Physics Beyond Colliders: Long Lived Particle Searches

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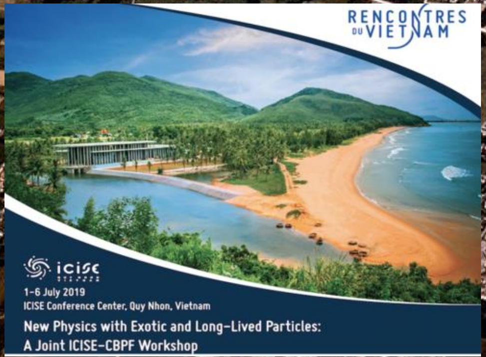
2nd July 2019



The European Strategy:

The European Strategy for Particle Physics (ESPP) is the process by which every ~ 7 years the European particle physics community updates the priorities and strategy of the field.
It also makes recommendations on related activities: education, communications and outreach, technology transfer, organisational aspects, etc.

First ESPP in 2006; first update in 2013; next update 2020.

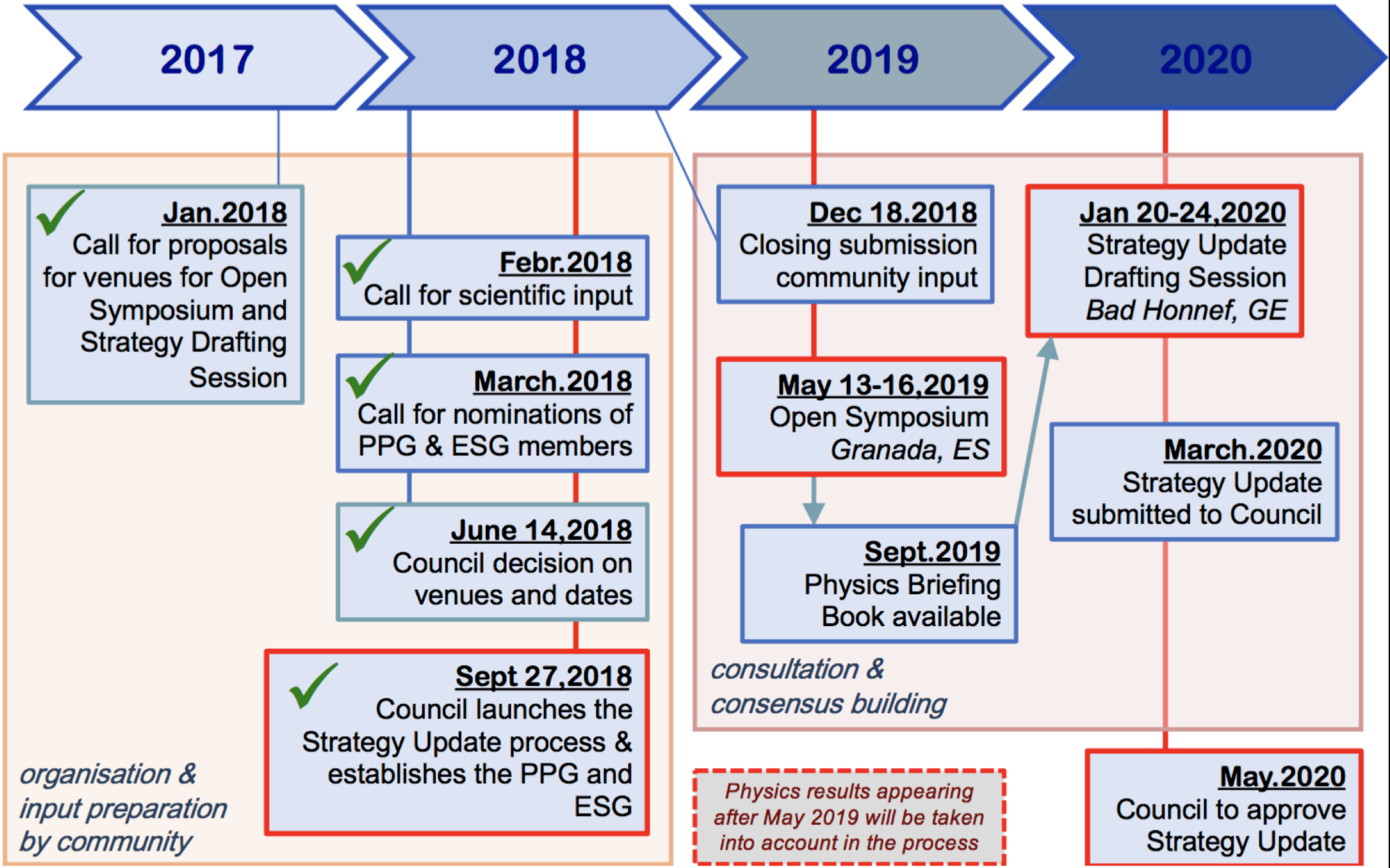
Bottom-up process involving the community. Driven by physics*, with awareness of financial and technical feasibility.

ESPP produces the European roadmap in the worldwide context of the field.
Note: particle physics requires global coordination, given the number, size and complexity of the projects → "alignment" of the European, US and Japanese roadmaps in recent years to optimise the use of resources

The Strategy is adopted by the CERN Council.
Individual (major) projects require dedicated approval: e.g. HL-LHC

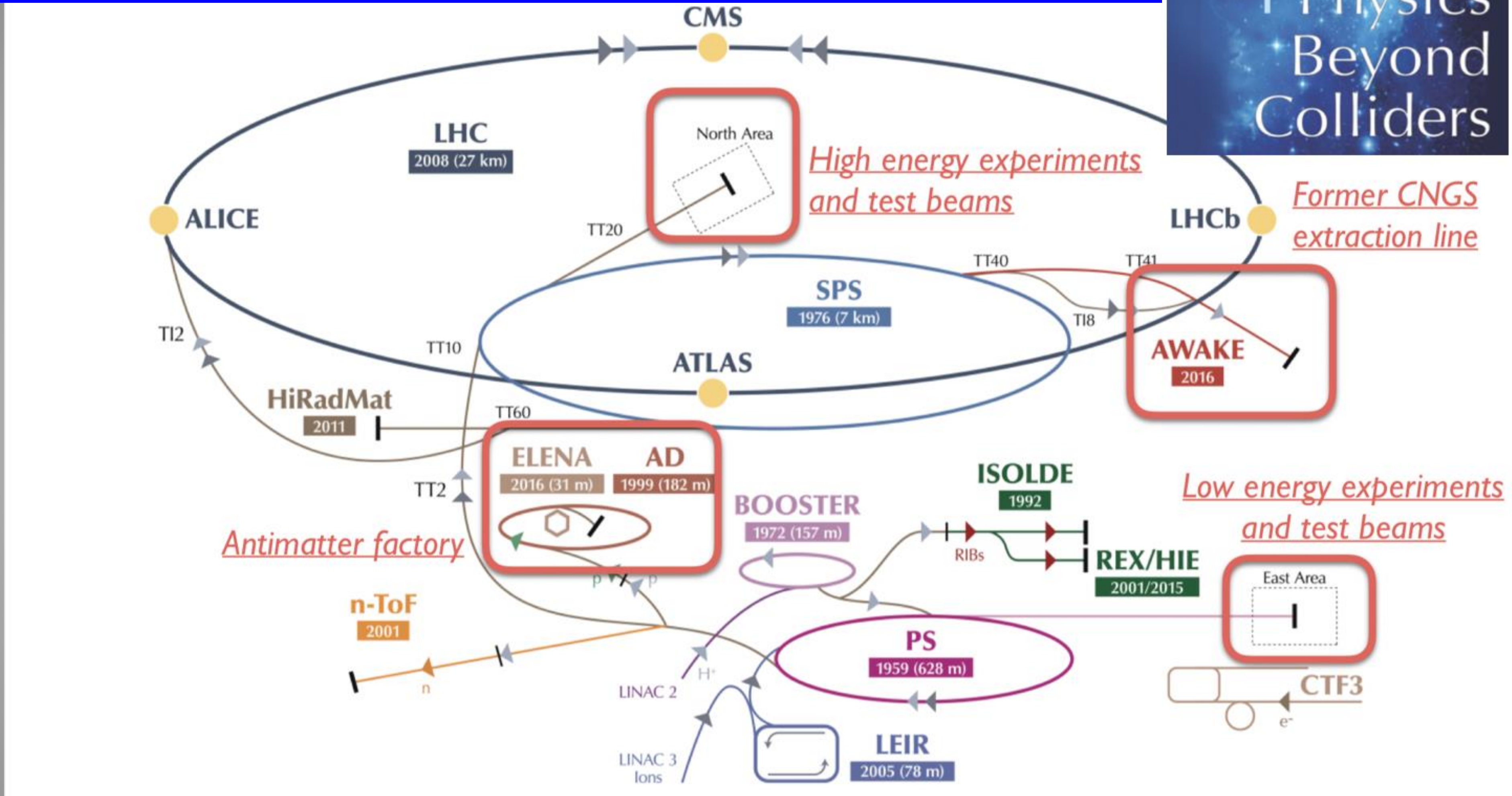
* The scientific input includes: physics results from current facilities from all over the world; physics motivations, design studies and technical feasibility of future projects; results of R&D work, etc.

2020 ESPP update: timeline and committees



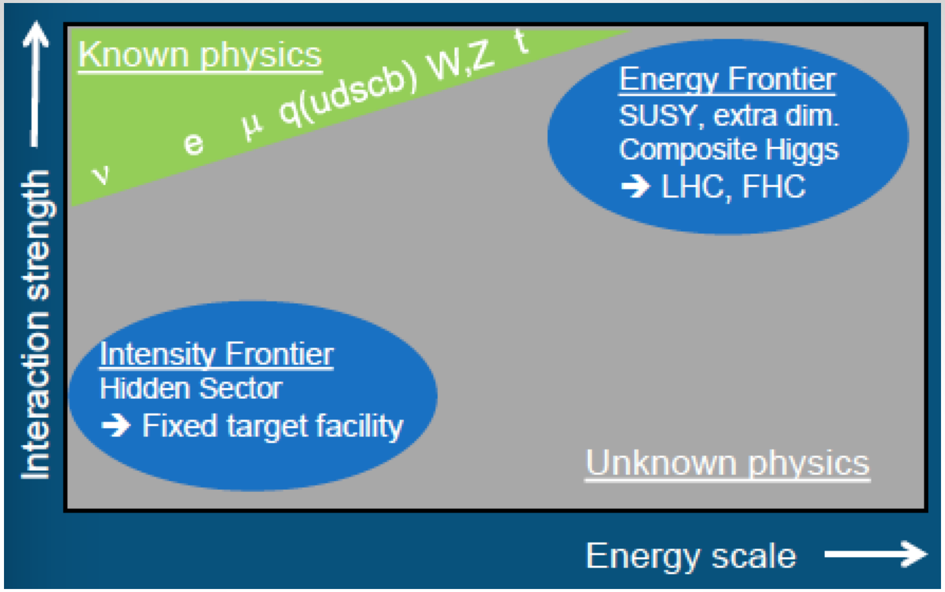
CERN: Intensity Frontier

Physics Beyond Colliders



Excerpt from the PBC mandate: “*Explore the opportunities offered by the CERN accelerator complex to address some of today’s outstanding questions in particle physics through experiments complementary to high-energy colliders and other initiatives in the world.*”
(Time scale of opportunities: next 2 decades)

Physics Beyond Colliders



PBC: a Study Group mandated by the CERN Management to prepare the next European HEP strategy update (2019-20)

Excerpt from the PBC mandate:

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

Time scale: next 2 decades

pbc.web.cern.ch

NB: PBC mandate recently extended up to May 2020 to support the EPPSU

Physics Beyond Collider Events

PBC EVENTS IN THE PAST 2 YEARS

PBC KICK-OFF WORKSHOP, CERN, September 2016

Call for abstracts → 20 selected for presentation

1st GENERAL WORKING GROUP MEETING, CERN, March 2017

Identification of main issues to be studied

2nd PBC WORKSHOP, CERN, November 2017

Working groups project reports

New call for abstracts → 7 selected for presentation

2nd GENERAL WORKING GROUP MEETING, CERN, June 2018

Status of studies for PBC deliverables

3rd PBC WORKSHOP: CERN, January 16-17, 2019

Summary of inputs to EPPSU and survey of future studies

Many slides borrowed from this workshop, especially from Gaia Lanfranchi

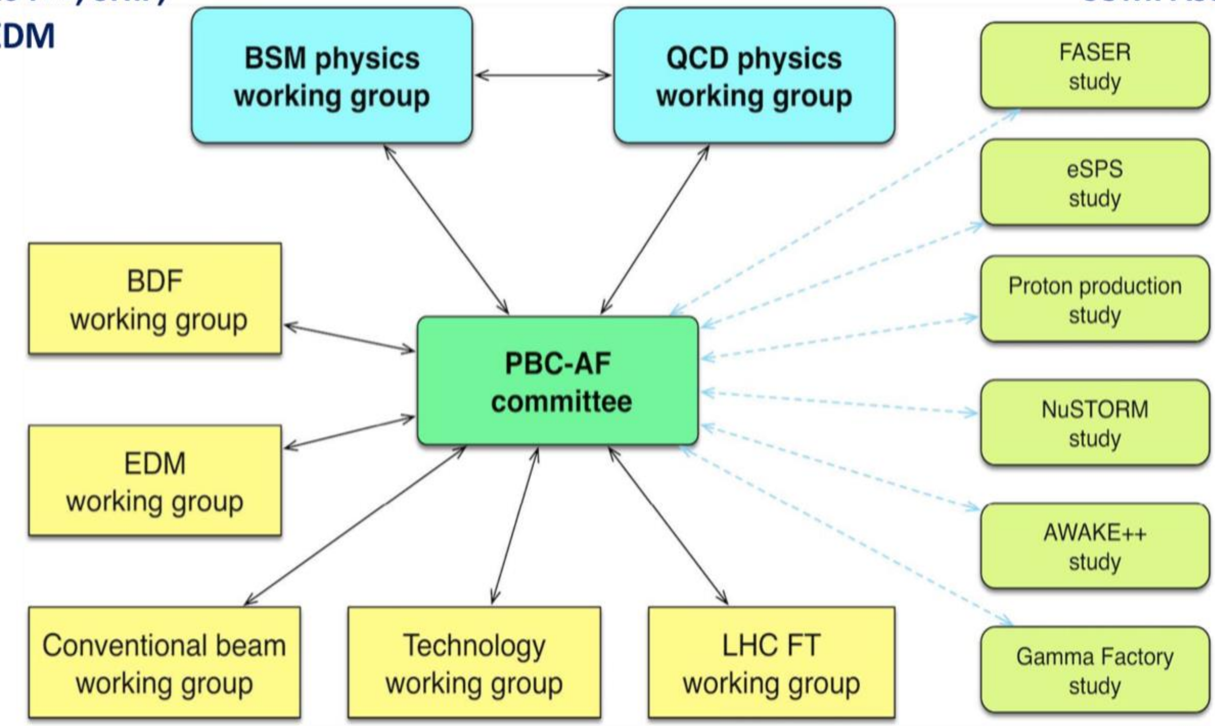
Next Meeting: November 5-6 2019 CERN

Physics Beyond Colliders

PBC WORKING GROUP STRUCTURE

BSM conveners: C. Burrage, G. Lanfranchi, S. Rozanov, G. Ruoso
+ ext. experts + projects representatives:
NA62++, KLEVER, NA64++, SHiP,
LDMX, IAXO, JURA, EDM

QCD conveners: M. Diehl, J. Pawlowski, G. Schnell
+ ext. experts + projects representatives:
COMPASS++, MUonE, DIRAC++
AFTER, CRYSTAL,
LHCb-FT, ALICE-FT
NA61++, NA60++



~100 core members in the Working Groups
> 200 WG meetings in the past 2 years

Physics Beyond Colliders

PBC DELIVERABLES: PHYSICS WGs

CERN-PBC-REPORT-2018-007
18 December 2018

Report of the BSM Working Group of the Physics Beyond Colliders at CERN

J. Beacham[1], C. Burrage[2,*], D. Curtin[3], A. De Roeck[4], J. Evans[5], J. L. Feng[6], C. Gatto[7], S. Gninenko[8], A. Hartin[9], I. Irastorza[10], J. Jaeckel[11], K. Jungmann[12,*], K. Kirch[13,*], F. Kling[6], S. Knapen[14], M. Lamont[4], G. Lanfranchi[15,*], C. Lazzeroni[16], A. Lindner[17], F. Martinez-Vidal[18], M. Moulson[15], M. Papucci[4,19], I. Pedraza[20], K. Petridis[21], M. Pospelov[22,*], A. Rozanov[23,*], G. Ruoso[24,*], P. Schuster[25], Y. Semertzidis[26], T. Spadaro[15], C. Vallée[23], and G. Wilkinson[27].

~140 pages

arXiv:1901.09966

CERN-PBC-REPORT-2018-008

Physics Beyond Colliders QCD Working Group Report

A. Dainese[1], M. Diehl[2,*], P. Di Nezza[3], J. Friedrich[4], M. Gaździcki[5,6] G. Graziani[7], C. Hadjidakis[8], J. Jäckel[9], M. Lamont[10] J. P. Lansberg[8], A. Magnon[10], G. Mallot[10], F. Martinez Vidal[11], L. M. Massacrier[8], L. Nemenov[12], N. Neri[11,13], J. M. Pawlowski[9,*], S. M. Puławski[14], J. Schacher[15], G. Schnell[16,*], A. Stocchi[17], G. L. Usai[18], C. Vallée[19], G. Venanzoni[20]

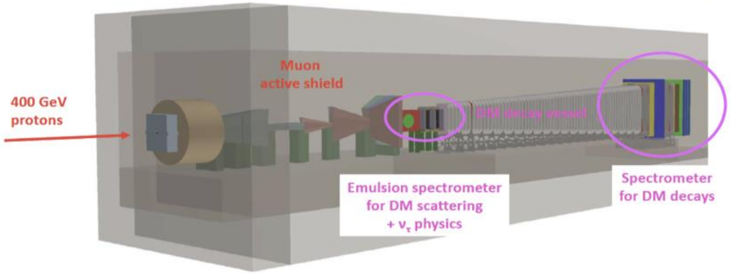
~80 pages

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

SHiP

Flagship programme for a comprehensive investigation of the Hidden Sector in the few GeV domain

Similar layout as NA62, with larger acceptance to reach the c / b mass range

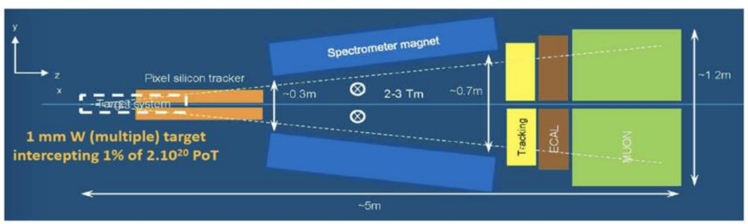


NB: NA62 plans to pave the way with short runs in beam dump mode after LS2

TauFV

Recently revived idea to intercept small BDF beam fraction to look for $\tau \rightarrow 3\mu$ decays

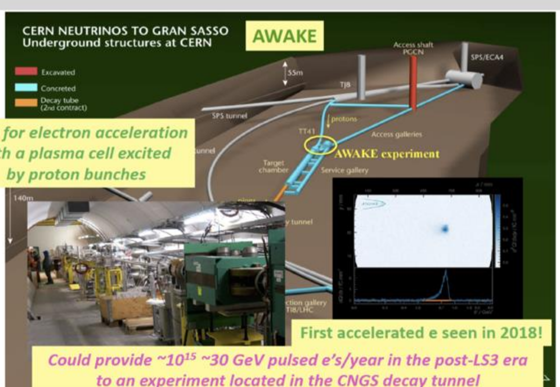
Could set limits on branching ratio better than 10^{-10} level (> BELLE-II reach)



Implementation layout upstream of BDF target under study

A promising option to maximize the physics reach of the Beam Dump Facility

AWAKE

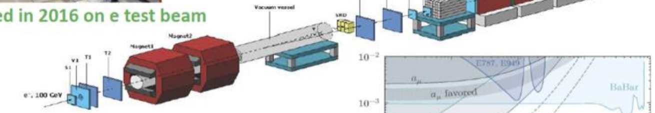


Examples of Beyond Collider Studies

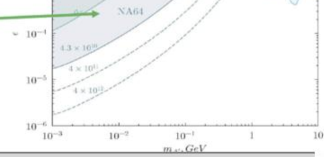
NA64

Implemented in 2016 on e test beam

Hidden sector search from invisible decays with missing energy



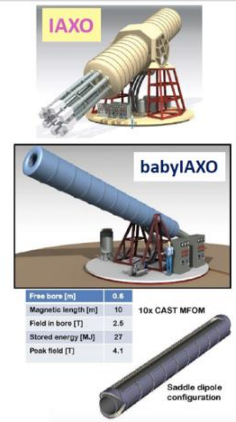
Fast analysis excluding $(g-2)_\mu$ interpretation confirms the potential of the method

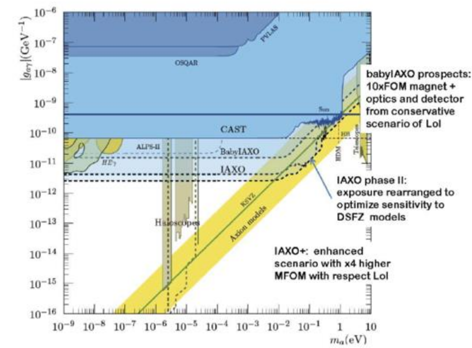


AFTER LS2:

Wish to extend the method to higher e intensity and μ / π / K / p beams

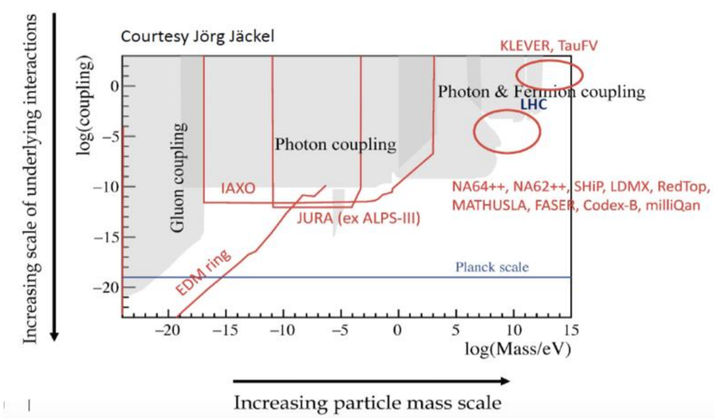
IAXO - next generation Axion helioscope beyond CAST





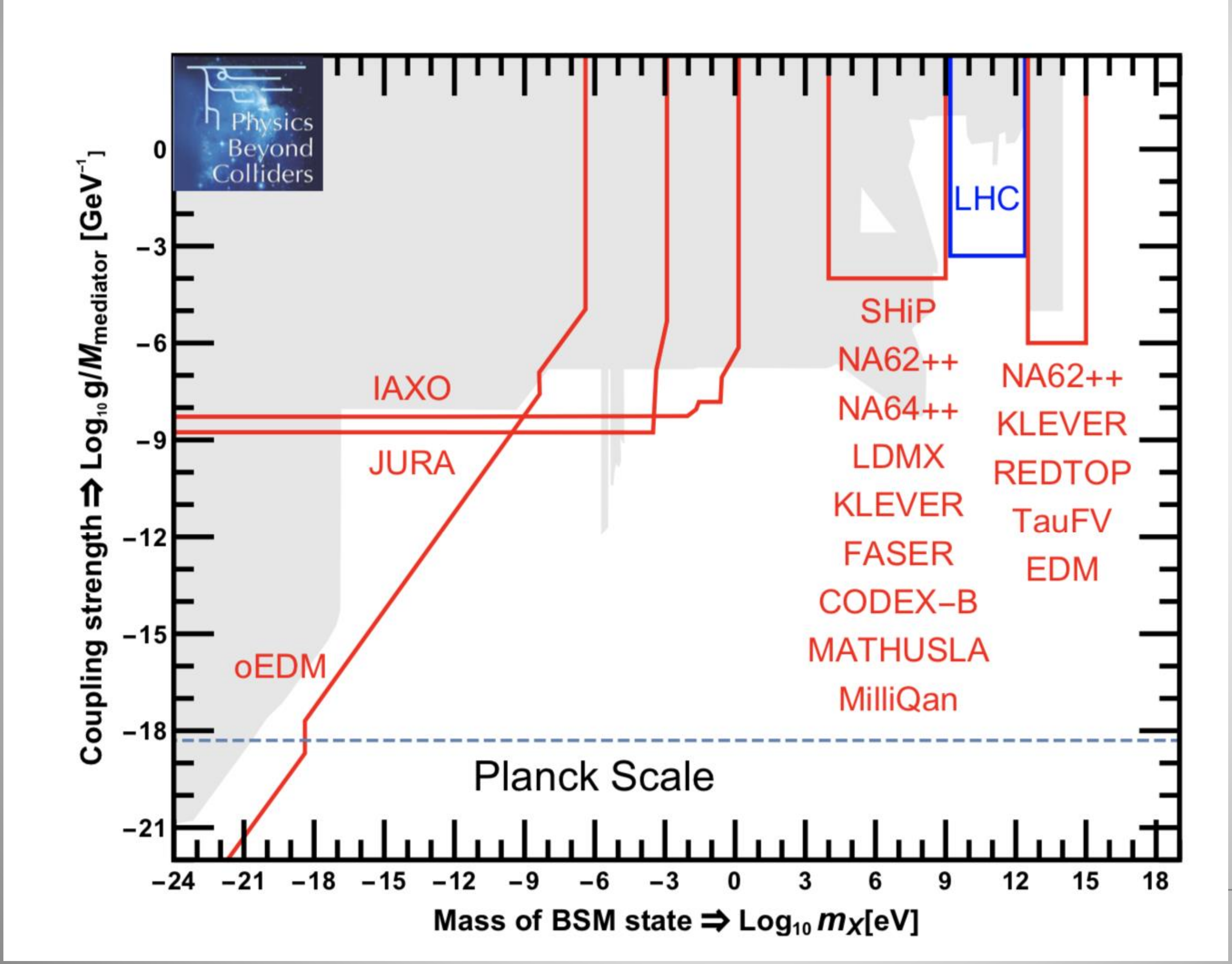
Support from CERN for magnet design within PBC

More than 20 proposed projects



New Possible Experiments

From the beyond collider study document: arXiv:1902.00260



Includes also new LHC experiments that have a similar physics search program

Feebly Interacting Particles

Particles that can interact even less than weakly…

A (very) limited list of examples

Experimental facts

Dark Matter:
candidates \w mass from 10^{-22} eV (light feeble scalars) to 10^{20} GeV (black holes).
⟶FIPs: if DM is a thermal relic, then mass is restricted o(10) keV – 100 TeV: MeV-GeV DM requires MeV-GeV mediators; 3.5 keV astrophysical line could be a sterile neutrino DM; ….

Neutrino masses and oscillations
explanation: RH neutrinos with masses from 10^{-2} eV to 10^{15} GeV.
⟶FIPs: If RHN have generic (feeble) Yukawa's + approximate $U(1)_L$, their masses can be below EW scale.

Matter-antimatter asymmetry
hard to associate scale, solutions of many orders of magnitudes:
⟶FIPs: baryogenesis via CPV relaxion-Higgs couplings;
⟶FIPs: baryogenesis though leptogenesis via oscillations of RHN with masses below EW scale.

Theoretical problems

Naturalness problem:
Symmetry-based solutions => TeV partners;
⟶FIPs: relaxion => light feeble Goldstone bosons (ALPs)

Strong CP problem:
⟶FIPs: axion => light feeble Goldstone boson;

………

CERN

Proposals considered in the Physics Beyond Colliders BSM report arXiv:1901.09966

sub-eV NP :
Axions with helioscopes, LSW and EDM rings

MeV-GeV NP:
Hidden Sector at accelerator-based experiments

Multi-TeV NP:
Ultra-rare/forbidden decays, EDM ring.

Proposal	Main Physics Cases	Beam Line	Beam Type	Beam Yield
sub-eV mass range:				
IAXO	axions/ALPs (photon coupling)	–	axions from sun	–
JURA	axions/ALPs (photon coupling)	laboratory	LSW	–
CPEDM	p, d oEDMs	EDM ring	p, d	–
	axions/ALPs (gluon coupling)		p, d	–
LHC-FT	charmed hadrons oEDMs	LHCb IP	7 TeV p	–
MeV-GeV mass range:				
SHiP	ALPs, Dark Photons, Dark Scalars	BDF, SPS	400 GeV p	$2 \cdot 10^{20}/5$ years
	LDM, HNLs, lepto-phobic DM, ..			
NA62^{++}	ALPs, Dark Photons,	K12, SPS	400 GeV p	up to $3 \cdot 10^{18}$/year
	Dark Scalars, HNLs			
NA64^{++}	ALPs, Dark Photons,	H4, SPS	100 GeV e^-	$5 \cdot 10^{12}$ eot/year
	Dark Scalars, LDM			
	$+ L_\mu - L_\tau$	M2, SPS	160 GeV μ	$10^{12} - 10^{13}$ mot/year
	+ CP, CPT, leptophobic DM	H2-H8, T9	~ 40 GeV π, K, p	$5 \cdot 10^{12}$/year
LDMX	Dark Photon, LDM, ALPs,...	eSPS	8 (SLAC) -16 (eSPS) GeV e^-	$10^{16} - 10^{18}$ eot/year
AWAKE/NA64	Dark Photon	AWAKE beam	30-50 GeV e^-	10^{16} eot/year
RedTop	Dark Photon, Dark scalar, ALPs	CERN PS	1.8 or 3.5 GeV	10^{17} pot
MATHUSLA200	Weak-scale LLPs, Dark Scalar,	ATLAS or CMS IP	14 TeV p	3000 fb^{-1}
	Dark Photon, ALPs, HNLs			
FASER	Dark Photon, Dark Scalar, ALPs,	ATLAS IP	14 TeV p	3000 fb^{-1}
	HNLs, $B - L$ gauge bosons			
MilliQan	milli charge	CMS IP	14 TeV p	300-3000 fb^{-1}
CODEX-b	Dark Scalar, HNLs, ALPs,	LHCb IP	14 TeV p	300 fb^{-1}
	LDM, Higgs decays			
>> TeV mass range:				
KLEVER	$K_L \to \pi^0 \nu \bar{\nu}$	P42/K12	400 GeV p	$5 \cdot 10^{19}$ pot /5 years
TauFV	LFV τ decays	BDF	400 GeV p	$o(2\%)$ of the BDF proton yield
CPEDM	p, d EDMs	EDM ring	p, d	–
	axions/ALPs (gluon coupling)		p, d	–
LHC-FT	charmed hadrons MDMs, EDMs	LHCb IP	7 TeV p	–

Fixed target & Beam dump experiments

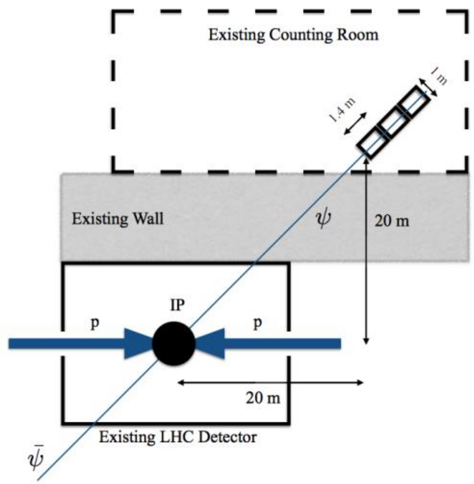
Non Accelerator-based

Accelerator-based

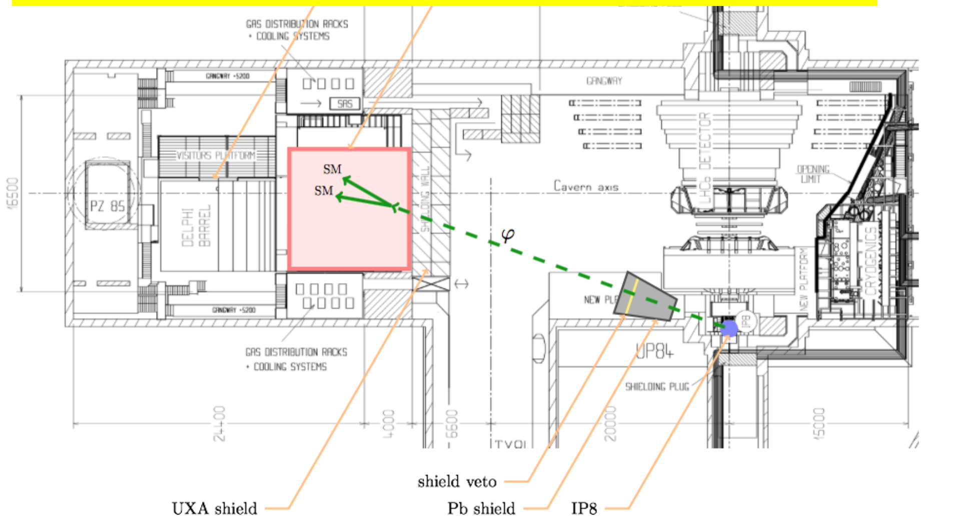
About 15 proposals have been considered in the BSM-WG so far

Proposals for New Experiments @LHC

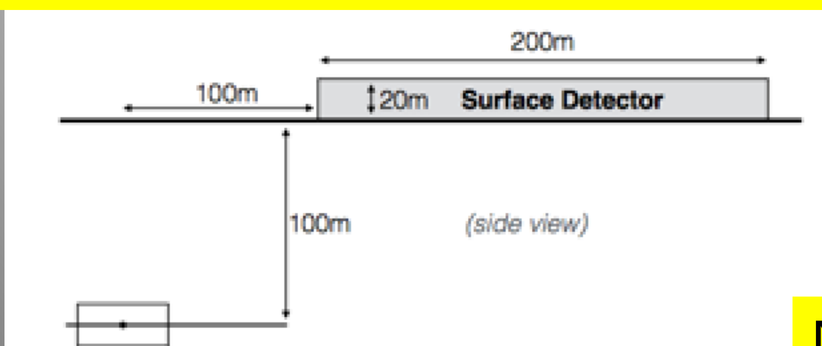
MilliQan: searches for millicharged particles
MAPP: Same from MoEDAL



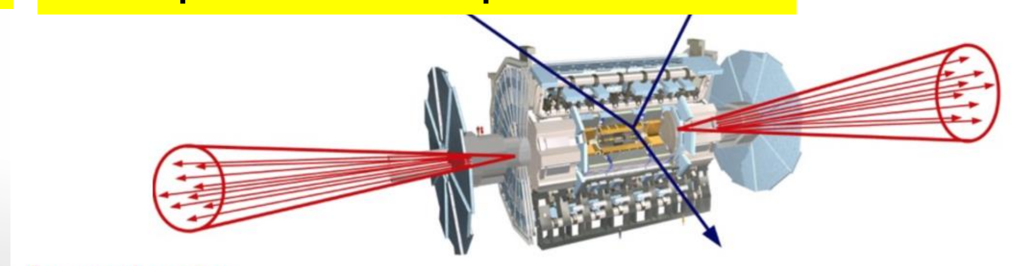
CODEX-b: searches for long lived weakly interacting neutral particles



MATHUSLA: searches for long lived weakly interacting neutral particles



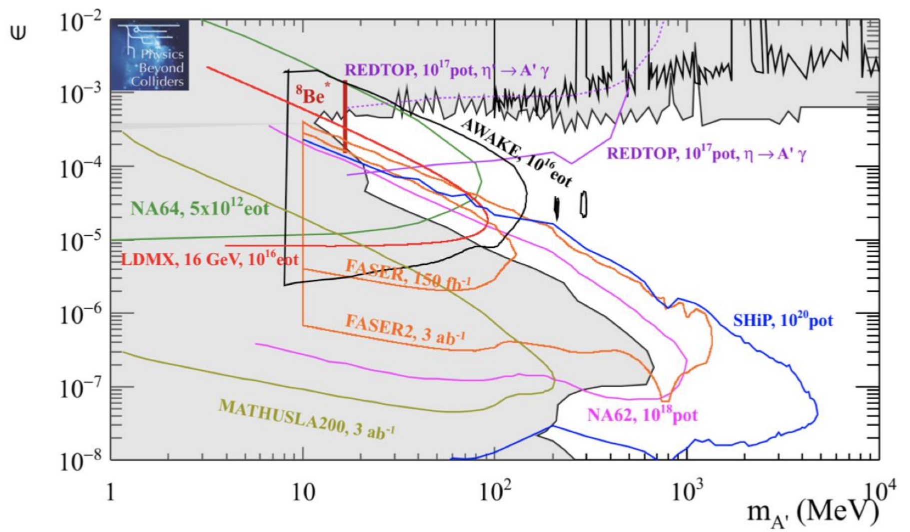
FASER: searches for long lived dark photons-like particles



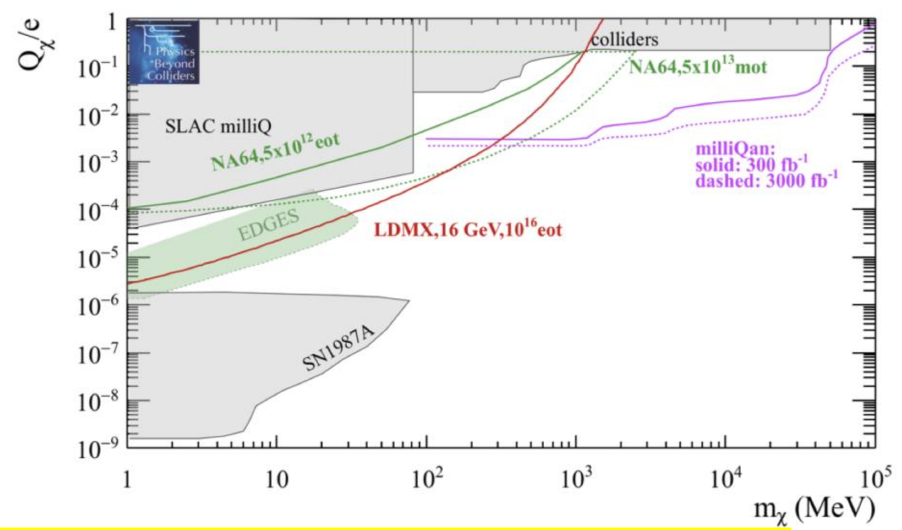
New: AL3X ('ALICE' for LLP arXiv.1810.03636)...

Sensitivity Summaries

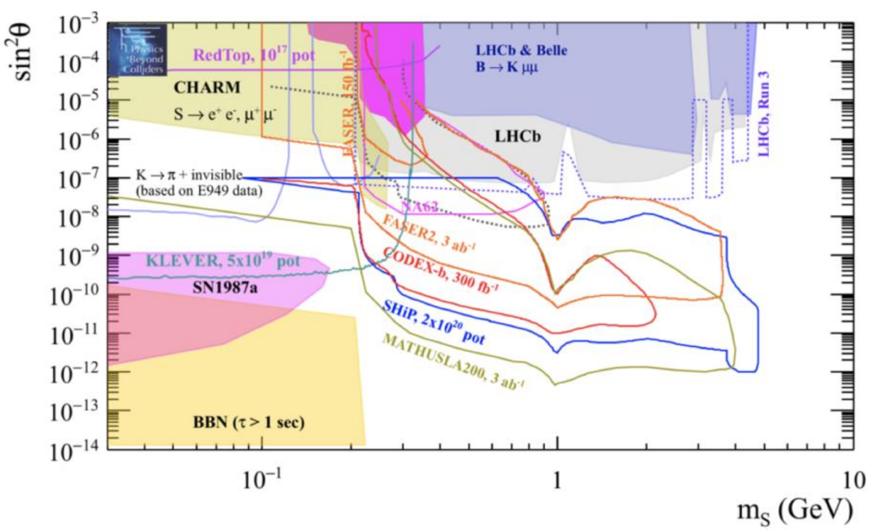
Search for dark photons (visible mode)



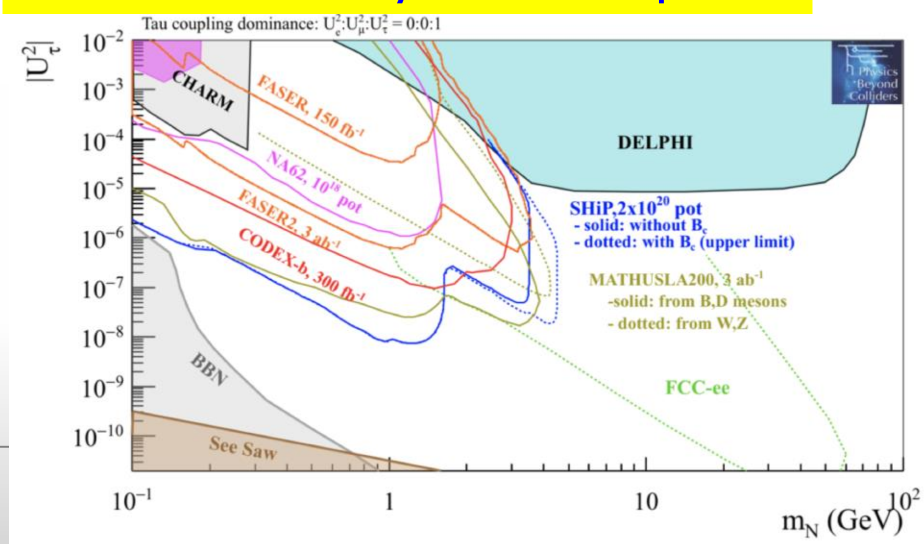
Search for millicharges



Search for dark scalars



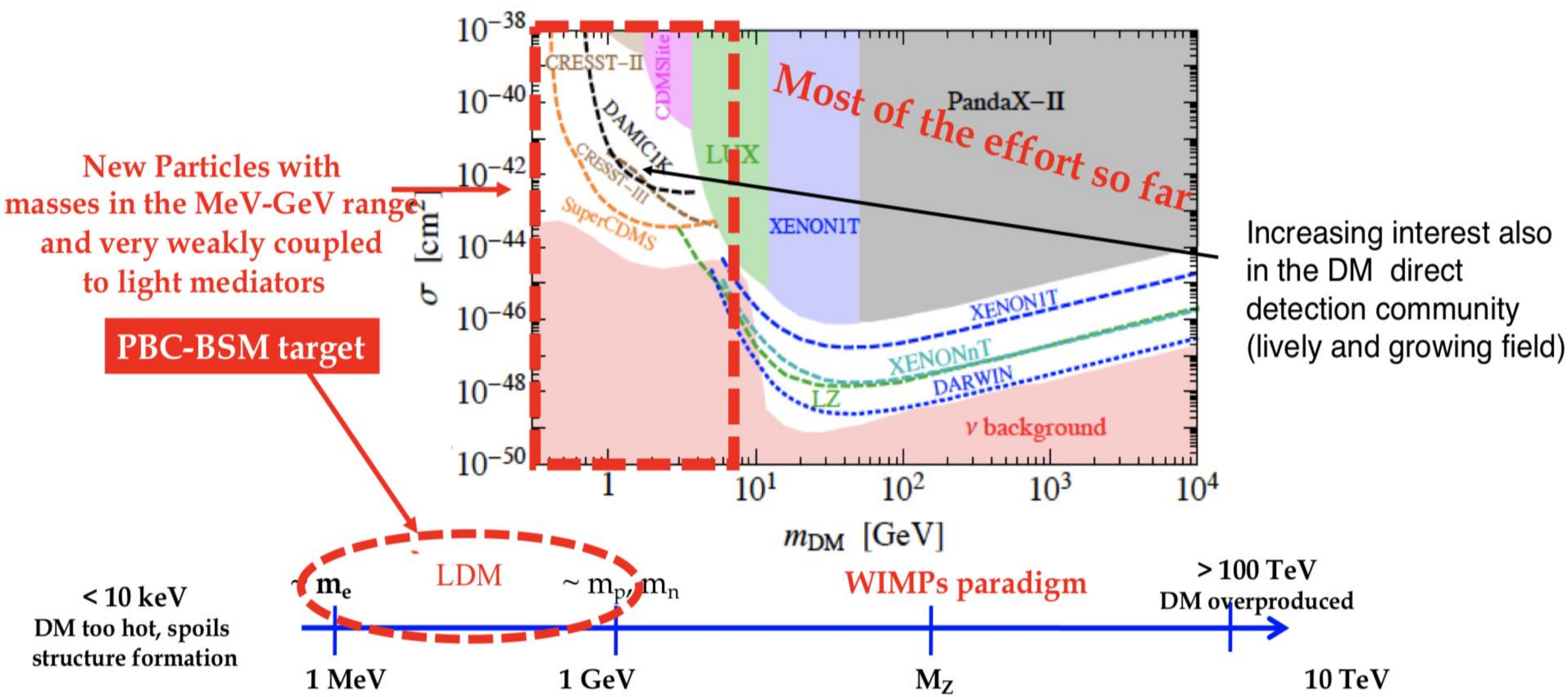
Search for heavy neutral leptons



PBC Physics Goals

PBC target: (Light) Dark Matter with thermal origin

DM candidates with thermal origin can have mass between 10 keV and 100 TeV.



PBC: Physics Goals

PBC target: (Light) Right-Handed Neutrinos

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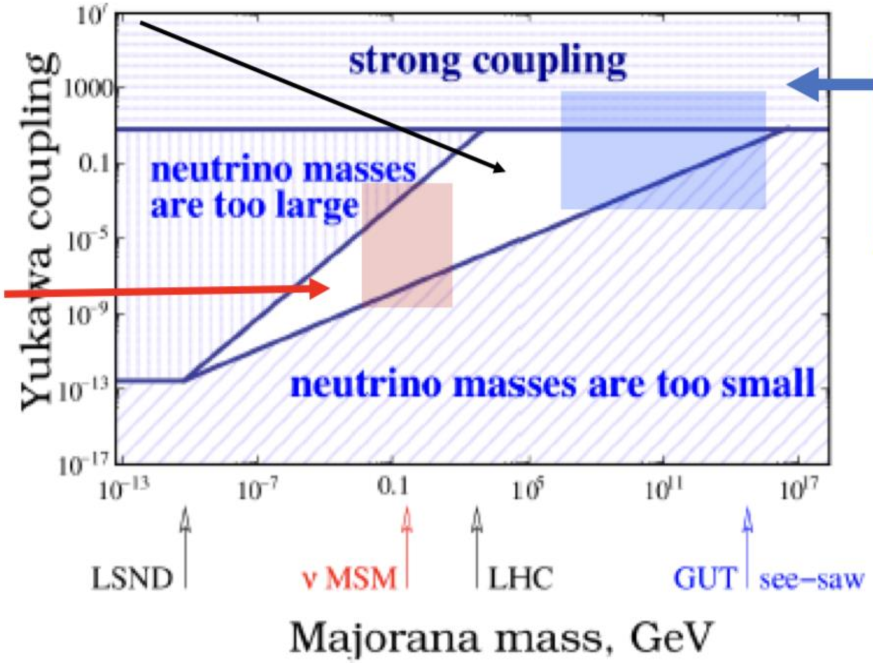
Neutrino portal extensions of the SM is motivated by the neutrino mass generation mechanism.
It is also motivated by cosmology: couplings between Right-Handed neutrinos can violate CP and generate matter-anti matter asymmetry in the early Universe.

Right handed neutrinos responsible of the see-saw mechanism can have any coupling/mass in the white area.

Alternative choice: EW see-saw (νMSM)

It is "natural" to assume that the masses of the RH neutrinos are at EW scale

PBC target



Popular choice: GUT see-saw

It "natural" to assume that Yukawa couplings of the RH neutrinos are similar to SM Yukawa.

PBC: Physics Goals

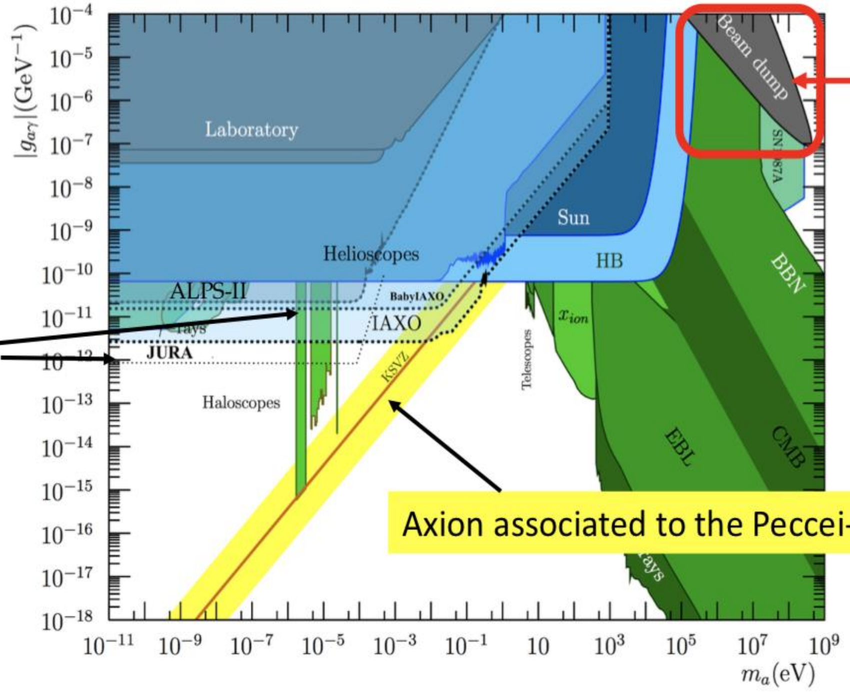
PBC target: Axion and Axion-Like Particles

Axion = Pseudo-Nambu Goldstone Boson associated to Peccei-Quinn symmetry, a global U(1), introduced to address the Strong QCD problem. Vast range of masses and couplings possible, with fixed relation.

Axion-Like Particle (ALP): a generalized version of the axion (at the cost of the original motivation from the strong CP problem). No direct relation between coupling and mass.

Axions and ALPs in the sub-eV mass range (lively and well-established community)

PBC target



Axion associated to the Peccei-Quinn symmetry

Interest to explore the MeV-GeV region at accelerator-based experiments

PBC target

Experiment Proposals

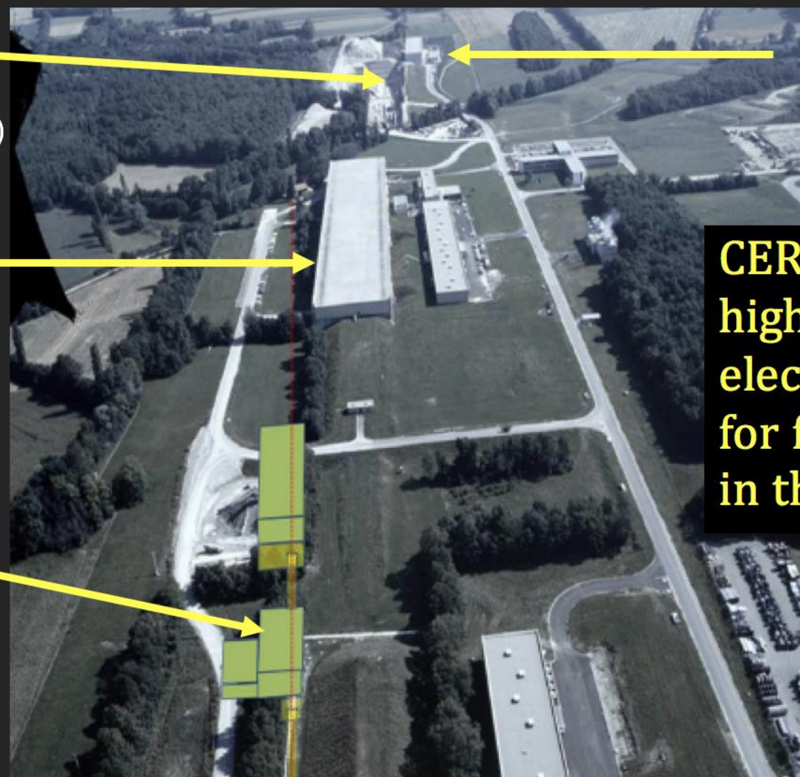
Opportunities @ CERN in the North Area

NA62-dump @ K12
400 GeV p beam
up to 3x10^{18} pot/year (now)

NA64^{++}(e) @ H4
(100 GeV e- beam
up to 5x10^{12} eot/year)

SHiP @ BDF
400 GeV p
up to 4x10^{19} pot/year

NA64^{++} (μ) @ M2
100-160 GeV muons,
up to 10^{13} μ/year



CERN can provide the highest energy proton, electron and muon beams for fixed target experiments in the world.

A possible "Hidden Sector Campus" (HSC)

NA64

The NA64 experiment in EHN1, H4

https://na64.web.cern.ch/

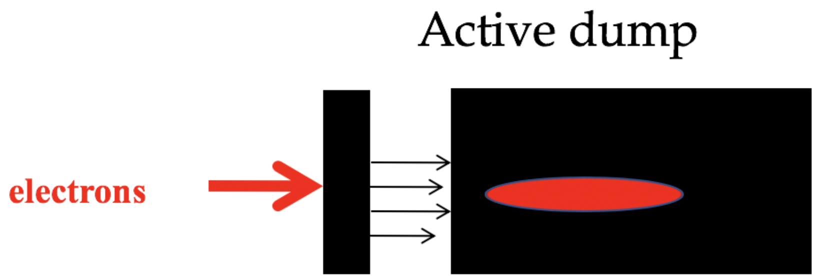
Current status: collected few o(10^{11}) eot.

In a few months of data taking has excluded Dark Photon as origin of the (g-2)μ discrepancy.

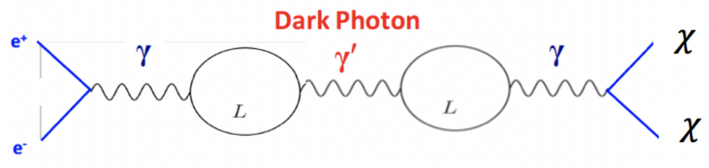
Na64: Experimental Technique

NA64: “ACTIVE” DUMP technique:

Any discrepancy between the energy of the electron measured before and in the active dump would be sign of the production of some non-interacting particles, as for example Dark Matter, or very long-lived light mediators as Dark Photons



$$A' \to \chi\chi$$



NA64++: Muons and Hadrons

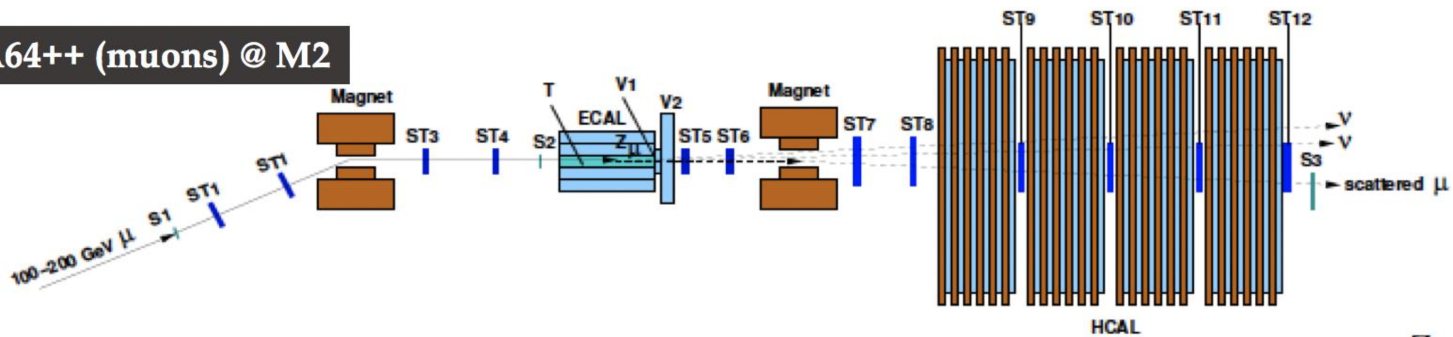
Proposal to extend the physics programme after LS2:

NA64++ (electrons): extension beyond 2021 to accumulate up to 5×10^{12} eot in H4

NA64++ (muons): use the 100-160 GeV muon beam in COMPASS area to study hidden sector with muon couplings. Very complementary to Dark Sector with electron couplings.

NA64++ ($K_{L,S}$, $\pi^0, \eta, \eta' \rightarrow$ invisible): produced via charge exchange reactions $\pi(K)\, p \rightarrow M^0\, n + E_{miss}$

NA64++ (muons) @ M2



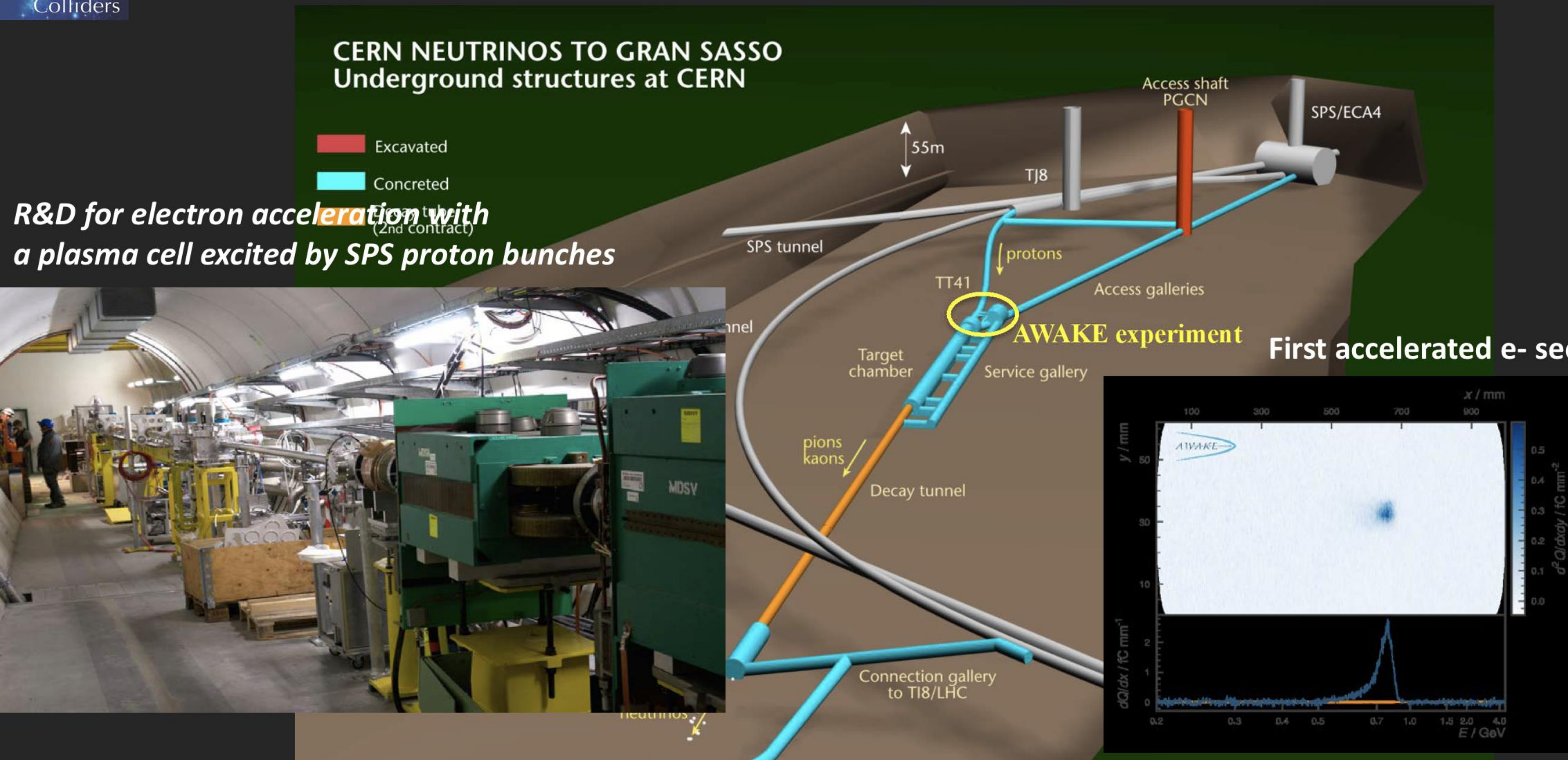
Eg: search for a Z_μ in the bremsstrahlung reaction: $\mu + Z \rightarrow \mu + Z + Z_\mu$

> Few months of data taking with muons would rule-out (confirm?) interpretation of the Z_μ as a responsible of the $(g-2)_\mu$ discrepancy

NA64++ with AWAKE

Longer timescale: NA64^{++} @ AWAKE

R&D for electron acceleration with a plasma cell excited by SPS proton bunches



First accelerated e- seen in 2018!

AWAKE could provide ~10^{16} ~30-50 GeV pulsed e's/year in the post-LS3 era to an experiment located in the CNGS decay tunnel

LDMX experiment

LDMX @ eSPS: Meyrin area

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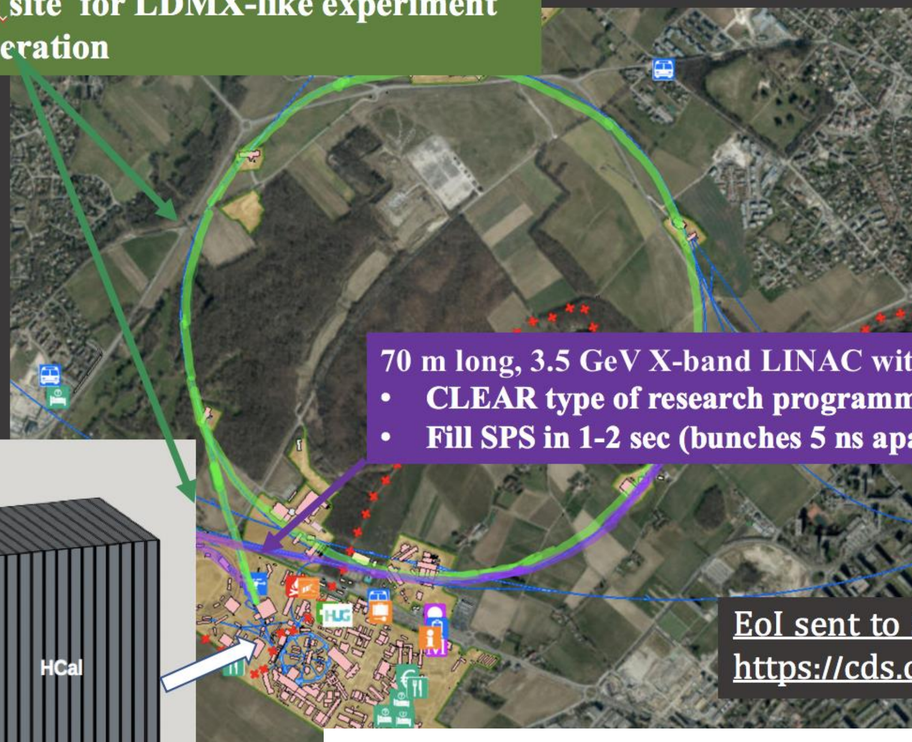
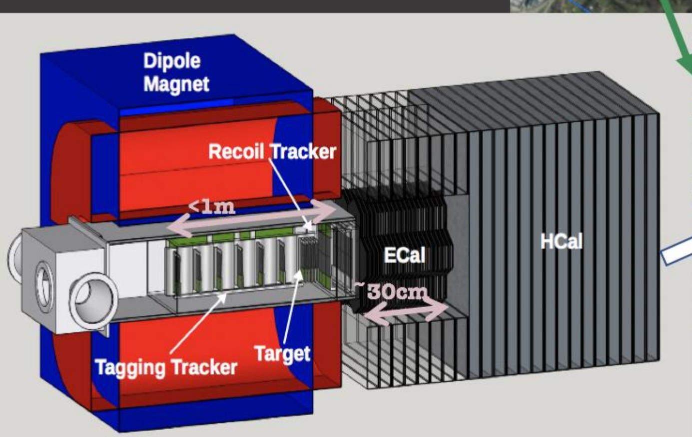
GREEN: ~16 GeV electron beam in SPS
slow extraction towards Meyrin site for LDMX-like experiment
Up to 10^{16} eot in o(1) year of operation



Electron beam impinging on target:
- multi-GeV electrons
- 1-200 MHz bunch spacing
- Ultra-low O(1-5) electrons per bunch

70 m long, 3.5 GeV X-band LINAC with excellent beam quality
- **CLEAR type of research programme.**
- **Fill SPS in 1-2 sec (bunches 5 ns apart) via TT60;**



EoI sent to SPSC in October 2018:
https://cds.cern.ch/record/2640784

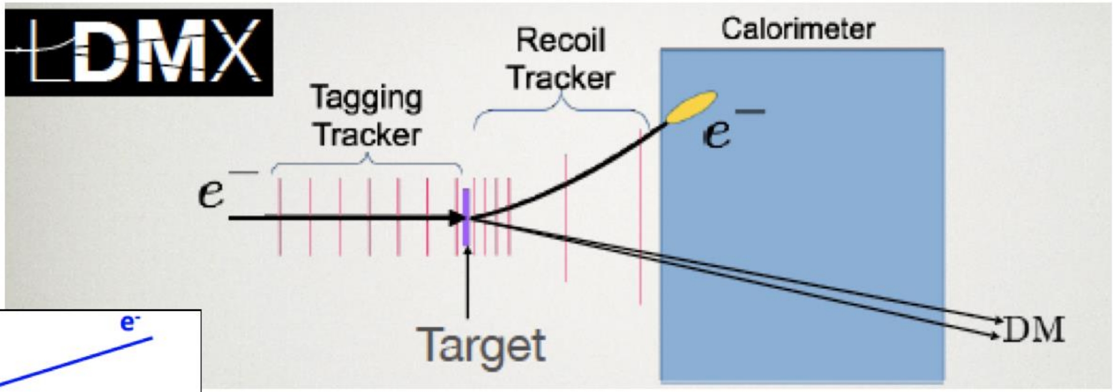
Also proposed for SLAC..

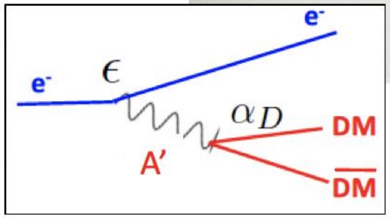
Experimental Technique

Experimental Techniques at fixed target/beam dump exps.

LDMX: Missing Momentum technique:

any discrepancy between the momentum of the electron/muon measured before and after the target would be sign of the production of some non-interacting particle, as for example Dark Matter





Project presented also at SLAC, pending approval of LCLS-II beam extraction
This would allow a faster & cheaper implementation, even if at a reduced energy (8 GeV @ SLAC versus 16 GeV @ SPS).

NA62

The NA62 experiment @ K12 in EHN3

(the "Kaon Factory")

https://na62.web.cern.ch/

NA62 currently running in K12. Main goal: measure the BR(K+ $\longrightarrow \pi\ \nu\ \nu$bar) with 10% accuracy.

NA62 current measurement : BR(K+ -> pi nu nubar) (NA62) < 14 x 10^{-10} @ 95% CL (PLB 2019)

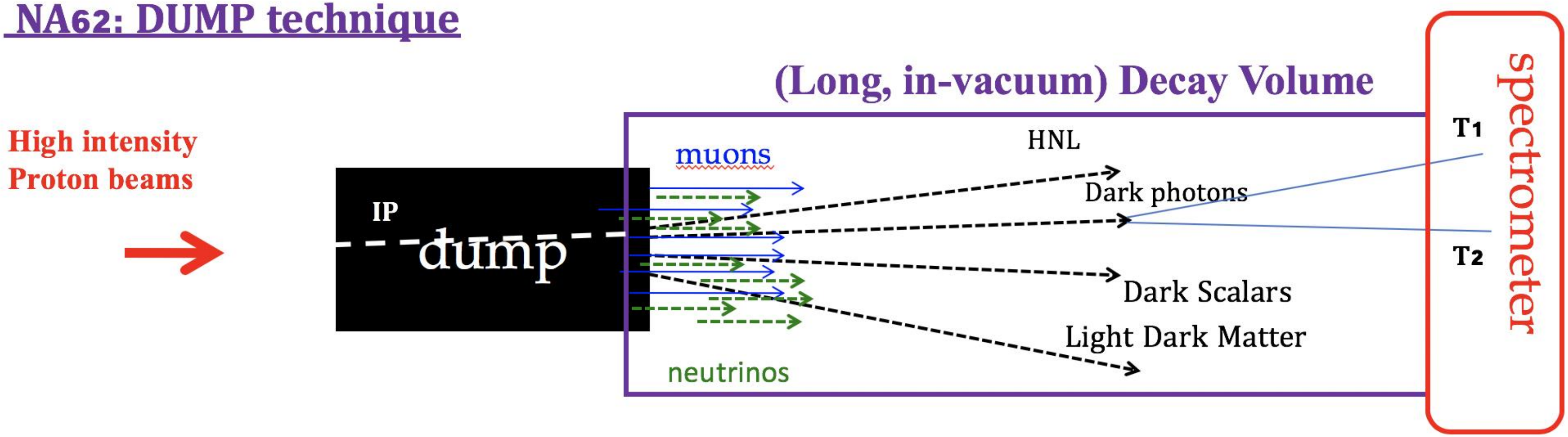
World best measurement E787/E949: $17.3\ ^{+11.5}_{-10.5}$ x 10^{-11}; Phys. Rev. Lett. 101 (2008) 191802.

SM prediction: (9.31 ± 0.76) 10^{-11} (Buras et al., 2015)

Experimental Technique

Experimental Techniques at fixed target/beam dump exps.

NA62: DUMP technique

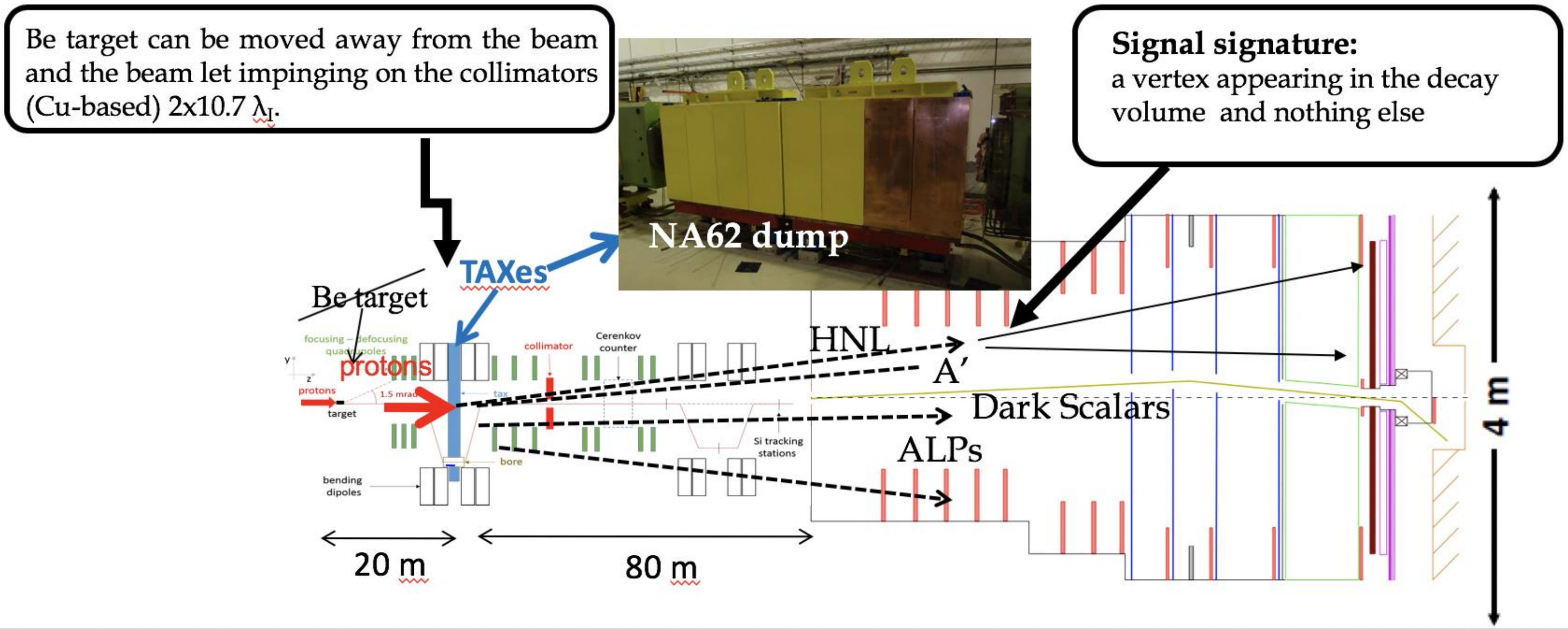


Crucial ingredients to disentangle signal from background:
timing (T1-T2) and pointing (IP)
(in addition to Veto and PID systems).

NA62 in Dump Mode

NA62 in "dump" mode

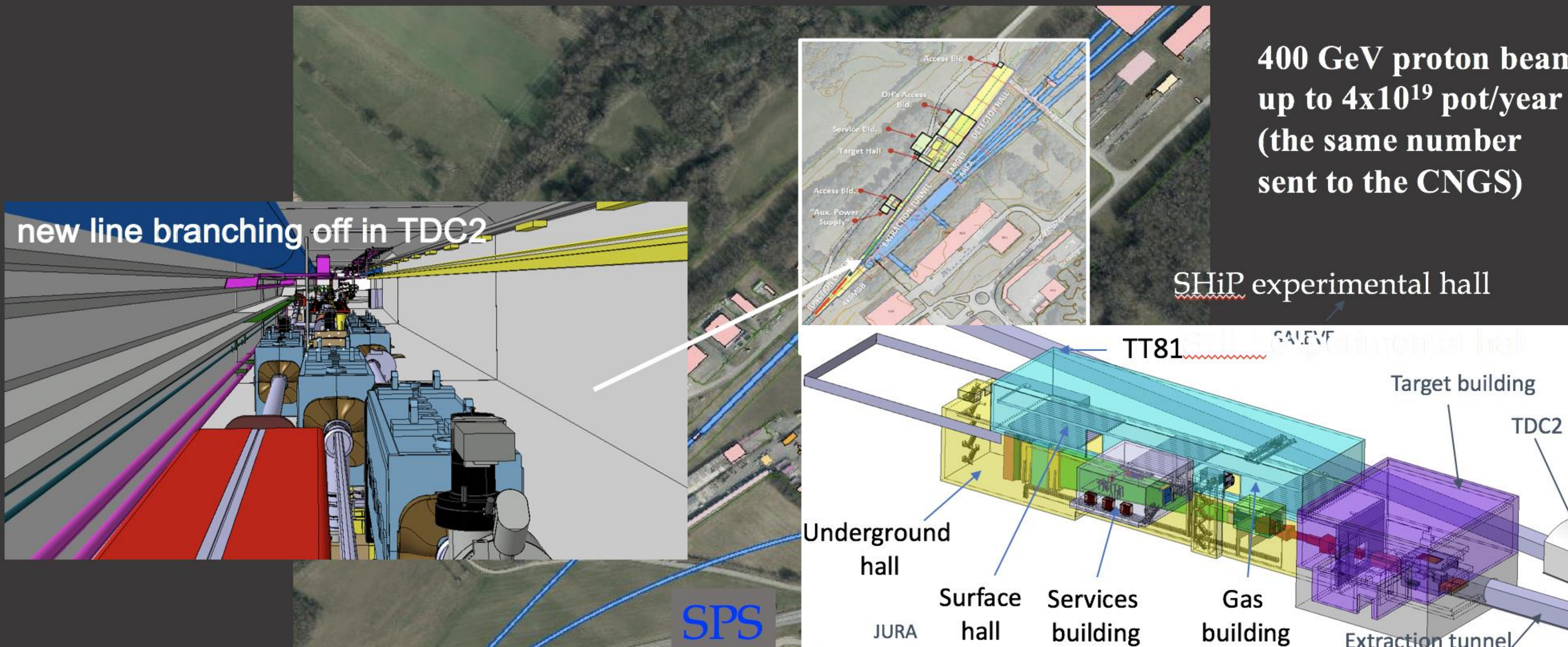
Dump mode allows NA62 to search for Hidden States above the K^+ mass.
Switch between kaon and dump mode possible within minutes.
~3x10^{16} pot collected in dump mode in 2016-2018 (~50 integrated hours of data taking)



Currently running to complete the Kaon programme, interplay with the dump under study.
To be competitive in searches above the K^+ mass, 10^{18} pot in dump-mode should be collected by Run 3.
This corresponds to 3-4 months of dedicated data taking.

Proposal for a beam dump Facility

The Beam Dump Facility (BDF) in the North Area



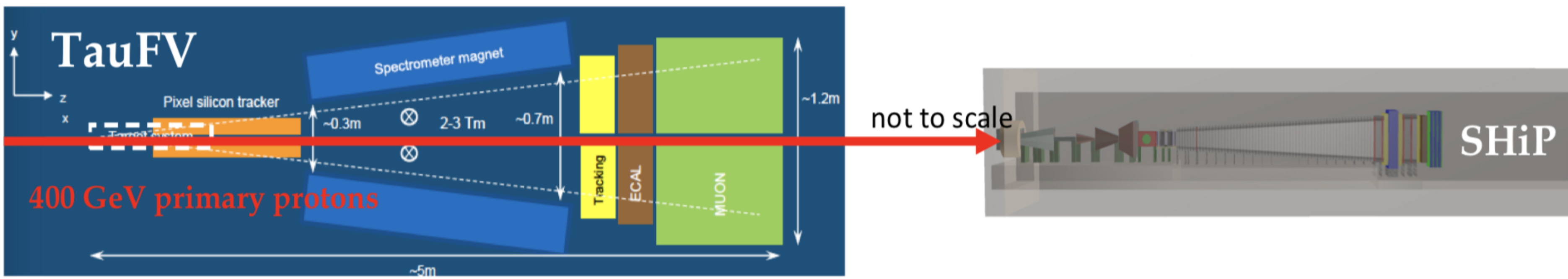
400 GeV proton beam up to 4x10^{19} pot/year (the same number sent to the CNGS)

Brand new high-intensity proton beam proposed in the North Area
Mature project: ready to be implemented if approved.

Beamp Dump Experiments TauFV

Search for NP at the multi-TeV scale: the TauFV Project

- ✓ Long-standing, and well motivated (particularly since the discovery of neutrino oscillations) program of searches for charged Lepton Flavour Violation.
- ✓ Study of tau LFV decays very timely: complement the quest for new physics in other cLFV modes, as mu2e @ FNAL and MEG/mu3e @ PSI.
- ✓ Located into the BDF line upstream of SHiP. Use ~**2%** of protons hitting on (probably) a wire target to study LFV decays of tau leptons.

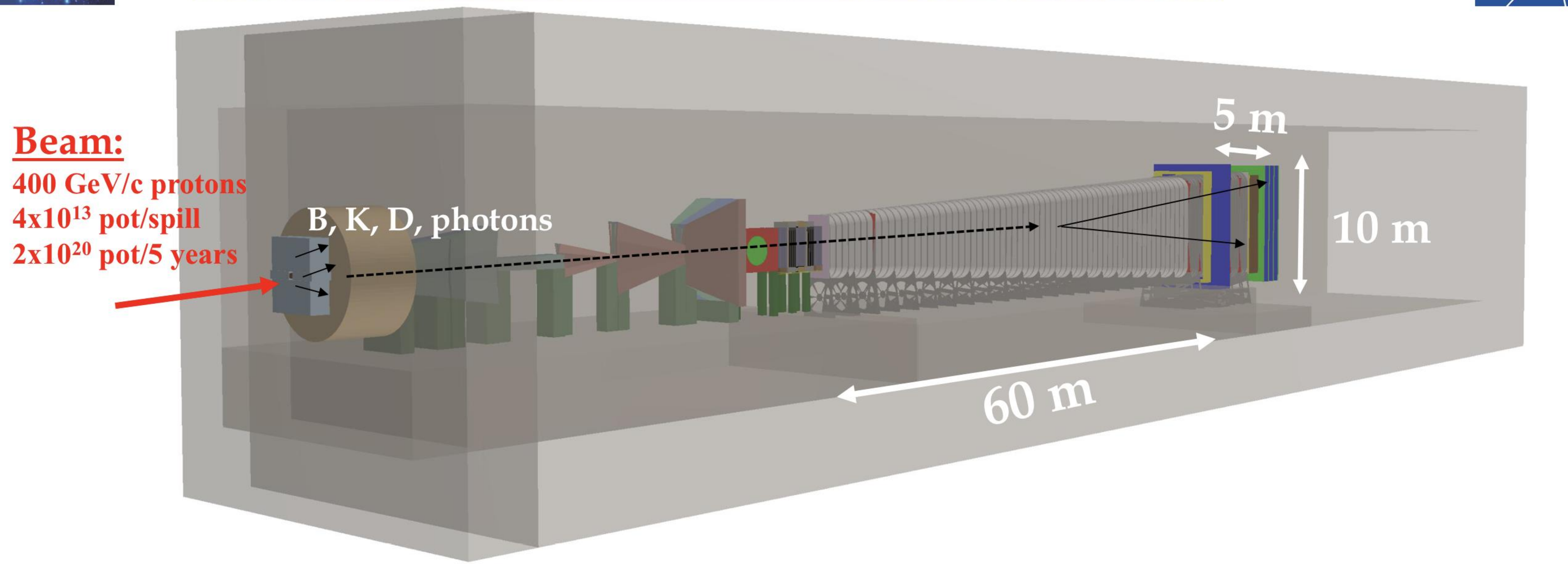


Profit of the higher signal yield than at any other facility:
Eg: $\tau \longrightarrow \mu\mu\mu$ yield assuming a BR ~ 10^{-9}

Future experiment	Yield	Extrapolated from
TauFV (4 x 10^{18} PoT)	8000	Numbers on this slide
Belle II (50 ab^{-1})	9	PLB 687 (2010) 139
LHCb Upgrade I (50 fb^{-1})	140	JHEP 02 (2015) 121
LHCb Upgrade II (300 fb^{-1})	840	ditto

SHiP: Search for Hidden Particles

SHiP experiment @ BDF

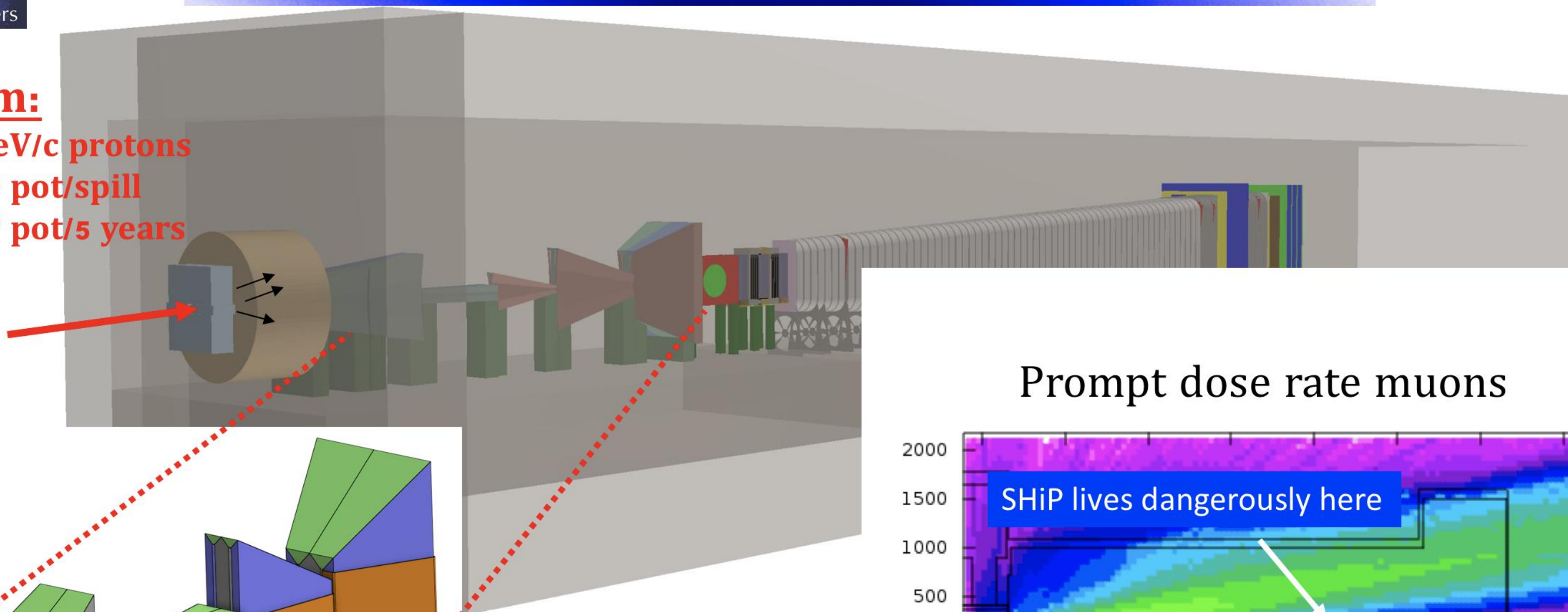


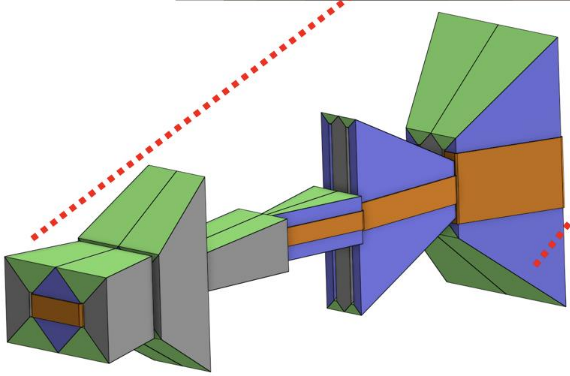
- ✓ Hidden particles have very feeble couplings, hence they are (very) long-lived:
  - The 60m-long, in-vacuum SHiP decay volume allows us to be sensitive to extremely low couplings
- ✓ Hidden particles from D and B decays have large p_T:
  - SHiP large geometrical acceptance maximizes detection of decay products

SHiP: the Active Muon Shield

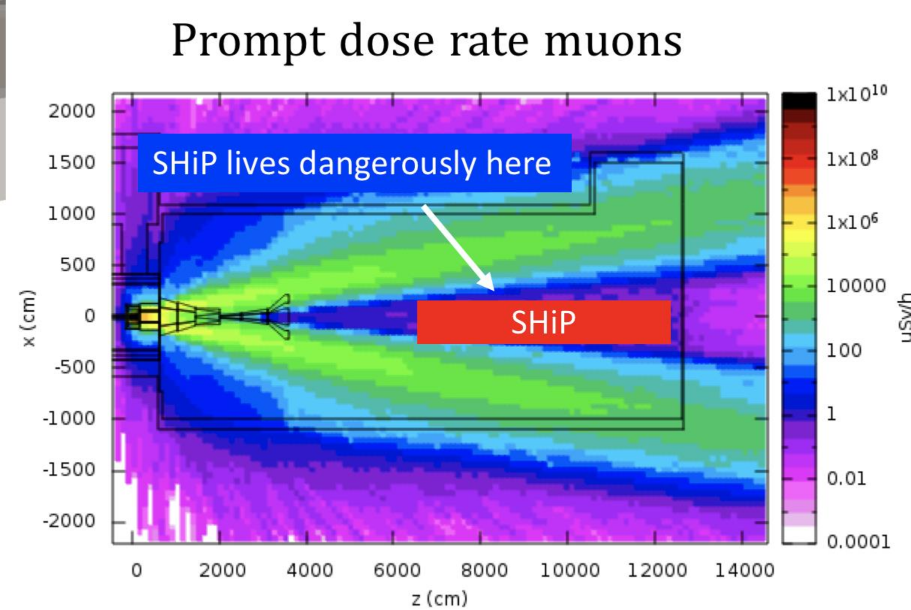
SHiP @ BDF: Active Muon Shield

Beam:
400 GeV/c protons
4×10^{13} pot/spill
2×10^{20} pot/5 years



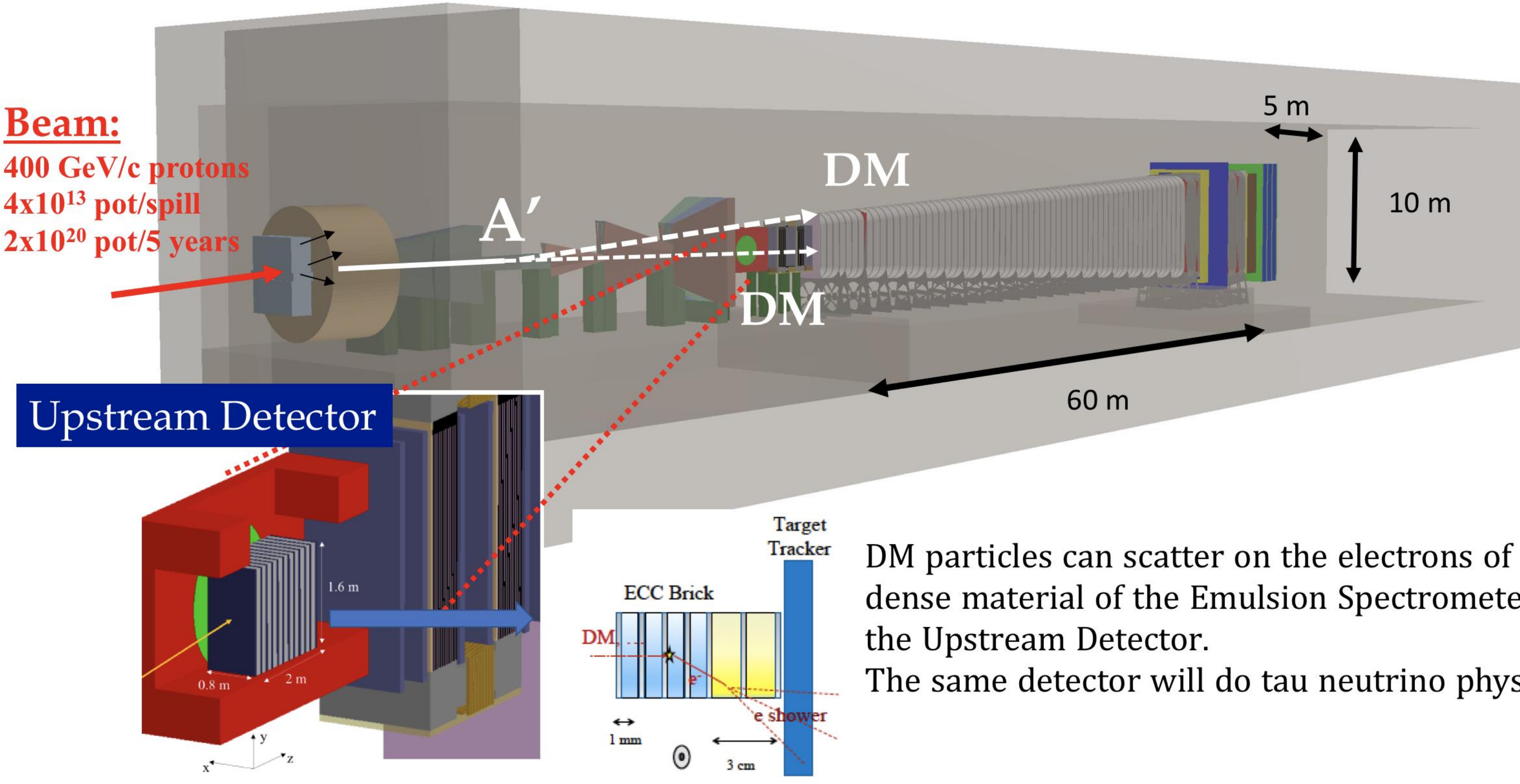


Active Muon Shield:
40 m long, 1400 t of magnets,
sweeps out muons emerging from the target.



SHiP: Direct Light Dark Matter Detection

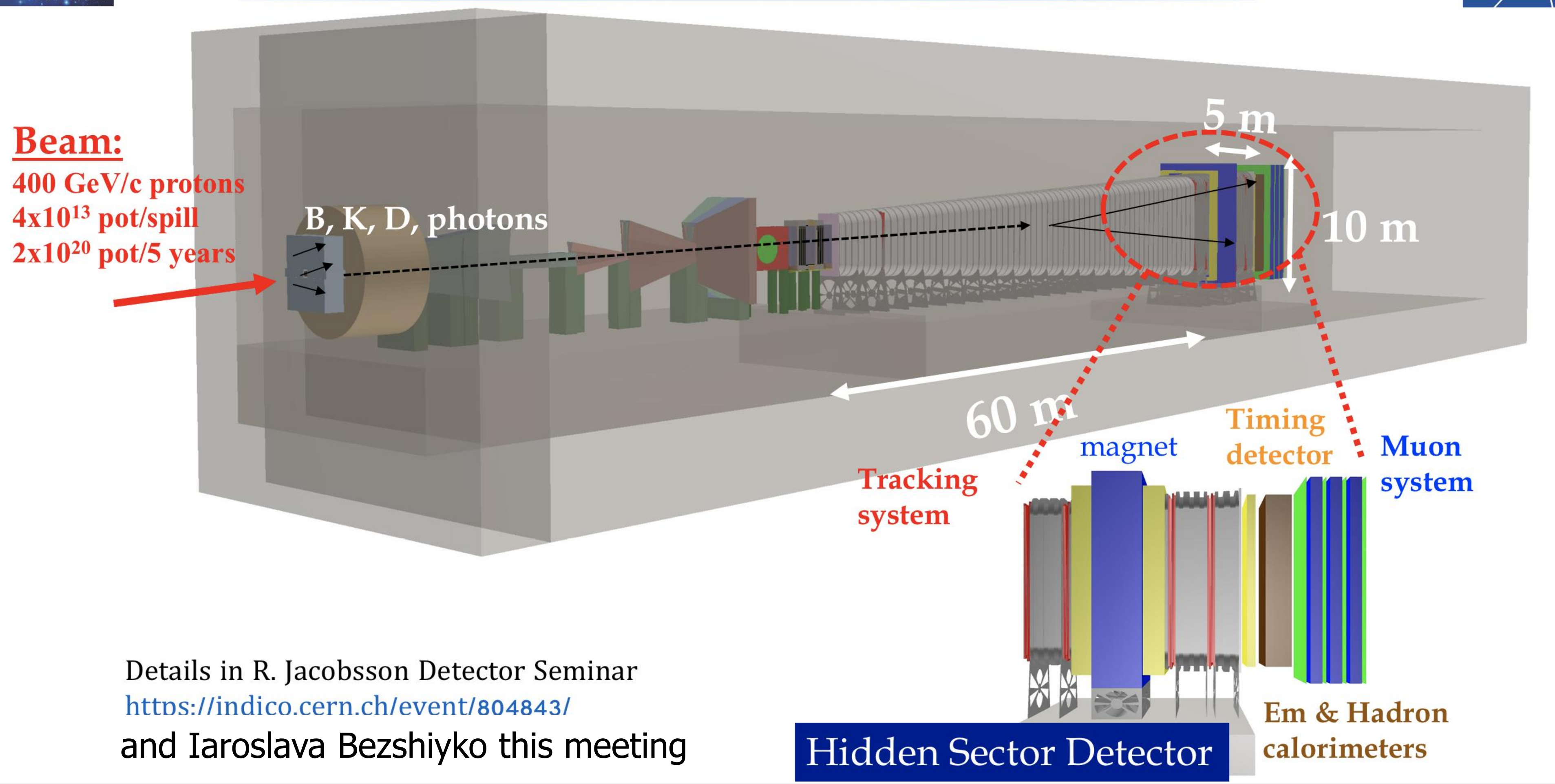
SHiP @ BDF: Light Dark Matter direct detection



DM particles can scatter on the electrons of the dense material of the Emulsion Spectrometer in the Upstream Detector.
The same detector will do tau neutrino physics.

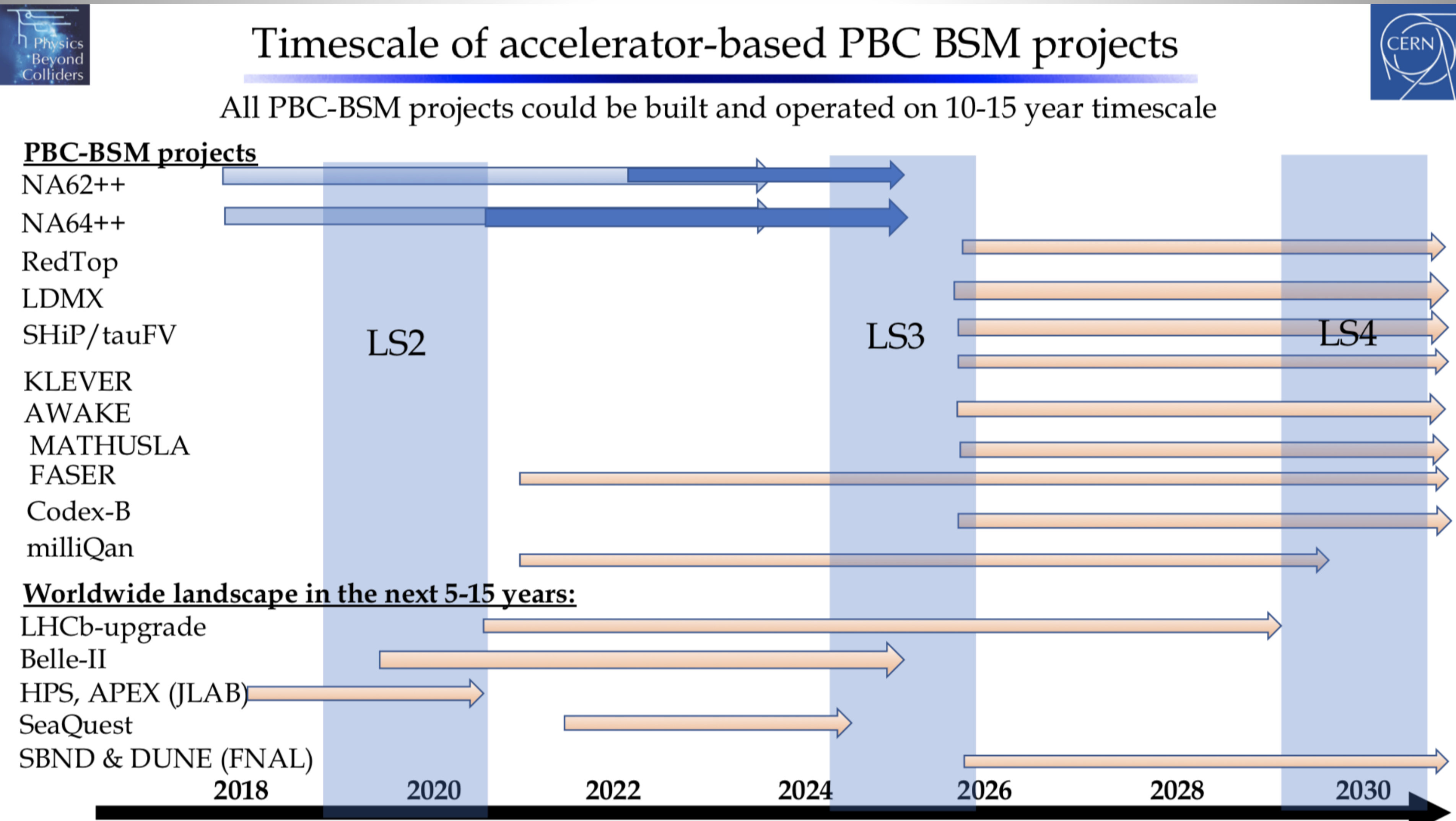
SHiP: Hidden Sector Search

SHiP @ BDF: Hidden Sector Spectrometer



Details in R. Jacobsson Detector Seminar
https://indico.cern.ch/event/804843/
and Iaroslava Bezshiyko this meeting

PBC BSM Experiments Timeline



Physics Targets

PBC-BSM: physics targets in the sub-eV and MeV-GeV ranges

HNLs, LDM & Light mediators, ALPs must be SM singlets, hence options limited by SM gauge invariance:
According to generic quantum field theory, the lowest dimension canonical operators are the most important:

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\delta_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$
Sterile Neutrino, N	$y_N L H N$

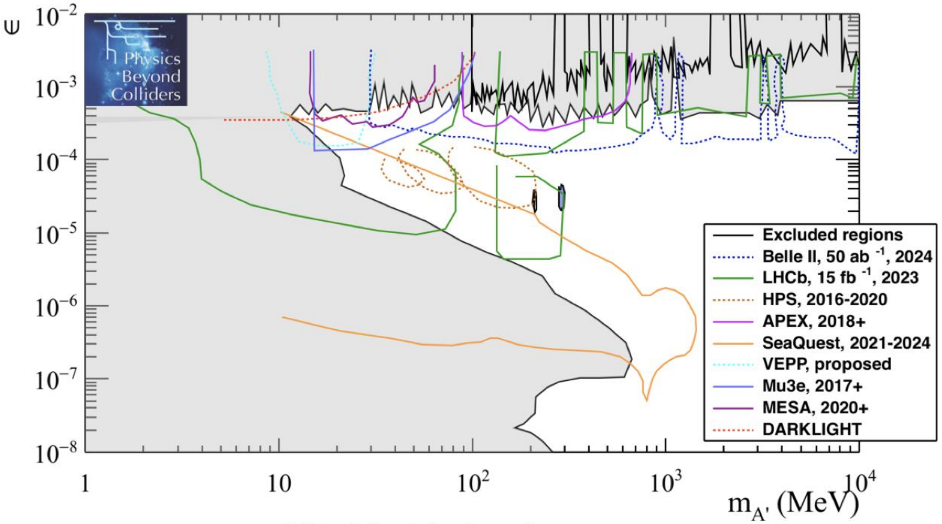
This is the set of the simplest fields and renormalizable interactions that can be added to the SM to answer the three fundamental questions: DM nature, neutrino masses and oscillations, baryogenesis

The PBC BSM WG has identified 11 benchmark cases used to evaluate the experimental sensitivities
A common ground to compare the proposals against each other and put them in worldwide context

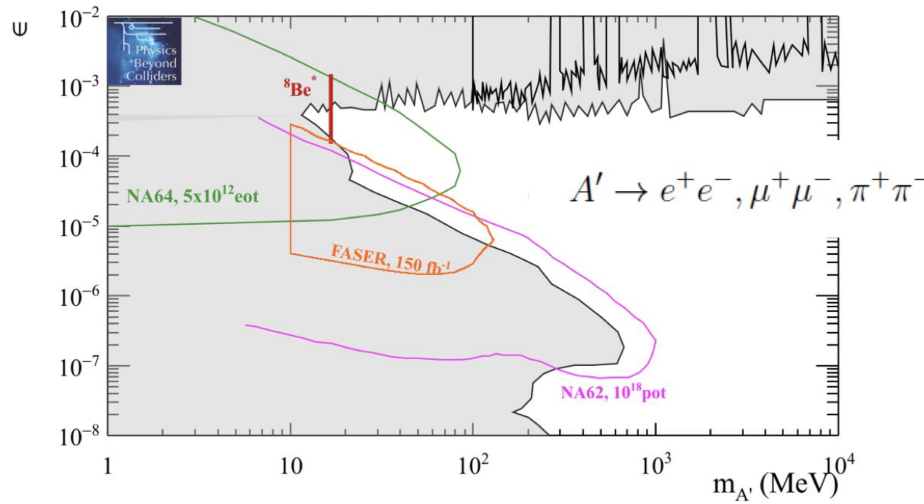
Vector Portals

Vector Portal: Dark Photon coupled to SM particles

Model where minimally coupled viable (WIMP-like) dark matter model can be constructed.
DM is charged under a broken $U(1)_D$ abelian gauge symmetry.
The parameter space for this model is $\{\alpha_D, \varepsilon, m_{A'}, m_\chi\}$.



Worldwide landscape



CERN: <u>5 years outlook</u>

NA62-dump competes with with FASER, SeaQuest, and LHCb;
NA64++(e) competes with LHCb Upgrade & JLAB experiments

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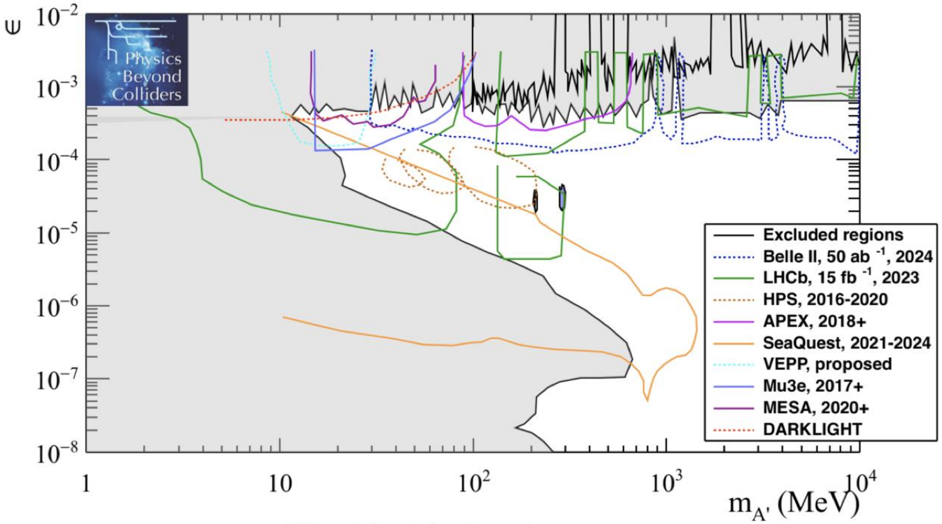
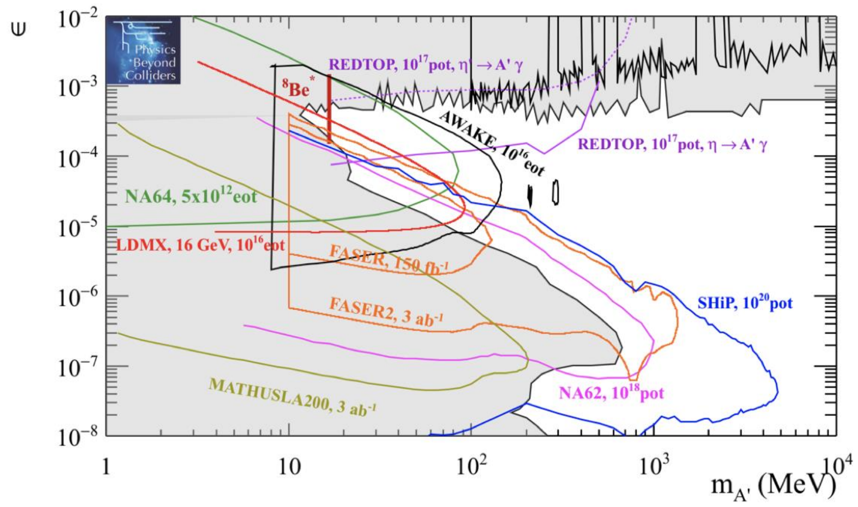


Worldwide landscape



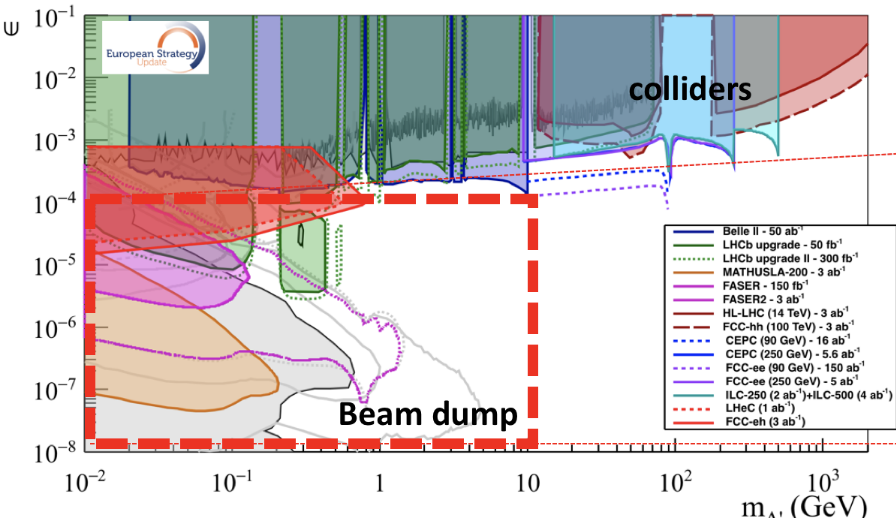
CERN: 10-15 years outlook

SHiP is world-leading in the MeV-GeV range with extremely low couplings ($\mathcal{E} \sim 10^{-5}$ - 10^{-8})

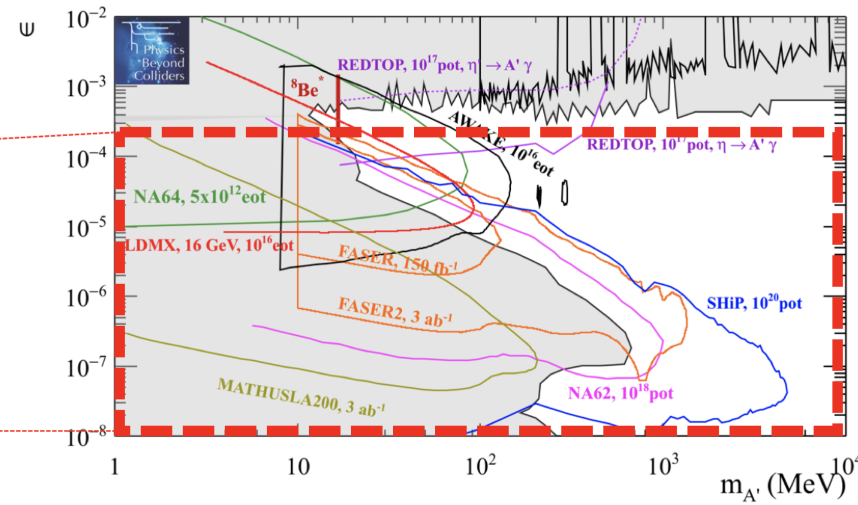
Vector Portals

Vector Portal: Dark Photon coupled to SM particles

Model where minimally coupled viable (WIMP-like) dark matter model can be constructed.
DM is charged under a broken $U(1)_D$ abelian gauge symmetry.
The parameter space for this model is $\{\alpha_D, \varepsilon, m_{A'}, m_\chi\}$.



Current & future colliders



CERN: 10-15 years outlook

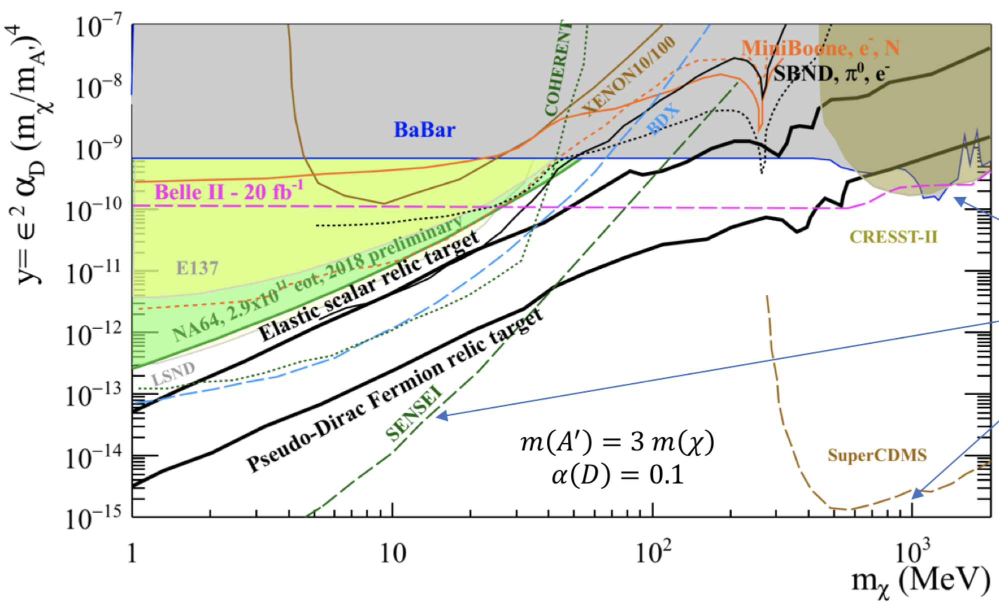
Nice complementarity between beam-dump and collider experiments
Beam-dump experiments have unique physics reach in the MeV-GeV region, very low couplings.

Vector Portals

Vector Portal: Dark Photon coupled to Dark Matter

Light Dark Matter in the MeV-GeV range

$$A' \to \chi\chi$$



Light DM direct detection experiments

Worldwide landscape in the MeV-GeV range

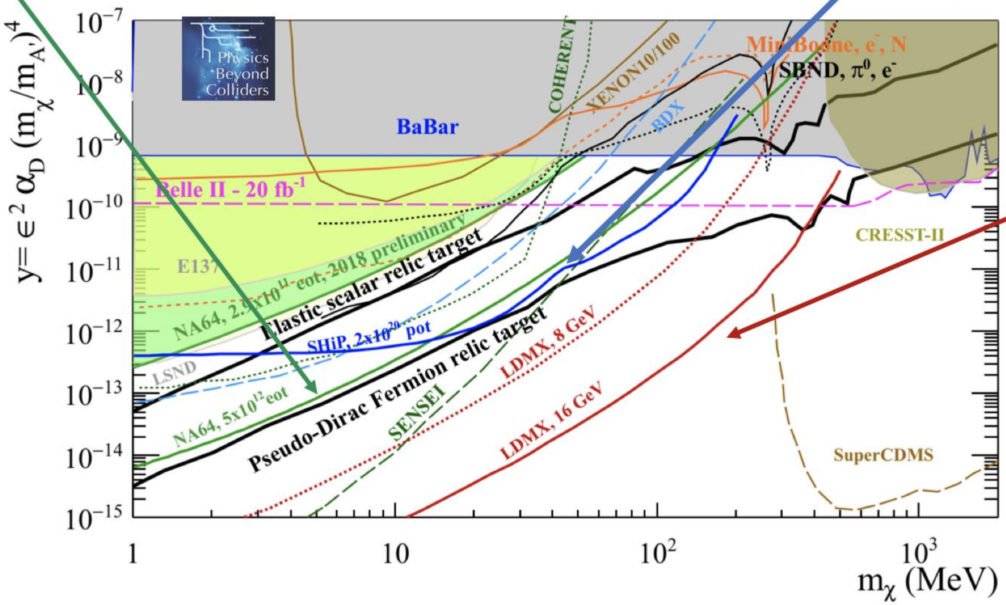
Vector Portals

Vector Portal: Dark Photon coupled to Dark Matter

Light Dark Matter in the MeV-GeV range: PBC projects

Unique **NA64++(e)** short term opportunity to explore relevant DM parameter space.

Complemented by **SHiP** with a totally different technique. Important cross-check in case of hint.



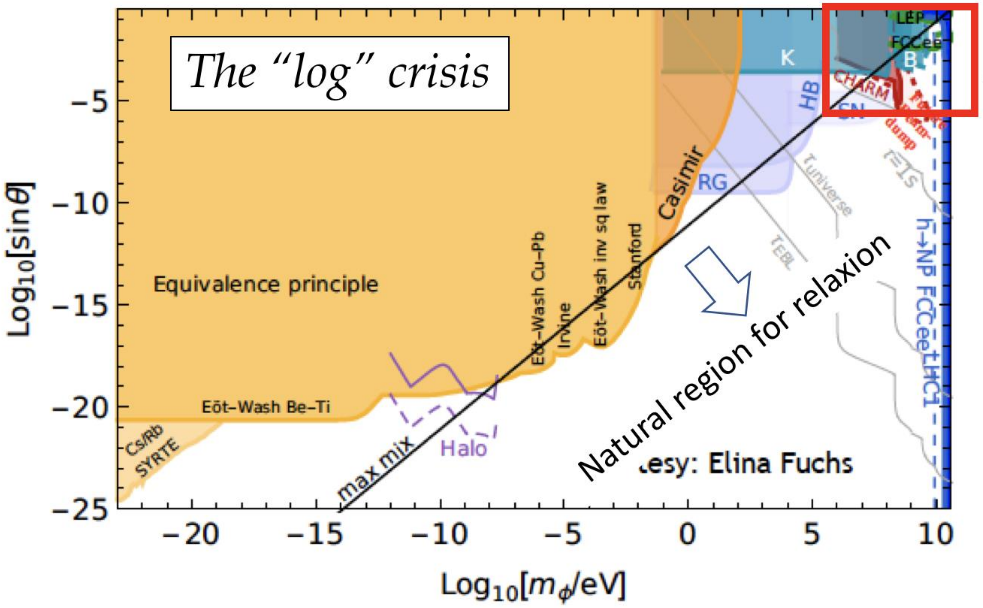
Significant higher reach of **LDMX@eSPS** to be put in regard with possible (faster&cheaper) implementation at SLAC (pending approval of the LCLS-II beam extraction)

Synergy between accelerator-based and direct detection experiments.
(important for cross-check in case of hint)

Scalar Portals

Scalar Portal: physics motivations

Relaxion: light feeble goldstone boson, with both CP-even and CP-odd couplings with the Higgs, may stabilize the Higgs mass against radiative corrections and provide baryogenesis.
Generic light scalar could also be light mediator between SM and LDM, in case of secluded annihilation.



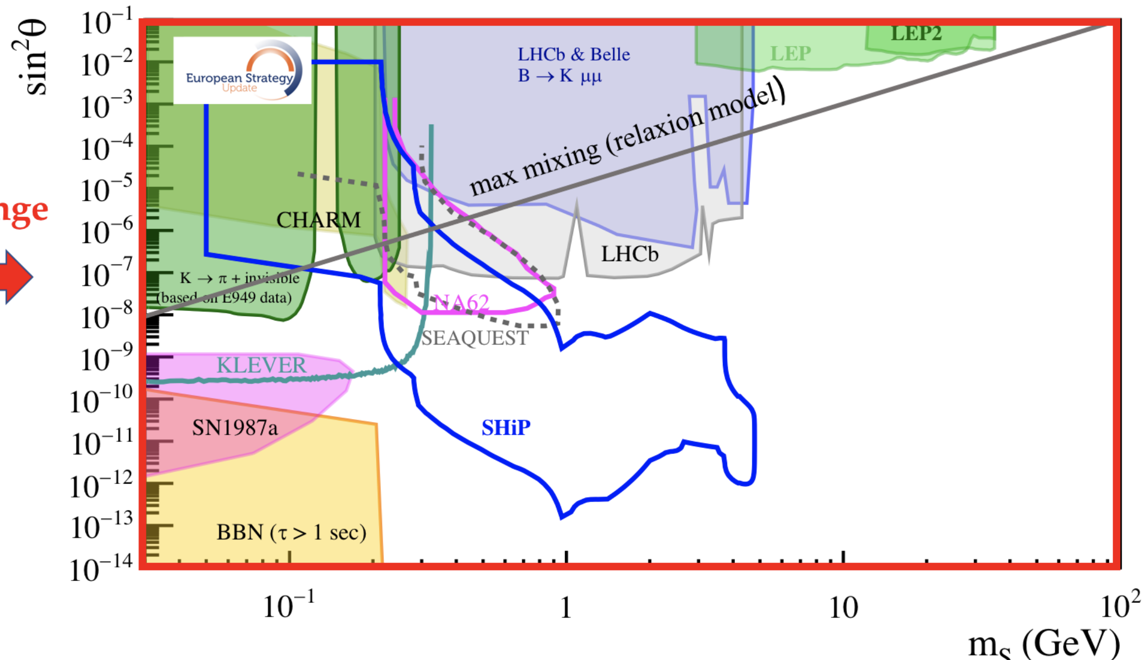
MeV-100 GeV range is accessible at accelerators' based experiments

Scalar Portals

Scalar Portal: Dark Scalar coupled to the Higgs

Existing limits and projections for future beam dump and fixed target experiments.

Zoom in the MeV-100 GeV range

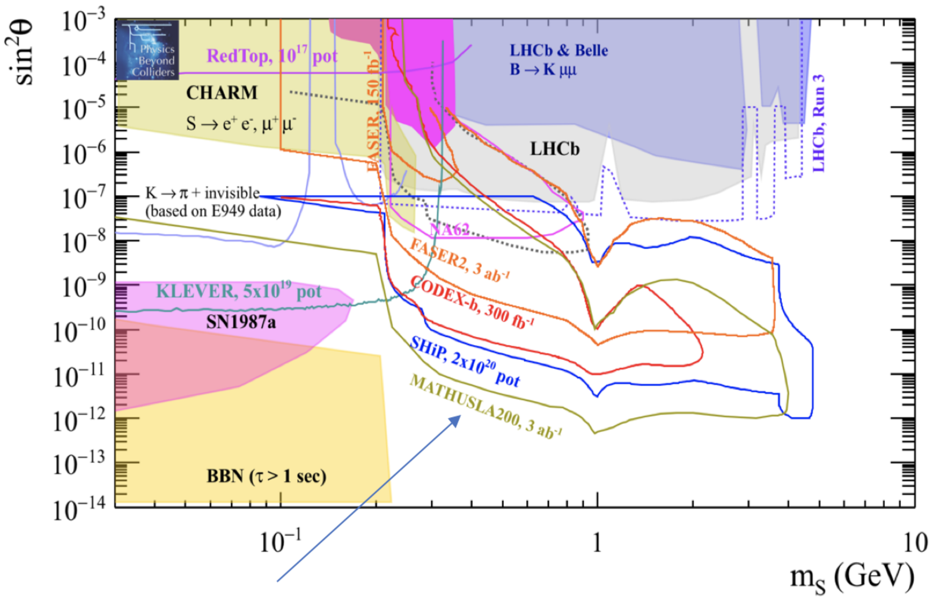


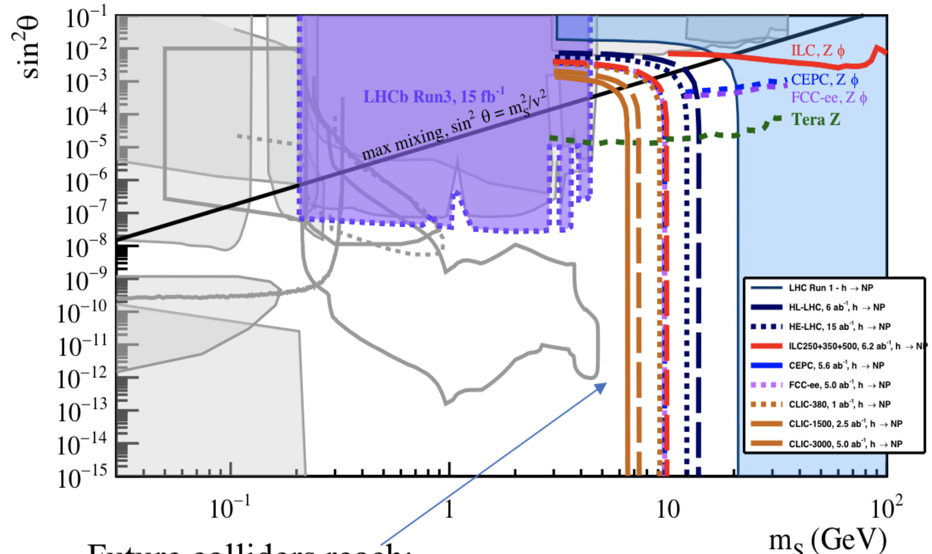
Source:
Physics Beyond Colliders BSM report, arXiv:1901.09966.

NA62 competes with SeaQuest.
SHiP will probe a large mass region below 5 GeV extending the explored range by several orders of magnitude

Scalar Portals

Scalar Portal: Dark Scalar coupled to the Higgs





<u>MATHUSLA</u> physics reach similar to SHiP (but also similar cost). For $\lambda \neq 0$ MATHUSLA sensitive to Dark Scalars up to m(Higgs)/2.

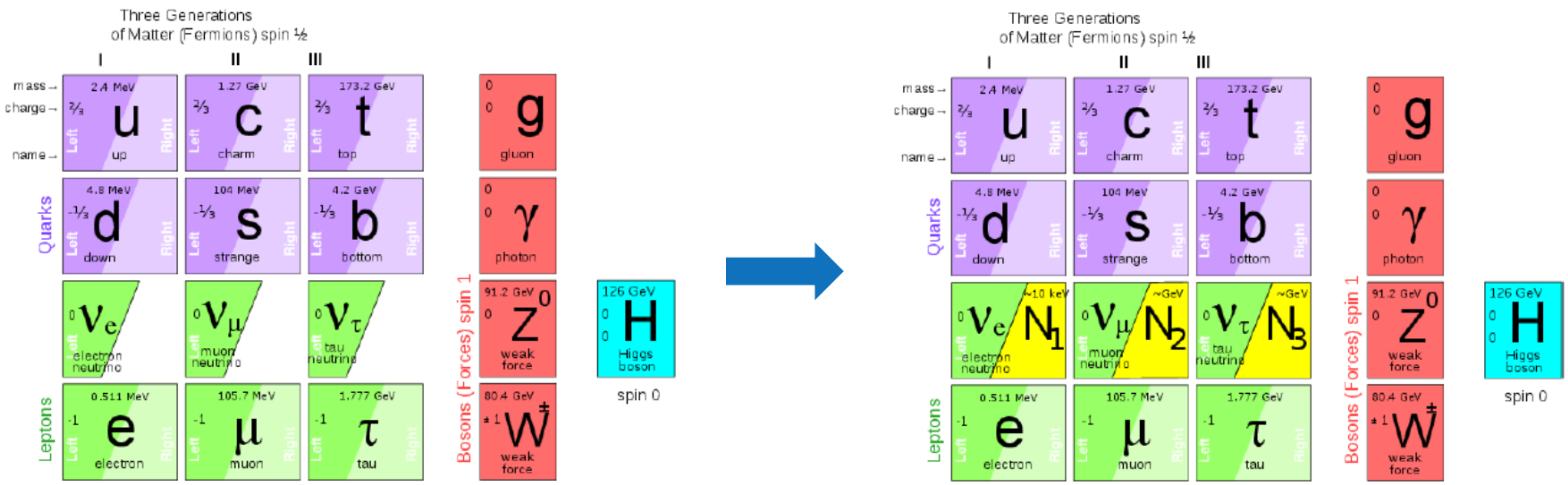
<u>Future colliders reach:</u>
Indirect limits from fit of Higgs width and Higgs BRs (model dependent):

$$\Gamma_h^{tot} = \cos^2\theta\, \Gamma_h^{tot,SM} + \Gamma_h^{NP} \quad \Gamma_h^{NP} = \Gamma(h \to \phi\phi)$$

Nice complementarity between beam-dump, astrophysics boundaries and colliders. Together they can explore a large fraction of the “natural” relaxion region.

Example Scenario

Neutrino portal: νMSM (Neutrino Minimal Standard Model)
Minimal extension of the SM fermion sector by three Right Handed (Majorana) Heavy Neutral Leptons (HNL): N1, N2, N3.



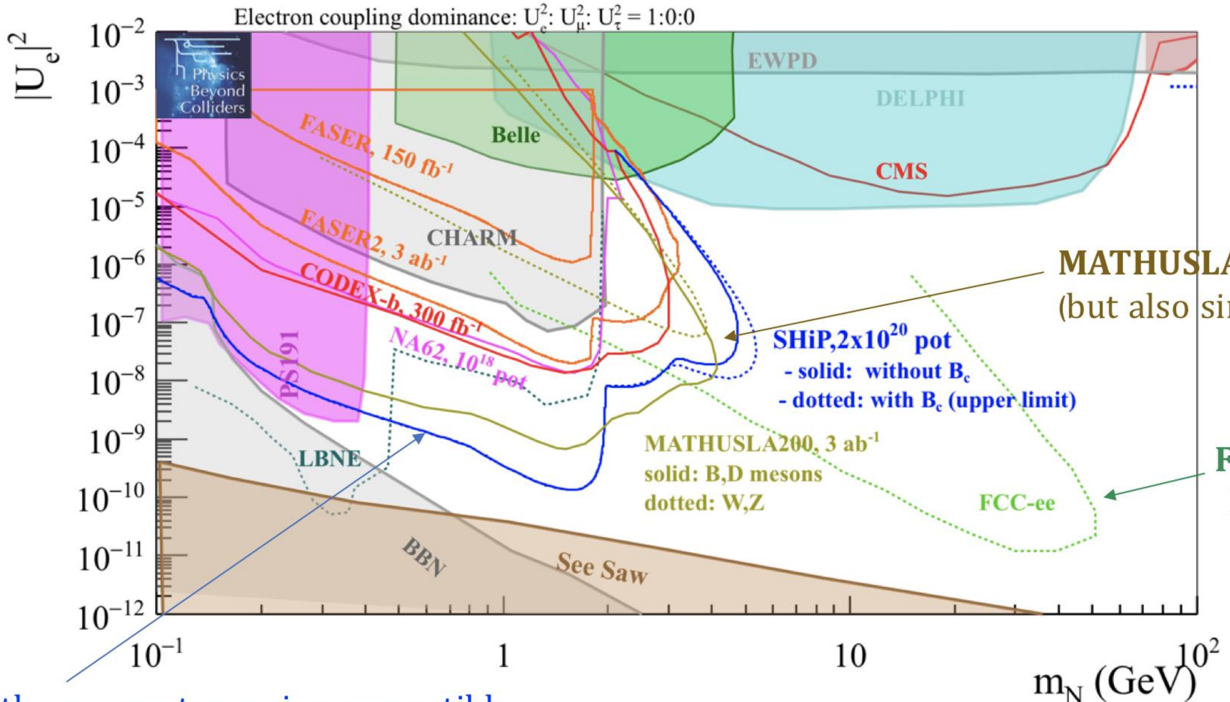
-The lightest singlet N_1 (mass ≈ KeV): good dark matter candidate.
-N_2, N_3 (mass in 100 MeV - GeV region):
- Mechanism to give masses to neutrinos
- Explain baryon asymmetry

D.Gorbunov, M.Shaposhnikov JHEP 0710 (2007) 015

Neutrino Portals

Fermion Portal: Heavy Neutral Leptons below/around EW scale

Current limits and projections for beam dumps (and other) experiments



MATHUSLA has similar reach (but also similar cost)

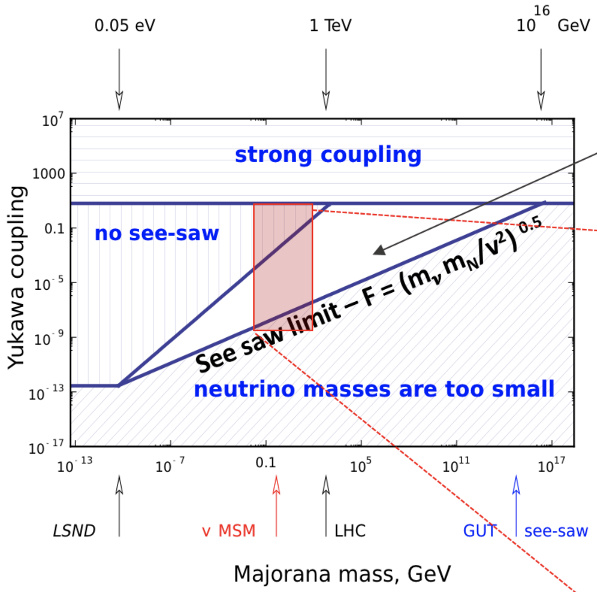
FCC-ee will lead in the high mass range with the Tera-Z option

SHiP can explore the parameter region compatible with leptogenesis down to the see-saw limit.

Neutrino Portals

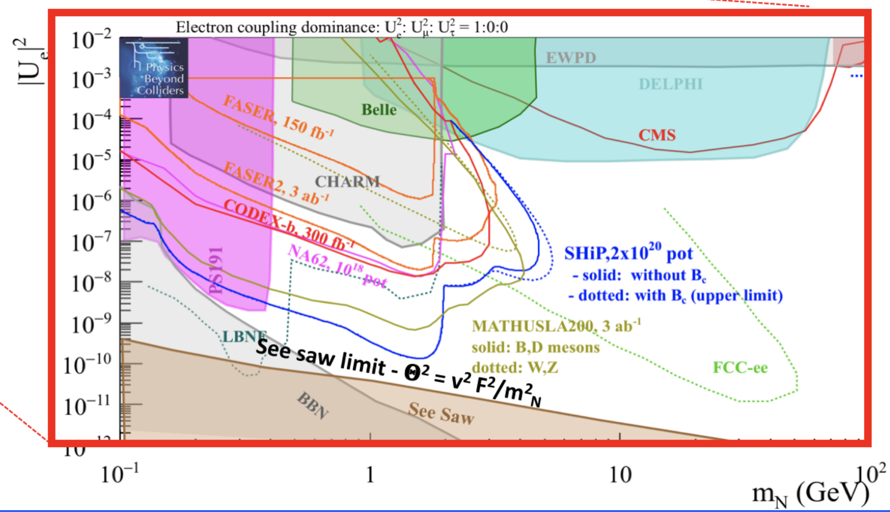
II. Majorana Neutrino (type I see-saw)

Origin of the neutrino masses and oscillations



Back to the initial plot:

SU(2)xU(1)$_L$ singlet Right Handed Neutrinos responsible of the neutrinos' mass generation can have any coupling/mass in the white area, assuming an approximate U(1)$_L$ global symmetry.



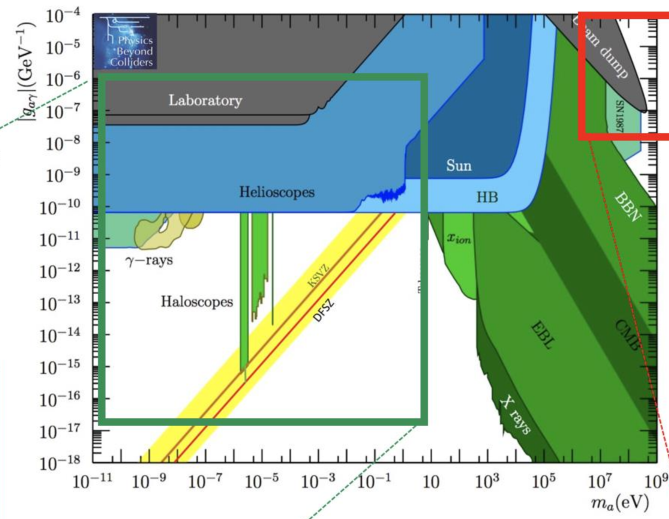
With beam dump and future colliders's experiments we can explore (light) RHN in the mass range 0.1-90 GeV compatible with leptogenesis almost down to the see-saw limit.

Axion-like Particles

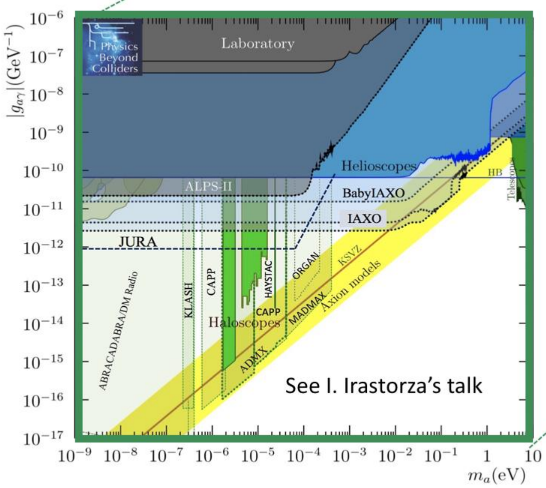
European Strategy Update

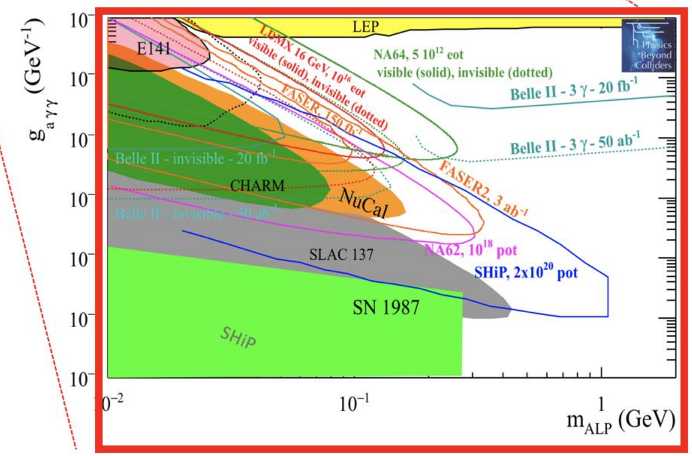
Pseudo-Scalar portal: ALPs with photon coupling

sub-eV range accessible at helioscopes and haloscopes



MeV- GeV range accessible at beam-dump experiments





Nice complementarity of accelerator-based experiments, experiments in the sub-eV range, and cosmological bounds

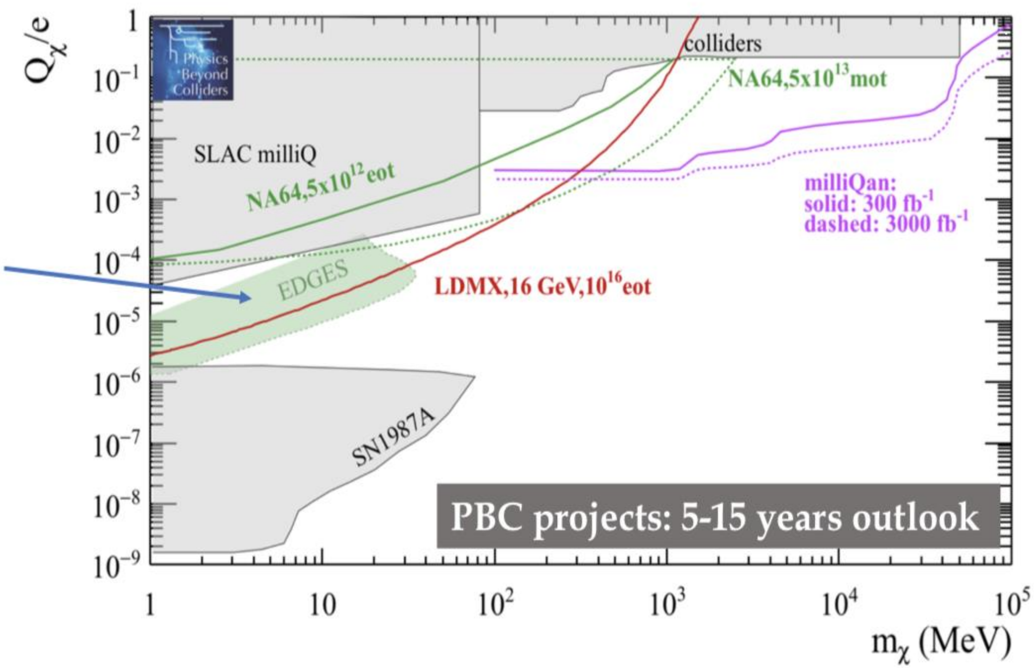
Millicharged Searches

Milli-charged particles (Benchmark #3)

Milli-charged particles can be seen as a specific limit of the vector portal when $m_{A'}$ goes to zero and the parameter space simplifies to the mass (m_χ) and effective charge ($|Q| = |\varepsilon g_D e|$) of milli-charged particles.

The unexpected strength of 21 cm line anomaly signal measured by the EDGES radio-telescope could be naturally explained if (even only a fraction of) DM is in form of milliQ particles.

CERN-PBC-REPORT-2018-007



Nice complementarity with colliders and astrophysical data

Project Status

PBC-BSM projects: current status of evaluation of backgrounds and other experimental effects

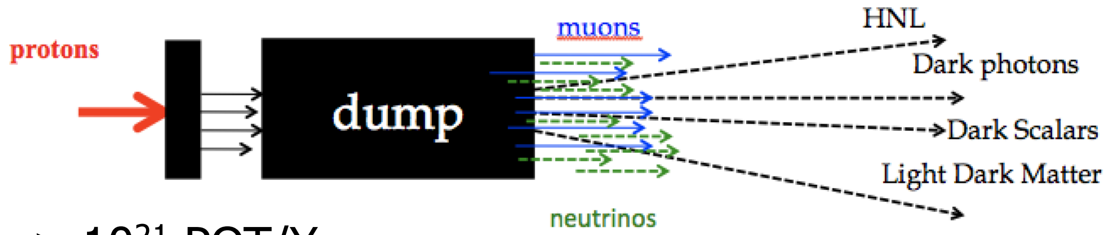
Proposal	Background	Efficiency	Based on
at the PS:			
RedTop	included	included	full simulation
at the SPS:			
KLEVER	$K_L \to \pi^0 \nu \overline{\nu}$, $K_L \to \pi^0 \pi^0$ bkgs included	included	Main backgrounds and efficiencies evaluated with fast simulation and partly validated with the full (NA62-based) Monte Carlo
LDMX	background included	included	full Geant4 simulation for 4 GeV beam
$NA62^{++}$	zero background proven for fully reconstructed final states	partially included	analysis of $\sim 3 \cdot 10^{16}$ pot in dump mode
$NA64^{++}(e)$	included	included	background, efficiencies evaluated from data
$NA64^{++}(\mu)$	in progress	in progress	test of the purity of the M2 line with COMPASS setup
$NA64^{++}(K_{S,L}, \eta, \eta')$	to be done	to be done	–
AWAKE/NA64	to be done	to be done	–
SHiP	zero background	included	Full Geant4 simulation, digitization and reconstruction $\nu-$ interactions based on 2×10^{20} pot $\mu-$ combinatorial and $\mu-$ interactions based on $\sim 10^{12}$ pot measurement of the muon flux at H4 performed in July 2018
at the LHC:			
CODEX-b	zero background assumed (preliminary GEANT simulation)	not included	Evaluation of background in progress with full MC
FASER	zero background assumed	not included	Fluka simulation and in-situ measurements
MATHUSLA200	zero background assumed	not included	FLUKA, Pythia and MadGraph simulation for $\nu-$, $\mu-$ fluxes from the LHC IP and cosmic rays background.
MilliQan	included	included	full Geant4 simulation of the detector

Just a starting point of a long way.

Not all experiment at the same level of detail yet

More Beam Dump Experiments

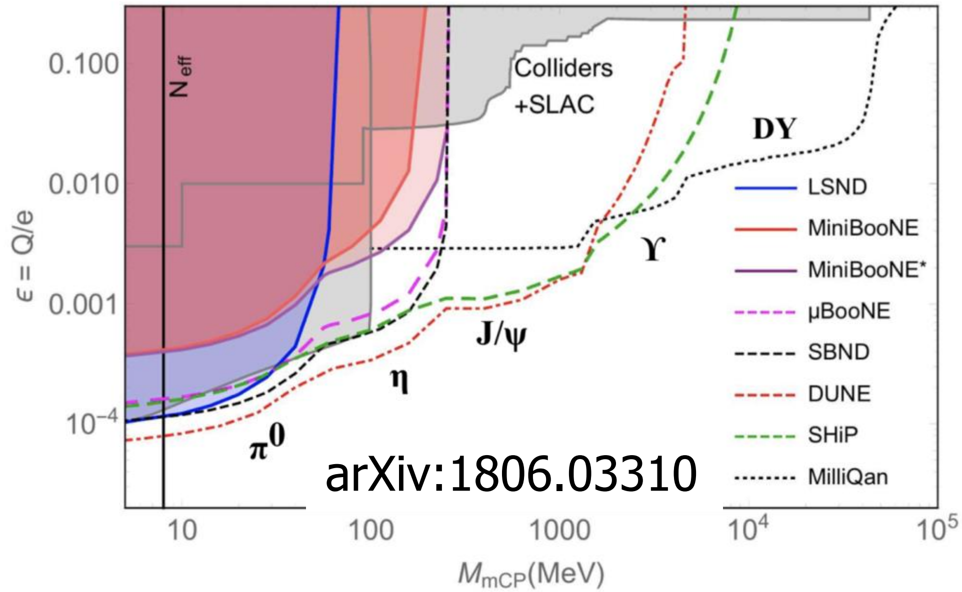
High intensity frontier for low mass particles with very weak couplings
->upcoming neutrino experiments (SBL, LBL) foresee very high intensity beams



> 10^{21} POT/Year

Near Detector: few 100m away from the dump

https://indico.fnal.gov/event/18430/



arXiv:1806.03310

These experiments can perform searches for low mass New Physics particles eg

-HNL/sterile neutrinos
-dark photons
-ALPs
-mini/millicharges
...

<- Example for millicharges
FerMINI @FNAL?

Physics Beyond Colliders Summary

Physics Beyond Colliders

CERN

Conclusions

- The target of the PBC-BSM activity is a broad, rich and compelling physics programme which addresses the open questions of particle physics in a complementary way to the LHC, HL-LHC, FCC and other initiatives in the world (e.g. DM direct detection, astrophysical data, experiments at JLAB, FNAL).
- This program aims at exploiting the unique CERN scientific infrastructure and accelerator complex on a 5-15 year timescale.
- A large and lively community with several different scientific proposals is growing at CERN and now is starting to speak a common language, to collaborate and to work in a coherent way.
- The experimental collaborations are backed by a very active theory community and the PBC has served as fertile ground where models have been developed, discussed, and improved.
- A preliminary set of comparative plots, based on theoretically and phenomenologically motivated models, shows the scientific potential and the impact that CERN could have on the international landscape in the next o(10-15) years in the quest for New Physics .
- The projects presented in the PBC-BSM framework could be a very attractive option while preparing the next big machine.