Highlights of the 2022 Physics Beyond Colliders Workshop at CERN

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Fermilab

Fermilab Theory Seminar · January 12, 2023

Physics Beyond Colliders Study Group (2016–)

Develop ideas to renew CERN's fixed-target program

Charge: 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.

Primarily investigate, and, where appropriate, provide support to, projects expected to be sited at CERN. May also examine ideas and provide initial support for contributions to projects external to CERN.

Create 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.

Example Physics Objectives

- Dedicated experiments for studies of rare processes and searches for feebly interacting particles
- Projects aimed at addressing fundamental particle physics questions using the experimental techniques of nuclear, atomic, and astroparticle physics
- Emerging technologies such as quantum sensors, that would benefit from the contribution of CERN competences and expertise
- Respond to community initiatives outside the current CERN program

Diversity and Scale Diversity

Project X at Fermilab (2013)

Recent Fermilab Community Engagement

Snowmass Neutrino Frontier, arXiv:2211.08641

Rare Processes and Precision Frontier, arXiv:2210.04765

Lightning Tour of Fermilab Program and Plans
Bonnie Fleming's December Colloquium slides and video

Lia's Planning for P5 Committee

Current PBC Organization

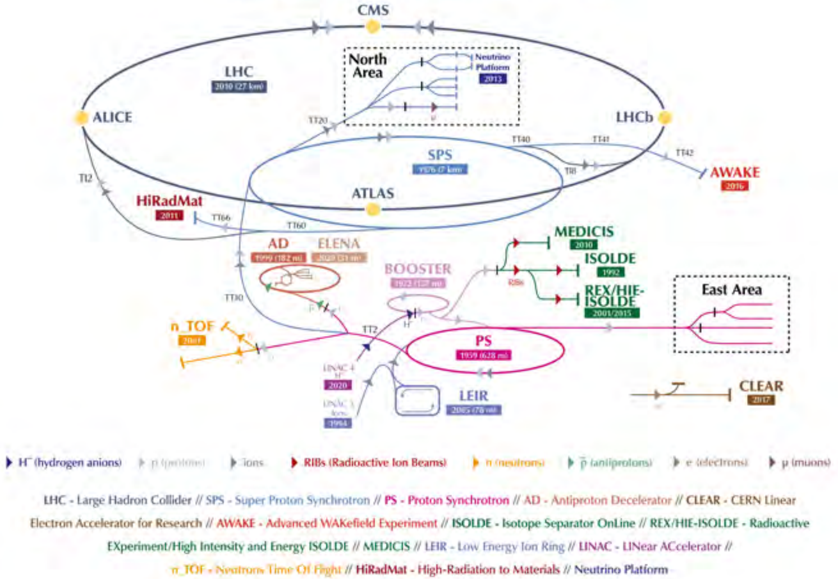
Coordinators

Gianluigi Arduini (CERN), ACC
Jörg Jaeckel (Heidelberg), TH
Claude Vallée (Marseille), EXP

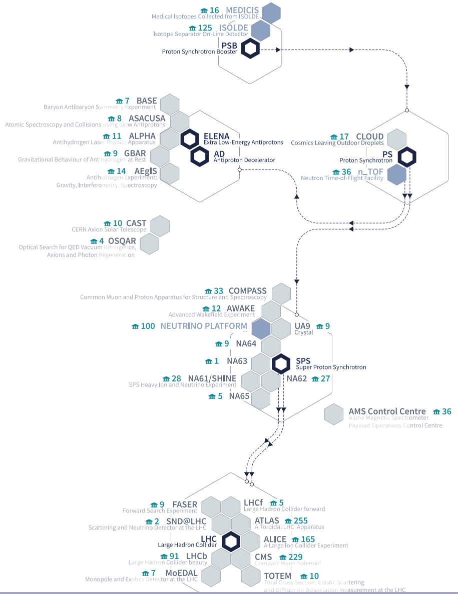
2019 Summary Report
arXiv:1902.00260
⇝ Eurostrategy Update

- Accelerator Complex Capabilities
- Beam Dump Facility
- BSM Physics Working Group
- Charged particle Electric Dipole Moment (cpEDM) measurement
- Conventional Beams
- Feebly Interacting Particles Physics Centre
- Forward Physics Facility
- Gamma Factory
- LHC fixed target

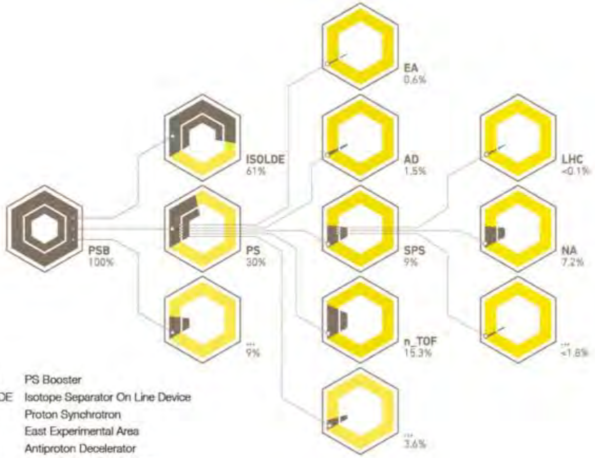
CERN Accelerator Complex



Where Protons Go



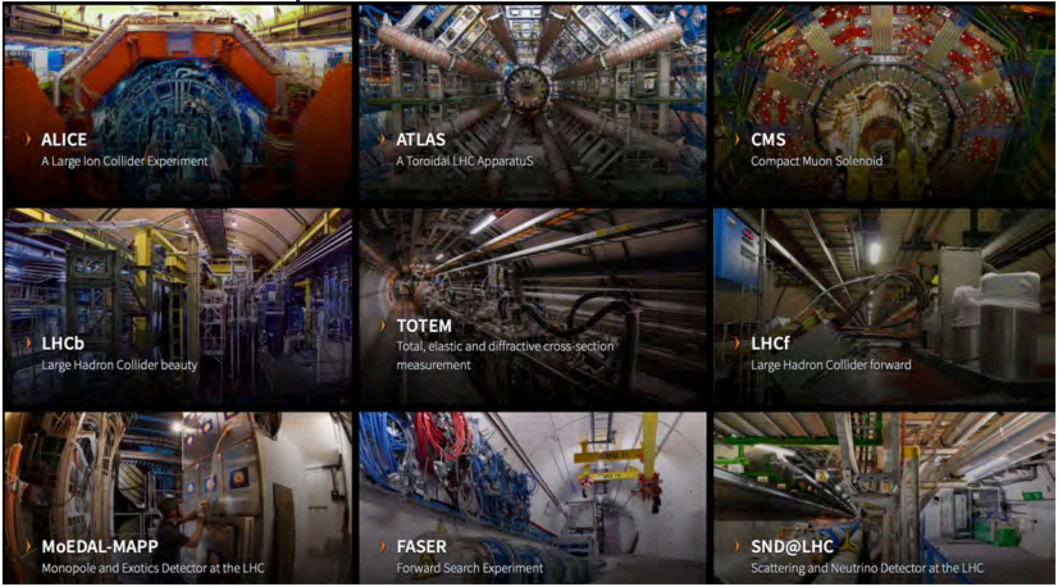
CERN Proton Economy



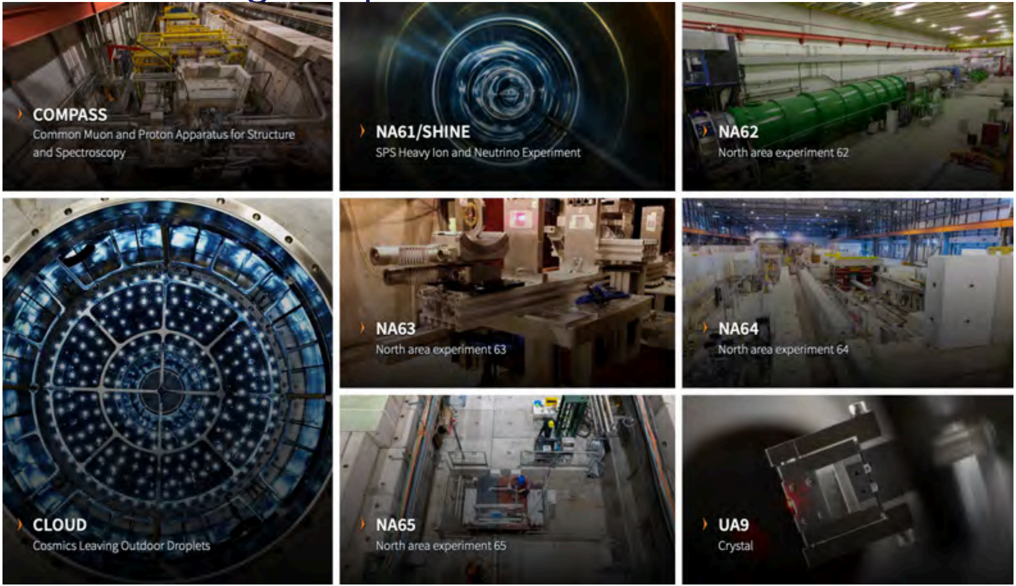
PSB	PS Booster
ISOLDE	Isotope Separator On Line Device
PS	Proton Synchrotron
EA	East Experimental Area
AD	Antiproton Decelerator
SPS	Super Proton Synchrotron
n_TOF	Neutron Time-of-Flight facility
LHC	Large Hadron Collider
NA	North Experimental Area
...	Other uses, including accelerator studies (machine development)

Quantity of protons used in 2016 by each accelerator and experimental facility, shown as a percentage of the number of protons sent by the PS Booster

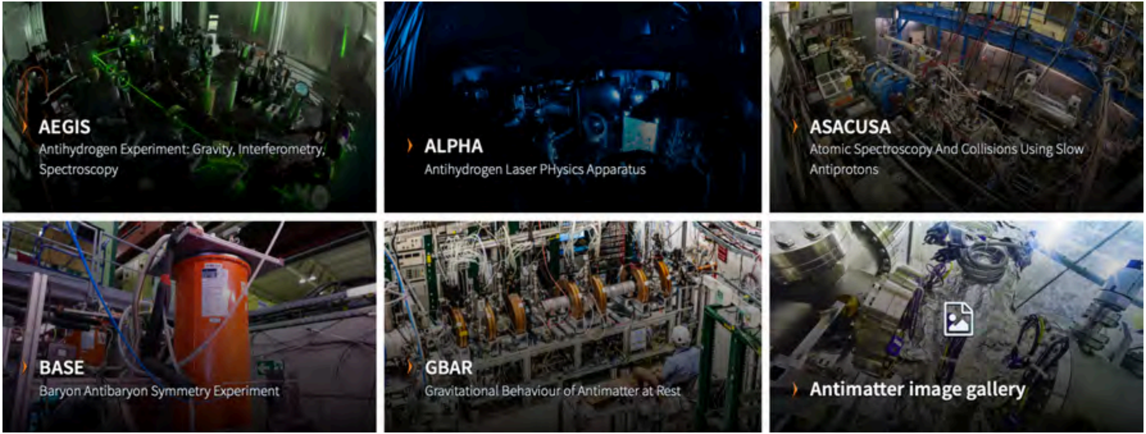
Current Collider Experiments



Current Fixed-Target Experiments



Current Antimatter Experiments



Externalities 1

Russia's invision of Ukraine → Council's main decisions:

- ❑ **Strongly supported the people of Ukraine as well as the independence, sovereignty and territorial integrity of Ukraine**

- ❑ **Condemned the military invasion of Ukraine by the Russian Federation** with the involvement of Belarus
- ❑ **Deplored the resulting loss of life** and the humanitarian impact

- ❑ Strongly condemned the statements of Russian institutes which had expressed support for the illegal invasion of Ukraine

- ❑ **Suspended the Observer's status of Russia and JINR**
- ❑ **Decided that CERN would not engage in new collaborations with Russia, Belarus and JINR**

- ❑ **Declared that it intends to terminate the International Cooperation Agreements (ICAs) between CERN and the Russian Federation and Belarus effective at their expiration dates** (Jun 2024 for Belarus and Dec 2024 for Russia) and **review CERN's future participation under the ICA concluded between CERN and JINR well in advance of its expiration date** (Jan 2025). **However, the situation will continue to be monitored** carefully and the Council stands ready to take any further decision in the light of developments of the situation in Ukraine

Externalities 2

- **Multi-pronged package of posssible measures developed, upon request by the Council**, **as risk mitigation strategy:** staging/descoping/termination of some CERN activities; reduction of personnel costs; additional contributions from the Member and Associate Member States.
  Presented to the Council in December → very well received.

- **Two measures will be implemented in 2023** to cope with high-inflation:
  - **reduction of the accelerator operation by 20%**
  - **2.5% "crisis levy" on staff basic salaries, as proposed by and discussed with the Staff Association** → THANK YOU!!

- **The other measures** (for 2024 and beyond) **will be implemented only if and when needed**, based on the evolution of the financial situation and CERN's priorities and needs with time, **with decision taken annually in the context of the Medium-Term Plan**.

- **Additional contributions from Member and Associate Member States being considered by the Council**
  → discussion will continue in March

Supply-chain issues: helium, argon, specialty gases, . . .

Expiration of highly favorable electricity contracts

Aspirations for HL-LHC, FCC, . . .

On the Agenda in November 2022

HIKE: High-Intensity Kaon Experiments
SHADOWS: Search for Hidden And Dark Objects With the SPS
SHiP @ECN3: Search for Hidden Particles
TauFV: "ultimate τ/charm factory"

Forward Physics Facility Design & Physics
FLARE: far-forward liquid argon ν detector

FIPs at Large Angle: ANUBIS, CODEX-b, MATHUSLA
First beam-gas events in LHCb/SMOG2
ALICE-FT: bent-crystal extraction

Double-crystal fixed-target physics: charm and τ magnetic moments
NA60++: Heavy Ions at SPS (high μ_B)
NA61++: Particle production at SPS
AMBER Phase-2: COMPASS follow-on
NA64++: Missing-energy events with $e^{\pm}, \mu, \pi, K, p$ beams
Gamma Factory @ SPS: circulating H-like Xe excited by laser $\rightsquigarrow$ HE γ
cpEDM: Electrostatic rings
$+$ nonaccelerator experiments, including AION-100 $\|$ MAGIS

Projects in and around NA62 enclosure (ECN3) 1

HIKE: High-Intensity Kaon Experiments (follow-on to NA62)

Phase 1: Multipurpose K^+ experiment

$K^+ \to \pi^+ \nu \bar{\nu}$ branching ratio to 5% relative precision, $\approx \delta_{\text{theory}}$.

Precision measurements of $K^+ \to \pi^+ \ell^+ \ell^-$; lepton universality test.

Search for lepton flavor/number violating decays; ℓ universality tests

Relative branching ratios of main modes to permille relative precision

Improvement of other existing rare decay modes

Searches for production of feebly-interacting particles in K^+ decays.

Collection of a dataset in beam-dump mode

Projects in and around NA62 enclosure (ECN3) 2

HIKE: High-Intensity Kaon Experiments (follow-on to NA62)

Phase 2: Multipurpose K_{L} experiment

Observe of the ultra-rare decays $K_{\mathrm{L}} \to \pi^0 \ell^+ \ell^-$ or set limit $\lesssim \mathrm{O}(10^{-11})$

easure $K_{\mathrm{L}} \to \mu^+ \mu^-$ branching ratio to 1%

Search for lepton flavor violating decays at the $\mathrm{O}(10^{-12})$ sensitivity

Relative branching ratios of main decay modes to permille precision

More beam dump running; Define neutral beam necessary for Phase 3.

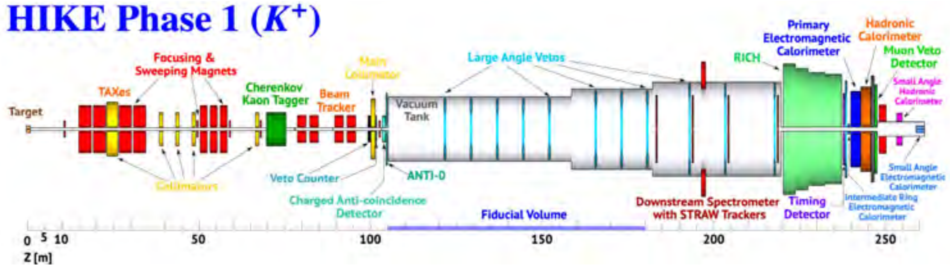
Phase 3: KLEVER

Measure $K_{\mathrm{L}} \to \pi^0 \nu \bar{\nu}$ to 20%

Search for production and decay of feebly-interacting particles

Search for additional FCNC K_{L} decays and forbidden K_{L} decays

Projects in and around NA62 enclosure (ECN3) 3



K^+ : 1.2 10^{13} protons on T10 per spill (4.8 sec)

- Decay in flight technique, experience from NA62 and similar layout
- Essential K^+ ID, momentum, space and time
- High-rate, precision tracking of pion
- Minimize material
- Highly efficient PID for photons, pions, electrons and muon vetoes
- Highly efficient and hermetic photon vetoes
- High-performance EM calorimeter (energy resolution, time, granularity)

Improved timing is the crucial element to be able to increase intensity 4 x NA62

Statistical power:
2 10^{13} Kaon decays in decay volume per year

Technological solutions exists for all detectors

LOI: arXiv:2211.16586

Projects in and around NA62 enclosure (ECN3) 4

SHADOWS: a "sidecar" to HIKE–DUMP

✓ SHADOWS is a proposed proton beam dump experiment for FIP physics that can be built in ECN3 and take data concurrently to HIKE (operated in beam-dump mode).

✓ SHADOWS ($5\mathrm{x}10^{19}$ pot) has similar/better sensitivity than CODEX-b ($300\ \mathrm{fb}^{-1}$) and FASER2 ($3\ \mathrm{ab}^{-1}$) for FIPs from charm/beauty:
⇨ It naturally complements HIKE-dump that is mostly sensitive to very forward objects, and HIKE-K that is mostly sensitive to FIPs below the K-mass.

✓ NaNu@SHADOWS can enrich the physics programme with active neutrino physics
⇨ it naturally complements FASERnu@LHC and SND@LHC covering a different region in phase space.

✓ ECN3 with SHADOWS+HIKE can become a "hot spot" on worldwide scale for FIP physics after LS3, fully compatible with a superb flavor programme in ECN3.

Projects in and around NA62 enclosure (ECN3) 5

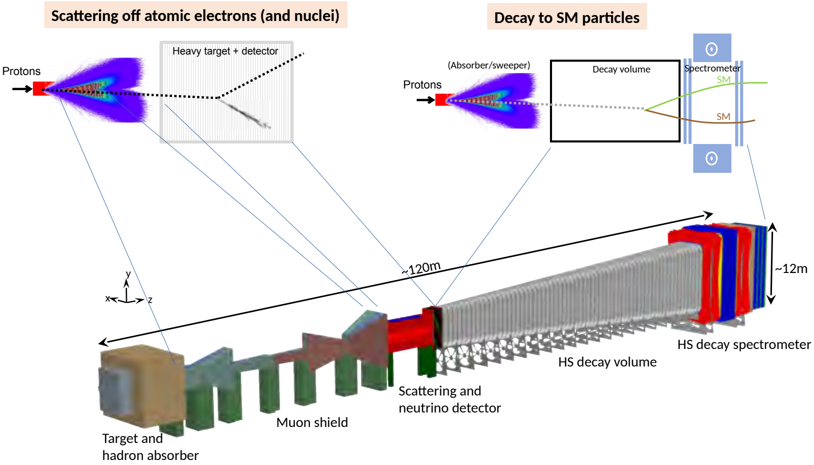
SHiP: Search for Hidden Particles

The SHiP experiment is designed to both search for decay signatures of models with Hidden Sector particles, such as heavy neutral leptons, dark photons, dark scalars, etc, by full reconstruction and particle identification of Standard Model final states, and to search for Light Dark Matter scattering signatures by the direct detection of recoil of atomic electrons (or nuclei) in a high-density medium. The experiment is also optimized to make measurements on tau neutrinos and on neutrino-induced charm production by all three species of neutrinos.

Projects in and around NA62 enclosure (ECN3)

SHiP as presented in CDS(ECN4) report

Dual-platform experiment combining two direct search techniques



Projects in and around NA62 enclosure (ECN3) 7

SHiP: Search for Hidden Particles

- ✓ ***ESPP concluded that BDF/SHiP as one of the front-runners among the larger scale new facilities investigated within CERN PBC.***
- ✓ ***But the project could not be recommended due to financial challenges associated with the other recommendations***

- ✓ *2020 Sep: CERN launches continued BDF R&D with SHiP MoU on top of existing collaboration agreement*

- ✓ *Extensive Layout and Location optimisation study at CERN*
  → BDF/SHiP @ ECN3 provides the best cost-effective solution (Facility cost at the existing ECN3 line is lower than the original cost by a factor)

- ✓ ***2022 July: CERN launches dedicated studies of future programme in ECN3 beam facility & decision process***

SHiP: Search for Hidden Particles

- ✓ ***BDF/SHiP @ ECN3 performance for HS exploration same as in CDS(ECN4) design: signal acceptance and „zero BG“ thanks to high redundancy in BG suppression strategy***
- ✓ ***LDM sensitivity under study and may even improve compared to CDS(ECN4), with very good prospects to have the same performance for the neutrino programme as in CDS(ECN4)***

- ✓ *Complementary to FIP searches at HL-LHC and future e^+e^- collider.*
  Clear window of opportunities to discover HS particles with SHIP/BDF @ECN3, with the best discovery potential in this parameter region and relatively modest investments.

- ✓ *The sensitivity of the discovery experiment crucially depends on the available pots, signal acceptance and background control. The 10 years of R&D and simulation studies of the BDF/SHiP performance were very useful to optimise these parameters.*

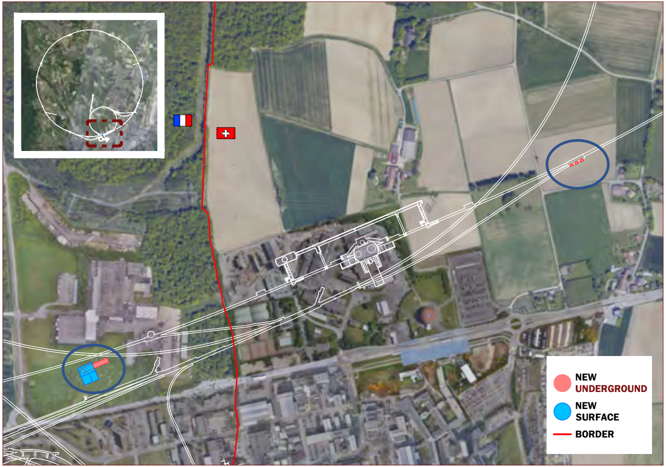
- ✓ *All relevant detector systems have undergone prototype testing in test beam (example: LS-SBT)*
  → Main technological challenges identified (with work packages defined in CDS report) which will be addressed during TDR phase with full-size prototype production

- ✓ *BDF/SHiP @ECN3 with 47 institutes from 17 countries and 237 participants ready to set off*

Forward Physics beyond FASER 1

Site Selection

K. Balazs, J. Osborne - SCE



After several studies by CERN civil engineering team, looking at options around both the ATLAS and CMS interaction points, two options were retained for further detailed study. After a preliminary costing of each we have now converged on the dedicated new facility in the SM18 area as the baseline proposal. This is ~600m from the ATLAS IP (to the west), and is situated on CERN land.

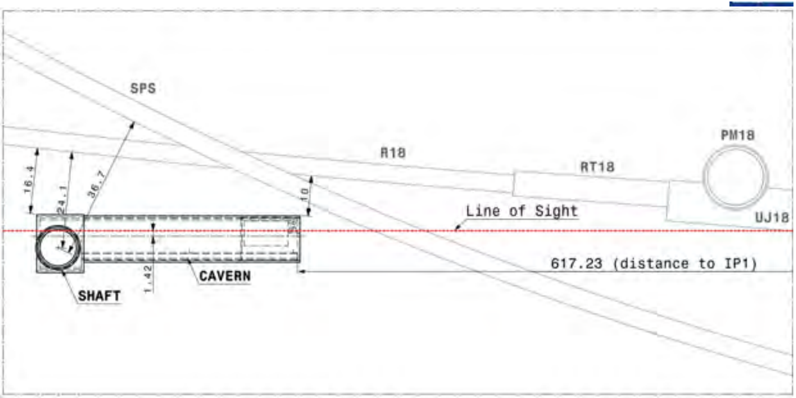
3

Forward Physics beyond FASER 2

FPF Facility:

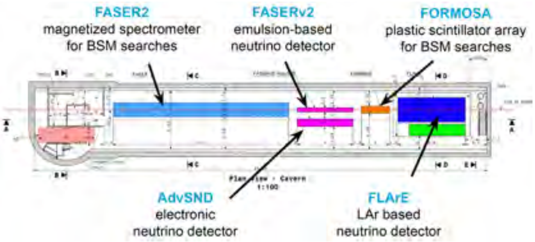
65m long, 9.7m wide, 7.7m high cavern.
Connected to surface through 88m high shaft (9.1m diameter): 617m from IP1.

Require that cavern is at least 10m from LHC for structural stability during digging.

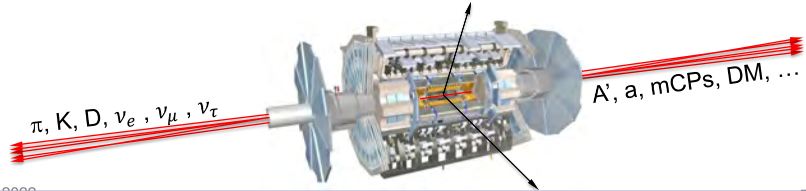


Forward Physics beyond FASER 3

- At present there are 5 experiments being designed to explore the breadth of SM and BSM topics. FPF covers $\eta > 5.5$, experiments on LOS cover $\eta \gtrsim 7$.



- Large far-forward fluxes are automatically provided by the LHC and can be exploited with small and inexpensive detectors. For example,
  - ~10^6 TeV-neutrino interactions per 10 tonnes.
  - ~10^6 dark photon decays can be observed in currently viable regions of param space.

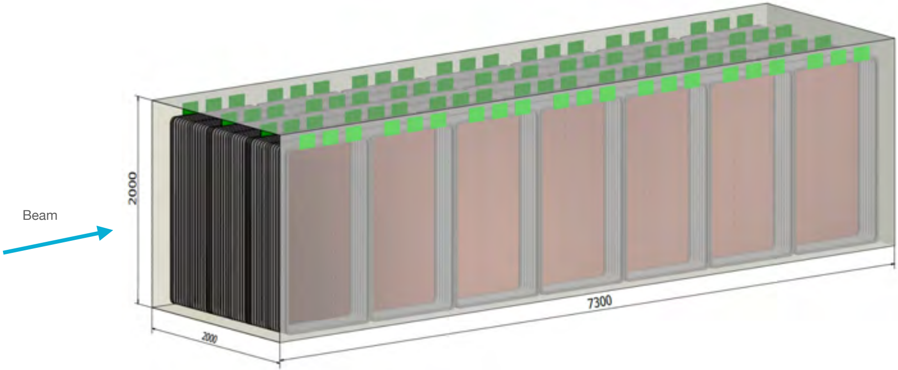


FLARE Rates in the HL-LHC Era

Neutrinos in TeV range: ∼20-50 events/ton/day 40 tons, 29 m^3 LAr

ν_τ flux and associated heavy flavor physics: 0.1-0.2 events/ton/day

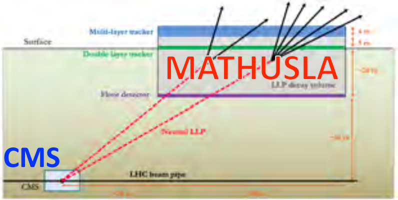
Light dark matter search with decays and interactions.

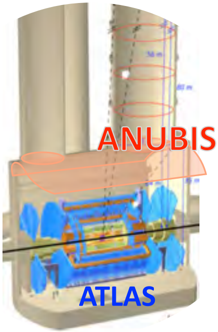


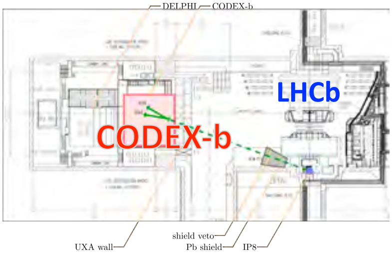
Transverse Searches for Long-Lived Particles

ANUBIS, CODEX-b, and MATHUSLA

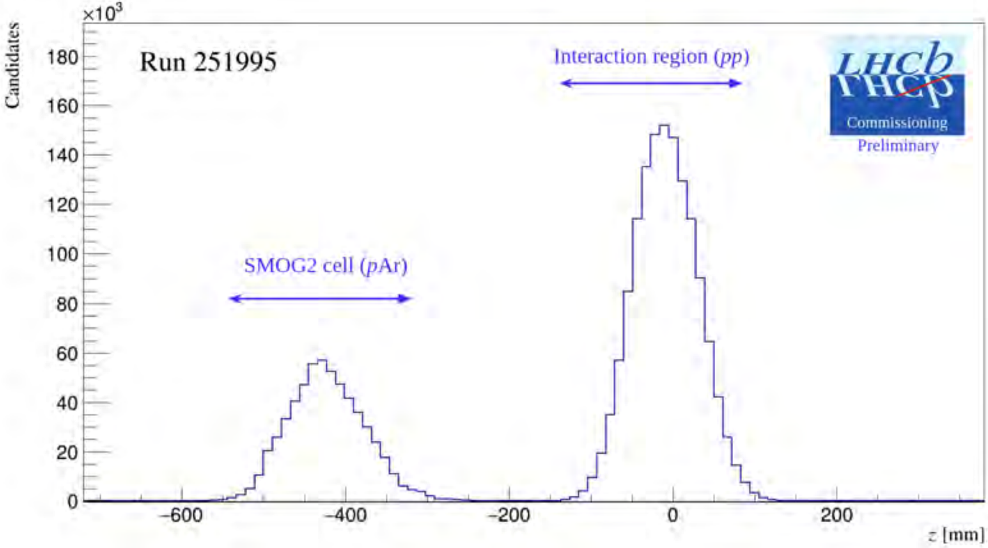
Shielded tracking volumes off-axis to the beam, and aligned with the main LHC detectors





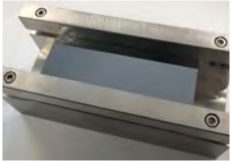


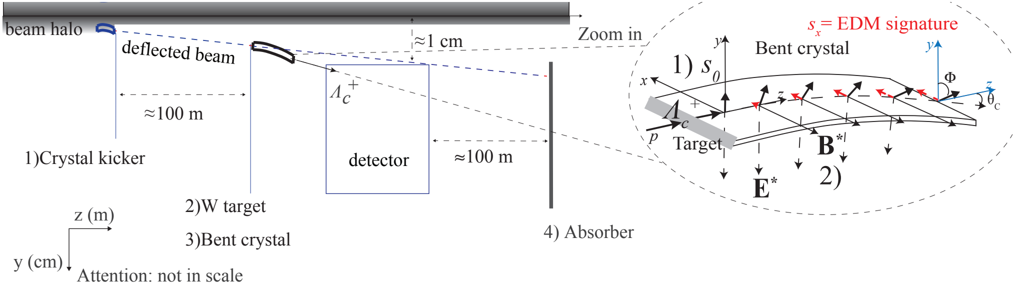
Second Interaction Region for LHCb: Gas Jet



Magnetic & Electric Dipole Moments (Bent Crystals @ LHCb)

- EDM/MDM from spin precession of channeled baryons in **bent crystals**





p extraction

Λ_c^+ polarised production

channeling

spin precession

event reconstruction

(My) Outlook . . .

ECN3 Verdict in Spring 2023?
FPF, ECN3 are coupled by fiscal unitarity
Hard to imagine both moving ahead quickly

Many imaginative ideas; how urgent, how practical?

Fermilab would benefit from similar engagement & enthusiasm
At CERN, presence of many gifted people running experiments is an asset

How can we cultivate a more diverse and inclusive suite of experiments?