PHYSICS BEYOND COLLIDERS PROJECTS at LHC and BEYOND

1. Post-EPPSU PBC mandate

2. LHC-related PBC projects: QCD, BSM, others
   ... and their “competition” at CERN
   ... in the worldwide context

NB: credit to PBC working groups and projects for most plots shown here
Excerpt from the 2016 PBC mandate:

“Explore the opportunities offered by the CERN accelerator complex and infrastructure to address some of today’s outstanding questions in particle physics through experiments complementary to high-energy colliders and other initiatives in the world.”

Deliverables to EPPSU:

PBC QCD Report: arXiv:1901.04482
PBC Accelerator Reports:
http://cds.cern.ch/collection/PBC%20Reports?ln=en
Takes into account EPPSU recommendations:

Increase synergies with cosmology, astroparticle, nuclear and atomic physics

Strengthen collaboration of CERN with large National Laboratories

Act as central forum of exchanges between theorists and experimentalists

NB: new proposed experiments@LHC dedicated to Long Lived Particles now explicitly in PBC mandate
3 MCHF/year secured in the CERN Medium Term Plan for PBC support

New ideas may be submitted any time to the PBC Coordinators along instructions given on the PBC web site http://pbc.web.cern.ch/
PBC QCD PROJECTS IN WORLDWIDE LANDSCAPE

Structure Functions

Unique reach of LHC-Fixed Target with high statistics at high-x / high $Q^2$

QCD Phase Transition

Unique reach of LHC-FT & SPS in transition region to high-$\mu_B$

Quark-gluon plasma

Hadronic matter
**LHC FIXED TARGET**

SMOG2 storage cell installed in LHCb for run3, promises FT lumi x ~100 vs SMOG

**Longer term developments under PBC**

**ALICE wire target** at z=-4.8m intercepting beam halo deflected by crystal

**Double crystal set-ups** for measurement of short-lived baryons electric and magnetic moments, either by LHCb or at IR3 dedicated location

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**LHCSpin study** of polarized storage cell for LHCb

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Beam halo particles that do not interact with the Target+Cryx2 assembly are intercepted by 4 double-sided LHC-type collimators

In the Detector the final polarisation of AC is reconstructed from the distribution of decay products

The second Crystal deflects AC with specific initial polarization. AC spin precession in the electric field of crystal planes is proportional to MOM (or EDM)

In the Target protons are converted to polarised /Acc

The first Crystal deflects protons from the LHC beam halo onto the Target
LHC-FT “competition” at CERN: AMBER QCD FACILITY (ex-COMPASS)

Short term (run 3): proton radius puzzle with $\mu$-p elastic scattering

Longer term (excerpts):

With existing beams:
Unique opportunity for higher precision
pion structure measurements

With new RF-separated K-beam:
(significant upgrade under study for post-LS3):
Comprehensive measurement of strange spectroscopy
PBC BSM PROJECTS IN WORLDWIDE LANDSCAPE

EDM & non-accelerator projects cover the very low-mass domain

Precision & rare processes experiments extend reach of high-E colliders

SPS beam dumps probe a specific MeV-GeV domain
LHC-LLP DEDICATED PROJECTS

Pioneered by FASER/SND@LHC/milliQan

FASER: Dark photons & TeV neutrinos
480m from ATLAS IP
Detector installed for run 3

SND@LHC: TeV neutrinos
Slightly off axis opposite to FASER
Detector in construction for run 3

milliQan: milli-charged particles
33m from CMS IP
Successful demonstrator in run 2
Detector in construction for run 3
LHC-LLP DEDICATED PROJECTS
FORWARD PHYSICS FACILITY

Options for a dedicated LHC Forward Facility under study within PBC

Goal is to provide enough space for larger scale forward detectors in the HL-LHC era

FLARE
FORMOSA
FASER 2

+ FACET@CMS

Forward Physics Facility
LHC-LLP DEDICATED PROJECTS

Larger scale projects at large angle

MATHUSLA

ANUBIS: similar concept as MATHUSLA but in ATLAS access shaft

Further demonstrators and detailed simulations planned during run 3
LHC-LLP “competition” at CERN: NA64 electron beam dump

Configuration optimized to detect dark photons from missing energy, adaptable to $e^+e^-$ visible decay mode
One key feature: precision initial $E_e$ tagging with synchrotron radiation

“Cheap” setup implemented in 2015 on H4 e test beam

Currently leading the field!

Permanent setup implemented for higher intensities in run 3

Similar searches in preparation with muon and hadron beams
LHC-LLP “competition” at CERN:
SPS proton beam dump with NA62 & SHADOWS

Some NA62 data in beam dump mode foreseen for run 3
Achieved by closing the TAX collimator \(\sim 10^{18}\) PoT in few months

Instrumentation of NA62
decay vessel well adapted to
searches in visible decay mode

New SHADOWS “low cost” detector slightly off axis
of TAX would increase acceptance at high mass
in a higher-intensity post-LS3 beam dump
LHC-LLP “competition” at CERN: SHiP ON THE BEAM DUMP FACILITY

State-of-the-Art Dual Spectrometer for hidden particle searches

High-precision spectrometer for DM scattering + $\nu_\tau$ physics

Spectrometer for DM decays

Active magnetic muon filter

DM decay vessel

Comprehensive Design Study done within PBC

Next step: prepare TDR in relation with updated BDF TDR with emphasis on muon shield and decay vessel prototyping as well as cost reduction
The proton Beam Dump Facility

Comprehensive Design Study of a new SPS facility done within PBC

Continued R&D towards TDR now focusing on slow extraction, target design, cost optimization incl. alternative siting

→ promising option identified in existing ECN3 underground hall (used by NA62), under evaluation with respect to alternative NA62 extension + SHADOWS option
PBC LLP PROJECTS IN THE WORLDWIDE CONTEXT: THE FIPs PHYSICS CENTRE

“FIPs Physics Centre” now embedded within PBC as a “portal” towards the external world for Feebly Interacting Particles

C. Vallée, Physics at LHC, May 2022
FPC THEORETICAL FRAMEWORK for comparison of projects reach

A highlight of PBC for EPPSU: definition and wide acceptation of hidden sector benchmark models to compare reach of projects under same assumptions

Benchmark extension to all domains dealing with Feebly Interacting Particles has started in FPC

see FIPs kick-off workshop https://indico.cern.ch/event/864648/ and report arXiv:2102.12143

Next FIPs workshop in October 2022: https://indico.cern.ch/event/1119695/
EXCERPTS OF COMPARISONS DONE FOR EPPSU

**BC1: Dark photon visible decay to SM**

- CHARM: $S \rightarrow e^+ e^-$, $e^+\mu^-$
- LHCb & Belle II: $B \rightarrow K \mu$
- KLEVER: $5 \times 10^{13}$ pot
- SN1987a

- RedTop, 10$^6$ pot, $\eta \rightarrow A' \gamma$
- REDTOP, 10$^7$ pot, $\eta \rightarrow A' \gamma$
- NA64, $5 \times 10^4$ col
- LDMX, 16 GeV, 10$^7$ pot
- FASER2, 3 ab$^{-1}$
- MATHUSLA290, 3 ab$^{-1}$
- NA62, 1.10$^7$ pot

**BC2: Dark photon decay to scalar DM**

- $\alpha_D = 0.1$, $m_\chi = 1/3 m_A'$
- Belle II: 30 fb$^{-1}$
- E137
- Na44, 5.10$^{10}$ pot, 2019 preliminary
- Elastic scalar rate target
- Na64, 5.10$^{10}$ pot
- SE-EB1
- LDMX, 16 GeV, 10$^8$ pot
- SuperCDMS

**BC4: Dark scalar mixing with Higgs**

- $\sin^2 \theta$
- CHARM
- S lattice, $e^+ e^-$, $e^+ \mu^-$
- LHCb & Belle II: $B \rightarrow K \mu$
- KLEVER: $5 \times 10^{13}$ pot
- SN1987a

- $m_S$ (GeV)
- $10^{a}$cts at LHC ann.

**BC8: Dark HNL coupling to $\tau$**

- $|U|^2$
- CHARM
- FASER, 150 fb$^{-1}$
- NA62, 1.10$^7$ pot
- MATHUSLA290, 3 ab$^{-1}$

- SHP, 2.10$^{10}$ pot
- - solid: without BR, $B_{ij}$
- - dotted: with BR, upper limit
- MATHUSLA290, 2 ab$^{-1}$
- - solid: from BR vs mass
- - dotted: from $W' Z$

- SHP, 2.10$^{10}$ pot
- - solid: without BR, $B_{ij}$
- - dotted: with BR, upper limit
- MATHUSLA290, 2 ab$^{-1}$
- - solid: from BR vs mass
- - dotted: from $W' Z$

- SE-EB1
- LDMX, 16 GeV, 10$^6$ pot
- SuperCDMS

being updated for new projects and benchmarks
Important milestone reached within PBC with successful acceleration and storage of Partially Stripped Ions in LHC

For applications in atomic, nuclear, particle and applied physics, see first general workshop: [https://indico.mitp.uni-mainz.de/event/214/overview](https://indico.mitp.uni-mainz.de/event/214/overview)

Goal of $10^7$ intensity gain versus existing facilities

New idea introduced within PBC

Proof of Principle experiment with full configuration in preparation at SPS
AION
Atom interferometry for ultra-light DM and mid-frequency gravitational waves
Proof-of-Principle 10m setup being built in UK
Possible siting of a 100m setup in a CERN LHC shaft under investigation in PBC

PTOLEMY
Measurement of cosmic neutrino background
New idea submitted to Snowmass and PBC

VMB@CERN
Vacuum Magnetic Bi-refringence
Optical set up being developed in Ferrara for a CERN implementation with (HL-)LHC magnets

A new field for PBC: QUANTUM SENSORS
(a few recent developments)
ANTIMATTER FACTORY

Recent ELENA upgrade enhances potential for next decade

Many quantum technologies at work for precision measurements:
CPT, fundamental constants, axion searches...

Six collaborations, pioneering work by Gabrielse, Oelert, Hayano, Hangst, Charlton et al.

BASE,
Fundamental properties of the antiproton

ALPHA,
Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

ASACUSA
Antiprotonic helium spectroscopy

ALPHA, AEgIS, GBAR
Test free fall/equivalence principle with antihydrogen

PUMA
Antiproton/nuclei scattering to study neutron skins
PROTON EDM RING

COSY at Jülich supported by EPPSU as possible site for developing the project

Prototype E/B ring
~30 m Ø

Ongoing precursor experiment at Jülich (magnetic ring)

TDR for prototype ring in preparation by CPEDM Collaboration (incl. CERN)

Many systematics issues to be solved: lattice, deflectors, RF cavities, B-shield, BPMs...

Design sensitivity: $4 \times 10^{-29} \text{ e.cm}$
SUMMARY & OUTLOOK

CERN PBC STUDY GROUP EXTENDED WITH UPDATED MANDATE
TAKING INTO ACCOUNT EPPSU RECOMMENDATIONS

OPEN TO NEW IDEAS AT ANY TIME

PRIORITY STUDIES TO PREPARE DECISIONS ON POST-LS3 OPTIONS:
FPF, BDF, ECN3, ion sources, QCD facility...

NEXT OPEN PBC WORKSHOP ON 7-9 NOVEMBER 2022 AT CERN:
https://indico.cern.ch/event/1137276/
ADDITIONAL SLIDES
A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world.

The particle physics community must further strengthen the unique ecosystem of research centres in Europe. In particular, cooperative programmes between CERN and these research centres should be expanded and sustained with adequate resources in order to address the objectives set out in the Strategy update.

Synergies between particle and astroparticle physics should be strengthened through scientific exchanges and technological cooperation in areas of common interest and mutual benefit.
These include measurements of electric or magnetic dipole moments of charged and neutral particles, atoms and molecules, rare muon decays with high intensity muon beams at PSI, FNAL and KEK, rare kaon decays at CERN and KEK, and a variety of charm and/or beauty particle decays at the LHC.

Accelerator-based beam-dump and fixed-target experiments can perform sensitive and comprehensive searches of sub-GeV dark matter and its associated dark sector mediators, complementary to high-energy colliders and other approaches.

Among the proposals for larger-scale new facilities investigated within the Physics Beyond Colliders study, the Beam Dump Facility at the SPS emerged as one of the frontrunners. However, such a project would be difficult to resource within the CERN budget, considering the other recommendations of this Strategy.

In addition to the examples already mentioned above, a broad programme of axion searches is proposed at DESY, a search for low-mass dark matter particles with a positron beam is under way at Frascati, and the COSY facility could be used as a demonstrator for measuring the electric dipole moment of the proton at Jülich. These initiatives should be strongly encouraged and supported.

The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied.

The design studies for next-generation long-baseline neutrino facilities should continue.
**UPDATED PBC MANDATE: SCIENTIFIC GOALS**

**Scientific goal**

The main goal of the Study Group remains to explore the opportunities offered by CERN’s unique accelerator complex, its scientific and technical infrastructure, and its know-how in accelerator and detector science and technology, to address today’s outstanding questions in particle physics through initiatives that complement the goals of the main experiments of the Laboratory’s collider programme. Examples of physics objectives include dedicated experiments for studies of rare processes and searches for feebly interacting particles. The physics objectives also include projects aimed at addressing fundamental particle physics questions using the experimental techniques of nuclear, atomic, and astroparticle physics, as well as emerging technologies such as quantum sensors, that would benefit from the contribution of CERN competences and expertise. The study group will primarily investigate, and, where appropriate, provide support to, projects expected to be sited at CERN. The study group may also examine ideas and provide initial support for contributions to projects external to CERN. The study group is also expected to act as a central forum for exchanges between the PBC experimental community and theorists for assessment of the physics reach of the proposed projects in a global landscape.
**UPDATED PBC MANDATE: ORGANIZATION**

**Organization**

The group will continue to be led by three coordinators representing the scientific communities of accelerator, experimental, and theoretical particle physics. The coordination team reports to the CERN Directorate. The coordinators will update the PBC working group structure to reflect the updated PBC mandate and input from the community.

The PBC study group will act as CERN’s initial portal for new ideas which may come in spontaneously or through specific calls launched by the PBC coordination team. The group will facilitate and support an initial evaluation of the relevance and technical feasibility of the ideas in a global context, and will regularly inform the CERN scientific committees (INTC, SPSC or LHCC) about their findings. Where appropriate, oversight of PBC studies will be passed to the relevant CERN scientific committee once they are adequately mature for scrutiny and review of possible implementation.
IMPLEMENTATION CONSTRAINTS OF NEW PROJECTS

Governed to a great extent by existing beamlines/halls/experiments

e.g. SPS North Area:

**EHN1**: general purpose hall with unique high-E / medium-I beams for all particles

**ECN3**: unique underground hall for high-I hadron beams

**EHN2**: unique high-E / high-I $\mu$-beam
DARK VECTORS

BC1 worldwide context

- Excluded regions:
  - Belle II, 50 ab⁻¹, 2024
  - LHCb, 15 fb⁻¹, 2023
  - HPS, 2016-2020
  - APEX, 2018+
  - SeaQuest, 2021-2024
  - VEPP, proposed
  - Mu3e, 2017+
  - MEGA, 2020+
  - DARKLIGHT

BC2

- Excluded regions:
  - LDMX, 16 GeV, 10⁶ fb⁻¹
  - FASER, 750 fb⁻¹
  - FASER, 3 ab⁻¹

BC3

- MATHUSLA200, 3 ab⁻¹
- NA62, 10¹⁹ pot
- NA64, 5x10¹² coll
- REDTOP, 10⁹ pot, \eta \rightarrow A⁺γ
- REDTOP, 10⁹ pot, \eta \rightarrow A⁺γ
- SHIP, 10⁹ pot
- LDMX, 16 GeV, 10¹⁶ coll
- SLAC milliQ
- NA64, 5x10¹² coll
- milliQan; solid: 300 fb⁻¹
dashed: 3000 fb⁻¹
- LDMX, 16 GeV, 10¹⁶ coll
- ENDM
- SN097A
DARK VECTORS IN DM PARAMETER SPACE (BC2)

$\alpha_D = 0.1 \quad m_\chi = 1/3 \ m_{A'}$
SENSITIVITIES TO DARK FERMIONS (HNL’s)

- Unique short term opportunities with NA62 Beam Dump and FASER
- SHiP has the highest reach on the long term
ALPS IN BEAMDUMPS
EXPLORATORY STUDY OF HIGHER-ENERGY BEAM DUMPS POTENTIAL

the example of ALPs

PBC projects have a similar reach as for visible $A'$ (similar signatures $\gamma\gamma$ and $e^+e^-$)

No real breakthrough of LHC/FCC beam dumps:

SPS seems to offer a quite optimal energy-intensity mix in the present context

arXiv:1902.04878
Further extension to all domains dealing with Feebly Interacting Particles has started
Neutron EDM is leading the field for hadrons

Catching up in precision is a challenge for the proton
Interception of small BDF beam fraction to look for $\tau \rightarrow 3\mu$ decays

Could set limits on branching ratio better than $10^{-10}$ level targeted by BELLE-II

Implementation layout under study

A small experimental hall upstream of BDF target could trigger a unique rare decay facility
3.5 GeV e-LINAC with CLIC technology connected to SPS for acceleration up to 16 GeV

Slow extraction of up to \( \sim 10^{16} \) e/year if 1/3 of SPS duty cycle reserved to facility

Conceptual Design Report released in 2020 under PBC

Project now on hold following positive momentum of LCLS-II/LDMX competitor at SLAC
NEW e-BEAM: AWAKE++

Electron acceleration on wake fields from proton micro-bunches in a plasma cell

Proof of principle validated in 2018 with electrons accelerated up to 2 GeV

Could serve the purpose of an electron beam dump experiment located in the CNGS decay tunnel in the post-LS3 era
R&D FOR NEUTRINO BEAMS

Recent new ideas of tagged $\nu$ beams being investigated for precision measurements and next generation LBL projects

**ENUBET:**
- $\nu_e$ beam monitored from K decays
- Prototyping ongoing in Neutrino Platform within ERC grant
- Possible implementation at CERN to be studied in PBC

**NuTAG:**
- $\nu_\mu$ beam with $(E_\nu, \theta_\nu, \phi_\nu)$ tagged from individual $\pi$ decays with HL-LHC silicon trackers
- **Feasibility and possible synergy with ENUBET to be studied in PBC**
Well controlled $\nu$ beam from a $\mu$ storage ring

Precise $\sigma(\nu)$ measurements and a path towards a $\nu$ factory or a $\mu$ collider.

Possible siting@CERN studied within PBC
Post-LS2:
- **Successful upgrades to study open charm close to expected CP-region.**
- Also unique measurements for $\nu$-beams and cosmic rays
- **To be followed by SPSC**

Post-LS3: *(preliminary ideas)*
- Finer grain 2-D scan to study onset of fireball
- Antiproton and low-E beams for baryon stopping studies
- Continued measurements for $\nu$-beams and cosmic rays
- **To be followed by PBC**
Revival of NA60 concept to measure caloric curve of 1st order QCD transition with low-E dimuons

- New location found on EHN1 H8 beam to avoid conflict with NA62 in ECN3 → impact of reduced intensity by factor 4 to be quantified
- Toroid design ongoing with PBC support, as well as detector developments in synergy with HL-LHC
New idea introduced within PBC: 

Direct measurement of HVP contribution to \((g-2)_\mu\) with \(\mu\)-e elastic scattering

Complementary to prediction based on dispersion relation with \(e^+e^-\) data

Very challenging experimentally:
\[10^{-5}\] (relative) precision required on cross-section

Pilot runs in 2022

Full data taking aimed for during run 3

Now in the hands of the SPSC
COMPASS\((R_p)\)

\(\mu\)-\(p\) elastic scattering

In competition with MUonE on same \(\mu\)-beam in EHN2

\(\rightarrow\) COMPASS spectrometer

new COMPASS TPC

Data taking planned during run 3 provided successful pilot run

*Project now in the hands of the SPSC*
$K \rightarrow \pi \nu \bar{\nu}$ \hspace{1cm} (BR $\sim 10^{-10}$)

**ULTRA-RARE K DECAYS**

**NA62 (K$^+$):**

Run 2: 20 events seen for 17 expected (10 SM + 7 BG)
Run 3: detector upgraded to reach $\sim$100 signal events

**Post-LS3 options:**

K$^+$ intensity increase by factor 4
K$^0$ beam (ex-KLEVER): $K^0$ decays complementary to $K^+$ decays for the CKM matrix and BSM searches.

K$^+$ and K$^0$ options now considered as an integrated project with a multi-parameter internal phasing:

- $K^+$ results $\leftrightarrow K^+/K^0$ sensitivity $\leftrightarrow$ B-anomalies $\leftrightarrow$ KOTO
- Competition in Japan
NA64 PROPOSED EXTENSIONS

**µ beams**

- After LS2: few months of µ beam would test a \( (g-2)_{\mu} \) interpretation
- Longer term: few years of µ beam would improve limits on µ-coupled dark sector

**Hadron beams**

Would improve limits on
- meson decays to invisible particles
- leptophobic dark vectors
Main issues:

- 2 GeV continuous proton beam (PS best option but non-nominal for REDTOP)
- Demanding detector technology (Optical TPC and dual readout calorimetry)
Similar technologies as at antimatter factory, with a fundamental physics potential for e.g.

- EW tests
- EDMs
- Spectroscopy of new states
- Nuclear clocks
- ...

EPIC proposal to upgrade ISOLDE to higher energy (2 GeV) and intensity with a new experimental hall
INTERNATIONAL AXION OBSERVATORY
(axion helioscope successor of CAST@CERN)

BabyIAXO precursor approved and in construction at DESY
CERN PBC support to magnet design expected to go on in construction stage
Unique physics reach for ALPs searches