CONFERENCE ON PHYSICS IN LHC AND BEYOND
12-15 May 2022, Matsue, Japan

Claude Vallée, CPPM Marseille

PHYSICS BEYOND COLLIDERS PROJECTS at LHC and BEYOND

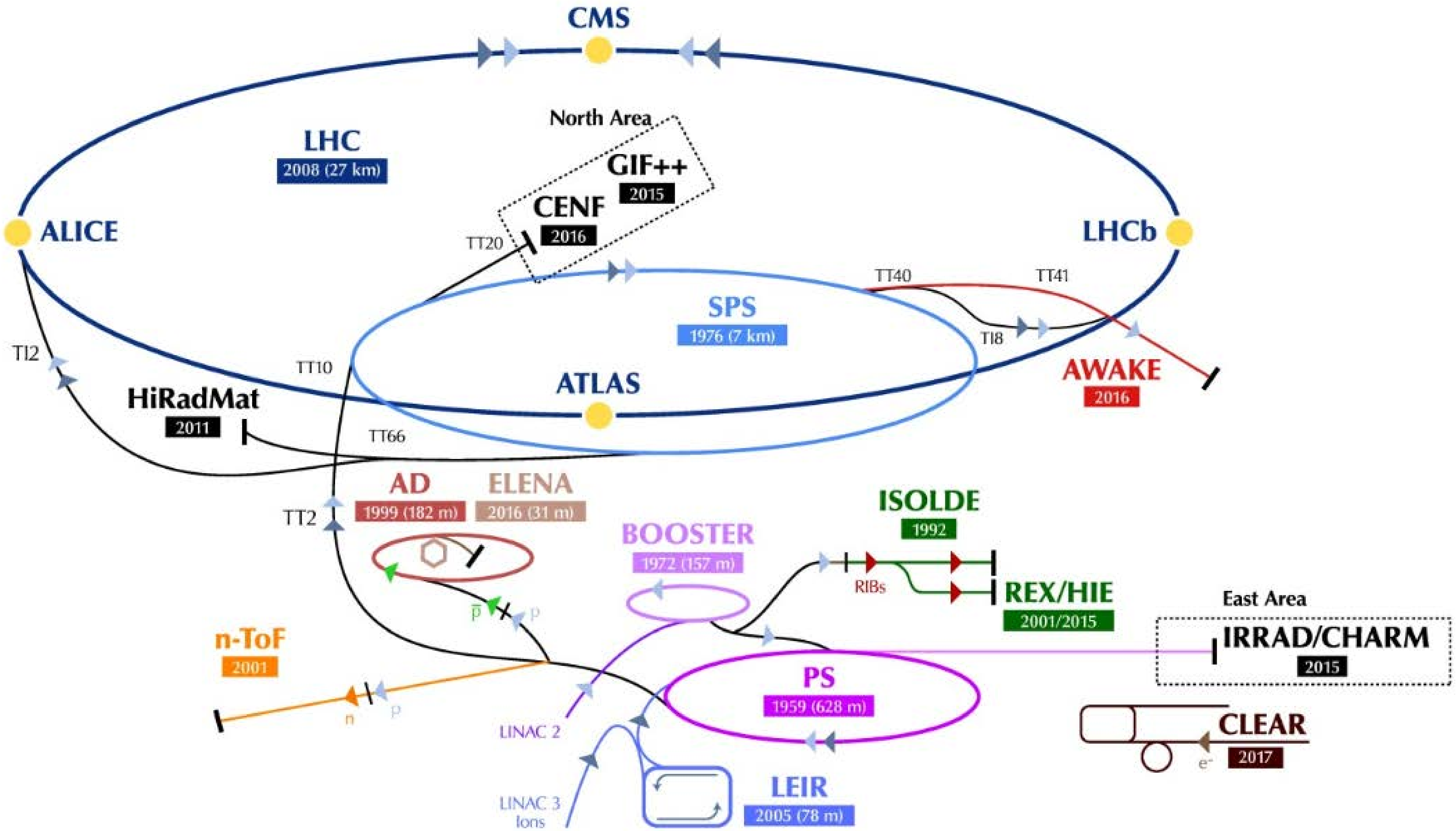
1. Post-EPPSU PBC mandate

2. LHC-related PBC projects: QCD, BSM, others
   … and their "competition" at CERN
   … in the worldwide context

NB: credit to PBC working groups and projects for most plots shown here

CERN ACCELERATOR FACILITIES

A very crowded complex!



INITIAL PBC MANDATE AND DELIVERABLES FOR EPPSU

Excerpt from the 2016 PBC mandate:

"Explore the opportunities offered by the CERN accelerator complex and infrastructure to address some of today's outstanding questions in particular physics through experiments complementary to high-energy colliders and other initiatives in the world."

Deliverables to EPPSU:

PBC Summary Report: arXiv:1902.00260

PBC BSM Report: arXiv:1901.09966

PBC QCD Report: arXiv:1901.04482

PBC Accelerator Reports:

http://cds.cern.ch/collection/PBC%20Reports?ln=en

UPDATED PBC MANDATE (2021)

Takes into account EPPSU recommendations:

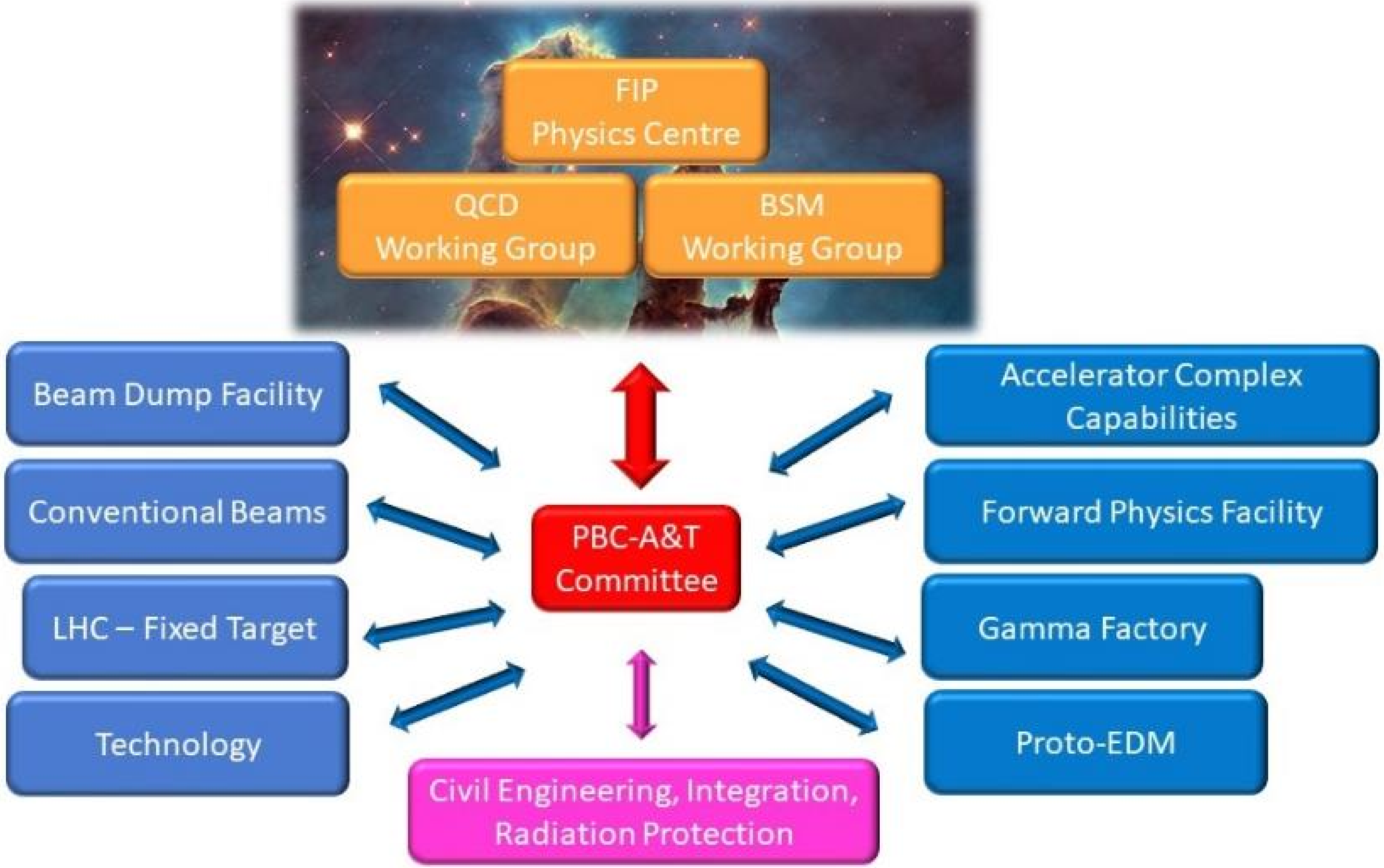
Increase synergies with cosmology, astroparticle, nuclear and atomic physics

Strengthen collaboration of CERN with large National Laboratories

Act as central forum of exchanges between theorists and experimentalists

NB: new proposed experiments@LHC dedicated to Long Lived Particles now explicitly in PBC mandate

PBC UPDATED ORGANISATION



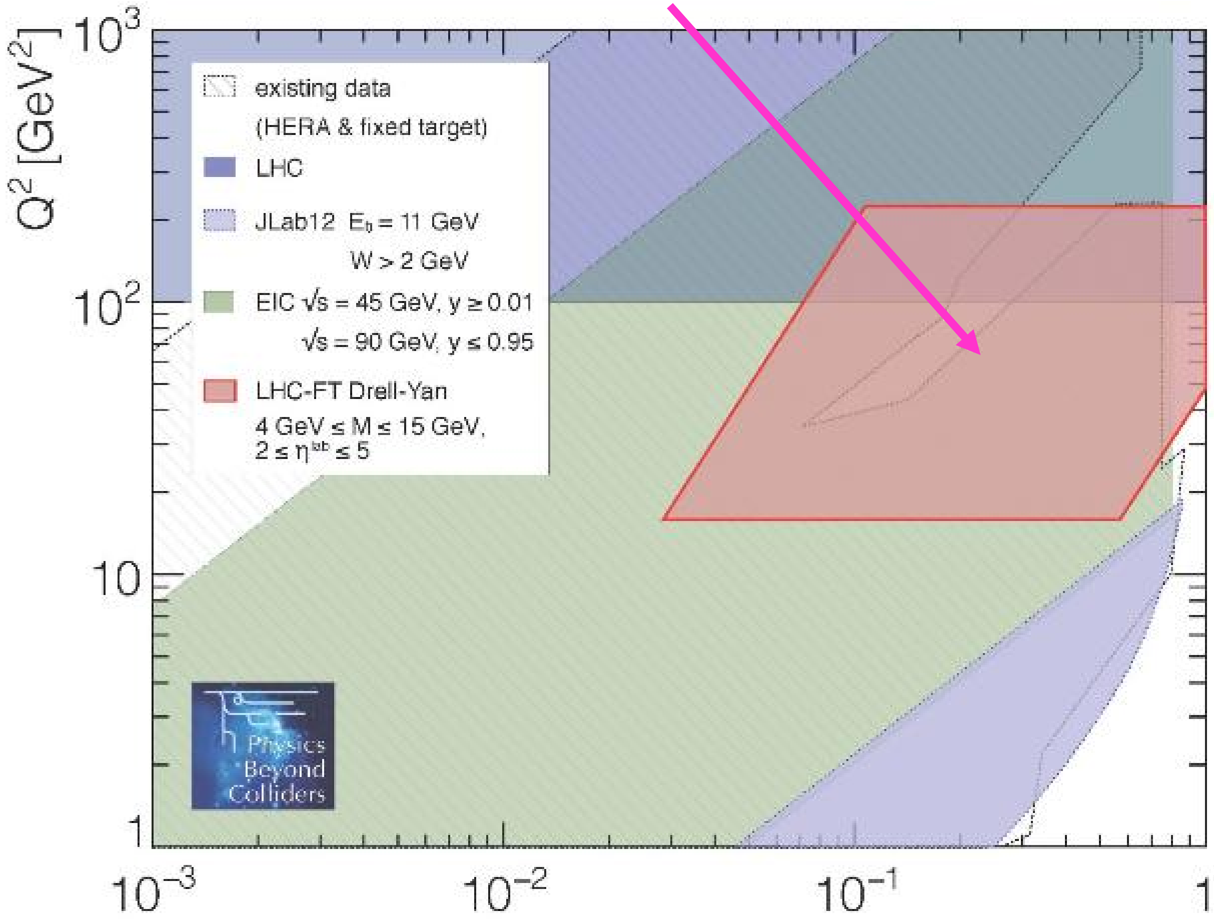
3 MCHF/year secured in the CERN Medium Term Plan for PBC support

New ideas may be submitted any time to the PBC Coordinators
along instructions given on the PBC web site http://pbc.web.cern.ch/

PBC QCD PROJECTS IN WORLDWIDE LANDSCAPE

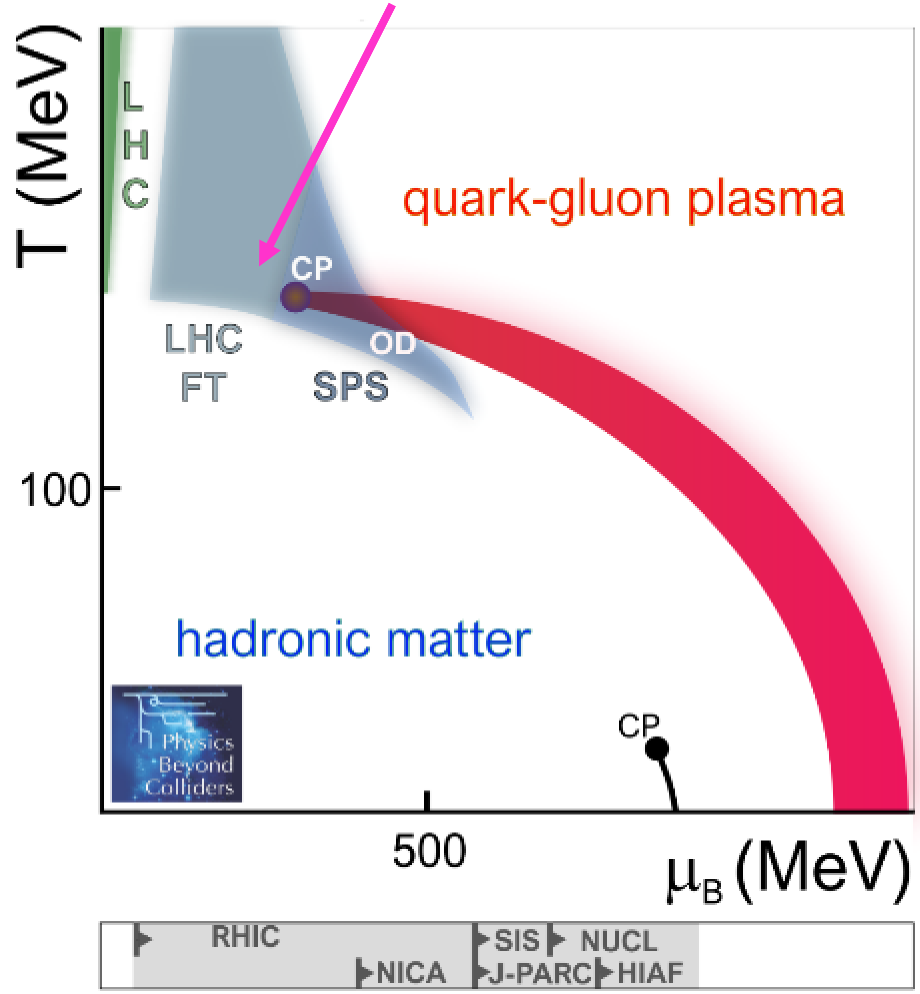
Structure Functions

Unique reach of LHC-Fixed Target with high statistics at high-x / high Q^2



QCD Phase Transition

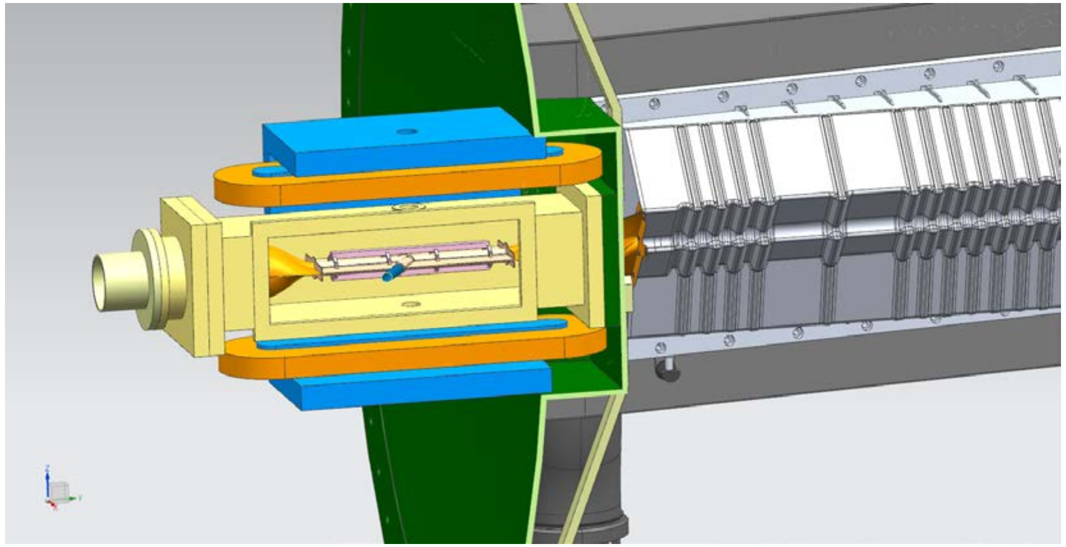
Unique reach of LHC-FT & SPS in transition region to high-μ_B



LHC FIXED TARGET

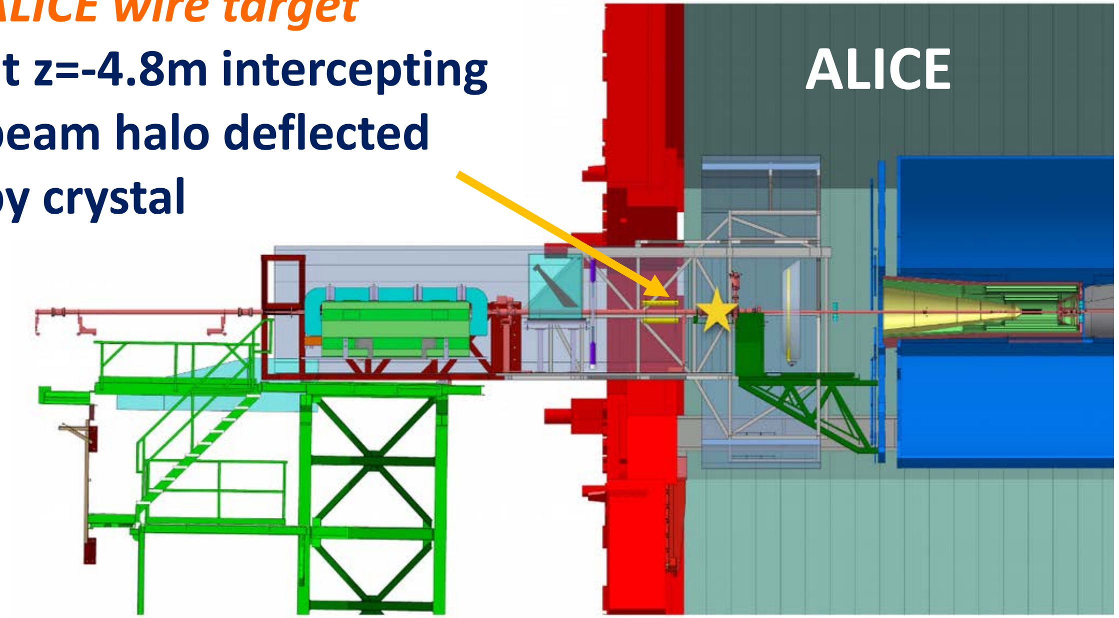
SMOG2 storage cell installed in LHCb for run3, promises FT lumi x ~100 vs SMOG

Longer term developments under PBC

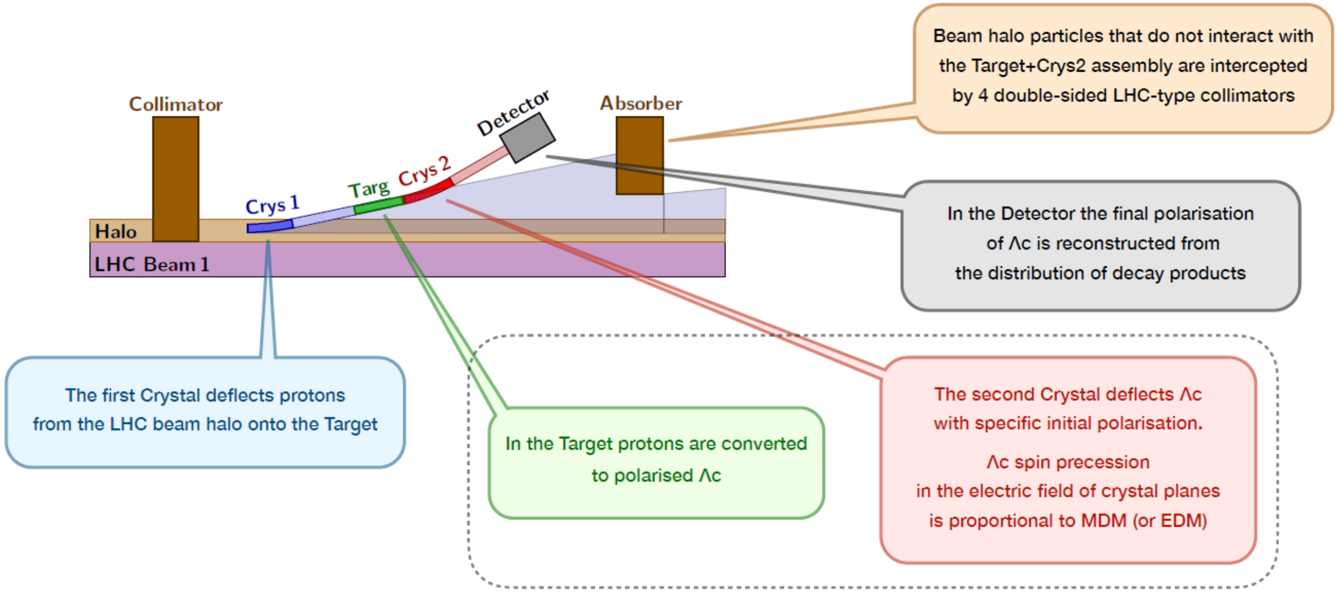


LHCSpin study of polarized storage cell for LHCb

ALICE wire target at z=-4.8m intercepting beam halo deflected by crystal



D. Mirarchi et al., Eur. Phys. J. C 80, 929 (2020)



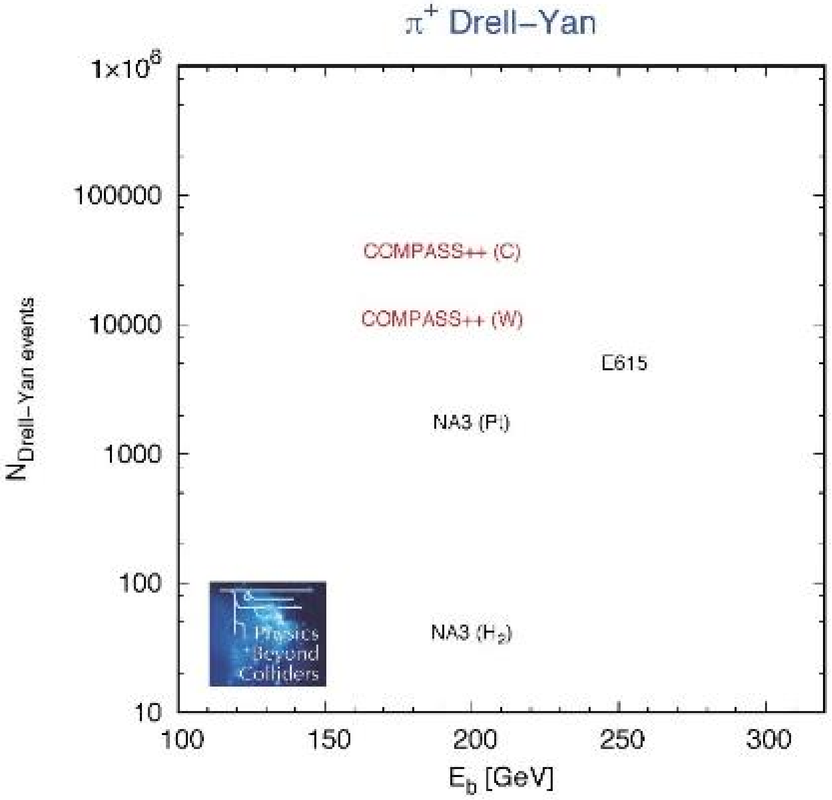
Double crystal set-ups for measurement of short-lived baryons electric and magnetic moments, either by LHCb or at IR3 dedicated location

beyond

LHC-FT "competition" at CERN: AMBER QCD FACILITY (ex-COMPASS)

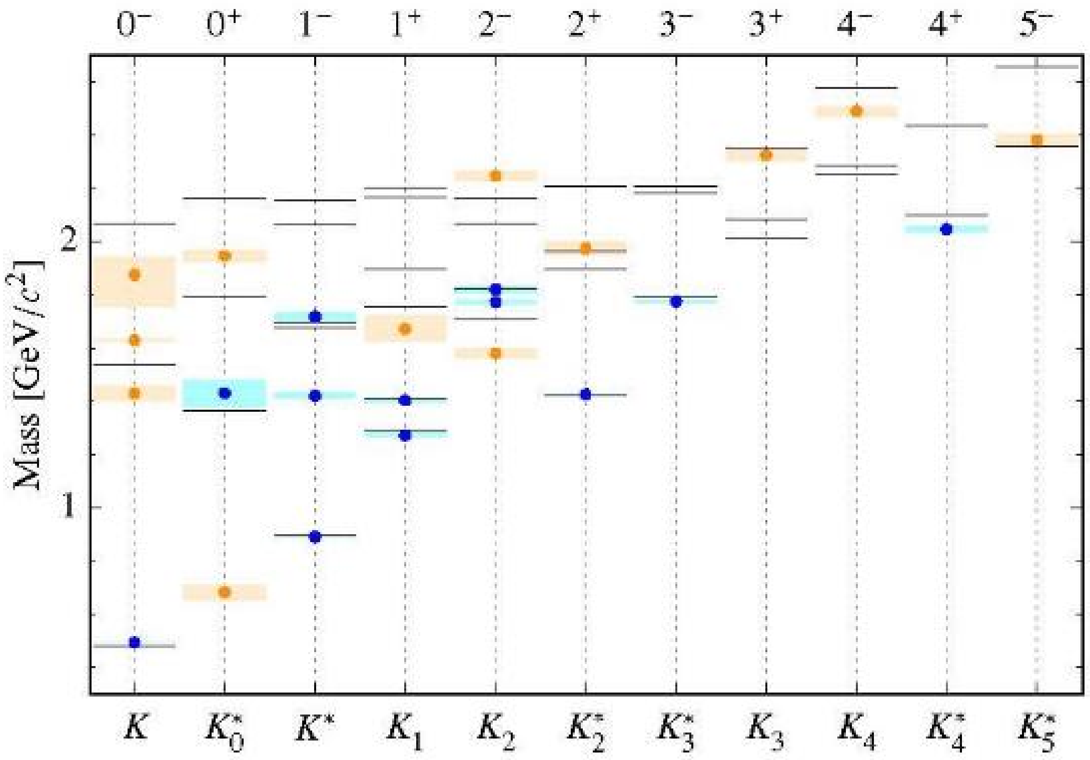
Short term (run 3): proton radius puzzle with μ-p elastic scattering

Longer term (excerpts):



With existing beams:

Unique opportunity for higher precision pion structure measurements



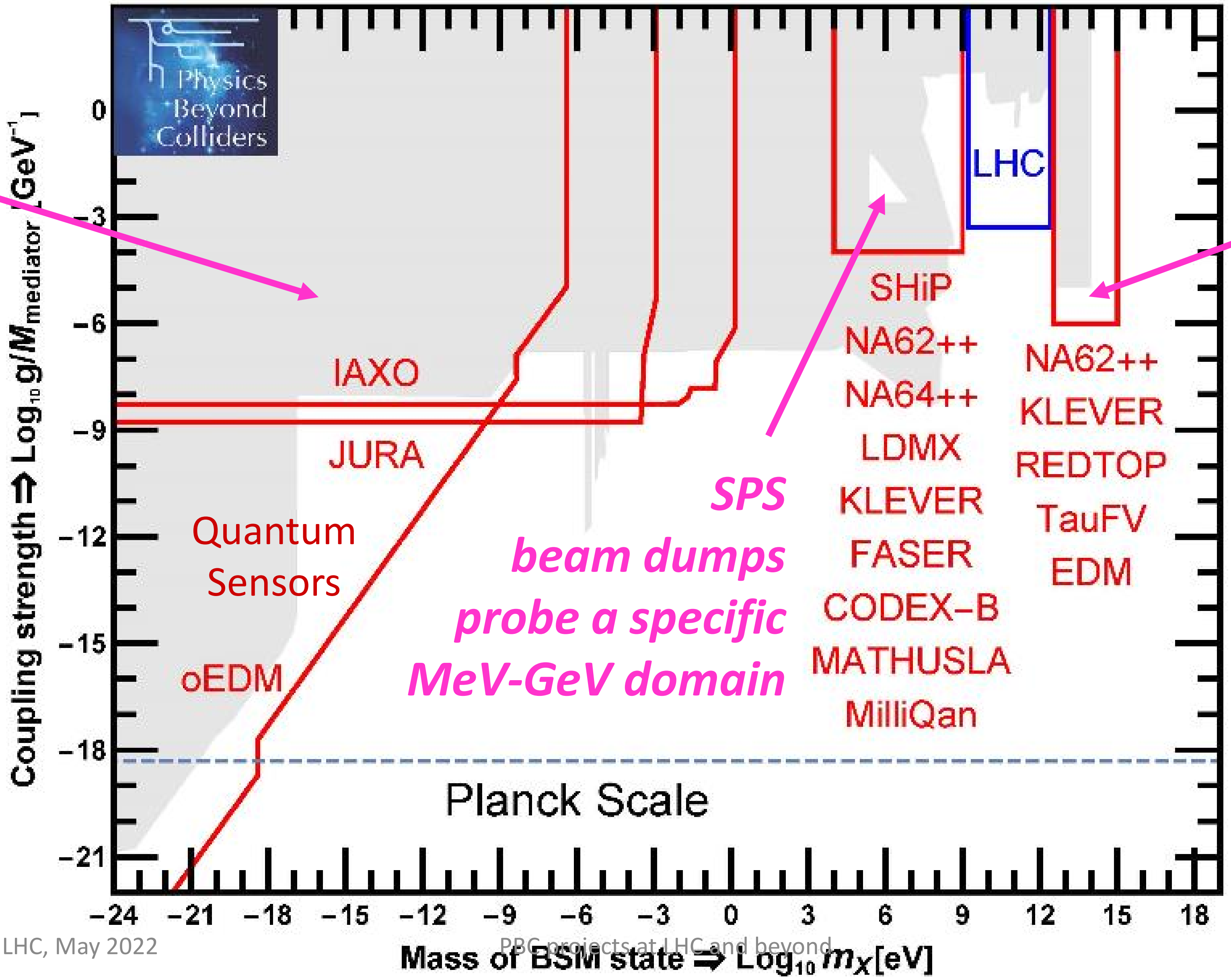
With new RF-separated K-beam:

(significant upgrade under study for post-LS3):

Comprehensive measurement of strange spectroscopy

PBC BSM PROJECTS IN WORLDWIDE LANDSCAPE

EDM & non-accelerator projects cover the very low-mass domain



SPS beam dumps probe a specific MeV-GeV domain

Precision & rare processes experiments extend reach of high-E colliders

LHC-LLP DEDICATED PROJECTS

Pioneered by FASER/SND@LHC/milliQan

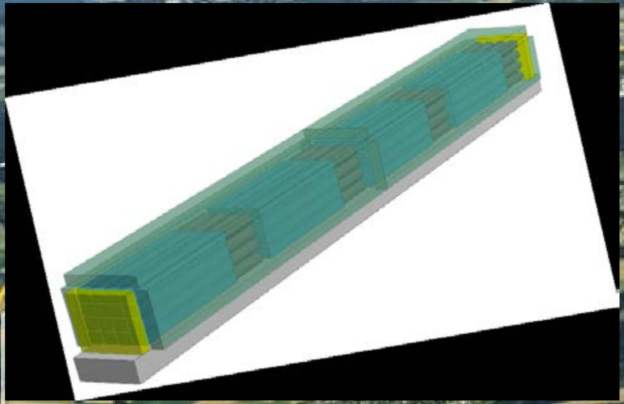
SUISSE
FRANCE
CMS
CERN Prévessin
ATLAS
CERN Meyrin
LHC 27 km

FASER:

Dark photons & TeV neutrinos

480m from ATLAS IP

Detector installed for run 3

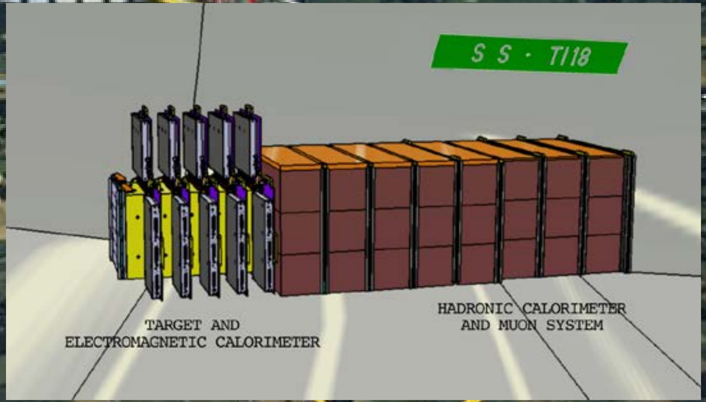


milliQan: milli-charged particles

33m from CMS IP

Successful demonstrator in run 2

Detector in construction for run 3



SND@LHC: *TeV neutrinos*

Slightly off axis opposite to FASER

Detector in construction for run 3

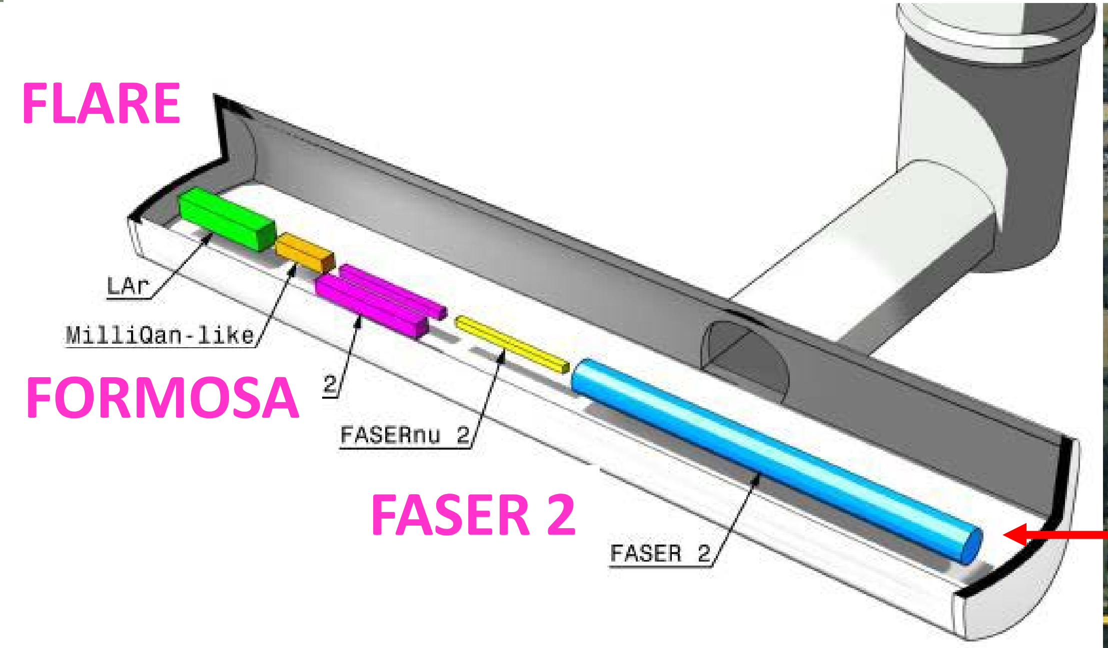
LHC-LLP DEDICATED PROJECTS

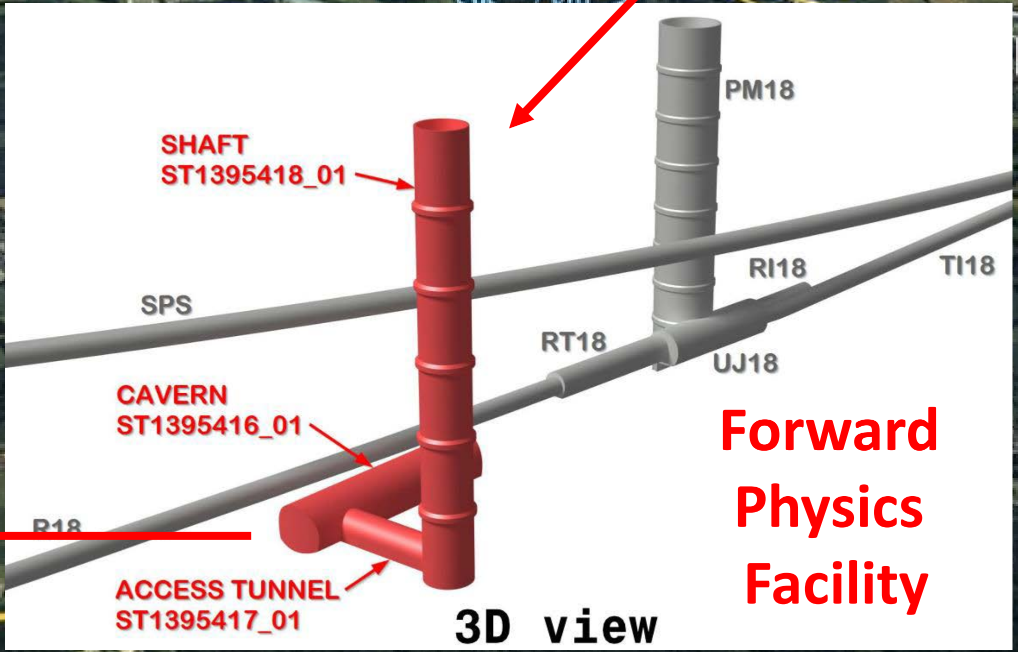
FORWARD PHYSICS FACILITY

Options for a dedicated LHC Forward Facility under study within PBC

+ FACET@CMS

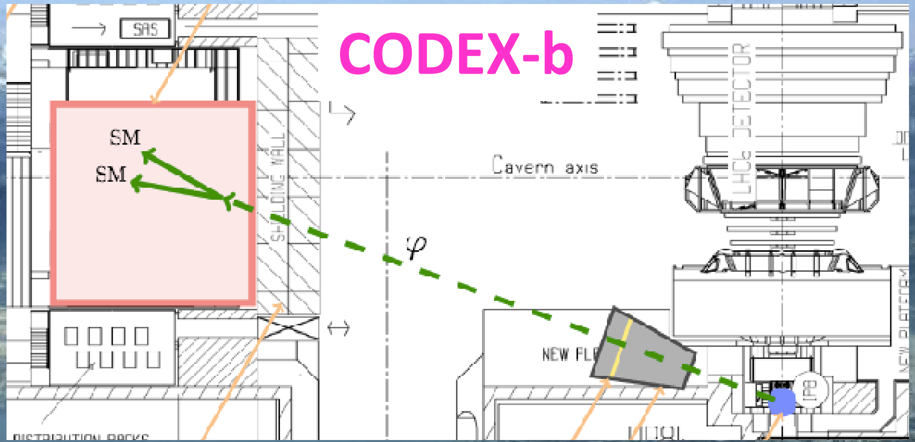
Goal is to provide enough space for larger scale forward detectors in the HL-LHC era

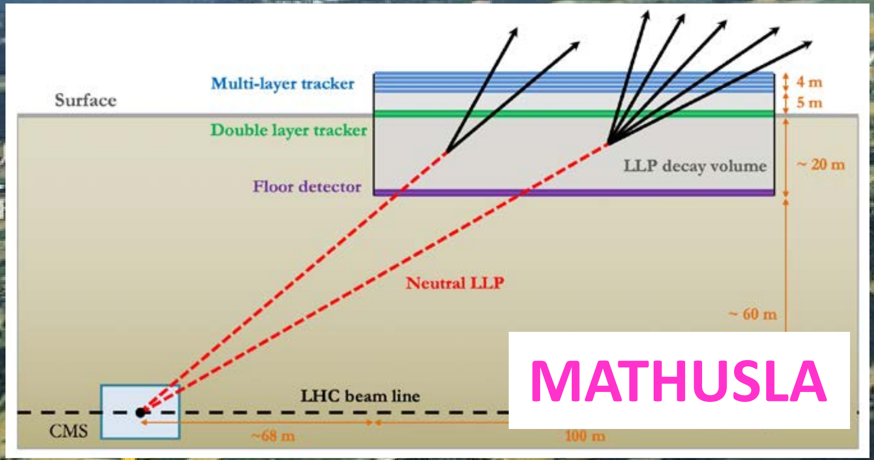


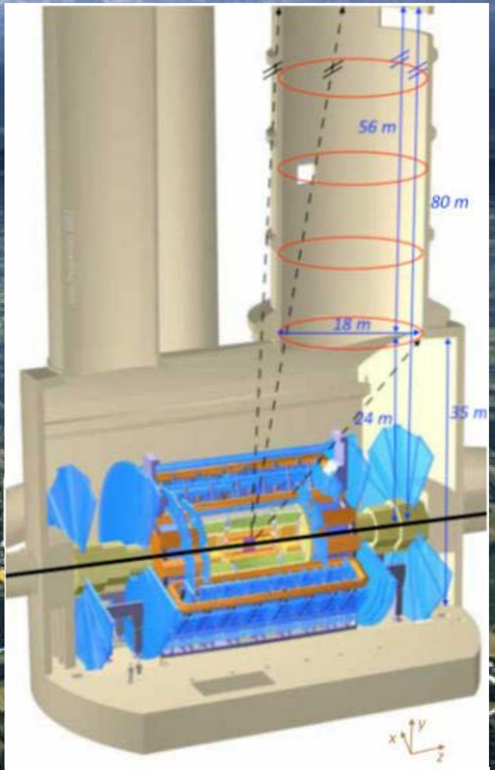


LHC-LLP DEDICATED PROJECTS

Larger scale projects at large angle







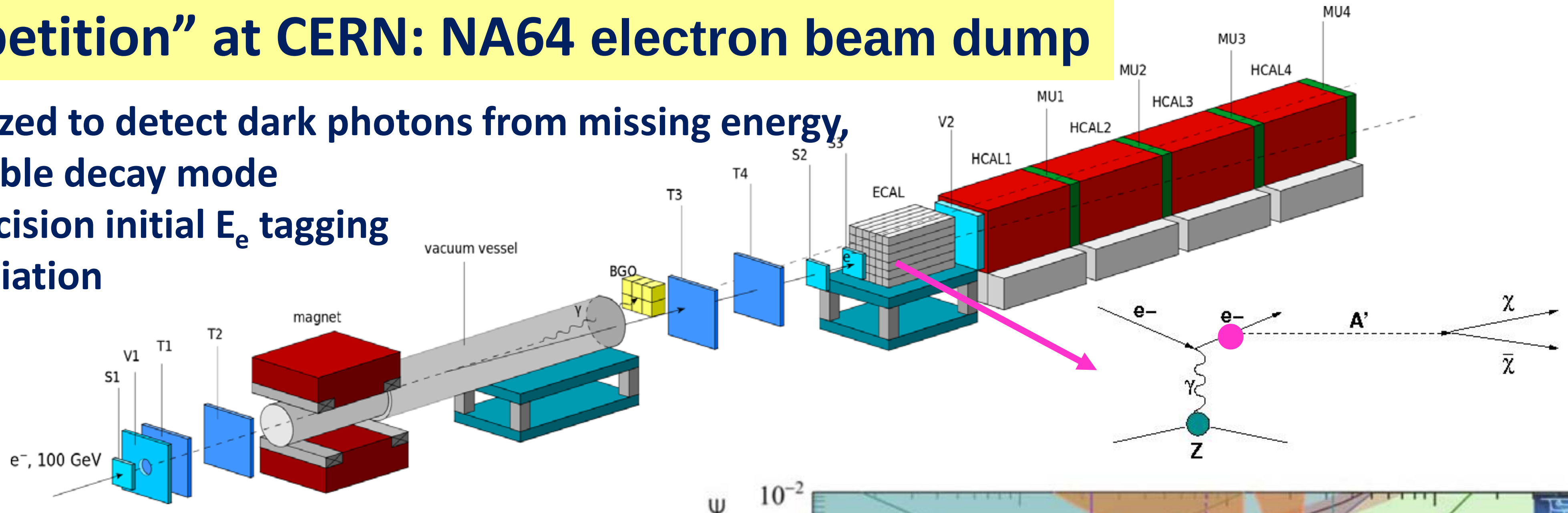
ANUBIS: similar concept as MATHUSLA but in ATLAS access shaft

Further demonstrators and detailed simulations planned during run 3

LHC-LLP "competition" at CERN: NA64 electron beam dump

Configuration optimized to detect dark photons from missing energy, adaptable to e^+e^- visible decay mode

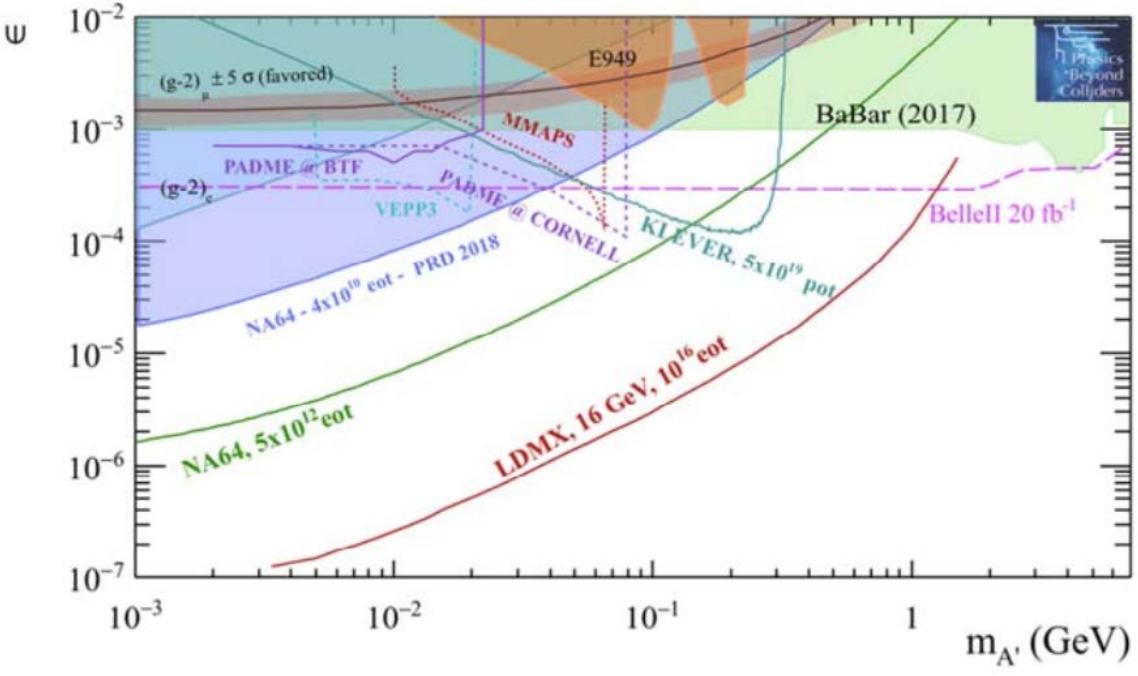
One key feature: precision initial E_e tagging with synchrotron radiation



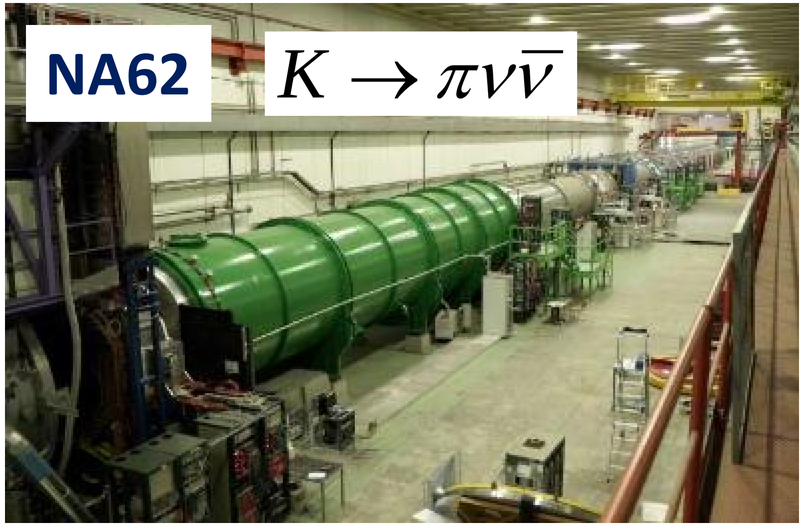
"Cheap" setup implemented in 2015 on H4 e test beam

Currently leading the field!

Permanent setup implemented for higher intensities in run 3



Similar searches in preparation with muon and hadron beams

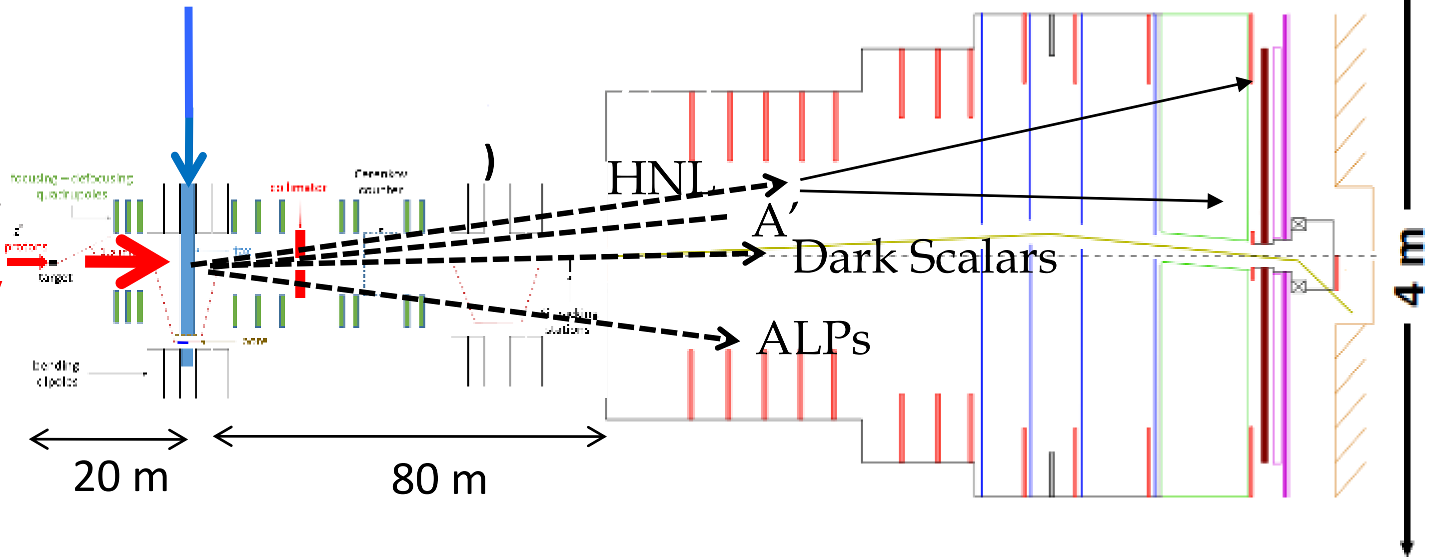


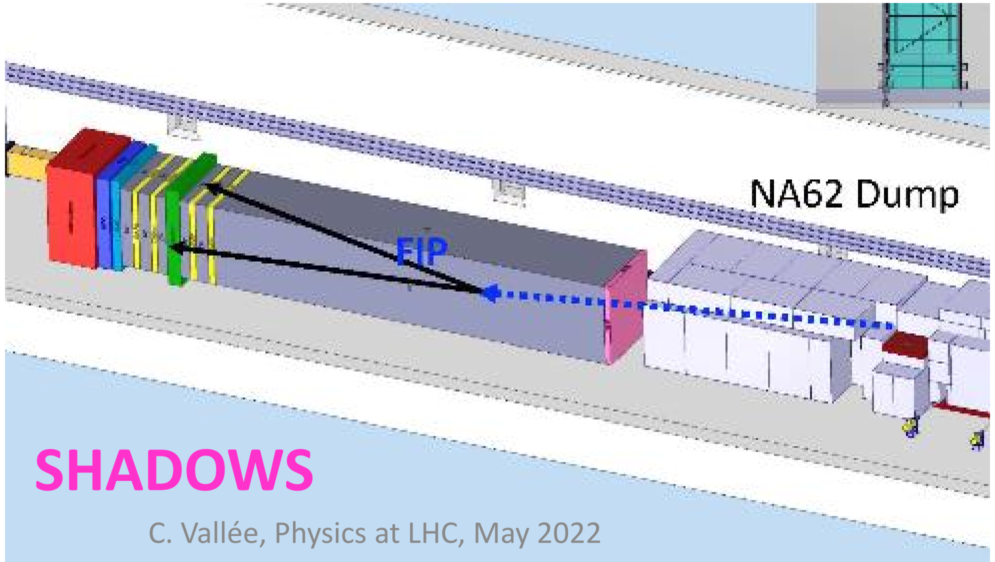
LHC-LLP "competition" at CERN:
SPS proton beam dump with NA62 & SHADOWS

Some NA62 data in beam dump mode foreseen for run 3

Achieved by closing the TAX collimator ~10^{18} PoT in few months

Instrumentation of NA62 decay vessel well adapted to searches in visible decay mode

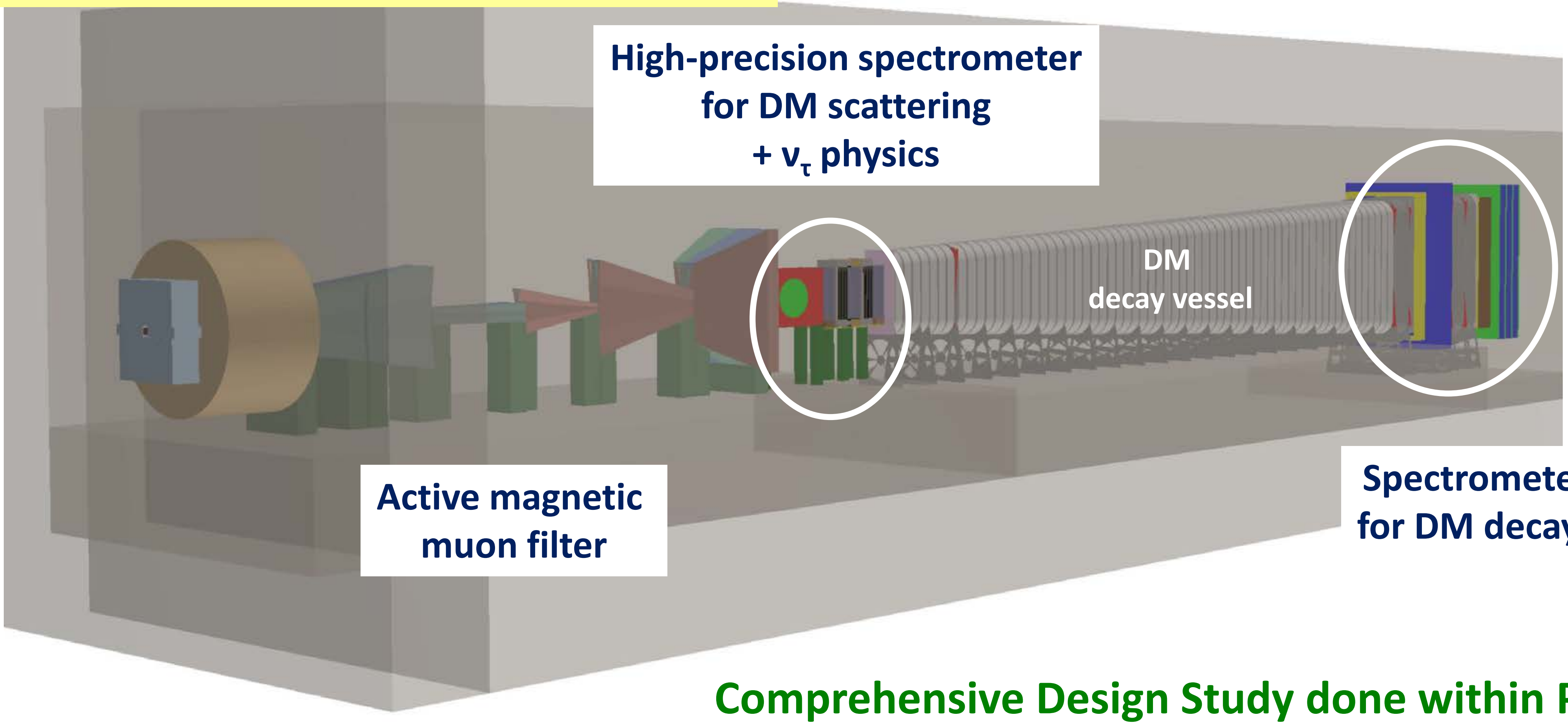




New SHADOWS "low cost" detector slightly off axis of TAX would increase acceptance at high mass in a higher-intensity post-LS3 beam dump

LHC-LLP "competition" at CERN: SHiP ON THE BEAM DUMP FACILITY

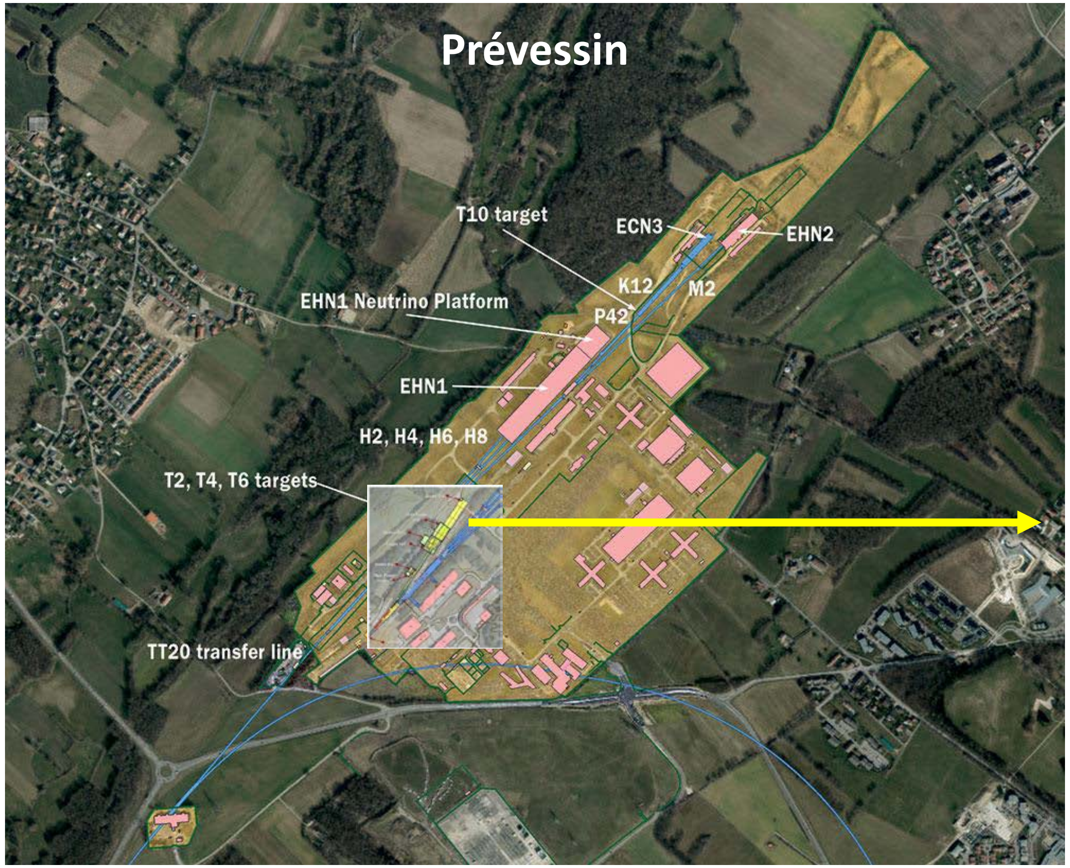
State-of-the-Art Dual Spectrometer for hidden particle searches



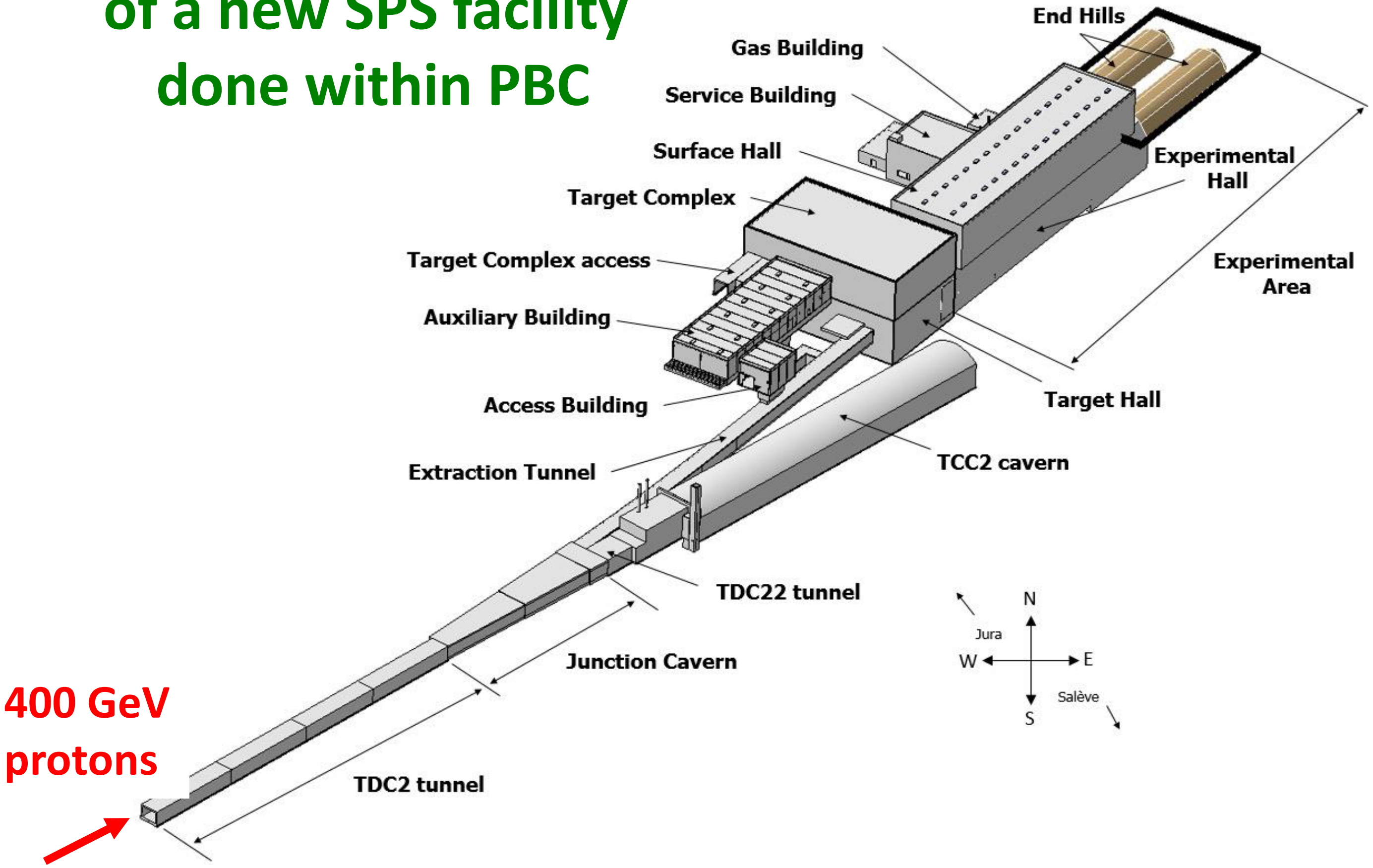
Comprehensive Design Study done within PBC

Next step: prepare TDR in relation with updated BDF TDR with emphasis on muon shield and decay vessel prototyping as well as cost reduction

The proton Beam Dump Facility



Comprehensive Design Study of a new SPS facility done within PBC

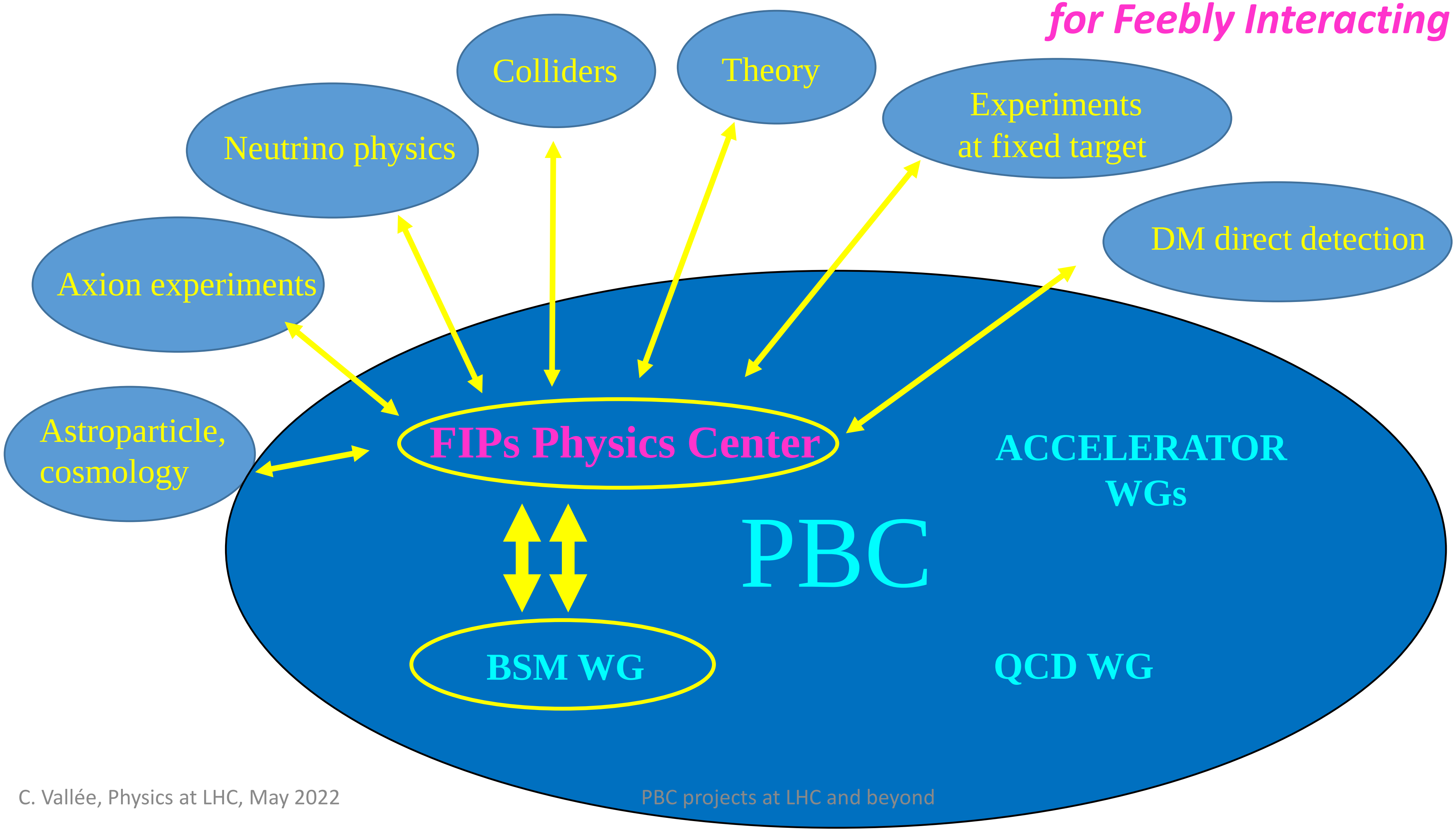


Continued R&D towards TDR now focusing on
slow extraction, target design, cost optimization incl. alternative siting

→ promising option identified in existing ECN3 underground hall (used by NA62),
under evaluation with respect to alternative NA62 extension + SHADOWS option

PBC LLP PROJECTS IN THE WORLDWIDE CONTEXT: THE FIPs PHYSICS CENTRE

"FIPs Physics Centre" now embedded within PBC as a "portal" towards the external world for Feebly Interacting Particles

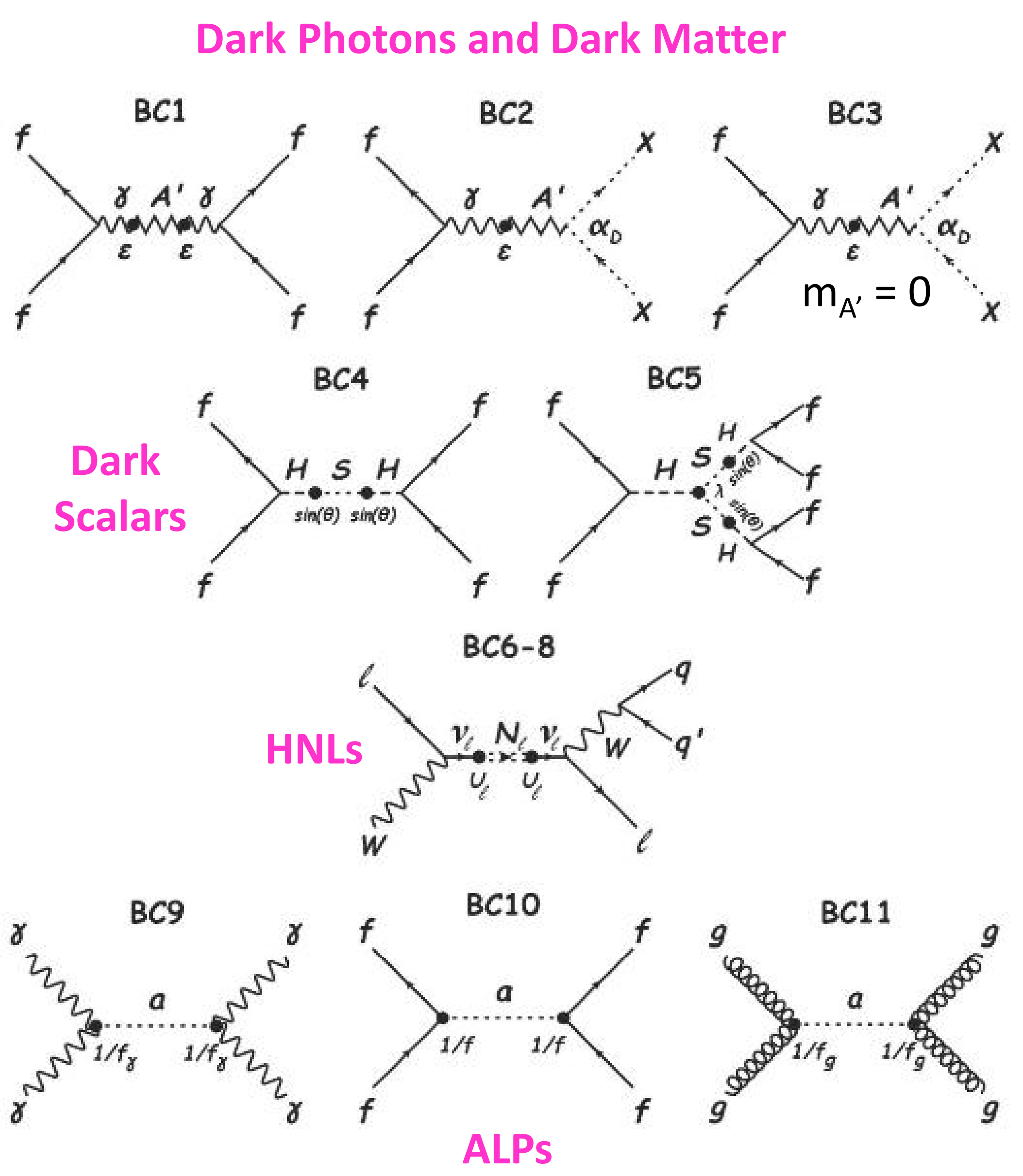


FPC THEORETICAL FRAMEWORK for comparison of projects reach

A highlight of PBC for EPPSU:
definition and wide acceptation of hidden sector benchmark models to compare reach of projects under same assumptions

Benchmark extension to all domains dealing with Feebly Interacting Particles has started in FPC

see FIPs kick-off workshop
https://indico.cern.ch/event/864648/
and report arXiv:2102.12143

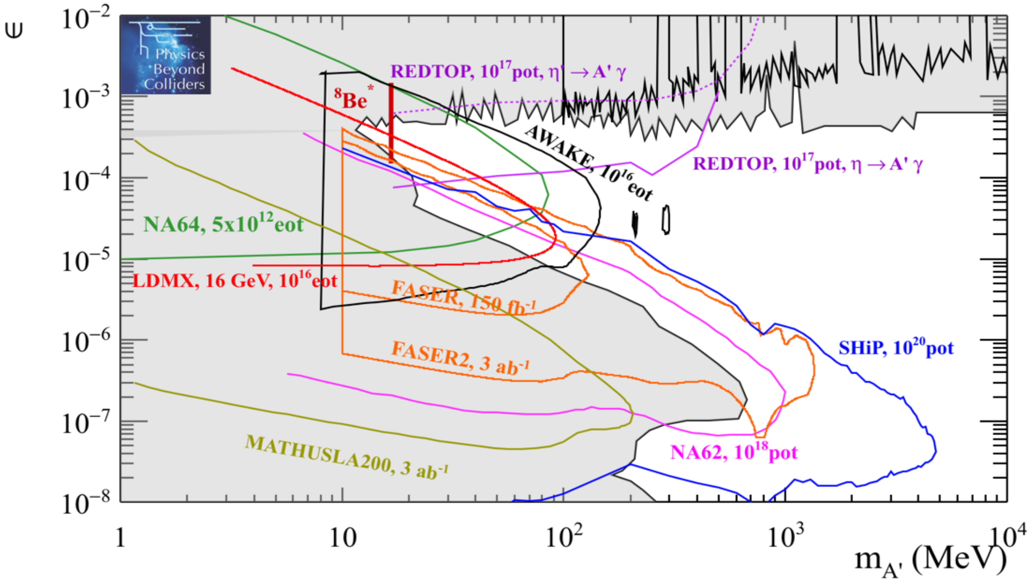


Next FIPs workshop in October 2022: https://indico.cern.ch/event/1119695/

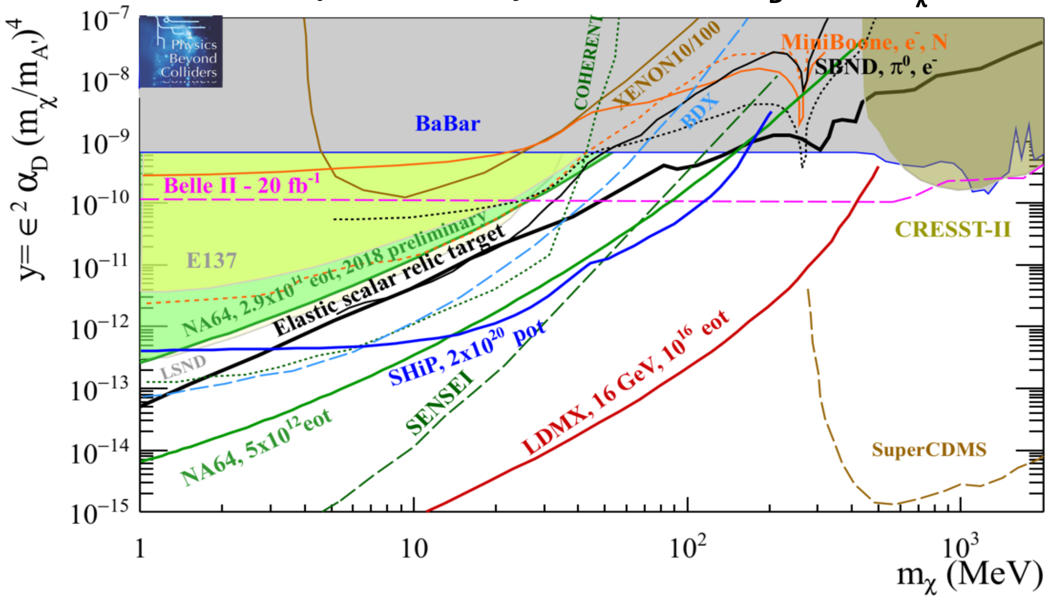
EXCERPTS OF COMPARISONS DONE FOR EPPSU

being updated for new projects and benchmarks

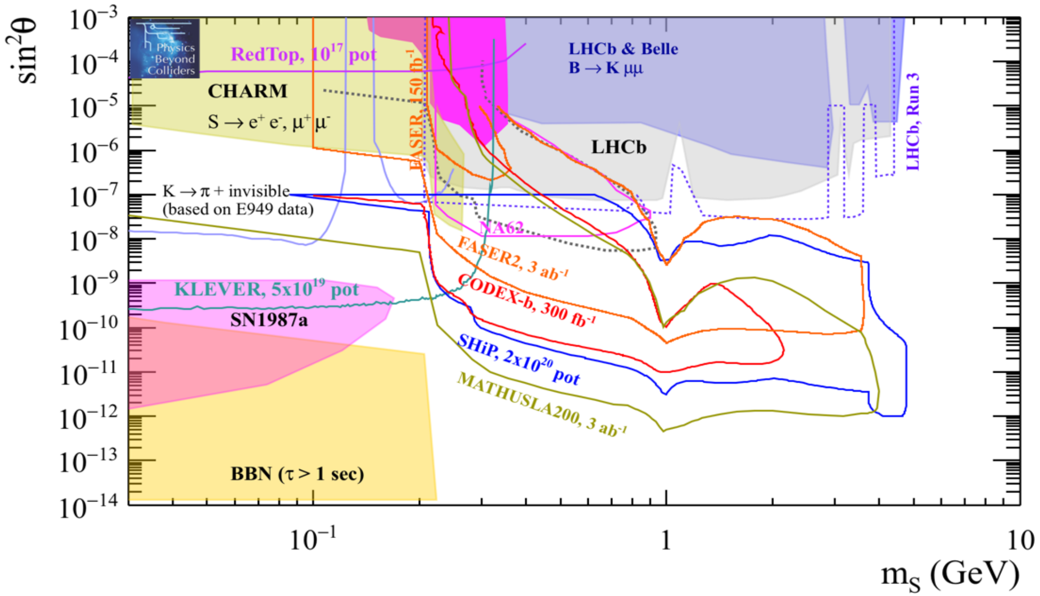
BC1: Dark photon visible decay to SM



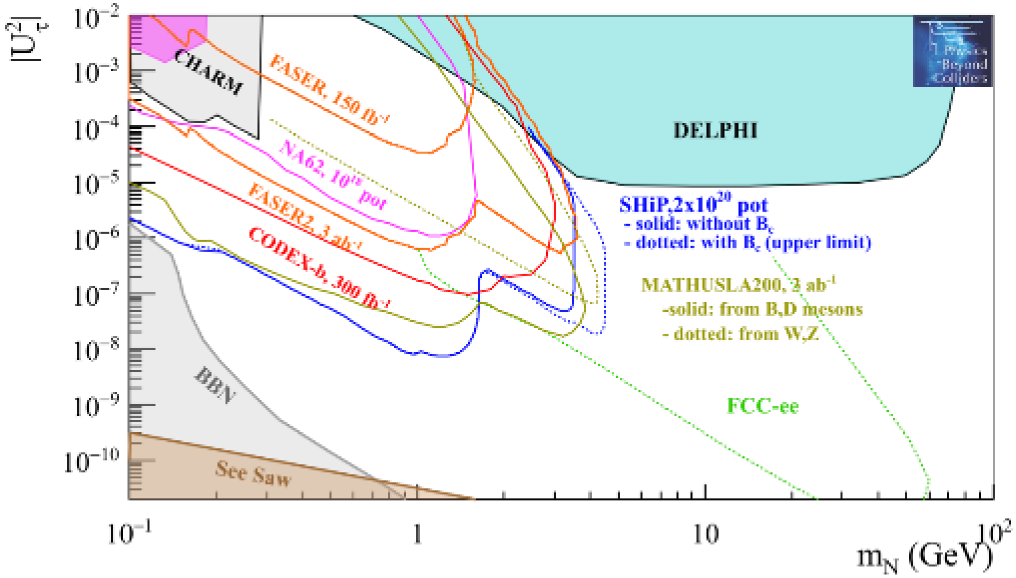
BC2: Dark photon decay to scalar DM $\alpha_D = 0.1$, $m_\chi = 1/3\ m_{A'}$



BC4: Dark scalar mixing with Higgs



BC8: dark HNL coupling to τ

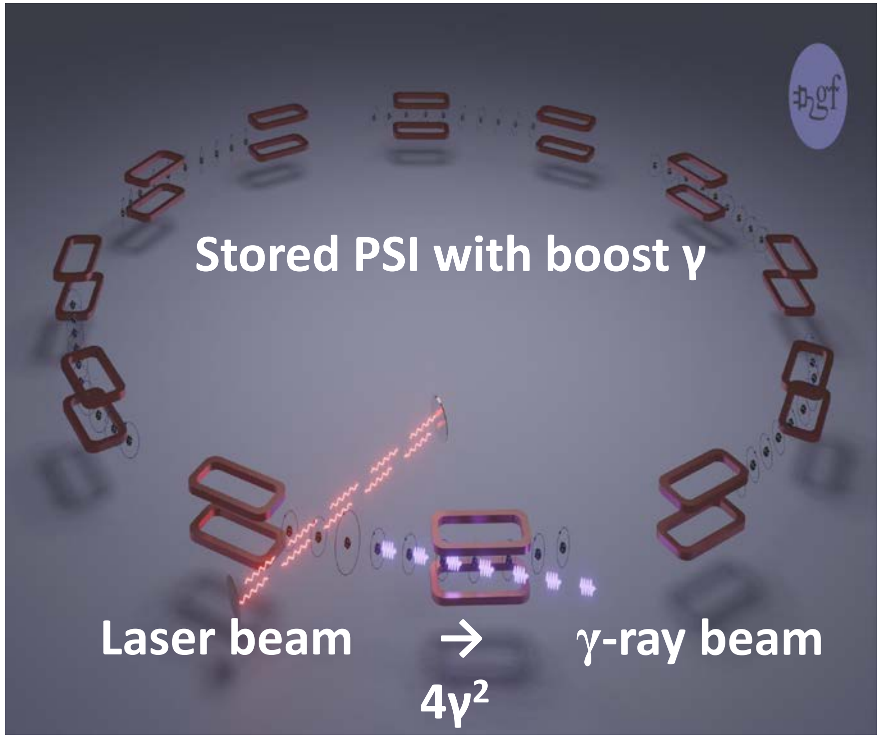


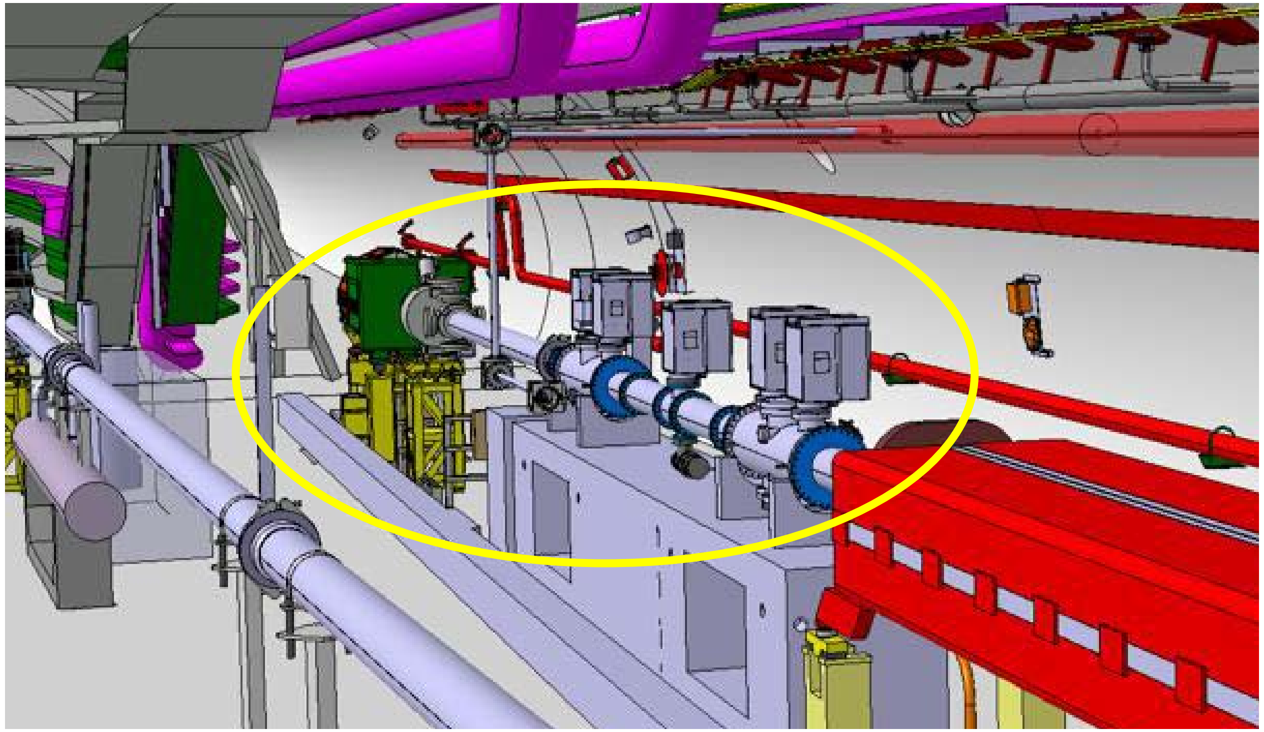
ects at LHC an

Goal of 10^7 intensity gain versus existing facilities

GAMMA FACTORY @LHC

New idea introduced within PBC

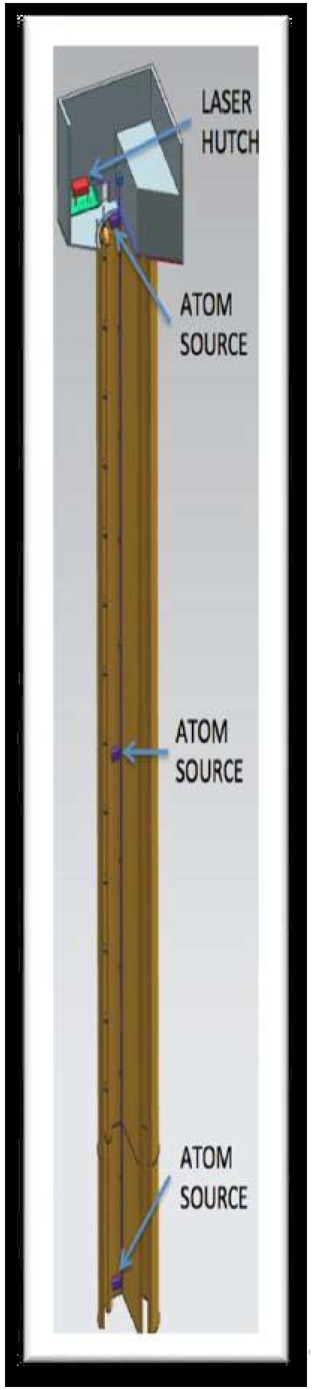




Important milestone reached within PBC with successful acceleration and storage of Partially Stripped Ions in LHC

Proof of Principle experiment with full configuration in preparation at SPS

For applications in atomic, nuclear, particle and applied physics, see first general workshop:
https://indico.mitp.uni-mainz.de/event/214/overview



AION

Atom interferometry for ultra-light DM and mid-frequency gravitational waves

Proof-of-Principle 10m setup being built in UK

Possible siting of a 100m setup in a CERN LHC shaft under investigation in PBC

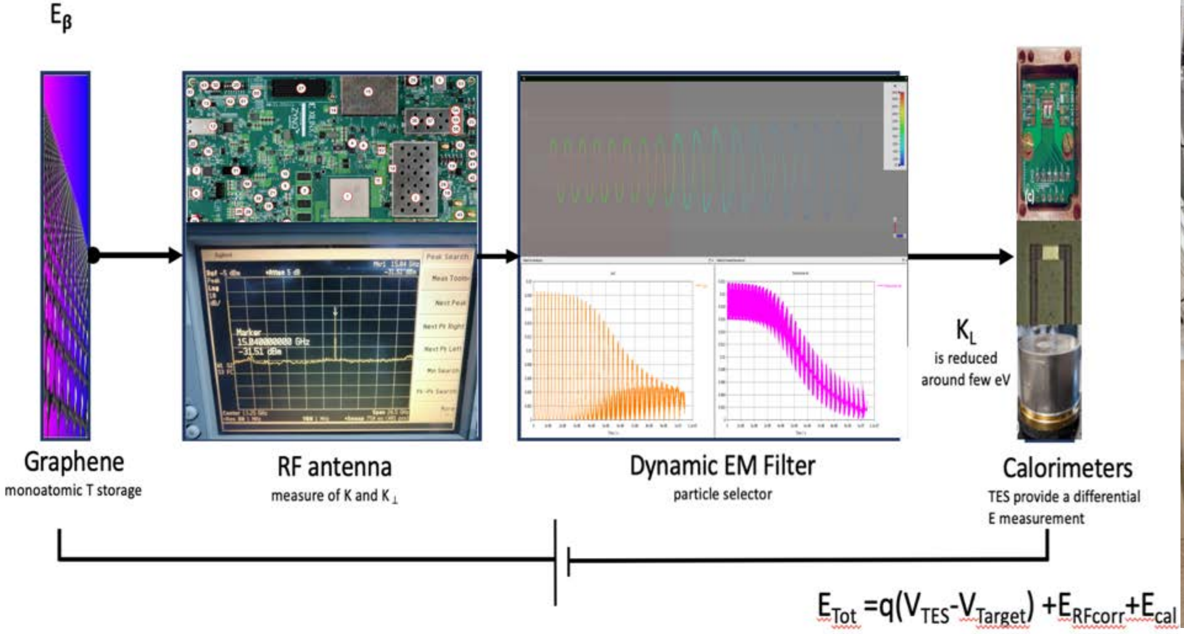
A new field for PBC: QUANTUM SENSORS

(a few recent developments)

PTOLEMY

Measurement of cosmic neutrino background

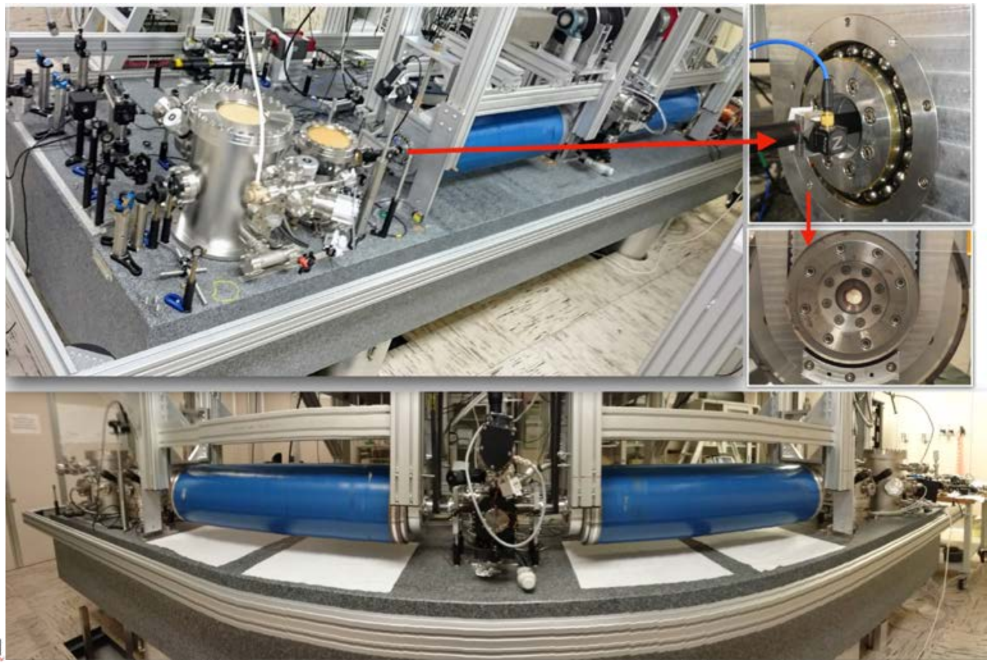
New idea submitted to Snowmass and PBC



VMB@CERN

Vacuum Magnetic Bi-refringence

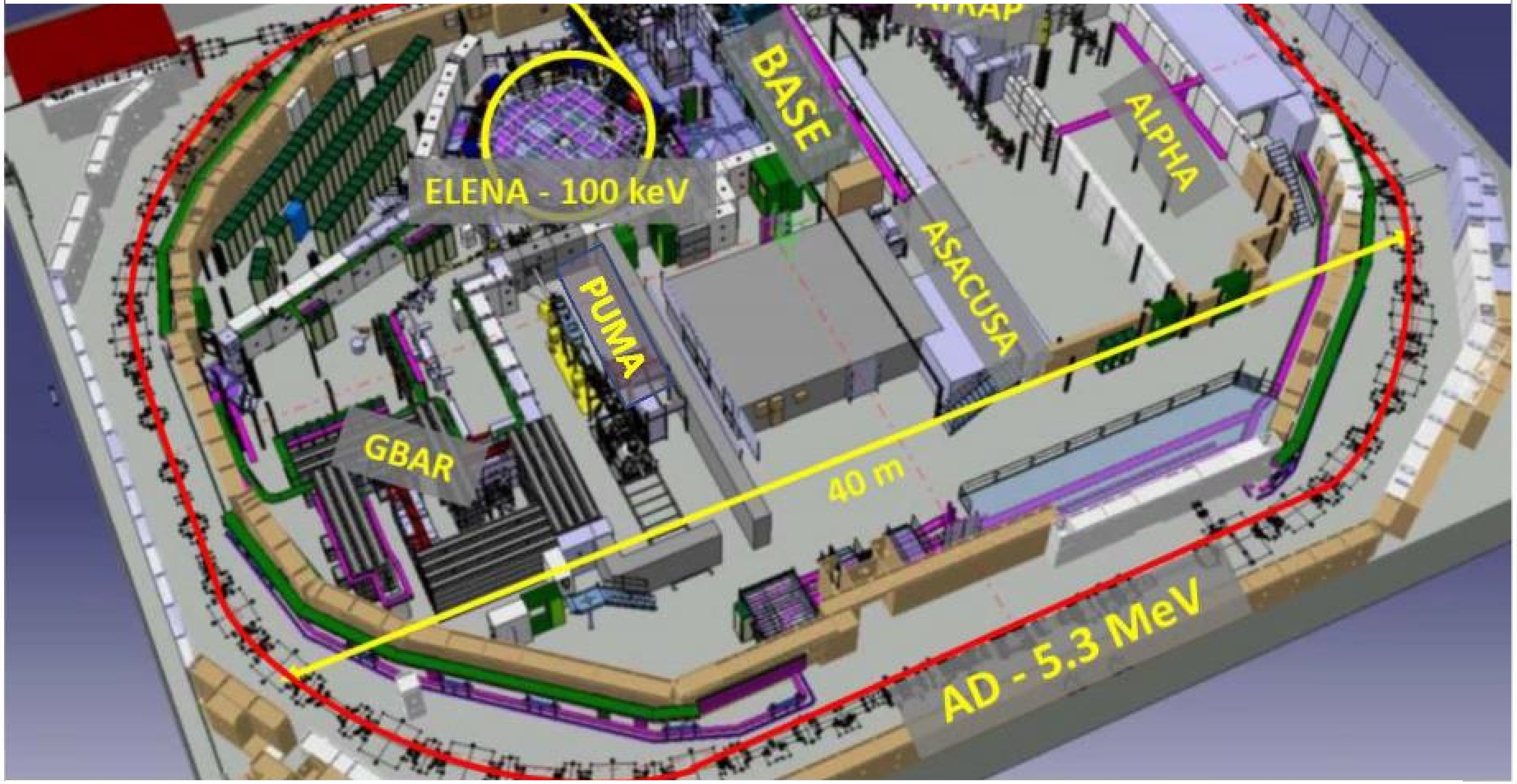
Optical set up being developed in Ferrara for a CERN implementation with (HL-)LHC magnets



ANTIMATTER FACTORY

Six collaborations, pioneering work by Gabrielse, Oelert, Hayano, Hangst, Charlton et al.

Many quantum technologies at work for precision measurements: CPT, fundamental constants, axion searches…



Recent ELENA upgrade enhances potential for next decade

BASE,
Fundamental properties of the antiproton

ALPHA,
Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

ASACUSA
Antiprotonic helium spectroscopy

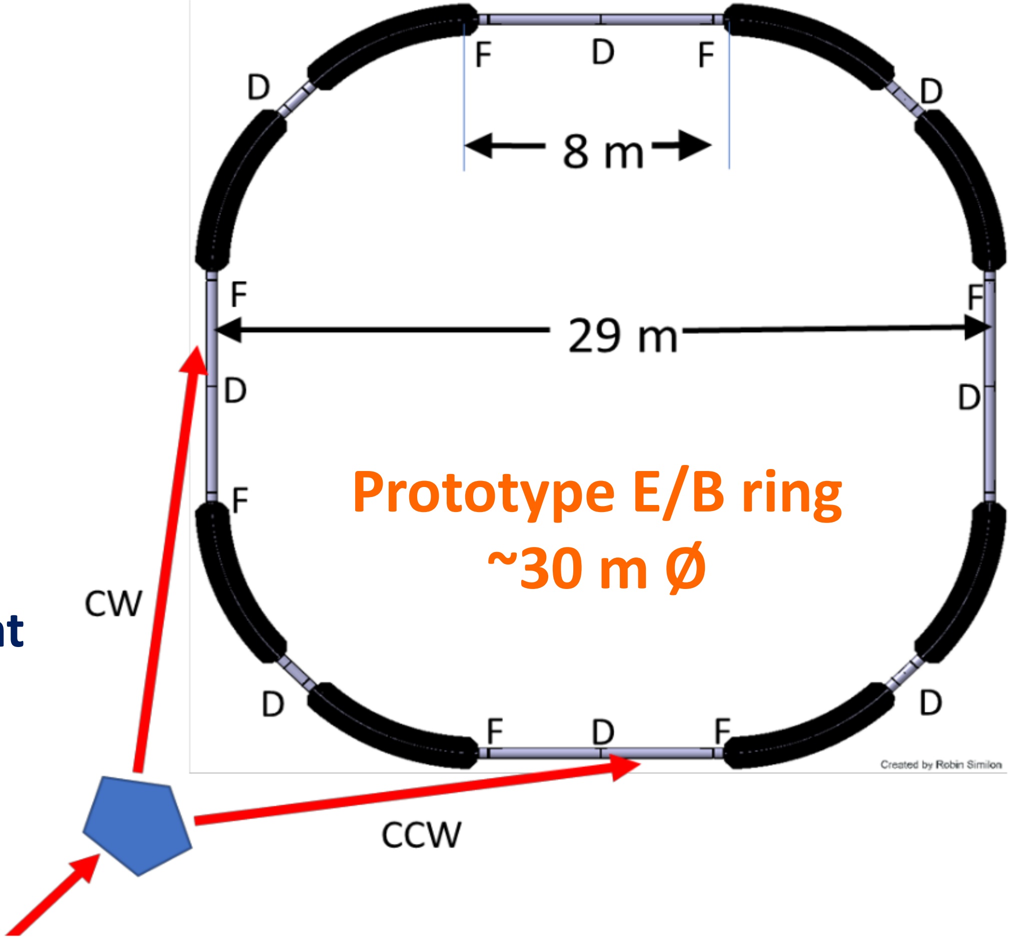
ALPHA, AEgIS, GBAR
Test free fall/equivalence principle with antihydrogen

PUMA
Antiproton/nuclei scattering to study neutron skins

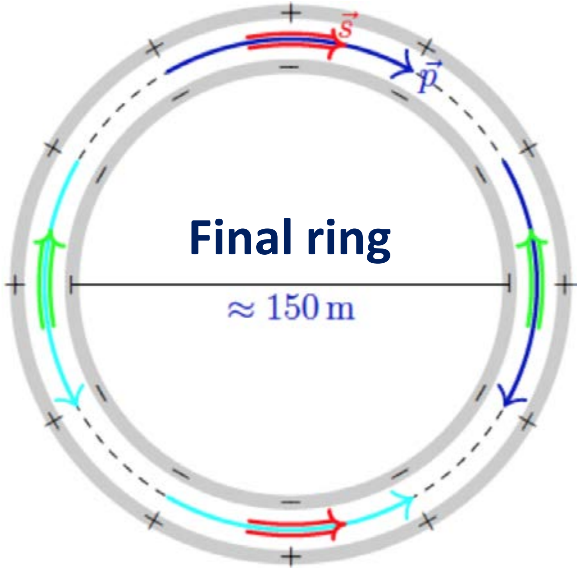
PROTON EDM RING

COSY at Jülich supported by EPPSU as possible site for developing the project

Ongoing precursor experiment at Jülich (magnetic ring)



Prototype E/B ring
~30 m Ø



Design sensitivity: 4. 10^{-29} e.cm

TDR for prototype ring in preparation by CPEDM Collaboration (incl. CERN)

Many systematics issues to be solved: lattice, deflectors, RF cavities, B-shield, BPMs…

SUMMARY & OUTLOOK

CERN PBC STUDY GROUP EXTENDED WITH UPDATED MANDATE TAKING INTO ACCOUNT EPPSU RECOMMENDATIONS

OPEN TO NEW IDEAS AT ANY TIME

PRIORITY STUDIES TO PREPARE DECISIONS ON POST-LS3 OPTIONS:
FPF, BDF, ECN3, ion sources, QCD facility…

NEXT OPEN PBC WORKSHOP ON 7-9 NOVEMBER 2022 AT CERN:
https://indico.cern.ch/event/1137276/

ADDITIONAL SLIDES

EPPSU DELIBERATION DOCUMENT

General statements of interest for PBC

…

A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. ***Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world.***

…

The particle physics community must further strengthen the unique ecosystem of research centres in Europe. In particular, cooperative programmes between CERN and these research centres should be expanded and sustained with adequate resources in order to address the objectives set out in the Strategy update.

…

Synergies between particle and astroparticle physics should be strengthened through scientific exchanges and technological cooperation in areas of common interest and mutual benefit.

…

EPPSU DELIBERATION DOCUMENT

A few specific projects mentioned…

…

These include measurements of electric or magnetic dipole moments of charged and neutral particles, atoms and molecules, rare muon decays with high intensity muon beams at PSI, FNAL and KEK, rare kaon decays at CERN and KEK, and a variety of charm and/or beauty particle decays at the LHC,

…

Accelerator-based beam-dump and fixed-target experiments can perform sensitive and comprehensive searches of sub-GeV dark matter and its associated dark sector mediators, complementary to high-energy colliders and other approaches.

…

Among the proposals for larger-scale new facilities investigated within the Physics Beyond Colliders study, the Beam Dump Facility at the SPS emerged as one of the frontrunners. However, such a project would be difficult to resource within the CERN budget, considering the other recommendations of this Strategy.

…

. In addition to the examples already mentioned above, a broad programme of axion searches is proposed at DESY, a search for low-mass dark matter particles with a positron beam is under way at Frascati, and the COSY facility could be used as a demonstrator for measuring the electric dipole moment of the proton at Jülich. These initiatives should be strongly encouraged and supported.

…

The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied.

…

The design studies for next-generation long-baseline neutrino facilities should continue.

UPDATED PBC MANDATE: SCIENTIFIC GOALS

Scientific goal

The main goal of the Study Group remains to explore the opportunities offered by CERN's unique accelerator complex, its scientific and technical infrastructure, and its know-how in accelerator and detector science and technology, to address today's outstanding questions in particle physics through initiatives that complement the goals of the main experiments of the Laboratory's collider programme. Examples of physics objectives include dedicated experiments for studies of rare processes and searches for feebly interacting particles. The physics objectives also include projects aimed at addressing fundamental particle physics questions using the experimental techniques of nuclear, atomic, and astroparticle physics, as well as emerging technologies such as quantum sensors, that would benefit from the contribution of CERN competences and expertise. The study group will primarily investigate, and, where appropriate, provide support to, projects expected to be sited at CERN. The study group may also examine ideas and provide initial support for contributions to projects external to CERN. The study group is also expected to act as a central forum for exchanges between the PBC experimental community and theorists for assessment of the physics reach of the proposed projects in a global landscape.

UPDATED PBC MANDATE: ORGANIZATION

Organization

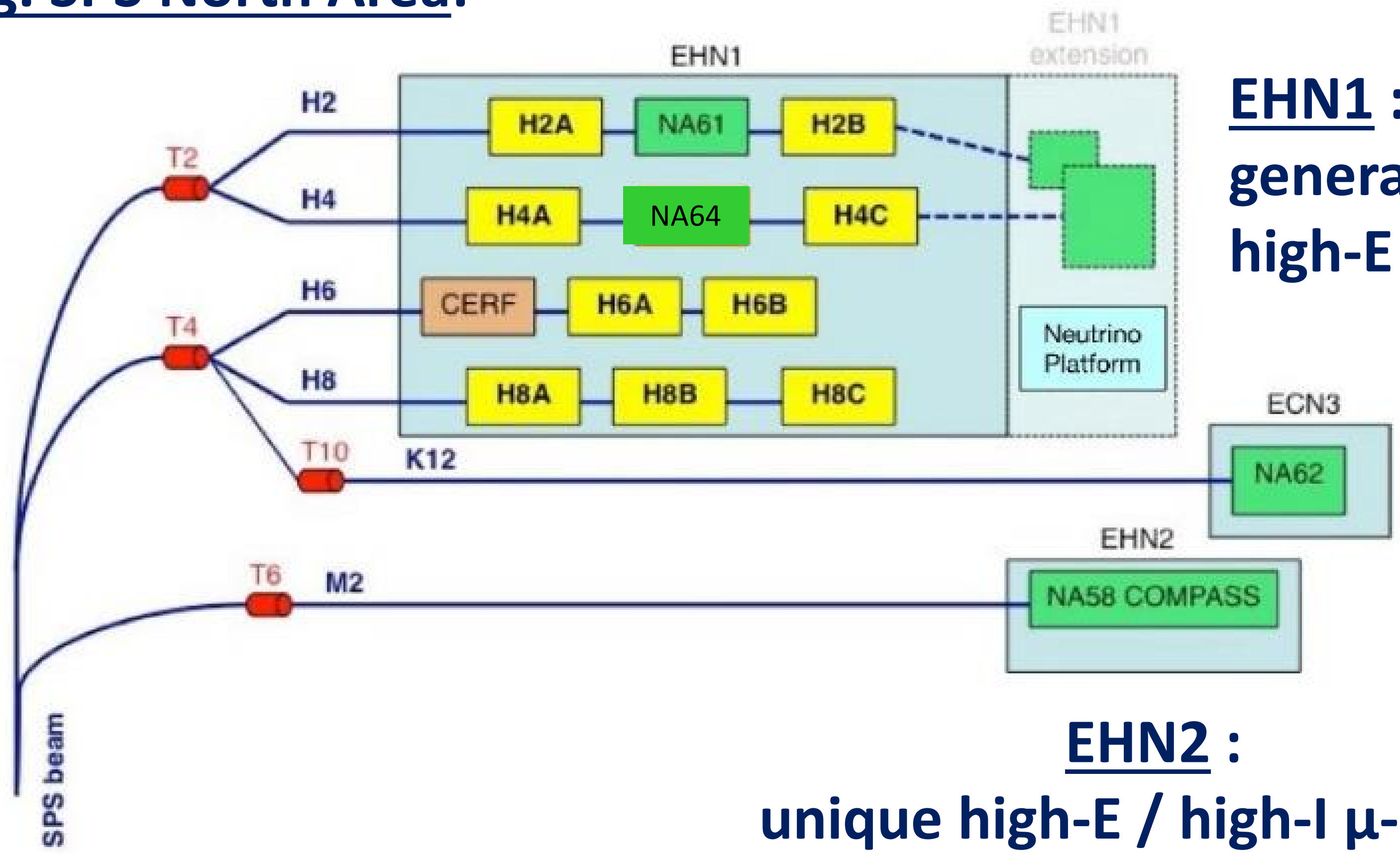
The group will continue to be led by three coordinators representing the scientific communities of accelerator, experimental, and theoretical particle physics. The coordination team reports to the CERN Directorate. The coordinators will update the PBC working group structure to reflect the updated PBC mandate and input from the community.

The PBC study group will act as CERN's initial portal for new ideas which may come in spontaneously or through specific calls launched by the PBC coordination team. The group will facilitate and support an initial evaluation of the relevance and technical feasibility of the ideas in a global context, and will regularly inform the CERN scientific committees (INTC, SPSC or LHCC) about their findings. Where appropriate, oversight of PBC studies will be passed to the relevant CERN scientific committee once they are adequately mature for scrutiny and review of possible implementation.

IMPLEMENTATION CONSTRAINTS OF NEW PROJECTS

Governed to a great extent by existing beamlines/halls/experiments

e.g. SPS North Area:



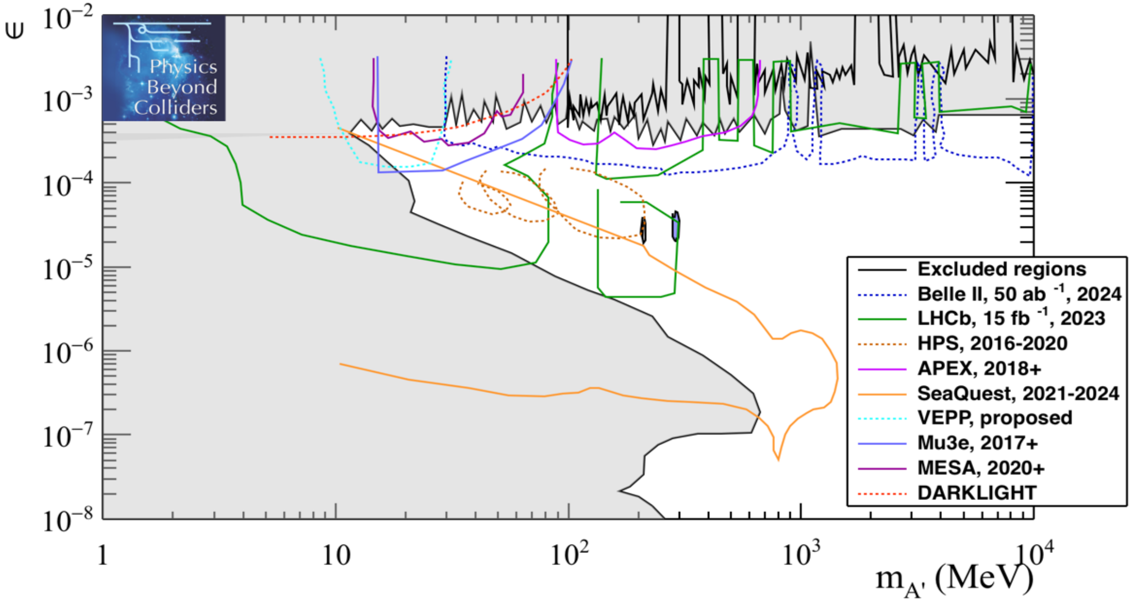
EHN1 :
general purpose hall with unique high-E / medium-I beams for all particles

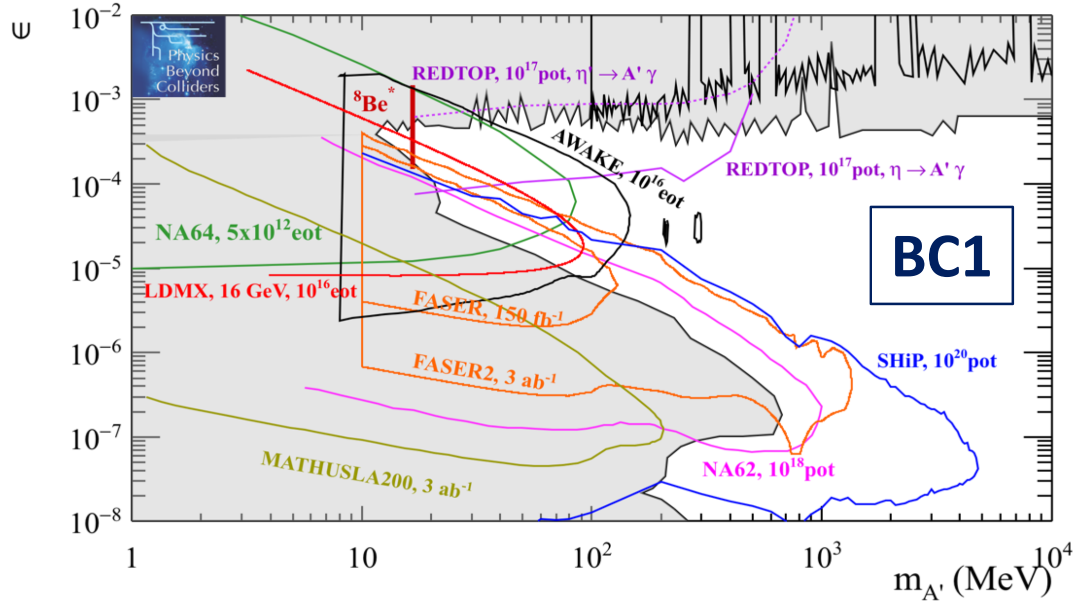
ECN3 :
unique underground hall for high-I hadron beams

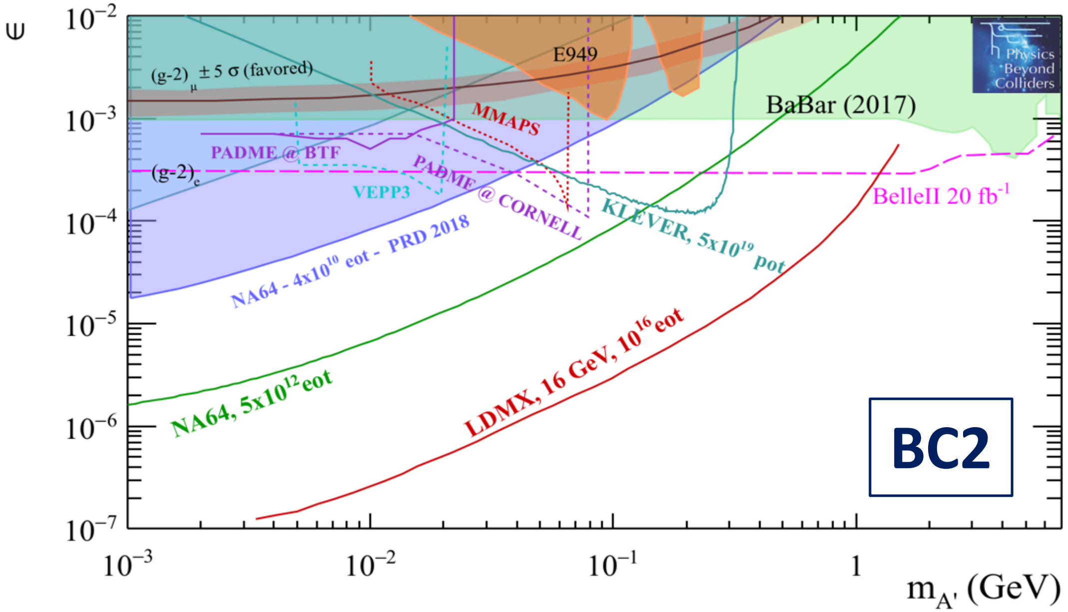
EHN2 :
unique high-E / high-I μ-beam

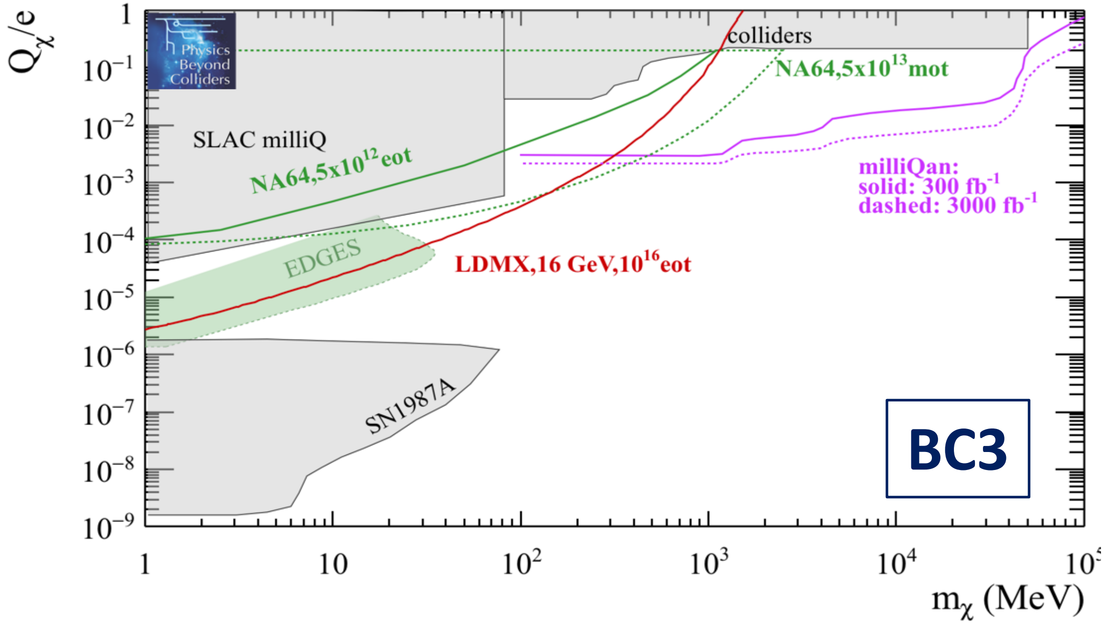
DARK VECTORS

BC1 worldwide context



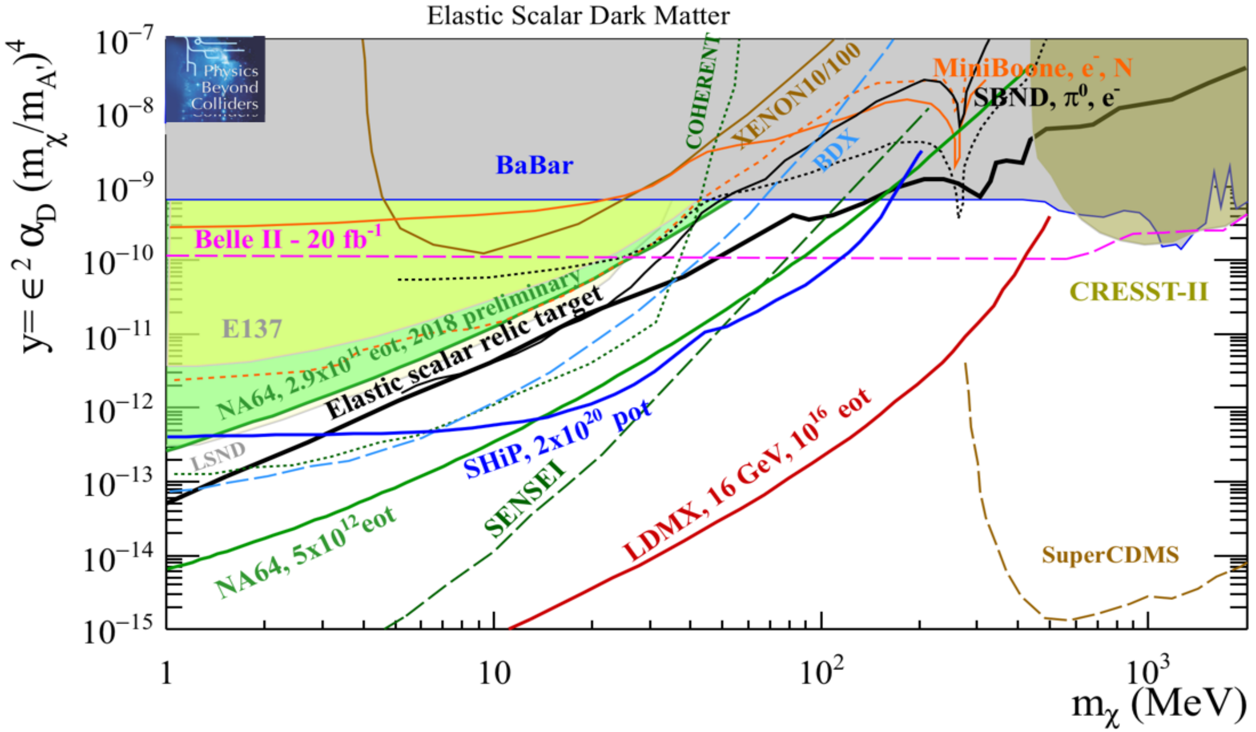


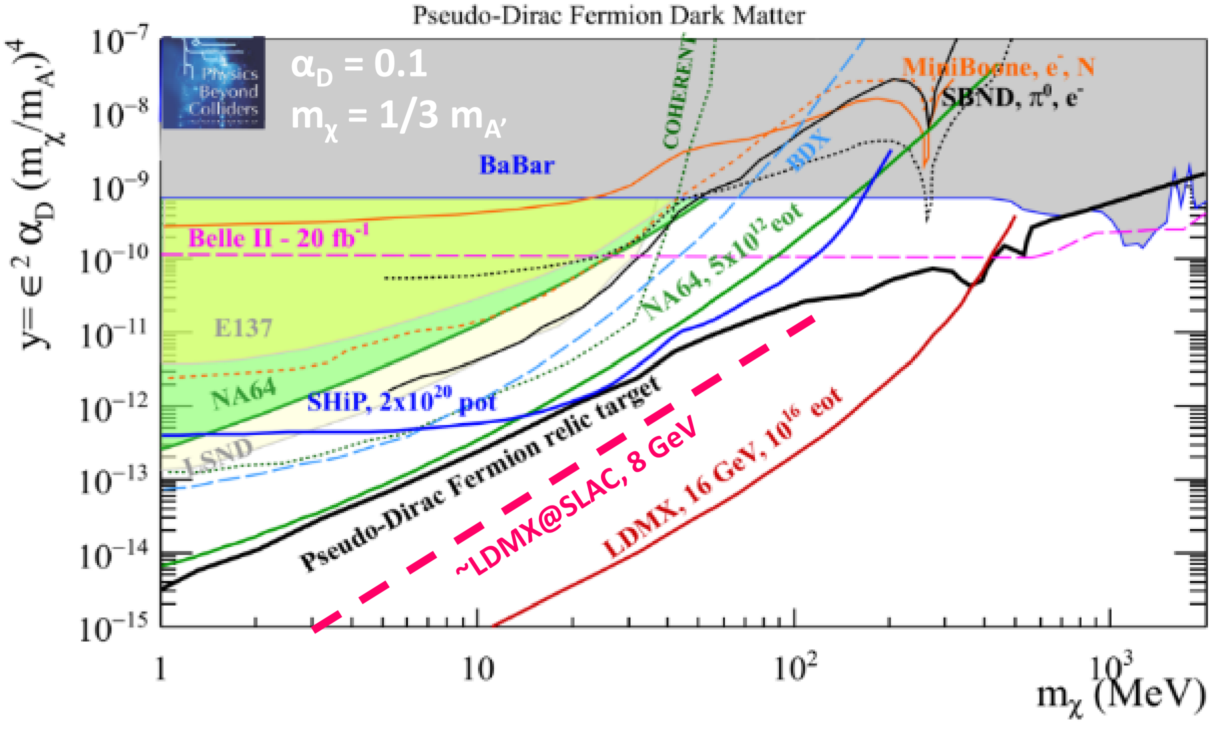




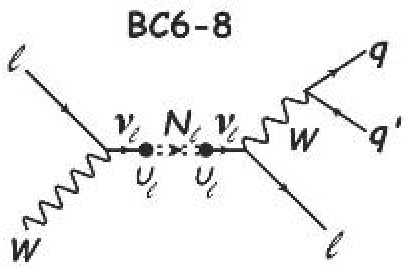
DARK VECTORS IN DM PARAMETER SPACE (BC2)

$\alpha_D = 0.1 \quad m_\chi = 1/3\ m_{A'}$

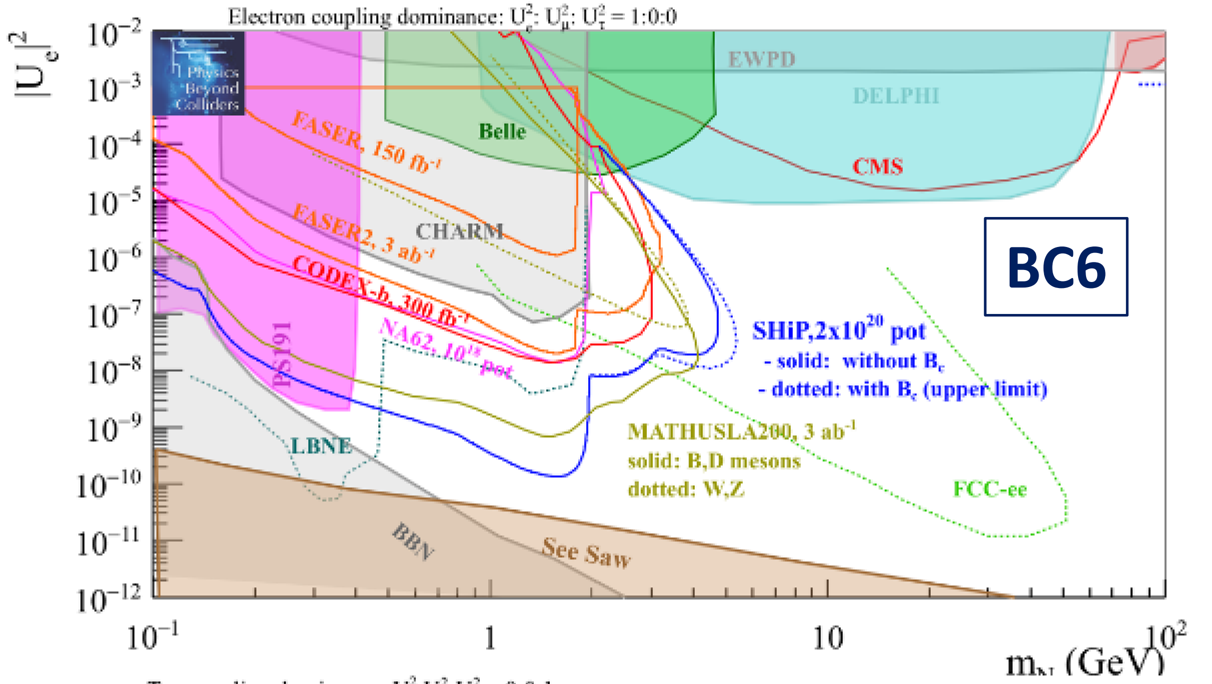


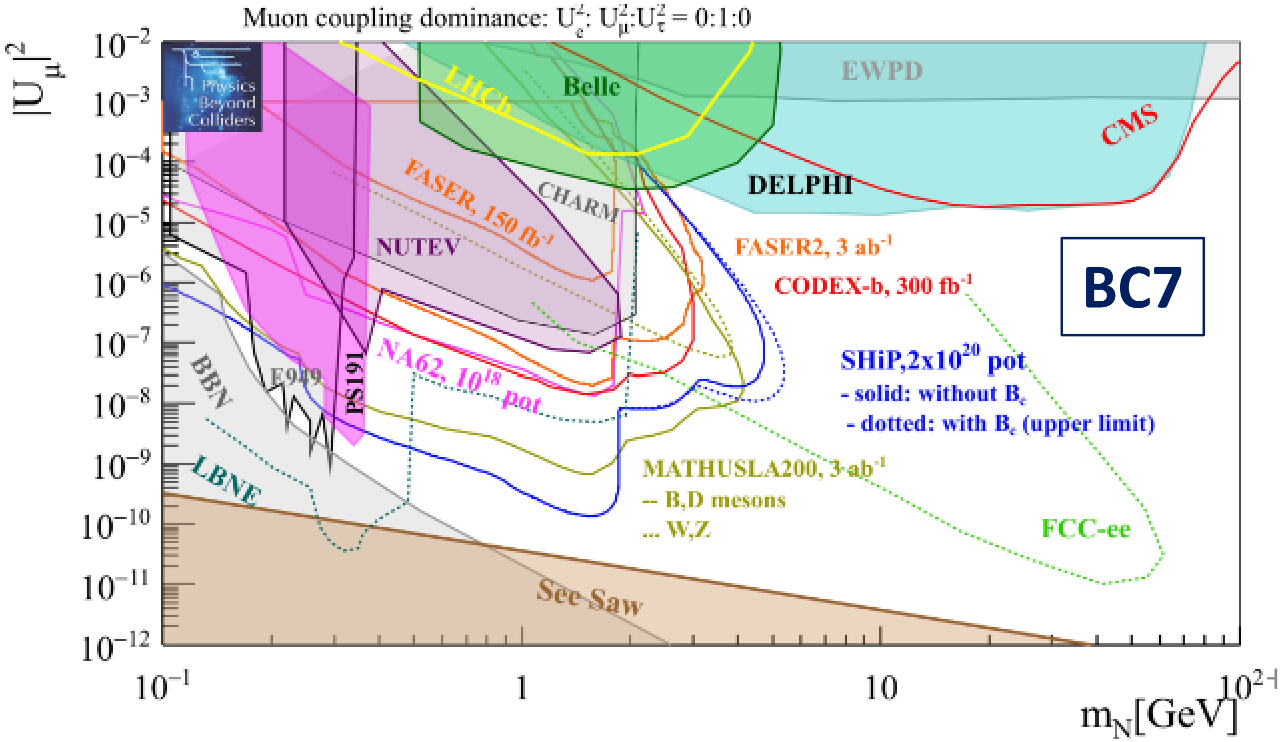


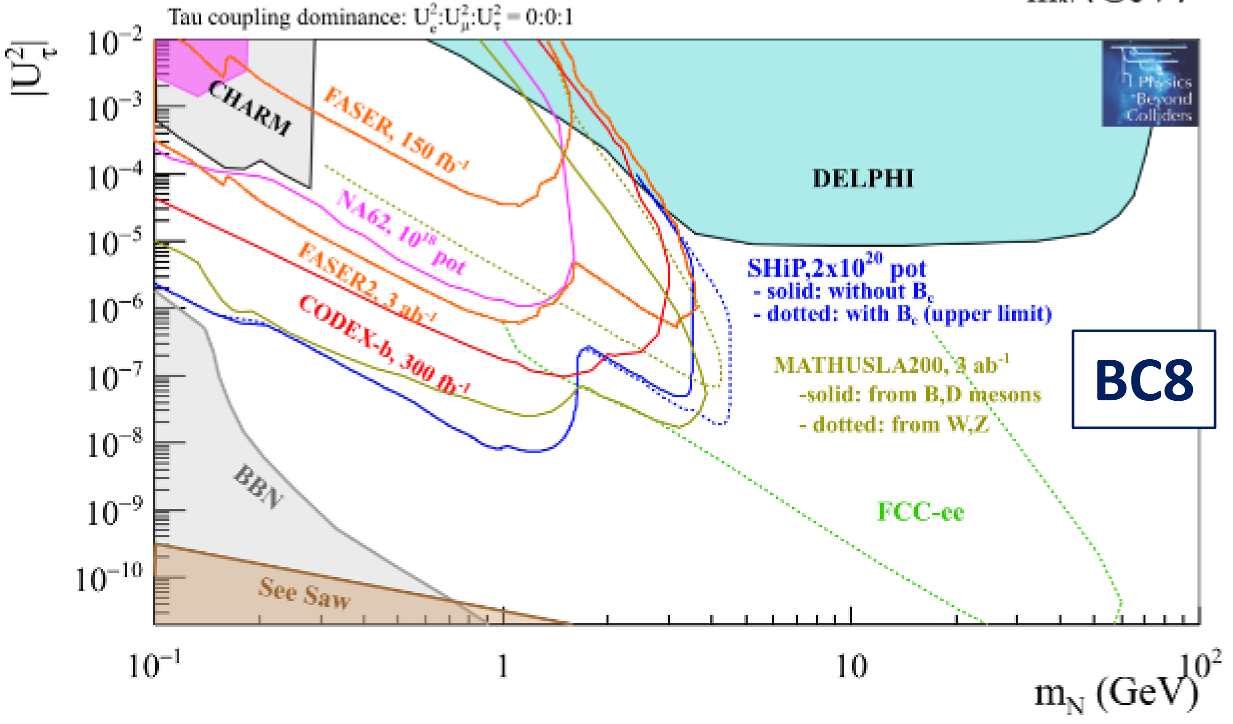
SENSITIVITIES TO DARK FERMIONS (HNL's)



- Unique short term opportunities with NA62 Beam Dump and FASER
- SHiP has the highest reach on the long term

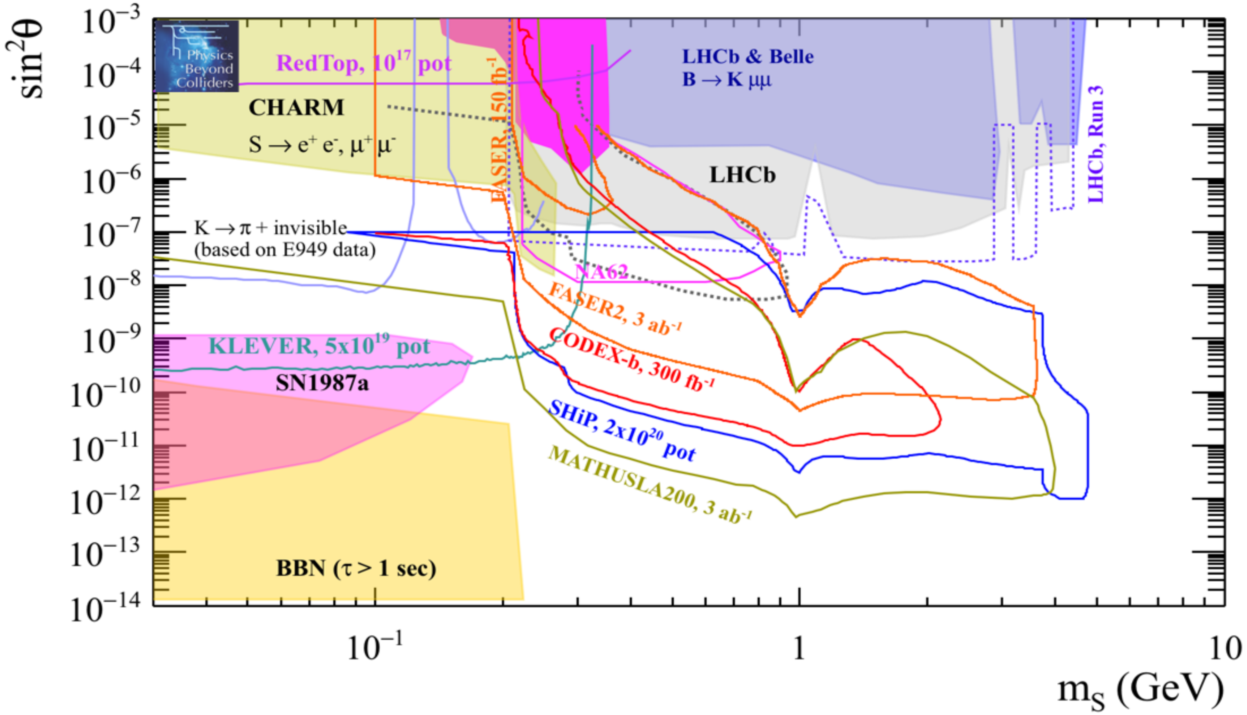




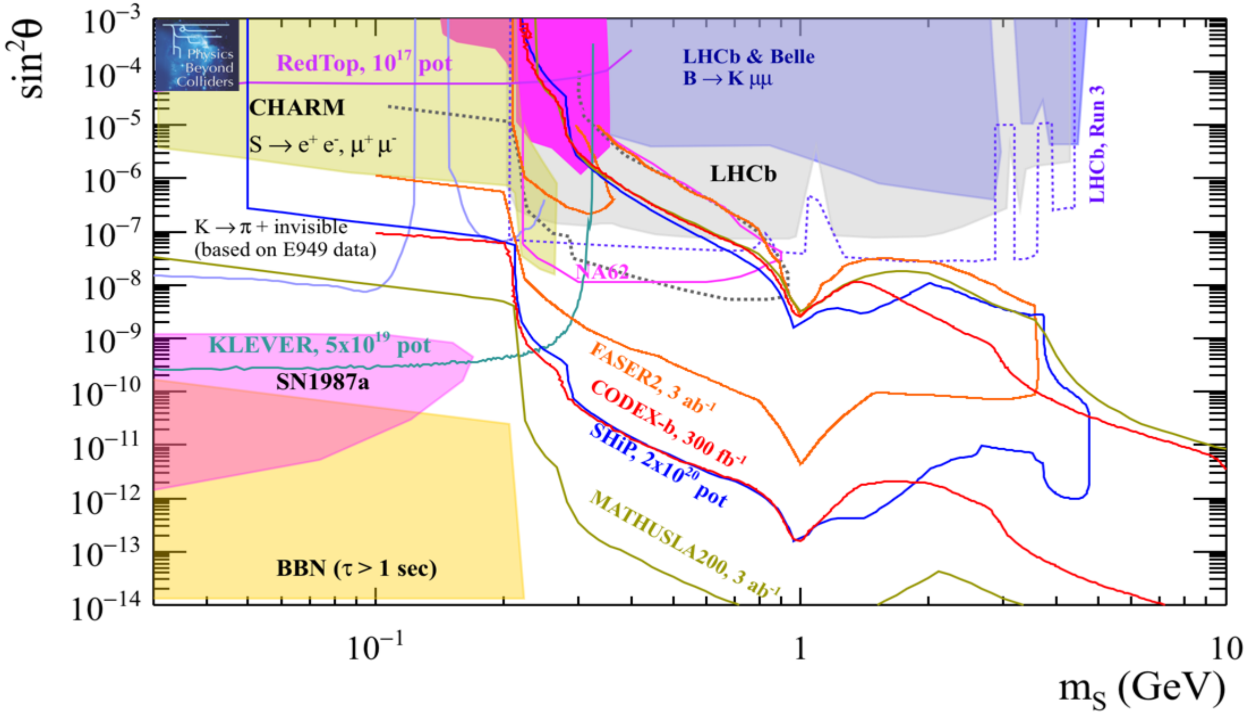


DARK SCALARS

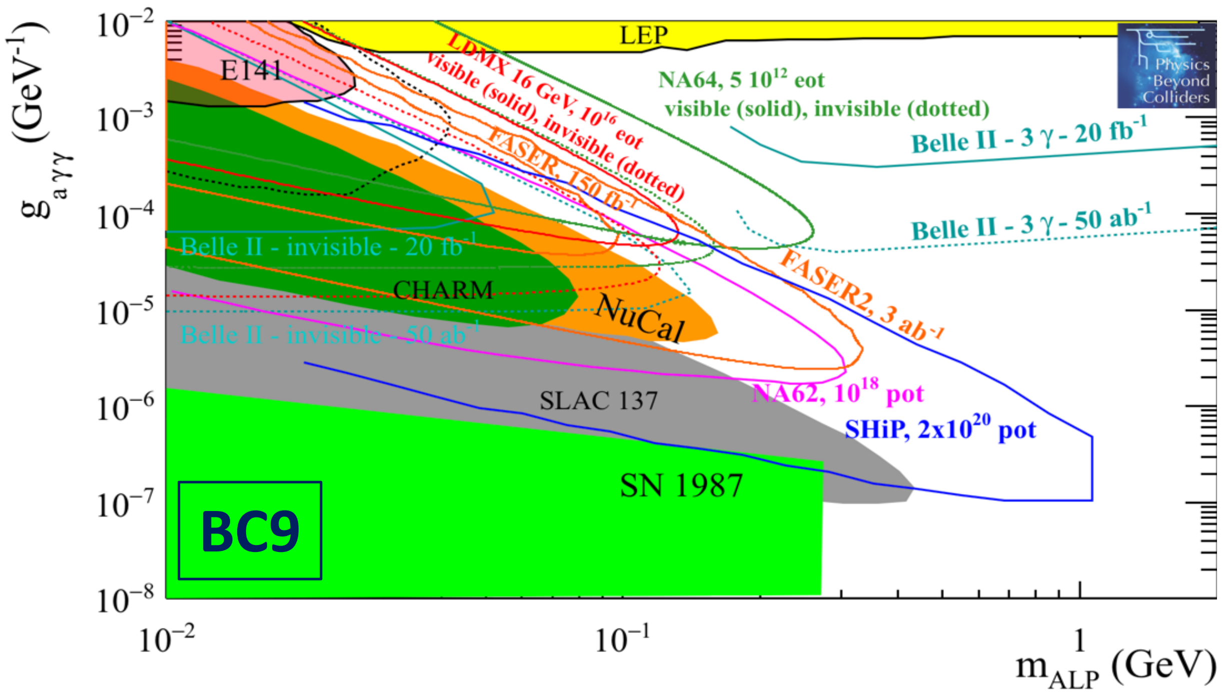
BC4

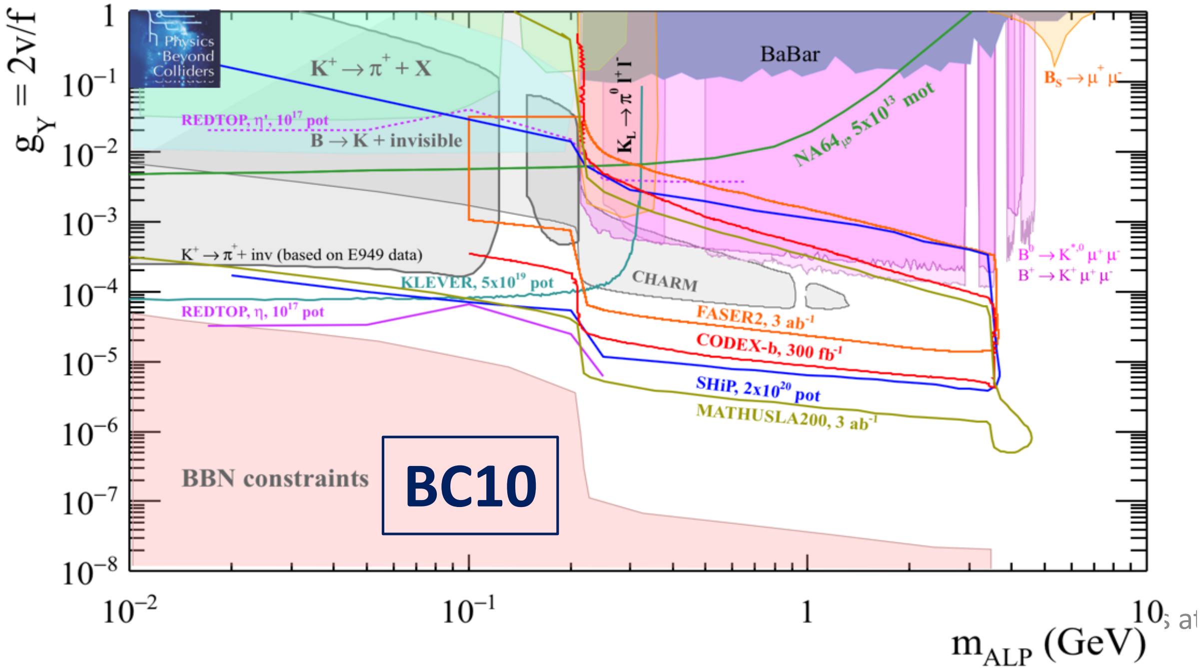


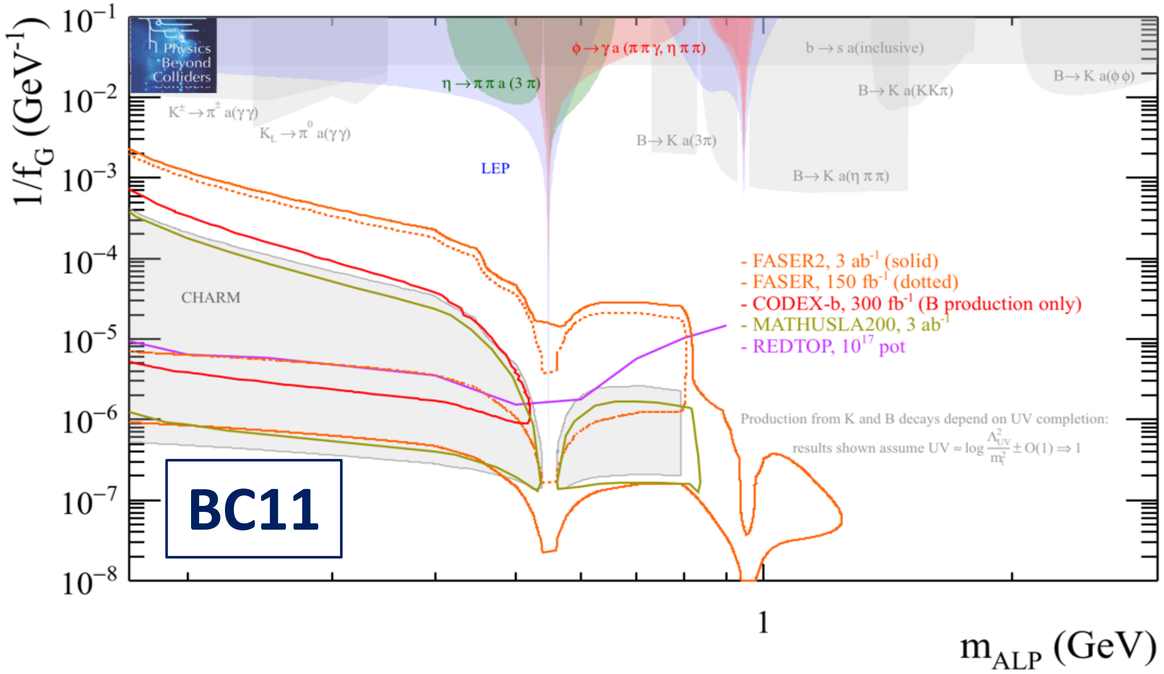
BC5



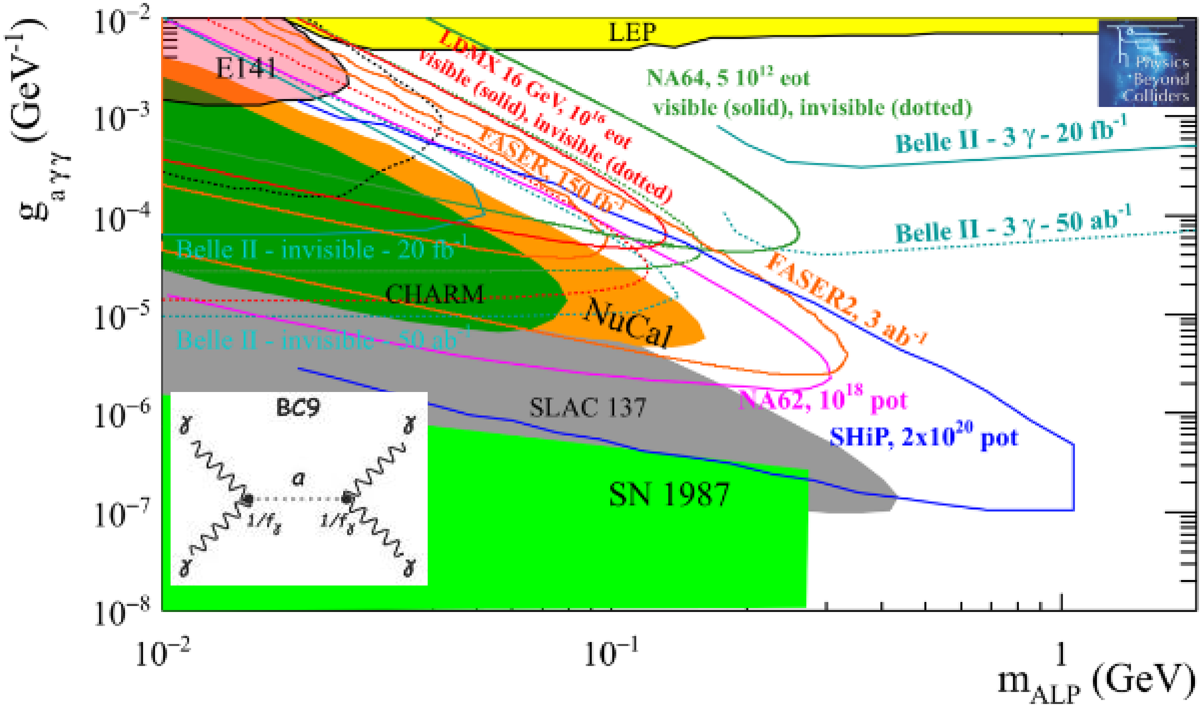
ALPS IN BEAMDUMPS

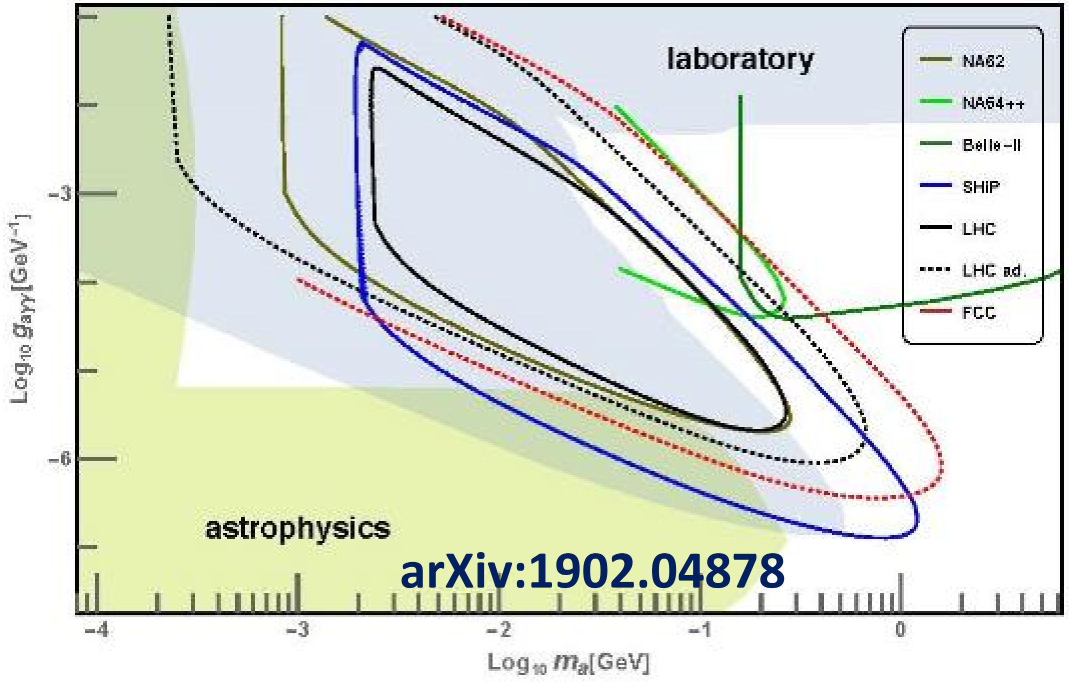






EXPLORATORY STUDY OF HIGHER-ENERGY BEAM DUMPS POTENTIAL
the example of ALPs





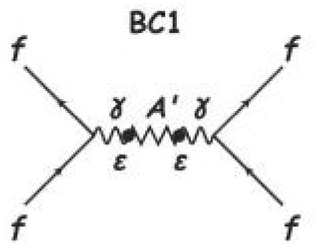
PBC projects have a similar reach as for visible A'
(similar signatures γγ and e^+e^-)

No real breakthrough of LHC/FCC beam dumps:

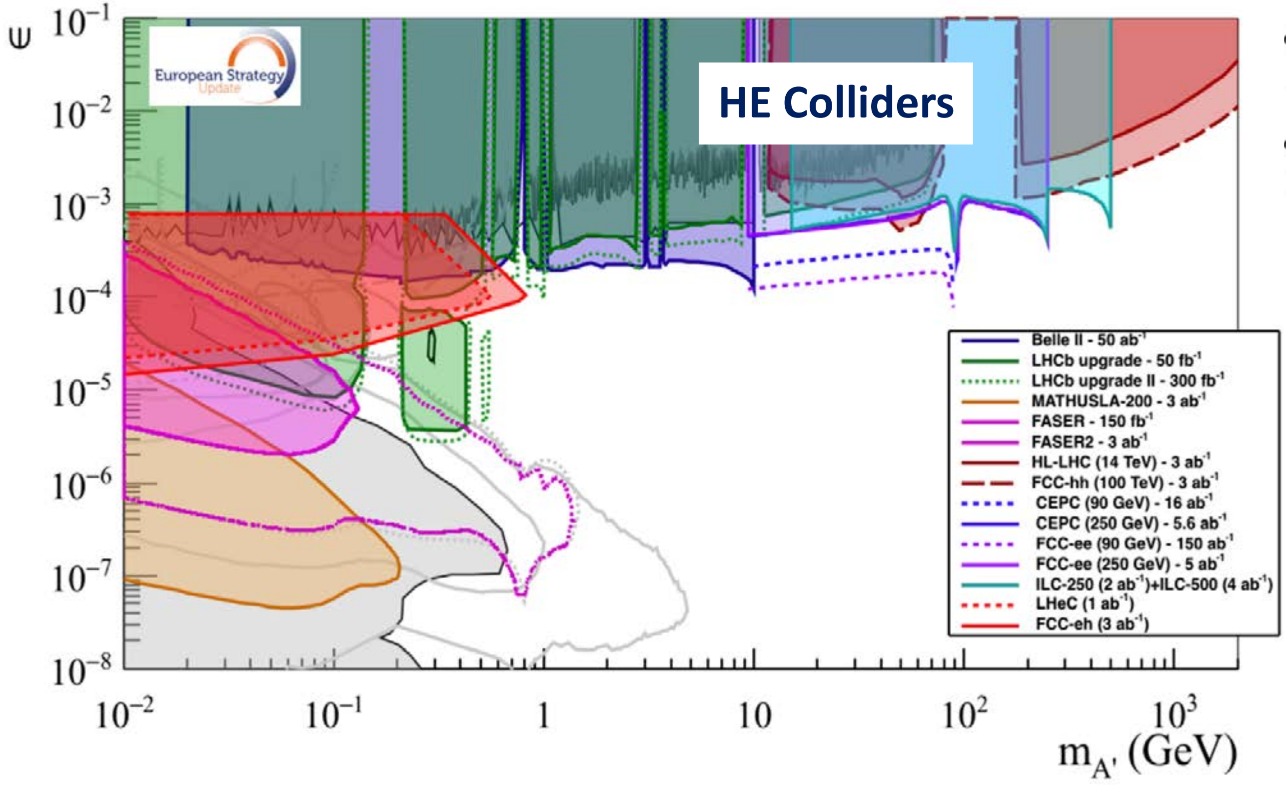
SPS seems to offer a quite optimal energy-intensity mix in the present context

NEW THEORETICAL DIRECTIONS

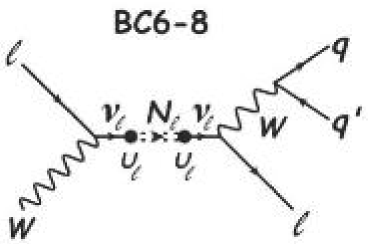
Method was extended to colliders for EPPSU Briefing Book

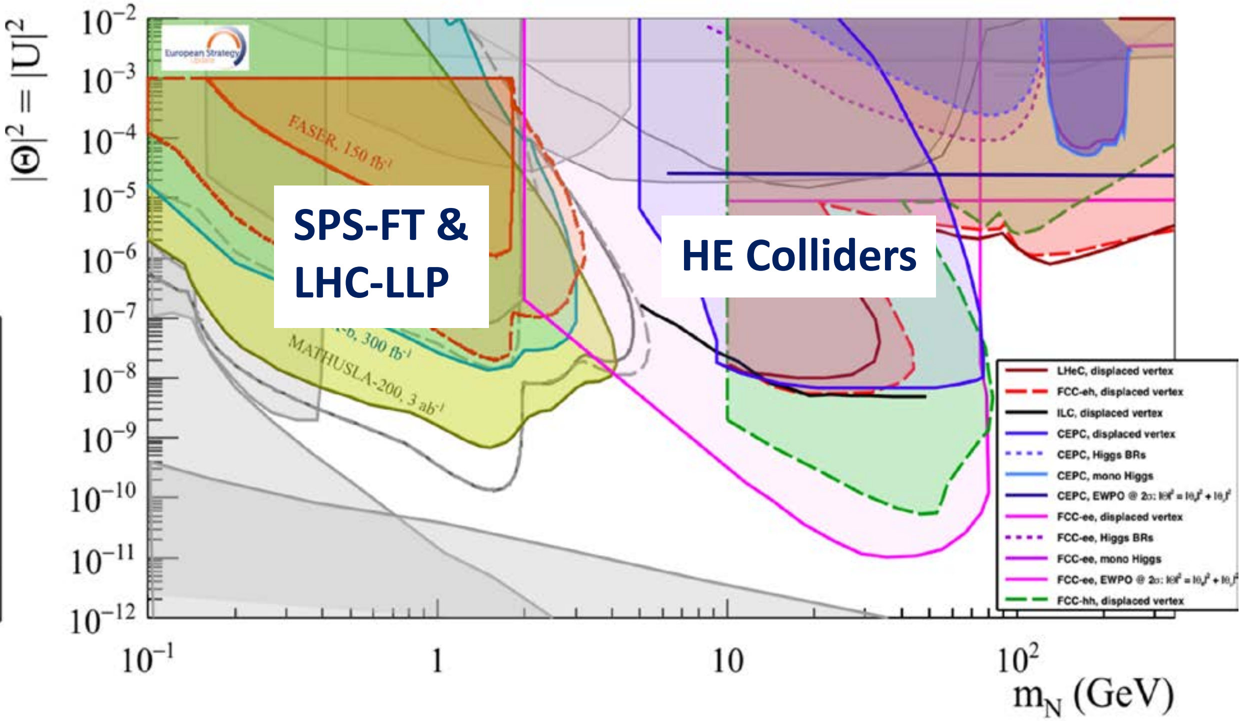


Dark Photons



HNLs

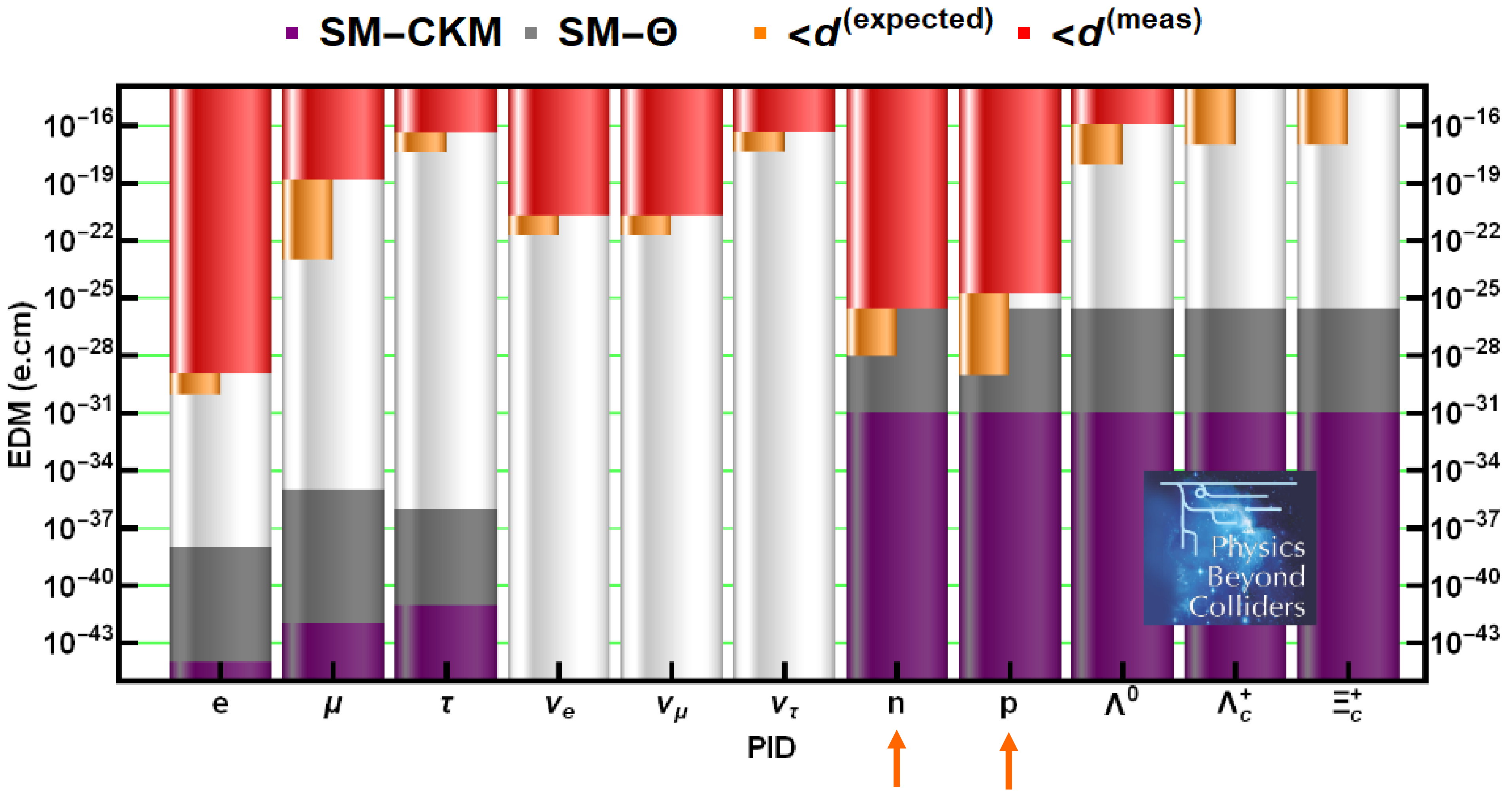




Further extension to all domains dealing with Feebly Interacting Particles has started

see FIPs kick-off workshop https://indico.cern.ch/event/864648/ and report arXiv:2102.12143

EDM LANDSCAPE



Neutron EDM is leading the field for hadrons

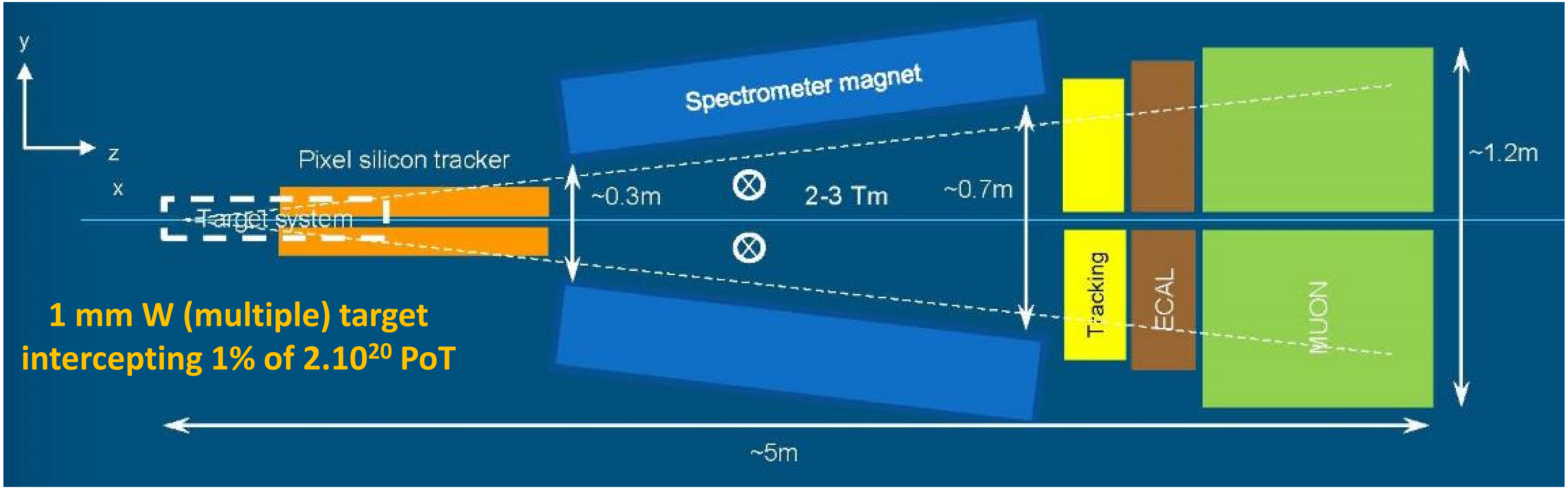
Catching up in precision is a challenge for the proton

TauFV

New idea introduced within PBC

Interception of small BDF beam fraction to look for τ → 3μ decays

Could set limits on branching ratio better than 10^{-10} level targeted by BELLE-II



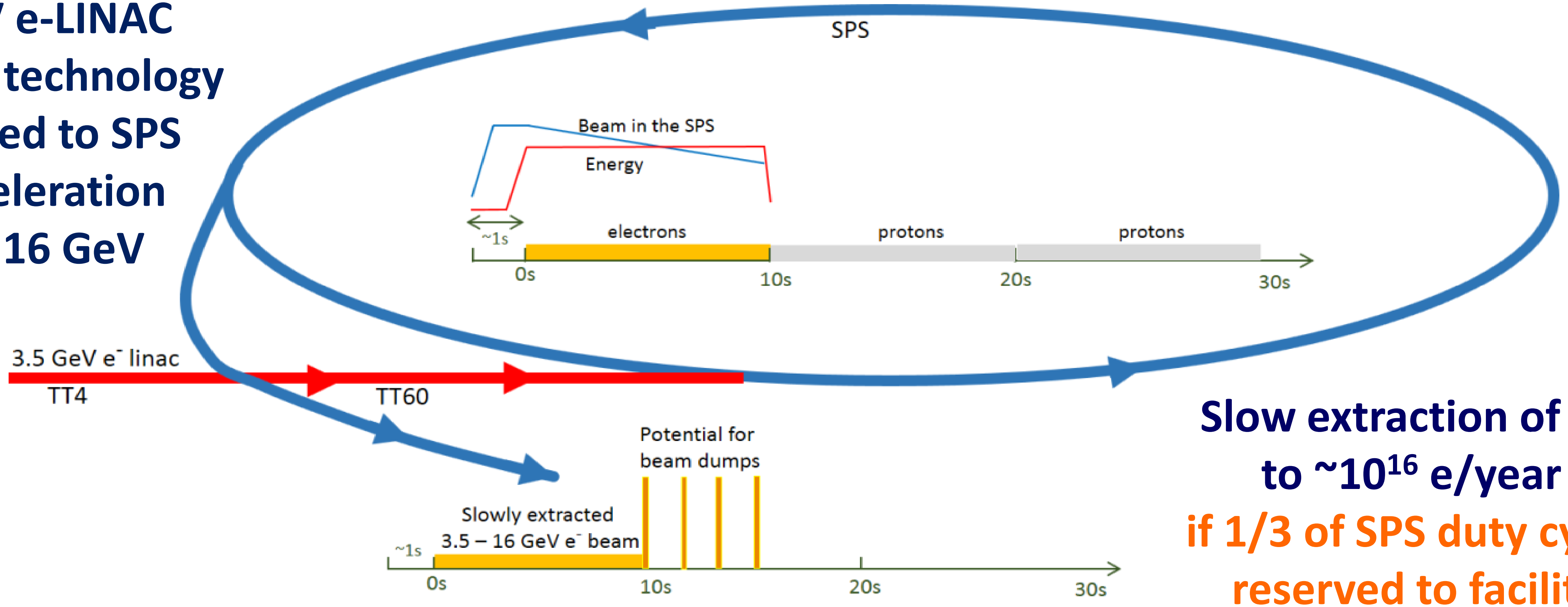
Implementation layout under study

A small experimental hall upstream of BDF target could trigger a unique rare decay facility

NEW e-BEAM: eSPS

… building on CLIC R&D

3.5 GeV e-LINAC with CLIC technology connected to SPS for acceleration up to 16 GeV



Slow extraction of up to ~10^{16} e/year

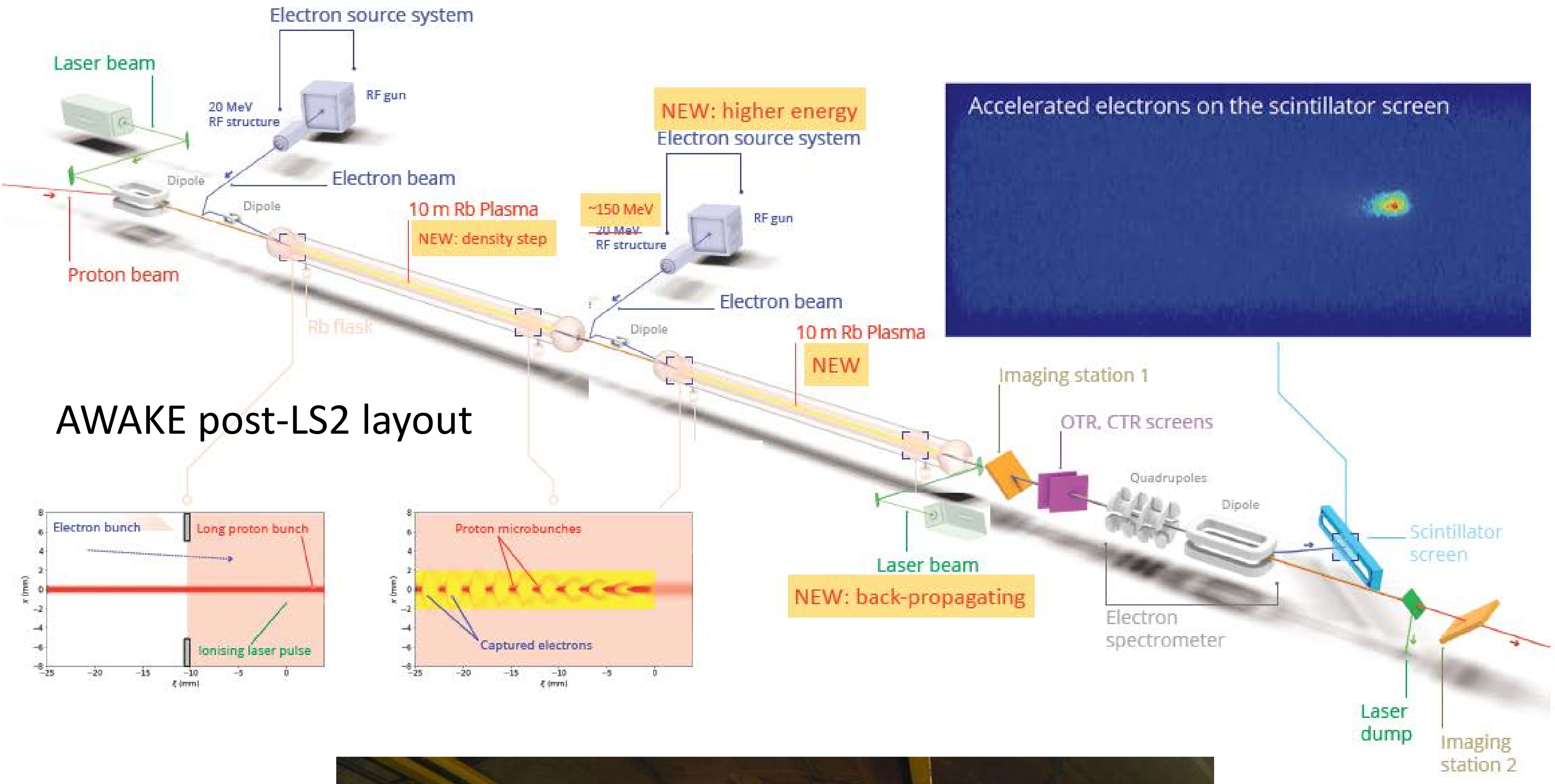
if 1/3 of SPS duty cycle reserved to facility

Conceptual Design Report released in 2020 under PBC

Project now on hold following positive momentum of LCLS-II/LDMX competitor at SLAC

NEW e-BEAM: AWAKE++

Electron acceleration
on wake fields from proton
micro-bunches in a plasma cell

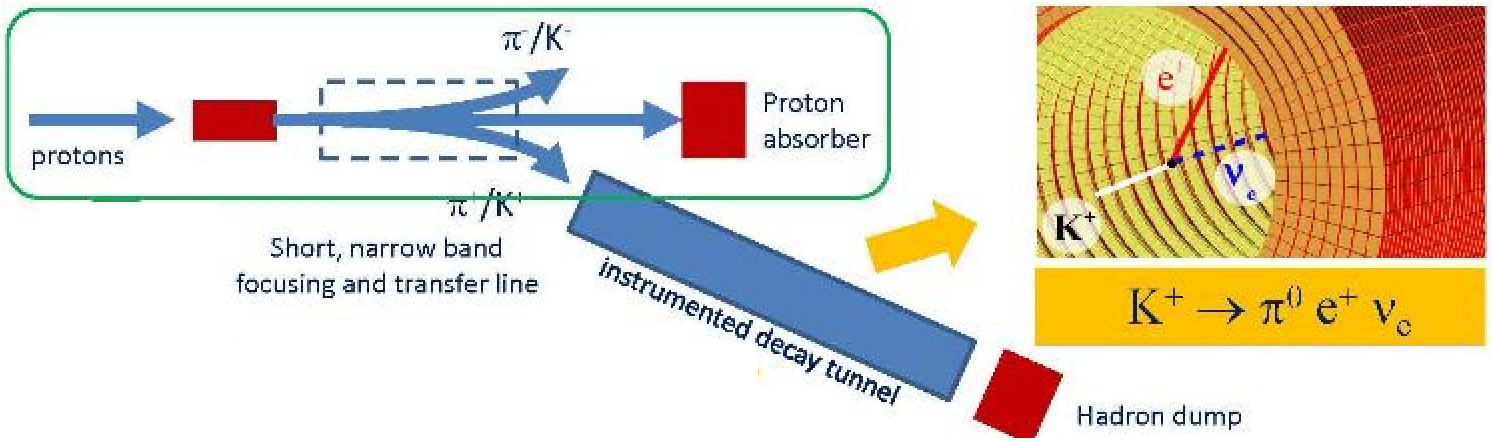


Proof of principle validated
in 2018 with electrons
accelerated up to 2 GeV

Could serve the purpose of
an electron beam dump experiment
located in the CNGS decay tunnel
in the post-LS3 era

R&D FOR NEUTRINO BEAMS

Recent new ideas of tagged ν beams being investigated for precision measurements and next generation LBL projects

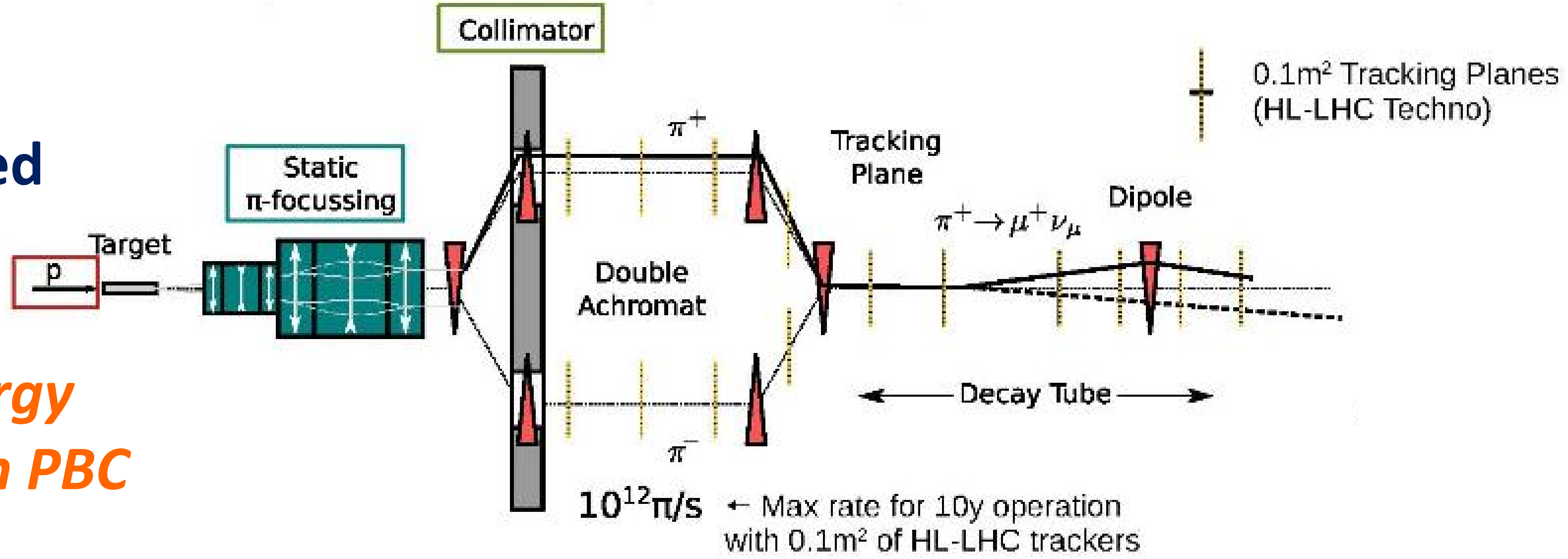


ENUBET:

- ν_e beam monitored from K decays
- Prototyping ongoing in Neutrino Platform within ERC grant
- *Possible implementation at CERN to be studied in PBC*

NuTAG:

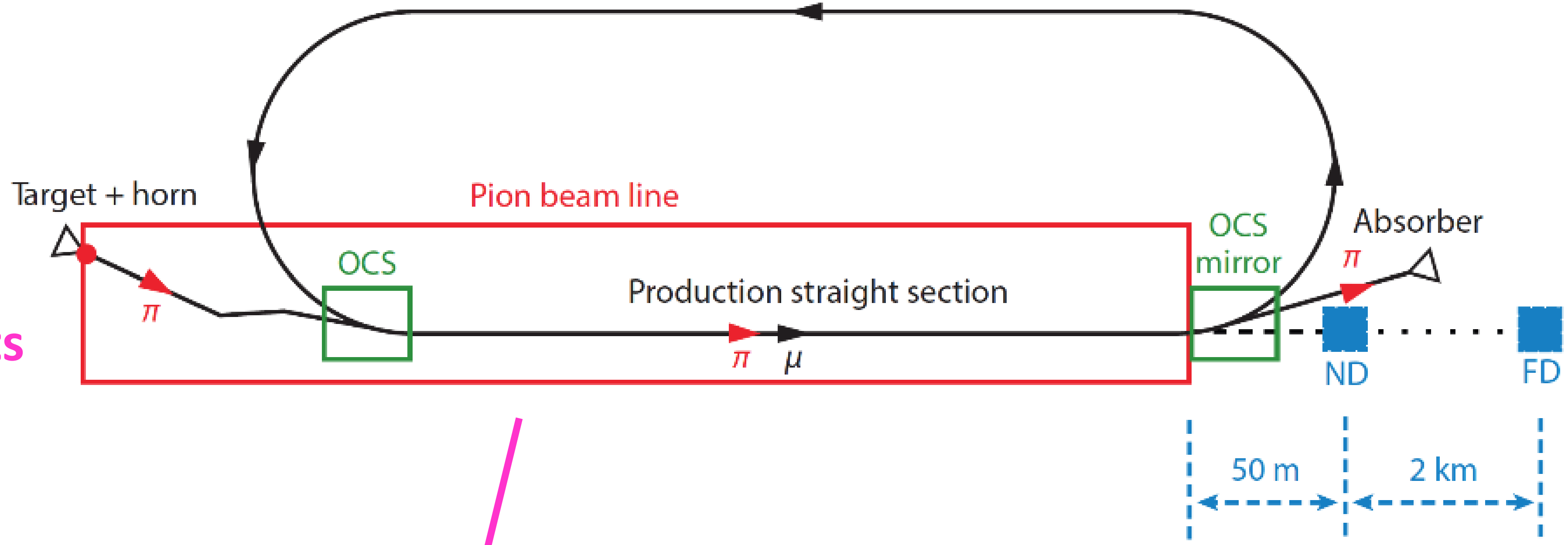
- ν_μ beam with $(E_\nu, \theta_\nu, \phi_\nu)$ tagged from individual π decays with HL-LHC silicon trackers
- *Feasibility and possible synergy with ENUBET to be studied in PBC*

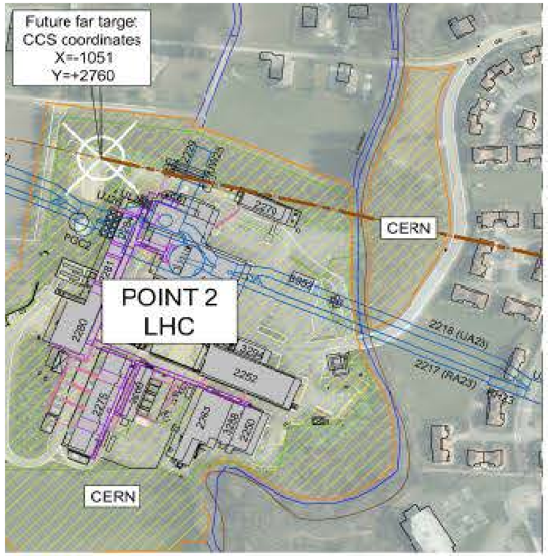


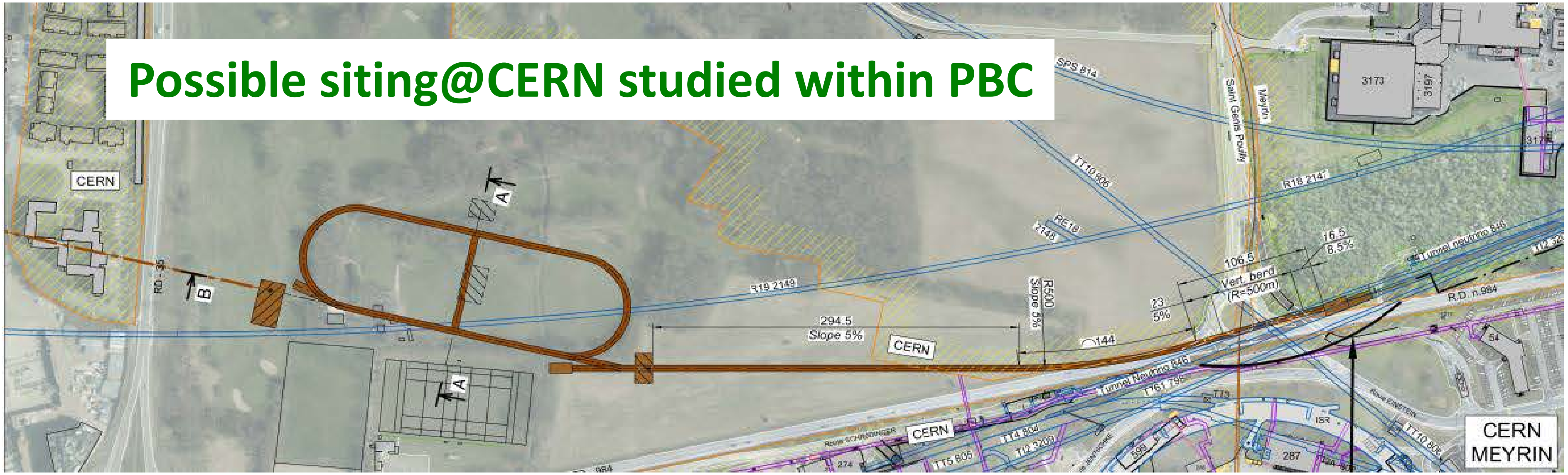
NuSTORM

Well controlled ν beam from a μ storage ring

Precise σ(ν) measurements and a path towards a ν factory or a μ collider.



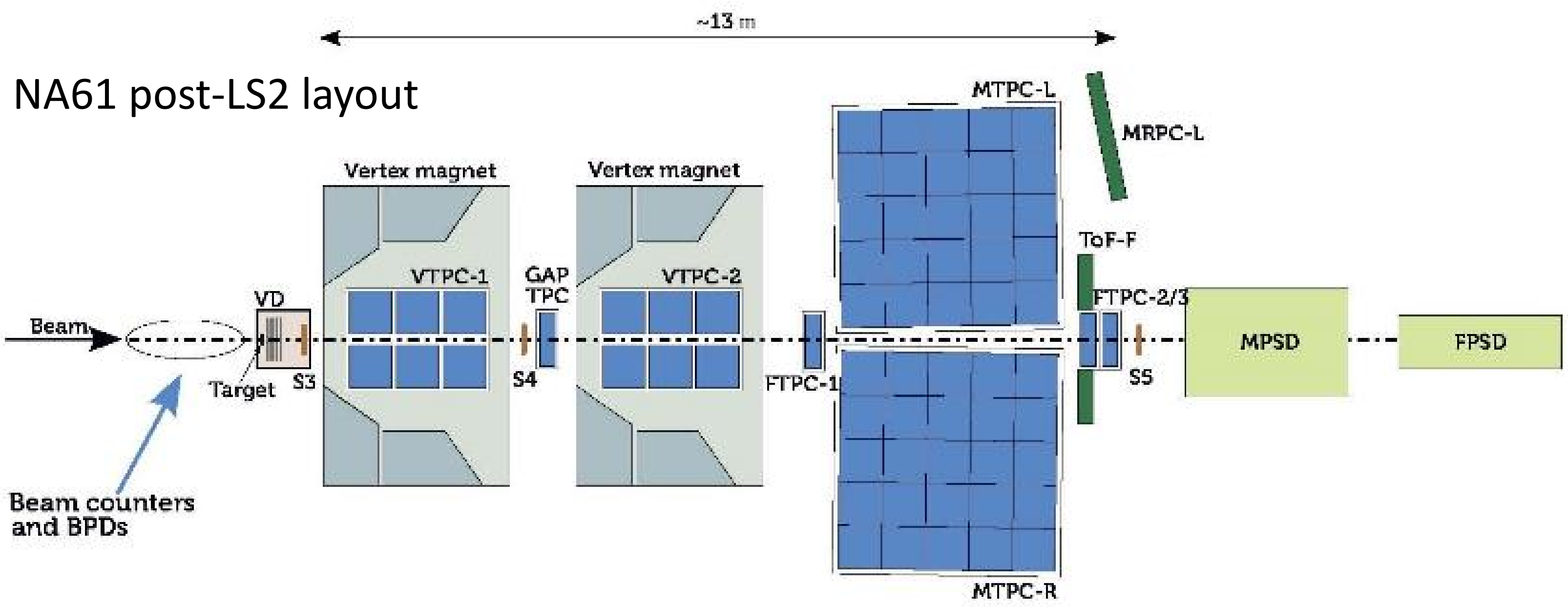




NA61

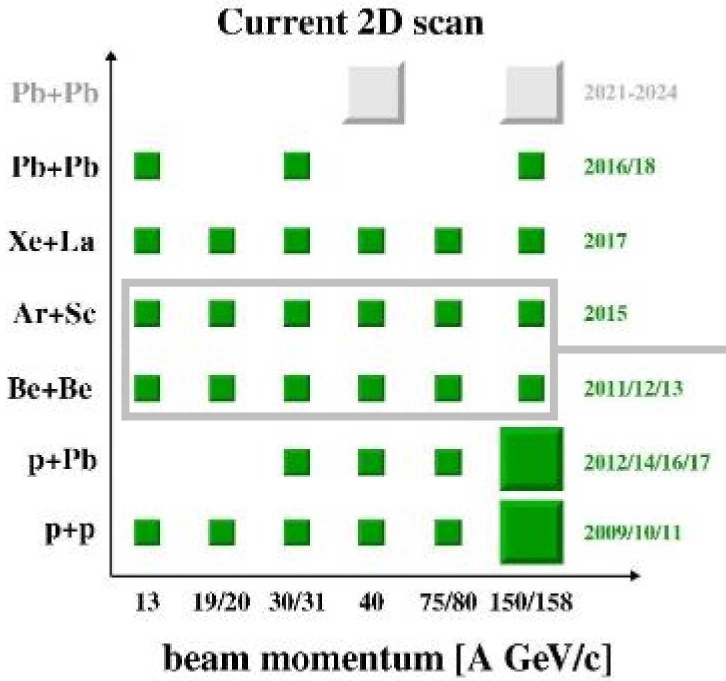
Post-LS2:

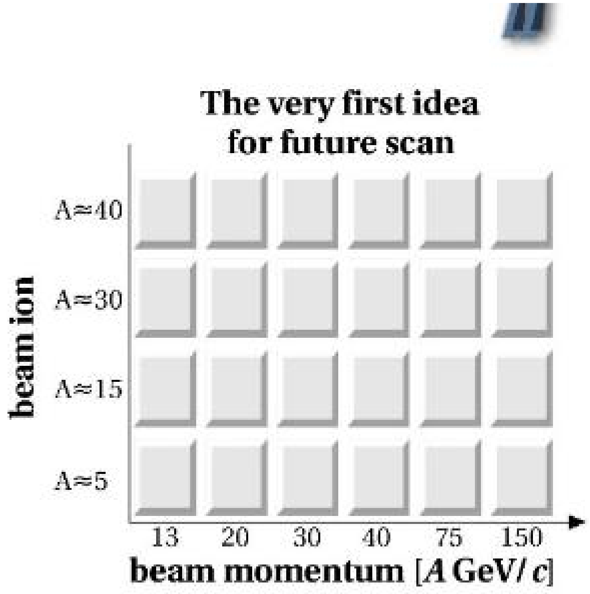
- ***Successful upgrades to study open charm close to expected CP-region.***
- Also unique measurements for ν-beams and cosmic rays
- ***To be followed by SPSC***



Post-LS3: *(preliminary ideas)*

- ***Finer grain 2-D scan to study onset of fireball***
- Antiproton and low-E beams for baryon stopping studies
- Continued measurements for ν-beams and cosmic rays
- ***To be followed by PBC***

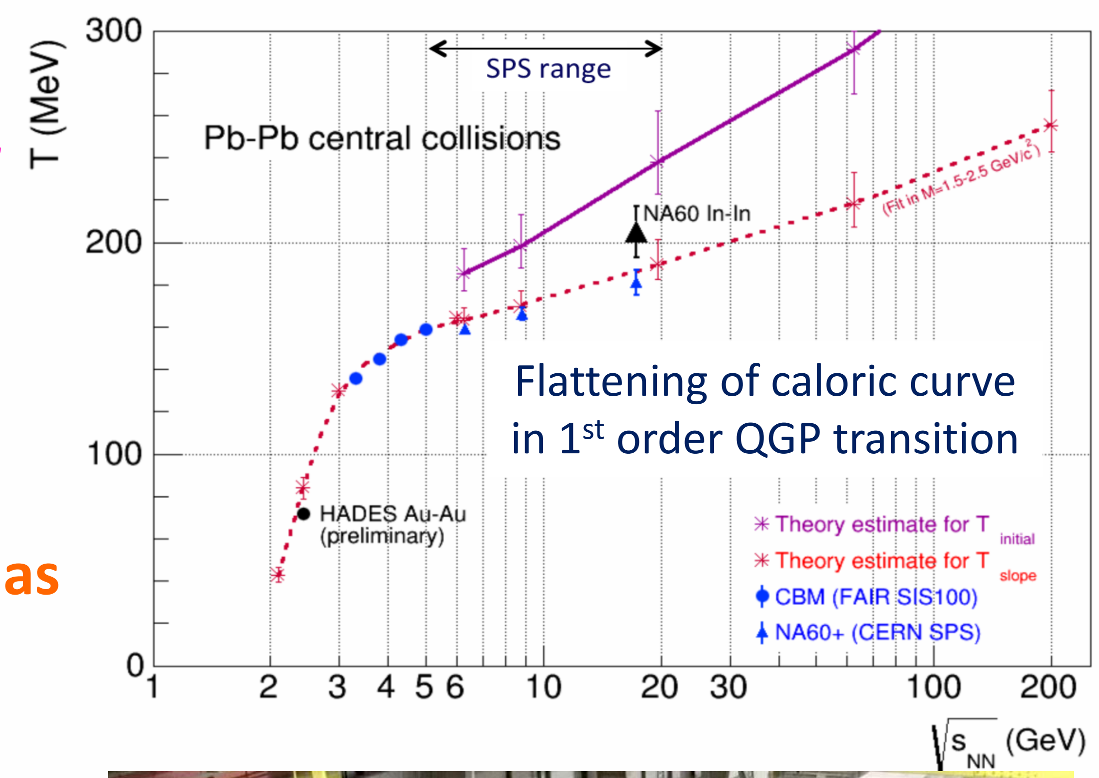


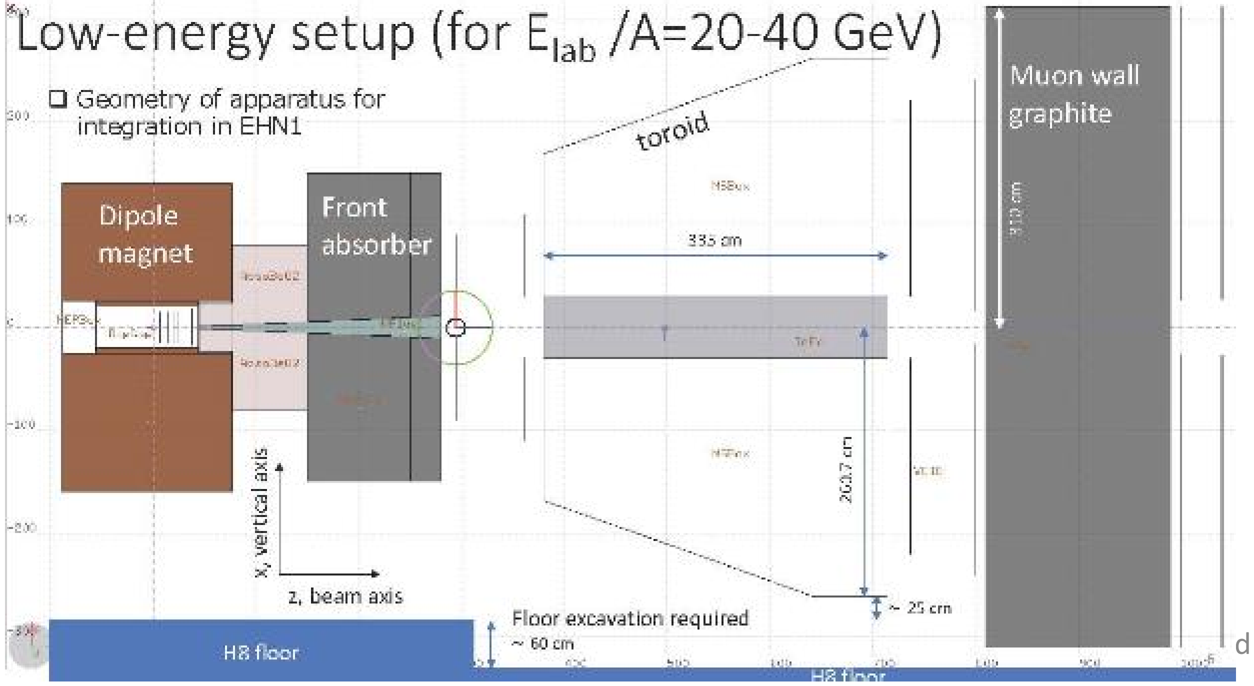


NA60++

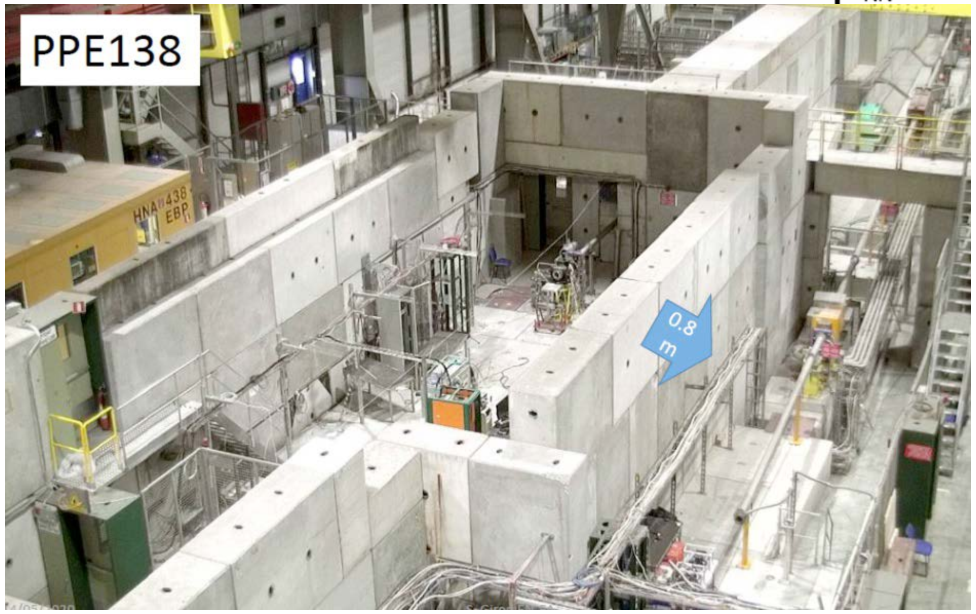
Revival of NA60 concept to measure caloric curve of 1st order QCD transition with low-E dimuons

- New location found on EHN1 H8 beam to avoid conflict with NA62 in ECN3 → *impact of reduced intensity by factor 4 to be quantified*
- Toroid design ongoing with PBC support, as well as detector developments in synergy with HL-LHC



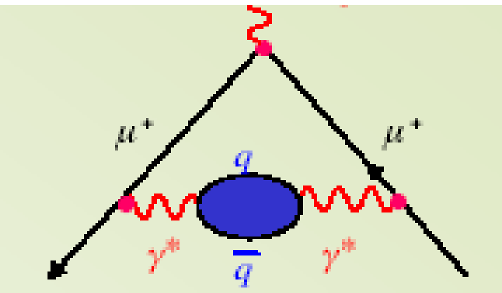


d beyond

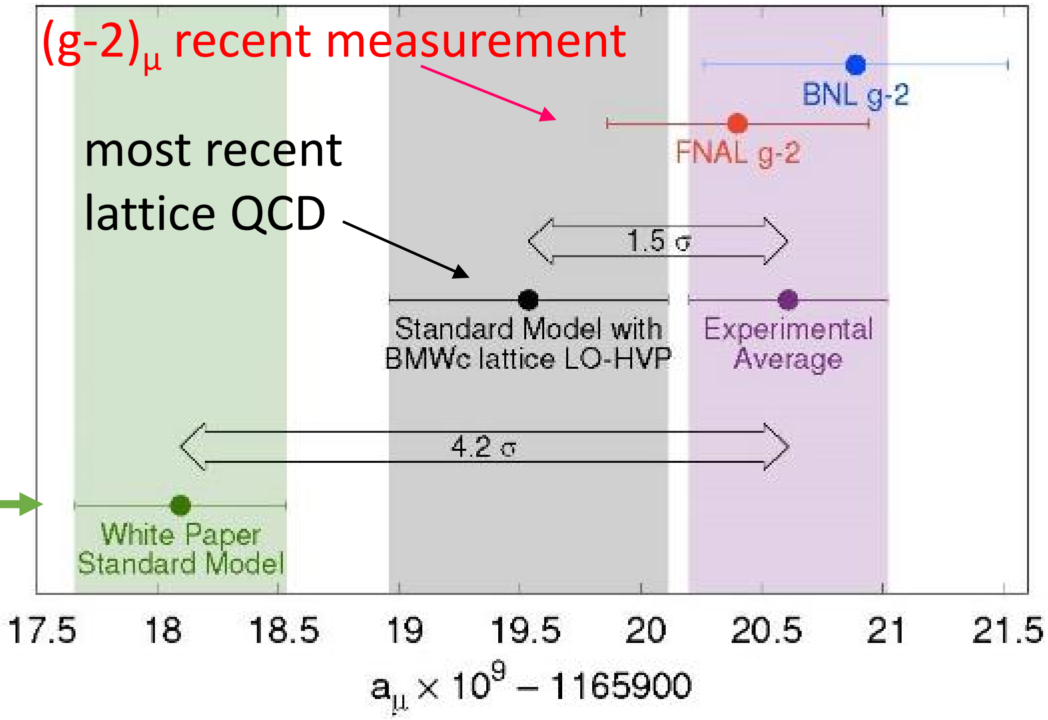


New idea introduced within PBC:

MUonE

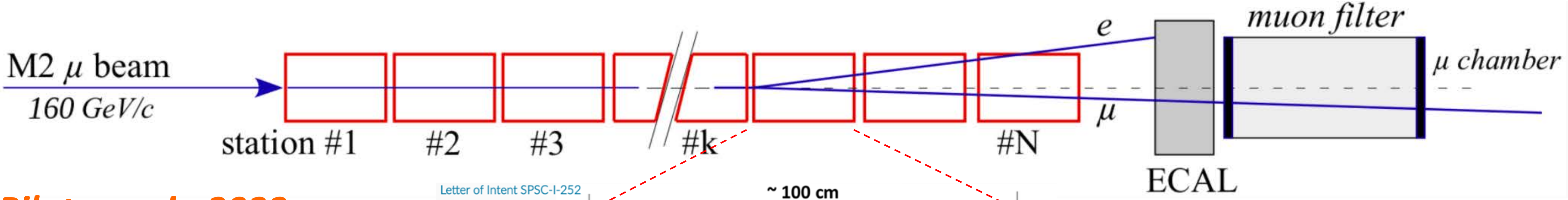


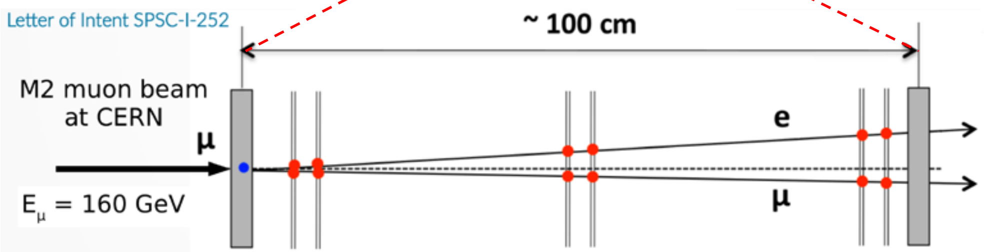
Direct measurement of
HVP contribution to $(g-2)_\mu$
with μ-e elastic scattering



Complementary to prediction based on dispersion relation with e^+e^- data

Very challenging experimentally:
10^{-5} (relative) precision required on cross-section





Pilot runs in 2022

Full data taking aimed for during run 3

Now in the hands of the SPSC

COMPASS(R_p)

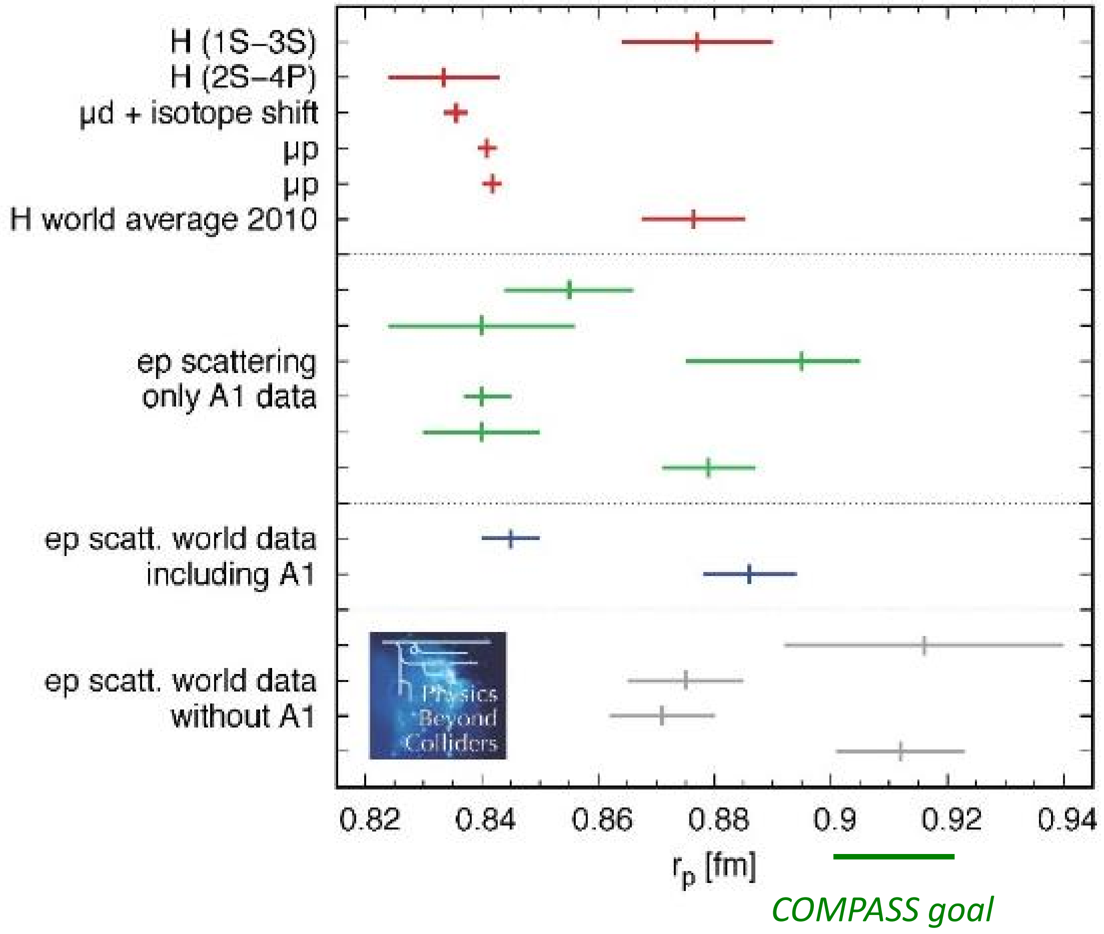
μ-p elastic scattering

In competition with MUonE on same μ-beam in EHN2

→ COMPASS spectrometer

new COMPASS TPC

Proton radius puzzle

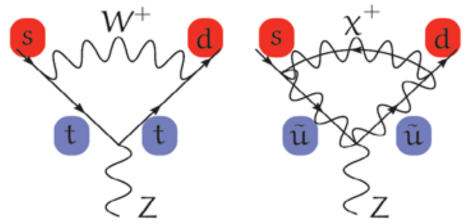


Data taking planned during run 3 provided successful pilot run

Project now in the hands of the SPSC

$K \to \pi\nu\bar{\nu}$ (BR ~ 10^{-10})

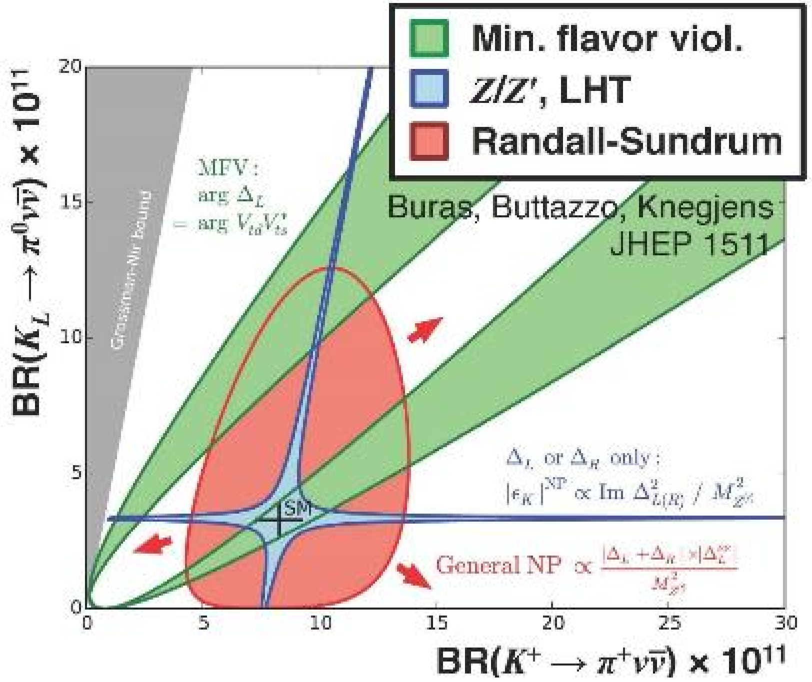
ULTRA-RARE K DECAYS



NA62 (K^+):

Run 2: 20 events seen for 17 expected (10 SM + 7 BG)

Run 3: detector upgraded to reach ~100 signal events



Post-LS3 options:

K^+ intensity increase by factor 4

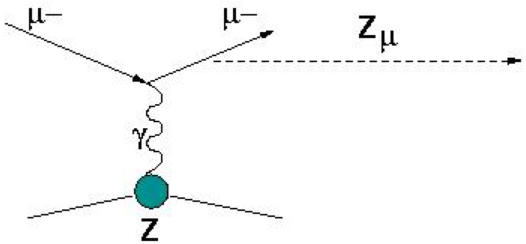
K^0 beam *(ex-KLEVER): K^0 decays complementary to K^+ decays for the CKM matrix and BSM searches.*

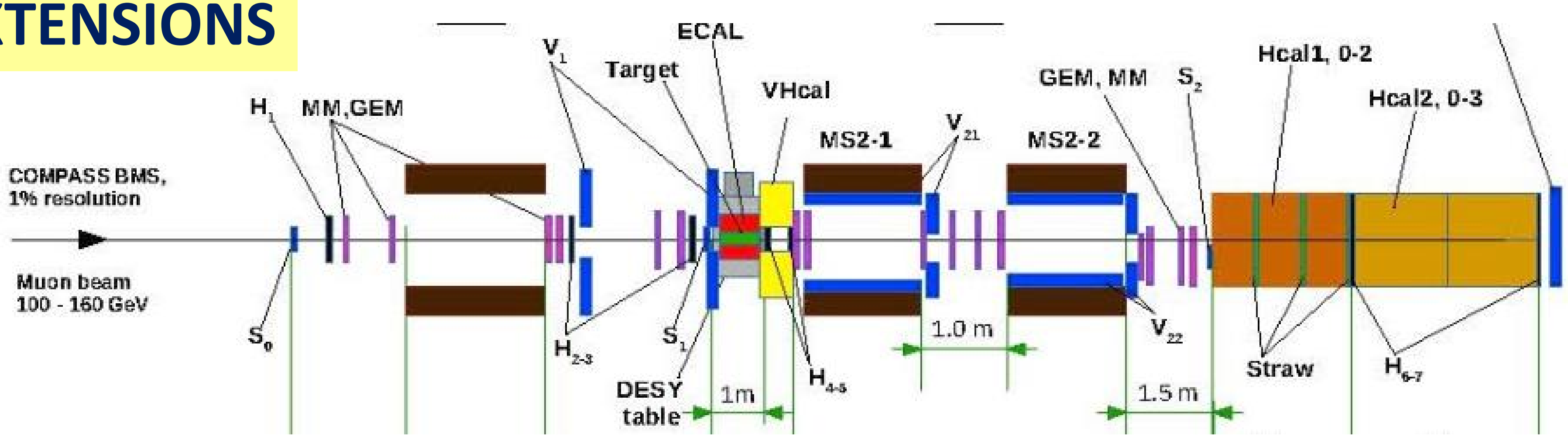
K^+ and K^0 options now considered as an integrated project with a multi-parameter internal phasing:

K^+ results ↔ K^+/K^0 sensitivity ↔ B-anomalies ↔ KOTO competition in Japan

NA64 PROPOSED EXTENSIONS

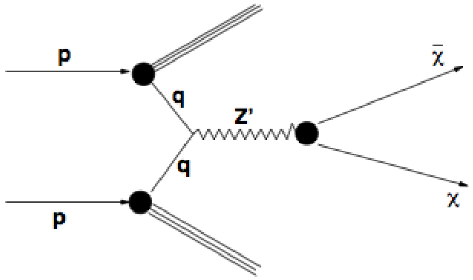
μ beams





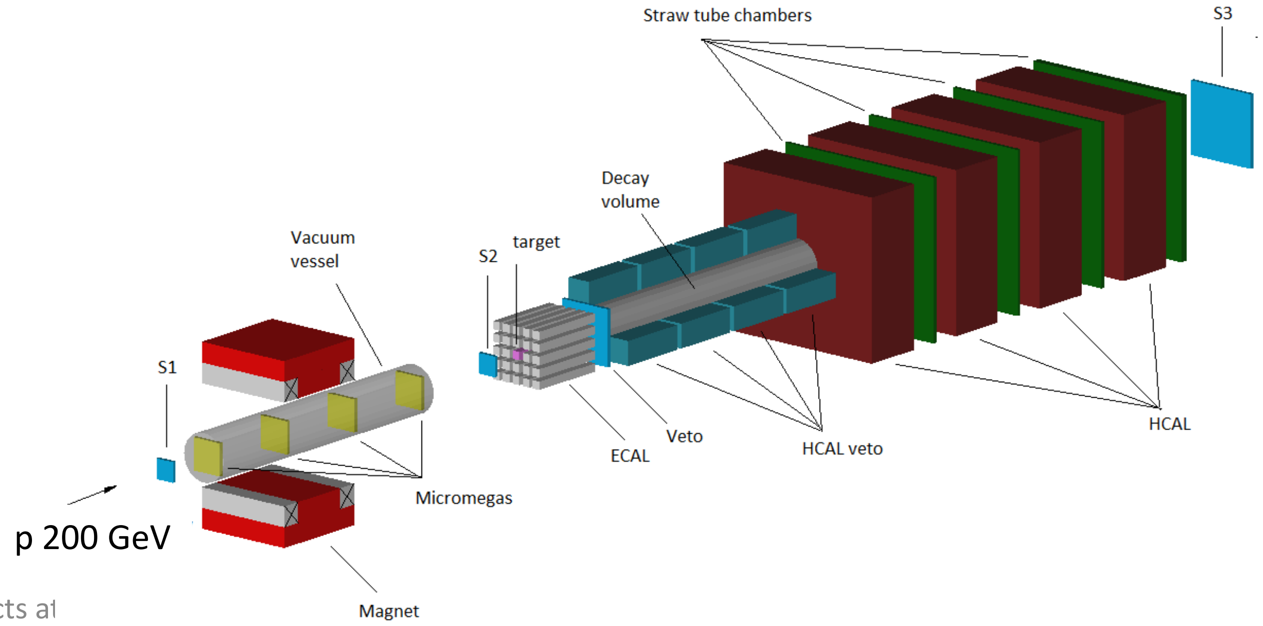
- After LS2: few months of μ beam would test a $(g\text{-}2)_\mu$ interpretation
- Longer term: few years of μ beam would improve limits on μ-coupled dark sector

Hadron beams



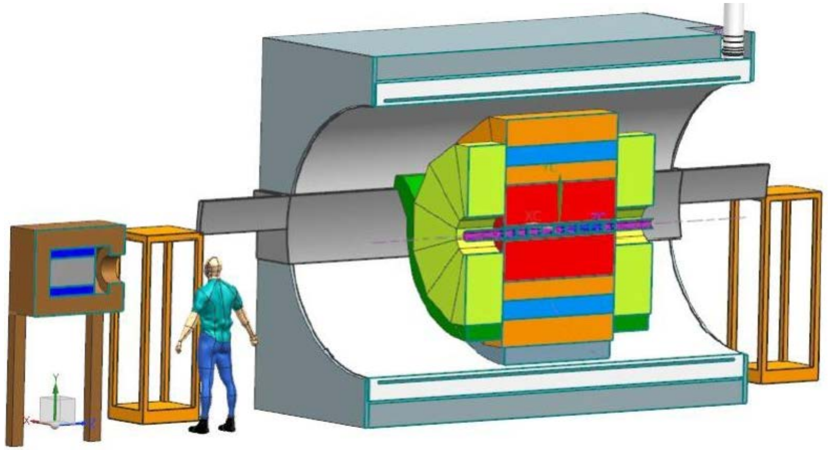
Would improve limits on

- meson decays to invisible particles
- leptophobic dark vectors



REDTOP η – η' factory

Also in discussion at FNAL



- It is a Goldstone boson → Symmetry constrains its QCD dynamics
- It is an eigenstate of the C, P, CP and G operators (very rare in nature): $I^G J^{PC} = 0^+ 0^{-+}$ → It can be used to test C and CP invariance.
- All its additive quantum numbers are zero (very clean state) Q = I = j = S = B = L = 0 → Its decays are not influenced by a change of flavor (as in K decays) and violations are "pure"
- All its possible strong decays are forbidden in the lowest order by P and CP invariance, G-parity conservation and isospin and charge symmetry invariance. EM decays are forbidden in lowest order by C invariance and angular momentum conservation → It is a very narrow state (Γ_η=1.3 KeV vs Γ_ρ=149 MeV) Contributions from higher orders are enhanced by a factor of ~100,000 Excellent for testing invariances

Main issues:

- 2 GeV continuous proton beam (PS best option but non-nominal for REDTOP)
- Demanding detector technology (Optical TPC and dual readout calorimetry)

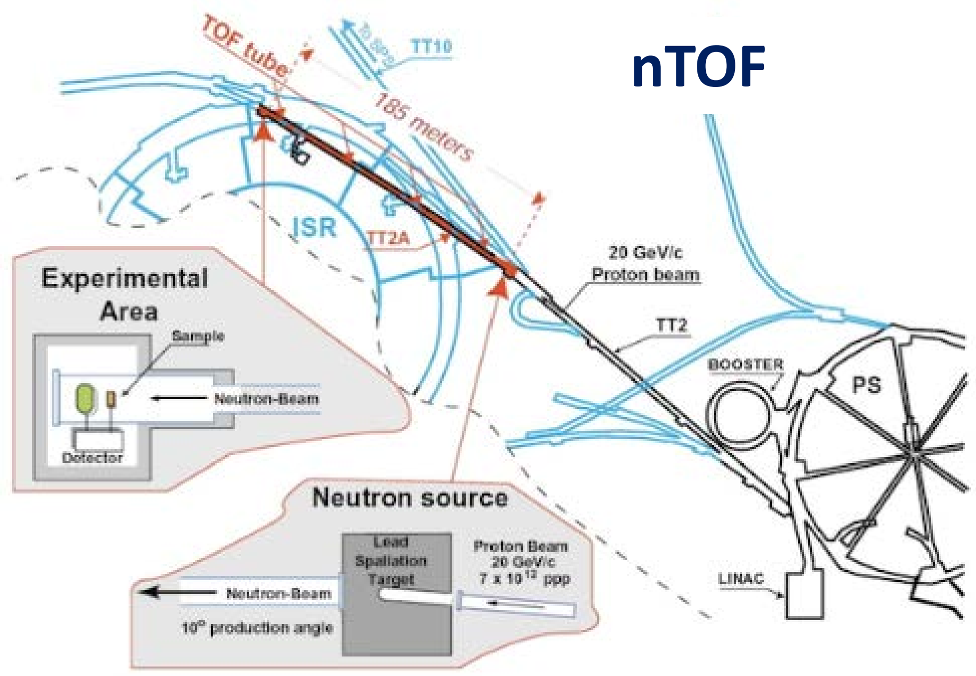
ISOLDE & nTOF

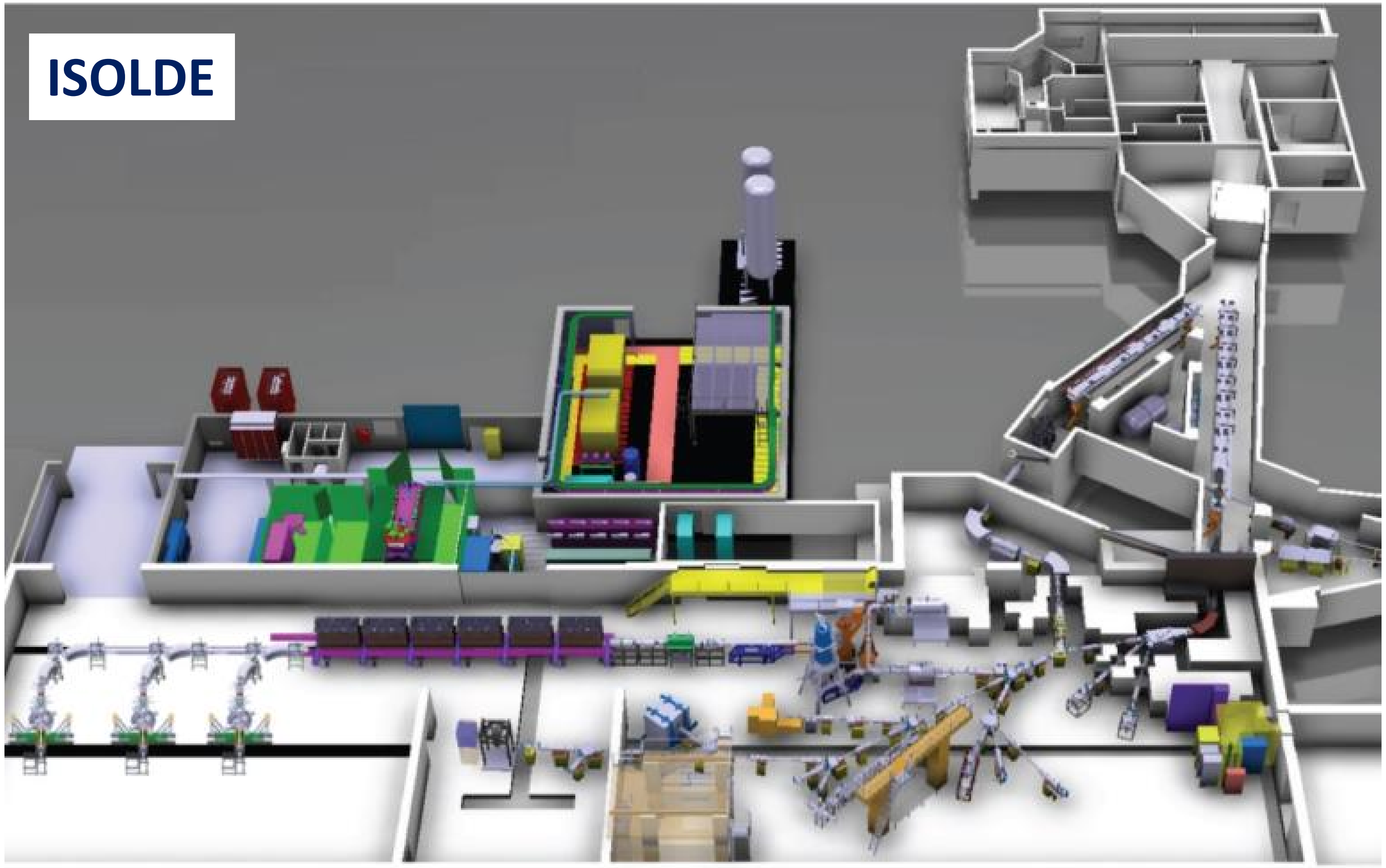
Similar technologies as at antimatter factory, with a fundamental physics potential for e.g.

- EW tests
- EDMs
- Spectroscopy of new states
- Nuclear clocks
- …

EPIC proposal to upgrade ISOLDE to higher energy (2 GeV) and intensity with a new experimental hall

nTOF



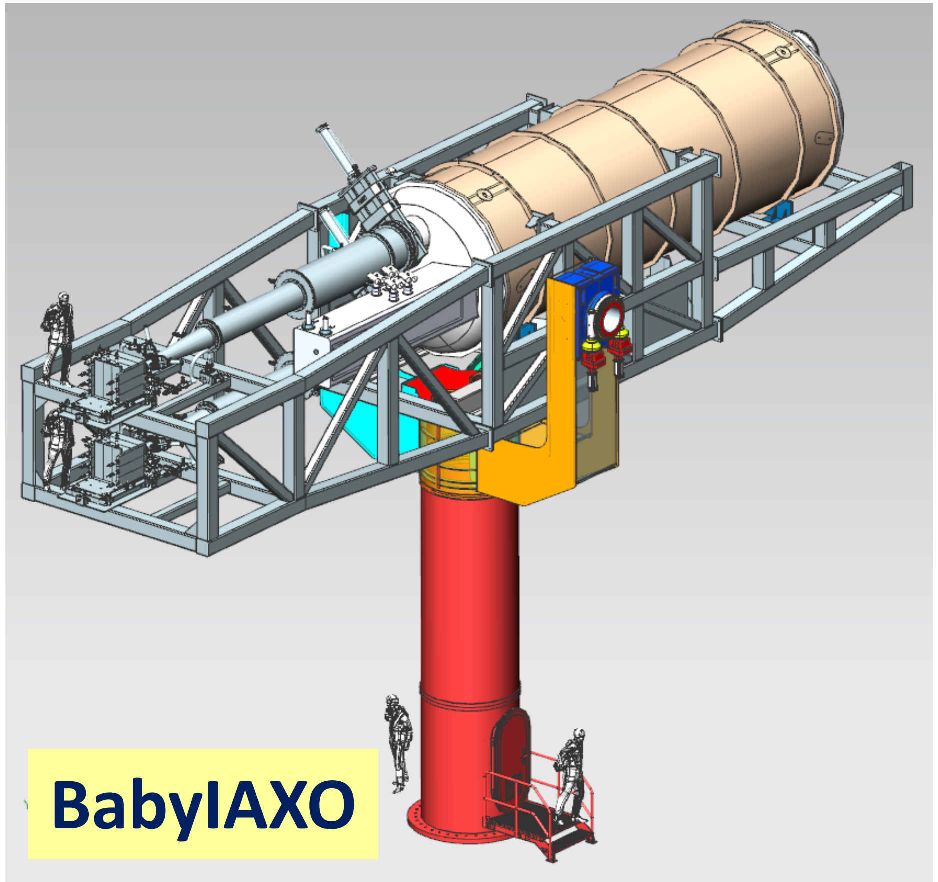


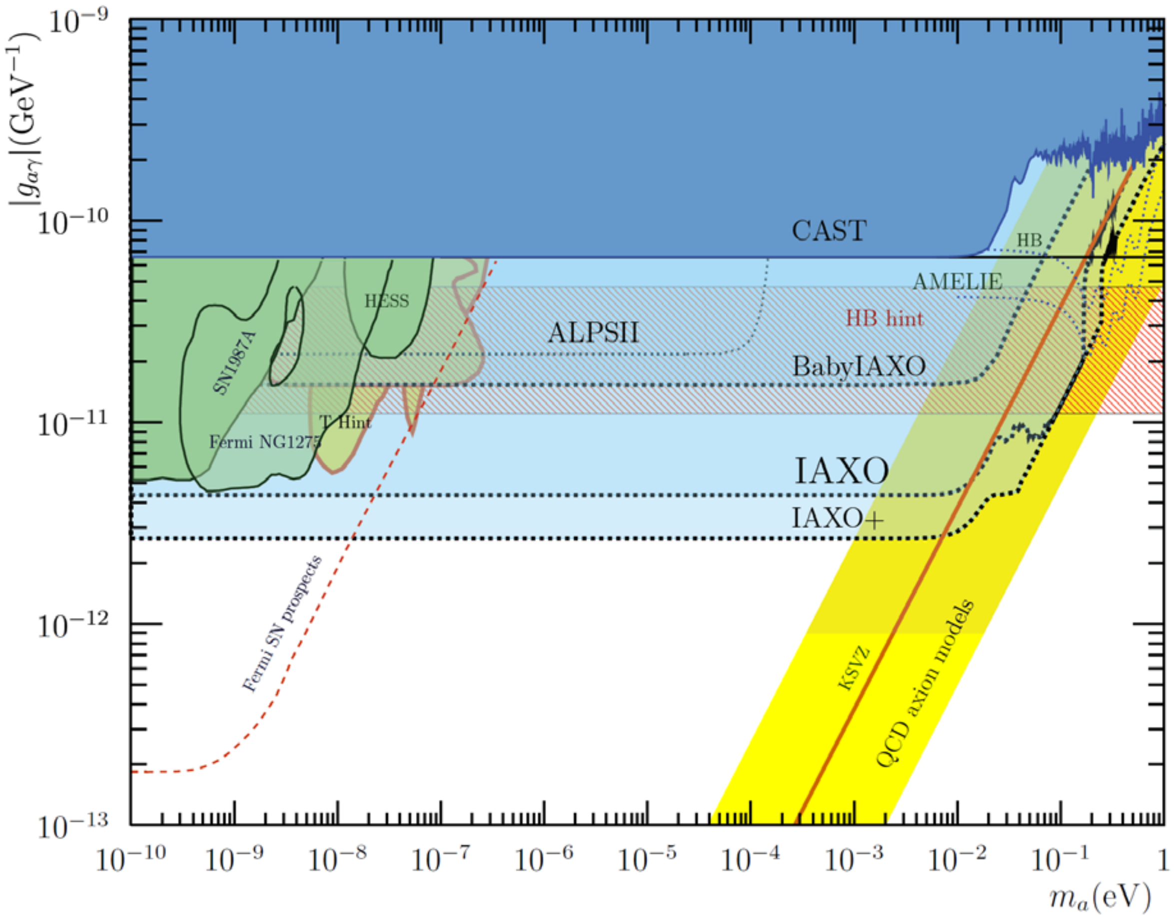
INTERNATIONAL AXION OBSERVATORY (axion helioscope successor of CAST@CERN)

BabyIAXO precursor approved and in construction at DESY

CERN PBC support to magnet design expected to go on in construction stage

Unique physics reach for ALPs searches





PBC pro