CERN Academic Lectures, 7th November 2023

Claude Vallée, CPPM Marseille

PHYSICS BEYOND COLLIDERS
Lecture 1: Experimental Overview

…a short glimpse of a very lively and diverse landscape with emphasis on CERN projects

Lowering the energy…

…from LHC collisions to non-accelerator experiments

+ a few insights into

R&D for longer-term future PBC facilities

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

More information on https://pbc.web.cern.ch/

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 particle 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:

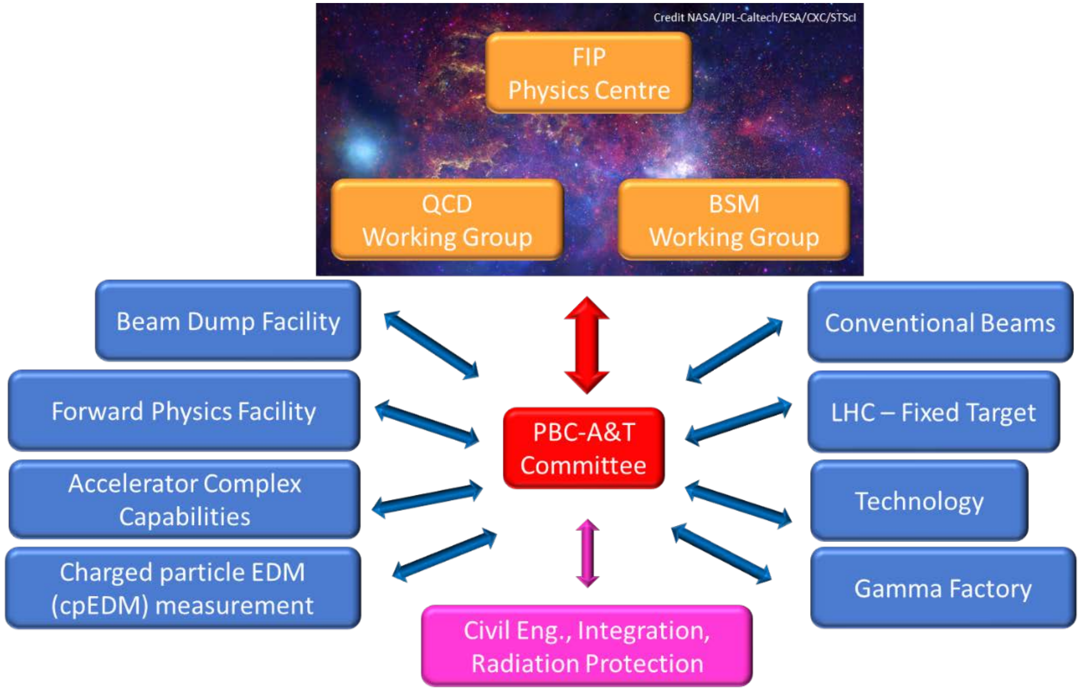
http://cds.cern.ch/collection/PBC%20Reports?ln=en

Post-EPPSU PBC RELAUNCH

Updated mandate taking 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

Current PBC organization



https://pbc.web.cern.ch/

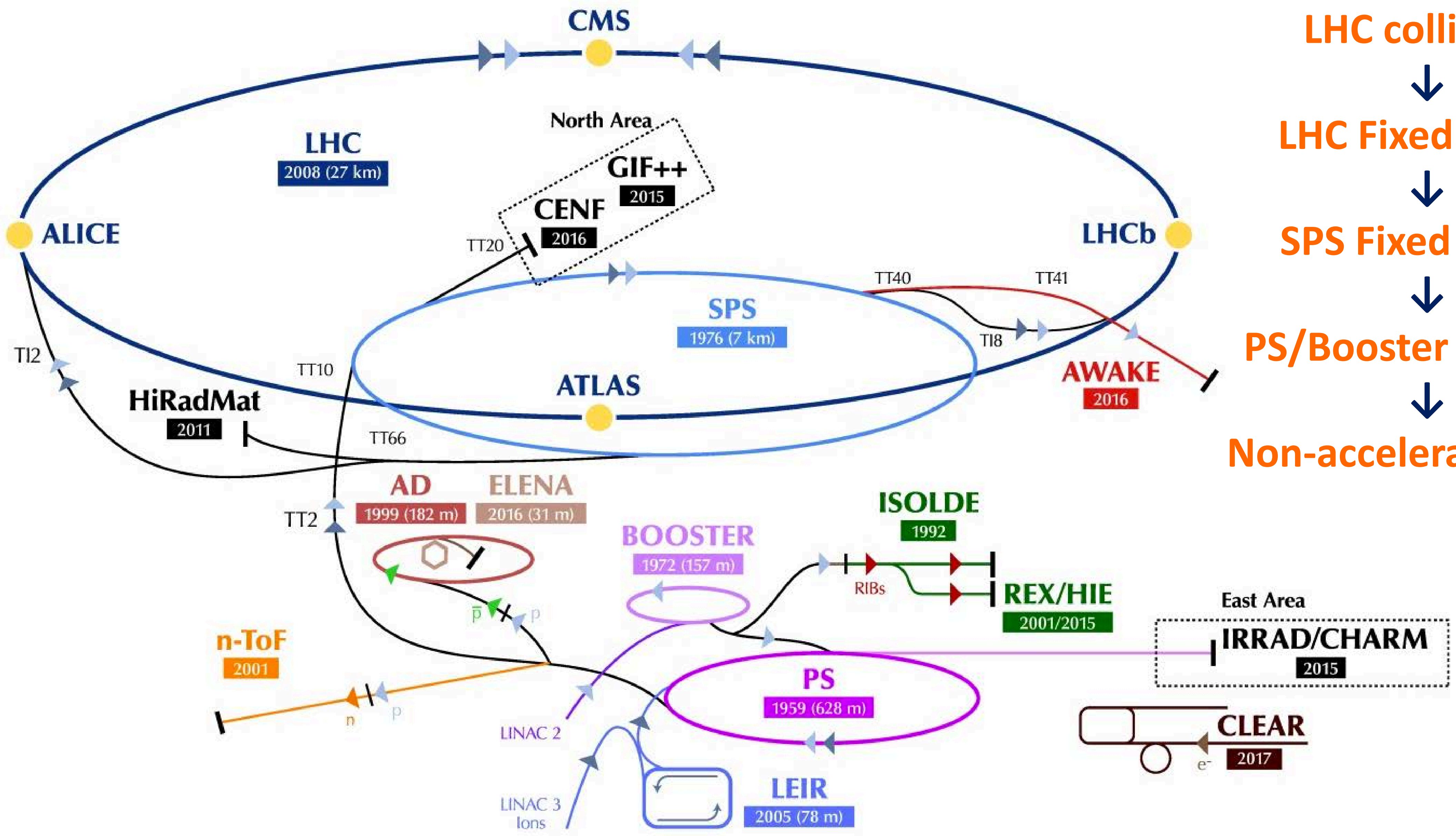
Post-EPPSU PBC events:

March 2021: First post-EPPSU workshop (indico) :
relaunch of PBC activities after EPPSU recommendations

December 2021: General working group meeting (indico) :
PBC updated organization and projects status

November 2022: PBC annual workshop (indico) :
focus on consolidations and preparations for post-LS3

THE CERN ACCELERATOR COMPLEX



Downwards energy steps:

LHC collisions

↓

LHC Fixed Target

↓

SPS Fixed Target

↓

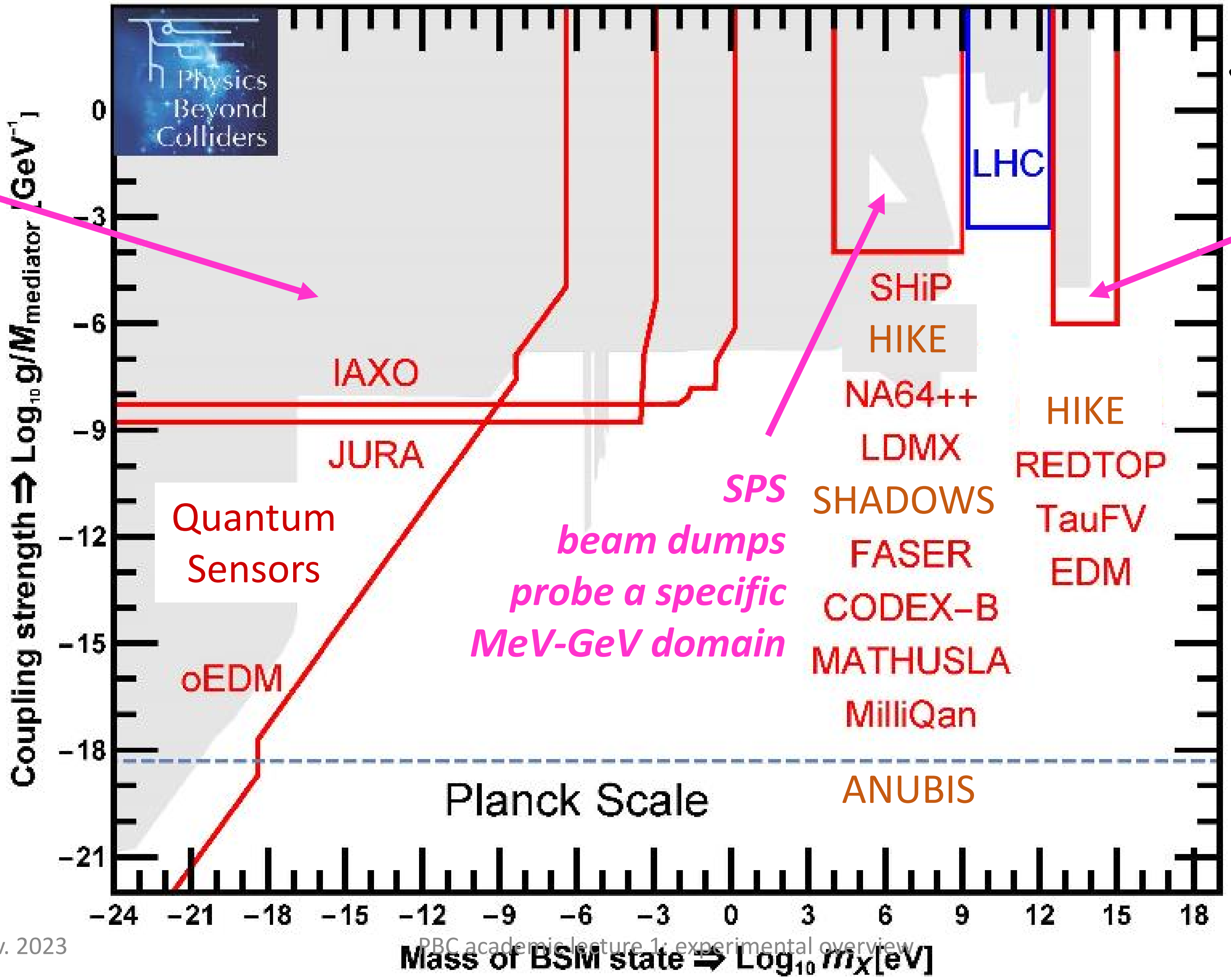
PS/Booster facilities

↓

Non-accelerator exp^{ts}

From high to low energies: global BSM landscape

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



SPS beam dumps probe a specific MeV-GeV domain

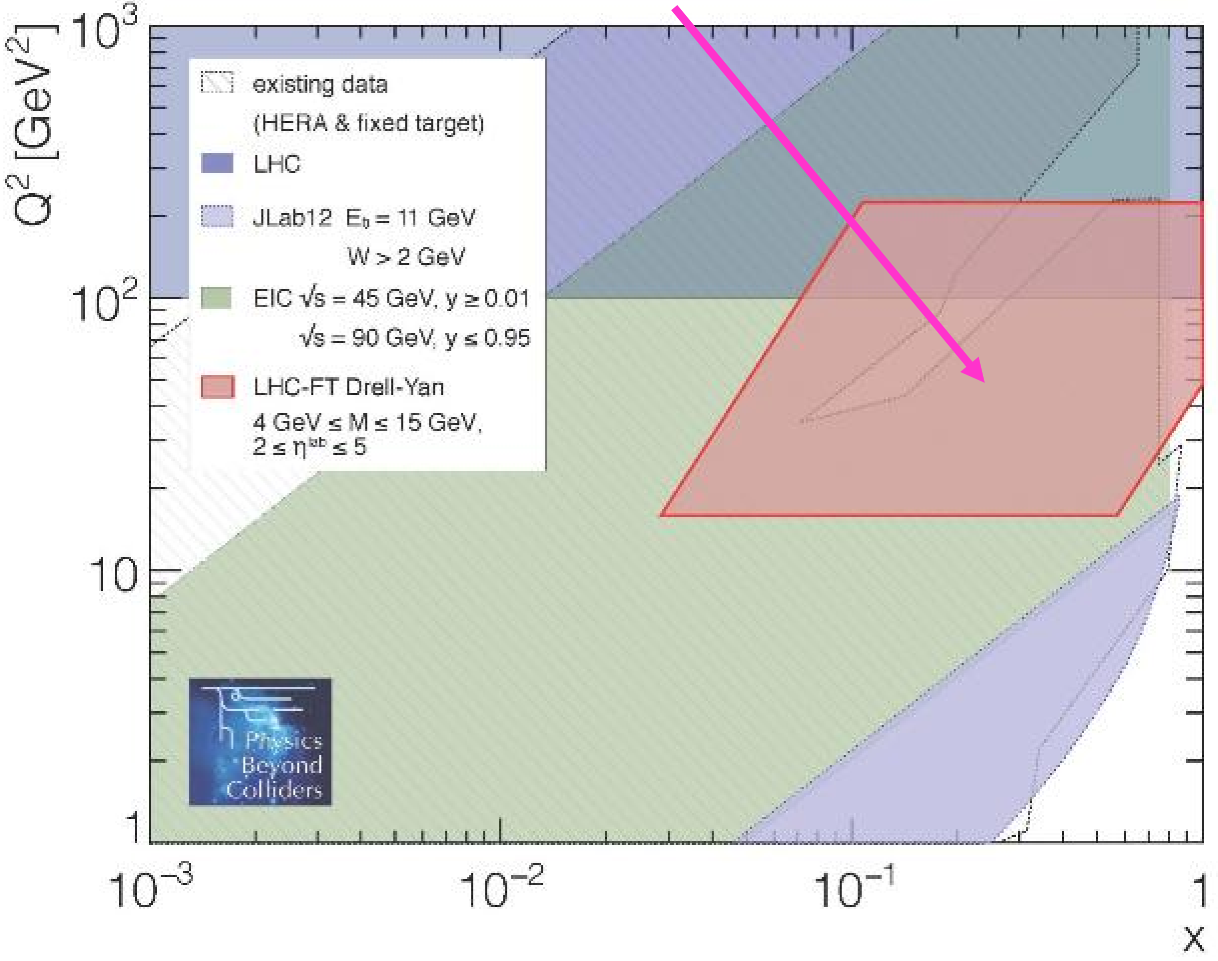
Precision & rare processes experiments extend reach of high-E colliders

See J. Jaeckel's lecture

From high to low energies: global QCD landscape

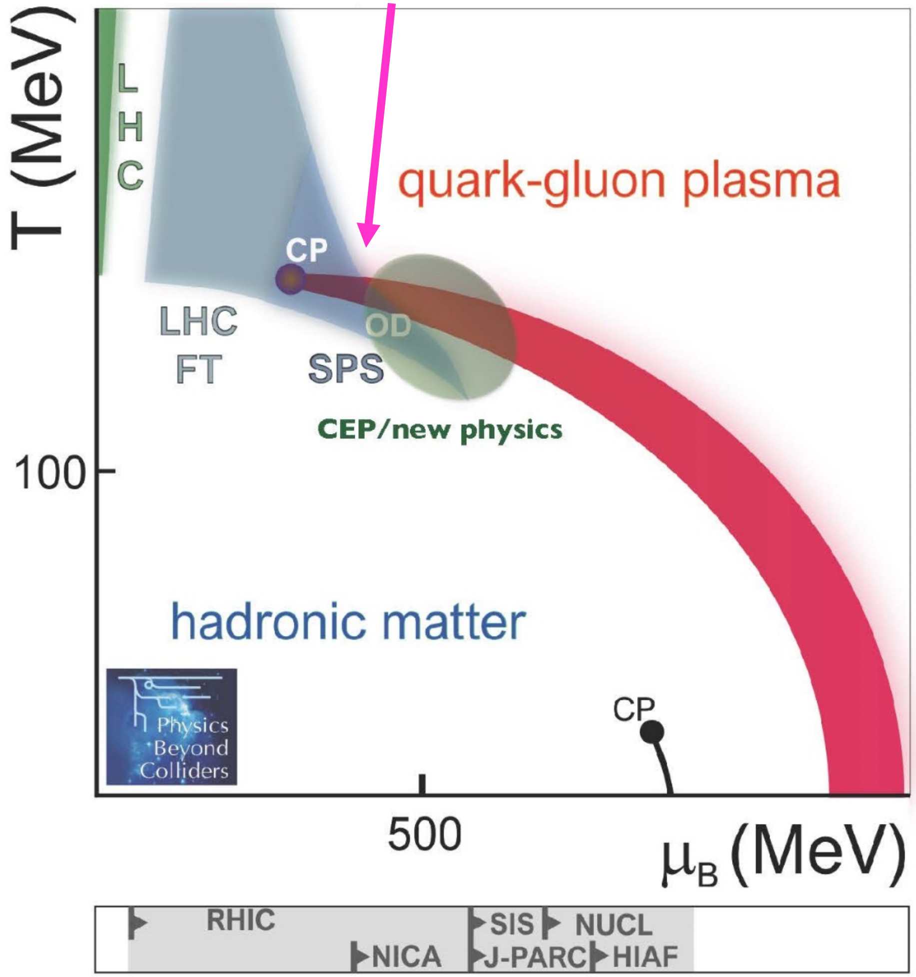
Structure Functions

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



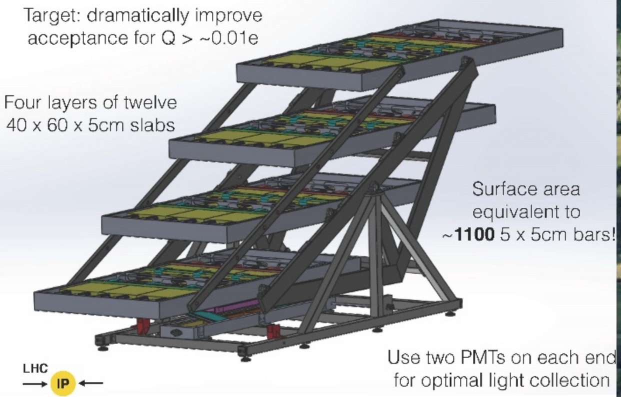
STARTING WITH LHC COLLISIONS:

DEDICATED LONG-LIVED PARTICLES (LLP) DETECTORS

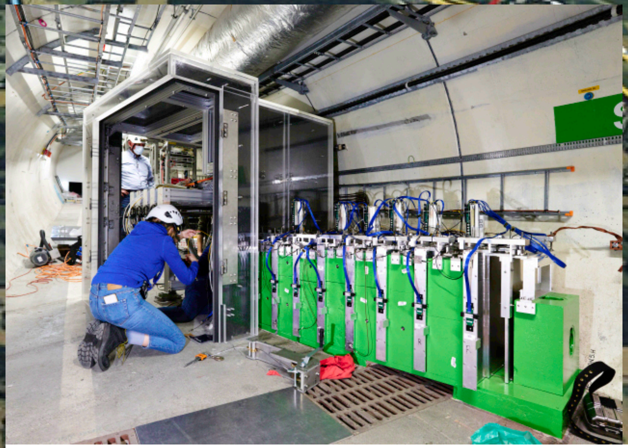
LHC-LLP DEDICATED PROJECTS

Pioneered in run 3 by FASER/SND@LHC/milliQan

FASER:
Dark photons & TeV neutrinos
480m from ATLAS IP

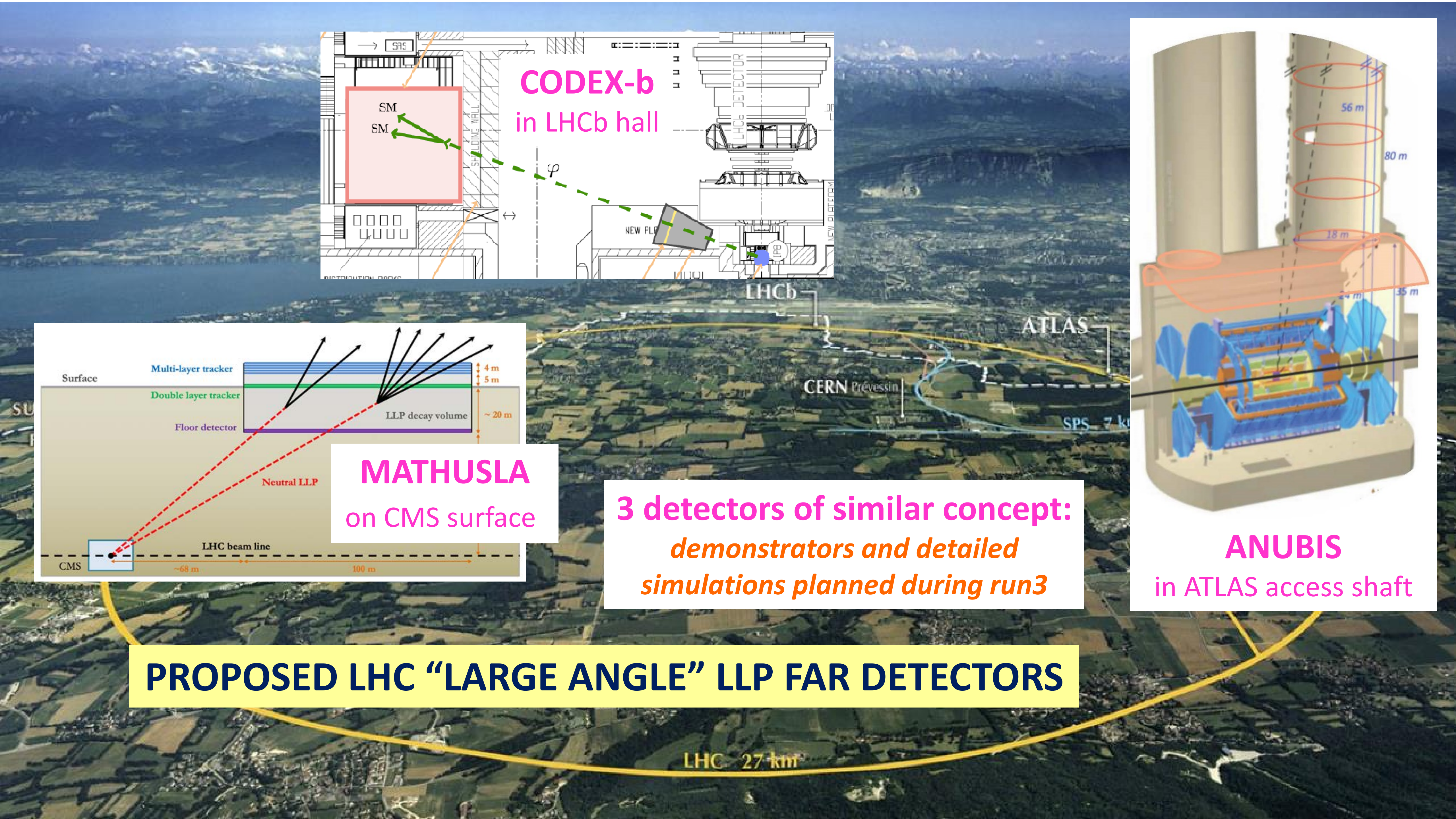


milliQan: milli-charged particles
33m from CMS IP



SND@LHC: *TeV neutrinos*
Slightly off axis opposite to FASER

SUISSE
FRANCE
CMS
ATLAS
CERN Meyrin
CERN Prévessin
ALICE
LHC 27 km

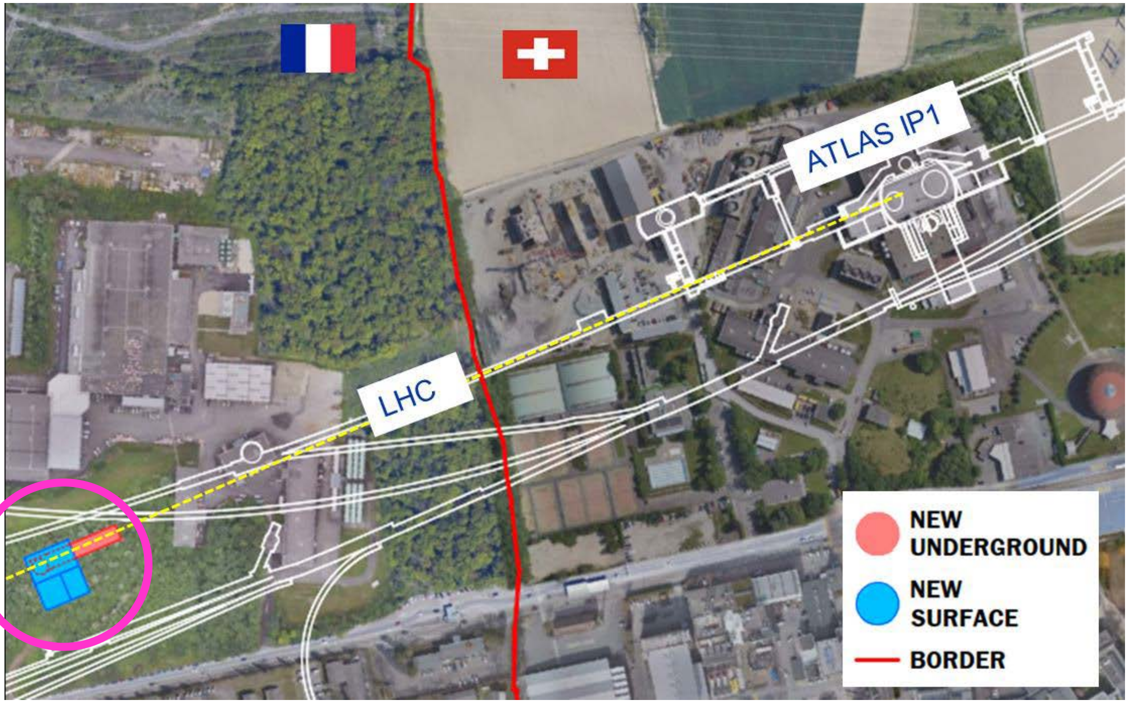


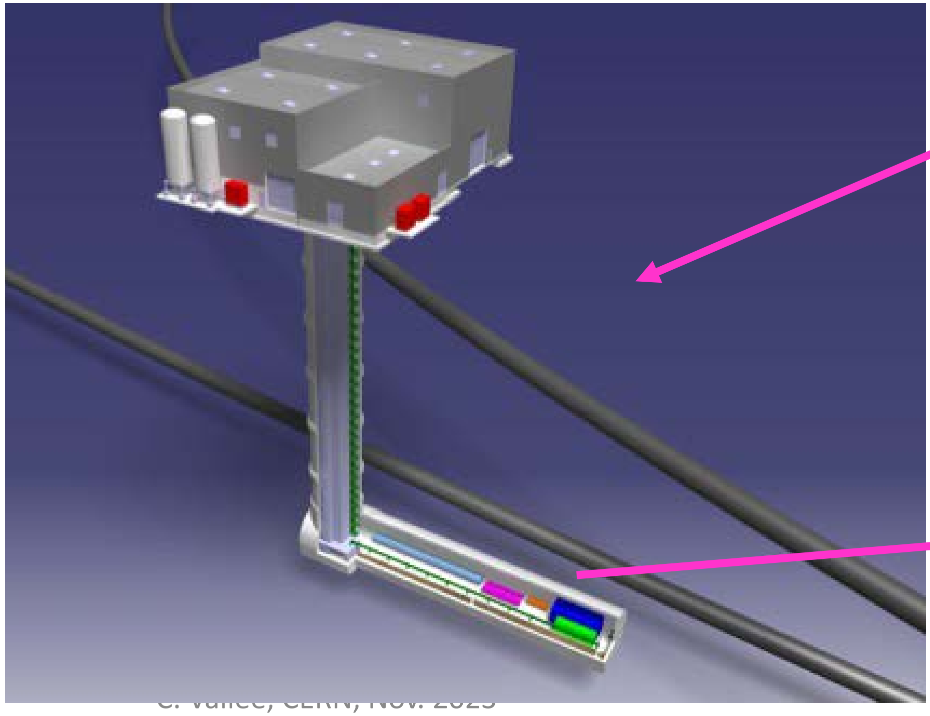
CODEX-b
in LHCb hall
SM
SM
NEW FL
LHCb
ATLAS
CERN Prévessin
SPS
Multi-layer tracker
Surface
Double layer tracker
Floor detector
LLP decay volume
4 m
5 m
~ 20 m
Neutral LLP
LHC beam line
CMS
~68 m
100 m
MATHUSLA
on CMS surface
3 detectors of similar concept:
demonstrators and detailed
simulations planned during run3
56 m
80 m
18 m
24 m
35 m
ANUBIS
in ATLAS access shaft
PROPOSED LHC “LARGE ANGLE” LLP FAR DETECTORS
LHC 27 km

PROPOSED LHC "FORWARD" LLP FAR DETECTORS:

FORWARD PHYSICS FACLILITY

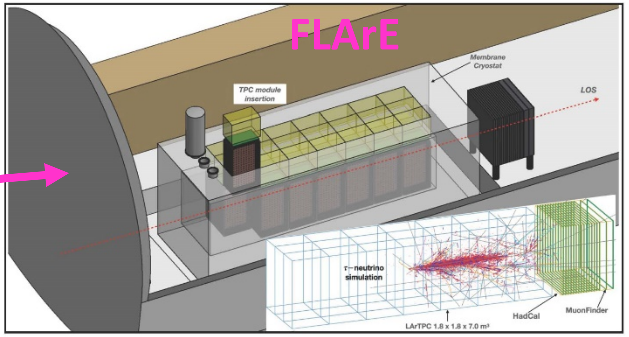
Proposal for a dedicated underground cavern aimed at maximizing the HL-LHC physics reach in the forward region (LLPs, ν's & QCD)

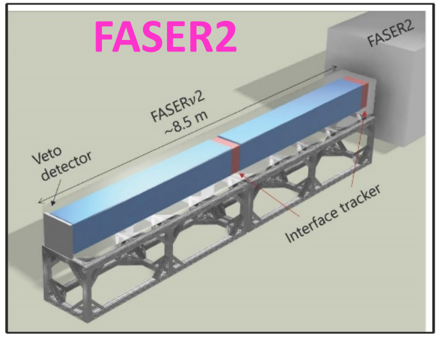


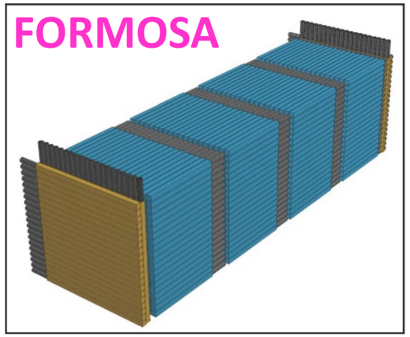


Conceptual design of the infrastructure well advanced

LoI to LHCC expected in 2025



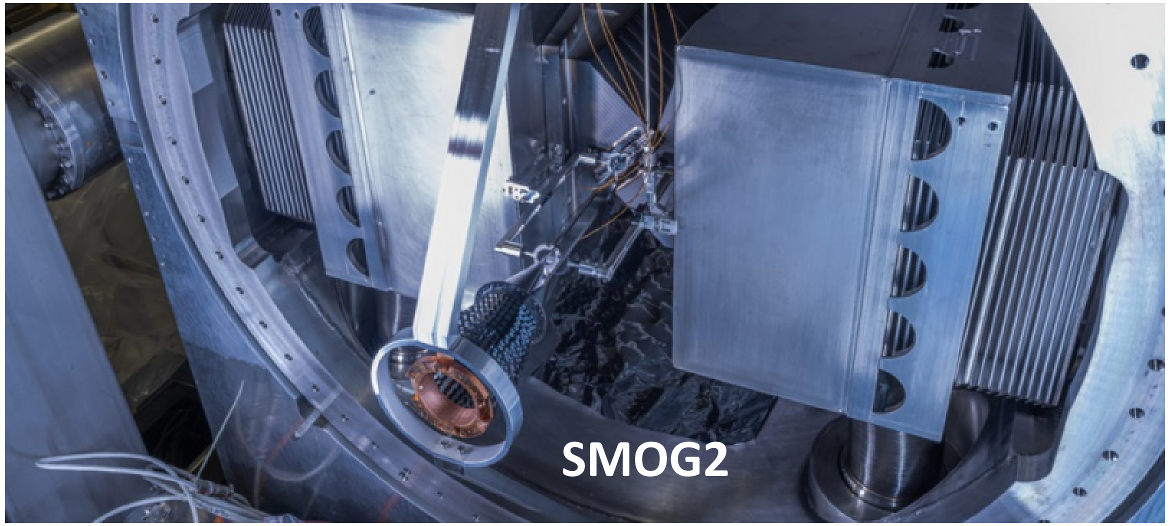


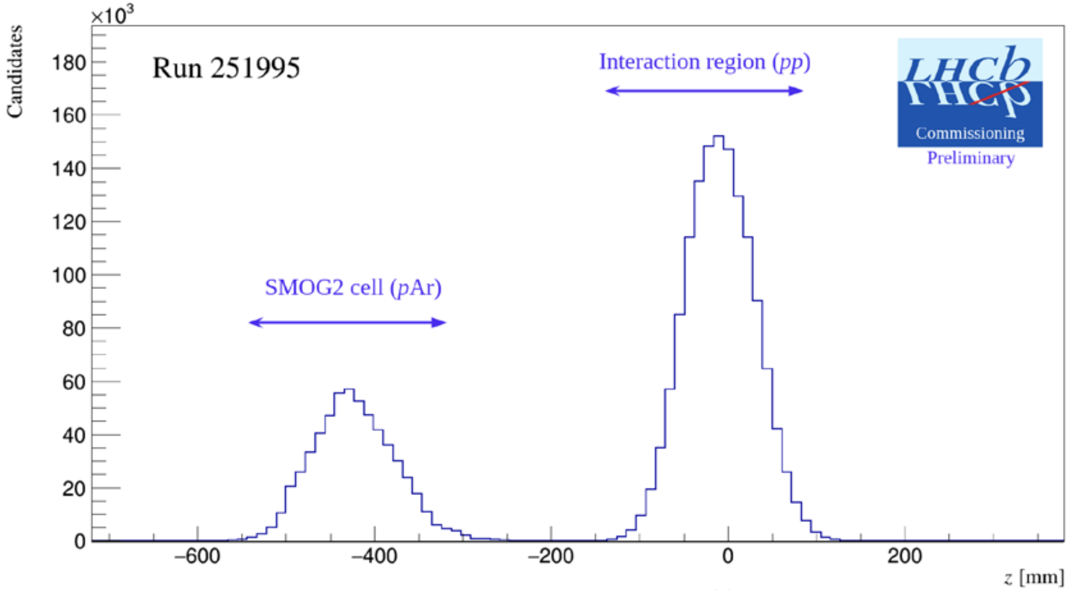


1^{ST} ENERGY STEP DOWNWARDS:

LHC FIXED-TARGET (FT@LHC)

FT@LHC: Gas Fixed Target with LHCb

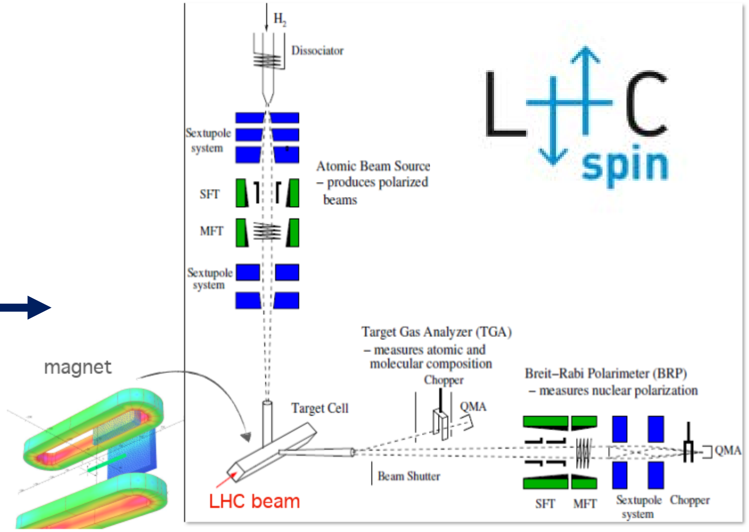




FT@LHC pioneered by LHCb with SMOG gas jets in run 2 and SMOG2 gas storage cell in run 3

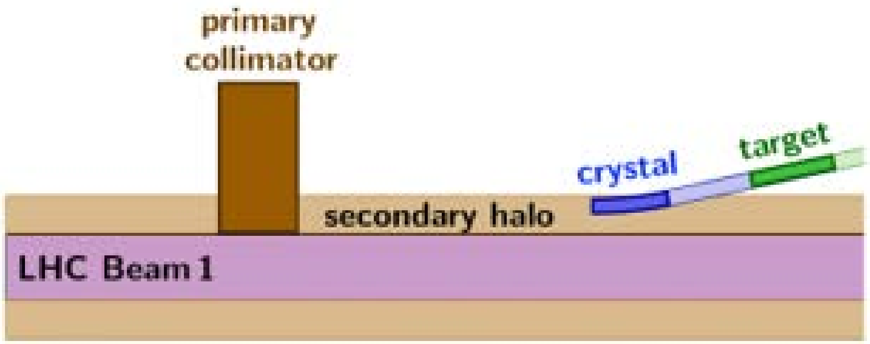
Impact of different types of gases (Kr, Xe, O_2, N_2, H_2, D_2) on LHC vacuum system under study

Development of a polarized gas storage cell also ongoing for future spin physics @LHC →

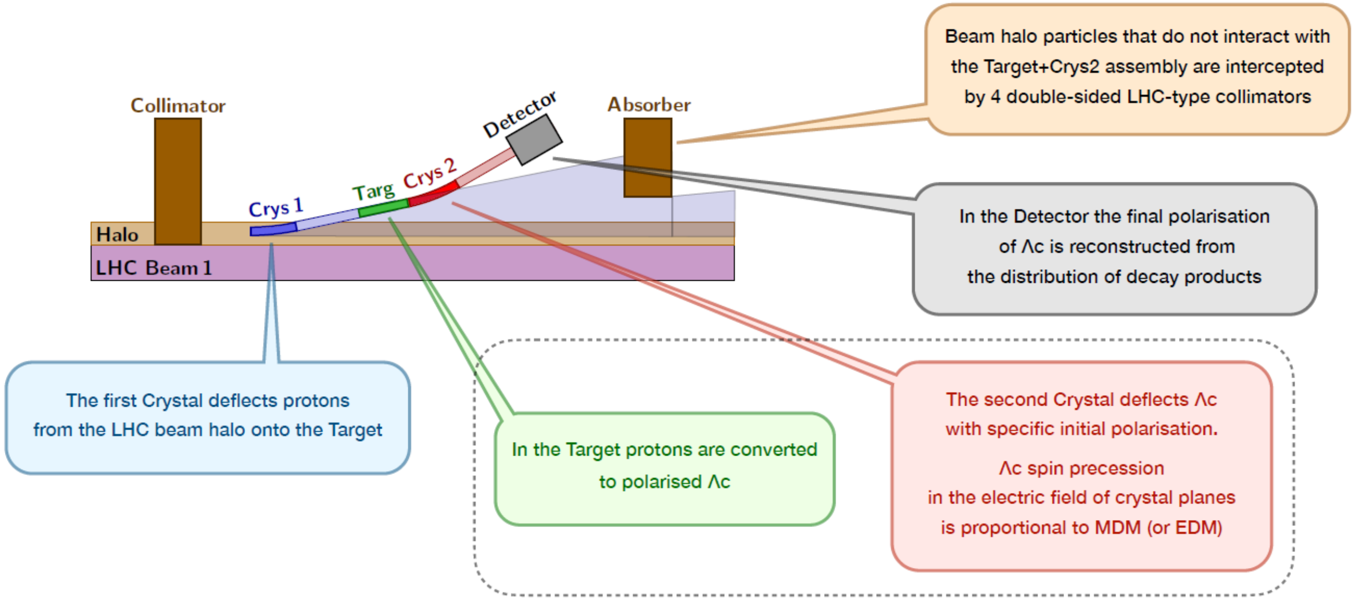


FT@LHC: Crystal Fixed Targets

Good progress in the design and preparation of crystal set-ups



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



Single crystal set-up:

developed for beam cleaning&collimation and possible FT physics

Double crystal set-up:

for measurement of MDM and EDM of short-lived baryons

Proof of Principle set-up in preparation for installation at LHC IR3 during run 3

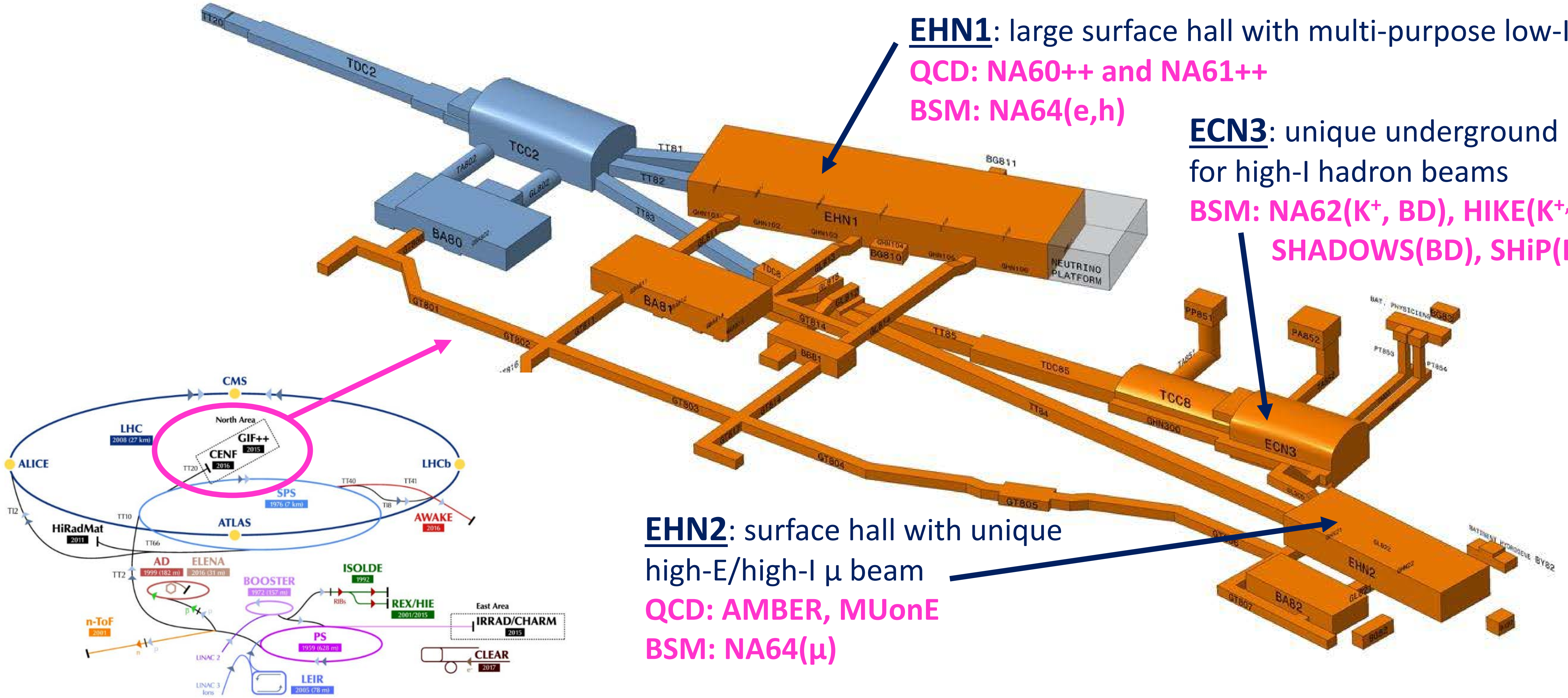
2ND ENERGY STEP DOWNWARDS:

SPC FIXED-TARGET (FT@SPS)

The WORKHORSE of FT@SPS: the SPS NORTH AREA

EHN1: large surface hall with multi-purpose low-I beams
QCD: NA60++ and NA61++
BSM: NA64(e,h)

ECN3: unique underground hall for high-I hadron beams
BSM: NA62(K^+, BD), HIKE($K^{+,0}$, BD)
SHADOWS(BD), SHiP(BD)



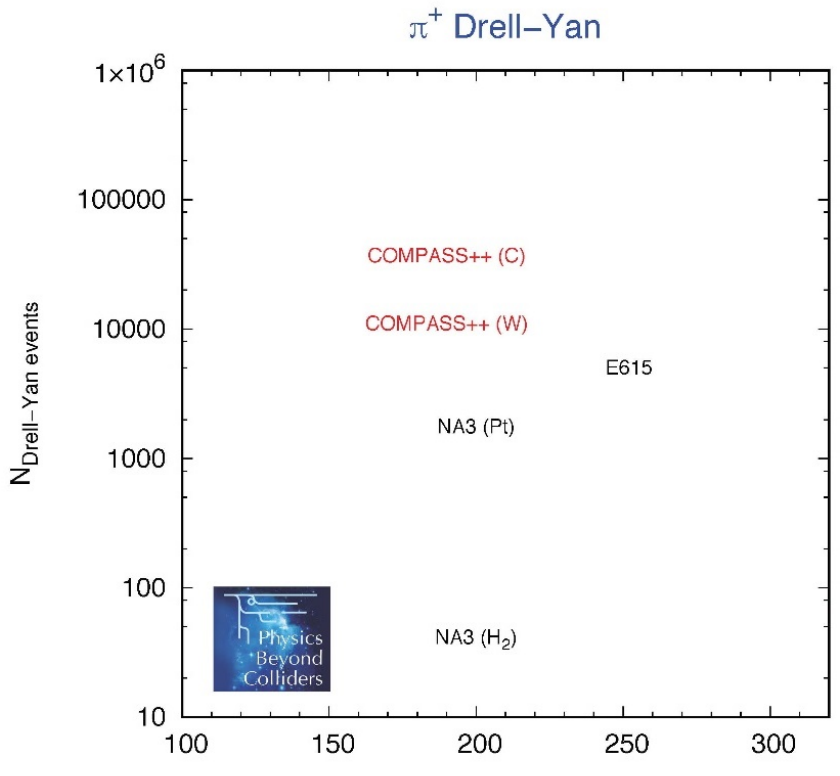
EHN2: surface hall with unique high-E/high-I μ beam
QCD: AMBER, MUonE
BSM: NA64(μ)

The planned consolidation of the NA provides an opportunity for new experimental projects

AMBER "QCD FACILITY" (COMPASS++)

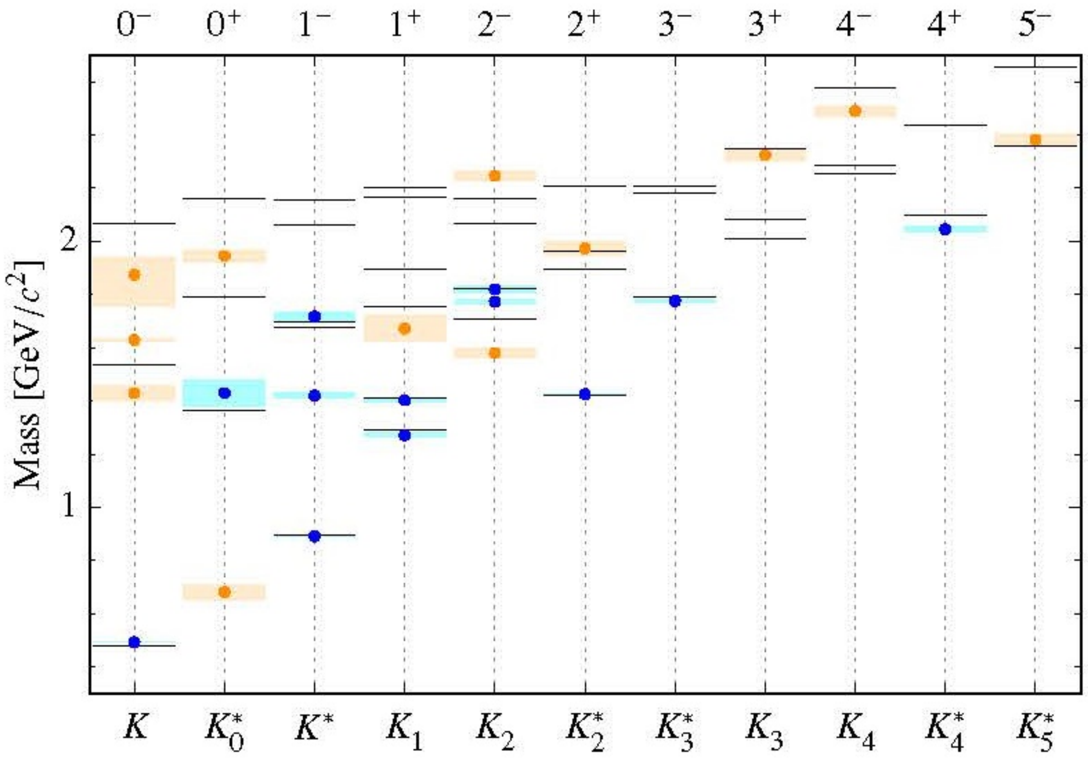
Short term (run3): proton radius puzzle with μ-p elastic scattering

Longer term (excerpts):



With existing beams:

Unique opportunity for higher precision pion structure measurements



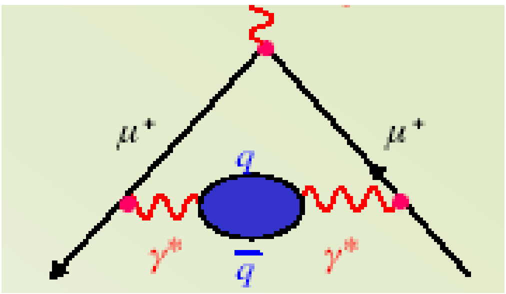
With upgraded K-beam:

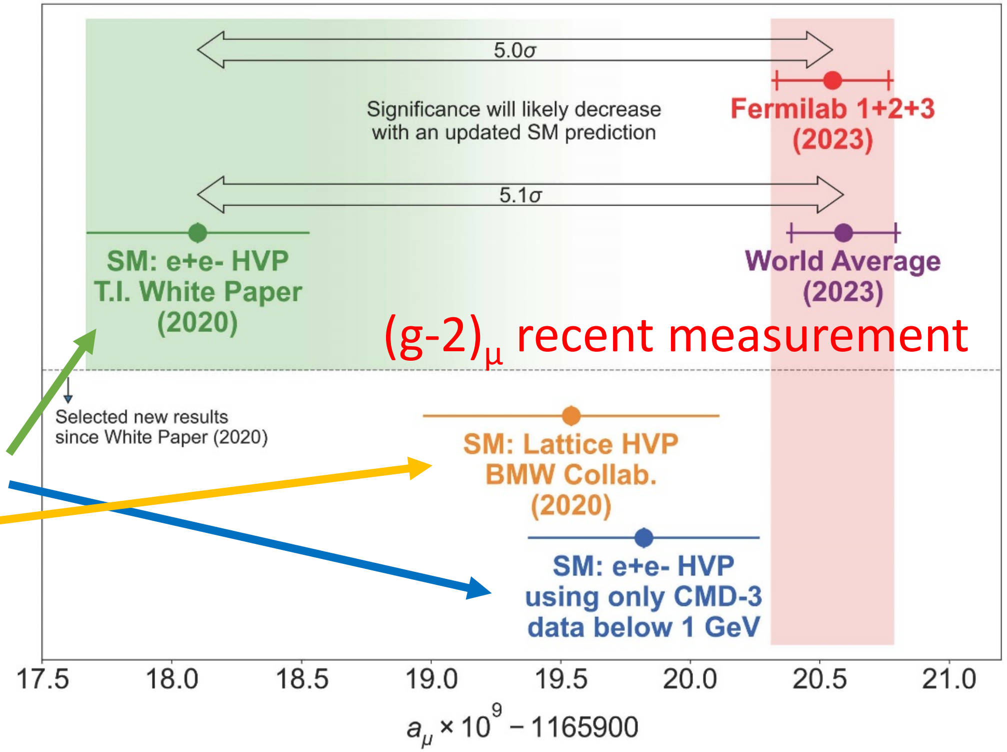
Comprehensive measurement of strange spectroscopy

New idea introduced within PBC:

MUonE

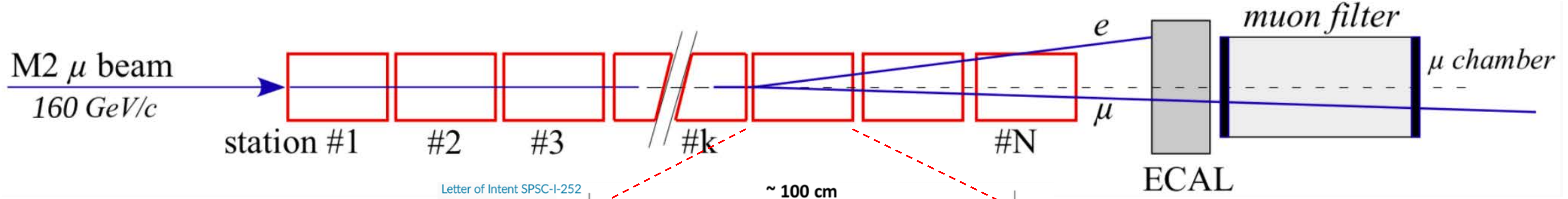
Direct measurement of HVP contribution to $(g-2)_\mu$ with μ-e elastic scattering

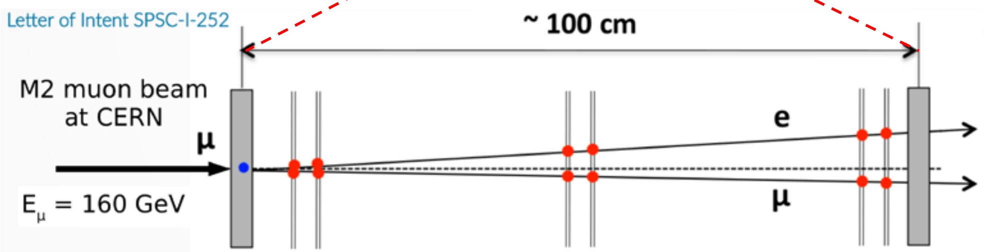




Complementary to predictions based on dispersion relation with e^+e^- data and on lattice QCD

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



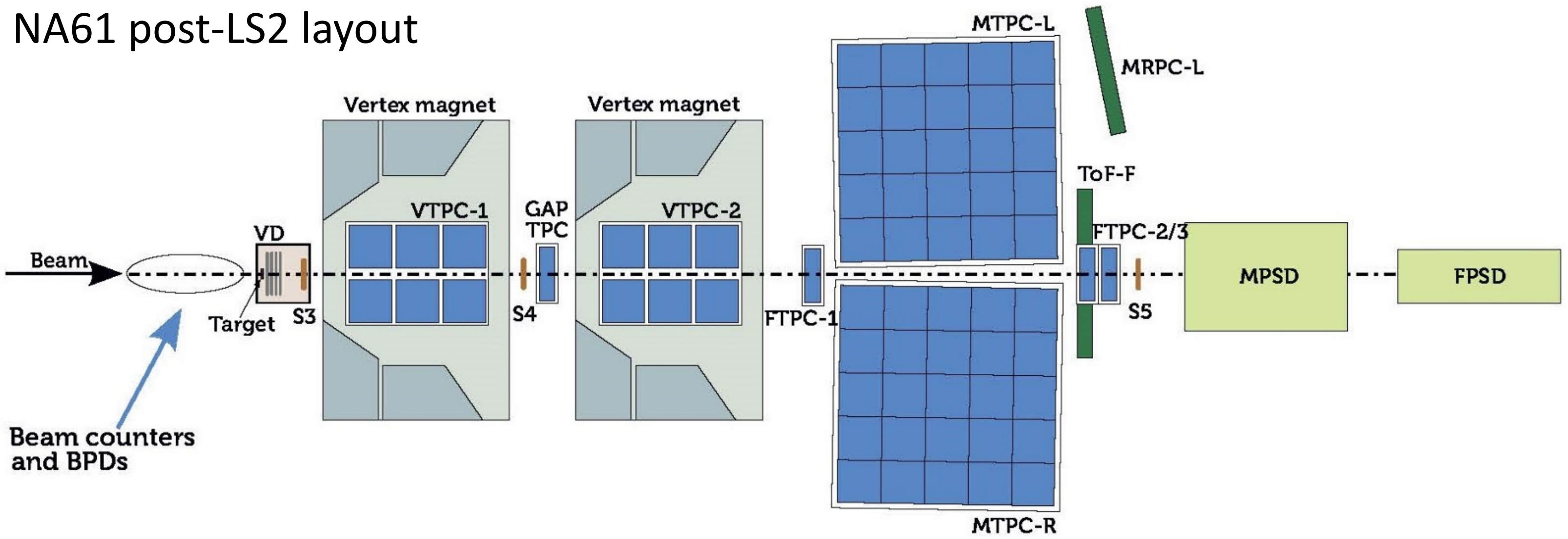


First data taking aimed for during run 3

FT@SPS ION PROGRAMME: NA61

Unique TPC detector for FT@SPS

NA61 post-LS2 layout

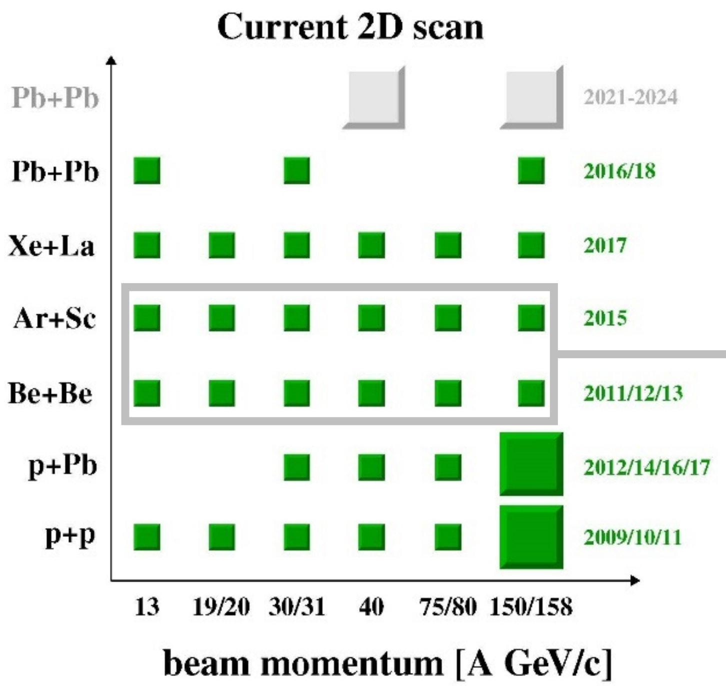


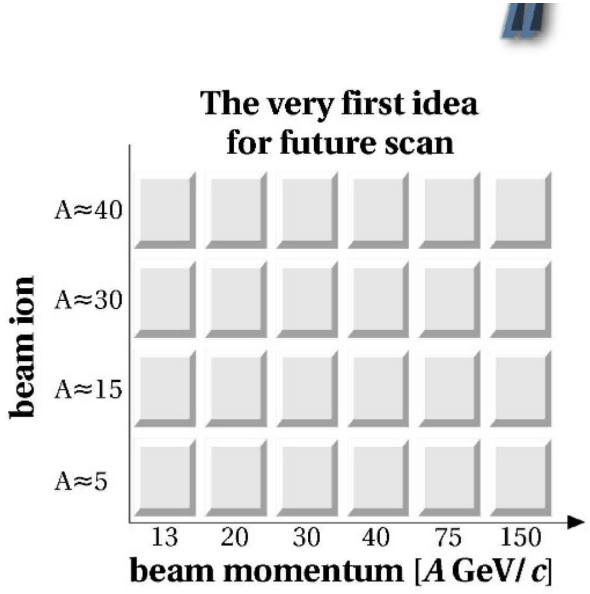
Ongoing (run 3):

- ***First study of open charm close to expected CP-region.***
- Also unique measurements for ν-beams and cosmic rays

Post-LS3: *(preliminary ideas)*

- ***Finer grain 2-D scan to study onset of fireball***
  → light ions production under study by CERN
- Antiproton and low-E beams for baryon stopping studies
- Continued measurements for ν-beams and cosmic rays

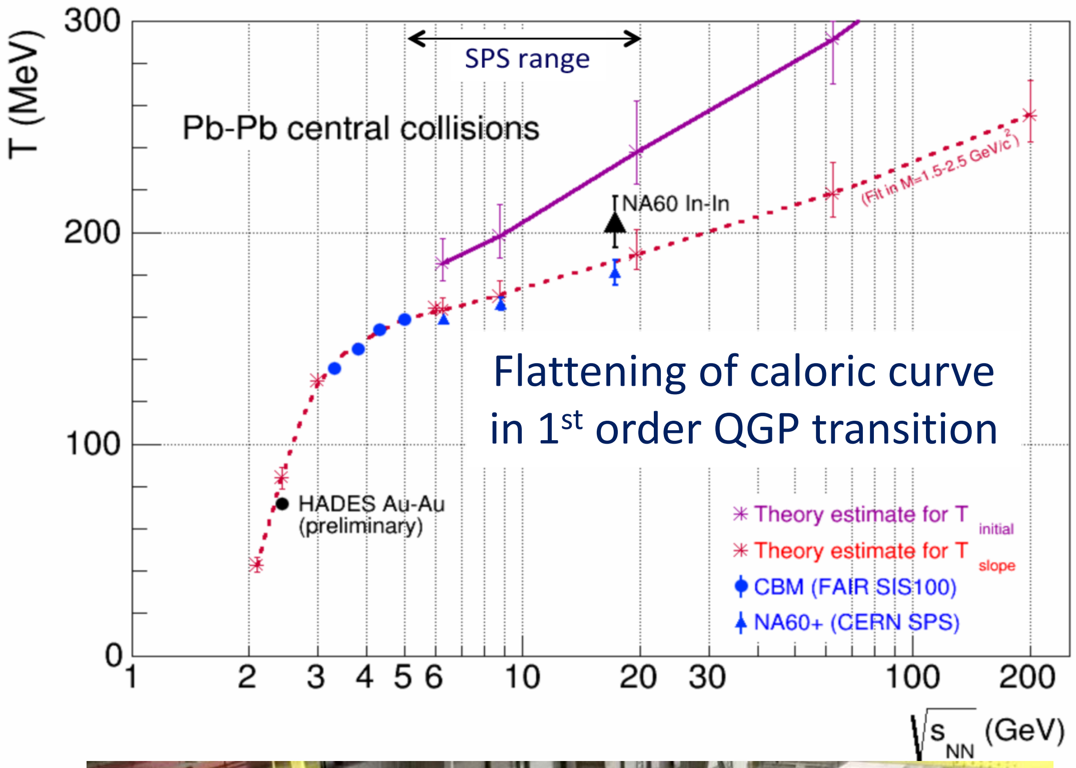


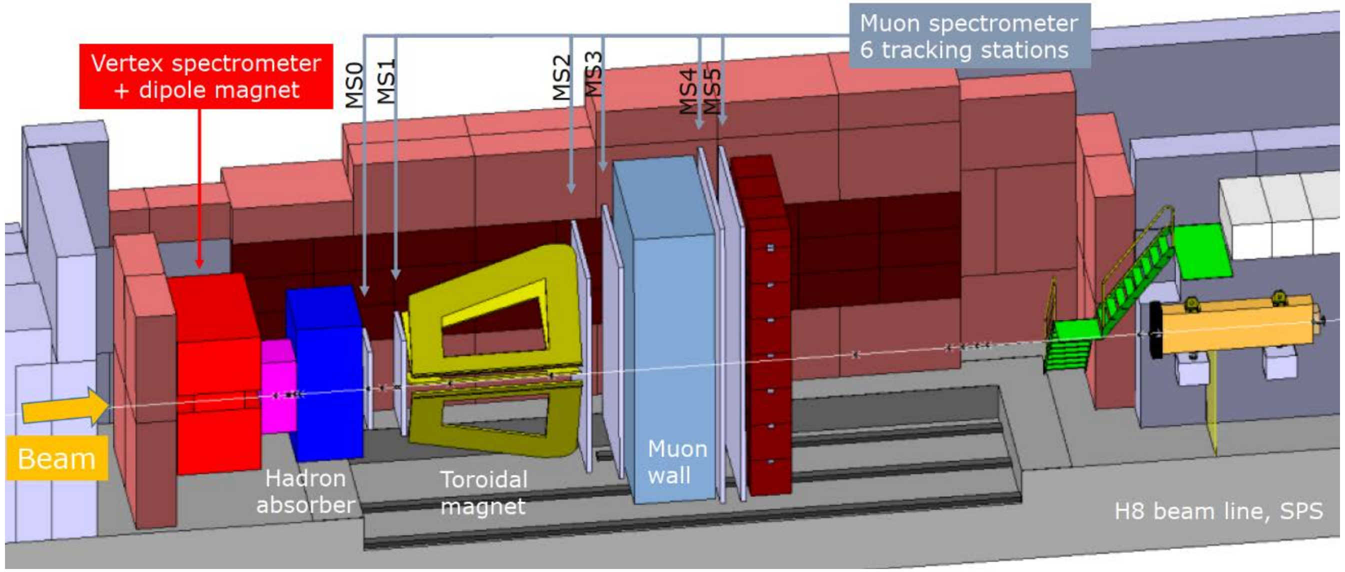


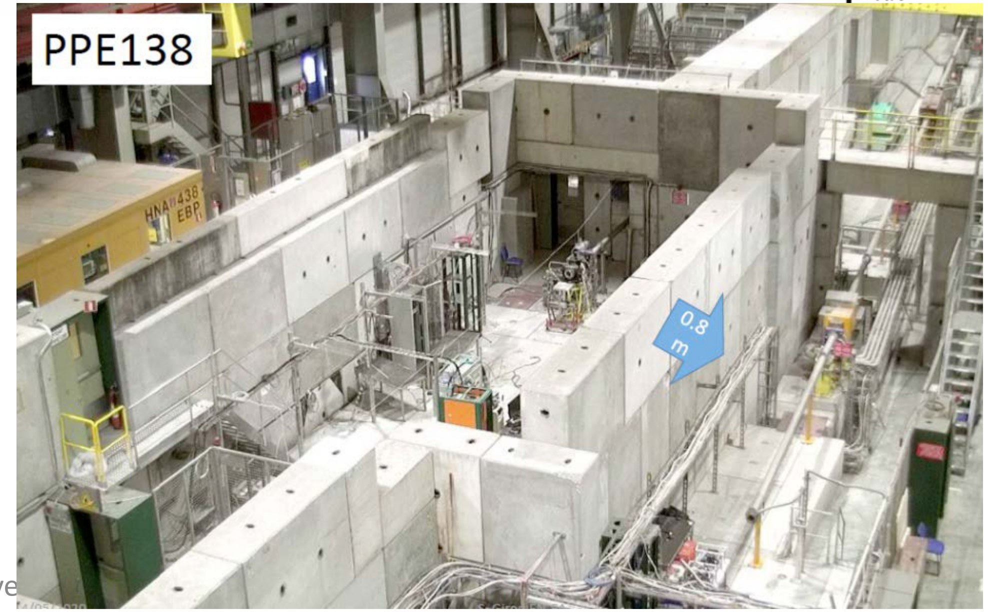
FT@SPS ION PROGRAMME cont'd: NA60++

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

New location found in EHN1 hall to avoid conflict with users of ECN3

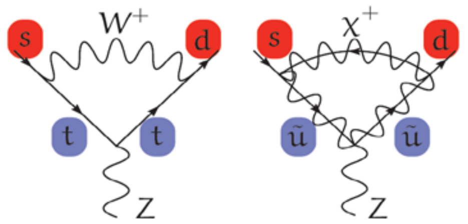






$K \to \pi\nu\bar{\nu}$ (BR ~ 10^{-10})

PRECISION FT@SPS: NA62



Ultra-rare K⁺ decays

Regular data taking since 2016

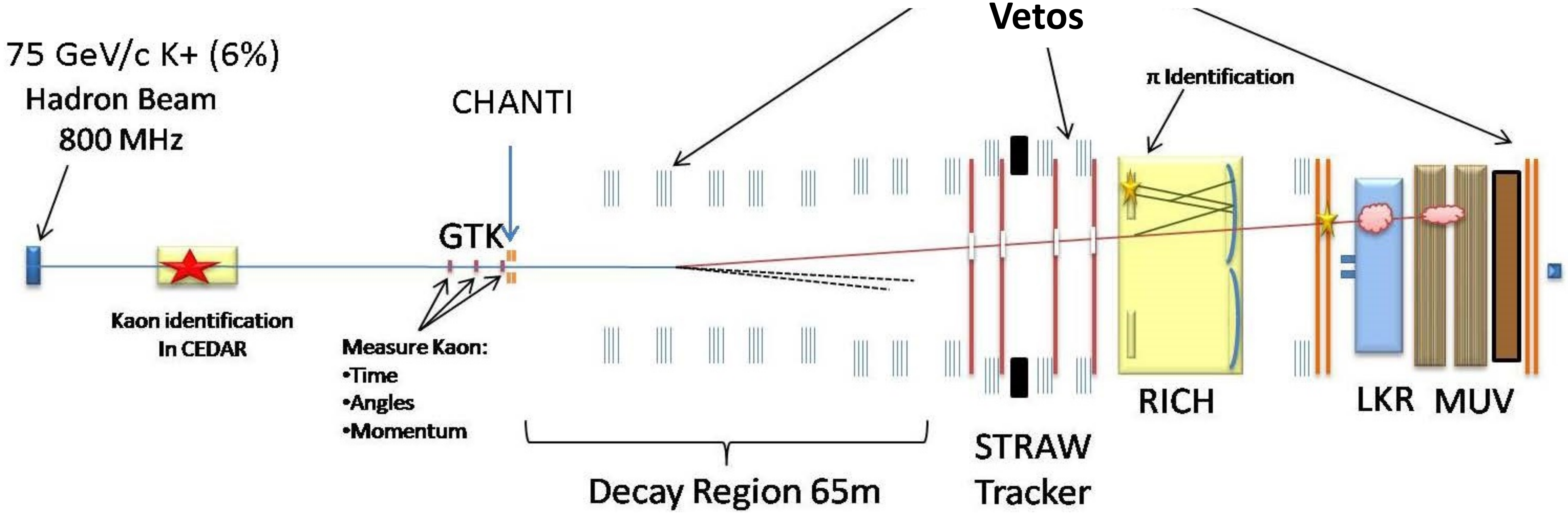
Run 2: 20 events seen for 17 expected (10 SM + 7 BG)

Run 3: detector upgraded to reach ~100 signal events

Post-LS3 proposal (HIKE):

K^+ intensity increase by factor ~4, followed by K^0 beam:

K^0 rare decays complementary to K^+ decays for BSM searches.

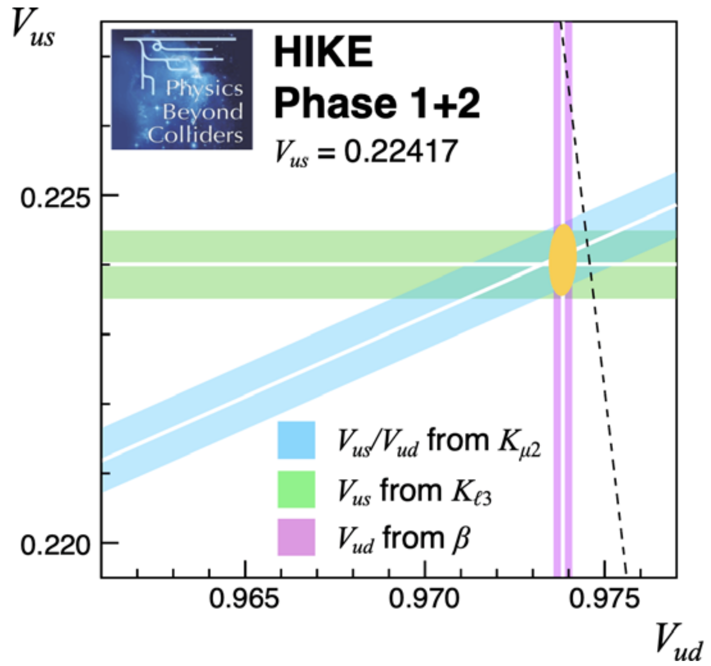


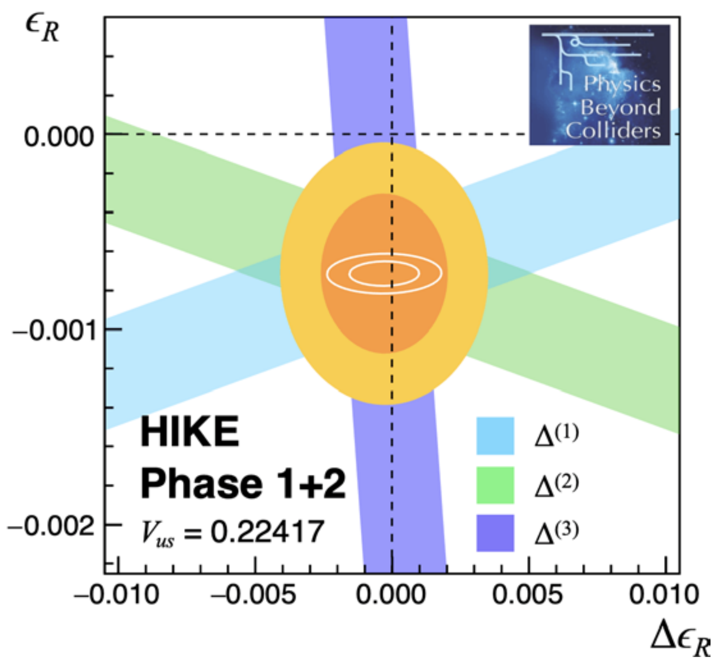
PRECISION FT@SPS: HIKE POTENTIAL OF KAON RARE DECAYS

See PBC ECN3 Report-2023-003

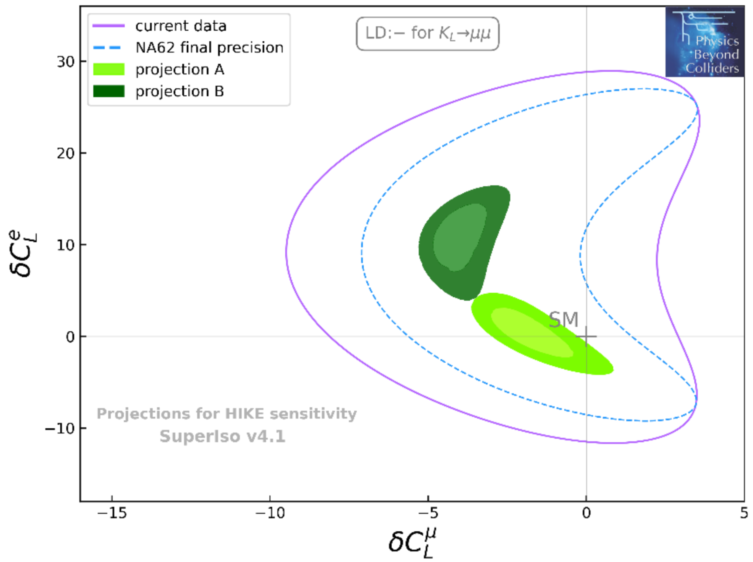
Two Highlights:

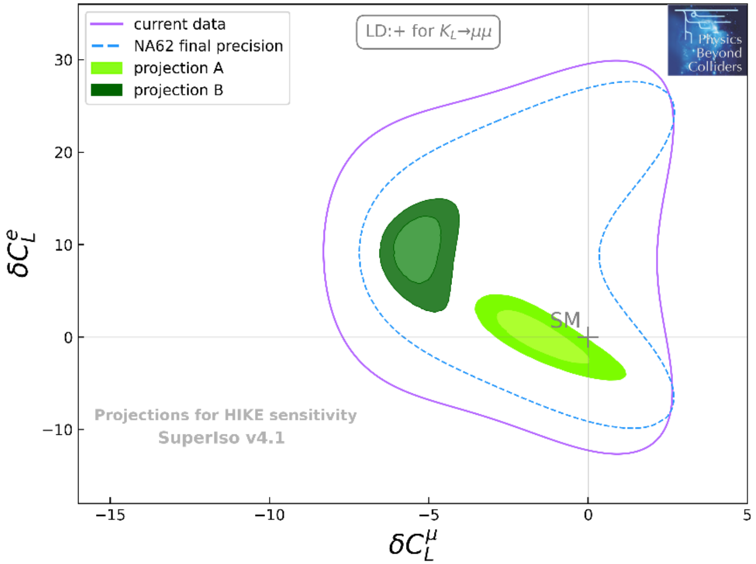
CKM matrix unitarity test





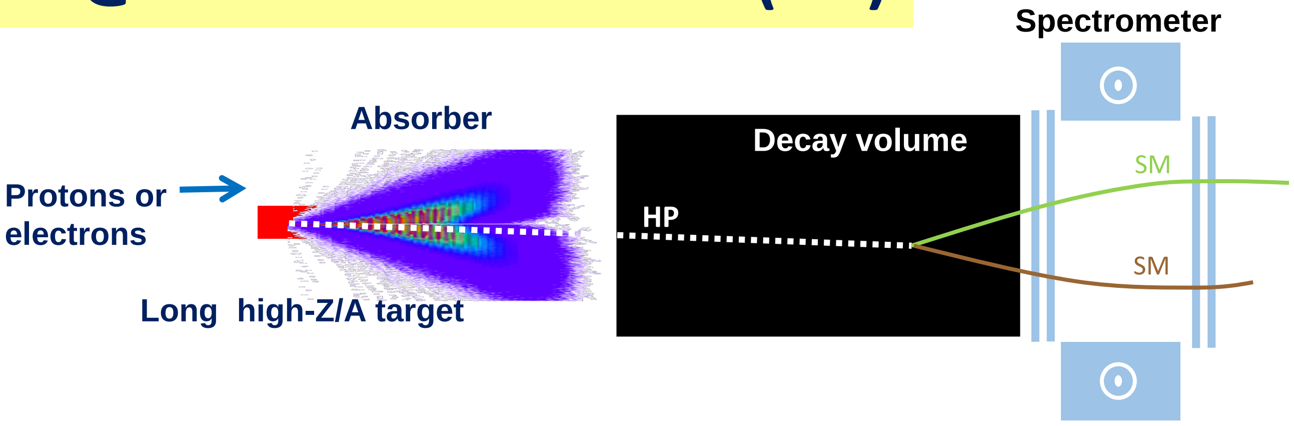
LFU: Kaons complementary to B mesons





FT@SPS: BEAM DUMPS (BD)

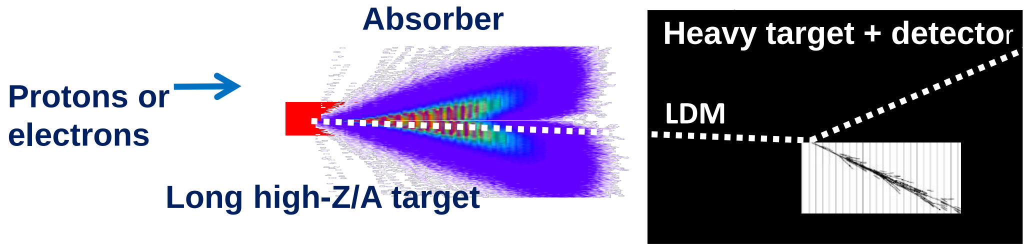
All experimental methods represented at CERN



Visible decay to SM particles

$signal \propto \epsilon^4$

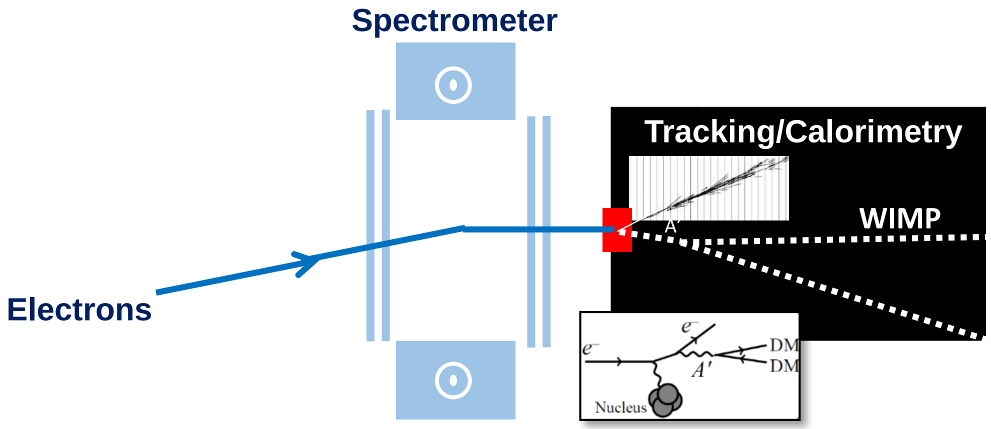
Critical: BG control



Recoil e/N from rescattering

$signal \propto \epsilon^4$

Critical: BG control



Missing energy from invisible decays

$signal \propto \epsilon^2$

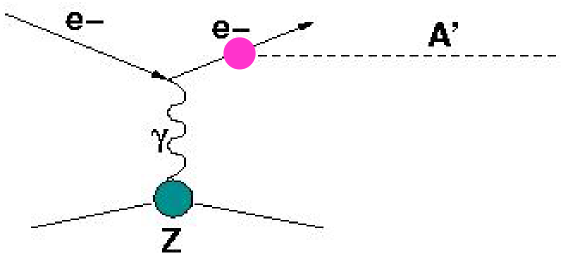
Critical: initial particle and pileup control

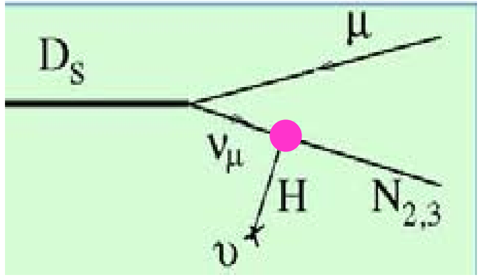
Graphics Courtesy Richard Jacobsson

NB: reach in (m,ε) depends on many parameters:

beam energy & intensity, decay vessel length, signatures, background …

HIDDEN SECTOR MAIN PRODUCTION MODES IN A BEAM DUMP





Primakov/Bremstrahlung:

Mass reach mainly in sub-GeV domain, weakly dependent on beam energy

Meson decays:

Mass reach in multi-GeV domain dependent on accessible meson mass thresholds (K,D,B)

EXPERIMENTAL VISIBLE SIGNATURES

Models	*Final states*
HNL, SUSY neutralino	$l^+\pi^-$, l^+K^-, $l^+\rho^-$ $\rho^+\rightarrow\pi^+\pi^0$
Vector, scalar, axion portals, SUSY sgoldstino	l^+l^-
HNL, SUSY neutralino, axino	$l^+l^-\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$

+ recoil particles or missing energy for rescattering / missing energy methods

DP = Dark Photon
DS = Dark Scalar
HNL = Heavy Neutral Lepton
ALP = Axion-Like Particle

MAIN BEAM DUMP PROJECTS OUTSIDE CERN

EXPERIMENT	PERIOD	BEAM	PARTICLES ON TARGET	SIGNATURE	MODELS
BDX @JLAB	~2024-25	e 11 GeV	$\sim 10^{22}$	recoil e	DP, ALPs
LDMX @SLAC	< 2030	e 4-8 GeV	$2\ 10^{16}$	invisible	DP, ALPs
SBND @FNAL	< 2030	p 8 GeV	$6\ 10^{20}$	recoil Ar	DP
DarkQuest @FNAL	2024	p 120 GeV	$10^{18} \rightarrow 10^{20}$	visible e^+e^-	DP, DS, HNL
LBND @FNAL	< 2040	p 120 GeV	$\sim 10^{21}$	recoil e, N	DP, DS, HNL

Recent dedicated experiments demonstrate a regain of interest for beam dumps

Flavour factories (BELLE II, …) have also some sensitivity from exotic decays

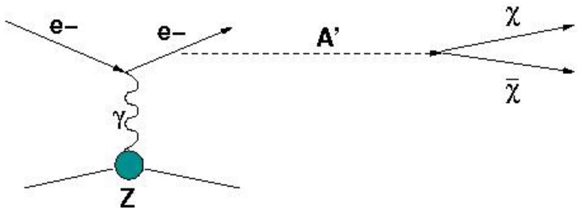
BEAM DUMP PROJECTS AT CERN

DP = Dark Photon
DS = Dark Scalar
HNL = Heavy Neutral Lepton
ALP = Axion-Like Particle

EXPERIMENT	PERIOD	BEAM	PARTICLES ON TARGET	SIGNATURE	MODELS
NA64(e)	ongoing	e 100 GeV	~5 10^{12}	invisible & visible e^+e^-	DP, ALPs
NA62-BD	2022-25	p 400 GeV	10^{18}	visible	DP, ALPs
HIKE/SHADOWS	2030-40	p 400 FeV	5 10^{19}	visible	DP, DS, HNL, ALPs
BDF/SHiP	2030-50	p 400 GeV	6 10^{20}	recoil & visible	DP, DS, HNL, ALPs
NA64(μ,h)	> 2024	μ,h > 100 GeV	2 10^{13}	invisible	DZ_{μ} , ALPs

NB: CERN offers unique opportunities with both lepton and hadron beams

LHCb and LHC-LLP dedicated projects have also sensitivity in similar mass range

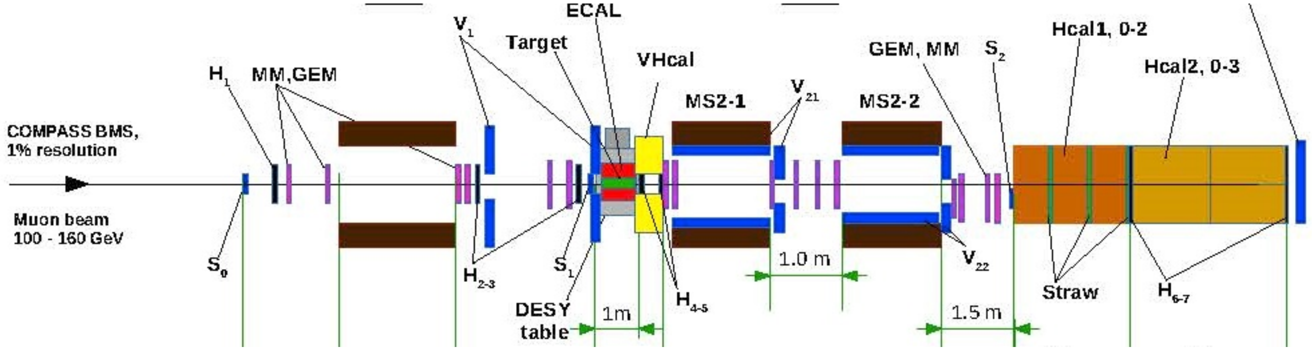


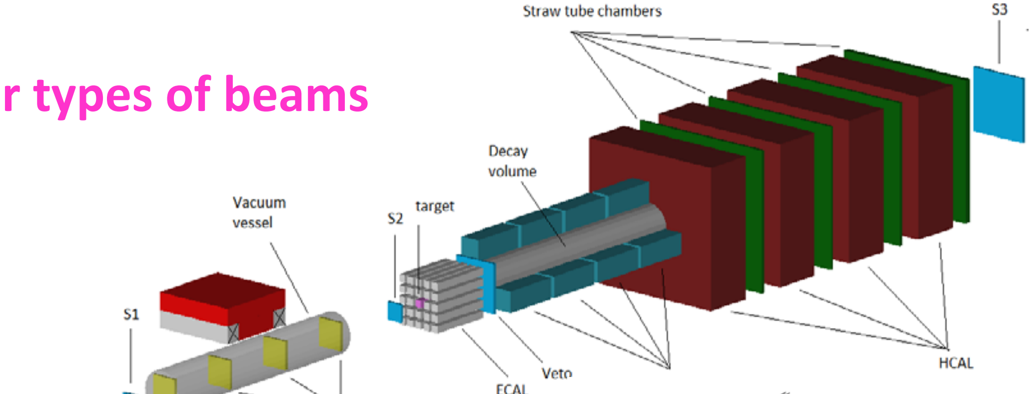
BD@SPS: NA64

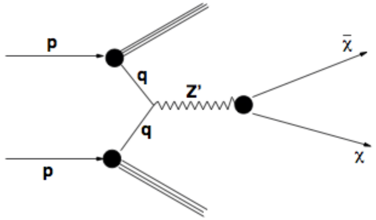
NA64(e):

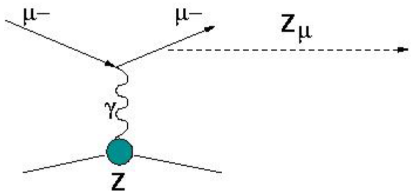
cheap e-beamdump setup implemented in 2015
on H4 e test beam, now permanent.
Optimized for invisible production,
currently leading the field for dark photons

NA64(μ,h): proposed extensions of the method to other types of beams









μ beams:

test of $(g\text{-}2)_\mu$ interpretations
and μ-coupled dark sector

Hadron beams:

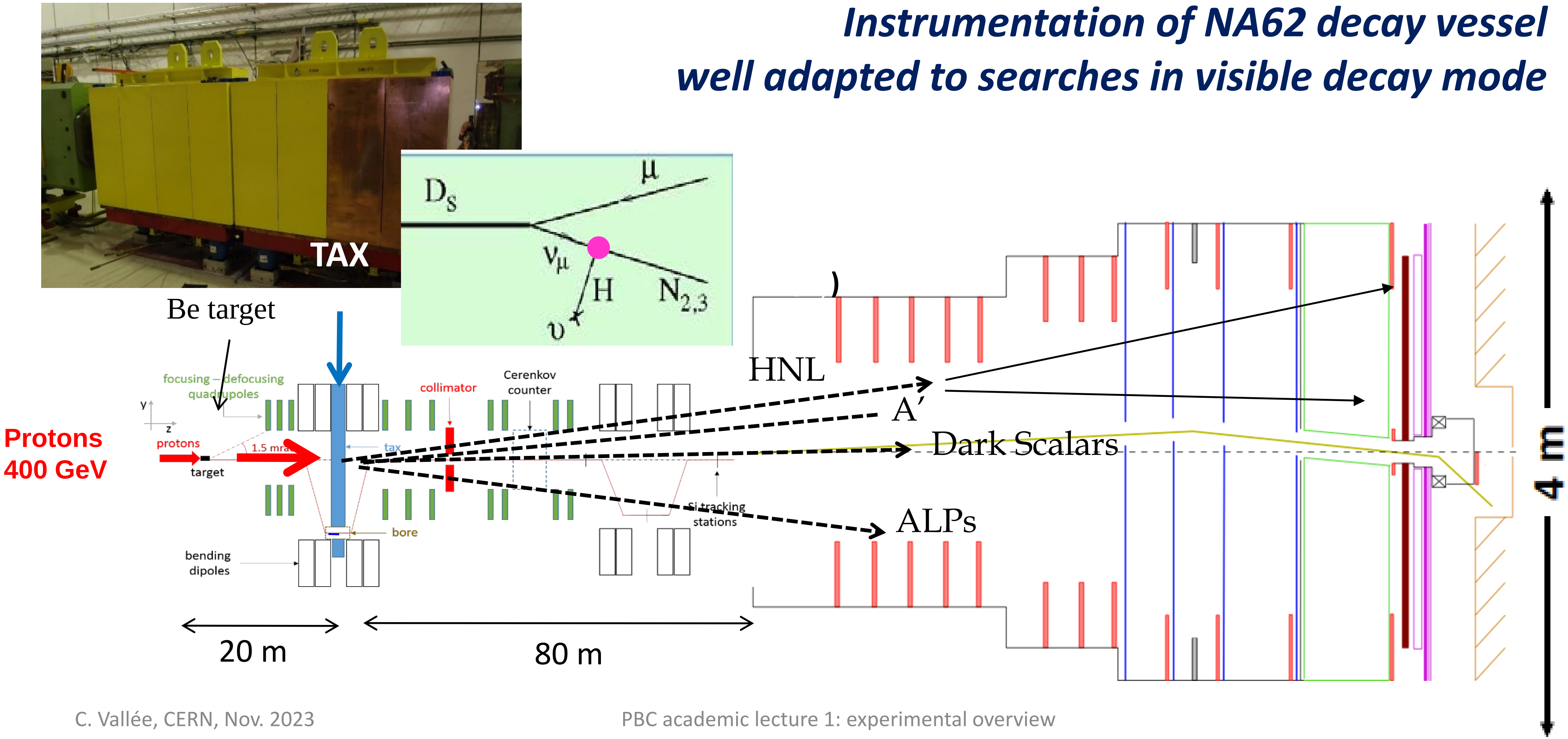
meson decays to invisible particles
and leptophobic dark sector

BD@SPS: NA62 PROTON BEAM DUMP MODE

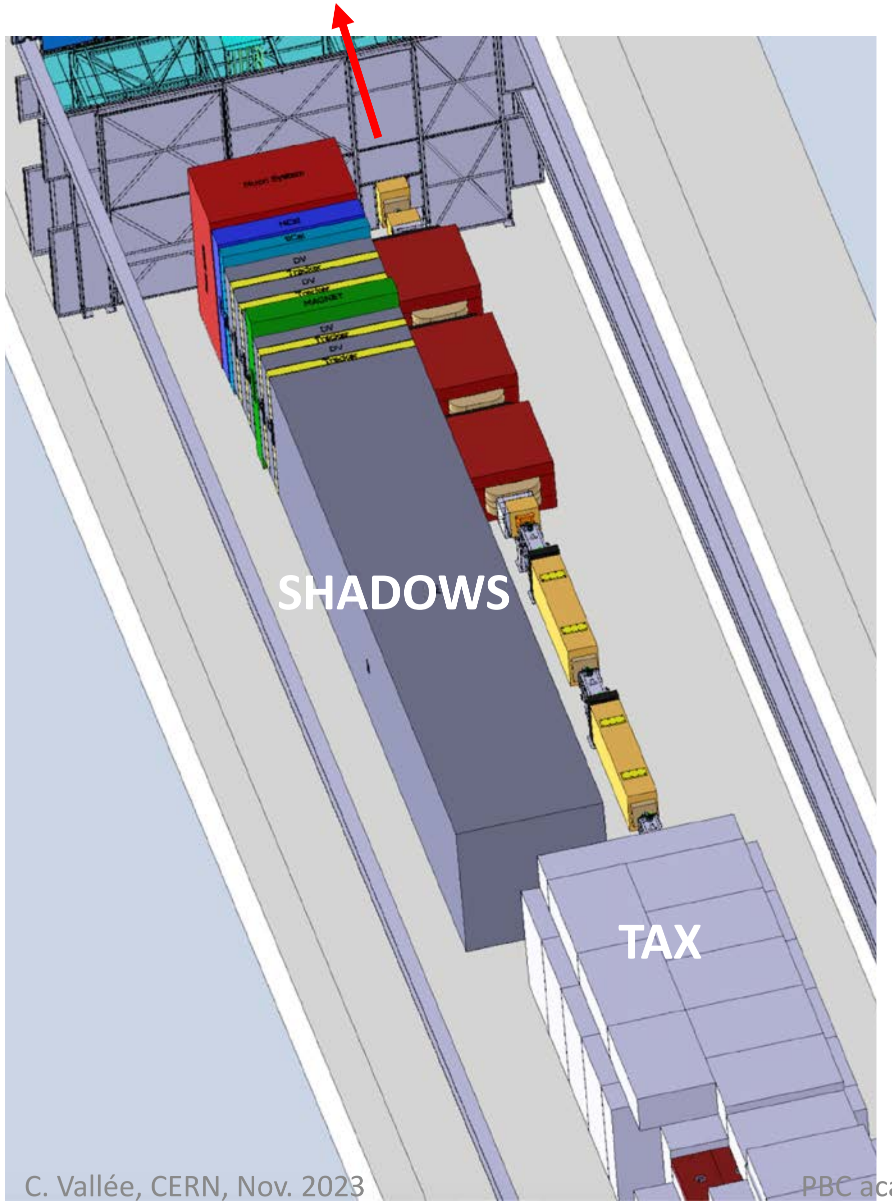
Some NA62 data taking in beam dump mode during run 3

Achieved by closing the TAX collimator, ~10^{18} PoT expected until LS3

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



HIKE DECAY SPECTROMETER
(NA62 UPGRADE)



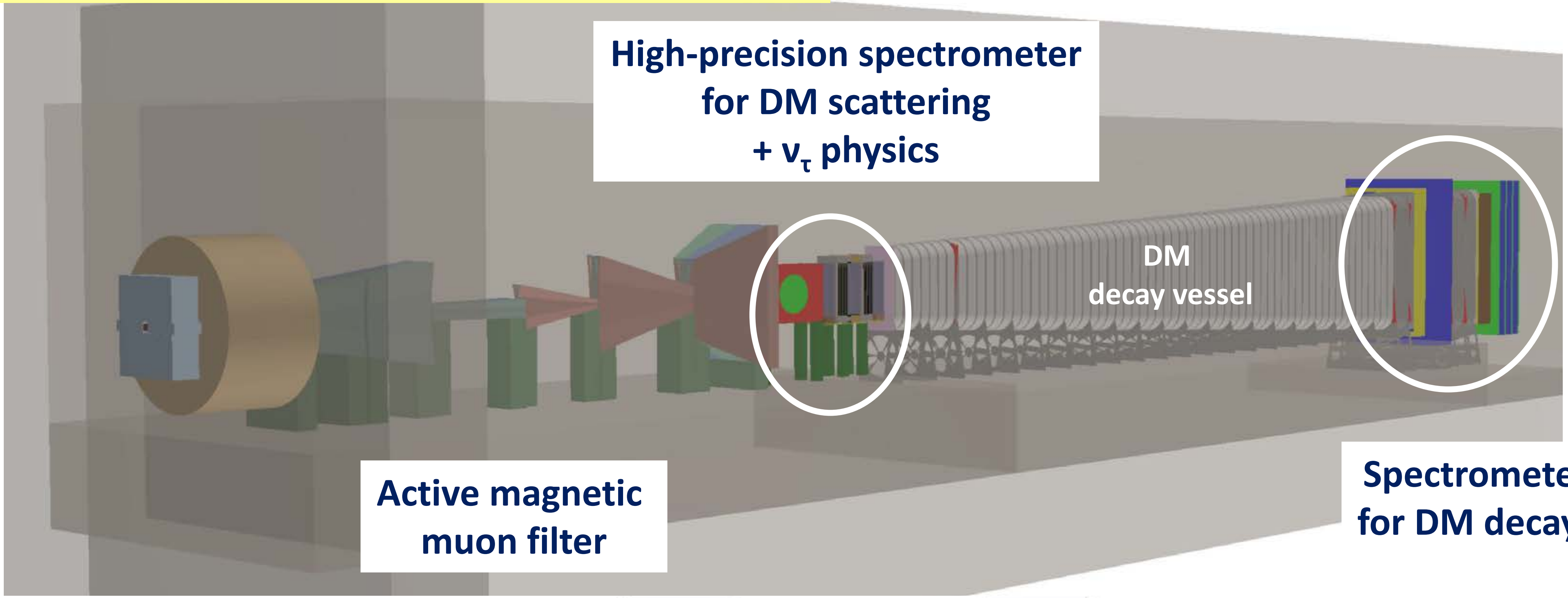
POST-LS3 BD@SPS PROPOSAL: HIKE & SHADOWS

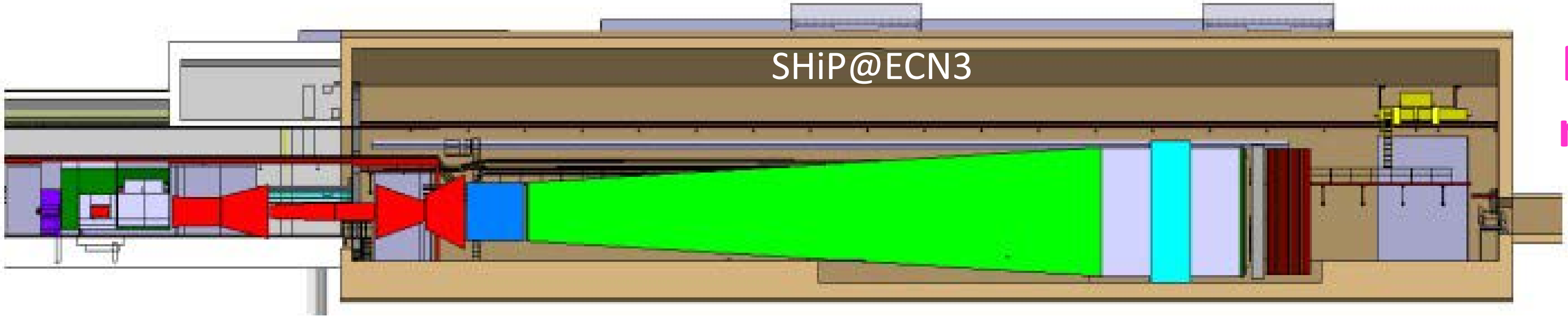
New SHADOWS detector
slightly off axis close to TAX dump collimator
would increase acceptance at high mass
of a high-intensity beamdump mode of HIKE

This post-LS3 BD option
could cumulate ~5. 10^{19} PoT
on the HL-LHC timescale

POST-LS3 BD@SPS PROPOSAL: BDF/SHiP@ECN3

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



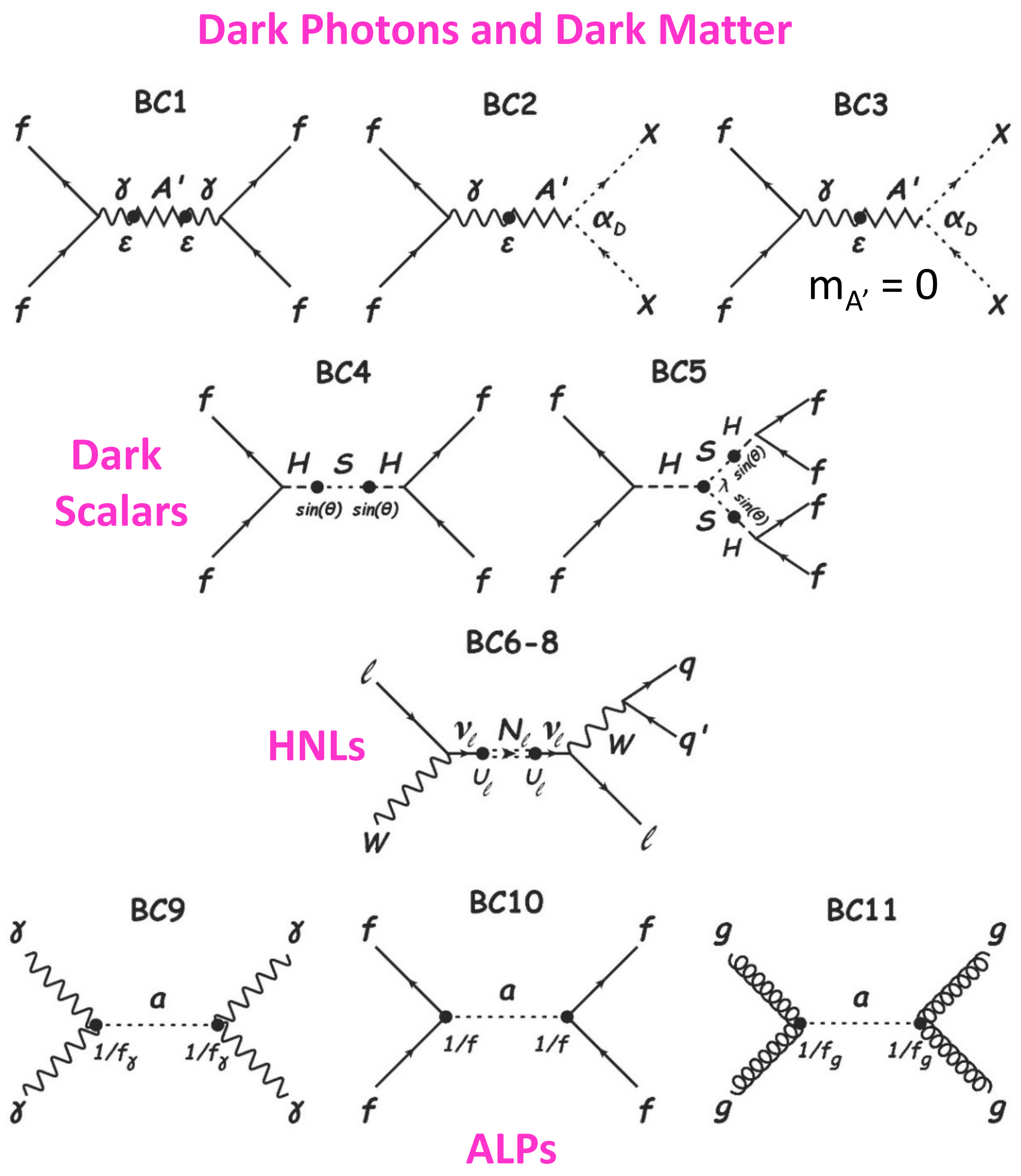


Relocation in ECN3 and re-optimization studied to reduce the overall BDF/SHiP cost

BD@SPS BSM SENSITIVTY: portals to Hidden Sector

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

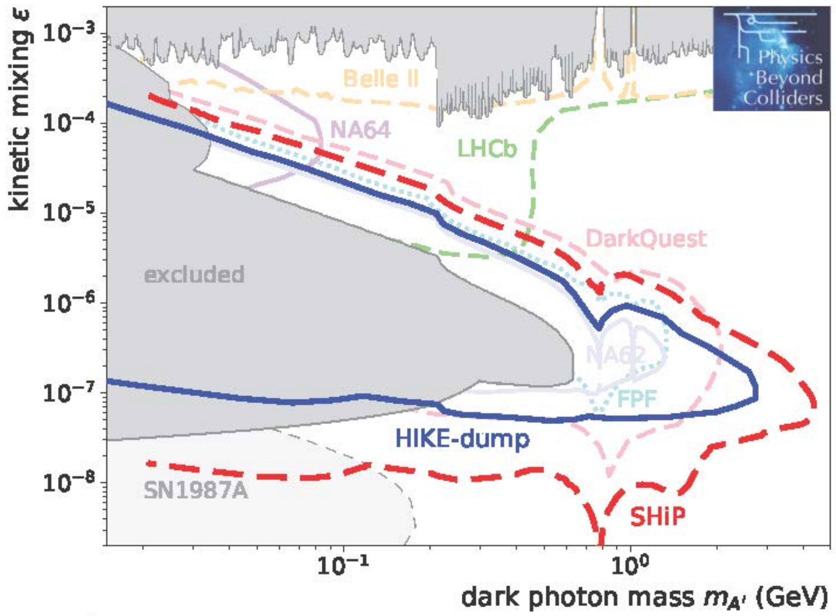
See FIPs2022 workshop proceedings arXiv:2305.01715 for details



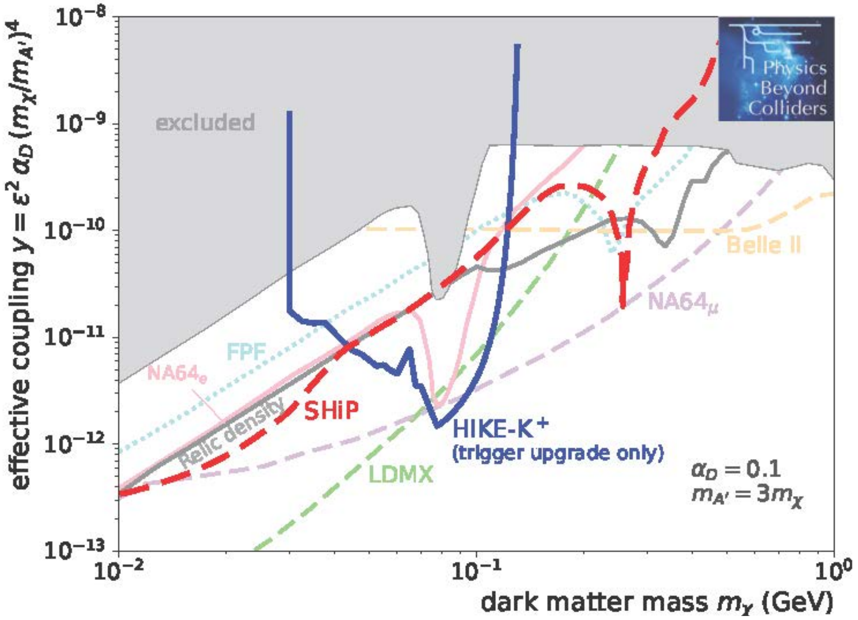
COMPARISONS OF PROJECTS REACH

See PBC ECN3 Report-2023-003

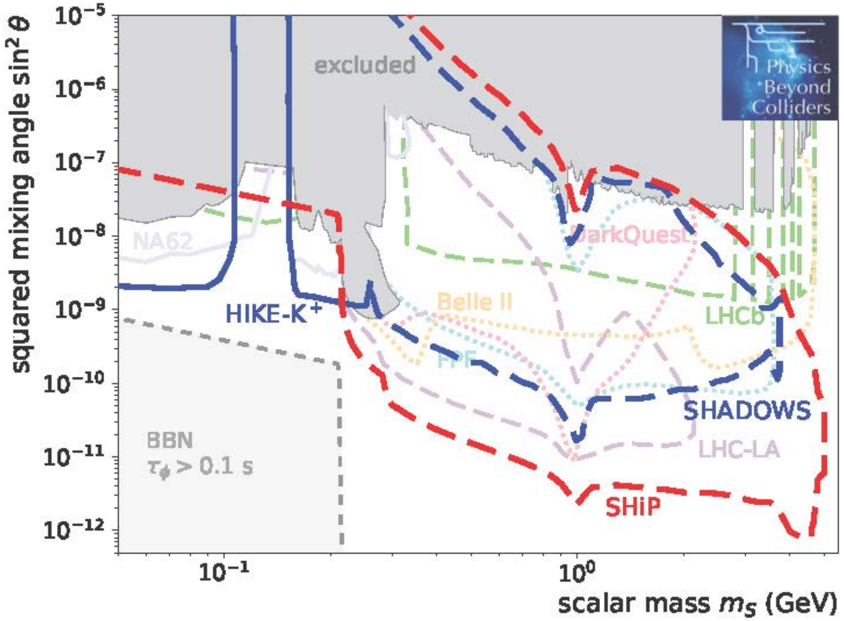
BC1
Dark photon visible decay to SM



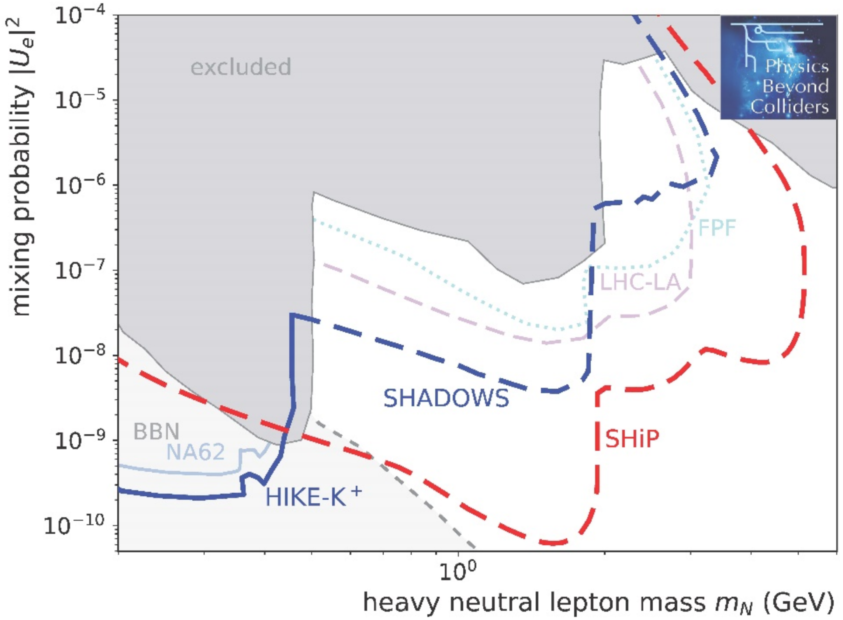
BC2
Dark photon decay to scalar DM
$\alpha_D = 0.1$
$m_\chi = 1/3\ m_{A'}$



BC4
Dark scalar mixing with Higgs



BC6
Dark HNL coupling to e



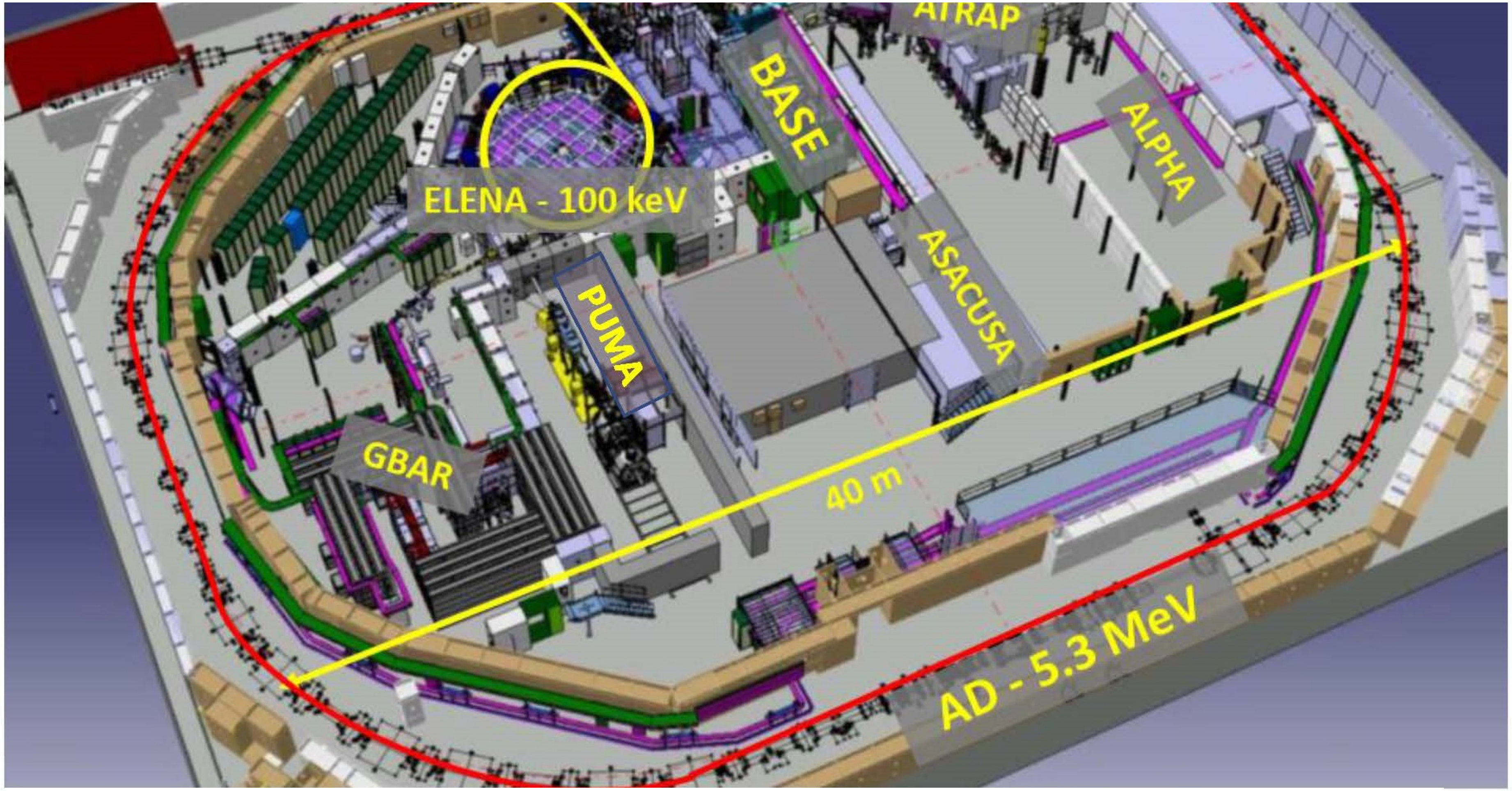
3rd ENERGY STEP DOWNWARDS:

PS AND LOW-E FACILITIES

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…



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

ELENA recent upgrade enhances potential for this decade

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…

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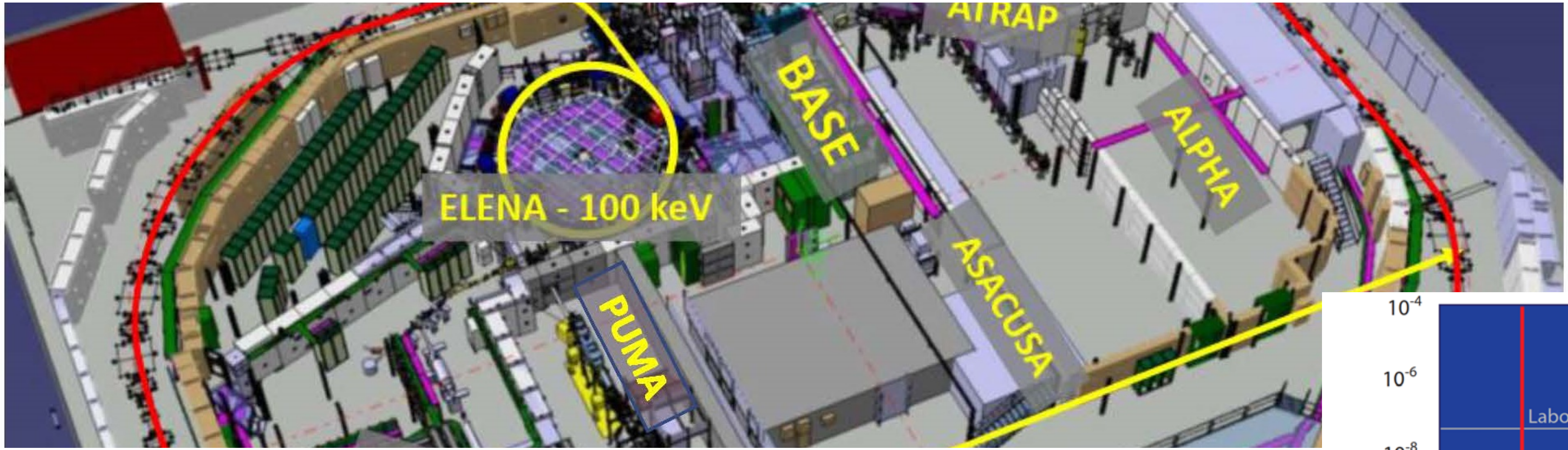
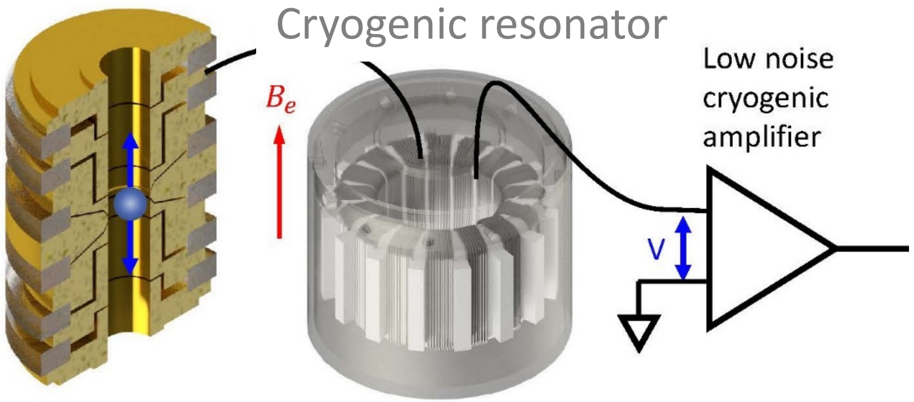
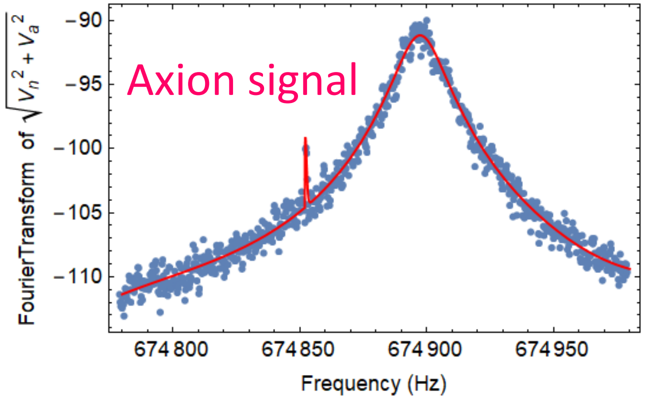
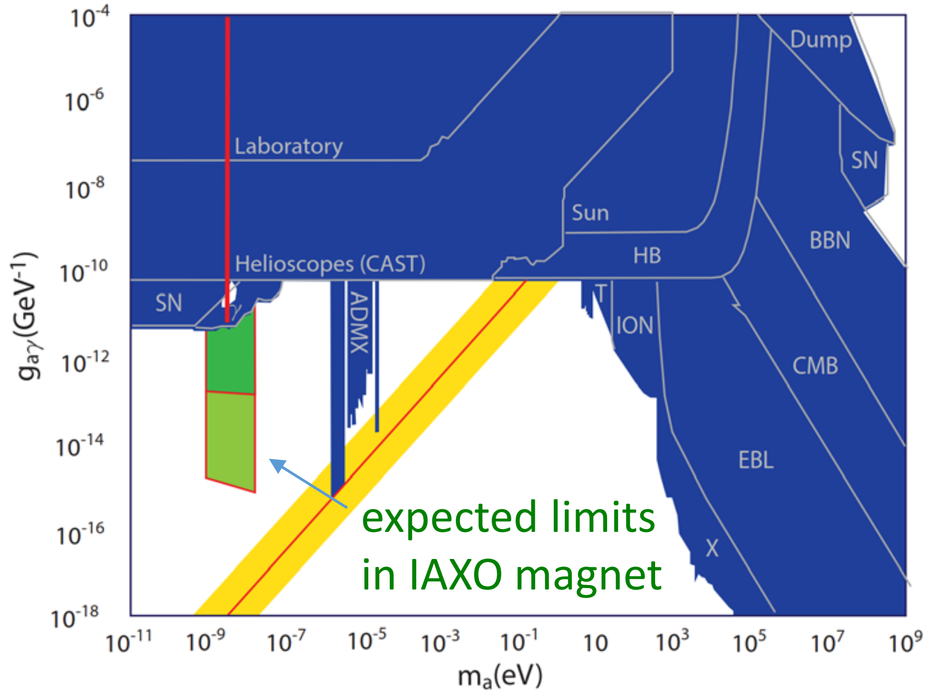


e.g. BASE DM axion searches





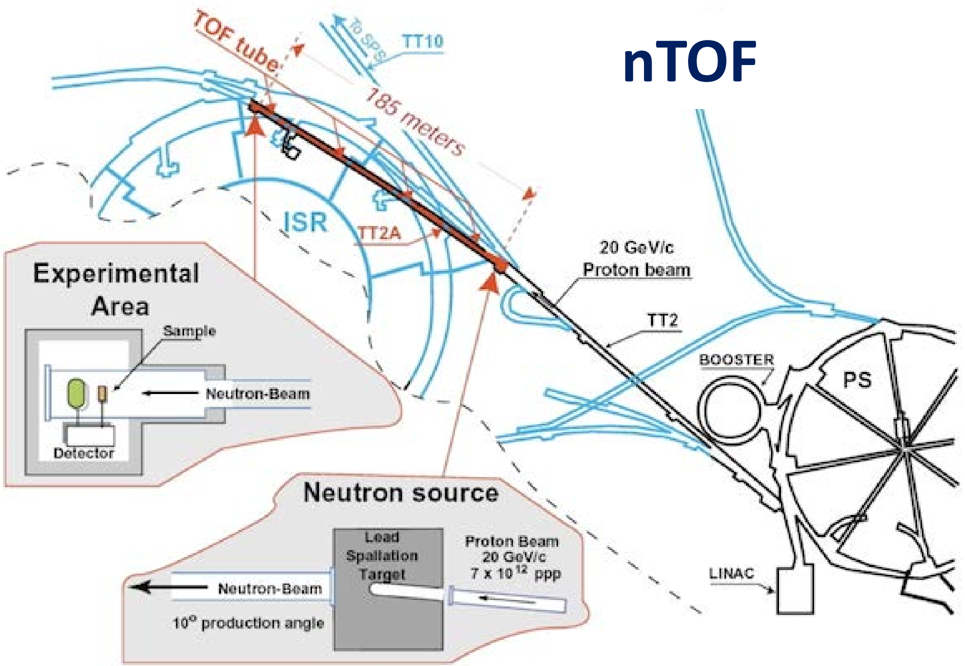


ISOLDE & nTOF

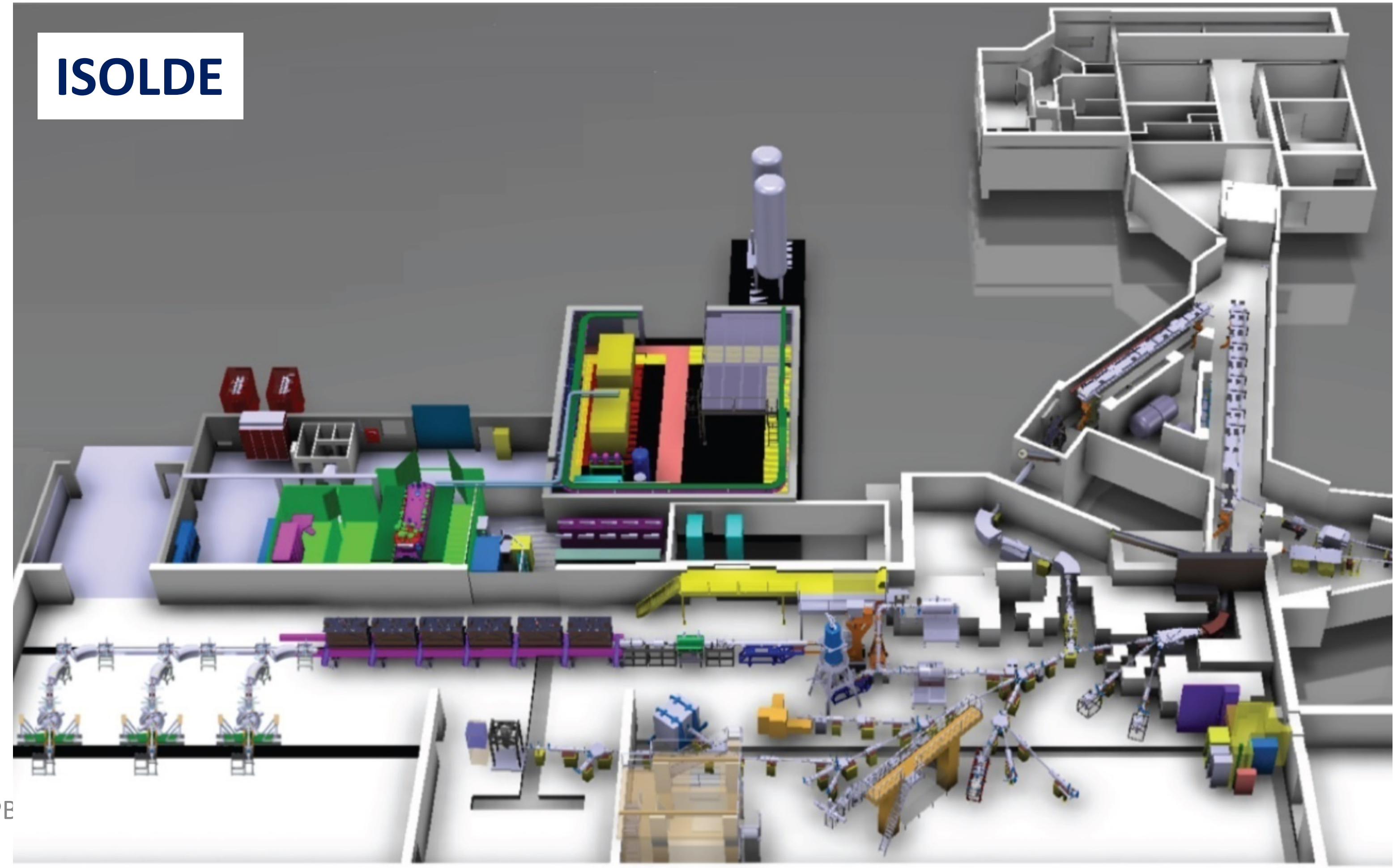
Similar technologies as at antimatter factory, with a fundamental physics potential for e.g.

- 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

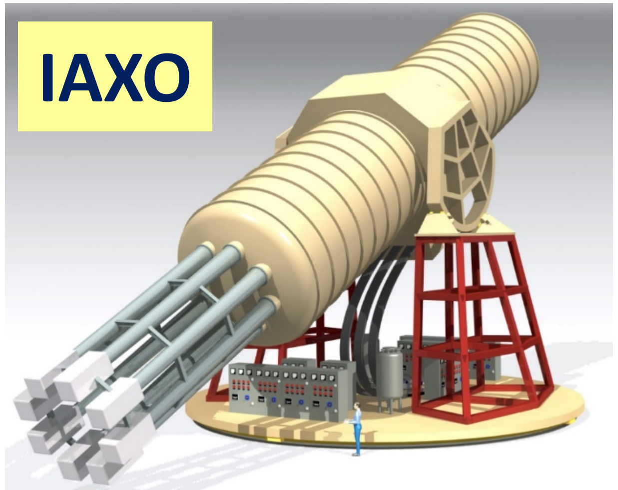


nTOF



4^{th} ENERGY STEP DOWNWARDS:

NON-ACCELERATOR EXPERIMENTS

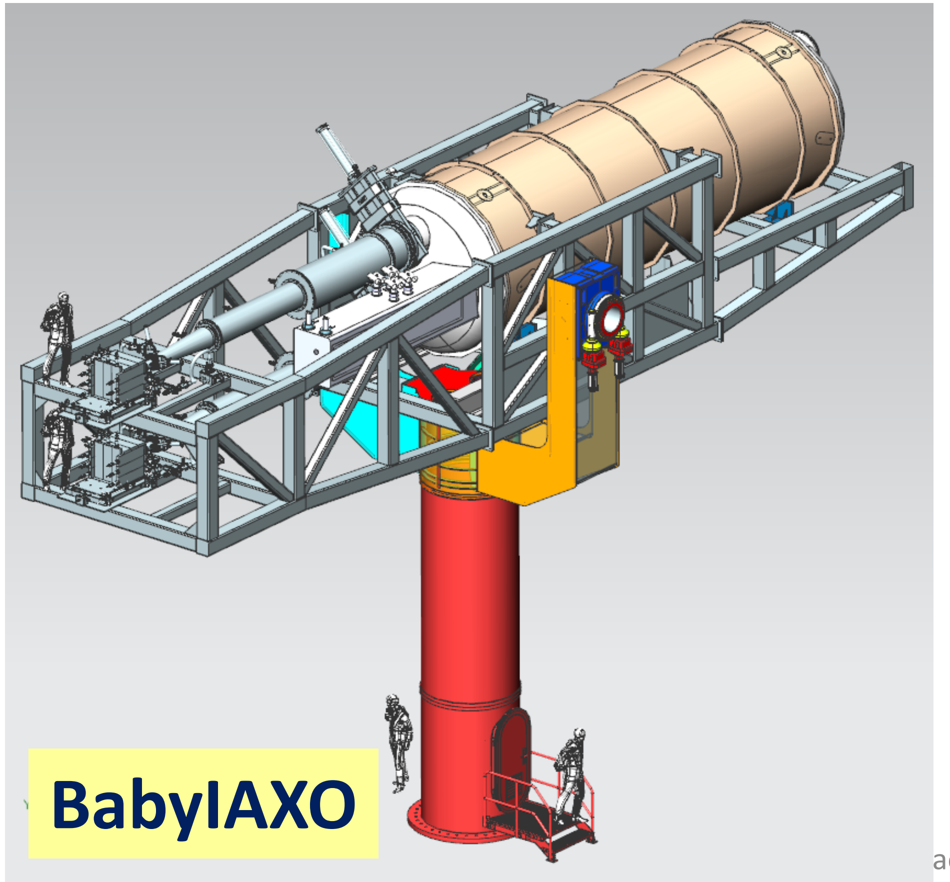


INTERNATIONAL AXION OBSERVATORY (axion helioscope successor of CAST@CERN)

BabyIAXO precursor approved and in construction at DESY

with CERN PBC support to magnet design

Unique physics reach for ALPs searches



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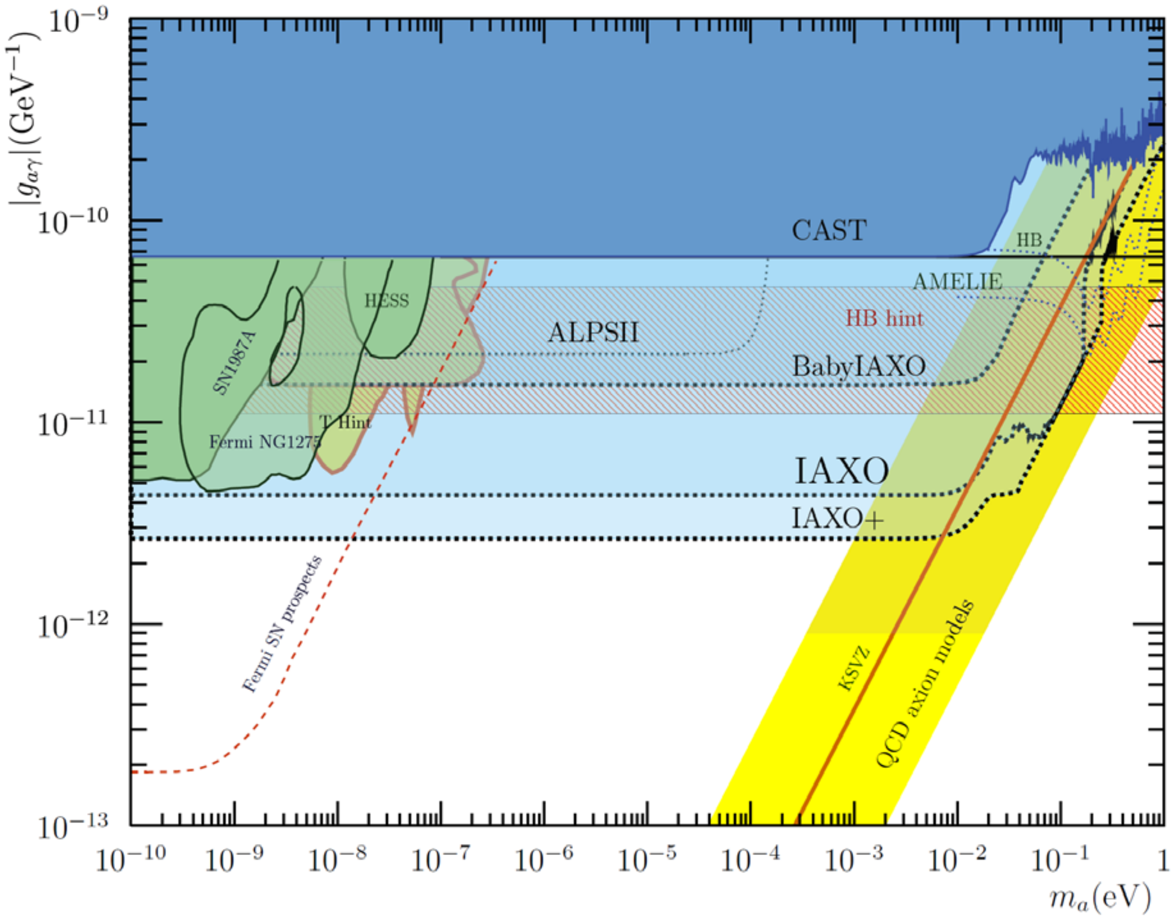


QUANTUM SENSORS

AION

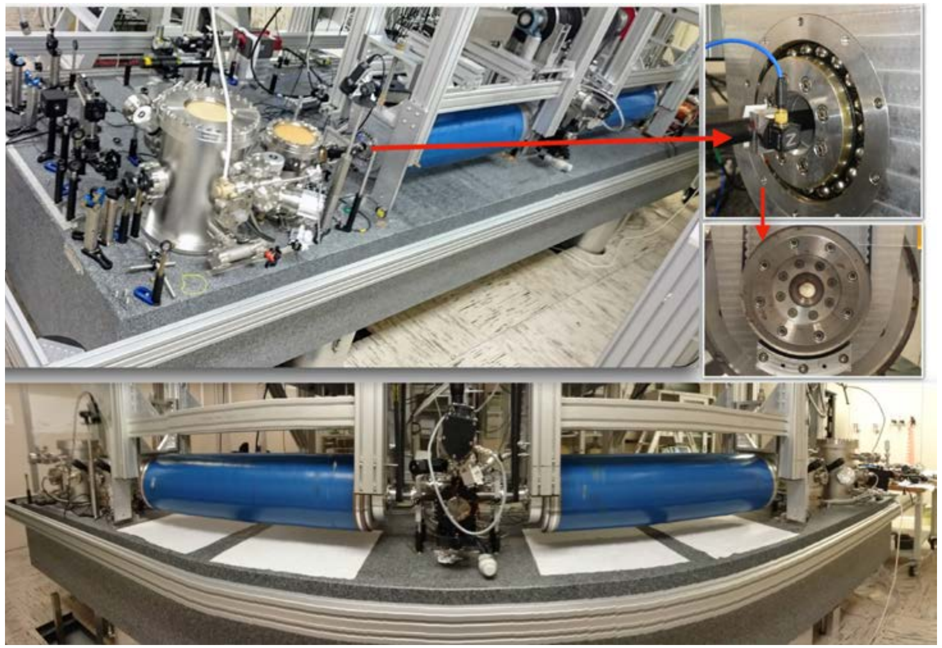
Atom interferometry for ultra-light DM and mid-frequency gravitational waves

- **PoP 10m setup being built in UK**
- **Possible siting of a 100m setup in a CERN LHC shaft investigated in PBC**
- **Longer Baseline Terrestrial Atom Interferometry already under study, e.g. workshop at CERN: (https://indico.cern.ch/event/1208783/)**

VMB@CERN

Vacuum Magnetic Bi-refringence

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



Among other studies:

- ***SC cavities and coating for novel relic axion detection***
- ***Setup for cosmic neutrino background measurement (PTOLEMY)***

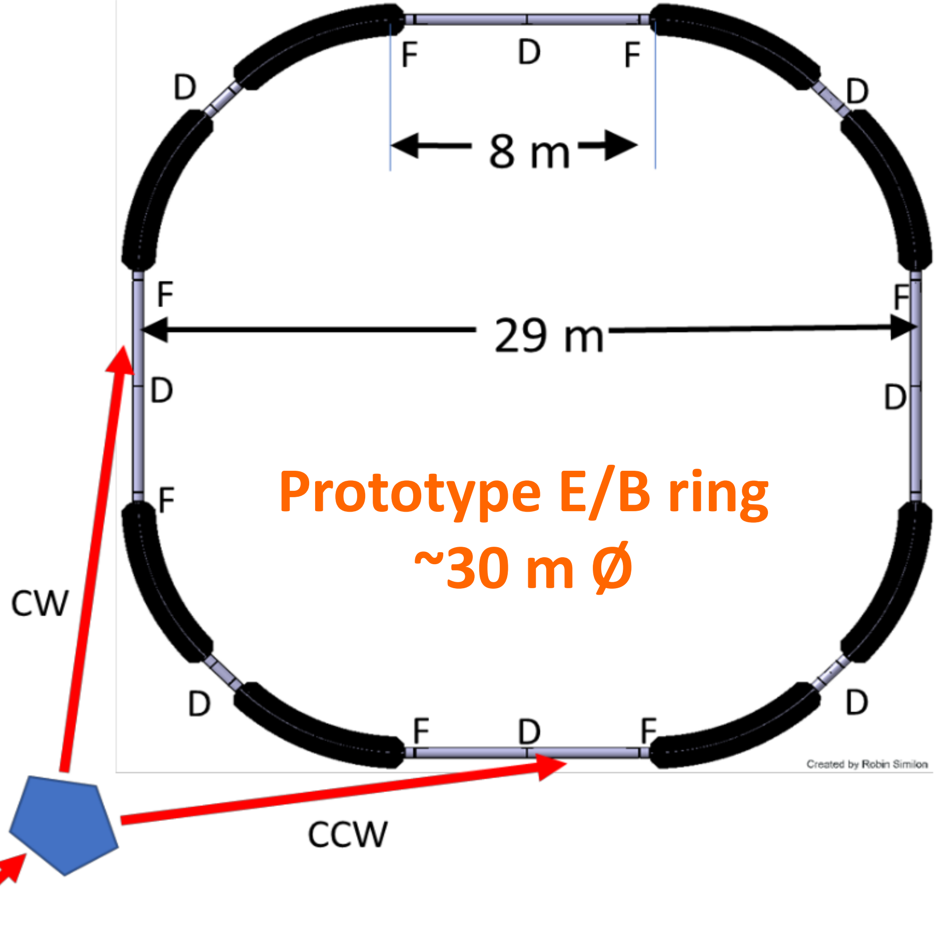
R&D FOR LONGER-TERM FUTURE PBC FACILITIES

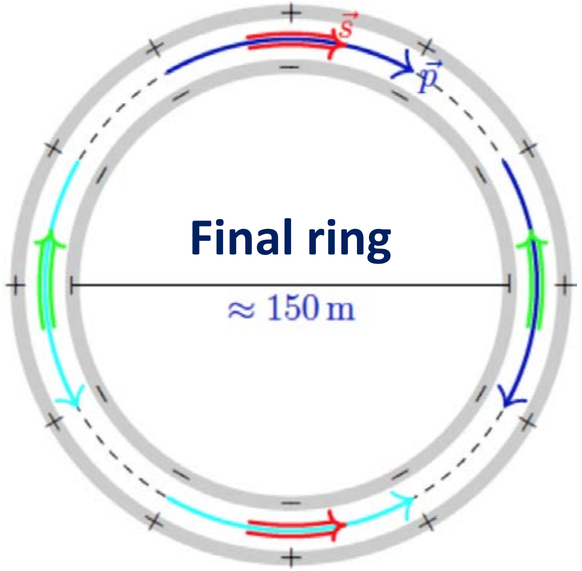
(excerpts)

PROTON EDM RING

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

Ongoing precursor experiment at Jülich (magnetic ring)





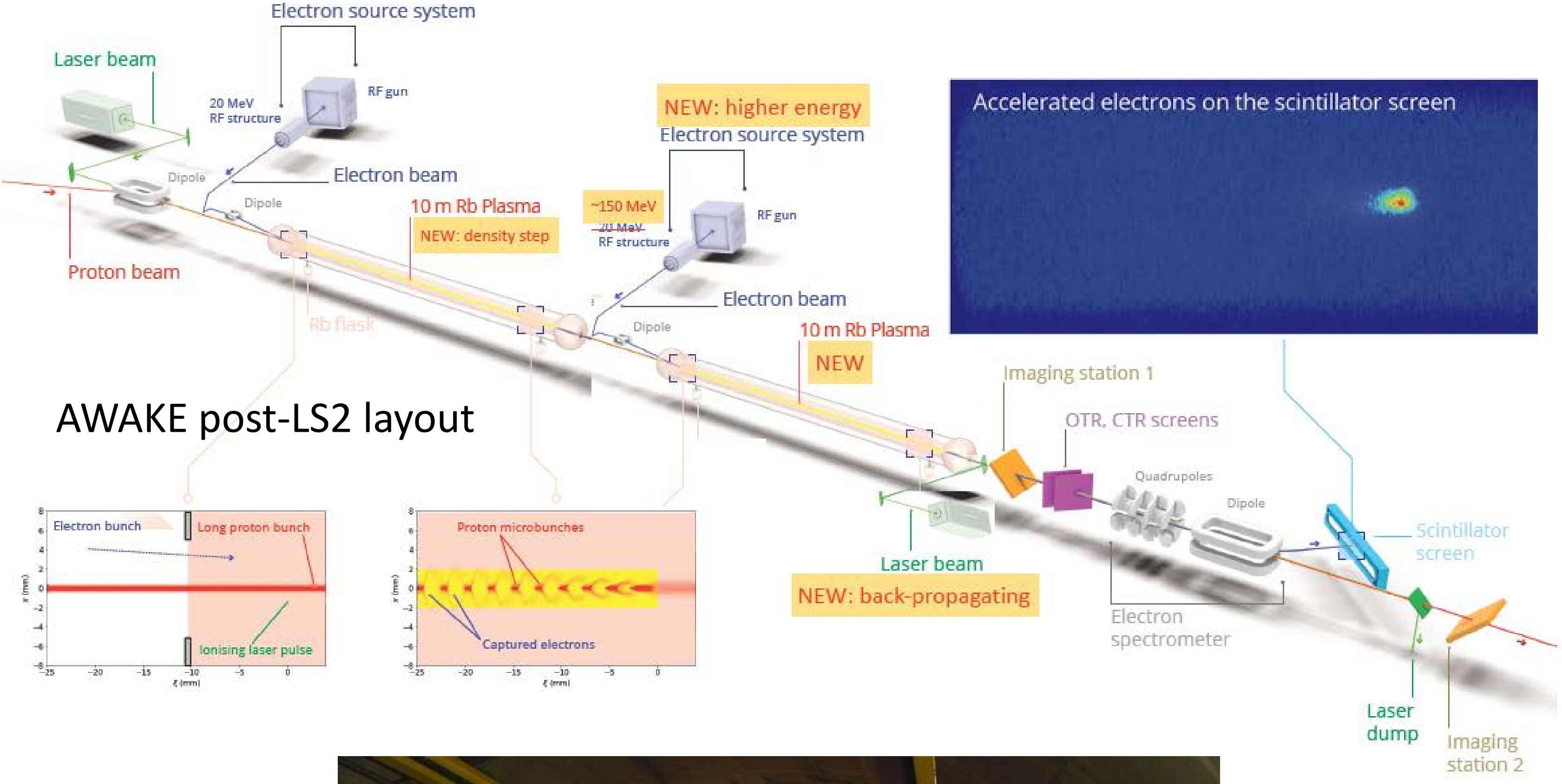
Design sensitivity: 4. 10^{-29} e.cm

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

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

Novel e-BEAM: AWAKE++

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



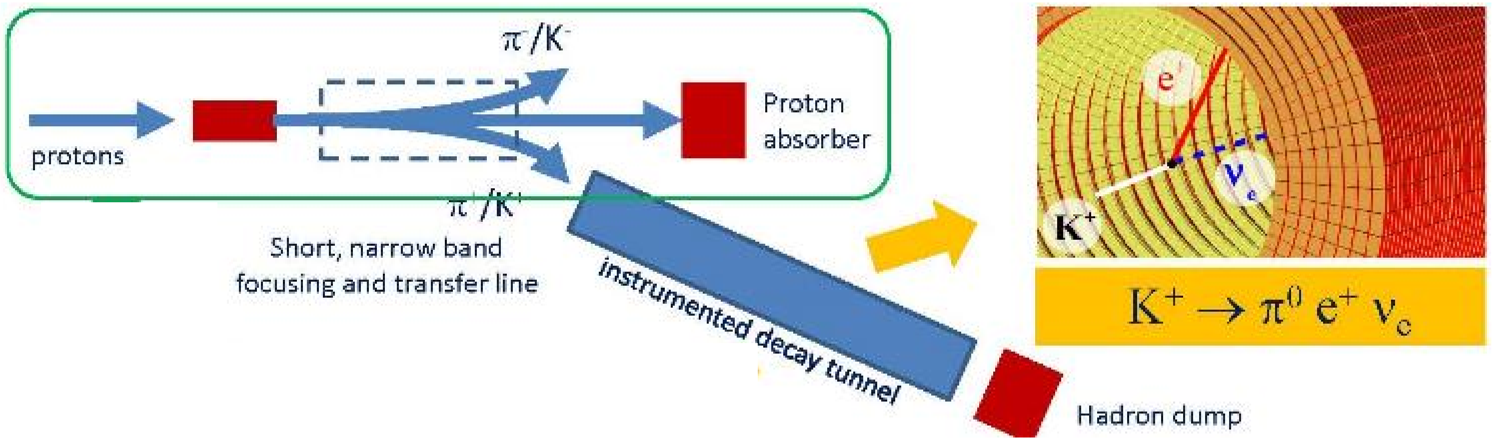
AWAKE post-LS2 layout

Proof of principle validated 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

Novel NEUTRINO BEAMS

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

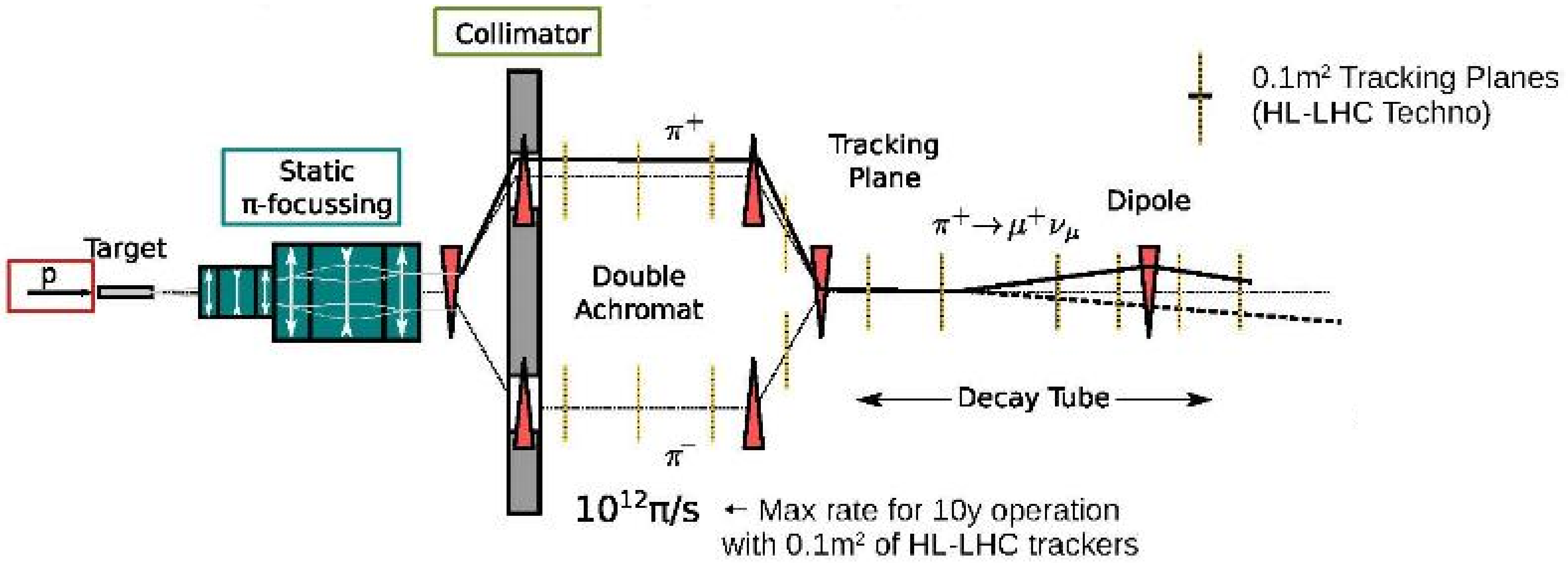


ENUBET:

- ν_e beam monitored from K decays
- Prototyping performed in Neutrino Platform

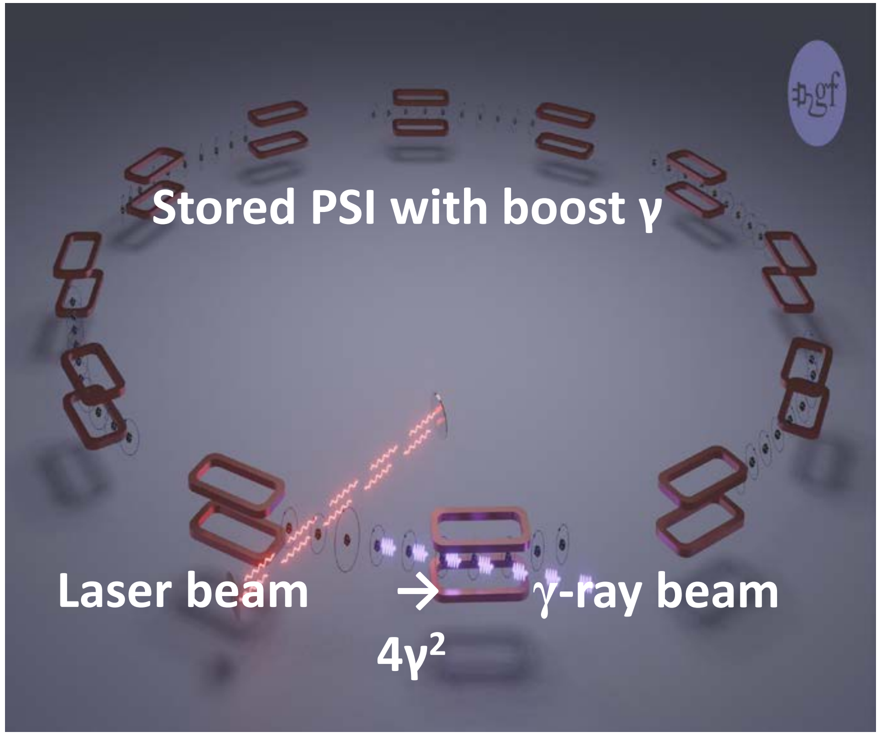
NuTAG:

- ν_μ beam with $(E_\nu,\theta_\nu,\phi_\nu)$ tagged from individual π decays with HL-LHC silicon trackers

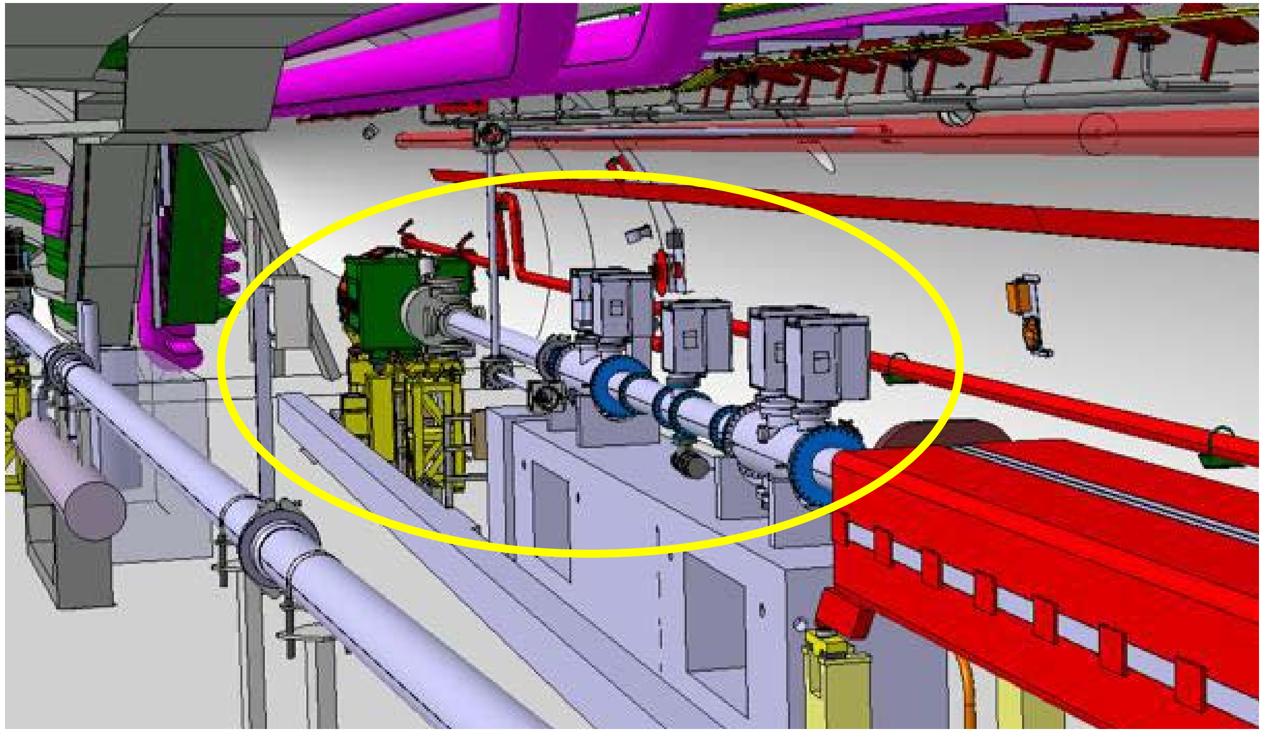


GAMMA FACTORY @LHC

Goal of 10^7 intensity gain vs existing facilities



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

Applications in atomic, nuclear, particle and applied physics discussed in many workshops and publications

OUTLOOK

Many opportunities for forefront physics

beyond LHC and future high-energy frontier colliders!

ADDITIONAL SLIDES

MAIN PAST BEAM DUMP PROJECTS

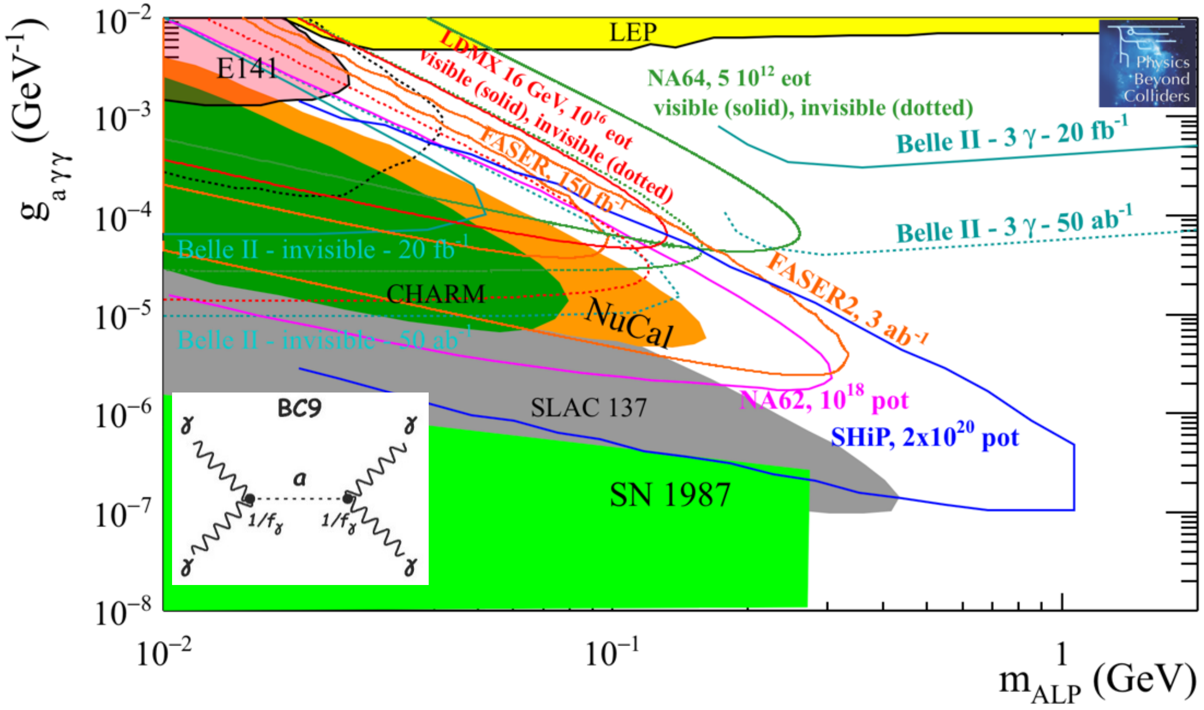
DP = Dark Photon
DS = Dark Scalar
HNL = Heavy Neutral Lepton
ALP = Axion-Like Particle

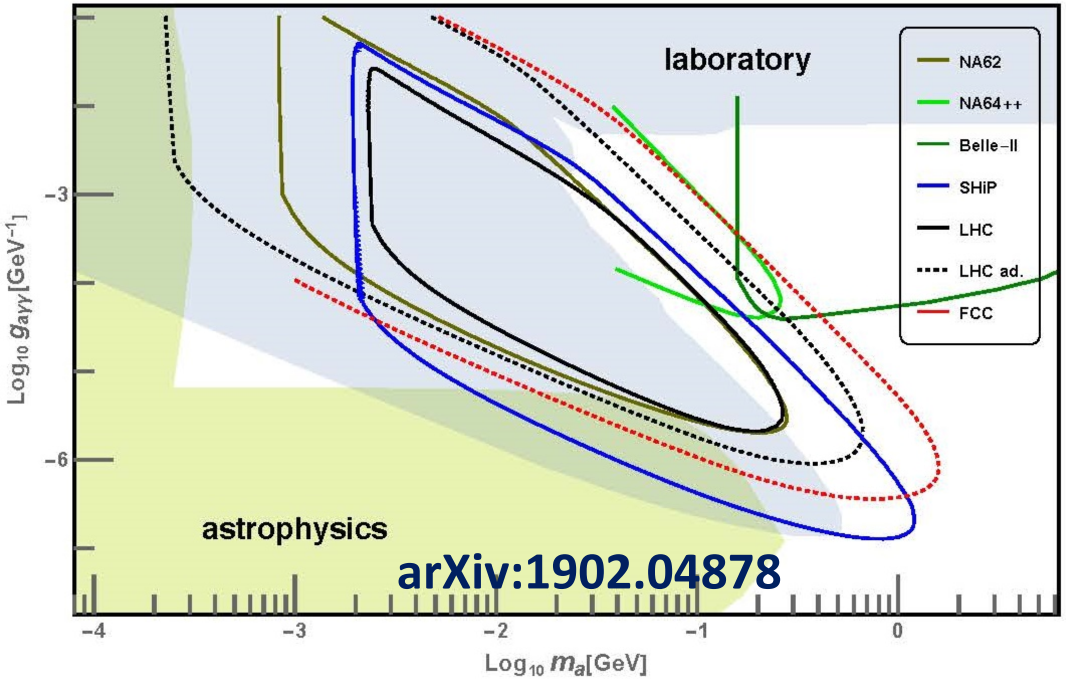
EXPERIMENT	PERIOD	BEAM	PARTICLES ON TARGET	SIGNATURE	MODELS
E137 @SLAC	80's	e 20 GeV	$2\ 10^{20}$	recoil e	DP, ALPs
E141 @SLAC	80's	e 9 GeV	$2\ 10^{15}$	visible e^+e^-	DP, ALPs
E774 @FNAL	80's	e 275 GeV	$5.2\ 10^{9}$	visible e^+e^-	DP
NuTeV @FNAL	90's	p 800 GeV	$2\ 10^{18}$	visible μ	HNL
NUCAL @Serpukhov	80's	p 70 GeV	$1.7\ 10^{18}$	visible $\gamma\gamma$, e^+e^-, $\mu^+\mu^-$	DP, DS, ALPs
PS191 @CERN	80's	p 19 GeV	$0.8\ 10^{19}$	visible	HNL
CHARM @CERN	80's	p 400 GeV	$2.4\ 10^{18}$	visible $\gamma\gamma$, e^+e^-, $\mu^+\mu^-$	DP, DS, HNL

NB: most past beam dumps were "cheap" by-products of other experiments

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

AMBER(R_p)

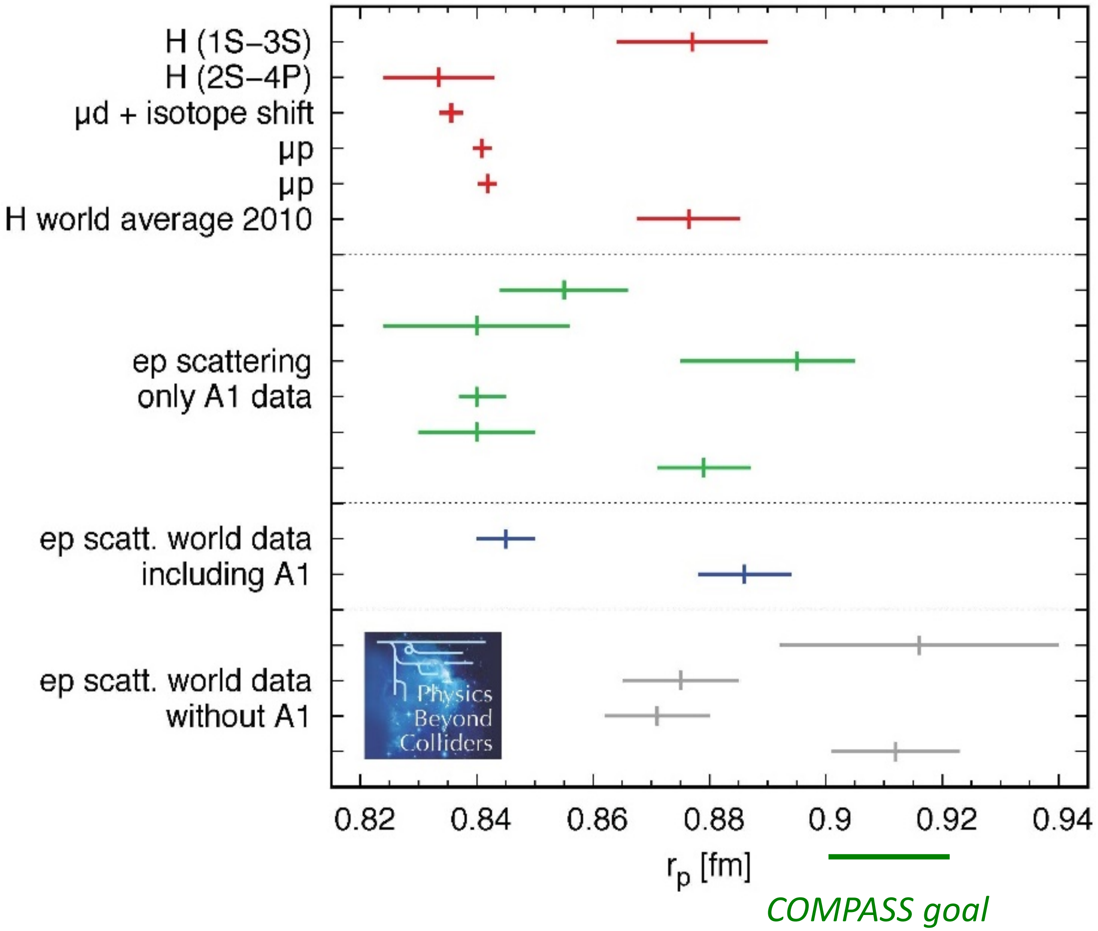
μ-p elastic scattering

In competition with MUonE on same μ-beam in EHN2

new AMBER TPC

→ AMBER Spectrometer (ex-COMPASS)

Proton radius puzzle



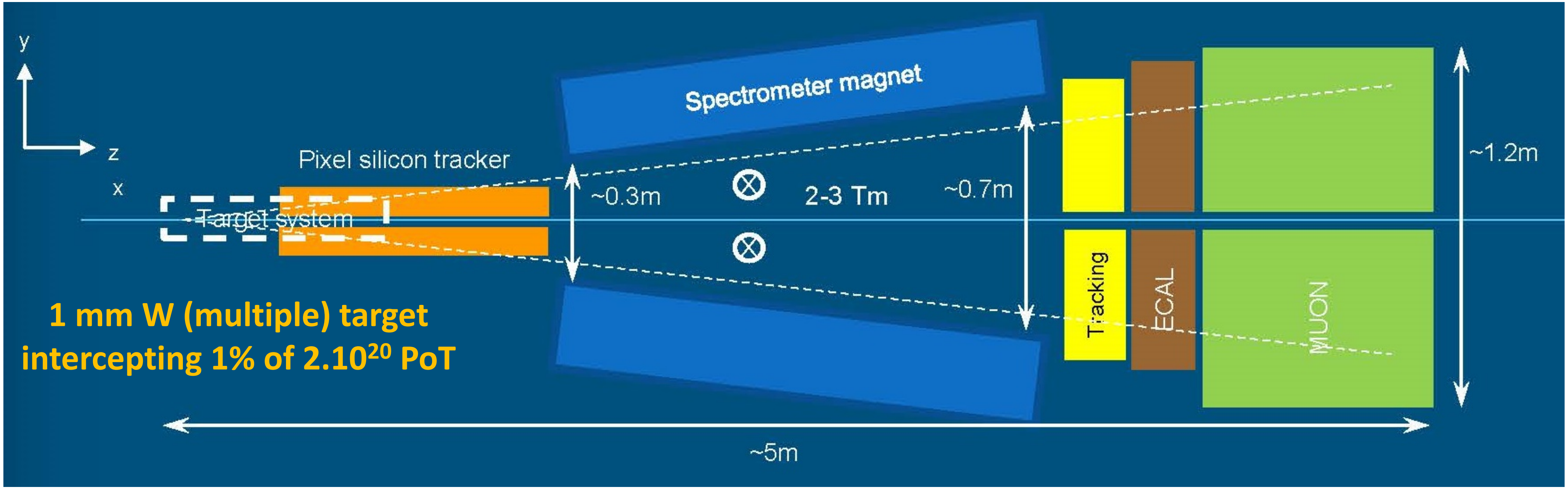
Data taking planned during run 3

TauFV

New idea introduced within PBC

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

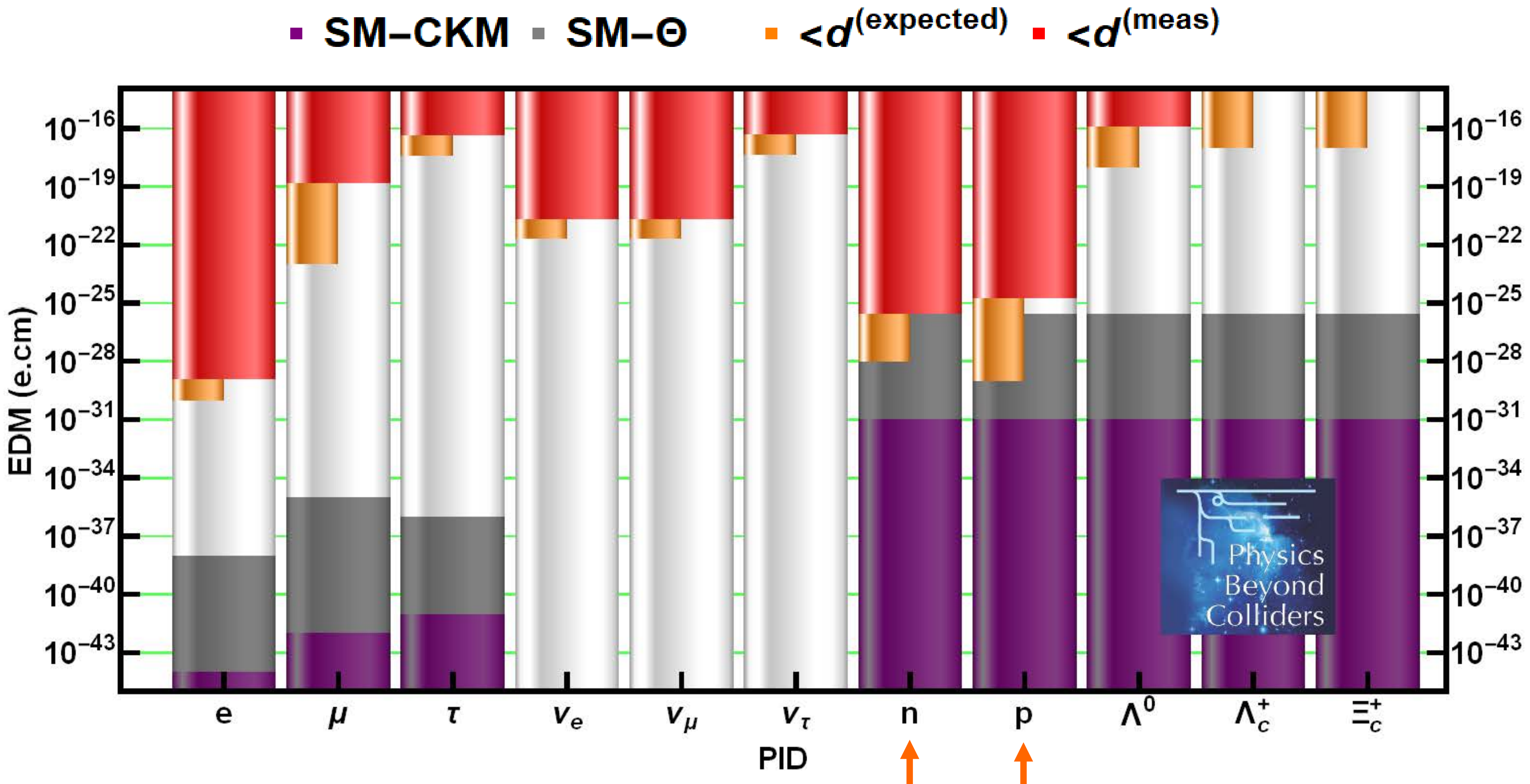
Could set limits on branching ratio better than 10^{-10} level targeted by BELLE-II



Implementation layout under study

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

EDM LANDSCAPE



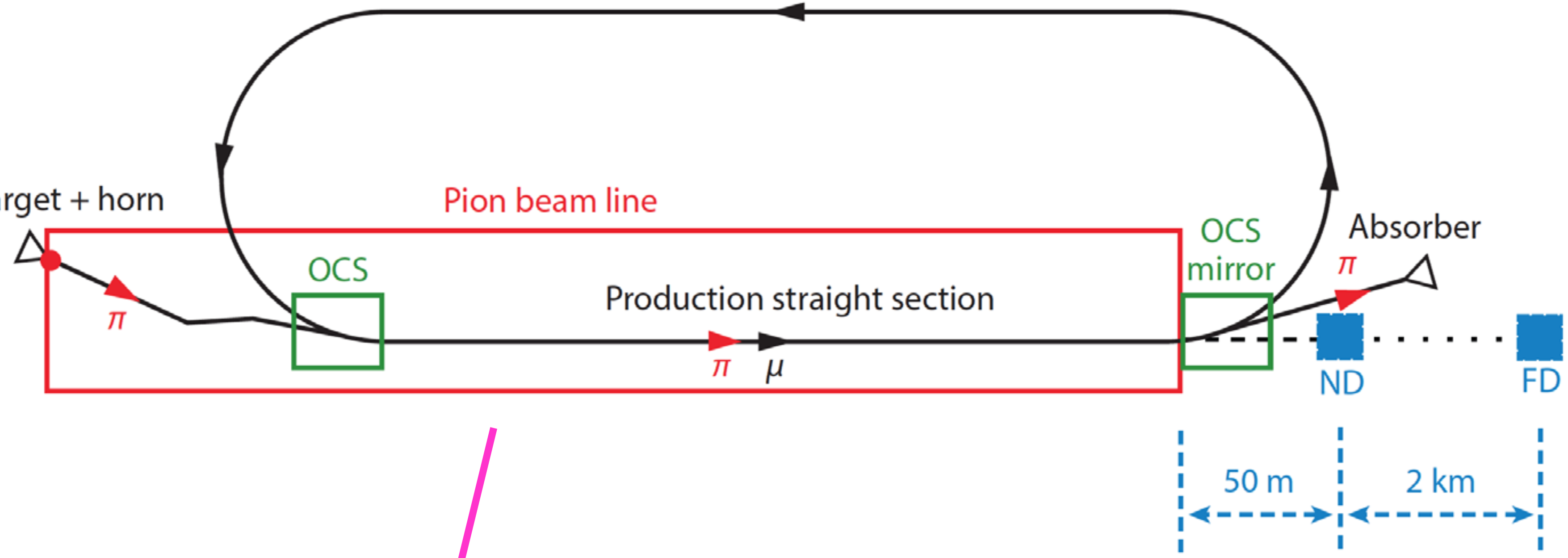
Neutron EDM is leading the field for hadrons

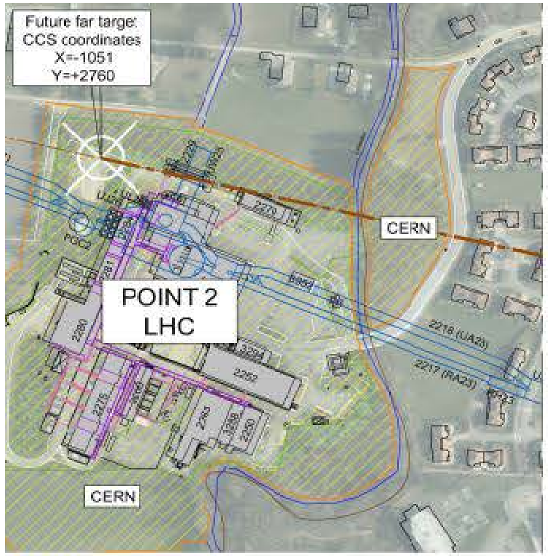
Catching up in precision is a challenge for the proton

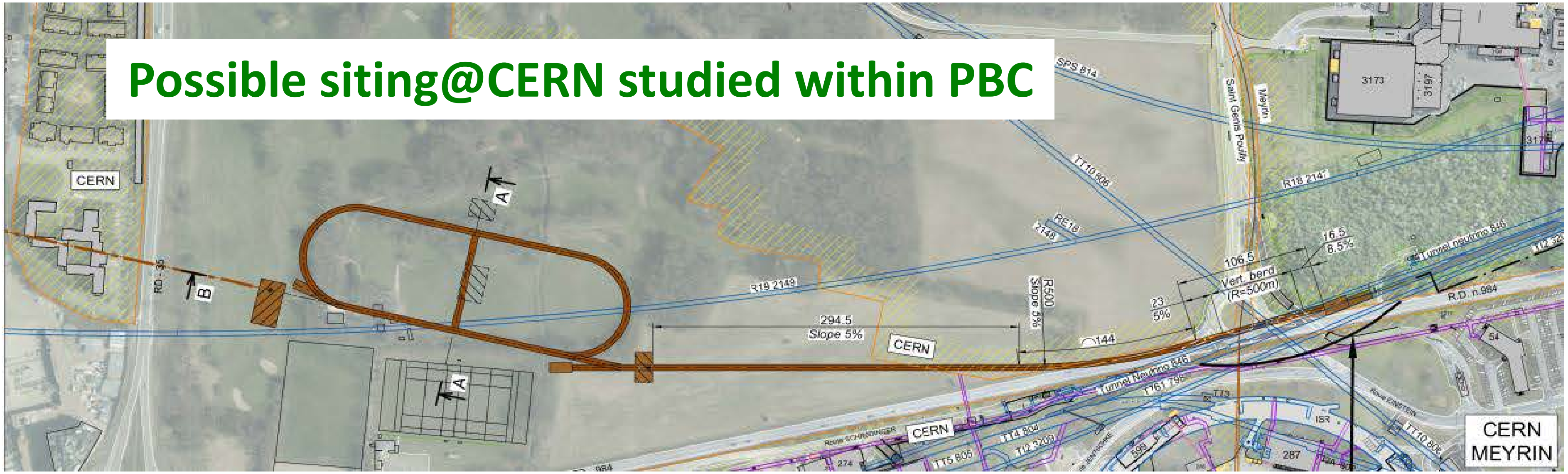
NuSTORM

Well controlled ν beam from a μ storage ring

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

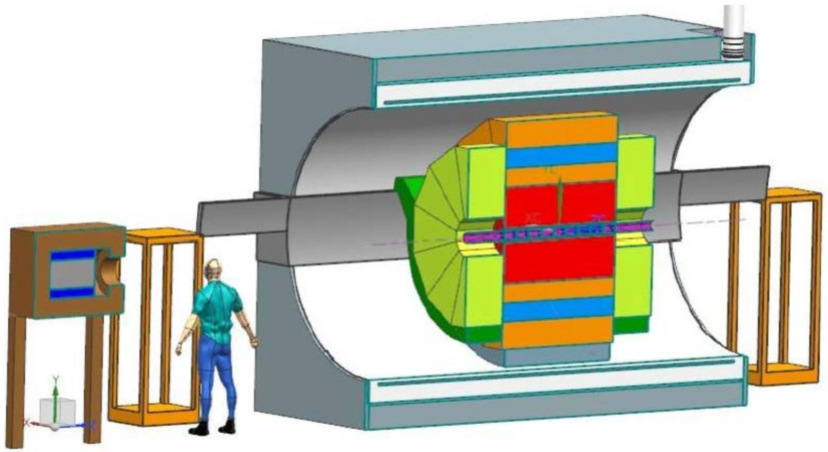






REDTOP η – η' factory

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)**