CERN-FNAL HCP Summer School, 22-31 August 2023
Claude Vallée, CPPM Marseille

PARTICLE PHYSICS BEYOND COLLIDERS

...a short glimpse of a very lively and diverse landscape with emphasis on CERN projects

Lowering the energy...
...from LHC collisions to non-accelerator experiments

+ a few insights into
R&D for longer-term future PBC facilities

NB: credit to PBC working groups and projects for most plots shown here

More information on https://pbc.web.cern.ch/
THE CERN ACCELERATOR COMPLEX

Downwards energy steps:

- LHC collisions
- LHC Fixed Target
- SPS Fixed Target
- PS/Booster facilities
- Non-accelerator experiments
From high to low energies: global BSM landscape

- EDM & non-accelerator projects cover the very low-mass domain
- Precision & rare processes experiments extend reach of high-E colliders

From high to low energies: global BSM landscape

- EDM & non-accelerator projects cover the very low-mass domain
- Precision & rare processes experiments extend reach of high-E colliders

From high to low energies: global BSM landscape

- EDM & non-accelerator projects cover the very low-mass domain
- Precision & rare processes experiments extend reach of high-E colliders
From high to low energies: global QCD 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-$\mu_B$

hadronic matter

quark-gluon plasma
STARTING WITH LHC COLLISIONS:

DEDICATED LONG-LIVED PARTICLES (LLP) DETECTORS
LHC-LLP DEDICATED PROJECTS

Pioneered in run 3 by FASER/SND@LHC/milliQan

FASER: Dark photons & TeV neutrinos
480m from ATLAS IP

milliQan: milli-charged particles
33m from CMS IP

SND@LHC: TeV neutrinos
Slightly off axis opposite to FASER
PROPOSED LHC “LARGE ANGLE” LLP FAR DETECTORS

3 detectors of similar concept: **demonstrators and detailed simulations planned during run3**

- **MATHUSLA** on CMS surface
- **ANUBIS** in ATLAS access shaft
- **CODEX-b** in LHCb hall

Potential locations of detectors:
- **MATHUSLA** on CMS surface
- **ANUBIS** in ATLAS access shaft
- **CODEX-b** in LHCb hall

**Diagram:**
- Surface view showing detector layouts and locations in relation to CMS, ATLAS, and LHCb areas.
PROPOSED LHC “FORWARD” LLP FAR DETECTORS:

FORWARD PHYSICS FACILITY

Proposal for a dedicated underground cavern aimed at maximizing the HL-LHC physics reach in the forward region (LLPs, ν’s & QCD)

Conceptual design of the infrastructure well advanced

LoI to LHCC expected in 2025
1ST ENERGY STEP DOWNWARDS:

LHC FIXED-TARGET (FT@LHC)
FT@LHC: Gas Fixed Target with LHCb

FT@LHC pioneered by LHCb with SMOG gas jets in run 2 and SMOG2 gas storage cell in run 3

Impact of different types of gases (Kr, Xe, O₂, N₂, H₂, D₂) on LHC vacuum system under study

Development of a polarized gas storage cell also ongoing for future spin physics @LHC
FT@LHC: Crystal Fixed Targets

Good progress in the design and preparation of crystal set-ups

Single crystal set-up:
developed for beam cleaning\&collimation
and possible FT physics

Double crystal set-up:
for measurement of MDM and EDM of short-lived baryons

Proof of Principle set-up in preparation for installation at LHC IR3 during run 3
2\textsuperscript{nd} ENERGY STEP DOWNWARDS:

SPC FIXED-TARGET (FT@SPS)
The WORKHORSE of FT@SPS: the SPS NORTH AREA

**EHN1**: large surface hall with multi-purpose low-I beams
- QCD: NA60++ and NA61++
- BSM: NA64(e,h)

**ECN3**: unique underground hall for high-I hadron beams
- BSM: NA62(K⁺, BD), HIKE(K⁺⁰, BD)
- SHADOWS(BD), SHiP(BD)

**EHN2**: surface hall with unique high-E/high-I μ beam
- QCD: AMBER, MUonE
- BSM: NA64(μ)

The planned consolidation of the NA provides an opportunity for new experimental projects
AMBER “QCD FACILITY” (COMPASS++)

**Short term (run3):** proton radius puzzle with μ-p elastic scattering

**Longer term (excerpts):**

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

**With upgraded K-beam:**
Comprehensive measurement of strange spectroscopy
New idea introduced within PBC:

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

Complementary to predictions based on dispersion relation with \(e^+e^-\) data and on lattice QCD

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

First data taking aimed for during run 3
Ongoing (run 3):
• First study of open charm close to expected CP-region.
• Also unique measurements for $\nu$-beams and cosmic rays

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

New location found in EHN1 hall to avoid conflict with users of ECN3
$K \rightarrow \pi \nu \bar{\nu}$ (BR $\sim 10^{-10}$)

**PRECISION FT@SPS: NA62**

**Ultra-rare $K^+$ decays**

Regular data taking since 2016

**Run 2**: 20 events seen for 17 expected ($10$ SM + $7$ BG)

**Run 3**: detector upgraded to reach $\sim 100$ signal events

**Post-LS3 proposal (HIKE):**

$K^+$ intensity increase by factor $\sim 4$, followed by $K^0$ beam: $K^0$ rare decays complementary to $K^+$ decays for BSM searches.

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**Diagram**

75 GeV/c $K^+$ (6%)

Hadron Beam

800 MHz

Kaon identification

In CEDAR

Measure Kaon:

- Time
- Angles
- Momentum

CHANTI

GTK

Kaon identification

Decay Region 65m

STRAW Tracker

RICH

Vetos

$\pi$ Identification

LKR

MUV

C. Vallée, HCP Summer School 2023 Particle Physics Beyond Colliders
Two Highlights:

CKM matrix unitarity test

LFU: Kaons complementary to B mesons
FT@SPS: BEAM DUMPS (BD)

Visible decay to SM particles

\[ \text{signal} \propto \epsilon^4 \]

Critical: BG control

Recoil e/N from rescattering

\[ \text{signal} \propto \epsilon^4 \]

Critical: BG control

Missing energy from invisible decays

\[ \text{signal} \propto \epsilon^2 \]

Critical: initial particle and pileup control

NB: reach in \((m, \epsilon)\) depends on many parameters:

beam energy & intensity, decay vessel length, signatures, background ...
HIDDEN SECTOR MAIN PRODUCTION MODES IN A BEAM DUMP

Primakov/Bremstrahlung:
Mass reach mainly in sub-GeV domain, weakly dependent on beam energy

Meson decays:
Mass reach in multi-GeV domain dependent on accessible meson mass thresholds (K,D,B)

EXPERIMENTAL VISIBLE SIGNATURES

<table>
<thead>
<tr>
<th>Models</th>
<th>Final states</th>
</tr>
</thead>
<tbody>
<tr>
<td>HNL, SUSY neutralino</td>
<td>$l^+\pi^-, l^+K^-, l^+\rho^- \rho^+ \rightarrow \pi^+\pi^0$</td>
</tr>
<tr>
<td>Vector, scalar, axion portals, SUSY sgoldstino</td>
<td>$l^+l^-$</td>
</tr>
<tr>
<td>HNL, SUSY neutralino, axino</td>
<td>$l^+l^-\nu$</td>
</tr>
<tr>
<td>Axion portal, SUSY sgoldstino</td>
<td>$\gamma\gamma$</td>
</tr>
</tbody>
</table>

+ recoil particles or missing energy for rescattering / missing energy methods
**MAIN BEAM DUMP PROJECTS OUTSIDE CERN**

<table>
<thead>
<tr>
<th>EXPERIMENT</th>
<th>PERIOD</th>
<th>BEAM</th>
<th>PARTICLES ON TARGET</th>
<th>SIGNATURE</th>
<th>MODELS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDX @JLAB</td>
<td>~2024-25</td>
<td>e 11 GeV</td>
<td>~10^{22}</td>
<td>recoil e</td>
<td>DP, ALPs</td>
</tr>
<tr>
<td>LDMX @SLAC</td>
<td>&lt; 2030</td>
<td>e 4-8 GeV</td>
<td>2 \times 10^{16}</td>
<td>invisible</td>
<td>DP, ALPs</td>
</tr>
<tr>
<td>SBND @FNAL</td>
<td>&lt; 2030</td>
<td>p 8 GeV</td>
<td>6 \times 10^{20}</td>
<td>recoil Ar</td>
<td>DP</td>
</tr>
<tr>
<td>DarkQuest @FNAL</td>
<td>2024</td>
<td>p 120 GeV</td>
<td>10^{18} \rightarrow 10^{20}</td>
<td>visible e^+e^-</td>
<td>DP, DS, HNL</td>
</tr>
<tr>
<td>LBND @FNAL</td>
<td>&lt; 2040</td>
<td>p 120 GeV</td>
<td>~10^{21}</td>
<td>recoil e, N</td>
<td>DP, DS, HNL</td>
</tr>
</tbody>
</table>

*Recent dedicated experiments demonstrate a regain of interest for beam dumps.*

Flavour factories (BELLE II, ...) have also some sensitivity from exotic decays.
### BEAM DUMP PROJECTS AT CERN

<table>
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<th>BEAM</th>
<th>PARTICLES ON TARGET</th>
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<th>MODELS</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA64(e)</td>
<td>ongoing</td>
<td>e 100 GeV</td>
<td>~5 (10^{12})</td>
<td>invisible &amp; visible e^+e^-</td>
<td>DP, ALPs</td>
</tr>
<tr>
<td>NA62-BD</td>
<td>2022-25</td>
<td>p 400 GeV</td>
<td>(10^{18})</td>
<td>visible</td>
<td>DP, ALPs</td>
</tr>
<tr>
<td>HIKE/SHADOWS</td>
<td>2030-40</td>
<td>p 400 FeV</td>
<td>(5 \times 10^{19})</td>
<td>visible</td>
<td>DP, DS, HNL, ALPs</td>
</tr>
<tr>
<td>BDF/SHiP</td>
<td>2030-50</td>
<td>p 400 GeV</td>
<td>(6 \times 10^{20})</td>
<td>recoil &amp; visible</td>
<td>DP, DS, HNL, ALPs</td>
</tr>
<tr>
<td>NA64(µ,h)</td>
<td>&gt; 2024</td>
<td>µ, h &gt; 100 GeV</td>
<td>(2 \times 10^{13})</td>
<td>invisible</td>
<td>DZ_µ, ALPs</td>
</tr>
</tbody>
</table>

**NB:** CERN offers unique opportunities with both lepton and hadron beams. LHCb and LHC-LLP dedicated projects have also sensitivity in similar mass range.

DP = Dark Photon  
DS = Dark Scalar  
HNL = Heavy Neutral Lepton  
ALP = Axion-Like Particle
BD@SPS: NA64

**NA64(e):**
cheap e-beamdump setup implemented in 2015 on H4 e test beam, now permanent.
Optimized for invisible production, currently leading the field for dark photons

**NA64(µ,h):** proposed extensions of the method to other types of beams

**μ beams:**
test of $(g-2)_µ$ interpretations and µ-coupled dark sector

**Hadron beams:**
meson decays to invisible particles and leptophobic dark sector
BD@SPS: NA62 PROTON BEAM DUMP MODE

Some NA62 data taking in beam dump mode during run 3

Achieved by closing the TAX collimator, $\sim 10^{18}$ PoT expected until LS3

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

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Particle Physics Beyond Colliders 25
POST-LS3 BD@SPS PROPOSAL: HIKE & SHADOWS

New SHADOWS detector slightly off axis close to TAX dump collimator would increase acceptance at high mass of a high-intensity beamdump mode of HIKE.

This post-LS3 BD option could cumulate ~5. $10^{19}$ PoT on the HL-LHC timescale.
POST-LS3 BD@SPS PROPOSAL: BDF/SHiP@ECN3

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

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

Active magnetic muon filter

Spectrometer for DM decays

DM decay vessel

Relocation in ECN3 and re-optimization studied to reduce the overall BDF/SHiP cost
A highlight of PBC for EPPSU: definition and wide acceptance of hidden sector benchmark models to compare reach of projects under same assumptions.

See FIPs2022 workshop proceedings arXiv:2305.01715 for latest news.
EXCERPTS OF FIPs2022 COMPARISONS OF PROJECTS REACH

**BC1**
Dark photon visible decay to SM

**BC2**
Dark photon decay to scalar DM
\[ \alpha_\Delta = 0.1 \]
\[ m_\chi = \frac{1}{3} m_{\Delta} \]

**BC4**
Dark scalar mixing with Higgs

**BC6**
Dark HNL coupling to e
BC1  Dark photon visible decay to SM

BC4  Dark scalar mixing with Higgs

BC2  Dark photon decay to scalar DM

BC6  Dark HNL coupling to e

NB: imminent update for ECN3 in CERN PBC  Report-2023-003!
3rd ENERGY STEP DOWNWARDS:

PS AND LOW-E FACILITIES
ANTIMATTER FACTORY

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

ELENA recent upgrade enhances potential for this decade

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
ANTIMATTER FACTORY

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

e.g. BASE DM axion searches

Axion signal

expected limits in IAXO magnet

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
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
4th ENERGY STEP DOWNWARDS:

NON-ACCELERATOR EXPERIMENTS
INTERNATIONAL AXION OBSERVATORY
(axion helioscope successor of CAST@CERN)

BabyIAXO precursor approved and in construction at DESY
with CERN PBC support to magnet design

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

Among other studies:
• SC cavities and coating for novel relic axion detection
• Setup for cosmic neutrino background measurement (PTOLEMY)

AION
Atom interferometry for ultra-light DM and mid-frequency gravitational waves
• PoP 10m setup being built in UK
• Possible siting of a 100m setup in a CERN LHC shaft investigated in PBC
• Longer Baseline Terrestrial Atom Interferometry already under study, e.g. workshop at CERN: (https://indico.cern.ch/event/1208783/)
R&D FOR LONGER-TERM FUTURE PBC FACILITIES

(excerpts)
PROTON EDM RING

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

Prototype E/B ring
~30 m Ø

Final ring
≈ 150 m

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...
Novel e-Beam: AWAKE++

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

Proof of principle validated 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
**Novel NEUTRINO BEAMS**

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

**ENUBET:**
- $\nu_e$ beam monitored from K decays
- Prototyping performed in Neutrino Platform

**NuTAG:**
- $\nu_\mu$ beam with $(E_\nu, \theta_\nu, \phi_\nu)$ tagged from individual $\pi$ decays with HL-LHC silicon trackers

![Diagram of neutrino beam production and detection](image)
Important milestone reached within PBC with successful acceleration and storage of Partially Stripped Ions in LHC

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

Proof of Principle experiment with full configuration in preparation at SPS

Applications in atomic, nuclear, particle and applied physics discussed in many workshops and publications
OUTLOOK

Many opportunities for forefront physics beyond LHC and future high-energy frontier colliders!

The choice is Yours...
ADDITIONAL SLIDES
## MAIN PAST BEAM DUMP PROJECTS

<table>
<thead>
<tr>
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<th>MODELS</th>
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<tbody>
<tr>
<td>E137 @SLAC</td>
<td>80’s</td>
<td>e 20 GeV</td>
<td>$2 \times 10^{20}$</td>
<td>recoil e</td>
<td>DP, ALPs</td>
</tr>
<tr>
<td>E141 @SLAC</td>
<td>80’s</td>
<td>e 9 GeV</td>
<td>$2 \times 10^{15}$</td>
<td>visible e$^+e^-$</td>
<td>DP, ALPs</td>
</tr>
<tr>
<td>E774 @FNAL</td>
<td>80’s</td>
<td>e 275 GeV</td>
<td>$5.2 \times 10^9$</td>
<td>visible e$^+e^-$</td>
<td>DP</td>
</tr>
<tr>
<td>NuTeV @FNAL</td>
<td>90’s</td>
<td>p 800 GeV</td>
<td>$2 \times 10^{18}$</td>
<td>visible $\mu$</td>
<td>HNL</td>
</tr>
<tr>
<td>NUCAL @Serpukhov</td>
<td>80’s</td>
<td>p 70 GeV</td>
<td>$1.7 \times 10^{18}$</td>
<td>visible $\gamma\gamma$, e$^+e^-$, $\mu^+\mu^-$</td>
<td>DP, DS, ALPs</td>
</tr>
<tr>
<td>PS191 @CERN</td>
<td>80’s</td>
<td>p 19 GeV</td>
<td>$0.8 \times 10^{19}$</td>
<td>visible</td>
<td>HNL</td>
</tr>
<tr>
<td>CHARM @CERN</td>
<td>80’s</td>
<td>p 400 GeV</td>
<td>$2.4 \times 10^{18}$</td>
<td>visible $\gamma\gamma$, e$^+e^-$, $\mu^+\mu^-$</td>
<td>DP, DS, HNL</td>
</tr>
</tbody>
</table>

**NB:** most past beam dumps were “cheap” by-products of other experiments

DP = Dark Photon  
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HNL = Heavy Neutral Lepton  
ALP = Axion-Like Particle
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
AMBER\( (R_p) \)  
\( \mu \)-\( p \) elastic scattering

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

\( \rightarrow \) AMBER Spectrometer  
(ex-COMPASS)

new AMBER TPC

Proton radius puzzle

Data taking planned during run 3
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
NEUTRON EDM IS LEADING THE FIELD FOR HADRONS
Catching up in precision is a challenge for the proton
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
Main issues:

- 2 GeV continuous proton beam (PS best option but non-nominal for REDTOP)
- Demanding detector technology (Optical TPC and dual readout calorimetry)

Also in discussion at FNAL