

**LOMONOSOV CONFERENCE, 19-25 August 2021**

Claude Vallée, CPPM Marseille

## **PHYSICS BEYOND COLLIDERS PROSPECTS AT CERN**

- 1) Post-EPPSU PBC mandate**
- 2) PBC science**
- 3) PBC updated organization**

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



# 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](https://arxiv.org/abs/1902.00260)**

**PBC BSM Report: [arXiv:1901.09966](https://arxiv.org/abs/1901.09966)**

**PBC QCD Report: [arXiv:1901.04482](https://arxiv.org/abs/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 National Laboratories**

**Act as central forum of exchanges between theorists and experimentalists**

# PBC SCIENCE

**1) NEW FACILITIES**

**2) QCD-ORIENTED EXPERIMENTS**

**3) BSM-ORIENTED EXPERIMENTS**

**4) NEW EXPERIMENTAL AND THEORETICAL DIRECTIONS**

**For details see PBC workshop of 1-4 March 2021**

**<https://indico.cern.ch/event/1002356/>**



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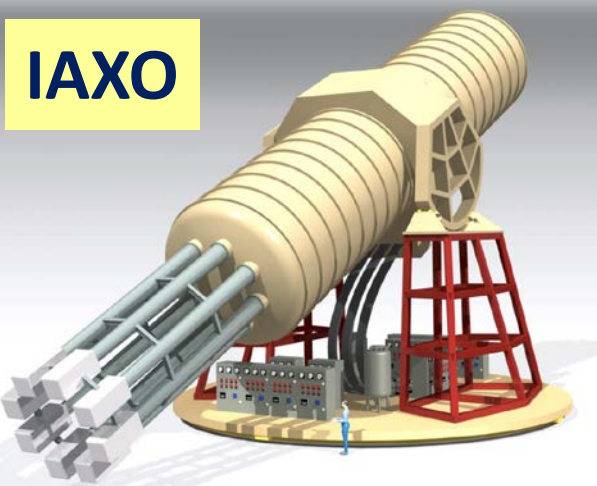
**3) BSM-ORIENTED EXPERIMENTS**

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IAXO

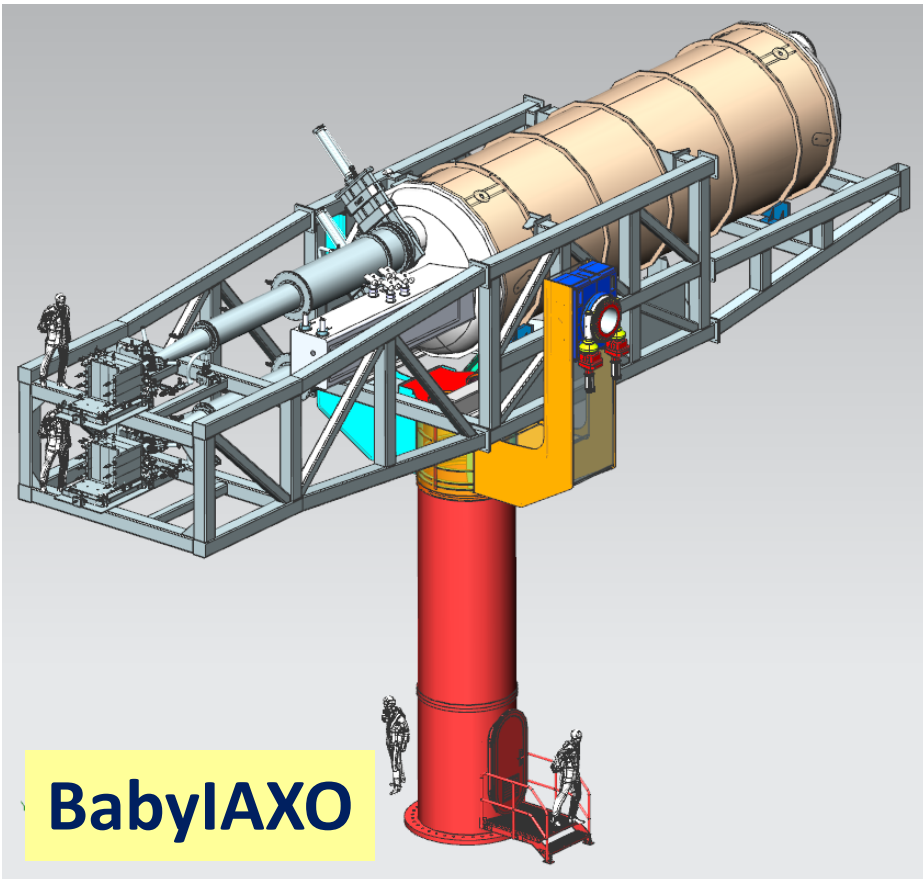


# INTERNATIONAL AXION OBSERVATORY (axion helioscope successor of CAST@CERN)

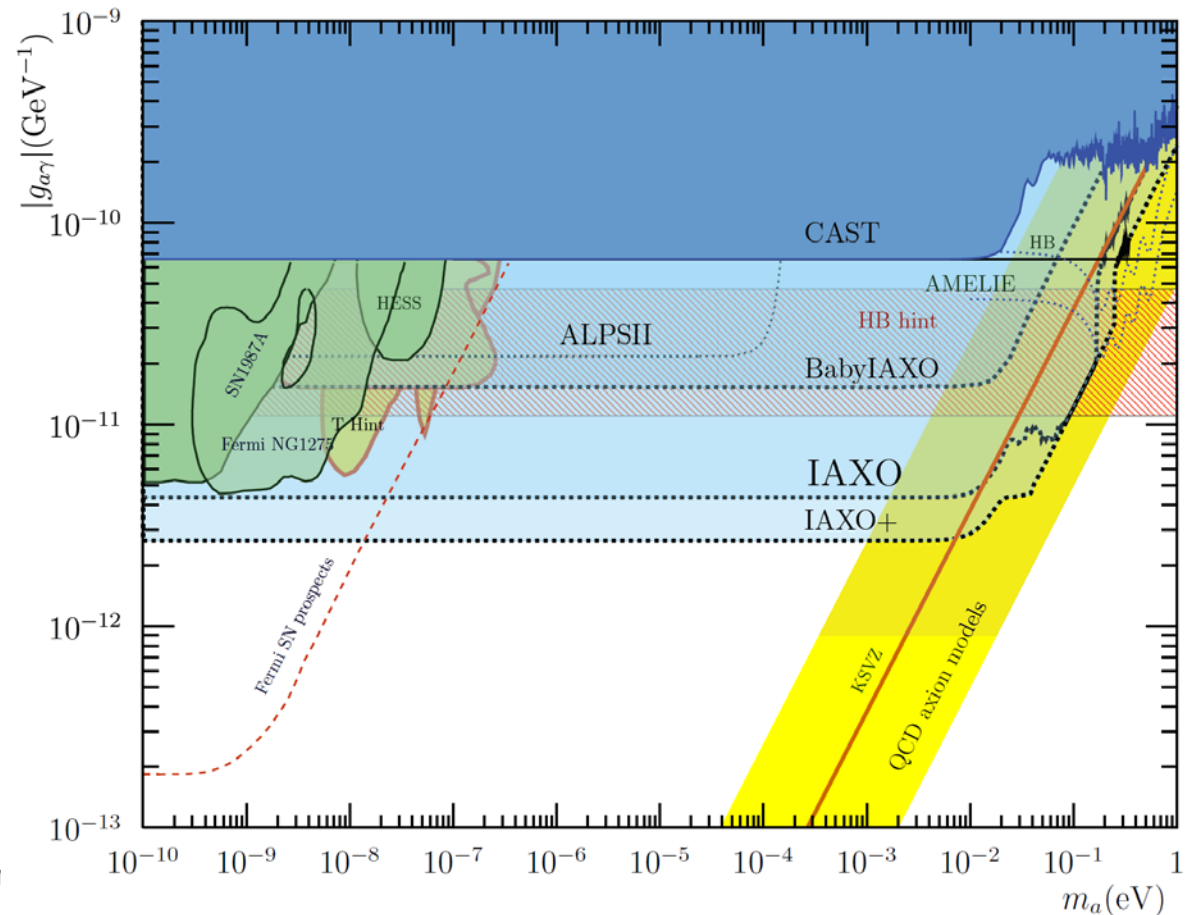
BabyIAXO precursor approved and in construction at DESY

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

Unique physics reach for ALPs searches



BabyIAXO



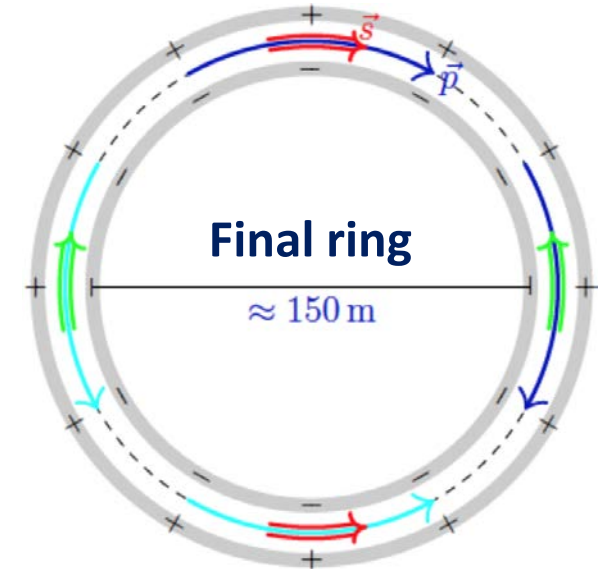
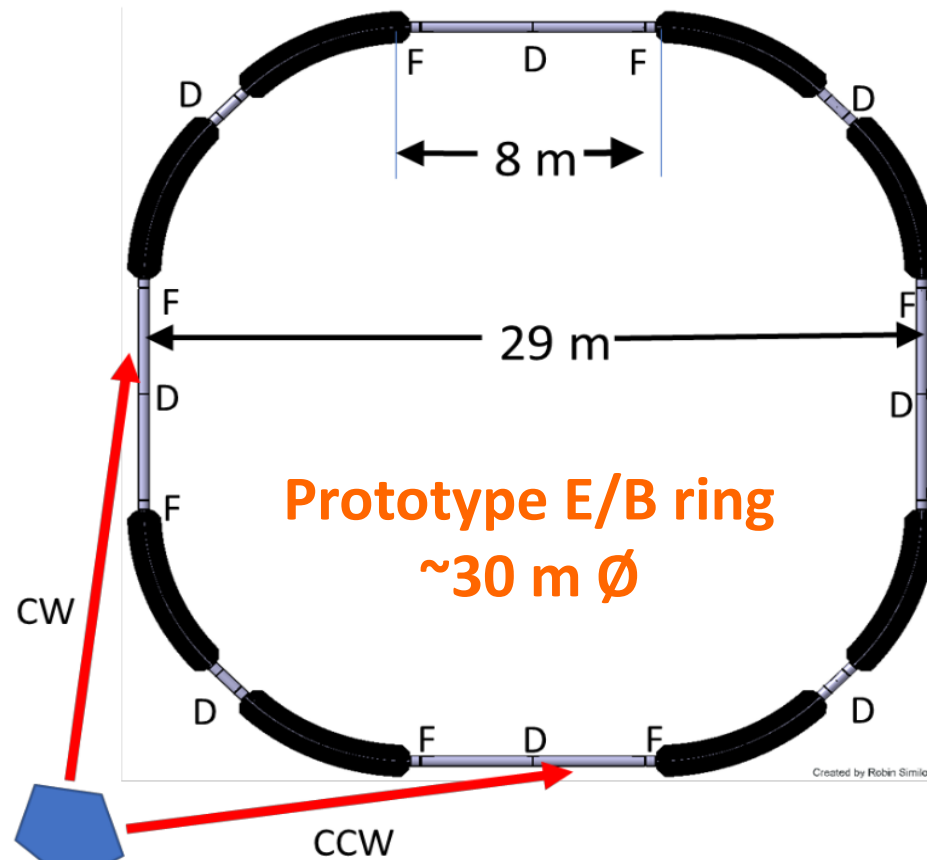
ysics Beyon

# PROTON EDM RING

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



Ongoing precursor experiment at Jülich (magnetic ring)

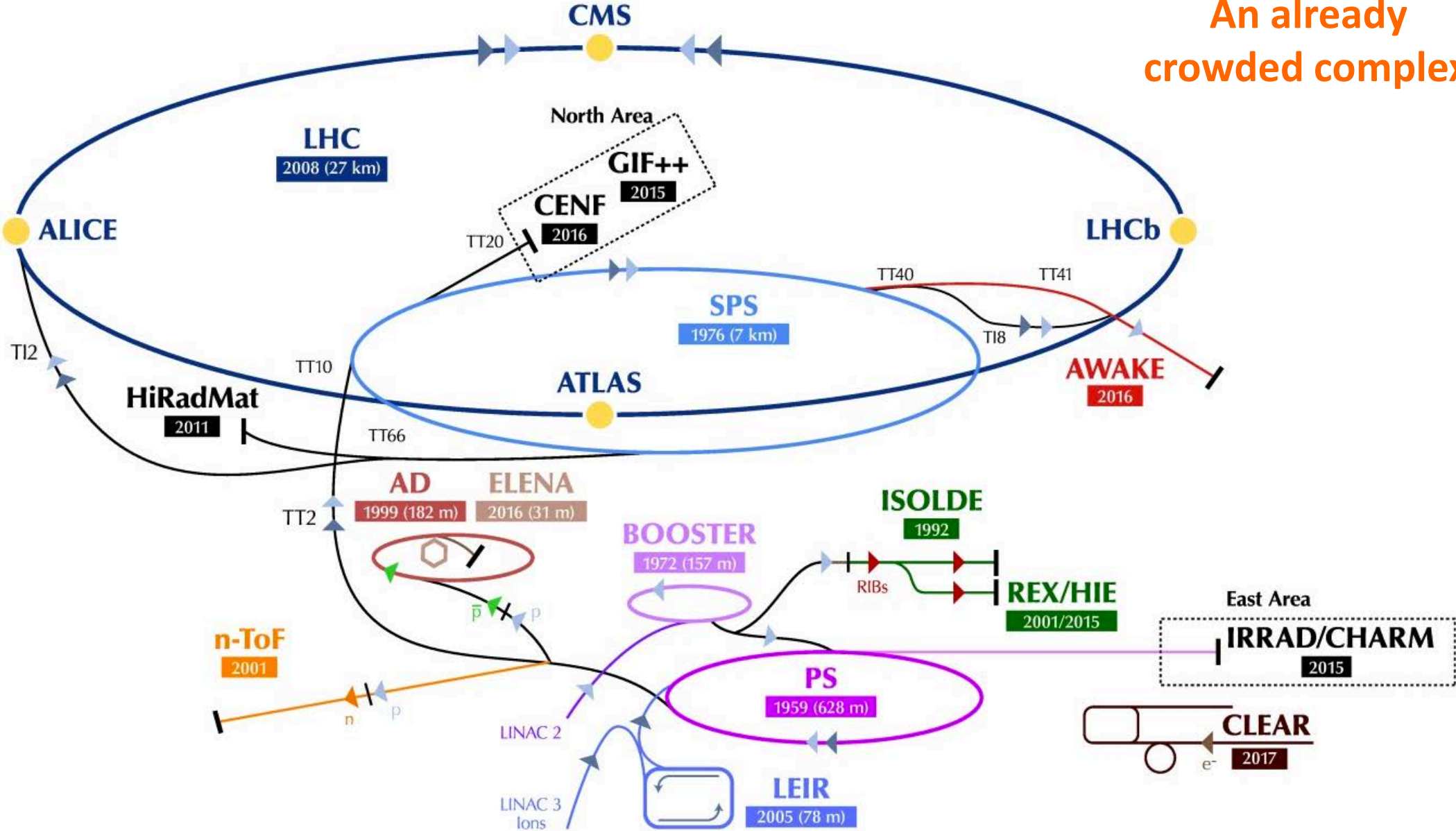


Design sensitivity:  $4 \cdot 10^{-29}$  e.cm

TDR for prototype ring in preparation by CPEDM Collaboration (incl. CERN)  
*Many systematics issues to be solved: lattice, deflectors, RF cavities, B-shield, BPMs...*

# NEW CERN ACCELERATOR FACILITIES

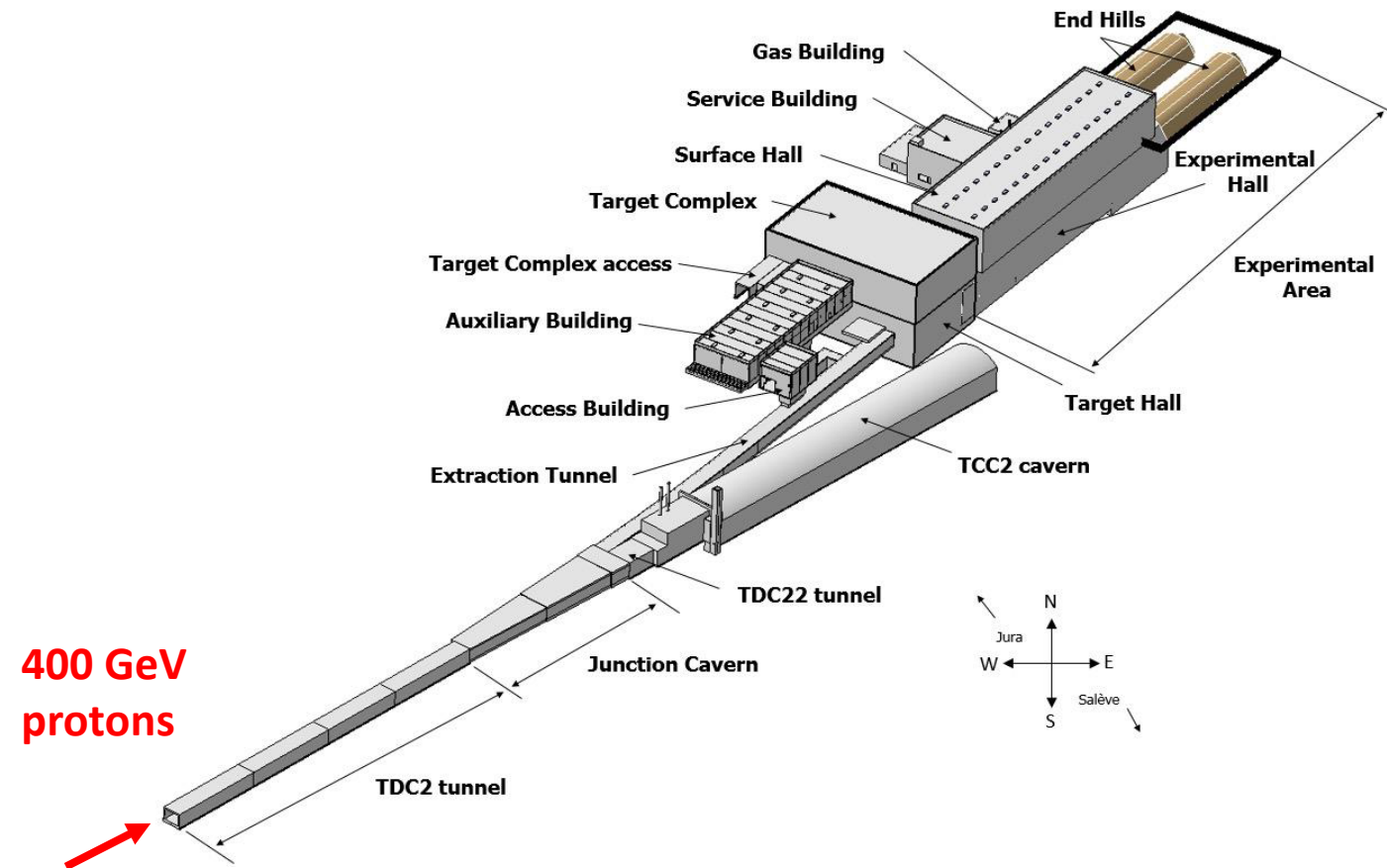
An already crowded complex!





# PROTON BEAM DUMP FACILITY

Comprehensive Design Study done within PBC



Continued R&D towards TDR for next EPPSU:

*Slow extraction, target design, cost optimization incl. alternative siting (CNGS, West Area)*

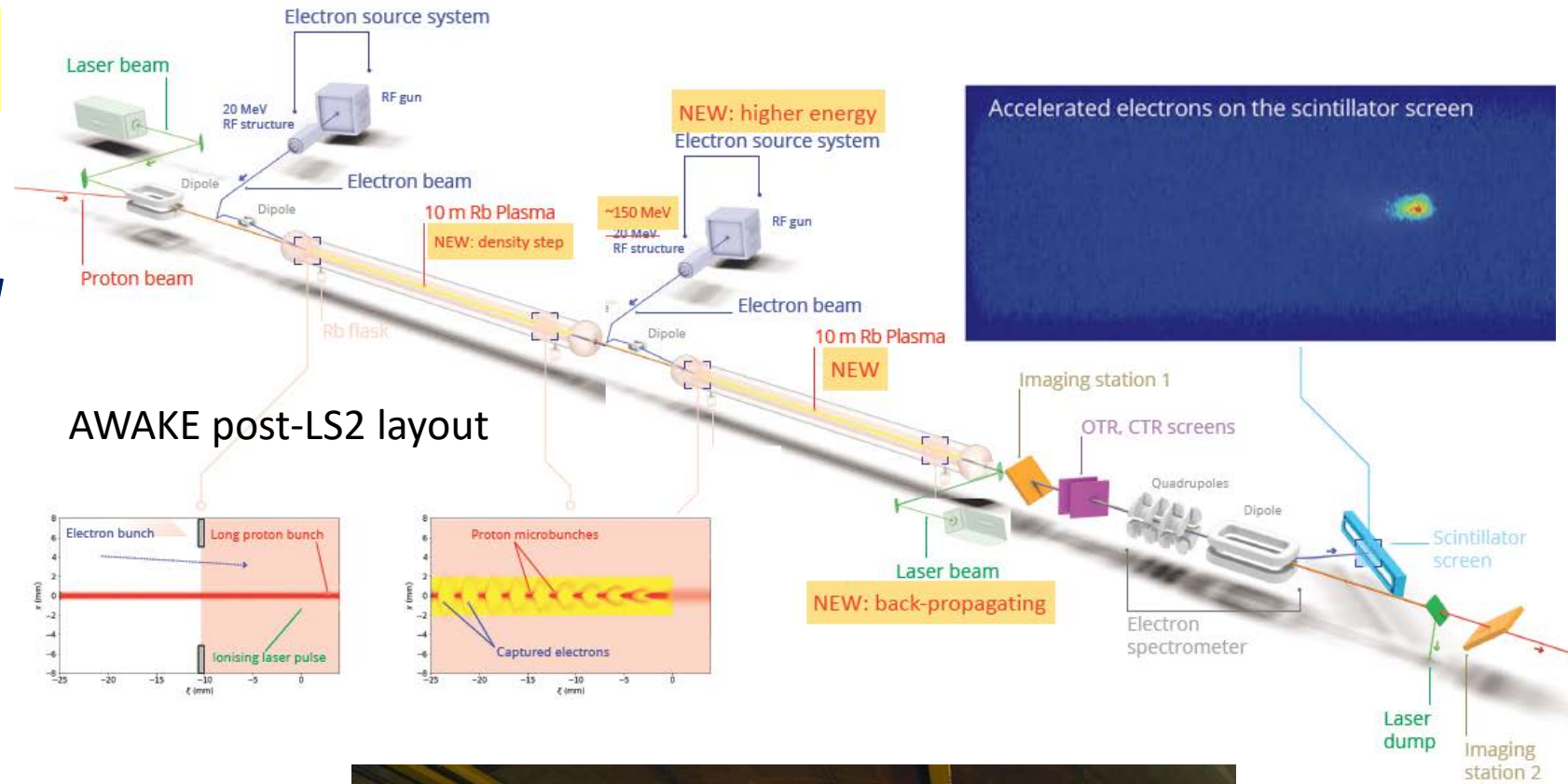
→ of general interest for intensity upgrades of other CERN extracted beams

# 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*

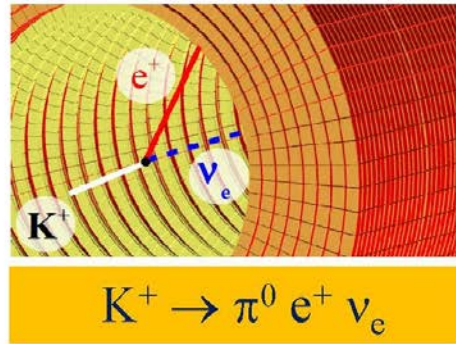
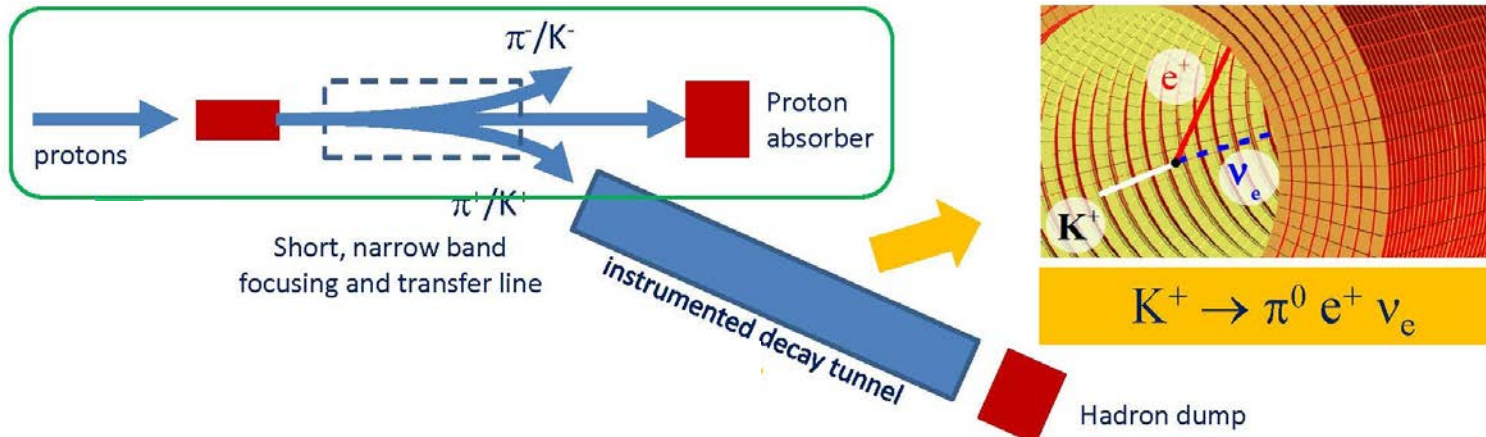


CNGS decay tunnel



# R&D FOR NEUTRINO BEAMS

Recent new ideas of tagged  $\nu$  beams being investigated for precision measurements and next generation Long Base Line projects

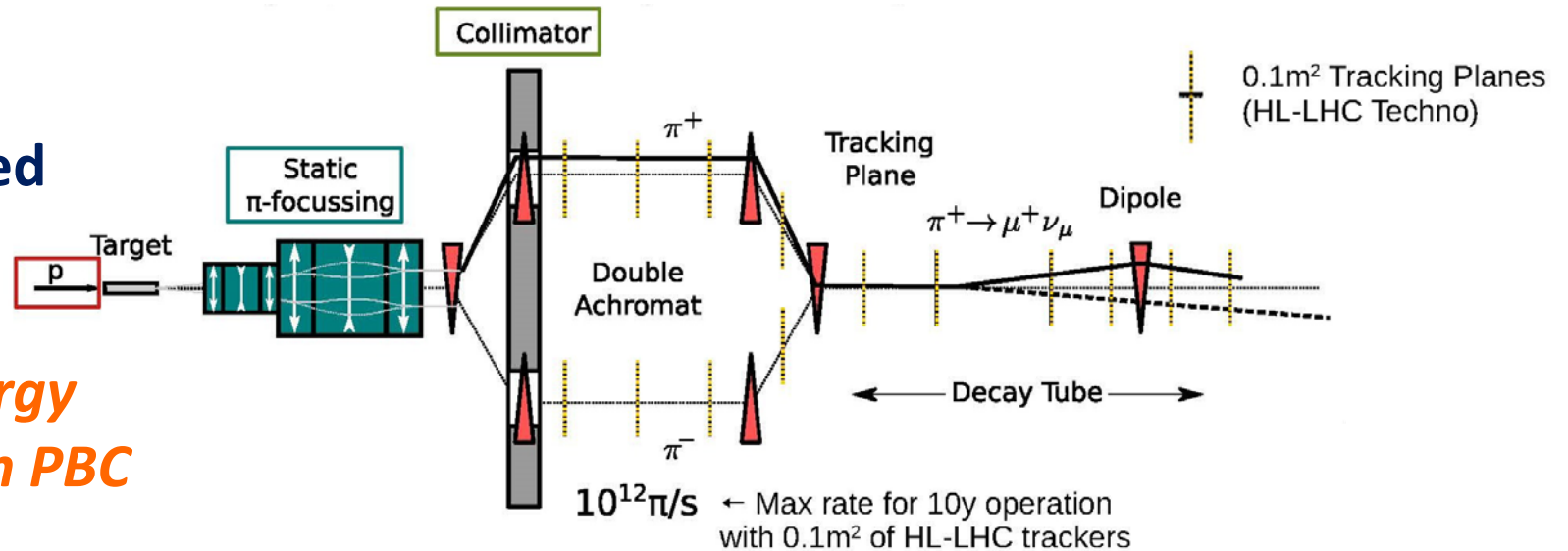


## ENUBET:

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

## NuTAG:

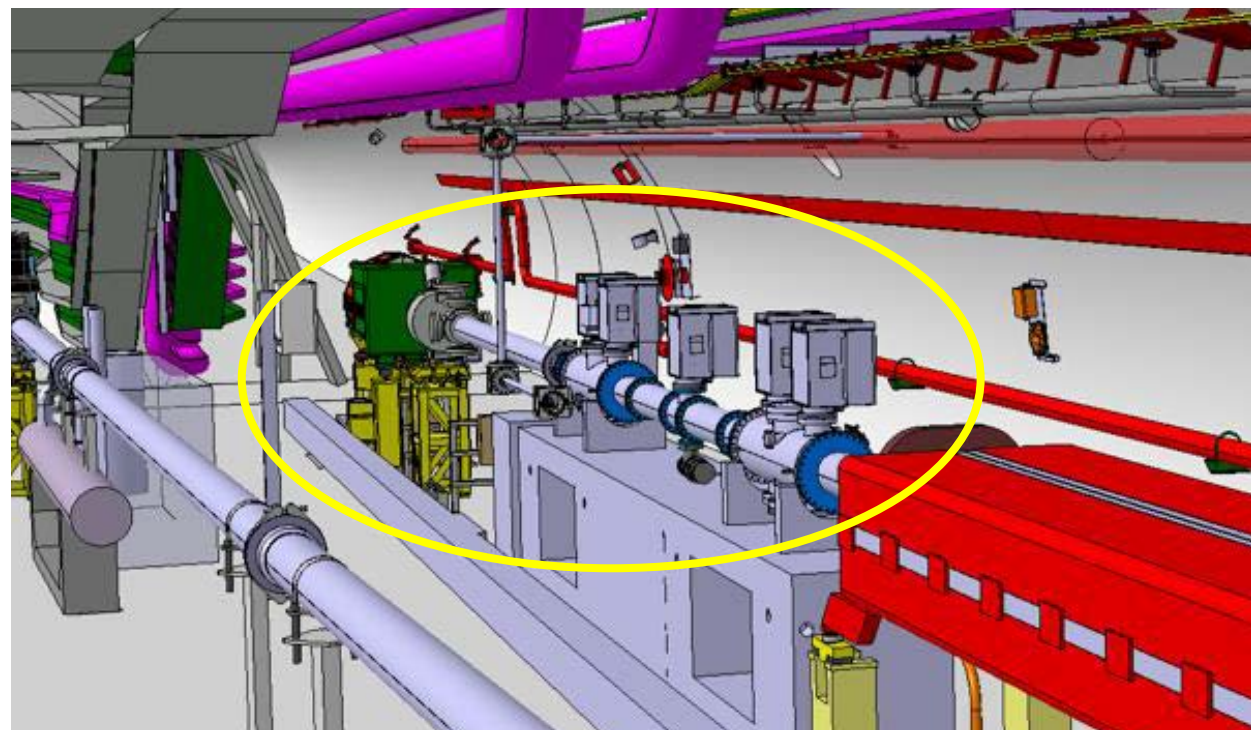
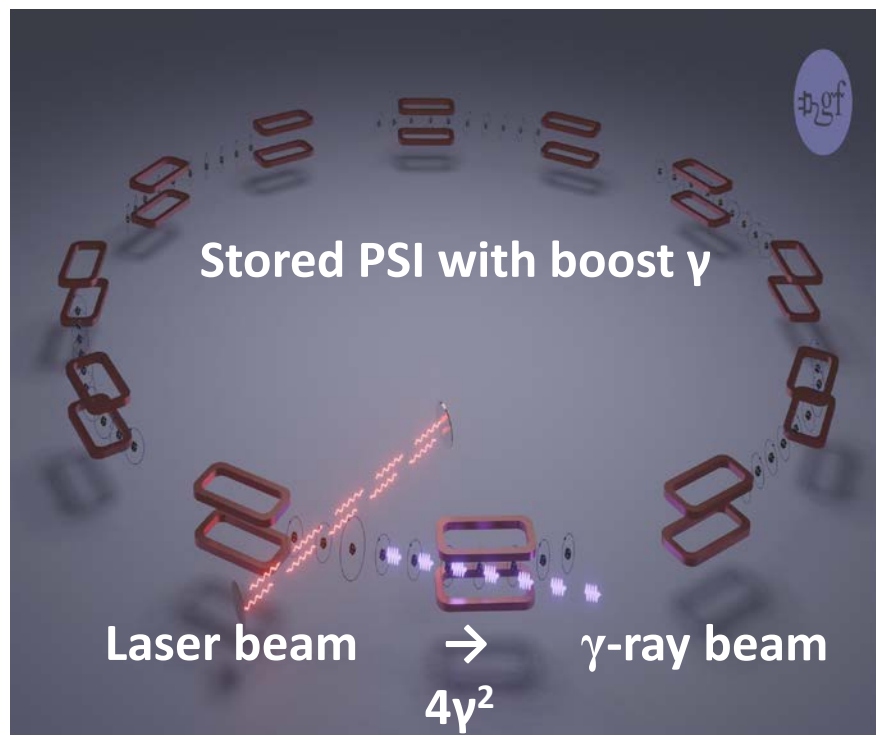
- $\nu_\mu$  beam with  $(E_\nu, \theta_\nu, \phi_\nu)$  tagged from individual  $\pi$  decays with HL-LHC silicon trackers
- *Feasibility and possible synergy with ENUBET to be studied in PBC*



*Goal of  $10^7$  intensity gain  
versus existing facilities*

## GAMMA FACTORY

*New idea introduced within PBC*



**Proof of Principle experiment with  
full configuration in preparation at SPS**

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

**First general workshop on applications in atomic, nuclear, particle and applied physics  
held end of 2020, see <https://indico.mitp.uni-mainz.de/event/214/overview>**



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**4) NEW EXPERIMENTAL AND THEORETICAL DIRECTIONS**

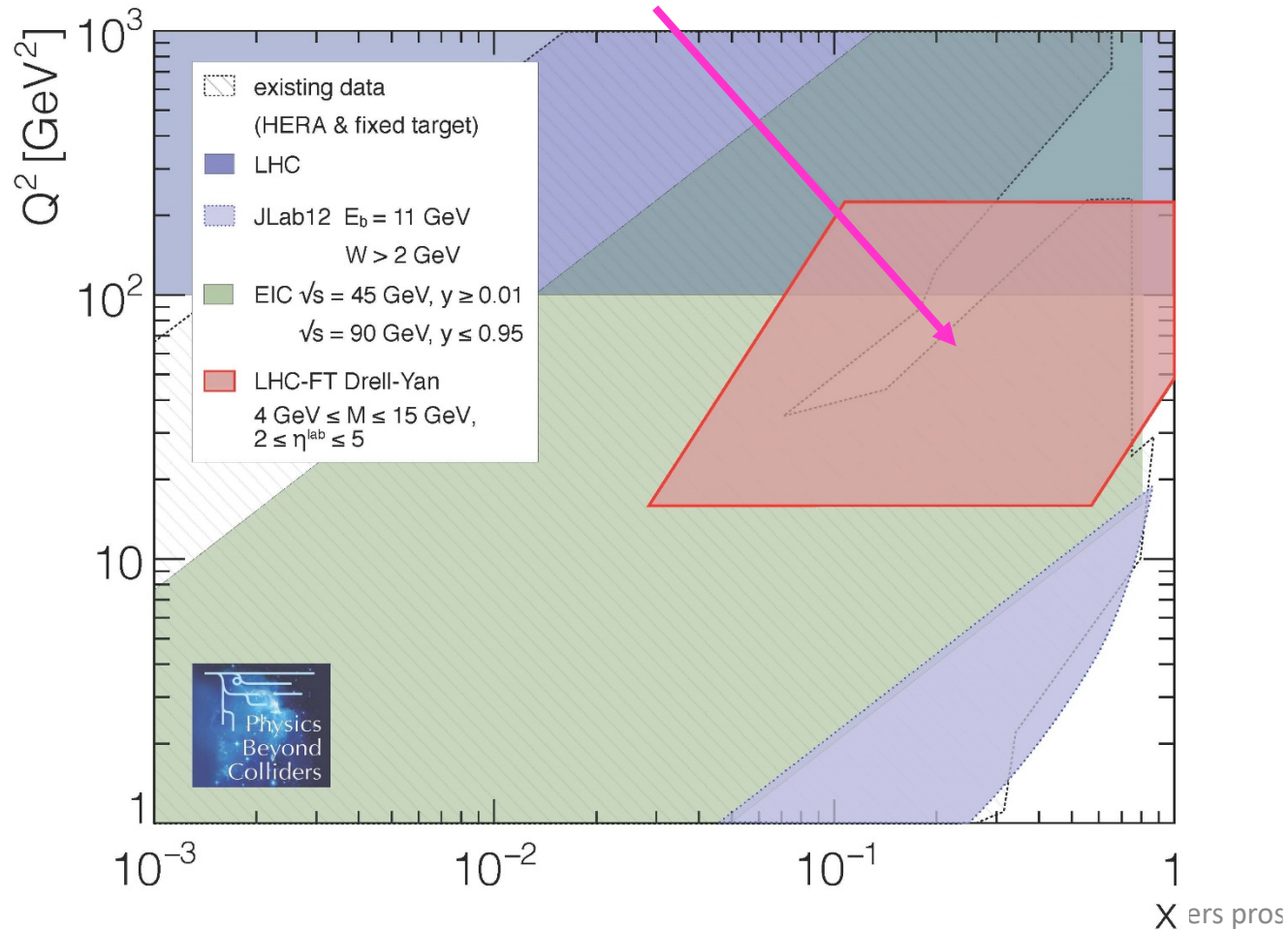
**For details see PBC workshop of 1-4 March 2021**

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# PBC QCD PROJECTS IN WORLDWIDE LANDSCAPE

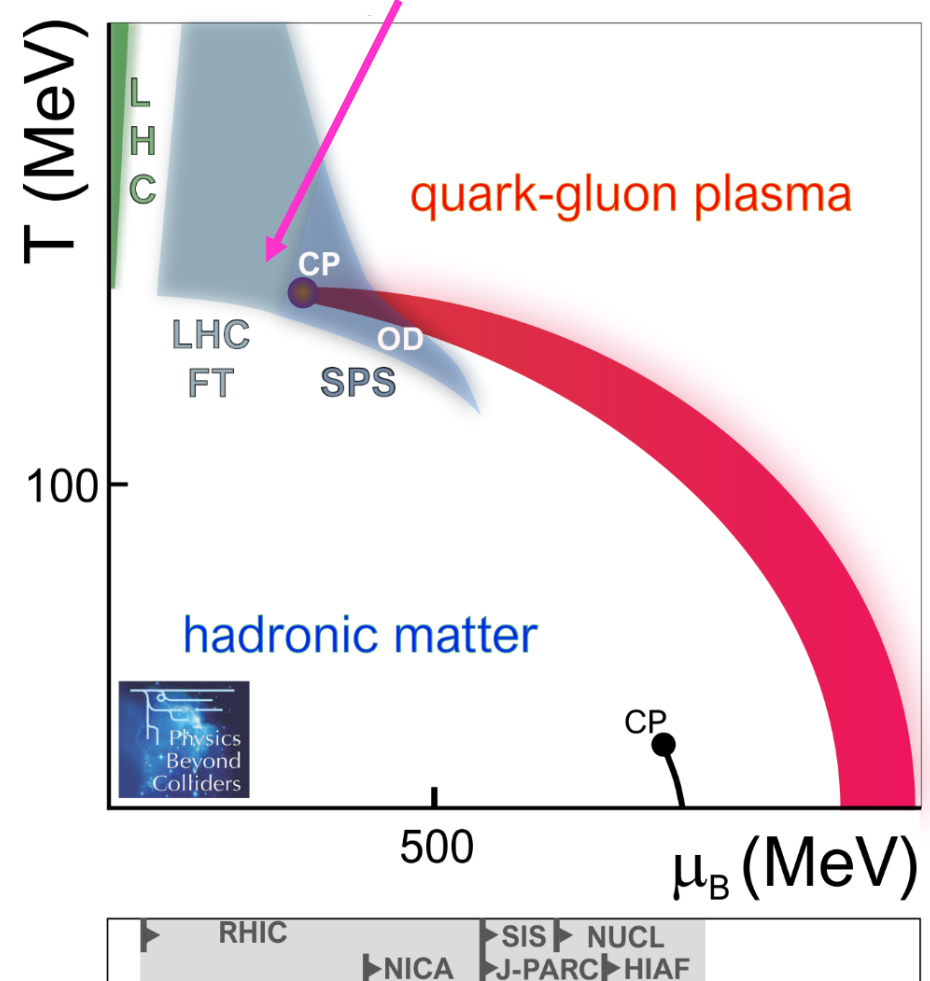
## Structure Functions

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



## QCD Phase Transition

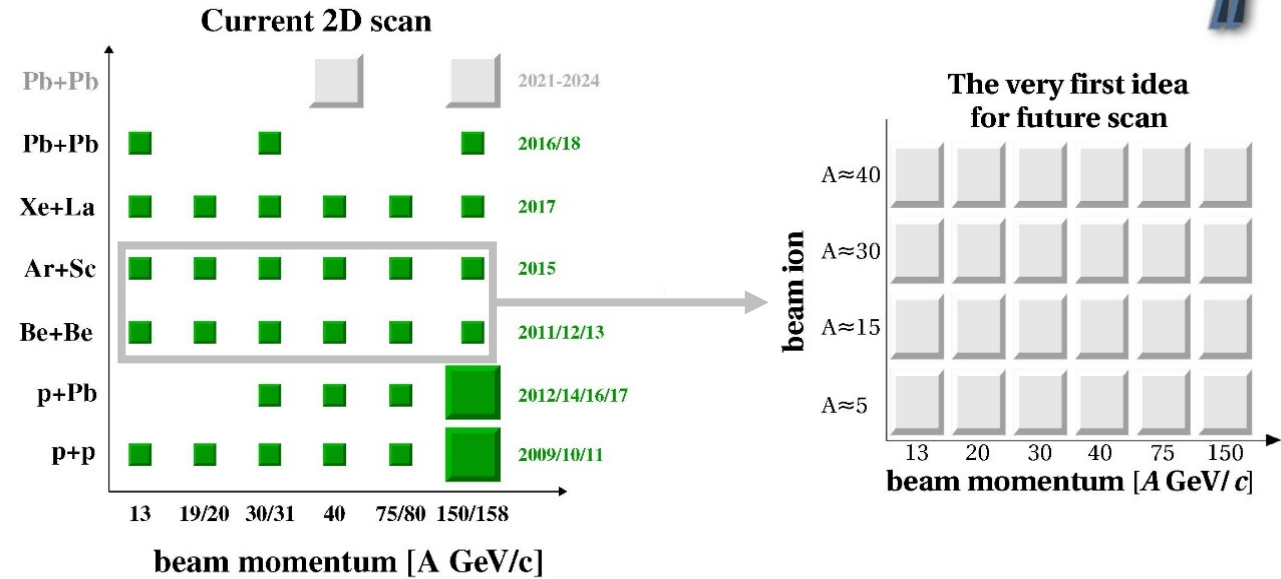
*Unique reach of LHC-FT & SPS in transition region to high- $\mu_B$*



# HEAVY ION PHYSICS AT SPS

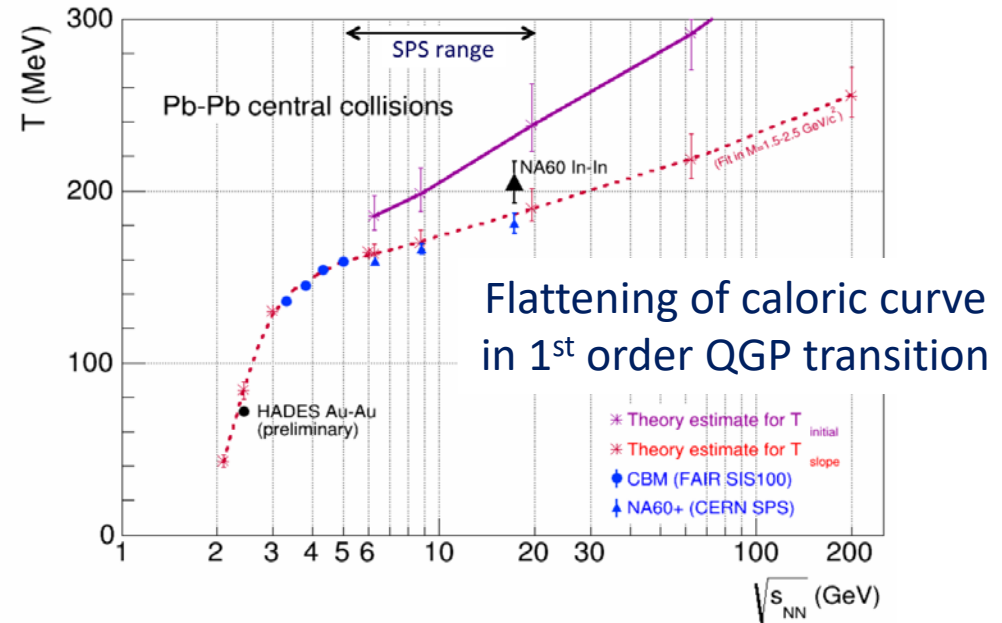
## NA61

- Upgraded to study open charm during run 3
- Finer grain 2-D scan to study onset of fireball foreseen after LS3



## NA60++

- Revival of NA60 concept to measure caloric curve of 1<sup>st</sup> order QCD transition with low-E dimuons
- Toroid design ongoing with PBC support, as well as detector developments in synergy with HL-LHC



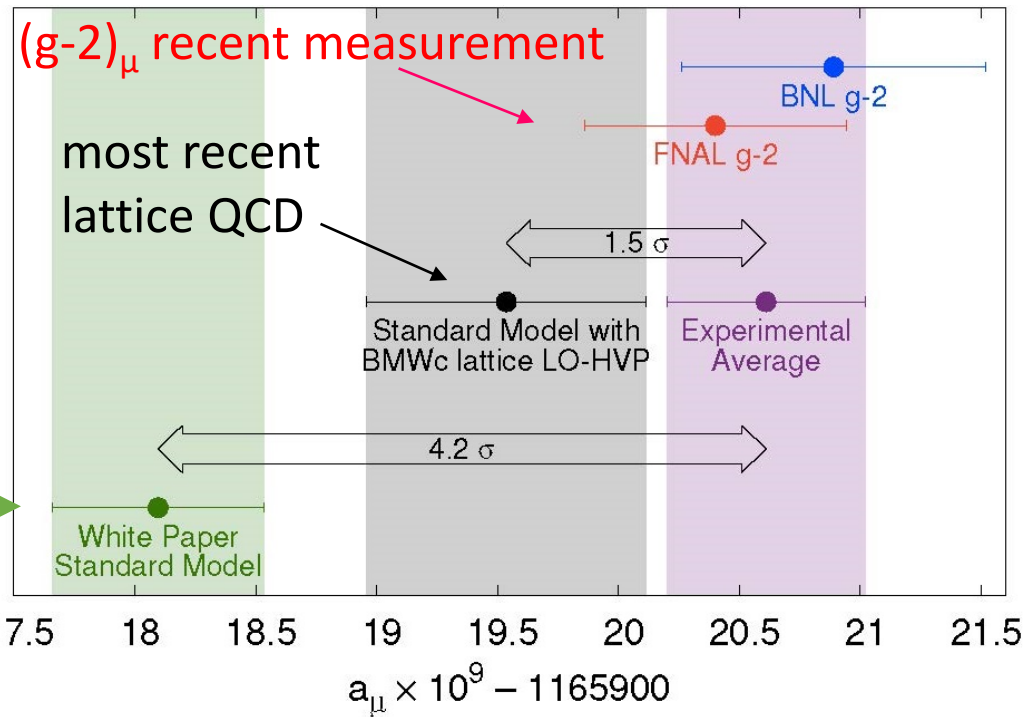
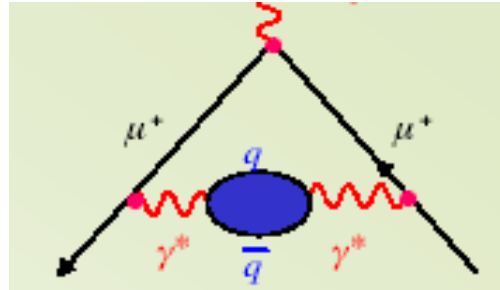
*New idea introduced within PBC:*

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

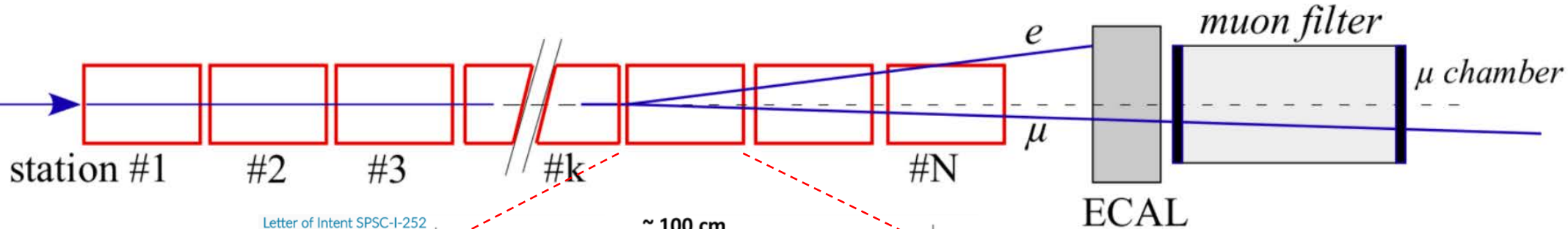
**Complementary to prediction based on dispersion relation with  $e^+e^-$  data**

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

## MUonE

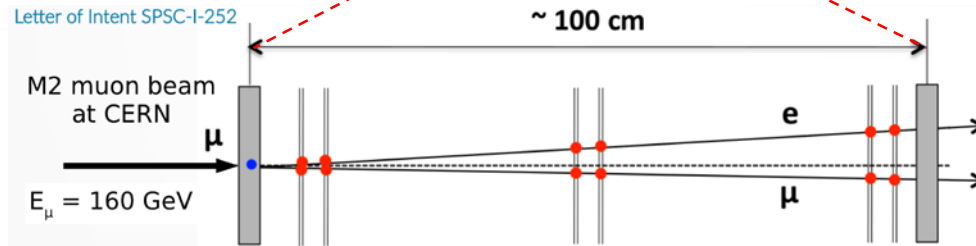


M2  $\mu$  beam  
160 GeV/c



**Pilot runs in 2022**

**Full data taking aimed for during run 3**

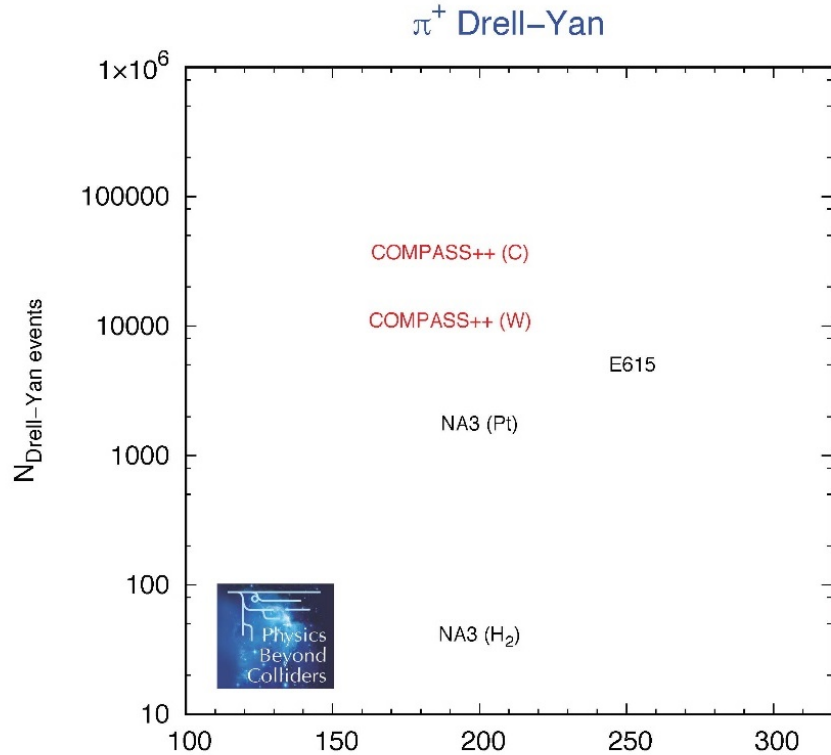


**Now in the hands of the SPSC**

# AMBER "QCD FACILITY" (COMPASS++)

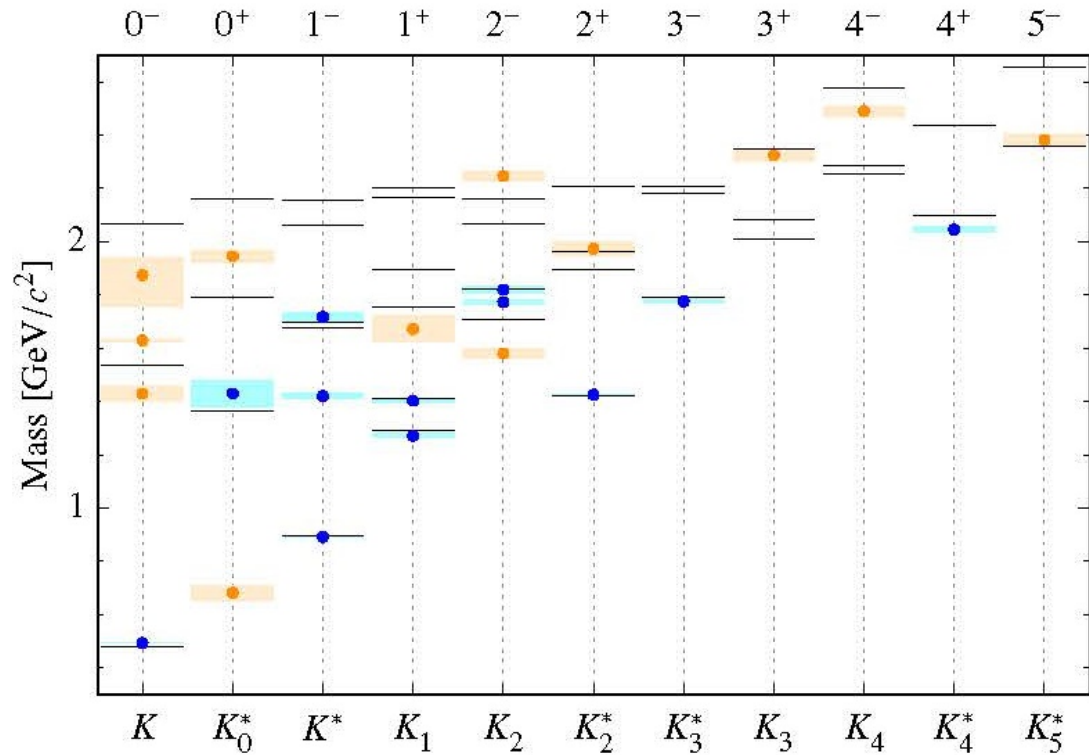
Short term (run3): proton radius puzzle with  $\mu$ -p elastic scattering

Longer term (excerpts):



**With existing beams:**

*Unique opportunity for higher precision pion structure measurements*



**With new RF-separated K-beam:**

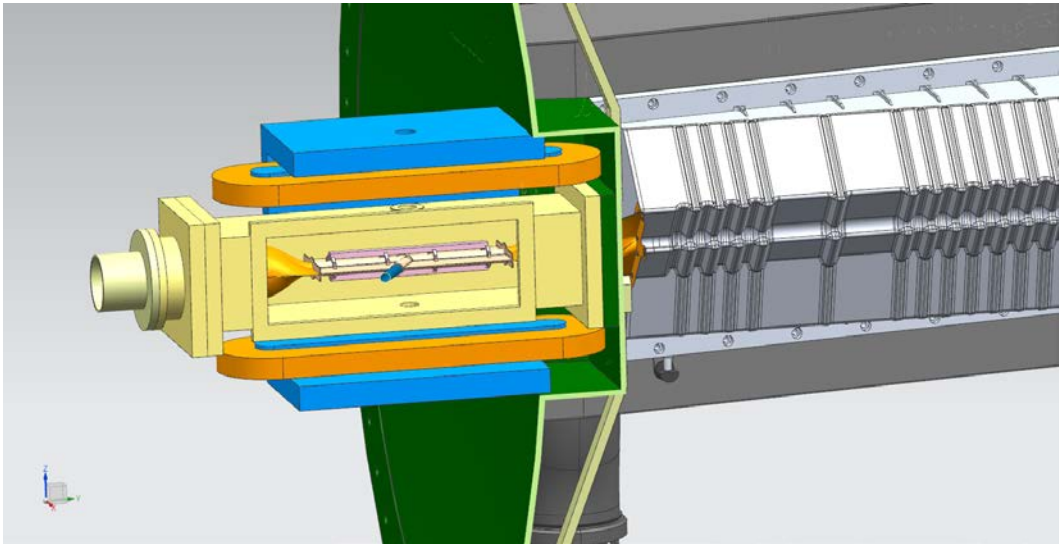
**(significant investment possible for post-LS3):**  
*Comprehensive measurement of strange spectroscopy*



# LHC FIXED TARGET

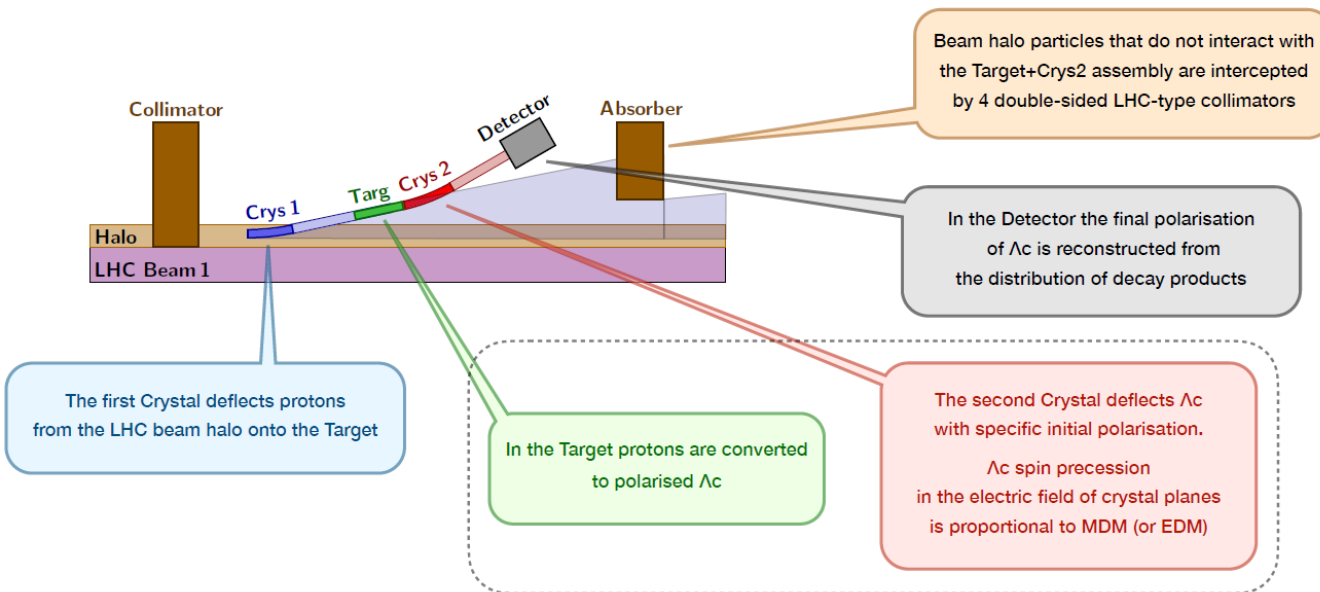
SMOG2 storage cell installed in LHCb for run3,  
promises FT lumi x ~100 vs SMOG

Longer term options studied under PBC

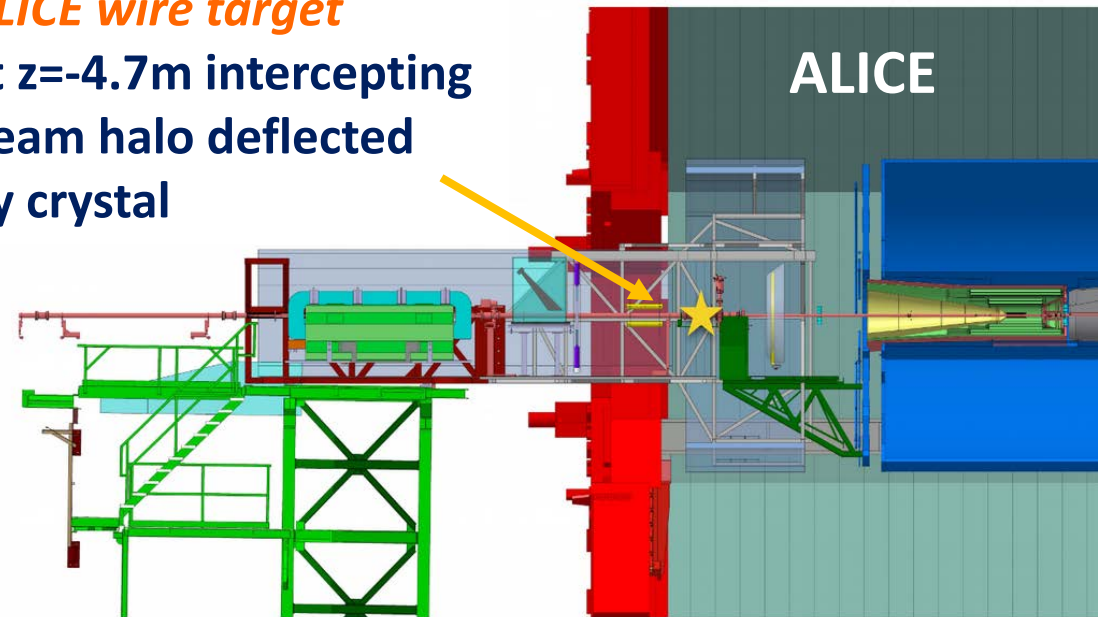


**LHCSpin study** of polarized storage cell for LHCb

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



ALICE wire target  
at z=-4.7m intercepting  
beam halo deflected  
by crystal



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

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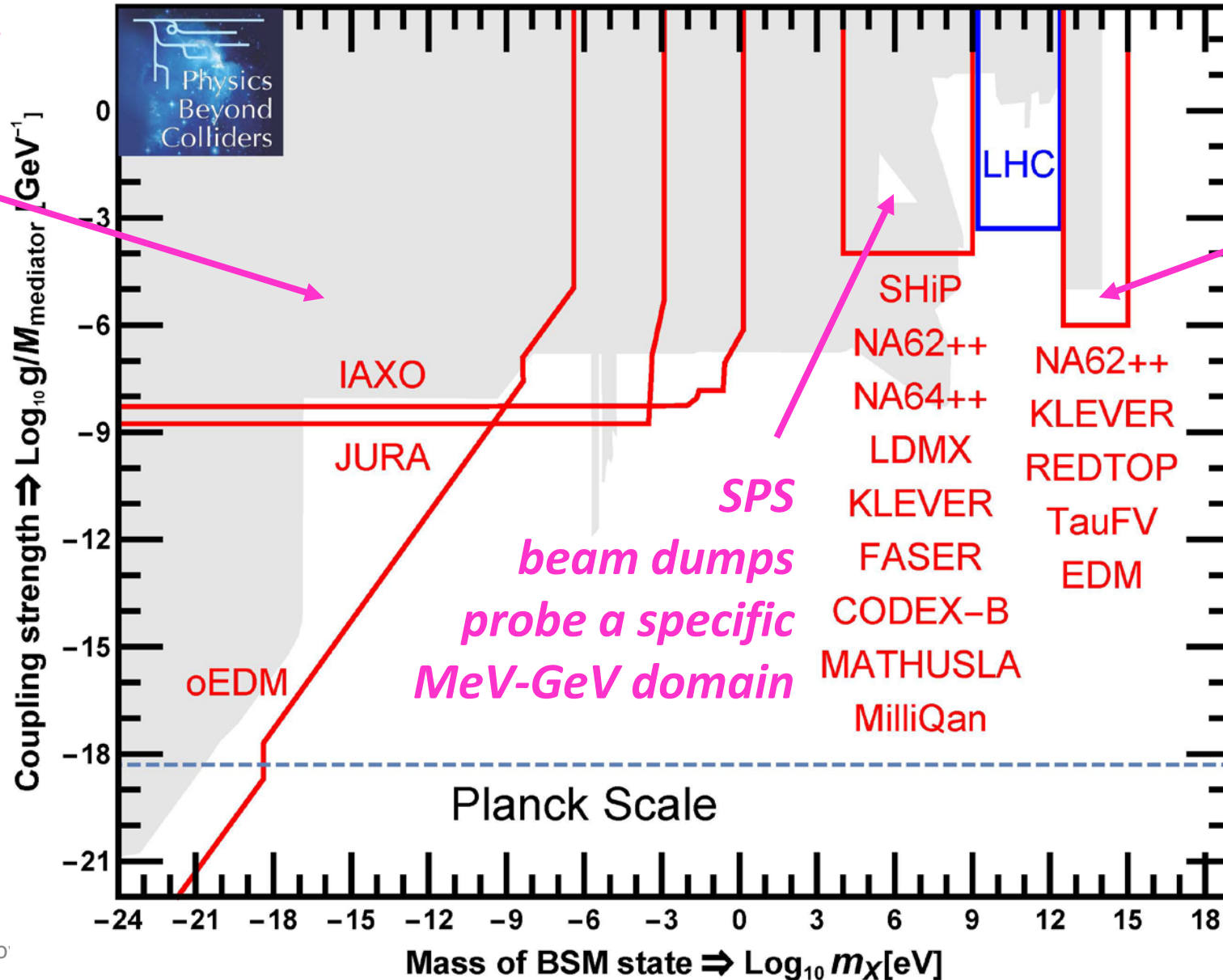
**4) NEW EXPERIMENTAL AND THEORETICAL DIRECTIONS**

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# PBC BSM PROJECTS IN WORLDWIDE LANDSCAPE

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



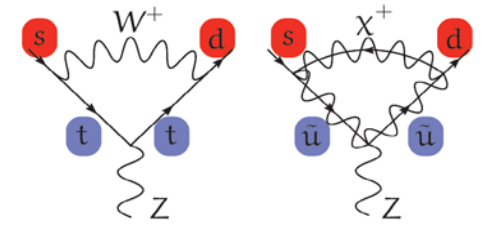
*Precision & rare processes experiments extend reach of high-E colliders*



$$K \rightarrow \pi \nu \bar{\nu} \quad (BR \sim 10^{-10})$$



# ULTRA-RARE K DECAYS

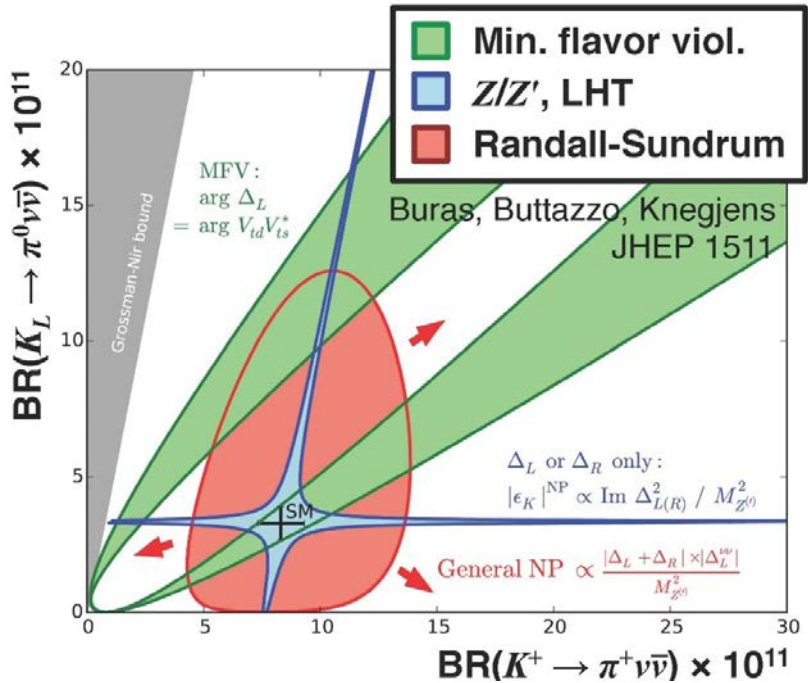


## NA62 (K+):

Run 2: 20 events seen for 17 expected (10 SM + 7 BG)  
 Run 3: detector upgraded to reach ~100 signal events

## Post-LS3 options:

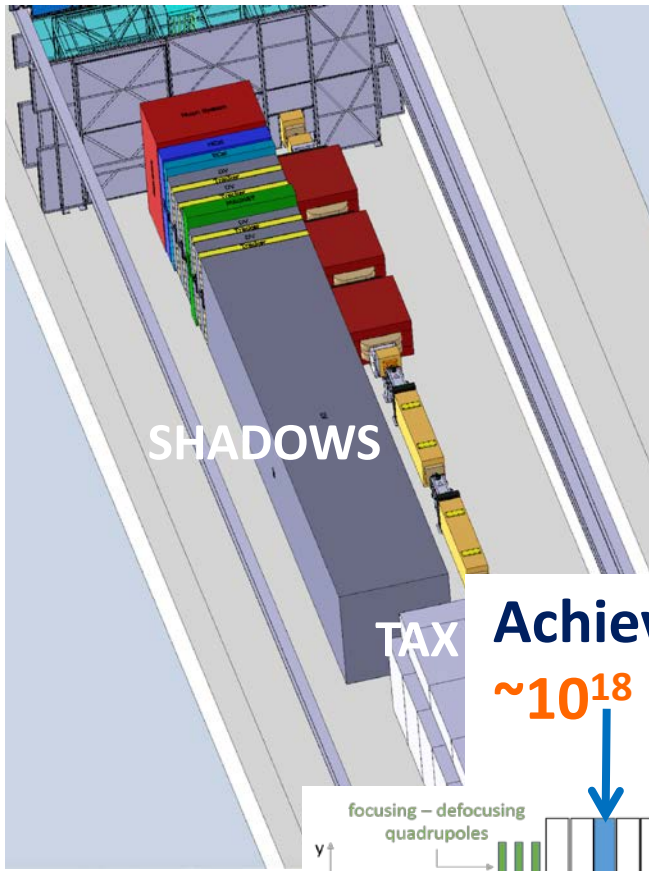
K+ intensity increase by factor 4  
 K0 beam (ex-KLEVER): K0 decays complementary to K+ decays for the CKM matrix and BSM searches.



K+ and K0 options now considered as an integrated project with a multi-parameter internal phasing:

K+ results ↔ K+/K0 sensitivity ↔ B-anomalies ↔ KOTO competition in Japan

# SPS PROTON BEAM DUMP: NA62 & SHADOWS



SHADOWS

TAX

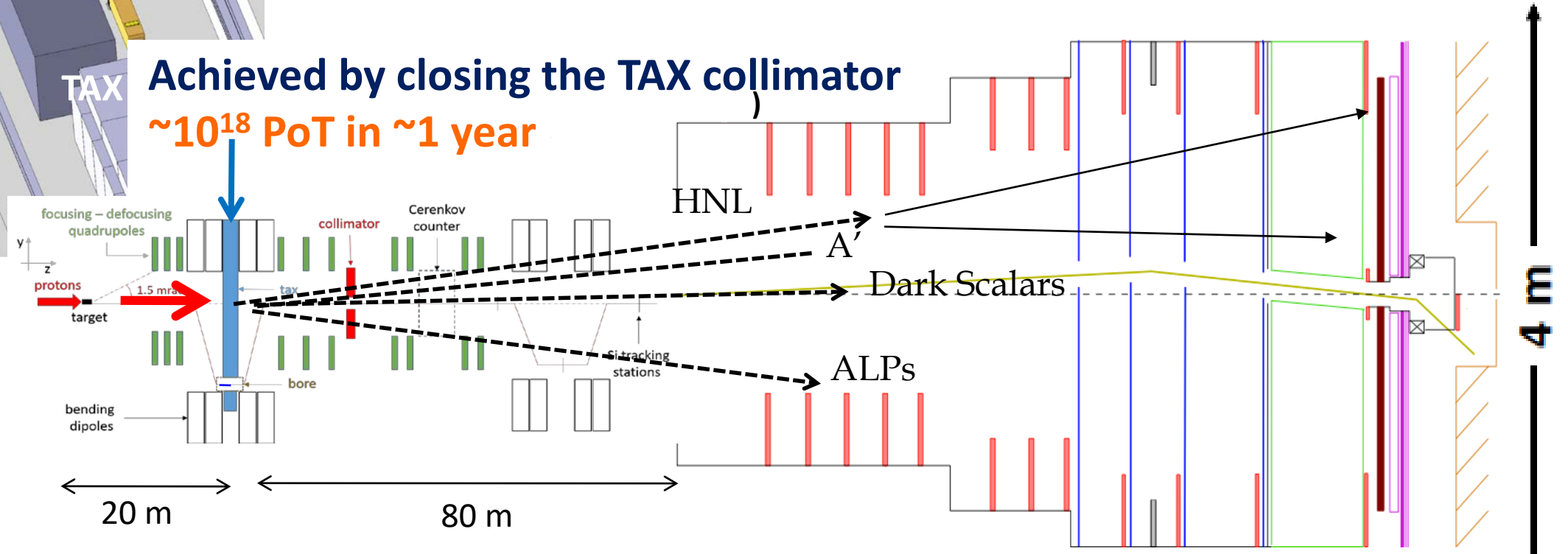
Some NA62 data taking in beam dump mode foreseen for run 3

*New SHADOWS “low cost” detector slightly off axis of TAX would increase acceptance at high mass in a higher-intensity post-LS3 beamdump*

Achieved by closing the TAX collimator

$\sim 10^{18}$  PoT in  $\sim 1$  year

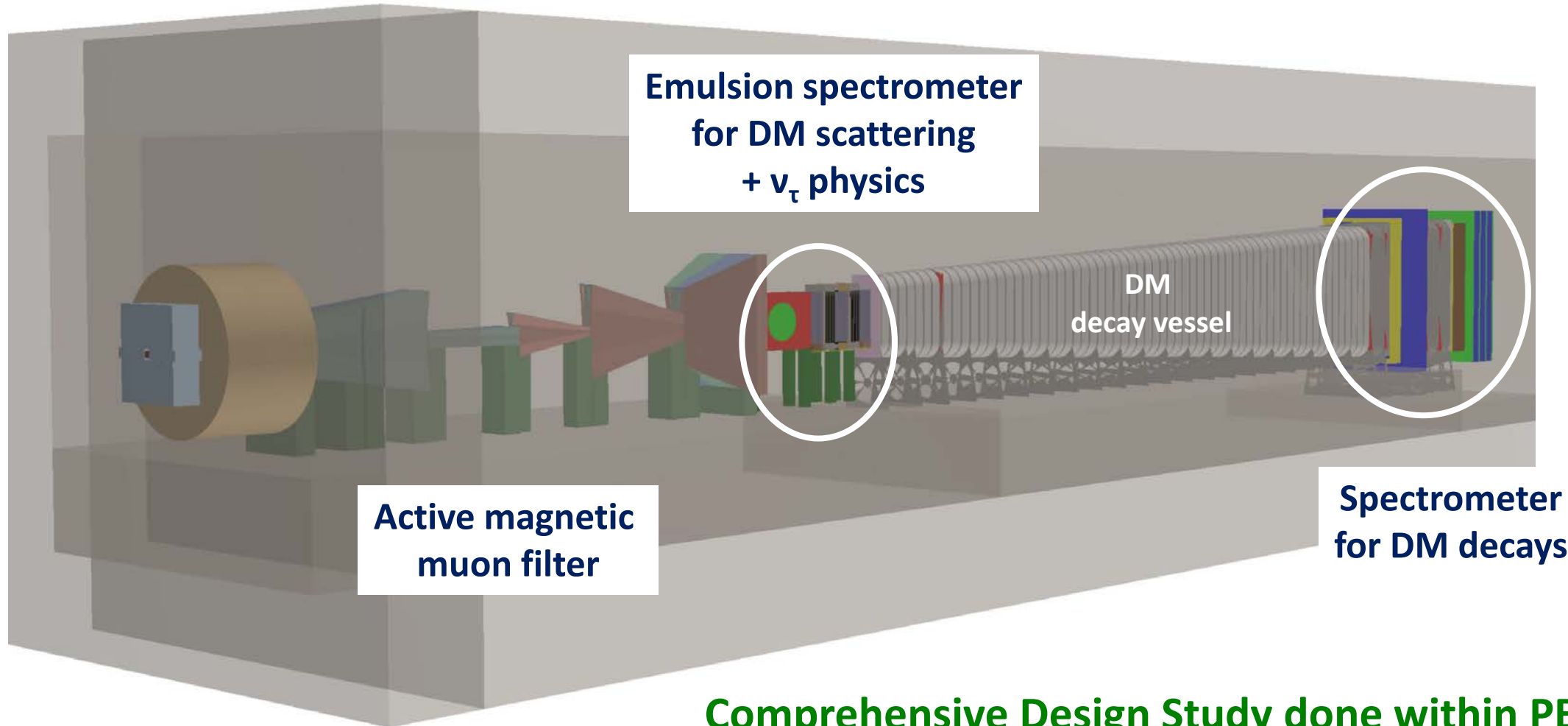
Protons  
400 GeV



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

# SHIP ON THE BEAM DUMP FACILITY

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



Active magnetic  
muon filter

Emulsion spectrometer  
for DM scattering  
+  $\nu_\tau$  physics

DM  
decay vessel

Spectrometer  
for DM decays

Comprehensive Design Study done within PBC

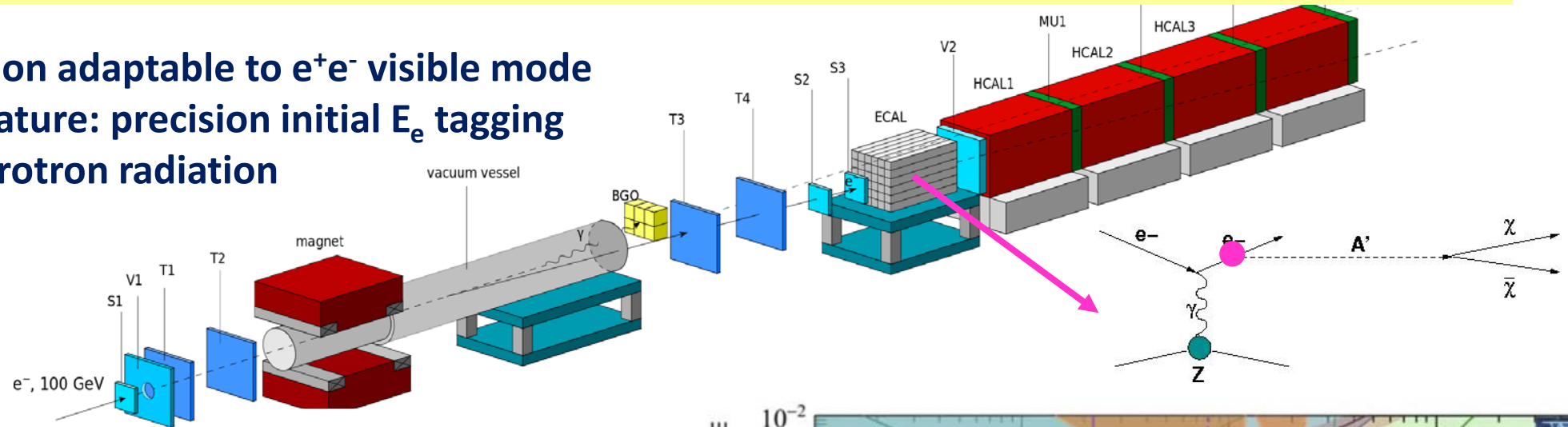
Next step: prepare TDR for next EPPSU

with emphasis on muon shield and decay vessel prototyping as well as cost reduction



# NA64: electron beam dump for Dark Photon search with missing energy

Configuration adaptable to  $e^+e^-$  visible mode  
 One key feature: precision initial  $E_e$  tagging  
 with synchrotron radiation

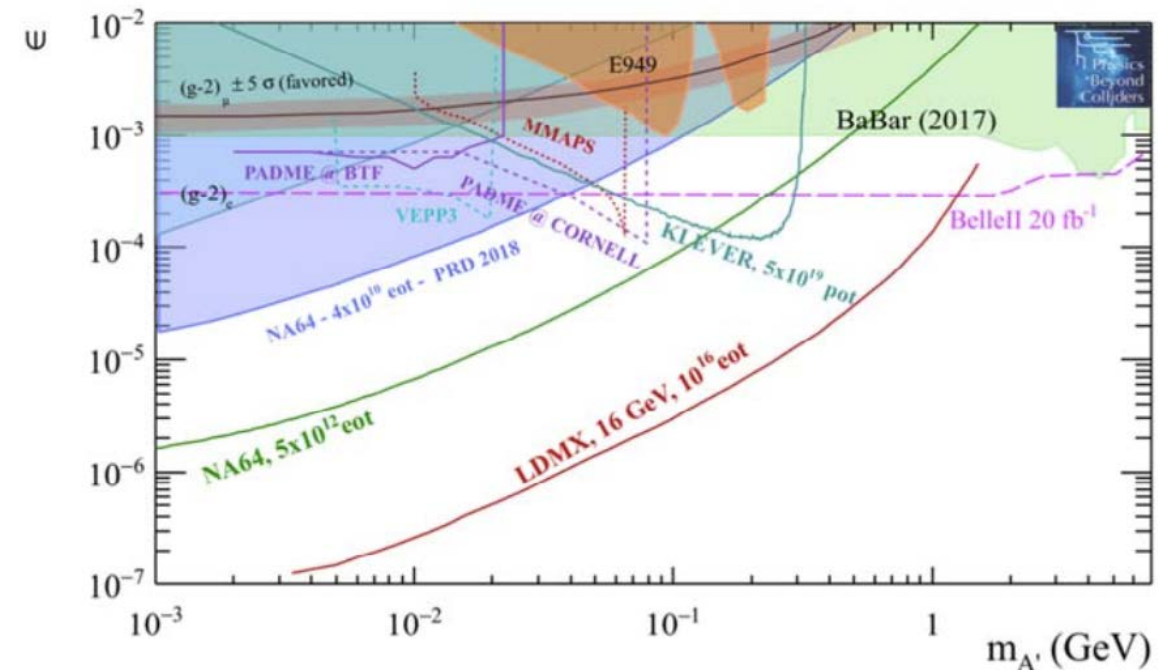


Currently leading  
 the field!

“Cheap” setup implemented  
 in 2015 on H4 e test beam



*Upgrades and  
 permanent setup  
 being implemented  
 for higher intensities  
 after LS2*



Similar searches in preparation with muon and hadron beams

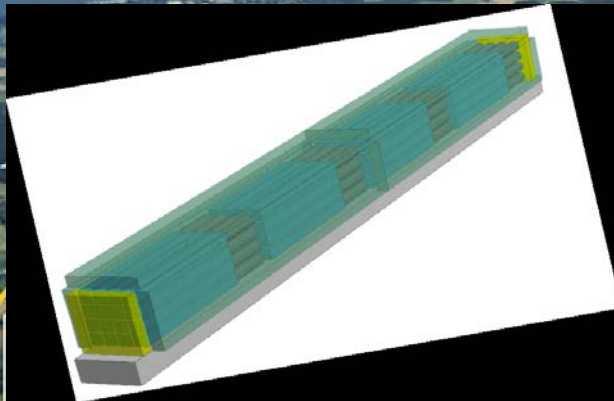


# LHC-LLP DEDICATED PROJECTS

Pioneered by FASER/SND@LHC/milliQan



**FASER:**  
*Dark photons & TeV neutrinos*  
480m from ATLAS IP  
Detector installed for run 3



CMS

*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 27 km



# LHC-LLP DEDICATED PROJECTS

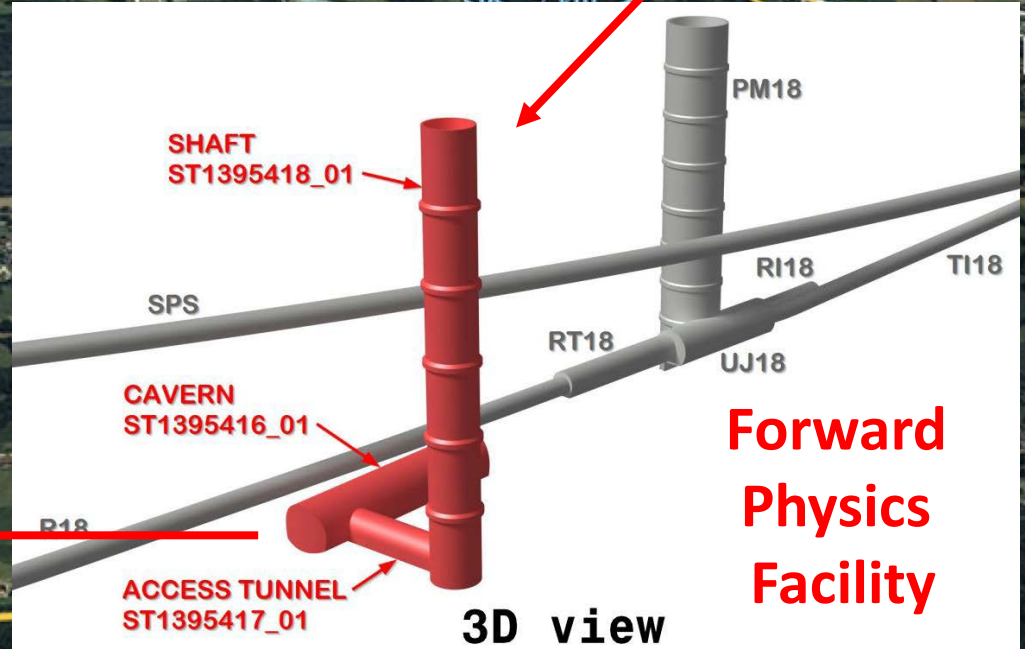
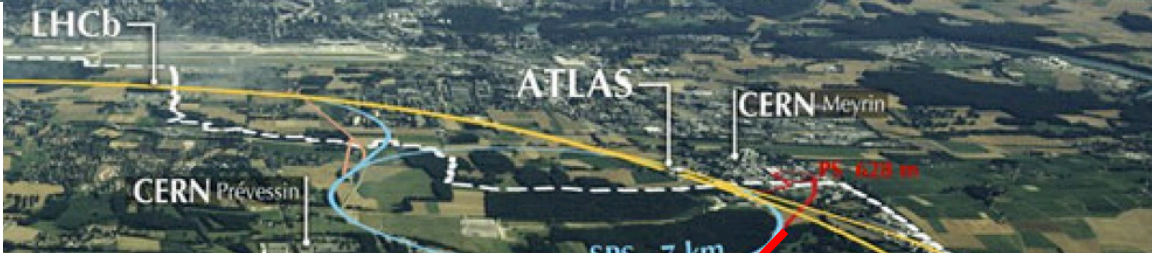
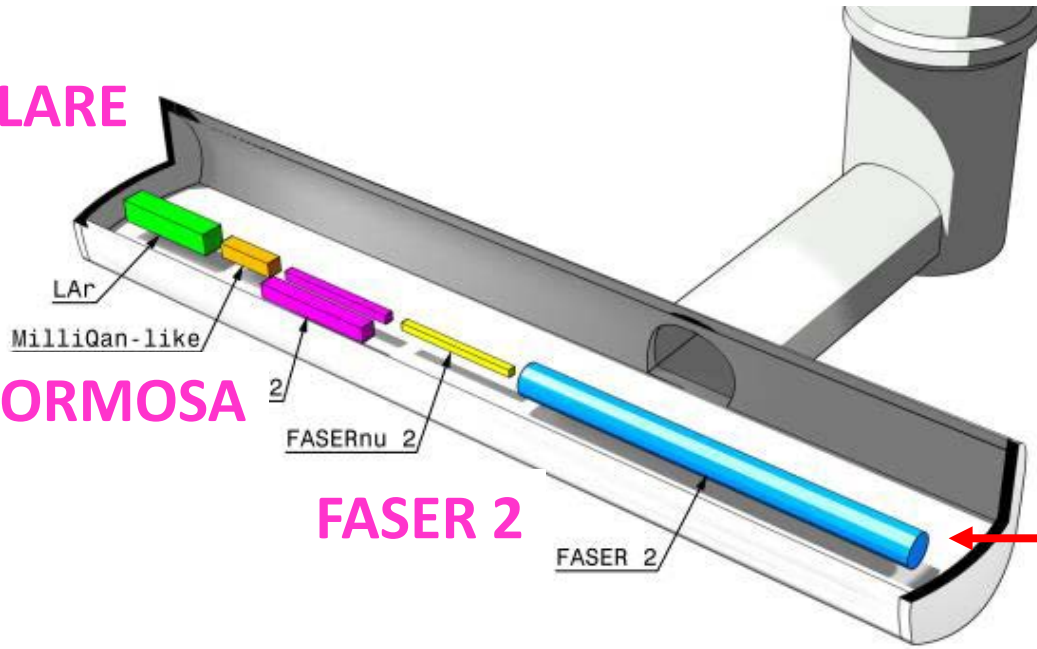
## Options for a Forward Physics Facility under study within PBC

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

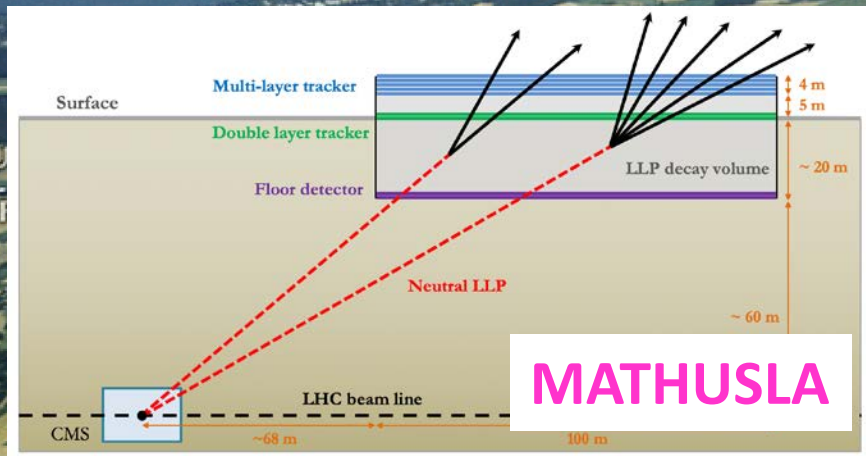
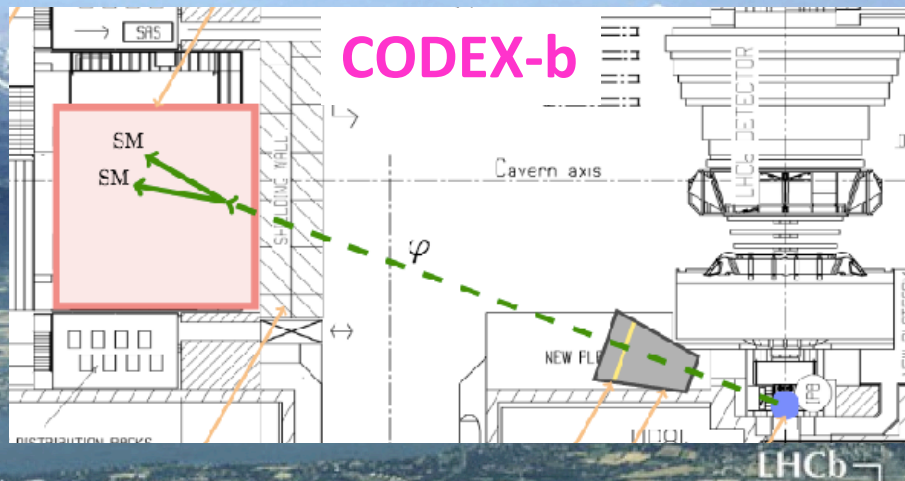
FLARE

FORMOSA

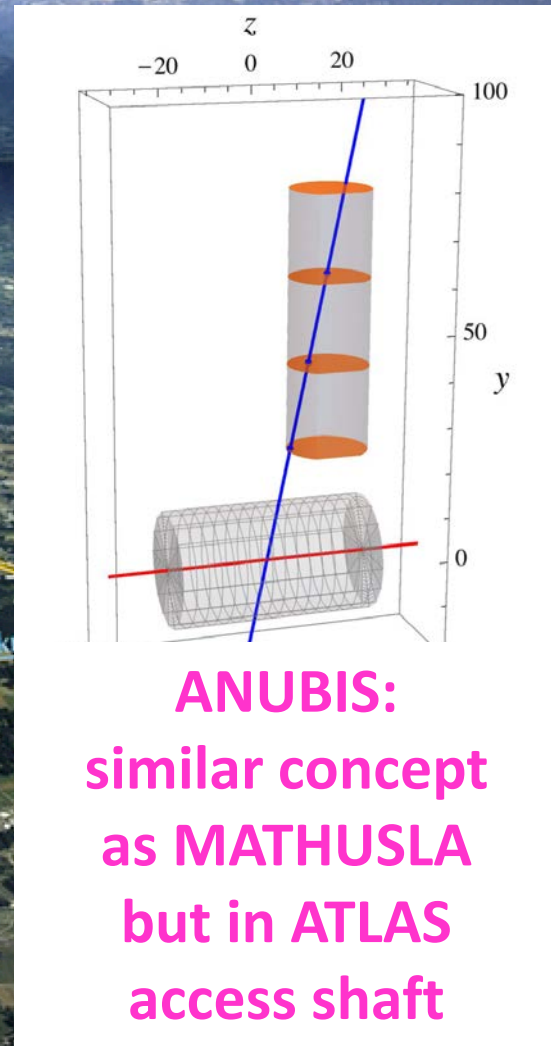
FASER 2







**Further demonstrators and detailed simulations planned during run 3**



**LHC-LLP DEDICATED PROJECTS**  
*Larger scale projects at large angle*

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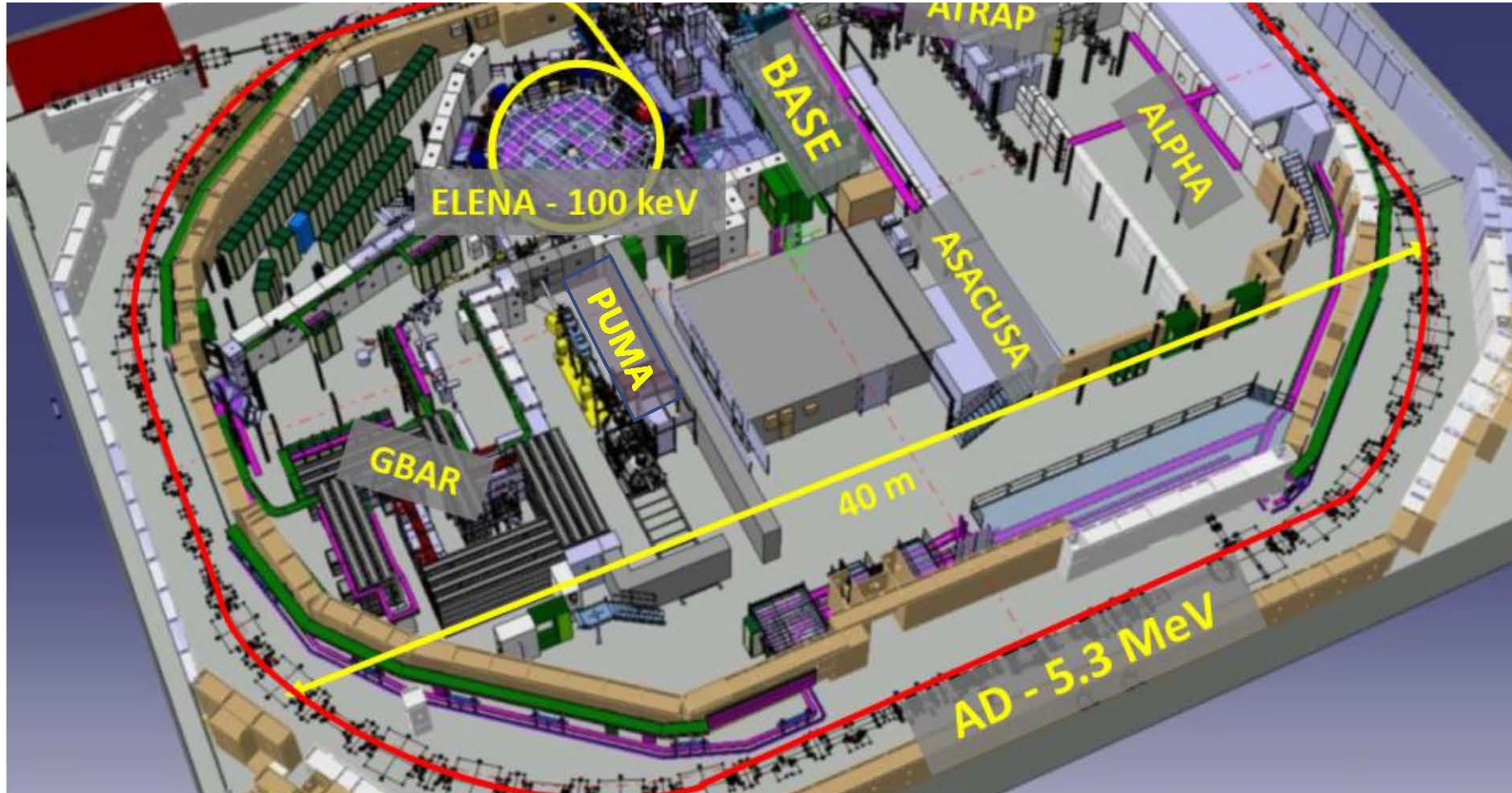




# ANTIMATTER FACTORY

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

AEGIS



*Recent ELENA upgrade enhances potential for next decade*

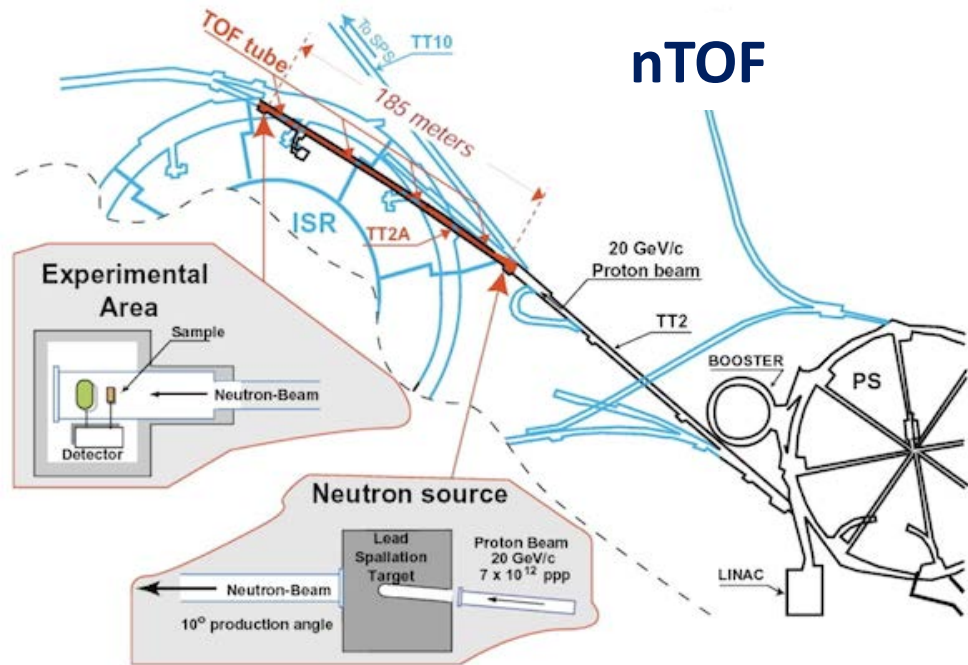


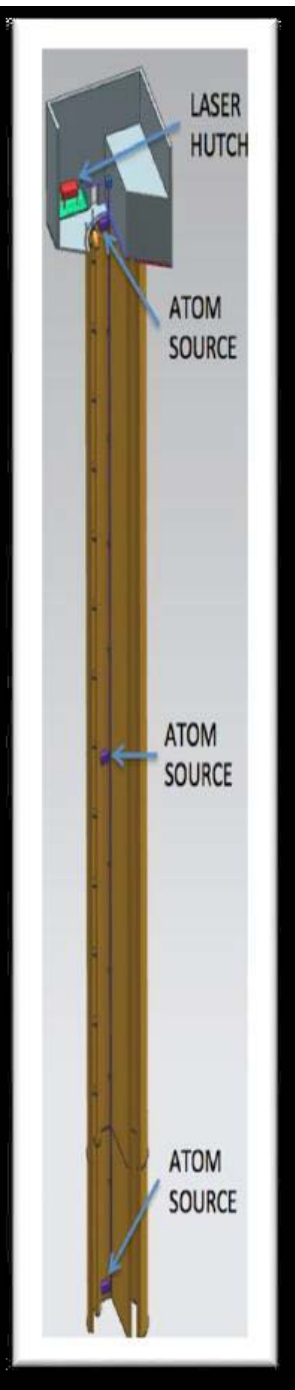
# ISOLDE & nTOF

*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**





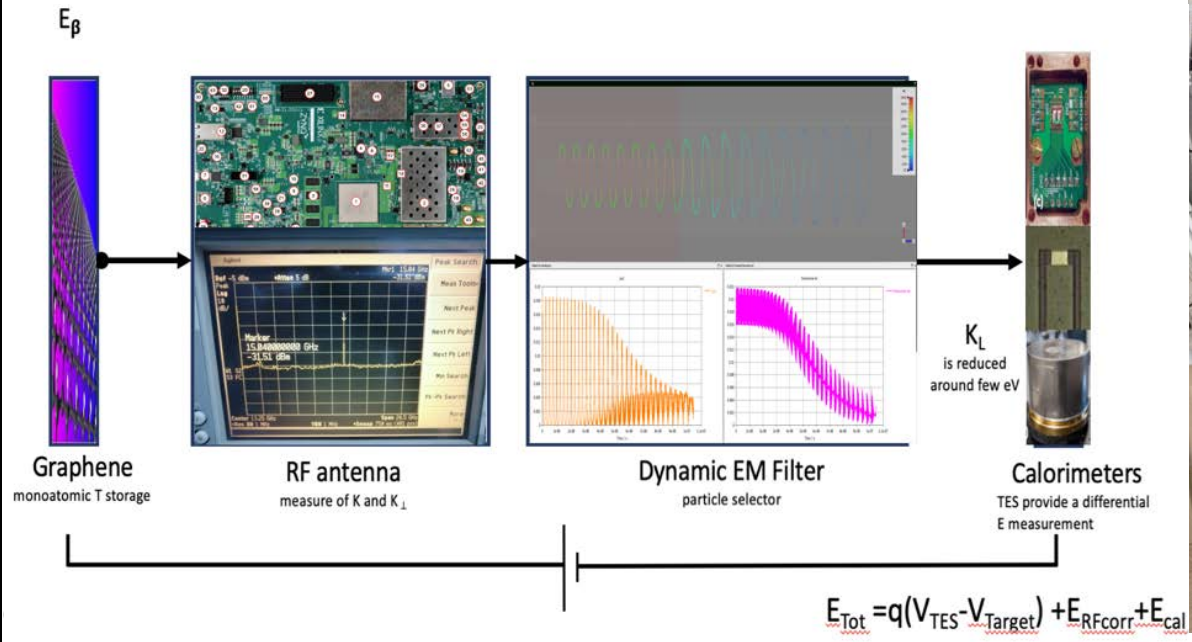
## AION

*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

## PTOLEMY

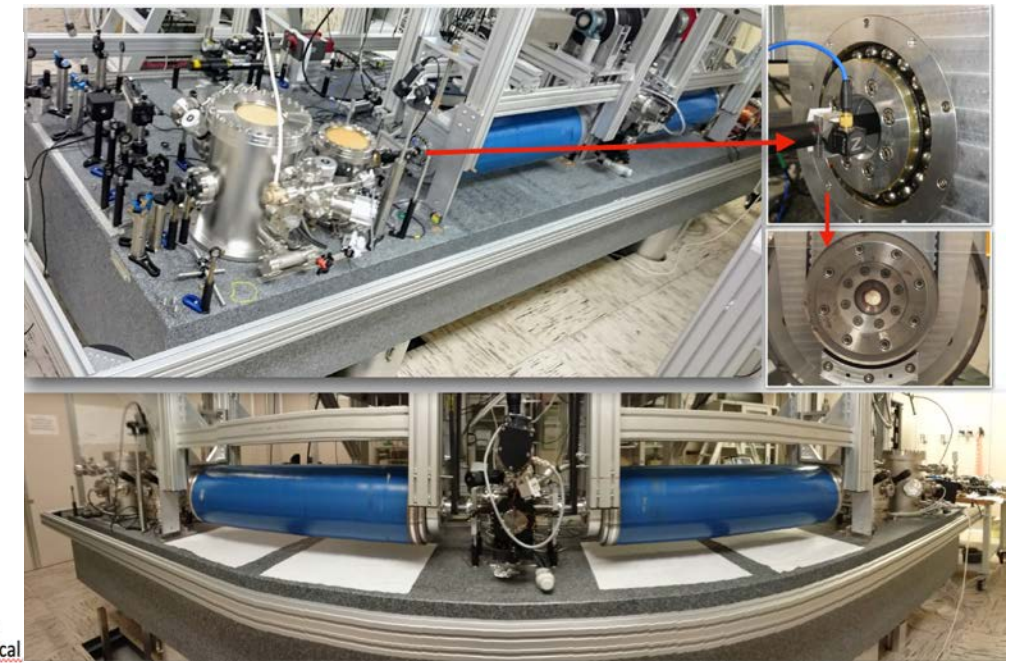
*Measurement of cosmic neutrino background*  
New idea submitted to Snowmass and PBC



# QUANTUM SENSORS a few recent developments

## VMB@CERN

*Vacuum Magnetic Bi-refringence*  
Optical set up being developed in Ferrara for a CERN implementation with (HL-)LHC magnets



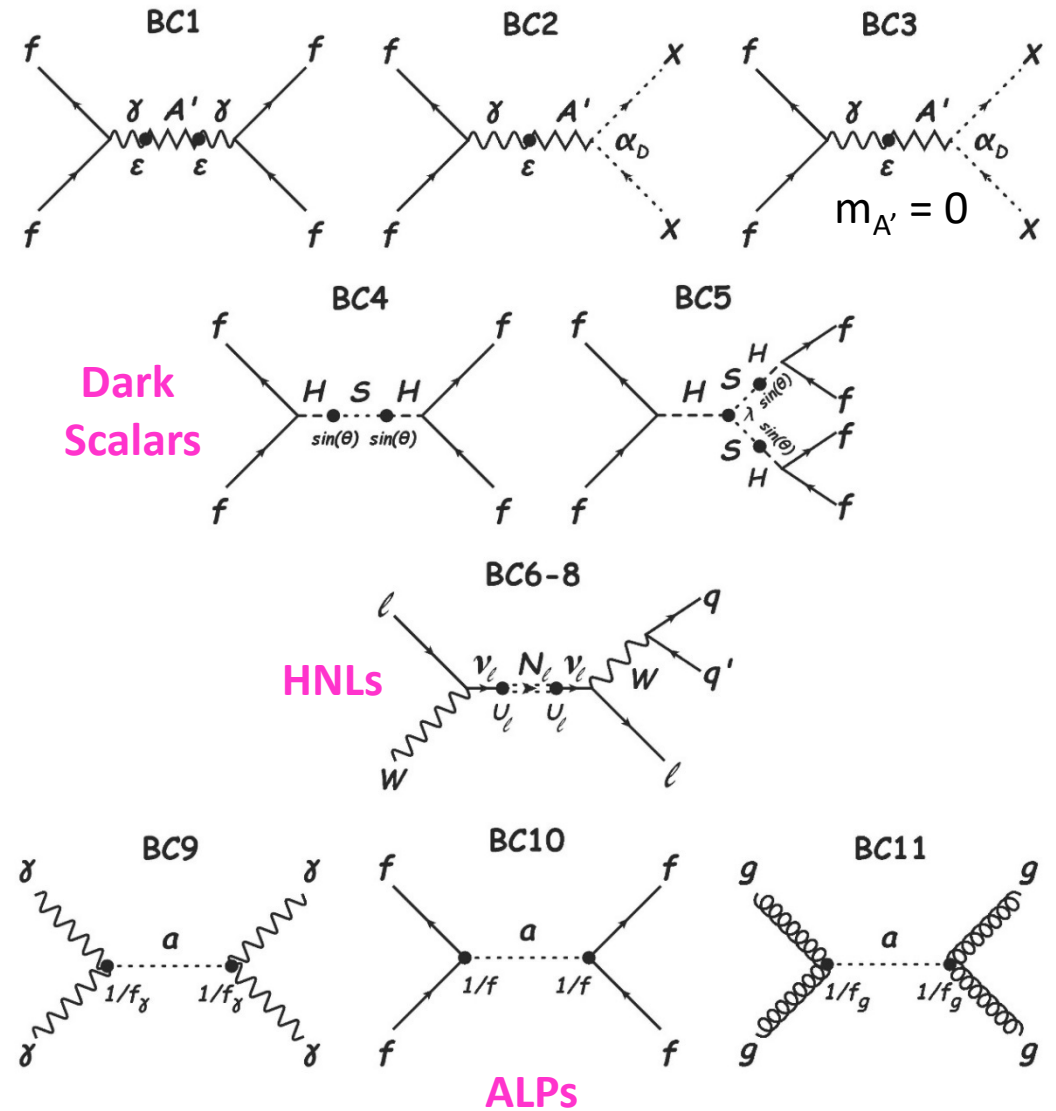
# NEW THEORETICAL DIRECTIONS

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

*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](https://arxiv.org/abs/2102.12143)

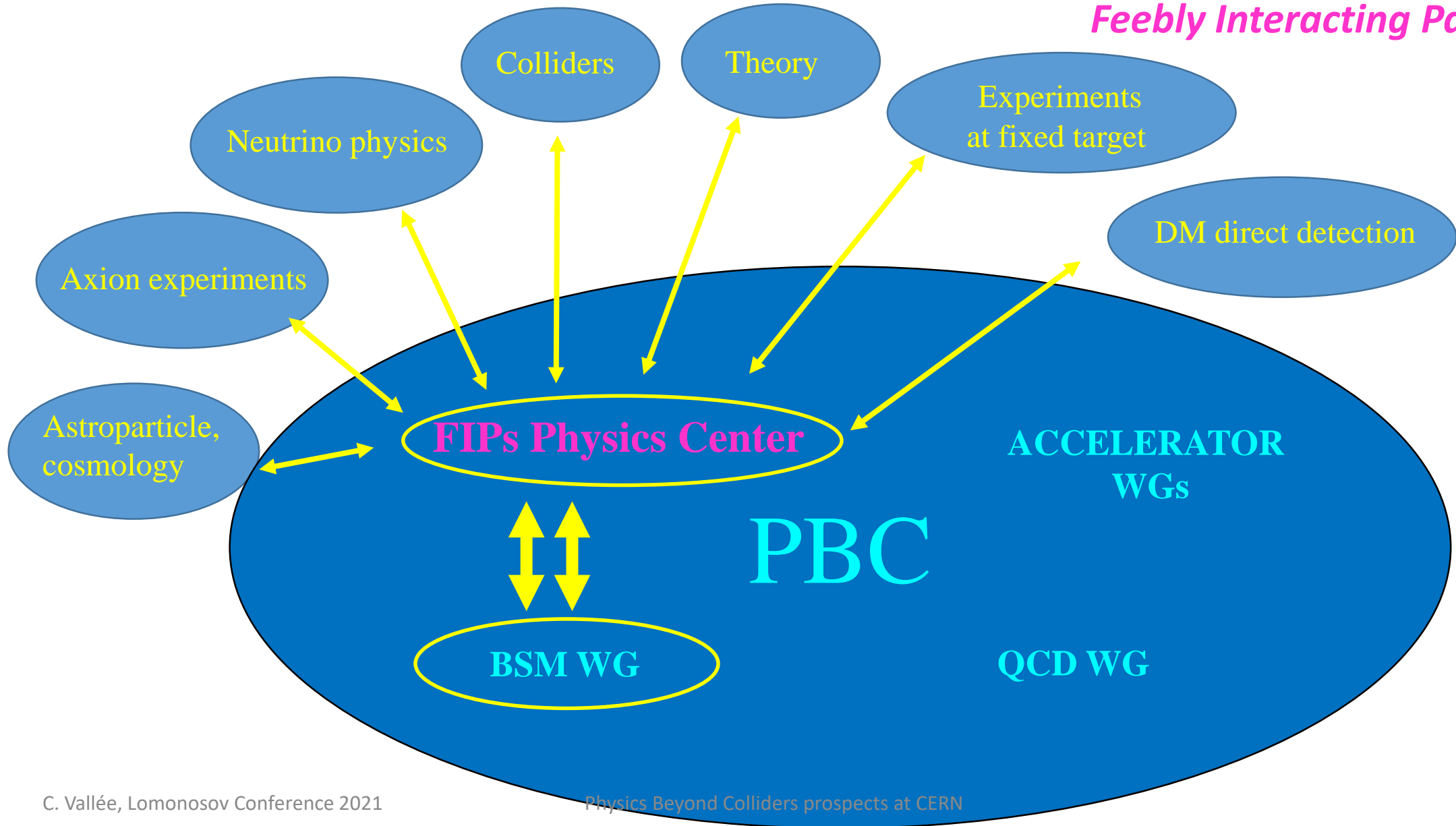
## Dark Photons and Dark Matter



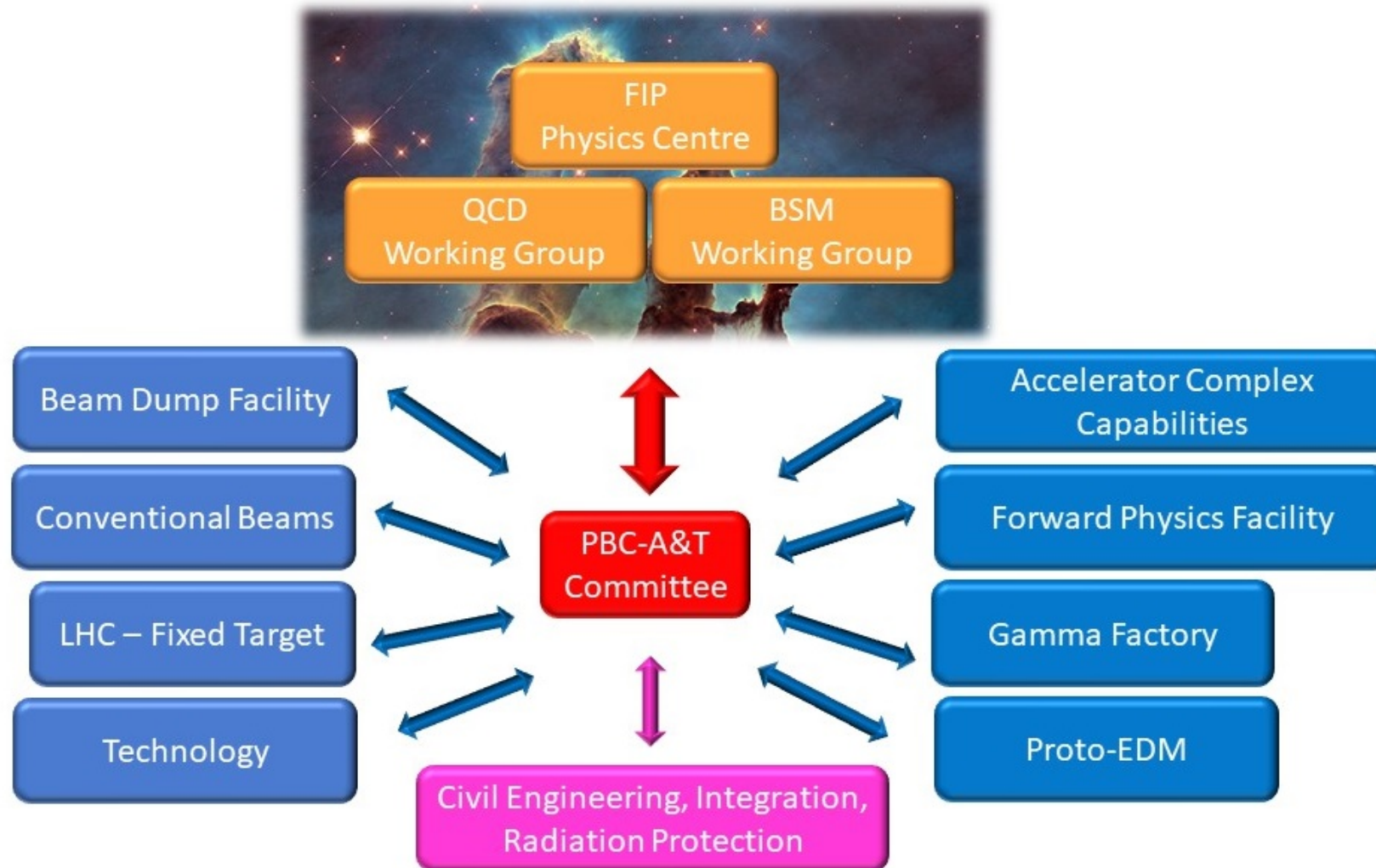


# FIPs PHYSICS CENTRE

*“FIPs Physics Center” now embedded within PBC as a “portal” towards the external world for Feebly Interacting Particles*



# OUTLOOK: 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/>*

**ADDITIONAL SLIDES**

# HISTORY OF PRE-EPPSU PBC EVENTS

**PBC KICK-OFF WORKSHOP, CERN, September 2016**

Call for abstracts → 20 selected for presentation

**1<sup>st</sup> GENERAL WORKING GROUP MEETING, CERN, March 2017**

Identification of main issues to be studied

**2<sup>nd</sup> PBC WORKSHOP, CERN, November 2017**

Working groups project reports

New call for abstracts → 7 selected for presentation

**2<sup>nd</sup> GENERAL WORKING GROUP MEETING, CERN, June 2018**

**3<sup>rd</sup> PBC WORKSHOP: CERN, January 16-17, 2019**

Summary of inputs to EPPSU and survey of future studies

**3<sup>rd</sup> GENERAL WORKING GROUP MEETING, CERN, 5-6 November 2019**

Updated status of projects before EPPSU drafting session



## PBC DELIVERABLES: ACCELERATOR WGs

Working group	10 pager for ESPP for 18th December - WG dependent	Possible proponents/clients submitting 10 pager to ESPP	PBC deliverable for 18th December * (referenced by 10 pager)
<b>AWAKE++</b>	Y	Proposed client experiment	Exploratory study
<b>BDF</b>	Y	SHiP, tauFV	Comprehensive Design Study - tauFV as appendix
<b>Conventional beams</b>	Y	NA61, NA62++, KLEVER etc.	Description of the conventional beam upgrades associated to the proposed projects
<b>EDM</b>	Y		3 appendices: COSY; prototype; full ring (feasibility study).
<b>eSPS</b>	Y	LDMX,BD	Technical report on possible implementation at CERN
<b>FASER acc.</b>	N	FASER	Technical report on possible implementation in LHC
<b>Gamma factory</b>	Y		Exploratory study
<b>LHC FT</b>	N	AFTER@LHC, LHCspin, MDM/EDM	Technical study of feasibility
<b>nuSTORM</b>	Y		Broad outline of a possible nuSTORM implementation at CERN
<b>Perf post-LIU</b>	N		Injector complex performance after LIU
<b>Technology</b>	Y	IAXO et al	Exploration and evaluation of possible technological contributions of CERN to non-accelerator projects possibly hosted elsewhere

Reports publicly available on CERN CDS: <http://cds.cern.ch/collection/PBC%20Reports?ln=en>

# 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.