Physics research at CERN

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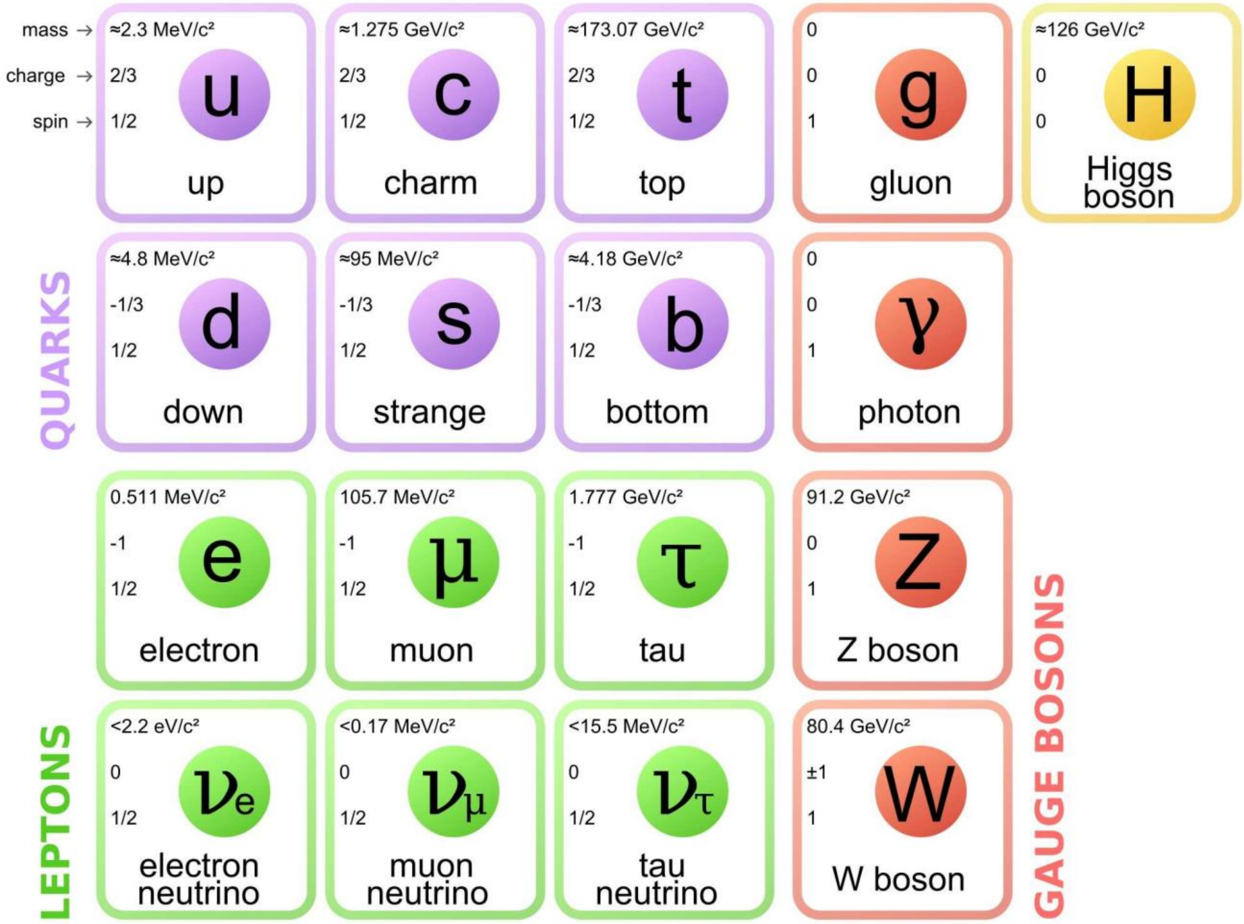
Introduction

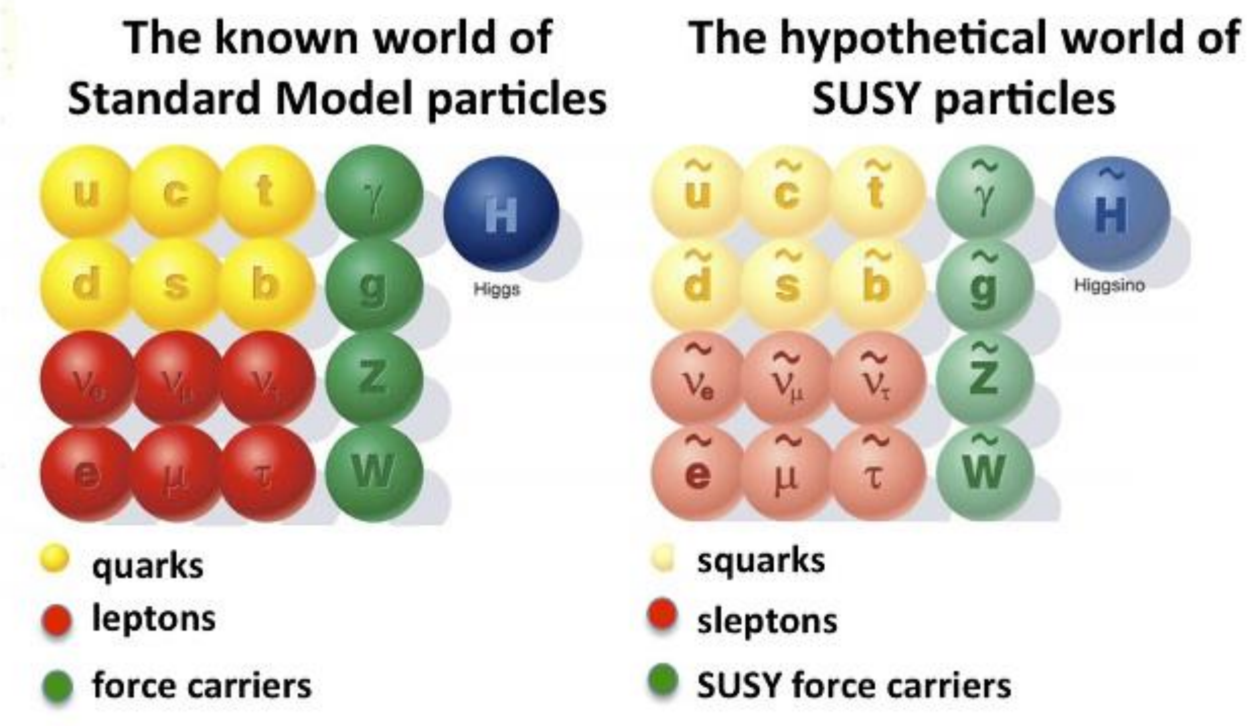
- Field of particle physics has its roots in the 20th century nuclear and quantum physics, which started to probe the nature of Universe at the microscopic scale
- Further research gave way to discoveries of elementary particles – starting from electrons to bosons, quarks and neutrinos
- Last 90 years of research have culminated in creation of The Standard Model of Elementary particles, from which all the fundemental particles have been discovered
- Eventhough SM predictions are being confirmed every day, we know that it is not a complete theory, as there are a lot of observations that are not explained by the SM
- The search for new/missing physics continues!



The elementary particles of the SM

Motivation – unanswered questions

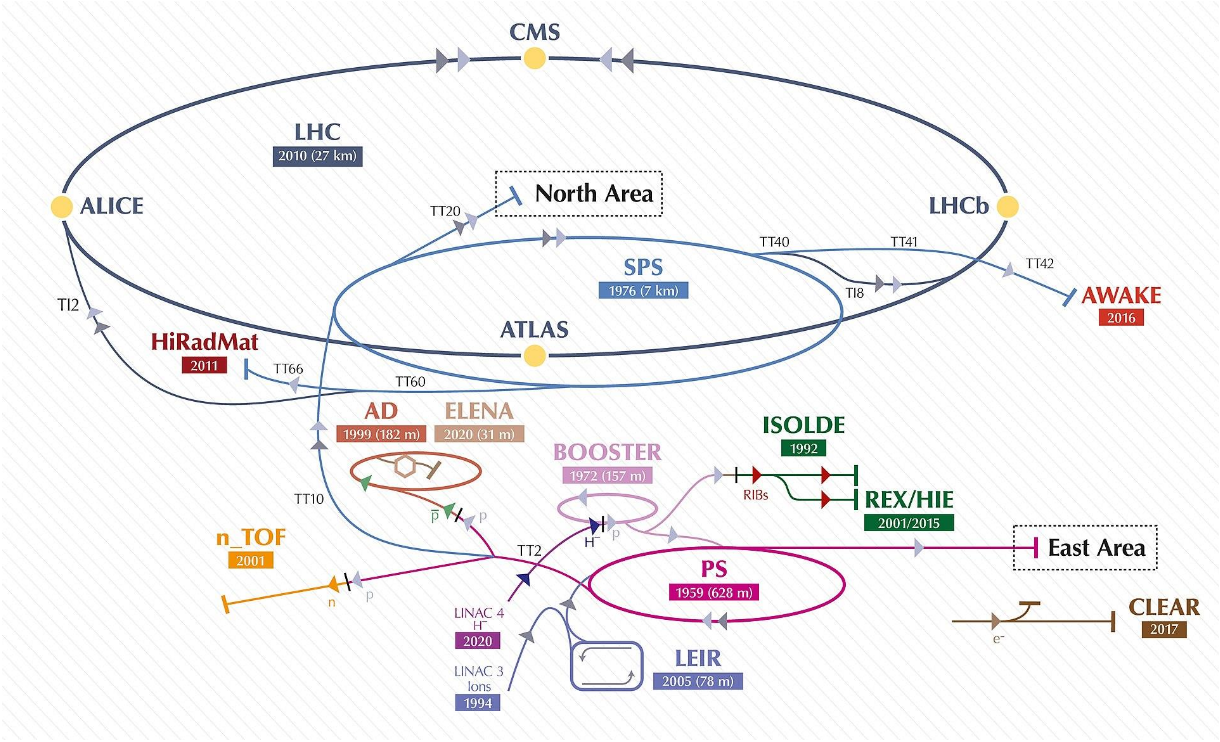
- Hierarchy problem – why gravity is such a weak force?
- Magnetic monopoles – do they exist?
- Generations of matter – why are there 3, why do they have such different masses?
- Neutrino – what are their masses? Are they Dirac or Majonara particles?
- Strong CP problem – why we observe no CP violation in QCD processes even if theory allows it?
- Anomolous magnetic dipol moment- measurements for muons shows excess (g-2 experiment)
- Supersymmetry – could explain dark matter
- And many other unresovled questions and BSM searches



SM particles and their supersymmetric companions

Overview

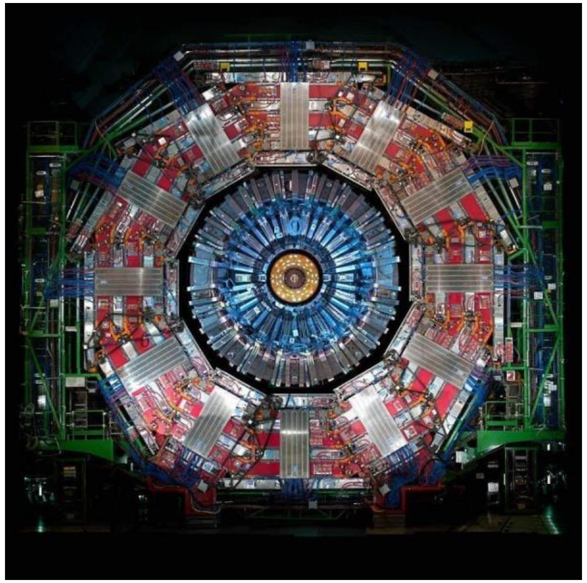
- CERN is the European laboratory of Particle physics
- Encompases 13000+ personel of scientists and engineers from at least 70 countries
- Flagship infrastructure – The LHC with 4 large detectors and various smaller experiments
- CERN cooperates with other particle physics laboratories around the world - FermiLab, DESY, KEK and others...
- CERN has multiple computing centers around the world

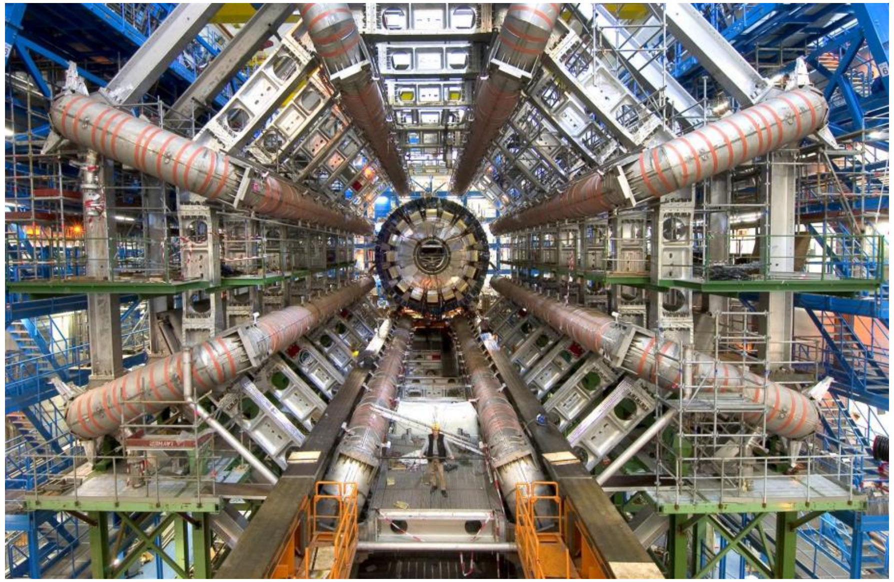


CERN experiment complex

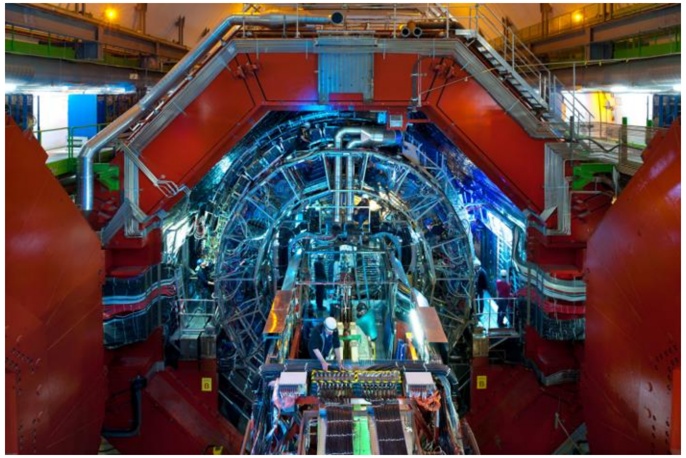
Main LHC experiments and corresponding physics

- The LHC hosts 4 large physics experiments – CMS, ATLAS, LHCb and ALICE
- Each experiment is a collaboration by itself with hundreds of institutions and thousands of scientists&engineers
- CMS and ATLAS are general purpose detectors – discovery machines
- LHCb and ALICE are specialized physics experiment


CMS

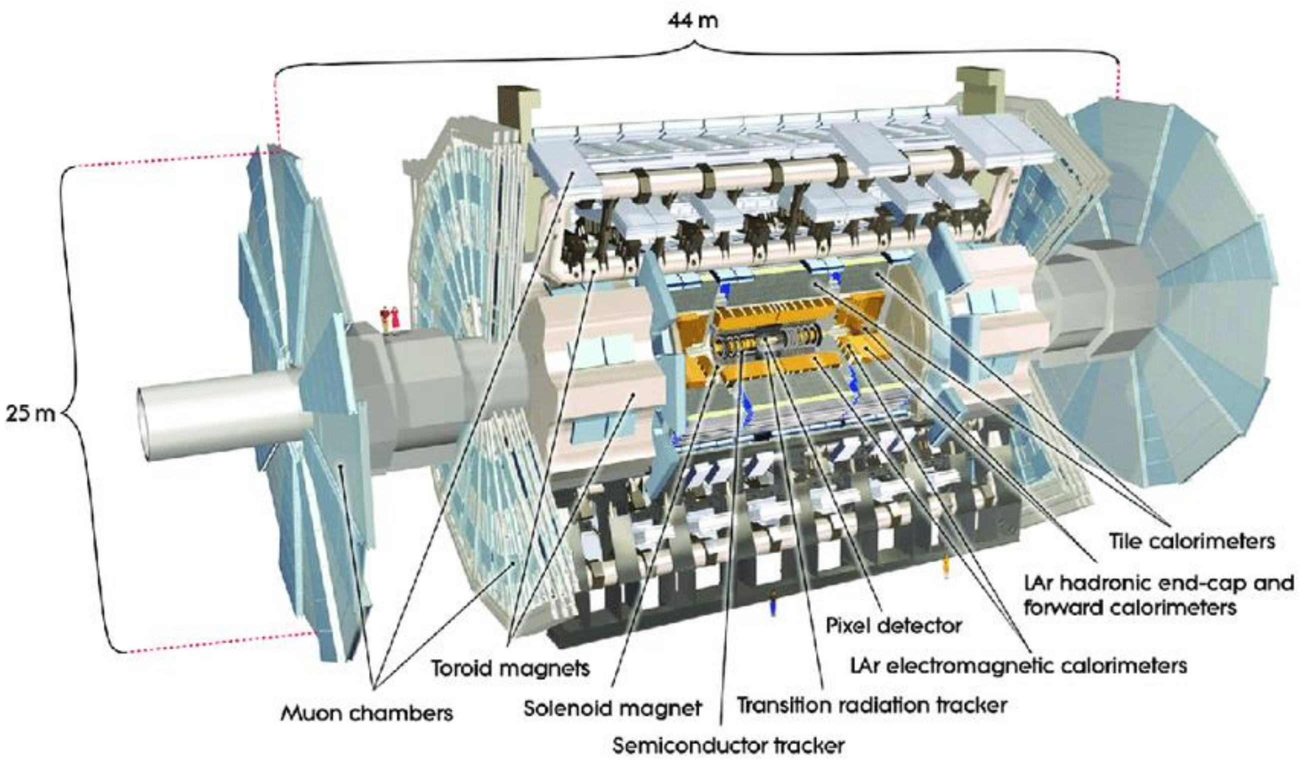

ATLAS

LHCb


ALICE

ATLAS

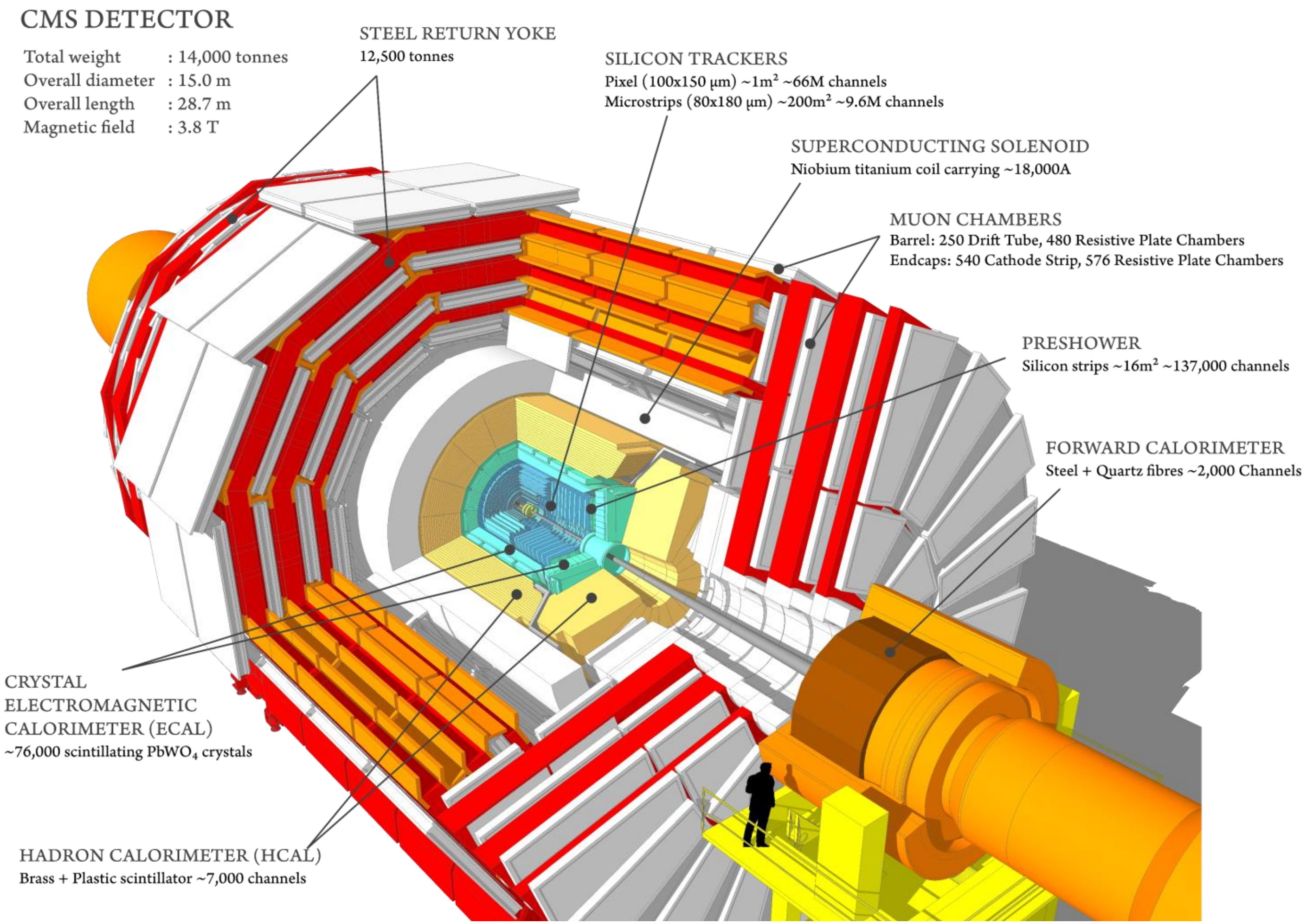
- ATLAS – **A** **T**oroidal **L**HC **A**paratu**S**
- ATLAS detector is built around a superconducting torodial magnet.
- Detector consists of 4 main parts – tracker, calorimeters, magnet and muon chambers
- The detector weighs 7000 tonnes.
- At 46 m long, 25 m high, the ATLAS detector is the largest particle detector in LHC.



Schematic view of ATLAS detector

CMS

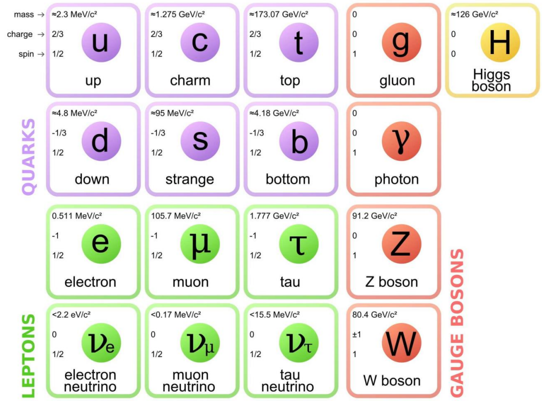
- CMS – **C**ompact **M**uon **S**olenoid (General purpose detector)
- The CMS detector is built around a huge solenoid magnet, made of cylindrical superconducting coil.
- Detector consists of 4 main parts – tracker, calorimeters, magnet and muon chambers, but with a different geometry than ATLAS detector
- The detector weighs 14,000 tonnes
- Unlike other LHC experiments, CMS was built in slices on ground level and then lowered+assembled underground
- The complete detector is 21 meters long, 15 meters wide, making it the heaviest particle detecto.



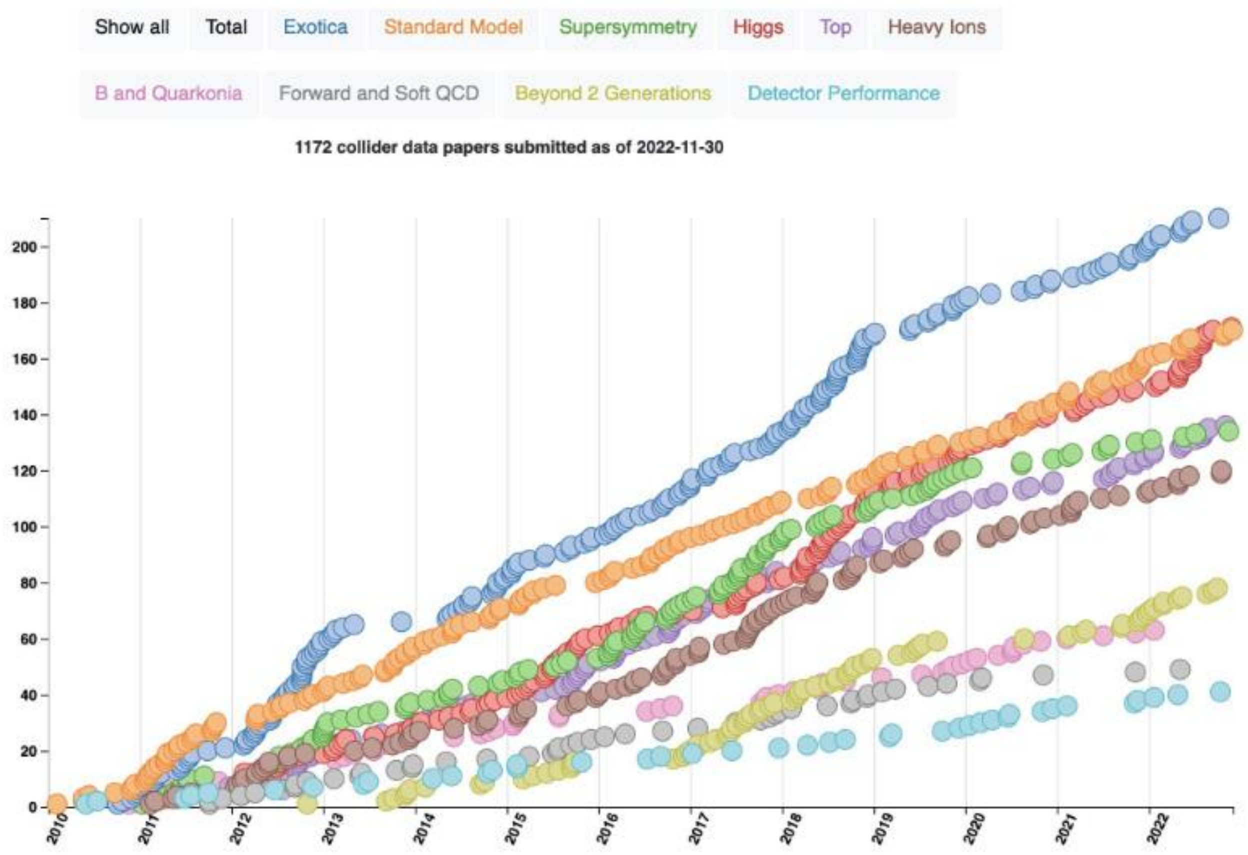
Schematic view of CMS detector

Physics program

- ATLAS and CMS experiments have overlaping and broad physics programs that cover most of the HEP fields
- A large focus is put on the studies of top quark and the higgs boson, but a lot of SM consistencity and heavy ion measurements are done as well
- By a large margin, the single most broad research field is ‘Exotica’, which covers the search for BSM particles that do not include supersymmetry



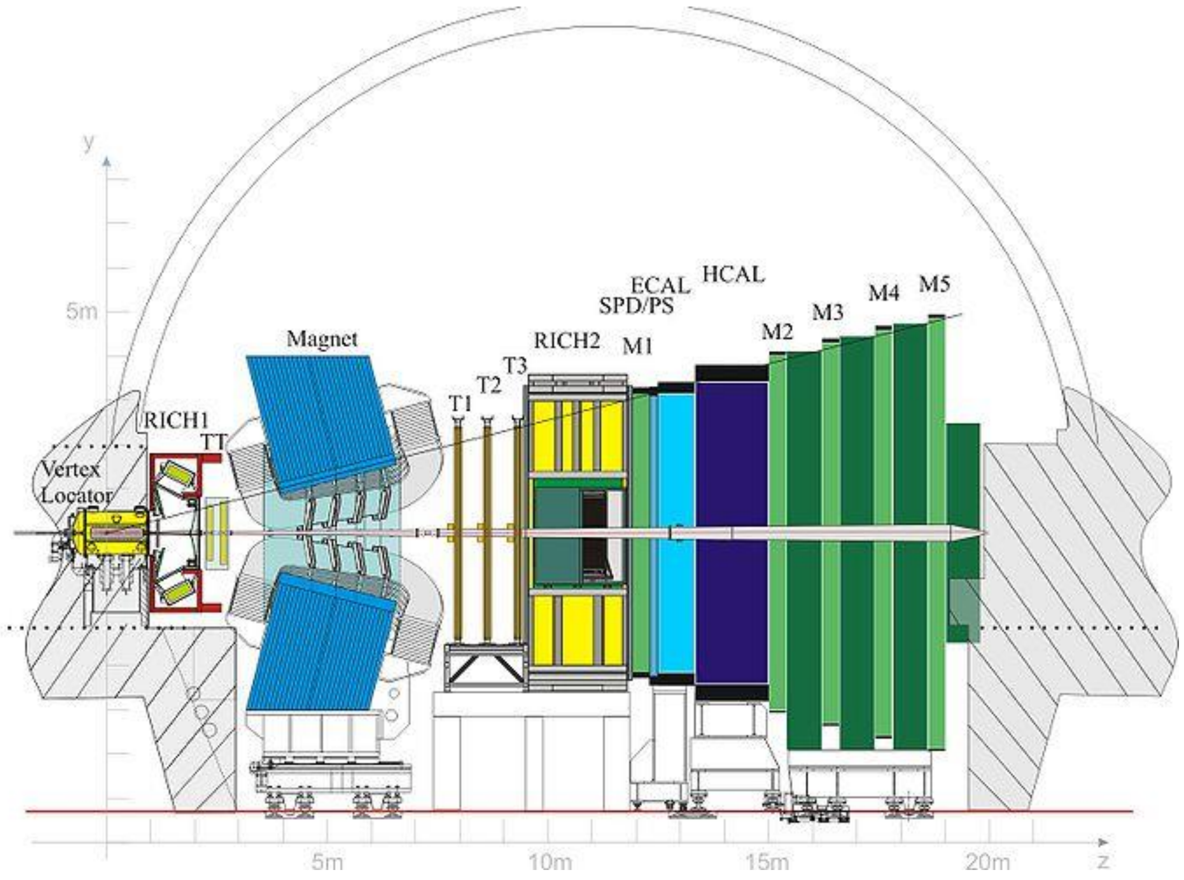
Elementary particles of SM



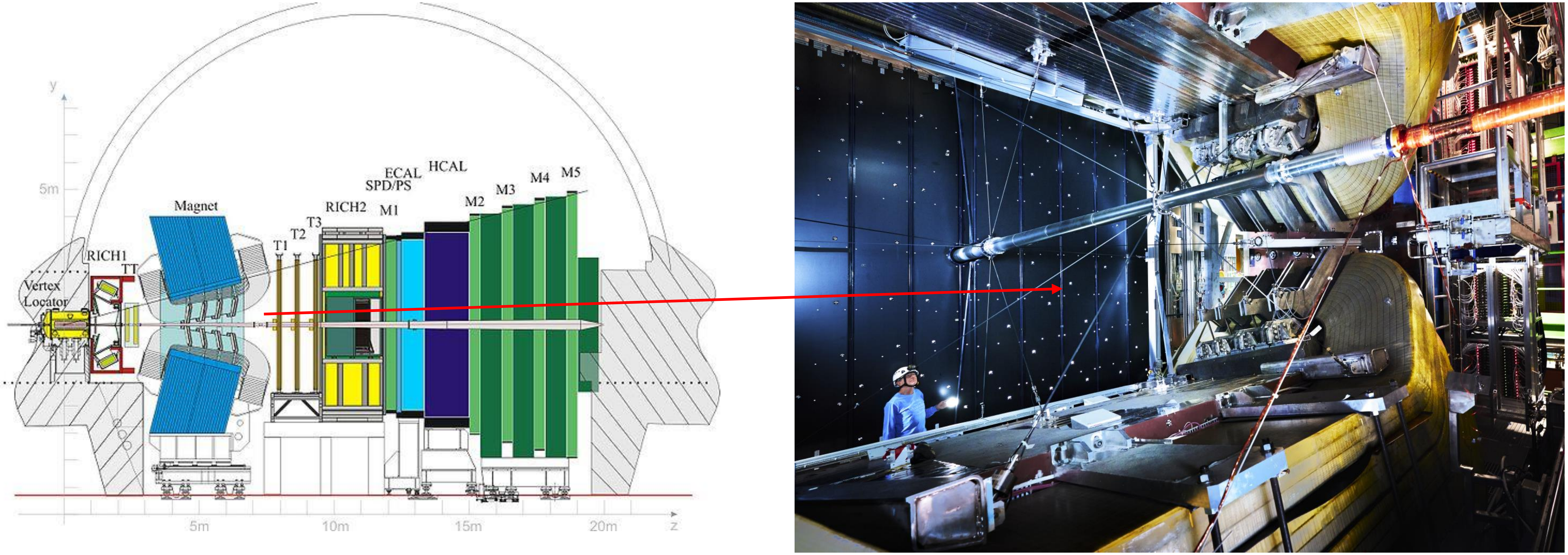
Count of CMS publications in particular analysis groups

LHCb

- LHCb – **L**arge **H**andron **C**ollider **b**eauty
- A specialised experiment for investigating the slight differences between matter and antimatter by studying a type of particle called the "beauty quark", or "b quark".
- The LHCb experiment uses a series of subdetectors to detect mainly forward particles – those thrown forwards by the collision in one direction
- The 5600-tonne LHCb detector is made up of a forward spectrometer and planar detectors. It is 21 meters long, 10 meters high and 13 meters wide.



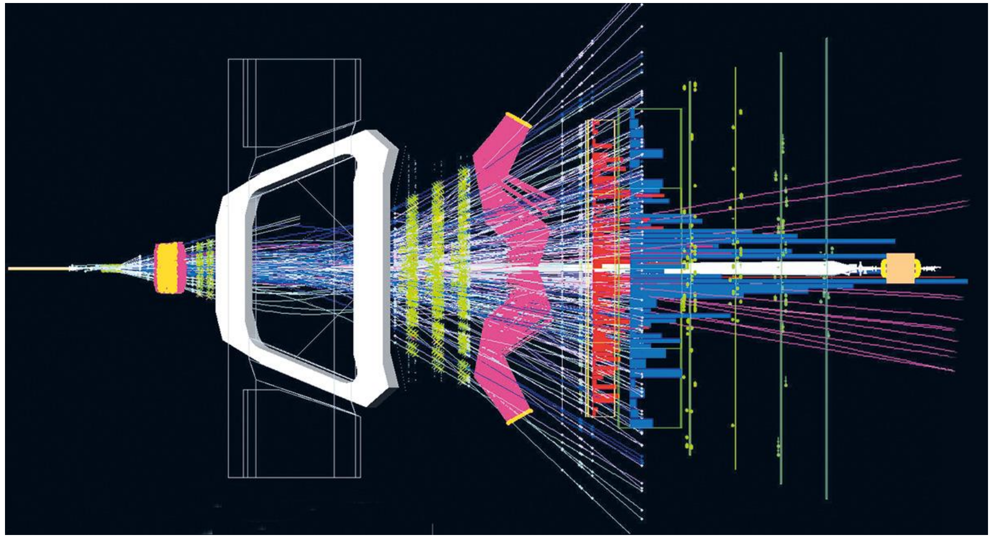
Schematic view of LHCb detector



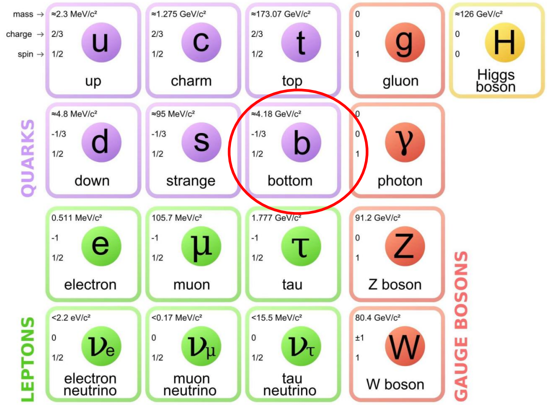
Schematic view of LHCb detector

Physics program

- LHCb physics program mainy focuses on b quark and its related B meson particle investigations
- The detector is specifically built in forward section of collisions
- These B meson decays allow us to investigate:
- CP symmetry violation in particle decays
- Observe rare particle decays
- Test underlying principles of SM, as an example - the lepton flavor universality measurements

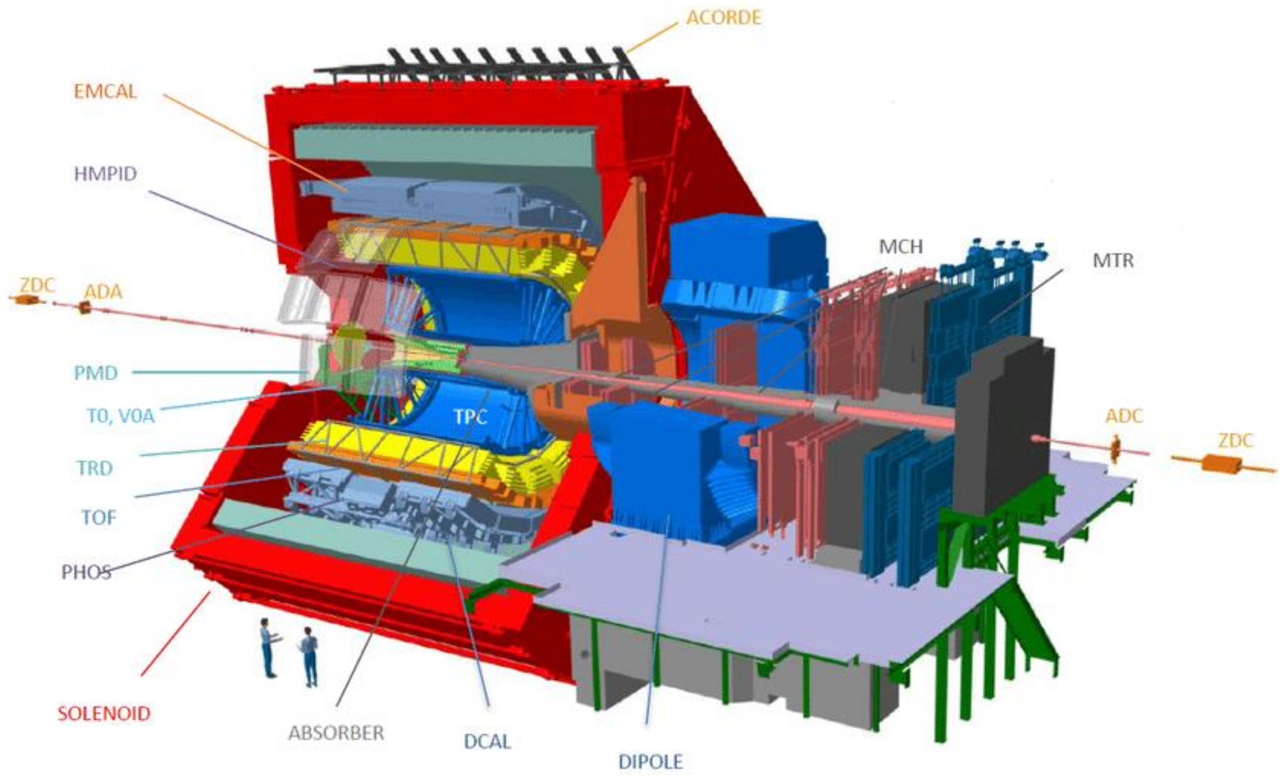


LHCb event display for single reconstructed collision event



ALICE

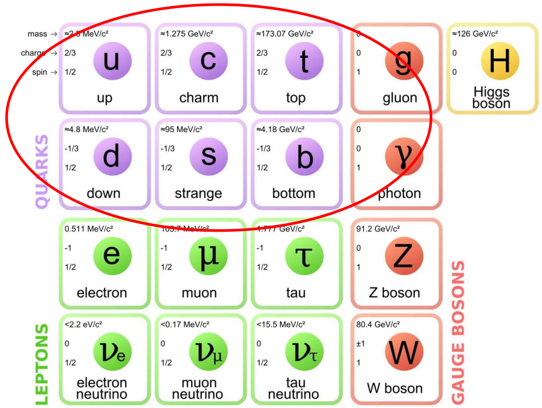
- ALICE – **A** **L**arge **I**on **C**ollider **E**xperiment
- A specialised experiment made to study the quark-gluon plasma, which is a condition of matter that existed in the early universe.
- The detector consists of a mix of subdetectors tailored for heavy ion collisions
- Experiment's main interest is the heavy ion collisions that happen at LHC for a few weeks each year (Pb-Pb)
- The ALICE collaboration uses the 10 000-tonne ALICE detector - 26 m long, 16 m high.

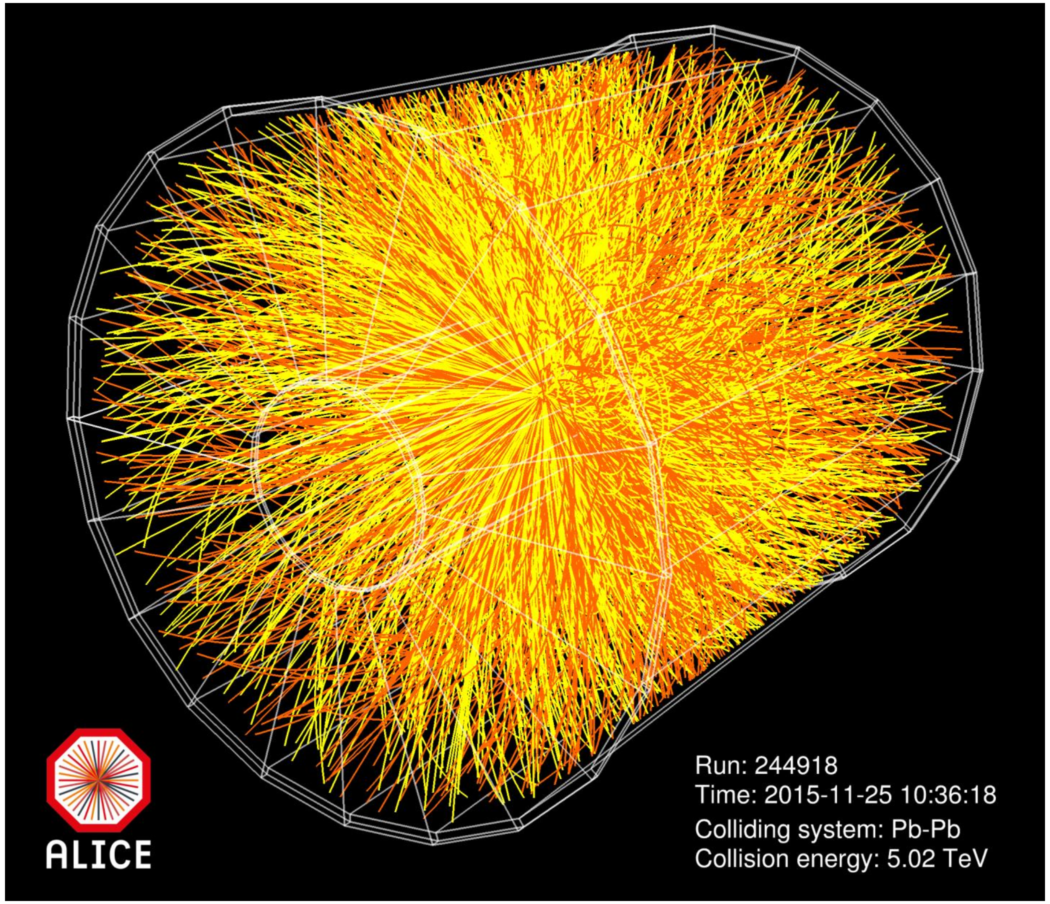


Schematic view of ALICE detector

Physics program

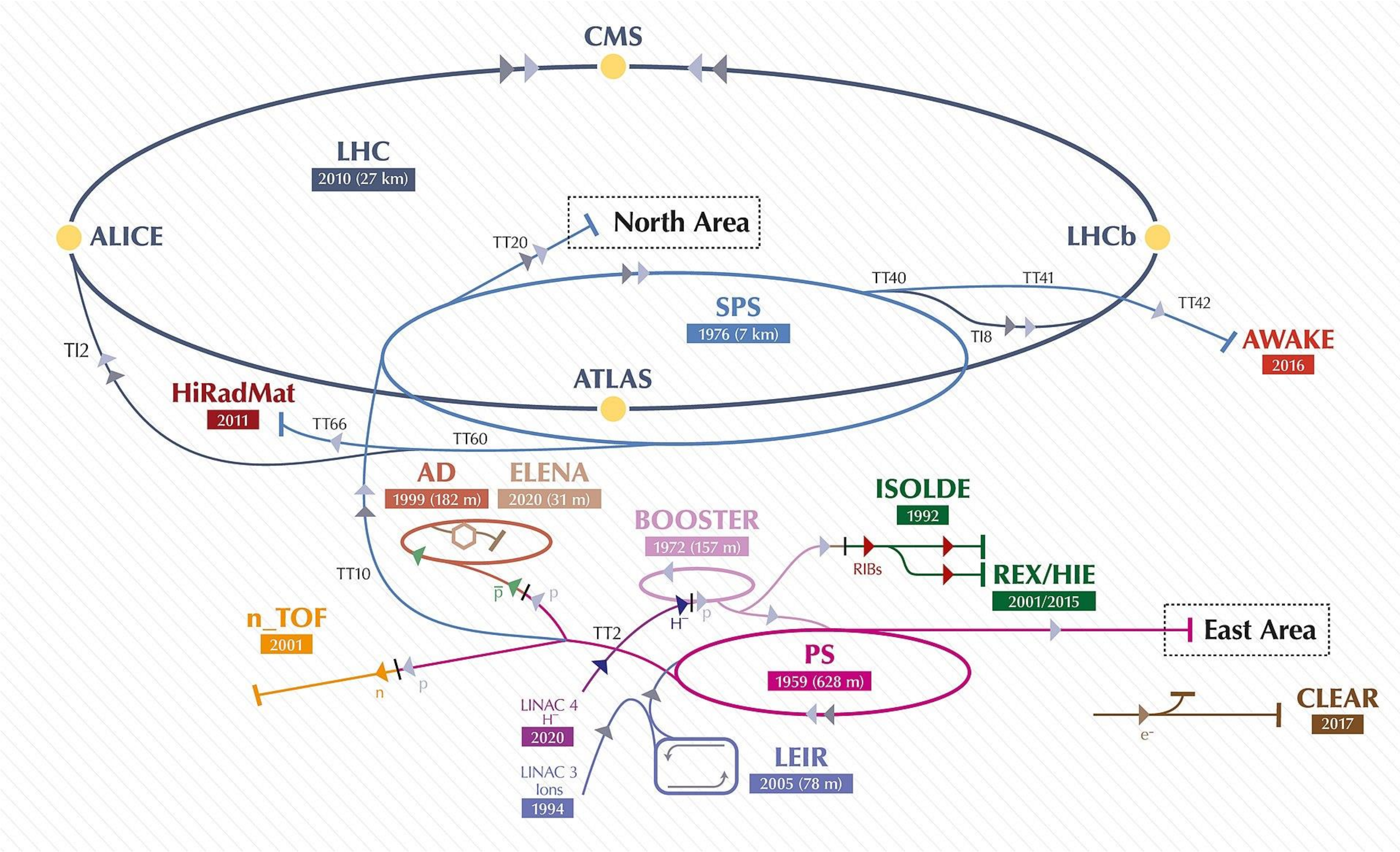
- As the experiment is optimised for heavy ion collisions, its main objective is to study the strongly interacting quark-gluon plasma
- Within this plasma, wide range of tests for QuantumChromoDynamics (QCD) can be performed
- Understanding of the physics processes in quark-gluon plasma, could potentially help us better understand the evolution of the early universe





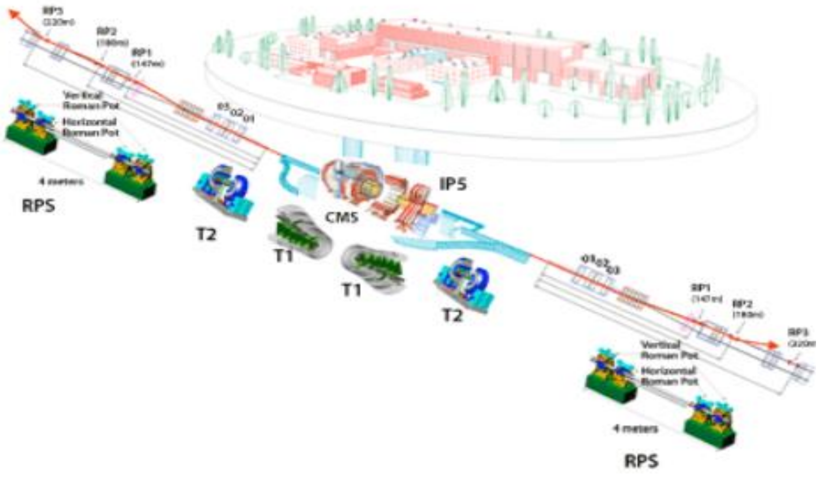
ALICE event display for single reconstructed Pb-Pb collision event

Smaller LHC and SPS experiments

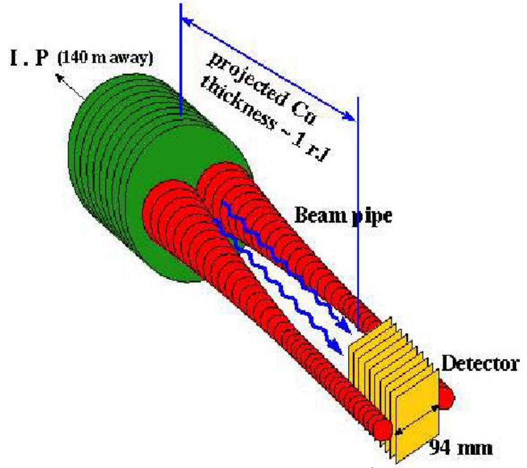


Forward experiments on LHC

- TOTEM – **Tot**al, **e**lastic and diffractive cross-section **m**easurement
  - Goal is to measure the total cross section, elastic scattering and diffraction processes of p-p collisions, while probing proton structure at the CMS interaction point
  - Detector consists of multiple subdetectors with a total length of ~200m along beamline on both sides of the CMS detector
- LHCf – **L**arge **H**adron **C**ollider **f**orward
  - Goal is to measure the energy of forward Pion particles created in ATLAS intercation point, to explain the origin of ultra high energy comsic rays.
  - Experiment is located on both sides of the ATLAS detector at a distance of 140m
  - Smallest LHC experiment



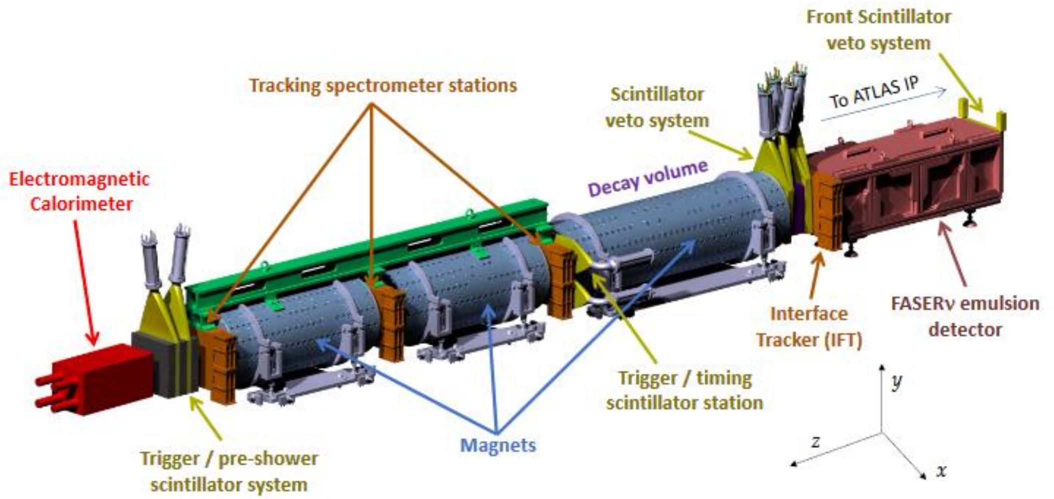
Schematic view of TOTEM subdetectors around CMS



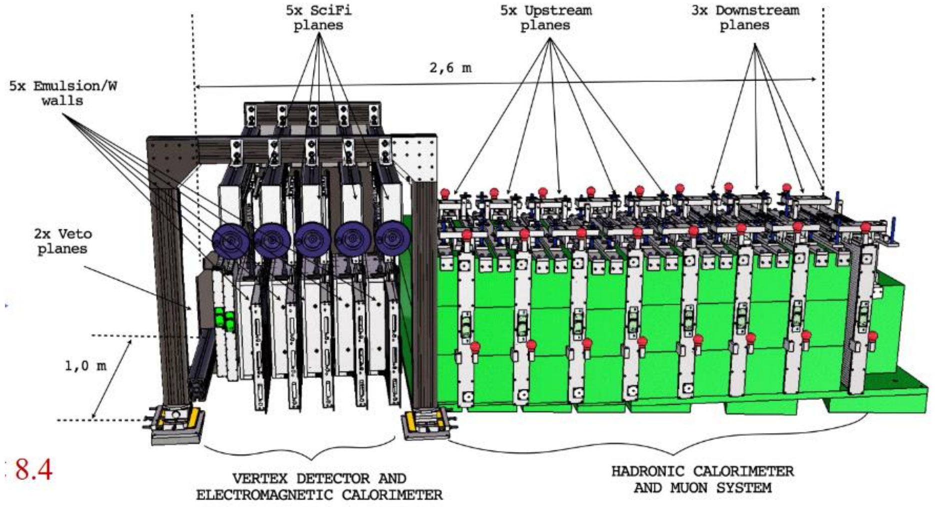
Schematic view of LHCf detector (located between the beamlines inside the LHC itself)

Forward experiments on LHC

- FASER – **F**orw**a**rd **S**earch **E**xpe**r**iment
  - Goal of the experiment is to search for new light and weakly interacting elementary particles (axions, dark photons, sterile neutrinos) in addition to studying interactions of high energy neutrinos
  - Experiment is located on the west side of ATLAS detector on a tangent line from the interaction point at a distance of 480 m
- SNP – **S**cattering and **N**eutrino **D**etector
  - Similar goal as FASER – search for new, light elementary particles and investigate high energy neutrinos coming from the LHC collisions
  - Companion detector on the eastern side of the ATLAS detector at the distance of 480 m
- Both experiments together plan to record **3000+** neutrino interactions!!!

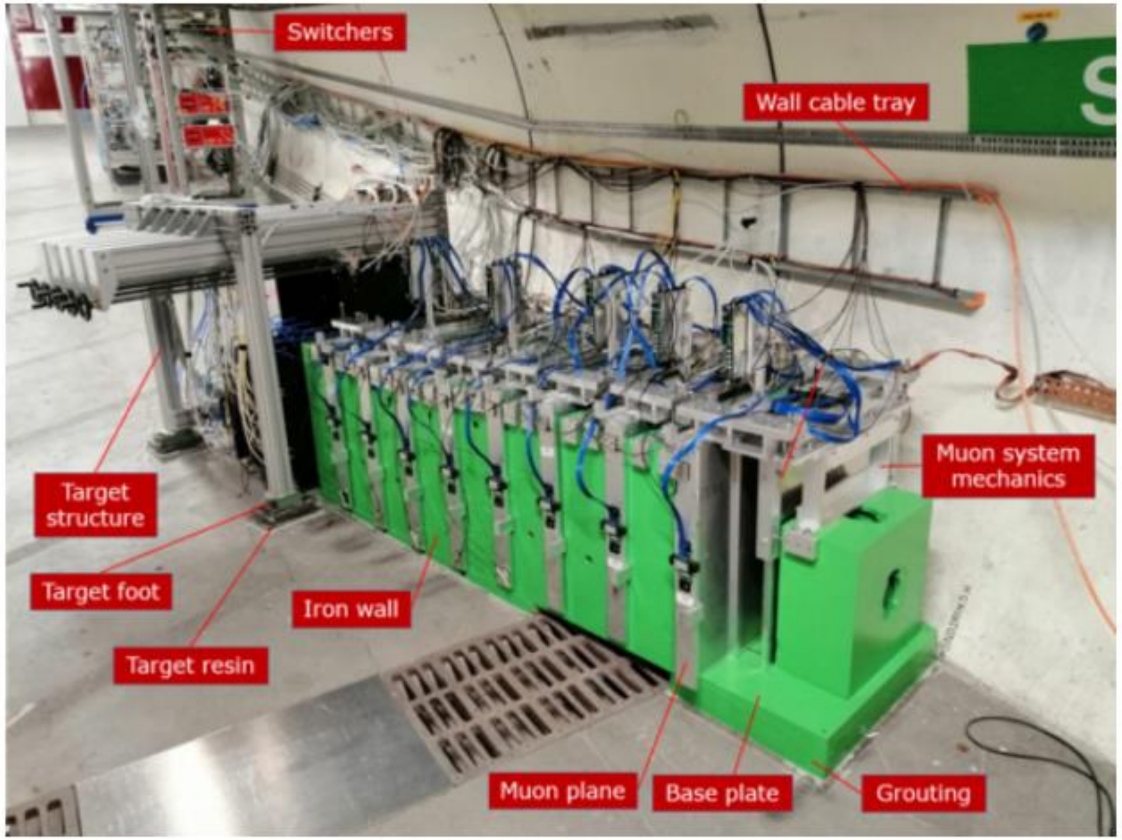


Schematic view of FASER detector

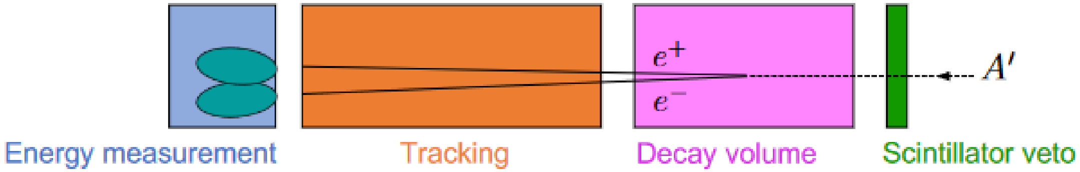


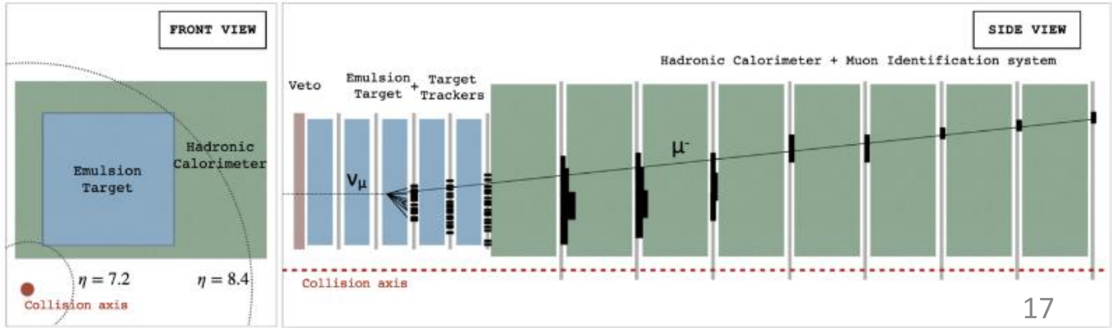
Schematic view of SNP detector

Figure 64: The FASER detector after installation in TI12.



(d) Rear view of the detector

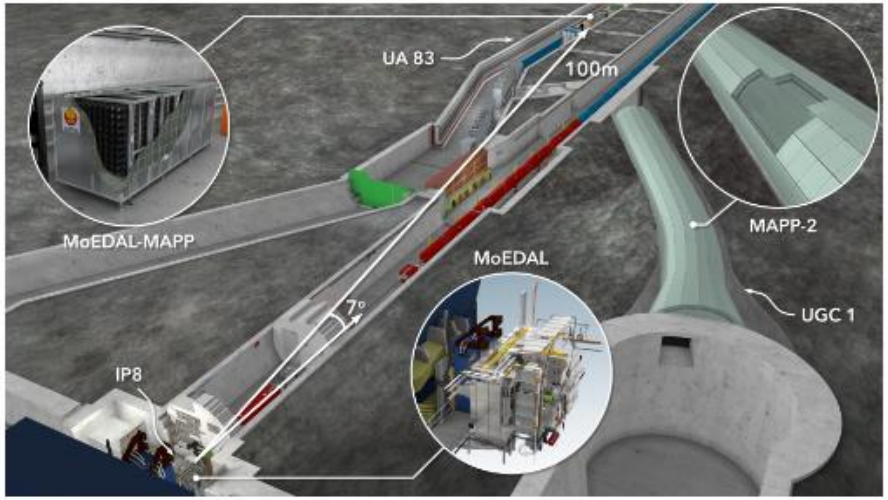




Other experiments on LHC and SPS

- HiRadMat – **Hi**gh **Rad**iation to **Mat**erials facility
  - Facility at CERN which gives scientists and engineers the abillity to access high-intensity pulsed particle beams for material sample and accelerator component irradiation tests
  - HiRadMat recieves the beam from the SPS
- MoEDAL-MAPP –> **Mo**nopole and **E**xotics **D**etector **a**t the **L**HC – **M**oEDAL **A**paratus for **P**enetrating **P**articles
  - The goal of the experiment is to search for magnetic monopoles (dyons) and other highly ionizing stable massive particles using nuclear track detectors
  - 2 part experiment shares an underground cavern with the LHCb experiment – one next to LHCb and the other 100m away from LHCb

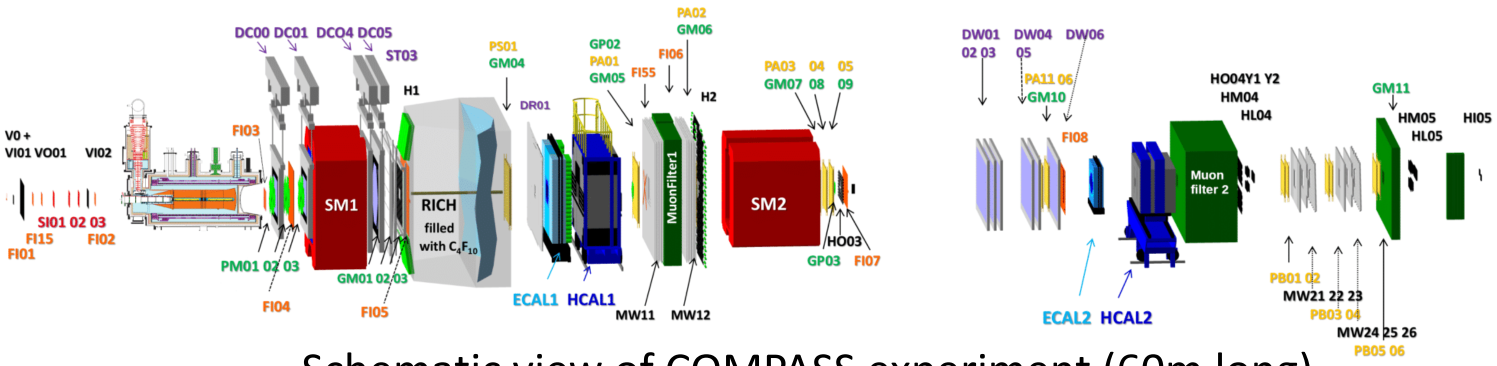
View of HiRadMat experimental zone



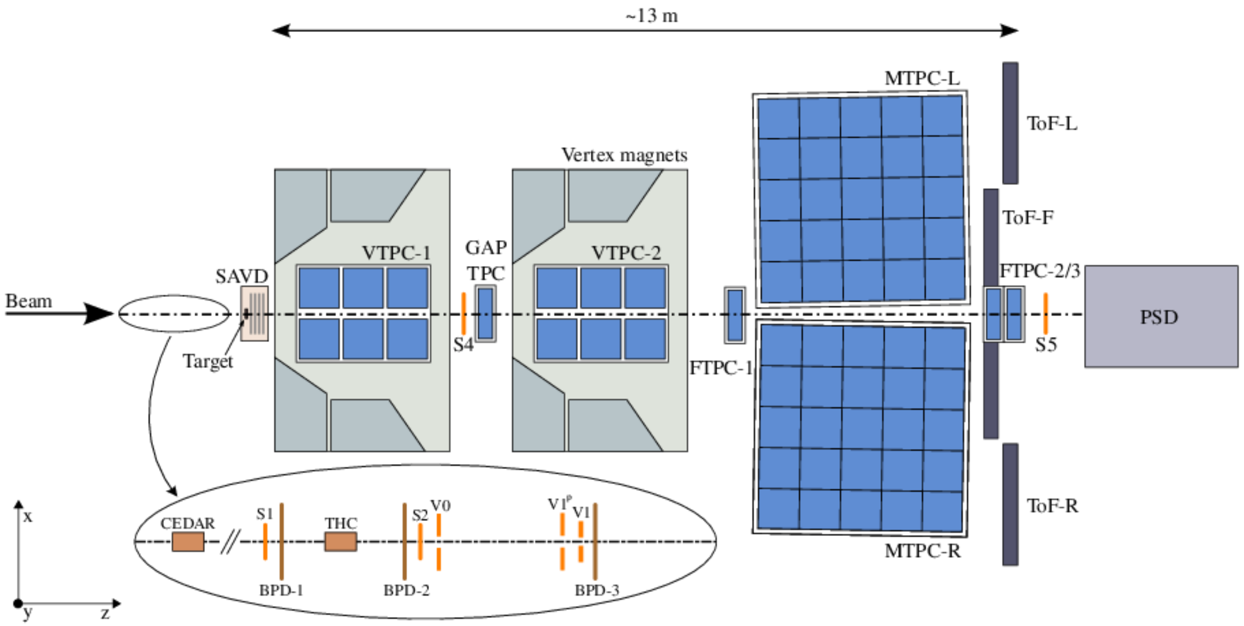
Schematic view of MoEDAL-MAPP detector

North Area experiments

- COMPASS (NA58) – **Co**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy
  - The goal of the experiment is to study the internal structure of protons and neutrons, while additionally trying to understand how quarks and gluons create the spin of these particles
  - Fixed target experiment (uses muons and pions)
  - Future upgrade to AMBER experiment (Apparatus for Meson and Baryon Experimental Research)
- SHINE (NA61) – **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment
  - Goal of experiment is to study properties of hadrons in collisions with fixed targets, which additionally allows investigating neutrino beam properties
  - Neutrino studies used in other experiments (T2k, NOvA, DUNE, KASCADE)

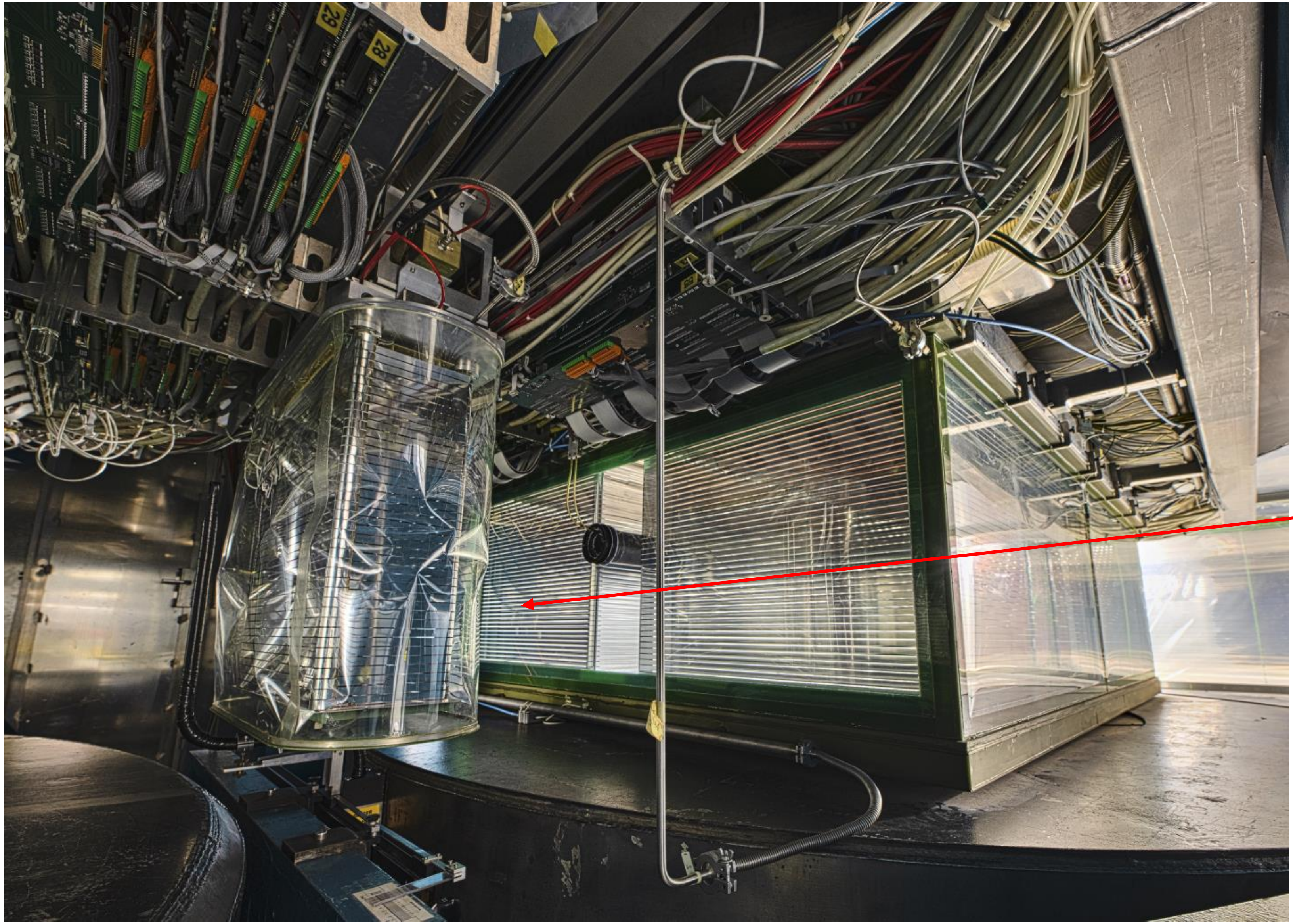


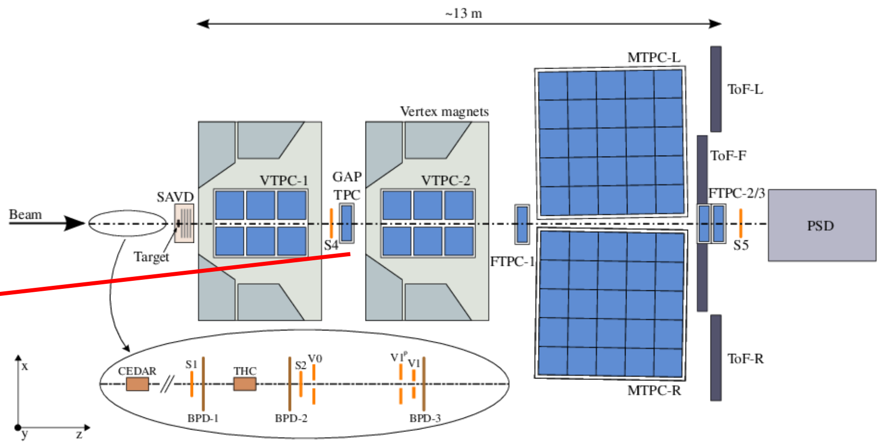
Schematic view of COMPASS experiment (60m long)



Schematic view of SHINE experiment

COMPASS experiment

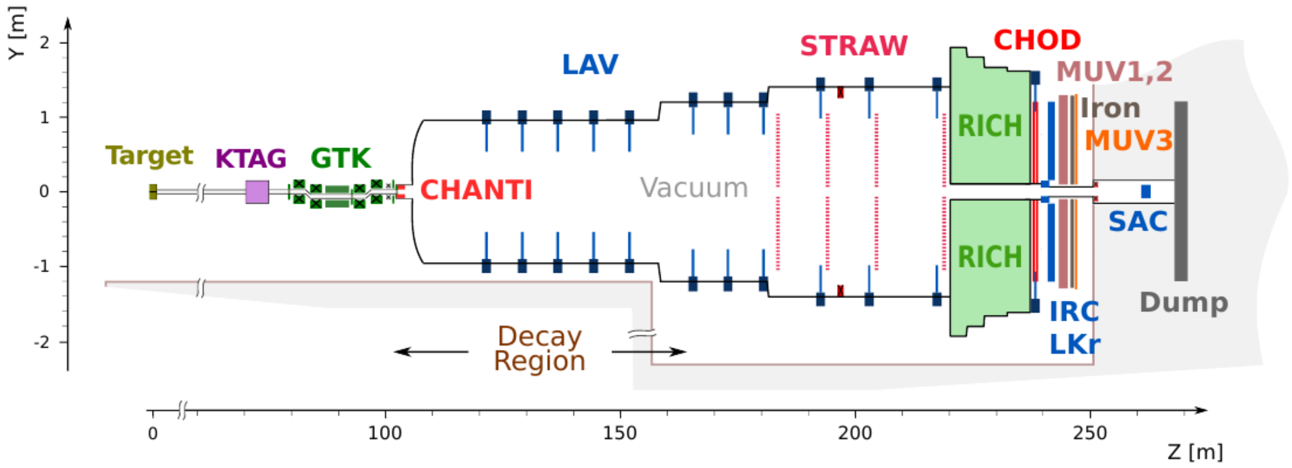




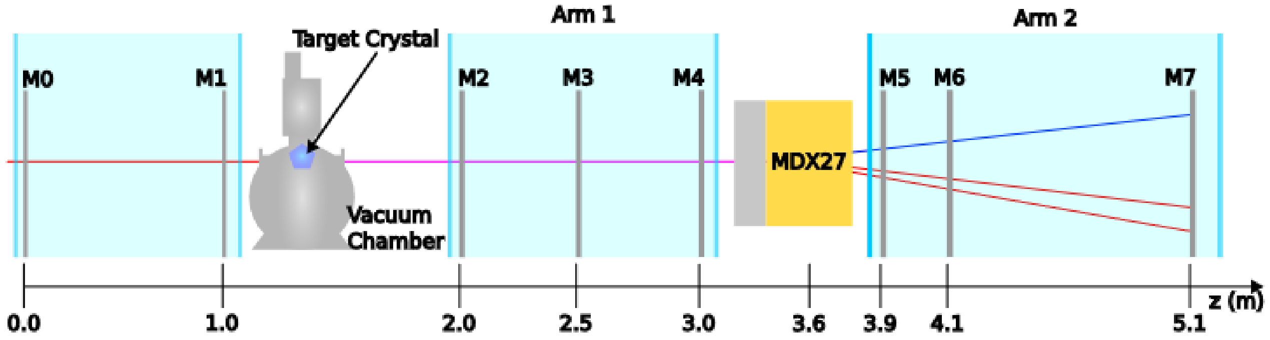
Part of SHINE experiment

North Area experiments

- NA62 experiment
  - The goal of this experiment is to study ultra rare Kaon meson decays
  - Kaons are created by proton collisions into fixed berilyum target
  - Experiment specifically measures the rate at which charged kaons decay into charged pions and neutrino-antineutrino pairs
- NA63 experiment
  - The goal of experiment is to study radiation processes in strong EM fields, which are created in electron/positron collisions with fixed targets
  - Research helps to understand beam-beam effects for linear colliders and various astrophyiscal phenomena

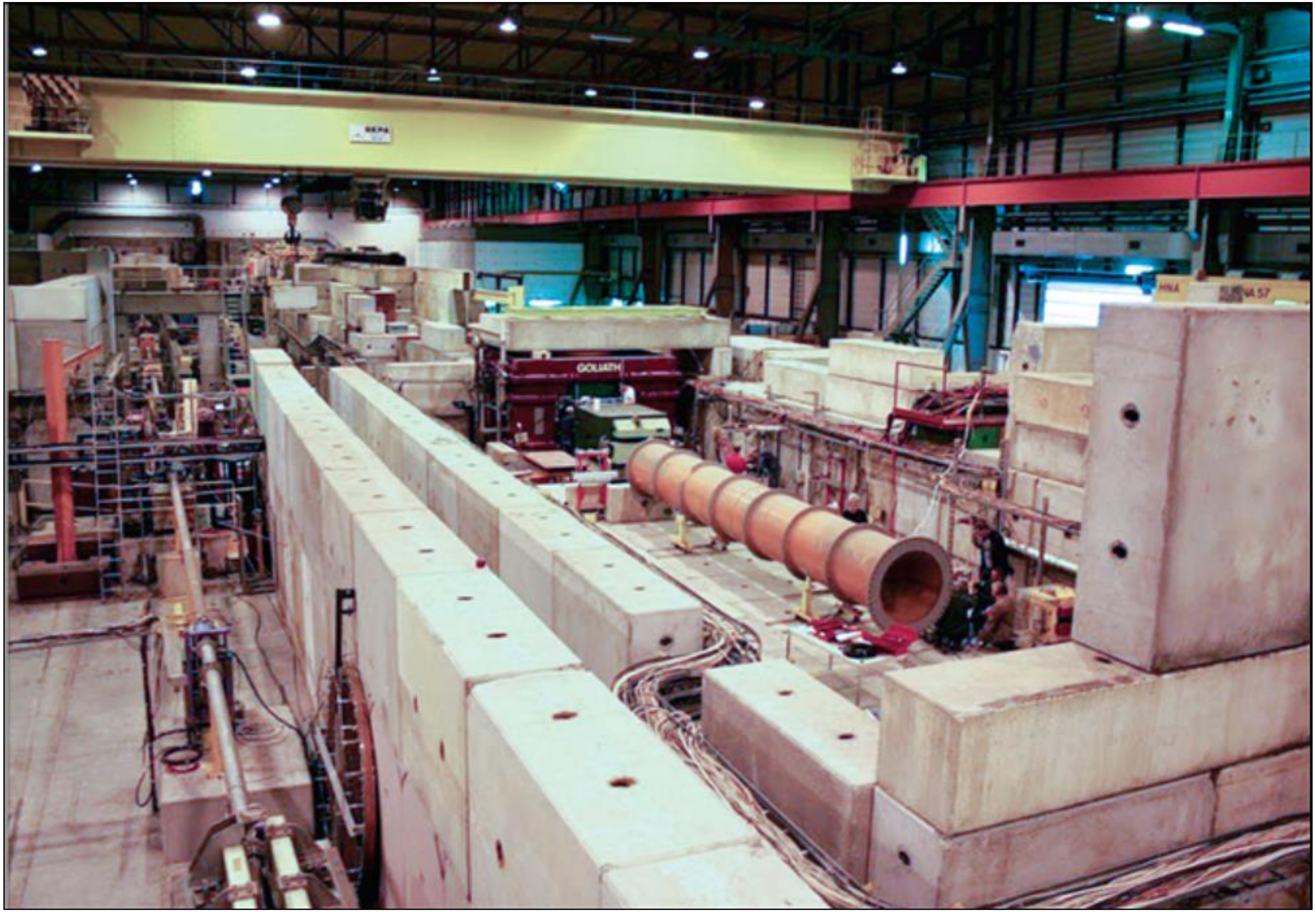


Schematic view of NA62 experiment



Schematic view of NA63 experiment

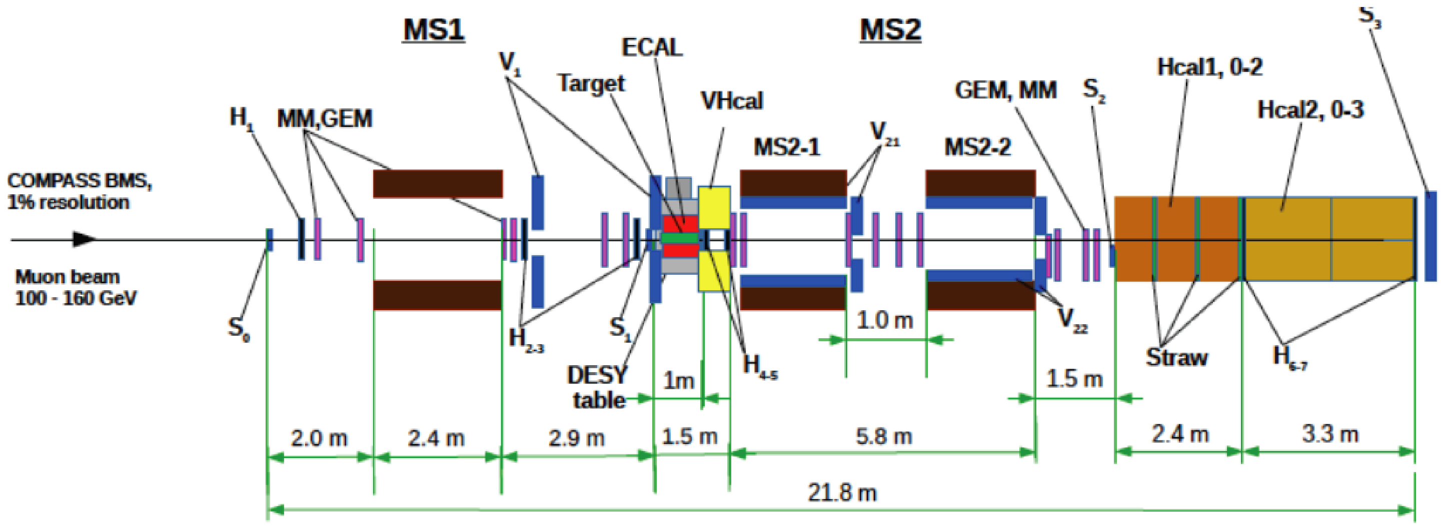
NA62 experiment facility



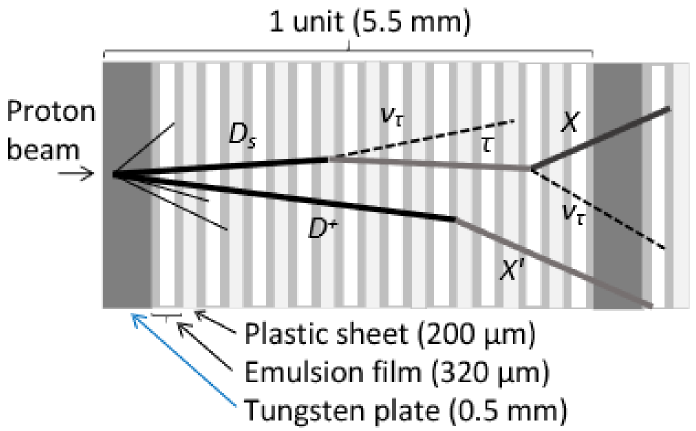
NA63 experimental area

North Area experiments

- NA64 experiment
  - Goal of the experiment is to seach for new particles in the ''dark sector'' - dark photons, with addition of searcing for axions
  - Experiment uses an electron beam directed at fixed target and looking at the collision products
  - Will use muons in future
- NA65 experiment
  - Goal of the experiment is to measure the rate at which tau neutrinos are produced from D meson decays
  - Tau neutrino is the least studied neutrino



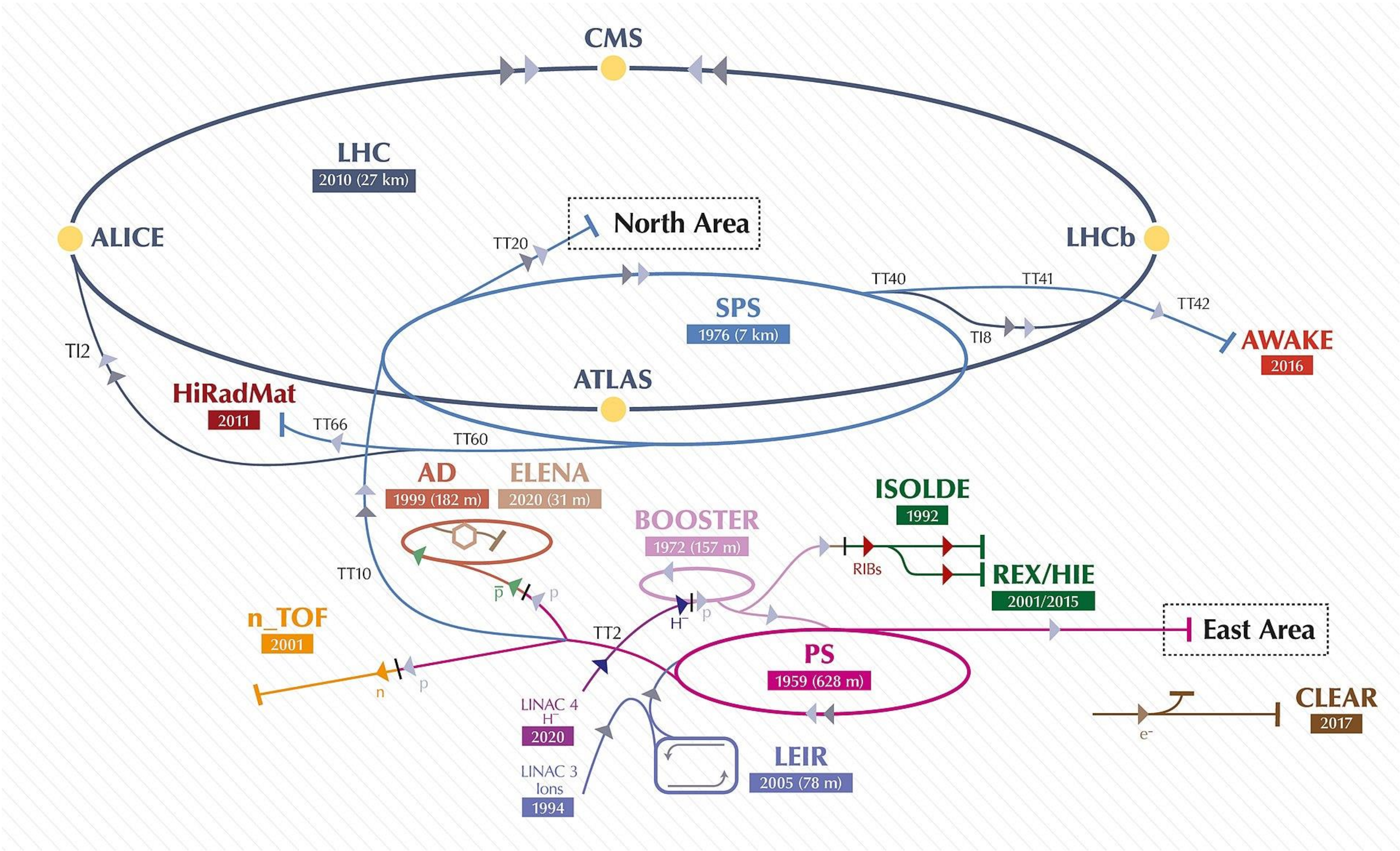
Schematic view of NA64 experiment



Schematic view of NA65 experiment

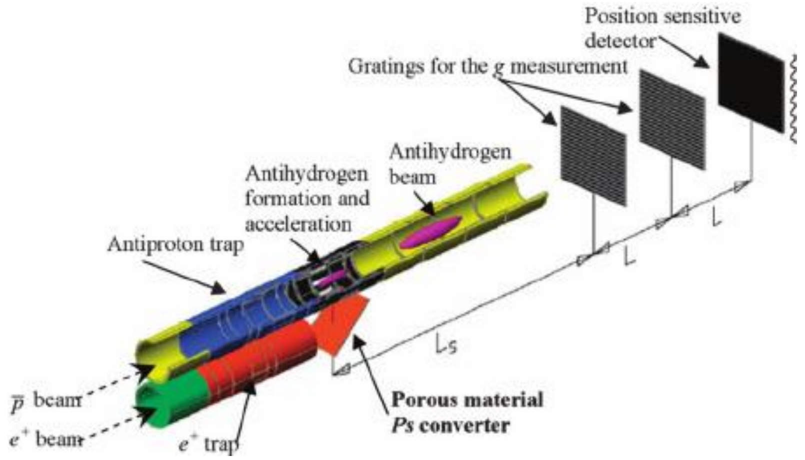
View of NA64 experiment area

Smaller experiments on PS and booster ring

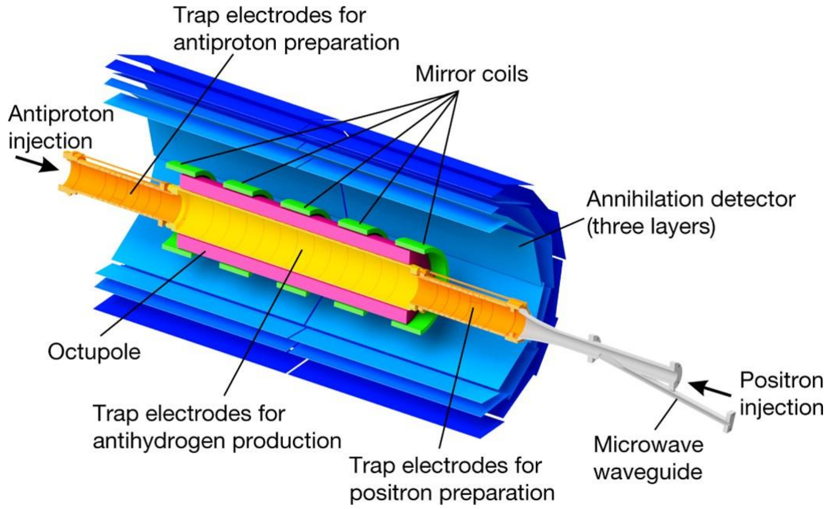


PS and Booster ring experiments – anti-Matter

- AEGIS – **A**nti-hydrogen **E**xperiment: **G**ravity, **I**nterferometry, **S**pectroscopy
  - The goal of the experiment is to measure the Earth's gravitational acceleration 'g' on antihydrogen atoms
  - A check whether anti-matter has the same gravitational constant as matter
- ALPHA – **A**ntihydrogen **L**aser **Ph**ysics **A**pparatus
  - Goal of the experiment is to test the CPT symmetry through comparison of atomic spectra between hydrogen and anti-hydrogen
  - Additionally, they are studying the gravitational properties of anti-matter

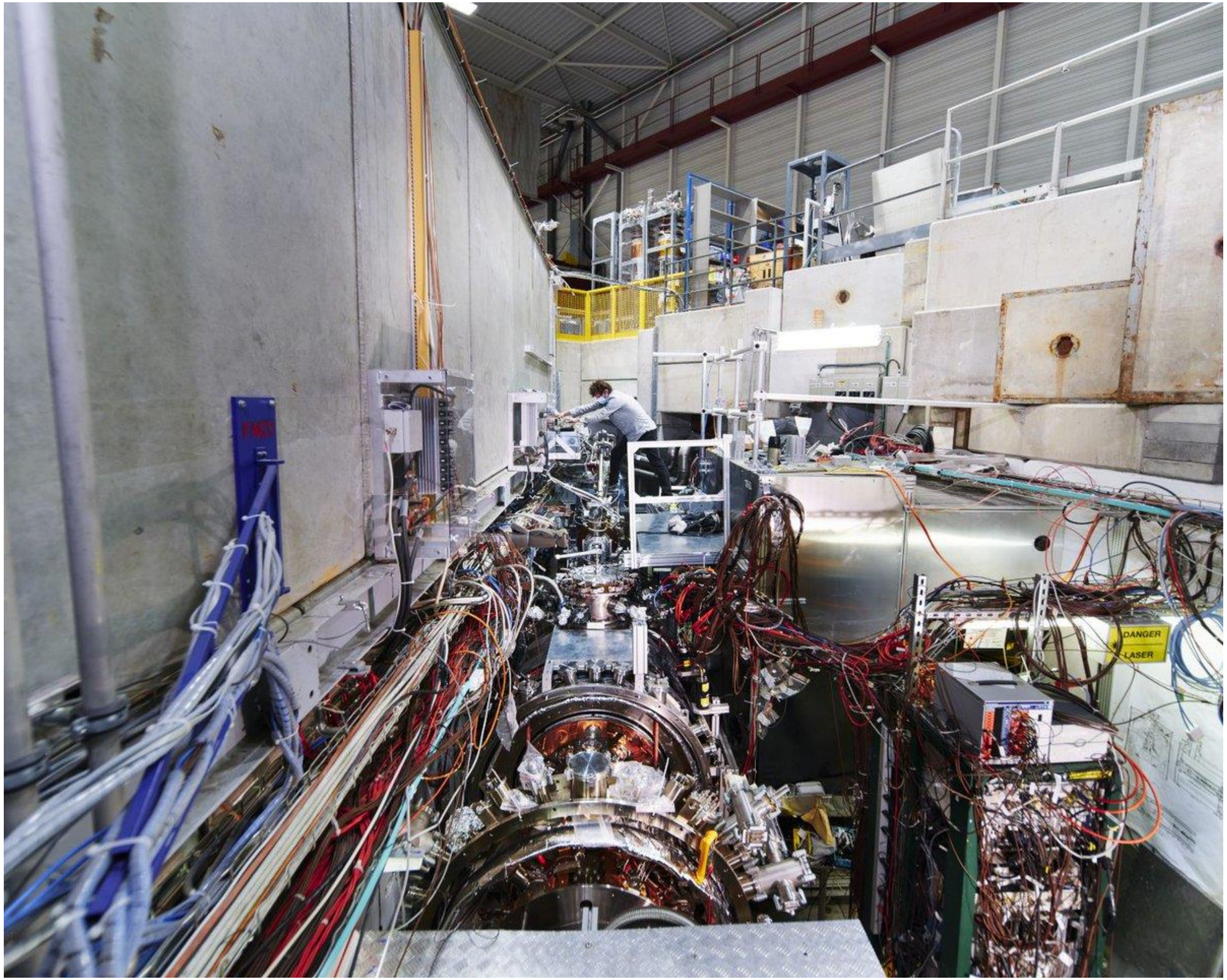


Schematic view of AEGIS experiment



Schematic view of ALPHA experiment

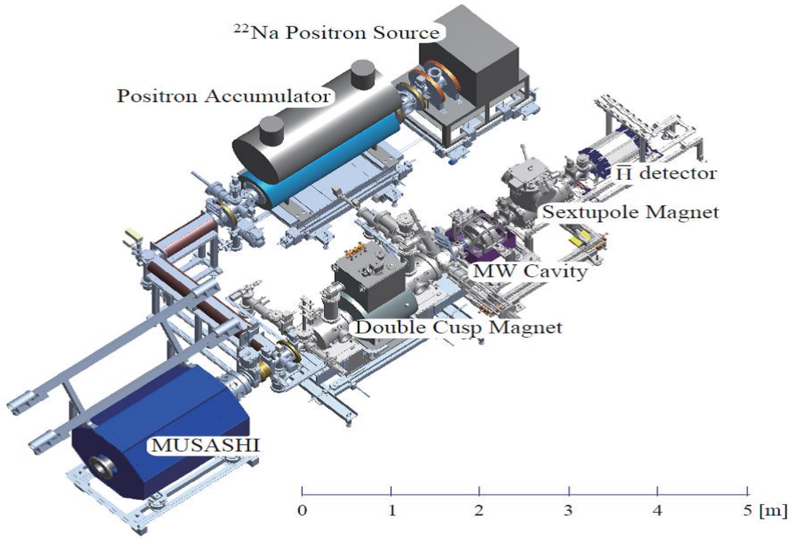
ALPHA experiment area in Anti-Matter factory



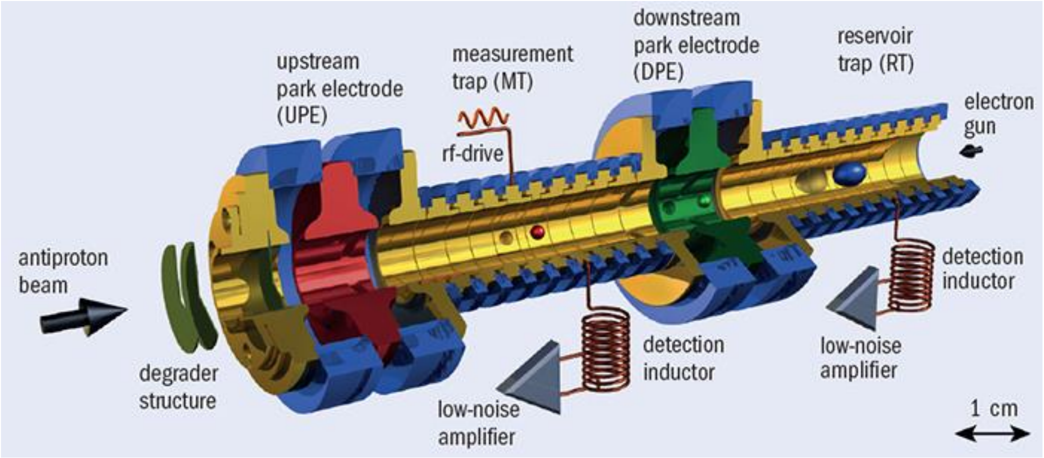
AEGIS experiment area in Anti-Matter factory

PS and Booster ring experiments – anti-Matter

- ASACUSA – **A**tomic **S**pectroscopy **A**nd **C**ollisions **U**sing **S**low **A**ntiprotons
  - Goal of the experiment is to study the symmetries between matter and anti-matter using precision spectroscopy in anti-hydrogen and antiprotonic-helium
  - Additionally, they investigate the interaction of matter and anti-matter atoms
- BASE – **B**aryon **A**ntibaryon **S**ymmetry **E**xperiment
  - Goal of the experiment is to compare the magnetic moments of protons and antiprotons to look for differences between matter and anti-matter

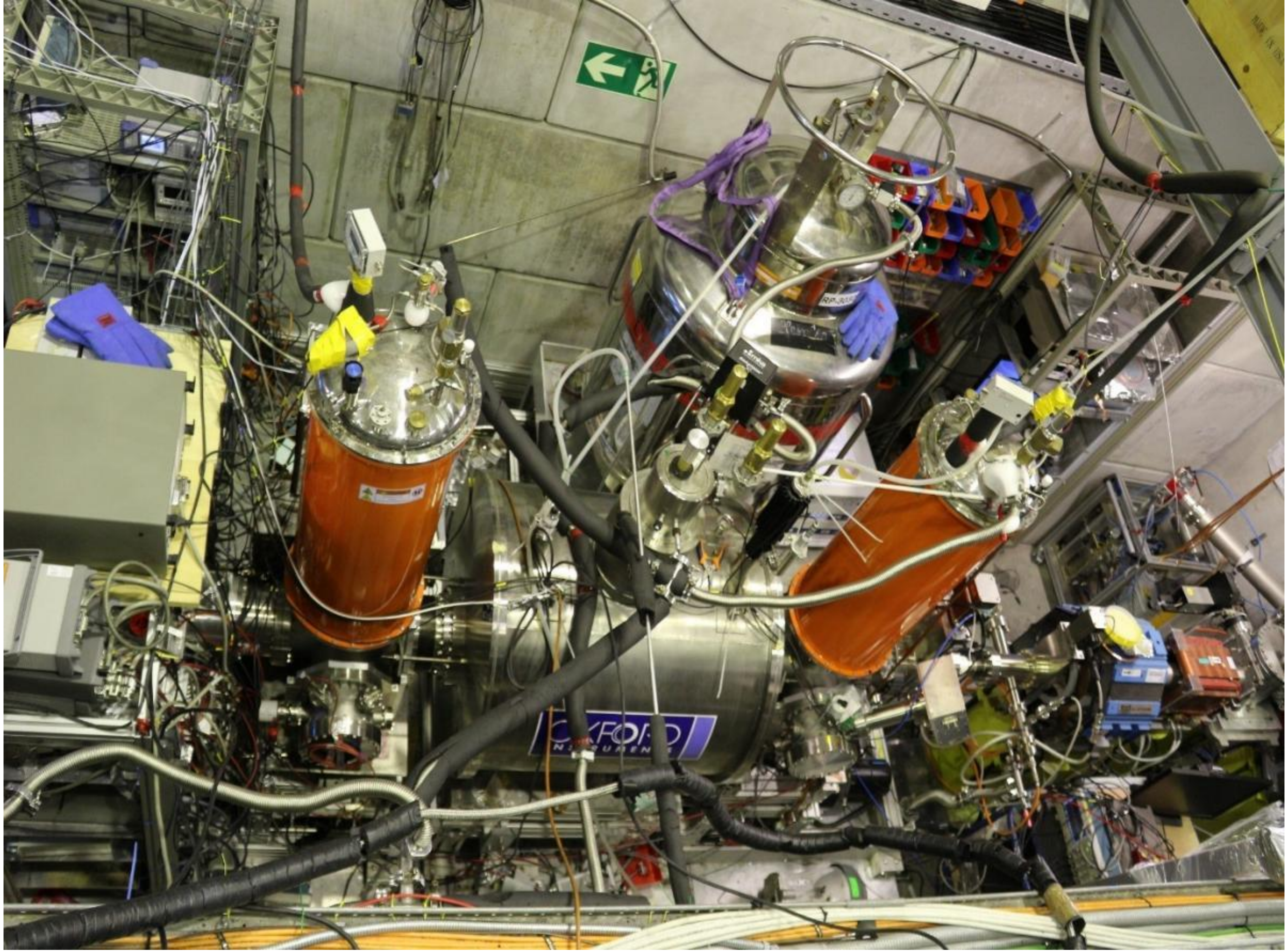


Schematic view of ASACUSA experiment



Schematic view of BASE experiment

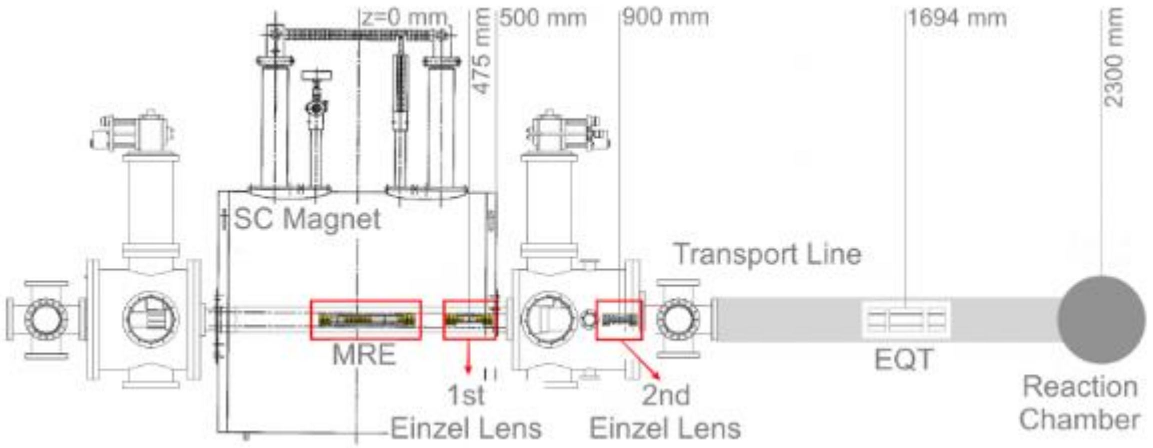
ASACUSA experiment and its team



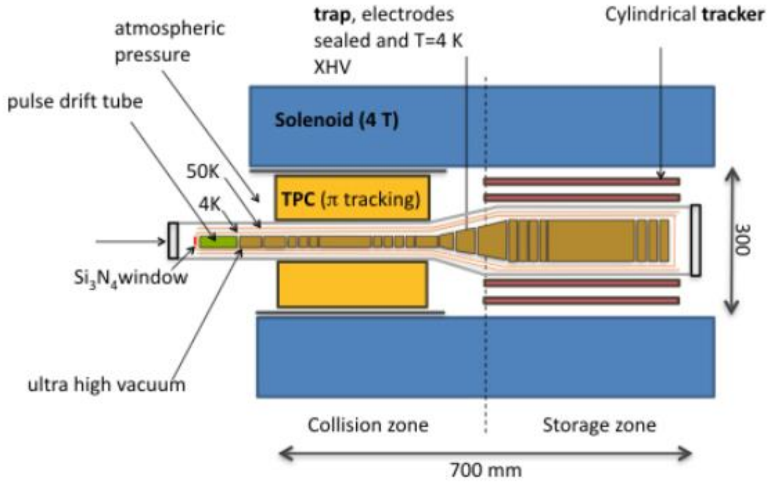
BASE experiment

PS and Booster ring experiments – anti-Matter

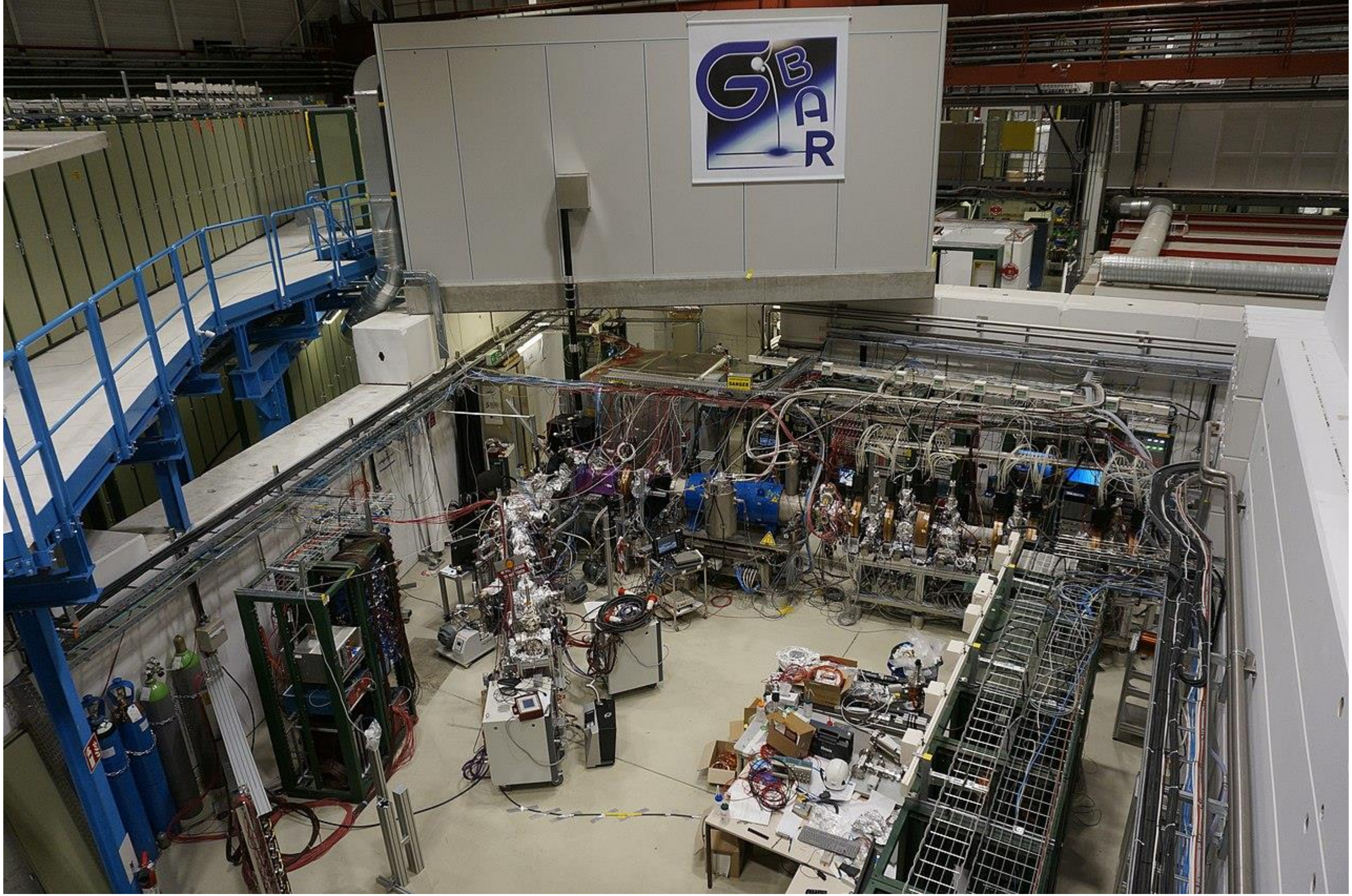
- GBAR – **G**ravitational **B**ehaviour of **A**nti-matter at **R**est experiment
  - Goal of the experiment is to measure the free fall acceleration of antimater – ‘g’ for anti-matter at earth’s surface
  - It is done by allowing traped anti-hydrogen atoms to drop for 20 cm in earth’s gravity
- PUMA – anti-**P**roton **U**nstable **M**atter **A**nnihilation experiment
  - Goal of the experiment is to investigate the annihilation process of antiprotons and unstable atomic nuclei, which could help understand the relative densities of protons and neutrons at the surface of the unstable nuclei
  - Such measurements can help to understand the nuclear processes within neutron stars



Schematic view of GBAR experiment



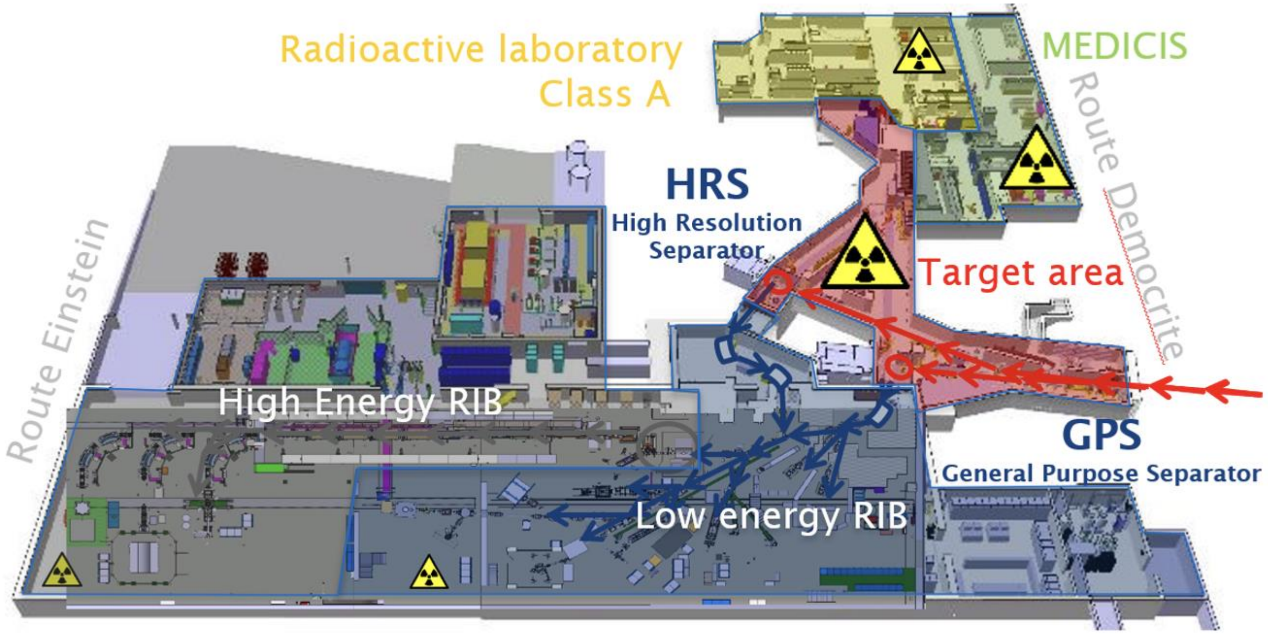
Schematic view of PUMA experiment



GBAR experiment area in Anti-Matter factory

PS and Booster ring experiments

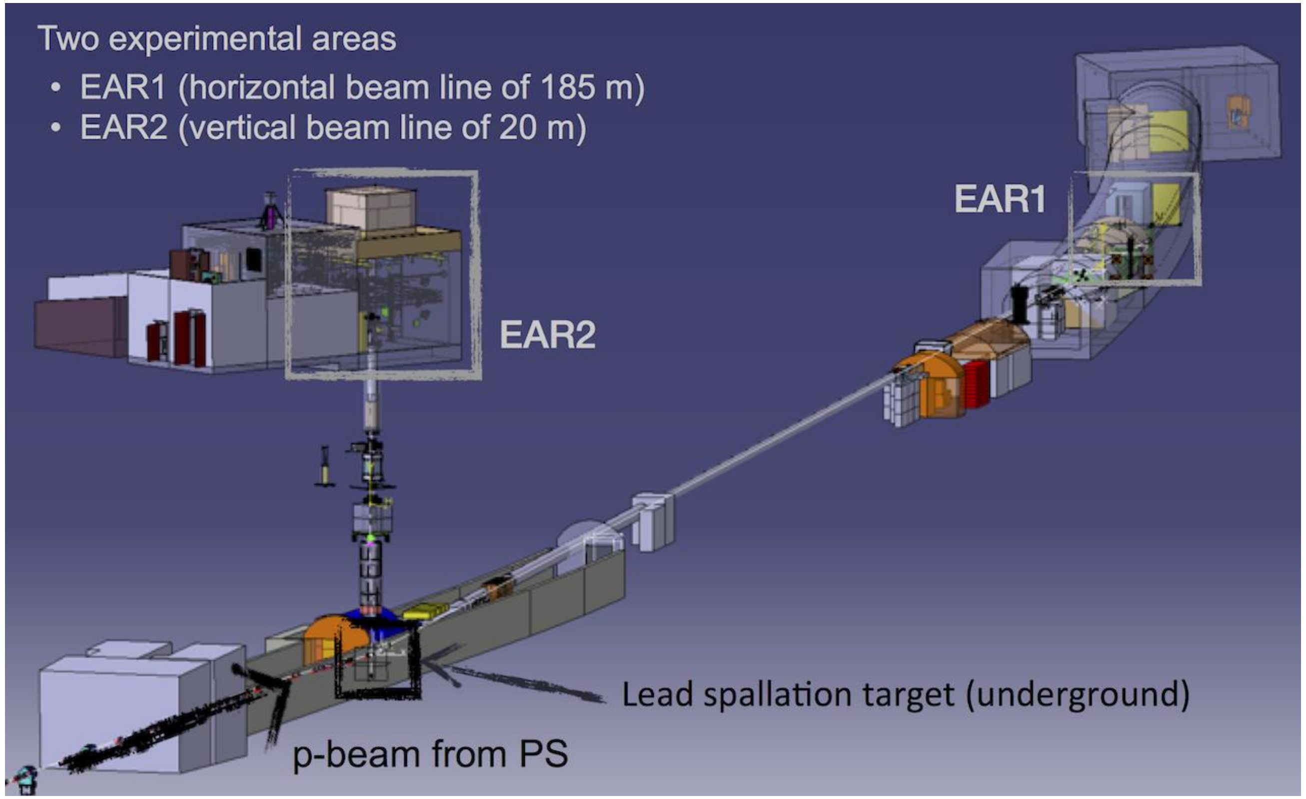
- ISOLDE – Isotope mass Seperator On-Line facility
  - Facility produces low-energy beams of radioactive nuclides, allowing research of such isotopes for various domains as nuclear structure studies, nuclear astrophysics, life sciences and others.
- MEDICIS – **Med**ical **I**sotopes **C**ollected from **IS**OLDE facility
  - Facility focues on medical research by producing novel radioisotopes for theranostics (treatment and diagnostics of cancers and other deseases)



Schematic view of ISOLDE and MEDICIS facility

PS and Booster ring experiments

- n_TOF – **N**eutron **T**ime **o**f **F**light Facility
  - Facility provides a pulsed neutron beam, which allows to investigate neutron-nucleus interactions in a wide energy range
  - Studies that are done in n_TOF are used in various physics fields:
  - Astrophysics to better understand stellar evolution and supernovae
  - Hadron therapy studies for tumor treatment
  - Nuclear technology as new ways how to reduce the amount of nuclear waste



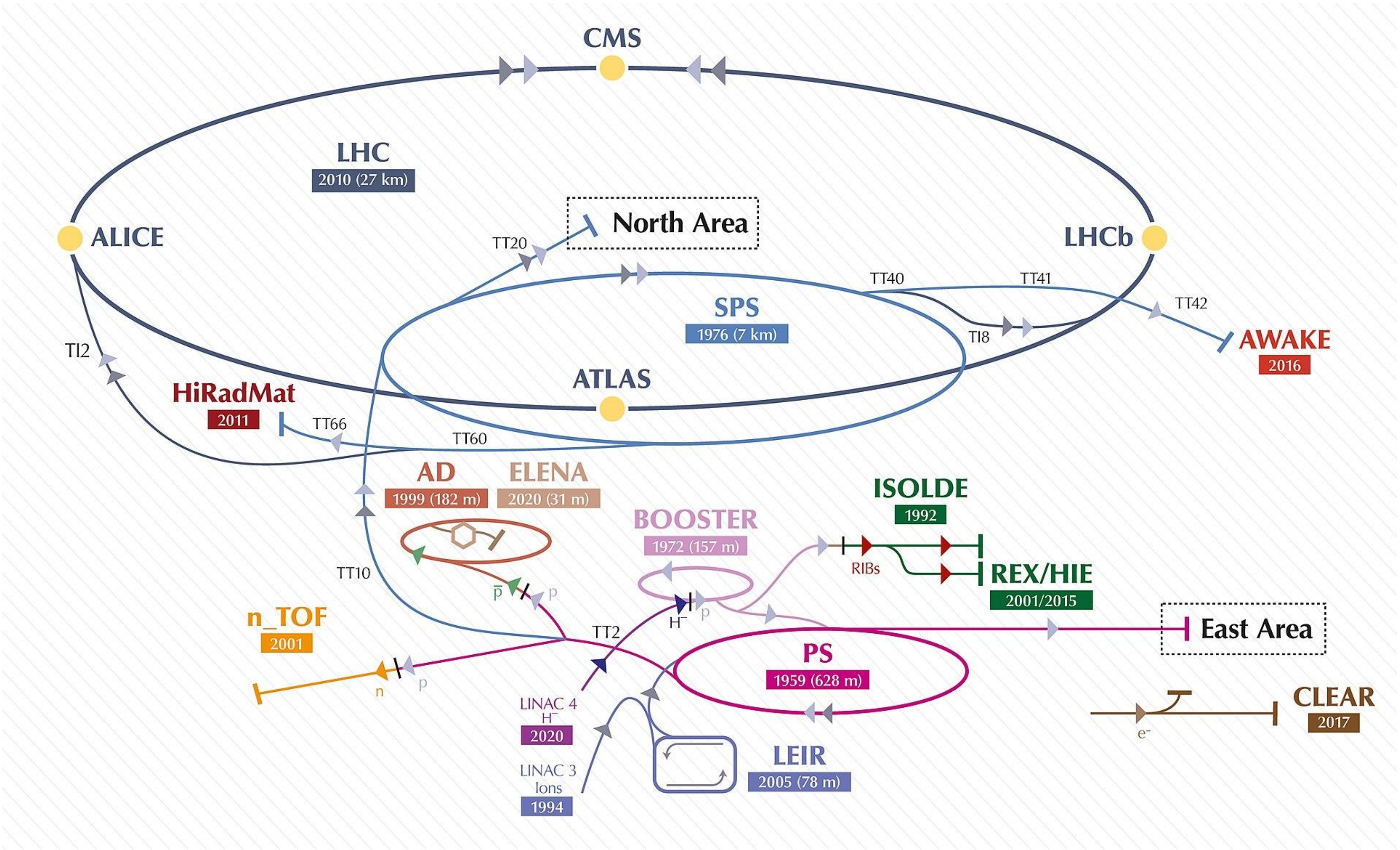
Schematic view of n_TOF facility

PS and Booster ring experiments

- CLOUD – Cosmics Leaving Outdoor Droplets experiment
  - Experiment uses special cloud chamber to study a link between galactic cosmic rays and cloud formation
  - First experiment that uses accelerator to study atmospheric and climate science
  - Studies aerosol formation and their influence on cloud formation

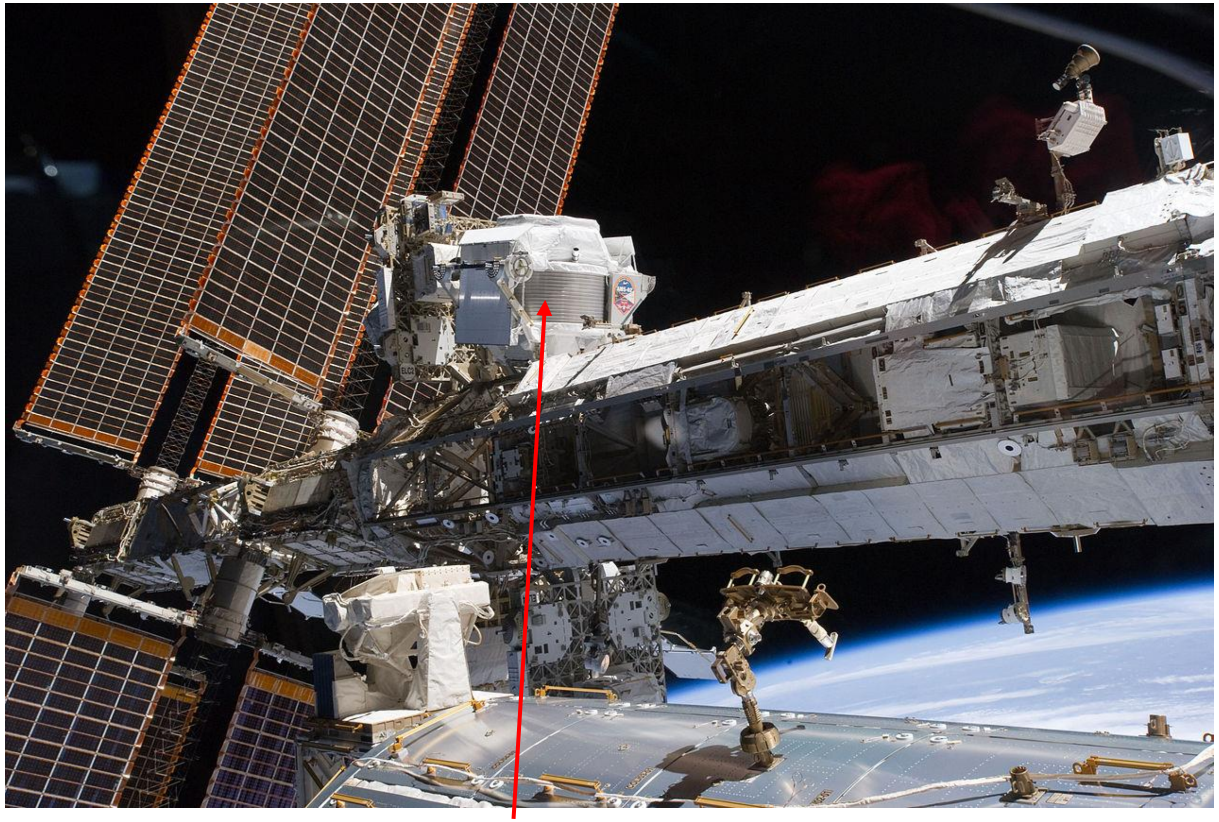
Cloud experiment area

Non-accelerator CERN experiments



Non-accelerator CERN experiments

- AMS – **A**lpha **M**agnetic **S**pectrometer
  - A particle physics experiment, which is located on ISS in Earth's orbit, with the detector's control room at CERN
  - Upgraded detector was lifted in orbit by the penultmate flight of the Space Shuttle (STS-134)
  - Goal of the experiment is to search for dark matter by investigating cosmic rays and cosmic anti-matter particles
  - As of 2023, the detector has detected 215 billion cosmic ray events



AMS experiment on ISS

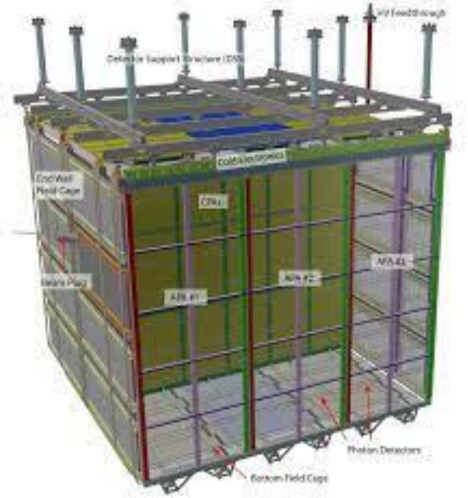
Non-accelerator CERN experiments

- CAST – **C**ERN **A**xion **S**olar **T**elescope
  - Goal of the experiment is to search for new light particles – axions originating from the Sun.
  - Idea of the detector lies in the assumption that solar axions might decay to x-rays in strong magnetic field
  - No axions found yet, limits are being set
  - Searcing for additional new dark matter particles
- OSQAR – **O**ptical **S**earch for **Q**ED Vacuum Bifringence, **A**xion and Photon **R**egeneration
  - Same goal as CAST, but searching for non-Solar axions

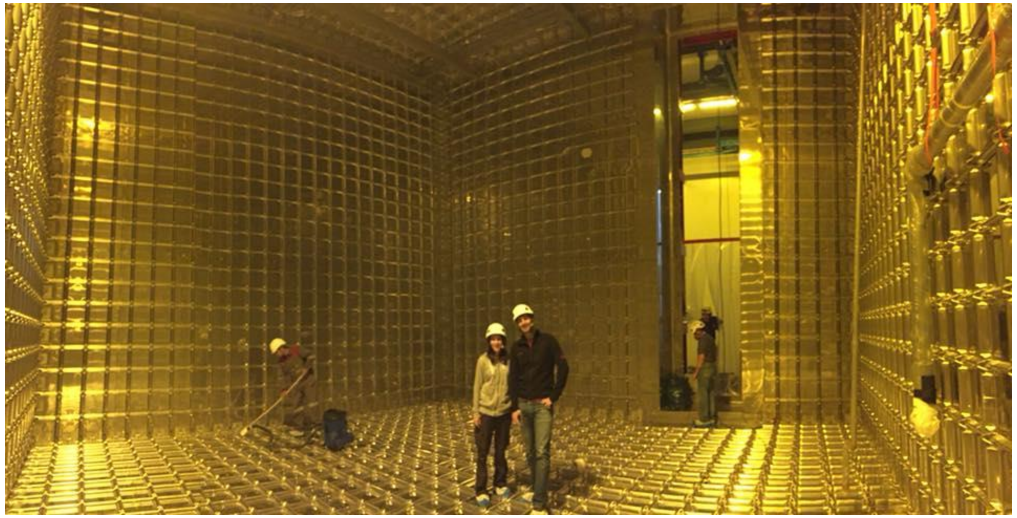
RADES detector in CAST telescope

Non-accelerator CERN experiments

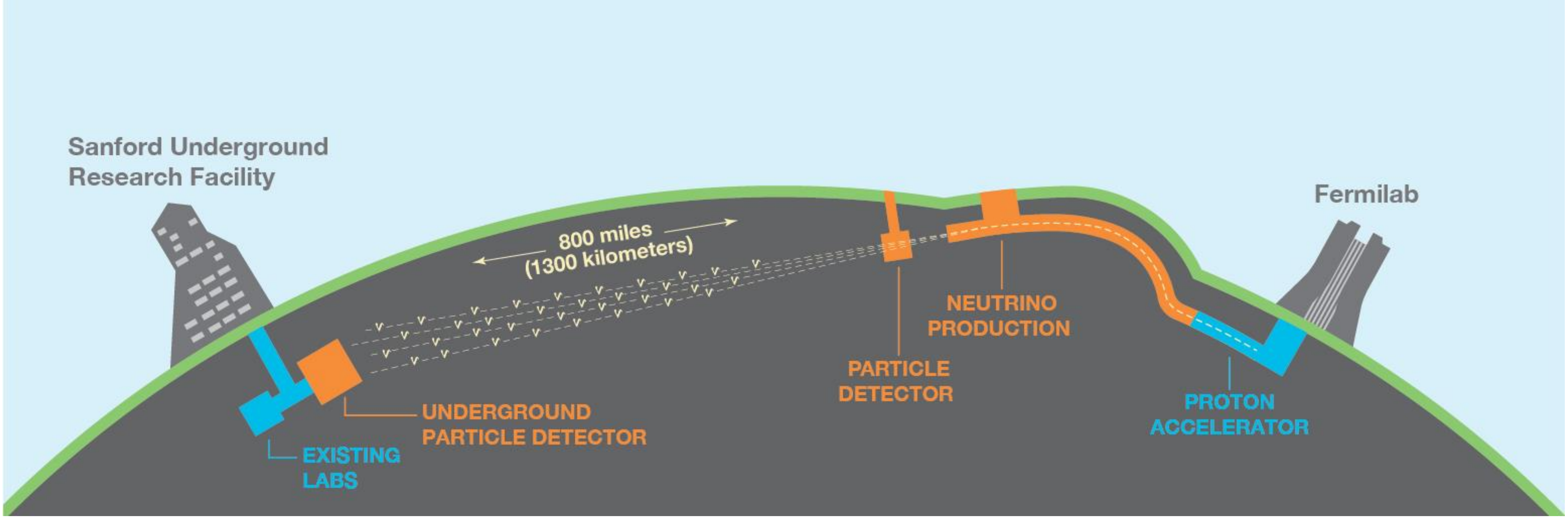
- ProtoDUNE – Proto **D**eep **U**nderground **N**eutrino **E**xperiment
- A test of a detector prototype at CERN for upcoming **DUNE** eperiment in USA
    - DUNE experiment will detect neutrinos that are created in accelerator complex at FermiLab from a 1300 km distance while being 1.5km underground
    - Main goals of the experiment are:
    - Investigating neutrino oscillations
    - Determine the ordering of neutrino masses
    - Study neutrinos from supernovae, neutron star and black hole creation events
    - Search for proton decay events
    - Experiment is planned to start workin in 2030’s with a data taking period of at least 20 years



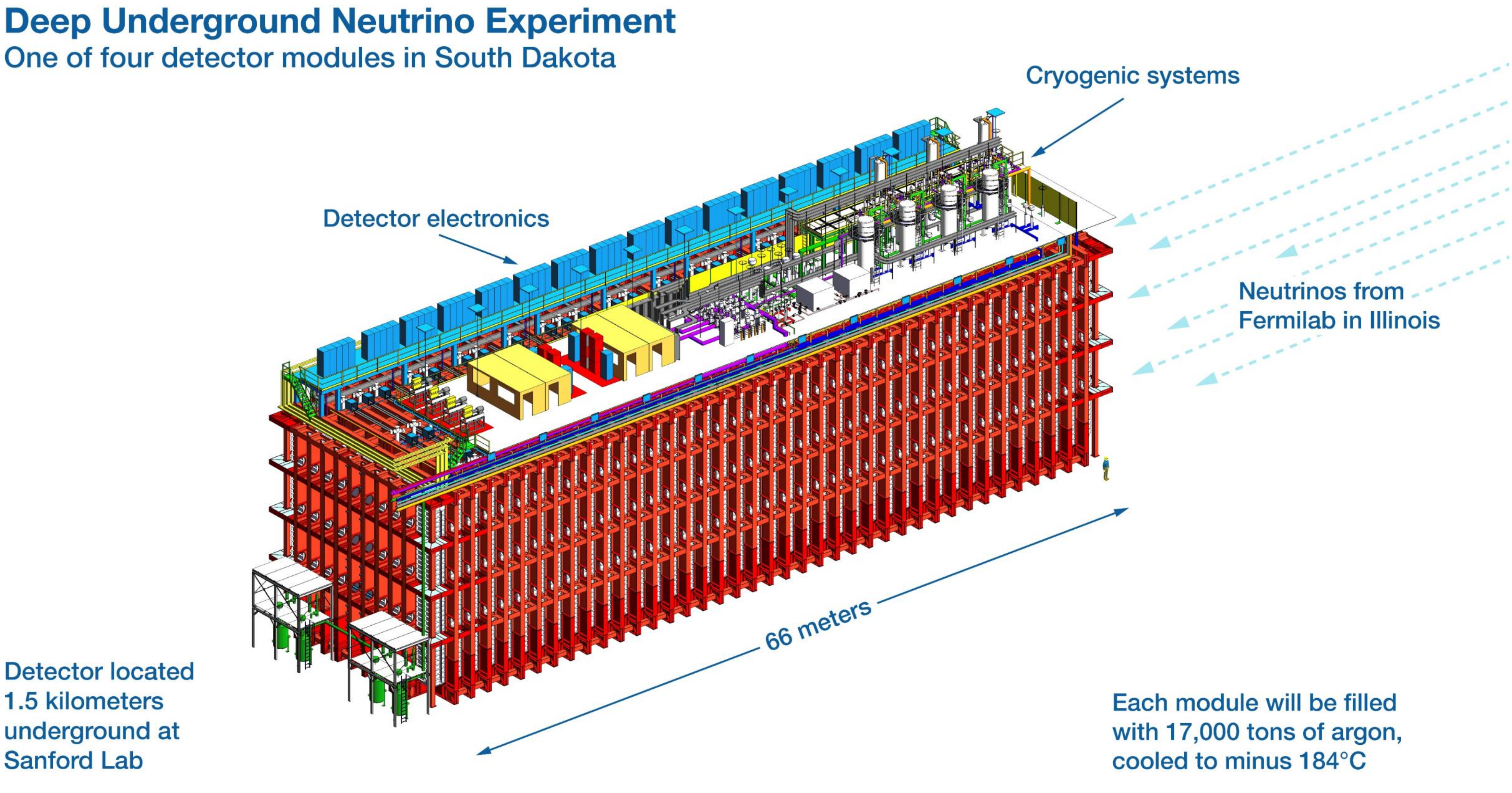
Schematic view of protoDUNE experiment detector



Inside view of protoDUNE experiment



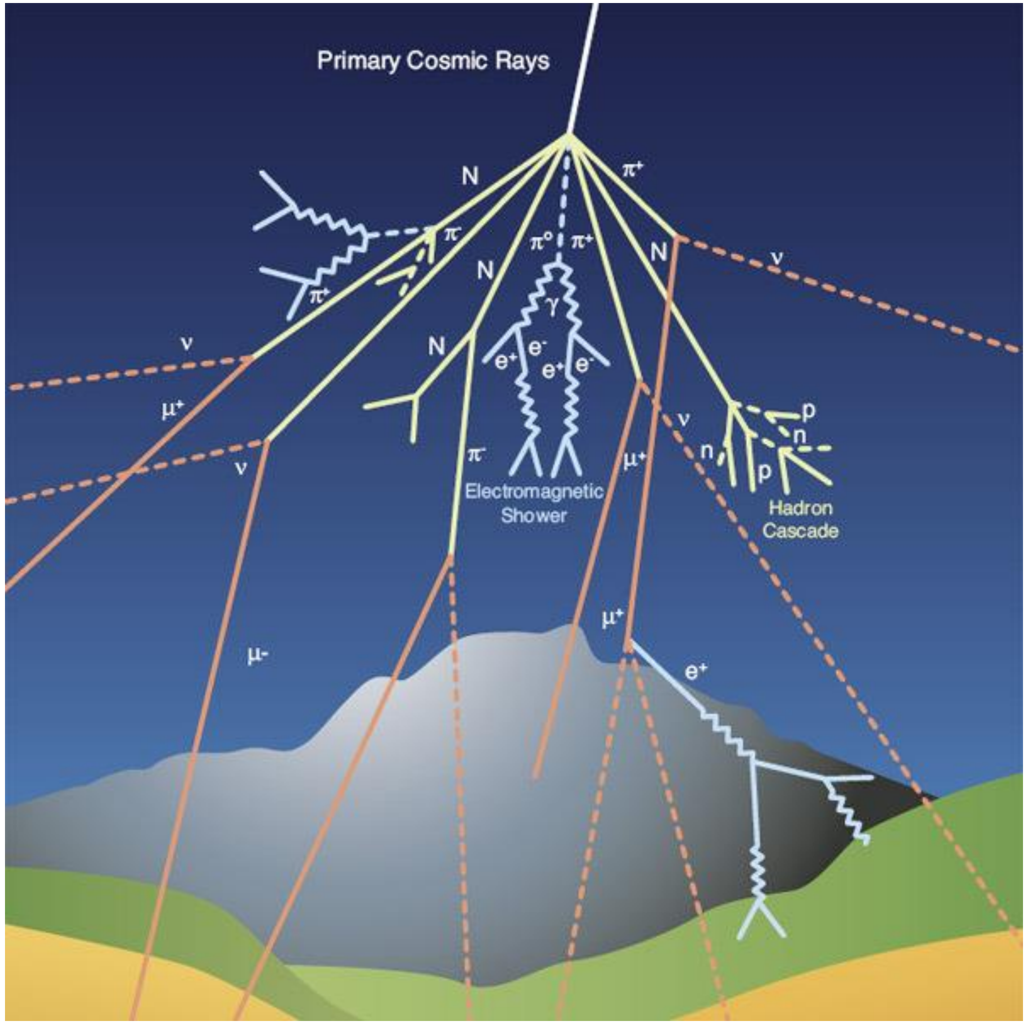
Schematic view of DUNE experiment



Schematic view of DUNE experiment's detector

CERN physics in my personal experience at school

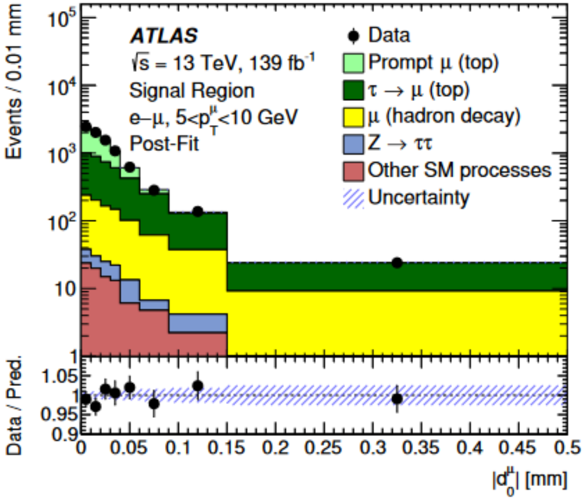
- Teaching astronomy at Riga State 1st Gymnasium for 6 years
- A lot of connections between particle physics and astronomy:
- Heavy Ion collisions – conditions of the Early Universe
- Dark matter searches – Responsable for early structure of universe and various observed astronomical phenomena
- Special relativity for particle lifetime (muons) – We see muons in atmospheric radiation created by cosmic rays
- Matter/Anti-Matter asymmetry – The existance of visible matter
- Neutrino detectors – Early supernovae warning system, uderstanding stellar evolution



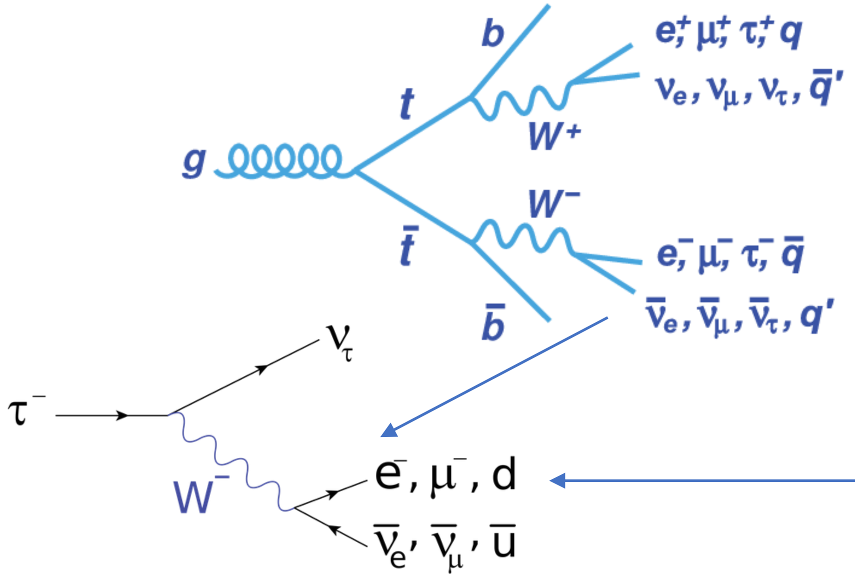
Cosmic ray shower schematic diagram

My PhD thesis research

- Recent results from LHCb have indicated inconclusive results for lepton flavor universality violations in B meson decays (saw deviations and now fixed them in one of the decay channels)
- I'll be investigating lepton flavor universality violations in top quark decays
- Idea is to test the decay ratio of tau vs electrons and tau vs muons from W boson decay
- Tau particle is unstable itself and decays to quarks or electron/muon
- I will use electrons and muons to identify tau particles



https://arxiv.org/pdf/2007.14040.pdf



Trigger events on **μ** or **e** from 1st **W** decay

Measure the ratio of 2nd **W** decays to **τ/μ/e**

τ are found by searching for displaced lower p_T **μ/e**

That’s all! Questions?