# Physics Beyond Colliders Kickoff Workshop

Tuesday, 6 September 2016 - Wednesday, 7 September 2016

CERN

# Book of Abstracts

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## Beam Possibilities in the North and East Areas

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In this presentation we will present the present possibilities and performance of the various beam lines in the North and East Areas, downstream of the primary targets. The limitations and restrictions on their performance will be outlined, First hints will be given on what is needed in terms of studies for upgrade to meet the requirements for the new proposals for experiments presented at this workshop.

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## Neutrinos from Stored Muons (nuSTORM)

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The Neutrinos from Stored Muons (nuSTORM) facility has been designed to deliver beams of nu_e and nu_mu from the decay of a stored beam. nuSTORM has the potential to:

- Serve the future long- and short-baseline neutrino-oscillation programmes by providing definitive measurements of ,nu_e N and nu_mu N scattering cross sections with percent-level precision; and
- Allow searches for sterile neutrinos of exquisite sensitivity.

nuSTORM is ideally matched to the development of the North Area at CERN where it could serve the experimental hall that will soon house the CERN Neutrino Platform.

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## Proton throughput in the LIU era

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The LHC Injectors Upgrade (LIU) project will implement significant upgrades across the complex during Long Shutdown 2 with the main goal to improve the performance of LHC beam production. Non-LHC physics beams might also potentially benefit from the LIU upgrades. Proton delivery through the CERN accelerator complex will be therefore discussed in view of the potential provided by LIU, including in the analysis:
• LHC and HL-LHC
• Existing non-LHC physics users and their future perspectives
• Potential new physics users, in particular SHiP
• Considerations on the optimisation of the delivery rates
• Limitations, areas of improvement, challenges

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## SPS slow extraction: challenges and possibilities for improvement

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Slow extraction from the SPS is essential for present and future Fixed Target beams in the North Area, and will be a key feature of the beam for the proposed Beam Dump Facility experiments like SHiP. The 3rd integer resonant extraction mechanism and accelerator components used to remove the beam from the accelerator intrinsically generate a few percent of beamloss, most of which is localised in the extraction channel in LSS2. The resulting activation, radiation dose to equipment and important restrictions on personnel doses in case of intervention are the main limitation on the number of protons that can be extracted per year. In addition, the extraction process is inherently sensitive to orbit stability, ripple in the SPS power supplies and beam structure, which produce detrimental frequency modulation in the spill and effectively increases the POT needed.

In this presentation we describe the features of the extraction mechanism and quantify the beamlosses and spill harmonic content. On this basis we extrapolate the activation levels and consequent operational restrictions in case of 4e19 POT per year, in the light of recent SPS operational experience. The required loss reduction factor, stability and spill quality are discussed, together with potential improvement directions for achieving the target flux.

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## Experience with multi-TeV beam channeling and crystal extraction at the LHC

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Bent crystals have been recently installed in the Large Hadron Collider for halo collimation studies. The first tests performed with hadron beams demonstrated channeling with good efficiency at energies up to 6.5 TeV and provided an initial feedback on the operation of crystals that are integrated in the transverse hierarchy of the LHC collimation system. Data collected also provide a benchmarks of simulation tools developed for predicting crystal-based collimation. In this contribution, the possibility to use crystal extraction for in-beam and external fixed targets at the LHC is discussed. Predicted performance for some example layouts are presented and ideas for further beam tests towards a demonstration of this concept are proposed.

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## Optical layout for the measurement of Short Living Baryon Magnetic Moment using Bended Crystals at LHC

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In this talk we investigate scenarios for an experiment to measure the magnetic moment of the Λc and other charmed charged baryons at LHC top energies. In the last decade, the UA9 Collaboration has developed the technology and more recently used it to demonstrate that bent silicon crystals can efficiently steer the diffusive halo surrounding the circulating beam in LHC, up to 6.5 TeV energy. A scenario is described here to deflect the halo particles in the vicinity of an interaction region of LHC. The deflected particles should be kept in the vacuum pipe and will follow trajectories well distinct from those of the circulating beam core. By approaching to the beam a target that intercepts the channelled beam, well separated from the beam core, the deflected halo can be efficiently used for fixed-target physics. In particular, by directing the deflected halo into another bent crystal tightly packed with a short and dense target, located in the LHC pipe just before an existing detector, living baryons should be produced and their polarization may be measured from the analysis of the decay products. An additional downstream collimation setup is also required to intercept halo particles non-interacting with the target and debris from the target itself, in order to ensure that losses remain safely below quench limits of superconducting magnets, thereby allowing the possibility of fixed-target operation in parasitic mode. As an example, a preliminary optical layout compatible with the existing installations in IR8 is presented.

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# SPS beam dump facility

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A preliminary conceptual design of a general-purpose fixed target facility with aim of accommodating high intensity dump experiments in the SPS complex, such as the proposed SHiP experiment, has been produced. The facility has been conceived to be sited in the CERN's North Area on the Prevessin site and to receive the full SPS beam. Its design also allows the possibility to retune the configuration of the target complex and therefore accommodate different experiments, effectively leading to a multi-purpose Beam Dump Facility for discovery physics.
The contribution will summarize the baseline design of the facility, the proposed beam extraction from the SPS, the design of the target complex, civil engineering design and radiation protection aspects as well as the R&D foreseen in the next few years.

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# EDM options

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The storage ring technique to search for the EMD of the proton and deuteron is introduced. The accelerator physics and technical challenges are outlined. Work is ongoing worldwide to address these challenges and progress is briefly summarised. Physics motivation is discussed in a companion presentation at this workshop - 'EDM measurement in a proton storage ring'.

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# Protons drivers - review of possibilites

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In the past CERN has explored in some depth options for upgrades or novel exploitation of the accelerator complex. These options are briefly revisited. Putting aside neutrinos, RIB, and neutrons, their possible application (or not) as a driver for muon physics - complementary to existing worldwide efforts - is considered. Finally an alternative approach is introduced.

**Close-out: the next steps / 65**

## Closeout

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**New experimental ideas / 10**

## The Gamma Factory initiative

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This contribution discusses the possibility of broadening the present CERN research programme by a new component, making use of a novel concept of the light source. The proposed, partially stripped ion beam driven, light source is the backbone of the Gamma Factory initiative. It could be realized at CERN by using the infrastructure of the already existing accelerators. It could push the intensity limits of the presently operating light-sources by at least 7 orders of magnitude, reaching the flux of the order of $10^{17}$ photons/s, in the particularly interesting $\gamma$-ray energy domain of \mbox{ $1 \leq E_{photon} \leq 400$ MeV.} This domain is out of reach for the FEL-based light sources based on sub-TeV energy-range electron beams. The unprecedented-intensity, energy-tuned, quasi-monochromatic gamma beams, together with the gamma-beams-driven secondary beams of polarized positrons, polarized muons, neutrinos, neutrons and radioactive ions would constitute the basic research tools of the proposed Gamma Factory. A broad spectrum of new opportunities, in a vast domain of uncharted fundamental and applied physics territories, could be opened by the Gamma Factory research programme.

**New experimental ideas / 19**

## Measurement of Short Living Baryon Magnetic Moment using Bent Crystals at SPS and LHC

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The magnetic moments of baryons containing u,d and s quarks have been extensively studied and measured. The experimental results are all obtained by a well-assessed method that consists in measuring the polarisation vector of the incoming particles and the precession angle when the particle is travelling through an intense magnetic field. The polarization is evaluated by analysing the angular distribution of the decay products. No measurement of magnetic moments of charm or beauty baryons (and τ leptons) has been performed so far. The main reason is the lifetimes of charm/beauty baryons, too short to measure the magnetic moment by standard techniques.
One proposal to meet the challenge of measuring the magnetic moments of baryons with heavy flavoured quarks is to use the strong effective magnetic field inside the channels of a bent crystal instead of the conventional magnetic field to induce the precession of the polarization vector and measure the magnetic moment. The detailed precession theory has been developed in Ref. [1]. E761 Collaboration (1992) had demonstrated the feasibility of this idea by measuring the magnetic moment of the strange Σ+ baryon [2] using the decay into pπ0.
In this talk we investigate scenarios and propose an experiment to measure the magnetic moment of the Λc and other charmed charged baryons at SPS and at LHC top energies. For the proposed experiments, the length and the crystal bending angle should be optimised at the different energies, to provide the maximal channelling efficiency. On the other hand, the crystal should be tightly packet with the target and tested to maximize the Λc yield taking into account the very short decay length of the charmed baryons. The detector should be very close to the crystal-target pack to maximize the yield. The unavoidable drawback would be the heavy background produced by the primary proton beam travelling close-by. The proposed experiment at SPS should be performed in the CERN North Area, whilst the LHC experiment should be kept in the LHC vacuum pipe and if possible use one of the existing LHC detectors.

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## Search for dark sector physics in missing energy events at the CERN SPS

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The NA64 is a fixed-target experiment aiming to search for dark sector physics with a high-energy electron beam at the CERN SPS. The experiment uses a new approach combining the active beam dump and missing energy techniques. We present the future NA64 research program which is significantly extended
%and has a certain advantages compared to the classical beam dump approach.
by the inclusion of measurements with high-energy $\mu,\ \pi,\ K$, and $p$ beams. The program will deliver a rich and compelling physics opportunity by performing the sensitive searches for new symmetries, rare decays, and weakly-interacting particles from the dark sector and is based on the following motivations:

i) In addition to gravity, there might be another very weak interaction between the ordinary and dark matter transmitted by a new $U'(1)$ gauge boson (dark photon). NA64 plans to search for visible, e.g. into
$e^+e^-, \quad \mu^+\mu^-$, and invisible, e.g. into dark sector particles, decays of sub-GeV dark photons. The experiment has the exciting opportunity to probe a substantial fraction of the currently unexplored dark photon parameter space, probing kinetic-mixing parameter $\epsilon$ as low as $\epsilon^2 \simeq 10^{-6} - 10^{-10}$ and masses $M_{A'} \leq 500$ MeV by using $\simeq 100$ GeV electron beams from the CERN SPS. The search will also cover the region
where the $(g-2)_\mu$ discrepancy between the measured and predicted anomalous magnetic moment

of the muon can be explained by an additional $U'(1)$ gauge boson which decays mostly invisibly. %With an expected number of electron on target $10^{12}(10^{13})$ in 2016-2017 (2018 and beyond).

ii) A new sub-GeV gauge boson
$zm$ (leptonic boson) from the $L_\mu - L_\tau$ flavor symmetry with couplings to $\mu$ and $\tau$, but not electrons, could explain the $(g-2)_\mu$ discrepancy and the gap of high-energy neutrinos in IceCube, and is well motivated by neutrino mixing angles.
The
$zm$ could be observed in the reaction
$react$ of high-energy muon scattering off nuclei by looking for an excess of events with the large missing muon beam energy in a detector due to the prompt bremsstrahlung
$zm$ decay
$zmnn$ into a couple of neutrino. \\
The availability of high energy ($\simeq 100$ GeV) and high intensity ($\simeq 10^6$/spill) muon beams at CERN SPS allows to search for the $Z'$ with the sensitivity in coupling constant $\alpha_\mu \simeq 10^{-11}$, which is three orders of magnitude higher than the value required to explain the
$(g-2)_\mu$ anomaly. This provides a unique opportunity either to discover or rule out the
$zm$ in the proposed search in the near future.
%The number of muons available at present is an order of $10^{15}$ $\mu$/year, and it is anticipated to have more like $10^{18} - 10^{19}$ $\mu$/year.

iii) In the standard model (SM) the rate of the neutral mesons $(M^0)$ $\pi^0, \eta, \eta', K_S, K_L \to \nu\overline{\nu}$ decays is predicted to be extremely small. The decay $K_L^0(K_S^0) \to invisible$ has never been experimentally tested. In the SM its branching ratio for the decay into two neutrinos is helicity suppressed and predicted to be $\leq 10^{-10}$. In several popular extensions of the SM, e.g. the two-Higgs doublet model, the helicity suppression factor can be avoided resulting in the enhanced $K_L^0$ rate e.g. into $\nu_\tau\overline{\nu}_\tau$ pair or pair of light scalars, and could be in the range $Br(K_L^0 \to invisible) \simeq 10^{-8} - 10^{-6}$, still allowed by the most stringent constraints from the
$K \to \pi\nu\nu$ decay. Another motivation to search for $K_S, K_L \to invisible$ decays is
related to the still open question on how possible contributions from these decays influence the Bell-Steinberger unitarity relation - a powerful tool for testing CPT symmetry in the
$K^0 - \overline{K}^0$ system. \\
The experiment utilizes the charge-exchange reactions of $\simeq$ $(20-50)$ GeV $\pi$ or $K$ on nucleons of an active target, e.g. $\pi^-(K^-) + p \to M^0 + n$, as a source of the well-tagged $M^0$s emitted in the forward direction with the beam energy. If the decay $M^0 \to invisible$ exists, it could be observed by looking for an excess of events with a specific signature: the complete disappearance of the beam energy in the detector. This unique signal of $M^0 \to invisible$ decays allows for searches of the $K_L^0(K_S^0) \to invisible$ decays with a sensitivity in the branching ratio $\simeq 10^{-8}(10^{-6})$, and $\pi^0, \eta, \eta' \to invisible$ decays with a sensitivity of a few orders of magnitude beyond the present experimental limits by using the beams with intensity $I_{\pi,K} \simeq (10^5 - 10^6)$/spill.
An experiment at such level of sensitivity would be a clean probe of new physics at and beyond the LHC mass scale. It is complementary to the search for rare $K \to \pi\nu\nu$ decay and thus
%and provide a strong motivation for its sensitive search in a near future experiment.
fits very well with the present kaon physics program at CERN.
%With an expected $10^{15}(5.5x10^{16})$ muon decays in 2015-2016 (2018 and beyond).

iv) Searches for sub-GeV leptophobic dark sector bosons $Z'$ coupled to quarks.
The $Z'$ could be produced in the high-energy proton collisions with nuclei of an active target, $pp \to Z' + X$, with the subsequent invisible decay $Z' \to \chi\overline{\chi}$ into lighter dark matter particles
$\chi$. The feasibility study shows that the NA64 can provide complementary coverage of the parameter space, which is intended to be probed by the planned experiment at the Main Injector at FNAL. In contrast to this project, the only assumption used in NA64 is that the $Z' \to \chi\overline{\chi}$ decay is predominant, but no assumptions are made on the value of the $\chi$ coupling strength to $Z'$. The experiment requires the use of the $\simeq (100-200)$ GeV proton beams with intensity $I_p \simeq (10^5 - 10^6)$/spill.

All these searches can be performed using a common experimental setup. Therefore, we regard all proposed measurements as a unified one NA64 experiment. Modifications to the existing NA64 setup are required. Some of the detector components have to be upgraded or newly made item-by-item to realize the final configurations.

**New experimental ideas / 14**

## A space-like measurement of the leading hadronic corrections to the muon g-2 with a muon beam

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The anomalous magnetic moment g-2 of the muon is a precision measurement which exhibits a 3.5$\sigma$ deviation between theory and experiment, and in the next few years will be measured at Fermilab and J-PARC with even higher precision.

The hadronic contribution to the muon g-2 ($a_\mu^{\mathrm{HLO}}$) is the most important one after the pure QED contribution. It is however affected by a large uncertainty which dominates the error on the theoretical prediction in the Standard Model. Considering the present observed deviation of the experimental measurement, it is extremely important to get an independent measurement of the hadronic contribution to g-2 to reduce its uncertainty.

We propose a novel approach to determine the leading hadronic corrections to the muon g-2.
It consists in a measurement of the effective electromagnetic coupling in the space-like region at low-momentum transfer.
We discuss the possibility to perform this measurement by taking advantage of the high energy muon beam in the CERN North Area.
We plan to realize a fixed target scattering experiment aiming at achieving a per mille accuracy on $a_\mu^{\mathrm{HLO}}$. Such an accuracy will allow an alternative determination of this fundamental quantity competitive with the present results obtained with the dispersive approach via time-like data.

Such precision would therefore allow a more stringent test of the Standard Model when compared with the g-2 measurements expected at Fermilab and J-PARC.

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## Experimental checks of precise QCD predictions by studying the π+K−, K+π− and π+π− atoms

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The lifetime of the short-lived ($\tau_{th}$ about $3 \times 10^{-15}$ s in the ground state) $\pi^+K^-$, $K^+\pi^-$, ($\pi^+\pi^-$ ) atoms($A_{\pi^+K^-}$, $A_{K^+\pi^-}$ and $A_{2\pi}$ ) is given within 1% (0.6%) precision by the S-wave $\pi K$ ($\pi\pi$) scattering length combination $|a_{1/2} - a_{3/2}|$ ($|a_0 - a_2|$), where 1/2, 3/2 (0, 2) are the isospin values. Furthermore, the study of long-lived $A_{2\pi}$ states (states with non-zero orbital momentum, $\tau \geq 1 \times 10^{-11}$ s) allows to measure the Lamb shift depending on another $\pi\pi$ scattering length combination $2a_0 + a_2$. Therefore, the investigation of dimesonic atoms is the tool to measure model-independently $\pi K$ and $\pi\pi$ scattering lengths, which have been calculated precisely in the framework of LQCD (Lattice QCD) and ChPT (Chiral Perturbation Theory). Up to now, dimesonic atoms have been investigated only in the experiment DIRAC, using the CERN PS 24 GeV/c proton beam.

The S-wave $\pi\pi$ scattering lengths described in QCD exploiting $SU(2)_L \times SU(2)_R$ symmetry breaking and confirmed experimentally with precision of about 4%. But these measurements - independently from their accuracy - cannot check the QCD predictions based on the chiral $SU(3)_L \times SU(3)_R$ symmetry breaking for strange sector. This check can be done by investigating the S-wave $\pi K$ scattering lengths, where the s quark is involved.

LQCD and ChPT give $|a_{1/2} - a_{3/2}|$ with a precision of about 5% and 10%, respectively. The best direct measurement of this combination has an average precision of 35% (DIRAC experiment, to be published). It is obvious that for the time being LQCD and ChPT predictions, based on chiral $SU(3)_L \times SU(3)_R$ symmetry breaking, have not be checked experimentally with enough accuracy. A recent study has shown that the $\pi^+\pi^-$ $\pi^+K^-$, and$K^+\pi^-$ atom production per time will be $12 \pm 2$, $53 \pm 11$ and $24 \pm 5$ times higher than in the previous DIRAC experiment, if the incident proton momentum raise from 24 to 450 GeV/c ($\theta_{lab} = 4°$) and take in to account the SPS beam duty factor. This significant increase in $A_{\pi^+K^-}$ and $A_{K^+\pi^-}$ production makes it possible to measure $|a_{1/2} - a_{3/2}|$ at the 5% precision level with DIRAC in a comparable running time. For the first time, our thinking about chiral $SU(3)_L \times SU(3)_R$ symmetry breaking in QCD could be checked. The setup upgrading and geometry modification will enable a significant precision improvement.

The $\pi\pi$ scattering lengths $a_0$, $a_2$ and their difference have been calculated in ChPT with precision of 2.3% and 1.5%, respectively. The accuracy of these parameters can be improved. In some recent works, $\pi\pi$ scattering lengths were calculated using LQCD: with precision about 5% and less than 1.5%. Currently, only $|a_0 - a_2|$ has been measured in the NA48 and DIRAC experiments with a precision of about 4%, confirming the theoretical predictions. The scattering length $a_2$ has been determined by NA48 with a precision of 22% . The strong increase of the $A_{2\pi}$ yield allows to improve the $|a_0 - a_2|$ precision and to begin the study of the long-lived atom $A_{2\pi}$, which has been observed by DIRAC in 2015.

For all investigation of dimesonic atoms, the DIRAC experiment uses very thin targets without disturbing the proton beam and, hence, can be installed upstream of other experiments in the same beam.

**New experimental ideas / 15**

# Search for Hidden Particles with the SHiP experiment

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The experimental evidence for BSM physics such as the non-zero neutrino masses, the baryon asymmetry in the Universe, and the presence of non-baryonic dark matter may have their origin in new physics involving very weakly interacting particles as predicted by models with a secluded or hidden sector of particles. In general, these models contain mediators that couple very weakly with SM particles, acting as portals to the hidden sector, e.g. dark photon, Majorana neutrinos, dark scalars, etc… Relatively light warm dark matter is naturally accommodated in these models. Given

the small coupling constants and typically long lifetimes, hidden particles have not been significantly constrained by previous experiments, and the reach at current experiments is limited by both luminosity and acceptance.

This talk will describe the recently proposed SHiP experiment at the SPS which is aiming at generically searching for hidden particles. The high power and unique operational mode of the SPS provide ideal conditions for accessing a wide variety of light long-lived very weakly interacting particles and light dark matter. With 2x1020 protons on target, SHiP is able to achieve sensitivities which are up to four orders of magnitude better than previous constraints, accessing a significant fraction of the unexplored parameter space. Such an experiment would be an essential complement to the LHC in the search for new physics at CERN.

The SHiP experiment is also ideally suited to study the interactions of tau neutrinos.

**New experimental ideas** / **3**

## EDM measurement in a proton storage ring

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A measurement of the proton EDM to better than 10-29ecm, or better, allows us to probe physics in a new regime up to ~3PeV mass scale. The use of the storage ring EDM technique permits 5 orders of magnitude improvement over current indirect measurements of dp (from Hg) and 3 orders magnitude more sensitivity on ⊠QCD inferred from neutron EDM measurements. Non-zero values of the pEDM would unambiguously point to the existence of NP. We describe the design of an electric-only ring that combines the frozen spin technique with counter-rotating proton beams that can deliver these physics objectives. The experimental and technological challenges have been addressed in detail over the last 5 years; developments in magnetic field shielding now make this a low risk and relatively low cost experiment. We present a summary of the major machine and detector components required to build this experiment.

**New experimental ideas** / **24**

## An electron beam for physics experiments based on AWAKE technology

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The AWAKE experiment [1] will be taking data over the next two years to establish the method of proton-driven plasma wakefield acceleration. An R&D programme is being formulated for post-LS2 in which the AWAKE experiment demonstrates [2] that bunches of about $10^9$ electrons with an energy of 10 GeV accelerated in about 10 m of plasma are achievable and that the energy gain is scalable with length. Given a clean electron beam of O(50 GeV) and of a much higher rate than from the SPS secondary beam, new and improved fixed-target or beam-dump experiments are possible. An example is the NA64 experiment [3] which is searching for hidden sector physics such as

dark photons using the secondary SPS electron beam at an intensity of $\sim 10^6$ $e^-$/s. With the expectation of being able to increase this rate by at least a factor of 100 using the AWAKE beam, sensitivity to new physics is correspondingly extended. An electron beam of O(50 GeV) is also planned for the LHeC which under the AWAKE scheme could be achieved in a plasma cell of ~50 m in length, although with modest luminosities. This could open up the possibility of an LHeC-type project at relatively low cost and focusing on physics at low Bjorken-$x$ such as saturation and QCD in general. An ultimate goal of the AWAKE technology is to use it to produce an electron beam of 3 TeV and collide with an LHC proton beam. This very high energy electron-proton collider [4] would probe a completely new regime in which QCD and the structure of matter is completely unknown. Again, this would be relatively low luminosity, but this is offset by the rapidly rising cross sections at low Bjorken $x$.

[1] AWAKE Coll., arXiv:1511.09032; arXiv:1512.05498

[2] E. Adli (AWAKE Coll.), IPAC2016 proceedings, p.2557-2560.

[3] https://na64.web.cern.ch

[4] A. Caldwell and M. Wing, arXiv:1606.00783

**New experimental ideas / 6**

## The International Axion Observatory (IAXO)

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Axions are a natural consequence of the Peccei-Quinn mechanism, the most compelling solution to the strong-CP problem. Similar axion-like particles (ALPs) also appear in a number of possible extensions of the Standard Model, notably in string theories. Both axions and ALPs woudl be copiously produced at the sun's interior, and in addition they are very well motivated candidates for the Dark Matter. They are object of increasing interest by experimentalists. A relevant effort during the last decade has been the CAST experiment at CERN, the most sensitive axion helioscope to-date. Here I will present an initiative born as a large-scale ambitious follow-up of CAST: the International Axion Observatory (IAXO). As its primary physics goal, IAXO will look for solar axions or ALPs with a signal to background ratio of about 5 orders of magnitude higher than CAST. For this IAXO envisions a large superconducting toroidal magnet designed optimizing the axion helioscope figure of merit, extensive use of x-ray focusing optics and low background x-ray detectors. IAXO will venture deep into unexplored axion parameter space, thus having discovery potential. IAXO has also potential to host additional detection setups. Most interestingly, the large magnetic volume of IAXO could be used to detect relic axion or ALPs potentially composing the galactic halo of Dark Matter. IAXO has the potential to serve as a multi-purpose facility for generic axion and ALP research in the next decade, making use of technology and know-how from CERN.

**New experimental ideas / 27**

## Investigating the QCD phase transitions with dileptons: new opportunities at the CERN SPS

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The theory of strong interactions, Quantum Chromodynamics (QCD), predicts a rich variety of different phases of strongly interacting matter. The QCD phase diagram is usually represented as a function of the temperature and baryon density. At sufficiently high temperatures, a transition from hadronic matter to a Quark-Gluon Plasma (QGP), a state where quarks and gluons are no more confined into hadrons, is predicted.

Experimentally, the conditions for the formation of the QGP can be reached in collisions of heavy nuclei at ultra-relativistic energies. The exploration of the QCD phase diagram is up to now mainly restricted to the region of low baryon density. In this regime, lattice QCD calculations predict a cross-over transition between hadronic matter and QGP, occurring at a temperature of 155 MeV [1]. On the other hand, the phase diagram for moderate temperatures and high baryon densities is largely unknown and the existence of a first order phase transition with coexistence of a mixed-phase was suggested. The first order transition line should end with a second order critical point [2]. The experimental test of this scenario is one of the outstanding questions in the field of non-perturbative QCD.

Furthermore, in vacuum, the light hadron masses are largely due to the spontaneous breaking of QCD chiral symmetry. At the phase boundary between hadronic matter and the QGP, chiral symmetry should be restored. This implies a change in the hadron mass spectrum, but how this is realized is not known.

In order to shed light on these fundamental phenomena, we propose to define a new experimental apparatus (here denoted NA60+) to measure the production of muon pairs with unprecedented precision in fixed-target nucleus-nucleus collisions in a low-energy scan at the CERN SPS [3]. The CERN SPS is unique for such systematic investigations, because it can deliver high-intensity beams to study, e.g., Pb-Pb collisions over the energy range from $\sqrt{s_{NN}}$ =5-6 up to 17 GeV in the centre-of-mass system.

In this energy regime, measurements of lepton pairs provide a rich set of observables. Dileptons are produced at all stages of the evolution of the created system, and offer the possibility to measure its temperature. The measurement for the first time of a caloric curve and the possible identification of a plateau can provide a direct and unambiguous evidence of a first-order phase phase transition. Chiral symmetry restoration can be also directly probed, by studying for the first time the mass modifications in a simultaneous measurement of the vector meson $\rho$ and its axial vector partner $a_1$ close to the onset of deconfinement.

In addition, the study of $J/\psi$ suppression and open-charm production are also expected to be sensitive to the onset of deconfinement.

High precision measurements of muon pairs were pioneered by the NA60 experiment, which coupled a traditional muon spectrometer to a silicon vertex tracker placed before the hadron absorber [4,5,6,7]. The NA60+ apparatus is meant as an evolution of NA60.
It aims at an increase in statistics by a factor $\sim 100$ over NA60 and even larger over RHIC and LHC experiments, while retaining a very good signal-to-background ratio even in central Pb-Pb collisions [3].

The CERN SPS appears to be the best facility for these measurements.
Thanks to the new injection scheme it can deliver intense ion beams leading to interaction rates exceeding 1 MHz.
An ion beam could be delivered to a fixed target experiment while the SPS is used as injector for LHC.
Presently the NA61 experiment, with an experimental program on hadronic observables, is running at the CERN SPS and has a physics program complementary to the one proposed for NA60+.

In comparison, the other facilities operating in collider mode (RHIC and NICA) provide interaction rates 2-3 orders of magnitude smaller than the SPS, so that high-precision measurements are not possible. In addition, FAIR SIS/100 is designed to provide high interaction rates but the energy coverage is extremely limited. FAIR SIS/300 might provide a larger coverage but it is not approved at present and its operation would in any case only start well beyond 2030.
Thus, no presently approved experiment is able to cover such a large energy interval and to collect at the same time the large statistics required for truly quantitative measurements. A high precision dilepton experiment at the CERN SPS as NA60+ would then represent a unique opportunity to investigate the QCD phase diagram in the next decade.

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## AFTER@LHC : A fixed-target programme at the LHC for heavy-ion, hadron, spin and astroparticle physics

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In this talk, we review a number of recent ideas* put forward in favour of a fixed-target programme at the LHC - AFTER@LHC- dedicated to heavy-ion, hadron, spin and astroparticle physics. By extracting the beam with a bent crystal or by using an internal gas target, the multi-TeV LHC beams allow one to perform the most energetic fixed-target experiments ever with which one can access the essentially uncharted backward kinematics with detectors similar to LHCb or ALICE.

In particular we argue that this allows one to study $pp$, $pd$ and $pA$ collisions at $\sqrt{s_{NN}}$ ≃115 GeV and Pb$p$ and Pb$A$ collisions at $\sqrt{s_{NN}}$ ≃72 GeV with extremely high precision with modern detection techniques. Such studies, including

- single transverse-spin asymmetries for hard and rare processes,
- suppression of heavy-flavours and quarkonia as well as azimuthal asymmetries down to the target rapidity in heavy-ion collisions,
- cold-nuclear matter effects,
- the physics involved in ultra-peripheral hadron and ion collisions,

- far backward gluon and heavy-quark sensitive processes,
- vector-boson production near threshold …,

would greatly complement collider experiments, in particular those of the Electron-Ion Collider project or RHIC (with luminosities larger by 1 to 3 orders of magnitude).

Such a mode indeed allows for a broad physics programme, covering the large-$x$ QCD frontier for particle and astroparticle physics, as well as spin and heavy-ion physics with respectively a polarised target and the LHC lead beam.

*: for a complete list of references see
http://after.in2p3.fr/after/index.php/Recent_published_ideas_in_favour_of_AFTER@LHC

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## The DarkSide Dark Matter Program

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The DarkSide-50 dark matter detector at LNGS is a two-phase argon TPC, installed at the center of two nested veto detectors, a 30-tonne liquid scintillator neutron veto and a 1,000-tonne water Cherenkov muon veto. While operating in 2014 with a fill of argon extracted from the atmosphere, DarkSide-50 demonstrated its capability to operate in a background-free mode even in presence of the strong radioactive background due to the 39Ar isotope produced by cosmic rays. In 2015 DarkSide was filled with 150 kg of argon extracted from deep underground reservoirs, which was demonstrated to be highly depleted in 39Ar. Today DarkSide-50 is the only noble liquid dark matter detector operating in background-free mode.
The combination of the DarkSide-50 results obtained with the atmospheric and underground argon fills allows to project that DarkSide-20k, a 20-tonne depleted argon detector proposed for construction at LNGS, will collect an exposure of 100 tonnes×year completely free of background. DarkSide-20k detector is set to start operating by 2020 and is projected to be the most sensitive dark matter experiment, with a sensitivity reaching well past the ultimate value possible for xenon-based detectors. DarkSide-20k will be followed after five years at LNGS by Argo, a 300-tonne dark matter detector capable to collect an exposure of 1,000 tonnes×year completely free of background, reaching the ultimate sensitivity before the onset of background due to nuclear recoils induced by neutrino coherent scattering. Argo will also be capable of performing a set of very high precision measurement of several solar neutrino sources.
The future DarkSide programs are made possible by special technological programs for the procurement of underground argon (Urania project), in its additional isotopic rejection of 39Ar (Aria project), and in the development of special SiPM to replace cryogenic PMTs for operation as photosensors at 87K (DarkSide@Abruzzo project).
We expressed our interest to assemble and operate at CERN the 1-tonne prototype of DarkSide-20k already under construction by the DarkSide Collaboration at this time. We anticipate that the prototype will be ready for assembly in the Summer 2017. Assembly and operation at CERN will enable to elicit strong participation in this activity from all DarkSide institution in a central location easily accessible to all of its groups. Operation of the 1-tonne prototype at CERN will help in quickly deploying the
readout and the data acquisition systems of the novel SiPM-based photosensors equipping the 1-tonne prototype.

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## Future options for searching axion-like particles through light-shining-through-a-wall experiments

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Weakly interacting slim particles (WISPs) are searched for in purely laboratory based experiments with the so-called light-shining-through-a-wall (LSW) approach. Here the detection of axion and axion-like particles, which seem to be the best motivated WISPs from theoretical considerations, requires the presence of a long and strong magnetic field perpendicular to the light path. Current experimental activities are OSQAR at CERN and ALPS II presently under preparation at DESY. At ALPS II, dedicated complex optics, largely based on experiences gained in the context of LIGO, new detector technologies and modified dipoles from the HERA proton ring will be combined.
In the future one could envisage a physics case strongly asking to increase the sensitivity of LSW experiments beyond the present scope. For example, direct dark matter experiments or solar observations might discover a light axion-like particle requiring to measure its properties unambiguously in a purely laboratory based experiment. In this contribution we will sketch scopes and limitations of "ultimate" LSW experiments based on advanced high field magnets presently under development in the frame of HL-LHC and FCC. It is evident that the corresponding high costs of such installations will require a very clear and convincing physics case.

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## Prospects for an experiment to measure BR(K_L to pi0nubarnu) at the CERN SPS

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Precise measurements of the branching ratios (BRs) for the flavor-changing neutral current decays $K \to \pi\nu\bar{\nu}$ can provide unique constraints on CKM unitarity and, potentially, evidence for new physics. It is important to measure both decay modes, $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$, since different new physics models affect the rates for each channel differently. The NA62 experiment at the CERN SPS is currently collecting data and should measure BR($K^+ \to \pi^+\nu\bar{\nu}$) to within 10% by 2018; there are plans to measure BR($K_L \to \pi^0\nu\bar{\nu}$) with similar precision at a successor to the KOTO experiment at J-PARC using a low-energy secondary beam, but no official proposal has yet been made. We are investigating the feasibility of performing a measurement of BR($K_L \to \pi^0\nu\bar{\nu}$) using a high-energy secondary neutral beam at the CERN SPS in a successor experiment to NA62.
The planned experiment would reuse some of the NA62 infrastructure, including possibly the NA48 liquid-krypton calorimeter; the measurement technique is complementary to that of KOTO Step 2 and would provide comparable sensitivity. The mean momentum of $K_L$s decaying in the fiducial volume is 70 GeV. This causes decay products to be boosted forward, so that less demanding performance is required from the large-angle photon veto detectors. On the other hand, the layout poses particular challenges for the design of the small-angle vetoes, which must reject photons from $K_L$

decays escaping through the beam pipe amidst an intense background from soft photons and neutrons in the beam. We present some preliminary conclusions from our feasibility studies, with an emphasis on the design challenges faced and the sensitivity obtainable for the measurement of BR($K_L \to \pi^0 \nu \bar{\nu}$).

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# Advanced-KWISP: investigating short-range interactions at sub-micron scales.

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Sensitive measurements on the short range interactions between macroscopic bodies provide a window on possible physics beyond the standard model, including extra-dimensions, scalar dark matter and dilatons. The sub-micron scale distances is presently not accessible to experimental investigation, and may hold the key to understanding at least part of the dark matter puzzle.
The *a*-KWISP (*advanced*-KWISP) proposal builds on the results obtained with the KWISP opto-mechanical force sensor, designed and constructed at INFN Trieste, and enters the short-distance interaction field with the novel "double-membrane" concept. Here interaction distances can be as short as 10 nm, much below the ≈10-30 micron distance which is the lower limit encountered by current experimental efforts. *a*-KWISP reaches the ultimate quantum-limited sensitivity by exploiting an array of technologies, and by achieving sub-Kelvin membrane temperatures with a combination of cryogenic and optical cooling.
Access to CERN infrastructure will be key to the success of aKWISP, in order to build upon the experience being matured with KWISP at CERN, and to have direct access to advanced technologies readily available at CERN, such as patterned thin-layer coatings and cryogenic cooling.

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# Probing the Standard Model with Radionuclides

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The search for physics beyond the Standard Model can be performed complementary to high-energy physics by conducting studies at lowest energies. The achieved extraordinary precision is needed for reaching similar or even improved sensitivity limits. Radionuclides provide in this respect an ideal laboratory for addressing properties of all known fundamental interactions. High-precision nuclear physics experiments have allowed for example to set stringent limits on the unitarity of the CKM quark-mixing matrix, on the validity of special relativity and isospin symmetry. Precision measurements of nuclear properties are used to constrain the electric dipole moment in radium-225 or as an essential input for experiments determining the electron neutrino mass in beta-decay and electron-capture processes. Often the interplay between experiment and theory stimulates both

the development of theoretical concepts or models and (beyond) state-of-the-art instrumentation. A summary of recent achievements as well as future perspectives in the field of nuclear physics research at ISOLDE and nToF for physics beyond the Standard Model will be presented.

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## Perspectives from NA62

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Searches for dark-matter (DM) candidates in the MeV to few-GeV mass range feebly interacting with SM particles are generating much interest: as suggested by different authors, thermal relics due to these long-lived particles might account for the observed DM abundance in the universe. Provided NA62 reaches its limiting sensitivity for the precise measurement of the ultra-rare FCNC K+ —> pi+ nu nu-bar decay, in 2021 and beyond its setup might be well suited for exploring different DM scenarios. In particular, after possible minor modifications to the apparatus, a one-year run in beam-dump mode should allow sensitivity in as-yet unexplored regions for various SM extensions. Different new-physics models can be tested, including those based on a new vector field mediator of a new U(1) force and coupled with the ordinary hypercharge (A' or "dark" photon), those built including a set of three sterile heavy neutrinos (heavy neutral leptons), and those based on axion-like particles (ALP's). Moreover, running with the charged kaon beam and using dedicated trigger strategies, a thorough test of lepton-flavour violation from three-track K+ decays can be pursued, which will improve on the present results by two orders of magnitude. On general grounds, this sensitivity corresponds to probing mediators of several hundreds of TeV in flavour-blind new-physics scenarios. Other possible channels that could be investigated with the current NA62 setup after minor modifications to the beam setup are under study, as well.

The result of preliminary feasibility studies and a set of minor possible modifications to the experimental setup will be discussed. The impact of these searches at NA62 after few years of run starting in 2021 will be compared to that of other initiatives in the field that are planned, approved, or running.

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## COMPASS, a Universal Facility for Hadron Structure and Spectroscopy Studies

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The high intensity secondary beams at the SPS M2 beam line in combination with the world's largest polarized nucleon targets as well as large liquid hydrogen and a broad variety of nuclear targets put the COMPASS collaboration in a unique position as a universal experimental facility to study previously unexplored aspects of meson and nucleon structure, QCD dynamics and hadron spectroscopy.

High intensity hadron beams have made COMPASS the world leading facility for hadron spectroscopy and hadron structure study through Drell-Yan production of di-muon pairs. High intensity muon beams in combination with the unique kinematical range covered by the COMPASS experiment enable a very competitive program of studying nucleon structure through semi-inclusive and exclusive hard scattering reactions off polarized targets or liquid hydrogen targets.

Upgrades of the M2 beam line resulting in high intensity RF-separated anti-proton- and kaon-beams would greatly expand the horizon of experimental possibilities at COMPASS: hadron spectroscopy with kaon beam, studies of transverse momentum dependent quark structure for protons, pions

and kaons, precise studies of nuclear effects and for the first time measurements of kaon quark-substructure.

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## Probing Fundamental Physics with Antimatter

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Experiments at the Antiproton Decelerator of CERN compare the fundamental properties of matter/antimatter conjugates at lowest energies and with great precision. Such efforts provide stringent tests of the fundamental charge-parity-time invariance of the Standard Model, and allow testing of the equivalence principle of general relativity. Using single particles in Penning traps the most stringent tests of CPT invariance with baryons were carried-out by comparing proton-to-antiproton charge-to-mass ratios and magnetic moments with fractional precisions at the level of <100 ppt and a few ppm, respectively. Methods have been developed to improve the latter by a factor of >1000. Precise two-photon laser spectroscopic measurements on exotic antiprotonic atoms determined the electron-to-antiproton mass ratio with sub ppm precision. In efforts to compare the spectroscopic properties of hydrogen and antihydrogen with high resolution several milestones were achieved. Trapping of the elusive antimatter atoms has been demonstrated first in 2010, driven antihydrogen hyperfine-transitions were observed and a beam of antihydrogen atoms was produced. These developments culminated in a recent high precision study of the charge-neutrality of antihydrogen, and the experiments are rapidly progressing towards performing first high-resolution electromagnetic spectroscopy measurements with antihydrogen. On top of these spectroscopic efforts experiments to study gravitational interactions between matter and antimatter are currently being commissioned. As a major upgrade to the AD-facility the 100keV ELENA antiproton synchrotron has been approved and is about to be commissioned to soon provide lower-energy antiproton beams at improved emittance and thus 100-fold improved integrated rate of antiprotons which can be trapped. The talk will summarize the achievements made by the AD community and give an outlook on the bright future of antiproton physics at CERN.

Stefan Ulmer (RIKEN, Wako, Saitama, Japan) for the AD-Collaborations

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## NA61/SHINE: physics and facility beyond 2020

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NA61/SHINE is a multi-purpose experimental facility to study hadron production in hadron-proton, hadron-nucleus and nucleus-nucleus collisions for physics of strong interactions, neutrinos and cosmic-rays. NA61/SHINE approved data taking programme should be completed by the end of 2018. This presentation summarizes requests for new measurements and necessary facility upgrades. The former includes precise measurements of open charm and multi-strange hyperon production, measurements of fluctuations and correlations in the full phase space as well as precise measurements of hadron emission from the replica target of the Long-Baseline Neutrino Facility (LBNF) at Fermilab required for the Deep Underground Neutrino Experiment (DUNE).

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## Setting the scene

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## Introduction

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## Axions, axion like-particles, astrophysical/cosmological motivations and experimental tests

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We review the theoretical and phenomenological motivation for axions, ALPs and other very light particles as well as the state of the art in present and future experimental searches with a particular emphasis on the possibility of them forming part of the dark matter of the Universe.

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## New Physics below the Fermi Scale

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The Standard Model may be a valid effective field theory all the way up to the Planck scale, still it suffers from a number of theoretical and observational shortcomings. I will overview the arguments for a possible existence of new particles with masses below the electroweak scale and discuss the experimental prospects to search for them.

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## Detecting Dark Energy with Atom Interferometry

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I will discuss the possibility that the nature of the dark energy driving the observed acceleration of the Universe on giga-parsec scales may be determined first through metre scale laboratory based atom interferometry experiments. I will begin by discussing why our attempts to solve the cosmological constant problem lead to the introduction of new, light degrees of freedom. In order to be

compatible with fifth force constraints these fields must have a screening mechanism to hide their effects dynamically. However, this doesn't mean that they are impossible to detect. I will discuss the constraints that arise from a range of laboratory experiments from precision atomic spectroscopy to collider physics. Finally I will show that atom-interferometry experiments are ideally suited to detect a large class of the screening mechanisms known as chameleon. This will then allow us to either rule out large regions of the chameleon parameter space or to detect the force due to the dark energy field in the laboratory.

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## Electric dipole moments and precision g-2 as a window to New Physics

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When the LHC results (no new physics yet, and the Higgs mass at 125 GeV) are interpreted in terms of pre-LHC expectations (SUSY), one faces a sobering thought of superpartner masses at or above 10 TeV. Only a very few types of indirect experiments are capable of probing these energy scales with radiative corrections. Electric dipole moments are perhaps the most promising avenue to access the extreme short distance scale physics. I give a brief introduction to the subject, and outline possible directions for future improvements. In the second half of my talk, I give an appraisal to the existing tension between theory and experiment in determining muon g-2. Interpretation of this tension as a sign of new physics points to two generic possibilities: either new physics in the leptonic sector around the weak scale and/or new light sub-GeV states coupled to muons. The latter possibility is being studied in the intensity frontier experiments, and I will briefly outline possibilities for improving sensitivity to light weakly coupled states.

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## Ultralight dark matter and experiments to search for it

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Precision measurement offers a powerful new approach for particle physics. Technologies such as atom interferometry, nuclear magnetic resonance, high precision magnetometry, and torsion balances allow novel, highly sensitive experiments for direct detection of dark matter and gravitational waves. These provide the optimal method for direct detection of light dark matter candidates such as the axion, often with relatively small-scale experiments. Searching for these light fields is additionally motivated since they are the crucial element in the recently proposed solution to the hierarchy problem using dynamical relaxation in the early universe. Thus precision measurement technologies open new avenues for probing the origin and composition of the universe.