deviations in the decay rates of rare processes, as discussed in section 4. In these cases, the evidence of new physics is indirect, often generated through higher order loop corrections. Here, we focus on direct searches for physics beyond the standard model, in which new particles are produced and directly observed.

Over the course of the current LHC program which ends in $\sim$ 2023 after acquiring 300 fb^{-1}, and the HL-LHC program which will acquire 10 times this dataset over a subsequent 10 years of running, physicists have a goal that dark matter will be identified and a means to stabilize the Higgs boson mass will be uncovered, along with other new, unexpected physics. Future particle colliders beyond the LHC have been proposed and are at various stages of R& D, including linear colliders with energies ranging from 500 to 3000 GeV center of mass, a circular lepton colliders of 90 - 350 GeV in new 50 - 100 km tunnels, and circular proton colliders of 50 - 100 TeV in these same tunnels. There is also an option to reuse the LHC tunnel, but replace the current 8.3 T dipole steering magnets with 16 T magnets to approximately double the energy of the LHC collisions. The primary challenge in higher energy circular machines is achieving these high magnetic fields at low enough cost and production reliability.

The current LHC experiments have implemented a comprehensive search strategy for the signatures of supersymmetry, dark matter, extra dimensions, composite Higgs sectors, extended Higgs doublet sectors, additional heavy quarks, and a variety of other models. These searches, although typically applied to specific models, would uncover a wide range of new physics scenarios. Searches for new unexpected resonances of leptons, quarks, or bosons would uncover new particles and forces at the TeV scale.

At the time of the Swiss strategy workshop, there was a culmination of excitement over the identification of an excess in the diphoton mass spectrum at 750 GeV that had been presented at the end of 2015 by both the CMS and ATLAS $\sqrt{s}$ =13 TeV data with 3.4 σ (1.6 σ) and 3.9 σ (2.1 σ) local (global) significance, respectively. The theoretical community had become fully engaged in speculating on the class of models which could produce such an excess given other experimental contraints, and also in predicting other possible new physics that could be expected at the LHC. While the excess was found not to persist in the 2016 data that was revealed 2 months later, the mobilization of the theoretical community had already produced more than 400 papers on the high energy physics e-print archive (arXiv) to address the implications of this possible signal. This signal forced the particle physics community to consider whether the current and future particle physics program was sufficient to address such implications.

One of the challenges exposed for future higher energy accelerators was the implication on particle identification and measurement. For particles produce with 7 times the energy as the LHC, some combination of a larger calorimeter, improved granularity for more objects being boosted closer together, muon chambers at higher radius, higher detector magnetic fields, a larger dynamic range of measurements, more forward-detection capability, as well as faster detectors, and a higher bandwidth and more intelligent trigger system would be necessary to maintain the same performance for objects at the highest in these future colliders as is for the current LHC on its highest energy objects produced from 13 TeV collisions. These numerous detector challenges will need to be pursued by the Swiss particle physics community over the upcoming years.

Another challenge of the LHC and future detectors is to ensure that unconventional, yet highly motivated new physics channels, are not missed due to detector and trigger design. Long-lived particles arise naturally in a wide range of models, and become more likely due to the absence of evidence for strongly produce new particles. The main challenges are low production rate compared to QCD multi-jet rates, low P_T objects that are difficult to trigger on, and non-standard algorithms for identifying particles decays outside of the standard interaction region inside the central pixel detectors. To search for such signatures, techniques such as providing dedicated physics streams of events with reduced trigger thresholds and reduced size, as well as specialized reconstruction algorithms must be implemented. Opportunities arise from high precision timing that future detectors will achieve and track triggers may provide new ways to search for such signals if they are implemented appropriately. A possible loss in future sensitivity arises from the lack of dE/dx information of future tracker designs, which is envisioned as necessary for reducing data rates, but will reduce the ability of trackers to identify highly ionizing particles.

Day 1 Summary: Discussion of Searches at the LHC

discussion leaders: B. Kilminster, T. Golling

The discussion was centered around BSM searches at the energy frontier and touched on the physics opportunities, the experimental challenges, and the long-term perspective, with focus on the Swiss perspective. The various new physics benchmarks that were discussed in the Session on Searches for BSM Physics at the LHC, see section 3, illustrated that higher integrated luminosities and the highest possible center-of-mass energy greatly benefit direct searches for new physics.

A discovery in Run 2 or shortly after would allow us to design a more coherent roadmap and would give us ammunition to make a more concrete physics case. The excess observed in the 2015 data set (but not confirmed with the 2016 data set) in the resonance search around a diphoton invariant mass of 750 GeV was used as an example to hypothesize what an impact such a discovery and the search for potentially associated new particles would have on our overall experimental strategy. The conclusion was that our current strategy holds in such a case and that the best bet is to continue the tradition of general-purpose detectors based on triggering, tracking and calorimetry capabilities. Many of the present searches (e.g. for unconventional signatures such as long-lived particles or highly boosted objects, or searches based on partial event readout) had not been anticipated at the time of the design of the LHC detectors. In order to prepare for a similar unforeseeable development in the future where the detectors would have to be used for unanticipated new signatures, the detectors should be designed with emphasis on redundancy, optimal resolution (energy, spatial, timing), read-out of as much additional information as possible (such as dE/dx), and in particular triggering and reconstruction capabilities of unconventional signatures (such as long-lived particles).

Tracking detectors were identified as a particularly promising direction for the Swiss community to invest in, given the extensive expertise on the R&D, construction and commissioning of the current and future ATLAS and CMS trackers, particularly regarding the pixel technologies. A clear target is a cost-effective, radiation-hard, low-mass all-pixel tracker with excellent spatial and timing resolution and track triggering capabilities. Resolution is needed for pile-up rejection in a HL-LHC environment or beyond, for fast pattern recognition, for excellent capabilities of flavor-tagging and reconstruction of long-lived particles, for a high p_T resolution, as well as substructure analysis of hadronically decaying top quarks, W, Z, or Higgs bosons with very high transverse momenta, resulting in collimated jets of particles which cannot be resolved anymore by the calorimeters. Extension to the forward direction beyond $|\eta|$ of 2.5 is also desirable. One promising avenue for our community was identified as the energy frontier with the current ultimate goal of a pp collider at a center-of-mass energy of 100 TeV (FCC). The machine's dipole magnet R&D is the key driver of the timescale and feasibility of this project. Investing in this magnet R&D was identified as an area of interest for our Swiss community. A $\sim$ 30 TeV (HE-LHC) could be a stepping stone for this technology. A discovery of high-mass new physics in Run 2 or 3 (such as the above-mentioned temporary excess at a mass of 750 GeV) would bolster the physics case for a HE-LHC. It should be considered to make sure that the design of the HL-LHC detectors does not result in limitations for a potential HE-LHC scenario.

An important figure of merit for future experiments is to retain maximum sensitivity for a set of ever-growing new physics benchmarks. A key role in the detector design plays the simulation of the detector configurations, the assessment of the physics opportunites for the simulated new physics benchmarking for the future machines under study, while also taking into account new software developments (such as machine learning or more concretely particle flow). A close loop needs to be kept where the benchmark analyses inform the detector design by giving feedback on detector requirements. Development of common tools and collaboration across current LHC experiments should be considered.

4 Session on Heavy Flavour Physics

editors: K. Kirch, O. Schneider, A. Signer

The Heavy Flavour session consisted of the following three experimental presentations:

- "Lepton violation", by Patrick Koppenburg (Nikhef, Amsterdam);
- "Rare decays at LHCb", by Nicola Serra (University of Zurich), delivered by Patrick Koppenburg;
- "CP violation and CKM physics", by Fred Blanc (EPFL, Lausanne).

The speakers were given the task to review their sub-fields (*i.e.*, lepton flavour violation and lepton flavour universality, rare decays and the V-A structure of weak interactions, CP violation and CKM measurements in b-, c-, and kaon physics) in a global manner, and focus on measurements which are of most relevance for the discussions of future strategies in high-energy particle physics in Switzerland. With various emphases, the speakers underlined the significant experimental progress achieved during the past several years in the search for New Physics in heavy-flavour decays, explained the current "flavour anomalies" that have appeared (and sometimes strengthened) in the past few years both at the B factory experiments (Babar and Belle) and at LHCb with Run 1 data, and discussed the motivation and prospects of already planned upgrades at LHCb and Belle II.

An emblematic check of the electron-muon universality in b decays is through the measurement of the ratio $R_K = \mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)/\mathcal{B}(B^0 \to K^{*0}e^+e^-)$ performed in the low $q^2(=m^2_{\ell^+\ell^-})$ region, where the theoretical prediction is the cleanest. The LHCb measurement falls 2.6σ below the Standard Model (SM) value of one, and is consistent with the statistically less powerful results of BaBar and Belle. On the other hand, results involving the tau lepton from semileptonic B decays exhibit a much more significant effect: the Babar, Belle and LHCb measurements of $R(D) = \mathcal{B}(B \to D\tau^+\nu_\tau)/\mathcal{B}(B \to D\ell^+\nu_\ell)$ and $R(D^*) = \mathcal{B}(B \to D^*\tau^+\nu_\tau)/\mathcal{B}(B \to D^*\ell^+\nu_\ell)$ ($\ell = e,\mu$) all consistently lie above the SM predictions, with a two-dimensional average presently providing a clear 4.0σ evidence of departure from lepton universality. Because non universality implies lepton flavour violation in many New Physics models, these experimental anomalies reinforce the motivation of the searches for decays where lepton numbers are violated. Decays such as $B^0_{(s)} \to e^\pm\mu^\mp$, $B^+ \to \mu^+\mu^+h^-$ and $D^0 \to e^\pm\mu^\mp$, where LHCb has the leading sensitivity, have been looked for but not seen so far. Lepton-flavour violating τ decays, where the B factories are leading but not signal is observed either, are also very promising.

In the rare decay sector, the joint observation of $B^0_s \to \mu^+\mu^-$ by CMS and LHCb, as well as the ATLAS result, set very strong constraints on models beyond the SM, basically ruling out SUSY with large tan(β) values, and more generally excluding large non-SM contributions to the Wilson coefficient C_{10}. The loop-suppressed decay $B^0 \to K^{*0}\mu^+\mu^-$, $K^{*0} \to K^-\pi^+$, is attracting a lot of theoretical and experimental interest. The kinematics of the four-body final state can be described in terms of $q^2 = m^2_{\mu^+\mu^-}$ and three helicity angles. A full angular analysis offers many q^2-dependent observables with clean SM predictions. For the first time LHCb has measured a complete set of observables for both B^0 and $\bar{B}^0$ decays. All observables are consistent with SM predictions, except one of them (called P'_5) in the low q^2 region, causing a fit to the C_9 Wilson to deviate by 3.4σ from the SM. The Belle data also displays a discrepancy in P'_5, in agreement with the more precise LHCb data. Interestingly, many exclusive $b \to s\mu^+\mu^-$ decays, such as $B^+ \to K^{(*)+}\mu^+\mu^-$, $B^0 \to K^0\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$ and $\Lambda_b \to \Lambda\mu^+\mu^-$ are found to have a differential branching fraction consistently smaller than the SM prediction in the low q^2 region; this is perhaps related to the "muon deficit" seen in the R_K observable mentioned above.

Radiative B decays can be used to test the V-A structure of weak interactions, through the measurement of the photon polarization which is sensitive to right-handed currents (Wilson coefficient C_7'). First results from LHCb are available using $B^0 \to K^{*0}e^+e^-$ (at $q^2 \to 0$), $B^+ \to K^+\pi^-\pi^+\gamma$ (exploiting three-body hadronic system) and $B_s^0 \to \phi\gamma$ (time-dependence). All are consistent with the SM, but will become constraining only with more data collected at Run 2 and beyond.

Measurements of CP violation and CKM observables got a big boost with LHC data. Notable advances are the measurements of the B_s^0-mixing induced phase ϕ_s in exclusive $b \to c\bar{c}s$ transitions, such as $B_s^0 \to J/\psi\phi$ from ATLAS, CMS and LHCb, and other modes from LHCb. The current determination of ϕ_s is consistent with the SM prediction. The precision on the CKM angle γ, which can be determined from $B \to DK$ tree decays only and hence constitutes an important reference in the precision test of the consistency of the CKM picture, is improving, with the current determination from LHCb being twice as more precise as that of Babar or Belle. A longstanding tension in this picture is that due to a 3σ inconsistency between B-factory determinations of $|V_{ub}|$ performed with exclusive and inclusive B decays. A new LHCb measurement with baryons (exclusive $\Lambda_b \to p\mu^-\bar{\nu}_\mu$), which has a different sensitivity to a possible enhancement of the right-handed contribution to the weak current, brings interesting new information but shows that the experimental results cannot be reconciled with such an enhancement.

In summary, a few $3-4\sigma$ deviations from SM expectations are seen in the heavy flavour sector, which could be due to New Physics or QCD effects. All the measurements are still dominated by statistical uncertainty, meaning that much more can be learned with more data. However, the timescale for settling these anomalies is much longer than needed for the 750 GeV bump seen in 2015 by the ATLAS and CMS experiments. In the immediate future, Run 2 data will multiply LHCb's heavy flavour statistics by at least four. Then the LHCb experiment will be upgraded to collect an order of magnitude more data. In parallel the Belle II experiment at Super-KEKB, which has very much complementary physics reach, will ramp up and shoot for 50 times the current Belle statistics. Switzerland is involved in this endeavour through the LHC experiments, mainly LHCb where EPFL and UZH have strong commitments including for the detector upgrade.

5 Session on Low Energy Physics

editors: K. Kirch, O. Schneider, A. Signer

The Low Energy Physics session consisted of the following three presentations:

- "Implications of the flavor anomalies", by Andreas Crivellin (PSI);
- "Searches on cLFV with muons and time reversal symmetry violation with neutrons", by Angela Papa (PSI);
- "Precision measurements with ultracold neutrons, muons, positrons, and antiprotons", by Andreas Knecht (PSI).

The session followed the one on precision heavy Flavour Physics and started with a bridging presentation by Andreas Crivellin who reflected on the recent and longer standing deviations of a few sigma each from the Standard Model in heavy flavour physics and discussed a few particularly attractive model scenarios to accommodate them. These could naturally be confronted with highly sensitive observables of low energy precision physics. To name a few, the muon anomalous magnetic moment, the charged lepton flavour violating muon decays, the proton charge radius, and the ratio of decays of charged pions to electrons versus muons. The following two experimental talks then focused on the Swiss landscape in low energy precision physics.

Angela Papa's presentation concentrated on aspects of the rare muon decay searches $\mu \to e\gamma$ and $\mu \to eee$ as well as on the search for the CP-violating electric dipole moment of the neutron (nEDM). The charged lepton flavour violating muon decays are the overall most sensitive rare decay searches. In all three so-called golden channels (the two mentioned above and the μ-e conversion channel), PSI has obtained the current best limits because of its superior muon beams. The most recent one was released by the international MEG collaboration in 2016. While strong collaborations pursue projects to improve the sensitivity for μ-e conversion at J-PARC and at FNAL, projects at PSI aim at pushing the searches for $\mu \to e\gamma$ (MEG-II) and $\mu \to eee$ (Mu3e) by one and 3-4 orders of magnitude, respectively, in the coming years. Swiss particle physics is in a pole position to assume leading roles in these experiments (so far: MEG: PSI, Mu3e: UGe, PSI, UZH, ETHZ). Mu3e is planned in phases and the second phase will need a new High Intensity Muon Beam (HiMB) to be built at PSI's HIPA facility with the strong support of the Swiss particle physics community.

The nEDM experiment is currently taking data at PSI's world leading source of ultracold neutrons (UCN). It will supersede the previous best result with its 2015/16 data set. The international nEDM collaboration (CH so far: Fribourg, PSI, ETHZ) will continue its activities with the new n2EDM experiment which will be set up around 2018 and gain another order of magnitude in sensitivity.

Andreas Knecht's presentation highlighted some Swiss activities in the low energy precision field besides the search experiments. The particles very conveniently available in Switzerland are the positrons at ETHZ, the antiprotons at CERN and the UCN and muons at PSI. The importance of hosting in our country some of the world's best particle sources cannot be overestimated. The range of fundamental physics questions which are being addressed with these probes is very broad: a hot topic is a measurement of the gravitational interaction of antimatter pursued by various projects with the neutral atoms of anti-hydrogen, positronium and muonium. All these are, together with a number of muonic atoms, also targets for high precision spectroscopy aiming at tests of QED and of the CPT symmetry, and at the determination of fundamental constants, masses as well as charge and magnetic radii of nucleons and light nuclei. UCN and the leptons are also being used in sensitive searches for exotic interactions, axions, axion-like particles, mirror matter and other dark matter candidates. These are complementarily covering regions of parameter space often not accessible to collider experiments or direct dark matter detection. Of particular importance are future improvements of the particle sources and Andreas Knecht emphasized the development of a very effective low energy muon cooling at PSI as well as the HiMB mentioned above already.

From the related discussions, one can conclude that the searches for cLFV with muons and for CPV with neutrons offer unique opportunities and considerable discovery potential. The low energy precision physics program and, in particular, an upgrade of the world-leading high intensity infrastructure at PSI require an active participation of the CHIPP community.

6 Session on Standard Model Physics

editors: F. Canelli, M. Weber

The Standard Model physics session consisted of the following two experimental and one experimental presentations:

- "Experimental overview of the EW and QCD", by Kostas Theofilatos (ETH Zurich);
- "Top quark physics results and prospects", by Richard Hawkings (CERN);
- "Motivations for future precision studies of EW and Higgs physics", by Francesco Riva (CERN).

The Standard Model (SM) has been developed and tested in the last decades through dedicated theoretical and experimental research to a very high level of accuracy. A robust program for precision measurements of the SM remains of key importance to the LHC. The physics of the SM and its rich phenomenology at the highest energy scale continues to be of prime scientific value. Moreover, deviations of precision measurements to theoretical expectations can probe physics beyond SM where new physics is not accessible at tree-level. A thorough understanding of the SM processes is key for understanding the background to possible discoveries. A summary of the SM measurements and expectations for results at the LHC is given below, as presented at the SWHEPPS workshop.

The Electro-Weak (EW) interaction

With the availability of the Higgs Boson mass measurement the global EW fit becomes over-constraint. The global fit prefers a slight lighter Higgs and although no evidence for an overall inconsistency is found, there are a number of tensions in the fit. In particular, the lepton asymmetry and the b forward backward asymmetry with a p-value of 0.2%. Measurements from the LHC have currently typical precisions at the level of 0.5%, and will be further improved to reach the precision similar to SLD and LEP (0.1%) and the Tevatron (0.2%). The measurement of the mass of the W Boson is a challenging example for a hadron collider. Special experimental (recoil, special runs, calibrations) measures have to be addressed as well as theoretical and PDF uncertainties considered. The expectation is that an uncertainty in the W Boson mass of order 10 MeV can be reached. Triple gauge and quartic gauge interactions are also important tests of the gauge structure. Strong limits on anomalous couplings have been set. Many multi-boson channels have been observed, but not all, and the precision frontier is yet to be reached. Thus more statistics and measurements are needed. Especially ratios between di-boson (including photons) production cross sections as well as new statistical techniques based on machine learning will enable to reach precision measurements in this field.

The Strong interaction (QCD)

Among the main observables to test the QCD asymptotic freedom (α_s) and advance the knowledge of PDFs are the jet transverse momentum and jet multiplicity spectra measured at the LHC (with jet of pt up to 3 TeV). Photon as well as Vector-Boson+jets differential cross sections also provide input to PDFs and α_s. This is a very active field, including efforts on mixed QCD-EW corrections in the matrix element and parton shower Monte Carlo simulation codes. Electro-Weak precision results at the LHC imply excellent understand of QCD.

The top quark

The top quark plays a prominent role as the most massive elementary particle, with a Yukawa coupling almost exactly unity. Events with top quarks are copiously produced at the LHC and thus it represents a laboratory for SM studies at the highest energies. It also represents one of the most important backgrounds in searches for new physics involving new heavy states. The phenomenology of the top quark is very well known for production and decay modes. Inclusive and differential cross section measurements are available, with experimental and theoretical systematic uncertainties around 4%. The uncertainty is yet slightly larger in Run-2, dominated by luminosity and modeling uncertainties, but significant improvements are expected as more data is collected. The differential cross sections as well as top quark production with heavy flavor jets or Vector Bosons probe in detailed the description of the kinematics in the theory calculations (up to NNLO) and MC simulation codes and provide inputs for their tuning, which is critical for many of the searches performed at the LHC. A difficulty to describe the transverse momentum of the top quarks persists and needs to be addressed. Also for boosted topologies, where the top quark decay products merge in singe reconstructed objects, it is important to improve the modelling to fully exploit the jet substructure. These are particularly important at 13 TeV and 14 TeV center of mass energy. For the electroweak production of top quarks, the measurements are generally in agreement with NLO+NNLL prediction with an experimental uncertainty of 9% to 14% with a theoretical precision of about 5%. Thus improvements are expected from the larger Run-2 and future data sets and from more differential measurements that allow for precise measurements of the couplings. As for the mass of the top quark, several measurement and analyses are performed, utilizing all decay modes of the top quark. The relative precision of the mass measurements is below 0.5%, however, global electro-weak fits need estimations of the pole mass, which is not directly accessible with the traditional analyses. Several alternate mass measurements are pursued (e.g. from the cross section or from m(ttj)), but the precision of these is still far behind the direct reconstruction techniques, thus representing a main effort in the future.

7 Session on Theory, Connection to other Fields

editors: G. Isidori, with T. Gehrmann and R. Rattazzi

The session consisted of the following four presentations:

- ”Beyond the SM: the big picture”, by Riccardo Barbieri (SNS Pisa & ITS-ETH);
- ”The flavor problem”, by Gino Isidori (University of Zurich);
- ”Perspectives for precision calculations”, by Babis Anastasiou (ETH Zurich);
- ”Connections between cosmology and high-energy physics”, by Andrey Katz (Universite de Geneve).

Riccardo Barbieri presented a general discussion about the main open problems in particle physics. He discussed various arguments why the SM cannot be considered a complete theory, emphasising in particular: i) the (electroweak) hierarchy problem (or the instability of the Higgs mass term, with respect to quantum corrections from high-energy degrees of freedom); ii) the flavour puzzle (or the lack of understanding for the large, and apparently non accidental, span of the entries of the SM Yukawa couplings); iii) the non-vanishing values of neutrino masses, that unambiguously signals the presence of physics beyond the SM; iv) the lack of an explanation, within the SM, for the quantization of the U(1) charges; v) the lack of understanding, within the SM, for the vanishing of CP violation in the QCD Lagrangian (that would naturally point to the presence of an axion). He presented some possible solutions to the above problems, some of which involving NP within the direct reach of the LHC, other with observables effects only via precision tests, and others with observables effects only at the cosmological level. He stressed that the way to extend this highly successful theory at high energies is, at present, very uncertain. This fact, and the very nature of Particle Physics, call for highly diverse frontiers of research, involving both low- and high-energy experiments at particle accelerators and beyond.

The presentation of Gino Isidori was focused on flavour physics. He emphasised, and demonstrated with a few examples, that flavour physics represents a very powerful tool for indirect searches of new physics. This is particularly true in the present scenario of large uncertainty about the nature of physics beyond the SM. He also stressed the strong connections of flavour physics (and, more generally, low-energy experiments) with the other "frontiers" of particle physics (in particular neutrino physics and high-pT physics). Finally, he emphasised that recent data have helped us to identify a very rich "new frontier" within flavour physics, namely the study of Lepton Flavor non Universality, whose interest was not properly recognised in the past.

Babis Anastasiou outlined the importance of precise theoretical calculations in high-energy physics. He emphasised that the combination of high-precision theory plus high-precision experiments is the recipe for making progress in the field: one cannot make progress without combining these two ingredients. He also briefly reported about the great progress achieved in the last few years on precise calculations in perturbative QCD (relevant for collider physics): NNLO calculations are reaching the maturing level, while the N3LO level has just been started. Finally, he stressed that Switzerland is at the very frontier of this field of research, and that precision phenomenology requires a long standing and stable support to flourish.

Andrey Katz presented the so-called "Hidden Valley" scenario as a general framework to highlight the connections between cosmology and high-energy physics. The basic idea of this class of models is that there can be low-scale new particles (e.g. with masses around or below 1 GeV), that couple to the SM very weakly, due to the exchange of very heavy (e.g. 1 TeV) new states. With a few examples he emphasised that this scenario can be a building block of models addressing Dark Matter and the matter-antimatter asymmetry, and where future cosmological observations might have direct implication for future LHC searches.

Day 2 Summary: Flavour and Low Energy Summary and Connection to other fields

discussion leaders: G. Isidori, O. Schneider

The discussion covered three main subjects: I) the prospects for indirect NP searches, mainly via flavour-physics measurements, within the LHC experiments (LHCb, but also ATLAS and CMS); II) the connections between low- (non-LHC) and high-energy physics experiments within the first pillar, with particular attention to the role of PSI; III) the connections between the first pillar and the other two pillars. The main points of discussions on these three main subjects can be summarised as follows.

- I.a *Flavour physics and indirect NP searches at ATLAS and CMS.* The question has been raised if ATLAS and CMS should consider possible modifications of their upgrade plans (for the HL phase) in view of present flavour anomalies, especially in the absence of direct signals of NP. These anomalies, and also various theoretical arguments, seem to suggest a particular interest in tau- and b-quark enriched final states and, more generally, in an optimal flavour-tagging (and flavour-discrimination) efficiency. After an extensive discussion, a consensus was reach on the fact that this request is already well addressed by the present upgrade plans of ATLAS and CMS, taking into account also the fact that these high-p_T experiments must optimize the NP sensitivity in all possible directions.

I.b *LHCb upgrade*. Motivated by the strong interest in an extension of the b-physics programme at the LHC, advocated in various theory talks at the meeting and reinforced by the recent interesting results in this sector, the possibility of a further upgrade of the LHCb experiment has been discussed. The already planned LHCb upgrade aims at collecting 50 fb^{-1} by 2030. In principle, a luminosity ~ 25 times higher would be available in the HL phase of the LHC. Can a further-upgraded LHCb stand such a luminosity (or a significant fraction of it)? Beside the maximal luminosity, can some of the present LHCb performances (e.g. on electron and tau modes) be increased in view of a further upgrade? The LHCb collaboration is considering this interesting option, but a detailed answer on its feasibility requires time.

II *Low-energy physics*. As outlined in the theory talks, the indirect NP searches performed at low-energies are extremely interesting and, to a large extent, independent from the direct searches performed at high energies. This point was further emphasized during the discussion session, with particular attention to the PSI programme. In particular, it was stressed that it is important to secure (both in terms of funding and manpower) the interesting and ambitious $\mu \to 3e$ phase-II programme, independently of the developments at the high-energy frontier. The point was raised that a potential firm evidence of lepton-flavour non-universality in B decays would, on general grounds, render the physics case of CLFV searches in μ decays even stronger. However, it was also concluded that the opposite is not true (CLFV in μ decays could occur independently of LFU in B decays), since the connections between these two sectors is very model dependent.

III.a *Connections with the neutrino programme.* The main issue discussed has been the possible interplay (or better the influence and the possible synergies) between the experimental programme at the high-energy frontier and the accelerator-based neutrino programme. While the ultimate physics goals of the two programmes are certainly connected, it has been concluded that the two programmes run essentially in parallel: the results of the former have very little influence on the latter, and vice-versa. On the other hand, possible synergies can be envisaged at a technical level.

III.b *Connections with the DM programme (direct & indirect DM searches).* Similarly, the interplay between the searches for DM candidates at colliders and the direct and indirect searches of DM, performed in underground laboratories or via astrophysical data, has been discussed. In this case there are certainly strong connections; however, these are very model dependent (being determined by unknown physics beyond the SM). At present is not possible to determine a clear influence of the results of direct and indirect searches of DM on the HEP programme. The situation may change in view of a positive evidence of physics beyond the SM. The importance of combined analyses of both high-energy data, underground searches, and astrophysical data, in case of a positive signal, has also been stressed.

8 Session on Future Accelerators

editor: L. Rivkin

The session of future accelerators consisted of the following three presentations:

- "Future hadron colliders: accelerator challenges", by Bernhard Auchmann (PSI/CERN);
- "Future lepton colliders: accelerator challenges", by Terry Garvey (PSI);
- "Accelerator R&D towards highest energies" by Rasmus Ischebeck (PSI);

The Future Accelerators session provided an overview of the present plans for future facilities on the high energy frontier. It covered the FCC hadron collider study, electron positron colliders, mainly concentrating on the linear colliders ILC and CLIC, and finally surveyed the present R&D on very high gradient acceleration.

The superconducting magnets R&D program towards 16 - 20 Tesla magnetic fields in the dipole magnets was the main topic of the Bernhard Auchmanns talk on the accelerator challenges for future hadron colliders. The goal of more than doubling the present state-of-the-art LHC magnets field can no longer be achieved with the NbTi technology and requires the use of the NbSn3 superconductor material for the 16 Tesla and HTS material for higher field. Present R&D effort, spearheaded by CERN, also involves European national laboratories in France, Italy, Spain and Switzerland, as well as the US DOE high field magnet program. Possible uses of such high filed magnets for synchrotron light sources and for medical applications are an important factor helping to drive this R&D. Present FCC study aims at producing a Conceptual Design Report by the end of 2018, including a first cost estimate of a possible FCC facility.

Terry Garvey concentrated mainly on the future plans for electron positron linear colliders, ILC and CLIC. While the superconducting RF technology based linear colliders are limited to below 50 MeV/m accelerating gradient and thus aim at energies below 1 TeV, the normal conducting accelerating structures of CLIC have demonstrated 100 MeV/m gradients, thus opening the possibility of reaching center-of-mass collision energies of several TeV. One of the challenges of these schemes is the high average power consumption and efforts are under way to improve the energy efficiency of the proposed schemes.

Rasmus Ischebeck provided an overview of the extensive R&D efforts around the world on the schemes to exceed present accelerating gradients by several orders of magnitude, employing laser and plasma acceleration. Proof-of-principle experiments have demonstrated accelerating gradients on the order of tens of GV/m. The high luminosity requirements for the high energy frontier colliders pose formidable challenges and most of the techniques reviewed still have a long way to go to demonstrate the required beam parameters. Nevertheless the present R&D efforts aim at possible high gradient accelerators for uses in other accelerator driven fields like compact synchrotron radiation sources and compact accelerators for medical applications.

The future accelerator facilities session made clear the need to increase the R&D efforts in order to be able to start on a construction of the next high energy frontier collider in the post HL-LHC era.

9 Session on Detector Technology

editors: S. Gonzalez-Sevilla, R. Horisberger

The detector technology session consisted of the following five presentations:

- "Detectors concepts for future colliders", by Didier Contardo (IPN Lyon CNRS/IN2P3);
- "Detector technologies for future colliders", by Philip Allport (Birmingham);
- "Tracking" by Mark Tobin (EPFL);
- "Calorimetry & Particle flow" by David Barney (CERN);
- " DAQ and Trigger", by Niklaus Berger (Univ. of Mainz)

The Detector Technology session aimed at discussing not only the current detector developments in the short-term but also at giving a prospective look to what the trend may be for future directions in detector R&D. The session was organized in five talks. General overview talks on new detector concepts and recent technological developments were given by Didier Contardo (IPN Lyon) and Philip Patrick Allport (University of Birmingham). Then, more specific talks covering major detector sub-systems as Trackers, Calorimeters and Trigger/DAQ were presented respectively by Mark Tobin (EPFL), David Barney (CERN) and Niklaus Berger (JGU Mainz). Naturally, in all cases more emphasis was given to the intensive R&D being performed for the various detector upgrades for the High-Luminosity LHC (HL-LHC). However, it was also noticed, and appreciated, the effort made by the speakers to provide some figures of merit for the next generation of detectors for long-term future accelerators, notably for electron-positron (ee) linear colliders (ILC, CLIC) and circular hadron-hadron (hh) colliders (FCC). We just include below in a non-exhaustive way some selected topics presented during the session. The reader may refer to the different talks for further details.

The various LHC experiments will be upgraded to operate at the HL-LHC scheduled to start delivering collisions around 2025. New tracking detectors, improvements in the calorimeters and new readout systems are foreseen for ATLAS, CMS and LHCb.

- Both ATLAS and CMS will install new all-silicon trackers with pixel sensors in the innermost layers and microstrip detectors at outer radii. LHCb will install a new pixel vertex detector and a scintillating fibre tracker with SiPM readout. For the pixel detectors of ATLAS and CMS, where radiation hardness, high granularity and low material budget are mandatory, n-in-p thin planar (with different isolation techniques) and 3D sensors are well-established technologies being tested up to very high fluencies ($\sim 10^{16}$ $\mathrm{n_{eq}/cm^2}$). In addition, many developments are being performed on detectors with increasing integration of the sensor and readout electronics (*e.g.* MAPS detectors are planned for both the ALICE upgrade and for the Mu3e tracker).

- Deep-submicron has been widely adopted for new readout chips, typically both 130 and 65 nm (CERN RD53 project) CMOS technologies, with pixel sizes down to 50×50 $\mu\mathrm{m}^2$. Special attention has to be paid though to total ionizing dose (TID) and short and narrow channel radiation-induced (RINCE, RISCE) effects.

- Both ATLAS and CMS experiments will increase their calorimetric hardware trigger granularity by upgrading both on- and off-detector readout electronics. CMS will install new high-granularity endcap calorimeters. "Particle Flow" starts to be widely adopted as main algorithm for jet reconstruction. This technique combines information from all sub-detectors to improve the jet measurement and mainly use the hadron calorimeter (having the worst energy resolution and hence limiting the jet performance) for neutral hadron reconstruction.

- Concerning the trigger scheme, while LHCb plans already to read the complete detector every 25 ns with an output data rate of 30 Tbps (Phase-1 upgrade in 2019), ATLAS and CMS are targeting for the HL-LHC rates of $\sim$1 MHz with the inclusion of the tracking information in the first trigger-level decision logic. CMS will install double-sided silicon "p_T-modules" to create stubs at the module level to identify high-p_T tracks; ATLAS plans to make use of large associative memories to perform track matching to stored patterns in banks. For data transmission new radiation-hard optical links (GBT/Versatile links) are being developed for rates of 5 Gbps.

- There are many other technological developments being pursued: new powering schemes (serial powering, DC-DC conversion), micro-channel cooling, new composite materials for lighter support structures, etc.

Concerning future detectors, their specific design will be mainly driven by the accelerator facility. Experiments for a large energy hh-collider will need to cope with very large radiation backgrounds and pile-up. In the case of ee-colliders, though radiation hardness is not an issue, very high precision detectors are required. Although the vast R&D being performed for the HL-LHC will set the ground base for the next generation of detectors, it is worth highlighting that:

- There is work in progress in the development of new silicon sensors with intrinsic gain to improve the timing performance and radiation hardness (*e.g.* low gain avalanche detectors exploiting charge multiplication in high electric field regions). The aim in this case is having trackers with excellent position and time resolutions to boost pattern recognition, to improve vertex identification and missing transverse energy resolution.

- New silicon-tungsten and crystal calorimeter prototypes are being investigated. DREAM (CERN RD52 project) aims at developing a detector to perform the simultaneous measurement of scintillation and Cherenkov light during the shower development.

- The design of the DAQ architecture mostly depends upon the necessity of a triggerless operation or not. While in a ee-collider the low duty cycles makes possible the complete readout of the detector by using large front-end (FE) buffers with commercial off-the-shelf components (FPGAs, GPUs, etc.) for offline processing, at hh-colliders it is required some local data processing at the FE level in custom-designed ASICs, with most probably the usage of a first-level track-trigger.

- For data transmission, some commercial optical links offer today rates up to 25 Gbps, so in that sense they do not seem to be a future limiting factor assuming they qualify in terms of radiation hardness. First prototypes already exist for multi-gigabit wireless data transmission (60 GHz band) that could potentially be used for detector readout and trigger implementation (inside-out radial data transfer to ease track-finding algorithms in on-detector logic).

10 Summary of the Workshop

discussion leader: T. Nakada

The Discussion Session on the future accelerators took place during the last day of the workshop. In the discussion, opinions were exchanged based on the current situation of physics and accelerator R&D and design studies presented throughout the Workshop.

There are several compelling observations that demonstrate the existence of physics beyond the Standard Model: non-zero mass of neutrinos, existence of dark matter and dark energy in the universe and the abundance of matter observed in the universe. Motivated by various theoretical considerations, it has been generally thought that energy threshold for new physics could be at around 1 TeV, i.e. accessible by the LHC. On the other hand, experiments with the energy frontier machines and precision experiments at various lower energies have not been able to establish an ambiguous effect of physics beyond the Standard model so far. Observed anomalies are either statistically not yet significant or suffer from systematic uncertainties. As a result, we have little idea where the energy scale for the new physics is.

Since there is little idea where the new physics lies, searches must be carried out at both energy and precision frontiers. As being done for the other particles, properties for the Higgs particle should be studied in precision to look for a deviation from the Standard Model predictions. An important question to be addressed is whether we need a dedicated machine, in addition to the LHC and its luminosity upgrade, and if yes, what kind of machine. Complementarity to the LHC calls for a lepton machine for its clean environment: the ILC, CLIC, FCC-ee, CEPC and a Muon-collider are being considered and are at various stages of development. It might be also advantageous to have a lepton machine for the top quark precision study. From the scale of machine, construction of some of those machines could be undertaken with a regional initiative with a large international participation. There is no clear motivation for a lepton collider that can reach a centre of mass energies beyond 1 TeV for those precision studies.

Hadron machines have traditionally been considered as a discovery machine where recent history shows that a factor of about ten increases in the centre of mass energies led to discoveries of new particles: notable examples have been the W and Z at SppS, the top quark at the Tevatron and the Higgs boson at the LHC, where the costs of machines have also progressively increased. Although running at high luminosities increases the energy reach, the energy is the key for the future hadron machines. Fcc-pp and SPPC are aiming at a centre of mass energy of 100 TeV, which should access the energy scale of 10 TeV. Given the very high cost associated for those machines, an expected level of guaranteed physics success from the public, policy makers and funding agencies could be very high for constructing such accelerators. Required cost and human resources required for such a project demands that a project must be initiated as a global project from the beginning among equally partners. Are we ready for this?

It has been well established that for deciding the next energy frontier machine, physics inputs from precision experiment at low energies are essential. Unlike the energy frontier machines, facilities for those experiments can be well accommodated by national laboratories, while the experiments are always operated by an international collaboration. After the High Luminosity LHC, CLIC with the low energy phase-1 and High Energy LHC upgrade appears to be the two most probable options for the future energy frontier machine. Participation in the ILC and/or CEPC depends solely on whether the Japanese or Chinese government, respectively, will make a firm declaration of intention to construct/host such machines. Muon colliders still need substantial R&D and without physics motivation far above 1 TeV, it would be difficult to justify it. While a Higgs factory can still be somewhat independently motivated, the LHC Run-2 results will have a big impact in the decision of the future high energy frontier machines.

What is commonly understood is that accelerator R&D are essential, for concrete accelerator studies and for more generic technological issues, including particle sources. It has an advantage that most of the technologies can be used in many other fields. This also apply for the detector R&D. In conclusion, we need to continue our discussion in a regular interval in the coming future as a part of the preparation for producing the Swiss Road Map for Particle and Astropartice physics in 2018.

11 Outlook

editors: T. Nakada

The European particle physics programme is clearly driven by the European Strategy for Particle Physics, where the current version was approved by CERN Council in May 2013. Since then, the HL-LHC project was approved and started at CERN and the neutrino platform has also been constructed at CERN. While the CLIC R&D continues to make advancements, a new study for a very large circular machine, FCC, has started, where both machines are an option for a future CERN energy frontier machine. Those three activities are among the four highest priorities given in the Strategy. The fourth one, ILC, depends on the decision by the Japanese Government.

The next European Strategy update is now anticipated in spring 2020. This means that a European wide community discussion will take place during 2019 and CHIPP must be prepared for this discussion. The Swiss high energy frontier group must now prepare a white paper, which should be an input for the new Swiss Roadmap for particle and astroparticle physics in 2018, which in turn should be the Swiss input to the European Strategy discussion in 2019. While the scale of the required infrastructure, cost, timescale, logistic complexity and social structure are very different between energy frontier experiments and precision physics experiments at lower energies, their complementarity in physics in the quest for the search of phenomena beyond the Standard Model has started to be well recognised. This became evident also in this workshop. For identifying and justifying the next high-energy frontier machines to be built, information from the both frontiers will be needed. Therefore, it is vital that the two community work together to establish the Swiss priority for the next machine and experiments.

For the Swiss Roadmap discussion in 2018, the LHC results from the 2017 data, including the ones from LHCb would be essential, together with the low energy precision data. The status of the high field magnet R&D might indicate a timescale and cost for a possible intermediate machine, HE-LHC. The cost estimates for the FCC as well as the cost and physics potential of the new baseline 380 GeV version of the CLIC are another important key issues. Status of the Japanese attempt to start a 250 GeV ILC with a later energy upgrade plan and a Chinese plan for the CEPC circular e+e- collider must also be followed in the Swiss discussion.

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