Physics Beyond Colliders

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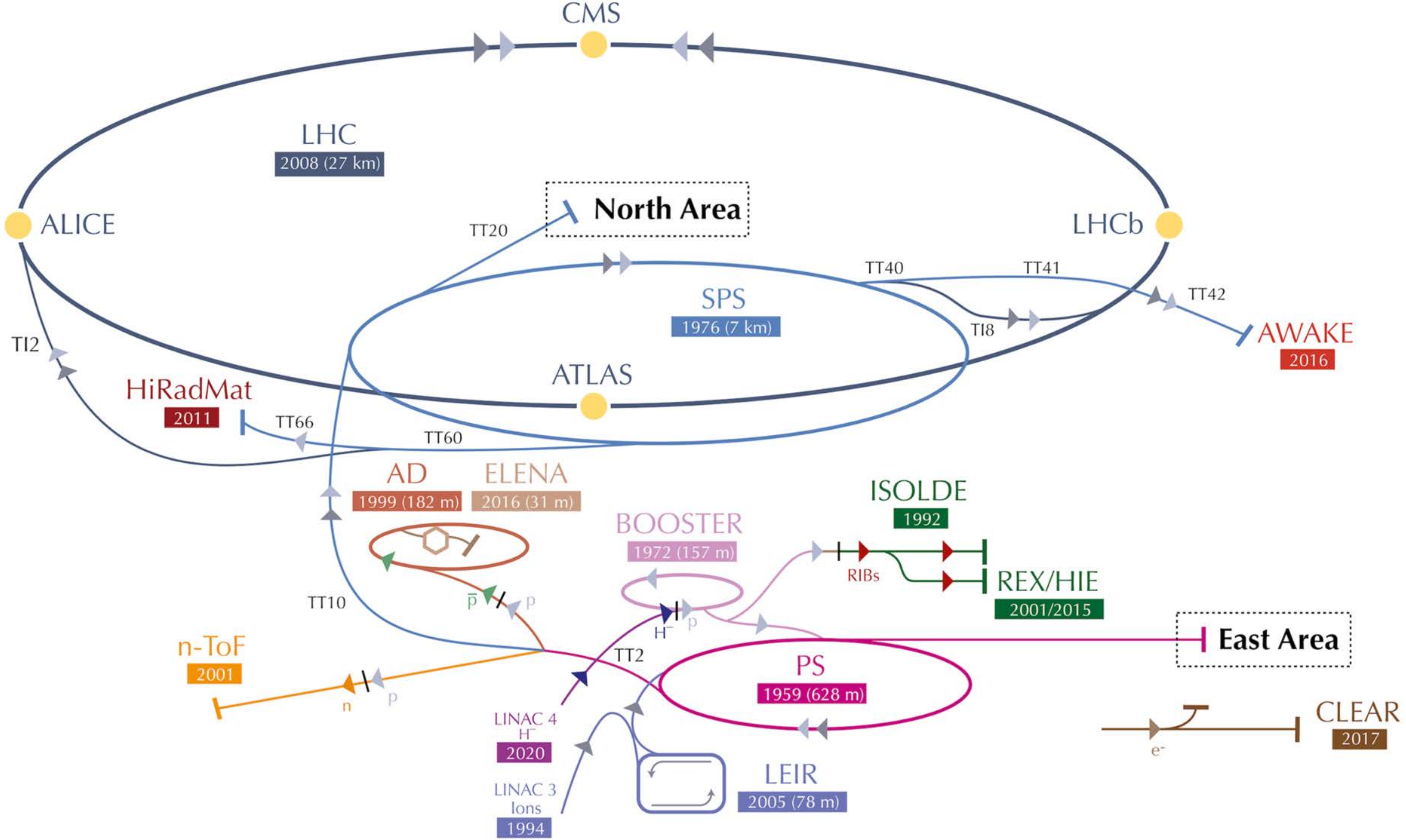
PBC working groups

The brief

Maximize physics reach of CERN's existing complex

Within the limits posed by an already vibrant and diverse physics program!

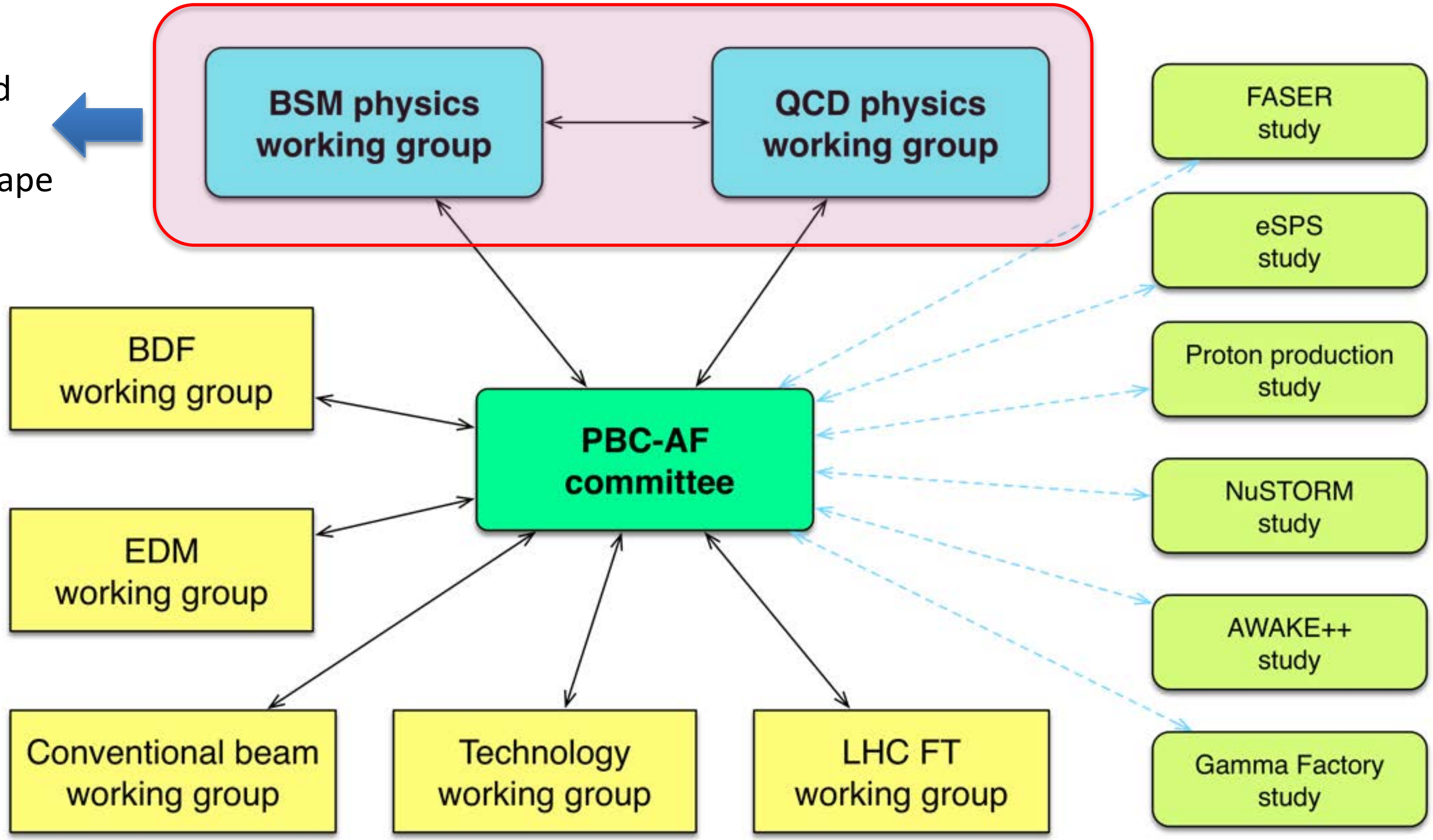
Evaluate the options' motivation and competitiveness in the worldwide landscape



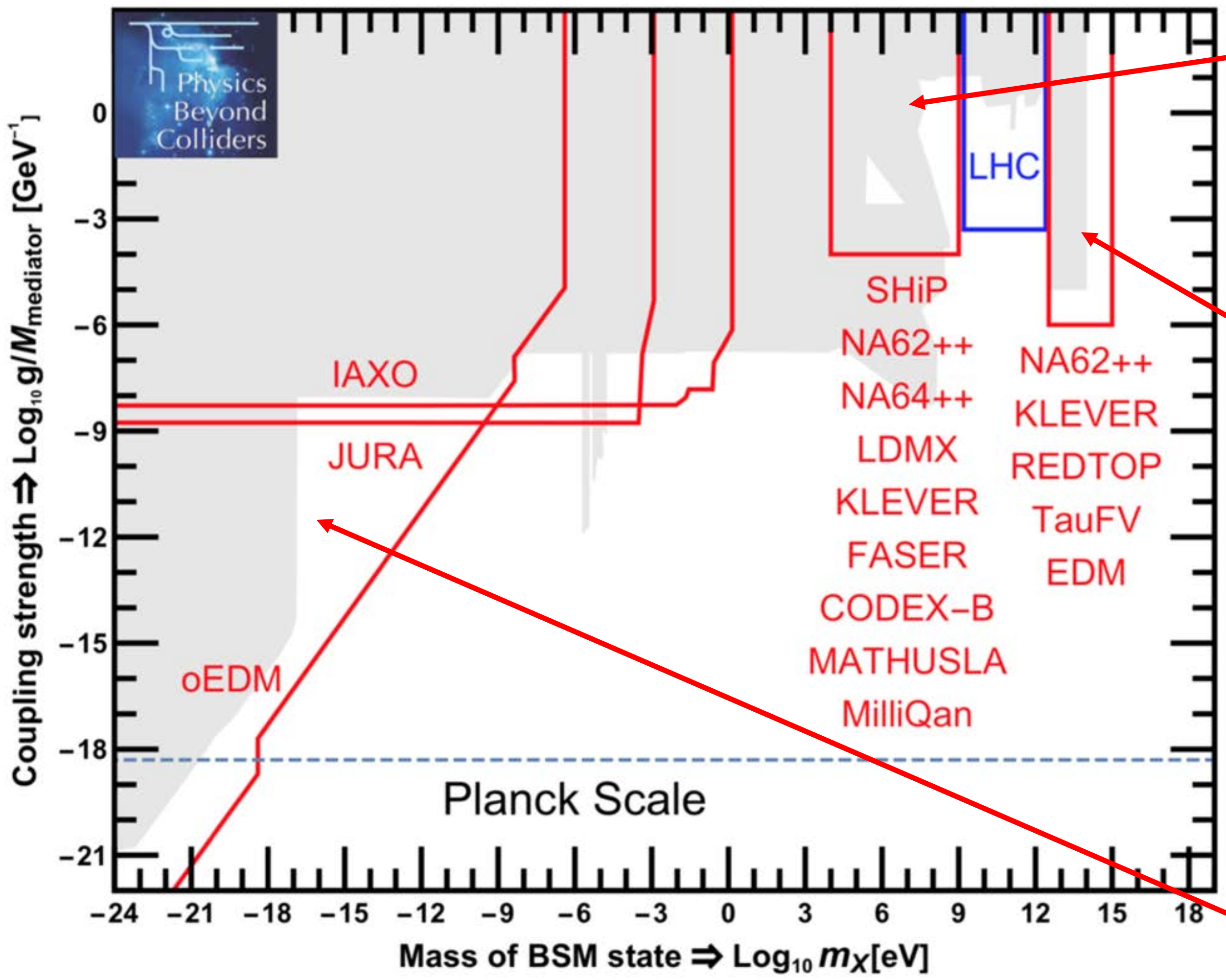
CMS
LHC
2008 (27 km)
North Area
TT20
ALICE
LHCb
TT40
TT41
TT42
SPS
1976 (7 km)
TI8
AWAKE
2016
TI2
ATLAS
HiRadMat
2011
TT66
TT60
AD
1999 (182 m)
ELENA
2016 (31 m)
ISOLDE
1992
BOOSTER
1972 (157 m)
RIBs
REX/HIE
2001/2015
TT10
p̄
p
H⁻
p
East Area
n-ToF
2001
TT2
PS
1959 (628 m)
n
p
CLEAR
2017
e⁻
LINAC 4
H⁻
2020
LINAC 3
Ions
1994
LEIR
2005 (78 m)

PBC structure

Evaluate proposed options in the worldwide landscape



Schematic overview of the BSM landscape

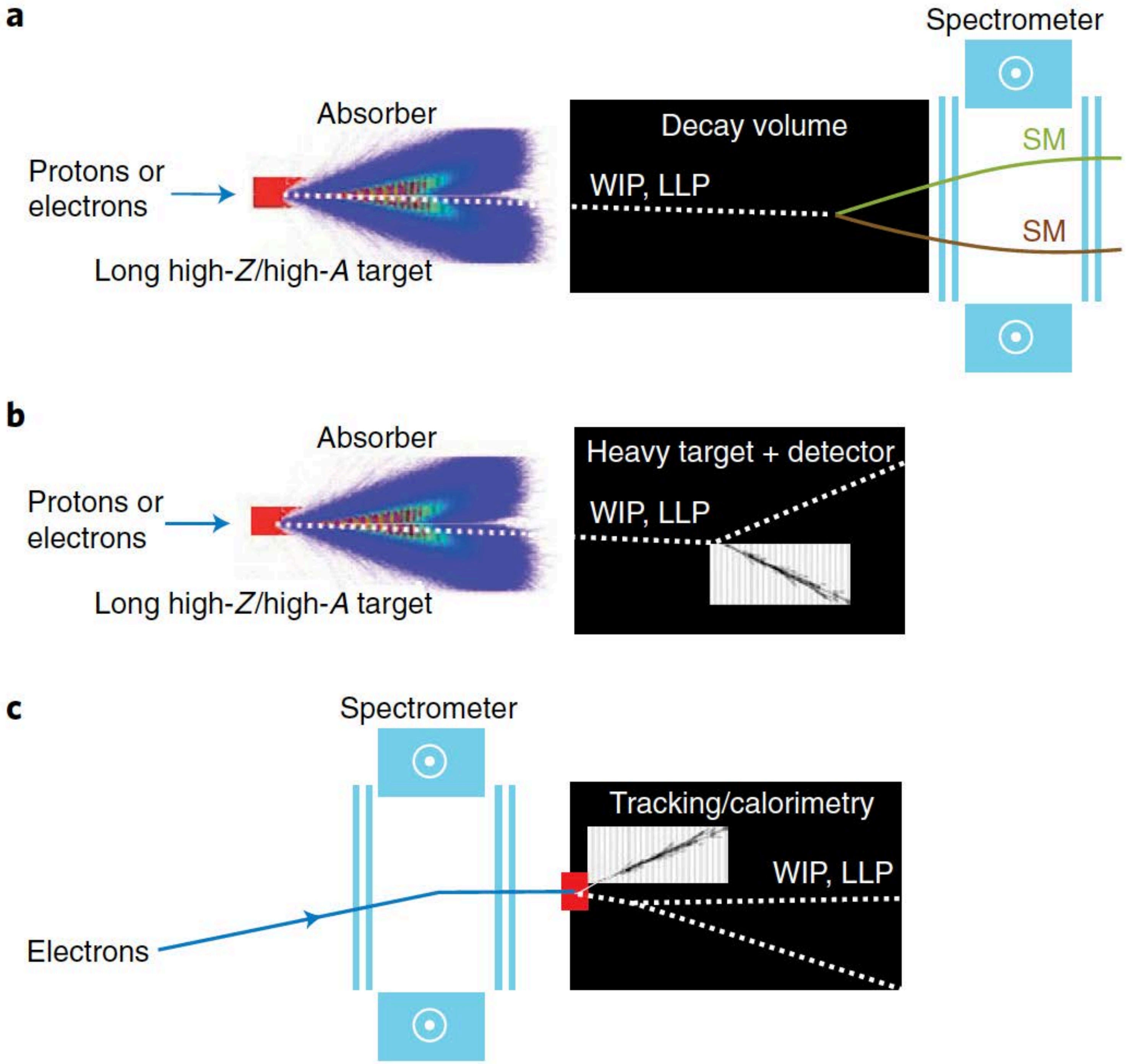


Beam dumps, Long Lived Particles
MeV – GeV (HNL, ALPS, Light Dark Matter)

Precision experiments
>>TeV (search for new physics in clean and very rare flavour processes or in EDMs)

Non-accelerator projects
Sub-eV (axions, ALPs)

Heavy Neutral Leptons (HNL), Axion-like particles (ALPS)


a
Spectrometer
Absorber
Decay volume
SM
Protons or electrons
WIP, LLP
SM
Long high-Z/high-A target
b
Absorber
Heavy target + detector
Protons or electrons
WIP, LLP
Long high-Z/high-A target
c
Spectrometer
Tracking/calorimetry
WIP, LLP
Electrons

North Area

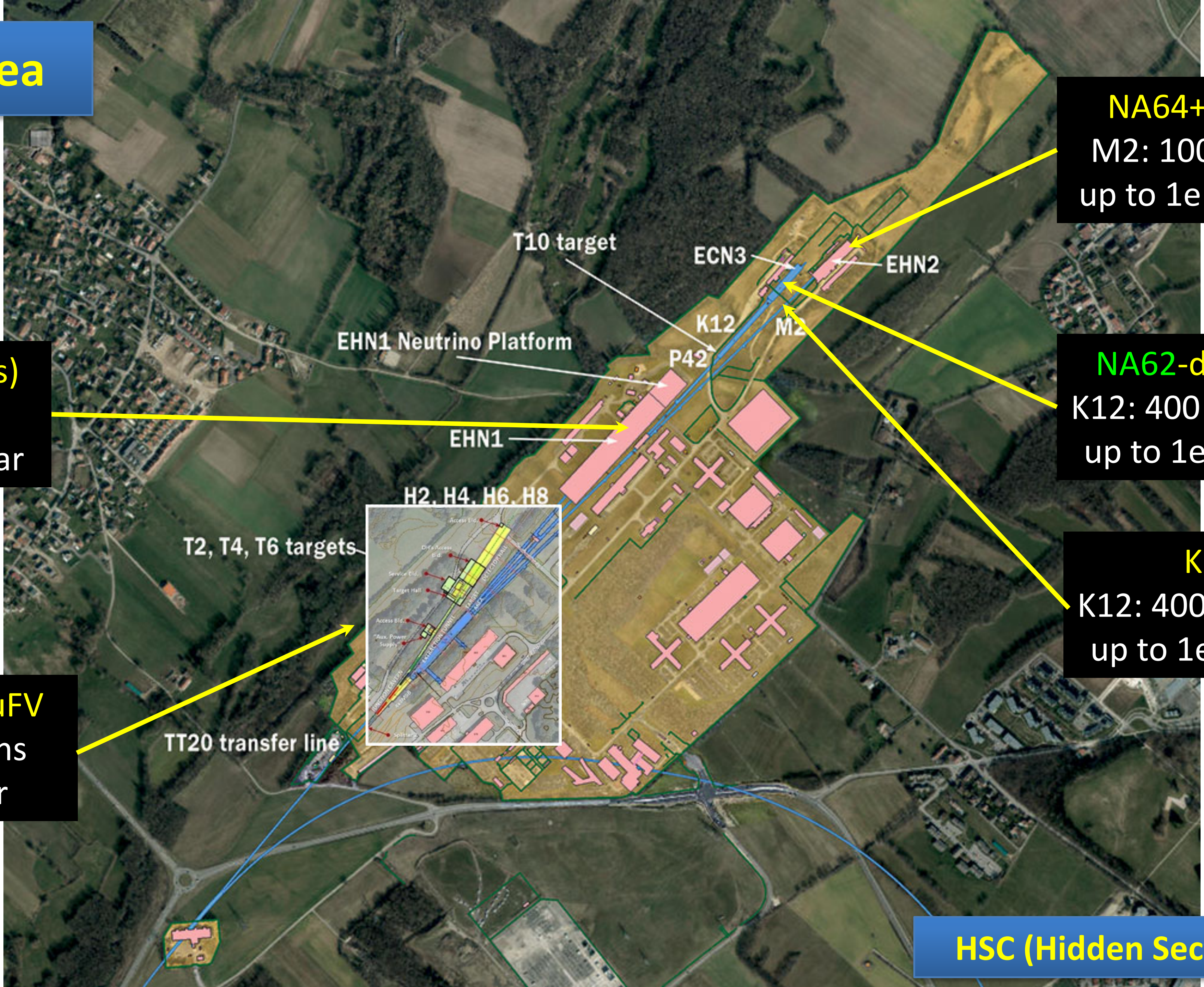
NA64++ (muons)
M2: 100 – 160 GeV
up to 1e13 mot/year

NA64++ (electrons)
H4: 100 GeV
up to 5e12 eot/year

NA62-dump mode
K12: 400 GeV protons
up to 1e19 pot/year

KLEVER
K12: 400 GeV protons
up to 1e19 pot/year

BDF -> SHiP, TauFV
400 GeV protons
4e19 pot/year



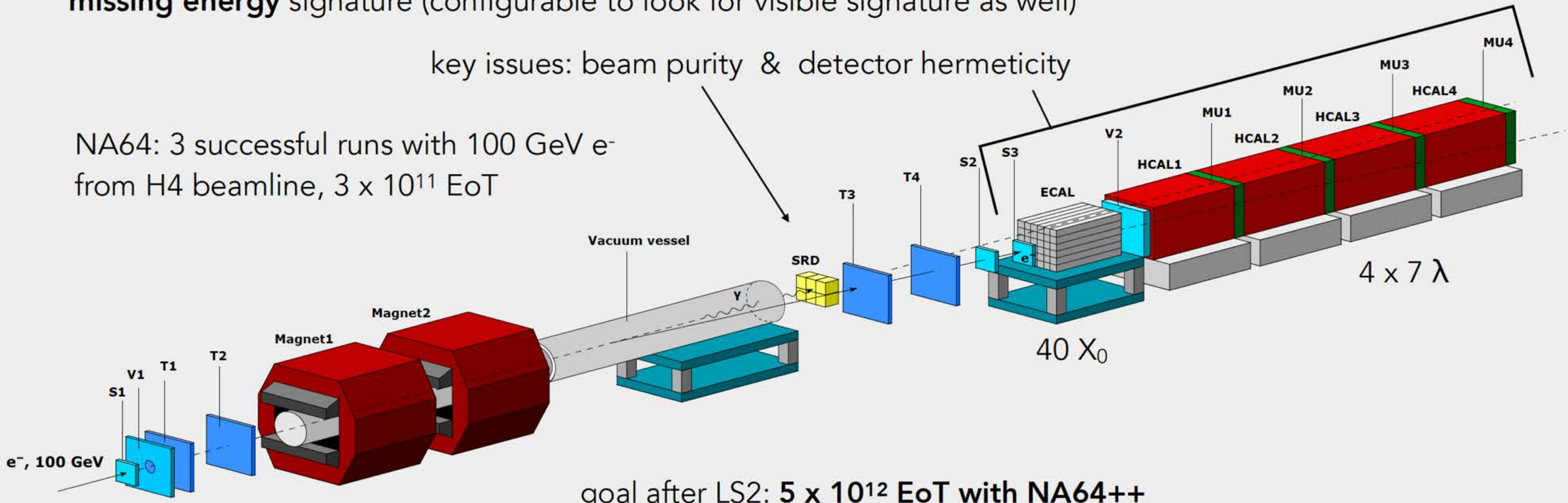
HSC (Hidden Sector Campus)

NA64++

missing energy signature (configurable to look for visible signature as well)

key issues: beam purity & detector hermeticity

NA64: 3 successful runs with 100 GeV e^- from H4 beamline, 3×10^{11} EoT



goal after LS2: **5×10^{12} EoT with NA64++**

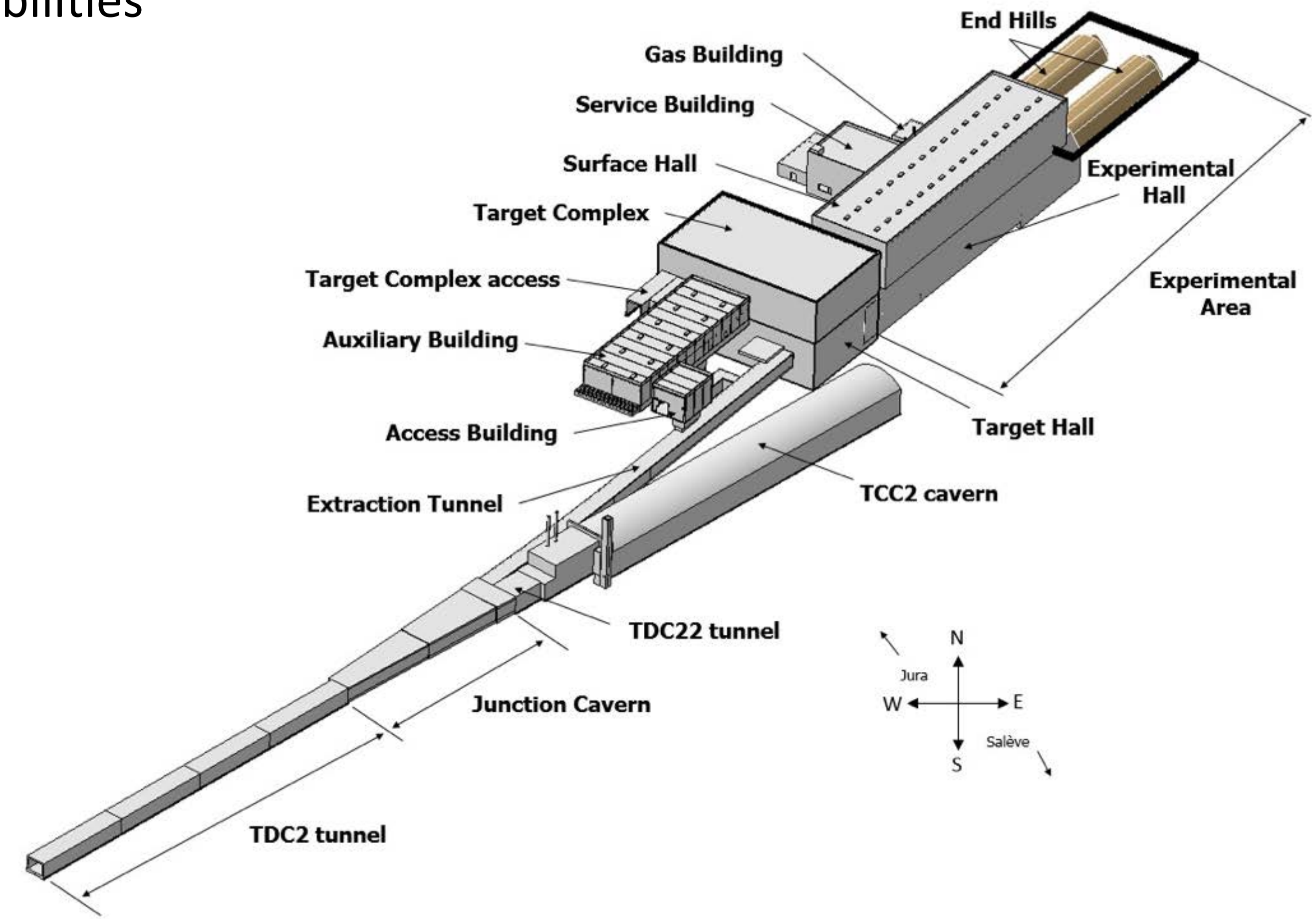
planned upgrades to detector/DAQ to circumvent pile-up limitations

in addition: extend Dark Photon search to muon beams (g-2, Dark Sector)

SPS Beam Dump Facility (BDF)

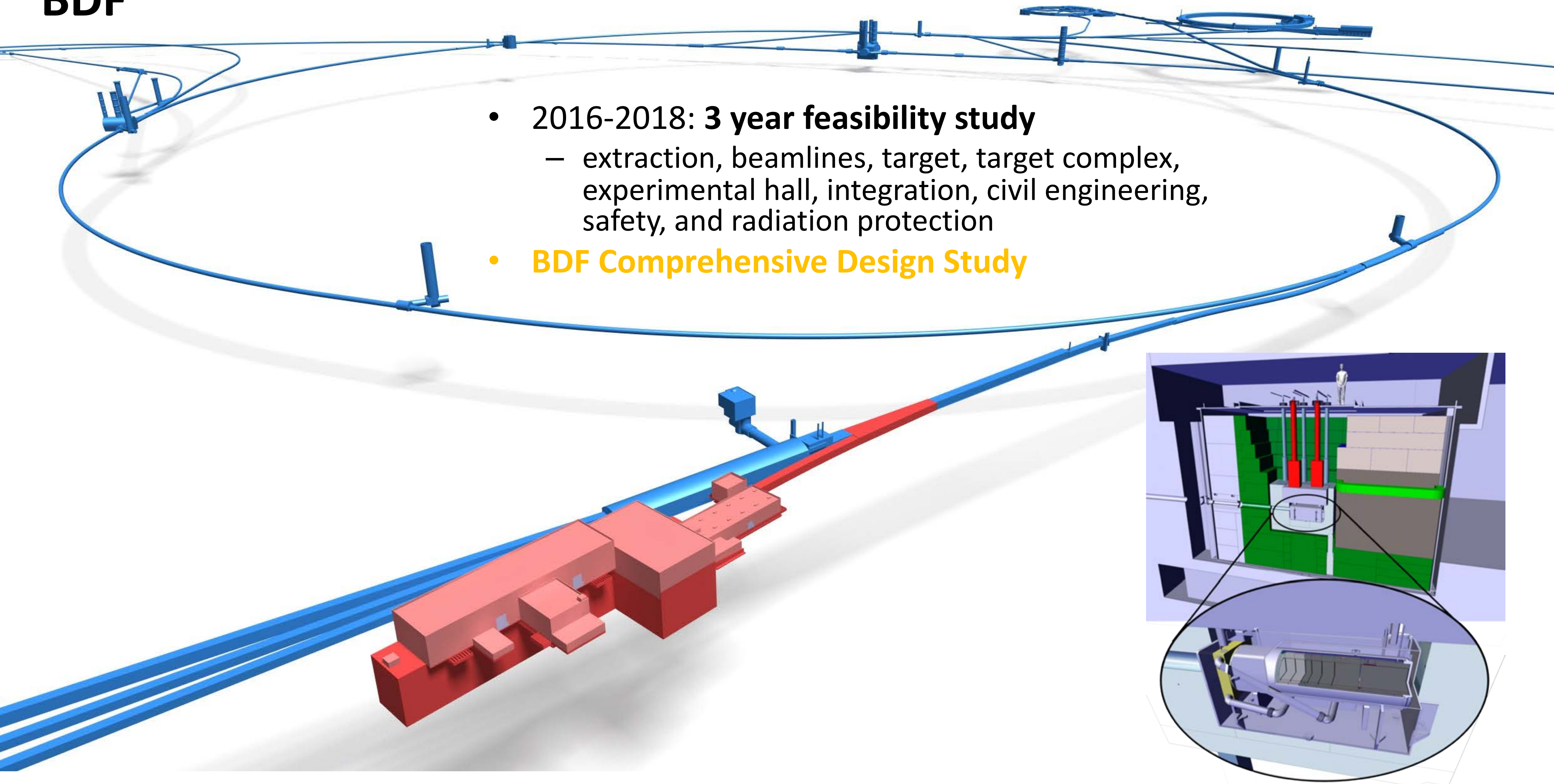
- Slow extraction from SPS into existing TT20 transfer line
- Switch to new transfer line at existing North Area splitters
- Heavy target plus magnetized hadron absorber
- Target complex with sophisticated handling capabilities
- Underground Experimental Hall

Momentum	400 GeV/c
Protons on target per cycle	4.0e13
Cycle length	7.2 s
Spill duration	1 s
Avg. power on target	355 kW
Avg. power on target during spill	2560 kW
Protons on target (PoT) per year	4e19
PoT in 5 years' data taking	2.0e20



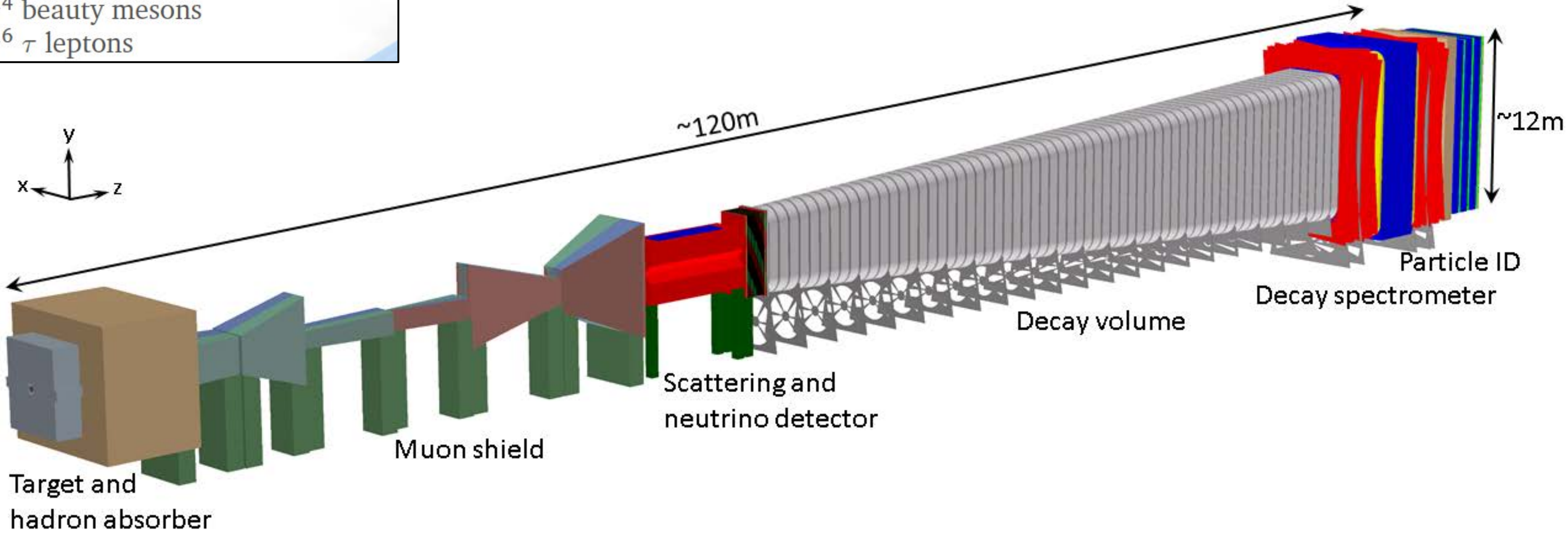
BDF

- 2016-2018: **3 year feasibility study**
  – extraction, beamlines, target, target complex, experimental hall, integration, civil engineering, safety, and radiation protection
- **BDF Comprehensive Design Study**



SHiP

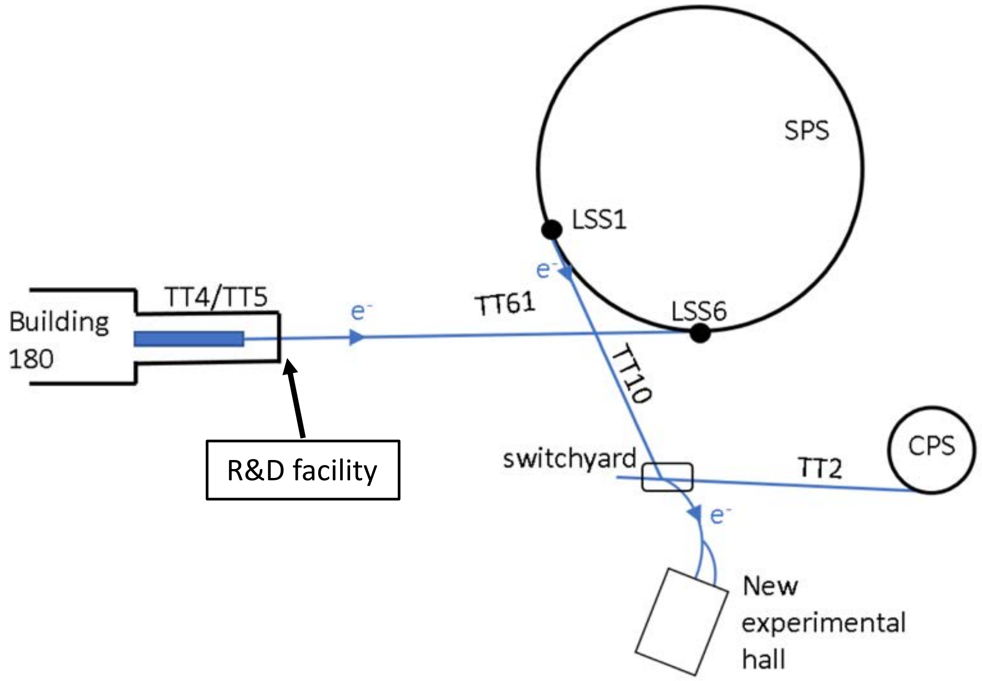
5 years of BDF @ SPS (2×10^{20} pot)
- 10^{18} charm mesons
- 10^{14} beauty mesons
- 10^{16} τ leptons

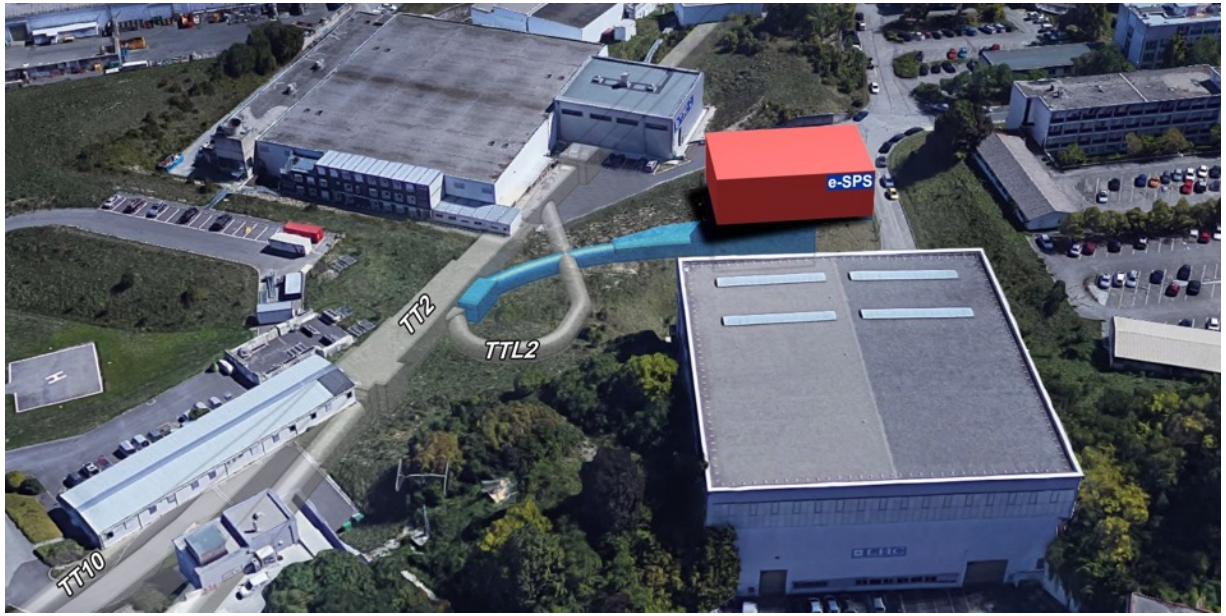


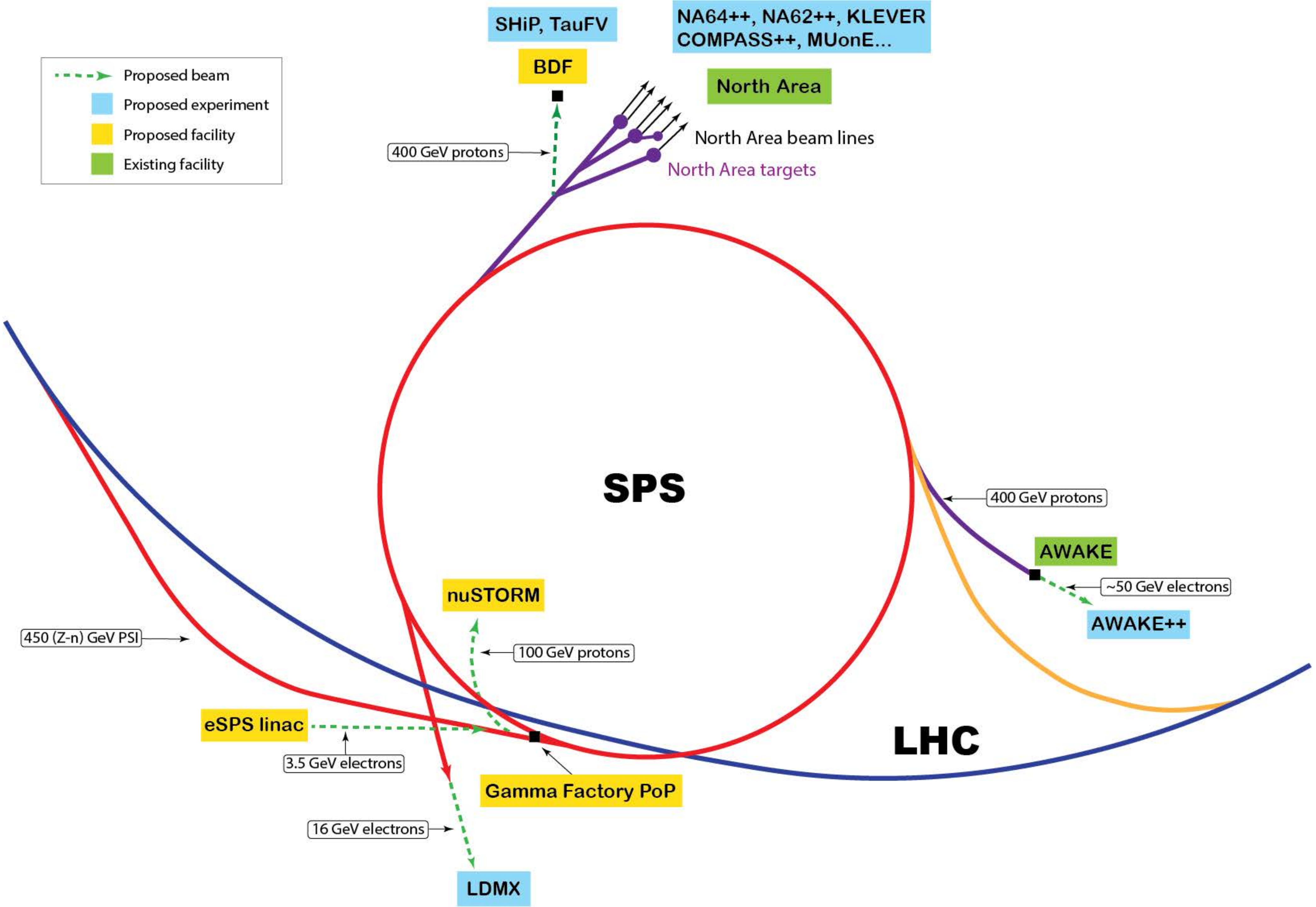
- A discovery machine for weakly coupled LLPs with a complementary detector for neutrino physics and LDM scattering signatures
- Large geometrical acceptance: long volume close to dump
- **“Zero” background**

eSPS

- ~70 m long X-band based linac (CLIC technology): e- to 3.5 GeV
- Acceleration to 16 GeV in the SPS
- Slow resonant extraction in ~10 s
- Beam delivered via the existing transfer line to the Meyrin site
- A new, short beamline would branch to an experimental hall
  - foreseen client is LDMX – a missing momentum active beam dump experiment



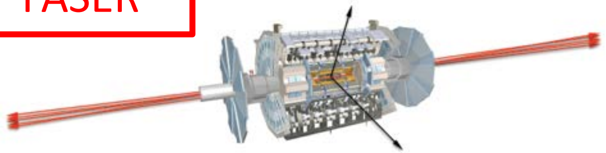




Proposed beam
Proposed experiment
Proposed facility
Existing facility
SHiP, TauFV
NA64++, NA62++, KLEVER
COMPASS++, MUonE...
BDF
North Area
400 GeV protons
North Area beam lines
North Area targets
SPS
400 GeV protons
AWAKE
~50 GeV electrons
AWAKE++
nuSTORM
100 GeV protons
450 (Z-n) GeV PSI
eSPS linac
3.5 GeV electrons
Gamma Factory PoP
LHC
16 GeV electrons
LDMX

Long Lived Particles at the LHC

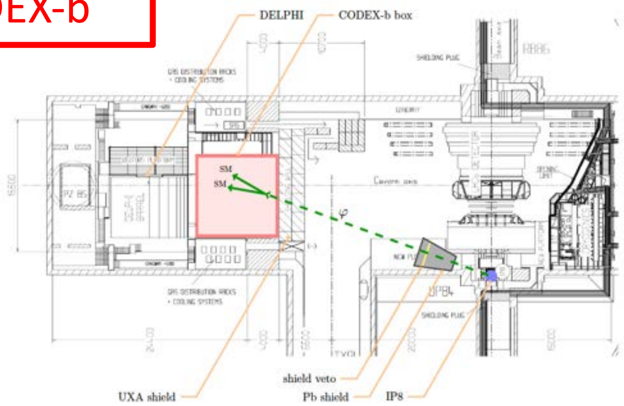
FASER



~1 m^3 ~ 5 μIKEAs

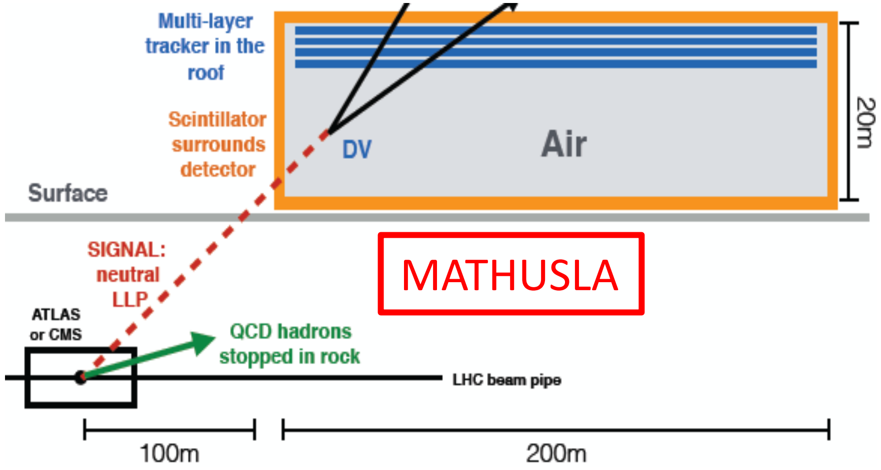
Feng, Galon, Kling, Trojanowski (2017)

CODEX-b



~1000 m^3 ~ 20 mIKEA

Gligorov, Knapen, Papucci, Robinson (2017)

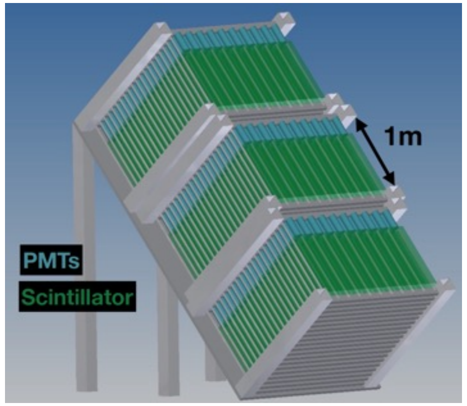


MATHUSLA

~800,000 m^3 ~ 4 IKEA

Chou, Curtin, Lubatti (2016)

milliQan

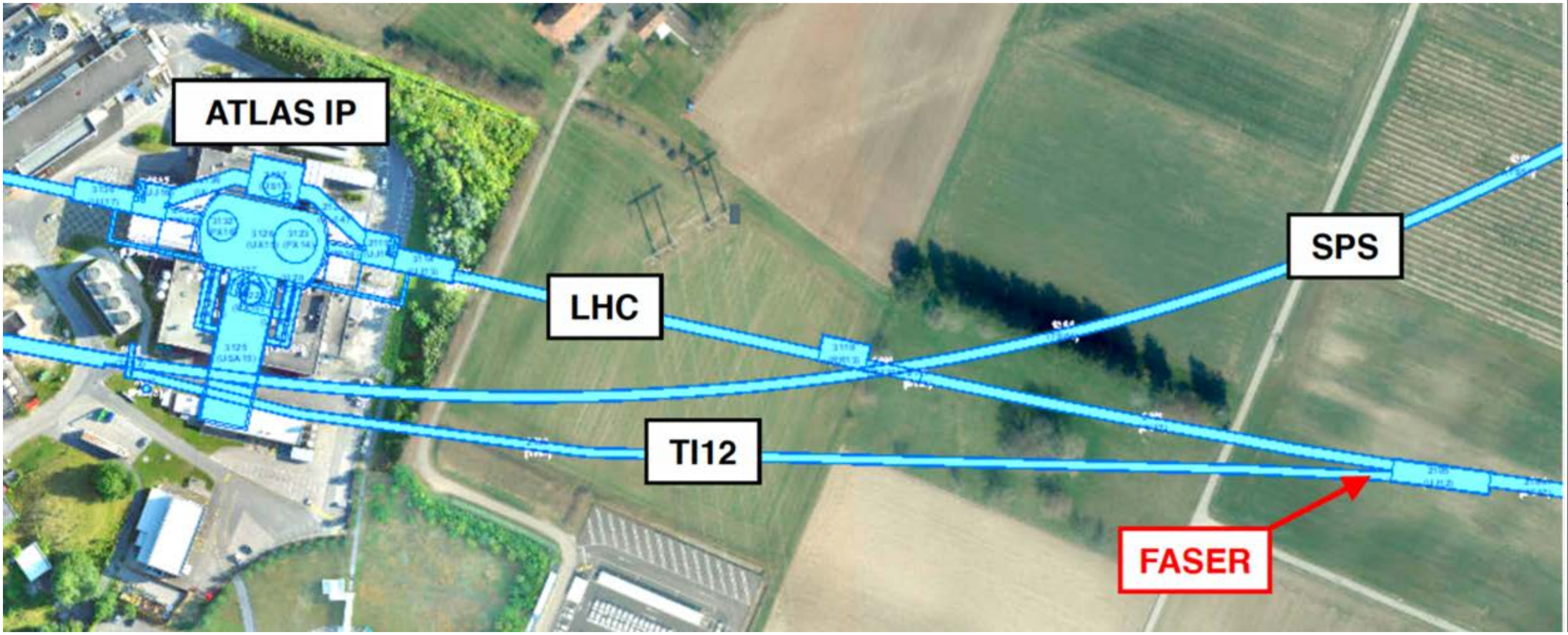


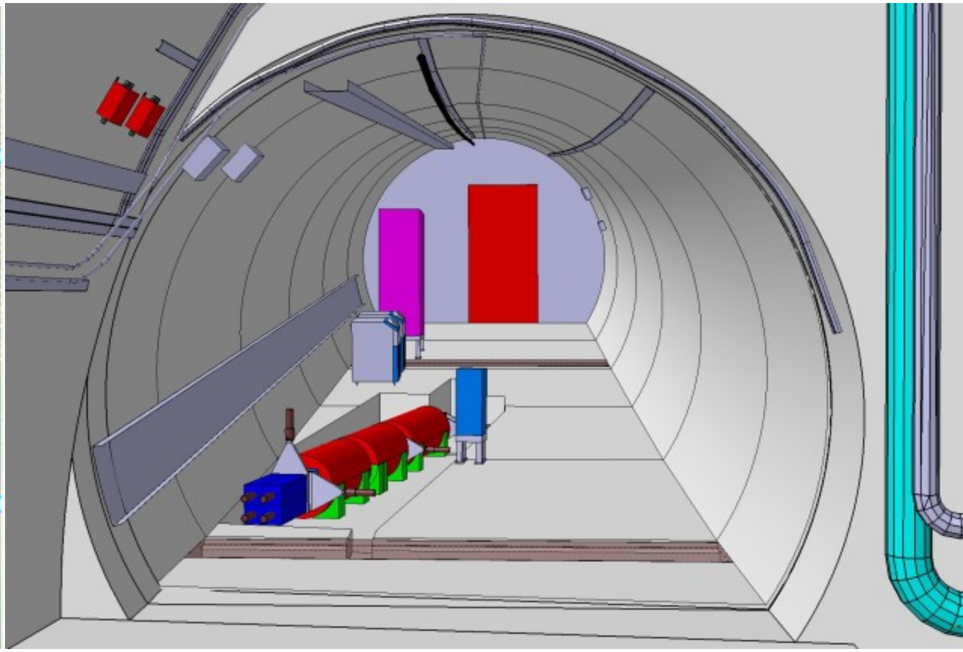
~9 m^3 ~ 35 μIKEAs

Long Lived Particles at the LHC

FASER: Installed in 2020

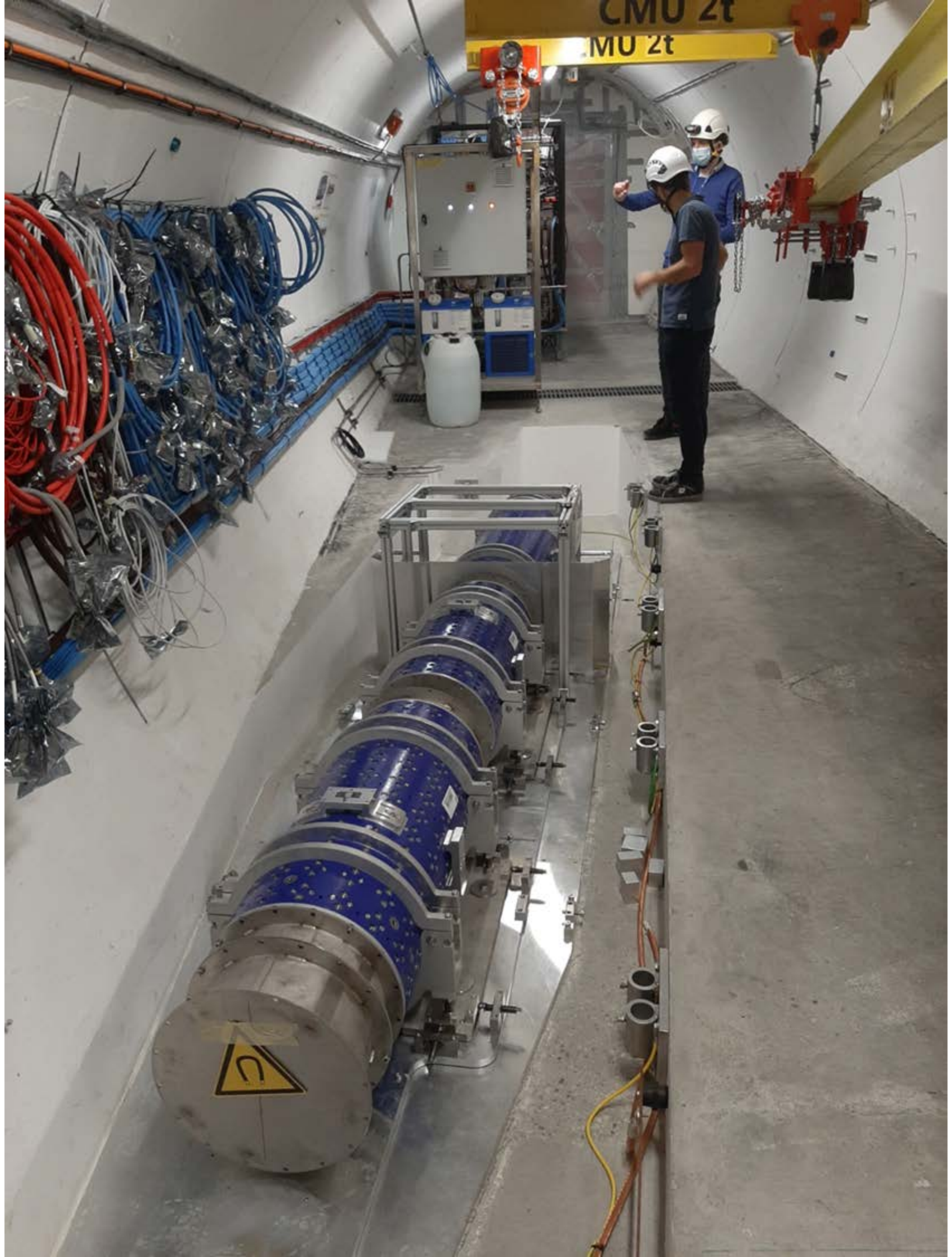
$pp \to \mathrm{LLP} + X, \quad \mathrm{LLP\ travels} \sim 480\ \mathrm{m}, \quad \mathrm{LLP} \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \gamma\gamma, \ldots$



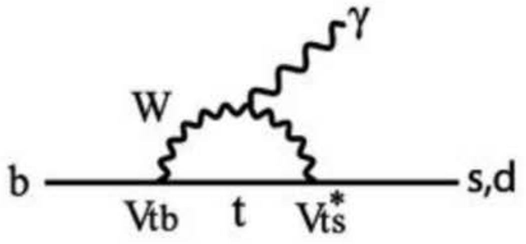


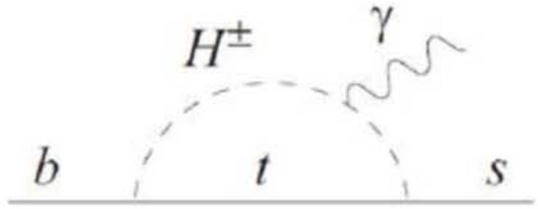
- FASER: sensitive to decays in a cylindrical region of radius R = 10 cm and length L = 1.5 m
- FASER2: R = 1 m and L = 5 m for construction in Long Shutdown 3


770


CMU 2t
MU 2t

Loop processes are sensitive to physics Beyond the Standard Model (BSM) since unobserved new particles might be able to enter in the loop.



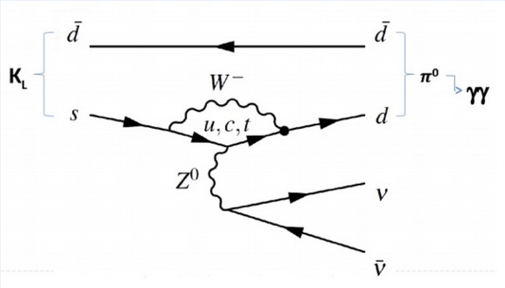


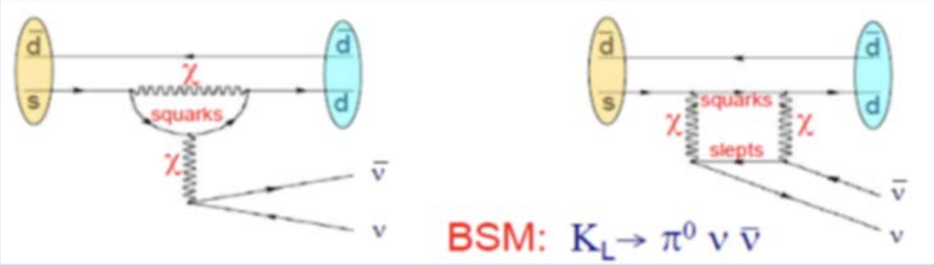
PRECISION

KLEVER

$K_L \to \pi^0 \nu\bar{\nu}$ **BR = (3.4 ± 0.6) × 10^{-11}**

BSM particle with loops can increase the rate by x10 with respect to SM

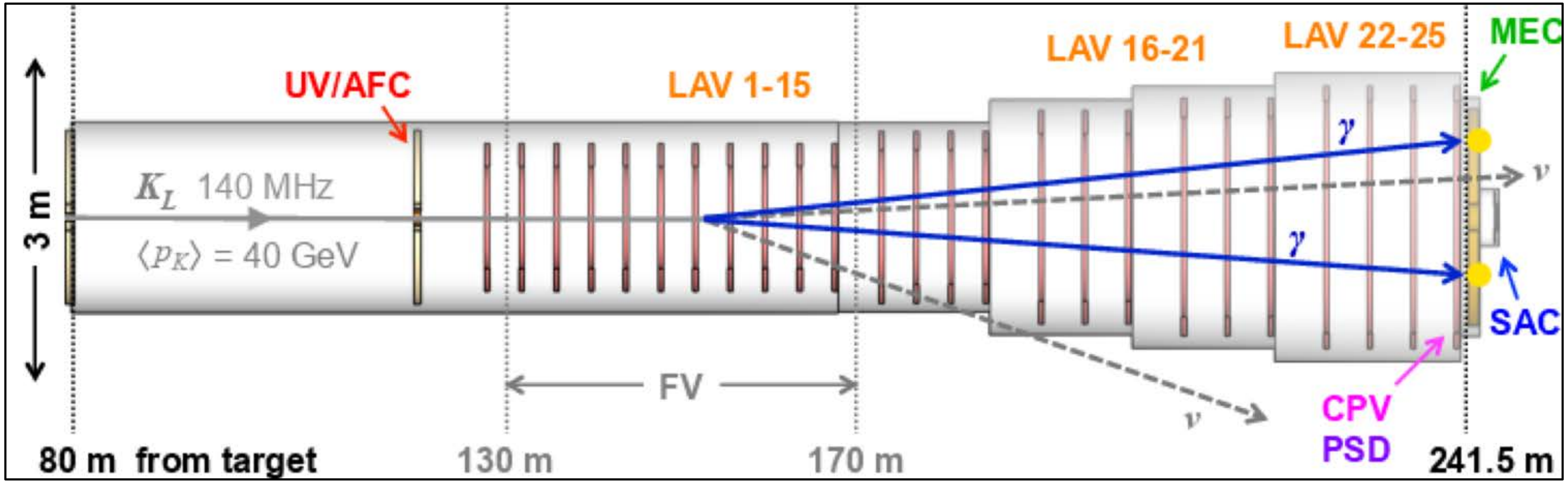




For 60 SM events, need:

5 × 10^{19} pot

e.g. 2 × 10^{13} ppp/16.8 s × 5 yrs

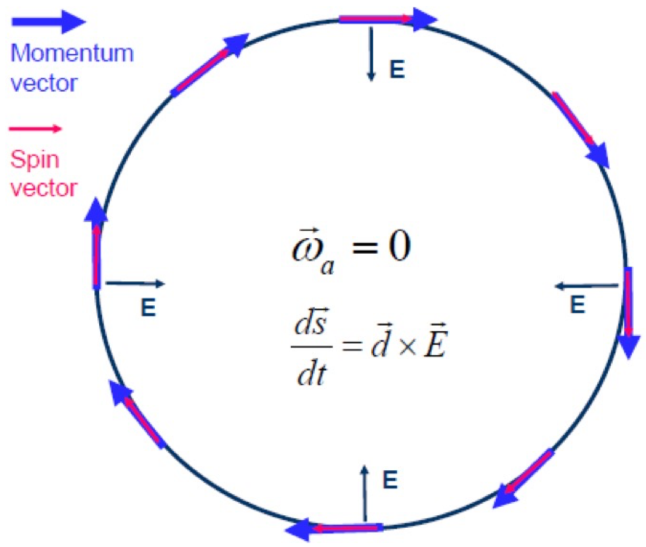


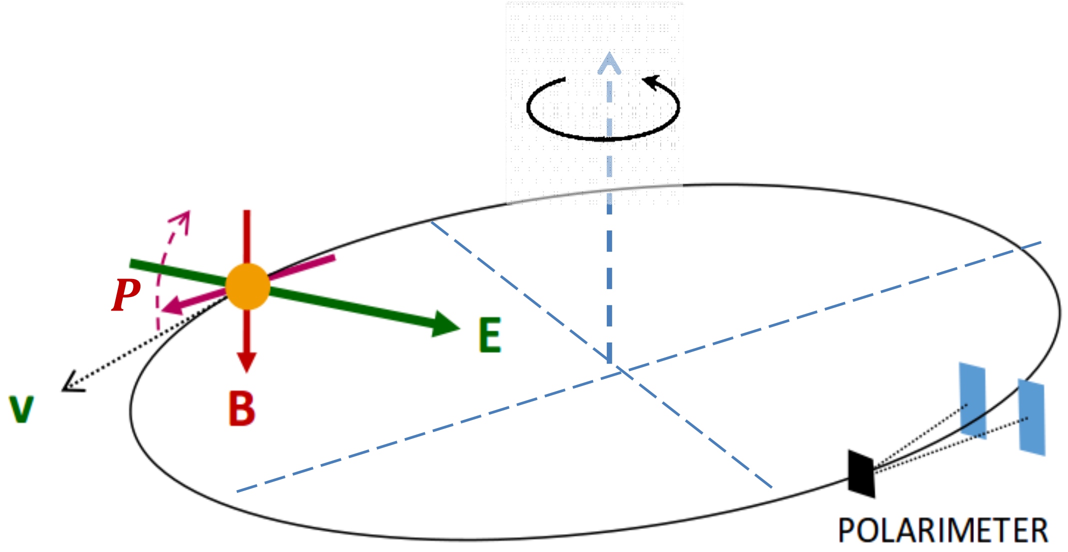
KLEVER experimental apparatus: upstream veto (UV), active final collimator (AFC), large-angle photon vetoes (LAV), main electromagnetic calorimeter (MEC), small-angle calorimeter (SAC), charged particle veto (CPV), pre-shower detector (PSD).

Study phase – start data taking ~2026

EDM Storage Ring

- Stored (proton) beam is spin polarized: begin with spins aligned along the momentum vector.
- Beam energy fixes the ratio between the magnetic and electric fields to keep the spin in the longitudinal direction (frozen spin)
  - For an all-electric proton ring E_{kin}=$\mathbf{232.8}$ MeV
- **An EDM generates a vertical spin component by coupling with radial E field**
- Difference in the scattering rate between the left and right directions is sensitive to the polarization.



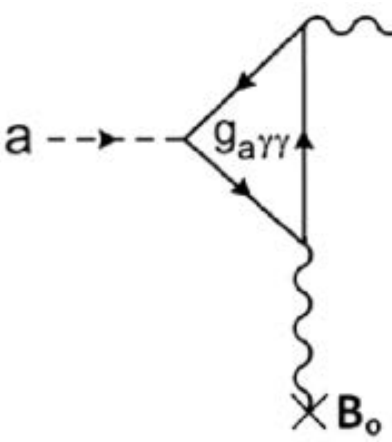


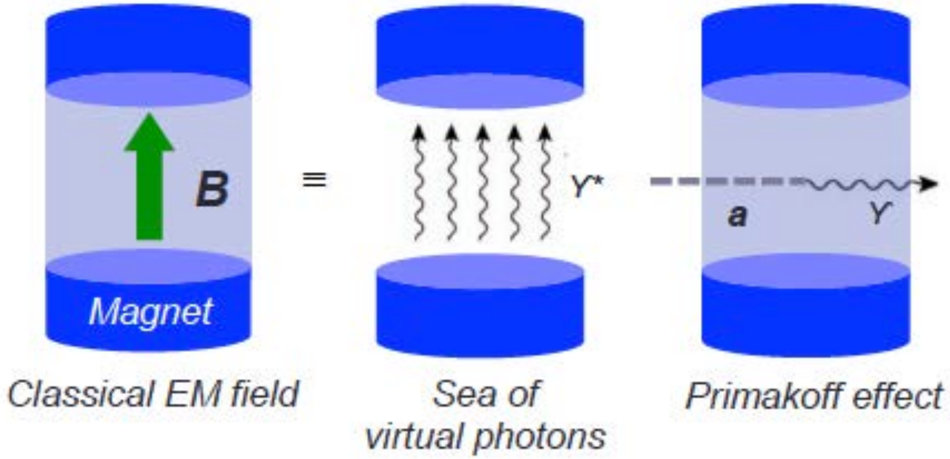
EDM Storage Ring

- Interesting potential statistical sensitivity (~10^{-29} e.cm)
- **Challenging systematics**
  – in particular parasitic radial magnetic field (~10 aT mimics 10^{-29} e.cm)
- **Extensive studies by EDM community**:
  – Polarimetry, deflectors, magnetic shielding, instrumentation
  – Optics, lattice, ring design, beam dynamics
  – Systematics and proposed mitigation measures, simulations

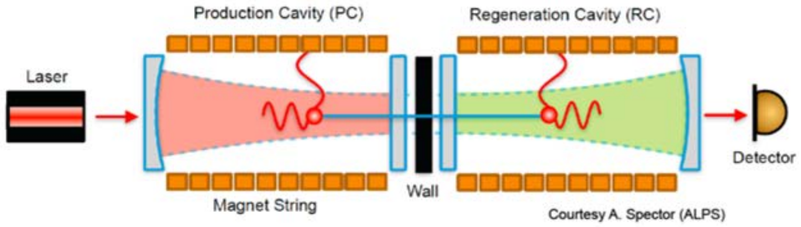
Prototype ring under consideration at COSY, IPK Jülich

Axion Detection

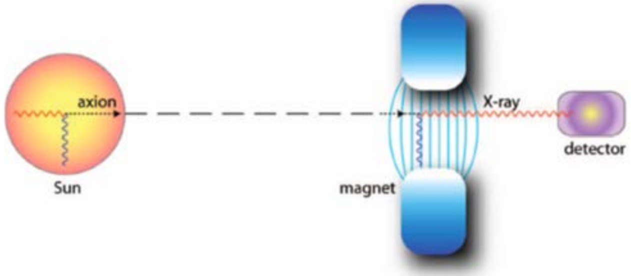




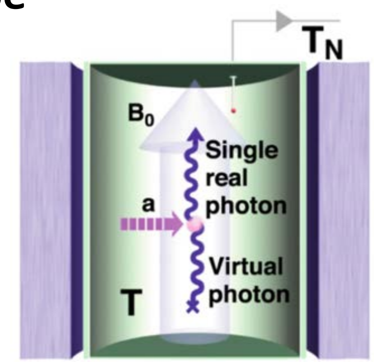
Light-shining-through-walls (LSW)



Helioscope



Haloscope



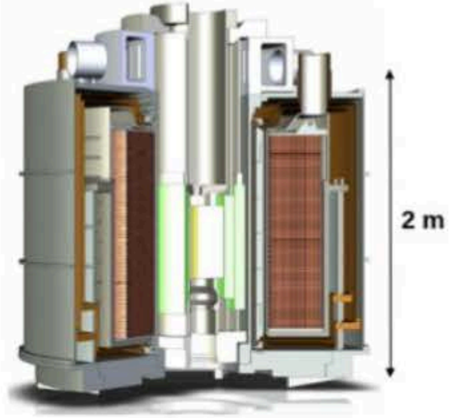
Detection of axions

Large complementarity among categories

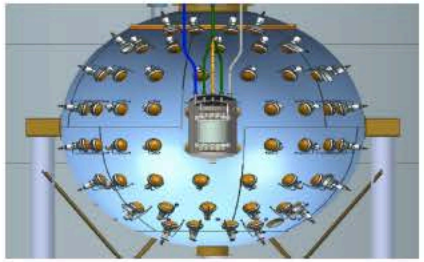
Source	Experiments	Model & Cosmology dependency	Technology
Relic axions 	ADMX, HAYSTAC, CASPEr, CULTASK, CAST-CAPP, MADMAX, ORGAN, RADES, QUAX, AXIOMA, ABRA, DM-Radio, …	High	New ideas emerging, Active R&D going on,…
Lab axions 	ALPS, JURA, OSQAR, CROWS, ARIADNE,…	Very low	Ready for large scale experiment
Solar axions 	SUMICO, CAST, (Baby)IAXO	Low	Ready for large scale experiment

Initiatives integrated into the Technology WG

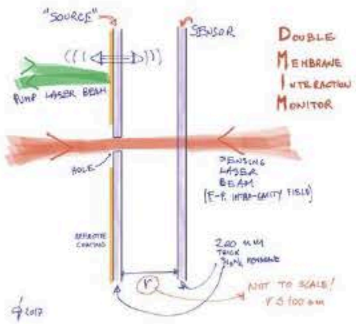
1) Haloscope LNCMI-Grenoble



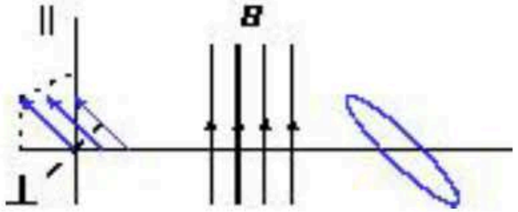
2) DarkSide

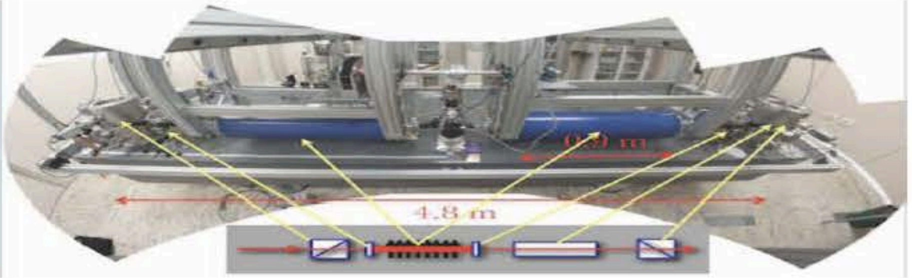


3) aKWISP

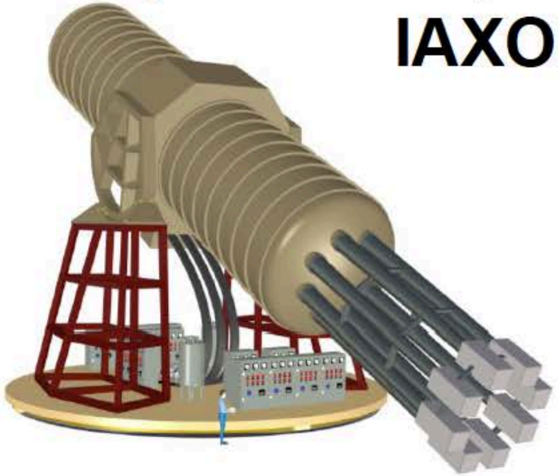


4) VMB@CERN

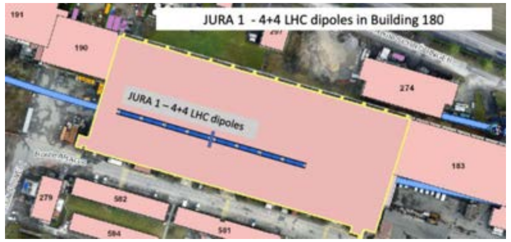




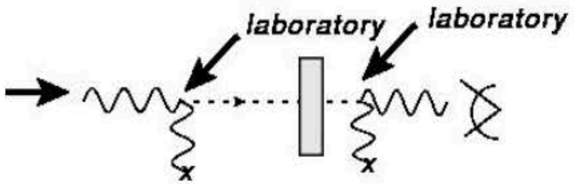
5) Helioscope IAXO



6) JURA (LSW combining ALPS-III and OSQAR+)

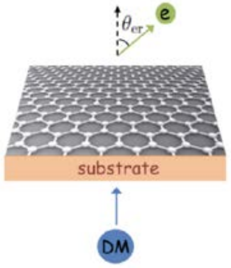


7) LSW-STAX

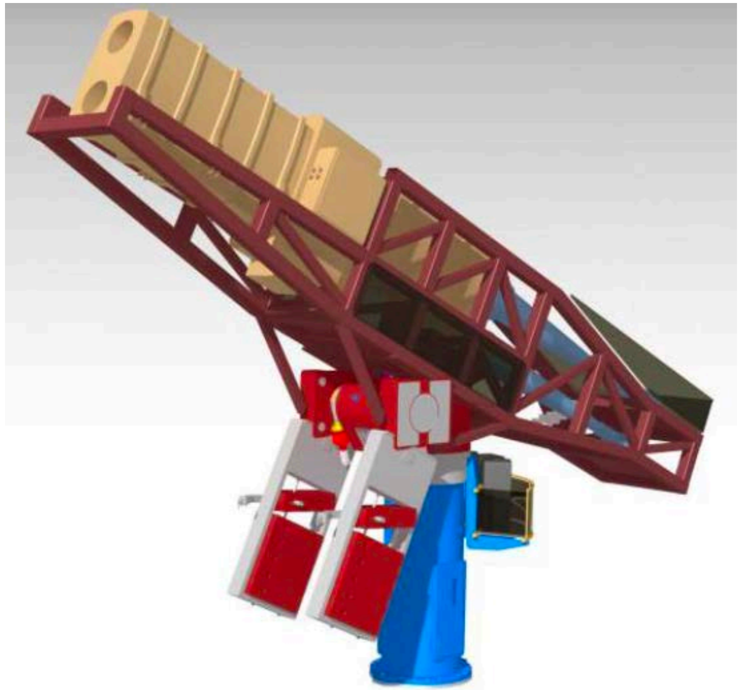


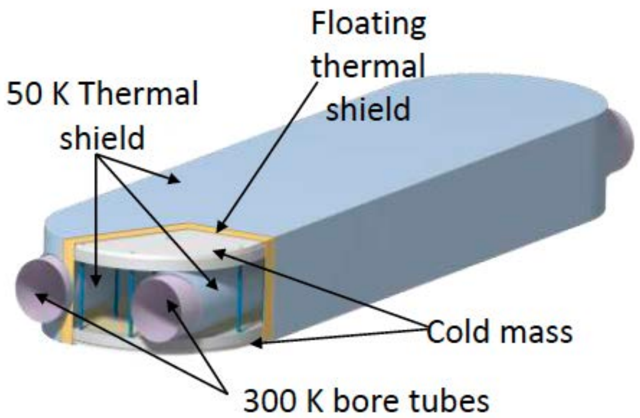
8) CNT Based DM Detector

PTOLEMY



IAXO by way of BabyIAXO





The Magnet Figure of Merit of an axion helioscope yields:

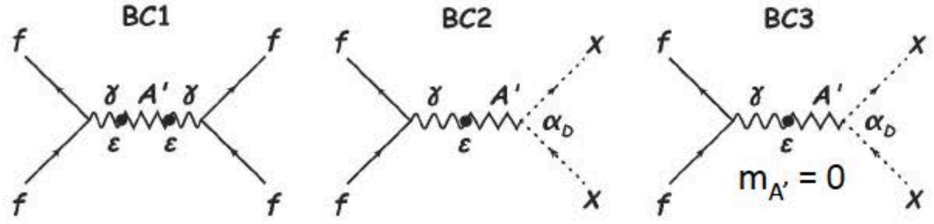
$$f_M \propto L^2 \int B^2(x,y)dx\,dy \rightarrow L^2B^2\mathrm{A}$$

Magnet design goal: maximize f_M while keeping cost down.

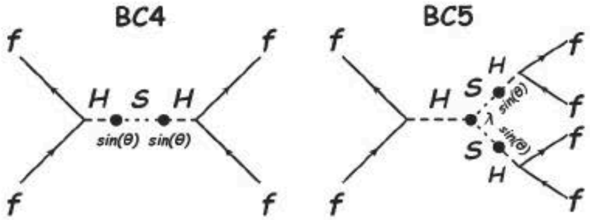
PBC BSM Benchmark Cases

The BSM WG selected a set of theoretically and phenomenologically motivated target areas used as benchmarks models to explore the physics reach of the received proposals and put them into the worldwide landscape.

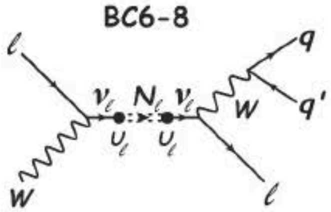
Dark Photons, Dark Matter & millicharged particles



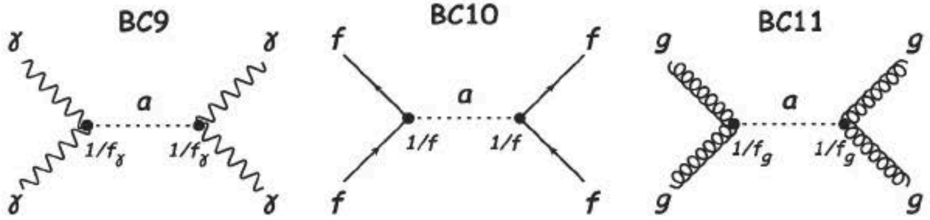
Dark Scalars



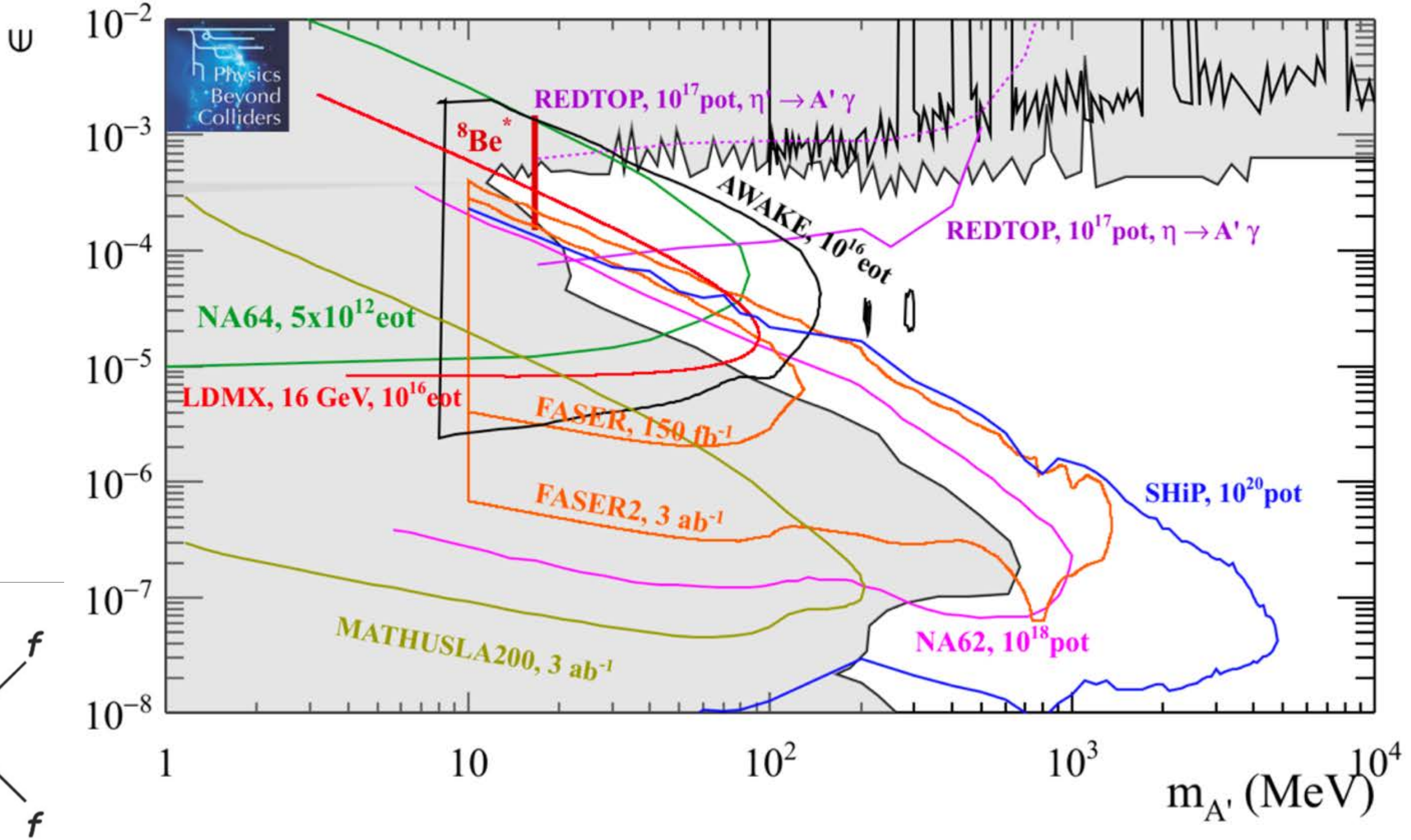
Heavy Neutral Leptons

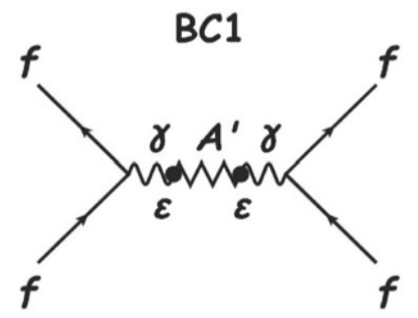


Axion-Like Particles



Dark photon – visible mode





Options - summary

Well motivated, competitive, cost-effective options, making good use of CERN's existing complex, beams, and expertise.

Rare decays and precise measurements
KLEVER ($K^0_L \rightarrow \pi^0 \nu\nu$)
TauFV@BDF: $\tau \rightarrow 3\mu$
REDTOP (η decays)
MUonE (hadronic vacuum polarization for ($g\text{-}2_\mu$))
EDM proton storage ring

Long-lived particles from LHC collisions
FASER, MATHUSLA, CODEX-b, milliQAN

Other facilities:
γ-factory via Partially Stripped Ions
nuSTORM

QCD measurements
COMPASS++, DIRAC++
NA61++, NA60++
Fixed target (gas, crystals) in ALICE & LHCb

Hidden sector with "beam dumps"
NA64++ (e,μ)
NA62++
Beam Dump Facility at North Area (SHiP)
LDMX@eSPS
AWAKE++

Non-accelerator projects
Exploit CERN's technology (RF, vacuum, magnets, optics, cryogenics) for experiments possibly located in other labs.
E.g. axion searches: IAXO (helioscope), JURA (Light Shining through Wall)

2020 Strategy Statements

4. Other essential scientific activities for particle physics

Diverse science at low energy: exploration of dark matter and flavour puzzle

- Change of paradigm for dark matter particles - could be as light as 10^{-22} eV to as heavy as primordial black holes of $10 \times M_{\odot}$
- Observed pattern of masses and mixings of quarks and leptons, remains a puzzle
- **Physics Beyond Colliders study identified many high impact options with modest investment**
- **Larger scale new facilities such a the Beam Dump Facility, and later LHeC option at CERN, difficult to resource within the CERN budget, considering the other recommendations of this Strategy**
- Improvements in the knowledge of the proton structure needed to fully exploit the potential of present and future hadron colliders - added value from fixed target experiments and from Electron Ion Collider (CD0) in BNL
- Given the challenges faced by CERN in preparing for the future collider, **the role of the National Laboratories in advancing the exploration of the lower energy regime cannot be over-emphasised** (ex. axions at DESY, rare muon decays in PSI, dark photon in Frascati)

a) The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through **precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions, dark sector candidates and feebly interacting particles**. There are many options to address such physics topics including energy-frontier colliders, accelerator and non-accelerator experiments. 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.*

Deliberation Doc - detail

- A dedicated Physics Beyond Colliders study group was set up at CERN to explore the opportunities offered by the CERN accelerator complex and infrastructure to gain new insights into some of the outstanding questions in particle physics through projects complementary to high-energy colliders and other initiatives in the world.
- This generated a lot of interest and became the de facto focal point for new research initiatives centred not only on the potential of the CERN facilities but also other facilities available throughout Europe in the National Laboratories and research institutes.

			2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
		SPS	LS2						LS3					
		LHC	LS2		Run 3				LS3			Run 4		
North Area	NA64-electron	Operational	LS2		Data Taking									
	NA64-mu	< 1 MCHF	Studies		Test	Pilot	Phase 1							
	NA61/Shine	< 2 MCHF	Detector upgrade		Data Taking					Data Taking				
	MUonE	< 2 MCHF	Preparation		Pilot	Run 1	Data Taking							
	NA62-beamdump	< 1 MCHF	Studies		1e18 PoT in Run 3									
	KLEVER	~40 MCHF	EoI/proposal		R&D/Construction				Installation	Data Taking				
	COMPASS++	~10 MCHF	Studies/proposal		Phase1 Data Taking/Studies/R&D				Installation	Data Taking				
LHC	ALICE fixed target	<5 MCHF			Design/tests				Preparation/Construction			Data Taking		
	LHCb fixed target	<5 MCHF		Design	Construction and testing			Data	LS3			Data Taking		
	LHC Spin	~5 MCHF	Study		R&D				Production/Installation			Data Taking		
	FASER	~5 MCHF	Installation		Data Taking				Upgrade - phase 2			Data Taking		
	MATHUSLA	<100 MCHF		Funding to test design			Construction					Data Taking		
	CODEX-b	<5 MCHF	EoI		Beta		Beta data taking		Production/Installation			Data Taking		
	MilliQan	<5 MCHF	Demonstrator		Funding/Construction				Upgrade			Data Taking		
SPS	LDMX/eSPS	<10 MCHF			Studies		Production/Installation			Data Taking				
	SHiP	~70 MCHF	CDR		TDR/Prototypes			Production/construction			Installation		Data Taking	
	TauFV	tbc	Design		CDR	TDR/Prototypes		Production/construction			Installation		Data Taking	
TECH	BabyIAXO (DE)	<5 MCHF		Production/construction			Commission	Data Taking						
	IAXO	~60 MCHF					Design, prototyping, construction, integration and commissioning (start tbc)							
	VMB	<5 MCHF	LoI	Studies										
	AION-100	tbc			Studies									
FACILITY	AWAKE	~15 MCHF	Prep/construction		AWAKE Run 2				LS3	AWAKE++?				
	eSPS	~80 MCHF	CDR		TDR		Preparation/Construction			Data Taking				
	Beam Dump Facility	~160 MCHF	CDR	TDR			Construction/Installation						Operation	
	Gamma Factory	~2 MCHF		CDR	SPS Proof of Principle/TDR				Preparation			LHC demo		
	nuSTORM	>160 MCHF	Study	CDR		TDR/Prototyping						Approval		
	CPEDM prototype (DE)	~20 MCHF	Study	CDR		TDR		Construction		Data Taking				

PBC Future

- Success of PBC recognized
  - Forum for presenting new experiments, novel adaptation of existing experiments, new approaches
  - Systematic evaluation of physics reach (BSM, QCD)
  - Fostering initiatives, development of proposals & novel applications, performance evaluation, improved performance, hardware developments, leveraging accelerator technology in experiments
- Agreed with CERN management that PBC continues
  - mandate to be revisited
  - re-kick-off PBC meeting foreseen early 2021
- Cross laboratory initiatives (e.g. IAXO, EDM) very much supported

MTP 2020

- A diverse scientific programme is strongly supported by the 2020 Strategy update, which also recognised the role of the **Physics Beyond Colliders** (PBC) study group as the focal point for promoting and channelling new research initiatives on non-collider physics at CERN and European national laboratories.
- A number of small-scale experiments considered in the PBC framework for the use of the injectors or for fixed-target studies at the LHC are now being assessed by the relevant scientific committees (SPSC and LHCC) or are in the process of being implemented.
- Examples of the latter include FASER, a small and inexpensive experiment designed to search for light, weakly-interacting particles produced at the LHC, extensions of the NA62 and NA64 experiments to search for such particles in beam-dump mode, and the SMOG-2 fixed-target studies at LHCb.
- Support is and will continue to be provided also to projects at European national laboratories, such as the BabyIAXO axion search experiment at DESY and a prototype storage ring for proton electric dipole moment studies at the Jülich research centre in Germany.
- Given the importance of a diverse scientific programme to addressing the outstanding questions in particle physics in a way complementary to high-energy colliders, PBC activities are funded with an increased budget of 3 MCHF/year in this MTP (up from 1 MCHF/year).

MTP 2020

(in MCHF, 2020 prices, rounded off to 0.1 MCHF until 2025, 1 MCHF thereafter)	Revised 2020 Budget	2021	2022	2023	2024	2025	**Total 2020-2025**	2026	2027	2028	2029	2030	**Total 2020-2030**
Scientific diversity projects	**14.6**	**23.8**	**23.9**	**23.5**	**23.1**	**22.5**	**131**	**15**	**15**	**15**	**20**	**28**	**224**
Neutrino Platform	*7.0*	*12.3*	*11.5*	*11.4*	*11.2*	*11.2*	*65*	*4*	*4*	*4*	*4*	*4*	*84*
Physics Beyond Colliders	*1.1*	*3.2*	*3.6*	*3.4*	*3.4*	*3.4*	*18*	*3*	*3*	*3*	*8*	*16*	*52*
EU supported computing R&D, support to external facilities	*6.4*	*8.3*	*8.8*	*8.6*	*8.5*	*8.0*	*49*	*8*	*8*	*8*	*8*	*8*	*89*

Preliminary PBC support summary

	Goal	PBC Support	Time frame
BDF	TDR	CE, Target, Beam Transfer, some material	20 - 23
eSPS	CDR	CE, Integration, Beam Transfer, [RF]	20
Conv. Beams	Proposals – studies/development	Personnel	20 - 25
LHC-FT crystals	Bent crystal developments	Personnel, material	20 - 25
(LHC-FT gas)	Development/deployment	[Machine side support for implementation]	20 - 25
Gamma Factory	**Proof of Principle staged deployment**	**Beam Transfer, Integration, material, personnel**	**20 - 25**
Technology	Proposal developments (IAXO,VMB…)	Personnel	20 - 25
EDM	CDR for prototype ring, prototypes	Continued CERN involvement - personnel	20 - 25
LHC-LLP	Development/deployment	CE, Integration, accelerator sector support	20 - 25
AION-100	Exploratory study	CE, Integration, accelerator sector support	21+
AWAKE++	Exploratory study	CE, Integration, accelerator sector support	21+

Generic support

- Essentially fellows (with group support) who multitask across PBC initiatives
  - very successful up to now – big thanks to the individuals involved
    - Civil engineering
    - Radiation protection
    - Integration
    - Beam transfer
    - Accelerator physics

Could provide all necessary PBC support to, say: TauFV, AION-100, LLP, eSPS…

Conclusions

- PBC delivered on its original mandate (BSM, QCD, ACC)
- Physics driven “diversity” remains strategically important
- In challenging circumstances, PBC has been given the opportunity to build on the achievements so far
- Details to be established – looking forward to re-engaging with the community, workshop planned early 2021
- Gamma Factory very much on the list!