The aim of the workshop is to explore the opportunities offered by the CERN accelerator complex and infrastructure to get new insights into some of today’s outstanding questions in particle physics through projects complementary to high-energy colliders and other initiatives in the world. The focus is on fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that may require different types of experiments. The kickoff workshop is intended to stimulate new ideas for such projects …
Mandate of the "Physics Beyond Colliders" Study Group

CERN Management wishes to launch an exploratory study aimed at exploiting the full scientific potential of its accelerator complex and other scientific infrastructure through projects complementary to the LHC and HL-LHC and to possible future colliders (HE-LHC, CLIC, FCC). These projects would target fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that require different types of beams and experiments.

This study should provide input for the future of CERN’s scientific diversity programme, which today consists of several facilities and experiments at the Booster, PS and SPS, over the period until ~2040. Complementarity with similar initiatives elsewhere in the world should be sought, so as to optimize the resources of the discipline globally, create synergies with other laboratories and institutions, and attract the international community.

Scientific goal

The main goal of the Study Group is to explore the opportunities offered by the CERN accelerator complex to address some of today’s outstanding questions in particle physics through experiments complementary to high-energy colliders and other initiatives in the world. These experiments would typically: (i) enrich and diversify the CERN scientific program, (ii) exploit the unique opportunities offered by CERN’s accelerator complex and scientific infrastructure, (iii) complement the laboratory’s collider programme (LHC, HL-LHC and possible future colliders). Examples of physics objectives include searches for rare processes and very-weakly interacting particles, measurements of electric dipole moments, etc.

Structure of the Study Group and deliverables

The group will be led by three coordinators representing the scientific communities of accelerator, experimental, and theoretical particle physics: Joerg Jaeckel (Heidelberg), Mike Lamont (CERN), Claude Vallée (CPPM, Marseille).

Following consultation with the relevant communities, they will define the structure and the main activities of the group and appoint conveners of thematic working groups as needed. They will call a kick-off meeting in 2016, organize regular meetings, and monitor the overall scientific activity. The scientific findings will be collected in a report to be delivered by the end of 2018. This document will also serve as input to the next update of the European Strategy for Particle Physics.
CERN 20-year schedule

**Long Shutdown (LS)**: 24 months + 3 months BC
- LS2 starting in 2019
- LS3 LHC: starting in 2024
  - Injectors: in 2025

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<td>Q1</td>
<td>Q2</td>
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<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
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</table>

**Run 2**
- 3–14 TeV: $1.7 \times 10^{34}, 300/fb$

**Run 3**
- LS 3

**Run 4**
- LS 4

**Run 5**
- LS 5

**14 TeV: $2 \times 10^{34}, 3000/fb$**

*outline LHC schedule out to 2035 presented by Frederick Bordry to the SPC and FC June 2015*
Fermilab

2013

Project X
Accelerator Reference Design, Physics Opportunities, Broader Impacts

Edited by Stuart D. Henderson, Stephen D. Holmes, Andreas S. Kronfeld, and Robert S. Tschirhart
Setting the scene
Theorists’ motivations, ideas, wishes
Accelerator & infrastructure opportunities at CERN
Potential future of existing programs
New experimental ideas

Full list of submitted abstracts
We know there is new physics.
We don’t know where it is.
We need to explore as broadly as possible.

Optimize the resources of the discipline globally.

« Diversity and scale diversity »
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
<th>Comment</th>
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<tbody>
<tr>
<td>AD2 (ATRAP)</td>
<td>Precise laser or microwave spectroscopy of trapped antihydrogen</td>
<td></td>
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<tr>
<td>AD3 (ASACUSA)</td>
<td>Atomic Spectroscopy And Collisions Using Slow Antiprotons</td>
<td></td>
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<tr>
<td>AD4 (ACE)</td>
<td>Relative Biological Effectiveness of Antiproton Annihilation</td>
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<td>AD5 (ALPHA)</td>
<td>Antihydrogen spectroscopy</td>
<td></td>
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<tr>
<td>AD6 (AEGIS)</td>
<td>Testing gravity with antimatter</td>
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<tr>
<td>AD7 (GBAR)</td>
<td>Testing gravity with antimatter</td>
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<tr>
<td>AD8 (BASE)</td>
<td>Comparisons of the fundamental properties of antiprotons and protons</td>
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<tr>
<td>PS212 (DIRAC)</td>
<td>Observation of mesonic atoms and tests of low energy QCD</td>
<td>finished data taking</td>
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<tr>
<td>PS215 (CLOUD)</td>
<td>Influence of galactic cosmic rays (GCRs) on aerosols and clouds</td>
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<tr>
<td>NA58 (COMPASS)</td>
<td>Study of hadron structure and hadron spectroscopy</td>
<td></td>
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<tr>
<td>NA61 (SHINE)</td>
<td>Strong interactions, neutrinos and cosmic rays</td>
<td></td>
</tr>
<tr>
<td>NA62</td>
<td>Measuring rare kaon decays</td>
<td></td>
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<tr>
<td>NA63</td>
<td>Electromagnetic Processes in strong Crystalline Fields</td>
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<tr>
<td>NA64</td>
<td>Search for dark sectors in missing energy events</td>
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<tr>
<td>UA9 (CRYSTAL)</td>
<td>Crystal Channeling</td>
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<tr>
<td>AWAKE</td>
<td>Advanced Proton-Driven Plasma Wakefield Acceleration Experiment</td>
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<tr>
<td>WA104 (NP01)</td>
<td>Refurbishment of the ICARUS Detector</td>
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<tr>
<td>ProtoDUNE-DP (NP02)</td>
<td>Neutrino Facility</td>
<td></td>
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<tr>
<td>ProtoDUNE-SP (NP04)</td>
<td>Prototype of a Double-Phase Liquid Argon TPC for DUNE</td>
<td></td>
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<tr>
<td>Baby MIND (NP05)</td>
<td>Prototype of a Magnetized Iron Neutrino Detector</td>
<td></td>
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<tr>
<td>CAST</td>
<td>non-accel. Experiments</td>
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<tr>
<td>OSQAR</td>
<td>Search for Axions and Axion-like particles</td>
<td></td>
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<tr>
<td>CNGS1 (OPERA)</td>
<td>Neutrino oscillation experiment at LNGS</td>
<td>finished data taking</td>
</tr>
<tr>
<td>CNGS2 (ICARUS)</td>
<td>Neutrino oscillation experiment at LNGS</td>
<td>finished data taking</td>
</tr>
</tbody>
</table>
The **neutrino platform** at CERN is currently constructed to develop and prototype the next generation of neutrino Liquid Argon (LAr) detectors. The neutrino platform at CERN is currently constructed to develop and prototype the next generation of neutrino Liquid Argon (LAr) detectors. The Cryostat for double phase LAr TPC prototype (ProtoDUNE-DP) and the Cryostat for single phase LAr TPC prototype (ProtoDUNE-SP) are currently under construction. The Cryostat for double phase LAr TPC prototype (ProtoDUNE-DP) and the Cryostat for single phase LAr TPC prototype (ProtoDUNE-SP) are currently under construction.

**Beam characteristics:**

- **H2 extension:** 1(0.5)÷12 GeV tertiary beam.
- **H4 extension:** 1(0.2)÷7(10)GeV tertiary beam.

**VLE beams:**

- Mixed hadrons ($\pi^\pm, \mu^\pm, K^\pm, p$), ~pure electron ($e^\pm$) beams.

**Secondary beam of 80 GeV ($\pi/p$, or $e$) produces the tertiary low-energy beams on a secondary target.**
Fermilab Accelerator Complex

Main Injector

Recycler Ring

Low-Energy Neutrino Experiments

High-Energy Neutrino Experiments

Fixed-Target Experiments, Test Beam Facility

Booster

Linac

Ion Source

Muon Delivery Ring

Muon Experiments

Link to experiments & projects
Theorists’ motivations, ideas, wishes

M. Shaposhnikov · New physics below the Fermi scale
M. Pospelov · EDMs & precision \((g-2)_\mu\)
A. Ringwald · Axions, ALPs: Astro/cosmo motivations & tests
C. Burrage · Detecting dark energy with atom interferometry
P. Graham · Precision measurement for particle physics
The LHC results must be reconciled with the evidence for new physics beyond the Standard Model:

- Observations of neutrino oscillations (in the SM neutrinos are massless and do not oscillate)
- Evidence for Dark Matter (SM does not have particle physics candidate for DM).
- No antimatter in the Universe in amounts comparable with matter (baryon asymmetry of the Universe is too small in the SM)
- Cosmological inflation is absent in canonical variant of the SM
- Accelerated expansion of the Universe (?) - though can be “explained” by a cosmological constant.
- Marginal evidence (less than $2\sigma$) for the SM vacuum metastability given uncertainties in relation between Monte-Carlo top mass and the top quark Yukawa coupling
Energy scale of new physics from experiment or theory:

- Neutrino masses and oscillations: the masses of right-handed see-saw neutrinos can vary from $\mathcal{O}(1)$ eV to $\mathcal{O}(10^{15})$ GeV

- Dark matter, absent in the SM: the masses of DM particles can be as small as $\mathcal{O}(10^{-22})$ eV (super-light scalar fields) or as large as $\mathcal{O}(10^{20})$ GeV (wimpzillas, Q-balls).

- Baryogenesis, absent in the SM: the masses of new particles, responsible for baryogenesis (e.g. right-handed neutrinos), can be as small as $\mathcal{O}(10)$ MeV or as large as $\mathcal{O}(10^{15})$ GeV

- Higgs mass hierarchy: models related to SUSY, composite Higgs, large extra dimensions require the presence of new physics right above the Fermi scale, whereas the models based on scale invariance (quantum or classical) may require the absence of new physics between the Fermi and Planck scales

Hidden particles: vSM as example
EDMs and New Physics

- EDM observable \( \sim \) 
  \( \sim [\text{some QCD/atomic/nuclear matrix elements}] \times \) 
  
  SM mass scale \((m_e, m_q) \times (\text{CP phase})_{\text{NP}}/\Lambda_{\text{NP}}^2\) 

With some amount of work all matrix elements can be fixed. For the flavor blind NP, \(d_i \sim m_i\). Unfortunately, we have no idea where actually \(\Lambda_{\text{NP}}\) is !!!

100 GeV, 1 TeV, 10 TeV, 100 TeV, 1000 TeV … GUT scale … \(M_P\)

After the LHC did not find the abundance of new states immediately above EW scale, “guessing EDMs” became even more difficult. What shall we put in the denominator? E.g. \((\text{TeV})^2\) or \((\text{PeV})^2\)?
New physics in \((g-2)_\mu\)

The New Physics contribution could be \(\sim a_{\mu}^{\text{NP}} = (26.1\pm8) \times 10^{-10}\).
This is \(\sim\) twice the size of the SM electroweak contribution, and in these units \emph{not small}.

Weak scale solutions.
Main challenges are to create such a large shift of \(a_{\mu}\) and stay undetected at LEP, Tevatron and LHC experiments

Sub-GeV scale solutions.
These must be additional electrically \emph{neutral} states, with small couplings to normal matter that somehow escape detection

\begin{itemize}
\item Many PBC opportunities
\end{itemize}
Axions & ALPs: astrophysical hints

Excess energy loss in stars
  = ALP emission?

Anomalous gamma transparency
  = photon–ALP conversion in magnetic fields?
Accelerator & infrastructure opportunities at CERN

G. Rumolo · Proton throughput (injector upgrades)
L. Gatignon · Beams in North & East Areas
M. Calviani · SPS beam dump facility
M. A. Fraser · SPS slow extraction
A. Lombardi · Proton drivers
S. Redaeli · Multi-TeV beam channeling …
W. Scandale · Bent-crystal baryon magnetic moment
M. Bai · EDM options
K. Long · nuSTORM
LHC Injector Upgrades

Goal for LS2: double brightness and intensity of LHC beams (<0.1% of proton delivery through HL-LHC)
LHC Injector Upgrades

Goal for LS2: double brightness and intensity of LHC beams (<0.1% of proton delivery through HL-LHC)

<table>
<thead>
<tr>
<th>Facility</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
<td>$3 \times 10^{17} \text{ p/y}$</td>
</tr>
<tr>
<td>SPS Beam Preparation</td>
<td>$\geq 3 \times 10^{17} \text{ p/y}$</td>
</tr>
<tr>
<td>nTOF</td>
<td>$1.9 \times 10^{19} \text{ p/y}$</td>
</tr>
<tr>
<td>Antiproton area</td>
<td>$2-4 \times 10^{18} \text{ p/y}$</td>
</tr>
<tr>
<td>East area</td>
<td>$10^{18} \text{ p/y}$</td>
</tr>
<tr>
<td>HiRadMat</td>
<td>$2 \times 10^{16} \text{ p/y}$</td>
</tr>
<tr>
<td>AWAKE</td>
<td>$10^{17} \text{ p/y}$</td>
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<tr>
<td>Beam Dump Facility (355 kW)</td>
<td>$4 \times 10^{19} \text{ p/y}$</td>
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<tr>
<td>North Area Beams</td>
<td>$10^{19} \text{ p/y}$</td>
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</table>
**Very low emittance muon beam using positron beam on target**

M. Antonelli, M. Biagini, M. Boscolo, A. Variola INFN/LNF, Frascati, Italy
P. Raimondi, ESRF Grenoble, France
G. Cavoto INFN Roma, Italy E. Bagli INFN Ferrara, Italy

**Abstract**

Muon beams are customarily obtained via $K/\pi$ decays produced in proton interaction on target. In this paper we investigate the possibility to produce low emittance muon beams from electron-positron collisions at centre-of-mass energy just above the $\mu^+\mu^-$ production threshold with maximal beam energy asymmetry, corresponding to a positron beam of about 45 GeV interacting on electrons on target. Performances on both amorphous and crystal target are presented, and the general scheme for the muon production will be given. We present the main features of this scheme with a first preliminary evaluation of the performances that could be achieved by a multi-TeV muon collider.

The very small emittance could allow high luminosity with modest muon fluxes reducing both the machine background in the experiments and more importantly the activation risks due to neutrino interactions.
nuSTORM overview

- Fast extraction at >~ 100 GeV from:
  - Main Injector at FNAL or SPS at CERN
- Conventional pion production and capture (horn)
  - Quadrupole transport of pions to decay ring
- “Stochastic injection” in “orbit combination section”
  - 52% pions decay to muons before first arc
- Neutrino flux:
  - $\nu_\mu$ flash from pions (and kaons) passing through injection straight
  - $\nu_\mu$ and $\nu_e$ from muons; around 30 turns in one “lifetime”

$10^{18}$ decays/y:

\[
\begin{align*}
\mu^+ & \rightarrow e^+ \nu_e \bar{\nu}_\mu \\
\mu^- & \rightarrow e^- \bar{\nu}_e \nu_\mu
\end{align*}
\]
Potential future of existing programs

O. Denisov · COMPASS: hadron structure & spectroscopy
M. Gazdzicki · NA61: SHINE beyond 2020
T. Spadaro · Perspectives from NA62 (K decay)
S. Ulmer · Fundamental physics with antimatter
K. Blaum · Probing the standard model with radionuclides
Universal and flexible apparatus. 
Most important features of the two-stage COMPASS Spectrometer:

1. Muon, electron or hadron beams with the momentum range 20-250 GeV and intensities up to $10^8$ particles per second
2. Solid state polarised targets ($\text{NH}_3$ or $^6\text{LiD}$) as well as liquid hydrogen target and nuclear targets
3. Advanced tracking (350 planes) and powerful PiD systems (Muon Walls, Calorimeters, RICH), new DAQ

Long term plans
- RF separated beam
- Spectroscopy
- Drell-Yan
- Exclusive measurements with muon and hadron beams
COMPASS QCD facility at SPS M2 beam line (CERN)
(secondary hadron and lepton beams)

Exotic state, chiral dynamics

Hadron Spectroscopy & Polarisability

3D hadron structure (TMDs, GPDs), spin decomposition

Polarised SIDIS

Polarised Drell-Yan

COMPASS-I
1997-2011

COMPASS-II
2012-2018

DVCS (GPDs) + unp. SIDIS
SPS Heavy-Ion and Neutrino Experiment

**NA61/SHINE: Physics and Facility**

**NA61/SHINE** - Unique multipurpose facility for measurements of hadron production in $h+p$, $h+A$ and $A+A$ interactions at $13A - 150A \ (400)$ GeV/c.

Approved data taking programme (2009-2018) covers measurements for physics of:
- strong interactions
- neutrinos
- cosmic rays
- **HADRON PRODUCTION MEASUREMENTS FOR T2K**
  - DATA TAKING: COMPLETED
  - ANALYSIS: ALMOST COMPLETED

- **HADRON PRODUCTION MEASUREMENTS FOR FERMILAB**
  - NEUTRINO BEAMS
  - DATA TAKING: STARTS NOW
  - ANALYSIS: TO BE STARTED
- A large acceptance (~50%) hadron spectrometer
- Beam particles measured by counters and MWPCs
- Charge particles measured by 5 (+2) TPCs
- PID via $dE/dx$ in TPCs and ToF in 3 ToF detectors
- Energy of projectile spectators measured in PSD
- Precise vertexing via small acceptance vertex detector
NA62: rare $K$ decays

Introduction

NA62 experiment approved to run until LS2

- **main goal**: measuring the BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$) with 10% accuracy;
- a broad physics program: searches for LFV/LNV modes, hidden sector particles

Present talk covers possible plans for dedicated searches in **Run3**

**Current Run**

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<td>Run 2</td>
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<td>LS2</td>
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**Run4**

- **LS2**: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, LNV/LFV decays, hidden sector searches in kaon decays
- **This talk**: NA62: rare $K$ decays
NA62 experiment: the goal

$K \to \pi \nu \bar{\nu}$ decays: FCNC $s-d$ loops, theoretically clean, sensitive to various NP models


$$\text{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \left( \frac{|V_{cb}|}{0.0407} \right)^{2.8} \left( \frac{\gamma}{73.2^\circ} \right)^{0.74} = (8.4 \pm 1.0) \cdot 10^{-11}$$

$$\text{BR}(K_L \to \pi^0 \nu \bar{\nu}) = (3.36 \pm 0.05) \cdot 10^{-11} \left( \frac{|V_{ub}|}{0.00388} \right)^2 \left( \frac{|V_{cb}|}{0.0407} \right)^2 \left( \frac{\sin \gamma}{\sin 73.2^\circ} \right)^2 = (3.4 \pm 0.6) \cdot 10^{-11}$$

**Experimental status:**

- $\text{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$ [Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)]
- $\text{BR}(K_L \to \pi^0 \nu \bar{\nu}) < 2.6 \times 10^{-8}$ (90% C.L.) [Phys. Rev. D 81, 072004 (2010)]

NA62 goal: measure $\text{BR}(K^+ \to \pi^+ \nu \bar{\nu})$ with $O(10\%)$ total uncertainty

7/9/2016

PBC Kickoff Meeting - CERN - T. Spadaro
Physics at NA62 in Run 3

A rich field to be explored with minimal/no upgrades to the present setup

1. Present setup for $K^+$ beam + dedicated triggers: complete LFV/LNV high-sensitivity studies based on $K^+ / \pi^0$:
   
   $K^+ \to \pi^+ \mu^+ e^\pm$, $K^+ \to \pi^- \mu^+ e^+$, $K^+ \to \pi^- e^+ e^+$, $K^+ \to \pi^+ \mu^+ \mu^+ (+ \text{radiative modes})$
   
   $\pi^0 \to \mu e, 3\gamma, 4\gamma, ee, eeee$

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, Axions/ALP’s, etc.

---

**Current Run**

*NA62: $K^+ \to \pi^+ \nu \nu$, LNV/LFV decays, hidden sector searches in K decays*

**Run 3**

*LFV/LNV @ ultimate sensitivity, hidden sector searches (beam dump)*

---

7/9/2016  PBC Kickoff Meeting - CERN - T. Spadaro
Fundamental Physics with Antimatter

Representing the AD Community

60 Research Institutes/Universities – 339 Researchers – 6 Collaborations

CPT tests, equivalence principle, anti-H spectroscopy
Pioneering Highlights

Production of 11(2) relativistic antihydrogen atoms at LEAR (PS210) in 1995.


Comparison of the proton to antiproton charge to mass ratio at fractional precision of 90 p.p.t.

\[
\frac{Q_p}{M_p}/\frac{Q_p}{M_p} = -0.999'999'999'91(9)
\]


Convinced CERN to start the AD program.
Extra Low-Energy Antiproton Ring

ELENA

- Antiprotons are caught in Penning traps using degraders – 99.9% of particles are lost.
- ELENA provides antiprotons decelerated to 100keV – compared to the AD – at improved beam emittance.
- Degrading at low particle energies is much more efficient

<table>
<thead>
<tr>
<th>Experiment</th>
<th>ELENA Gain Factor</th>
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<tbody>
<tr>
<td>ALPHA</td>
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<tr>
<td>ATRAP</td>
<td>100</td>
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<tr>
<td>ASACUSA</td>
<td>10</td>
</tr>
<tr>
<td>AEgIS</td>
<td>100</td>
</tr>
</tbody>
</table>

- ELENA will be able to deliver beams almost simultaneously to all experiments resulting in an essential gain in total beam time for each experiment. This also opens up the possibility to accommodate an extra experimental zone

Provides bright future perspective for antiproton-physics at CERN
Standard-model tests with radionuclides

Locations
The ISOLDE radioactive beam facility

Decay spectroscopy
Coulomb excitation
Transfer reactions
Laser spectroscopy
Beta-NMR

Penning traps
Applications:
  Solid state
  Life Sciences

>500 users, about 100 institutions, >800 isotopes

238U → 1 GeV protons

201Fr
11Li
143Cs

Spallation
Fragmentation
Fission

(1) (2) (3) (4) (5) (6) (7)

(2/3): MINIBALL – REX
(4,5): COLLAPS/CRIS
(6): ISOLTRAP

(1): IDS
(2/3): MINIBALL – REX
(4,5): COLLAPS/CRIS
(6): ISOLTRAP
(7): ISOLTRAP

HRS
GPS
MEDICIS

1.4 GeV
1 GeV

protons
n
p

201Fr
11Li
143Cs

1 GeV protons

protons
1 GeV

238U
Radionuclides for the standard model and beyond

**CKM unitarity test through superallowed β-decay**

\[ V_{ud} (\text{nuclear } \beta\text{-decay}) = 0.97417(21) \]

\[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99978(55) \]

ν mass in \(^{163}\text{Ho}\) electron capture

**EDM search in (pear-shaped) \(^{255}\text{Ra}\)**
New Experimental Ideas

A. Golutvin · Search for Hidden Particles
S. Gninenko · NA64: Dark sector in missing-energy events
T. Bowcock · Proton EDM
M. Moulson · $K_L \rightarrow \pi^0\nu\bar{\nu}$ (NA62 evolution)
G. Venanzoni · Hadronic corrections to $a_\mu$ by $\mu e$ scattering
L. Nemenov · Dimeson atoms ($\pi, K$)–($\pi, K$)
G. Usai · QCD phase transitions with dileptons
M.W. Krasny · The Gamma Factory Initiative
J.-P. Lansberg · AFTER: TeV fixed-target beams
A. Stocchi · Crystals for short-lived baryon magnetic moments
M. Wing · AWAKE
**The SHiP experiment at SPS**

( as implemented in Geant4 for TP )

**“Zero background” experiment**
- Muon shield
- Surrounding Veto detectors

>5×10^{18} D, >10^{16} \tau, >10^{20} \gamma

for 2×10^{20} pot (in 5 years)

~150m

SHiP Technical Proposal: 1504.04956

*Search for Hidden Sector particles (decays in the decay volume)*

*Search for DM (scattering on atoms)*

*v_\tau physics (specific event topology)*

Hope approval 2020, begin running 2026
NA64 : Dark sector through missing energy (active beam dump)

Dark photons: invisible or $e^+e^-$
$L_\mu$–$L_T$ gauge boson in $\mu$ beam
$\pi, K, p$ beams to invisible decays

First run October 2016
\[ p \text{ electric dipole moment storage ring} \]

\[ p \text{EDM measured to be small} \]

<table>
<thead>
<tr>
<th>EDMs</th>
<th>10^{-26} e cm</th>
<th>Technique</th>
<th>Arxiv</th>
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<tbody>
<tr>
<td>proton</td>
<td>(</td>
<td>d_p</td>
<td>&lt; 79)</td>
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<tr>
<td>\textit{proposal}</td>
<td>(&lt; 10^{-3})</td>
<td>srEDM(I)</td>
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</tr>
<tr>
<td>neutron</td>
<td>(</td>
<td>d_n</td>
<td>&lt; 2.9)</td>
</tr>
<tr>
<td>deuteron</td>
<td>(&lt; 10^{-3})</td>
<td></td>
<td>1201.5773</td>
</tr>
</tbody>
</table>

This implies a very small \(\bar{\theta}\)

\[ \bar{\theta} \leq 2 \times 10^{-10} \quad \Rightarrow \quad \bar{\theta} \leq 3 \times 10^{-14} \]

Axioms? ...

Proposal to improve by orders of magnitude

\(p\)EDM is more than an order of magnitude more sensitive than current nEDM plans

All-electric storage ring; magic momentum 0.7 GeV
KLEVER: $K_L \rightarrow \pi^0\nu\bar{\nu}$ at the SPS

Can a competitive measurement of $\text{BR}(K_L \rightarrow \pi^0\nu\bar{\nu})$ be made at the SPS?

NA62-16-03

Status report on design studies for an experiment to measure $\text{BR}(K_L \rightarrow \pi^0\nu\bar{\nu})$ at the CERN SPS


April 27, 2016

Interesting features:

• High-energy experiment: Complementary approach to KOTO
• Photons from $K_L$ decays boosted forward
  • Makes photon vetoing easier - veto coverage only out to 100 mrad
• Possible to re-use LKr calorimeter, NA62 experimental infrastructure?
Summary and outlook

1. Flavor will play an important role in identifying new physics, even if NP is found at the LHC

   - **New physics found at LHC**
     - Explore flavor structure of “new” SM
     - Obtain **precision information** from measurements of $K \to \pi \nu \bar{\nu}$

   - **No new physics from LHC**
     - Explore extremely high mass scales with indirect probes
     - $K \to \pi \nu \bar{\nu}$ uniquely sensitive

2. NA62 and KOTO Step 1 results will arrive within next few years

   - **NA62/KOTO obtain unexpected results**
     - Precise measurement of $\text{BR}(K_L \to \pi^0 \nu \bar{\nu})$ extremely interesting

   - **NA62/KOTO obtain SM results**
     - $\text{BR}(K_L \to \pi^0 \nu \bar{\nu}) \sim (0.5 - 2) \text{ SM}$
     - Not excluded: precise measurement may still reveal NP

3. An experiment to measure $\text{BR}(K_L \to \pi^0 \nu \bar{\nu})$ with $\sim 60 \text{ SM event sensitivity}$ and $S/B \sim 1$ can be performed at the CERN SPS with $5 \times 10^{19}$ pot
AFTER: Fixed-target experiment using LHC beams

Gas-jet target, wire target, or crystal

<table>
<thead>
<tr>
<th>pp</th>
<th>pA</th>
<th>PbA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{O}(10 \text{ fb}^{-1}\text{yr}^{-1})$</td>
<td>$\mathcal{O}(0.1 - 1 \text{ fb}^{-1}\text{yr}^{-1})$</td>
<td>$\mathcal{O}(1 - 50 \text{ nb}^{-1}\text{yr}^{-1})$</td>
</tr>
</tbody>
</table>

4 decisive features
- accessing the **high** $x$ frontier
- achieving **high** luminosities,
- varying the atomic mass of the **target** almost at will,
- polarising the **target**.

3 physics cases
- High-$x$ gluon, antiquark and heavy-quark content in the **nucleon & nucleus**
- Transverse dynamics and spin of gluons inside (un)polarised nucleons
- **Heavy-ion** physics between SPS & RHIC energies towards **large rapidities**
Spin precession in a bent crystal channel

E761 Collaboration. Measurement of the $\Sigma^+$ magnetic moment - 1

First Observation of Magnetic Moment Precession of Channeled Particles in Bent Crystals

Proton (800GeV/c) + Cu $\rightarrow$ $\Sigma^+$ n particles

$\Sigma^+ \rightarrow p \pi^0$

As illustrated in Fig. 1, a vertically polarized $\Sigma^+$ beam [14] was produced by directing the Fermilab Proton Center extracted 800-GeV/c proton beam onto a Cu target (T). The resulting $\Sigma^+$ were produced alternately at a $+3.7$- or $-3.7$-mrad horizontal targeting angle relative to the incident proton beam direction. This allowed the polarization direction to be periodically reversed. The mean

The two bending crystals. Each crystal precess the channelled particle’s spin in opposite direction

$\pm 20\%$ measurement $\mu(\Sigma^+)$

The deflection of the channeled particles was measured to be $\omega = 1.649 \pm 0.043$ and $-1.649 \pm 0.030$ mrad for the up- and down-bending crystals, respectively. For 375-GeV/c $\Sigma^+$ this corresponds to an effective magnetic field of $B_x \approx 45$ T in the crystals. The magnetic moment [6] of the $\Sigma^+$ should precess by $\varphi \approx 1$ rad in such a field.

1/4000 channeled; rest made background

What would $\mu(\Lambda_c)$ teach us?
AWAKE: proton driven plasma wakefield experiment

- Demonstration experiment to show effect for first time and obtain $GV/m$ gradients.
- Use 400 GeV SPS proton bunches with high charge.
- To start running this year and first phase to continue to LS2.
- Apply scheme to particle physics experiments leading to shorter or higher energy accelerators.

?? Increase NA64 $e^-$ flux $\times$ 1000??
New Experimental Ideas

I. G. Irastorza · International Axion Observatory
G. Cantatore · Advanced KWISP: membrane force sensors
A. Lindner · Light shining through a wall
C. Galbiati · DARKSIDE
IAXO – Conceptual Design

- Large toroidal 8-coil magnet $L \approx 20$ m
- 8 bores: 600 mm diameter each
- 8 x-ray telescopes + 8 detection systems
- Rotating platform with services

$\text{SNR} = 10^4 \times \text{CAST}; \ R&D, TDR \ encouraged$
Ingredients for an “ALPS III” experiment

“ALPS III” sketch based on the following assumptions:

- Magnetic field strength: 13 T
- Magnetic length: 426 m
- Light wavelength: 1064 nm
- Circulating light power: 2.5 MW
  - Photons against the wall: $1.4 \cdot 10^{25}$ s$^{-1}$
- Power built-up behind the wall: $10^5$
- Detector sensitivity: $10^{-4}$ s$^{-1}$

- Resulting sensitivity for $g_{\alpha\gamma}$:
  $1 \cdot 10^{-12}$ GeV$^{-1}$ for $m < 0.06$ meV
"ALPS III" in context

"ALPS III"

> would dramatically increase the sensitivity for purely laboratory based experiments searching for axion-like particles.

> would surpass even IAXO for very low mass ALPs.

> would definitely probe astrophysics hints for ALPs.

> would probe "dark matter" ALPs.

> would perfectly complement IAXO!
DARKSIDE: zero background dark-matter search

Liquid Argon TPC
153 kg $^{39}$Ar-Depleted
Underground Argon Target

4 m Diameter
30 Tonnes
Liquid Scintillator
Neutron Veto

10 m Height
11 m Diameter
1,000 Tonnes
Water Cherenkov
Muon Veto
Next steps:
Form working groups
Work
Solicit new ideas
Prepare Yellow report(s) … 2018
Present to European Strategy Update