# Physics Beyond Colliders at CERN

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# Introduction

Physics Beyond Colliders (PBC) is an exploratory study aimed at exploiting the full scientific potential of CERN's accelerator complex and technical infrastructure, as well as its know-how in accelerator and detector science and technology. PBC projects complement the goals of the main experiments of the Laboratory's collider programme. They target fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but require different types of beams and experiments

Accelerator Complex Capabilities

BDF

LHC fixed targets

Forward Physics Facility

Neutrino physics

Conventional Beams

Gamma Factory



# Working Groups

# Complex Overview

Beyond the LHC Experiments:

- CERN's accelerator complex serves not only the Large Hadron Collider (LHC) but also a diverse range of cutting-edge physics experiments.
- **Fixed-Target (FT) Experiments:**
  - Aim to explore and understand novel phenomena in particle physics.
  - Offer a complementary approach to the high-energy physics conducted at the LHC.

## Key Facilities and Experiments:

### ISOLDE (Isotope Separator On-Line Device):

- Produces radioactive ion beams for nuclear physics research.

### Antiproton Decelerator (AD) & Extra Low ENergy Antiproton (ELENA):

- Focus on antimatter research and precision studies with antiprotons.

### n-ToF (Neutron Time-of-Flight Facility):

- Specializes in neutron physics experiments.

### HiRadMat:

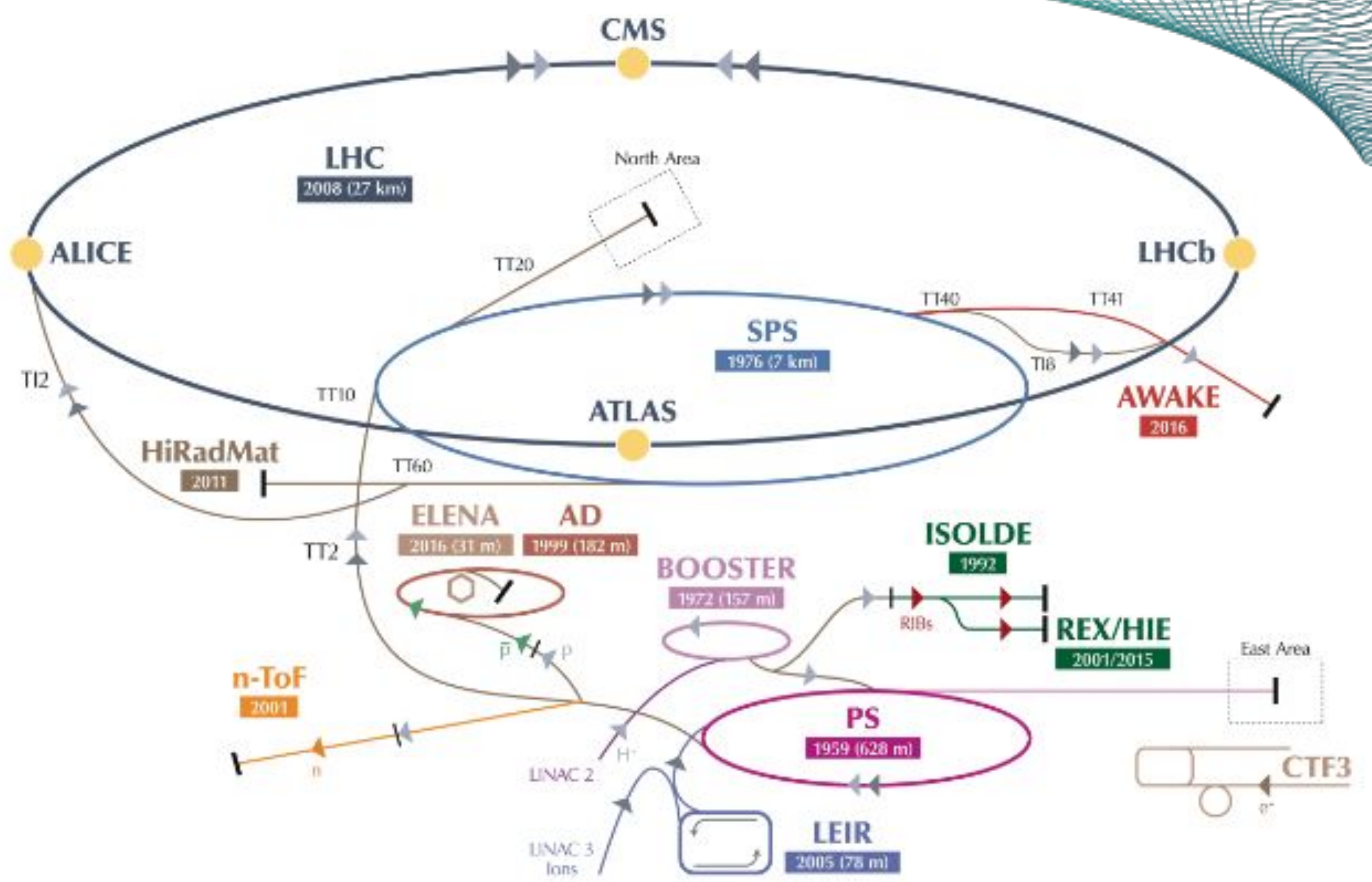
- Studies materials under extreme radiation conditions.

### North & East Area:

- Supports various fixed-target experiments with a diverse range of beam types.

### AWAKE (Advanced WAKEfield Experiment):

- Investigates novel acceleration techniques using plasma wakefield technology.



# Accelerator Complex Capabilities

**Performance Assessment:**

- **Focus on Fixed Target Proton and Ion Beams**:
  - Evaluation across the entire CERN Accelerator Complex.
  - Maximize the use of recent LHC injector upgrades.

**Identifying and Addressing Limitations:**

- **Beam Intensity, Quality, and Availability**:
  - Assess current constraints and performance bottlenecks.

**Optimization and Solutions:**

- **Enhancing Beam Delivery:**
  - Propose and document improvements for delivering protons and ions.
  - Ensure support for current and future physics experiments.

## Injector Upgrade (LIU)

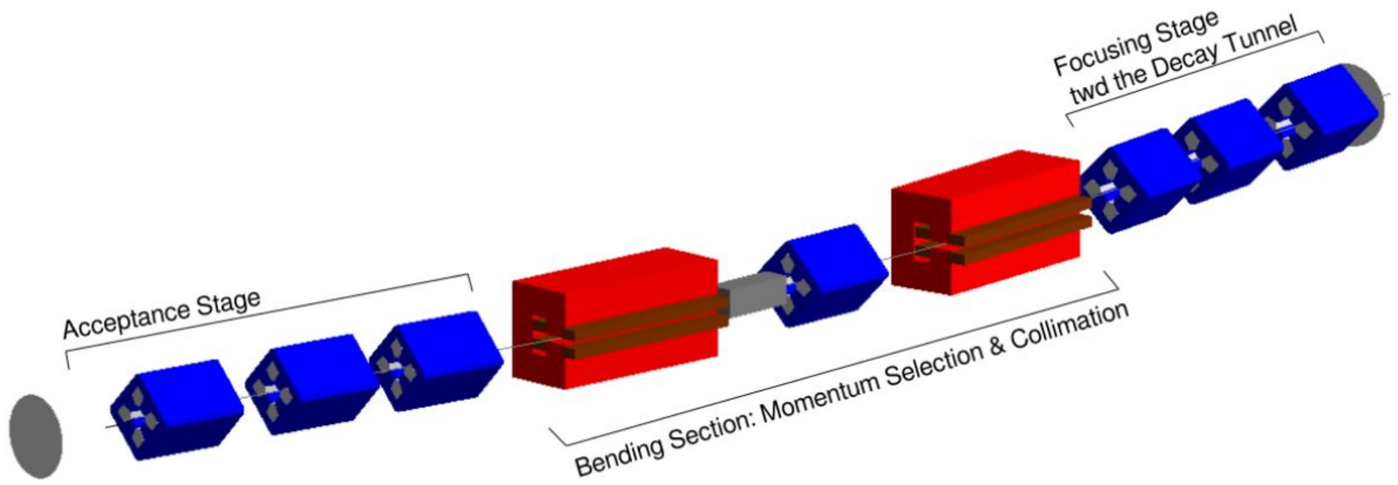
The Injector Upgrade (LIU) program was initiated to enhance the performance of CERN's accelerator complex, specifically the injectors that feed beams into the Large Hadron Collider (LHC)

**Key Upgrades:**

- Linac 4:
  - Replaces Linac 2 as the new linear accelerator, providing higher energy protons (160 MeV) to the Proton Synchrotron Booster (PSB).
  - Improved injection efficiency and reduced beam loss.
- Proton Synchrotron Booster (PSB):
  - Enhanced to handle the higher energy input from Linac 4.
  - Upgrades include new RF systems and increased beam intensity capacity.
- Proton Synchrotron (PS):
  - Upgrades to increase intensity and flexibility, including a new RF system for better beam quality.
  - Modifications to allow the PS to accelerate different types of particles more efficiently.
- Super Proton Synchrotron (SPS):
  - Equipped with new RF power systems to handle higher beam intensities.
  - Improved beam stability and loss control through upgraded vacuum systems and new collimators.

**Goals and Impact:**

- Support the HL-LHC:
  - The upgrades are essential to produce the higher luminosity beams required by the HL-LHC, enabling more precise and varied physics experiments.
- Enhanced Beam Quality:
  - The LIU project significantly improves beam intensity, quality, and reliability across the entire CERN accelerator complex.




# Neutrino Physics

- Bring together similar initiatives
- Optimize the resources globally to reach a common goal
- Promote scientific development efficiently.

This working group currently includes two novel neutrino tagged beams projects, ENUBET and NUTAG.

Neutrino tagging is considered very important to measure CP violation in the neutrino sector and explore topics that require a high precision measurement of the neutrino cross-section.

## NA61/SHINE

Measures hadron production cross-sections.

Aids T2K by reducing flux uncertainty to ~5%.

**Upcoming Enhancement:**

- New Tertiary Beamline Proposal:
  - Designed for the H2 line at CERN.
  - Will provide low-energy hadron beams down to 2 GeV/c.
  - Enables new measurements in the neutrino-interesting energy range.

**Requirements:**

- Beam Specifications:
  - Flexible pions, kaons, protons.
  - Momentum range: 2 to 13 GeV/c.
  - Momentum spread: <5%.
  - Variable purities and rates.

## NuTAG

**Goals:**

- Refine neutrino oscillation measurements using pion decays ($\pi \rightarrow \mu\nu$).
- Employ advanced trackers to reconstruct pion decays from $\pi$ and $\mu$ tracks.
- Improve neutrino energy reconstruction and reduce beam-related systematic uncertainties.

**Beam Design:**

- Conventional Narrow-Band Beam:
  - Components:
    - Short pion momentum-selecting beam line.
    - 300-meter long decay tunnel.

## ENUBET

**Goals:**

- Produce a beam of electron neutrinos from kaon decays (e.g., $K^+ \rightarrow \pi^0 e^+ \nu_e$).
- Achieve precision improvement to 1% through event-by-event tagging of neutrinos.

**Beam Design:**

- Narrow-band beam.
- Short transfer line (~30 m) and 40 m long decay tunnel.
- Focus and momentum-select secondary kaons.
- Monitor neutrino flux by detecting large-angle positrons with a segmented calorimeter in the decay tunnel.

## SBN

**Goals:**

- Develop a shared beamline for both ENUBET and NuTag experiments.
- Produce monitored and tagged $K^+$ and $\pi^+$ beams.
- Create a tagged neutrino beam in the 1–10 GeV/c range.

**Enhanced Design Overview:**

- Builds on the ENUBET beamline developed within CBWG.
- Silicon Pixel Detectors Integration: Incorporates NuTag's high-resolution pixel detectors.
- Optimization Method:
  - Multi-Objective Genetic Algorithm (MOGA): Optimizes 26 beamline parameters simultaneously.

## North Area Facility

- **Proton Beam:** Max momentum of 400 GeV/c from the SPS.
- **Ion Beams:** Corresponding rigidity to protons.

**Flat Top Duration:**
Typically 4.8 seconds, adjustable for different physics programs.

**Beam Intensity:**
Max: 3.5 × $10^{13}$ ppp per spill.
Future Goal: 4 × $10^{13}$ ppp per spill.

## North Area Hall

EHN 1 (Surface Hall):

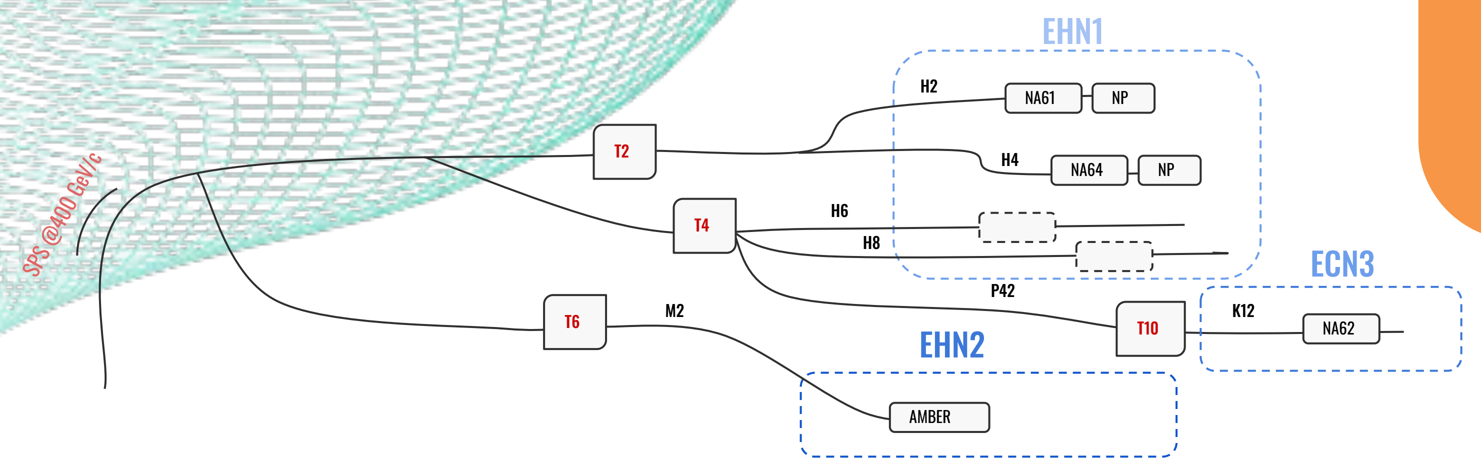
- Largest surface hall at CERN (330m x 50m)
- Houses H2, H4, H6, and H8 beam lines

EHN2 (Surface Hall):

- Served by M2 beam line
- Supports muon, hadron, and electron beams
- Current experiment: COMPASS

ECN3 (Underground Cavern):

- Hosts the NA62 experiment for rare kaon decays
- Served by K12 beam line




# Conventional Beams Group

**Role:** Manages and operates the conventional beam lines used for fixed-target experiments and other research.

**Support:** Provides beam facilities for experiments and works on optimizing beam quality and delivery.

## List of proposed experiments

| | |
|---|---|
| Na61++ | Run NA61 at higher intensity and with better machine protection |
| AMBER | Study new requests from COMPASS++, including RF separated beam |
| MuonE | Study possibility to implement experiment in M2 beam with μ and e |
| Dirac ++ | Study implementation options for DIRAC follow-up at SPS |
| Na60+ | Study implementation options for NA60 follow-up at SPS |
| SBN | A kaon/pion-tagged electron neutrino beam |
| True Monium | A search for true muonium in fixed target experiment |
| Na64++ | Increase electron flux and optimise hadron beams in H4 and muons in M2. |

# Forward Physics Facility

Focuses on studying forward physics in proton-proton collisions at the LHC.
Explores new physics in the far-forward region, beyond the reach of traditional detectors.

**Underground Facility:**

Situated ~480 meters from the ATLAS interaction point.

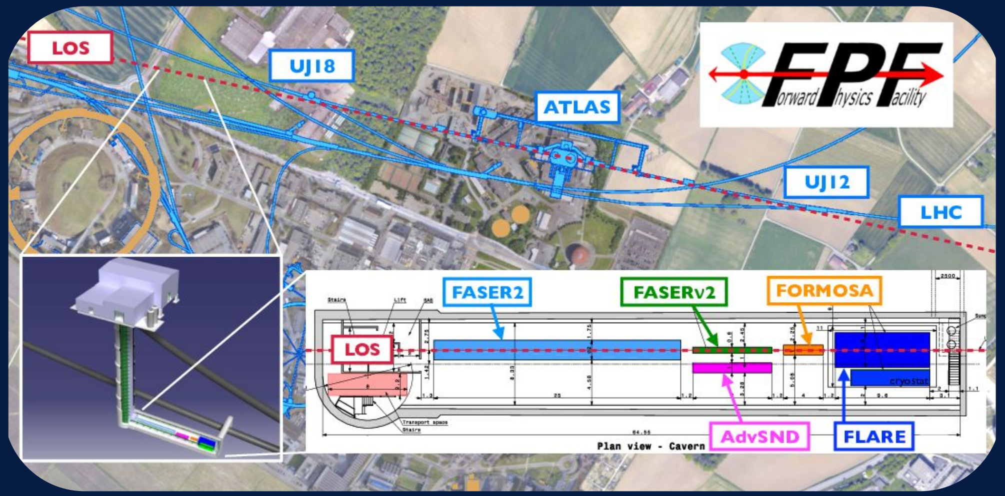
Shielded by rock to minimize background noise.

**Complementary to LHC:**

- Extends the physics reach of CERN by investigating regions not accessible by current detectors.
- Aims to advance the understanding of neutrino physics, dark matter, and beyond.

**Timeline:**

- Integrated with the High-Luminosity LHC (HL-LHC) upgrade.
- Expected to play a crucial role in physics research during the 2030s.




## Key Experiments:

FASER:

- Searches for light, weakly interacting particles like dark photons.
- Detects neutrinos from LHC collisions.

FASERν:

- Dedicated to neutrino detection, measuring interactions of high-energy neutrinos.

FORMOSA:

- Probes milli-charged particles with extremely small electric charges.

Advanced SND:

- Aims to study neutrinos from a broader range of energies, complementing FASERν.

FLArE (Forward Liquid Argon Experiment):

- Utilizes liquid argon technology to study neutrino interactions and other rare processes.

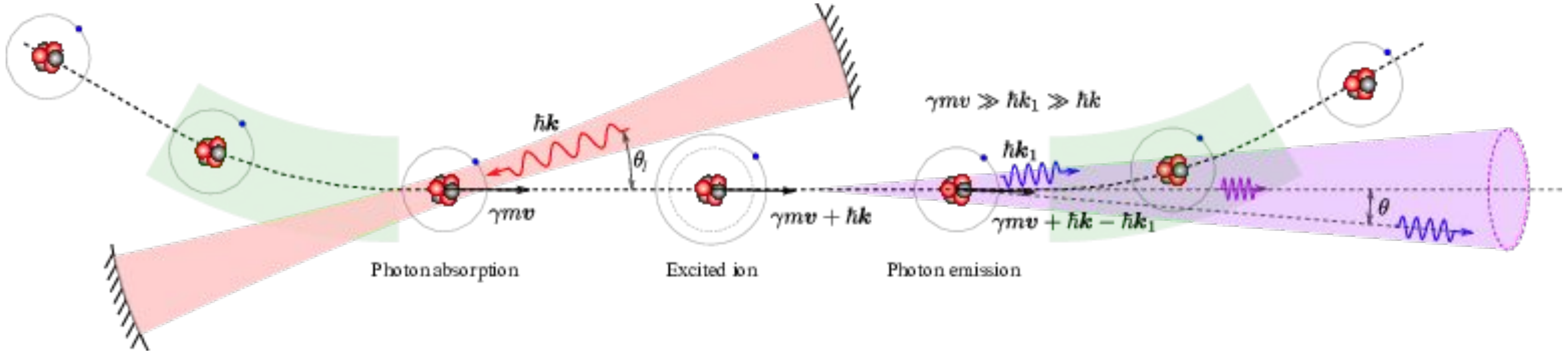
# Gamma Factory

The Gamma Factory is a novel research initiative aimed at producing high-intensity, high-energy gamma rays.
These gamma rays are intended for a wide range of applications in fundamental physics, including particle physics, nuclear physics, and atomic physics.

- Key Concept:
  - Uses highly charged ions circulating in the Large Hadron Collider (LHC) or the Super Proton Synchrotron (SPS).
  - These ions are excited by a laser beam, causing them to emit gamma rays when they de-excite.
- Production Process:
  - Laser Excitation:
    - A laser beam is directed at the ions, exciting them to higher energy states.
  - Gamma-Ray Emission:
    - As the ions return to their ground state, they emit gamma rays.
  - Resulting Gamma Rays:
    - The emitted gamma rays can have energies in the GeV range, much higher than those achievable by traditional methods.

**Applications:**

- **Nuclear Physics:**
  - Enables the study of photonuclear reactions at previously inaccessible energies.
- **Particle Physics:**
  - Potential to explore new physics phenomena, including searches for dark matter and other beyond Standard Model particles.
- **Material Science:**
  - High-intensity gamma rays could be used to probe the internal structure of materials with unprecedented precision.
- **Medical Physics:**
  - Applications in advanced imaging techniques and potentially in cancer treatment through precision gamma-ray therapies.




**Current Status:**

- Research and Development:
  - The Gamma Factory is currently in the R&D phase, with experiments being conducted to refine the technology and improve the efficiency of gamma-ray production.

**Future Prospects:**

- Integration with LHC Upgrades:
  - Potential to be integrated with future LHC upgrades, enhancing the research capabilities of CERN.

# LHC Fixed Targets

Objective:

- Explore new physics beyond the Standard Model using fixed-target experiments at the LHC.

Concept:

- A fixed-target setup involves directing a particle beam from the LHC onto a stationary target, producing a wide variety of particles for analysis.

## Key Experiments:

1. AFTER@LHC:
   - Focus:
     - Studies of Quark-Gluon Plasma (QGP) and the spin structure of the proton.
   - Beam:
     - Uses the LHC proton and heavy-ion beams on fixed targets.
   - Applications:
     - Probing the structure of nuclear matter and precision measurements in Quantum Chromodynamics (QCD).
2. LHCSpin:
   - Focus:
     - Investigating spin effects in particle interactions.
   - Setup:
     - Polarized gas targets are integrated with the LHC beam.
   - Goals:
     - Understanding the spin structure of protons and the dynamics of QCD in new kinematic regions.
3. SMOG2 (LHCb):
   - Focus:
     - Extending the LHCb experiment's capabilities to fixed-target physics.
   - Beam:
     - Injection of noble gases into the LHCb interaction region, creating a fixed-target environment.
   - Applications:
     - Studies of cosmic rays, antimatter production, and heavy-ion physics.

# QCD Physics Group

Understand the strong force that binds quarks and gluons within protons, neutrons, and other hadrons.

**Proton Structure:**

- **Goal:**
  - Probe the internal structure of protons, including parton distribution functions (PDFs).
- **Method:**
  - Utilize high-energy fixed-target experiments and collider data.

**Quark-Gluon Plasma (QGP):**

- **Goal:**
  - Study the properties of QGP, a state of matter created at extreme temperatures where quarks and gluons are free.
- **Method:**
  - Conduct heavy-ion collisions and analyze the resultant particle interactions.

**Spin Physics:**

- **Goal:**
  - Investigate the spin composition of protons, particularly the contribution of gluon and sea quark spins.
- **Method:**
  - Perform spin-polarized experiments using advanced fixed-target setups.

**Hadronization:**

- **Goal:**
  - Understand how quarks and gluons form hadrons (such as protons and pions) after being produced in high-energy collisions.
- **Method:**
  - Study particle production mechanisms in various energy regimes.

Key Experiments and Projects:

- **AFTER@LHC**:
  - Focus:
    - QCD studies in a fixed-target environment using LHC beams.
- **COMPASS++/AMBER:**
  - Focus:
    - Precision measurements of hadron structure and interactions using high-intensity muon and hadron beams.
- **NA61/SHINE**:
  - Focus:
    - Investigate hadron production in proton-proton and heavy-ion collisions, providing essential data for QCD studies.

# How PBC Research is conducted?

## Identifying Physics Opportunities:

Mandate:

Evaluate the potential of CERN's existing accelerators and facilities for non-LHC (Large Hadron Collider) experiments.

Focus:

Address open questions in particle physics

## Feasibility Studies:

Simulations & Design:

Use advanced simulations to optimize beamlines, target designs, and detector setups for proposed experiments.

## Testing

Prototype Development:

- Build and test prototypes for critical components like detectors, beam monitors, and target materials.

Beam Tests:

- Conduct beam tests in CERN's existing facilities, such as the North Area or the PS East Area, to validate experimental setups.

WG

## Publication & Dissemination:

**Documentation:**

**Publish findings in scientific journals, CERN Yellow Reports, and other platforms to share results with the global physics community.**

**Strategy Updates:**

**Contribute to strategic documents like the European Strategy for Particle Physics to influence the future direction of CERN's research program.**

By following this structured approach, the PBC initiative ensures that research is thorough, collaborative, and aligned with the broader goals of the global physics community.

# Impacts

PBC explores the vast potential of CERN's non-LHC facilities, opening new avenues for discovering physics beyond the Standard Model (BSM) and addressing fundamental questions in particle physics.

New Technologies

PBC fosters the development of cutting-edge experimental techniques, such as precise beam instrumentation, novel detector technologies, and advanced target designs, which have applications both within and outside particle physics.

The discoveries and technological advancements resulting from PBC research have the potential to influence the field of particle physics for decades, paving the way for future breakthroughs.

Training the Next Generation:

- Educational Impact:
  - PBC provides a valuable platform for training young scientists and engineers, equipping them with skills in experimental design, data analysis, and advanced technology development.
- Inspiring Future Research:
  - The initiative inspires new generations of physicists by demonstrating the potential for groundbreaking discoveries through innovative, non-collider experiments.

Global Scientific Collaboration:

- International Partnerships:
  - PBC promotes global collaboration by involving a wide network of researchers and institutions, facilitating the exchange of knowledge and expertise across borders.
- Influencing Global Strategy:
  - The findings and recommendations from PBC studies contribute to shaping the European Strategy for Particle Physics, guiding future research directions at CERN and beyond.

# Conclusions

Throughout this presentation, we've explored the exciting work being done under the Physics Beyond Colliders program at CERN. We discussed the diverse range of experiments and projects aimed at probing the frontiers of physics beyond the scope of traditional high-energy colliders.

The PBC initiative is critical in expanding our understanding of the universe. By complementing the Large Hadron Collider with smaller, specialized experiments, we can explore new physics, such as dark matter, rare processes, and precision measurements that could reveal hidden layers of fundamental physics.

In the pursuit of knowledge, the work being done at CERN's PBC is not just about answering today's questions, but about asking tomorrow's. Let's continue to push the boundaries of what we know and venture into the unknown realms of physics.

# Thank you for your attention!