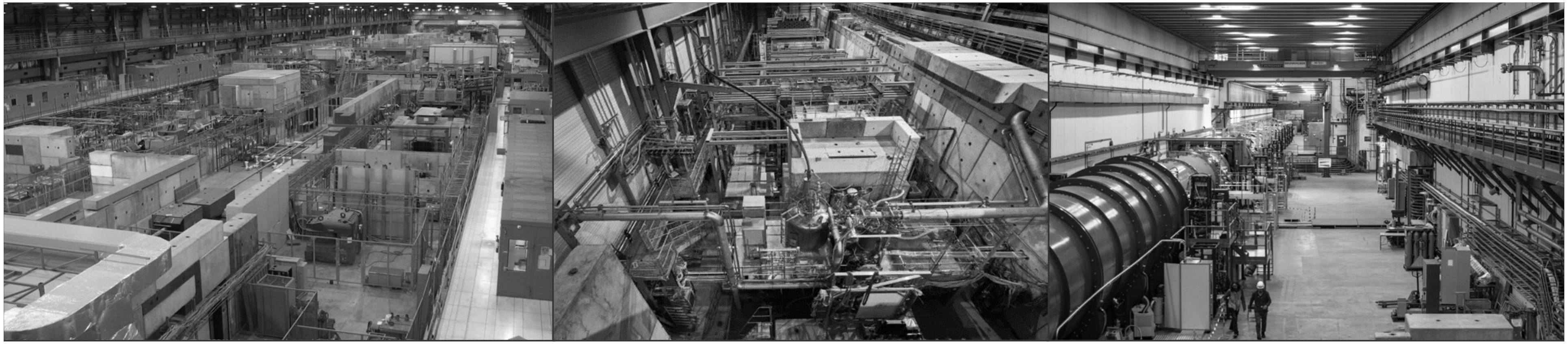

Physics Beyond Colliders at CERN:
New discoveries aside of new supercolliders?

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On behalf of CERN BE-EA-LE

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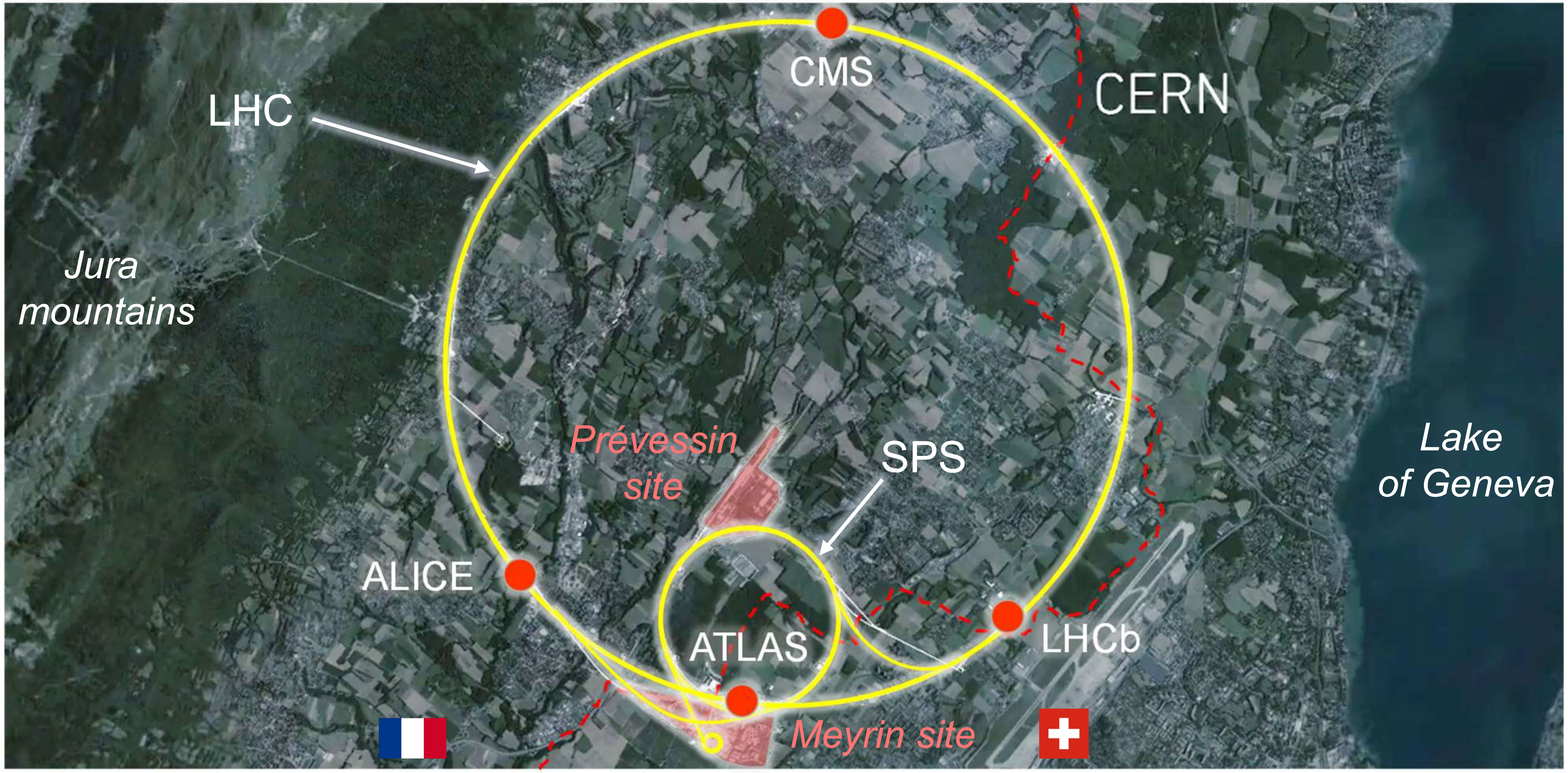
CERN: Organisation Européenne pour la Recherche Nucléaire

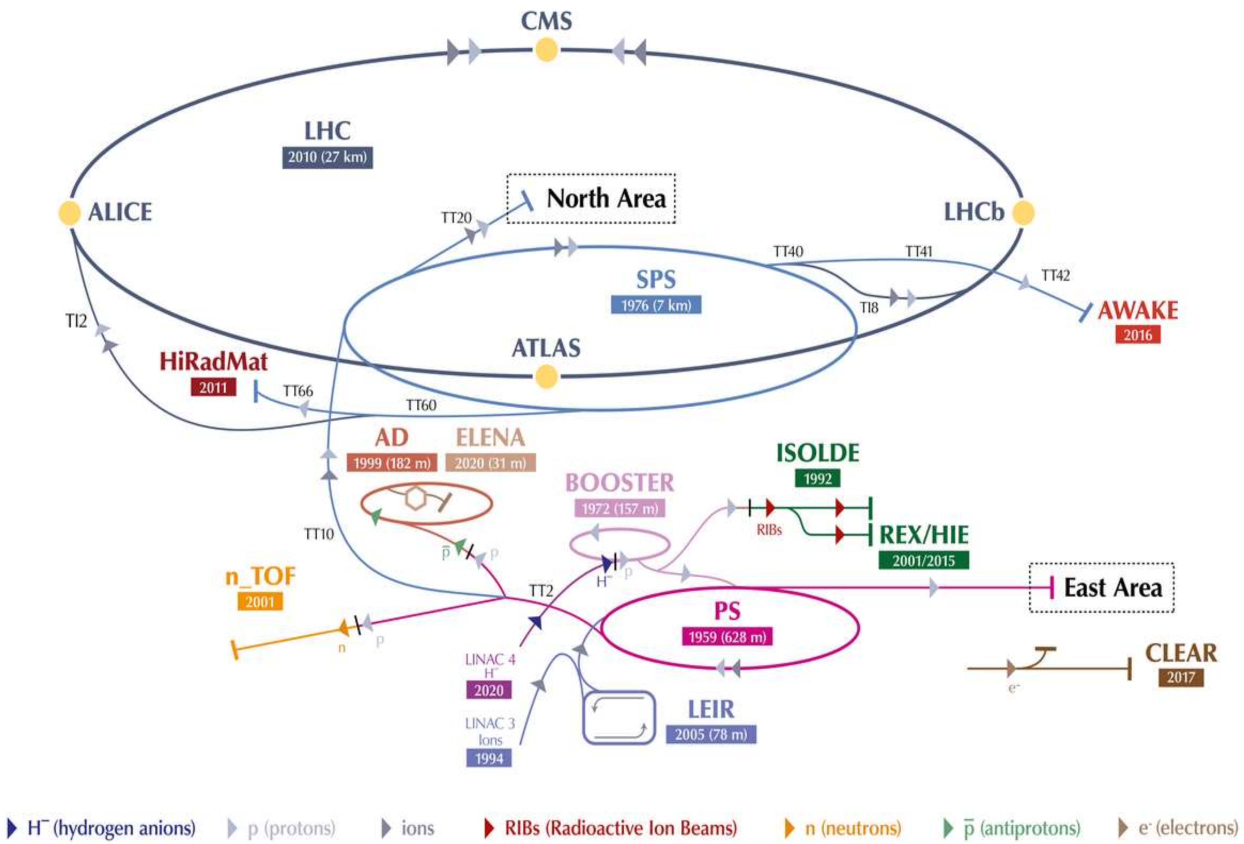
- World's largest Particle Physics Laboratory (1954)
- 23 Member States (+ 6 Associate)
- Yearly budget ≈ 1200 MCHF

- *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


CMS
LHC
CERN
Jura
mountains
Prévessin
site
SPS
Lake
of Geneva
ALICE
ATLAS
LHCb
Meyrin site

The CERN accelerator complex



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

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)

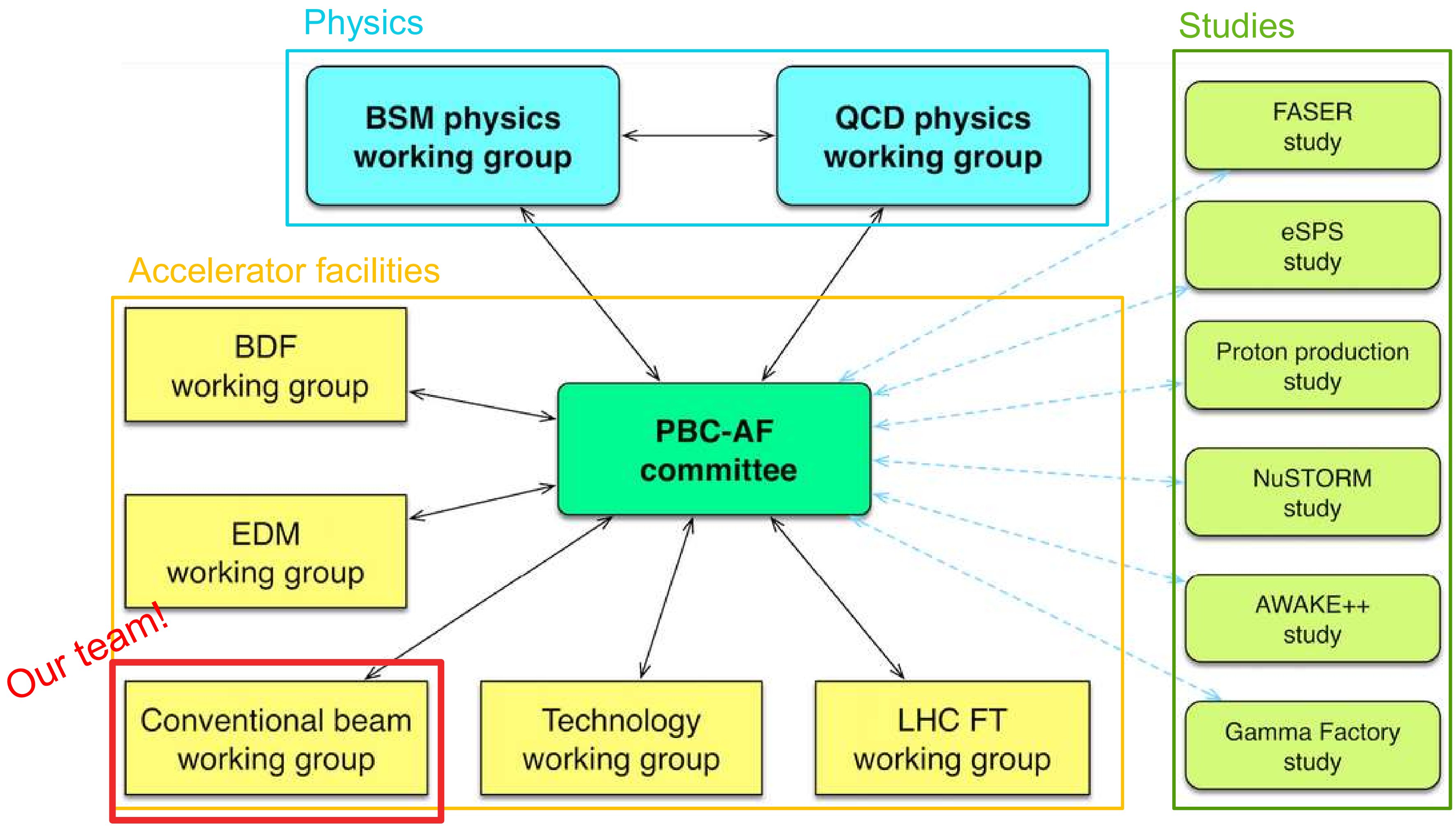
Content

- 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)

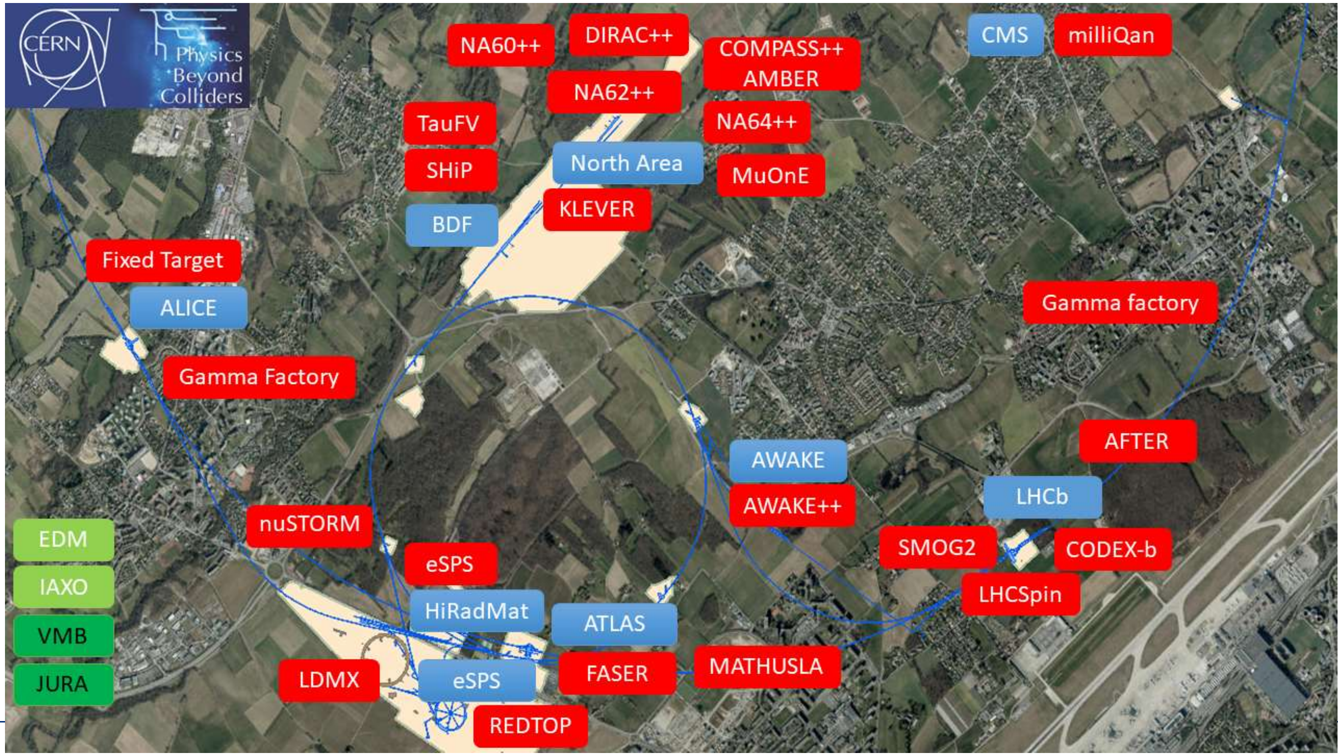


Physics Beyond Colliders (PBC) (2)

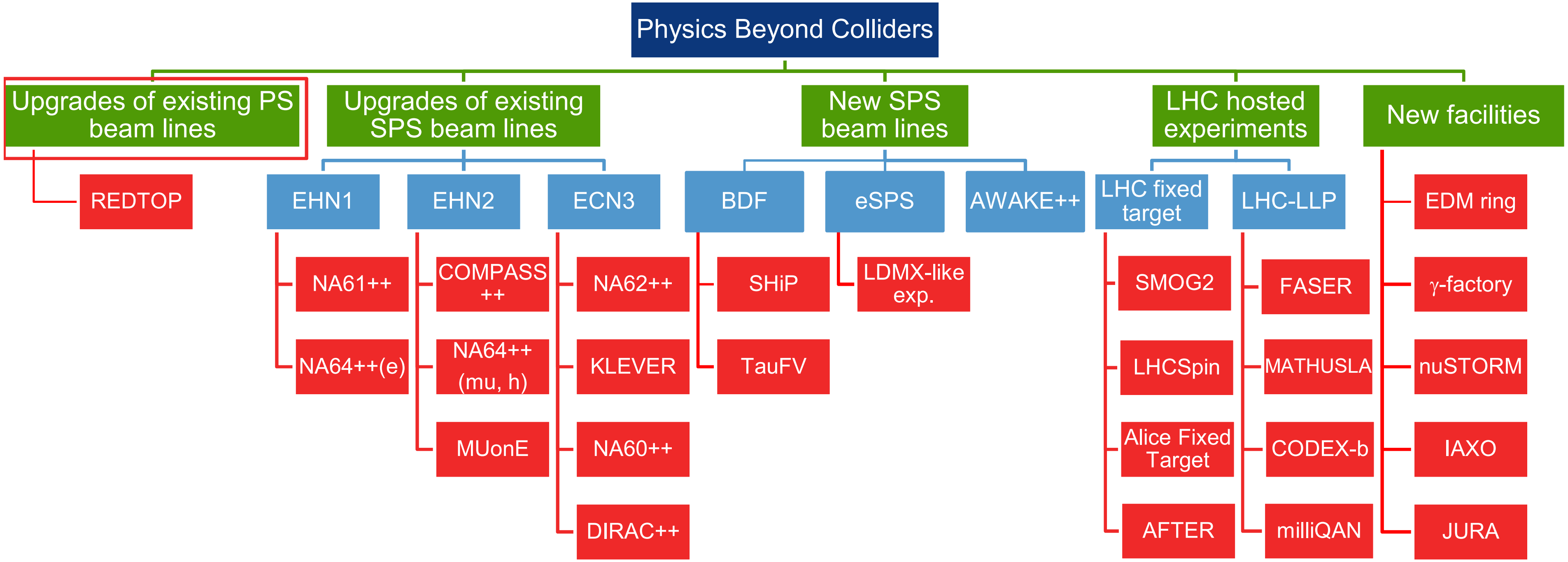
PBC

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)



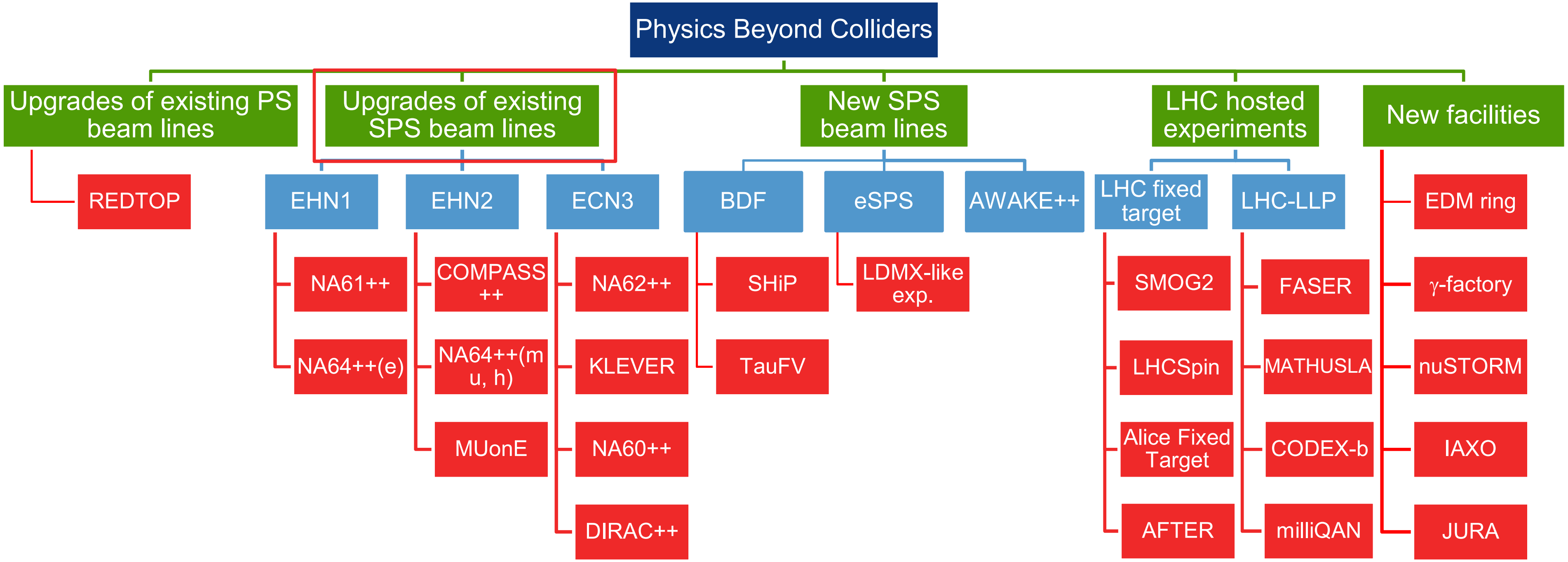
Upgrades of existing PS beam lines

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)

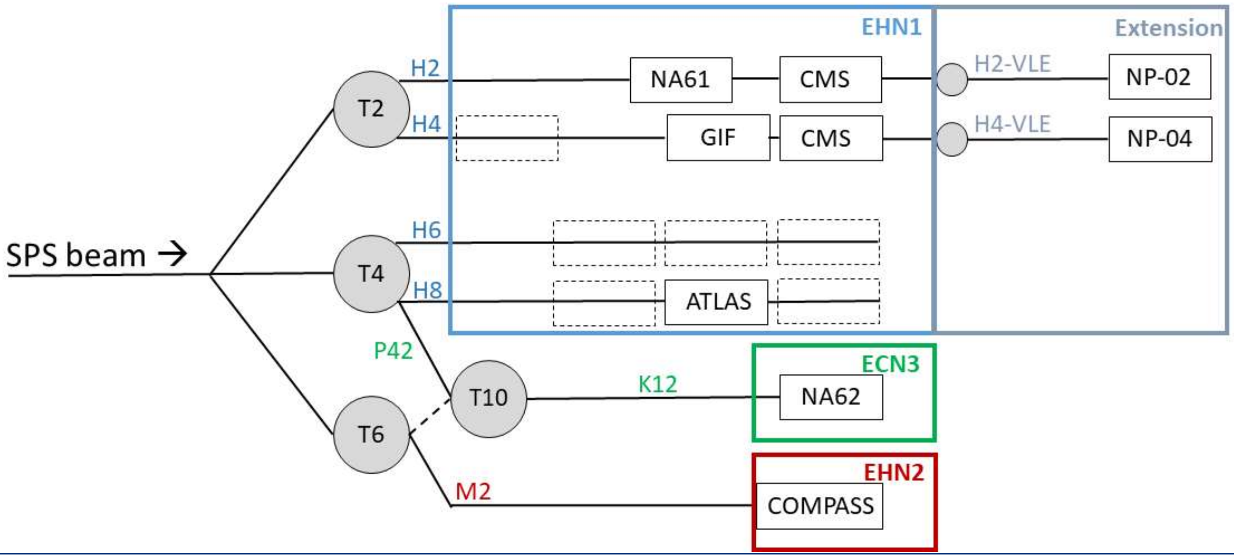


North Area current beam lines

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

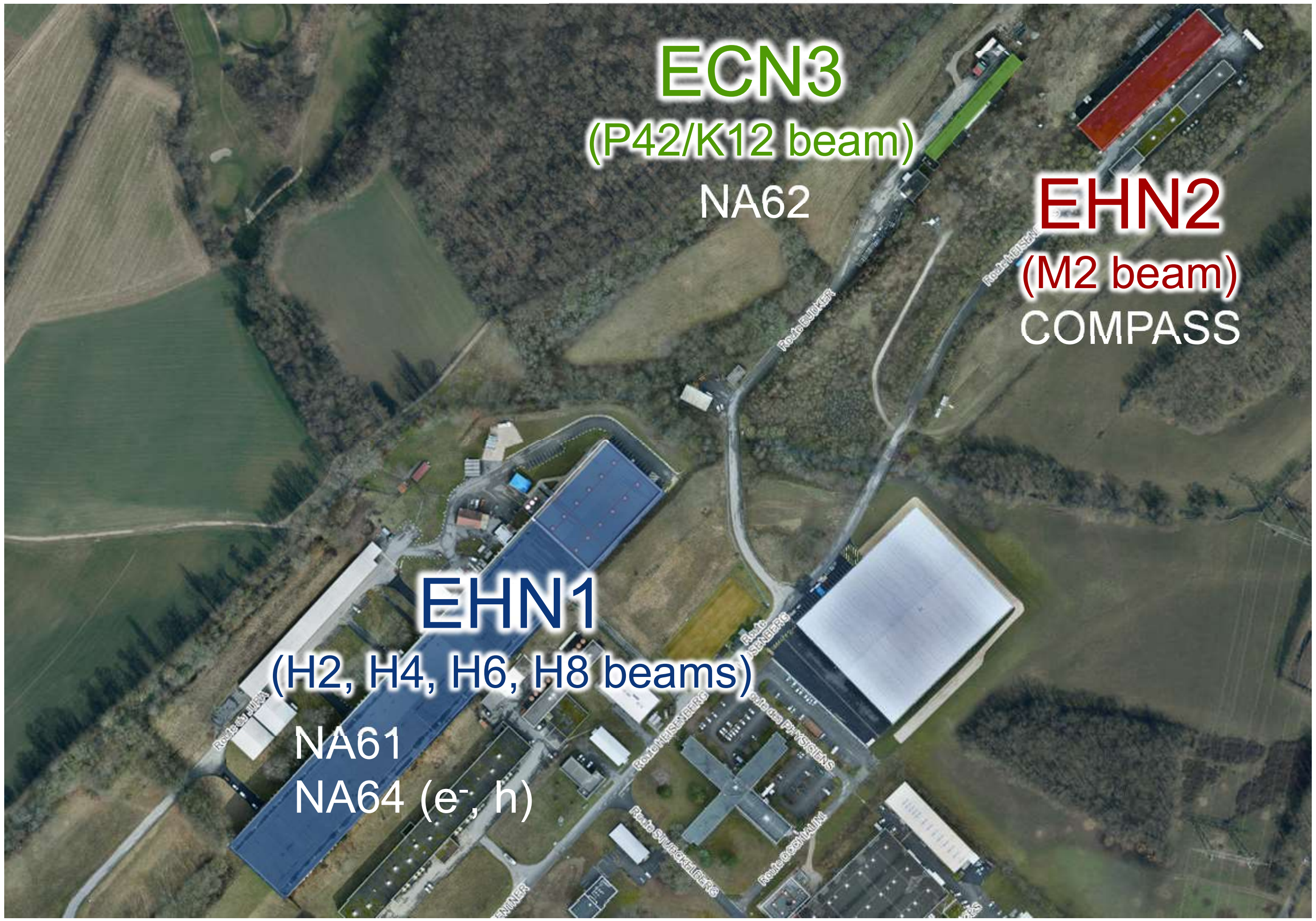
- Principle taken from cosmic radiation
- Particles are produced in a large momentum range

SPS beam

Position	Material	Length (mm)	Height (mm)	Width (mm)
0	*Air/OUT*	-	-	-
1	Be	500	2	160
2	Be	300	2	160
3	Be	180	2	160
4	Be	100	2	160
5	Be	40	2	160
5x plates, 40 mm inter-plate distance				

North Area

North Area : EHN1, EHN2 and ECN3 halls



Physics Beyond Colliders studies in North Area

PBC studies: fixed-target experimental proposals

EHN1

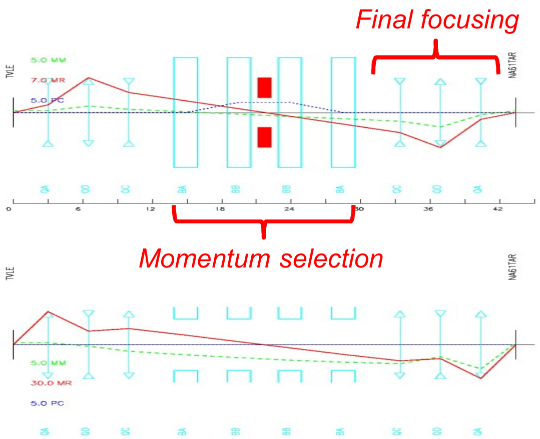
EHN1 (1)

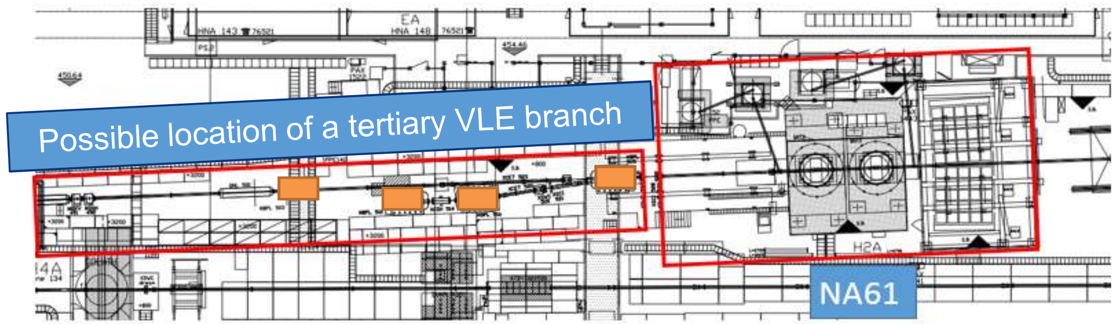
Experiment	Physics	Requirements	Deadline
NA61++	Heavy ion experiment	• Run NA61 at higher intensity and with better machine protection • Study the possibility to have a local low energy hadron beam	• Short-term • Mid-term?

- Improved shielding, which will allow **higher ion intensities:**

  10^6 ions/spill in 2021 ≠ 10^5 ions/spill (≤ 2018)

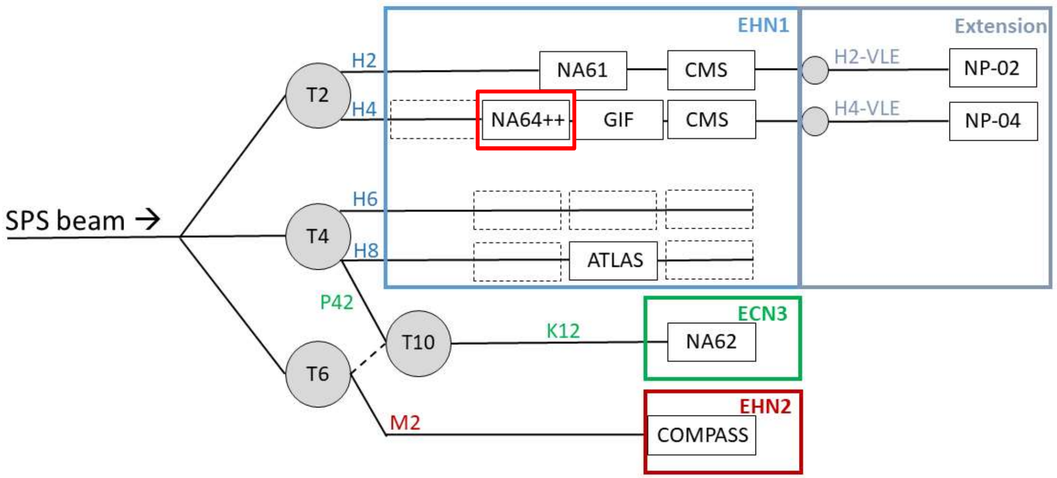
- Studies on a **Very Low Energy beam** (<30 GeV/c hadrons/protons) ongoing

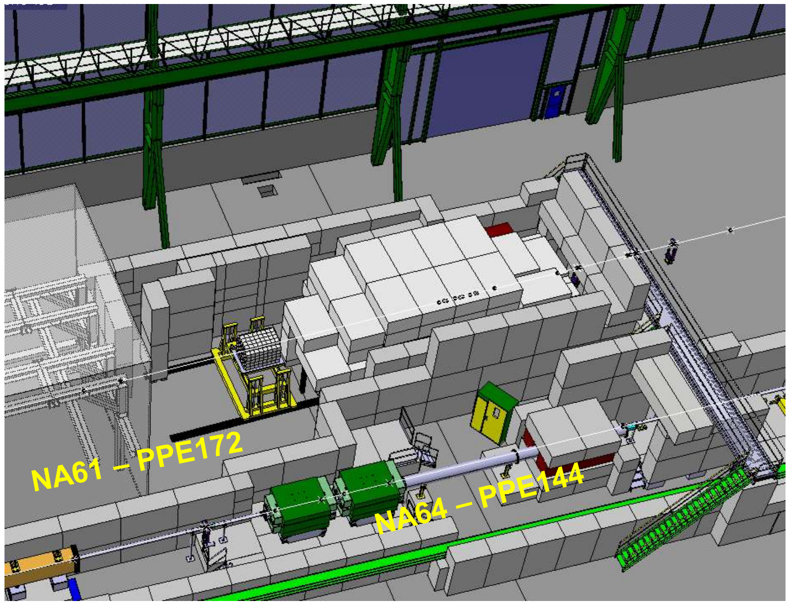




EHN1 (2)

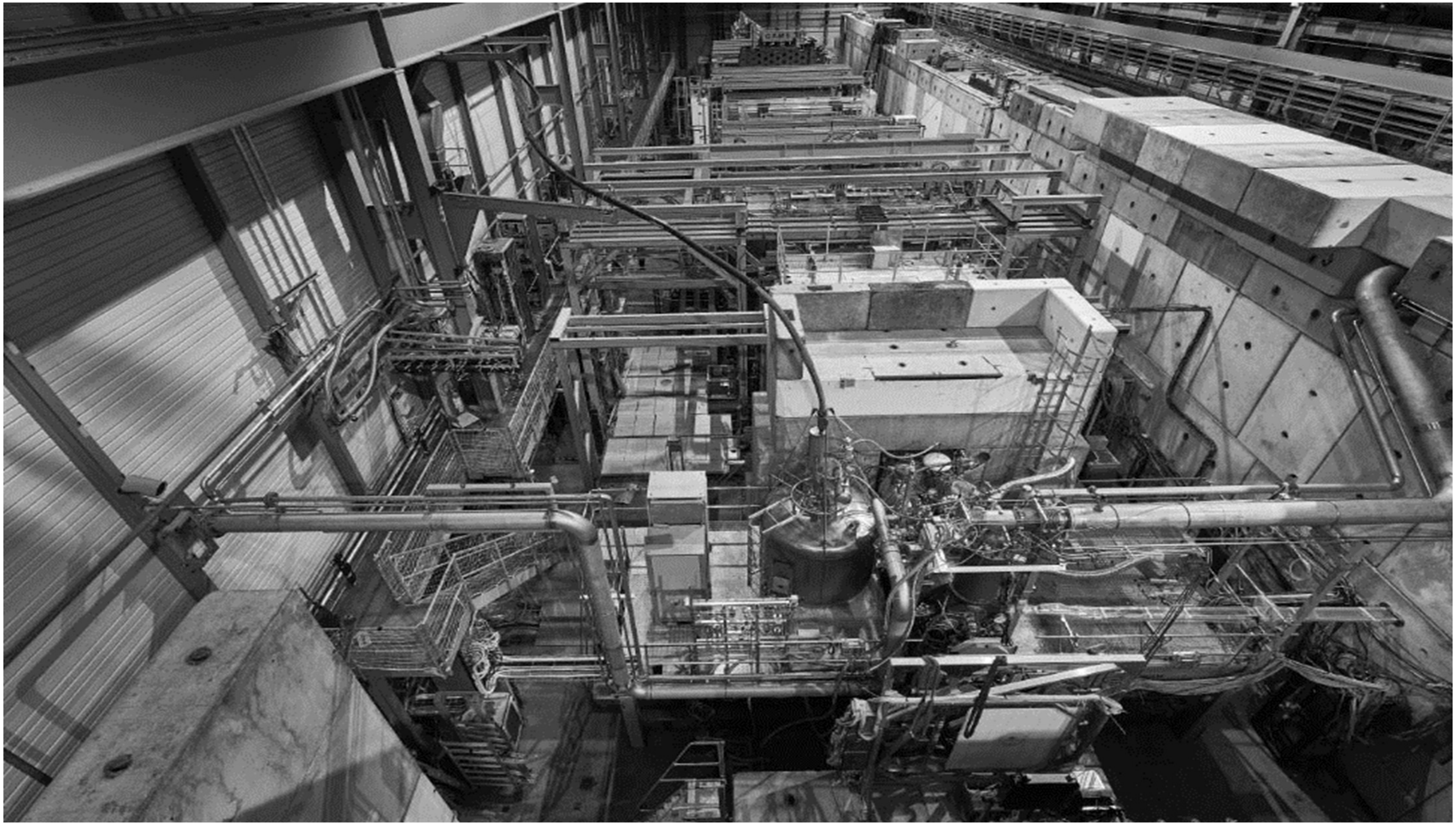
Experiment	Physics	Requirements	Deadline
NA64++	Search for A'	Increase electron flux and optimise hadron beams in H4	Short term (2021)





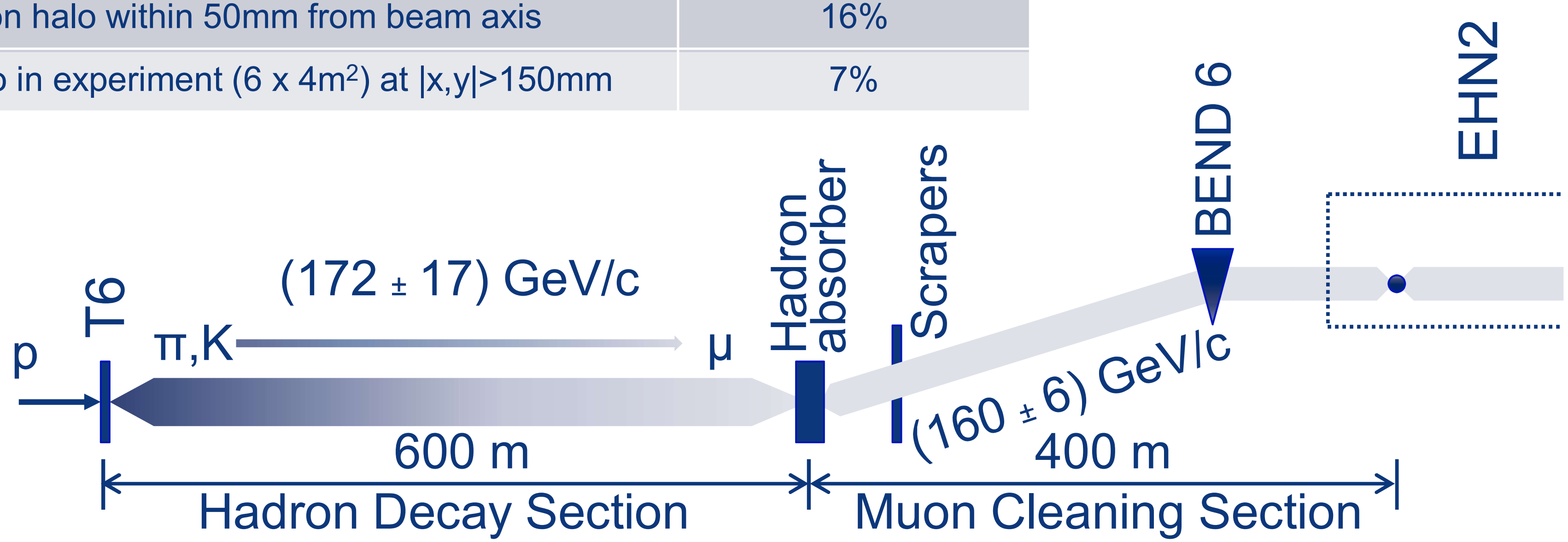
➡ New area with NA64 as first user

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	$1.5\ 10^{13}$
Muon flux at COMPASS per SPS cycle	$2.5\ 10^{8}$
Beam polarisation	-80% ± 4%
Spot size at COMPASS target (σ_x x σ_y)	8mm x 8mm
Divergence at COMPASS target (σ_{dx} x σ_{dy})	0.4mrad x 0.8mrad
Muon halo within 50mm from beam axis	16%
Halo in experiment (6 x 4m²) at |x,y|>150mm	7%



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	~10^8 2.5 10^8	3%	8 x 8 mm	80%	IN 10^{-5} impurity
Hadrons	+190 -190 Max. 280	10^8 (RP) 4 10^8 (with dedicated dump)	_	5 x 5 mm	_	OUT
Electrons	-10 to -40	< 2 10^4	_	> 10 x 10 mm	_	OUT

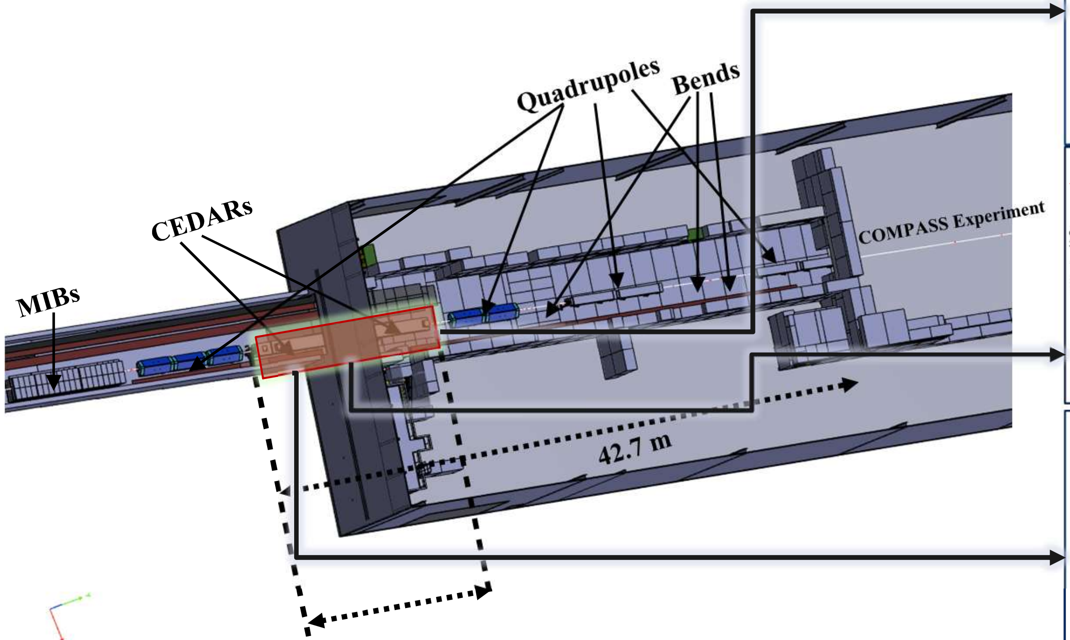
EHN2 (1)

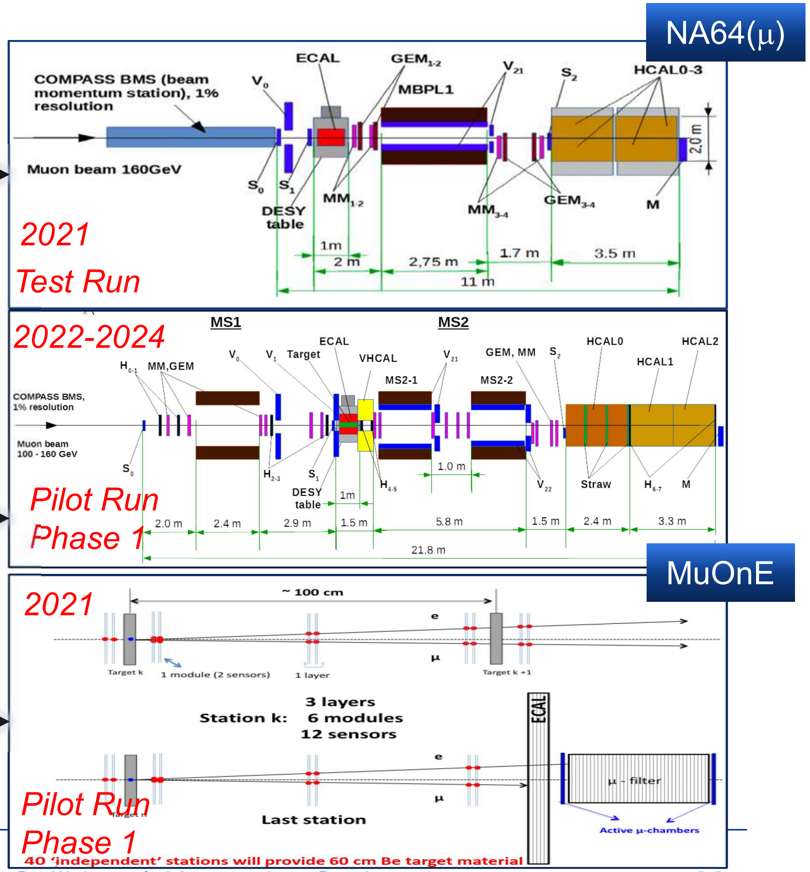
Experiment	Physics	Requirements	Deadline
NA64++ (μ)	Search for A'	Run NA64-like experiment with muons in M2 (100-150 GeV/c) Setup ≈ 15 - 20 m long (phase 1)	Short term (Phase 1: 2021) Mid term (Phase 2: 2023)
MuOnE	μe elastic scattering (g_μ-2)	Implement experiment in M2 beam with 150 GeV/c muons Setup ≈ 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 ≈ 15 - 20 m long (phase 1)	Short term (Phase 1: 2021) Mid term (Phase 2: 2025?)
MuOnE	μe elastic scattering (g_μ-2)	Implement experiment in M2 beam with 150 GeV/c muons Setup ≈ 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	QCD & spectroscopy	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

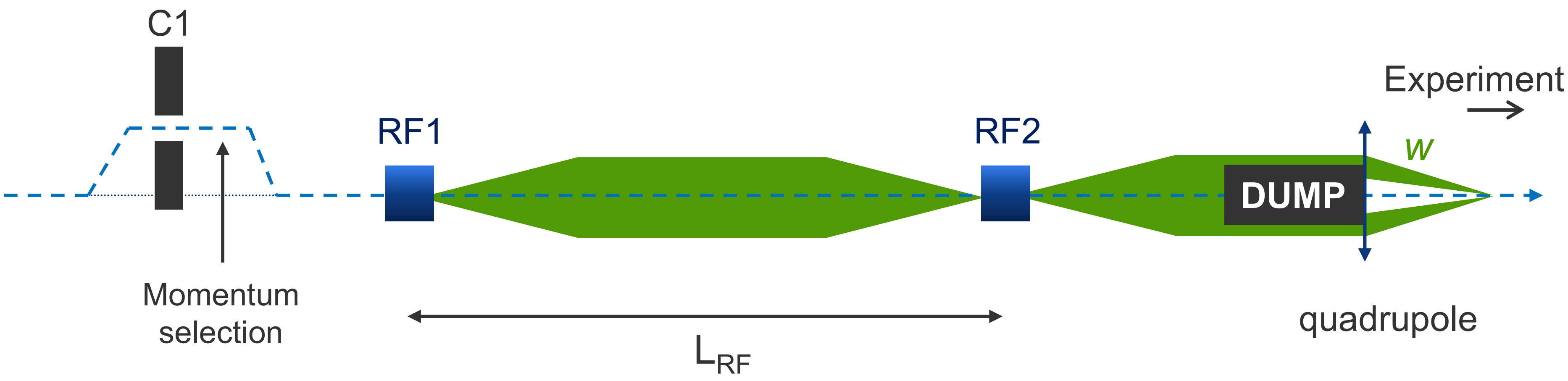
➡ **RF-separated beam technique**

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

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

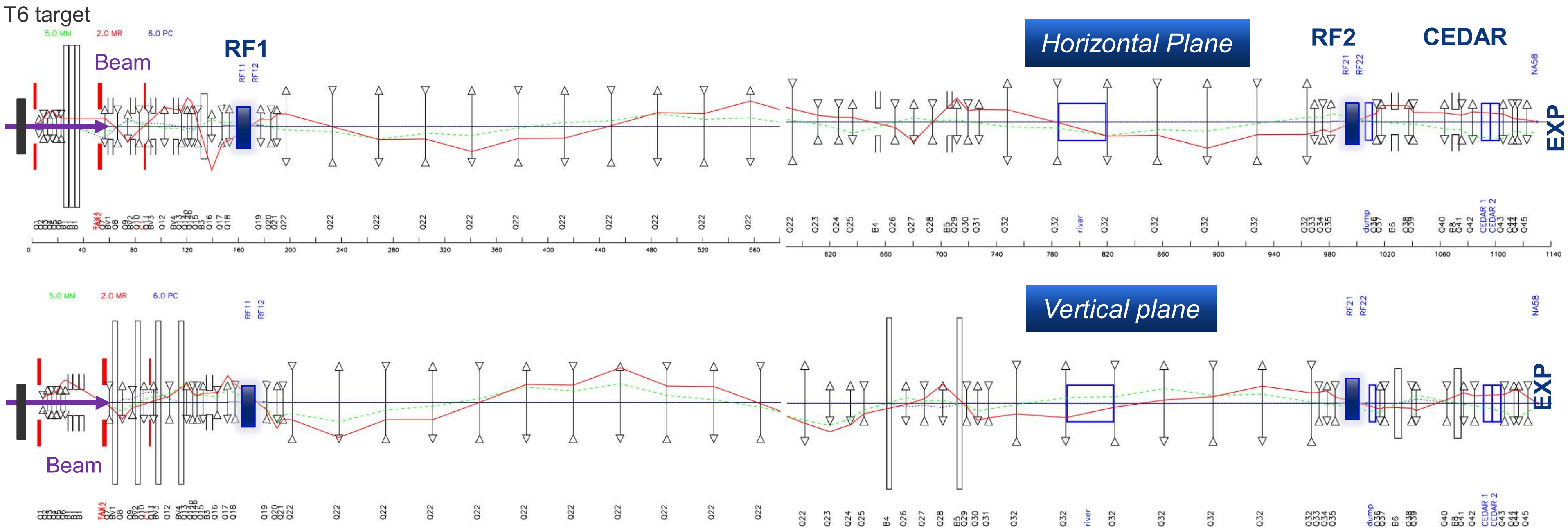
u: unwanted, w: wanted particles



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

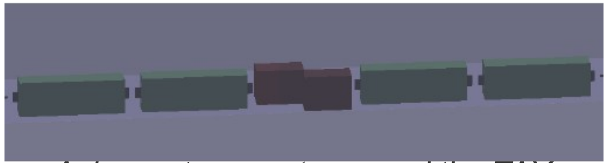
➡ **Compromise** between the highest achievable momentum, frequency and acceptance of the RF cavities. Studies for the RF system to be launched.

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 $K_L \to \pi^0 \nu\nu$	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

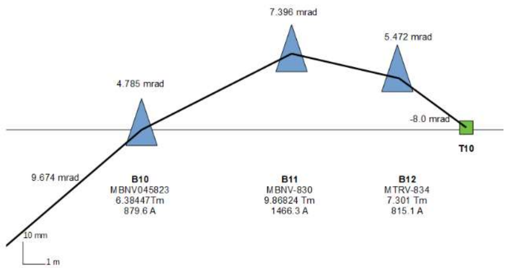
ECN3 (2)



Achromat magnets around the TAX

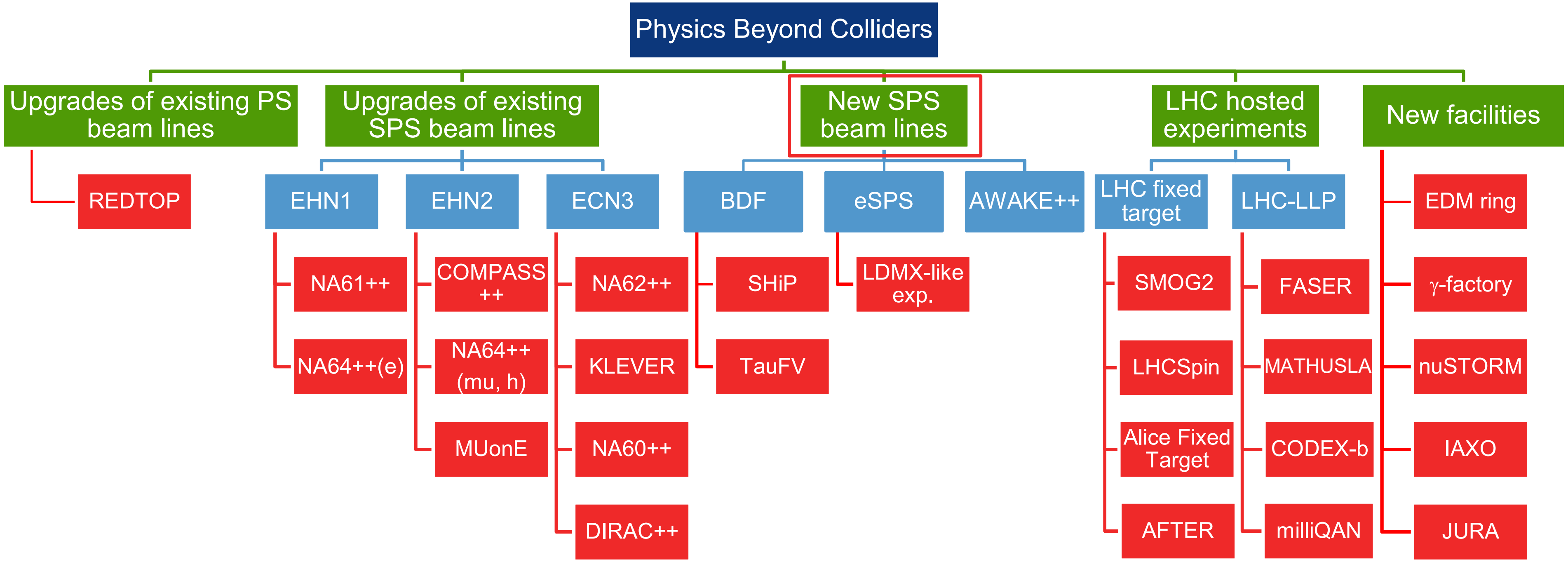
- *NA62++:*
  - *Aim:* Identify dark sector particles
  - *Idea:* transfer full proton intensity on TAX with T10 target out and reduce rate of produced pions and kaons decaying to muons

    ➡ **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 ~3.10^{-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

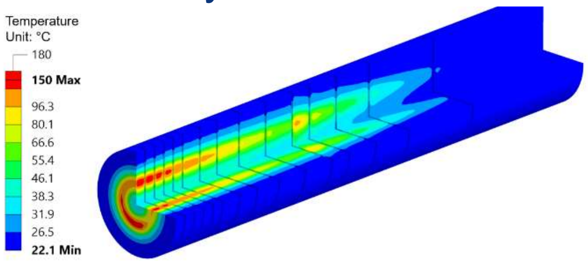
Physics Beyond Colliders (PBC)



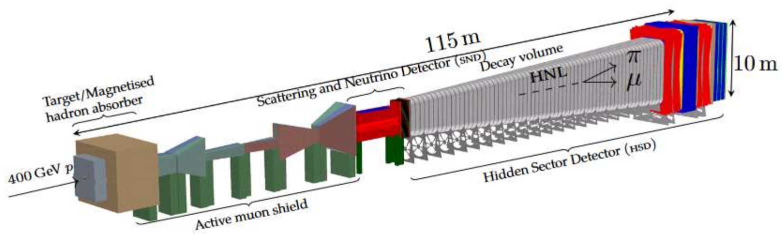
New SPS beam lines (1)

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!)
  - 4.10^{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

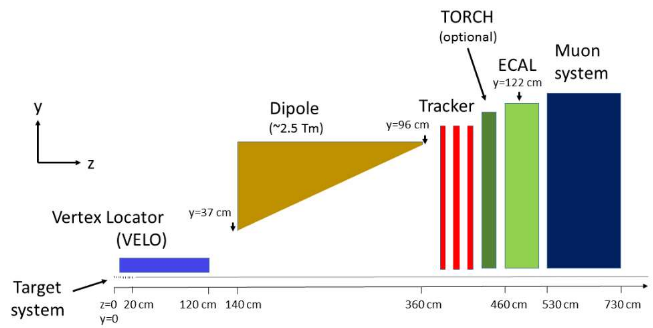


New SPS beam lines (2)



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*

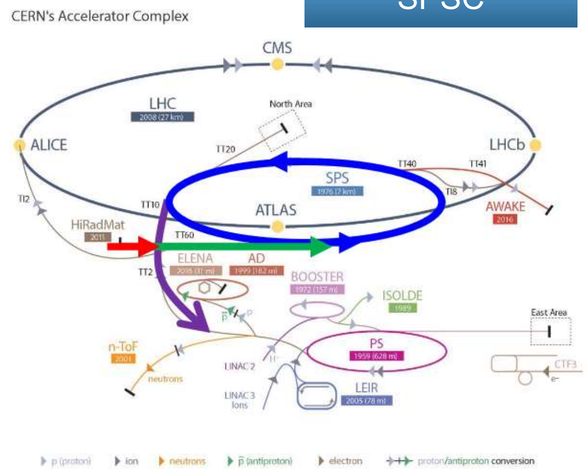
- Search for τ-rare decays ($\tau \rightarrow \mu\mu\mu$ and others)
- Detector (equivalent to LHCb) placed upstream of SHiP: vertex locator followed by a dipole, high precision trackers and calorimeters
- Possible addon with minimum modification of the BDF project (takes 2% of the beam delivered to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

New SPS beam lines (3)

Submitted to SPSC

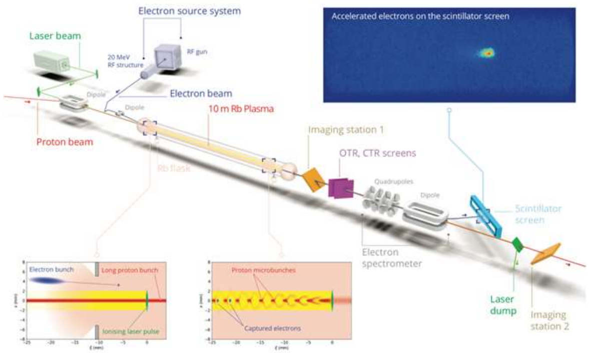
eSPS: *New high intensity primary electron beam facility*

- 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*

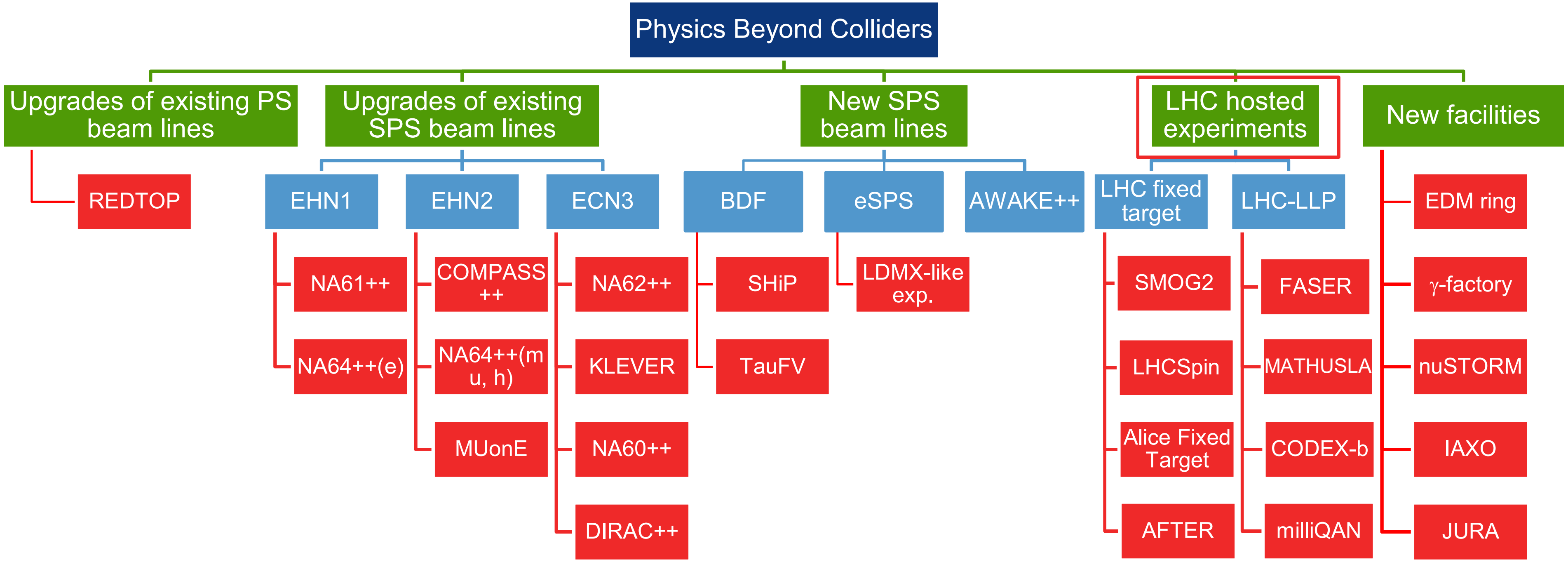


Run I	Run II	After Run II	*time*
2 GeV	5-10 GeV	50 GeV	*Energy of accelerated e-*

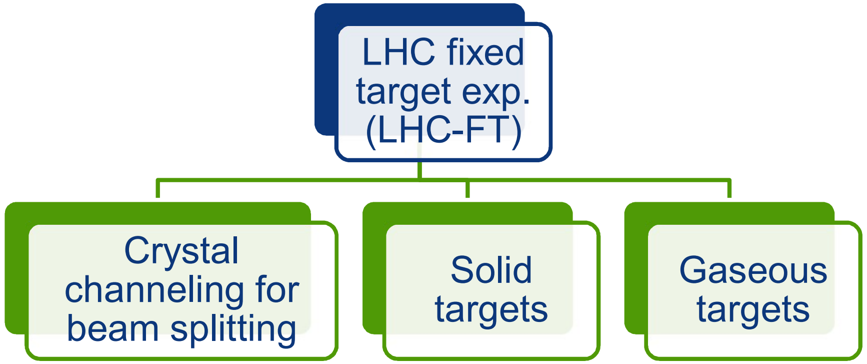
↓

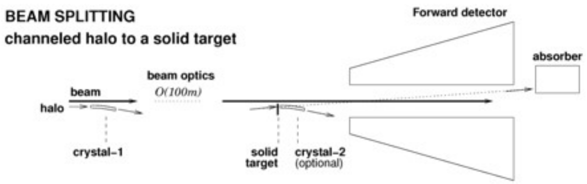
e^- beam dump experiment NA64 (dark photon)
10^{16} EoT per year

Physics Beyond Colliders (PBC)

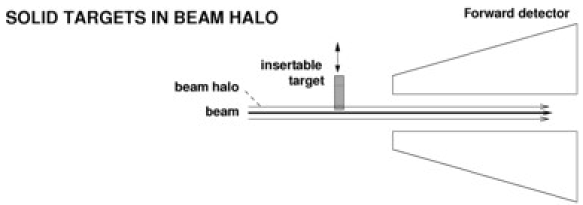


LHC hosted experiments (1)

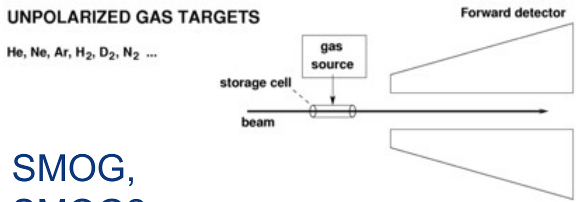




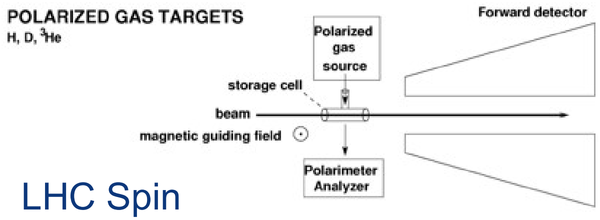
Alice FT



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 m^3 « 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 m^3 plastic scintillator array to detect small ionisation

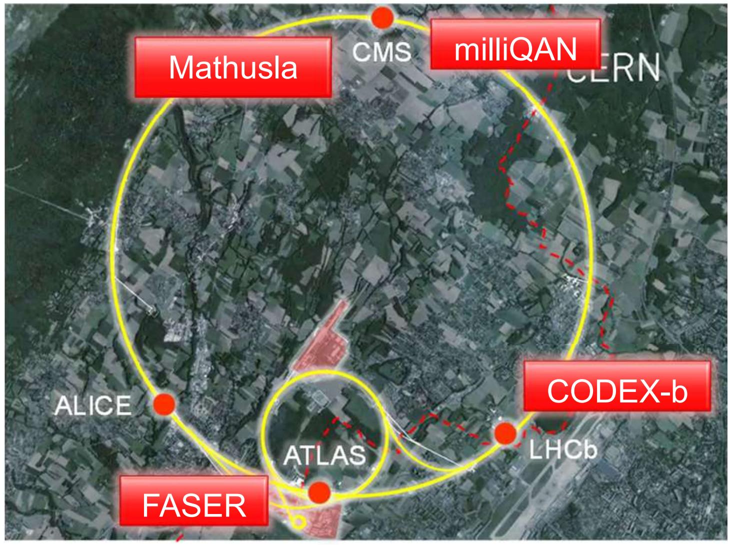
CODEX-b (search for wide range of LLPs)

- Modest size of the detector (10x10x10 m^3)

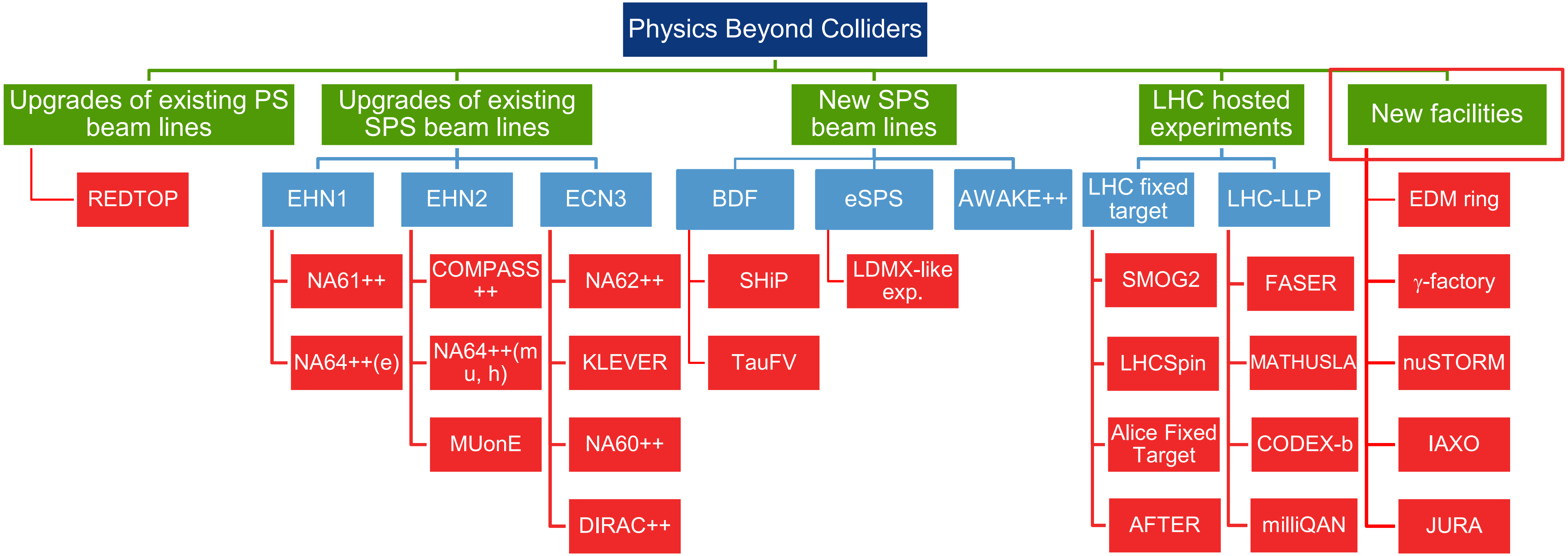
FASER (search for light, weakly interacting particles + study interaction of HE neutrinos)

Approved!

- Small detector located along the beam axis, 480 m from the collision point
- 2 phases: (1) taking data in 2021, (2) larger detector

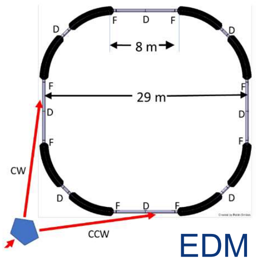


Physics Beyond Colliders (PBC)

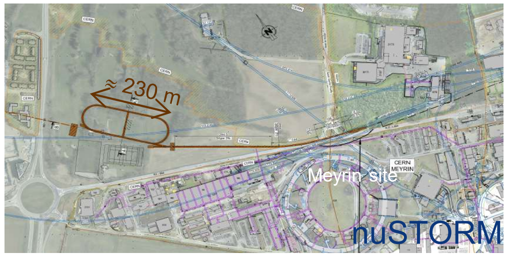


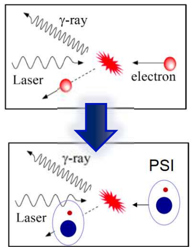
New facilities

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)	4th generation axion helioscope	BSM	Axions from the Sun		DESY (babyIAXO)

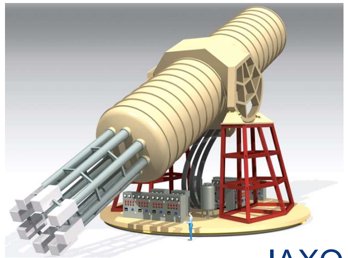


EDM





γ-factory


IAXO

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:*

Rare decays and precise measurements
- KLEVER
- TauFV@BDF
- REDTOP
- MuOnE
- EDM

Long-lived particles from LHC
- FASER
- MATHUSLA
- CODEX-b
- milliQAN

QCD measurements
- COMPASS++/AMBER
- DIRAC++
- NA61++
- NA60++
- FT (ALICE, LHCb)

Hidden sector with beam dumps
- NA64++
- NA62++
- BDF + SHiP
- LDMX@eSPS
- AWAKE++

Non-accelerator projects
- IAXO
- JURA

Other facilities
- Gamma factory
- nuSTORM

- *Mandate:* explore **unique opportunies** 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

Physics Beyond Colliders

CERN

Thank you for your attention!