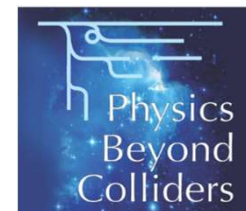


Physics Beyond Colliders at CERN: New discoveries aside of new supercolliders?

Alexander Gerbershagen

On behalf of CERN BE-EA-LE



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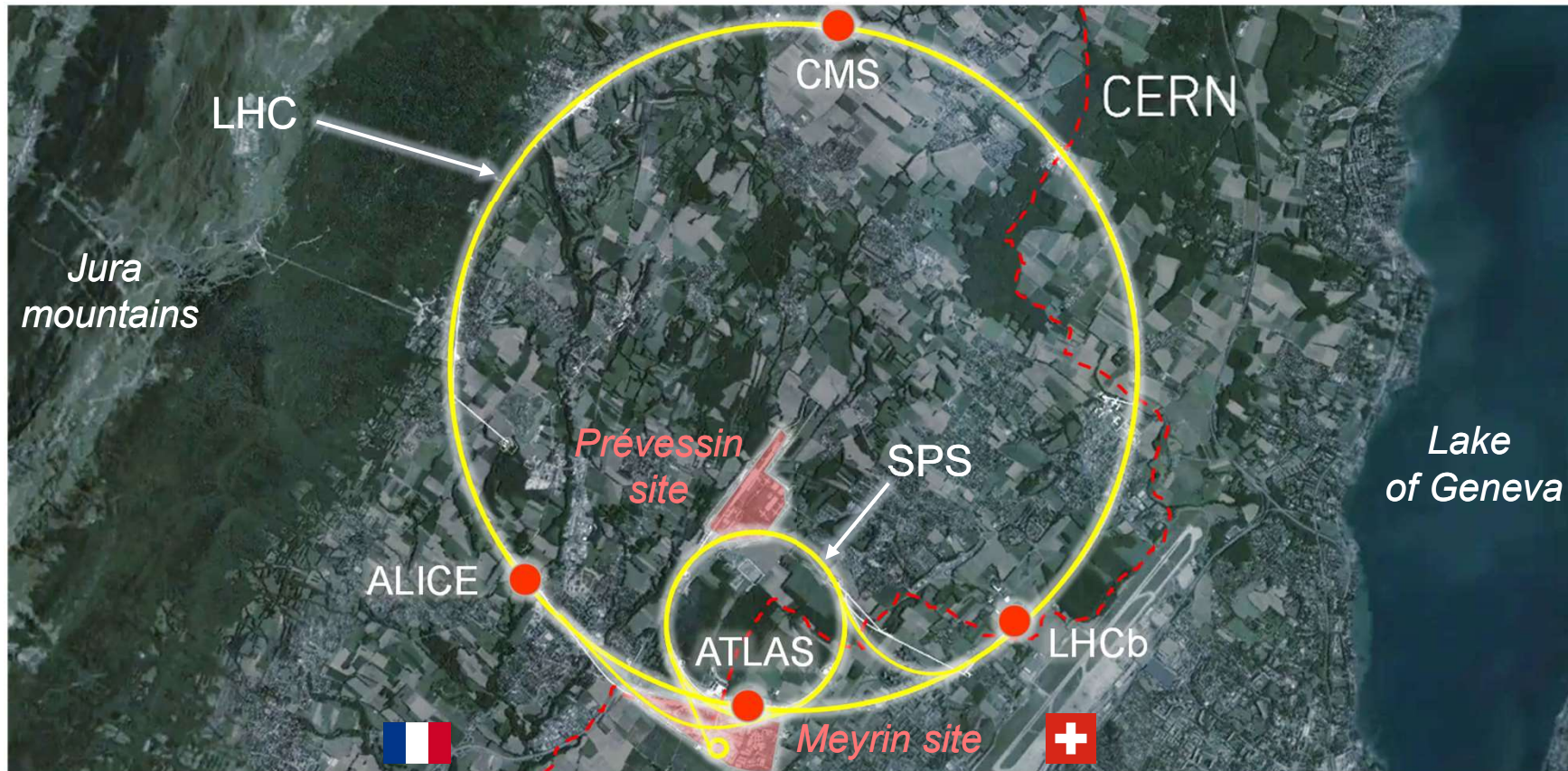
CERN: Organisation Européenne pour la Recherche Nucléaire

- World's largest Particle Physics Laboratory (1954)
- 23 Member States (+ 6 Associate)
- Yearly budget \approx 1200 MCHF

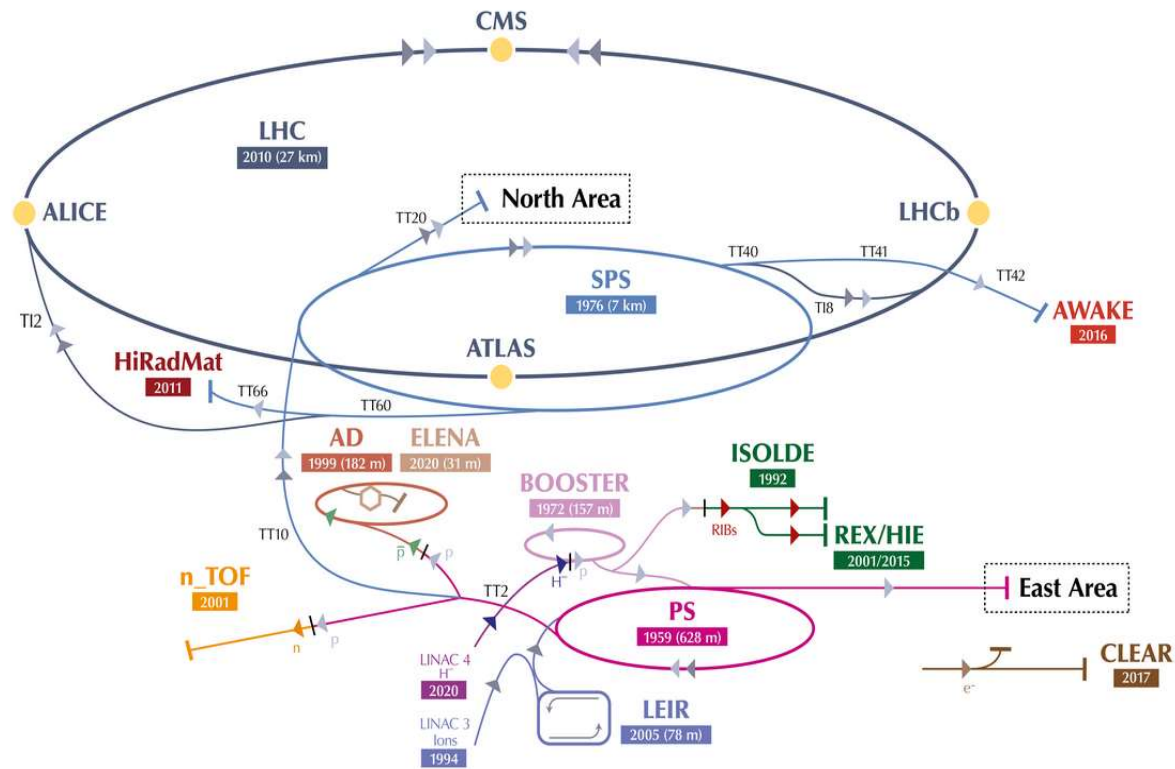


- *Missions of CERN:*
 - Push forward the frontiers of knowledge
 - e.g. the secrets of the Big Bang ... what was the matter like within the first moments of the Universe's existence?
 - Develop new technologies for accelerators and detectors
 - Information technology - the Web and the GRID
 - Train the scientists and the engineers of tomorrow
 - Unite people from different countries and cultures

CERN Maps



The CERN accelerator complex



The CERN Accelerators

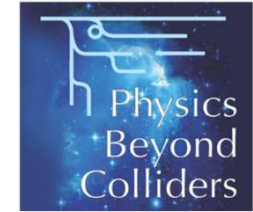
- Source + Linacs
- PSB (2 GeV/c, 4 x 157 m)
- LEIR (ions, 80 m)
- PS (26 GeV/c, 628 m)
- SPS (450 GeV/c, 6.9 km)
- LHC (14 TeV, 27 km)

▶ H^- (hydrogen anions) ▶ p (protons) ▶ ions ▶ RIBs (Radioactive Ion Beams) ▶ n (neutrons) ▶ \bar{p} (antiprotons) ▶ e^- (electrons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKEfield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive Experiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials



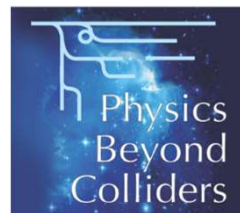
Content



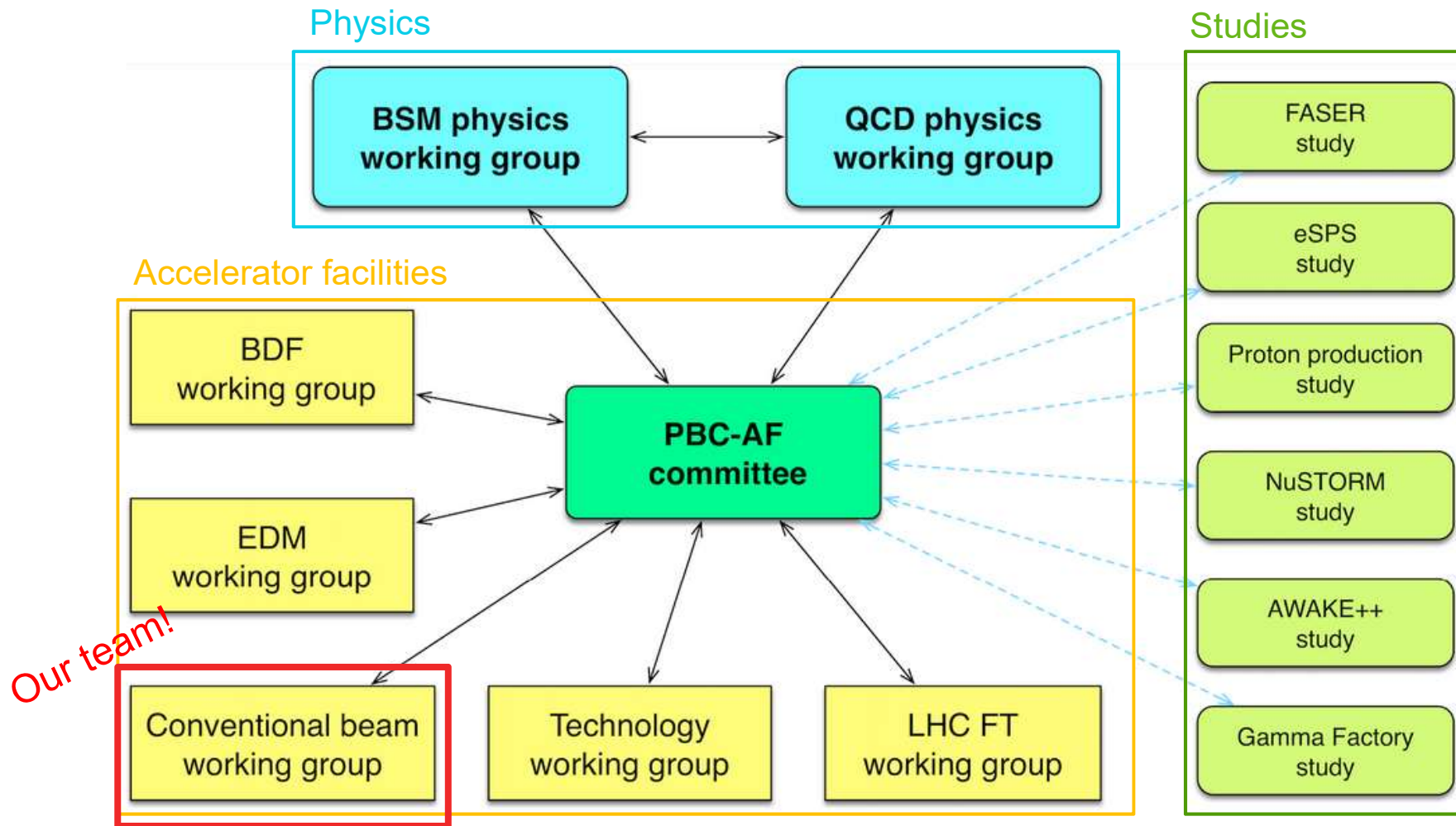
- Different types of experiment proposals require
 - Upgrades of SPS beam lines
 - New SPS beam lines
 - LHC hosted experiments
 - New facilities
- CERN's North Area and its beam lines
 - PBC studies in the North Area
 - EHN1
 - EHN2
 - ECN3
- Conclusions and Outlook
- Documentation

The Physics Beyond Colliders programme

- Aim of this exploratory study launched in 2016:
 - Enrich and diversify the CERN scientific programme
 - Exploit the unique opportunities offered by CERN's accelerator complex and scientific infrastructure
 - Complement the lab's collider programme
- \approx 100 contributors!
- Supported by the European Strategy for Particle Physics 2020
 - *“A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy.”*



Physics Beyond Colliders (PBC) (1)



Physics Beyond Colliders (PBC) (2)

PBC

Our team!

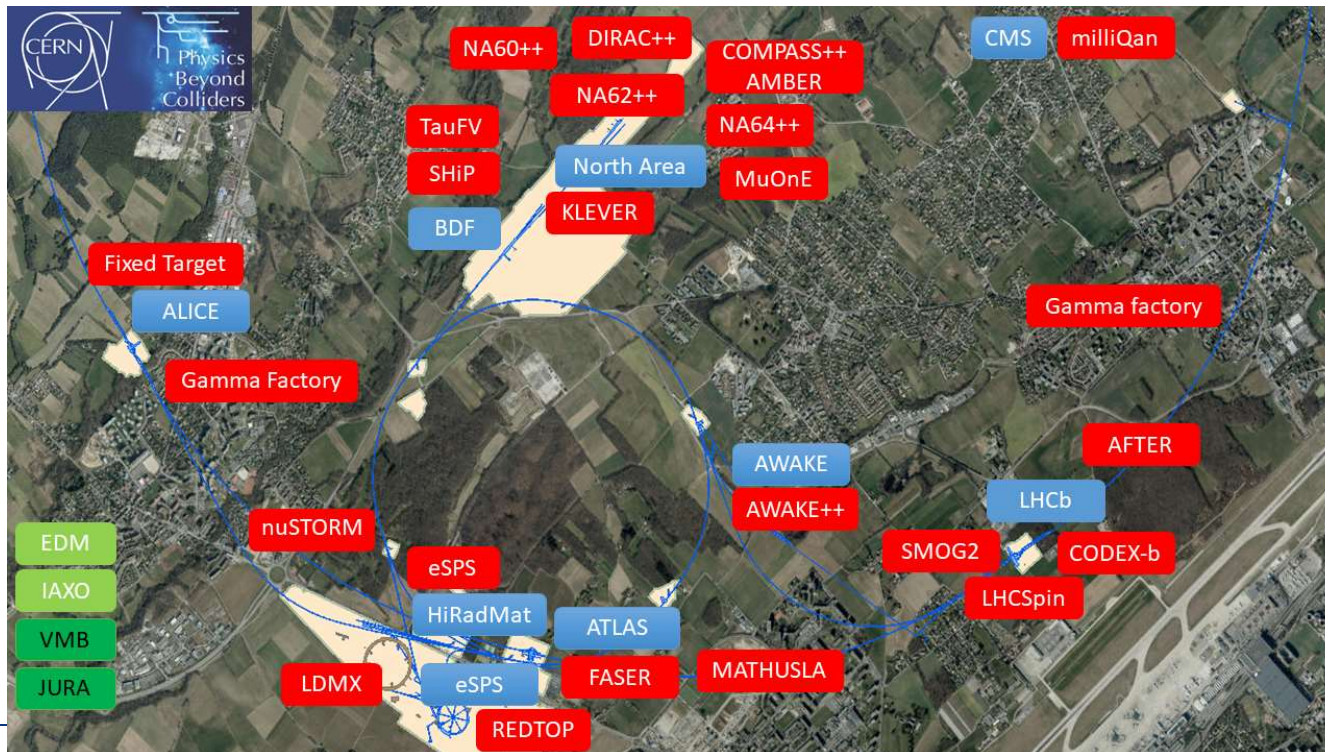
Upgrades of existing PS beam lines

Upgrades of existing SPS beam lines

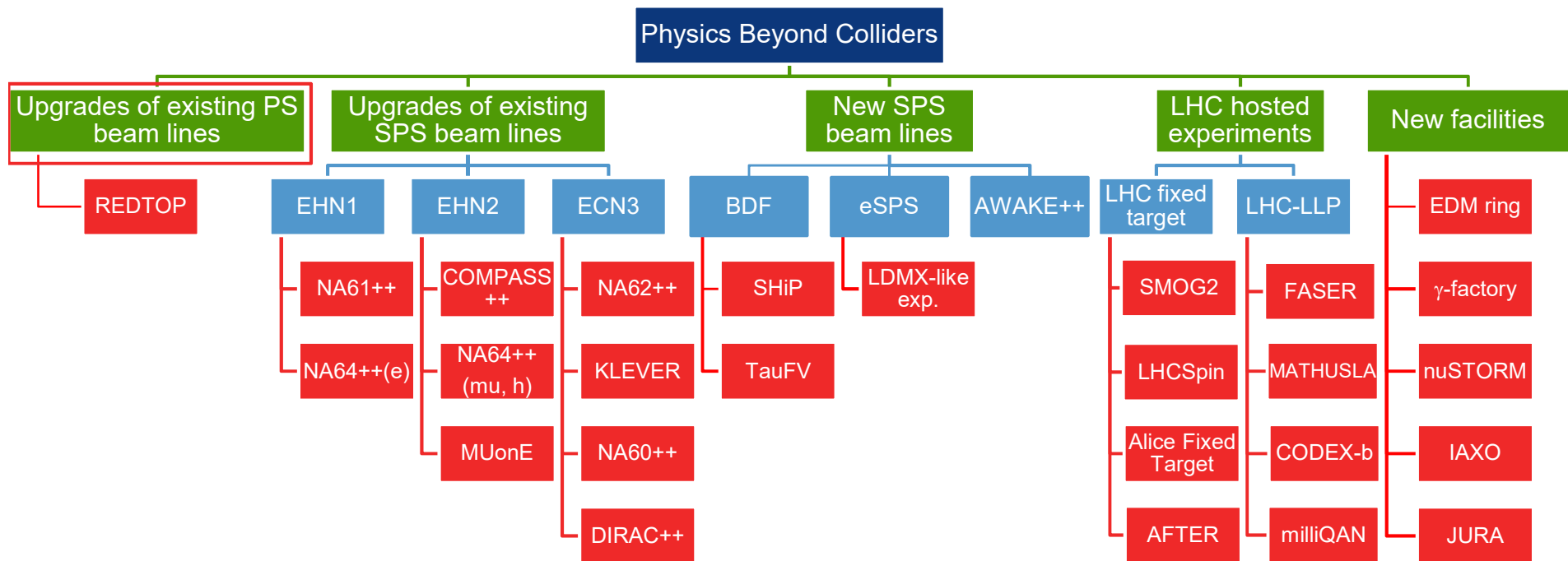
New SPS beam lines

LHC hosted experiments

New facilities



Physics Beyond Colliders (PBC)

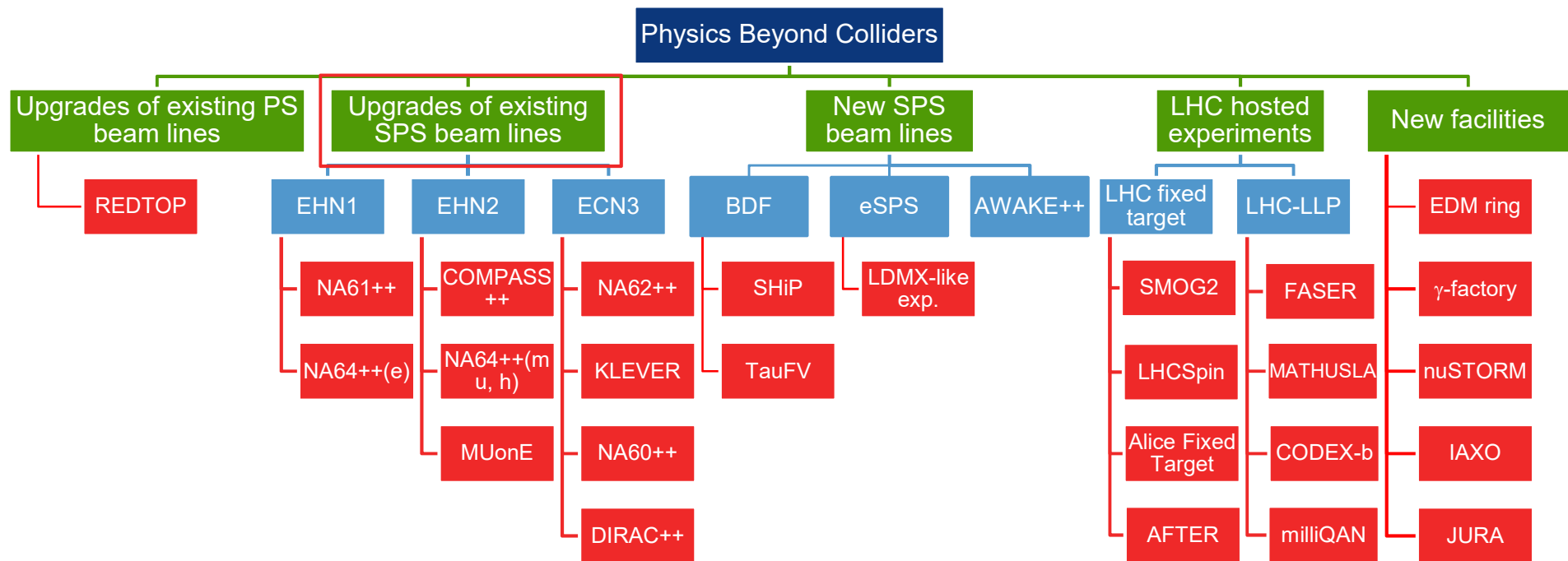


Upgrades of existing PS beam lines

Experiment	Physics	Requirements
REDTOP	Search for very rare η decays	2 GeV proton beam with a very high duty cycle (80 %)

- Implementation in LEIR, PS Booster and PS
- *Most economical solution:* implement REDTOP at an extracted 2 GeV beam from the PS
- But it would require machine studies and reduced duty cycle with reference to initial proton request.
 - ➔ Significant impact on CERN physics program

Physics Beyond Colliders (PBC)

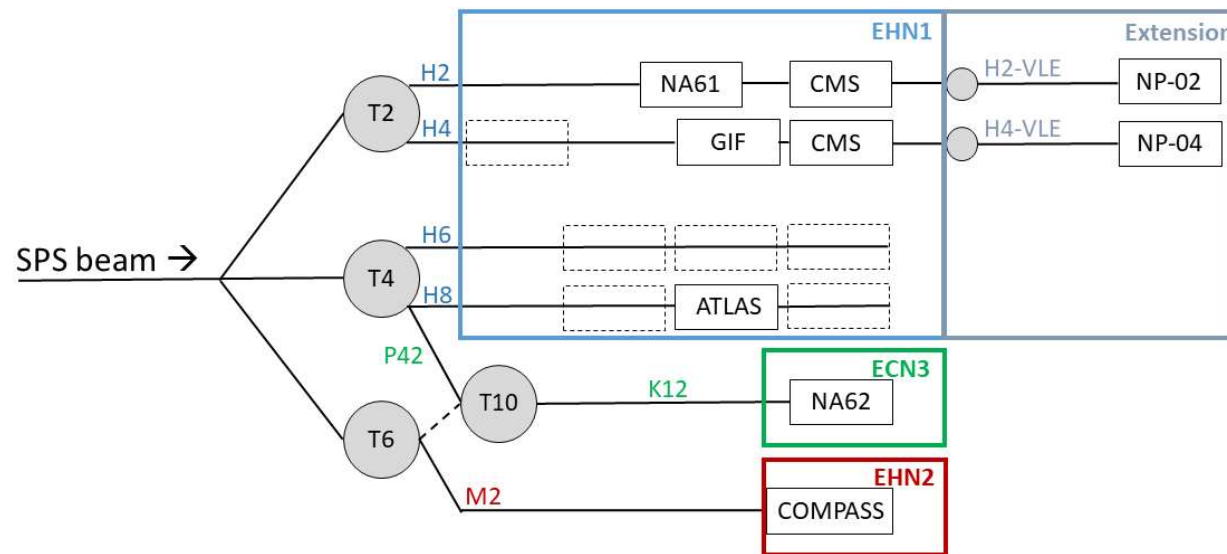


North Area current beam lines

Some particles produced in a secondary beam: hadrons (e.g. kaons, pions,...), electrons, muons

CERN's largest experimental area:

- 3 experimental halls
- Experimental areas for test beam campaign and long-term fixed-target experiments and facilities
- Primary beam coming from the SPS: 400 GeV/c protons
- 4 primary targets: T2, T4, T6 and T10
- 6 secondary beam lines



Targets and particle production

- Principle taken from cosmic radiation
- Particles are produced in a large momentum range



SPS beam

North Area

North Area : EHN1, EHN2 and ECN3 halls



Physics Beyond Colliders studies in North Area

PBC studies: fixed-target experimental proposals



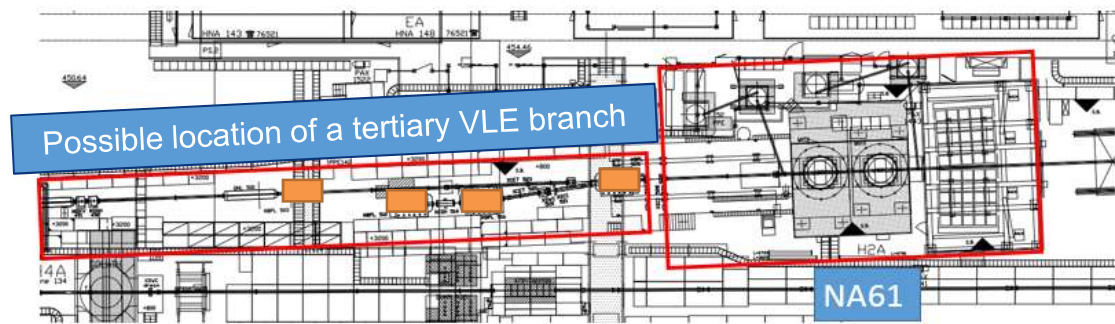
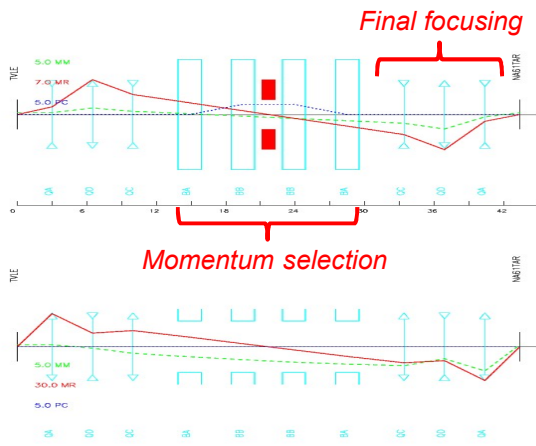
EHN₁



EHN₁ (1)

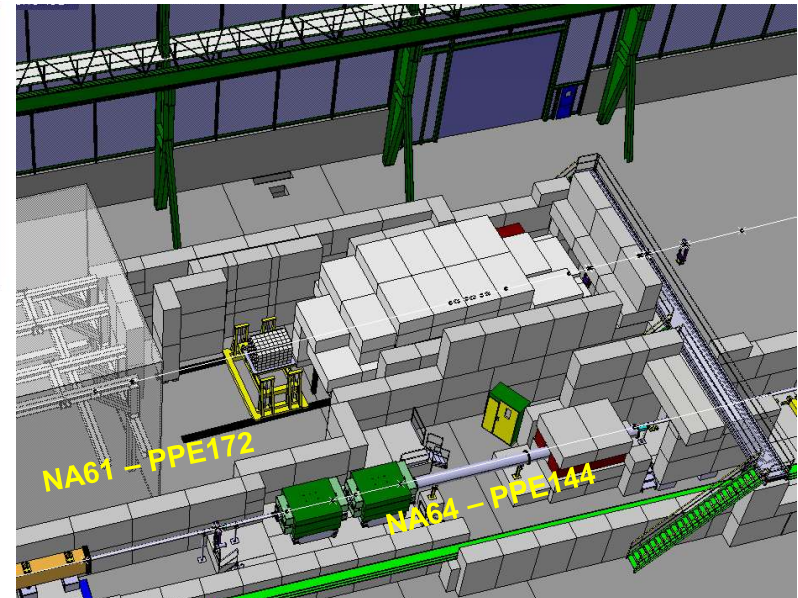
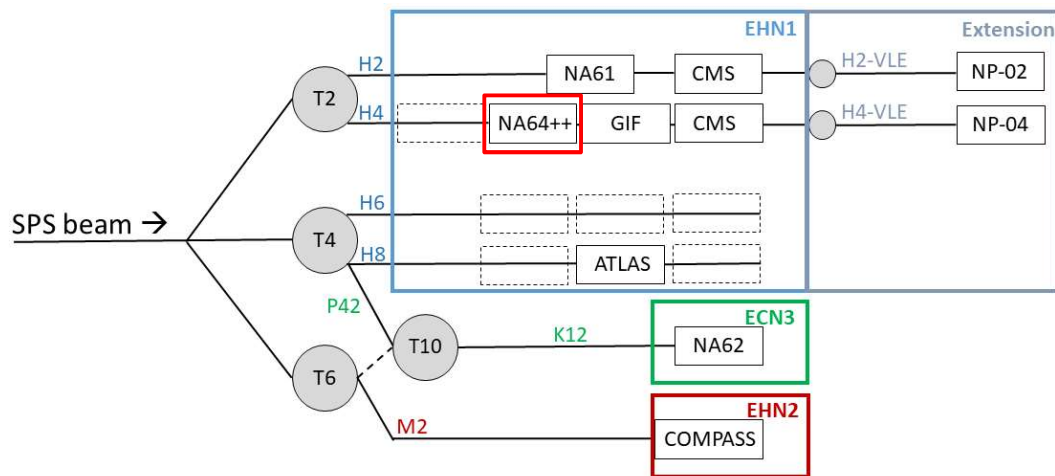
Experiment	Physics	Requirements	Deadline
NA61++	Heavy ion experiment	<ul style="list-style-type: none"> Run NA61 at higher intensity and with better machine protection Study the possibility to have a local low energy hadron beam 	<ul style="list-style-type: none"> Short-term Mid-term?

- Improved shielding, which will allow **higher ion intensities**:
 10^6 ions/spill in 2021 \neq 10^5 ions/spill (\leq 2018)
- Studies on a **Very Low Energy beam** (<30 GeV/c hadrons/protons) ongoing



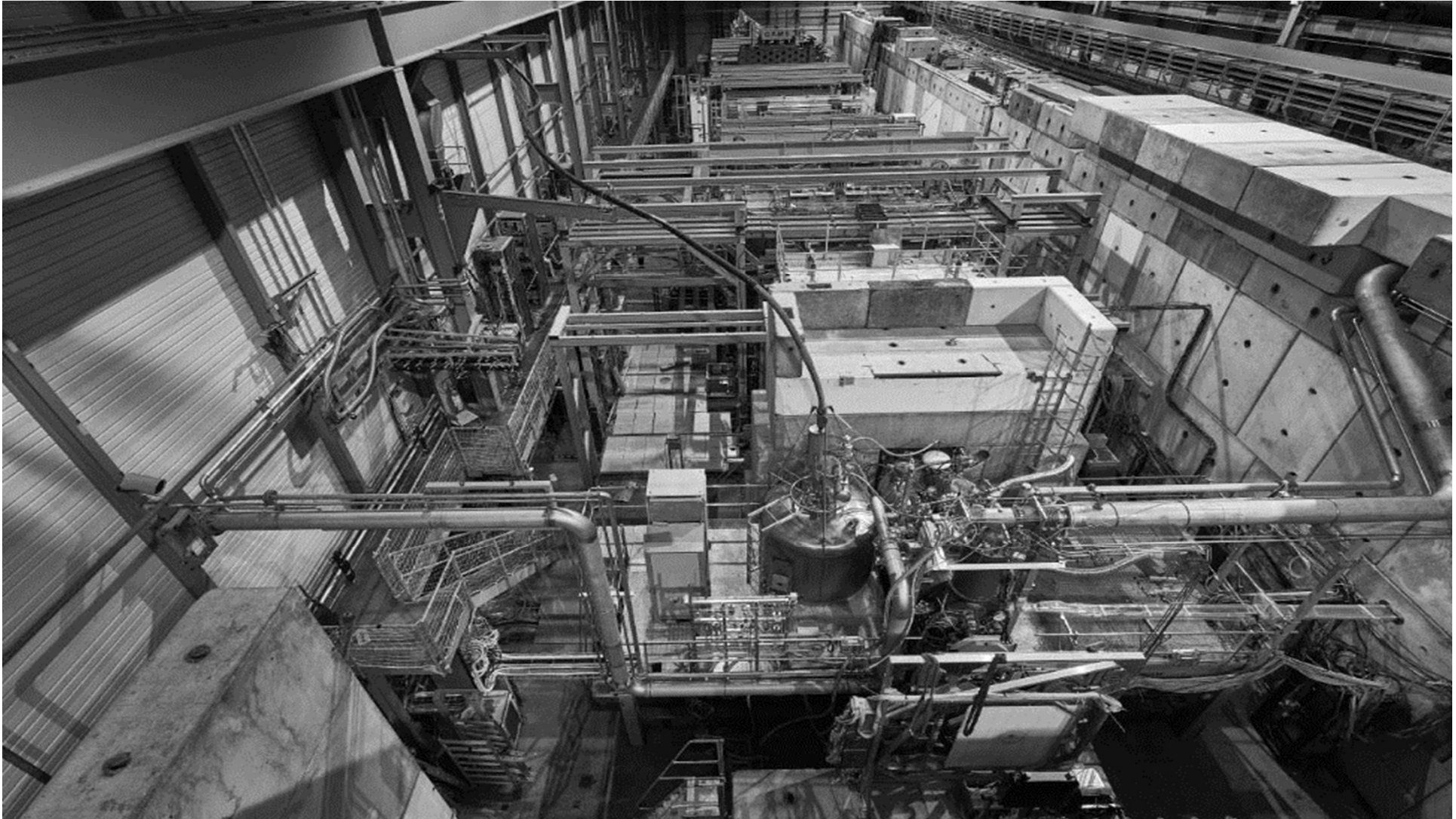
EHN1 (2)

Experiment	Physics	Requirements	Deadline
NA64++	Search for A'	Increase electron flux and optimise hadron beams in H4	Short term (2021)



➡ New area with NA64 as first user

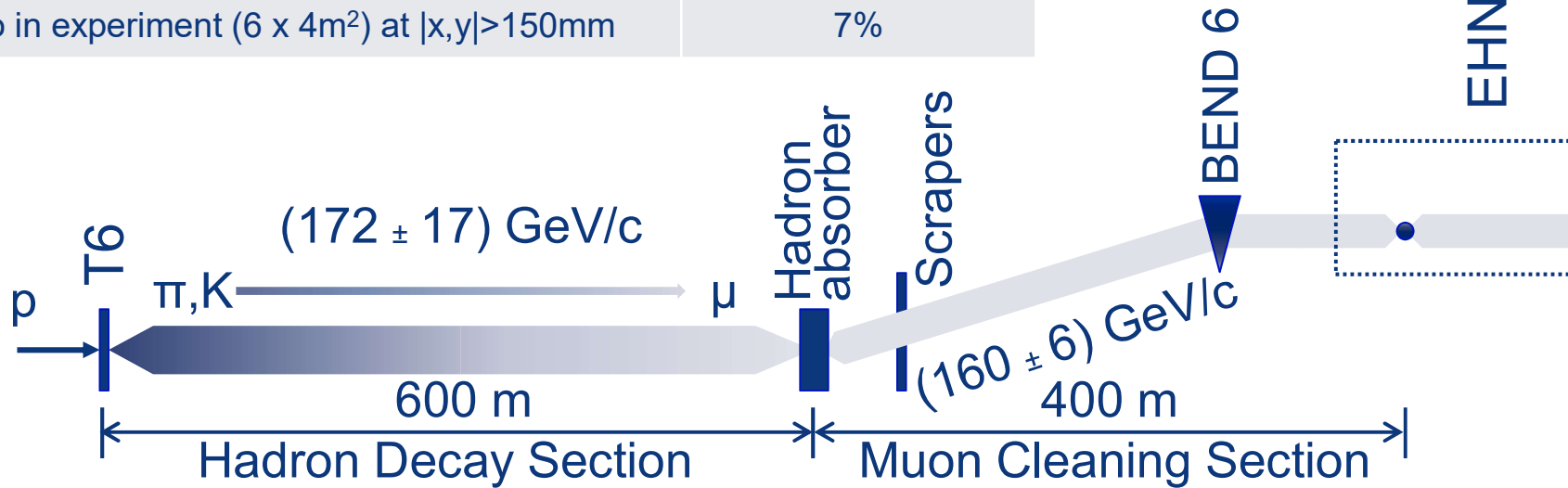
EHN₂



The M2 Beam

Beam Parameters for COMPASS	Measured
Beam momentum p_μ/p_π	160 / 172 GeV/c
Proton flux on T6 per SPS cycle	$1.5 \cdot 10^{13}$
Muon flux at COMPASS per SPS cycle	$2.5 \cdot 10^8$
Beam polarisation	$-80\% \pm 4\%$
Spot size at COMPASS target ($\sigma_x \times \sigma_y$)	8mm x 8mm
Divergence at COMPASS target ($\sigma_{dx} \times \sigma_{dy}$)	0.4mrad x 0.8mrad
Muon halo within 50mm from beam axis	16%
Halo in experiment ($6 \times 4\text{m}^2$) at $ x,y >150\text{mm}$	7%

M2



The M2 Beam

3 main operation modes:

- High-energy, high-intensity **muon** beam. Normally for muon momenta up to 200 GeV/c. Higher momenta up to 280 GeV/c are possible, but the flux drops very rapidly with beam momentum.
- High-intensity secondary **hadron** beam for momenta up to 280 GeV/c with radiation protection constraints.
- Low-energy, low-intensity (and low-quality) in-situ **electron** calibration beam.

Beam Mode	Momentum (GeV/c)	Max. Flux (ppp / 4.8s)	Typical $\Delta p/p$ (%)	Typical RMS spot at the exp. target	Polarisation	Absorber (9.9 m Be)
Muons	+208/190 +172/160	$\sim 10^8$ $2.5 \cdot 10^8$	3%	8 x 8 mm	80%	IN 10^{-5} impurity
Hadrons	+190 -190 Max. 280	10^8 (RP) $4 \cdot 10^8$ (with dedicated dump)	-	5 x 5 mm	-	OUT
Electrons	-10 to -40	$< 2 \cdot 10^4$	-	$> 10 \times 10$ mm	-	OUT

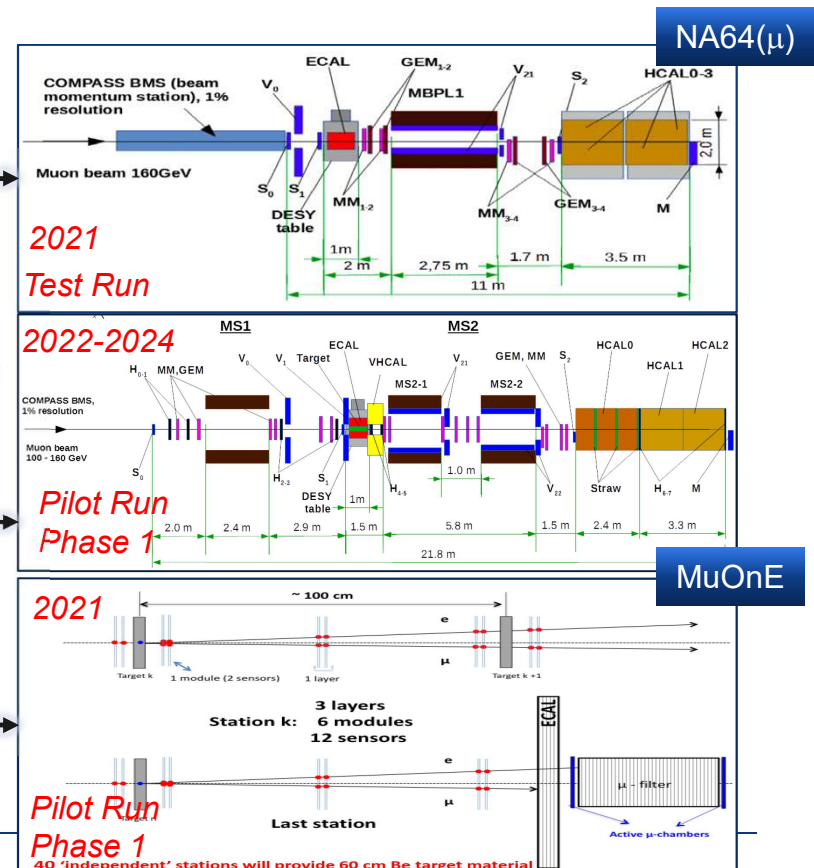
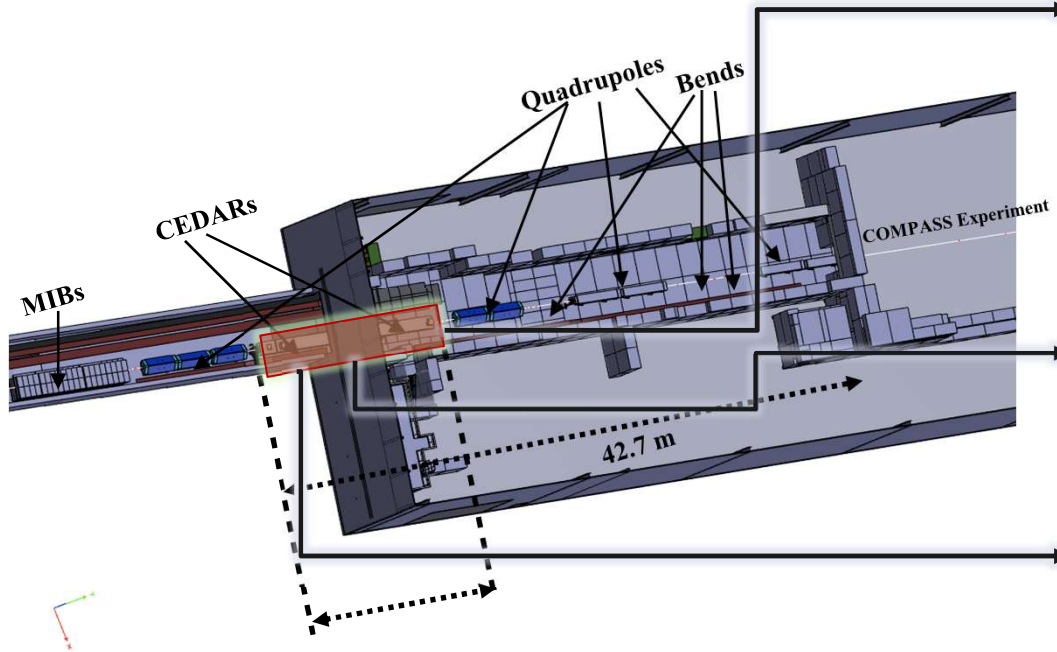
EHN₂ (1)

Experiment	Physics	Requirements	Deadline
NA64++ (μ)	Search for A'	Run NA64-like experiment with muons in M2 (100-150 GeV/c) Setup \approx 15 - 20 m long (phase 1)	Short term (Phase 1: 2021) Mid term (Phase 2: 2023)
MuOnE	μe elastic scattering ($g_{\mu}-2$)	Implement experiment in M2 beam with 150 GeV/c muons Setup \approx 40 m long	Short term (2021)
COMPASS++/ AMBER	QCD & spectroscopy	New requests with upgraded COMPASS spectrometer. Currently 55 m long setup	Short and mid term (2021-2023)
COMPASS++/ AMBER		RF-separated beams	Long term ($>$ 2024)

EHN2 (2)

- *Aim:* **Maximize** the physics research **potential** because the M2 beam is unique, by studying **user requirements** on the beam: momentum, intensity, divergence, beam spot size,...
- Optics calculated for each experiment

➔ **Simultaneous operation not possible**



EHN₂ (3)

Experiment	Physics	Requirements	Deadline
NA64++ (μ)	Search for A'	Run NA64-like experiment with muons in M2 (100-160 GeV/c) Setup \approx 15 - 20 m long (phase 1)	Short term (Phase 1: 2021) Mid term (Phase 2: 2025?)
MuOnE	μ e elastic scattering ($g_\mu-2$)	Implement experiment in M2 beam with 150 GeV/c muons Setup \approx 40 m long	Short term (2021)
COMPASS++/ AMBER	QCD & spectroscopy	New requests from COMPASS. Currently 55 m long setup	Short and mid term (2021-2023)
COMPASS++/ AMBER		RF-separated beams	Long term ($>$ 2026)

EHN2: RF-separated beam (1)

- *COMPASS++/AMBER*: new QCD facility* requiring higher content of antiprotons or kaons in the beam

Particle type	Fraction at the target T6
pbar	1.7 %
K ⁻	5.8 %
π ⁻	84.5 %
e ⁻	8.0 %

- K and pbar flux limited by total flux because of radioprotection
- *Solution*: particles separation with the help of radiofrequency

➡ **RF-separated beam technique**



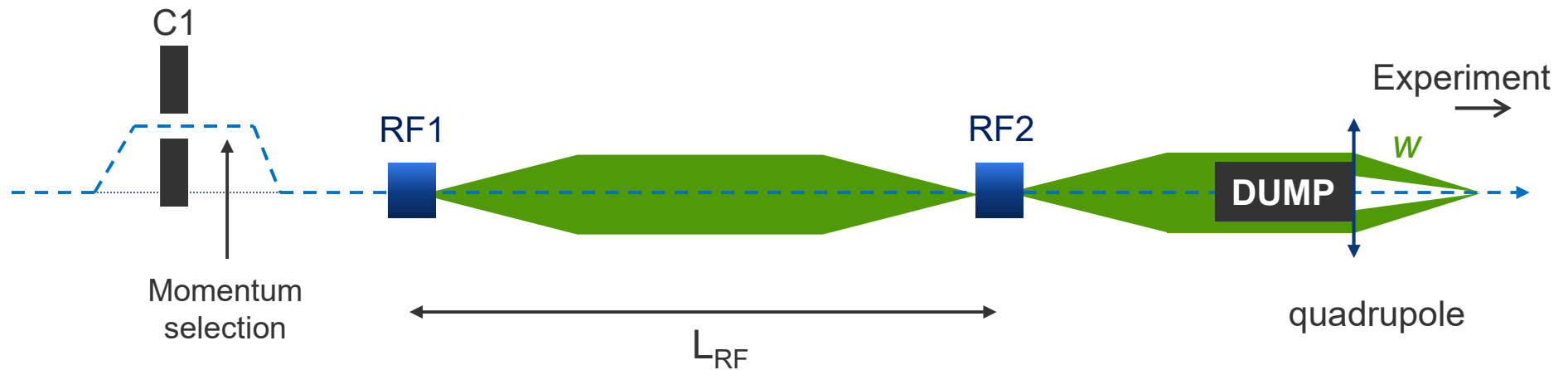
*A New QCD facility at the M2 beam line of the CERN SPS (*COMPASS++/AMBER*) 25

EHN2: RF-separated beam (2)

- *Panofsky-Schnell system (CERN 68-29):*
 - Particle species discrimination: same momentum but different velocities
 - Time-dependent transverse kick by RF cavities in dipole mode
 - RF1 kick compensated or amplified by RF2

$$\Delta\Phi = \frac{2\pi L_{RF} f}{c} \frac{m_u^2 - m_w^2}{2p^2}$$

u: unwanted, w: wanted particles

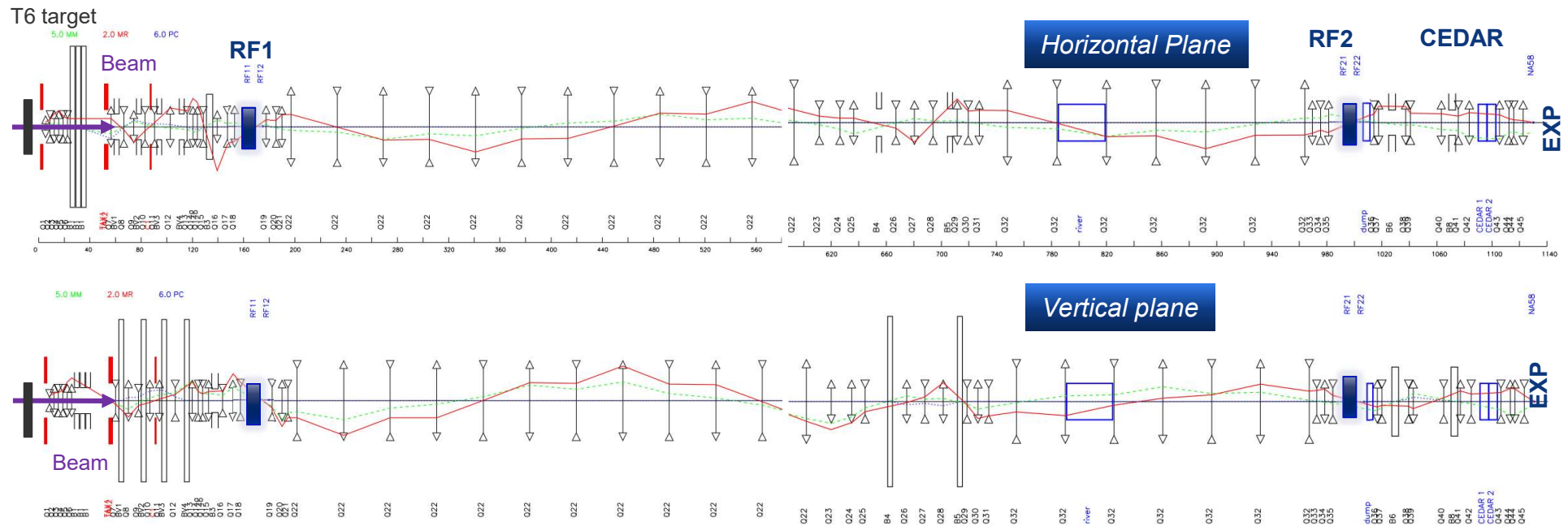


EHN2: RF-separated beam (3)

- *Design challenges:*
 - Tunnel shape
 - Momentum selection not precise enough
 - No space available in the current M2 beam to insert RF cavities
 - No space to insert the dump
 - Focus of the beam at the entrance of RF cavities
 - Focus the desired particles



EHN2: RF-separated beam (4)



- First optics until the COMPASS Target position done with momentum resolution $< 1\%$ dp/p ($\neq 10\%$ acceptance)
 - Beam spot in the cavities optimised
 - Distance between the cavities maximized for first iteration (> 800 m!)
- Studies to evaluate the **feasibility for physics** now starting

➡ **Compromise** between the highest achievable momentum, frequency and acceptance of the RF cavities. Studies for the RF system to be launched.

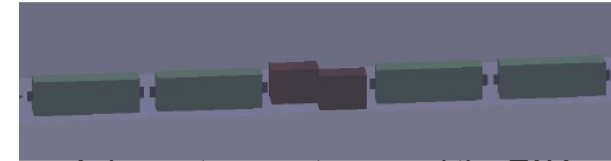
ECN₃



ECN₃ (1)

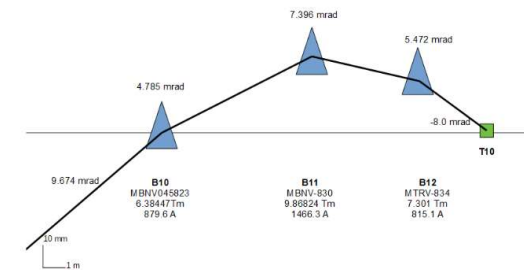
Experiment	Physics	Requirements
NA62++ (BD)	Search of HNL, axions	Optimise conditions for NA62 in beam dump mode
KLEVER	Study beam delivery for $K_L \rightarrow \pi^0 \nu \nu$	Run at very high proton flux
DIRAC++	$\pi\pi$, $K\pi$ atoms	Implement options for DIRAC at SPS
NA60++	Open charm in PbPb	Implement options for NA60 at SPS

ECN₃ (2)

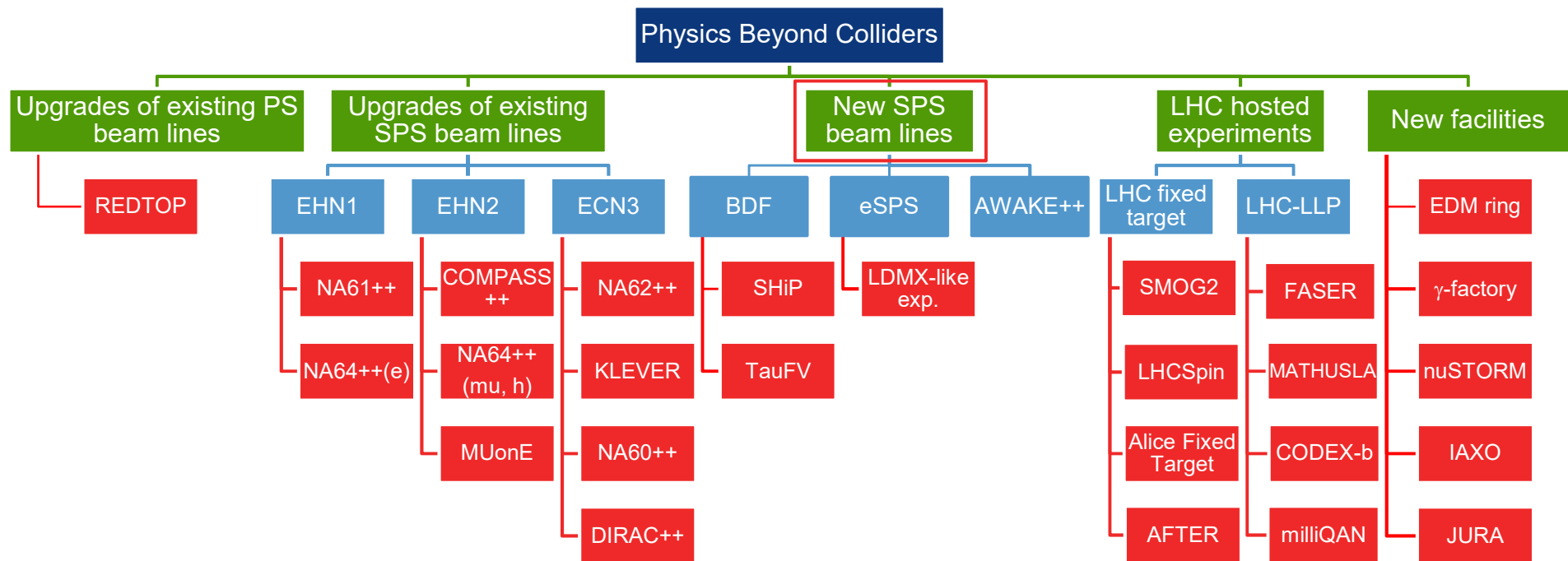


Achromat magnets around the TAX

- **NA62++:**
 - *Aim:* Identify dark sector particles
 - *Idea:* transfer full proton intensity on TAX with T10 target out and reduce rate of produced pions and kaons decaying to muons
 - ➡ **Dark sector particles** produced in TAX
 - Minimisation of background muons mandatory: detailed muon sweeping studies completed
 - **Reduction** of muon background by a **factor 4** by re-cabling of achromat dipoles
 - *Alternative:* installation of a new beam dump downstream
- **KLEVER:**
 - *Aim:* measurement of the BR of the very rare decay $K_L \rightarrow \pi^0 \nu \nu$ (SM prediction $\sim 3 \cdot 10^{-11}$).
 - Modification and optimization of the proton beam transport in P42 beam line to the T10 target, with production angle increased from 2.4 to 8 mrad
 - **Redesign** of the neutral K12 beam



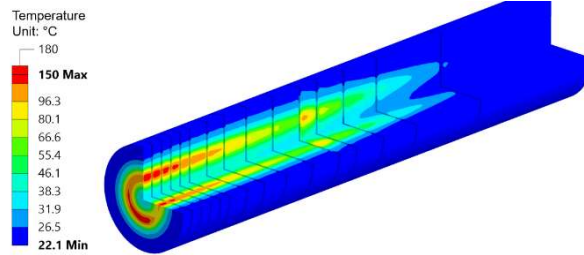
Physics Beyond Colliders (PBC)



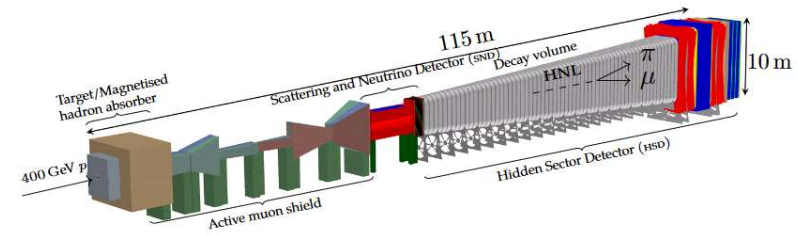
New SPS beam lines (1)

BDF: Beam Dump Facility

- New fixed target facility integrated in the North Area for beam dump experiments
- Target whose aim is to fully absorb the 400 GeV/c SPS proton beam (length: 1.5 m!)
 - $4 \cdot 10^{19}$ PoT/year
 - Beam power: 355 kW
- 350 m long new beam line
- First user: SHiP experiment (see next slide)
- Estimated cost of the facility: 160 MCHF
- Comprehensive Design Study published and project under evaluation!
- Possible to run > 10 years from now

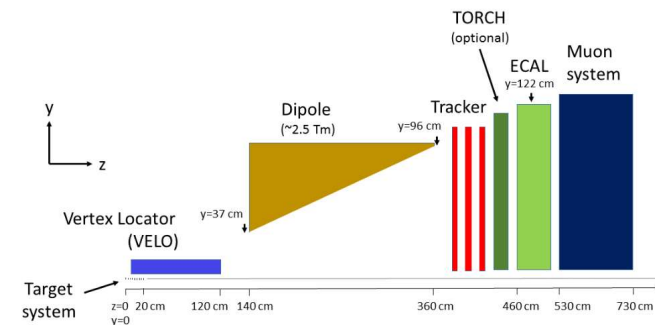


New SPS beam lines (2)



SHiP: Search for Hidden Particles, i.e. very weakly long interacting particles

- Targeted physics: HNL and light supersymmetric particles, new physics in the MeV-GeV region
- Detector: large vacuum decay vessel followed by a high precision tracker spectrometer
- Estimated cost: 60 MCHF
- Construction and installation after LS3 (2025?)



TauFV: Tau Flavour Violation

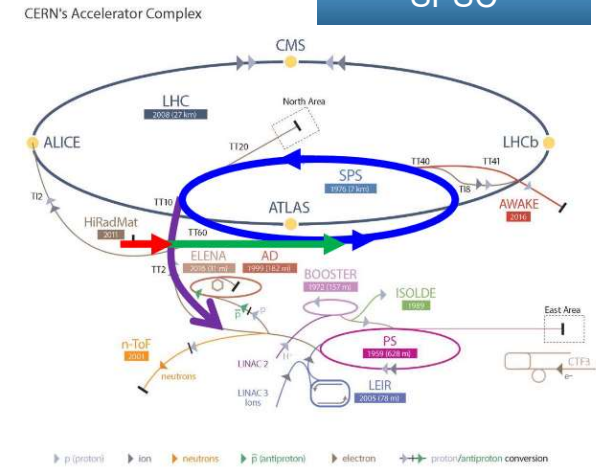
- Search for τ -rare decays ($\tau \rightarrow \mu\mu\mu$ and others)
- Detector (equivalent to LHCb) placed upstream of SHiP: vertex locator followed by a dipole, high precision trackers and calorimeters
- Possible add-on with minimum modification of the BDF project (takes 2% of the beam delivered to the BDF target)

New SPS beam lines (3)

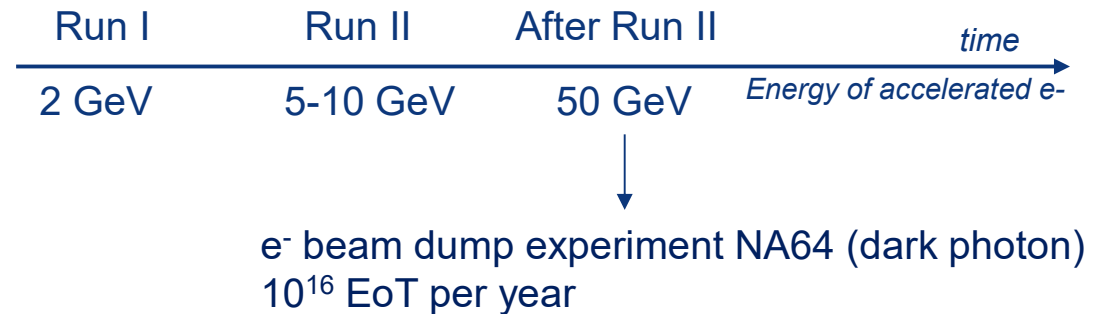
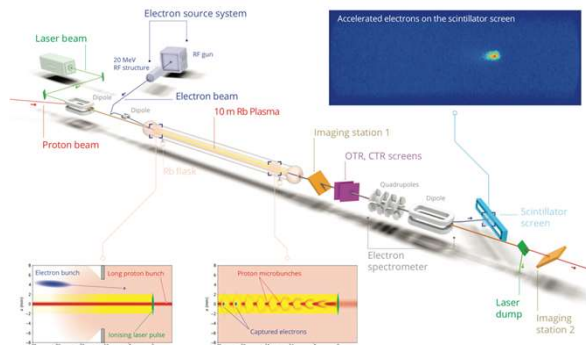
Submitted to SPSC

eSPS: New high intensity primary electron beam facility

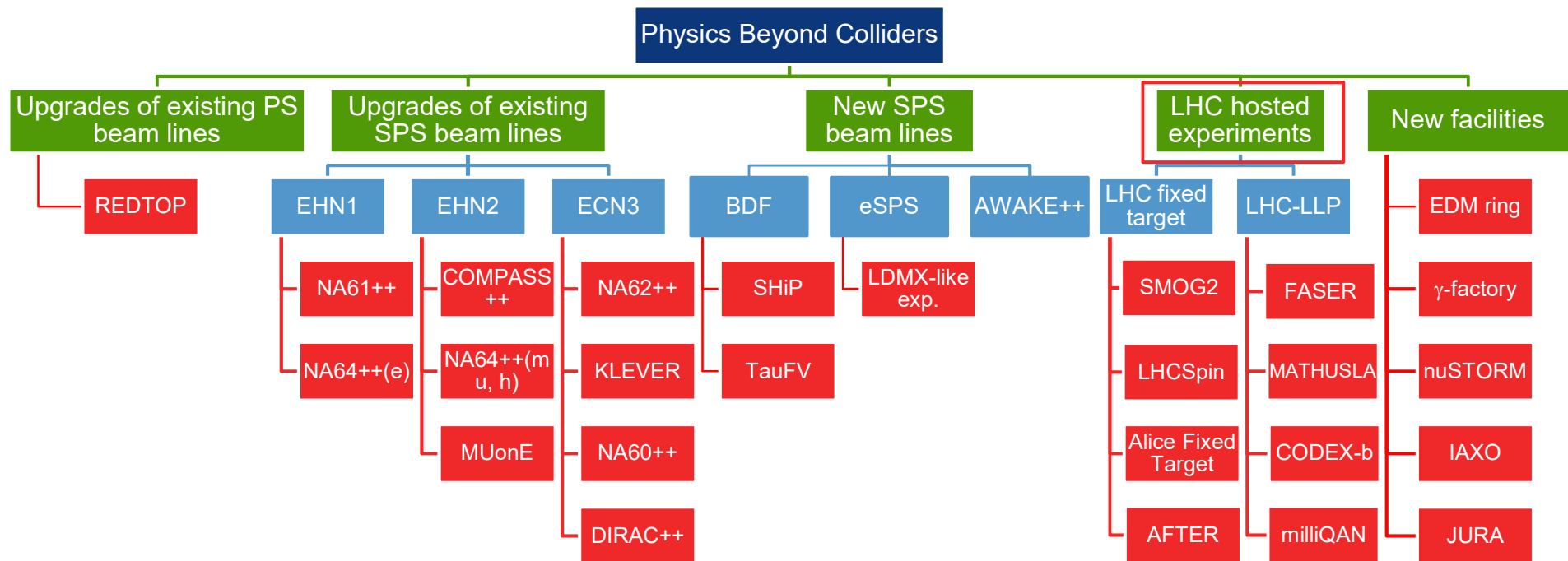
- Electrons accelerated to 16 GeV:
 - ≈ 70 m long linac (electrons accelerated to 3.5 GeV)
 - Transfer to SPS and fill in 1-2 s
 - Acceleration of electrons to 16 GeV
 - Slow extraction in 10 s and delivery of the beam on the Meyrin site
- Estimated cost: 80 MCHF
- Construction could be executed within the 5 years
- LDMX-like experiment would benefit from it! (Hidden sector in the invisible decay channels)



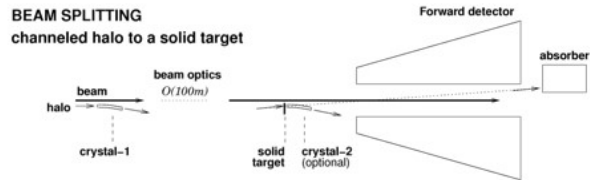
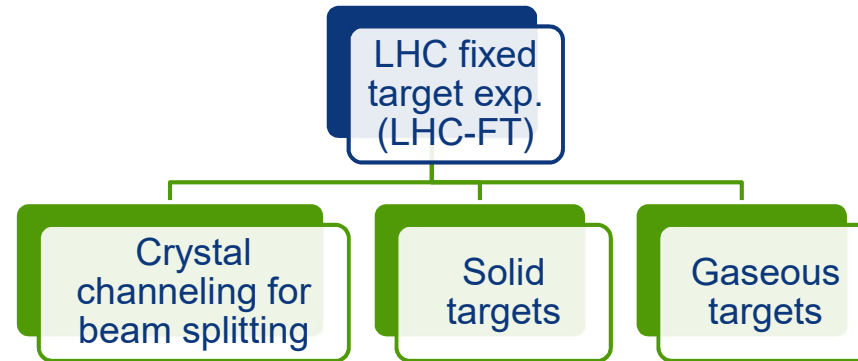
AWAKE++: Advanced Proton Driven Plasma Wakefield Acceleration Experiment



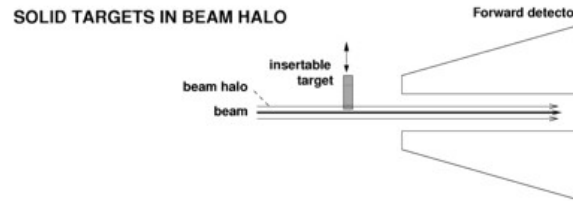
Physics Beyond Colliders (PBC)



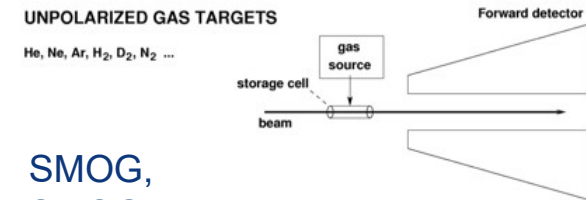
LHC hosted experiments (1)



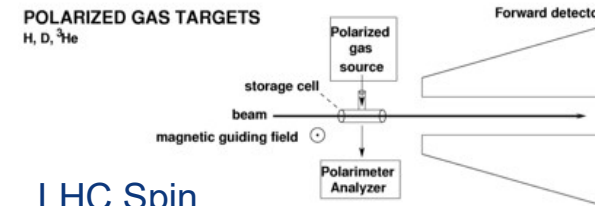
Alice FT



Not possible because of machine protection issues



SMOG, SMOG2, LHCb



LHC Spin

Physics motivation: precise hadron and heavy ion measurements (QCD)

Main issue: possible interference with LHC physics (collider mode)

Costs: small compared to those of LHC upgrades

LHC hosted experiments (2)

Physics motivation: Search for new particles produced in LHC collisions with a too long lifetime or a too small electric charge to be detected in the main detectors

MATHUSLA (search for neutral LLPs)

- 200x200x20 m³ « box » containing a 5 m thick tracker, located at the surface of CMS or ATLAS
- Cost: < 100 MCHF

milliQAN (search for particles with very small electric charge)

- Link between SM and hidden sector
- 1x1x3 m³ plastic scintillator array to detect small ionisation

CODEX-b (search for wide range of LLPs)

- Modest size of the detector (10x10x10 m³)

FASER (search for light, weakly interacting particles + study interaction of HE neutrinos)

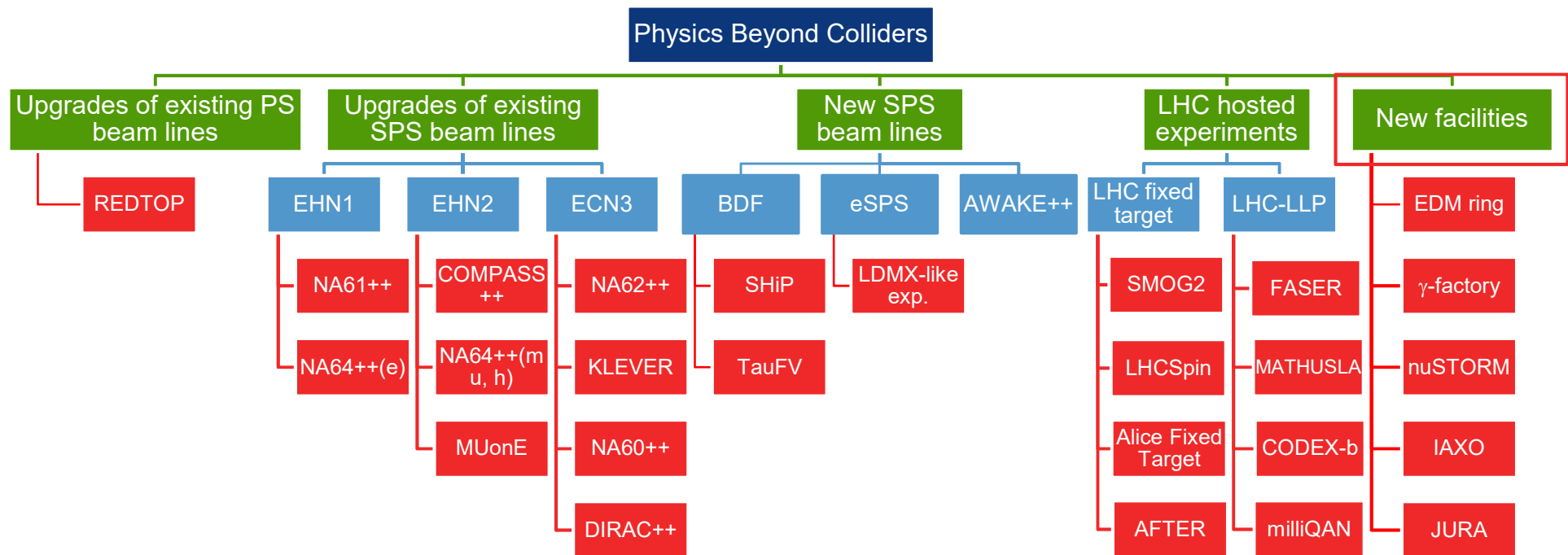
Small detector located along the beam axis, 480 m from the collision point

- 2 phases: (1) taking data in 2021, (2) larger detector



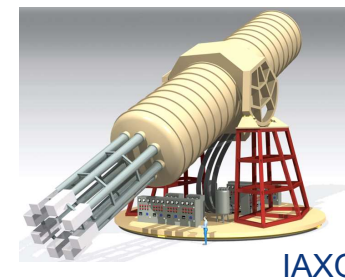
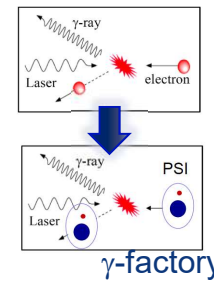
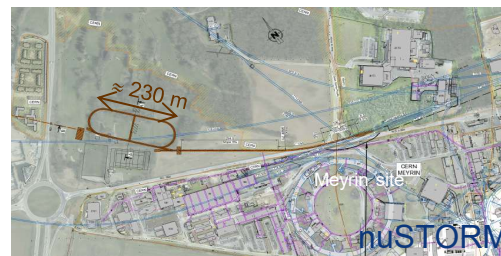
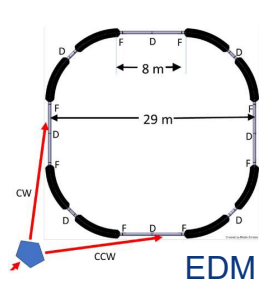
Approved!

Physics Beyond Colliders (PBC)



New facilities

Facility	Type	Physics motivation	Primary beam	Status	Possible location
EDM (Electric Dipole Moment)	Storage ring of ~ 100 m long circumference	CP violation	Polarized protons	Feasibility	COSY site at Juelich (Germany)
nuSTORM (NeUtrinos from STORed Muons)	Low-energy muon decay ring	CP violation Sterile neutrino search	100 GeV protons	Feasibility	SPS, CERN
γ -Factory	High-energy (400 MeV) ring of γ -rays	QCD measurements	Partially Stripped ions (ions with 1 e-)	Feasibility	LHC, CERN
IAXO (International Axion Observatory)	4 th generation axion helioscope	BSM	Axions from the Sun		DESY (babyIAXO)

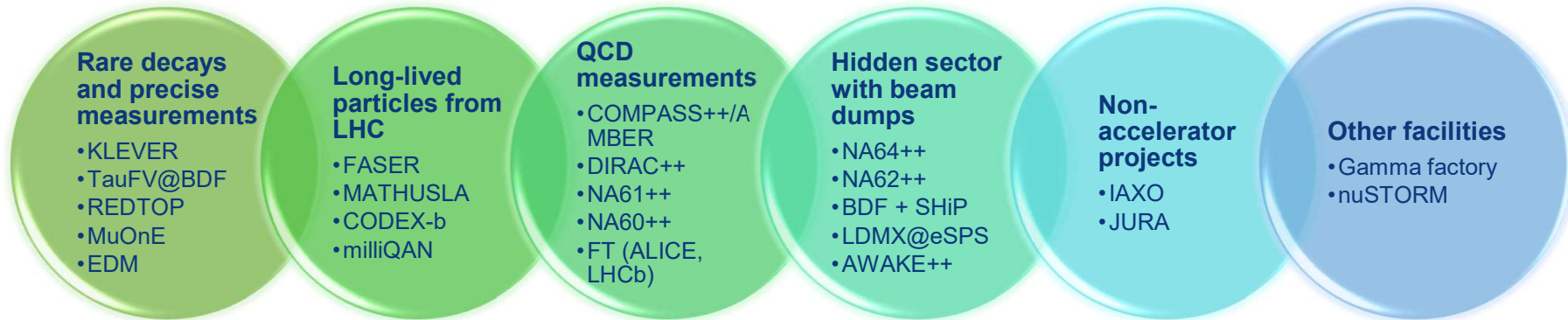


Conclusions and Outlook of the CBWG

- *Aims of the Conventional Beam Working Group:*
 - Provide feasibility studies in the framework of the **Physics Beyond Colliders** programme
 - Give **scientific results** and **cost estimates** of more than 10 studies
- *Studies:*
 - Numerous **simulation** tools (Fortran-based programs, Geant4, G4BL, FLUKA, BDSIM) used by a **team of 10 physicists (EN-EA-LE)**
 - Evaluation by the **SPSC**, providing results by CBWG
 - **Deadline:** short-term (after LS2, 2021) to long-term (up to 2040)
 - First proposals (NA61, AMBER) have been approved and will run with beam this year!
 - **Basis** of 3D integration, tests preparation, civil engineering checks
 - Need to **continue**, especially for the RF-separated beam in M2
 - Work in synergy with **other groups** of CERN

General conclusions and outlook

- *New physics without new colliders at CERN:*



- *Mandate:* explore **unique opportunities** offered by the **CERN** accelerator complex to address outstanding **questions in particle physics** through projects (intensity frontier)
 - Complementary to high-energy colliders (HL-LHC, CLIC, FCC)
 - There is new physics, we don't know where it is
 - Need to be as broad as possible in the exploratory approach!
 - Complementary to other efforts in the world
 - Optimise the resources of the discipline, create synergies with other labs

Documentation

- Physics Beyond Colliders website: <https://pbc.web.cern.ch/>
- Summary report of PBC at CERN: [Summary report](#)

- CBWG full report: [CBWG report](#)

140 pages !

- CBWG executive summary: [CBWG summary](#)

Discussed at ESPP



Summary Report of Physics Beyond Colliders at CERN

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Studies of the conventional beams working group within the physics beyond colliders framework at CERN

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ABSTRACT

An exploratory study has been launched at CERN in 2016 aiming at exploiting the full scientific potential of CERN's conventional beams and its versatile infrastructure through projects complementary to the LHC, HL-LHC and other possible future colliders. These projects will address possible experiments over the period from 2022 to about 2030. The role of the Conventional Beams Working Group (CBWG) is to study the technical feasibility of a

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Physics Beyond Colliders

PBC CONVENTIONAL BEAMS

Executive summary

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Abstract:

Studies for New Experiments at the CERN M2 Beamline within "Physics Beyond Colliders": AMBER/COMPASS++, NA64μ, MuonE

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Abstract: The "Physics Beyond Colliders (PBC)" study explores fundamental physics opportunities at the CERN accelerator complex complementary to collider experiments. Three new collaborations aim to exploit the M2 beamline in the North Area with existing high-intensity muon and hadron beams, but also aspects go beyond the current M2 capabilities with RF-separated, high-precision hadron beams, under study. The AMBER/COMPASS++ collaboration proposes an ambitious program with a measurement of the proton radius, with muon beams, as well as QCD-related studies from pion PER / Deut-Yan cross section measurements for dark sector searches. Assuming feasibility of the RF-separated beams, the spectrum of strange mesons would enter a high precision on-site kaon PDG as well as neutron TMDs would be accessible via Deut-Yan reactions. The NA64μ collaboration proposes to search for dark sector mediators such as a dark scalar A' or hypothetical Z_d using the M2 muon beam and complementing their on-going A' searches with electron beams. The MuonE collaboration intends to assess the hadronic component of the muon beam. This document provides a high-level overview of the three experimental areas (EIN2).

PROCEEDINGS OF SCIENCE

Search for Dark Sector Physics at the NA64 experiment in the context of the Physics Beyond Colliders Project

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The NA64 electron beam program consists of high sensitivity searches for visible and invisible

THE K12 BEAMLINE FOR THE KLEVER EXPERIMENT

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Abstract

The KLEVER experiment is proposed to run in the CERN conventional beams from 2026 onward. The goal of the experiment is to measure $BR(K^+ \rightarrow \pi^0 \nu \bar{\nu})$, which could yield information about potential new physics. It is studied in combination with the measurement of $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ of NA62. A full description will be given of the considerations in designing the new K12 beamline for KLEVER, as obtained from a purpose-made simulation with FLUKA. The high intensities required by KLEVER, 2×10^{10} protons on target every 16.8 ns, with 5×10^9 protons accumulated over 5 years, place stringent demands on adequate muon sweeping to minimize backgrounds in the detector. The target and primary dump need to be able to survive these demanding conditions, while respecting strict radiation protection criteria. A series of design choices will be shown to lead to a neutral beamline efficiently capable of suppressing relevant backgrounds, such as photons generated by π^0 decays in the target, and $A' \rightarrow \pi^0 \nu \bar{\nu}$ decays, which mimic the signal decay.

Figure 1: SM prediction for $BR(K^+ \rightarrow \pi^0 \nu \bar{\nu})$ with new physics scenarios overlaid. From left to right: model with minimal flavor violation (green), model with flavor violating interactions which left-handed or right-handed couplings dominate (blue) and more general models (e.g. Randall-Sundrum, red).

INTRODUCTION

The measurement of the branching ratio $BR(K^+ \rightarrow \pi^0 \nu \bar{\nu})$ offers exciting prospects for testing potential models for new physics [1]. The KLEVER experiment would be the unique in CERN kaon program, following the NA49, NA62 and NA62 experiments. This paper will briefly lay out the physics case for KLEVER, and then focus on the challenges the proposed measurement poses for the adaptation required in the K12 beamline.

MOTIVATION

The measurement of the branching ratio $BR(K^+ \rightarrow \pi^0 \nu \bar{\nu})$ offers exciting prospects for testing potential models for new physics [1]. The KLEVER experiment would be the unique in CERN kaon program, following the NA49, NA62 and NA62 experiments. This paper will briefly lay out the physics case for KLEVER, and then focus on the challenges the proposed measurement poses for the adaptation required in the K12 beamline.

MUON BACKGROUND STUDIES FOR BEAM DUMP OPERATION OF THE K12 BEAM LINE AT CERN

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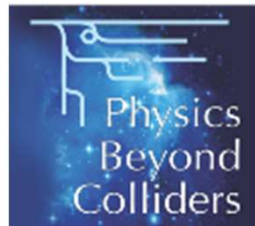
Abstract

In the scope of the Physics Beyond Colliders study at CERN a future operation of the NA62 experiment in beam dump mode is discussed, enabling the search for dark sector particles, e.g. heavy neutral leptons, dark photons and axions. For this purpose, the 400 GeV/c primary proton beam, extracted from the SPS, will be dumped on a massive dump collimator located in the front end of the K12 beam line. Muons originating from interactions and decays form a potential background for this kind of experiment. To reduce this background, the optimization of the magnetic sweeping along the K12 beam line is performed. Monte Carlo studies based on the program G4beamline [4] have been combined with analytical parametrizations of the muon distributions to reduce the computational demands. In this contribution, benchmarking results with simulated data as well as first results from the optimization studies are shown.

THE K12 BEAM LINE MODEL

The simulation of production and transport of the muon background is computationally highly expensive and requires the precise knowledge of the magnetic field map





Thank you for your attention!