

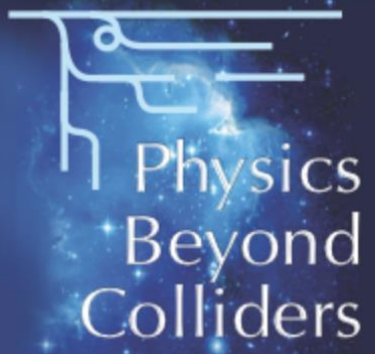
# ***BSM Physics with Beam Dump Experiments: Future options***

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Antwerp University Belgium  
UC-Davis California USA  
NTU, Singapore

13<sup>th</sup> April 2019



# CERN: Beam Dump Experiment



## Physics Beyond Colliders Annual Workshop

CERN is the home of the LHC

Strong interest in general in BSM physics in particular for Long-Lived particles

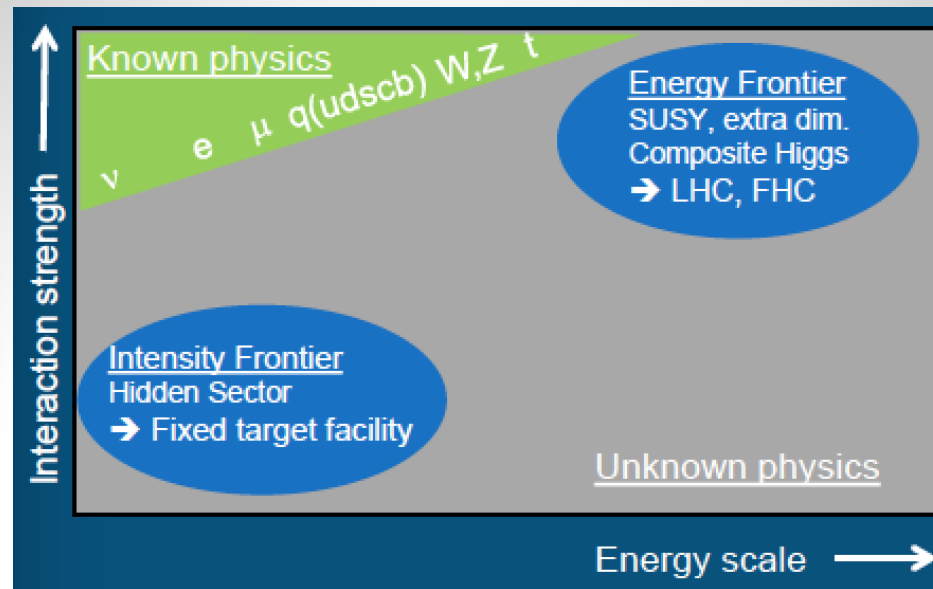
Since 2 years CERN is also investigating how to use it's accelerator park for searches to **BSM physics in the low mass-low coupling sector.**

Some of these projects make use of a beam dump set-up.

**A study was launched in 2016** to prepare for the European Strategy Meeting

**The best known of these proposals for new experiments is SHIP**

# 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](http://pbc.web.cern.ch)

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

# 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.

The success of the LHC is proof of effectiveness of the **European organisational model for particle physics, founded on the sustained long-term commitment of the CERN Member States** and of the national institutes, laboratories and universities closely collaborating with CERN. *Europe should preserve this model in order to keep its leading role, sustaining the success of particle physics and the benefits it brings to the wider society.*

Europe's **top priority** should be the **exploitation of the full potential of the LHC**, including the **high-luminosity upgrade** of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.

→ HL-LHC approved by Council 2016

CERN should undertake **design studies** for accelerator projects in a global context, **with emphasis on proton-proton and electron-positron high-energy frontier machines**. These design studies should be coupled to a **vigorous accelerator R&D programme ...**

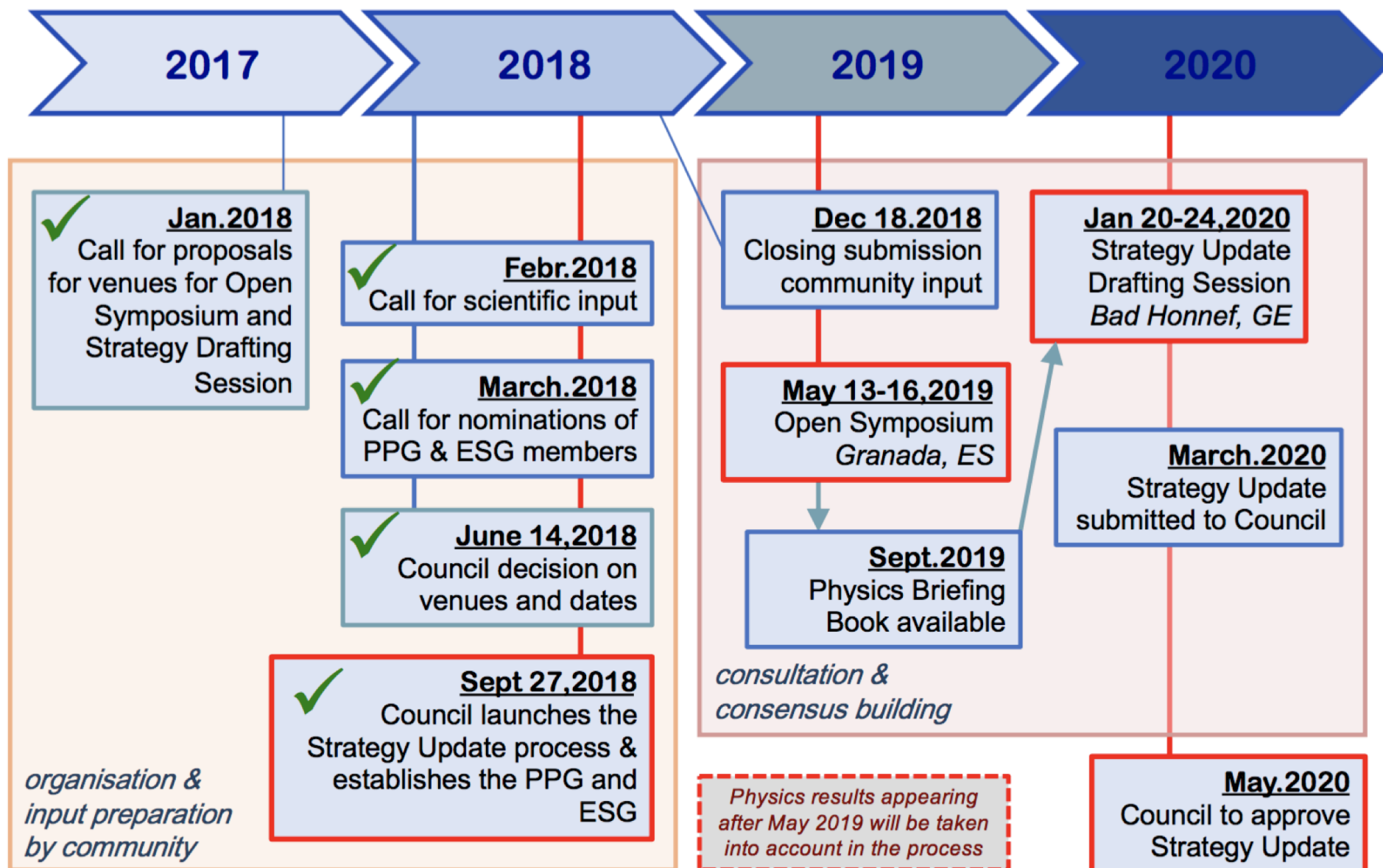
→ Continuation of CLIC, FCC started 2014

CERN should develop a **neutrino programme to pave the way for a substantial European role in future long-baseline experiments**. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

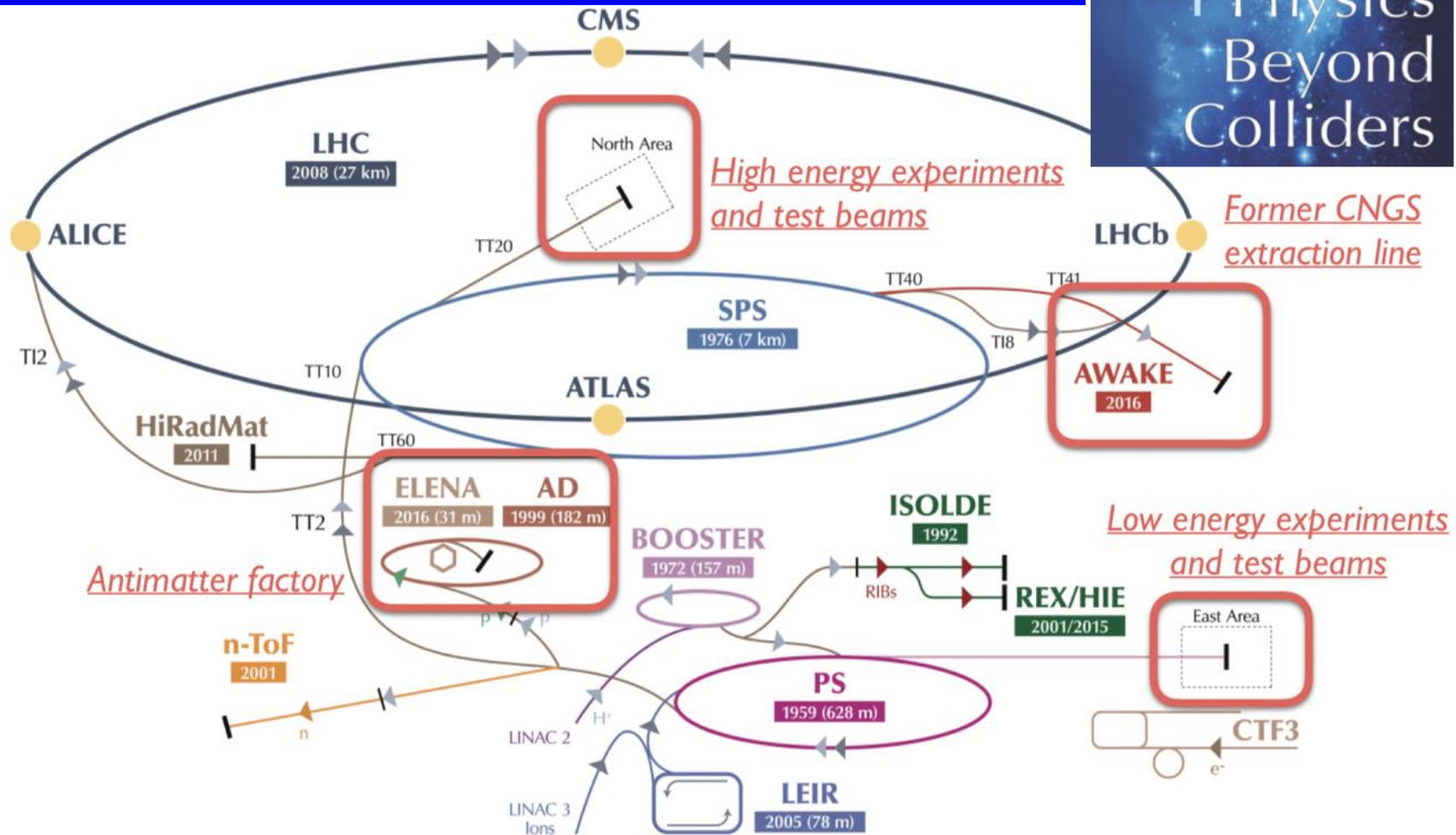
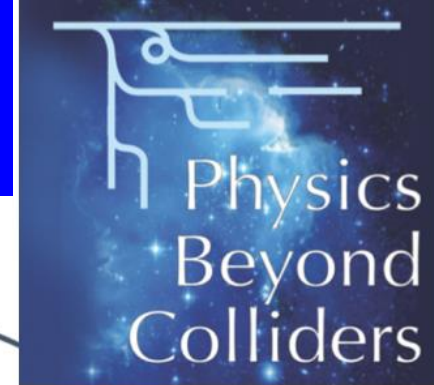
→ Neutrino Platform started 2014

CERN, together with national funding agencies, institutes, laboratories and universities, should continue supporting and further develop **coordinated programmes of education and training**.

# 2020 ESPP update: timeline and committees



# CERN: Intensity Frontier



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 Collider Events

## PBC EVENTS IN THE PAST 2 YEARS

**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**

Status of studies for PBC deliverables

**3<sup>rd</sup> 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. Russo

+ ext. experts + projects representatives:

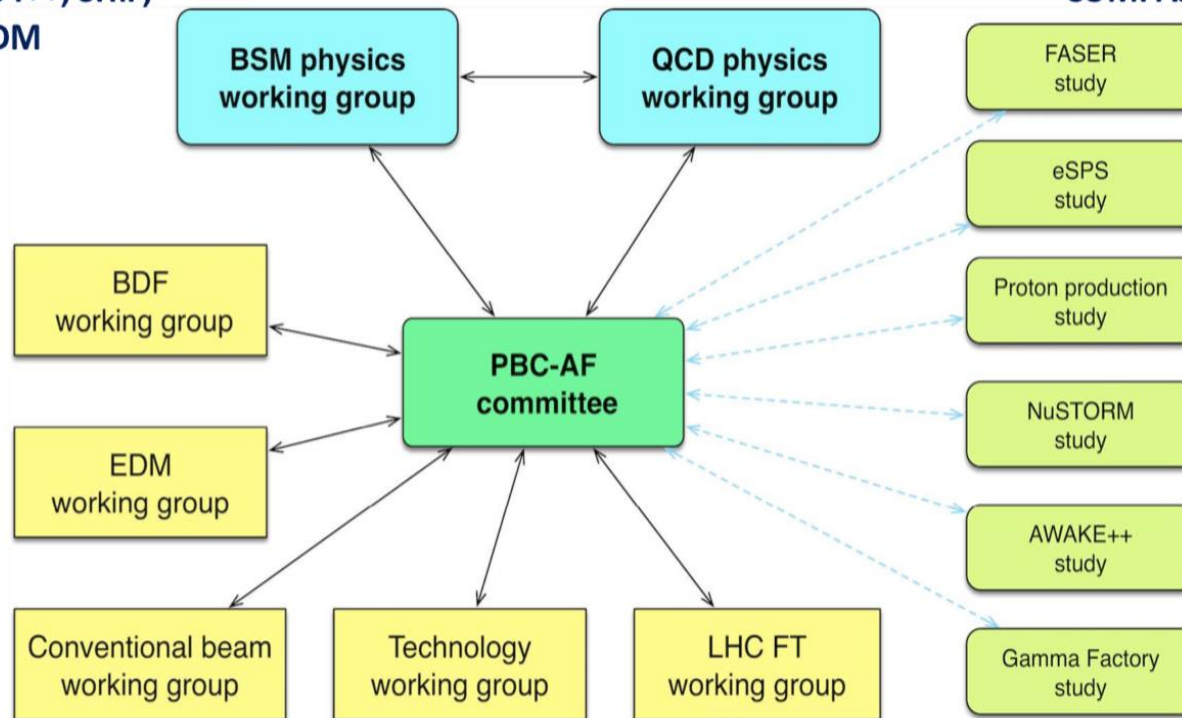
NA62++, KLEVER, NA64++, SHiP,  
LDMX, IAXO, JURA, EDM

QCD conveners: M. Diehl, J. Pawlowski, G. Schnell

+ ext. experts + projects representatives:

COMPASS++, MUonE, DIRAC++

AFTER, CRYSTAL,  
LHCb-FT, ALICE-FT  
NA61++, NA60++



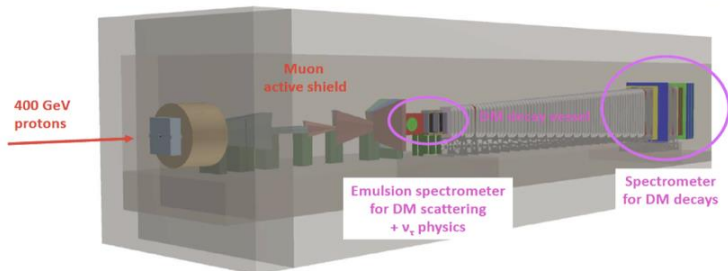
**~100 core members in the Working Groups**  
**> 200 WG meetings in the past 2 years**

# SHiP



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

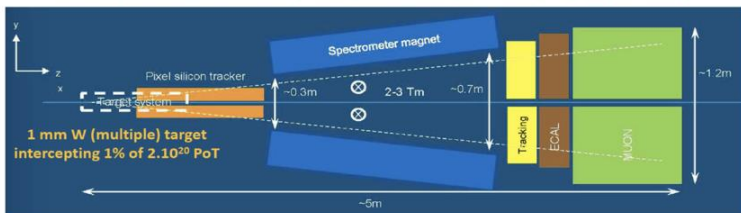
Similar layout as NA62, with larger acceptance to reach the  $c/b$  mass range



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 ( $> \text{BELLE-II reach}$ )



Implementation layout upstream of BDF target under study

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

## AWAKE

CERN NEUTRINOS TO GRAN SASSO Underground structures at CERN

AWAKE

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



First accelerated  $e^-$  seen in 2018!

Could provide  $\sim 10^{15}$   $\sim 30$  GeV pulsed  $e^-$ 's/year in the post-LS3 era to an experiment located in the CNGS decay tunnel

## Examples of Beyond Collider Studies

## More than 20 proposed projects

# NA64



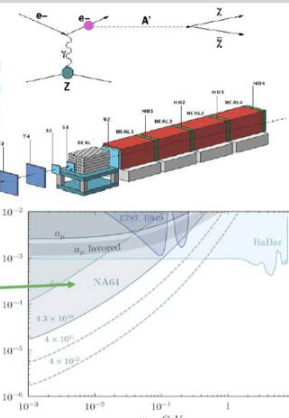
Hidden sector search from invisible decays with missing energy

Implemented in 2016 on  $e^-$  test beam

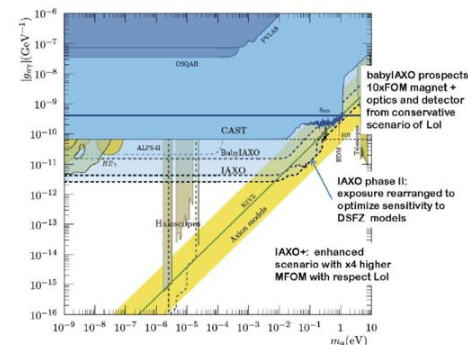
Fast analysis excluding  $(g-2)_\mu$  interpretation confirms the potential of the method

AFTER LS2:

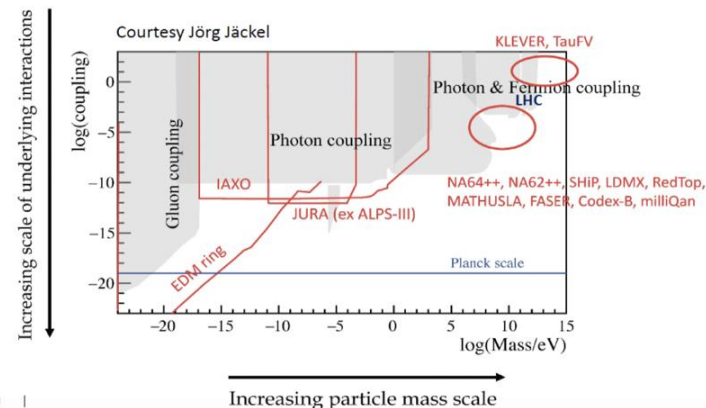
Wish to extend the method to higher  $e^-$  intensity and  $\mu^-/\pi^-/K^-/p^-$  beams



## IAXO - next generation Axion helioscope beyond CAST

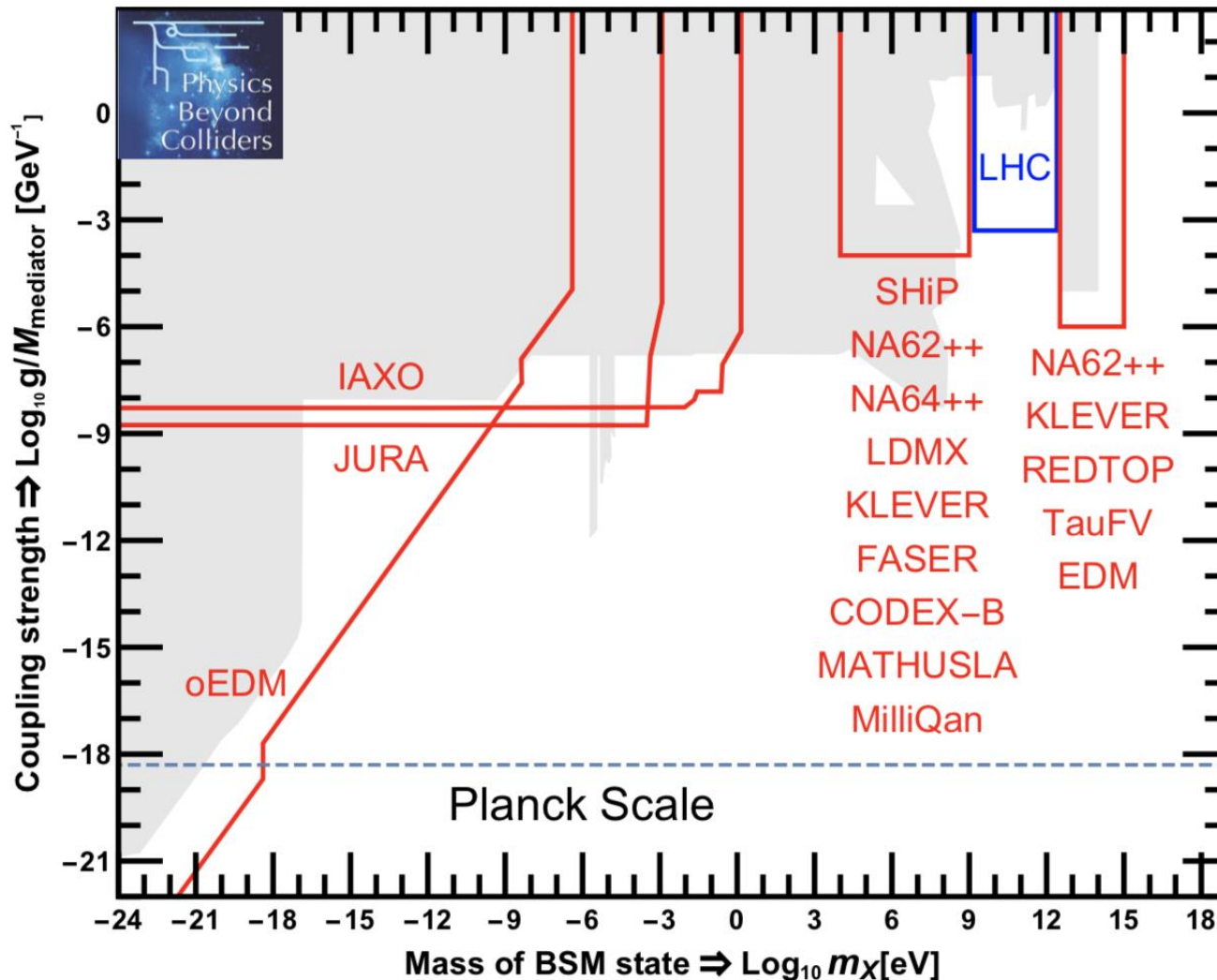


Support from CERN for magnet design within PBC



# New Possible Experiments

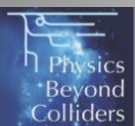
From the beyond collider study document: [arXiv:1902.00260](https://arxiv.org/abs/1902.00260)



Beam dump  
Experiments:

SHIP  
NA62  
TauFV

# Proposed Experiments



## BSM Experimental Proposals and Physics Programme



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

Since the TeV scale is very well explored at the LHC, focus on the sub-eV, MeV-GeV and multi-TeV scales:

### 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.

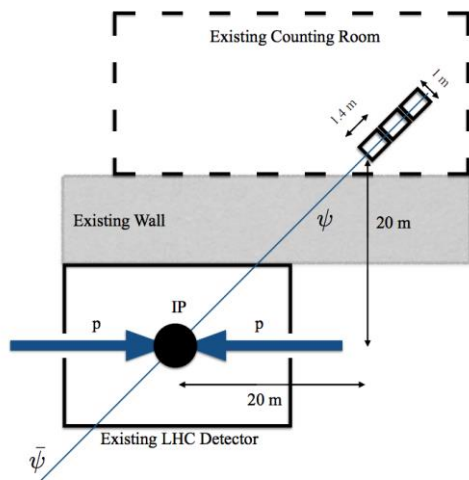
Proposal	Main Physics Cases	Beam Line	Beam Type	Beam Yield
<b>sub-eV mass range:</b>				
IAXO	axions/ALPs (photon coupling)	—	axions from sun	—
JURA	axions/ALPs (photon coupling)	laboratory	LSW	—
CPEDM	$p, d$ oEDMs	EDM ring	$p, d$	—
	axions/ALPs (gluon coupling)		$p, d$	—
LHC-FT	charmed hadrons oEDMs	LHCb IP	7 TeV $p$	—
<b>MeV-GeV mass range:</b>				
SHIP	ALPs, Dark Photons, Dark Scalars	BDF, SPS	400 GeV $p$	$2 \cdot 10^{20}/5$ years
	LDM, HNLs, leptophobic DM, ..			
NA62 <sup>++</sup>	ALPs, Dark Photons, Dark Scalars, HNLs	K12, SPS	400 GeV $p$	up to $3 \cdot 10^{18}/\text{year}$
NA64 <sup>++</sup>	ALPs, Dark Photons, Dark Scalars, LDM	H4, SPS	100 GeV $e^-$	$5 \cdot 10^{12}$ eot/year
	$+ L_\mu - L_\tau$	M2, SPS	160 GeV $\mu$	$10^{12} - 10^{13}$ mot/year
	$+ \text{CP, CPT, leptophobic DM}$	H2-H8, T9	$\sim 40$ GeV $\pi, K, p$	$5 \cdot 10^{12}/\text{year}$
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, Dark Photon, ALPs, HNLs	ATLAS or CMS IP	14 TeV $p$	$3000 \text{ fb}^{-1}$
FASER	Dark Photon, Dark Scalar, ALPs, HNLs, $B - L$ gauge bosons	ATLAS IP	14 TeV $p$	$3000 \text{ fb}^{-1}$
MilliQan	milli charge	CMS IP	14 TeV $p$	$300-3000 \text{ fb}^{-1}$
CODEX-b	Dark Scalar, HNLs, ALPs, LDM, Higgs decays	LHCb IP	14 TeV $p$	$300 \text{ fb}^{-1}$
<b>&gt;&gt; TeV mass range:</b>				
KLEVER	$K_L \rightarrow \pi^0 \nu \bar{\nu}$	P42/K12	400 GeV $p$	$5 \cdot 10^{19}$ pot /5 years
TauFV	LFV $\tau$ decays	BDF	400 GeV $p$	$\mathcal{O}(2\%)$ 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 $p$	—

Non  
Accelerator-based  
Accelerator-based

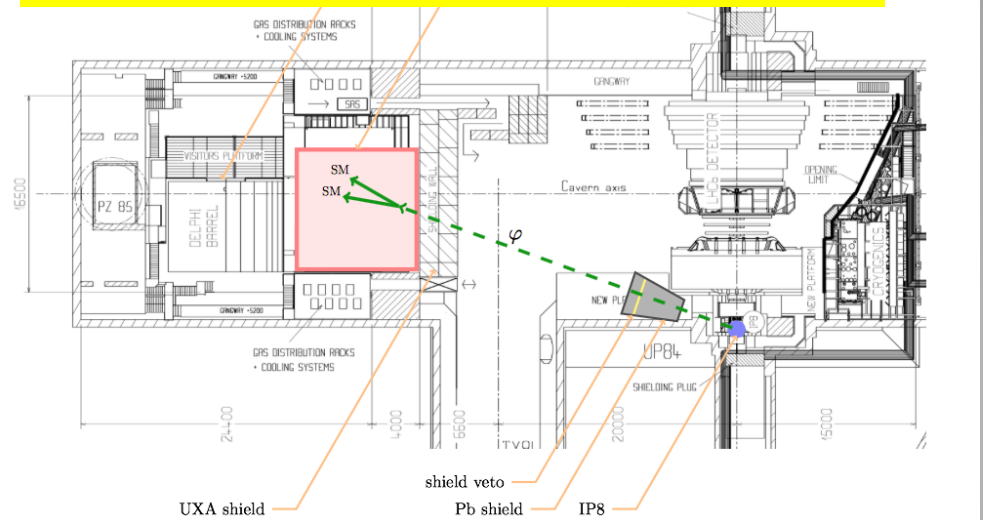
# Proposals for New Experiments @LHC

**MilliQan:** searches for millicharged particles

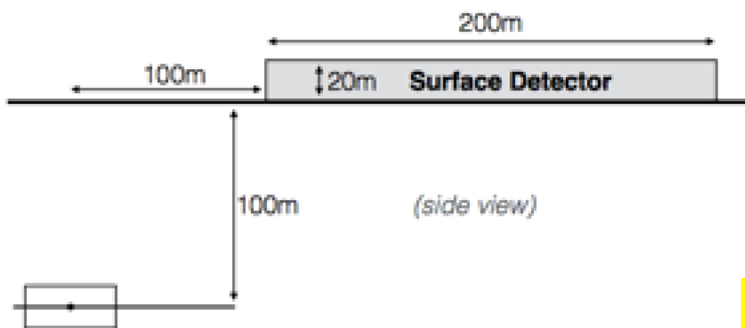
**MAPP:** Same from MoEDAL



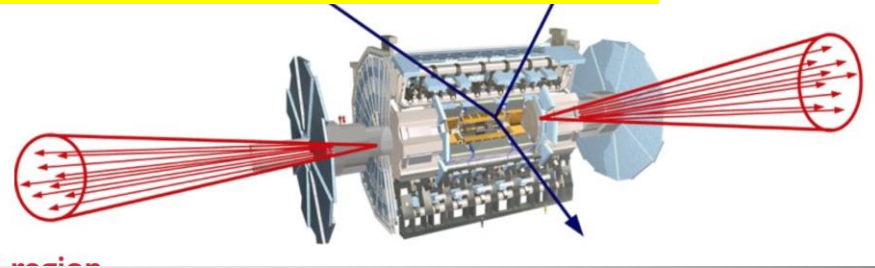
**CODEX-b:** searches for long lived weakly interacting neutral particles



**MATHUSLA:** searches for long lived weakly interacting neutral particles



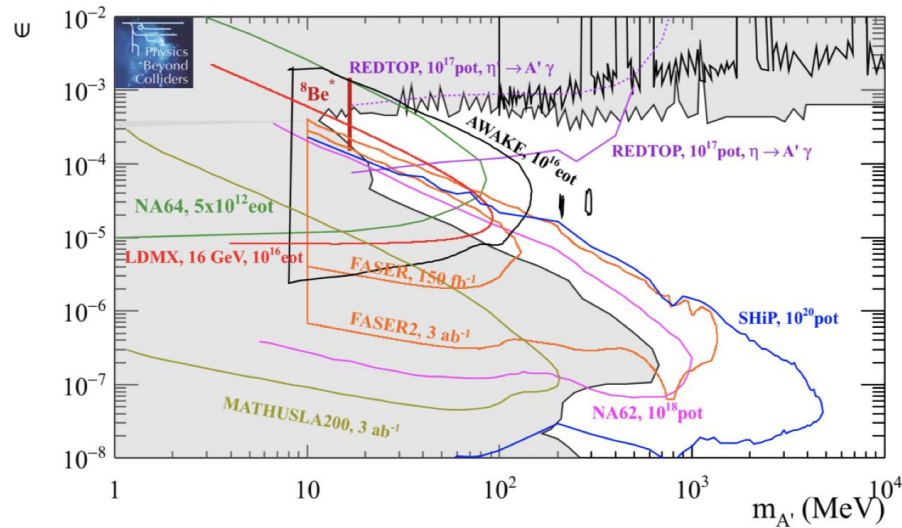
**FASER:** searches for long lived dark photons-like particles



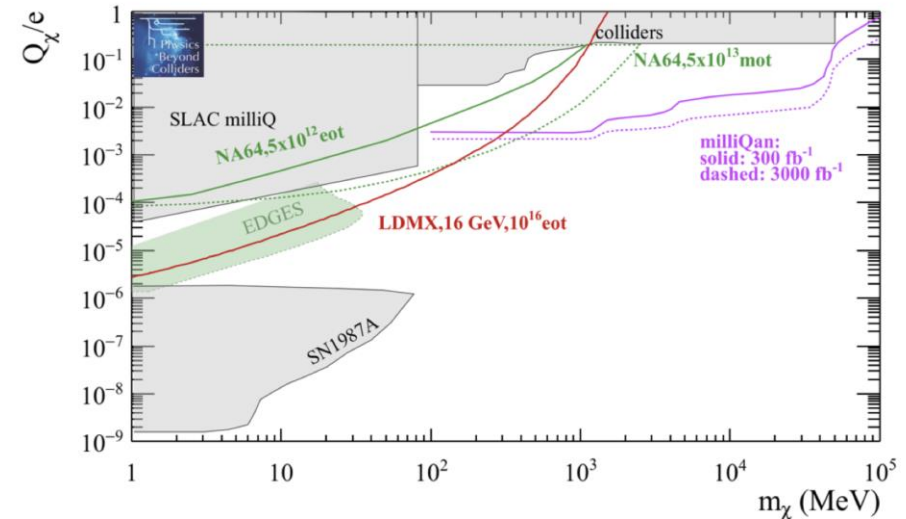
New: **AL3X** ('ALICE' for LLP arXiv.1810.03636)...

# Sensitivity Summaries

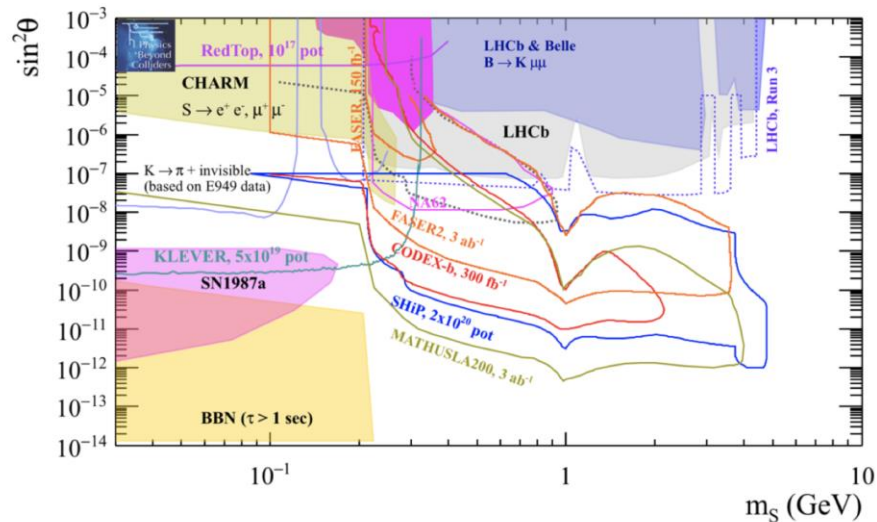
## Search for dark photons (visible mode)



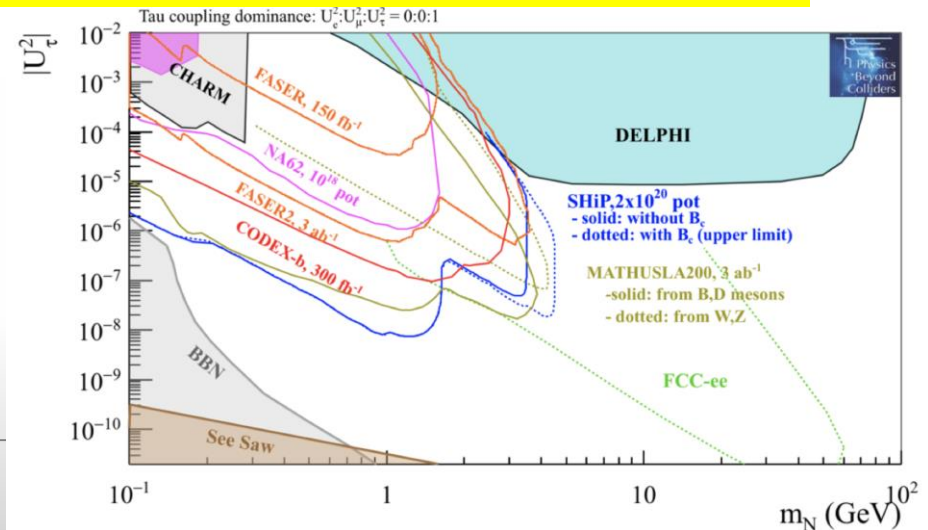
## Search for millicharges



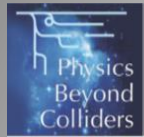
## Search for dark scalars



## Search for heavy neutral leptons

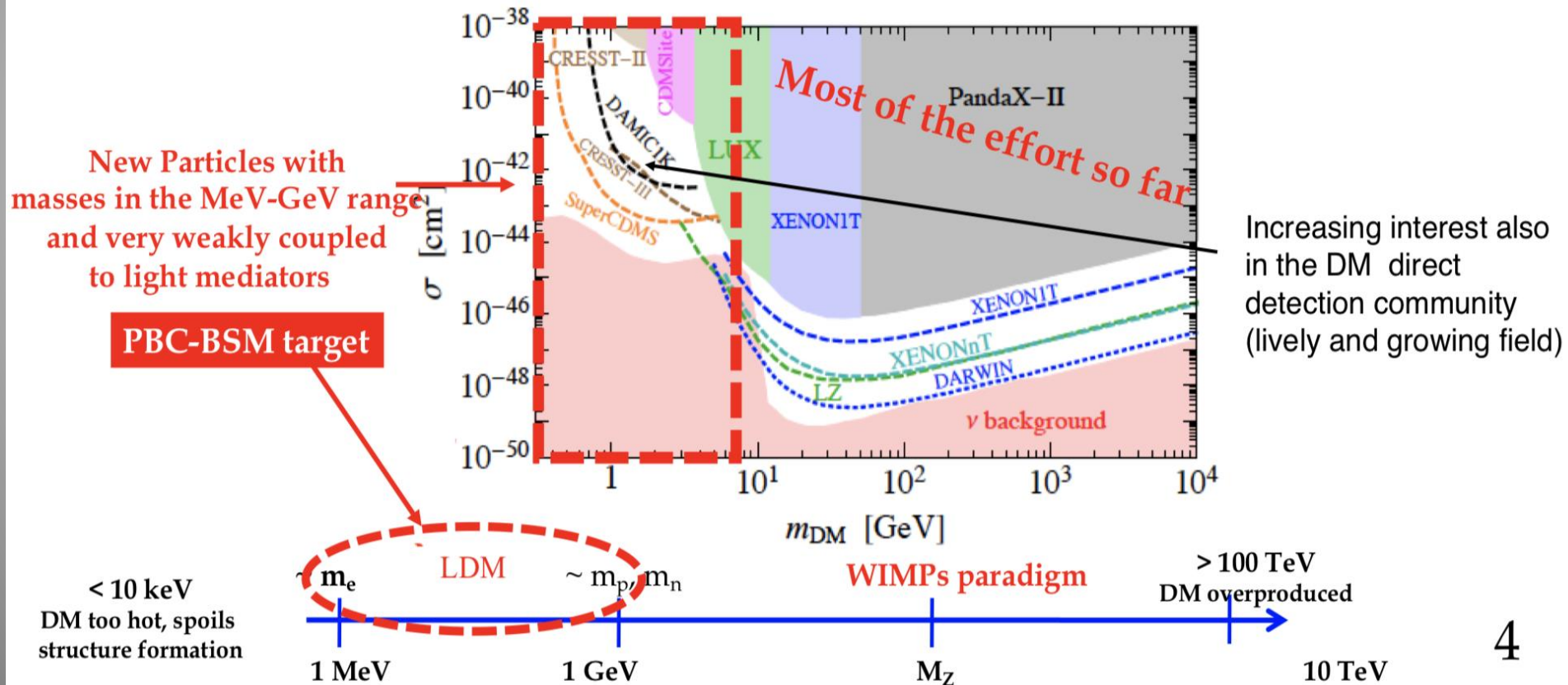


# PBC Physics Goals



PBC target: (Light) Dark Matter with thermal origin

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

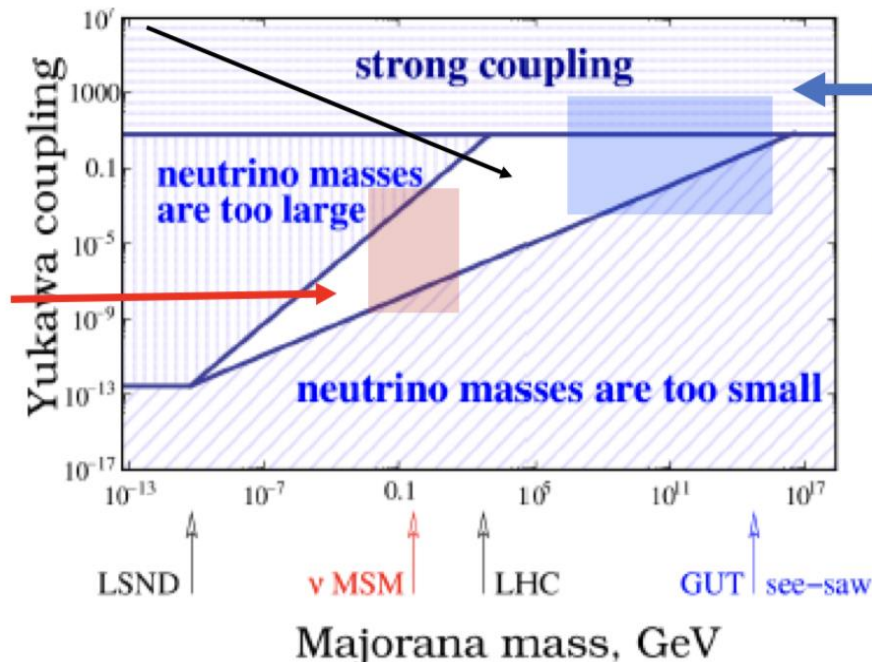


# PBC: Physics Goals

## PBC target: (Light) Right-Handed Neutrinos

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.



**Popular choice:**  
**GUT see-saw**

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

**Alternative choice:**  
**EW see-saw ( $\nu$ MSM)**

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

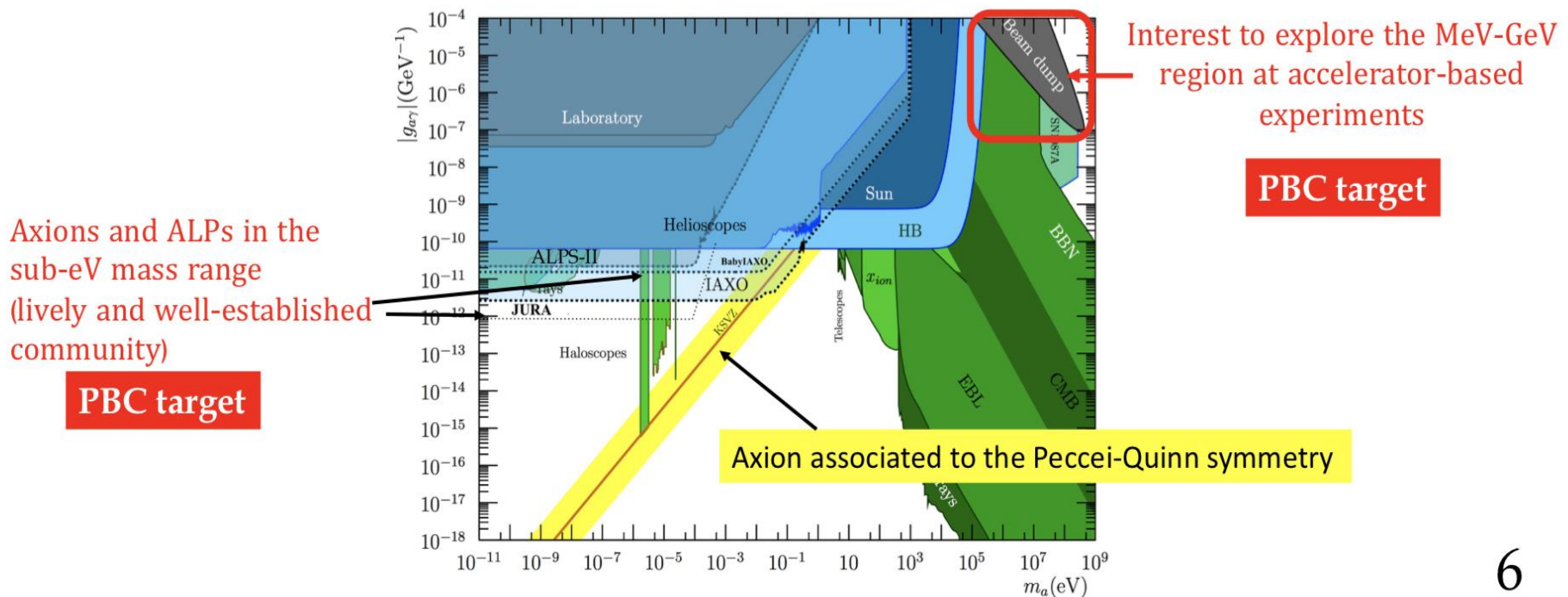
**PBC target**

# PBC: Physics Goals

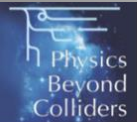
## PBC target: Axion and Axion-Like Particles

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.



# Experiment Proposals



## PBC-BSM Proposals in the North Area

### **NA62<sup>++</sup>, KLEVER @ K12**

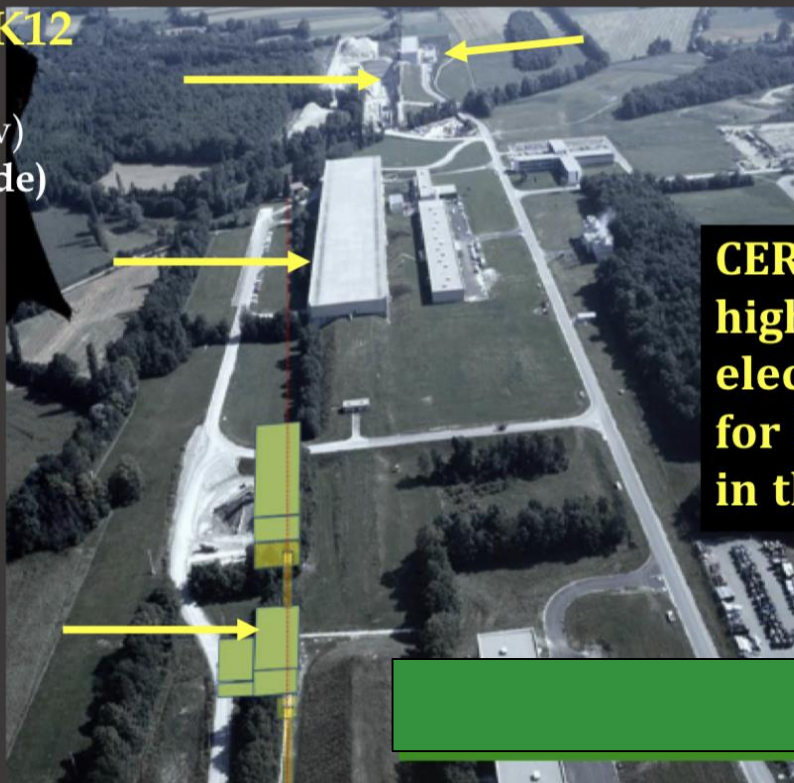
400 GeV p beam  
up to  $3 \times 10^{18}$  pot/year (now)  
up to  $10^{19}$  pot/year (upgrade)

### **NA64<sup>++</sup>(e) @ H4**

(100 GeV e- beam  
up to  $5 \times 10^{12}$  eot/year)

### **SHiP, TauFV @ BDF**

400 GeV p  
up to  $4 \times 10^{19}$  pot/year



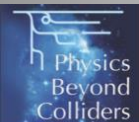
### **NA64<sup>++</sup>( $\mu$ ) @ M2**

100-160 GeV muons,  
up to  $10^{13}$   $\mu$ /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)*

# Experiment Proposals



## REDTOP @ CERN PS: Meyrin area

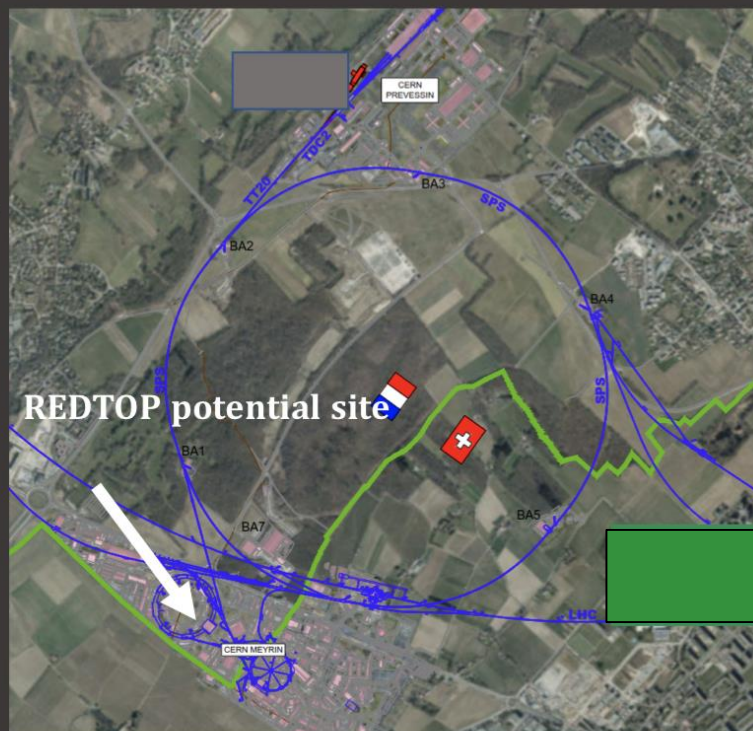
1.8 or 3.5 GeV proton beam under study at the CERN PS

Use narrow eta/eta' resonances to look for Dark Scalar/Dark Photons in the reactions:

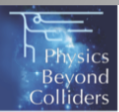
$$pLi \rightarrow \eta, \eta' \rightarrow A'\gamma \rightarrow \ell^+ \ell^- \gamma \quad (\ell = e, \mu)$$

$$pLi \rightarrow \eta \rightarrow S\pi^0 \rightarrow \ell^+ \ell^- \gamma \gamma$$

Request of  $\sim 10^{18}$  pot put strong constraint on duty cycle and could potentially affect other PS users. Studies with  $10^{17}$  pot have been performed within the Conventional Beams WG.



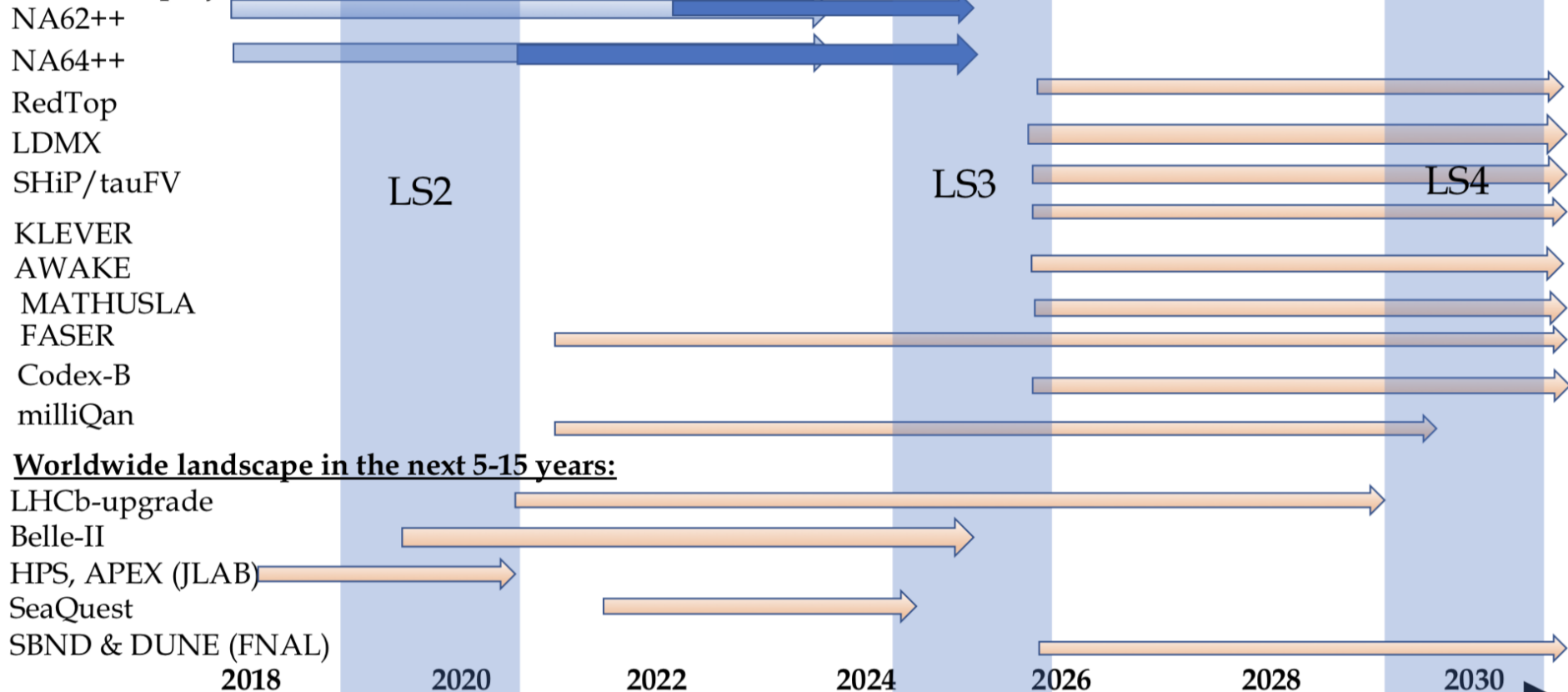
# PBC BSM Experiments Timeline



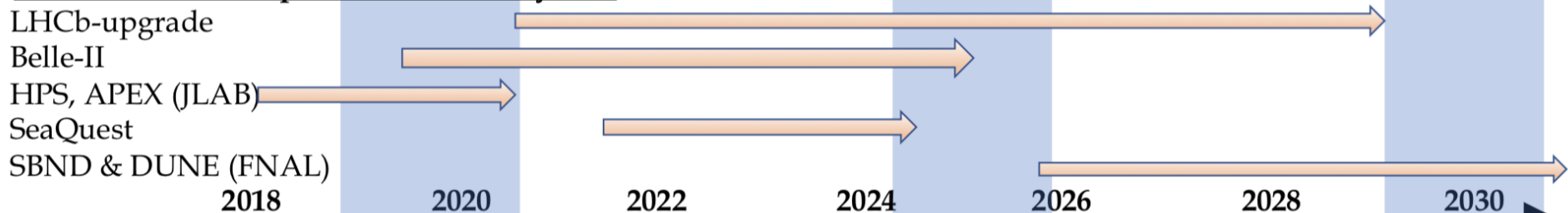
## Timescale of accelerator-based PBC BSM projects

All PBC-BSM projects could be built and operated on 10-15 year timescale

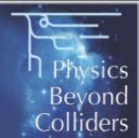
### PBC-BSM projects



### Worldwide landscape in the next 5-15 years:



# 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, $A_\mu$	$-\frac{\epsilon}{2 \cos \theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, $S$	$(\mu S + \lambda S^2) H^\dagger H$
Axion, $a$	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}, \frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}, \frac{\delta_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$
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

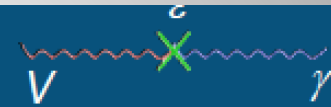
# Details on the Portals

- **D = 2: Vector portal**

- Kinetic mixing with massive dark/secluded/paraphoton  $V$ :  $\frac{1}{2} \varepsilon F_{\mu\nu}^{SM} F_{HS}^{\mu\nu}$

→ Motivated in part by idea of “mirror world” restoring left and right symmetry, constituting dark matter, g-2 anomaly, ...

- Production: proton bremsstrahlung, direct QCD production  $q\bar{q} \rightarrow V$ ,  $qg \rightarrow Vq$ , meson decays ( $\pi^0, \eta, \omega, \eta', \dots$ )

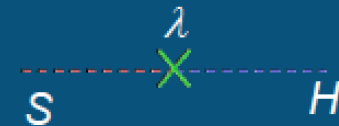


- **D = 2: Scalar portal**

- Mass mixing with dark singlet scalar  $\chi$ :  $(gS + \lambda S^2)H^\dagger H$

→ Mass to Higgs boson and right-handed neutrino, inflaton, dark phase transitions BAU, dark matter, “dark naturalness”,

- Production: Direct  $p + target \rightarrow X + S$ , meson decays e.g.  $B \rightarrow KS$ ,  $K \rightarrow \pi S$

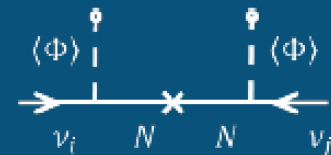


- **D = 5/2: Neutrino portal**

- Mixing with right-handed neutrino  $N$  (Heavy Neutral Lepton):  $Y_{I\ell} H^\dagger \bar{N}_I L_\ell$

→ Neutrino oscillation, baryon asymmetry, dark matter

- Production: Leptonic, semi-leptonic decays of heavy hadrons



- **D = 4: Axion portal**

- Mixing with Axion Like Particles, pseudo-scalars pNGB, axial vectors  $a$ :  $\frac{a}{F} G_{\mu\nu} \tilde{G}^{\mu\nu}$ ,  $\frac{\partial_\mu a}{F} \bar{\psi} \gamma_\mu \gamma_5 \psi$ , etc

→ Generically light pseudo-scalars arise in spontaneous breaking of approximate symmetries at a high mass scale  $F$

→ Extended Higgs, SUSY breaking, dark matter, possibility of inflaton, ...

- Production: Primakoff production, mixing with pions and heavy meson decays

- **And higher dimensional operator portals**

- Chern-Simons portal (vector portal)

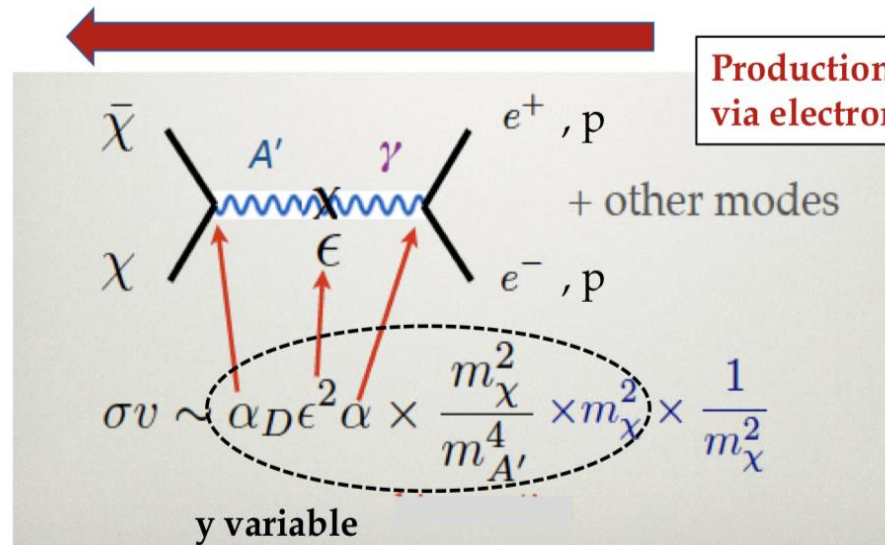
# Dark Photons

## Dark Photon coupled to Light Dark Matter: connection with DM direct detection and cosmological bounds

Model where minimally coupled viable WIMP dark matter model can be constructed.  
The parameter space for this model is  $\{m_{A'}, \epsilon, m_\chi, \alpha_D\}$

$$A' \rightarrow \chi\chi$$

Direct DM scattering  
with e/protons:  
Direct Detection  
experiments



Direct DM annihilation (main process to  
get the thermal relic abundance)

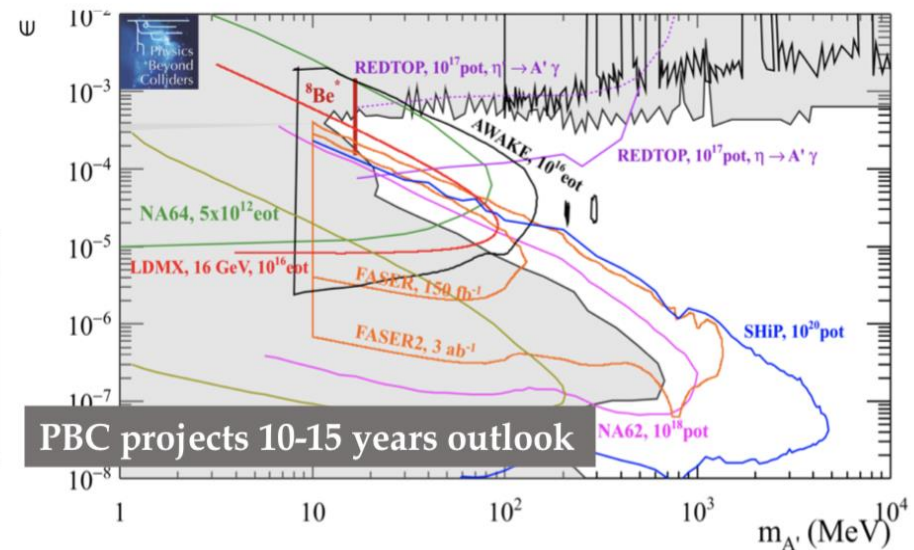
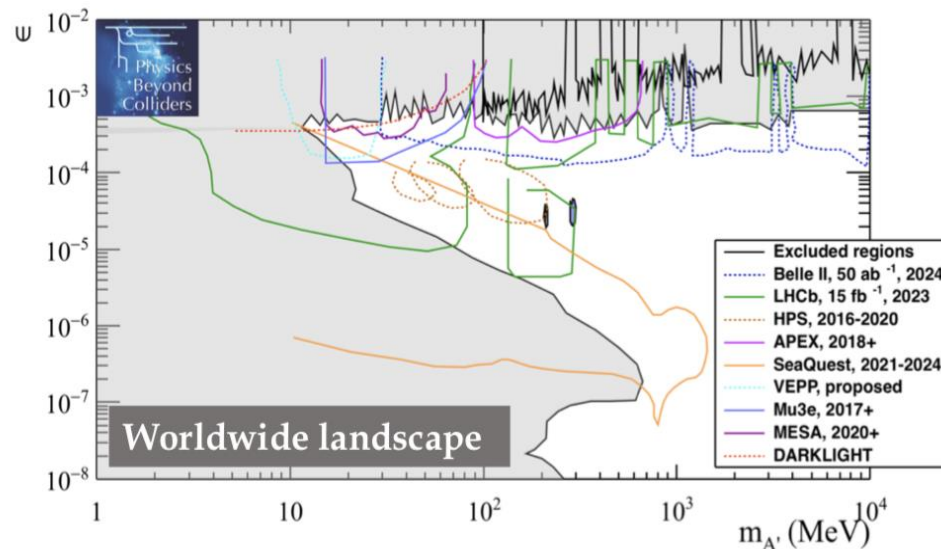
# Dark Photons

## Dark Photon coupled to SM particles (Benchmark #1)

The SM is augmented by a single new state  $A'$ . DM is assumed to be either heavy or contained in a different sector.

$$A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \dots$$

CERN-PBC-REPORT-2018-007



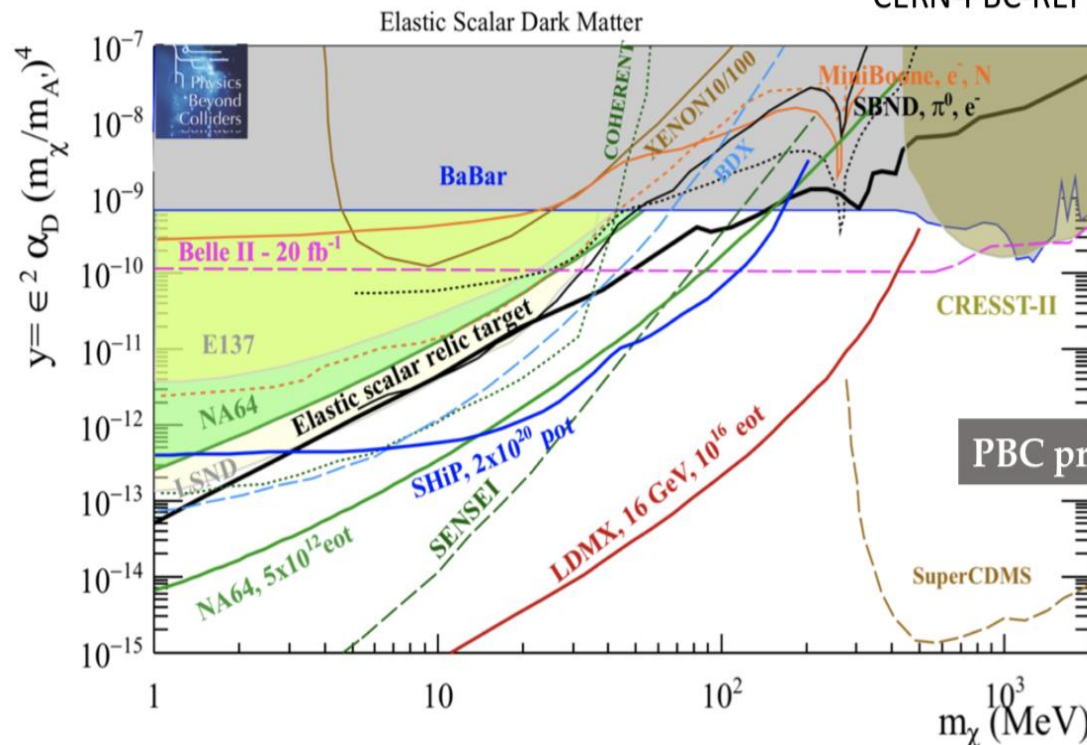
Nice complementarity/competition  
with experiments in Japan, FNAL, JLAB, Mainz, PSI.....



Physics  
Beyond  
Colliders



CERN-PBC-REPORT-2018-007


$$A' \rightarrow \chi\chi$$

$$\begin{aligned} m(A') &= 3 \, m(\chi) \\ \alpha(D) &= 0.1 \end{aligned}$$

## PBC projects: 5-15 years outlook

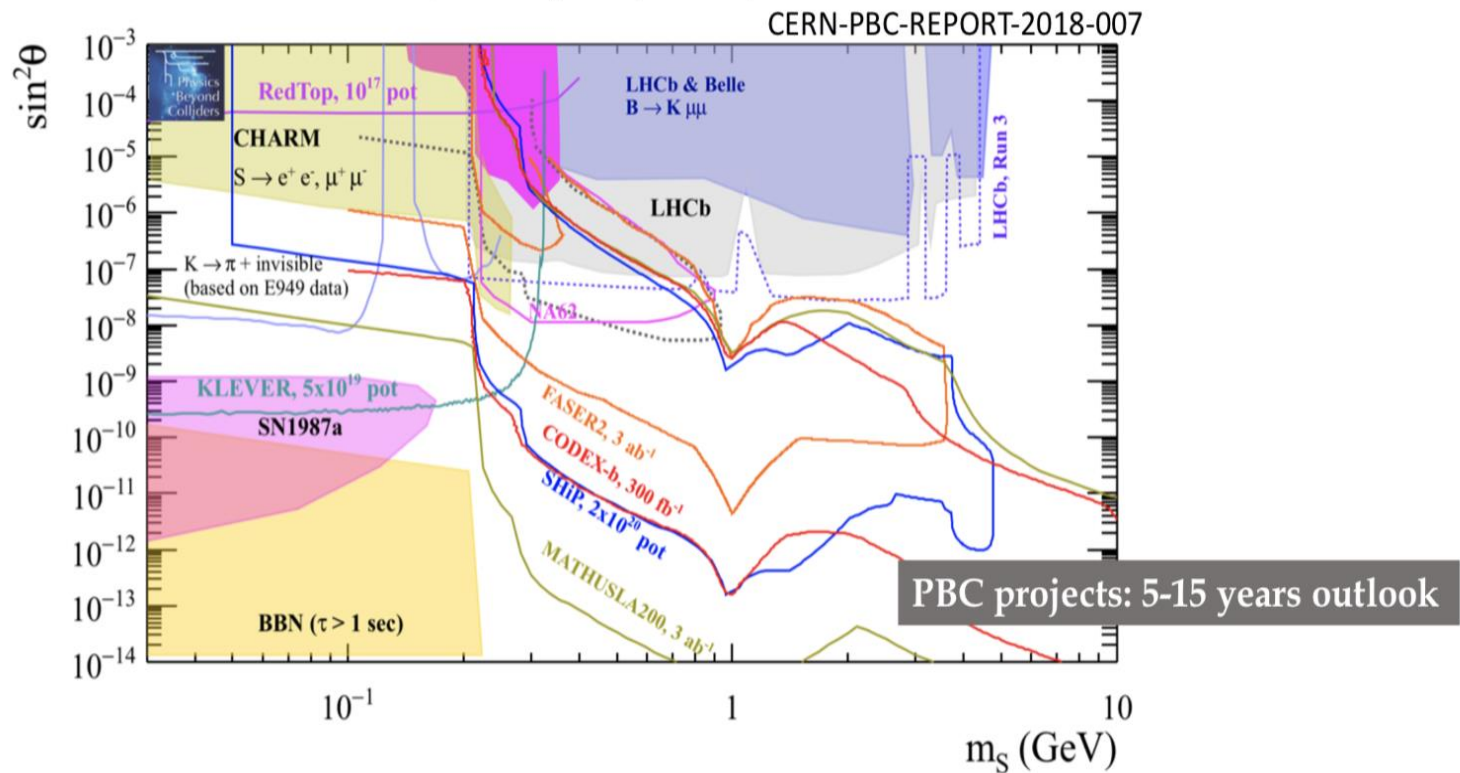
Nice complementarity  
between accelerator-based proposals and Light DM direct detection experiments.

# Dark Scalars

## Dark Scalar coupled to the Higgs (Benchmarks #4-5)

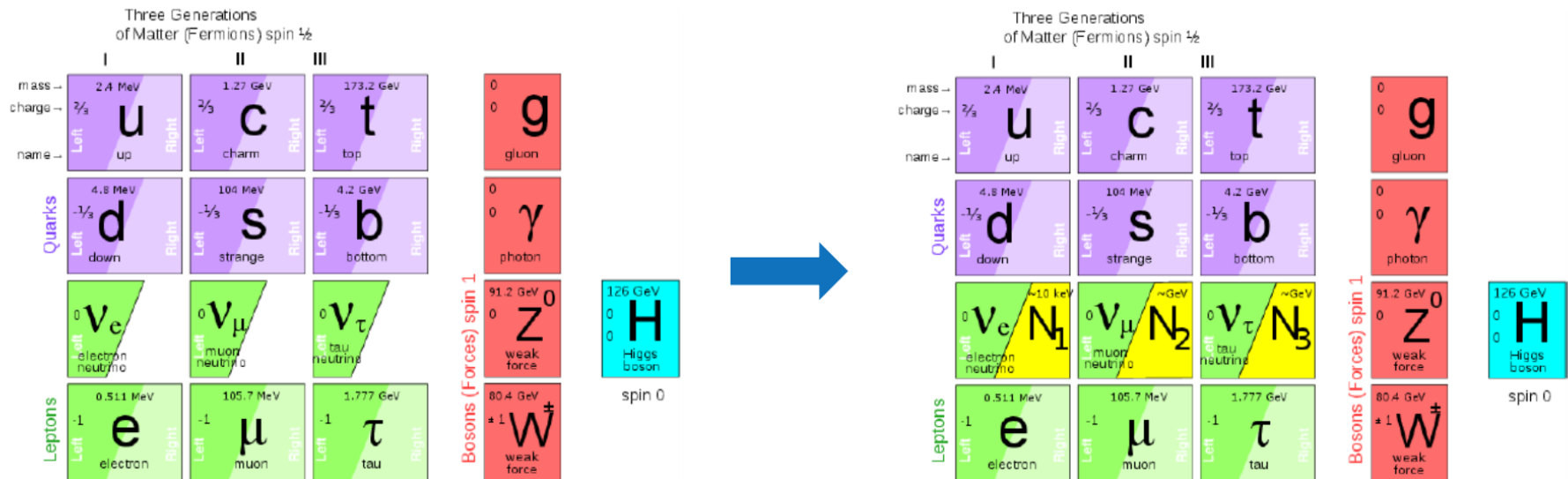
The Higgs portal couples the dark sector to the Higgs boson via the bilinear  $H^\dagger H$  operator of the SM. The minimal scalar portal model operates with one extra singlet field  $S$  and two types of couplings,  $\mu$  and  $\lambda$ .

Benchmark 5: assumes  $\lambda \neq 0$ , namely  $\text{BR}(H \rightarrow SS) \sim 1\%$ .



# Example Scenario

**Neutrino portal:** vMSM (Neutrino Minimal Standard Model)  
Minimal extension of the SM fermion sector by three Right Handed (Majorana) Heavy Neutral Leptons (**HNL**):  $N_1, N_2, N_3$ .

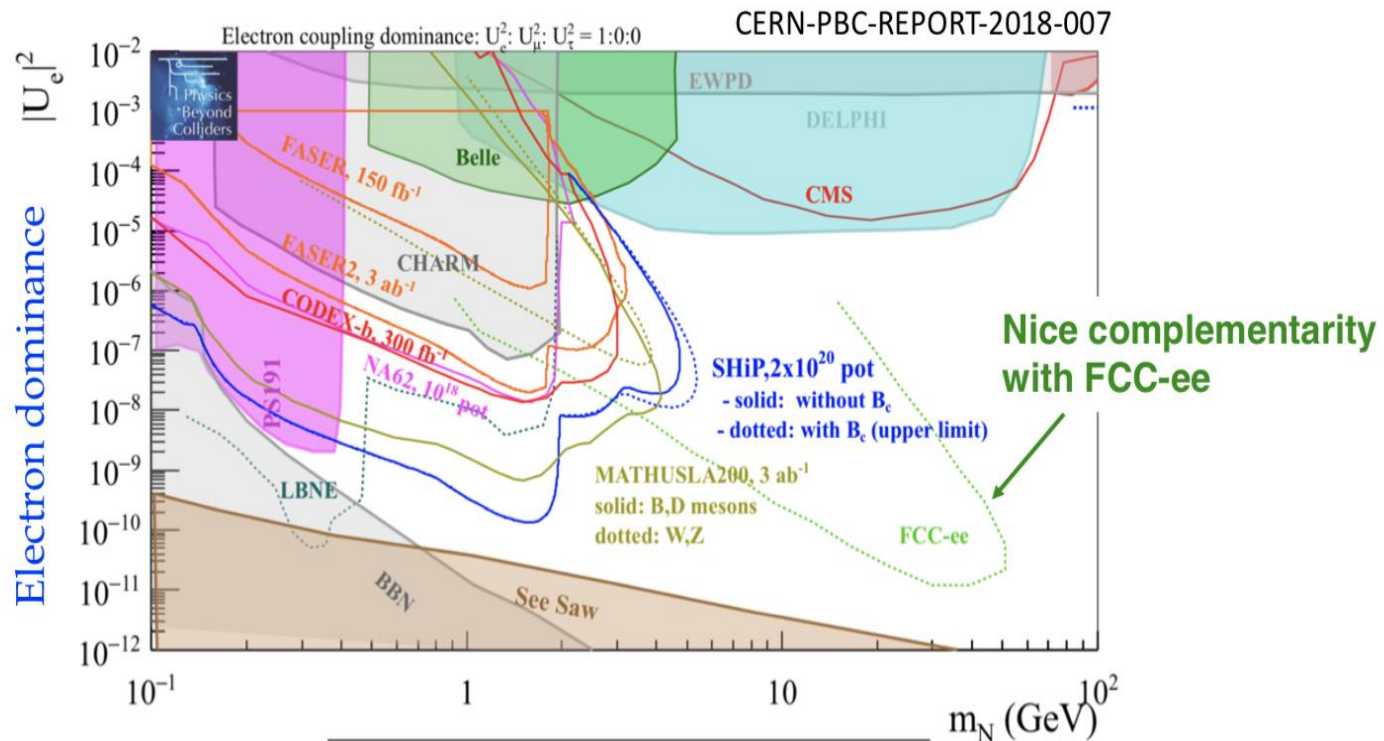


- The lightest singlet  $N_1$  (mass  $\approx$  KeV): good dark matter candidate.
- $N_2, N_3$  (mass in 100 MeV - GeV region):
  - Mechanism to give masses to neutrinos
  - Explain baryon asymmetry

# Heavy Neutral Leptons

## Benchmarks 6,7,8: HNLs below the EW scale:

Neutrino portal extension of the SM is very motivated by the fact that it can be tightly related with the neutrino mass generation mechanism: Heavy Neutral Leptons or HNLs. Choice of the PBC is to assume the single-flavor dominance, eg. HNLs couple only with one flavor of the active neutrinos at the time.

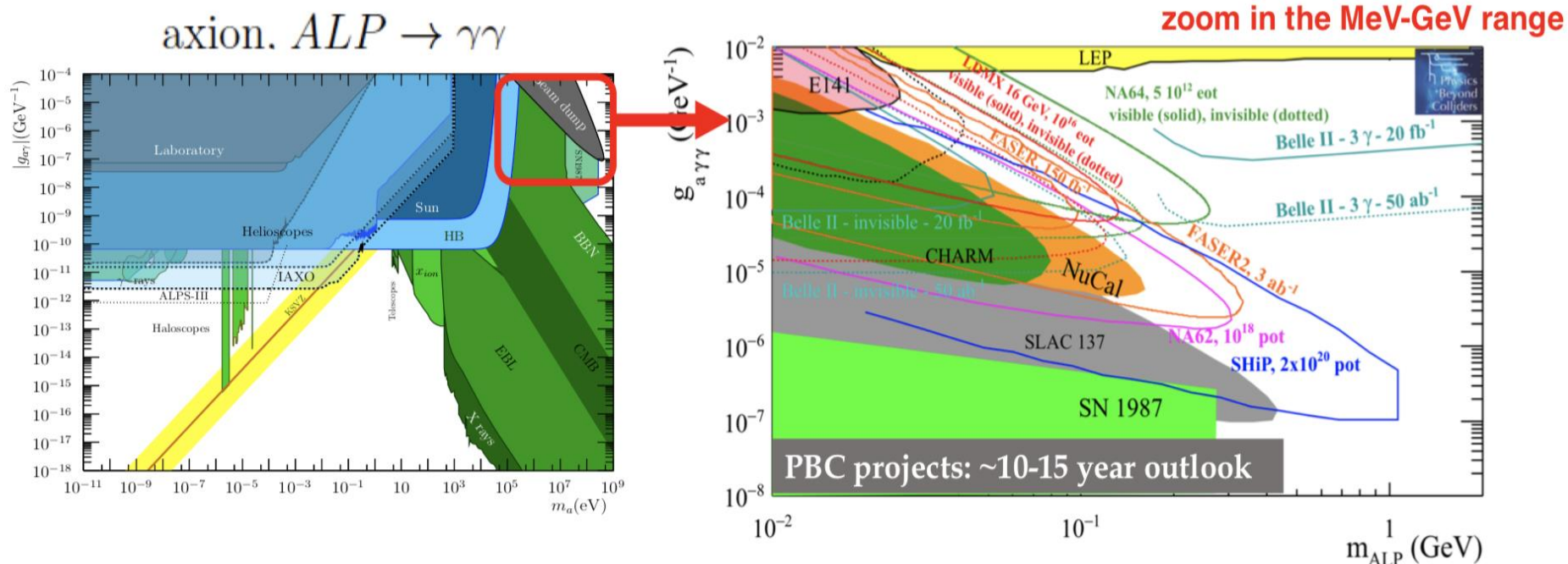


PBC projects: ~10-15 year outlook

# Axions and ALPs

## Axions and ALPs with photon coupling in the MeV-GeV mass range

Search for axions/ALPs: extremely lively and established field, mostly in the sub-eV mass range  
Need of a systematic investigation in the MeV-GeV range.

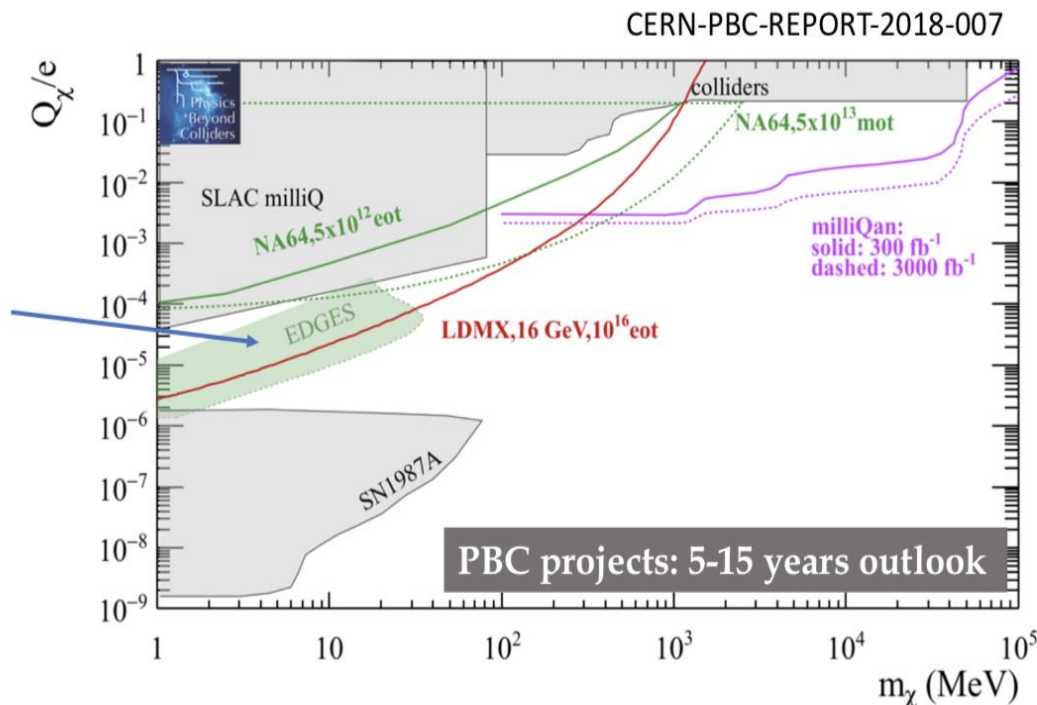


Nice complementarity of accelerator-based experiment  
with experiments in the sub-eV range and cosmological bounds

# Millicharged Searches

## Milli-charged particles (Benchmark #3)

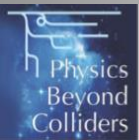
Milli-charged particles can be seen as a specific limit of the vector portal when  $m_{A'}$  goes to zero and the parameter space simplifies to the mass ( $m_\chi$ ) and effective charge ( $|Q| = |E_{g_D}|$ ) of milli-charged particles.



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.

Nice complementarity with colliders and astrophysical data

# Project Status

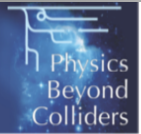


## PBC-BSM projects: current status of evaluation of backgrounds and other experimental effects

Proposal	Background	Efficiency	Based on
<b>at the PS:</b>			
RedTop	included	included	full simulation
<b>at the SPS:</b>			
KLEVER	$K_L \rightarrow \pi^0 \nu \bar{\nu}$ , $K_L \rightarrow \pi^0 \pi^0$ bkg 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 <sup>++</sup>	zero background proven for fully reconstructed final states	partially included	analysis of $\sim 3 \cdot 10^{16}$ pot in dump mode
NA64 <sup>++</sup> (e)	included	included	background, efficiencies evaluated from data
NA64 <sup>++</sup> (μ)	in progress	in progress	test of the purity of the M2 line with COMPASS setup
NA64 <sup>++</sup> ( $K_{S,L}, \eta, \eta'$ )	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 $2 \times 10^{20}$ pot $\mu$ – combinatorial and $\mu$ – interactions based on $\sim 10^{12}$ pot measurement of the muon flux at H4 performed in July 2018
<b>at the LHC:</b>			
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

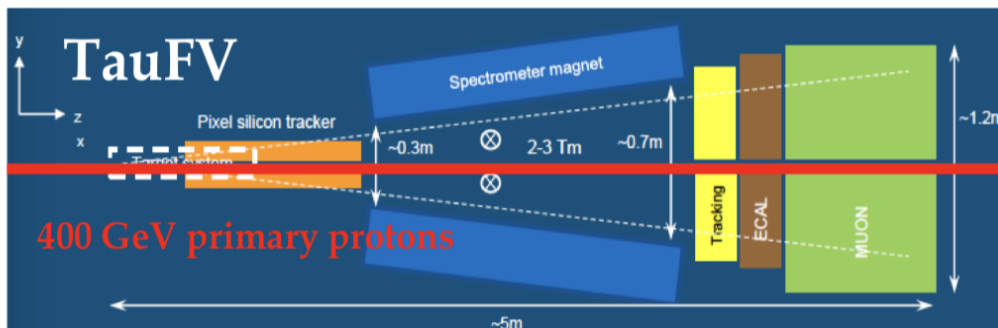
Just a starting point of a long way.

# Beamp Dump Experiments TauFV

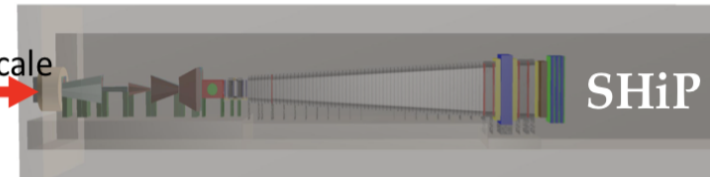


## Search for NP at the multi-TeV scale: the TauFV Project

- ✓ 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  $\mu\text{ze}$  @ FNAL and MEG/ $\mu\text{3e}$  @ PSI.
- ✓ Located into the BDF line upstream of SHiP. Use  $\sim 2\%$  of protons hitting on (probably) a wire target to study LFV decays of tau leptons.



not to scale



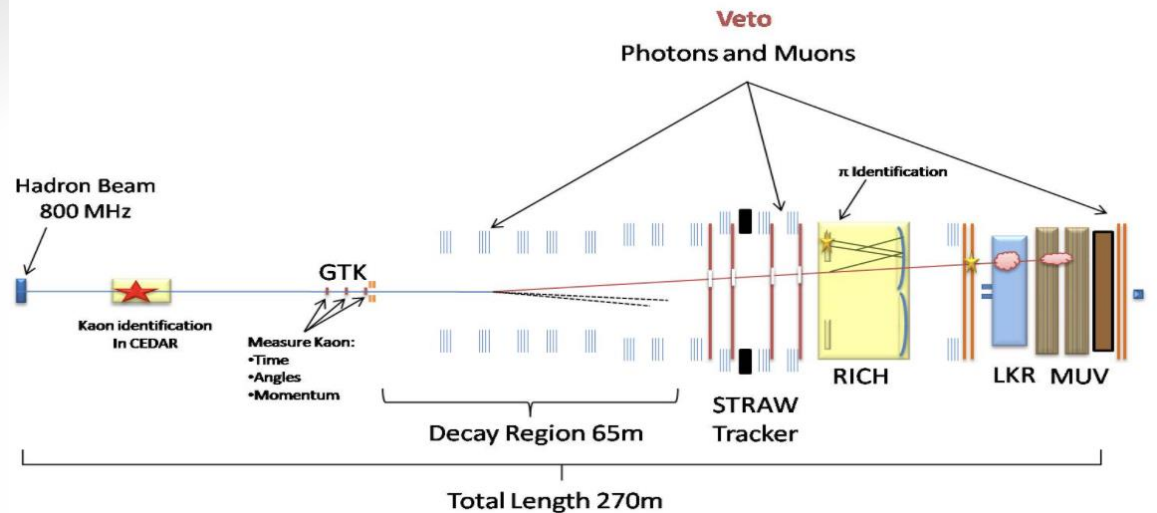
**Profit of the higher signal yield than at any other facility:**

Eg:  $\tau \rightarrow \mu\mu\mu$  yield assuming a BR  $\sim 10^{-9}$

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

# NA62 Beam Dump

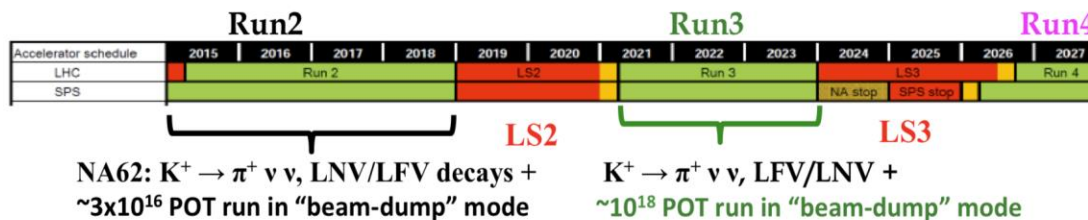
Experiment designed for detecting very rare Kaon decays



## NA62++: Dump mode in Run 3

Searches for MeV-GeV mass hidden-sector candidates  
A rich field to be explored with optimized setup in dump mode

In Run3 :  $\sim 10^{18}$  POT run in “beam-dump” mode for hidden sector



# The SHiP Experiment



CERN-SPSC-2015-017  
SPSC-P-350-ADD-1  
9 April 2015

## Search for Hidden Particles

Strained west-south-west, and encountered a heavier sea than they had met with before in the whole voyage. Saw particles and a green fish near the vessel. The crew of the Patri saw a case and a bag, they also picked up a stick which appeared to have been carved with an iron tool, a piece of cane, a glass which pricks on land, and a brand. The crew of the Nova saw other signs of land, and a shrike loaded with rose berries. These signs encouraged them, and they all grew cheerful. Sailed this day till sunset, twenty-seven leagues.

After sunset steered their original course west and called twelve miles on hour till two hours after midnight, going twenty miles, which was twenty-two leagues and a half and at the Patri was the western side, and kept ahead of the Patri.

the discovered land



Physics Proposal

SHiP is a proposal for a new facility at the CERN SPS accelerator:

- Hidden Sector search detector
- Facility for  $\nu_\tau$  physics

240 experimentalist from 46 institutes and 15 countries + CERN (2017)

Technical proposal submitted in April 2015 (arXiv:1504.04956)

Physics proposal signed by 85 theorists (arXiv:1504.0855)

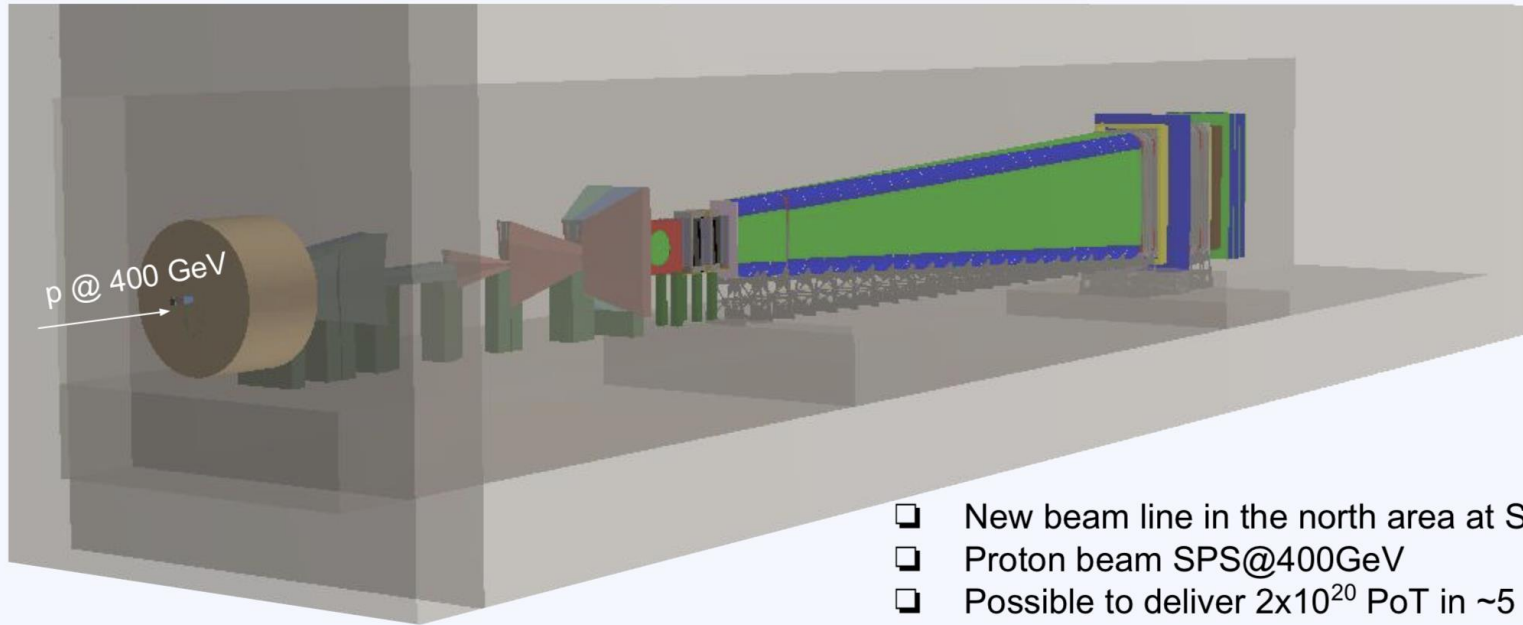
SPSC gave a positive recommendation in January 2016 for continuing study. A comprehensive design study requested by 2019. Approval decision in 2019/2020.

Physics in 2026???

# SHiP Beam Dump Experiment Proposal

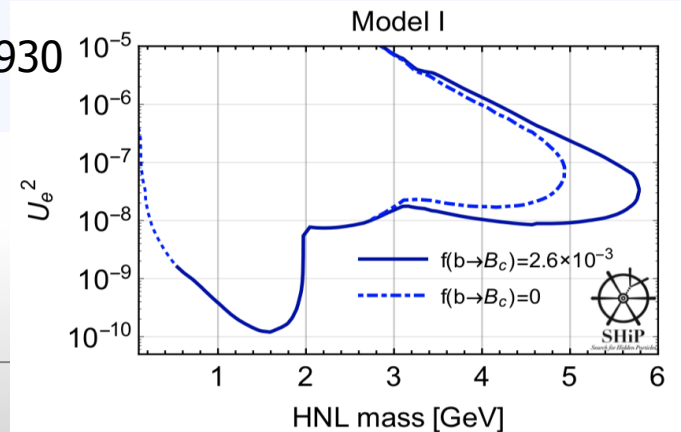
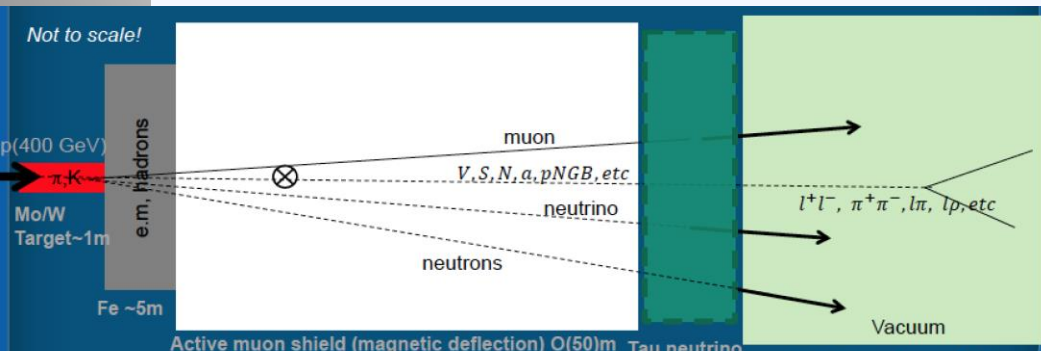
SHiP is a proposed intensity-frontier experiment aiming to search for neutral hidden particles with mass up to  $O(10)$  GeV and weak couplings, down to  $10^{-10}$ .

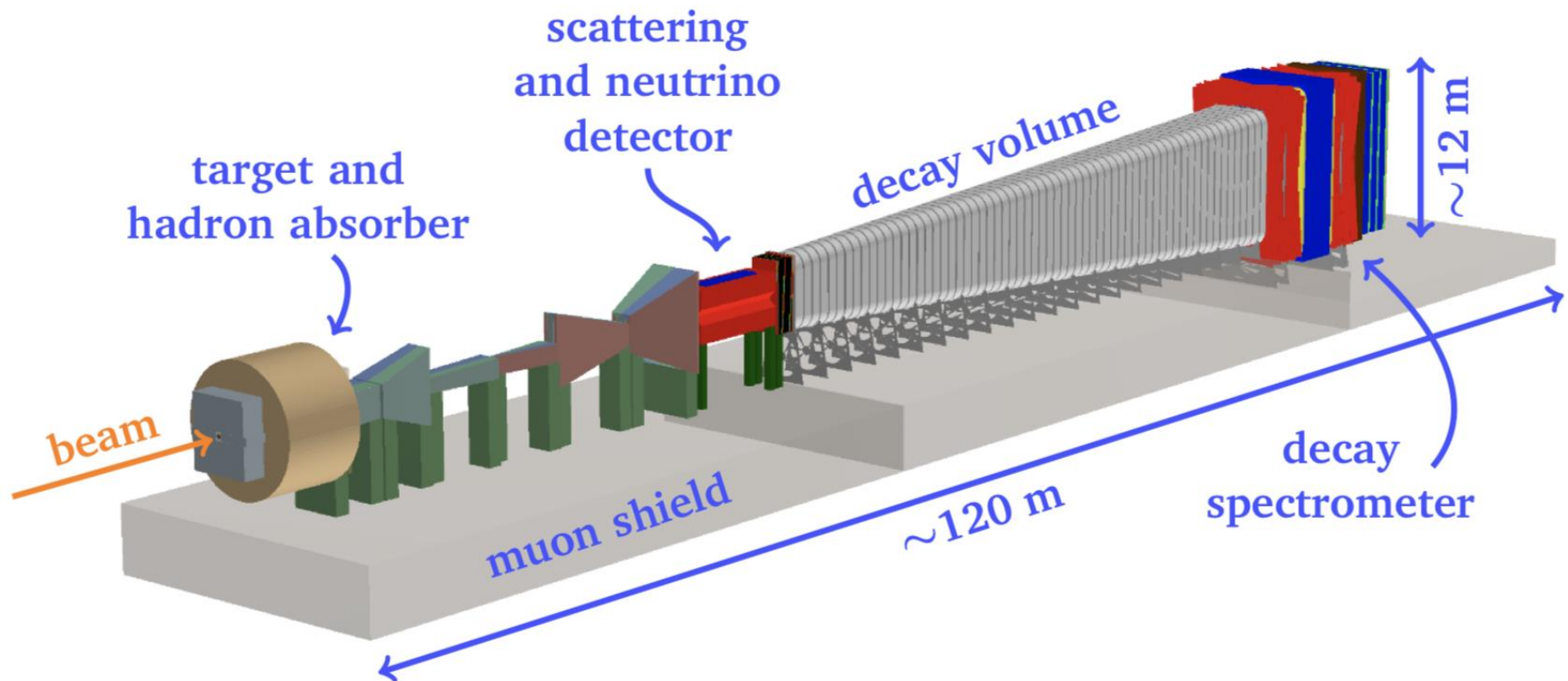
arXiv:1504.04956



- ❑ New beam line in the north area at SPS
- ❑ Proton beam SPS@400GeV
- ❑ Possible to deliver  $2 \times 10^{20}$  PoT in ~5 years

arXiv:1811.00930





- ▶  $2 \times 10^{20}$  *pot* in 5 years:  $> 10^{18}D$ ,  $> 10^{16}\tau$
- ▶ zero background beam dump expt. with spectrometry and PID
- ▶ large geometrical acceptance: long volume close to dump
- ▶ complementary detectors for scattering/decay signatures

# Neutrino Detector & Program

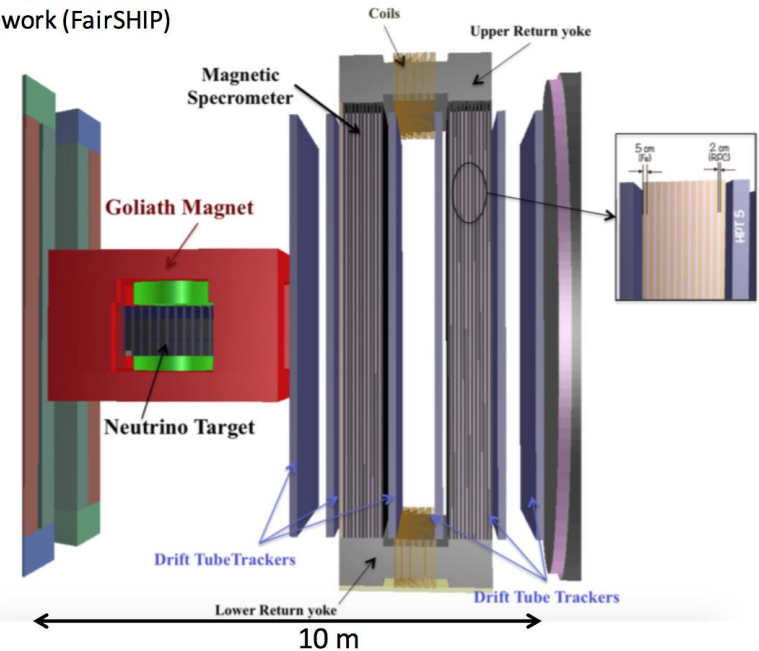
Note: anti- $\nu_\tau$  has never been observed

**SHiP neutrino program**  
 $\sim 8k$  expected  $\nu_\tau$  and  $\sim 4k$  anti- $\nu_\tau$  interactions in the target

- First observation of anti- $\nu_\tau$
- Sufficient statistics to perform  $\nu_\tau$  and anti- $\nu_\tau$  cross section measurement.
- First measurement of structure function  $F_4$  and  $F_5$  entering in DIS neutrino-nucleon cross section

Follows the OPERA concept

Implementation in dedicated CERN framework (FairSHIP)



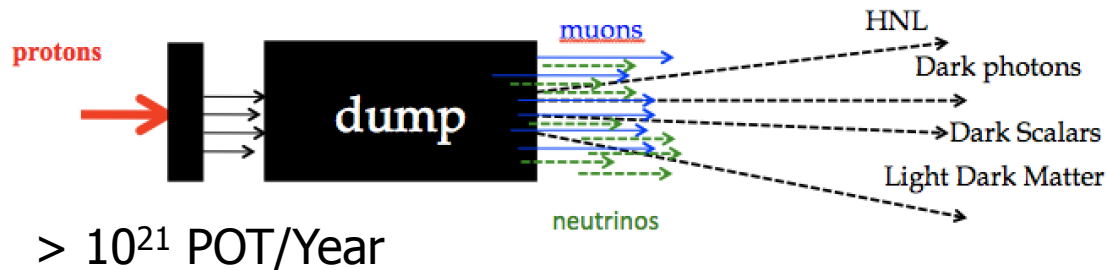
	$\langle E \rangle$ (GeV)	Interactions
$N_{\nu_e}$	46	$2.5 \times 10^5$
$N_{\nu_\mu}$	29	$1.7 \times 10^6$
$N_{\nu_\tau}$	59	$7.4 \times 10^3$
$N_{\bar{\nu}_e}$	46	$9.0 \times 10^4$
$N_{\bar{\nu}_\mu}$	28	$6.7 \times 10^5$
$N_{\bar{\nu}_\tau}$	58	$3.7 \times 10^3$

Neutrino interactions for 5 year running

# Beam Dump Experiments

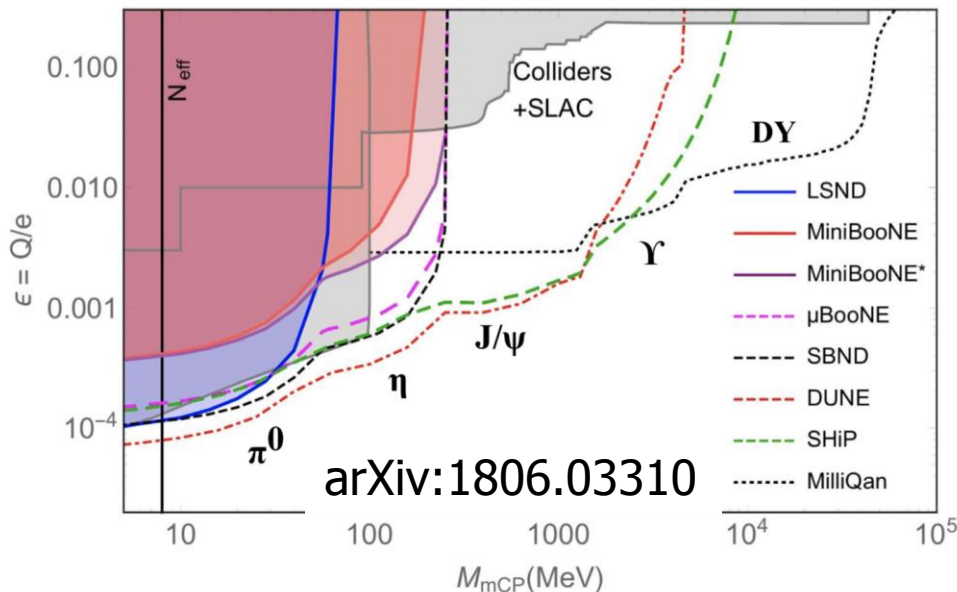
High intensity frontier for low mass particles with very weak couplings

-> upcoming neutrino experiments (SBL, LBL) foresee very high intensity beams



Near Detector:  
few 100m away  
from the dump

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



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

-HNL/sterile neutrinos

-dark photons

-ALPs

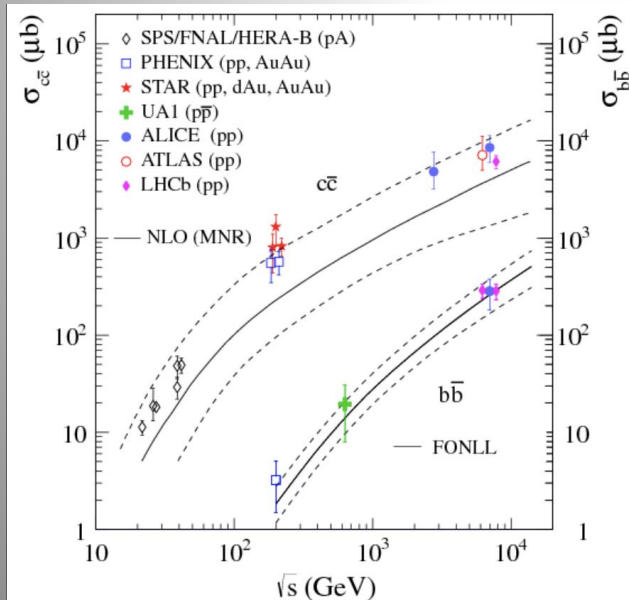
-mini/millicharges

...

<- Example for millicharges  
FerMINI @FNAL?

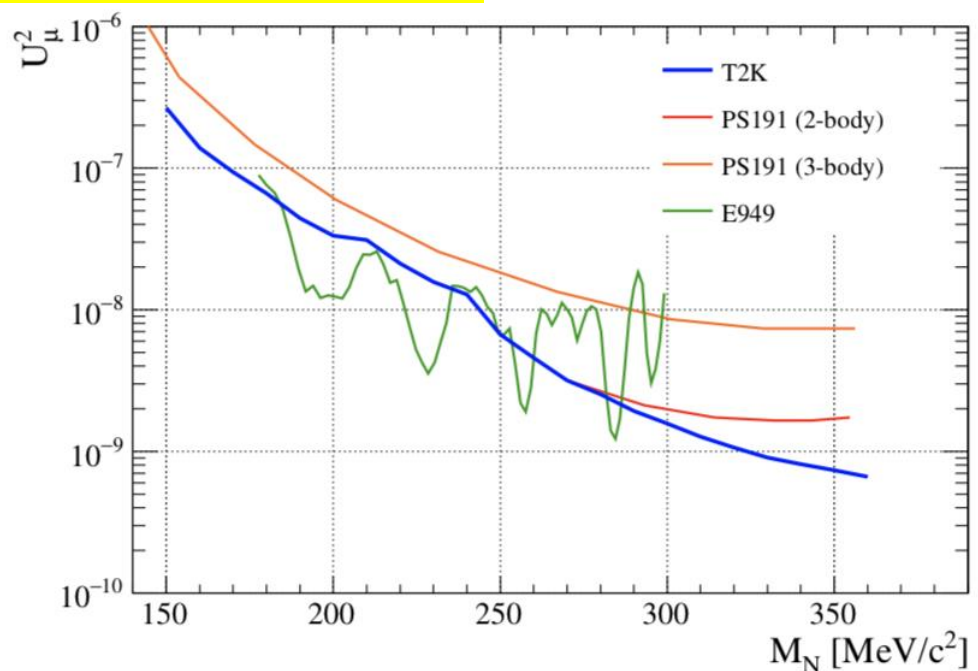
# SHiP Versus Neutrino Beam Dump

- SHiP: 400 GeV protons with  $4e19$  POT/year
- DUNE: 80/120 GeV protons with  $1-2e21$  POT/year
- **Optimized acceptance for SHiP**
- For the NDs the HNL search is not their main program
- Example HNLs via heavy flavor decays: cross sections strongly energy dependent



## T2K recent results

arXiv:1902.07598



# Status of the Various LHC Projects

## Lifetime frontier

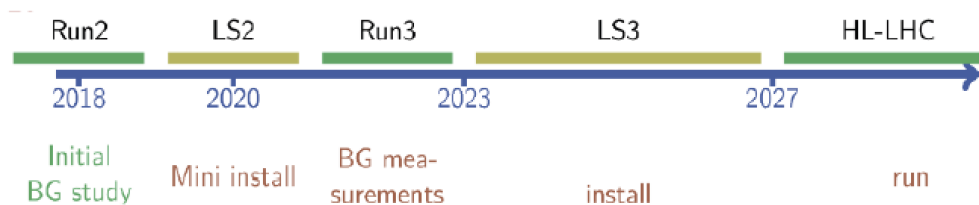
Simon Knapen FNAL seminar fall 2018

### Supplementary detectors

	Higgs decay	B-meson decay	$\pi, \eta$ -decay (dark photon)	Progress	Cost
FASER		✓	✓	Collaboration formed	\$
CODEX-b	✓	✓		sub-collaboration formed	\$
SeaQuest			✓	experiment exists	\$
AL3X	✓	✓	✓	Proof of concept	\$\$
MATHUSLA	✓	(✓)		Letter of intent	\$\$
SHiP		✓	✓	Technical design report	\$\$\$

MOEDAL: monopoles, already running

MiliQan: milicharged particles, phase 1 detector in place



Similar timelines for  
MATHUSLA, MilliQan  
CODEX-b, FASER

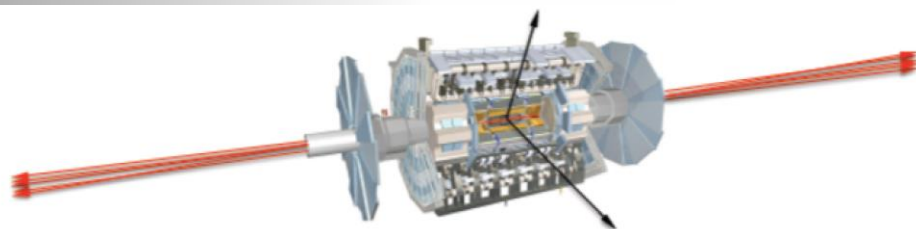
# FASER Approval

Breaking news: the FASER experiment (phase-I) has been approved March 5th

INTERACTIONS.ORG  
PARTICLE PHYSICS NEWS AND RESOURCES

FASER: CERN approves new experiment to look for long-lived, exotic particles

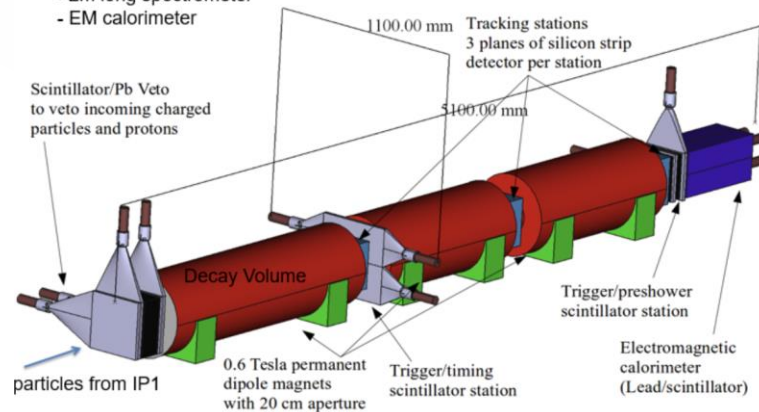
*Date Issued*  
March 5th, 2019



## THE FASER DETECTOR

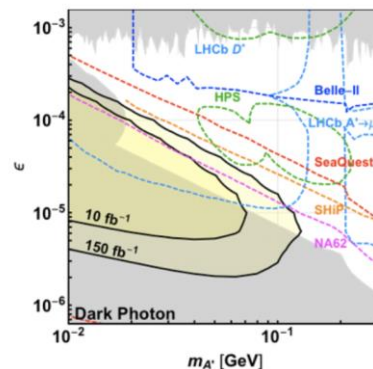
The detector consists of:

- Scintillator veto
- 1.5m long decay volume
- 2m long spectrometer
- EM calorimeter

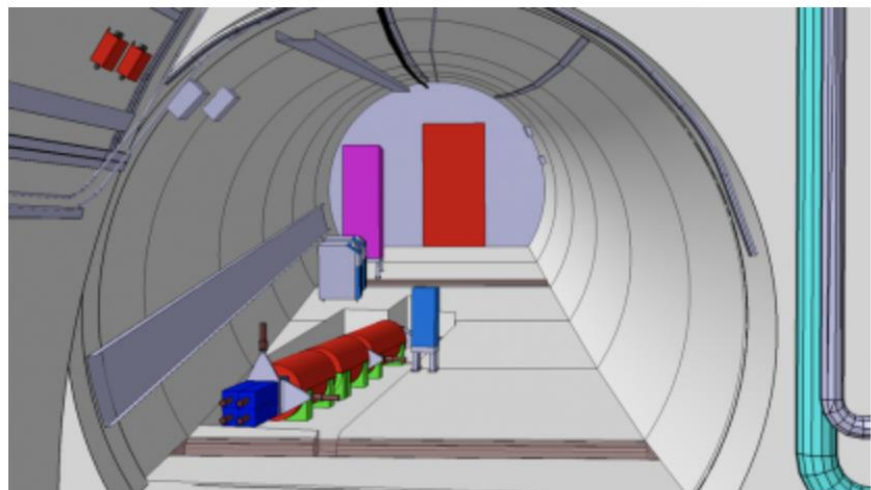


## EXPECTED SENSITIVITY

- Sensitivity for dark photons
  - Assuming no background and 100% signal efficiency
  - Curves only slightly effected by  $O(1)$  changes in efficiency

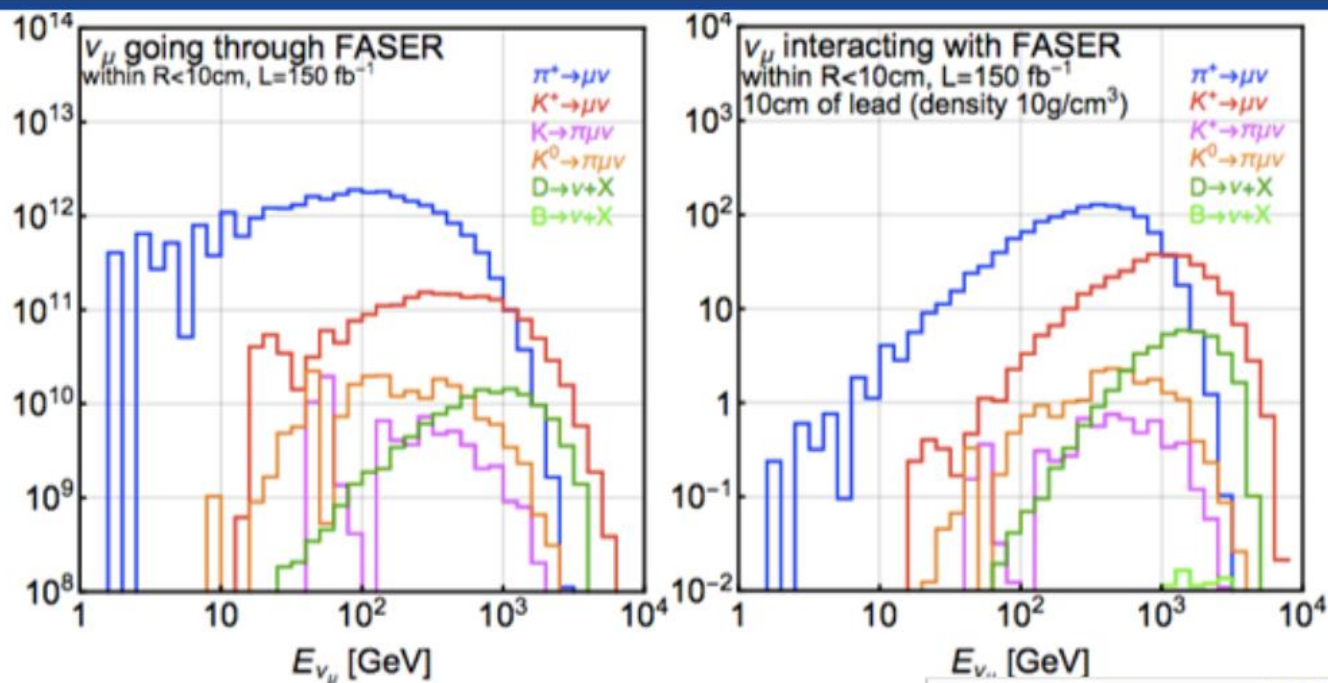


Even with 10/fb (to be collected by end of 2021?) have sensitivity to uncharted territory. With full Run 3 dataset (150/fb) significant discovery potential.



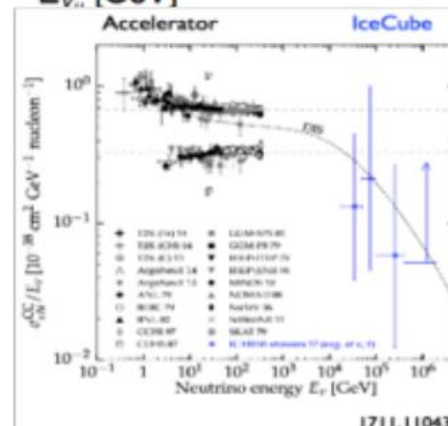
# FASER @LHC

## POSSIBLE NEUTRINO MEASUREMENTS



Huge flux of neutrinos through FASER could allow for interesting neutrino measurements e.g.  $\nu_\mu$  CC cross section in unexplored region  $E > 400$  GeV.

There could also be interesting possibilities for  $\nu_\tau$  measurements at the FASER location (e.g. using emulsion detectors)



# 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

~140 pages

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

arXiv:1901.09966



CERN-PBC-REPORT-2018-008

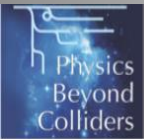
### Physics Beyond Colliders QCD Working Group Report

~80 pages

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

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

# PBC Summary



## 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  $\mathcal{O}(10-15)$  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.

**BACKUP**