The CERN Fixed Target Program - Beyond Collider

Eva Barbara Holzer
SPS and PS Physics Coordinator

UK Accelerator Institutes Seminar Series
May 30th, 2024
https://indico.cern.ch/event/1410360/

CERN “Injector Complex”

- World class fixed-target research program, which complements CERNs flag-ship collider physics program
- Highly versatile test beam and irradiation program, essential for the design, prototyping and construction of future physics experiments and new accelerator generations.

Related Recent UK Accelerator Institutes Seminars

This seminar builds on and complements the “Physics at the CERN Secondary Beamlines” seminar from 15 February 2024

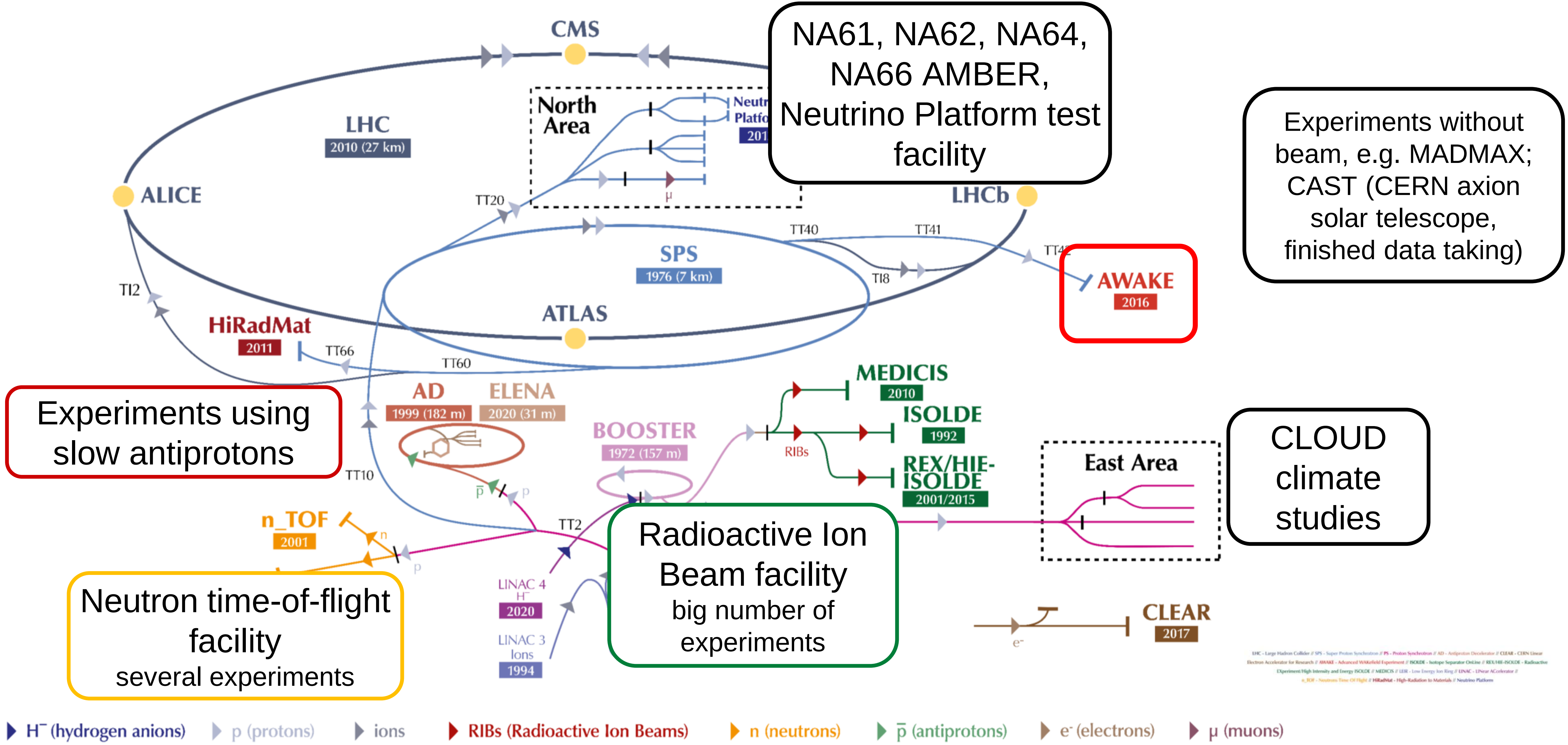
- Physics at the CERN Secondary Beamlines (Nikolaos Charitonidis)
  - SPS North Area, available beams and mayor experiments
    - NA61, NA62, NA64, NA66 AMBER
  - PS East Area and CLOUD Experiment

- Antimatter Gravitation Studies with Trapped Antihydrogen (William Alan Bertsche)
  - ALPHA experiment at the CERN AD/ELENA antiproton decelerators
- AWAKE: beam-plasma interaction studies, and plasma wakefield acceleration for application to particle physics (Patric Muggli)
  - AWAKE experiment at the SPS

Outline

- The CERN “Injector Complex”
- ISOLDE
- AD/ELENA
- East Area, North Area Proposals and Future Projects
- New Detector Research and Development Collaborations

What physics is there at CERN, other than the LHC?



NA61, NA62, NA64, NA66 AMBER, Neutrino Platform test facility

Experiments without beam, e.g. MADMAX; CAST (CERN axion solar telescope, finished data taking)

Experiments using slow antiprotons

CLOUD climate studies

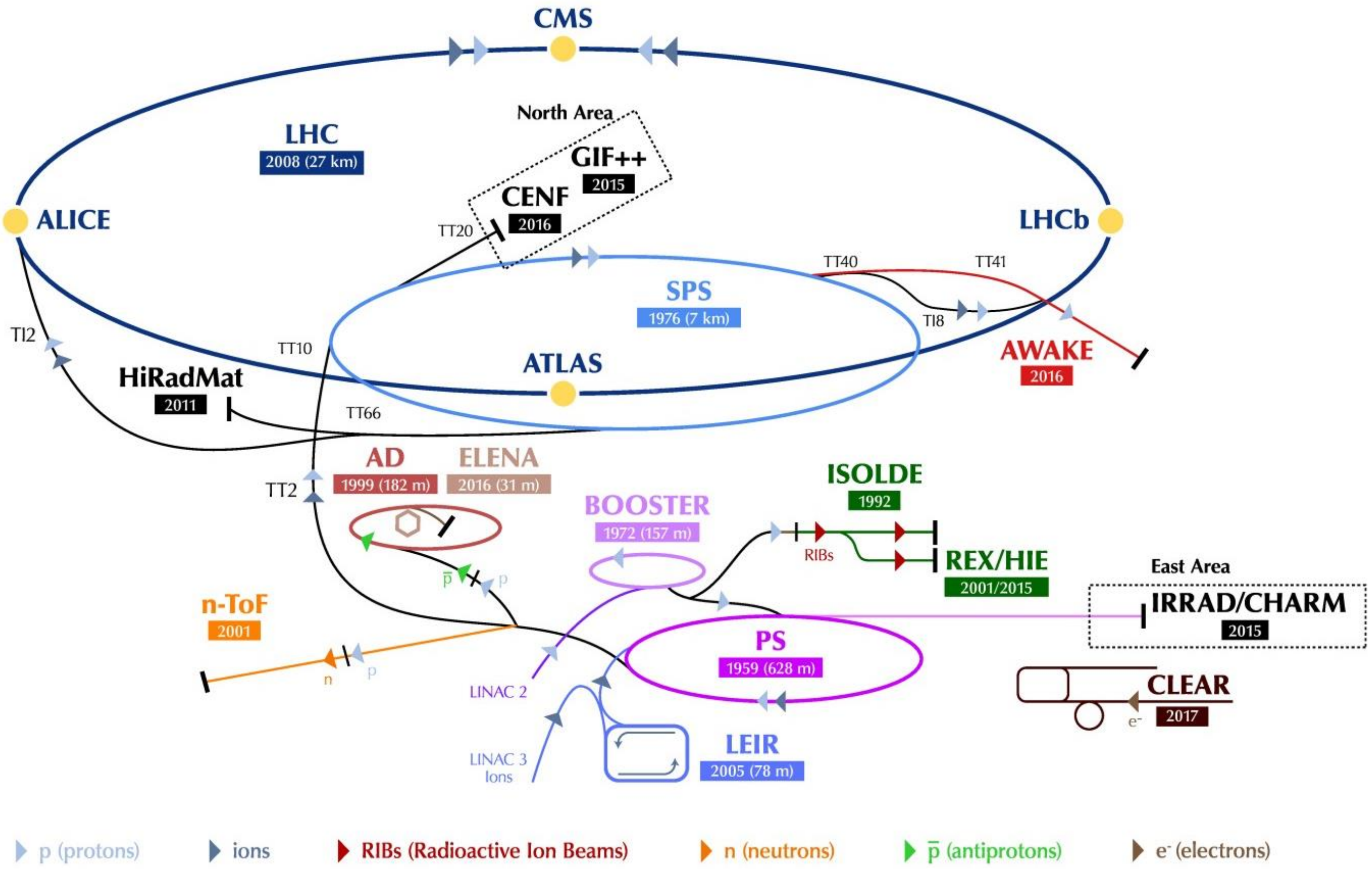
Neutron time-of-flight facility

several experiments

Radioactive Ion Beam facility

big number of experiments

CERN Beam Driven Irradiation Facilities



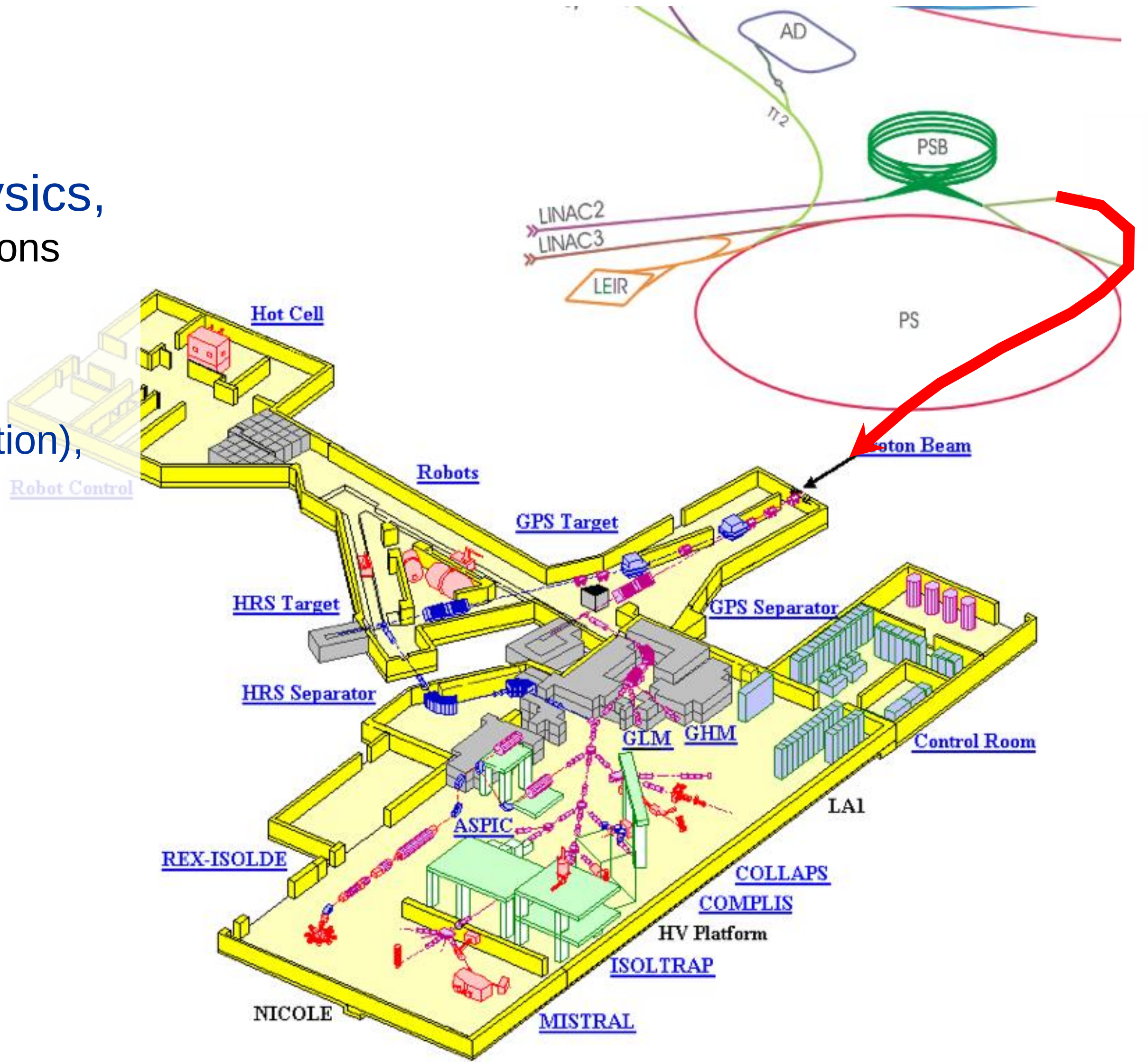
- PS East Area:
  - Proton: CHARM, IRRAD
  - Ions: CHIMERA/HEARTS
- Neutron facility at nTOF
- SPS North Area: CERF, GIF++
- HiRadMat
- CLEAR (CERN Linear Electron Accelerator for Research): vesper
- https://irradiation-facilities.web.cern.ch/

ISOLDE — Isotope mass Separator On-Line facility

ISOLDE — Isotope mass Separator On-Line facility

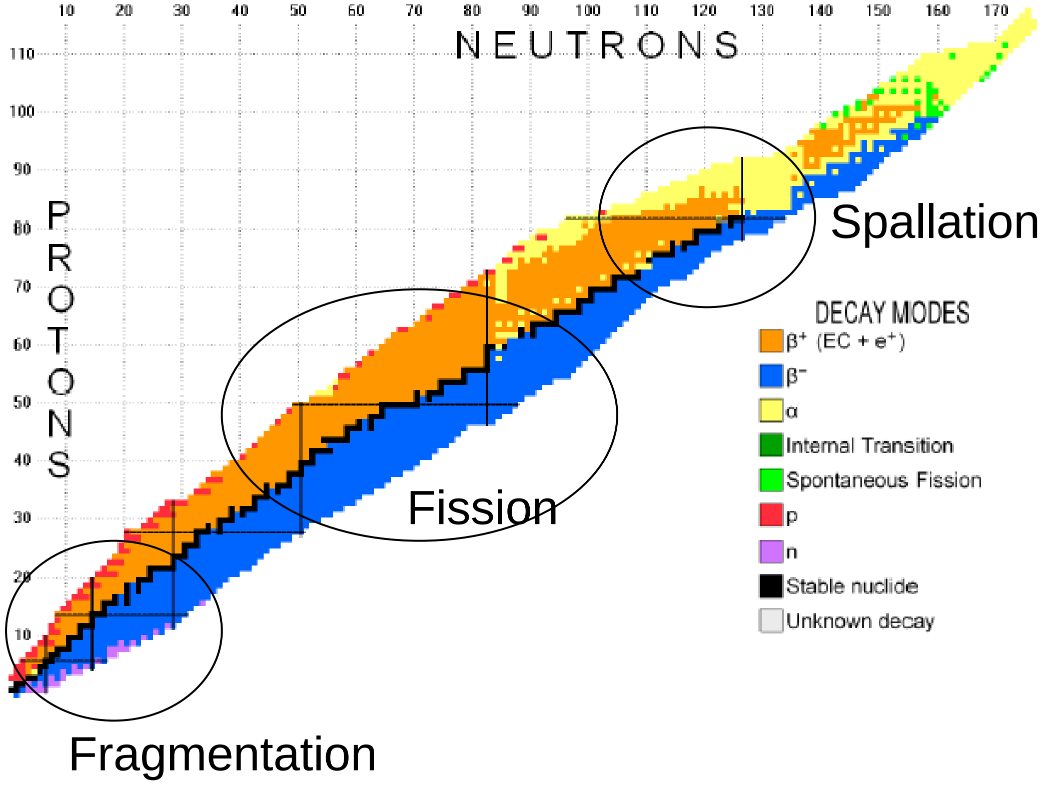
- Large variety of radioactive ion beams
  - **largest range of isotopes worldwide: over 1300 isotopes of more than 70 elements**
- Weak interactions and nuclear and atomic physics, e.g.: nuclear shapes, lifetimes, beta-decay & EW interactions
- Solid state physics and material science, e.g.: implantation of radioisotopes in semi-conductors
- Astrophysics, e.g.: triple-alpha to 12C rate (star formation), nuclear processes occurring during supernovae
- Biological systems, medical applications, e.g.: detoxification of mercury in bacteria, sensitive diagnostics

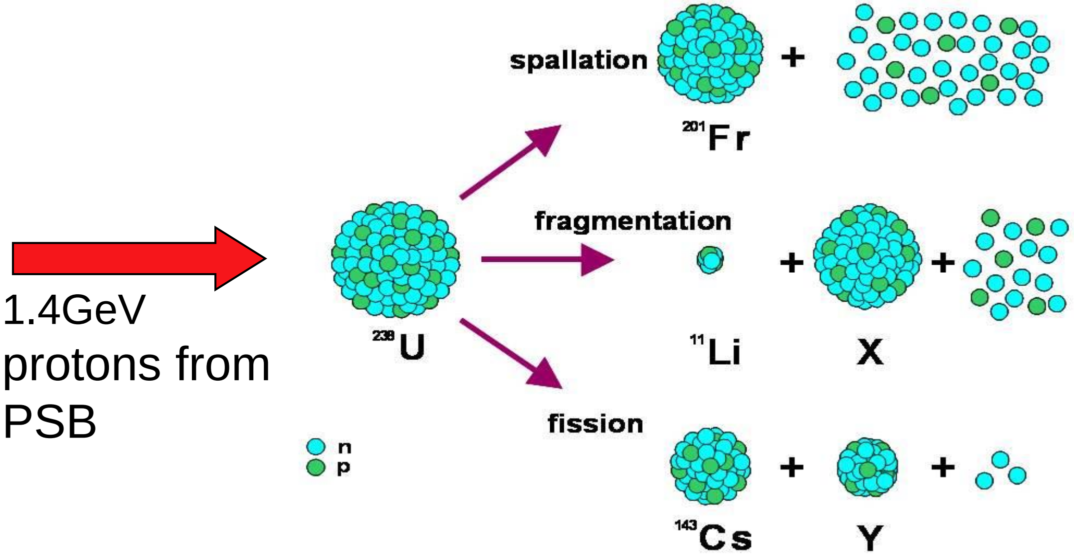
- ≈ 500 users, small experiments, about 60 experiments per year
- **60 to 70% of CERNs protons go to ISOLDE (<0.03% go to LHC)**
- 57 years of physics at ISOLDE!
  - first experiments started at the PS in 1967



Nuclear Physics at ISOLDE

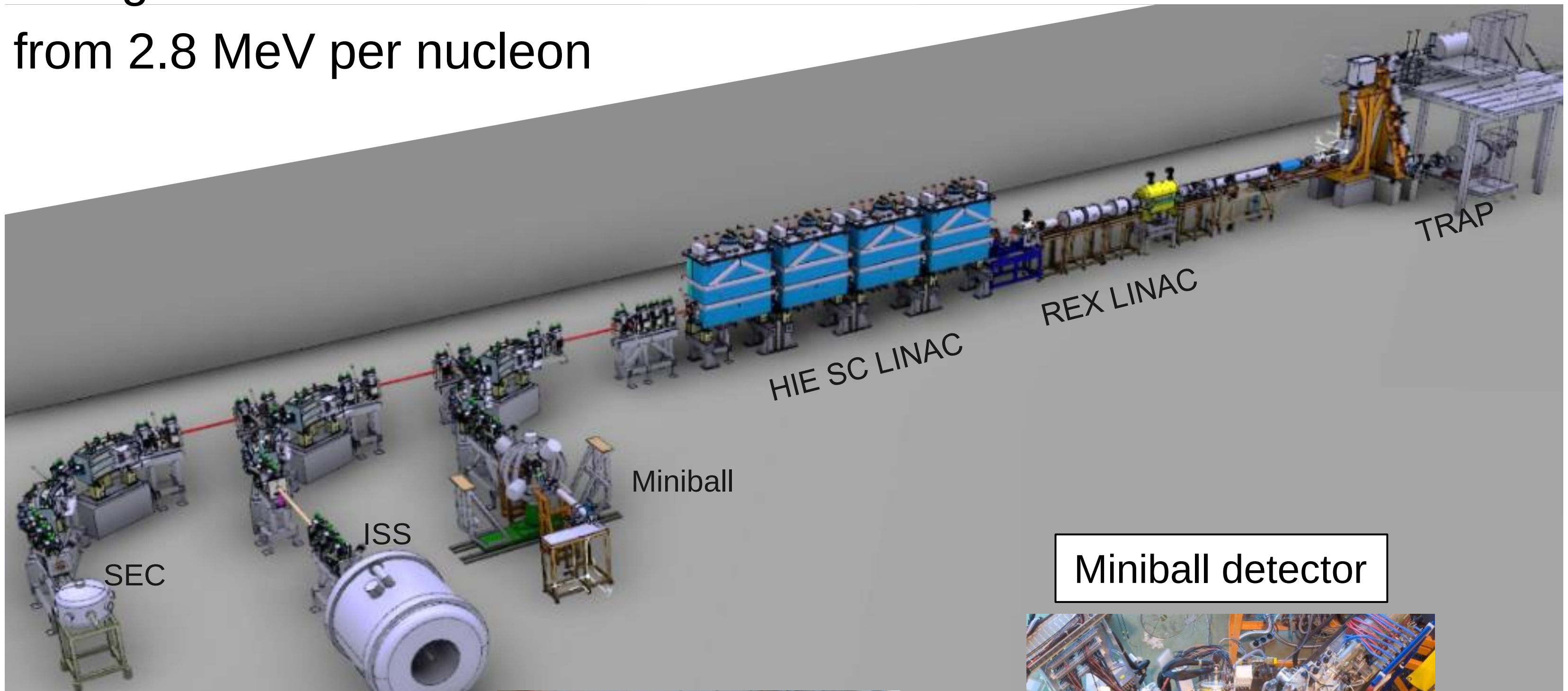
- How to create radioisotopes that do not exist on earth?




1.4GeV protons from PSB

REX and HIE-ISOLDE: High Energy and Intensity Upgrade

- Major upgrade of the REX post-accelerator to the HIE-ISOLDE (High Intensity and Energy Upgrade) superconducting linear accelerator in 2018
- Increase the energy from 2.8 MeV per nucleon to 10 MeV/u
- 3 beamlines:




Scattering chamber

Superconducting solenoid

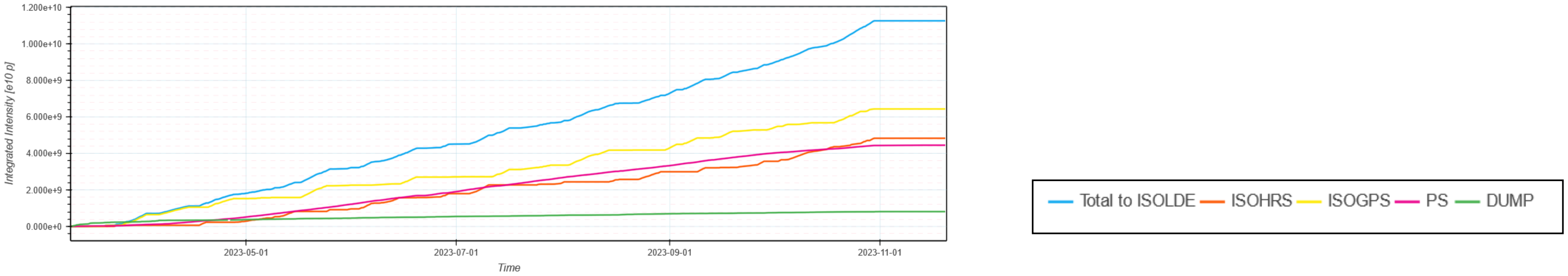
Miniball detector

ISOLDE in 2023

- About 470 shifts in 2023, 122 of them for HIE ISOLDE
- About 40% of the shifts to be scheduled are for HIE ISOLDE
  → shorter physics period for HIE ISOLDE is problematic
- "Winter Physics" Program extends beyond the operation of the Booster accelerator by using pre-irradiated targets

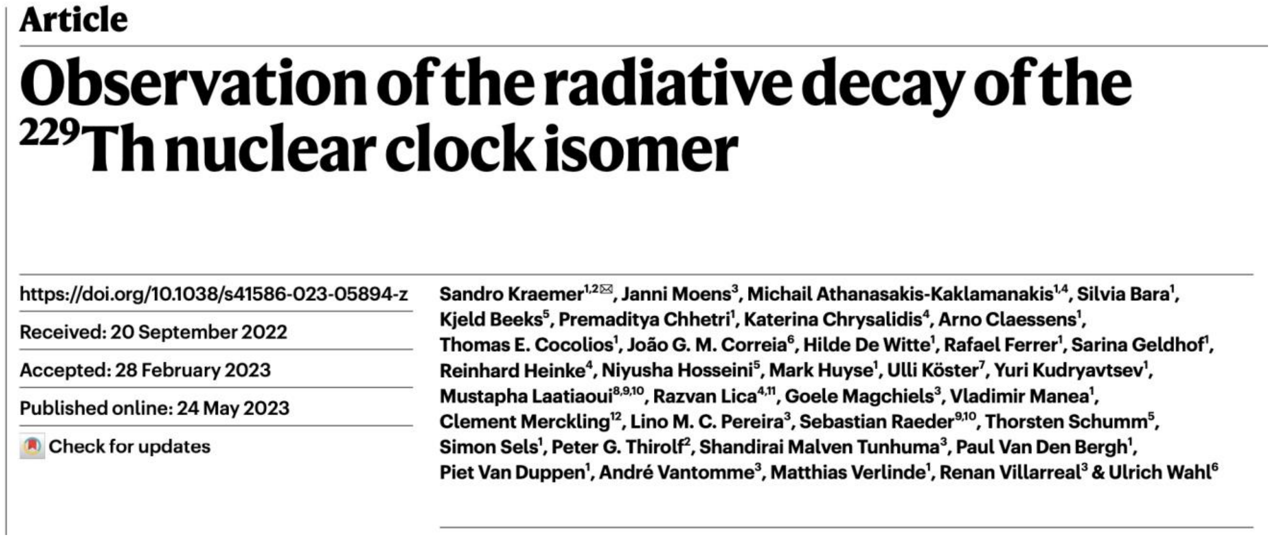
HIE-ISOLDE: 21 July

Winter Physics: 30 Oct.



ISOLDE Highlight I in 2023

- Background:
  - The radionuclide thorium-229 features an isomer with an exceptionally low excitation energy that enables direct laser manipulation of nuclear states.
  - It constitutes one of the leading candidates for a nuclear clocks
  - Such a nuclear clock would use the frequency of the nuclear transition as a reference frequency – in the same way as the atomic clock uses the frequency of an electronic transition in the atom shell.



Article

Observation of the radiative decay of the ^{229}Th nuclear clock isomer

https://doi.org/10.1038/s41586-023-05894-z

Received: 20 September 2022

Accepted: 28 February 2023

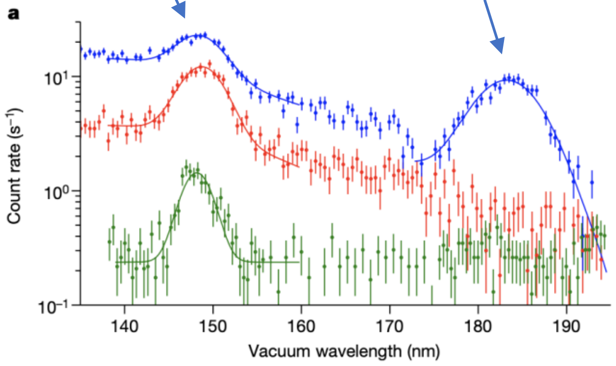
Sandro Kraemer[1,2]✉, Janni Moens[3], Michail Athanasakis-Kaklamanakis[1,4], Silvia Bara[1], Kjeld Beeks[5], Premaditya Chhetri[1], Katerina Chrysalidis[4], Arno Claessens[1], Thomas E. Cocolios[1], João G. M. Correia[6], Hilde De Witte[1], Rafael Ferrer[1], Sarina Geldhof[1], Reinhard Heinke[4], Niyusha Hosseini[5], Mark Huyse[1], Ulli Köster[7], Yuri Kudryavtsev[1], Mustapha Laatiaoui[8,9,10], Razvan Lica[4,11], Goele Magchiels[3], Vladimir Manea[1], Clement Merckling[12], Lino M. C. Pereira[3], Sebastian Raeder[9,10], Thorsten Schumm[5], Simon Sels[1], Peter G. Thirolf[2], Shandirai Malven Tunhuma[3], Paul Van Den Bergh[1], Piet Van Duppen[1], André Vantomme[3], Matthias Verlinde[1], Renan Villarreal[3] & Ulrich Wahl[6]

Implantation of A=229 and 230 in three different hosts to search for and identify the uv transitions with ^{229}Th and to exclude artifacts.

Implantation of A=229

^{229}Th isomer decay

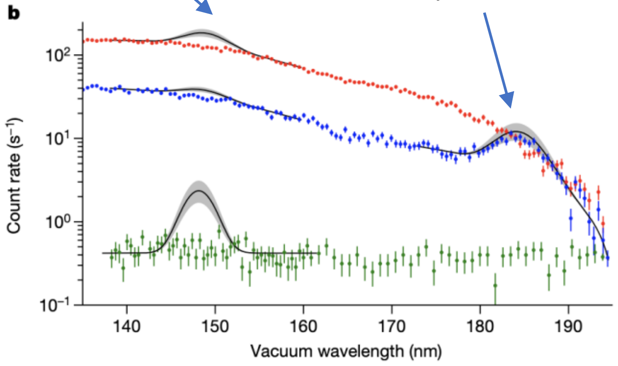
artifact: crystal defects



Implantation of A=230

no isomer

artifact: crystal defects



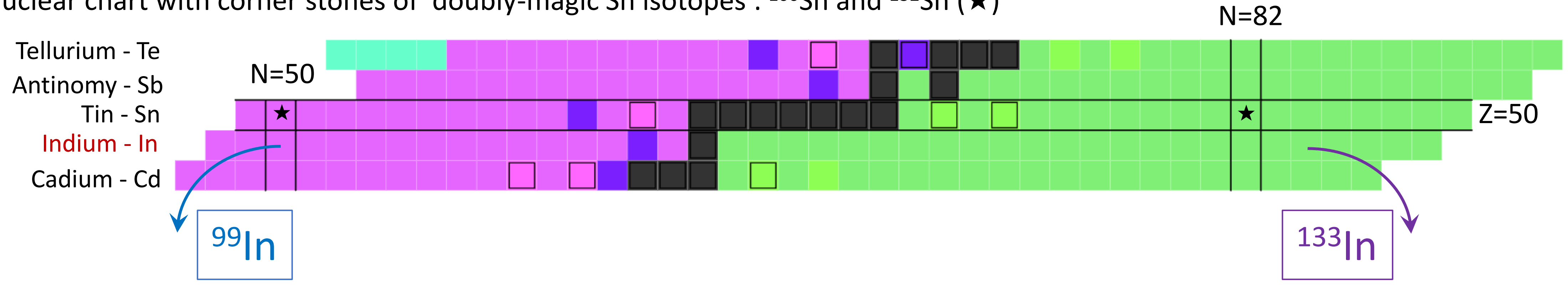
- **First direct evidence of very low-lying state in ^{229}Th** via measurement of the uv decay.
- More precise measurement of energy than indirect measurements, giving only 8.338(24) eV
- Measurement of $\tau_{1/2}$ for isomer embedded in MgF_2 670(102)s

- **Nucleus exited state**: Low energy enables potential direct excitation by lasers and therefore use as a **nuclear clock.**
- Nuclear clock **much less sensitive to environmental effects than atomic clocks so more precise**.
- A nuclear clock would be a unique tool for many **precision tests of fundamental physics.**
- The observation of radiative decay in large band-gap crystal is a huge step forward in design of such a clock.
- Reduction in precision of energy significantly eases the search for direct laser excitation as lasers have narrow bandwidth compared to uncertainty in energy.

Slides from Sean Freeman

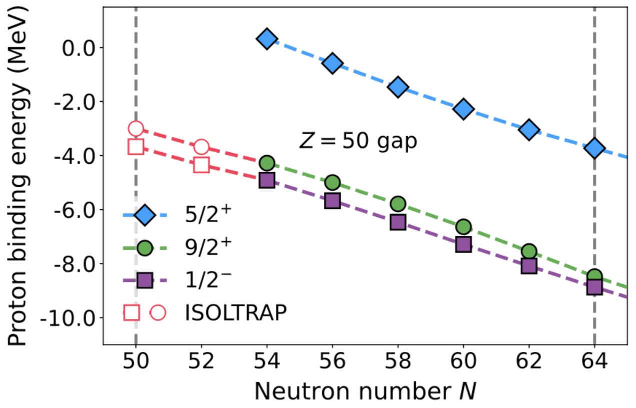
Indium – from one extreme to the other - *two back-to-back ISOLDE PRL's in July*

Part of nuclear chart with corner stones of doubly-magic Sn isotopes : ^{100}Sn and ^{132}Sn (★)



PHYSICAL REVIEW LETTERS **131,** 022502 (2023)

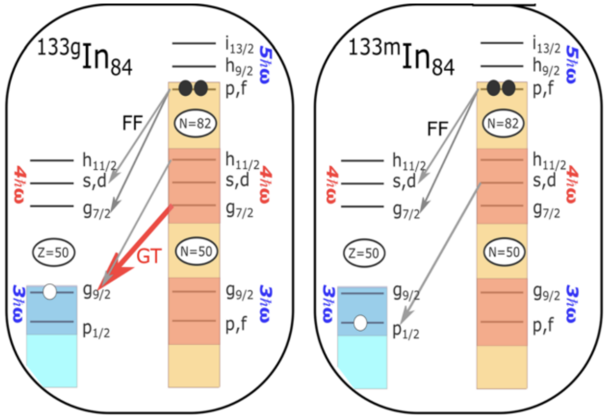
Isomeric Excitation Energy for ^{99}In^m from Mass Spectrometry Reveals Constant Trend Next to Doubly Magic ^{100}Sn



- Precision measurement of ground and isomeric state using ISOLTRAP.
- Excitation of isomer extremely constant across In
- In contrast to measurements of magnetic moment, which increases near N=50 - also ISOLDE experiment from 2022!
- Very difficult to reproduce with modern calculations and may point to missing physics.

PHYSICAL REVIEW LETTERS **131,** 022501 (2023)

^{133}In: A Rosetta Stone for Decays of *r*-Process Nuclei



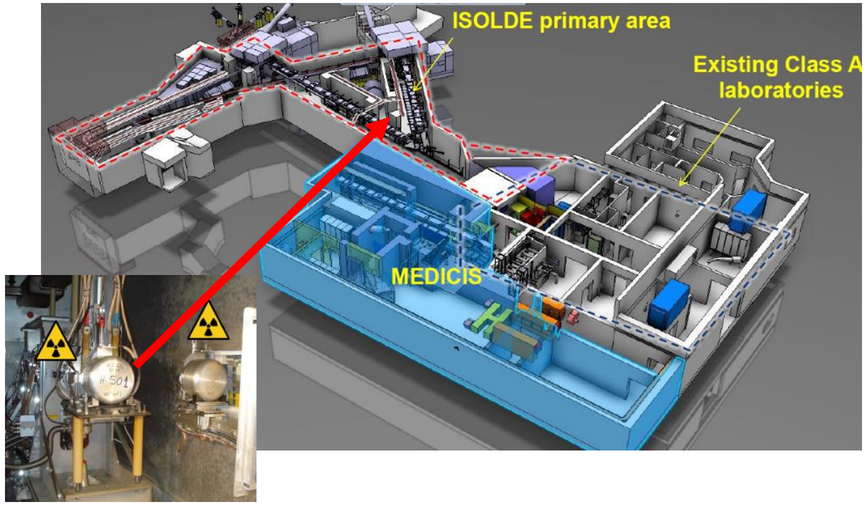
- Measured β decays from ground and isomeric levels using ISOLDE DECAY STATION.
- Decays populate just a few unbound levels in ^{133}Sn.
- Measured resonance properties that are critical for benchmarking models of the *astrophysical r process* that manufactures many of the heavy chemical elements.

Good example of versatility of ISOLDE – precision studies of both neutron-rich and neutron-deficient exotic isotopes separated by 34 neutrons!

Slides from Sean Freeman

Medical Isotopes Collected from ISOLDE

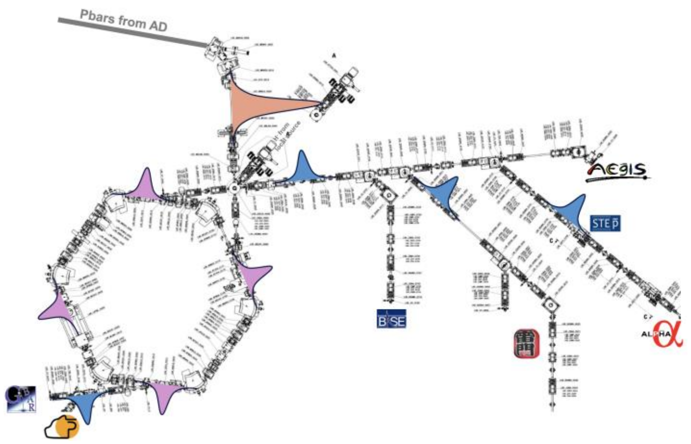
- Fundamental studies in cancer research
- ISOLDE target only absorbs about 10% of the beam protons → MEDICIS uses a second target behind
- MEDICIS can also use pre-irradiated targets that are provided by external institutions → was operating during ‘Long Shutdown 2’
- Produce and test unconventional radioisotopes for the development of new imaging and therapy protocols
- Isotopes produced at ISOLDE / MEDICIS are mainly to be delivered to hospitals and research centres in Switzerland and Europe.
- The first batch produced in the new facility (December 2017) was Terbium ^{155}Tb, a promising radioisotope for diagnosing prostate cancer
- Terbium is also a possible candidate for Theranostics (treatments aiming to combine therapy and diagnostics)
- Bernerd, C. et. al (2023-09-01). "Production of innovative radionuclides for medical applications at the CERN-MEDICIS facility". Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms. **542**: 137–143.

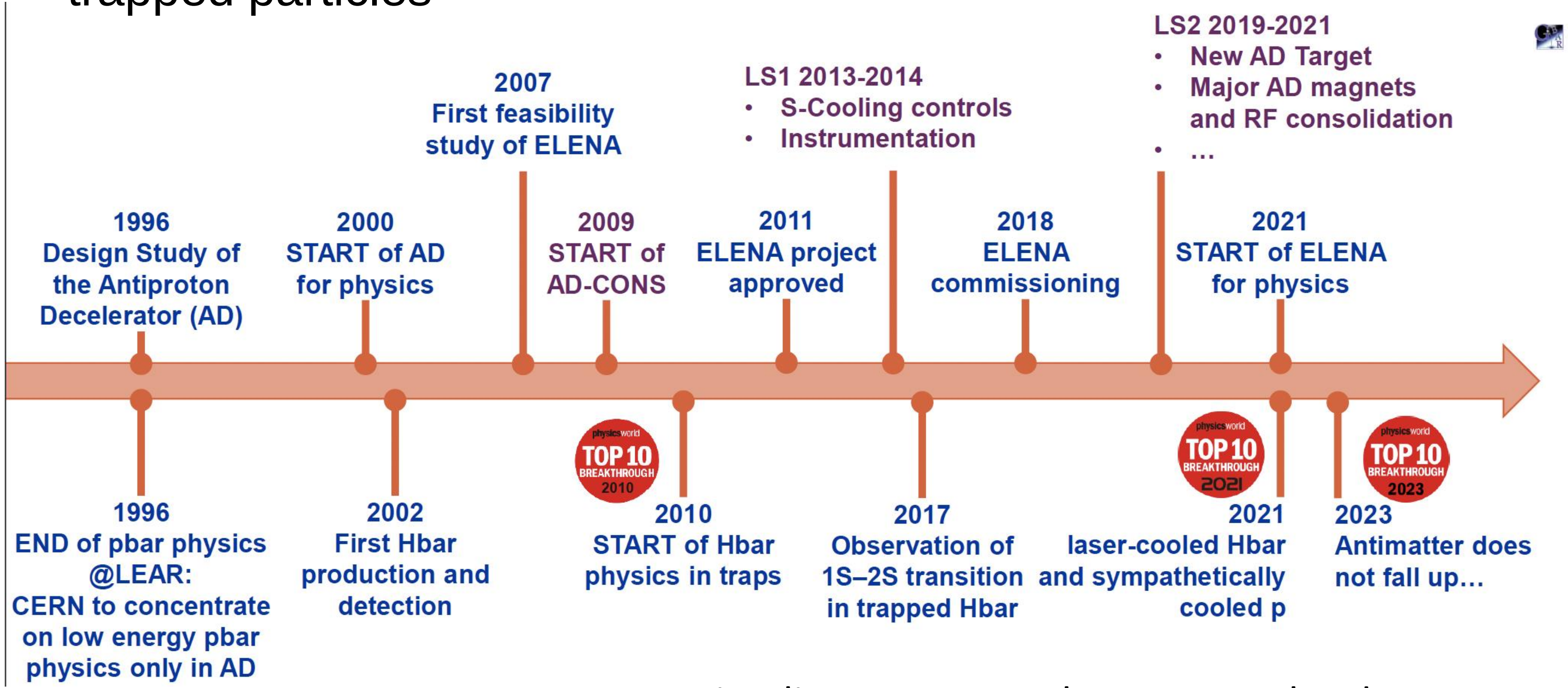


Antiproton Decelerators: AD/ELENA

AD and ELENA – the CERN anti-proton Experiments

- Precision measurements and anti-gravitation measurements: BASE, BASE-STEP, ALPHA, GBAR, ASACUSA, AEgIS and PUMA
- Experiments constantly pushing the limits for particle trapping (charged ions and neutral atoms) and cooling of trapped particles





2007
First feasibility study of ELENA

LS1 2013-2014
- **S-Cooling controls**
- **Instrumentation**

LS2 2019-2021
- **New AD Target**
- **Major AD magnets and RF consolidation**
- **…**

1996
Design Study of the Antiproton Decelerator (AD)

2000
START of AD for physics

2009
START of AD-CONS

2011
ELENA project approved

2018
ELENA commissioning

2021
START of ELENA for physics

1996
END of pbar physics @LEAR: CERN to concentrate on low energy pbar physics only in AD

2002
First Hbar production and detection

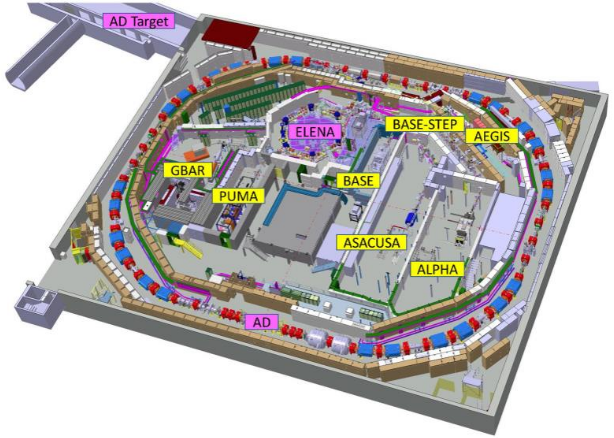
2010
START of Hbar physics in traps

2017
Observation of 1S–2S transition in trapped Hbar

2021
laser-cooled Hbar and sympathetically cooled p

2023
Antimatter does not fall up…

Timeline courtesy Johannes Bernhard

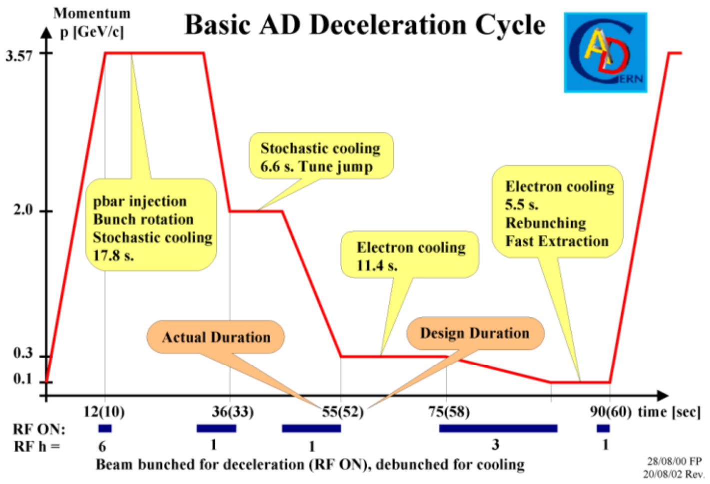


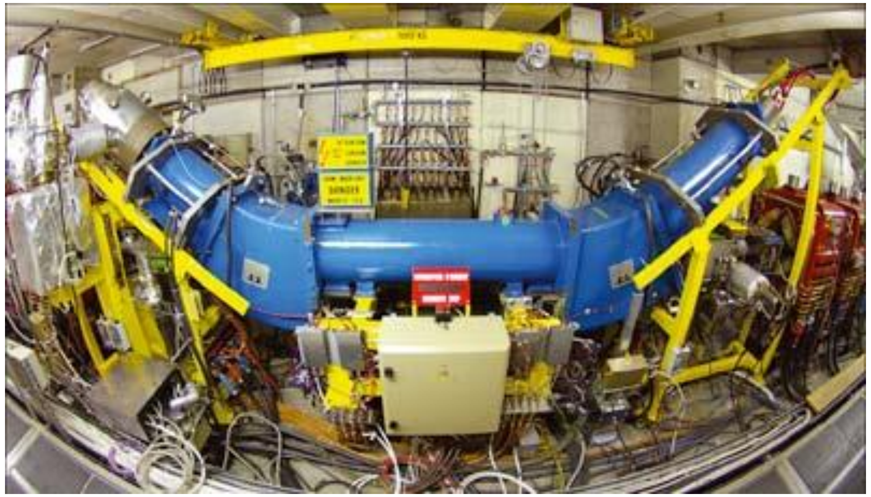
AD – Antiproton Decelerator

- Started Physics in 2000
- PS protons at 26 GeV/c on target
- Antiprotons captured at 3.57 GeV/c
- Deceleration and cooling
- Extraction of 2-4 10^7 antiprotons at 100 MeV/c (5.3 MeV) every ~100s for

Stochastic Cooling

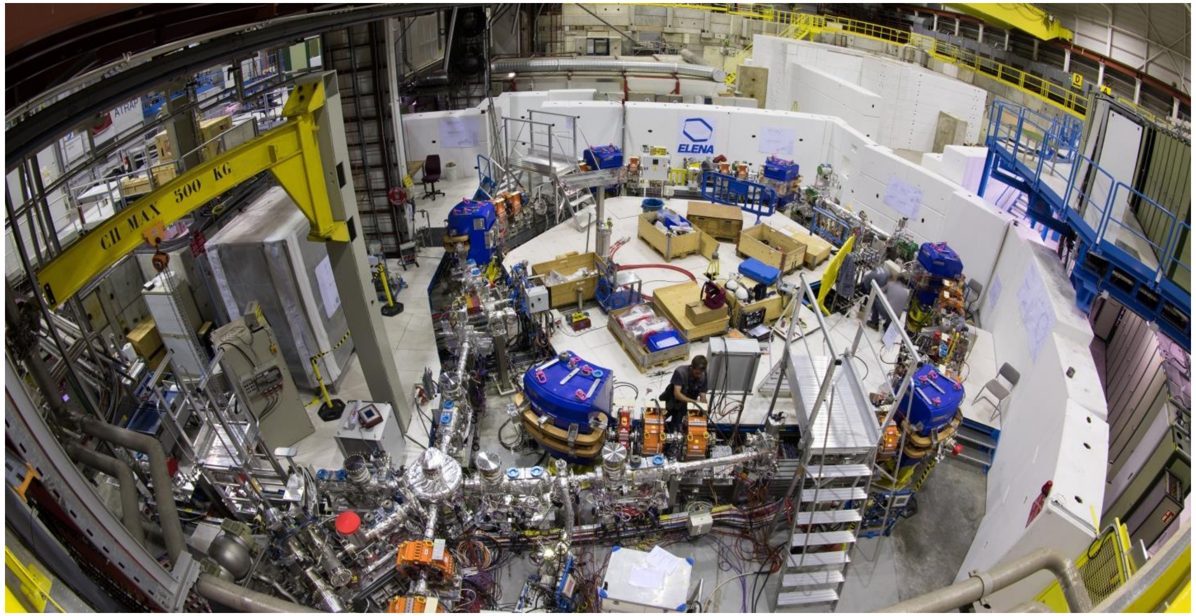
- Invented at CERN by Simon van der Meer
  → discovery W, Z bosons
  → Nobel Prize 1984
- Cooling power decreases with decreasing energy
  → Electron Cooling

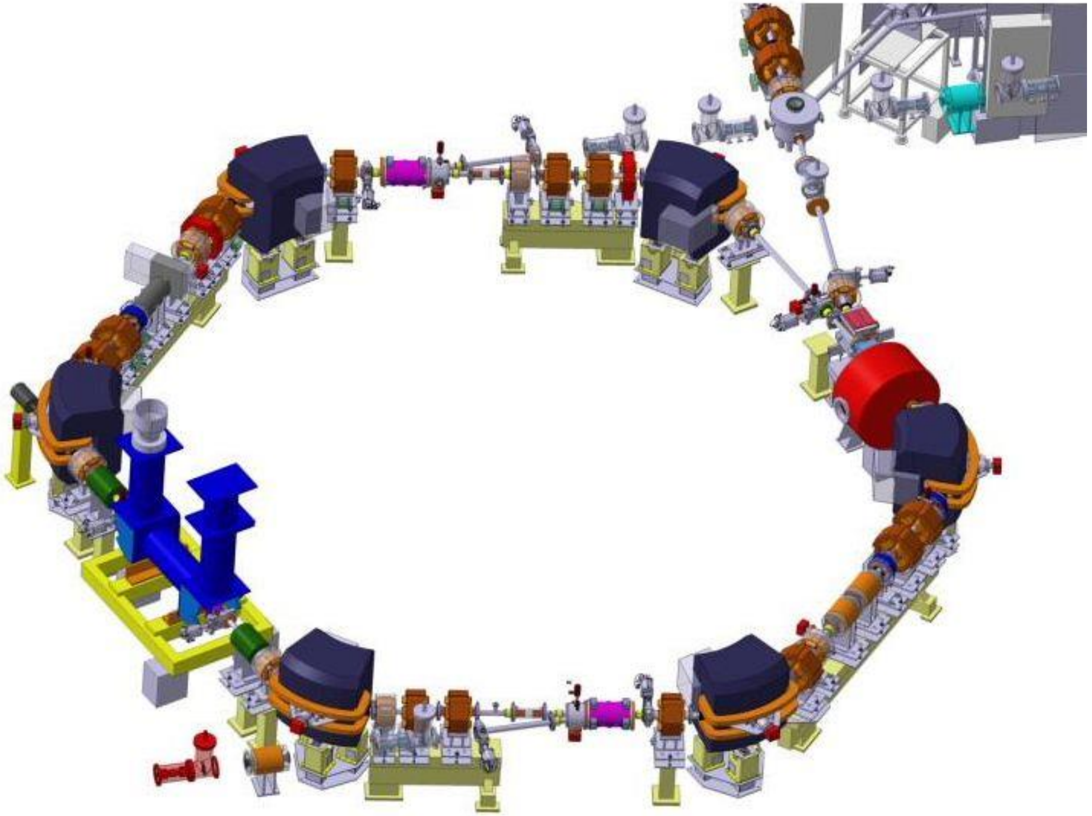




ELENA

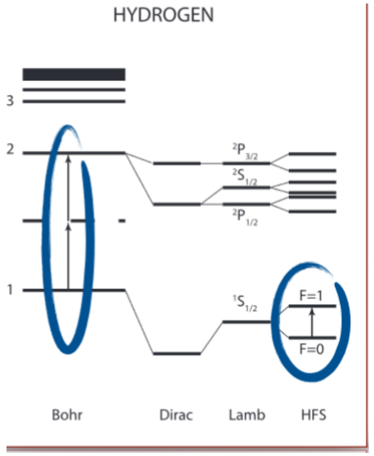
- Started Physics in 2021
- Deceleration from 5.3 MeV to 100 keV
- Improve capture efficiency of experiments - new types of experiments (GBAR) become possible

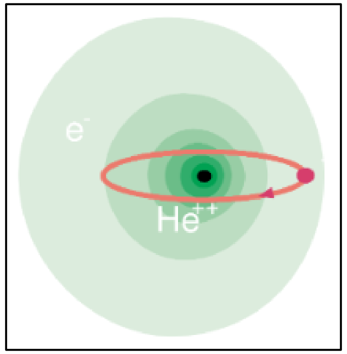




Aim of AD Experiments

- Main goals: compare Hydrogen to Antihydrogen
  - Comparison of hydrogen and antihydrogen atomic spectra: CPT symmetry test to 10^{-13} using mK atoms / antiatoms
  - Gravitational measurement of antimatter
- Secondary goals: compare proton and antiproton (CPT symmetry), evaluate radiation-therapy potential of antiprotons, …



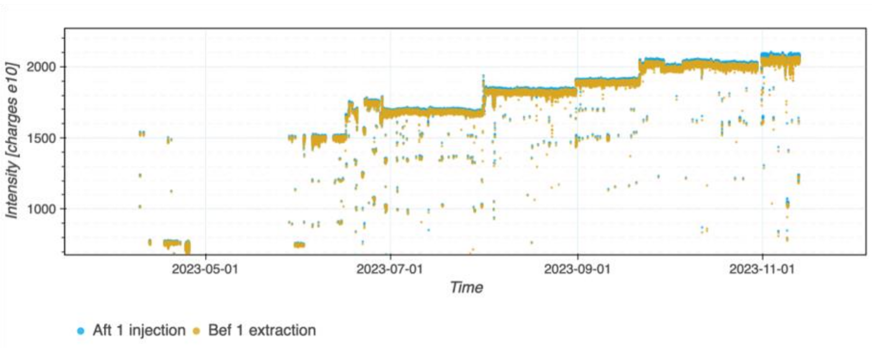


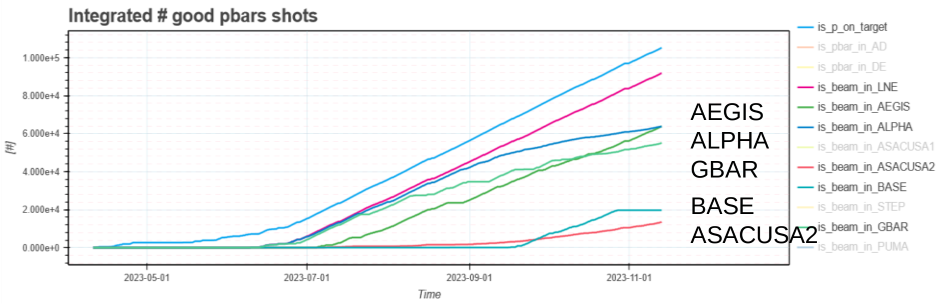
Spectroscopy on antihydrogen and more exotic objects

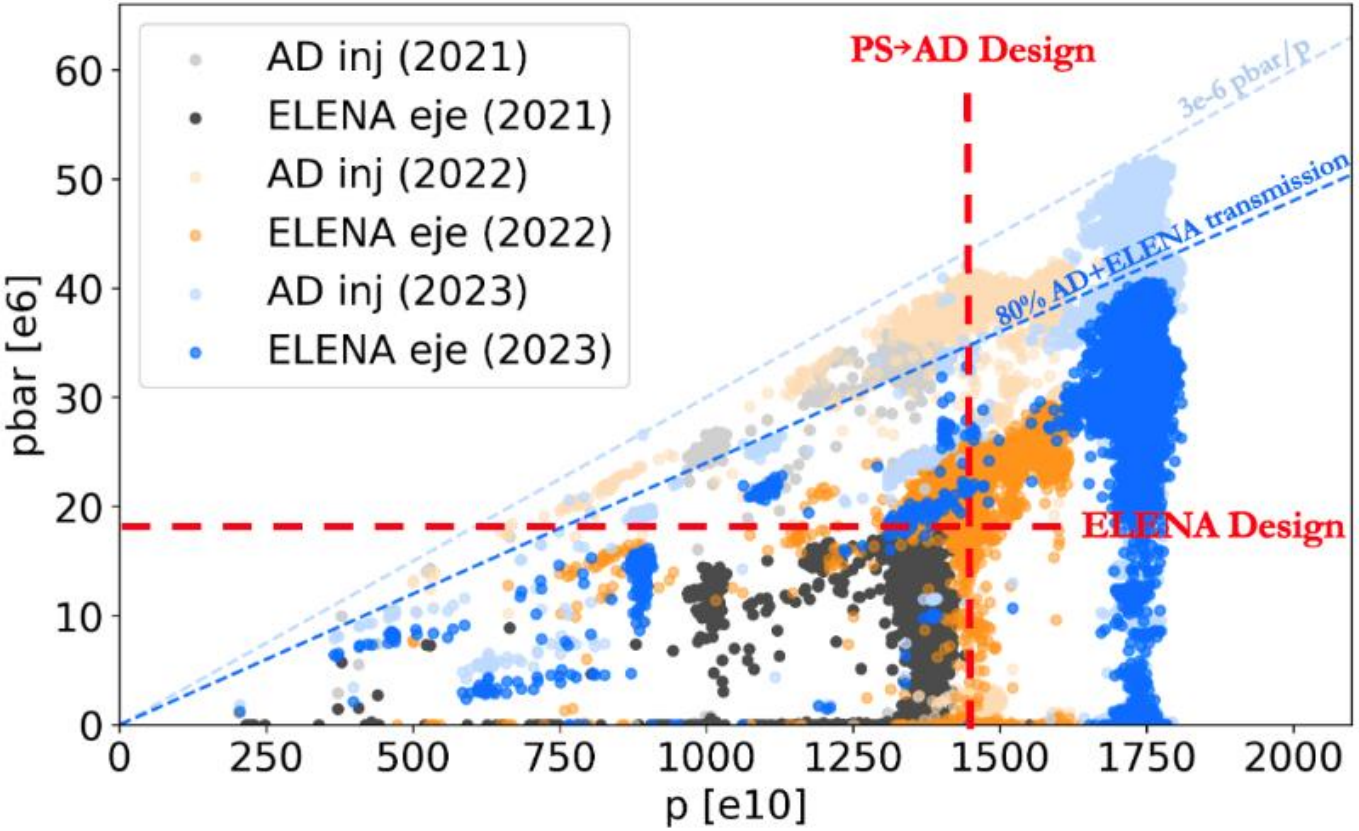
Gravitational Experiments

AD / ELENA in 2023

- **2023**: twice the ELENA design pbar / shot
  - AD extraction increased to 2000E10 p (target limitation)
  - Optimisation of transmission efficiency in AD and ELENA → **record bunch intensities of 1x10^7 pbars per bunch**







Antimatter Gravity – ALPHA: Physics Highlights

Article

Observation of the effect of gravity on the motion of antimatter

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Accepted: 9 August 2023

E. K. Anderson[1], C. J. Baker[2], W. Bertsche[3,4,✉], N. M. Bhatt[2], G. Bonomi[5], A. Capra[6], I. Carli[6], C. L. Cesar[7], M. Charlton[2], A. Christensen[8], R. Collister[4,9], A. Cridland Mathad[2], D. Duque Quiceno[6,9], S. Eriksson[2], A. Evans[6,9], N. Evetts[9], S. Fabbri[3,10], J. Fajans[8,✉], A. Ferwerda[11], T. Friesen[12], M. C. Fujiwara[6], D. R. Gill[6], L. M. Golino[2], M. B. Gomes Gonçalves[2], P. Grandemange[6], P. Granum[1], J. S. Hangst[1,✉], M. E. Hayden[13], D. Hodgkinson[3,8], E. D. Hunter[8], C. A. Isaac[2], A. J. U. Jimenez[6], M. A. Johnson[3,4], J. M. Jones[2], S. A. Jones[14], S. Jonsell[15], A. Khramov[6,9,16], N. Madsen[2], L. Martin[6], N. Massacret[6], D. Maxwell[2], J. T. K. McKenna[1,3], S. Menary[11], T. Momose[6,9,17], M. Mostamand[6,17], P. S. Mullan[2,18], J. Nauta[2], K. Olchanski[6], A. N. Oliveira[1], J. Peszka[2,18], A. Powell[12], C. Ø. Rasmussen[19], F. Robicheaux[20], R. L. Sacramento[7], M. Sameed[3,21], E. Sarid[22,23], J. Schoonwater[2], D. M. Silveira[7], J. Singh[3], G. Smith[6,9], C. So[6], S. Stracka[24], G. Stutter[1,25], T. D. Tharp[26], K. A. Thompson[2], R. I. Thompson[6,12], E. Thorpe-Woods[2], C. Torkzaban[8], M. Urioni[5], P. Woosaree[12] & J. S. Wurtele[8]

Einstein's general theory of relativity from 1915[1] remains the most successful description of gravitation. From the 1919 solar eclipse[2] to the observation of gravitational waves[3], the theory has passed many crucial experimental tests. However, the evolving concepts of dark matter and dark energy illustrate that there is much to be learned about the gravitating content of the universe. Singularities in the general theory of relativity and the lack of a quantum theory of gravity suggest that our picture is incomplete. It is thus prudent to explore gravity in exotic physical systems. Antimatter was unknown to Einstein in 1915. Dirac's theory[4] appeared in 1928; the positron was observed[5] in 1932. There has since been much speculation about gravity and antimatter. The theoretical consensus is that any laboratory mass must be attracted[6] by the Earth, although some authors have considered the cosmological consequences if antimatter should be repelled by matter[7–10]. In the general theory of relativity, the weak equivalence principle (WEP) requires that all masses react identically to gravity, independent of their internal structure. Here we show that antihydrogen atoms, released from magnetic confinement in the ALPHA-g apparatus, behave in a way consistent with gravitational attraction to the Earth. Repulsive 'antigravity' is ruled out in this case. This experiment paves the way for precision studies of the magnitude of the gravitational acceleration between anti-atoms and the Earth to test the WEP.

The weak equivalence principle (WEP) has recently been tested for matter in Earth's orbit[11] with a precision of order 10^{-15}. Antimatter has hitherto resisted direct ballistic tests of the WEP due to the lack of a stable, electrically neutral, test particle. Electromagnetic forces on charged antiparticles make direct measurements in the Earth's gravitational field extremely challenging[12]. The gravitational force on a proton at the Earth's surface is equivalent to that from an electric field of about 10^{-7} V m^{-1}. The situation with magnetic fields is even more dire: a cryogenic antiproton[13] at 10 K would experience gravity-level forces in a magnetic field of order 10^{-10} T. Controlling stray fields to this level to unmask gravity is daunting. Experiments have, however, shown that confined, oscillating, charged antimatter particles behave as expected when considered as clocks[14–16] in a gravitational field. The abilities to produce[17] and confine[18] antihydrogen now allow us to employ stable,

[1]Department of Physics and Astronomy, Aarhus University, Aarhus, Denmark. [2]Department of Physics, Faculty of Science and Engineering, Swansea University, Swansea, UK. [3]School of Physics and Astronomy, University of Manchester, Manchester, UK. [4]Cockcroft Institute, Sci-Tech Daresbury, Warrington, UK. [5]University of Brescia, Brescia and INFN Pavia, Pavia, Italy. [6]TRIUMF, Vancouver, British Columbia, Canada. [7]Instituto de Física, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil. [8]Department of Physics, University of California at Berkeley, Berkeley, CA, USA. [9]Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada. [10]Accelerator and Technology Sector, CERN, Geneva, Switzerland. [11]Department of Physics and Astronomy, York University, Toronto, Ontario, Canada. [12]Department of Physics and Astronomy, University of Calgary, Calgary, Alberta, Canada. [13]Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada. [14]Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, Groningen, The Netherlands. [15]Department of Physics, Stockholm University, Stockholm, Sweden. [16]Department of Physics, British Columbia Institute of Technology, Burnaby, British Columbia, Canada. [17]Department of Chemistry, University of British Columbia, Vancouver, British Columbia, Canada. [18]Institute for Particle Physics and Astrophysics, ETH, Zurich, Switzerland. [19]Experimental Physics Department, CERN, Geneva, Switzerland. [20]Department of Physics and Astronomy, Purdue University, West Lafayette, IN, USA. [21]Accelerator Systems Department, CERN, Geneva, Switzerland. [22]Soreq NRC, Yavne, Israel. [23]Department of Physics, Ben Gurion University, Beer Sheva, Israel. [24]INFN Pisa, Pisa, Italy. [25]School of Mathematical and Physical Sciences, University of Sussex, Brighton, UK. [26]Physics Department, Marquette University, Milwaukee, WI, USA. ✉e-mail: william.bertsche@cern.ch; joel@physics.berkeley.edu; jeffrey.hangst@cern.ch

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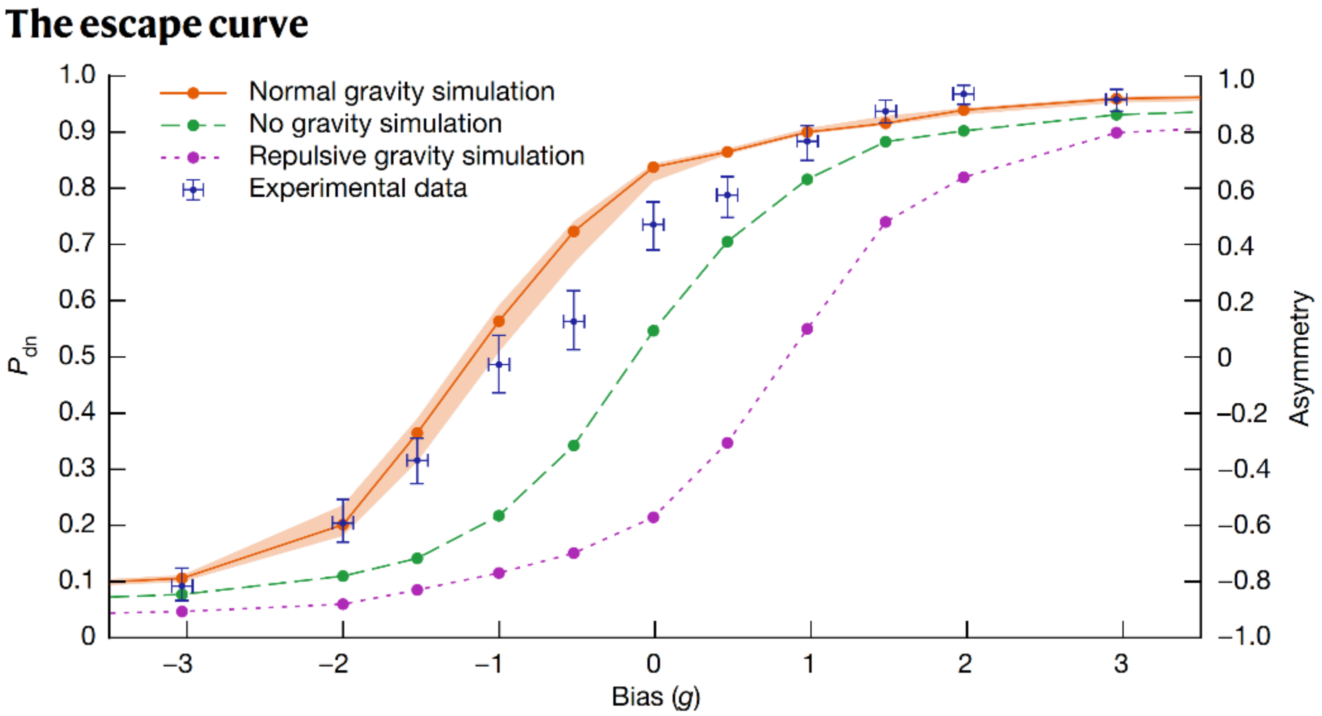
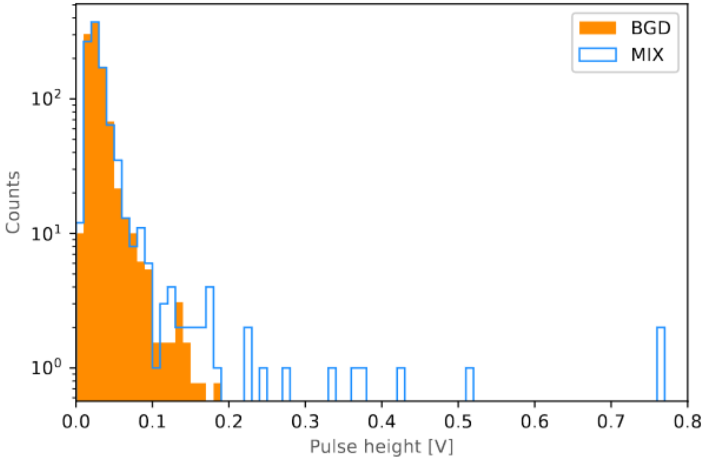


$$a = \left(0.75\,(13)_{\text{stat,sys}}\,(16)_{\text{sim}}\right) \times g$$

- First measurement of direction of gravitational force on anti-matter, which is entirely model independent

Further AD Physics Highlights

- **GBAR** published **production of antihydrogen atoms** by 6 keV antiprotons through a positronium cloud
  https://arxiv.org/abs/2306.15801



THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Production of antihydrogen atoms by 6 keV antiprotons through a positronium cloud

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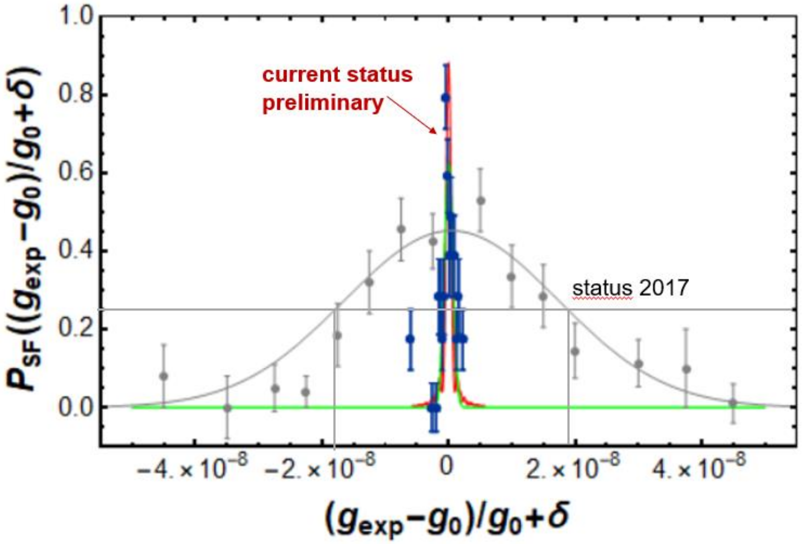
Abstract We report on the first production of an antihydrogen beam by charge exchange of 6.1 keV antiprotons with a cloud of positronium in the GBAR experiment at CERN. The 100 keV antiproton beam delivered by the AD/ELENA facility was further decelerated with a pulsed drift tube. A 9 MeV electron beam from a linear accelerator produced a low energy positron beam. The positrons were accumulated in a set of two Penning–Malmberg traps. The positronium target cloud resulted from the conversion of the positrons extracted from the traps. The antiproton beam was steered onto this positronium cloud to produce the antiatoms. We observe an excess over background indicating antihydrogen production with a significance of 3–4 standard deviations.

1 Introduction

The GBAR experiment at CERN aims at a precise measurement of the free fall acceleration of neutral antihydrogen

Published online: 06 November 2023

- **Preliminary Result: BASE** performed the **first ever coherent quantum spectroscopy with a single nuclear spin**, reducing g-Factor (magnetic moment) line width by more than a factor of 20.
- Aim: Precision measurement comparing proton to anti-proton g-factor as stringent test of CPT invariance.



Some Recent Technical Highlights

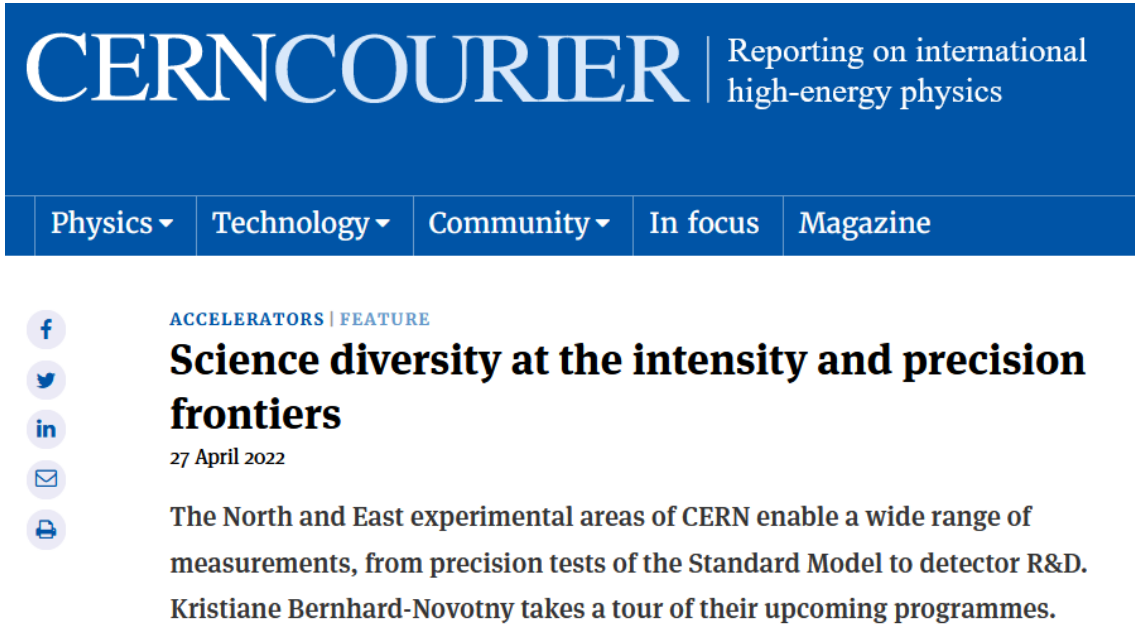
BASE	**Winter Physics using antiprotons stocked in the reservoir trap (30 $\bar{p}$) to measure during the period when the accelerator is not operating (quiet environment required);** 1 $\bar{p}$ per month required
PUMA	Aim: Transport of $\bar{p}$ from ELENA to ISOLDE; measure charged pions from annihilation with low energy ions from ISOLDE → neutron-to-proton annihilation ratio • Antiproton beam line (deceleration with PDT to 4 keV) validated with beam • Plans first trapping and transport in 2024 • Plans to be ready for first experiments at ISOLDE in 2025.
New Test Beam Line TELMAX	• First slow anti-proton test beam line • Planning to be ready for internal and external users by the end of summer 2024 • Invitation to apply for beam time to be sent out soon

East Area and North Area – Quick Recap

- Already covered by Nikos in February

East Area and North Area – Recap

- https://cerncourier.com/a/science-diversity-at-the-intensity-and-precision-frontiers/



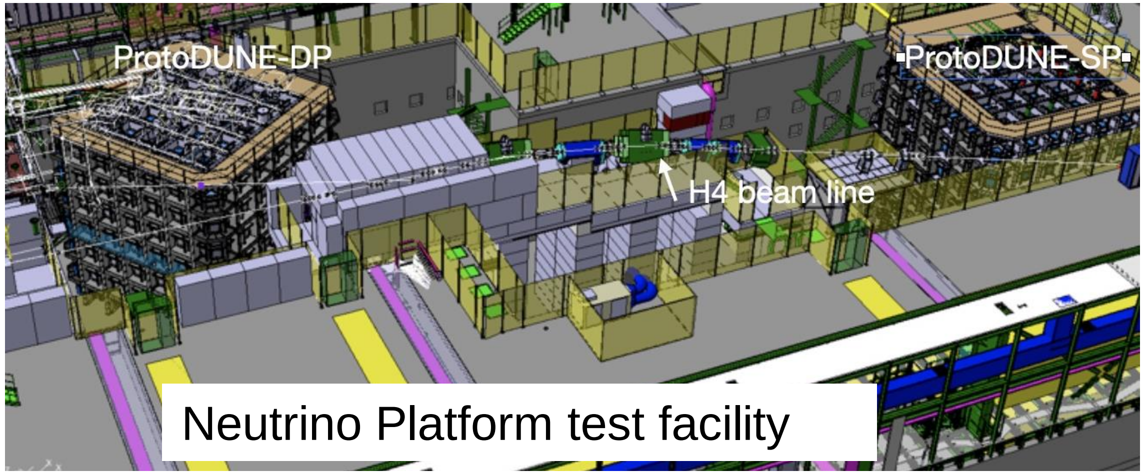
CERNCOURIER | Reporting on international high-energy physics

ACCELERATORS | FEATURE

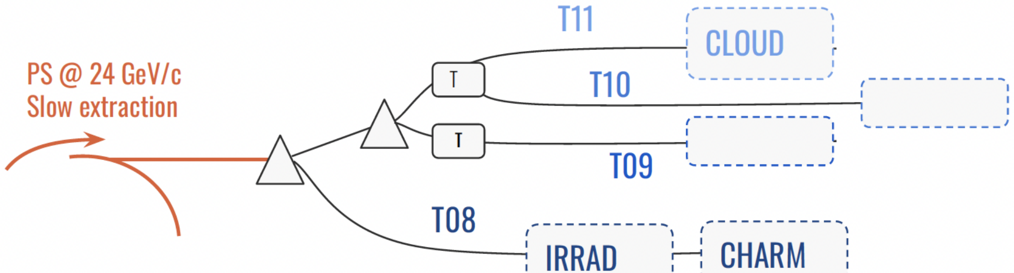
Science diversity at the intensity and precision frontiers

27 April 2022

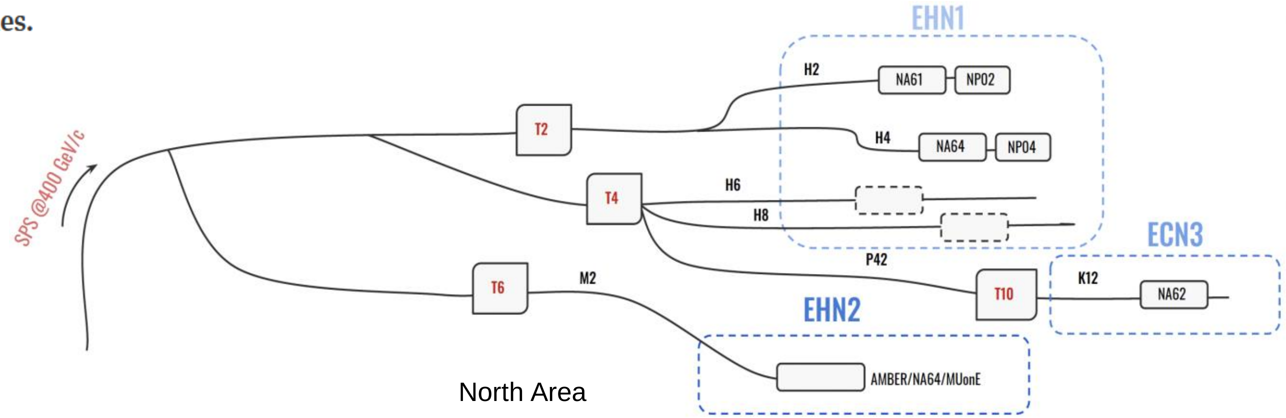
The North and East experimental areas of CERN enable a wide range of measurements, from precision tests of the Standard Model to detector R&D. Kristiane Bernhard-Novotny takes a tour of their upcoming programmes.



Neutrino Platform test facility



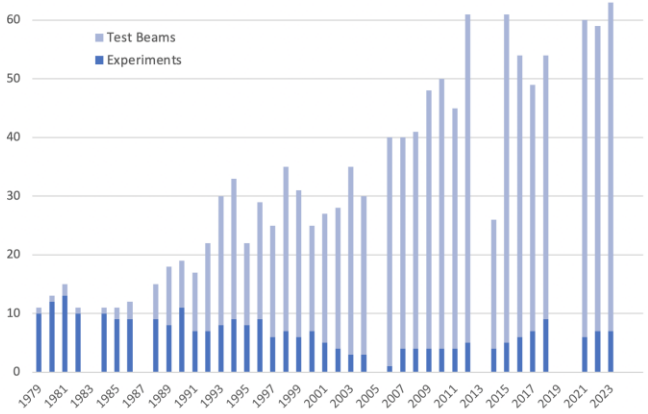
East Area



North Area

PS and SPS Experimental Facilities

- Highly diverse and versatile experimental facilities. Proton, hadron, electron, muon, and ion beams to more than 100 user teams per year for detector R&D, irradiations and physics experiments.
  - PS: n-TOF (neutrino Time of Flight facility), IRRAD, CHARM, CHIMERA, CLOUD experiment, two test beam lines
  - SPS: AWAKE, HiRadMat, NA61, NA62, NA64, and NA66/AMBER experiments, the two large neutrino platform cryostats, GIF++ and CERF irradiation facilities, 4 test beam lines, with combined more than 2000 users
- Increasing levels of over-booking of the beam lines
  → partially absorbed by parallel running
  - Some lines have typically three or more set-ups share the same beam whenever possible
- Recently conducted survey covering until 2041 (until the end of High Lumi LHC)
  → estimate similar levels of beam time overbooking for the future

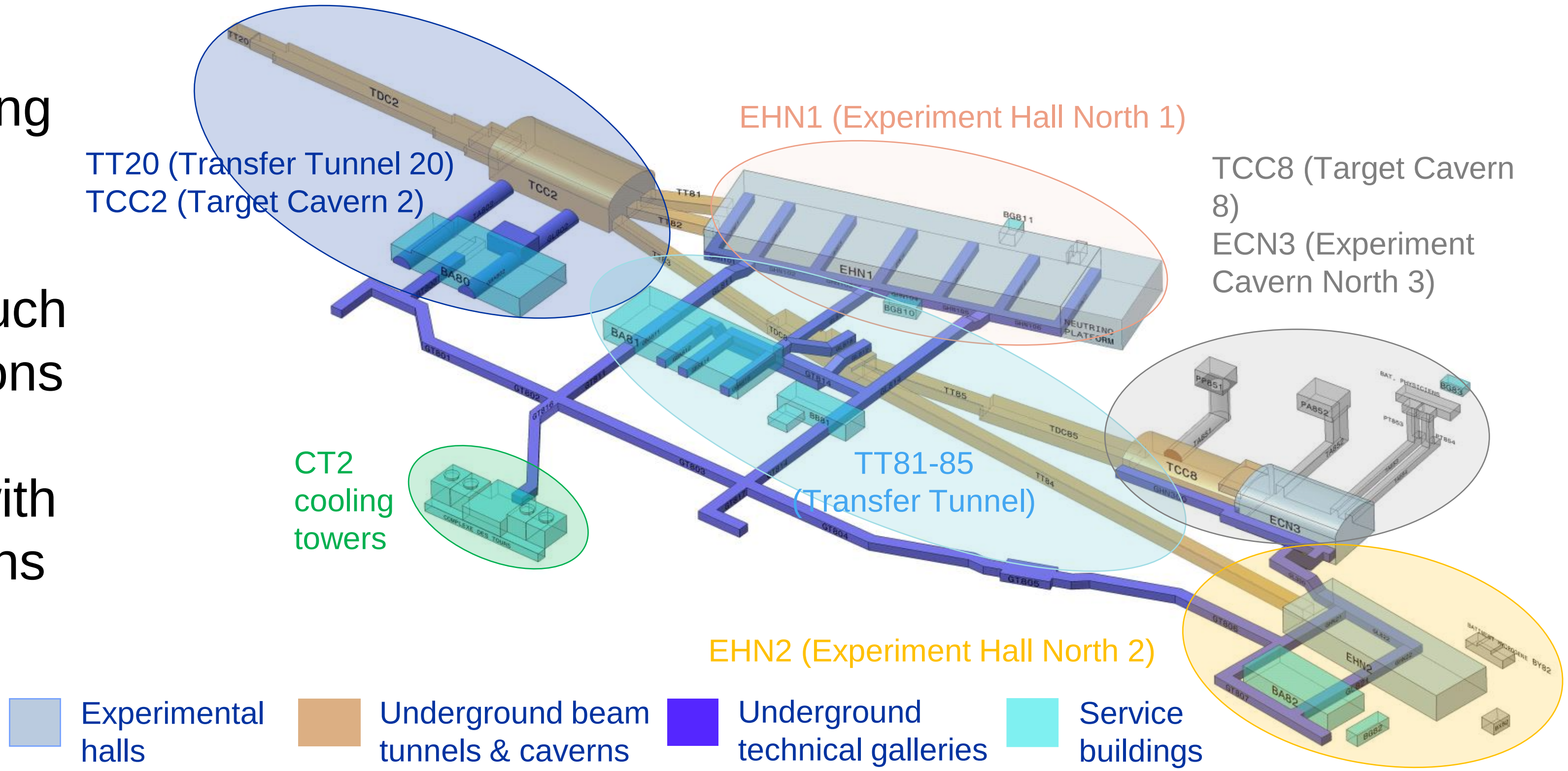


courtesy Johannes Bernhard and Lau Gattignon

North Area Consolidation and High Intensity Upgrade

North Area Consolidation Project

- North Area (NA) experimental halls and transfer tunnels were built in 1970s
  - About **60 000 square metres,** including North Experimental Halls 1 and 2 (EHN1 and EHN2) and underground cavern ECN3
  - **Equipment** such a power converters **exceeded the intended lifetime**
- Initial Consolidation work concentrating on the safety of the installations during Long Shutdown 2 (starting 2019)
- Recent years concentrating on **safety-related works** (such as fire safety) and preparations for the Long Shutdown 3 (starting November 2025), with **mayor de-cabling** campaigns
- Planned to be ready for beam again in Q3 2028



TT20 (Transfer Tunnel 20)
TCC2 (Target Cavern 2)

EHN1 (Experiment Hall North 1)

TCC8 (Target Cavern 8)
ECN3 (Experiment Cavern North 3)

CT2 cooling towers

TT81-85 (Transfer Tunnel)

EHN2 (Experiment Hall North 2)

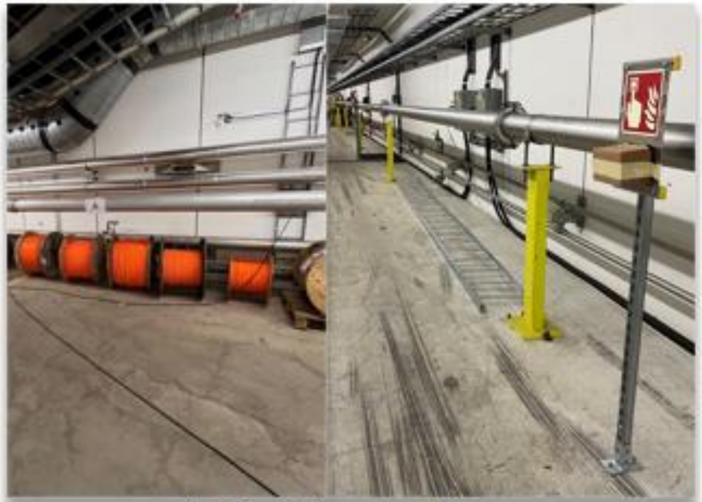
- ▨ Experimental halls
- ▨ Underground beam tunnels & caverns
- ▨ Underground technical galleries
- ▨ Service buildings

Winter Shutdown 2023/2024 Consolidation Highlights


De-cabling - TT


Chilled water piping distribution network - EHN1


Ventilation in galleries - EHN1 and EHN2

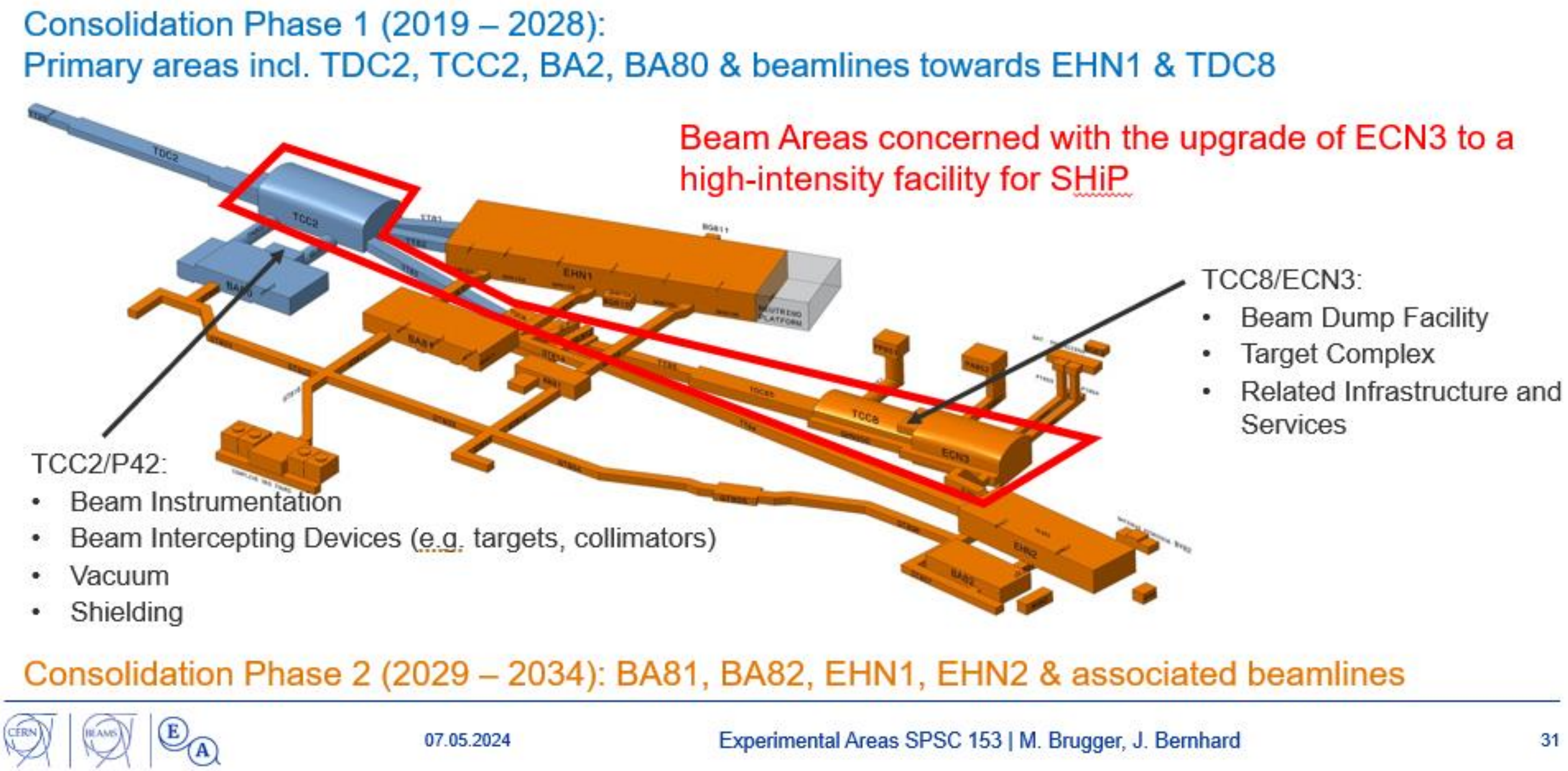

New fire detection system - TT


New fire doors - EHN1 and EHN2


New sprinkler station - BA80


New ventilation units - TT

Phased Approach to Consolidation and High Intensity Upgrade



Consolidation Phase 1 (2019 – 2028):
Primary areas incl. TDC2, TCC2, BA2, BA80 & beamlines towards EHN1 & TDC8

Beam Areas concerned with the upgrade of ECN3 to a high-intensity facility for SHiP

TCC8/ECN3:

- Beam Dump Facility
- Target Complex
- Related Infrastructure and Services

TCC2/P42:

- Beam Instrumentation
- Beam Intercepting Devices (e.g. targets, collimators)
- Vacuum
- Shielding

Consolidation Phase 2 (2029 – 2034): BA81, BA82, EHN1, EHN2 & associated beamlines

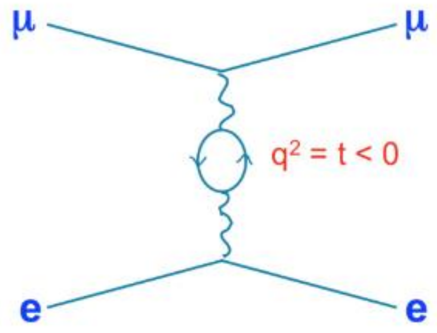
07.05.2024 Experimental Areas SPSC 153 | M. Brugger, J. Bernhard 31

Future Experiments and Projects

- New Physics Experiments: MUONE and SHIP
- Neutrino Related Projects from the Physics Beyond Collider (PBC) Study Group (https://pbc.web.cern.ch/)
- Continued heavy demand for test beams (High Lumi LHC upgrades, new projects)

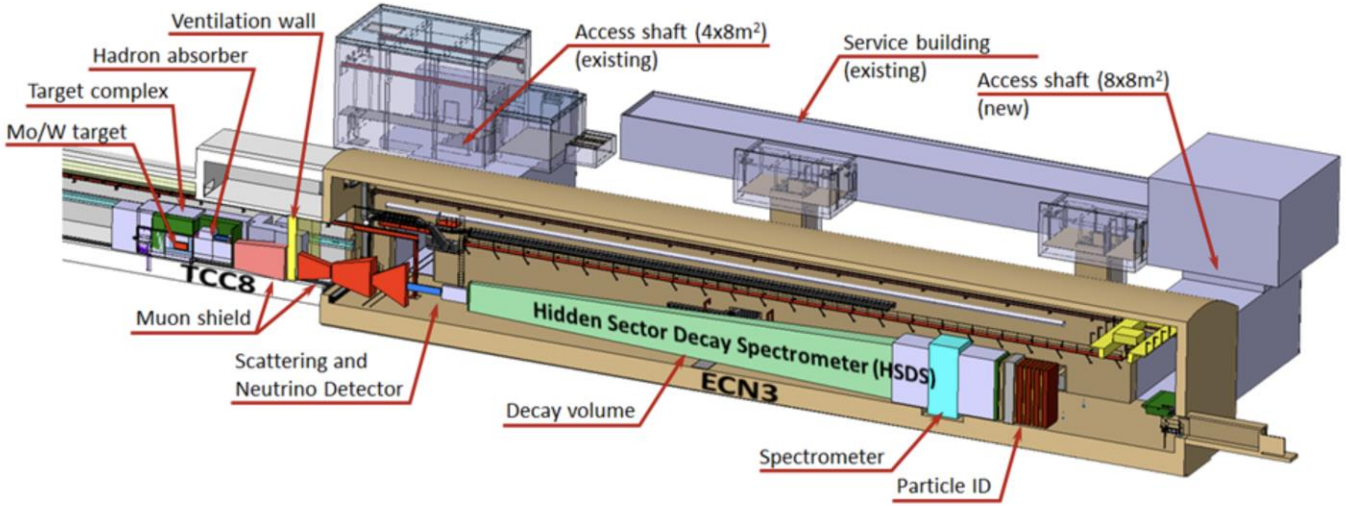
MUONE (MUon ON Electron elastic scattering)

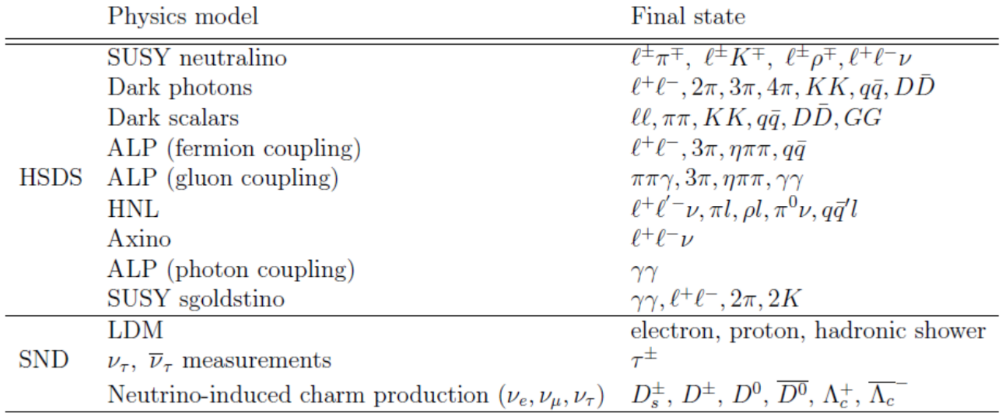
- Proposal
  - „An alternative evaluation of the leading-order hadronic contribution to the muon g-2 with MUonE", Phys. Lett. B 848 (2024), 138344; doi:10.1016/j.physletb.2023.138344 https://www.sciencedirect.com/science/article/pii/S0370269323006780
- Purpose: measure the leading hadronic contributions to anomalous magnetic moment of muons (g-2) to sub-percent level https://web.infn.it/MUonE/
  - Long-standing discrepancy between measurement and Standard Model (SM) prediction for g-2
  - Recent lattice QCD results lie between the measurement and SM calculation using $e^+e^- \longrightarrow$ hadrons
  - MUonE will measure the same quantity that is calculated with lattice QCD, testing directly the theoretical expectation value
- Measuring muon elastic scattering on electrons in a target
- 160 GeV/c muon beam; 3 full years of data taking post LS3 (2028 onwards)
- Intermediate measurement step in 2025 (EM contribution and 10% precision of the hadronic contribution)



SHiP (Search for Hidden Particles) at the ECN3 High-Intensity Facility

- General-purpose intensity-frontier experimental facility operating in “beam-dump mode”
  (BDF/SHiP at the ECN3 high-intensity facility, Proposal, CERN-SPSC-2023-033)
- Search for feebly interacting GeV-scale particles
- Perform measurements in neutrino physics
- Two main detector components: SND (scattering and neutrino detector) and HSDS (hidden sector decay spectrometer)
- Data taking envisaged 2031 to 2048
- Examples of the physics models and final state that can be measured:

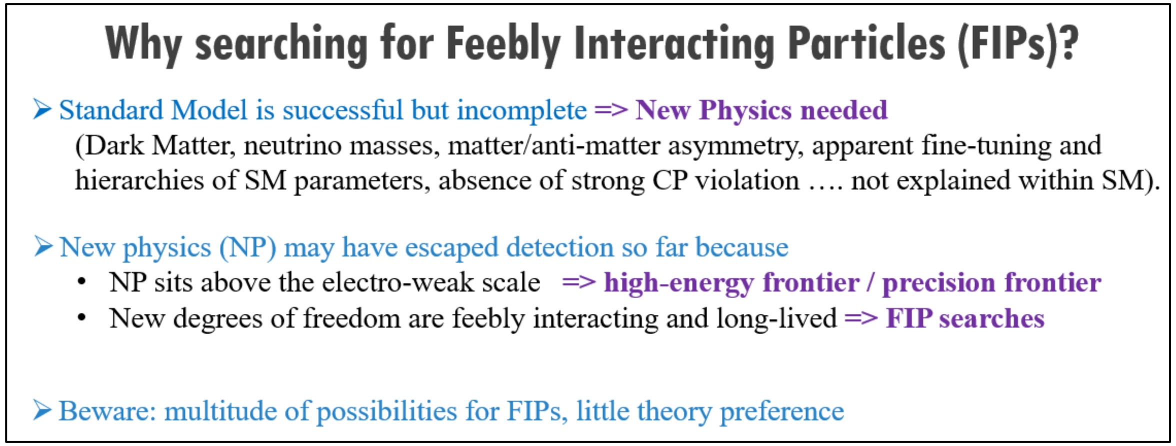




	Physics model	Final state
HSDS	SUSY neutralino	$\ell^\pm\pi^\mp,\ \ell^\pm K^\mp,\ \ell^\pm\rho^\mp, \ell^+\ell^-\nu$
	Dark photons	$\ell^+\ell^-, 2\pi, 3\pi, 4\pi, KK, q\bar{q}, D\bar{D}$
	Dark scalars	$\ell\ell, \pi\pi, KK, q\bar{q}, D\bar{D}, GG$
	ALP (fermion coupling)	$\ell^+\ell^-, 3\pi, \eta\pi\pi, q\bar{q}$
	ALP (gluon coupling)	$\pi\pi\gamma, 3\pi, \eta\pi\pi, \gamma\gamma$
	HNL	$\ell^+\ell'^-\nu, \pi l, \rho l, \pi^0\nu, q\bar{q}'l$
	Axino	$\ell^+\ell^-\nu$
	ALP (photon coupling)	$\gamma\gamma$
	SUSY sgoldstino	$\gamma\gamma, \ell^+\ell^-, 2\pi, 2K$
SND	LDM	electron, proton, hadronic shower
	ν_τ, $\overline{\nu}_\tau$ measurements	$\tau^\pm$
	Neutrino-induced charm production $(\nu_e, \nu_\mu, \nu_\tau)$	$D_s^\pm$, $D^\pm$, D^0, $\overline{D^0}$, Λ_c^+, $\overline{\Lambda_c}^-$

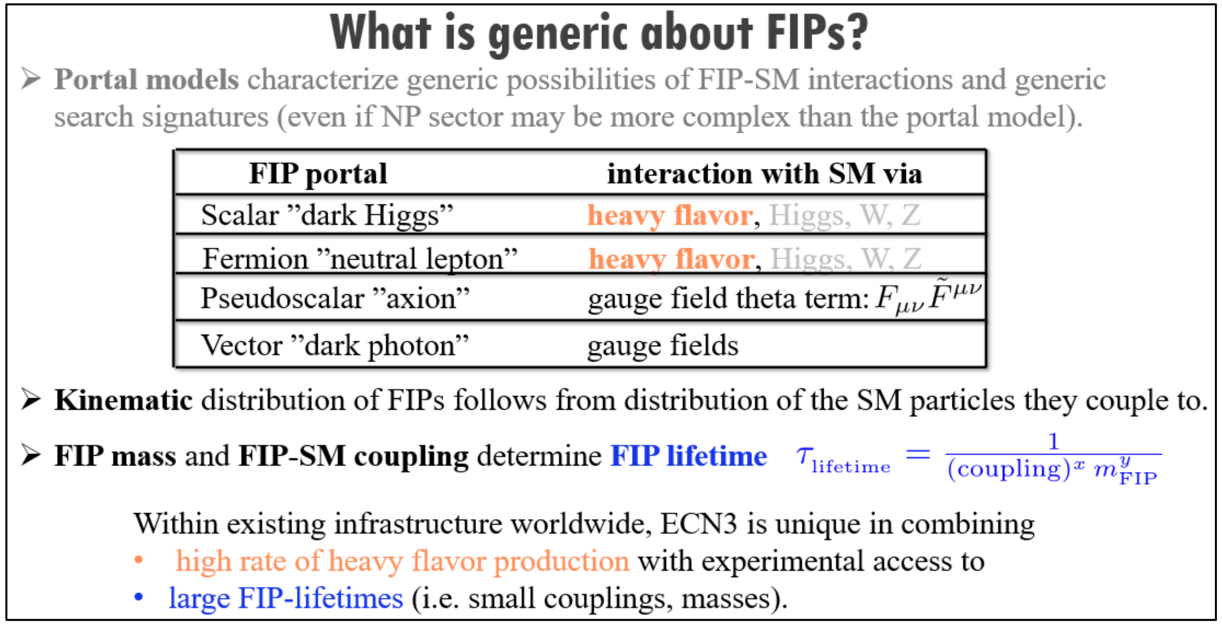
SHIP Motivation

- Urs Wiedemann, ECN3 Physics experiments: HIKE/SHADOWS – SHiP, Chamonix Workshop 2024, https://indico.cern.ch/event/1343931



Why searching for Feebly Interacting Particles (FIPs)?

- Standard Model is successful but incomplete => **New Physics needed**
  (Dark Matter, neutrino masses, matter/anti-matter asymmetry, apparent fine-tuning and hierarchies of SM parameters, absence of strong CP violation …. not explained within SM).
- New physics (NP) may have escaped detection so far because
  - NP sits above the electro-weak scale => **high-energy frontier / precision frontier**
  - New degrees of freedom are feebly interacting and long-lived => **FIP searches**
- Beware: multitude of possibilities for FIPs, little theory preference



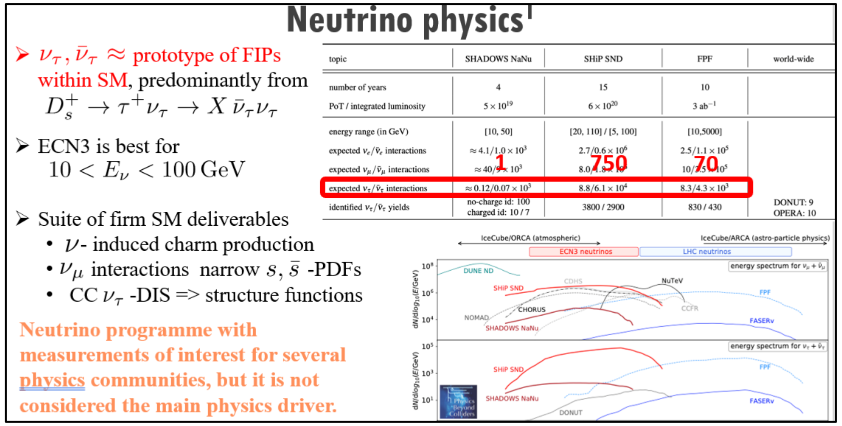
What is generic about FIPs?

- **Portal models** characterize generic possibilities of FIP-SM interactions and generic search signatures (even if NP sector may be more complex than the portal model).

FIP portal	interaction with SM via
Scalar ”dark Higgs”	**heavy flavor**, Higgs, W, Z
Fermion ”neutral lepton”	**heavy flavor**, Higgs, W, Z
Pseudoscalar ”axion”	gauge field theta term: $F_{\mu\nu}\tilde{F}^{\mu\nu}$
Vector ”dark photon”	gauge fields

- **Kinematic** distribution of FIPs follows from distribution of the SM particles they couple to.
- **FIP mass** and **FIP-SM coupling** determine **FIP lifetime** $\tau_{\text{lifetime}} = \frac{1}{(\text{coupling})^x \, m_{\text{FIP}}^y}$

Within existing infrastructure worldwide, ECN3 is unique in combining
- high rate of heavy flavor production with experimental access to
- large FIP-lifetimes (i.e. small couplings, masses).



Neutrino physics[1]

- $\nu_\tau, \bar{\nu}_\tau \approx$ prototype of FIPs within SM, predominantly from $D_s^+ \to \tau^+ \nu_\tau \to X\, \bar{\nu}_\tau \nu_\tau$
- ECN3 is best for $10 < E_\nu < 100\,\text{GeV}$
- Suite of firm SM deliverables
  - ν- induced charm production
  - ν_μ interactions narrow $s, \bar{s}$ -PDFs
  - CC ν_τ -DIS => structure functions

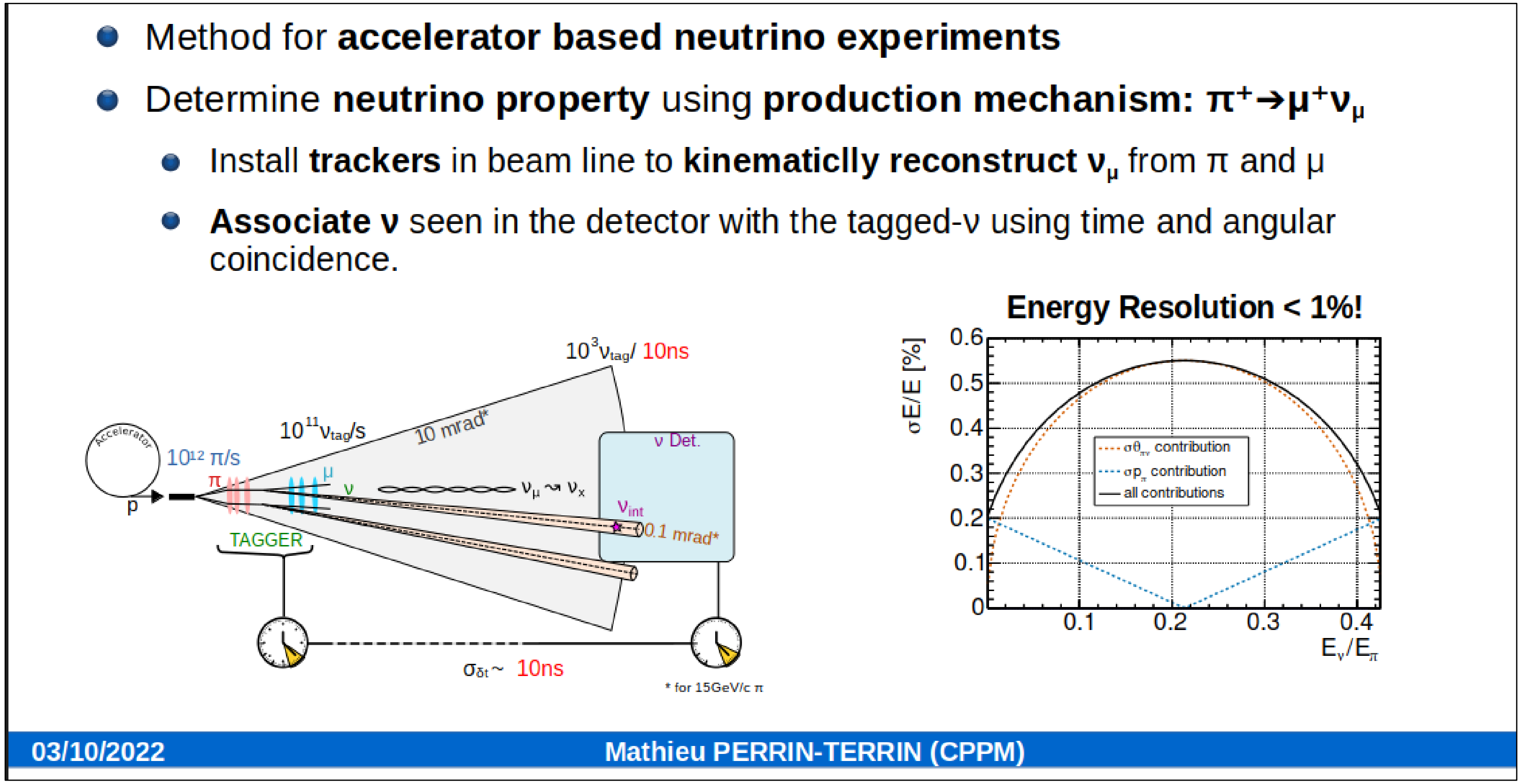
Neutrino programme with measurements of interest for several physics communities, but it is not considered the main physics driver.

topic	SHADOWS NaNu	SHiP SND	FPF	world-wide
number of years	4	15	10	
PoT / integrated luminosity	5×10^{19}	6×10^{20}	3 ab^{-1}	
energy range (in GeV)	[10, 50]	[20, 110] / [5, 100]	[10,5000]	
expected $\nu_e/\bar{\nu}_e$ interactions	$\approx 4.1/1.0 \times 10^3$	$2.7/0.6 \times 10^6$	$2.5/1.1 \times 10^5$	
expected $\nu_\mu/\bar{\nu}_\mu$ interactions	$\approx 40/9 \times 10^3$	$8.0/1.8 \times 10^6$	$10/7.5 \times 10^5$	
expected $\nu_\tau/\bar{\nu}_\tau$ interactions	$\approx 0.12/0.07 \times 10^3$	$8.8/6.1 \times 10^4$	$8.3/4.3 \times 10^3$	
identified $\nu_\tau/\bar{\nu}_\tau$ yields	no-charge id: 100 charged id: 10 / 7	3800 / 2900	830 / 430	DONUT: 9 OPERA: 10

1 750 70

Neutrino Related PBC Projects – Currently No Time-Line Available

- Dealt with at the PBC (Physics Beyond Collider), conventional beam working group, Neutrino Beams subgroup,
  https://indico.cern.ch/event/1137276/contributions/4950763/attachments/2543792/4380179/PBC_ENUBET_NUTAGv5.pdf
- **NA61 Low Energy Beamline** (very low energy beamline): under review with the SPSC
  - 2 to 13 GeV/c hadron beams to NA61 set-up in the SPS NA H2 beam line
  - Measurements of particle yield and cross sections → reduce uncertainty in atmospheric neutrino flux
- **NuTAG:** tagged (energy, direction measured) ν beams for next generation long-baseline experiments

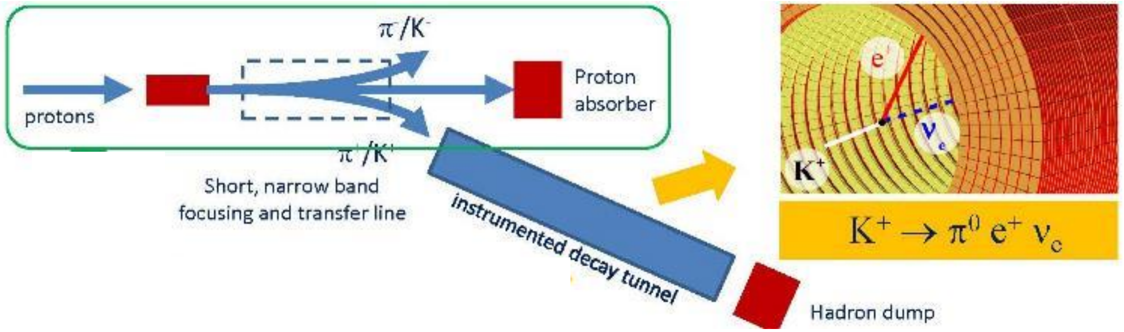


- Method for **accelerator based neutrino experiments**
- Determine **neutrino property** using **production mechanism: $\pi^+ \rightarrow \mu^+ \nu_\mu$**
  - Install **trackers** in beam line to **kinematicly reconstruct ν_μ** from π and μ
  - **Associate ν** seen in the detector with the tagged-ν using time and angular coincidence.

03/10/2022 **Mathieu PERRIN-TERRIN (CPPM)**

Neutrino Related PBC Projects, cont’d

- **NP06 ENUBET:** Monitored (flux measurement) ν beams for precision ν cross section
  - aim at reducing cross section uncertainties from 10% - 30% down to 1% level
  - $K^+ \rightarrow \pi^0 e^+ \nu_e$ and other channels (e.g $K^+ \rightarrow \mu^+ \pi_0 \nu_\mu$)
  - Assuming 4.5x10^19 p/year @ 400 GeV/c and using ProtoDUNE-SP as detector (NA extension) ENUBET would aim to collect a total of 1E4 events in 2 years.
  - 8.5 GeV/c baseline design; alternative Multi-Momentum” beam line design (4, 6 & 8.5 GeV/c) studied as well
  - Test beam phase nearing completion: PS T9 (2017, 2018, 2022, 2023, 2024)



- **SBL@PBC**: Efforts towards a short-baseline proposal that combines both projects with a reasonable number of POT/y within the Conventional Beams – Neutrino Beams WG (https://indico.cern.ch/category/14358/)
  - Ongoing study, feasibility to be established. Possibly submit proposal to SPSC in 2026 (dedicated SPS NA beam line; 5 years data taking; would require neutrino beam; <5 10^18 pot/year.

Eur.Phys.J.C 83 (2023) 10, 964
https://indico.cern.ch/event/1353517/

New DRD Collaborations (Detector Research and Development)

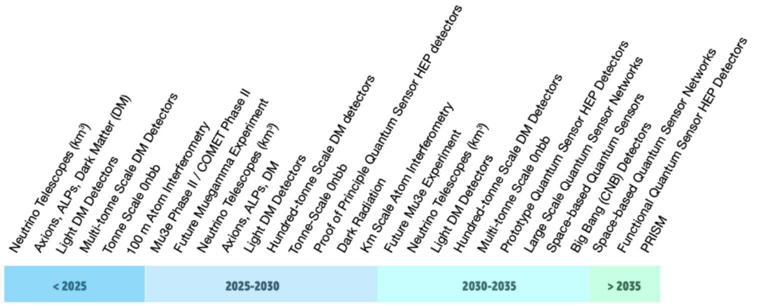
- DRD1 – Gaseous Detectors
- DRD2 – Liquid Detectors
- DRD3 – Semiconductor Detectors
- DRD4 – Photodetectors and Particle ID
- DRD5 – Quantum and Emerging Technologies
- DRD6 – Calorimetry
- DRD7 – Electronics and On-Detector Processing
- DRD8 – Integration

ECFA Detector R&D Roadmap

- Based on European Strategy for Particle Physics Update 2020 recommendation
- The European Committee for Future Accelerators (ECFA) released in 2021 "The 2021 ECFA Detector Research and Development Roadmap": full document (200 pages) ; synopsis (https://indico.cern.ch/event/957057/overview)
- Overview of **future facilities** (EIC, ILC, CLIC, FCC-ee/hh, Muon collider) and **major upgrades** (ALICE, Belle-II, LHC-b,…) and their **timeline**
- Corresponding mayor **Detector R&D Themes (DRDTs)**

THE 2021 ECFA DETECTOR
RESEARCH AND DEVELOPMENT ROADMAP

The European Committee for Future Accelerators
Detector R&D Roadmap Process Group



"Technical" Start Date of Facility
(This means, where the dates are not known, the earliest technically feasible start date is indicated - such that detector R&D readiness is not the delaying factor)

Figure 4: (Representative) Smaller Accelerator and Non-Accelerator Based Experiments Start Dates (*not intended to be at all an exhaustive list*).

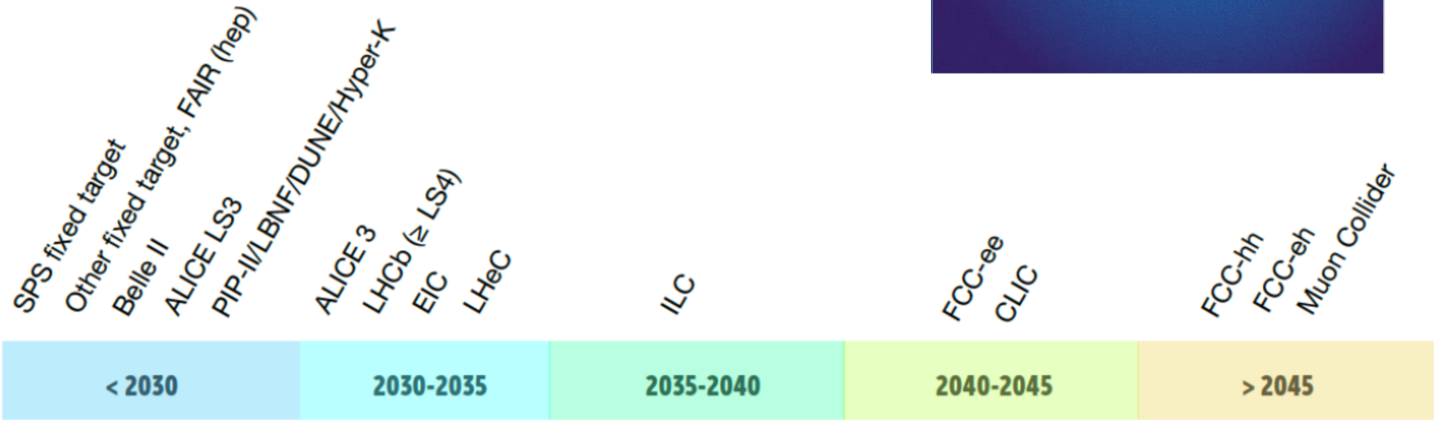
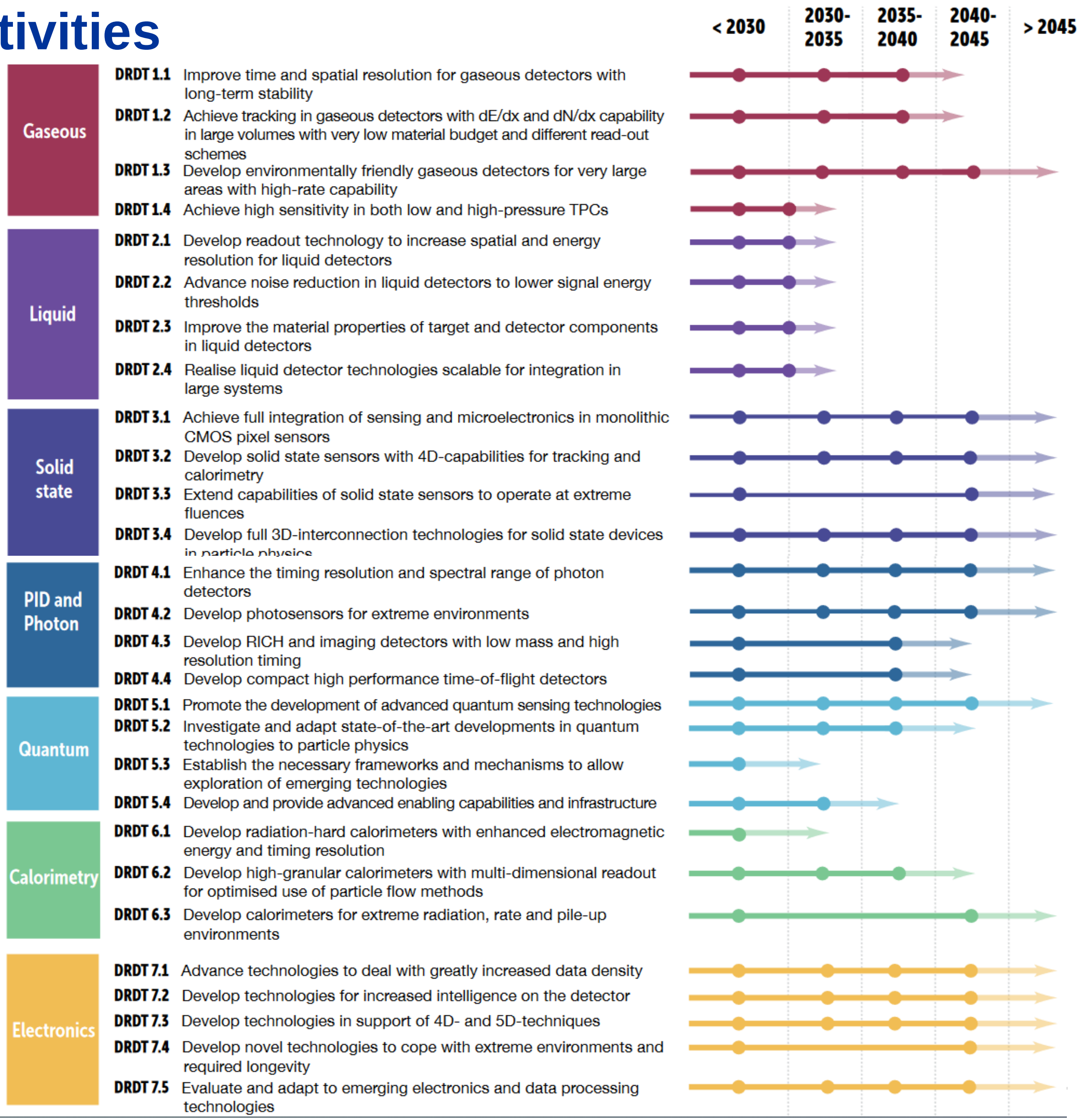


Figure 3: Large Accelerator Based Facility/Experiment Earliest Feasible Start Dates.

Timeline of the Identified DRDT Activities

- ECFA Detector R&D Roadmap describes **Strategic R&D** towards **necessary** technologies **to build future facilities and experiments**
- But it also asks for DRD collaborations to include a small scale “blue-sky” R&D
- **Very diverse Test Beam needs** during all the stages starting from blue-sky until production (batch) validation**:**
  - DRD1, DRD3, DRD7: heavy parallel running possible
  - DRD4: some parallel running possible
  - DRD2, DRD6: require dedicated beam time → substantial requests expected for beam time

- **Last Dot**: Target date completion of the **R&D** required by the latest known future facility/experiment (**earlier dots** represent intermediate facilities/experiments)
- **Arrow**: further time to be anticipated for experiment-specific **prototyping**, procurement, **production validation**, construction, installation and commissioning.
- R&D for Liquid Detectors will be needed far into the future, but estimates do not exist



DRDT 1.1 Improve time and spatial resolution for gaseous detectors with long-term stability
DRDT 1.2 Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes
DRDT 1.3 Develop environmentally friendly gaseous detectors for very large areas with high-rate capability
DRDT 1.4 Achieve high sensitivity in both low and high-pressure TPCs
DRDT 2.1 Develop readout technology to increase spatial and energy resolution for liquid detectors
DRDT 2.2 Advance noise reduction in liquid detectors to lower signal energy thresholds
DRDT 2.3 Improve the material properties of target and detector components in liquid detectors
DRDT 2.4 Realise liquid detector technologies scalable for integration in large systems
DRDT 3.1 Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors
DRDT 3.2 Develop solid state sensors with 4D-capabilities for tracking and calorimetry
DRDT 3.3 Extend capabilities of solid state sensors to operate at extreme fluences
DRDT 3.4 Develop full 3D-interconnection technologies for solid state devices in particle physics
DRDT 4.1 Enhance the timing resolution and spectral range of photon detectors
DRDT 4.2 Develop photosensors for extreme environments
DRDT 4.3 Develop RICH and imaging detectors with low mass and high resolution timing
DRDT 4.4 Develop compact high performance time-of-flight detectors
DRDT 5.1 Promote the development of advanced quantum sensing technologies
DRDT 5.2 Investigate and adapt state-of-the-art developments in quantum technologies to particle physics
DRDT 5.3 Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies
DRDT 5.4 Develop and provide advanced enabling capabilities and infrastructure
DRDT 6.1 Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution
DRDT 6.2 Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods
DRDT 6.3 Develop calorimeters for extreme radiation, rate and pile-up environments
DRDT 7.1 Advance technologies to deal with greatly increased data density
DRDT 7.2 Develop technologies for increased intelligence on the detector
DRDT 7.3 Develop technologies in support of 4D- and 5D-techniques
DRDT 7.4 Develop novel technologies to cope with extreme environments and required longevity
DRDT 7.5 Evaluate and adapt to emerging electronics and data processing technologies

Roadmap Concludes with 10 General Strategic Recommendations (GSR)

- GSR1: Supporting R&D facilities
  - It is recommended that the structures to provide Europe-wide coordinated infrastructure in the areas of: test beams, large scale generic prototyping and irradiation be consolidated and enhanced to meet the needs of next generation experiments … and to maintain a network structure for existing distributed facilities, e.g. for irradiation.
- GSR 2: Engineering support for detector R&D
- GSR 3: Specific software for instrumentation
- GSR 4: International coordination and organisation of R&D activities
  - … refresh the CERN RD programme structure … revisit and streamline the process of creating and reviewing these programmes, with an extended framework to help share the associated load and increase involvement, while enhancing the visibility of the detector R&D community and easing communication with neighbouring disciplines → **A Detector R&D Committee (DRDC) was formed in 2023 to deal with new detector R&D collaborations.** https://committees.web.cern.ch/
- GSR 5: Distributed R&D activities with centralised facilities
- GSR 6: Establish long-term strategic funding programmes
- GSR 7: "Blue-sky" R&D
  - … unlocking new physics may only be possible by unlocking novel technologies in instrumentation … past examples include … the World Wide Web, Magnetic Resonance Imaging, Positron Emission Tomography and X-ray imaging …
- GSR 8: Attract, nurture, recognise and sustain the careers of R&D experts
- GSR 9: Industrial partnerships
- GSR 10: Open Science

CERN Scientific Committees

The CERN Scientific Committees are of two types: the Experiment Committees, which review the physics, and the Resources and Finance Review Boards.

Experiment Committees

Research Board Chairperson: Director-General Scientific Secretary: Roger Forty (EP)	**DRDC - Detector R&D Committee** Chairperson: Thomas Bergauer Scientific Secretary: Jan Troska (EP)	**REC - Recognized Experiments Committee** Chairperson: Director for Research Scientific Secretary: Helge Meinhard (RCS)
INTC - ISOLDE and n_TOF Experiments Committee Chairperson: Marek Pfutzner Scientific Secretary: Hanne Heylen (EP)	**LHCC - LHC Experiments Committee** Chairperson: Frank Simon Scientific Secretary: Lorenzo Moneta (EP)	**SPSC - SPS and PS Experiments Committee** Chairperson: Jordan Nash Scientific Secretary: Carlos Lourenço (EP)

General Strategic Recommendation #1 – Excerpt from the Full Text

On the increasing requirements for test beams and infrastructure for test beams:

“ … Firstly, coordinated access to test-beam facilities should be continued and enhanced to meet the needs of next generation detector development. A small number of world leading facilities at major laboratories support access to test beams [Ch10-2], [Ch10-3], where detectors and detector systems can be tested under realistic conditions and their response to a range of particle types can be evaluated. Given the different functions of different sub-detector systems, **beams of charged hadrons, electrons and muons at different momenta and rates are vital**. The **cryogenics, gases, cooling, magnets, electrical services and readout**, along with provision of the beams themselves, represent a considerable annual cost that host laboratories supply to the community. In addition, **further detector systems** (“beam hodoscopes”) are required to provide **increasingly accurate tracking and timing information** of the individual incoming particles, and further instrumentation is required to **determine particle energies, monitor particle fluxes and determine beam compositions**.

For large scale system tests, the engineering and other infrastructure required can approach the cost and complexity of a small-scale experiment.
…”

→ PS EA multipurpose test beam lines (H2, H4, H6, H8)

→ SPS NA: EHN1 multipurpose test beam lines (T9, T10)

General Strategic Recommendation #1 – Excerpt from the Full Text

On the increasing demands for radiation testing

"… **Support for radiation testing should be continued and enhanced** to meet the needs of next generation detector development. In many experiments, even modest levels of radiation exceed those to which any commercially available equipment has been designed to withstand. Unless fully customised components can be afforded, the impact of this is that **sample (batch) testing of all commercially sourced equipment is needed** to check that no design or process changes (which would typically be commercially confidential) could have resulted in reductions in the radiation tolerance properties and to be able to track such changes over time. **Even fully customised designs targeting radiation hardness still typically involve commercial partners whose detailed device processing may vary**. Establishing a design and a process to the most extreme levels of radiation hardness requires both a high degree of testing at irradiation facilities [Ch10-3], [Ch10-4] and a deep understanding of the physics of the radiation damage mechanisms themselves, often requiring a major simulation effort to model the measured macroscopic degradation with irradiation in terms of the microscopic changes in the heavily exposed materials. Facilities are needed to allow **irradiation at a range of energies with neutrons, photons, protons and (ideally) pions** (since the latter dominate the actual particle mix for sensors closest to the collision point in many experiments with the most severe requirements). Reactors, x-ray and gamma-ray sources, low energy cyclotrons and beams at accelerator laboratories are all needed, with a wide range of instantaneous particle fluxes and achievable integrated fluences, for these studies. …"

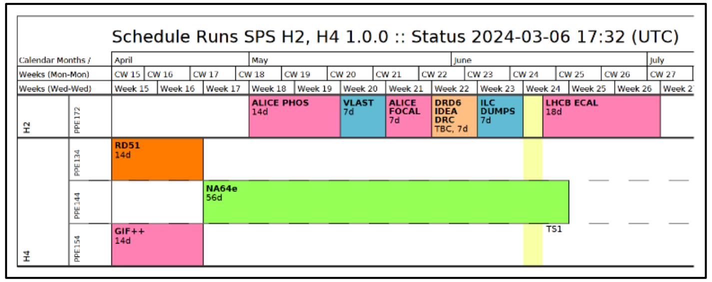
→ PS EA T8: IRRAD/CHARM and CHIMERA/HEARTS

→ SPS NA: GIF++ and CERF

→ SPS HiRadMat

First DRD1 Test Beam

- Eight DRD1 set-ups successfully operated in parallel
- Operating in parallel to GIF++ facility (taking muon beam behind)



Schedule Runs SPS H2, H4 1.0.0 :: Status 2024-03-06 17:32 (UTC)

Calendar Months /		April			May					June				July
Weeks (Mon-Mon)		CW 15	CW 16	CW 17	CW 18	CW 19	CW 20	CW 21	CW 22	CW 23	CW 24	CW 25	CW 26	CW 27
Weeks (Wed-Wed)		Week 15	Week 16	Week 17	Week 18	Week 19	Week 20	Week 21	Week 22	Week 23	Week 24	Week 25	Week 26	Week 2
H2	PPE172				ALICE PHOS 14d		VLAST 7d	ALICE FOCAL 7d	DRD6 IDEA DRC TBC, 7d	ILC DUMPS 7d	LHCB ECAL 18d			
H4	PPE134	RD51 14d												
	PPE144			NA64e 56d										
	PPE154	GIF++ 14d									TS1			

Generic and Application driven R&D

Technologies: Micromegas, uRWELL, uRGroove, GEM
Application: High Rate, Timing, Large Area
Readout: Capacitive Coupling, Resistive Sharing

Project driven R&D

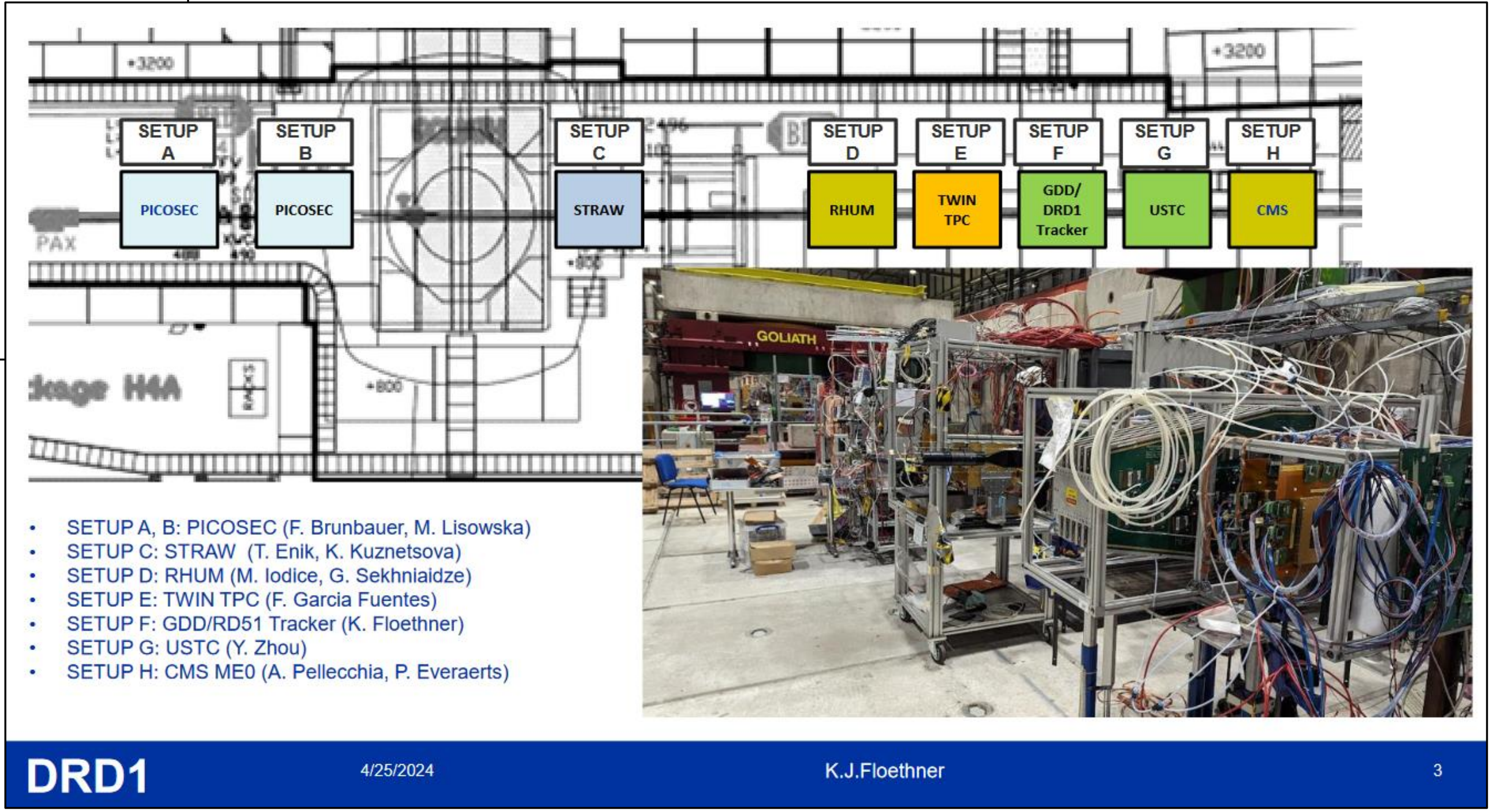
CMS ME0

Detector Commissioning

Twin TPC for MIXE, G4G (AMBER)

FE electronics and DAQ

Straw, VMM3a and TPC



- SETUP A, B: PICOSEC (F. Brunbauer, M. Lisowska)
- SETUP C: STRAW (T. Enik, K. Kuznetsova)
- SETUP D: RHUM (M. Iodice, G. Sekhniaidze)
- SETUP E: TWIN TPC (F. Garcia Fuentes)
- SETUP F: GDD/RD51 Tracker (K. Floethner)
- SETUP G: USTC (Y. Zhou)
- SETUP H: CMS ME0 (A. Pellecchia, P. Everaerts)

DRD1 4/25/2024 K.J.Floethner 3

END