Physics Beyond Colliders: Long Lived Particle Searches

Albert De Roeck
CERN, Geneva, Switzerland
Antwerp University Belgium
UC-Davis California USA
NTU, Singapore

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The European Strategy:

The European Strategy for Particle Physics (ESPP) is the process by which every ~ 7 years the European particle physics community updates the priorities and strategy of the field. It also makes recommendations on related activities: education, communications and outreach, technology transfer, organisational aspects, etc.

First ESPP in 2006; first update in 2013; next update 2020.

Bottom-up process involving the community. Driven by physics*, with awareness of financial and technical feasibility.

ESPP produces the European roadmap in the worldwide context of the field.
Note: particle physics requires global coordination, given the number, size and complexity of the projects → “alignment” of the European, US and Japanese roadmaps in recent years to optimise the use of resources

The Strategy is adopted by the CERN Council.
Individual (major) projects require dedicated approval: e.g. HL-LHC

* The scientific input includes: physics results from current facilities from all over the world; physics motivations, design studies and technical feasibility of future projects; results of R&D work, etc.
2020 ESPP update: timeline and committees

- **2017**
  - Jan.2018: Call for proposals for venues for Open Symposium and Strategy Drafting Session

- **2018**
  - Feb.2018: Call for scientific input
  - March.2018: Call for nominations of PPG & ESG members
  - June 14, 2018: Council decision on venues and dates
  - Sept.27, 2018: Council launches the Strategy Update process & establishes the PPG and ESG

- **2019**
  - Dec 18, 2018: Closing submission community input
  - May 13-16, 2019: Open Symposium Granada, ES
  - Sept. 2019: Physics Briefing Book available
  - Jan 20-24, 2020: Strategy Update Drafting Session Bad Honnef, GE

- **2020**
  - March 2020: Strategy Update submitted to Council
  - May 2020: Council to approve Strategy Update
  - Physics results appearing after May 2019 will be taken into account in the process
  - Organisation & input preparation by community
Excerpt from the PBC mandate: “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.”
(Time scale of opportunities: next 2 decades)
Physics Beyond Colliders

PBC: a Study Group mandated by the CERN Management to prepare the next European HEP strategy update (2019-20)

Excerpt from the PBC mandate:

“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.”

Time scale: next 2 decades

[link to PBC website]

NB: PBC mandate recently extended up to May 2020 to support the EPPSU
PBC EVENTS IN THE PAST 2 YEARS

PBC KICK-OFF WORKSHOP, CERN, September 2016
Call for abstracts → 20 selected for presentation

1st GENERAL WORKING GROUP MEETING, CERN, March 2017
Identification of main issues to be studied

2nd PBC WORKSHOP, CERN, November 2017
Working groups project reports
New call for abstracts → 7 selected for presentation

2nd GENERAL WORKING GROUP MEETING, CERN, June 2018
Status of studies for PBC deliverables

3rd PBC WORKSHOP: CERN, January 16-17, 2019
Summary of inputs to EPPSU and survey of future studies

Many slides borrowed from this workshop, especially from Gaia Lanfranchi

Next Meeting: November 5-6 2019 CERN
Physics Beyond Colliders

PBC WORKING GROUP STRUCTURE

**BSM conveners:** C. Burrage, G. Lanfranchi, S. Rozanov, G. Ruoso
+ ext. experts + projects representatives:
NA62++, KLEVER, NA64++, SHiP, LDMX, IAXO, JURA, EDM

**QCD conveners:** M. Diehl, J. Pawlowski, G. Schnell
+ ext. experts + projects representatives:
COMPASS++, MUonE, DIRAC++
AFTER, CRYSTAL, LHCb-FT, ALICE-FT
NA61++, NA60++

~100 core members in the Working Groups
> 200 WG meetings in the past 2 years
Physics Beyond Colliders

PBC DELIVERABLES: PHYSICS WGs

Report of the BSM Working Group of the Physics Beyond Colliders at CERN

18 December 2018

CERN-PBC-REPORT-2018-007


CERN-PBC-REPORT-2018-008

Physics Beyond Colliders
QCD Working Group Report


Reports publicly available on CERN CDS: http://cds.cern.ch/collection/PBC%20Reports?ln=en

arXiv:1901.09966

~140 pages

~80 pages
More than 20 proposed projects

Examples of Beyond Collider Studies

SHiP
Flagship programme for a comprehensive investigation of the Hidden Sector in the few GeV domain
Similar layout as NA62, with larger acceptance to reach the c / b mass range
400 GeV protons
Muon active shield
Spectrometer for DM decays
Emulsion spectrometer for DM scattering + γ, physics

NB: NA62 plans to pave the way with short runs in beam dump mode after LS2

NA64
Hidden sector search from invisible decays with missing energy
Implemented in 2016 on e test beam
Fast analysis excluding (g-2), interpretation confirms the potential of the method
AFTER LS2:
Wish to extend the method to higher e intensity and μ / π / K / p beams

IAXO - next generation Axion helioscope beyond CAST
Support from CERN for magnet design within PBC

TauFV
Recently revived idea to intercept small BDF beam fraction to look for τ → 3µ decays
Could set limits on branching ratio better than 10^{-10} level (> BELLE-II reach)
Implementation layout upstream of BDF target under study
A promising option to maximize the physics reach of the Beam Dump Facility

AWAKE
R&D for electron acceleration with a plasma cell excited by proton bunches
First accelerated e+ seen in 2018
Could provide ~10^{11} ~30 GeV pulsed e+ year in the post-LS3 era to an experiment located in the CNGS decay tunnel

CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN

(Information on more projects and collaborations is not visible in the image.)
New Possible Experiments

From the beyond collider study document: arXiv:1902.00260

Includes also new LHC experiments that have a similar physics search program.
Feebly Interacting Particles

Particles that can interact even less than weakly...

A (very) limited list of examples

Dark Matter:
candidates \ w mass from $10^{-22}$ eV (light feeble scalars) to $10^{20}$ GeV (black holes).

→ FIPs: if DM is a thermal relic, then mass is restricted o(10) keV – 100 TeV: MeV-GeV DM requires MeV-GeV mediators; 3.5 keV astrophysical line could be a sterile neutrino DM; ....

Neutrino masses and oscillations
explanation: RH neutrinos with masses from $10^{-2}$ eV to $10^{15}$ GeV.

→ FIPs: If RHN have generic (feeble) Yukawa’s + approximate $U(1)_L$, their masses can be below EW scale.

Matter-antimatter asymmetry
hard to associate scale, solutions of many orders of magnitudes:

→ FIPs: baryogenesis via CPV relaxion-Higgs couplings;

→ FIPs: baryogenesis though leptogenesis via oscillations of RHN with masses below EW scale.

Naturalness problem:
Symmetry-based solutions => TeV partners;

→ FIPs: relaxion => light feeble Goldstone bosons (ALPs)

Strong CP problem:

→ FIPs: axion => light feeble Goldstone boson;

........
Proposals considered in the Physics Beyond Colliders BSM report arXiv:1901.09966

<table>
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<th>Proposal</th>
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<th>Beam Yield</th>
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<td>IAXO</td>
<td>axions/ALPs (photon coupling)</td>
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<td>JURA</td>
<td>axions/ALPs (photon coupling)</td>
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<td>LHC-FT</td>
<td>charmed hadrons EDMs</td>
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<td></td>
<td>sub-eV mass range:</td>
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<tr>
<td>NA62++</td>
<td>ALPs, Dark Photons, Dark Scalars, LDM</td>
<td>K12, SPS</td>
<td></td>
<td>up to 3: 10^{18}/year</td>
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<tr>
<td>NA64++</td>
<td>ALPs, Dark Photons, Dark Scalars, LDM</td>
<td>H4, SPS</td>
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<td>5 \cdot 10^{12} eot/year</td>
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<td>LDMX</td>
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<td>10^{12} - 10^{13} mot/year</td>
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<tr>
<td>AWAKE/NA64</td>
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<td></td>
<td>10^{14} - 10^{15} eot/year</td>
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<td>MATHUSLA200</td>
<td>Weak-scale LLPs, Dark Scalar, Dark Photo</td>
<td>ATLAS or CMS IP</td>
<td>3000 fb^{-1}</td>
<td></td>
</tr>
<tr>
<td>FASER</td>
<td>Dark Photons, Dark Alphas, HNLs, B - L gauge bosons</td>
<td>ATLAS IP</td>
<td>14 TeV p</td>
<td>3000 fb^{-1}</td>
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<tr>
<td>MilliQan</td>
<td>Dark Scalars, HNLs, ALPs, LDM</td>
<td>CMS IP</td>
<td>14 TeV p</td>
<td>300000 fb^{-1}</td>
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<tr>
<td>CODEX-b</td>
<td>Dark Scalars, HNLs, ALPs, LDM</td>
<td>LHCb IP</td>
<td>14 TeV p</td>
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<td>MeV-GeV mass range:</td>
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<td>multi-TeV mass range:</td>
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<td>KLEVER</td>
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<td>400 GeV p</td>
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<tr>
<td></td>
<td>TauLV</td>
<td>BDF</td>
<td></td>
<td>5 \cdot 10^{10} p /5 years</td>
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<td></td>
<td>CPEDM</td>
<td>EDM ring</td>
<td></td>
<td>p, d</td>
</tr>
<tr>
<td></td>
<td>LHC-FT</td>
<td>LHCb IP</td>
<td>7 TeV p</td>
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**sub-eV NP:**
Axions with helioscopes, LSW and EDM rings

**MeV-GeV NP:**
Hidden Sector at accelerator-based experiments

**Multi-TeV NP:**
Ultra-rare/forbidden decays, EDM ring.

About 15 proposals have been considered in the BSM-WG so far
Proposals for New Experiments @LHC

**MilliQan**: searches for millicharged particles

**MAPP**: Same from MoEDAL

**CODEX-b**: searches for long lived weakly interacting neutral particles

**MATHUSLA**: searches for long lived weakly interacting neutral particles

**FASER**: searches for long lived dark photons-like particles

New: **AL3X** (‘ALICE’ for LLP arXiv.1810.03636)
Sensitivity Summaries

Search for dark photons (visible mode)

Search for millicharges

Search for dark scalars

Search for heavy neutral leptons
PBC Physics Goals

PBC target: (Light) Dark Matter with thermal origin

DM candidates with thermal origin can have mass between 10 keV and 100 TeV.

New Particles with masses in the MeV-GeV range and very weakly coupled to light mediators

PBC-BSM target

< 10 keV
DM too hot, spoils structure formation

1 MeV

1 GeV

\( m_e \sim m_p, m_n \)

WIMPs paradigm

> 100 TeV
DM overproduced

10 TeV

Increasing interest also in the DM direct detection community (lively and growing field)
PBC target: (Light) Right-Handed Neutrinos

Neutrino portal extensions of the SM is motivated by the neutrino mass generation mechanism. It is also motivated by cosmology: couplings between Right-Handed neutrinos can violate CP and generate matter-anti matter asymmetry in the early Universe.

Right handed neutrinos responsible of the see-saw mechanism can have any coupling/mass in the white area.

Alternative choice: EW see-saw ($\nu$MSM)
It is “natural” to assume that the masses of the RH neutrinos are at EW scale

Popular choice: GUT see-saw
It “natural” to assume that Yukawa couplings of the RH neutrinos are similar to SM Yukawa.
PBC target: Axion and Axion-Like Particles

Axion = Pseudo-Nambu Goldstone Boson associated to Peccei-Quinn symmetry, a global $U(1)$, introduced to address the Strong QCD problem. Vast range of masses and couplings possible, with fixed relation.

Axion-Like Particle (ALP): a generalized version of the axion (at the cost of the original motivation from the strong CP problem). No direct relation between coupling and mass.

Axions and ALPs in the sub-eV mass range (lively and well-established community)

Axion associated to the Peccei-Quinn symmetry

Interest to explore the MeV-GeV region at accelerator-based experiments
Opportunities @ CERN in the North Area

**NA62-dump @ K12**
400 GeV p beam
up to $3 \times 10^{18}$ pot/year (now)

**NA64**(e) @ H4
(100 GeV e- beam
up to $5 \times 10^{12}$ eot/year)

**SHiP @ BDF**
400 GeV p
up to $4 \times 10^{19}$ pot/year

**NA64**(μ) @ M2
100–160 GeV muons,
up to $10^{13}$ μ/year

CERN can provide the highest energy proton, electron and muon beams for fixed target experiments in the world.

A possible “Hidden Sector Campus” (HSC)
The NA64 experiment in EHN1, H4
https://na64.web.cern.ch/

Current status: collected few $o(10^{11})$ eot. In a few months of data taking has excluded Dark Photon as origin of the $(g-2)\mu$ discrepancy.
NA64: “ACTIVE” DUMP technique:

Any discrepancy between the energy of the electron measured before and in the active dump would be sign of the production of some non-interacting particles, as for example Dark Matter, or very long-lived light mediators as Dark Photons.
Proposal to extend the physics programme after LS2:

**NA64++ (electrons):** extension beyond 2021 to accumulate up to $5 \times 10^{12}$ eot in H4

**NA64++ (muons):** use the 100-160 GeV muon beam in COMPASS area to study hidden sector with muon couplings. Very complementary to Dark Sector with electron couplings.

**NA64++ ($K_{L,S}$, $\pi^0$, $\eta$, $\eta'$ → invisible):** produced via charge exchange reactions $\pi(K)$ $p → M^0$ $n + E_{\text{miss}}$

**Eg:** search for a $Z_\mu$ in the bremsstrahlung reaction:

$$\mu + Z \rightarrow \mu + Z + Z_\mu$$

Few months of data taking with muons would rule-out (confirm?) interpretation of the $Z_\mu$ as a responsible of the $(g-2)_\mu$ discrepancy.
NA64++ with AWAKE

Longer timescale: NA64++ @ AWAKE

AWAKE could provide $\sim 10^{16}$ ~30-50 GeV pulsed e’s/year in the post-LS3 era to an experiment located in the CNGS decay tunnel.
LDMX experiment

LDMX @ eSPS: Meyrin area

GREEN: ~16 GeV electron beam in SPS
slow extraction towards Meyrin site for LDMX-like experiment
Up to $10^{16}$ cts in o(1) year of operation

Electron beam impinging on target:
- multi-GeV electrons
- 1-200 MHz bunch spacing
- Ultra-low O(1-5) electrons per bunch

70 m long, 3.5 GeV X-band LINAC with excellent beam quality
- CLEAR type of research programme.
- Fill SPS in 1-2 sec (bunches 5 ns apart) via TT60;

EoI sent to SPSC in October 2018:
https://cds.cern.ch/record/2640784

Also proposed for SLAC..
**Experimental Technique**

**Experimental Techniques at fixed target/beam dump exps.**

**LDMX: Missing Momentum technique:**
any discrepancy between the momentum of the electron/muon measured before and after the target would be sign of the production of some non-interacting particle, as for example Dark Matter

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Project presented also at SLAC, pending approval of LCLS-II beam extraction. This would allow a faster & cheaper implementation, even if at a reduced energy (8 GeV @ SLAC versus 16 GeV @ SPS).
The NA62 experiment @ K12 in EHN3 (the “Kaon Factory”)

NA62 currently running in K12. Main goal: measure the \( \text{BR}(K^+ \rightarrow \pi \nu \bar{\nu}) \) with 10% accuracy.

NA62 current measurement: \( \text{BR}(K^+ \rightarrow \pi \nu \bar{\nu}) \) (NA62) < 14 \times 10^{-10} \) @ 95\% CL (PLB 2019)


SM prediction: \( (9.31 \pm 0.76) \times 10^{-11} \) (Buras et al., 2015)
Experimental Techniques at fixed target/beam dump exps.

**NA62: DUMP technique**

Crucial ingredients to disentangle signal from background: **timing** (T1-T2) and **pointing** (IP) (in addition to Veto and PID systems).
NA62 in “dump” mode

Dump mode allows NA62 to search for Hidden States above the K⁺ mass. Switch between kaon and dump mode possible within minutes. ~3×10¹⁶ pot collected in dump mode in 2016-2018 (~50 integrated hours of data taking)

Be target can be moved away from the beam and the beam let impinging on the collimators (Cu-based) 2×10.7 λi.

Signal signature: a vertex appearing in the decay volume and nothing else

Currently running to complete the Kaon programme, interplay with the dump under study. To be competitive in searches above the K⁺ mass, 10¹⁸ pot in dump-mode should be collected by Run 3. This corresponds to 3-4 months of dedicated data taking.
Proposal for a beam dump Facility

The Beam Dump Facility (BDF) in the North Area

400 GeV proton beam up to $4 \times 10^{19}$ pot/year (the same number sent to the CNGS)

Brand new high-intensity proton beam proposed in the North Area Mature project: ready to be implemented if approved.
Search for NP at the multi-TeV scale: the TauFV Project

- Long-standing, and well motivated (particularly since the discovery of neutrino oscillations) program of searches for charged Lepton Flavour Violation.
- Study of tau LFV decays very timely: complement the quest for new physics in other cLFV modes, as mu2e @ FNAL and MEG/mu3e @ PSI.
- Located into the BDF line upstream of SHiP. Use ~2% of protons hitting on (probably) a wire target to study LFV decays of tau leptons.

Profit of the higher signal yield than at any other facility:
Eg: $\tau \rightarrow \mu\mu\mu$ yield assuming a BR $\sim 10^{-9}$

<table>
<thead>
<tr>
<th>Future experiment</th>
<th>Yield</th>
<th>Extrapolated from</th>
</tr>
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<tbody>
<tr>
<td>TauFV (4 x 10^{18} PoT)</td>
<td>8000</td>
<td>Numbers on this slide</td>
</tr>
<tr>
<td>Belle II (50 ab^{-1})</td>
<td>9</td>
<td>PLB 687 (2010) 139</td>
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<tr>
<td>LHCb Upgrade I (50 fb^{-1})</td>
<td>140</td>
<td>JHEP 02 (2015) 121</td>
</tr>
<tr>
<td>LHCb Upgrade II (300 fb^{-1})</td>
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</tbody>
</table>
SHiP: Search for Hidden Particles

SHiP experiment @ BDF

Beam:
400 GeV/c protons
4x10^{13} pot/spill
2x10^{20} pot/5 years

B, K, D, photons

5 m
10 m
60 m

✓ Hidden particles have very feeble couplings, hence they are (very) long-lived:
  - The 60m-long, in-vacuum SHiP decay volume allows us to be sensitive to extremely low couplings
✓ Hidden particles from D and B decays have large p_T:
  - SHiP large geometrical acceptance maximizes detection of decay products
**Beam:**
400 GeV/c protons
4x10^{13} pot/spill
2x10^{20} pot/5 years

**Active Muon Shield:**
40 m long, 1400 t of magnets, sweeps out muons emerging from the target.

**Prompt dose rate muons**

SHiP lives dangerously here
SHiP: Direct Light Dark Matter Detection

SHiP @ BDF: Light Dark Matter direct detection

Beam:
400 GeV/c protons
4x10^{13} pot/spill
2x10^{20} pot/5 years

DM particles can scatter on the electrons of the dense material of the Emulsion Spectrometer in the Upstream Detector. The same detector will do tau neutrino physics.
SHiP: Hidden Sector Search

SHiP @ BDF: Hidden Sector Spectrometer

Beam:
400 GeV/c protons
4x10^{13} pot/spill
2x10^{20} pot/5 years

Details in R. Jacobsson Detector Seminar
https://indico.cern.ch/event/804843/
and Iaroslava Bezshiyko this meeting
PBC BSM Experiments Timeline

Timescale of accelerator-based PBC BSM projects

All PBC-BSM projects could be built and operated on 10-15 year timescale

PBC-BSM projects
- NA62++
- NA64++
- RedTop
- LDMX
- SHiP/tauFV
- KLEVER
- AWAKE
- MATHUSLA
- FASER
- Codex-B
- milliQan

Worldwide landscape in the next 5-15 years:
- LHCb-upgrade
- Belle-II
- HPS, APEX (JLAB)
- SeaQuest
- SBND & DUNE (FNAL)

2018  2020  2022  2024  2026  2028  2030
Physics Targets

PBC-BSM: physics targets in the sub-eV and MeV-GeV ranges

HNLs, LDM & Light mediators, ALPs must be SM singlets, hence options limited by SM gauge invariance:

According to generic quantum field theory, the lowest dimension canonical operators are the most important:

<table>
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<th>Portal</th>
<th>Coupling</th>
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<tr>
<td>Dark Photon, $A_\mu$</td>
<td>$-\frac{e}{2\cos\theta_W} F'_\mu\nu B^{\mu\nu}$</td>
</tr>
<tr>
<td>Dark Higgs, $S$</td>
<td>$(\mu S + \lambda S^2) H^\dagger H$</td>
</tr>
<tr>
<td>Axion, $a$</td>
<td>$\frac{a}{f_a} F^{\mu\nu}, \frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}, \frac{\delta a}{f_a} \psi \gamma^\mu \gamma^5 \psi$</td>
</tr>
<tr>
<td>Sterile Neutrino, $N$</td>
<td>$y_N LHN$</td>
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This is the set of the simplest fields and renormalizable interactions that can be added to the SM to answer the three fundamental questions: DM nature, neutrino masses and oscillations, baryogenesis.

The PBC BSM WG has identified 11 benchmark cases used to evaluate the experimental sensitivities. A common ground to compare the proposals against each other and put them in worldwide context.
Vector Portals

Vector Portal: Dark Photon coupled to SM particles

Model where minimally coupled viable (WIMP-like) dark matter model can be constructed.
DM is charged under a broken $U(1)_D$ abelian gauge symmetry.
The parameter space for this model is $\{\alpha_D, \epsilon, m_{A'}, m_\chi\}$.

Worldwide landscape

CERN: 5 years outlook

NA62-dump competes with with FASER, SeaQuest, and LHCb;
NA64++(e) competes with LHCb Upgrade & JLAB experiments
Vector Portals

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**Worldwide landscape**

**CERN: 10-15 years outlook**

SHiP is world-leading in the MeV-GeV range with extremely low couplings ($\mathcal{E} \sim 10^{-5} - 10^{-8}$)
Vector Portals

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Model where minimally coupled viable (WIMP-like) dark matter model can be constructed. DM is charged under a broken $U(1)_D$ abelian gauge symmetry.

The parameter space for this model is $\{\alpha_D, \epsilon, m_{A'}, m_{\chi}\}$.

Current & future colliders

CERN: 10-15 years outlook

Nice complementarity between beam-dump and collider experiments

Beam-dump experiments have unique physics reach in the MeV-GeV region, very low couplings.
Vector Portals

Vector Portal: Dark Photon coupled to Dark Matter

Light Dark Matter in the MeV-GeV range

\[ A' \rightarrow \chi \chi \]

Worldwide landscape in the MeV-GeV range
Vector Portals

Vector Portal: Dark Photon coupled to Dark Matter

Light Dark Matter in the MeV-GeV range: PBC projects

Unique NA64++(e) short term opportunity to explore relevant DM parameter space.

Complemented by SHiP with a totally different technique. Important cross-check in case of hint.

Significant higher reach of LDMX@eSPS to be put in regard with possible (faster&cheaper) implementation at SLAC (pending approval of the LCLS-II beam extraction)

Synergy between accelerator-based and direct detection experiments. (important for cross-check in case of hint)
Scalar Portals

Scalar Portal: physics motivations

Relaxion: light feeble goldstone boson, with both CP-even and CP-odd couplings with the Higgs, may stabilize the Higgs mass against radiative corrections and provide baryogenesis. Generic light scalar could also be light mediator between SM and LDM, in case of secluded annihilation.

The “log” crisis

MeV-100 GeV range is accessible at accelerators’ based experiments
Scalar Portal: Dark Scalar coupled to the Higgs

Existing limits and projections for future beam dump and fixed target experiments.

Zoom in the MeV-100 GeV range

Source:
Physics Beyond Colliders
BSM report,

**NA62** competes with SeaQuest.
**SHiP** will probe a large mass region below 5 GeV extending the explored range by several orders of magnitude
Scalar Portals

Scalar Portal: Dark Scalar coupled to the Higgs

MATHUSLA physics reach similar to SHiP (but also similar cost). For $\lambda \neq 0$ MATHUSLA sensitive to Dark Scalars up to $m(Higgs)/2$.

Future colliders reach:
Indirect limits from fit of Higgs width and Higgs BRs (model dependent):

$$\Gamma_h^{\text{tot}} = \cos^2 \theta \Gamma_h^{\text{tot,SM}} + \Gamma_h^{\text{NP}} \quad \Gamma_h^{\text{NP}} = \Gamma(h \rightarrow \phi\phi)$$

Nice complementarity between beam-dump, astrophysics boundaries and colliders. Together they can explore a large fraction of the “natural” relaxion region.
Example Scenario

Neutrino portal: vMSM (Neutrino Minimal Standard Model)
Minimal extension of the SM fermion sector by three Right Handed (Majorana) Heavy Neutral Leptons (HNL): N1, N2, N3.

- The lightest singlet $N_1$ (mass $\approx$ KeV): good dark matter candidate.
- $N_2, N_3$ (mass in 100 MeV - GeV region):
  - Mechanism to give masses to neutrinos
  - Explain baryon asymmetry

Neutrino Portals

Fermion Portal: Heavy Neutral Leptons below/around EW scale

Current limits and projections for beam dumps (and other) experiments

\[ |U_{e2}|, |U_{e3}|, |U_{\tau}| = 1:0:0 \]

- SHiP can explore the parameter region compatible with leptogenesis down to the see-saw limit.
- MATHUSLA has similar reach (but also similar cost).
- FCC-ee will lead in the high mass range with the Tera-Z option.
II. Majorana Neutrino (type I see-saw)
Origin of the neutrino masses and oscillations

Back to the initial plot:
SU(2)xU(1)L singlet Right Handed Neutrinos responsible of the neutrinos' mass generation can have any coupling/mass in the white area, assuming an approximate U(1)L global symmetry.

With beam dump and future colliders's experiments we can explore (light) RHN in the mass range 0.1-90 GeV compatible with leptogenesis almost down to the see-saw limit.
Axion-like Particles

Pseudo-Scalar portal: ALPs with photon coupling

- sub-eV range accessible at helioscopes and haloscopes
- MeV-GeV range accessible at beam-dump experiments

Nice complementarity of accelerator-based experiments, experiments in the sub-eV range, and cosmological bounds

See I. Irastorza’s talk
Milli-charged particles (Benchmark #3)

Milli-charged particles can be seen as a specific limit of the vector portal when $m_{A'}$ goes to zero and the parameter space simplifies to the mass ($m_{\chi}$) and effective charge ($|Q| = |\varepsilon_{D} e|$) of milli-charged particles.

The unexpected strength of 21 cm line anomaly signal measured by the EDGES radio-telescope could be naturally explained if (even only a fraction of) DM is in form of milliQ particles.

Nice complementarity with colliders and astrophysical data
## Project Status

PBC-BSM projects: current status of evaluation of backgrounds and other experimental effects

<table>
<thead>
<tr>
<th>Proposal</th>
<th>Background</th>
<th>Efficiency</th>
<th>Based on</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>at the PS:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RedTop</td>
<td>included</td>
<td>included</td>
<td>full simulation</td>
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<tr>
<td><strong>at the SPS:</strong></td>
<td></td>
<td></td>
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<tr>
<td>KLEVER</td>
<td>$K_L \to \pi^0\nu\overline{\nu}$, $K_L \to \pi^0\pi^0$ bkgs included</td>
<td>included</td>
<td>Main backgrounds and efficiencies evaluated with fast simulation and partly validated with the full (NA62-based) Monte Carlo</td>
</tr>
<tr>
<td>LDMX</td>
<td>background included</td>
<td>included</td>
<td>full Geant4 simulation for 4 GeV beam analysis of $\sim 3 \cdot 10^{16}$ pot in dump mode</td>
</tr>
<tr>
<td>NA62++</td>
<td>zero background</td>
<td>partially included</td>
<td></td>
</tr>
<tr>
<td>NA62++(e)</td>
<td>included</td>
<td>included</td>
<td>background, efficiencies evaluated from data test of the purity of the M2 line with COMPASS setup</td>
</tr>
<tr>
<td>NA62++(μ)</td>
<td>in progress</td>
<td>included</td>
<td>test of the purity of the M2 line with COMPASS setup</td>
</tr>
<tr>
<td>NA62++($K_{S,L,\eta,\eta'}$)</td>
<td>to be done</td>
<td>to be done</td>
<td></td>
</tr>
<tr>
<td>AWAKE/NA64</td>
<td>to be done</td>
<td>to be done</td>
<td></td>
</tr>
<tr>
<td>SHiP</td>
<td>zero background</td>
<td>included</td>
<td></td>
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<tr>
<td><strong>at the LHC:</strong></td>
<td></td>
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<tr>
<td>CODEX-b</td>
<td>zero background assumed</td>
<td>not included</td>
<td>Evaluation of background in progress with full MC</td>
</tr>
<tr>
<td>(preliminary GEANT simulation)</td>
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<tr>
<td>FASER</td>
<td>zero background assumed</td>
<td>not included</td>
<td>Fluka simulation and in-situ measurements</td>
</tr>
<tr>
<td>MATHUSL A2000</td>
<td>zero background assumed</td>
<td>not included</td>
<td>FLUKA, Pythia and MadGraph simulation for $\nu-$, $\mu-$ fluxes from the LHC IP and cosmic rays background.</td>
</tr>
<tr>
<td>MilliQan</td>
<td>included</td>
<td>included</td>
<td>full Geant4 simulation of the detector</td>
</tr>
</tbody>
</table>

Just a starting point of a long way.

Not all experiment at the same level of detail yet
More Beam Dump Experiments

High intensity frontier for low mass particles with very weak couplings

->upcoming neutrino experiments (SBL, LBL) foresee very high intensity beams

These experiments can perform searches for low mass New Physics particles eg
-HNL/sterile neutrinos
-dark photons
-ALPs
-mini/millicharges
...

<- Example for millicharges
FerMINI @FNAL?

Near Detector:
few 100m away from the dump

> 10^{21} \text{ POT/Year}

https://indico.fnal.gov/event/18430/

arXiv:1806.03310
Physics Beyond Colliders Summary

Conclusions

- The target of the PBC-BSM activity is a broad, rich and compelling physics programme which addresses the open questions of particle physics in a complementary way to the LHC, HL-LHC, FCC and other initiatives in the world (e.g. DM direct detection, astrophysical data, experiments at JLAB, FNAL).

- This program aims at exploiting the unique CERN scientific infrastructure and accelerator complex on a 5-15 year timescale.

- A large and lively community with several different scientific proposals is growing at CERN and now is starting to speak a common language, to collaborate and to work in a coherent way.

- The experimental collaborations are backed by a very active theory community and the PBC has served as fertile ground where models have been developed, discussed, and improved.

- A preliminary set of comparative plots, based on theoretically and phenomenologically motivated models, shows the scientific potential and the impact that CERN could have on the international landscape in the next o(10-15) years in the quest for New Physics.

- The projects presented in the PBC-BSM framework could be a very attractive option while preparing the next big machine.