Big fundamental questions still open today:

Which is the origin of baryogenesis? Which is the nature of Dark Matter? Which is the origin of neutrino masses and oscillations?

So far the experimental efforts have been concentrated on the discovery of **new particles with masses at (or slightly above) the EW scale** and **sizeable couplings with SM particles**. Other viable possibilities are that the new particles are **below the EW scale and couple very weakly with SM particles** or that they are **at a very high mass scale** so that their effects can only indirectly be observed.

Experimental proposals considered in the BSM WG focus on **low-energy processes that can answer in a complementary way the same fundamental questions of present (or future) high-energy accelerator facilities** and in which **CERN can play a unique role**;

Projects presented at CERN so far (in random order):

*SHiP, NA62++, NA64++, KLEVER, IAXO, LSW, EDM*
Baryogenesis
(or search for new sources of CP violation)
EDMs as a Window for New Physics

Electric dipole moment: \( \frac{1}{2} \bar{\psi} i \hat{F}_{\mu\nu} \sigma^{\mu\nu} \psi \)

Only CP-violating interactions induce it:
- search for EDM == search for CP violation, if CPT holds.

It is a precision tool “automatically” as SM (apart from strong CP caveat) does not induce large EDMs. It is one of the most promising low energy measurements sensitive to the fundamental particle physics.

Typical energy resolution in modern EDM experiments (eg: neutron EDM):
\[ \Delta E \sim 10^{-6} \text{ Hz} \sim 10^{-21} \text{ eV} \]

translate to limits to EDM:
\[ |d| < \Delta E/\text{Electric Field} \sim 10^{-25} \text{ e cm} \]

Comparing with theoretically inferred scaling:
\[ |d| \sim 10^{-2} \times 1 \text{ MeV}/\Lambda_{\text{CP}}^2 \]

We get sensitivity to:
\[ \Lambda_{\text{CP}} \sim 1 \text{ TeV} \]

An improvement from 10^{-25} to 10^{-29} would scale up the sensitivity to 100 TeV!
Lines of attack towards an EDM

Free Particles

- neutron
- muon
- deuteron
- proton
- ...

→ particle EDM
→ unique information
→ new insights
→ new techniques
→ challenging technology

Electric Dipole Moment

**goal:** new source of $\bar{CP}$

Atoms

- Hg
- Xe
- Tl
- Cs
- Rb
- Ra
- Rn
- Fr
- ...

→ electron EDM
→ nuclear EDM
→ enhancements
→ challenging technology

Condensed State

- BaF, YbF
- PbO, WC
- PbF, ThO
- Hff$^+$, ThF$^+$
- ...

→ electron EDM
→ strong enhancements
→ new techniques
→ systematics

Molecules

- garnets
- $\text{Gd}_3\text{Ga}_5\text{O}_{12}$
- $\text{Gd}_3\text{Fe}_2\text{Fe}_3\text{O}_{12}$
- solid He?
- liquid Xe
Lines of attack towards an EDM

**Free Particles**
- Neutron
- Muon
- Deuteron
- Proton
- ... [Particle EDM]
- Unique information
- New insights
- New techniques
- Challenging technology

**Atoms**
- Hg
- Xe
- Tl
- Cs
- Rb
- Ra
- Rn
- Fr
- ... [Electron EDM]
- Strong enhancements
- Systematics

**Molecules**
- BaF
- YbF
- PbO, WC
- PbF, ThO
- HfF⁺, ThF⁺
- ... 
- Garnets
- Gd₃Ga₅O₁₂
- Gd₃Fe₂Fe₃O₁₂
- Solid He?
- Liquid Xe

**Condensed State**
- Solid He?
- Liquid Xe

**Electric EDM**
EDMs in hadronic systems is related to $\theta_{QCD}$

**Goal:**
Measure of EDM is also a measure of $\theta_{QCD}$
- **Electron EDM:**
  leading experiment is the Harvard/Yale ACME collaboration using ThO polar molecules with an enormous EDM enhancement factor in excited molecular states.
  \[ |d_e| < 8.7 \times 10^{-29} \text{ e cm} \text{ (2013 result)} \]

- **Proton EDM:** (G. E. Harrison et al Phys. Rev. Lett. 22, 1263 (1969)), old experiment using a molecular beam:
  \[ |d_p| < 7 \times 10^{-21} \text{ e cm} \]
  best limit today from 199Hg analysis: \[ |d_p| < 5.4 \times 10^{-24} \text{ e cm}, \text{ (PRL 91, 212303 (2003))} \]

- **Neutron EDM:** leading experiment by the nEDM collaboration at PSI.
  Many ideas/projects around the world (PSI, ILL, SNS, TRIUMF/Japan, LANL, TUM, > PNPI, …,ESS, ..) :
  \[ |d_n| < 3 \times 10^{-26} \text{ e cm} \text{ (90\% CL, 2006, 2015 result)} \]

- **“Diamagnetic” EDM:** World leading experiment uses 199Hg (U Washington, Seattle) :
  measure of neutron EDMs in a nuclear environment:
  \[ |d_{\text{Hg}}| < 7.4 \times 10^{-30} \text{ e cm} \text{ (95\% CL)} \]

EDM of 129Xe (Mainz, Heidelberg, Groningen, Jülich), using spin polarized noble gas technology could compete with 199Hg on a reasonable time scale.

- **Muon EDM:** \[ 1.8 \times 10^{-19} \text{ e cm} \text{ (95\% CL) (2009)} \] (Bennett et al., PRD80(2009)052008)
Limit on EDM vs Time

\[ d_e (\text{SM}) < 10^{-37} \]

Hg: B. Graner et al. PRL 116, 161601 (2016) [Seattle]
e\text{-}: J. Baron et al., Science 343, 269 (2014) [Harward, Yale]
Limit on EDM vs Time

R.G.E. Timmermans (‘14):
SM value will be reached
-2075 for neutron
-2115 for electron ...

199Hg (2009)

Hg: B. Graner et al. PRL 116, 161601 (2016) [Seattle]
e−: J. Baron et al., Science 343, 269 (2014) [Harward, Yale]
Opportunity for CERN to pursue the EDM projects (proton, deuteron, and in the future possibly more complicated nuclei). A breakthrough down to $10^{-29}$ e cm sensitivity level has been claimed possible. pEDM is more than an order of magnitude more sensitive than current nEDM plans.

The muon/deuteron/proton etc. ideas to search for EDMs in storage rings is by now ~50 years old. Technology proven in connection with muon g-2, however, not a single experiment to go beyond could be started, yet.

The name of the game is: systematic uncertainties!
ex: extremely good control of the external fields over an extended period of time.

The proven part of the technology is some 7 orders of magnitude behind state-of-the-art with other methods. And the forefront is moving: ~$10^{-31}$ e cm can be expected for atoms like $^{129}$Xe (Mainz, Heidelberg, Juelich, Groningen) or $^{199}$Hg (Seattle) within less than a decade.

Extremely challenging (but promising) project.
Baryogenesis
(or the strong CP problem → axions)
Axions at a glance

Axion: Pseudo Nambu-Goldstone boson associated with Peccei-Quinn symmetry, a global U(1), introduced to address the strong CP problem

[Pseudo: the U(1)$_{PQ}$ is not exact, and gives a small mass to the axion]

$f_a$ (axion decay constant) = U(1)$_{PQ}$ symmetry breaking scale

$$m_a \approx 0.5 \frac{f_\pi m_\pi}{f_a}, \quad G_{agg} \approx \frac{1}{2} \frac{\alpha_S}{f_a}, \quad G_{a\gamma\gamma} \approx \frac{1}{2} \frac{\alpha_{EM}}{f_a} \mathcal{O}(1)$$

Axion coupling is almost determined once its mass is given. \( \frac{G_{a\gamma\gamma}}{m_a} \approx \frac{10^{-9}}{\text{eV}} \)

Axon-Like Particle (ALP): a generalized version of the axion (at the cost of original motivation from the strong CP problem). No direct relation between $G_{a\gamma\gamma}$ and $m_a$. 

Courtesy of H.-S. Lee
Oscillating nEDM as a probe for axions/ALPS via gluon-coupling

See: Graham, Rajendran, PRD88(2013)035023
Budker et al., PRX4(2013)1
Stadnik, Flambaum, PRD89(2014)043522
Kim, Marsh, PRD90(2016)025027

 Courtesy: M. Rawlik
Axion-photon coupling – current exclusion plot

Axion mass range studied via photon coupling

Axion relation (Yellow band) $\frac{G_{a\gamma\gamma}}{m_a} \sim 10^{-9} \text{ GeV}^{-1} \text{ eV}$
Detecting axions via axion-photon coupling

Production and detection of axions in a terrestrial laboratory

Polarization experiments

Regeneration experiments

Detection of axions coming from external sources (Sun) - Helioscopes

Detection of axions present into the Galactic Halo - Haloscopes

Comparison

Lab Experiments
- Axion Like Particle
- Wide band experiment
- Optical photons
- Model independent
- Low axion flux
- Low sensitivity to alps coupling

Helioscopes
- ALPS & QCD Axion
- Wide band experiment
- X rays photons
- Model dependent
- Medium axion flux
- Good sensitivity to alps coupling

Haloscopes
- ALPS & QCD Axion
- Resonance experiment
- Microwave photons
- Strong model dependency
- High axion flux
- Reaches KSVZ axion model

(a) Diagram of a laboratory setup with a laser, magnets, and a detector. A signal is processed through an amplifier, mixer, and FFT (Fast Fourier Transform) to analyze the axion signal.
### Recent experiments (partial list)

#### Lab Experiments
- regeneration - optical
  - **ALPS, OSQAR** –
    - ALPS II upgrade in progress, expected large sensitivity improvement. **ALPS III foreseen**
  - regeneration - microwave
    - STAX
  - polarization
  - **PVLAS, BMV** – large improvement of current results difficult

### Helioscopes
- **SUMICO**
- **CAST** - presently with best limits, small upgrade possible (?)

#### Haloscopes
- **IAXO** – **large scale evolution of CAST**
- **Sikivie type** – μeV range
  - **ADMX**, WISPDMX, CAPP
- **Sikivie type** – higher masses
  - **ADMX-HF(Yale)**, ORGAN, ORPHEUS
  - Conversion @ surfaces
  - **MADMAX**

#### Other searches
- Search for **axion mediated long range forces**
  - ARIADNE – precision magnetometry, μeV to meV range
  - Experiments on spin precession in magnetic field, He-3 depolarization
- Search for anomalies in **gamma ray astronomy**
  - **MAGIC, HESS**, CTA – Cherenkov telescopes
Coupling to photons – Projected exclusion plot

- LSW (OSQAR) (ALPS)
- VMB (PVLAS)
- ALPS II
- ALPS III
- Haloscopes (CAST)
- IAXO
- Few meV scale QCD axion accessible to IAXO & ALPS-II
- Transparency ALP hints accessible to IAXO & ALPS-II
- Axion Coupling IG_{A\gamma\gamma} (GeV^{-1})
- Axion Mass m_A (eV)

1. LSW (OSQAR) (ALPS)
2. VMB (PVLAS)
3. ALPS II
4. ALPS III
5. Haloscopes (CAST)
6. IAXO
7. Few meV scale QCD axion accessible to IAXO & anomaly cooling hints
8. Transparency ALP hints accessible to IAXO & ALPS-II

Graphical representation of axion coupling versus axion mass.
IAXO experiment

- IAXO → legacy of CAST in the “axion helioscope frontier”:
- IAXO is unique technique to search part of the axion/ALP parameter space:
  → highly complementary with other efforts in the community
- Good technological synergies with magnet and x-ray optics communities:
  → important role for CERN
- Opportunity for other European centers to host the experiment (DESY?…)
- Additional physics opportunities (generic axion ALP infrastructure)

- Project in the TDR phase, roadmap to construction being defined, collaboration getting established; An intermediate stage (mini-IAXO) to test new magnet configuration and provide intermediate physics under consideration as part of TDR.
**ALPS-II, almost running**
just about to be started in the HERA tunnel:
( uses 20 HERA dipole magnets (5.3 T, 8.8 m magnetic length).

<table>
<thead>
<tr>
<th></th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPS IIa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(without magnets)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>risk assessments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALPS IIc</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**ALPS-III, conceptual idea:**
would dramatically increase the sensitivity for purely laboratory based experiments searching for axion-like particles by combining
> present day expertise in optics (ALPS II lessons learned from LIGO)
> present day expertise in detectors or very low photon fluxes (ALPS II)
with new dipole magnets under development at CERN for future accelerators.

A possible site for ALPS-III could be CERN
Expanding the ALPS exclusion limits in the “high” mass region

ALPS at (proton) beam dump facilities:

GeV-scale ALPs can be produced from the fusion of two coherently emitted photons
(Primakoff production)
ALPS contour limit from past and future beam-dump experiments in the “high” mass region (0.1-1.0) GeV

Dobrich et al., arXiv:1512.03069

(*) NA62++ (dump mode), 1 day
(**) NA62++ (dump mode) 1 month
Light Dark Matter and Light Mediators

511 keV motivated

what about here?

WIMP Range

Most money spent

Courtesy of M. Pospelov
As universe cools below DM mass, density decreases as $\exp\{-m/T\}$
- DM interacts with SM to stay in equilibrium
- eventually DM particles can't find each other to annihilate
- and a (minimal) DM abundance is left over the present day.

**Equilibrium reached easily with a tiny DM-SM coupling.**
DM annihilation cross-section necessary to obtain the relic density:
$$\sigma_v \text{ (relic)} = 3 \times 10^{-26} \text{ cm}^3/\text{s}$$

The equilibrium can be reached:
- either with traditional WIMP at TeV scale with Z mediator (excluded by current limits)
- or with light DM with light mediator (hence new forces).

Light mediators must be SM singlet, options limited by SM gauge invariance:
1) Vector Portal; 2) Scalar Portal; 3) Neutrino Portal
Light Dark Matter and Light Mediators: Vector Portal
Vector Portal: Dark Photons in visible modes

90% UL exclusion

Kinetic mixing $\epsilon \sim 10^{-3}$-$10^{-4}$ motivated by theory (linked to GUT scale $\sim 10^{16}$ GeV) but other ranges are certainly viable…
Limits on the kinetic mixing of a hidden photon - ordinary photon: expanded scale

J. Jaeckel, arXiv:1303:1821
**Vector Portal:** a window for light dark matter current and proposed experiments searching for **Dark Photons**

**Searches for \( A' \rightarrow \text{visible states} \)**

<table>
<thead>
<tr>
<th>Name</th>
<th>Where</th>
<th>Source</th>
<th>Intensity</th>
<th>Production mode</th>
<th>Detection mode</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle-II</td>
<td>Super KEK-B</td>
<td>( e^+e^- \rightarrow T(3S) )</td>
<td>&gt; 100 fb(^{-1}) @ T(3S)</td>
<td>( T(3S) \rightarrow \gamma A' )</td>
<td>( A' \rightarrow e^+e^- , \mu^+\mu^- )</td>
<td>Commis. 2018</td>
</tr>
<tr>
<td>Apex</td>
<td>JLAB</td>
<td>( e^- , 2 \text{ GeV} )</td>
<td>( 10^9 \text{ EOT (W)} )</td>
<td>( A'\text{-strahlung} )</td>
<td>( A' \rightarrow e^+e^- )</td>
<td>Commis. 2018</td>
</tr>
<tr>
<td>HPS</td>
<td>CEBAF12 @ JLAB</td>
<td>( e^- , 1-2 \text{ GeV} )</td>
<td>( 10^{14} \text{ EOT (W)} )</td>
<td>( A'\text{-strahlung} )</td>
<td>( A' \rightarrow e^+e^- )</td>
<td>Commis. 2020</td>
</tr>
<tr>
<td>MAGIX</td>
<td>MESA @ Mainz</td>
<td>( e^- , 155 \text{ MeV} )</td>
<td>( 10^{16} \text{ EOT (Xe gas)} )</td>
<td>( A'\text{-strahlung} )</td>
<td>( A' \rightarrow e^+e^- )</td>
<td>Commis. 2017</td>
</tr>
<tr>
<td>Mu3e</td>
<td>( \pi E5 ) @ PSI</td>
<td>( \mu^- , 28 \text{ MeV} )</td>
<td>( 10^{15-16} )</td>
<td>( \mu \rightarrow \nu\nu A' )</td>
<td>( A' \rightarrow e^+e^- )</td>
<td>Commis. 2017</td>
</tr>
<tr>
<td>ATLAS/CMS</td>
<td>LHC @ CERN</td>
<td>( pp, 8, 13 \text{ TeV} )</td>
<td>few fb(^{-1})</td>
<td>( H \rightarrow 4l + \text{MET} )</td>
<td>( A' \rightarrow \mu^+\mu^- )</td>
<td>Running 2016-20</td>
</tr>
<tr>
<td>LHCb</td>
<td>LHC @ CERN</td>
<td>( pp, 13 \text{ TeV} )</td>
<td>15 fb(^{-1})</td>
<td>( D^+ \rightarrow D A' )</td>
<td>( A' \rightarrow e^+e^- , \mu^+\mu^- )</td>
<td>Running</td>
</tr>
<tr>
<td>NA62</td>
<td>APS @ CERN</td>
<td>( p, 400 \text{ GeV} )</td>
<td>( 2 \times 10^{18} \text{ POT} )</td>
<td>Meson, ( A'\text{-strahlung} )</td>
<td>( A' \rightarrow e^+e^- , \mu^+\mu^- )</td>
<td>Running 2018</td>
</tr>
<tr>
<td>SeaQuest</td>
<td>Main Inj. @ FNAL</td>
<td>( p, 120 \text{ TeV} )</td>
<td>1.5</td>
<td>Meson, ( A'\text{-strahlung} )</td>
<td>( A' \rightarrow \mu^+\mu^- )</td>
<td>Proposed 2017-19</td>
</tr>
<tr>
<td>SHiP</td>
<td>APS @ CERN</td>
<td>( p, 400 \text{ GeV} )</td>
<td>( 2 \times 10^{20} \text{ POT} )</td>
<td>Meson, ( A'\text{-strahlung} )</td>
<td>( A' \rightarrow e^+e^- , \mu^+\mu^- )</td>
<td>Proposed 2026</td>
</tr>
</tbody>
</table>

**Searches for \( A' \rightarrow \text{Light Dark Matter (invisible states)} \)**

**Direct detection of LDM via the process \( A' \rightarrow \text{LDM} \rightarrow \text{LDM scattering in the detector} \)**

<table>
<thead>
<tr>
<th>Name</th>
<th>Where</th>
<th>Source</th>
<th>Intensity</th>
<th>Production mode</th>
<th>Detection mode</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBND</td>
<td>FNAL</td>
<td>( e^- , 4 \text{ GeV} )</td>
<td>( e^-N \rightarrow e^-N A' )</td>
<td>( 10^{11-12} \text{ EOT} )</td>
<td>detect ( e^- + E_{\text{miss}} )</td>
<td>Running 2016-17</td>
</tr>
<tr>
<td>T2K</td>
<td>Tokai-Kamioka</td>
<td>( p, 9 \text{ GeV} )</td>
<td>( 2 \times 10^{20} \text{ POT} )</td>
<td>Meson, ( A'\text{-strahlung} )</td>
<td>detect ( \phi @ 110 \text{ m} )</td>
<td>Under study</td>
</tr>
<tr>
<td>COHERENT</td>
<td>SNS @ Oak Ridge</td>
<td>( p, 1 \text{ GeV} )</td>
<td>( 10^{23} \text{ POT} )</td>
<td>Meson, ( A'\text{-strahlung} )</td>
<td>detect ( \phi @ 20 \text{ m} 2^-\text{OA} )</td>
<td>Proposed</td>
</tr>
<tr>
<td>SHiP</td>
<td>APS @ CERN</td>
<td>( p, 400 \text{ GeV} )</td>
<td>( 2 \times 10^{20} \text{ POT} )</td>
<td>Meson, ( A'\text{-strahlung} )</td>
<td>detect ( \phi @ 100 \text{ m} )</td>
<td>Proposed 2026</td>
</tr>
<tr>
<td>LBNF</td>
<td>DUNE @ FNAL</td>
<td>( p, 120 \text{ GeV} )</td>
<td>( 3 \times 10^{21} \text{ POT} )</td>
<td>Meson, ( A'\text{-strahlung} )</td>
<td>detect ( \phi @ 500 \text{ m} )</td>
<td>Under study 2020</td>
</tr>
</tbody>
</table>

Experiments proposed at CERN: SHiP, NA62++ (proton dump), NA64 (e- dump)
- **SHiP** can search simultaneously for visible decays of DP and direct LDM observation.
- **NA64 & NA62** can search for visible and invisible decays with different methods.
Fixed Target Experiments @ CERN

Highest energy proton beam delivered for fixed target experiments in the world
How to search for Hidden Particles in a beam dump?

Light and feebly-interacting particles can be originated by the decay of beauty, charm and strange hadrons and by photons produced in the interaction of protons with a target. Their couplings to SM particles are very suppressed leading to expected production rates of $10^{-10}$ or less. As the charm and beauty cross-sections increase steeply with the energy, a high-intensity, high-energy proton beam (and secondary beams) is needed to improve over the current results:

→To date the world best line to produce high intensity fluxes of beauty and charm hadrons and photons through the interactions of protons on a high-Z target is a 400 GeV/c proton beam line extracted from the CERN SPS

The smallness of the couplings implies that the hidden sector mediators are also very long-lived compared to the bulk of the SM particles:

an HNL with $m=1$ GeV has $\tau\sim10^{-5}$ sec and an average flight distance of $>10$ km at the SPS energies.

→The decays to SM particles can optimally be detected only using experiment with decay volume tens of meters long followed by a spectrometer with particle identification capabilities.
Dedicated experiment to explore Hidden Sector models with vector, scalar, neutrino, axion-like SM portals (and other):

Strategy: “zero background” experiment as close as possible to target:
- high A,Z target to maximize production of D,B, photons while stopping π,K before decay to reduce ν,µ –flux;
- Active muon shield and decay volume in vacuum;
- Vetoes for ν- and µ- interactions;

Status: Proposal
2016-2018: Comprehensive Design Study as input to the European Strategy
Data taking: 2026++
Fixed Target Experiments @ CERN: SHiP

- SHiP is the **only place** to search for Hidden Sector particles in the mass range of up to O(10 GeV) in **zero-background conditions** (powerful muon shield!);

- SHiP is sensitive to a **wide range of final states**, both fully and partially reconstructed with leptons and charged or neutral hadrons in final state:

  e.g: Hidden Particle $\rightarrow \mu \mu \nu$, $K^- l^+ \pi^0$, etc

- Spectrometer system to measure momenta and identify vertex, combination of calorimeter and muon systems allow for $e/\mu$ and $\pi/\mu$ separation

- Can **simultaneously search for Hidden Particle decays to SM** sector, as well as for the **DM candidate of the Hidden sector** in the region between 10 MeV – 1 GeV where direct searches are less sensitive, via the process:
Dark Photons in invisible modes: direct detection of LDM current and future sensitivities

De Niverville, Chen, Pospelov, Ritz, arXiv:1609.01770v3

(plot to be updated with recent BaBar & NA64 results)
Fixed Target Experiments @ CERN: NA62

400 GeV proton beam; $10^{12}$ pot/sec; $\sim$(1-2) $10^{18}$ pot/year;
Current status: running with a $K^+$ beam;
goal: measure of $\text{BR}(K^+ \rightarrow \pi^+ \nu \text{ anti-}\nu)$ with 10% accuracy by 2018
Physics at NA62++ in Run 3

A rich field to be explored during Run3:

1. Present setup for $K^+$ beam and dedicated triggers: complete LFV/LNV high-sensitivity studies based on $K^+\pi^0$:

   $$K^+ \rightarrow \pi^+\mu^\pm e^\mp, \quad K^+ \rightarrow \pi^-\mu^\pm e^\mp, \quad K^+ \rightarrow \pi^0\mu^+\mu^- (+\text{radiative modes})$$

   $$\pi^0 \rightarrow \mu e, \quad 3\gamma, \quad 4\gamma, \quad ee, \quad eee$$

2. Year-long run in “beam-dump” mode, new program of NP searches for MeV-GeV mass hidden-sector candidates: Dark photons, Heavy neutral leptons, Dark Scalars, Axions/ALP’s, etc.
Dark Photons in visible modes: past and future sensitivities

\[ A' \rightarrow \text{visible modes} \]

90% UL exclusion

\[ m(A') \ (\text{MeV/c}^2) \]

- Belle II, 50 ab \(^{-1}\), 2024
- LHCb, 15 fb \(^{-1}\), 2023
- HPS, 2016-2020
- APEX, 2018+
- SeaQuest, 2017-2019
- VEPP, proposed
- Mu3e, 2017+
- MESA, 2020+
- SHiP, 2026++
- NA62, mesons&brem., 2021+


NA62++ in dump mode (only mesons & brem.)
Fixed Target Experiments @ CERN: NA64

Approved in March’16 for dark photon to invisible searches with 100 GeV e⁻ beam; electron beam dump, search for missing energy.

Current status: running
Dark Photons in invisible modes: past and future sensitivities

Searches for $A' \rightarrow$ Light Dark Matter (invisible states)

- $10^{-2}$
- $10^{-3}$
- $10^{-4}$
- $10^{-5}$

$\epsilon$

$90\%$ UL exclusion

$(g-2)_e \pm 5 \sigma$ (favored)

NA64 - $10^9$ eot (PRL 2017)

NA64 - $10^{10}$ eot (2016)

NA64 - $10^{11}$ eot (2017)

NA64 - $10^{12}$ eot (2018 and >)

NA64 with $100$ GeV $e$- beam

NA62 in kaon mode

BaBar (2017)

arXiv:1702.03327

NA62 (30\% of nominal year)

$\sigma_{(g-2)}^5 \pm \mu$

$e(g-2)$

$\nu$

NA64 - $10^9$ eot (2017)

$\sigma_{5}^{\pm \mu}$
Research program of NA64++

1) **Electron beam, 100 GeV**
- Search for invisible (e+e-) decays of dark photon $A' \rightarrow \text{invisible}(e+e-)$
- Search for the new boson $X \rightarrow e^+e^-$ from 8Be excess.
- Search for any light particles in active electron beam dump
- Search for millicharged particles

2) **Muon beam, 150 GeV**
- Search for $L_\mu - L_\tau Z'$ boson. Could explain the $(g-2)_\mu$ anomaly
- Search for light scalars from dark sector
- Search for $\mu \rightarrow \tau$ conversion (LFV)

3) **Pion and kaon beams, 50 GeV**
- Search for invisible decays $K_{L,S} \rightarrow \nu\nu$. Complementary to $K_L \rightarrow \pi^0 \nu\nu$,
  Bell-Steinberger Unitarity, heavy neutrino.
- Search for $\pi^0, \eta, \eta' \rightarrow \text{invisible decays}, \sim \text{sub-GeV DM}$

4) **Proton beam, 250 –300 GeV**
- Search for sub-GeV – GeV range particles coupled to quarks, $\sim \text{GeV DM}$
- Search for axion-like particles

The searches for $A' \rightarrow \text{invisible decays, new light states coupled to muon, invisible decays of } K_{L,S} \text{ and } \eta, \eta' \text{ are highly competitive and could provide the most precise probe of dark sector physics.}$
Light Dark Matter and Light Mediators: Scalar Portal
Dark Scalars in visible modes: past and future sensitivities

Secluded annihilation via mediators (only possibility compatible with CMB and rare mesons decays constraints), mediators decay to SM particles

\[ g_{\chi} = \sin \theta \]

NA64 can search for Dark Scalars in the reaction: 
\[ e^+ e^- \rightarrow S, S \rightarrow \text{invisible} \]
Results from the 2016 data sample are being finalized.

Baryogenesis (through leptogenesis), Light Dark Matter and origin of neutrino masses and oscillations: the neutrino portal

Eg: vMSM (M. Shaposhnikov et al.):
$N_1$ keV cold-DM candidate; CP-violating resonant oscillations between $N_2$ and $N_3$ produce sufficient lepton asymmetry that then transforms in baryon asymmetry
Heavy Neutral Leptons: past and future sensitivities

\[ |U_{\mu}|^2, U_{\mu} \cdot U_{\tau} = 1:16:3.8 \]

Normal hierarchy of active neutrino masses

See A. Alekhin et al., The SHiP Physics case, arXiv:1504.04855 and references therein

NB: 1 SHiP year ~ 500 NA62 years
Rare mesons decays as a probe for New Physics
**K → πν̅ν̅: an overview**

Extremely rare decays with rates very precisely predicted in SM:

<table>
<thead>
<tr>
<th>SM predicted rates*</th>
<th>Experimental status</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K^+ → π^+ν̅ν̅)</td>
<td>(BR = (8.4 \pm 1.0) \times 10^{-11})</td>
</tr>
<tr>
<td>(K_L → π^0ν̅ν̅)</td>
<td>(BR = (3.4 \pm 0.6) \times 10^{-11})</td>
</tr>
</tbody>
</table>

7 evts from BNL787
BR to 10% from NA62 by 2018

Only limits at present
KOTO (JPARC): ~few SM events by 2021

New physics affects \(K^+\) and \(K_L\) differently
Measurements of both can discriminate among NP scenarios

**K\(_L\)EVER sensitivity**
5 years starting Run 4
60 SM \(K_L → π^0ν̅ν̅\) events
S/B \~ 1

\(BR(K_L → π^0ν̅ν̅) \sim 20\%\)

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Buras, Buttazzo, Knegjens
JHEP 1511

Buras et al, JHEP 1511*
**K_{L}EVER**, an experiment to measure $K_{L} \rightarrow \pi^{0} \nu \bar{\nu}$

For 60 SM events, need:

5 x 10^{19} \text{ pot}

E.g. 2 x 10^{13} \text{ ppp/16.8 s x 5 yrs}

$\langle p_{K} \rangle = 70 \text{ GeV}$ for decays in FV

Photons from $K_{L} \rightarrow \pi^{0} \pi^{0}$ boosted forward for easier vetoing

Much higher energy than KOTO: Complementary approach

**Main detector/veto systems:**

- **AFC**: Active final collimator/upstream veto
- **LAV1-26**: Large-angle vetoes (26 stations)
- **LKr**: NA48 liquid-krypton calorimeter
- **IRC/SAC**: Small-angle vetoes
- **CPV**: Charged-particle veto
Main competitor: $K_L \rightarrow \pi^0\nu\nu$ at J-PARC

Primary beam: $30$ GeV $p$

$\langle p_K \rangle = 2.1$ GeV

Current status:

- Reached $42$ kW of slow-extracted beam power in 2015
- Preliminary results: $10\%$ of 2015 data (signal box not unblinded yet)
  
  SES = $5.9 \times 10^{-9}$, exp. bkg: $0.17$
- Expect to reach SM sensitivity by 2021

KOTO step-2 upgrade:

- strong intention to **upgrade to o(100) events sensitivity** (but no proposal yet...)
- explore machine (>100 kW) and detector upgrades to increase sensitivity;
- Indicative time scale for data taking: 2025++
Conclusions

Experimental proposals considered in the BSM WG focus on low-energy processes that can answer in a complementary way the same fundamental questions of present (or future) high-energy accelerator facilities;

Projects presented at CERN so far:
- SHiP, NA62++, NA64++, KLEVER, IAXO, LSW, EDM cover a wealth of highly-justified physics cases where CERN can play a leading and unique role.

The aim of the BSM WG in the coming two years will be to analyse in detail the proposals and understand how they are placed in the world-wide physics landscape.
….We are beginning a two-year journey...

Thank you for your attention!