Beyond Colliders

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PBC working groups

PBC - Brief

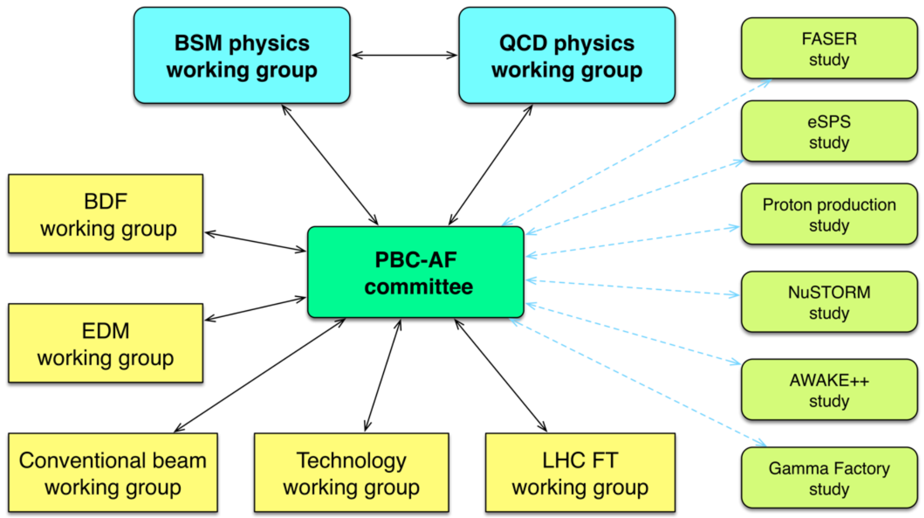
- **Maximize physics reach of existing complex**
  - New facilities exploiting existing complex
  - Novel exploitation of existing facilities
  - Provide support for novel off-site facilities
  - Harness the existing expertise and resources

Within the limits posed by an already vibrant and diverse physics program (beam, resources)

Evaluate these options motivation and competitiveness in a world wide scape

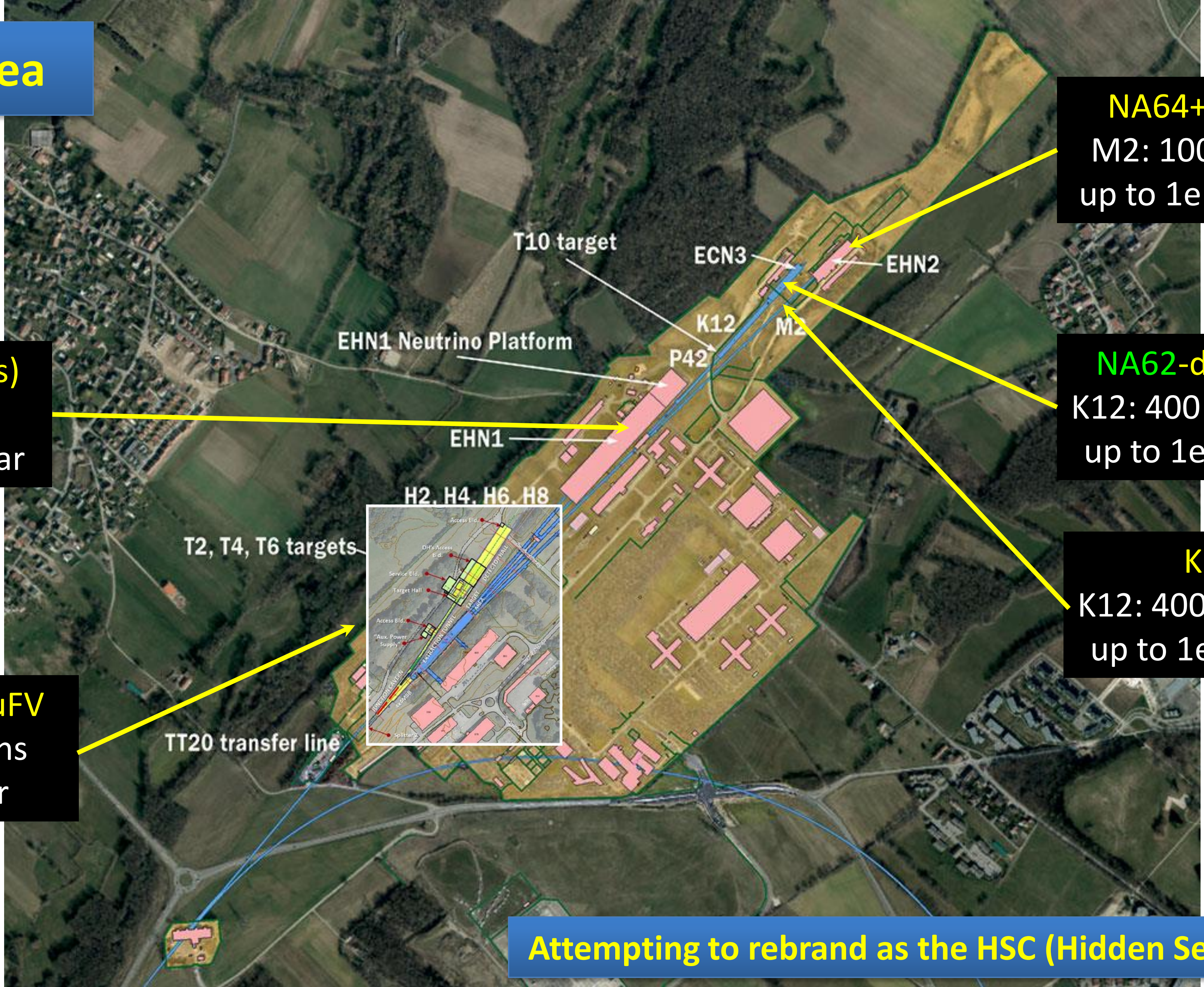
PBC accelerator side - main themes

- **Exploitation of SPS/North Area**
  - **Conventional North Area beams, BDF for SHiP/TauFV, eSPS, nuSTORM**
- **Novel approaches**
  - **EDM storage ring, Gamma Factory,** AWAKE++
- **LHC**
  - LHC fixed target (gas, crystals), Long Lived Particles
- **Technology**
  - Leveraging CERN's technical expertise - **various options (IAXO, LSW, VMB…)**



Covered here

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

Attempting to rebrand as the HSC (Hidden Sector Campus)

Conventional Beams at the North Area

Proposals followed by the CB WG - healthy mix of HS/QCD

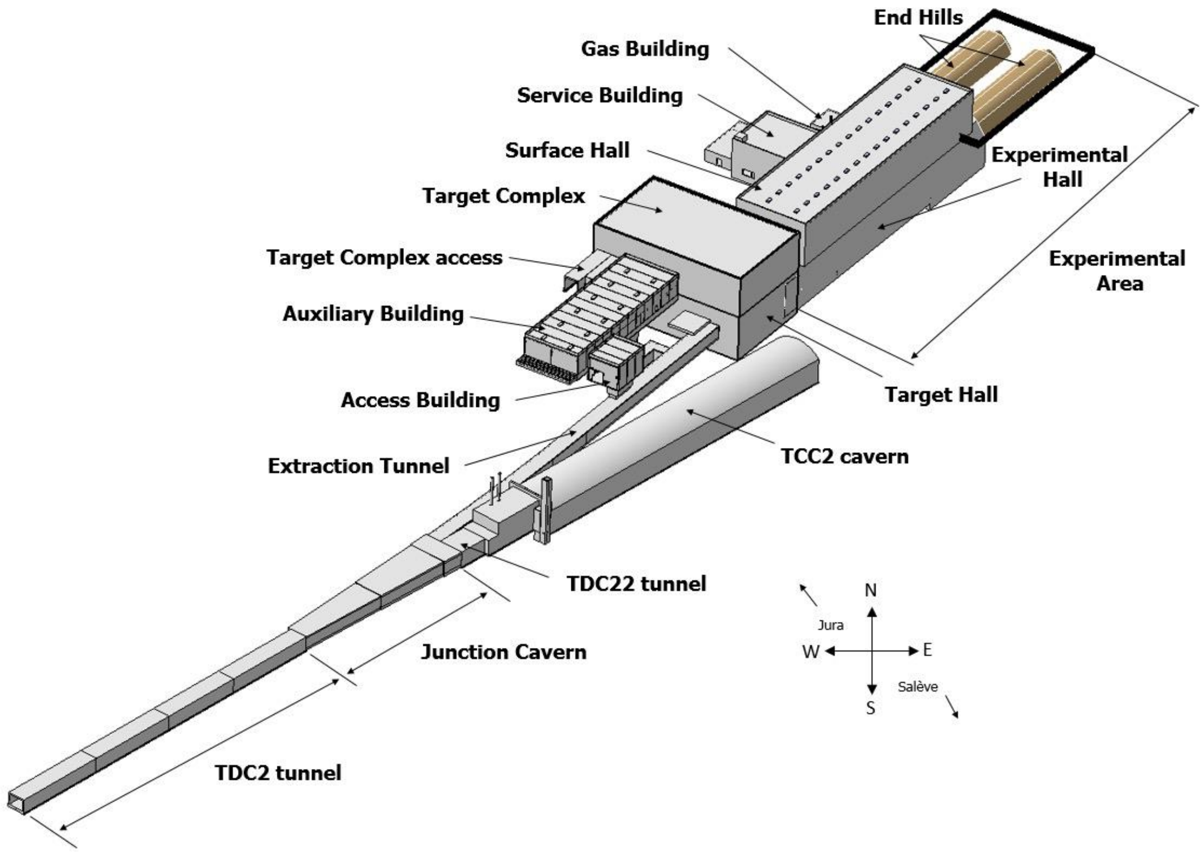
NA62++	Dark Sector	Optimise conditions for NA62 in beam dump mode
NA64++ (e,h)	Dark Sector	Increase electron flux and optimise hadron beams in the H4 line
NA64++ (u)	Dark Sector	Study a NA64-like experiment with muons in EHN2
KLEVER	$K_0 \rightarrow \pi^0 \nu\bar{\nu}$	New beam for a rare decays with high proton flux
NA61++	QGP charm	Higher intensity with better protection
COMPASS++	Full QCD program	Study new requests from COMPASS, including a RF separated beam
MUonE	HVP (g-2)	Implementation for operation with μ and e beams
DIRAC++	Chiral QCD	Options for a DIRAC follow-up experiment at the SPS
NA60++	QGP phase	Options for a NA60 follow-up experiment with heavy ion beams

- **Maturity of proposals and the effort required varies considerably**
- **Follow-up dictated by collaboration strength and CERN side resources; overseen by CERN committees**

SPS Beam Dump Facility (BDF)

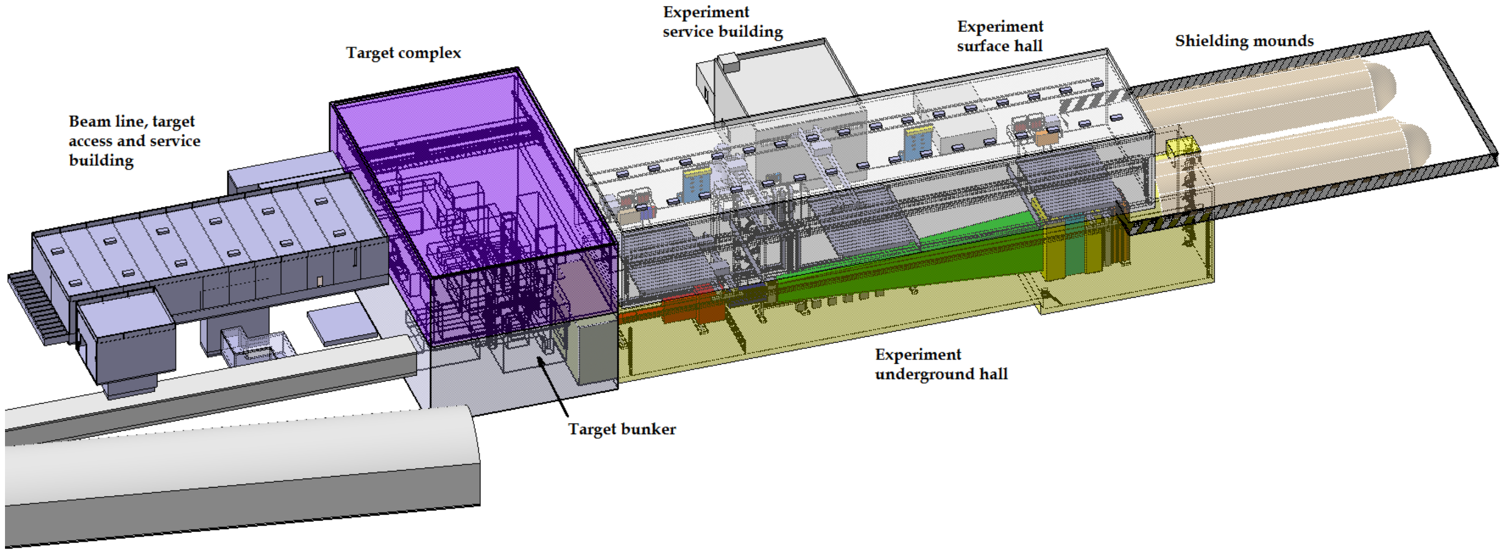
- Slow extraction from SPS into existing TT20 transfer line
- Switch to new transfer line at existing North Area splitters
- Heavy target plus hadron absorber
- Target complex with sophisticated handling capabilities
- Underground Experimental Hall

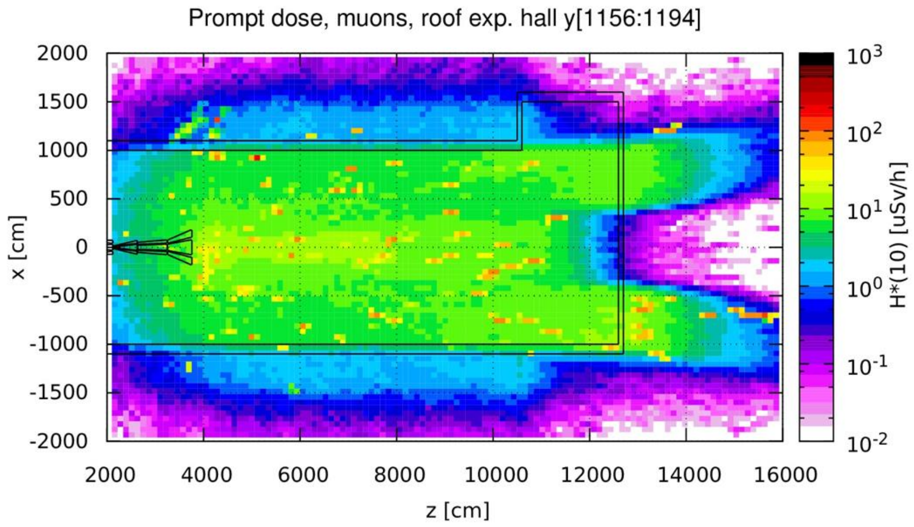
Momentum	400 GeV/c
Beam intensity on target per cycle	4.0e13
Cycle length	7.2 s
Spill duration	1 s
Avg. power on target	355 kW
Avg. power on target during spill	2560 kW
Protons on target (PoT) per year	4e19
PoT in 5 years' data taking	2.0e20



BDF Study

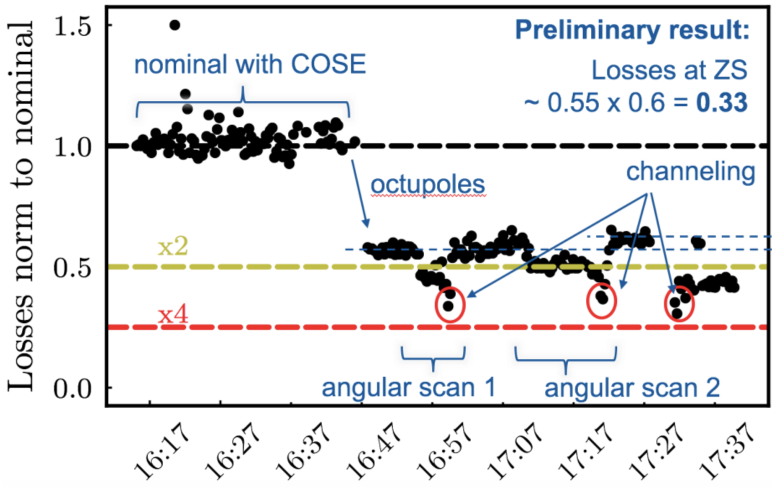
- 2016-2018: **3 year feasibility study** following work since EOI 2013
  - extraction, beamlines, target, target complex, experimental hall, integration, civil engineering, safety, and radiation protection
- BDF Comprehensive Design Study in pre-publication



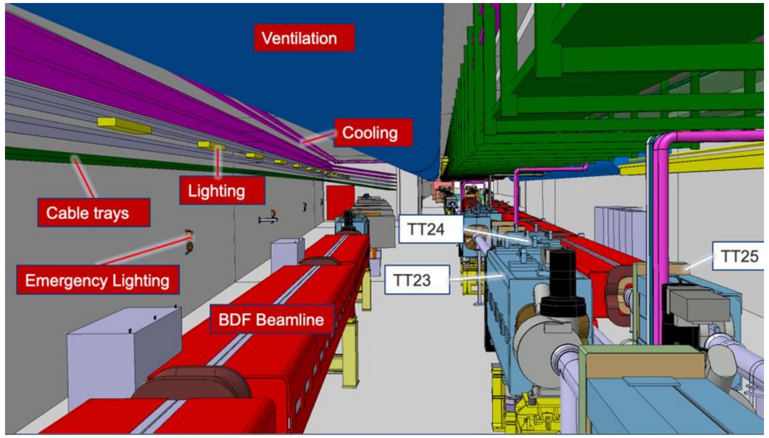


BDF Study

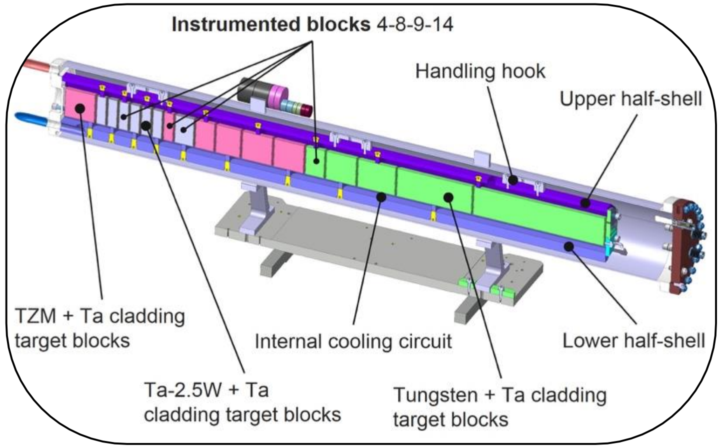
- **Feasibility confirmed:**
  - factor 3 reduction in SPS slow extraction losses demonstrated – confident to reach required x4
  - transfer line and dilution – well within CERN's established capabilities
  - target – challenging – extensive studies – prototype built and tested with beam
  - fully developed target complex study in collaboration with external company
  - phase 1 civil engineering and integration studies completed
  - RP studies showed the general feasibility in terms of radiation/radiological impact on the environment



Extraction losses



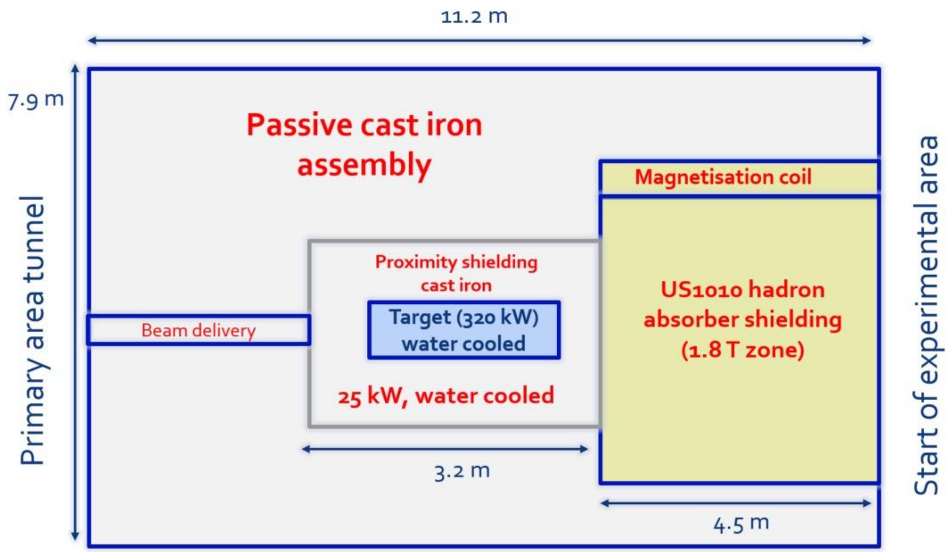
New BDF beamline

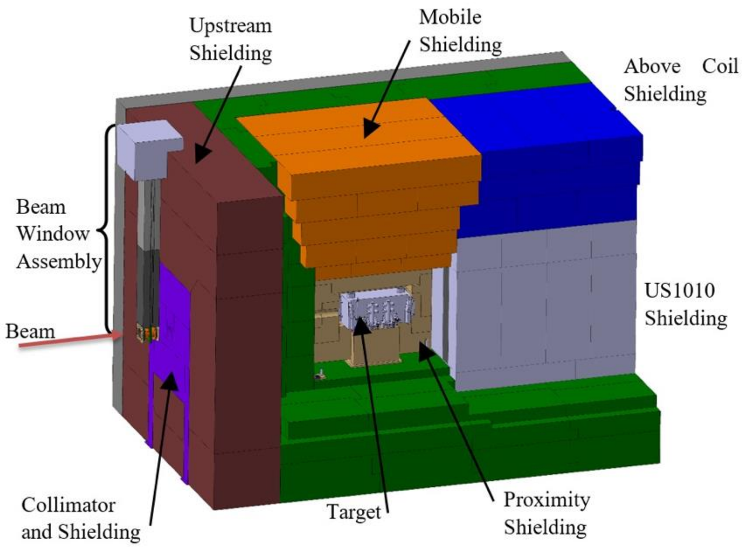


Target prototype

BDF - Summary

- **The study is mature.**
- Operationally it will be challenging but no show stoppers were identified.
- Possible time-line:
  - continued design studies and prototyping
  - ~3 years for TDR, followed by preparation for construction, component production
  - Construction of BDF ~5 years
    - Civil engineering for junction cavern/first part of new transfer line during LS3 (North Area stop)
  - Operation in Run 4
- Material cost: ~160 MCHF (class 4 estimate)





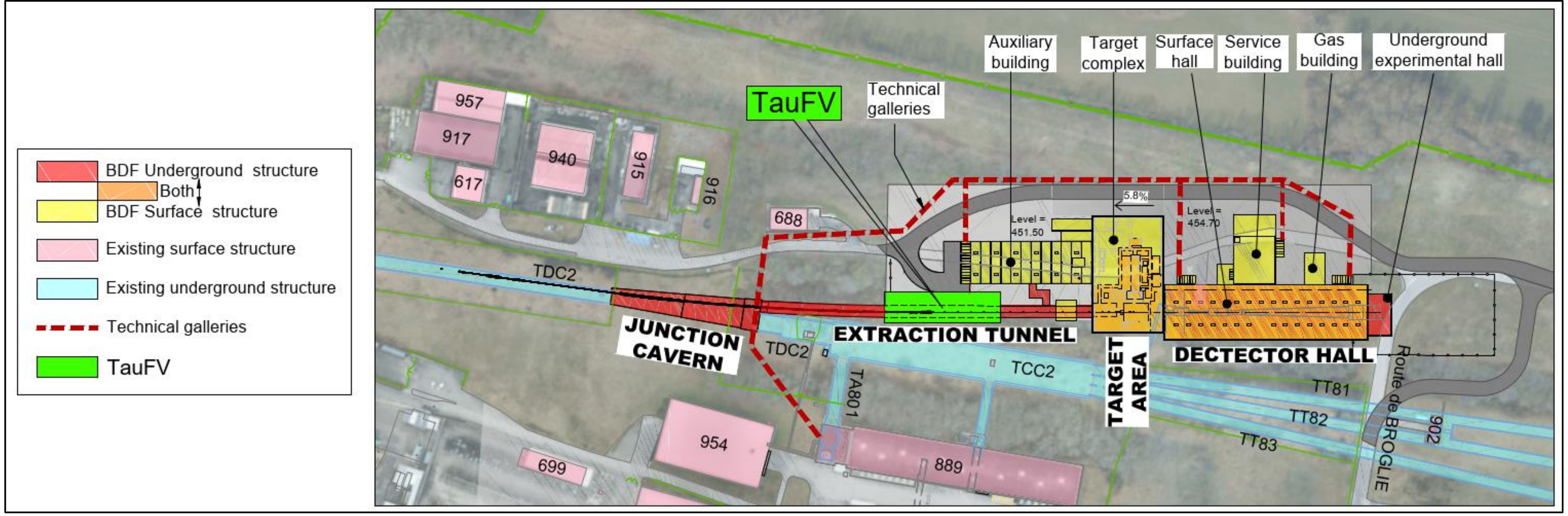
TauFV

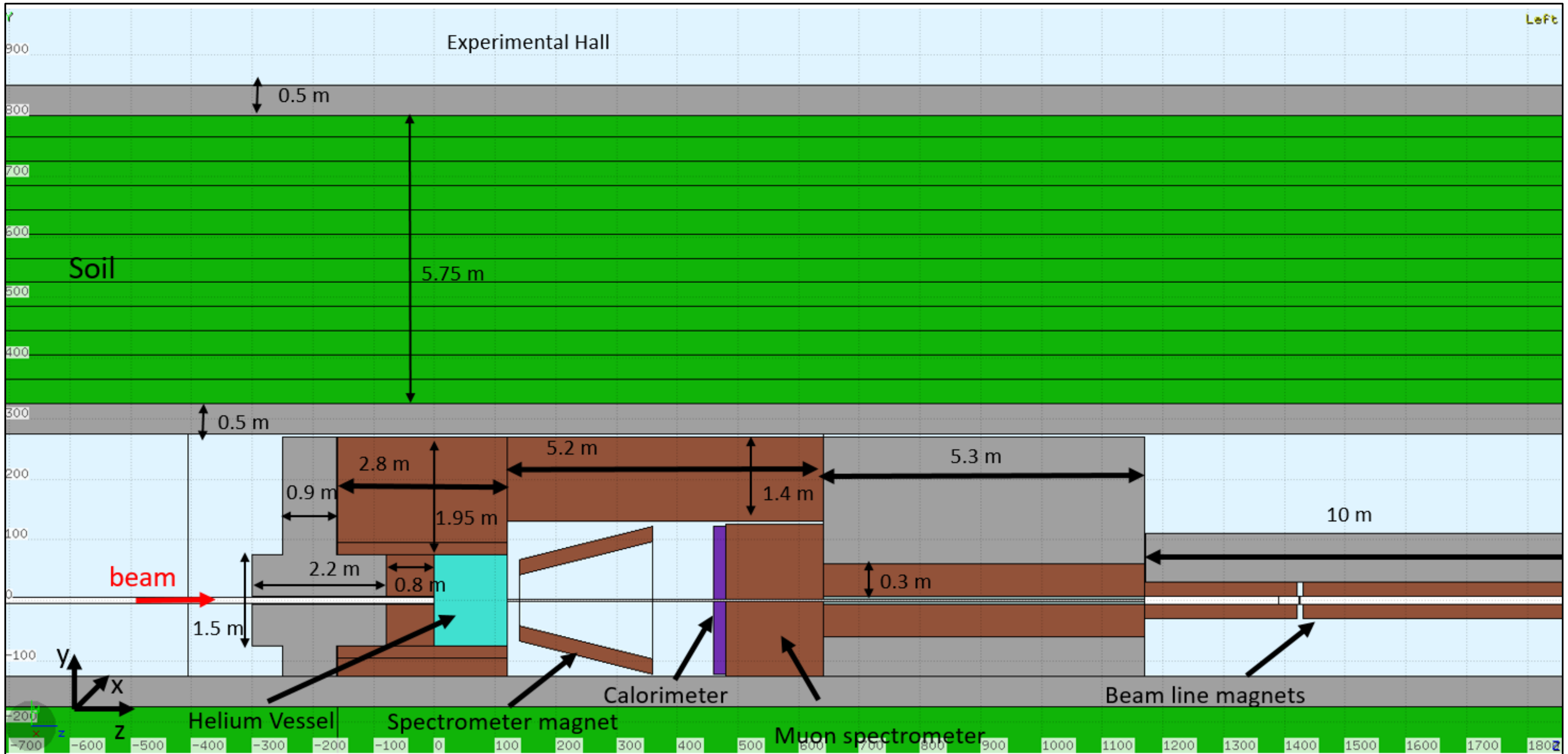
Search for Lepton Flavour Violation and rare decays

Using a thin in-line target to intercept about 2% of the intensity delivered to the SHiP target

Would have access to close to 8e13 tau lepton and 5e15 D_0 meson decays

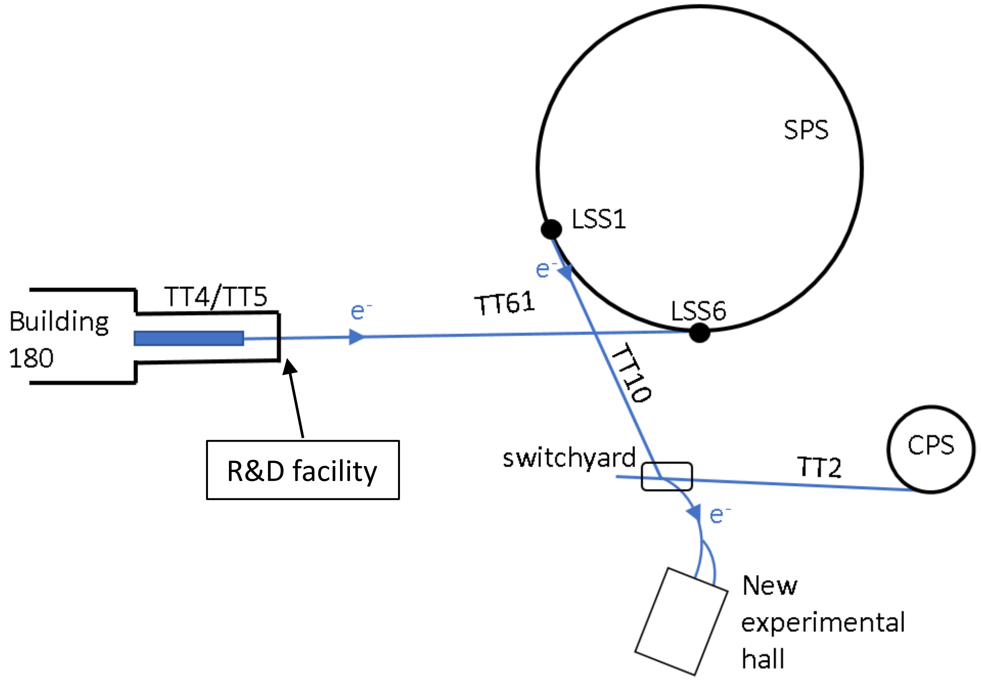
Proposal under development (appendix in BDF CDS)

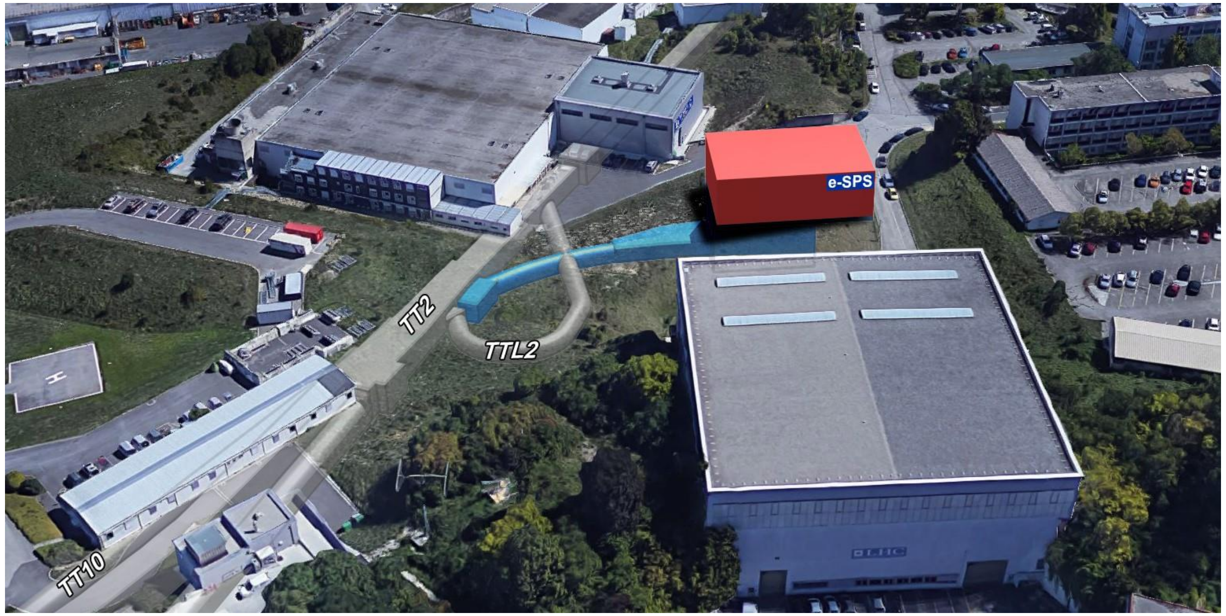




eSPS

- ~70 m long X-band based linac (CLIC technology) in TT4-5 accelerates e- to 3.5 GeV
- SPS filled in 1 to 2 s via TT60
- Acceleration to 16 GeV in the SPS
- Slow resonant extraction down the TT10 transfer line in ~10 s
- Beam delivered via the existing TT10 line to the Meyrin site
- A new, short beamline would branch from TT10 to the experimental hall (LDMX)





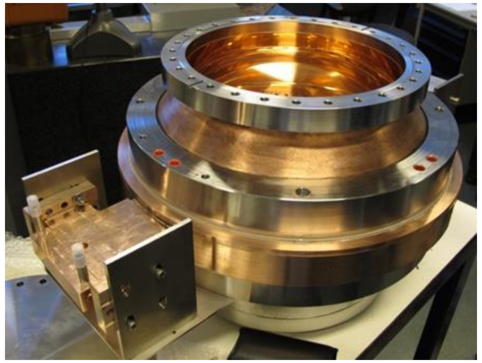
eSPS: Feasibility

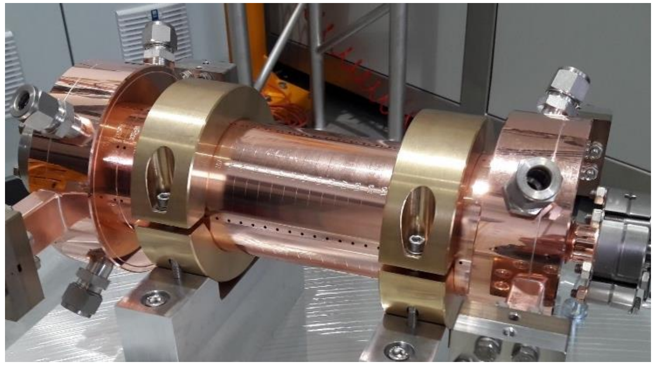
- **Feasibility – following initial study looks good**
  - Additional RF in SPS to be studied (old LEP or FCC-ee cavities)
- Maximal use of existing structures, small foot print, and thus relatively inexpensive.
- SPS cycle sharing implications
  - ~12 s cycle, 10 s slow extraction giving 1e8 – 1e9 EOT/s
- Material cost: ~80 MCHF

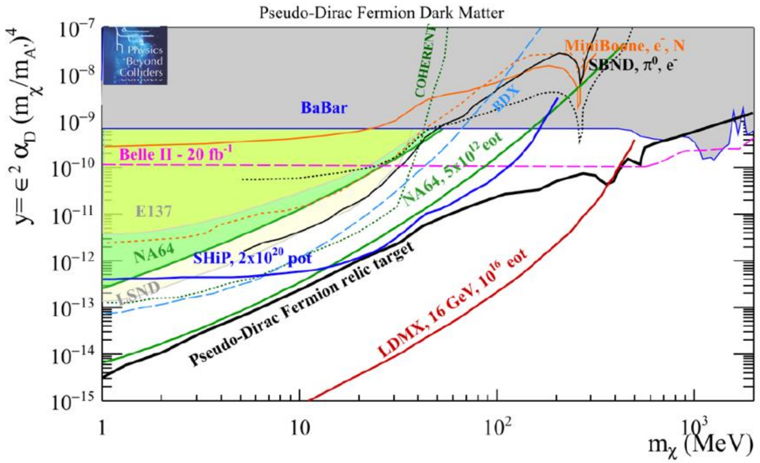
Well developed proposal:
"Dark Sector Physics with a Primary Electron Beam Facility at CERN"
presented as EoI to SPSC

eSPS: Motivation

- **Electrons back in the complex** – good given CERN's apparent long term options
- **Staged deployment of X-band** – return on the significant investment
- Possible deployment of **FCC-ee RF cavities and high-efficiency power generation**
- Strong case made for **accelerator based R&D** and other studies at the linac R&D facility
- Physics case - **unique LDM search reach**

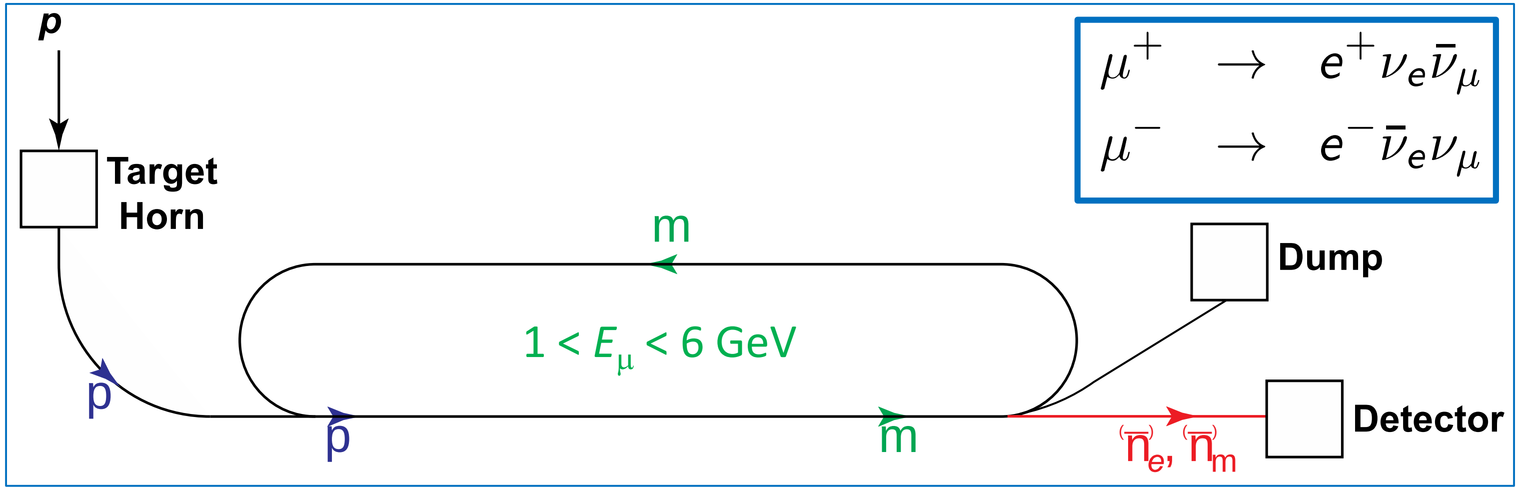






Preparing for future – staged deployment of FCC-ee/CLIC technology while preparing the long term strategic vision; at the same time performing a competitive LDM search - a game changer in the case of positive result and naturally important input to future plans.

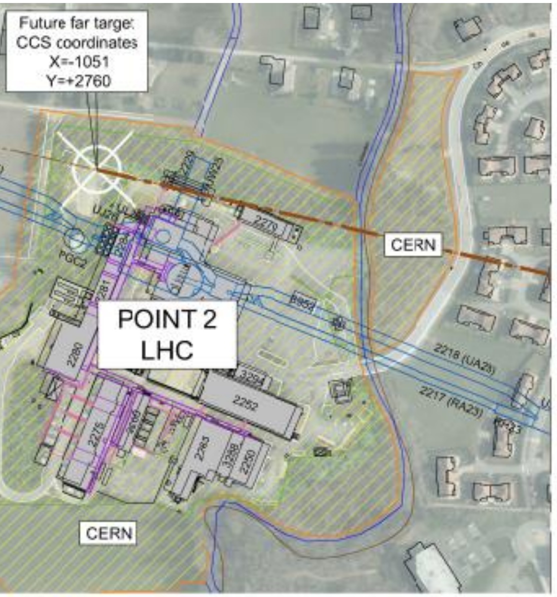
nuSTORM

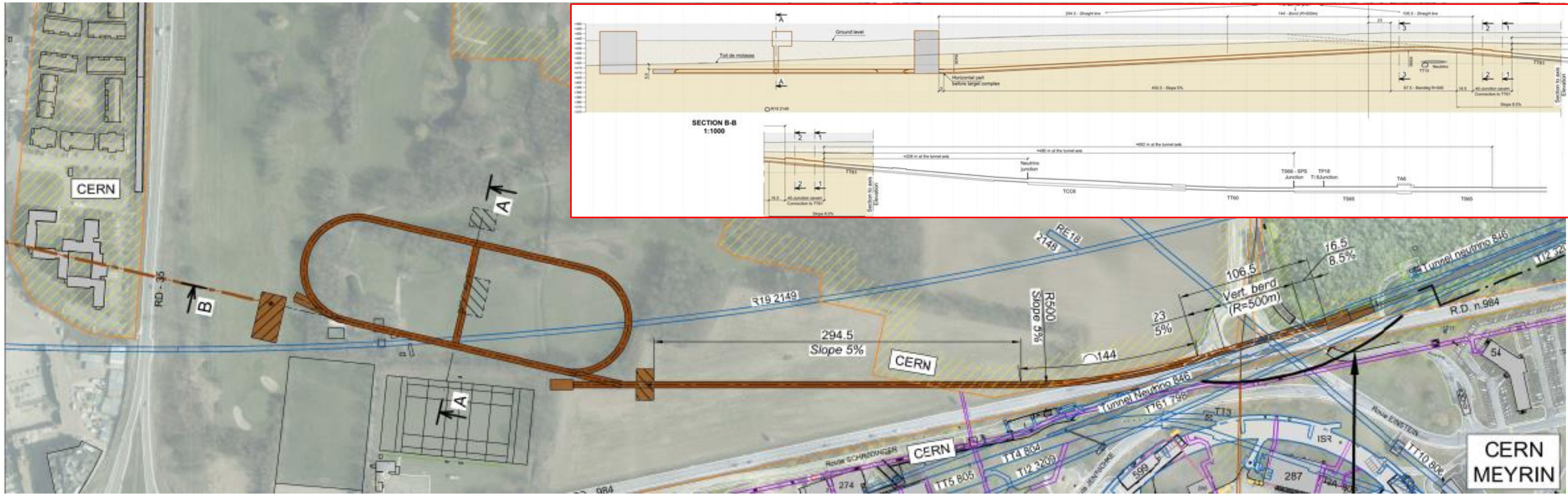


- **Well developed proposal for possible siting at FNAL circa 2013**
- **Siting at CERN – exploratory study:**
  - Via existing fast extraction system at SPS point 6 into a new transfer line
  - Graphite target, magnetic horn
  - Target complex design based exploits extensive work done for CENF
  - Containment and transport of pion beam
  - New design for decay ring (SC FFA):
    - Central momentum between 1 GeV/c and 6 GeV/c;
    - Momentum acceptance of up to ±16%

nuSTORM

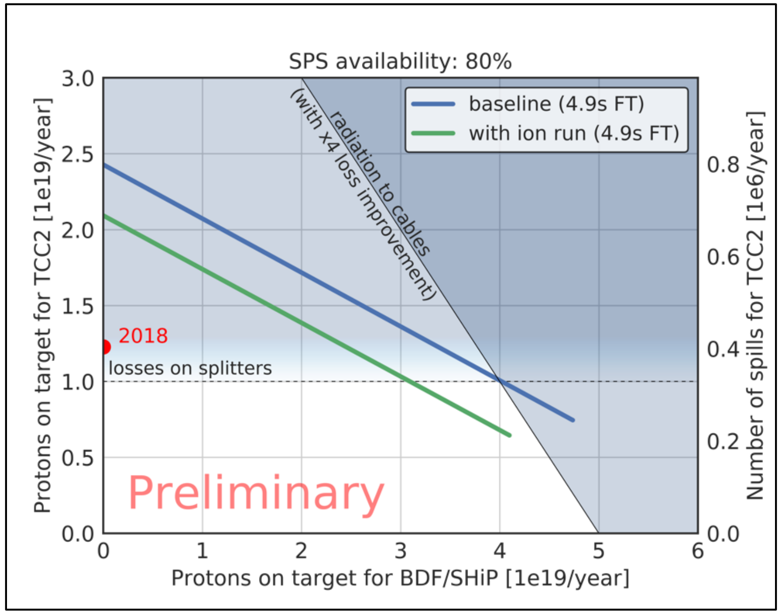
- Fast extraction, transfer, target/horn within CERN's established expertise
- Potential green field site with appropriate geology
- Study in early stages. Muon storage ring is certainly challenging.





Potential major SPS/North Area users

	Momentum GeV/c	Int/Cycle	Flat top length	POT/year
NA CB	400	2 – 4.9e13	4.8	~1e19
SHiP	400	4e13	1.2	4e19
KLEVER	400	~2e13	4.8	1e19
ENUBET	400	4.5e13	4.8	5.2e19
nuSTORM	100	4e13	1.0	4e19
eSPS	16	~3.1e11	10.0	1e18 EOT

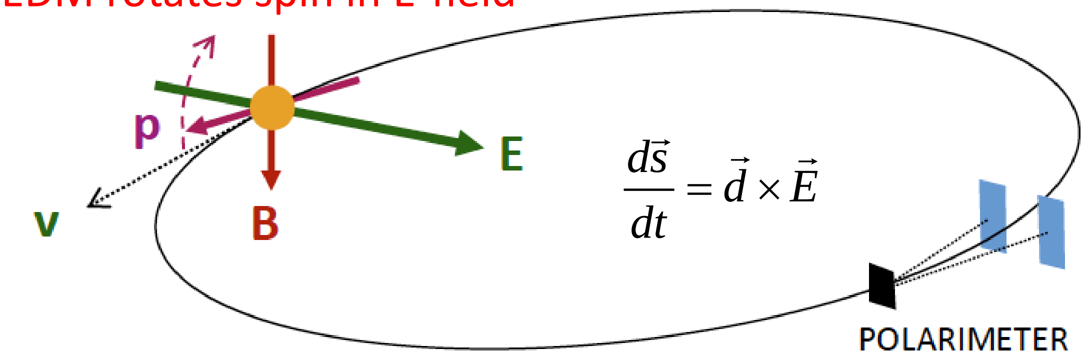


- **Standard NA operations compatible with BDF for SHiP/TauFV**
- KLEVER in parallel would be possible – with some penalties
- Another major user (eSPS, nuSTORM, ENUBET) would imply compromise or temporal separation

EDM Storage Ring

- Principles of **all electric proton storage ring with frozen spin at "magic momentum"** well established
- 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

EDM rotates spin in E-field



$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

EDM rotation detected here

EDM Roadmap

1 Precursor Experiment →	2 Prototype Ring →	3 All-electric Ring
dEDM proof-of-capability (orbit and polarization control; first dEDM measurement)	**pEDM proof-of-principle** (key technologies, first direct pEDM measurement)	**pEDM precision experiment** (sensitivity goal: 10^{-29} e cm)
- Magnetic storage ring - Polarized deuterons - d-Carbon polarimetry - Radiofrequency (RF) Wien-filter	- High-current all-electric ring - Simultaneous CW/CCW op. - Frozen spin control (with combined E/B-field ring) - Phase-space beam cooling	- Frozen spin all-electric (at p = 0.7 GeV/c) - Simultaneous CW/CCW op. - B-shielding, high E-fields - Design: cryogenic, hybrid, …
Ongoing at COSY (Jülich) 2014 → 2021	Ongoing within CPEDM 2017 → 2020 (CDR) → 2022 (TDR) Start construction > 2022	After construction and operation of prototype > 2027

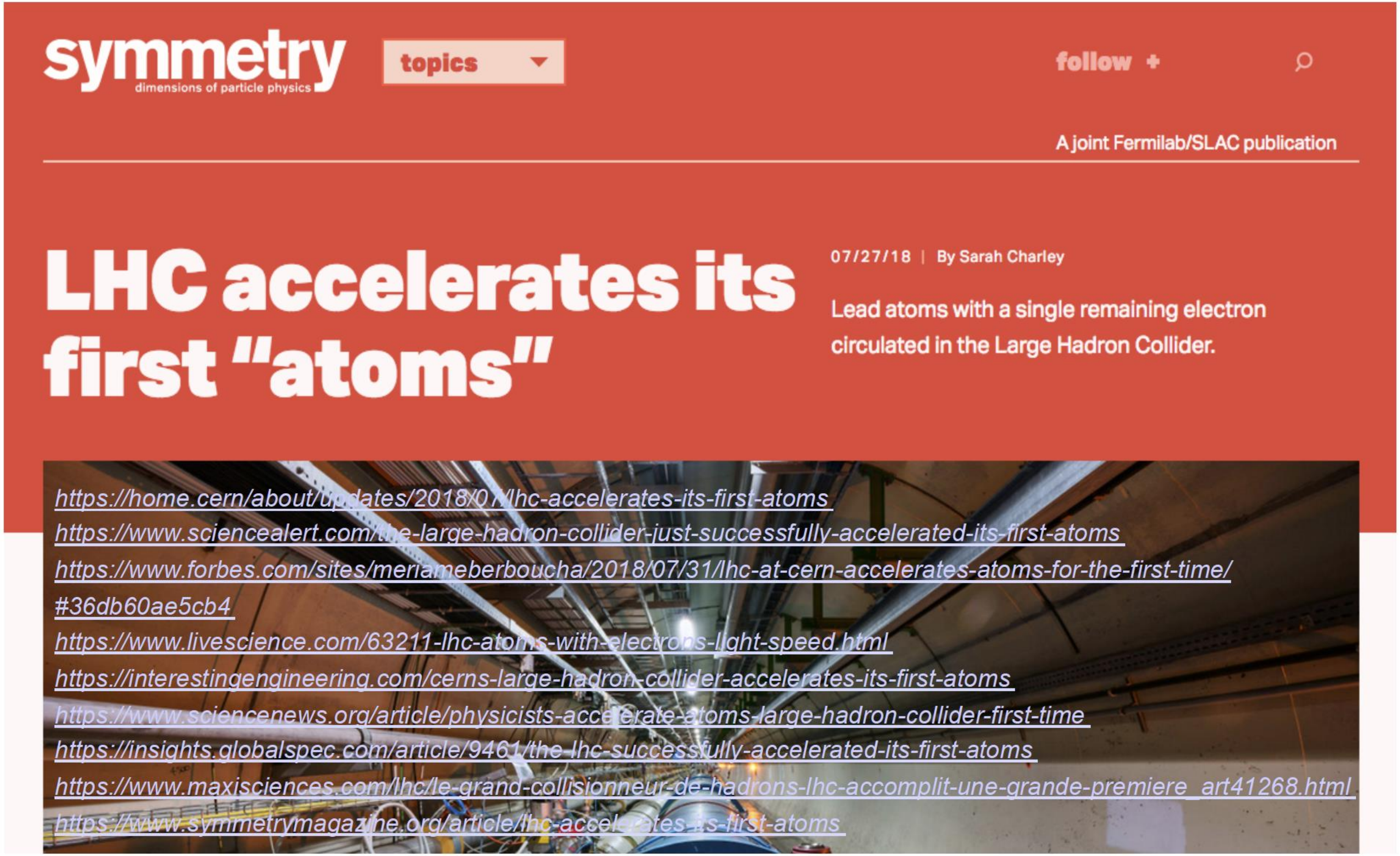
Impressive "precursor" results at COSY with polarized deuterons in magnetic storage ring

PROTOTYPE SEEN AS ESSENTIAL NEXT STEP

- Small (100 m circum.) designed to operate 2 modes: all-electric at 30 MeV; and combined electric and magnetic fields to allow frozen spin operation at 45 MeV.
- Lattice design will mimic that of the full ring in order to test as many features as possible on a smaller scale.
- If the prototype is at COSY, takes advantage of the existing facility for the production of polarized proton (and deuteron) beams, beam bunching, and spin manipulation.

Yellow report in pre-publication – includes preliminary design of prototype

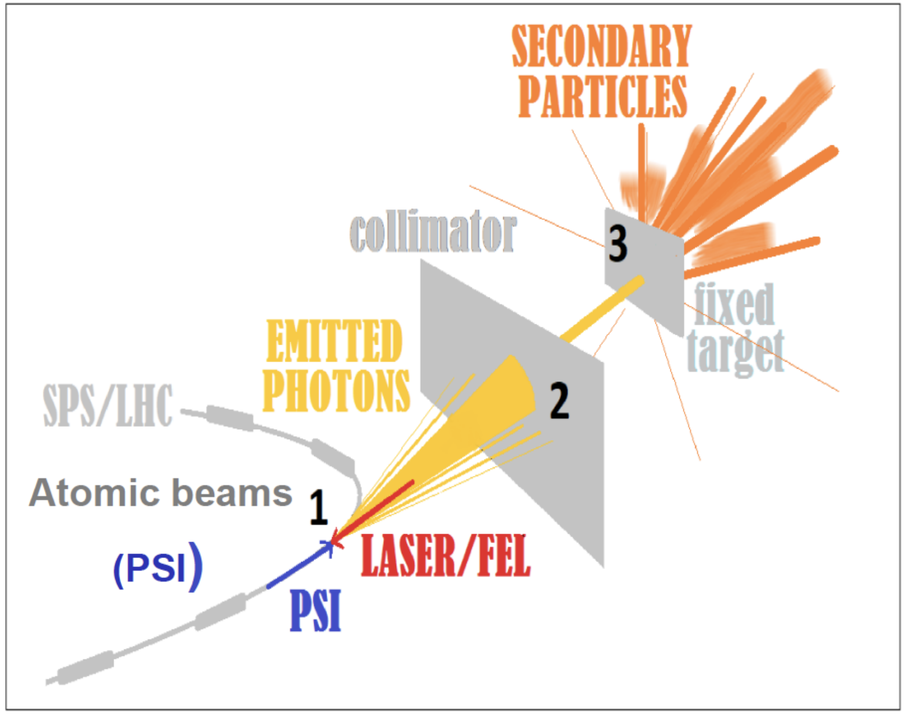
July 2018: Birth of Atomic Physics research at CERN



https://home.cern/about/updates/2018/07/lhc-accelerates-its-first-atoms
https://www.sciencealert.com/the-large-hadron-collider-just-successfully-accelerated-its-first-atoms
https://www.forbes.com/sites/meriameberboucha/2018/07/31/lhc-at-cern-accelerates-atoms-for-the-first-time/#36db60ae5cb4
https://www.livescience.com/63211-lhc-atoms-with-electrons-light-speed.html
https://interestingengineering.com/cerns-large-hadron-collider-accelerates-its-first-atoms
https://www.sciencenews.org/article/physicists-accelerate-atoms-large-hadron-collider-first-time
https://insights.globalspec.com/article/9461/the-lhc-successfully-accelerated-its-first-atoms
https://www.maxisciences.com/lhc/le-grand-collisionneur-de-hadrons-lhc-accomplit-une-grande-premiere_art41268.html
https://www.symmetrymagazine.org/article/lhc-accelerates-its-first-atoms

Gamma factory

- Accelerate and store high energy beams of highly ionised atoms and excite their atomic degrees of freedom by laser photons to produce:



Witek Krasny

primary beams:

- partially stripped ions
- electron beam (for LHC)
- gamma rays

secondary beam sources:

- polarised electrons,
- polarised positrons
- polarised muons
- neutrinos
- neutrons
- vector mesons
- radioactive nuclei

"Tools Made from Light"

collider schemes:

$\gamma-\gamma$ collisions,
E_{CM} = 0.1 – 800 MeV

$\gamma-\gamma_L$ collisions,
E_{CM} = 1 – 100 keV

γ–p(A), ep(A) collisions,
E_{CM} = 4 – 200 GeV

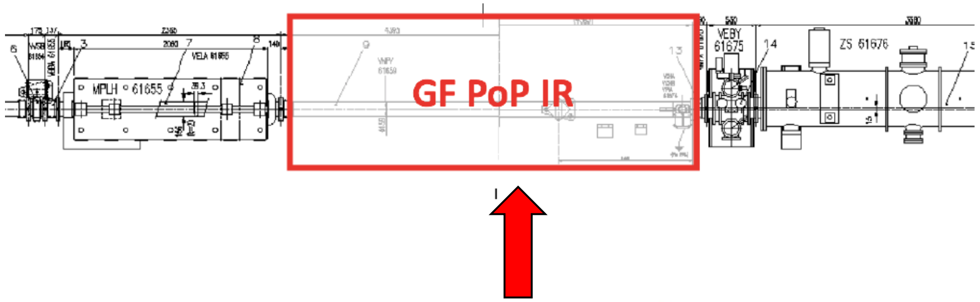
Gamma Factory project milestones

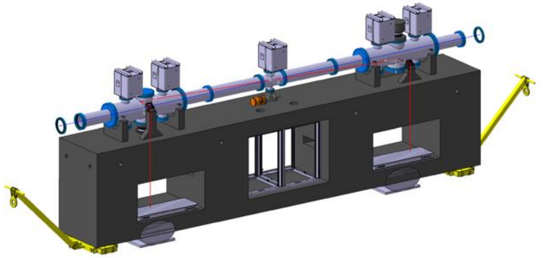
1. ***Production**, **acceleration** and **storage** of **"atomic beams"** at CERN accelerator complex.*
2. ***Proof-of-Principle** (PoP) experiment in the SPS tunnel.*
3. ***Development** "ab nihilo" the requisite Gamma Factory **software tools**.*
4. ***Realistic assessment** of Gamma Factory **performance figures**.*
5. ***Physics highlights** of Gamma Factory based **research programme**.*
6. *Gamma Factory **TDR**.*

Early stages of a well developed program – significant potential

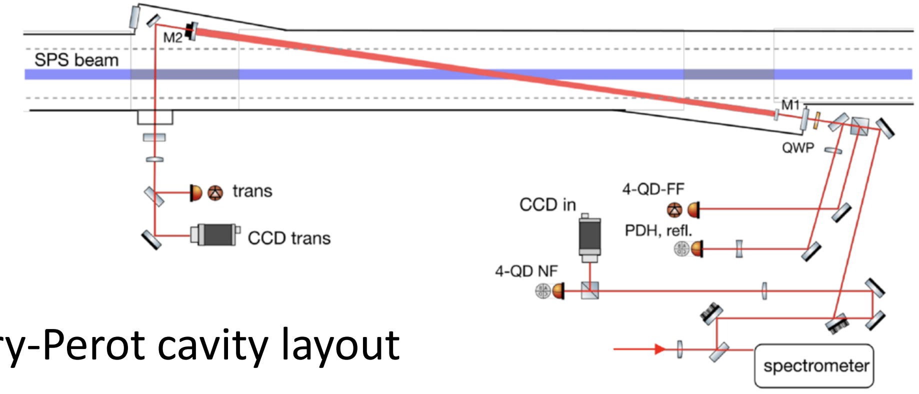
Next step: Proof of principle in SPS

4.4 m flange-flange between MPLH and ZS (VV)



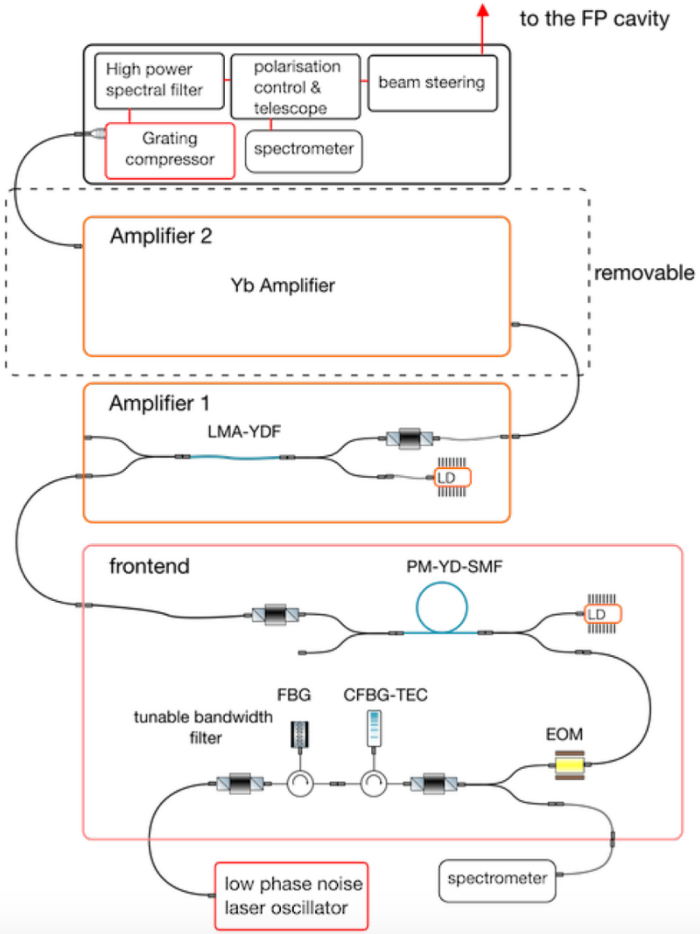


Mechanical frame of F-P cavity



Fabry-Perot cavity layout

Laser system



Letter of Intent to SPSC incoming

Technology

Exploration and evaluation of possible technological contributions of CERN to non-accelerator projects possibly hosted elsewhere:

Magnets

Optics

RF

Cryo

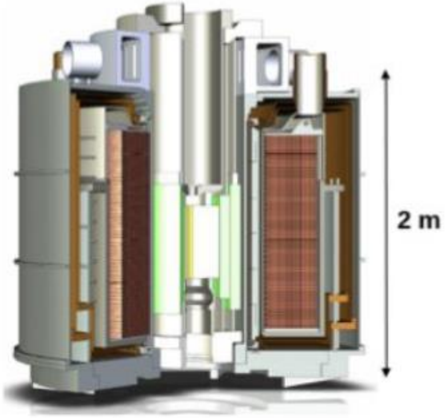
Vacuum

Technology concerned	benefit from CERN	benefit to CERN	how facilitate?	Exps concerned
Magnet, concretely: high-field, large-bore	availability of strong fields, CERN expertise to build custom magnets	make optimal physics use of magnet resources (spares)	advertise magnet usage times, provide expertise in magnet design, PBC-fellow for IAXO	IAXO, JURA, STAX, VMB@CERN
Optics/Optics sensing, concretely: Fabry Perot, membranes	surface coating, possibility to combine magnet with optics	add local expertise on cavity optics technologies	"optics hub", as described in the document	aKWISP, VMB@CERN, JURA
Radiofrequency cavities, concretely: design for axion searches	experience in design and production	new cavity designs for various physics purposes, tuning and characterization in cryogenic environment	mandate for cavity experts to aid in design	Grenoble initiative, & other Haloscope initiatives operating already at CERN, STAX
Cryogenics, concretely: large-scale: helium, argon, krypton from 120K to mK	availability of cryogenic facilities	participate in research beyond collider	mandate through TE-CRG	DarkSide, aKWISP, VMB@CERN, IAXO
Vacuum, concretely: large-scale leak testing	experience & availability	participate in research beyond collider	mandate through TE-VSC	DarkSide, JURA, aKWISP, CNT

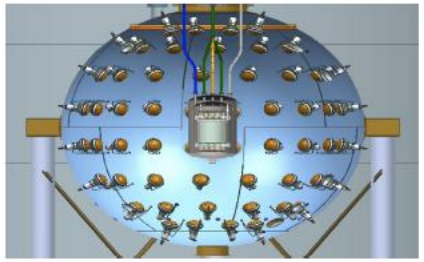
Andrzej Siemko, Babette Dobrich et al

Initiatives integrated into the Techno WG

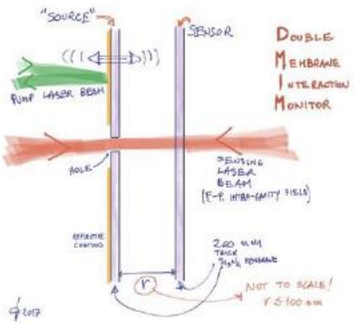
1) Haloscope LNCMI-Grenoble



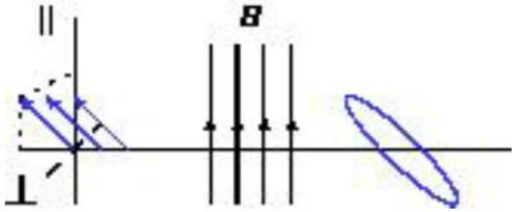
2) DarkSide

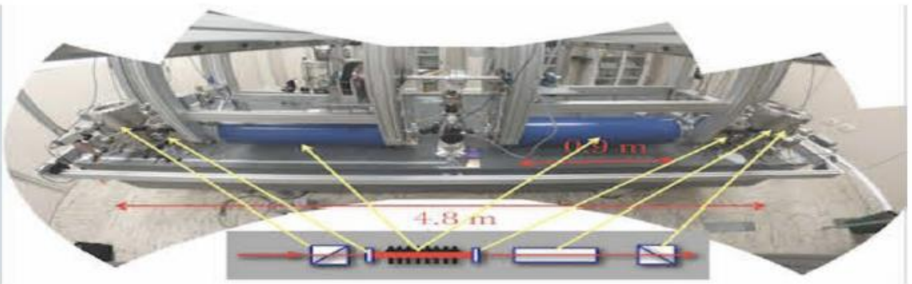


3) aKWISP

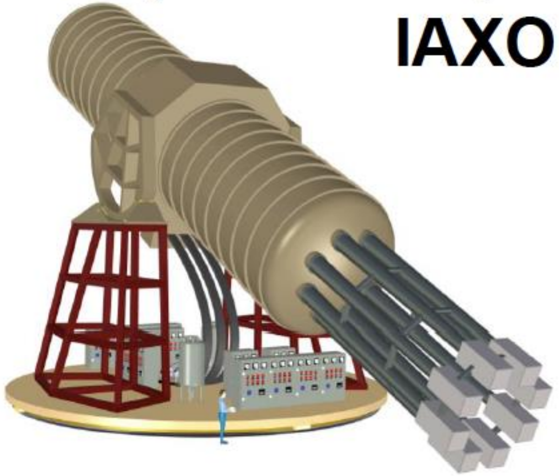


4) VMB@CERN

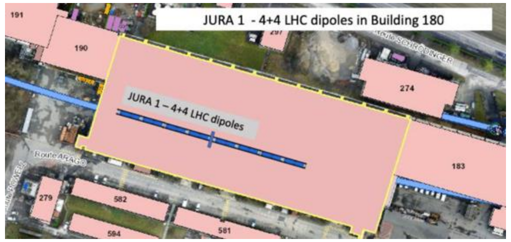




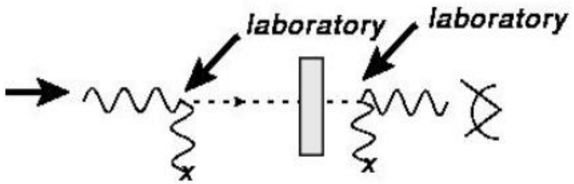
5) Helioscope IAXO



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

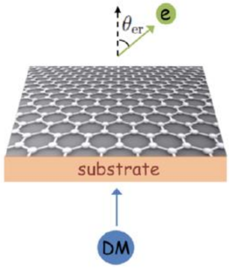


7) LSW-STAX



8) CNT Based DM Detector

PTOLEMY



Technology: Summary

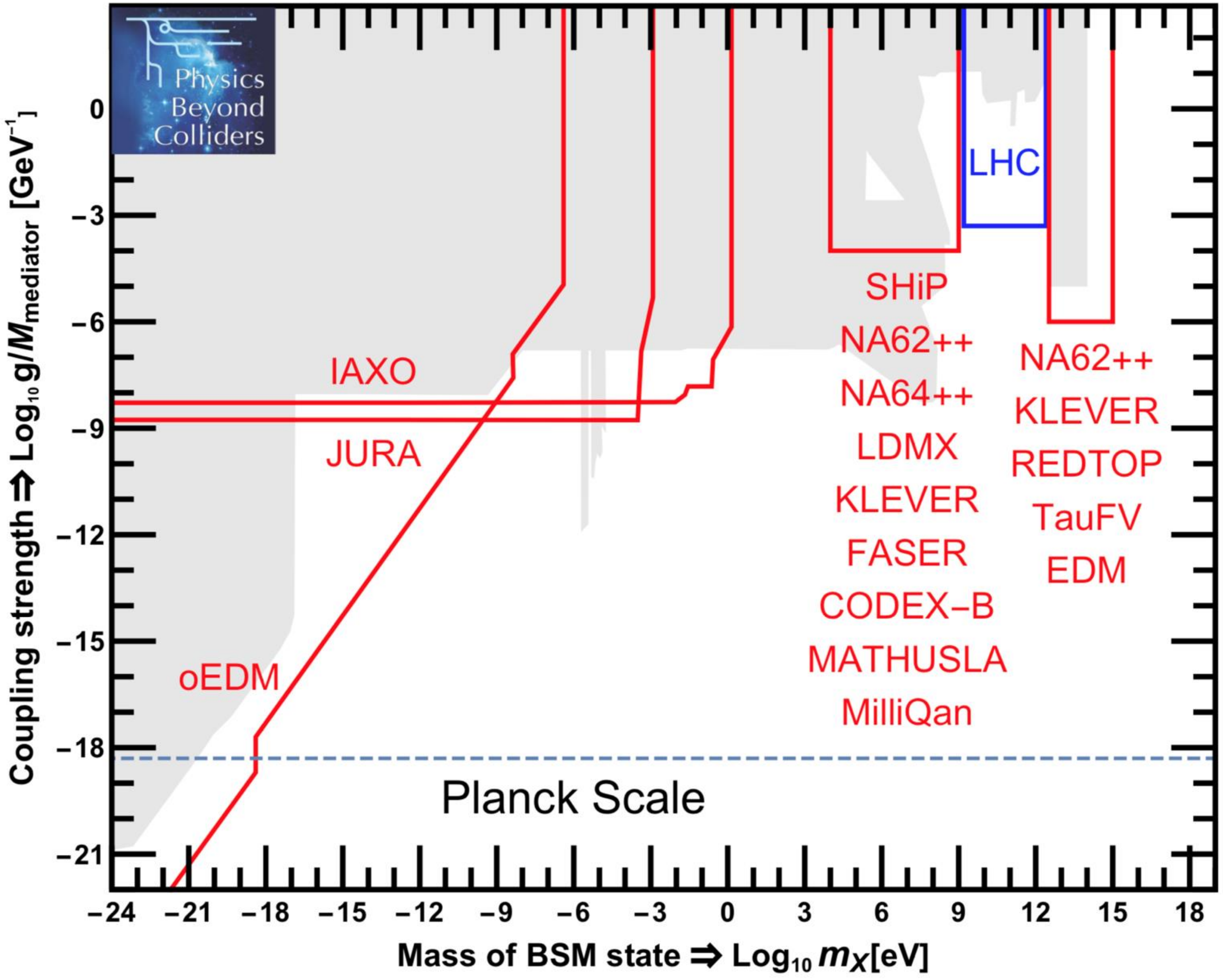
"In summary, albeit CERN being an accelerator lab, also non-accelerator experiments can profit from CERN expertise and bring further diversity to CERN."

Initiative	Goal		Tech	CERN
VMB@CERN	VMB	Search for Vacuum Magnetic Birefringence	optics, magnets	Y
JURA	LSW/ALPS	Via optics, detector development at ALPS II + FCC magnets	magnets	Y
STAX	LSW/ALPS	transition-edge-sensors (TES); high Q Fabry-Perot cavities	magnets, cryo, RF	P
BabyIAXO/IAXO	Helioscope	Next generation CAST, independent collaboration	magnets	N
DarkSide	WIMPs	Independent collaboration	vac, cryo, SIPM	N
Carbon Nano Tubes	CNB, DM	Electron recoils in large arrays of parallel carbon nanotubes - DM target for PTOLEMY	new material studies, neutrons	N
aKWISP	Chameleons	short-distance interactions at sub-micron scales	cryo, thin films..	N
Optics Technology Hub		Advanced optics technologies	optics	Y

Also considered

- **LHC fixed target**
  - Standard and polarized gaseous targets
  - Crystals: single to target; double (Λ MDM), triple (Ds -> tau)…
- **LHC LLP**
  - FASER – for installation in LS2
  - MATHUSLA, CODEX-b, milliQan considered by BSM WG
- **AWAKE++**
  - Possible use of PWFA in an electron beam dump experiment
- **REDTOP**
  - eta factory, possible at PS but POT would conflict with existing users

Physics Motivation (BSM)



- **Sub-eV:** axions, axion-like particles
- **MeV – GeV:** RH neutrinos below the EW scale, Axion-Like Particles, Light Dark Matter
- **>>TeV:** search for NP in clean and very rare flavour processes or in EDMs

The **BSM PBC projects** offer significant discovery potential over a wide range of masses and couplings.

- Very sensitive low energy experiments target the sub-eV mass area.
- SPS Fixed Target beam-dump-like experiments and long lived particle searches at LHC have unique capabilities to target the MeV-GeV domain
- The precision tests of flavor violation (lepton and quark), as well as of CP violation, probe new particles in a mass range exceeding LHC direct searches.

in addition: QCD and others facilities

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

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

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

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

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)

Other facilities:
γ-factory from Partially Stripped Ions; nuSTORM

courtesy FG

Conclusions

- Interesting exercise, fostered a number of options to exploit the complex and technology - mix of:
  - smaller scale options which can be addressed within CERN's remit
  - promising novel proposals – venture capital
  - larger scale projects
- Initiatives are :
  - well motivated by their physics potential in interesting times;
  - cost-effective opportunities to make a significant contribution and provide important input to future plans;
  - allow full exploitation of the complex in parallel to the LHC and preparation for the longer term.

BACKUP

Reports

Submission to ESPP update/recent summary as appropriate

Document	Submitted by	Link to document
Summary Report of Physics Beyond Colliers at CERN	PBC coordination	CDS
Physics Beyond Colliders QCD Working Group Report	QCD Working Group	CDS
Report of the BSM Working Group of the Physics Beyond Colliders at CERN	BSM Working Group	CDS
SPS Beam Dump Facility Comprehensive Design Study	BDF Working Group	CDS (to be published)
Report from the Conventional Beams Working Group...	Conventional Beams Working Group	CDS
AWAKE++: The AWAKE Acceleration Scheme for New Particle Physics Experiments at CERN	AWAKE++ Working Group	CDS (to be published)
PBC technology subgroup report	Technology Working Group	CDS
Dark Sector Physics with a Primary Electron Beam Facility at CERN	eSPS	CDS
Report from the LHC Fixed Target working group of the CERN Physics Beyond Colliders forum	Fixed Target Working Group	CDS
TECHNICAL PROPOSAL: FASER, THE FORWARD SEARCH EXPERIMENT AT THE LHC	FASER collaboration	CDS
The CERN Gamma Factory Initiative: An Ultra-High Intensity Gamma Source	Gamma Factory collaboration	IPAC (report in prep.)
Feasibility Study for a storage ring to search for an Electric Dipole Moment of charged particles	CPEDM	CDS (to be published)
nuSTORM at CERN: Feasibility Study	nuSTORM Working Group	CDS (to be published)
SPS Operation and Future Proton Sharing scenarios for the SHiP experiment at the BDF facility	Proton perf. post-LIU WG	CDS

see http://pbc.web.cern.ch/

Summary

HSC	Status	Deploy	Cost	Physics
BDF/SHiP,tauFV	CDS	LS3+	C6	Hidden Sector
eSPS/LDMX	EoI	<LS3	C5	DM
nuSTORM	→CDS	LS3++	C6	Neutrinos
CB/KLEVER	EoI	LS3+	C3	Precision
CB/COMPASS-RFSB	EoI/proposal	LS3+	C4	QCD
NA62++	studies	Run 3	C1	Hidden Sector
NA64++	OP	Run 3	C1	DM
MUonE	proposal	Run3	C2	muon anomaly
LHC				
LHC FT - gas	TP	Run 3	C1	PDF,DY,spin
LHC FT - crystal	proto	Run 3	C2	MDM/EDM
FASER	TP/approval	Run 3	C2	LLP
MATHUSLA	LOI	LS3	C5	LLP
CODEX-b	LOI	LS3	C3	LLP
milliQan	demo	Run 3	C2	LLP
NOVEL				
Gamma Factory PoP	→EoI	Run 3	C2	PSI/Laser
pEDM protype	→CDS	2022	C4	EDM
AWAKE++	exploratory	LS3+	C4	DM
PS				
REDTOP	proposal	LS3+	C3	BSM+
TECHNOLOGY				
VMB	LOI	Run 3	C2	VMB
BabyJURA, JURA1, JURA 2	proposal	2023	C2,C2,C4	ALPs
BabyIAXO/IAXO	advanced	2023	C3,C4	Axions

- Class 4 for BDF, eSPS;
- Preliminary for nuSTORM
- Conventional beams – see PBC report
- Technology – all options – see PBC report

Cost Scale

C1	< few 100 kCHF
C2	From few 100 KCHF to 1-2 MCHF
C3	From 1-2 to 5-10 MCHF
C4	~10-50 MCHF
C5	> 50 MCHF
C6	> 150 MCHF

Approximate “ideal” timelines