The PBC(–BSM WG) mandate

https://pbc.web.cern.ch/

“Physics Beyond Colliders is an exploratory study aimed at exploiting the full scientific potential of CERN’s accelerator complex and its scientific infrastructure through projects complementary to the LHC, HL-LHC and other possible future colliders. 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.”

Some outstanding fundamental open questions in particle physics:
- Origin of the neutrino masses and oscillations
- Nature of Dark Matter
- Mechanism of Baryogenesis
Many TeV-scale ideas/models have been scrutinized. Need a systematic approach for the high intensity frontier: main target of the PBC-BSM activity.
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

Most of the effort so far

Increasing interest also in the DM direct detection community (lively and growing field)
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.

It is “natural” to assume that Yukawa couplings of the RH neutrinos are similar to SM Yukawa.

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

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

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

Interest to explore the MeV-GeV region at accelerator-based experiments

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

Axion associated to the Peccei-Quinn symmetry
BSM Experimental Proposals and Physics Programme

About 15 proposals have been considered in the BSM WG so far. Since the TeV scale is very well explored at the LHC, focus on the sub-eV, MeV-GeV and multi-TeV scales:

**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.

<table>
<thead>
<tr>
<th>Proposal</th>
<th>Main Physics Cases</th>
<th>Beam Line</th>
<th>Beam Type</th>
<th>Beam Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHP</td>
<td>ALPs, Dark Photons, Dark Scalars</td>
<td>BDF, SPS</td>
<td>400 GeV $p$</td>
<td>2.10$^{20}$/5 years</td>
</tr>
<tr>
<td>NA62$^{++}$</td>
<td>ALPs, Dark Photons, Dark Scalars, HNLs, lepto-phobic DM, ..</td>
<td>K12, SPS</td>
<td>400 GeV $p$</td>
<td>up to 3.10$^{18}$/year</td>
</tr>
<tr>
<td>NA64$^{++}$</td>
<td>ALPs, Dark Photons, Dark Scalars, LDM</td>
<td>H4, SPS</td>
<td>100 GeV $e^-$</td>
<td>5.10$^{16}$ et/years</td>
</tr>
<tr>
<td>LDMX</td>
<td>Dark Photons, LDM, ALPs, .., + CP, CPT, lepto-phobic DM</td>
<td>oSPS (SLAC)</td>
<td>10$^{12}$ - 10$^{13}$ mot/year</td>
<td></td>
</tr>
<tr>
<td>AWAKE/NA64</td>
<td>Dark Photon</td>
<td>AWAKE beam</td>
<td>20-50 GeV $e^-$</td>
<td>10$^{16}$ et/years</td>
</tr>
<tr>
<td>Redisp</td>
<td>Dark Photon, Dark scalar, ALPs</td>
<td>CERN PS</td>
<td>1.8 or 3.5 GeV</td>
<td>10$^{17}$ pot</td>
</tr>
<tr>
<td>MATHUSLA200</td>
<td>Weak-scale LILPs, Dark Scalars, Dark Photon, ALPs, HNLs</td>
<td>ATLAS or CMS IP</td>
<td>14 TeV $p$</td>
<td>3000 fb$^{-1}$</td>
</tr>
<tr>
<td>FASER</td>
<td>Dark Photon, Dark Scalar, ALPs, HNLs, $B - L$ gauge bosons</td>
<td>ATLAS IP</td>
<td>14 TeV $p$</td>
<td>3000 fb$^{-1}$</td>
</tr>
<tr>
<td>MilliQan</td>
<td>Dark Scalar, HNLs, ALPs, milli charge</td>
<td>CMS IP</td>
<td>14 TeV $p$</td>
<td>300-3000 fb$^{-1}$</td>
</tr>
<tr>
<td>CODEX-$b$</td>
<td>Dark Scalar, HNLs, ALPs, LDM</td>
<td>LHCb IP</td>
<td>14 TeV $p$</td>
<td>300 fb$^{-1}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Proposal</th>
<th>Main Physics Cases</th>
<th>Beam Line</th>
<th>Beam Type</th>
<th>Beam Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>KLEVER</td>
<td>$\pi^0 \rightarrow \pi^+\pi^-$</td>
<td>P42/K12</td>
<td>400 GeV $p$</td>
<td>5.10$^{15}$ pot/5 years</td>
</tr>
<tr>
<td>TanfV</td>
<td>$\tau$ decays</td>
<td>BDF</td>
<td>400 GeV $p$</td>
<td>10$^{17}$ pot</td>
</tr>
<tr>
<td>CPEDM</td>
<td>$p, d$ EDMs</td>
<td>EDM ring</td>
<td>$p, d$</td>
<td>10$^{17}$ pot</td>
</tr>
<tr>
<td>LHC-FT</td>
<td>charmed hadrons MDMs, EDMs</td>
<td>LHCb IP</td>
<td>7 TeV $p$</td>
<td>10$^{17}$ pot</td>
</tr>
</tbody>
</table>
PBC-BSM Proposals in the North Area

**NA62++ , KLEVER @ K12**
400 GeV p beam
up to $3 \times 10^{18}$ pot/year (now)
up to $10^{19}$ pot/year (upgrade)

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

**SHiP, TauFV @ 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)*

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 $\sim$0(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;

(see R. Pottgen’s talk today and S. Stapnes’s talk tomorrow)
Use narrow eta/eta’ resonances to look for Dark Scalar/Dark Photons in the reactions:

\[ p\pi \rightarrow \eta, \eta' \rightarrow A'\gamma \rightarrow \ell^+\ell^-\gamma (\ell = e, \mu) \]

\[ p\pi \rightarrow \eta \rightarrow S\pi^0 \rightarrow \ell^+\ell^-\gamma \gamma \]

Request of \( \sim 10^{18} \) pot put strong constraint on duty cycle and could potentially affect other PS users. Studies with \( 10^{17} \) pot have been performed within the Conventional Beams WG.

See R. Carosi’s talk today and J. Bernhard’s talk tomorrow morning.
MilliQan, MATHUSLA, FASER, CODEX-b @ LHC IPs

C. Alpigiani, B. Dey, F. Kling talks today

Beam Dump Technique
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)
Physics Reach of the PBC-BSM projects in a Worldwide Context
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>
<thead>
<tr>
<th>Portal</th>
<th>Coupling</th>
</tr>
</thead>
<tbody>
<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>$\frac{a}{f_a} F_{\mu \nu} \tilde{F}^{\mu \nu}$, $\frac{a}{f_a} G_{i, \mu \nu} \tilde{G}<em>{i}^{\mu \nu}$, $\frac{\delta</em>{\mu, a}}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$</td>
</tr>
<tr>
<td>Sterile Neutrino, $N$</td>
<td>$y_N LHN$</td>
</tr>
</tbody>
</table>

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.
Dark Photon coupled to Light Dark Matter: connection with DM direct detection and cosmological bounds

Model where minimally coupled viable WIMP dark matter model can be constructed. The parameter space for this model is \( \{m_{A'}, \epsilon, m_\chi, \alpha_D\} \)

Direct DM scattering with e/protons: Direct Detection experiments

Production of DM at accelerators via electron or proton bremsstrahlung

Direct DM annihilation (main process to get the thermal relic abundance)
Dark Photon coupled to Light Dark Matter (Benchmark #2)

Model where minimally coupled viable WIMP dark matter model can be constructed. The parameter space for this model is: \( \{m_{A'}, \epsilon, m_{\chi}, \alpha_D\} \).

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\[
m(A') = 3 m(\chi) \\
\alpha(D) = 0.1
\]

Worldwide landscape outside PBC

Nice complementarity between accelerator-based proposals and Light DM direct detection experiments.
Model where minimally coupled viable WIMP dark matter model can be constructed. The parameter space for this model is: \( \{m_{A'}, \epsilon, m_\chi, \alpha_D\} \).

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\[ m(A') = 3 \, m(\chi) \]
\[ \alpha(D) = 0.1 \]

PBC projects: 5-15 years outlook

Nice complementarity between accelerator-based proposals and Light DM direct detection experiments.
Dark Photon coupled to SM particles (Benchmark #1)

The SM is augmented by a single new state $A'$. DM is assumed to be either heavy or contained in a different sector.

$$A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-, ....$$

Worldwide landscape

PBC projects 5 years outlook

Nice complementarity/competition with experiments in Japan, FNAL, JLAB, Mainz, PSI…..
Dark Photon coupled to SM particles (Benchmark #1)

The SM is augmented by a single new state $A'$. DM is assumed to be either heavy or contained in a different sector.

$$A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-, ....$$

Nice complementarity/competition with experiments in Japan, FNAL, JLAB, Mainz, PSI.....
Dark Scalar coupled to the Higgs (Benchmark #4-5)

The Higgs portal couples the dark sector to the Higgs boson via the bilinear $H\dagger H$ operator of the SM. The minimal scalar portal model operates with one extra singlet field $S$ and two types of couplings, $\mu$ and $\lambda$.

Benchmark 4: assume $\lambda=0$.

Relaxion DM?

Nice complementarity with colliders and astrophysical data
Dark Scalar coupled to the Higgs ( Benchmarks #4-5)

The Higgs portal couples the dark sector to the Higgs boson via the bilinear $H^\dagger H$ operator of the SM. The minimal scalar portal model operates with one extra singlet field $S$ and two types of couplings, $\mu$ and $\lambda$.

Benchmark 4: assume $\lambda=0$.

CERN-PBC-REPORT-2018-007

PBC projects: 10-15 year outlook

Nice complementarity with astrophysical data

Relaxion DM?
HNLs below the EW scale (benchmarks #6,7,8):

Neutrino portal extension of the SM is very motivated by the fact that it can be tightly related with the neutrino mass generation mechanism: Heany Neutral Leptons or HNLs. Choice of the PBC is to assume the single-flavor dominance, eg. HNLs couple only with one flavor of the active neutrinos at the time.
Neutrino portal extension of the SM is very motivated by the fact that it can be tightly related with the neutrino mass generation mechanism: Heany Neutral Leptons or HNLs. Choice of the PBC is to assume the single-flavor dominance, eg. HNLs couple only with one flavor of the active neutrinos at the time.

**Benchmarks 6, 7, 8: HNLs below the EW scale:**

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**Nice complementarity with FCC-ee**

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**Electron coupling dominance:** $U_e^2$: $U_e^2$: $U_e^2 = 1:0:0$

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**PBC projects: ~10-15 year outlook**
Axions and ALPS with photon coupling in the sub-eV mass range: PBC-BSM projects: baby-IAXO, IAXO and Jura

IAXO and JURA mostly considered in the Technology WG for support in:

- High Field Magnets
- Optics/optics sensing
- RF cavities
- Cryogenics
- Vacuum

(see I. Irastorza’s & A. Lindner’s talks today)
Axions and ALPS with photon coupling in the MeV-GeV mass range

Search for axions/ALPs: extremely lively and established field, mostly in the sub-eV mass range
Need of a systematic investigation in the MeV-GeV range.

Similar sensitivity plots for ALPs with fermion and gluon couplings in the PBC-BSM document

Nice complementarity of accelerator-based experiment with experiments in the sub-eV range and cosmological bounds
**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>
</tr>
<tr>
<td><strong>at the SPS:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KLEVER</td>
<td>$K_L \rightarrow \pi^0\nu\bar{\nu}$, $K_L \rightarrow \pi^0\pi^0$ 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</td>
</tr>
<tr>
<td>NA62++</td>
<td>zero background</td>
<td>partially included</td>
<td>analysis of $\sim 3 \cdot 10^{16}$ pot in dump mode</td>
</tr>
<tr>
<td>NA64++(e)</td>
<td>included</td>
<td>included</td>
<td>background, efficiencies evaluated from data</td>
</tr>
<tr>
<td>NA64++(μ)</td>
<td>in progress</td>
<td>in progress</td>
<td>test of the purity of the M2 line with COMPASS setup</td>
</tr>
<tr>
<td>NA64++($K_{S,L},\eta,\eta'$)</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>Full Geant4 simulation, digitization and reconstruction \n$\nu-$ interactions based on $2 \times 10^{20}$ pot \n$\mu-$ combinatorial and $\mu-$ interactions based on $\sim 10^{12}$ pot \nmeasurement of the muon flux at H4 performed in July 2018</td>
</tr>
<tr>
<td><strong>at the LHC:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<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>FASER</td>
<td>zero background assumed</td>
<td>not included</td>
<td>Fluka simulation and in-situ measurements</td>
</tr>
<tr>
<td>MATHUSLA200</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.
Axions and ALPS with gluon coupling as probes of the multi-TeV range

Study of the permanent EDMs in proton/deuteron and in charmed and strange baryons with the CP-EDM and LHC-FT proposals as probe of multi-TeV NP scale.

Current limits on EDMs of fundamental particles;

Expected improvements in the next o(10-20) years

White regions: safe BSM discovery territory;

SM estimates from $\theta_{QCD}$

Neutron EDM is leading the field for hadrons

EDMs of fundamental particles

PBC targets (CP-EDM and LHC-FT proposals)

See N.Neri's today and J.Pretz's talk tomorrow

SM estimates from CKM CP violation
KLEVER target:
measure $\sim 60$ SM $K_L \to \pi^0\nu\nu$ with S/B $\sim 1$, hence precision of 20% on the BR with 5 years running starting in Run 4. This requires x6 increase beam intensity wrt NA62.

Competition:
KOTO (JPARC) expects to reach SM sensitivity in 2021; Strong intention to integrate o(100) events with a major upgrade of line and detector but no official proposal yet.

New Physics can affect differently $K^+$ and $K_L$ channels

<table>
<thead>
<tr>
<th>Model</th>
<th>$\Lambda$ [TeV]</th>
<th>Effect on BR($K^+ \to \pi^+\nu\bar{\nu}$)</th>
<th>Effect on BR($K_L \to \pi^0\nu\bar{\nu}$)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptoquarks, most models</td>
<td>1–20</td>
<td>Very large enhancements; mainly ruled out</td>
<td></td>
<td>[338]</td>
</tr>
<tr>
<td>Leptoquarks, $U_1$</td>
<td>1–20</td>
<td>+10% to +60%</td>
<td>+100% to +800%</td>
<td>[338]</td>
</tr>
<tr>
<td>Vector-like quarks</td>
<td>1–10</td>
<td>−90% to +60%</td>
<td>−100% to +30%</td>
<td>[339]</td>
</tr>
<tr>
<td>Vector-like quarks + $Z'$</td>
<td>10</td>
<td>−80% to +400%</td>
<td>−100% to 0%</td>
<td>[339]</td>
</tr>
<tr>
<td>Simplified modified $Z$, no tuning</td>
<td>1</td>
<td>−100% to +80%</td>
<td>−100% to −50%</td>
<td>[340]</td>
</tr>
<tr>
<td>General modified $Z$, cancellation to 20%</td>
<td>1</td>
<td>−100% to +400%</td>
<td>−100% to +500%</td>
<td>[340]</td>
</tr>
<tr>
<td>SUSY, chargino $Z$ penguin</td>
<td>4–6 TeV</td>
<td>0% to +60%</td>
<td>−100% to −40%</td>
<td>[341]</td>
</tr>
<tr>
<td>SUSY, gluino $Z$ penguin</td>
<td>3–5.5 TeV</td>
<td>Small effect</td>
<td>−20% to +60%</td>
<td>[342]</td>
</tr>
<tr>
<td>SUSY, gluino $Z$ penguin</td>
<td>10</td>
<td></td>
<td>0% to +300%</td>
<td>[343]</td>
</tr>
<tr>
<td>SUSY, gluino box, tuning to 10%</td>
<td>1.5–3</td>
<td>±10%</td>
<td>±20%</td>
<td>[344]</td>
</tr>
<tr>
<td>LHT</td>
<td>1</td>
<td>±20%</td>
<td>−10% to −100%</td>
<td>[345]</td>
</tr>
</tbody>
</table>

(See M. Moulson’s talk today and J. Bernhard’s talk tomorrow)
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>
</thead>
<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>
</tr>
<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>
<td>840</td>
<td>ditto</td>
</tr>
</tbody>
</table>

See P.Collins’s talk today
PBC-BSM target: Axion and Axion-Like Particles

Schematic Physics Reach of PBC projects for axion/ALPs coupled to photons and gluons, compared to the LHC.

Large complementarity with the LHC, HL-LHC and future colliders programme.
PBC-BSM Working Group deliverables

✓ PBC-BSM work summarized in a ~140 pp long report: CERN-PBC-REPORT-2018-007 will be submitted to arXiv next week. as a support document of the main PBC document submitted to the ESPP update.

✓ Individual contributions submitted to the ESPP update: - REDTOP, IAXO, NA64++, KLEVER, SHiP, LDMX, TauFV, FASER, MATHUSLA.
  - IAXO and JURA also part of the document: “A European Strategy Towards Finding Axions and Other WISPs

✓ Food for thought for the ESPP Physics Preparatory Group....
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.
A warm thank you to the PBC main conveners (Claude, Joerg, Mike) and all the BSM WG members for the hard but very interesting work we have done together.
SPARES
**LHC-FT: EDMs in charmed hadrons**

EDM searches in different systems are complementary to disentangle the underlying source of CPV. Charmed hadrons EDMs predicted to be $\sim 10^{-32}$ e cm in SM (EPJC 77 (2017) 102).

If CP is broken maximally by some ”unspecified” strong interactions at a scale $\sim 1$-10 TeV that also does not respect chiral symmetry then

$$d \sim e \nu_{EW} / \Lambda^2 \sim \text{starts at} \ (10^{-17} - 10^{-18}) \text{ e cm}$$

If democratic among families – then of course excluded. ”Needs” a model that emphasizes charm quark.

- If perturbative: $x \sim 10^{-2}$, down to $(10^{-19} - 10^{-20})$ e cm level and below.
- If respecting chiral dynamics: $x \gamma_c \sim 10^{-2}$, down to $10^{-22}$ e cm

Use deflected beam halo to W target followed by a second bent crystal. Measure $s_x$ component of the spin precession in the E of the crystal.

See S. Radaelli’s talk this afternoon
KLEVER @ K12: an experiment to measure $K_L \to \pi^0 \nu \nu$ branching fraction

Current status: \[ \text{BR}(K_L \to \pi^0 \nu \nu) \text{ (SM)} = (3.4 \pm 0.6) \times 10^{-11} \]
\[ \text{BR}(K_L \to \pi^0 \nu \nu) \text{ (E391a)} < 2.6 \times 10^{-8} \text{ (90% CL)} \]
Axions with gluon coupling as DM candidates in sub-eV range

If the EDMs in proton, deuteron are generated by oscillating axions search for EDMs \(\rightarrow\) search for axions.

Interpretation of results is controversial because exclusion limits are strictly valid only for axions: they can be interpreted either as sensitivity plots or as exclusion plots of more complicated (controversial) models.
Search for axions/ALPs: extremely lively and established field, mostly in the sub-eV mass range
Need of a systematic investigation in the MeV-GeV range.

ALPS with fermion coupling in the MeV-GeV mass range
Search for axions/ALPs: extremely lively and established field, mostly in the sub-eV mass range
Need of a systematic investigation in the MeV-GeV range.
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 ($|Q| = |\varepsilon g D e|$) 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
The Higgs portal couples the dark sector to the Higgs boson via the bilinear \( H^\dagger H \) operator of the SM. The minimal scalar portal model operates with one extra singlet field \( S \) and two types of couplings, \( \mu \) and \( \lambda \).

Benchmark 5: assumes \( \lambda \neq 0 \), namely BR(H\( \rightarrow \)SS) \( \sim \) 1%.