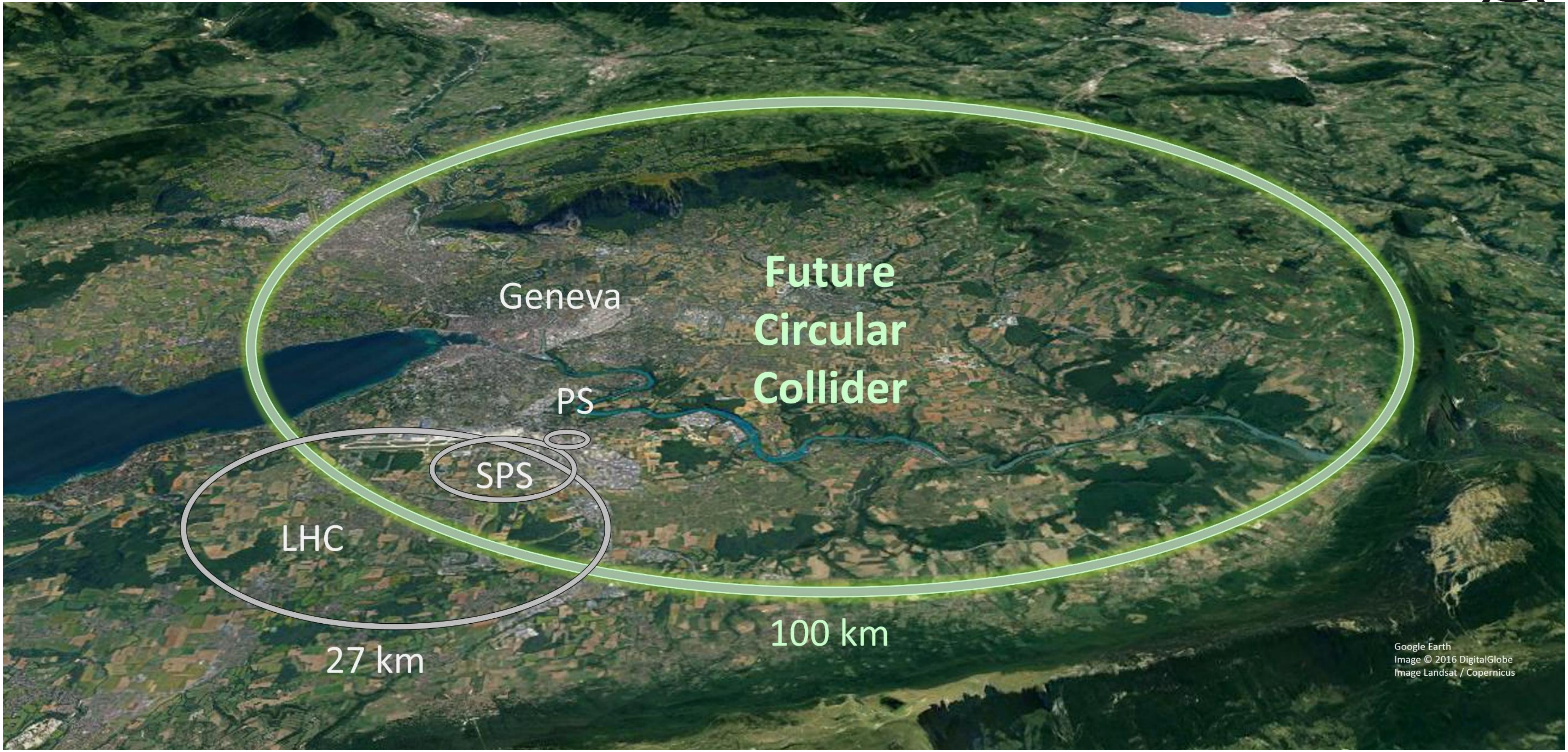
SHiP experiment at the SPS Beam Dump Facility

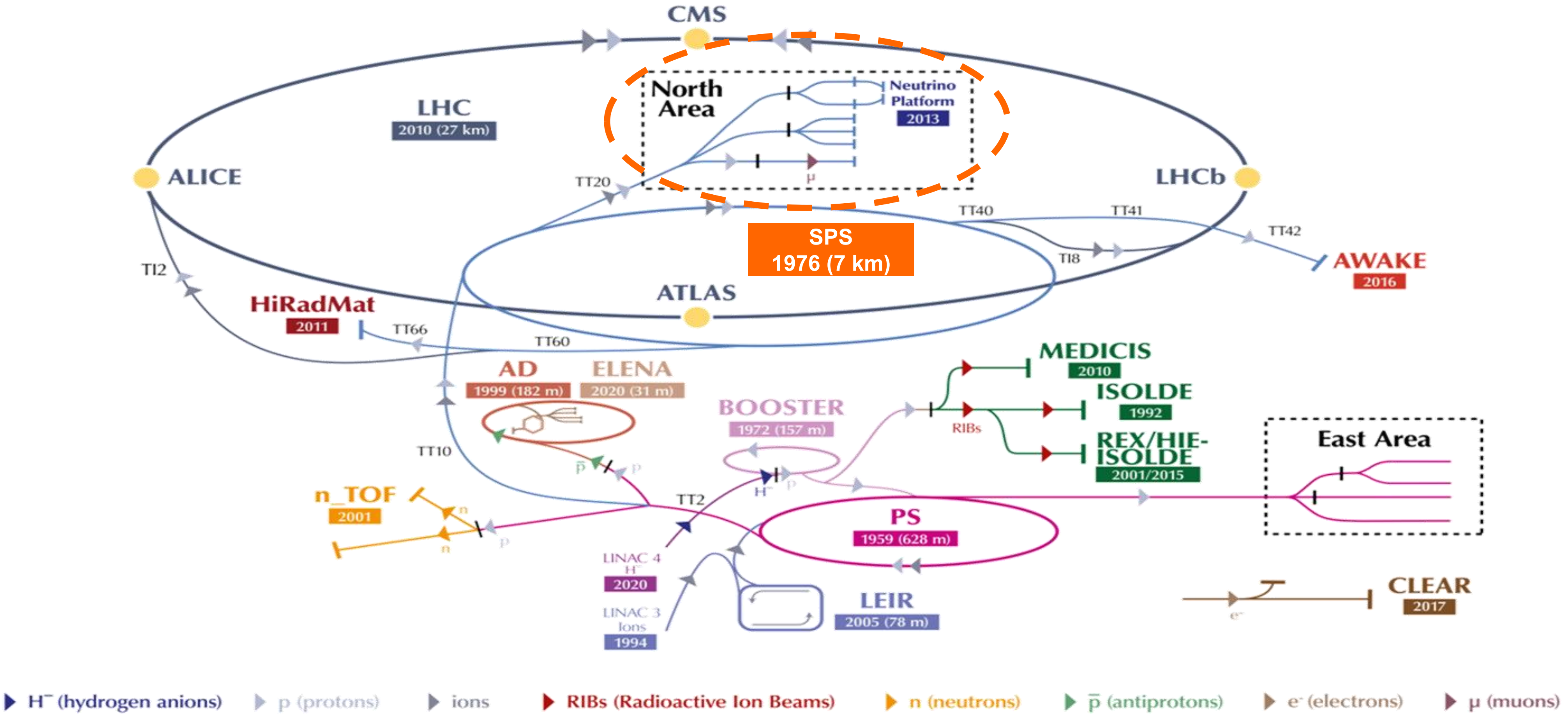
New scientific program approved by the CERN Research Board and Council in June 2024

➔ Now in technical design phase

CERN's accelerator complex

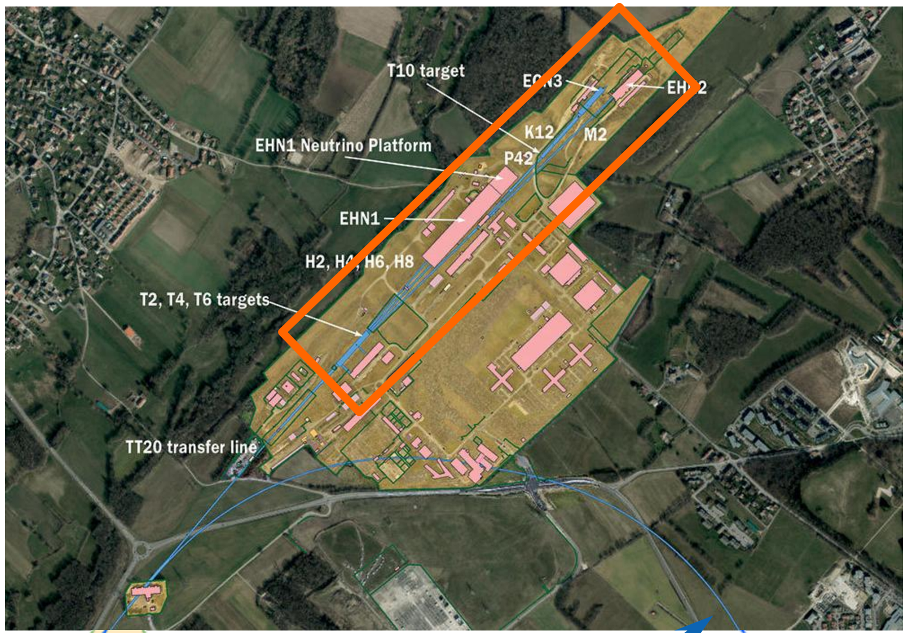


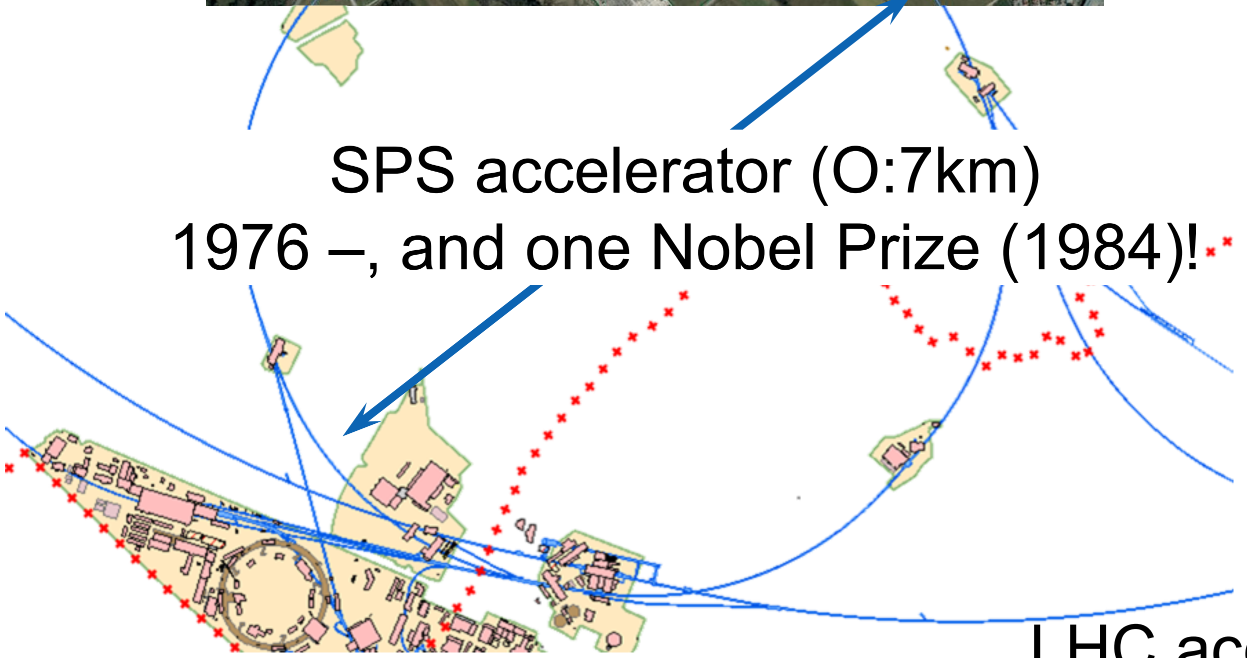
CERN's *current* accelerator complex



LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

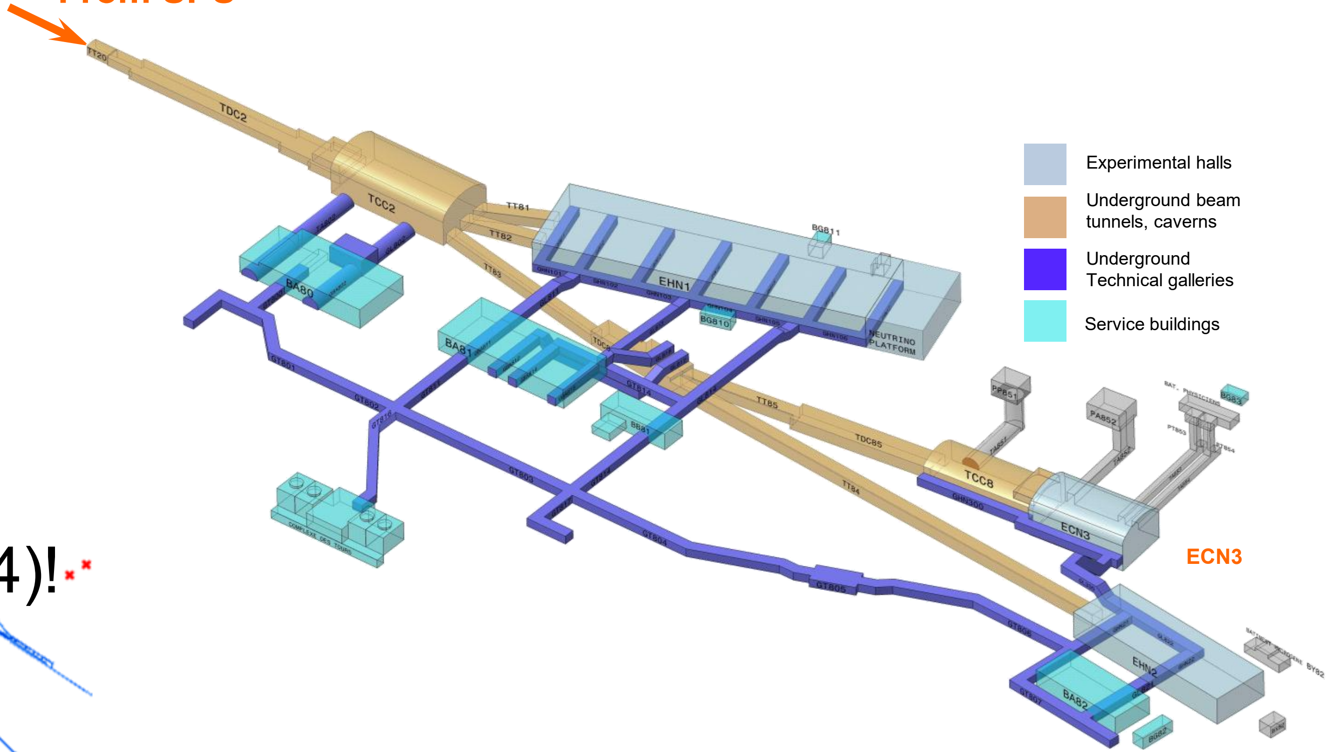
CERN's North Area beam facilities





SPS accelerator (O:7km)
1976 –, and one Nobel Prize (1984)!

LHC accelerator



North Area experiments and timelines

Y. Kadi (CERN)

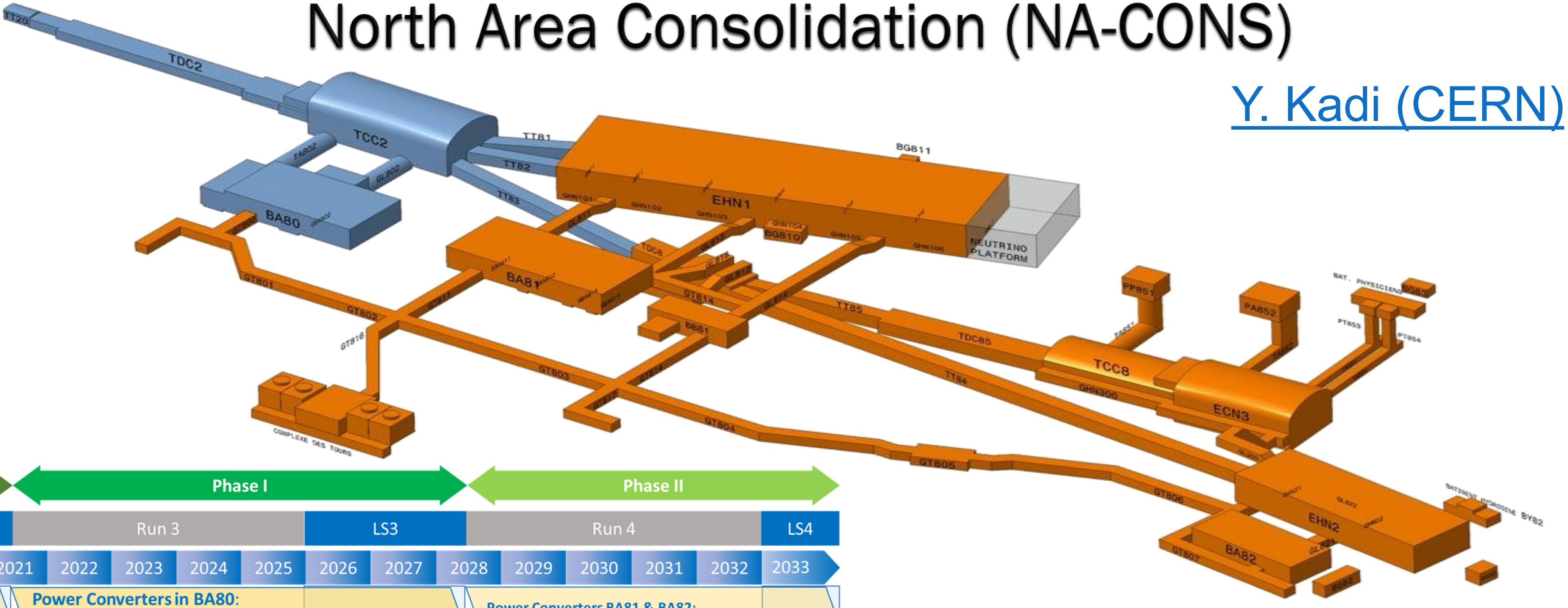
Category	Exp.	Beam line	Target(s)	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
R&D	HL-LHC, FCC, NA physics, R2E, muon collider, space / satellites	H2	T2																				
		H4 & GIF++	T2																				
		H6 & CERF	T4																				
		H8	T4																				
Dark Matter and FIPS	NA64-e	H4	T2																				
	NA64-h	H4/H6/H8	T2/T4																				
	NA64-μ	M2	T6																				
	SHiP	ECN3	T4																				
	MADMAX	H8, w/o beam, YETS	N/A																				
Precision Physics	NA62	K12	T4/T10																				
	MUonE	M2	T6																				
	NA63	H4	T2																				
	DsTau	H2	T2																				
QCD	COMPASS	M2	T6																				
	AMBER-antip	M2	T6																				
	AMBER-Rp	M2	T6																				
	AMBER-DYn	M2	T6																				
	AMBER-HI	M2	T6																				
	AMBER-RF	M2	T6																				
	NA61 & NA61++	H2	T2																				
	NA60++	H8	T4																				
Neutrino-related Beams	ProtoDUNE-SP	H4	T2																				
	ProtoDUNE-VD	H2	T2																				
	ENUBET & NuTAG	TCC2/SPS?	tbc																				
	NA61 low energy	H2	T2																				
	DsTau	H2/H4	T2																				

Cons. Requirement

- R&D: **Reliability and safety of equipment**. Stabilise **beam uptime**. **Adapt infrastructures**. Consolidate **cooling** capacity and **exp. magnets**
- Dark Matter and FIPS: **Precise & reliable beam instrumentation.** Increase beam intensity
- Precision Physics: **Adapt beam instrumentation** and **increase beam intensity. Magnet and PC reliability**
- QCD: ncrease equipment's **reliability and safety**, and beam uptime. **Adapt beam instrumentation** and **increase beam intensity**.
- Neutrino-related Beams: **ncrease reliability, safety,** and **beam uptime**. Consolidate **beam instrumentation** and **stability** of **power supplies**

North Area Consolidation (NA-CONS)

Y. Kadi (CERN)



Pre-Phase I	Phase I	Phase II
LS2 (2019–2020)	Run 3 (2021–2025), LS3 (2026–2027)	Run 4 (2028–2032), LS4 (2033)
Power Converter Consolidation study	**Power Converters in BA80:** • PC & E.E. for vertex1&2 + H8 Morpurgo (YETS 21/22) • 50% of the power converters • 50% of availability recovered (TT20, TDC2, start of NA)	**Power Converters BA81 & BA82:** • 50% of the power converters • 100% of availability recovered
Beam Instrum: review & analysis Crates consolidation Electrical non conformities	**Beam Instrumentation**: 60% of consolidation	Consolidation & Upgrade for higher intensity: remaining 40%
Civil Eng.: roof of gas barracks BA gate doors	**Civil Engineering**: BA80, 5th cell for CT2 Light repairs elsewhere	**Civil Eng.**: EHN1, EHN2, ECN3, BA81, BA82
Tech.Services: CT2, cooling plant, Chilled water piping, Irrad cables TDC2, Lift for TCC8	**Technical Services:** EL: BA80, TDC2, TCC2, UPS, secured network CV: underg. ventil, chilled water, cooling station,CT2, new cooling station for converters in BA80	**Technical Services:** EL: BA81, BA82, EHN1, EHN2, ECN3 CV: ventil. surf bldg., primary pumps circuits, new cooling station in BA81 and 82 (for PC) CRG: centrifugal helium pumps
Safety: Gas network, Gas detection, ATEX ventil. SUSI 918, EHN2 video ECN3, EHN2	**Safety (95%):** - Underground & Surface Fire detection & Alarm. - Fire detection in false floors BA80 - Sprinklers underground (shafts) - Fire detection EHN2 galleries - Pilot test for new access control system	**Safety (remaining 5%):** - Fire detection in ventilation and in false floors for BA81 & BA82 - Access system deployment

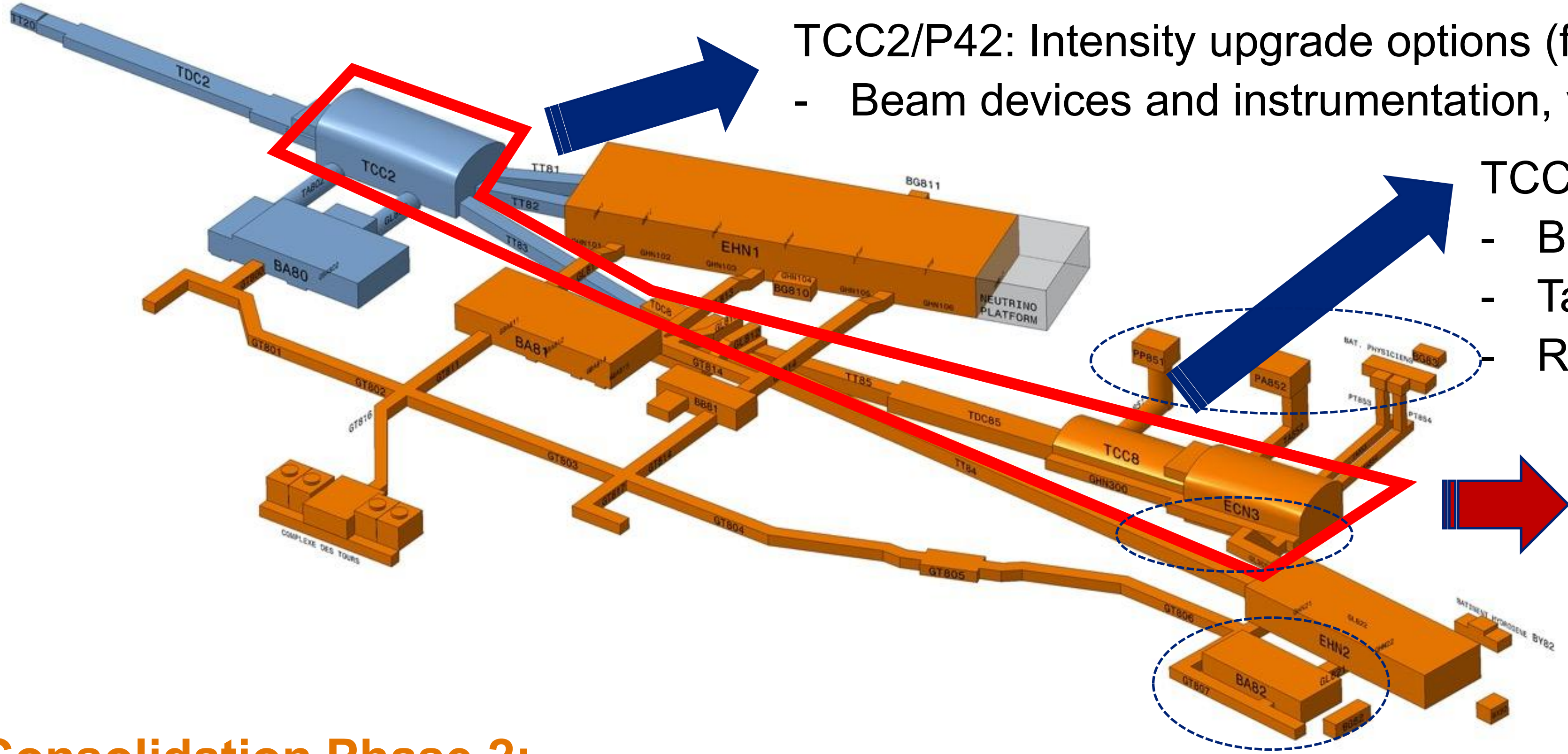
Phase I allocated in CERN's Medium-Term Plan

➔ Procurement well underway

NA-CONS -> Intensity upgrade for SHiP

Y. Kadi (CERN)

Consolidation Phase 1:
2019 – 2028: primary areas (incl. BA2), BA80 & beamlines towards EHN1 & TDC8



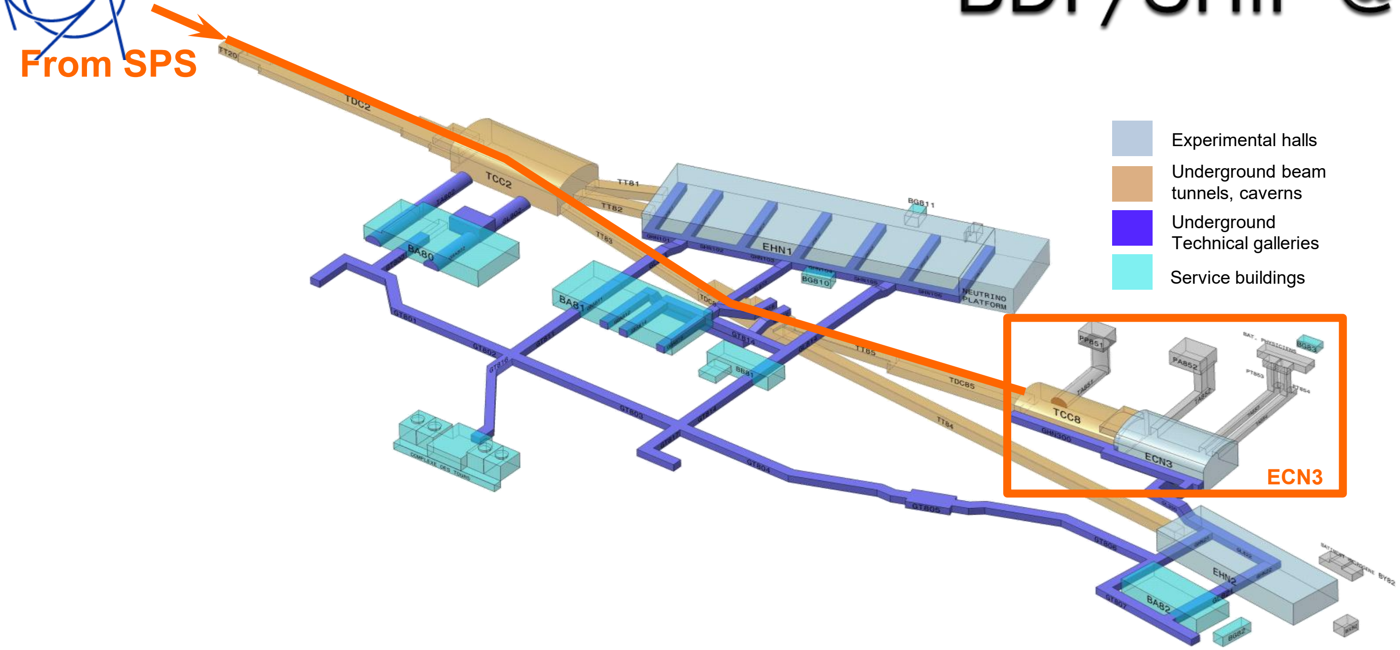
TCC2/P42: Intensity upgrade options (for all experiments)
- Beam devices and instrumentation, vacuum, shielding

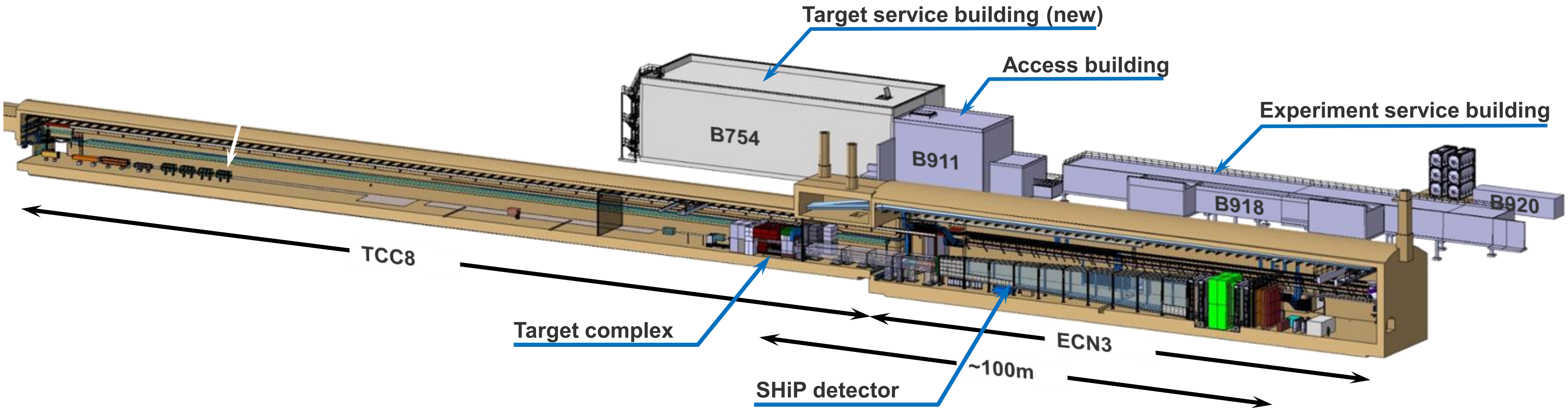
TCC8/ECN3: Experiment specific:
- Beam Dump Facility
- Target complex
- Related infr. & services

ECN3 Beam Facility concerned with the upgrade for SHiP (underground!)

Consolidation Phase 2:
2029 – 2034: BA81, BA82, EHN1, EHN2 & associated beamlines

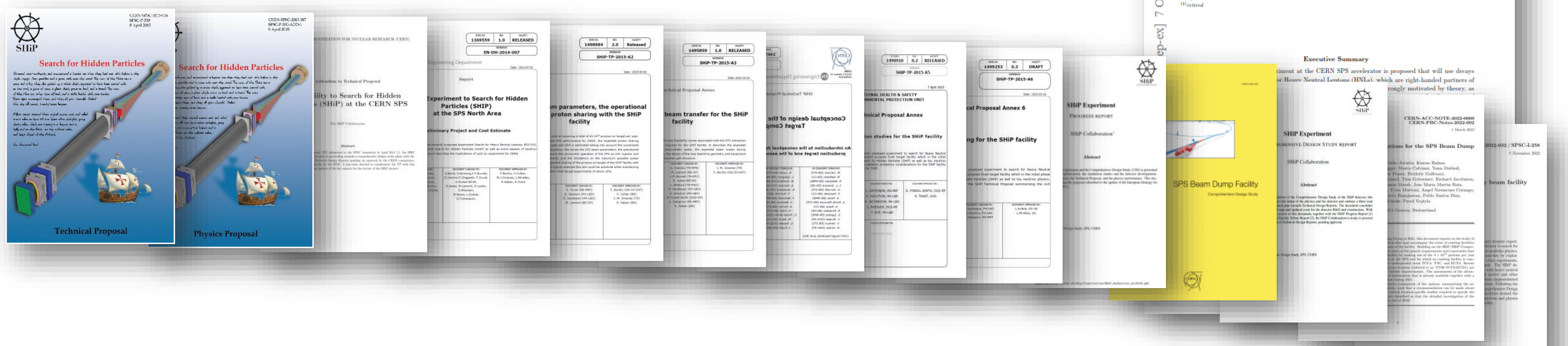
BDF/SHiP @ SPS


From SPS
Experimental halls
Underground beam tunnels, caverns
Underground Technical galleries
Service buildings
ECN3


Target service building (new)
Access building
Experiment service building
B754
B911
B918
B920
TCC8
ECN3
~100m
Target complex
SHiP detector

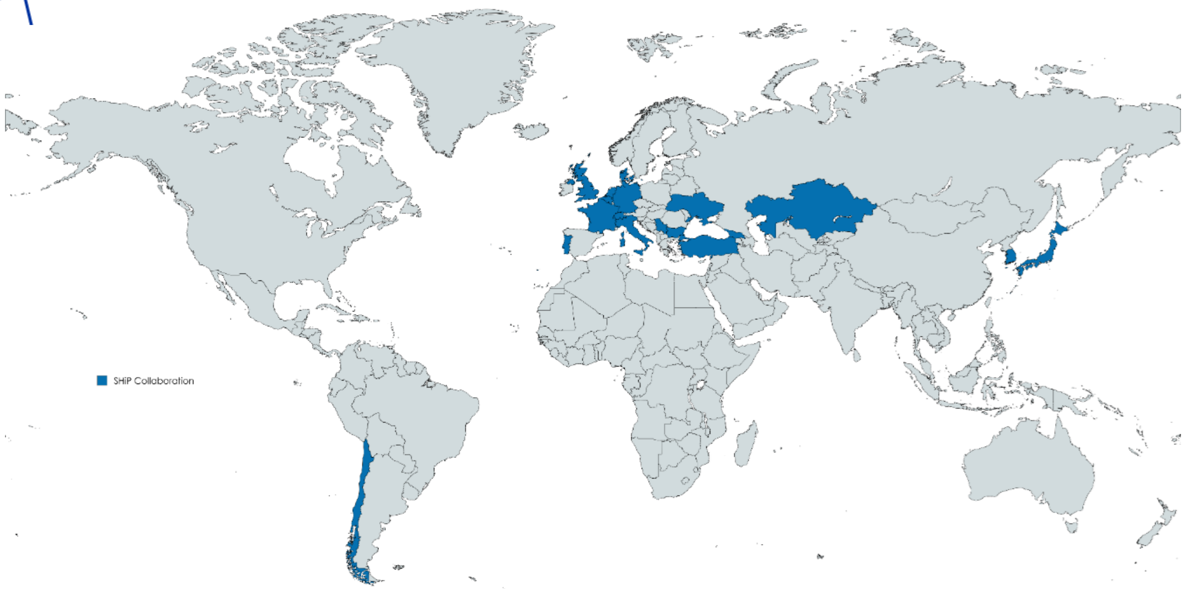
SHiP - from proposal to approval

- **2013 Oct: Seminal paper with the first proposal by a group of 16 researchers**

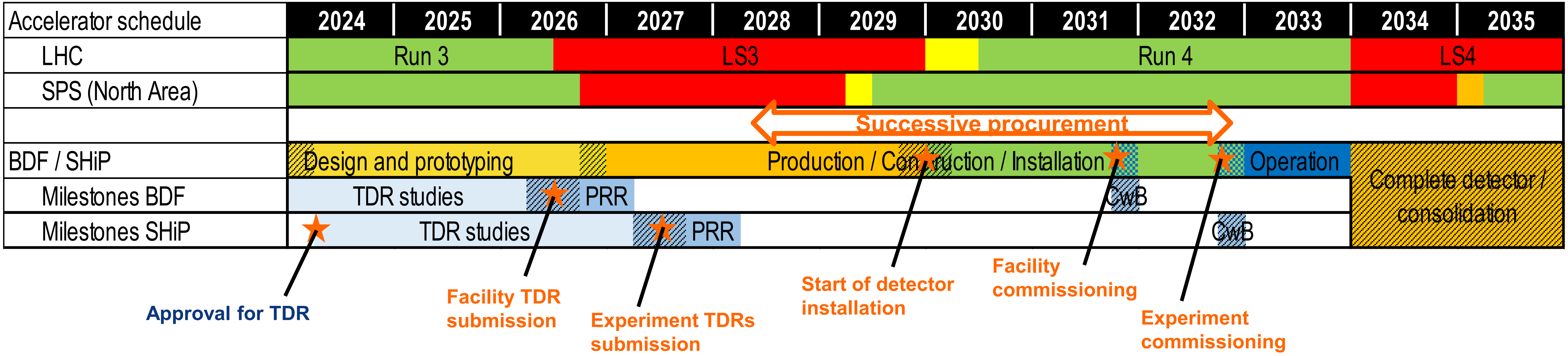


- 2014 Jan: Immediate support from CERN management to form collaboration and prepare technical proposal
- 2016 Jan: Technical proposal accepted and recommendation to proceed to Comprehensive Design Study (CDS) of the Beam Dump Facility (BDF) for SHiP and the experiment
- 2019 Dec: CDS reports on Beam Dump Facility and SHiP experiment submitted to CERN's committees
- 2020 Sep: CERN launches BDF/SHiP study towards implementation in existing experimental area at CERN
- **2024 Jun: Approval of BDF and SHiP for implementation in the SPS ECN3 area ➔ Technical Design phase**

SHiP collaboration and schedule



34 institutes and 8 additional associate institutes in 18 countries, and CERN and JINR

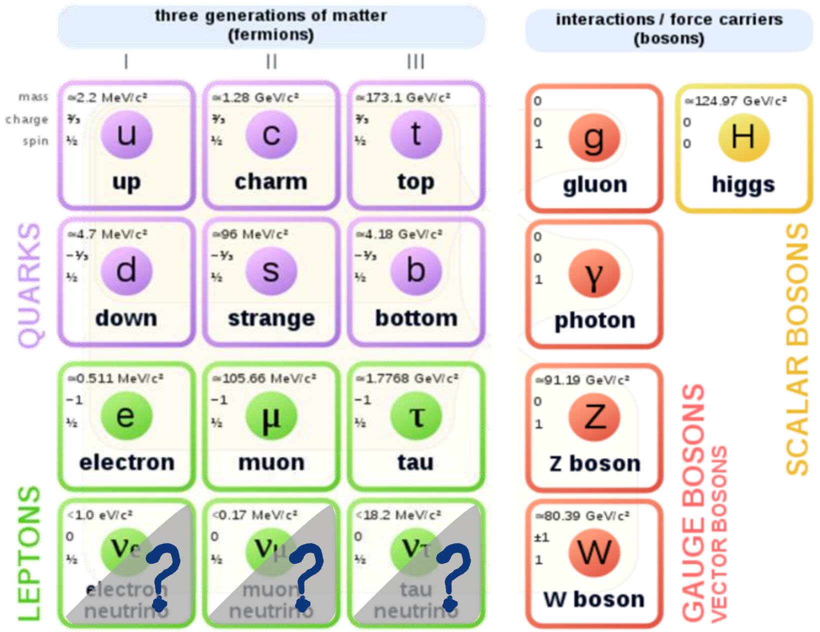


➔ 15 years of physics exploration

Search for Hidden Particles?

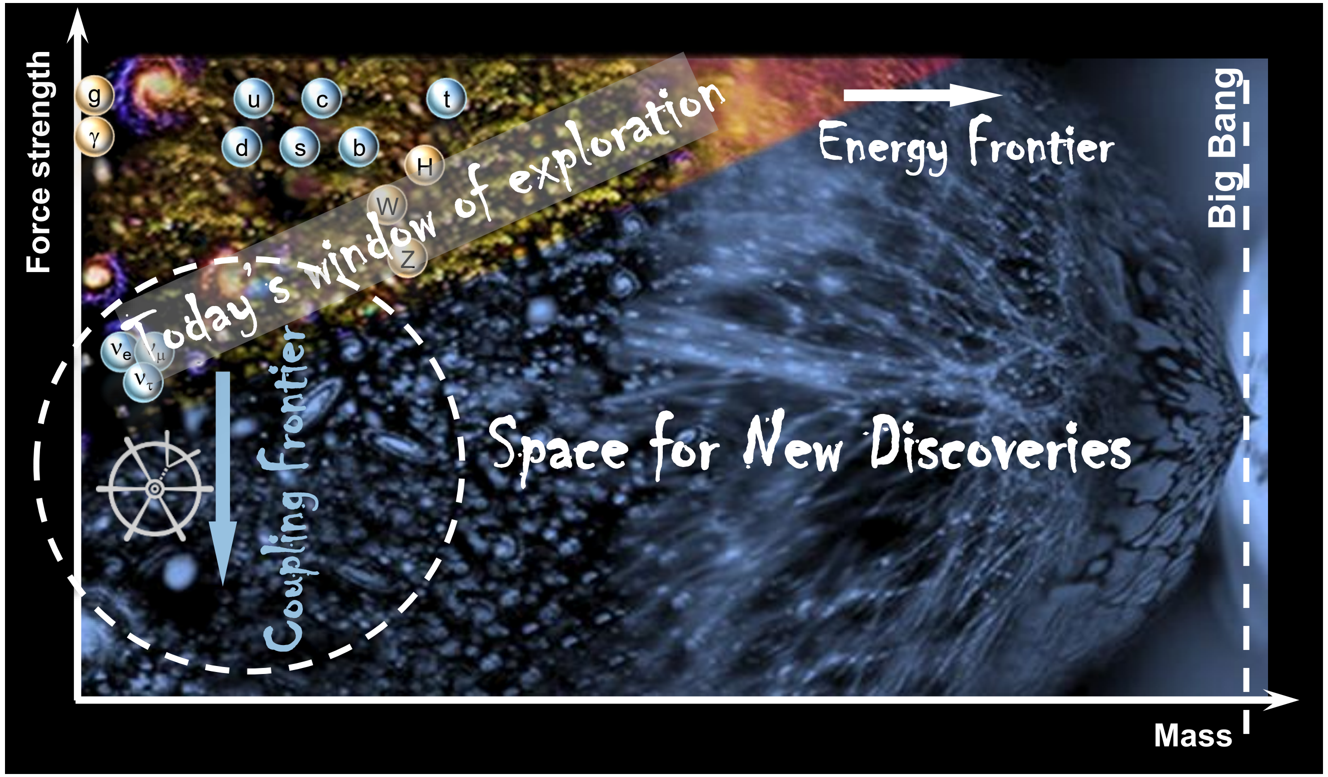
Two of today's ***most outstanding*** fundamental questions are ***Dark Matter and Nature of Neutrinos***

Today's knowledge of particles and forces



Dark Matter?

Dark Forces?



The particles involved in the explanation are either too heavy OR *interact too weakly* to have been discovered with today's facilities and instruments!

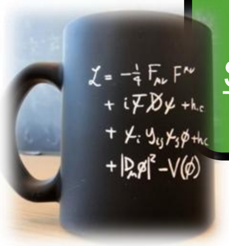
➔ **SHiP's proposal is an *entirely new and unique world-wide facility to explore* these two questions and many other – realization that CERN has world's most powerful accelerator for this purpose, the SPS!**

Theory of a Hidden Sector with Dark Matter?

Standard Model has given us plausible tools to implement Hidden Sector with well-defined phenomenology

<u>In the Standard Model language</u>

$$\mathcal{L}_{Universe} = \mathcal{L}_{Visible} + \mathcal{L}_{portals} + \mathcal{L}_{Hidden\ Sector}$$



<u>Visible Sector</u>
<u>Standard Model</u>

"Portal interaction"

<u>Hidden Sector</u>
<u>"Dark standard model"</u>

Portal interactions may "drive" dynamics observed in the Visible Sector!

- Dark Matter (trivial)
- Neutrino mass and oscillations
- Matter-antimatter imbalance
- Mass of Higgs Boson
- Structure formation
- Inflation and Dark Energy
- ….

Theory of a Hidden Sector with Dark Matter?

Standard Model has given us plausible tools to implement Hidden Sector with well-defined phenomenology

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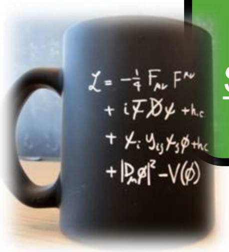

<u>Visible Sector</u>
<u>Standard Model</u>

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<u>Hidden Sector</u>
<u>"Dark standard model"</u>

Portal interactions may "drive" dynamics observed in the Visible Sector!

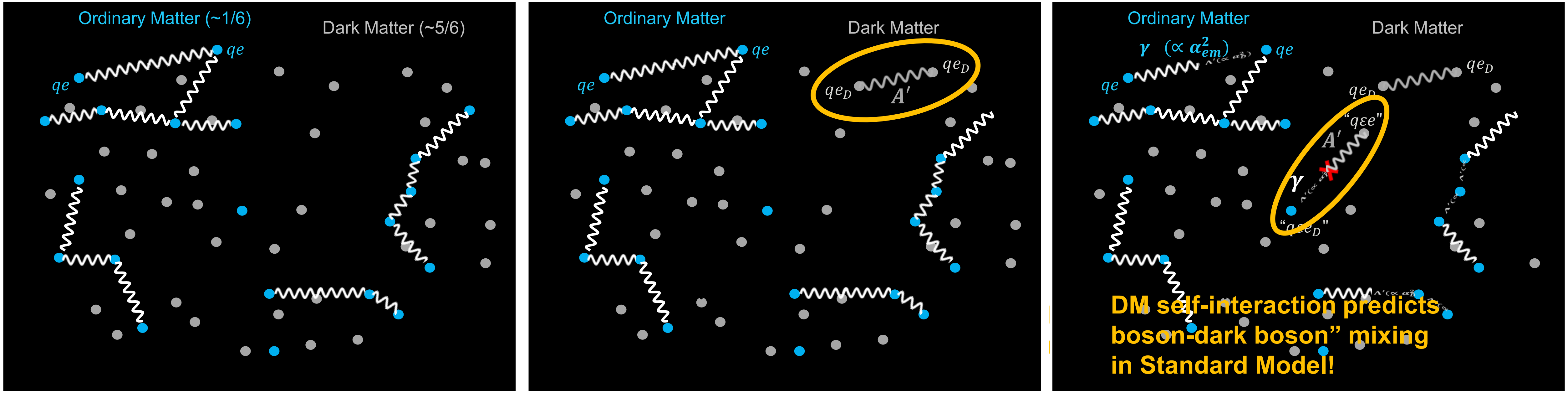
- Dark Matter (trivial)
- Neutrino mass and oscillations
- Matter-antimatter imbalance

➔ $\mathcal{O}(1000)$ *scientific theory papers developing ideas around this since the 90's*

➔ Up to now, this sector of physics only explored in exotic studies as by-product of experiments built for other purposes !

Experimental idea

Example of Hidden Sector physics case

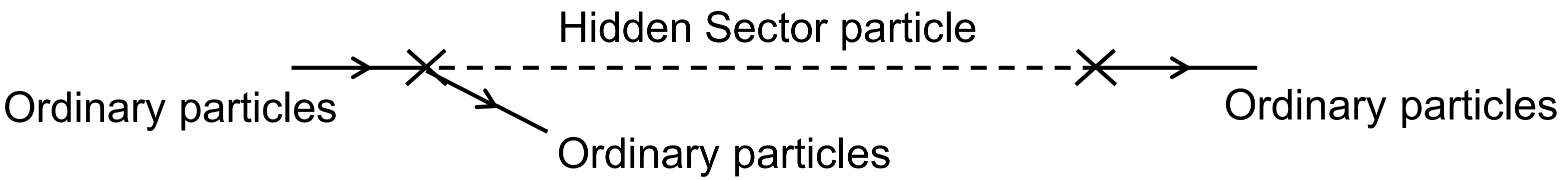


Profiting from "portal" coupling at accelerator!

➔ Light Hidden Sector particles are long-lived, travel metres-kilometres

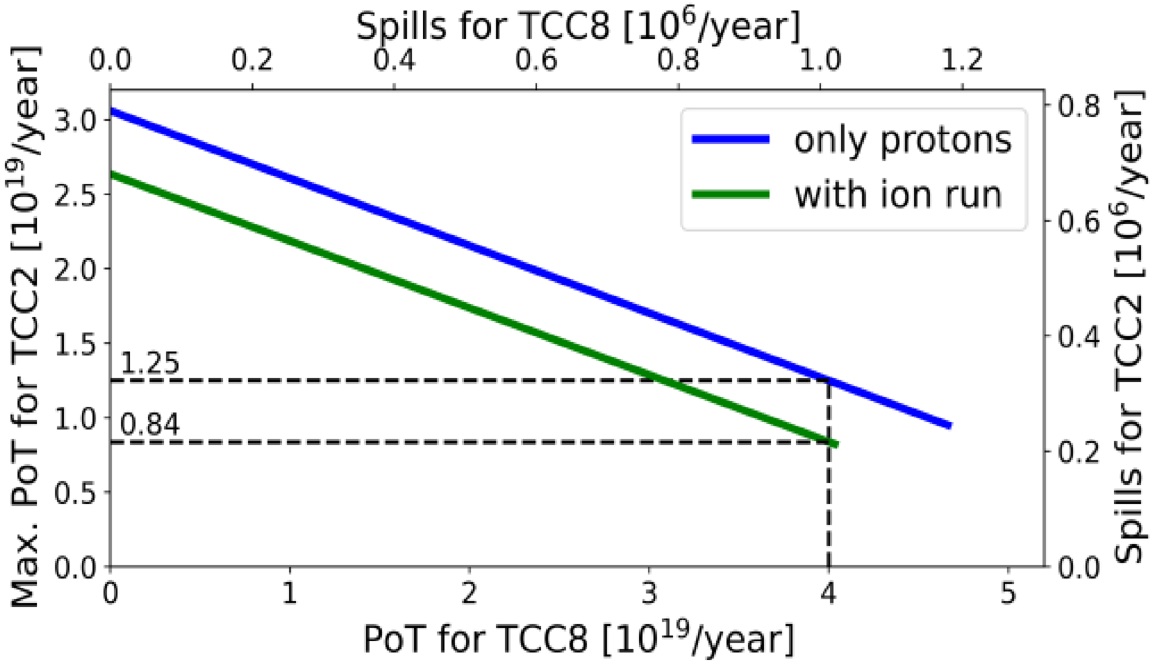
Production

Detection



SPS physics potential

4x10^19 protons per year available in SPS since 2013 (end of CNGS facility)



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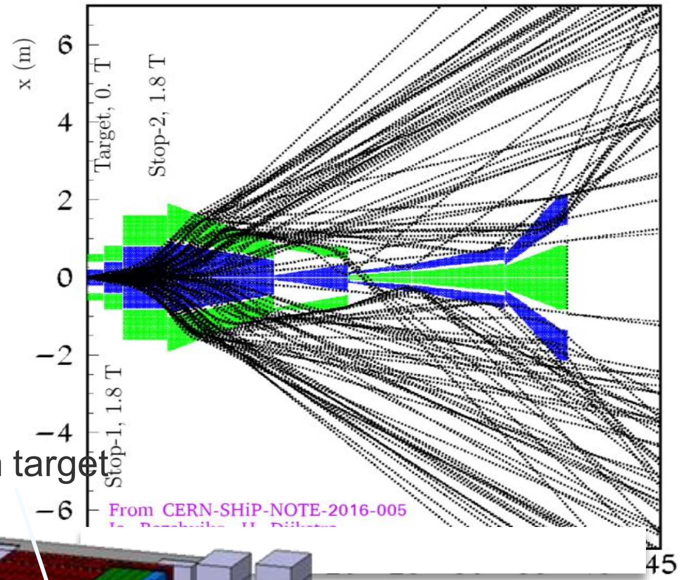
- ➔ BDF luminosity with the optimised target and 4x10^19 protons on W target per year *currently available* in the SPS
  - ➔ BDF@SPS $\mathcal{L}_{int}[year^{-1}]$ = >4 x 10^{45} cm^{-2}
  - ➔ HL-LHC $\mathcal{L}_{int}[year^{-1}]$ = 10^{42} cm^{-2}

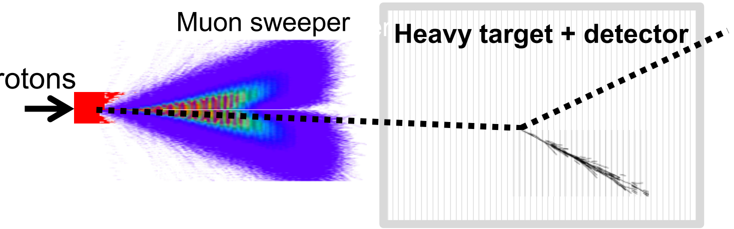
E.g. ~ 2×10^{17} charm particles (>10 times the yield at HL-LHC)

SHiP detector – two detection techniques

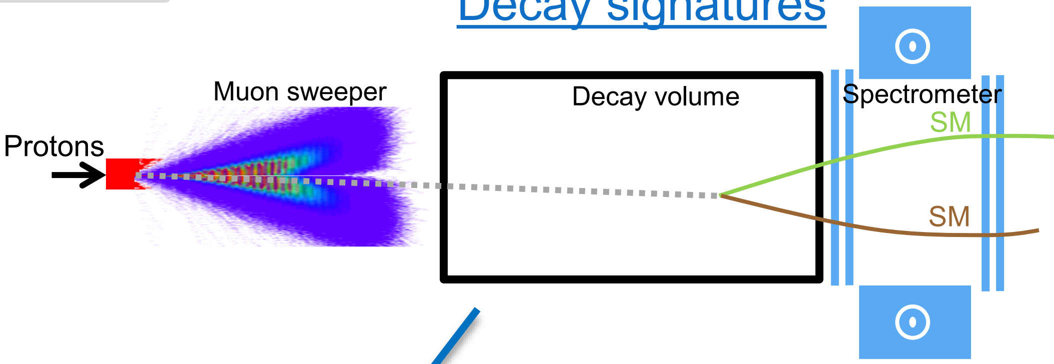
Muon deflection technique

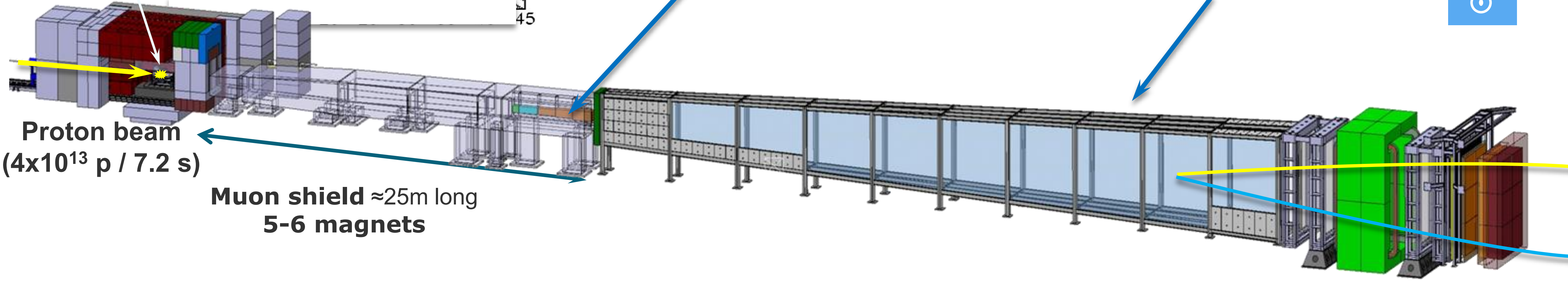


Scattering signatures



Decay signatures





Proton beam
(4x10^{13} p / 7.2 s)

Muon shield ≈25m long
5-6 magnets

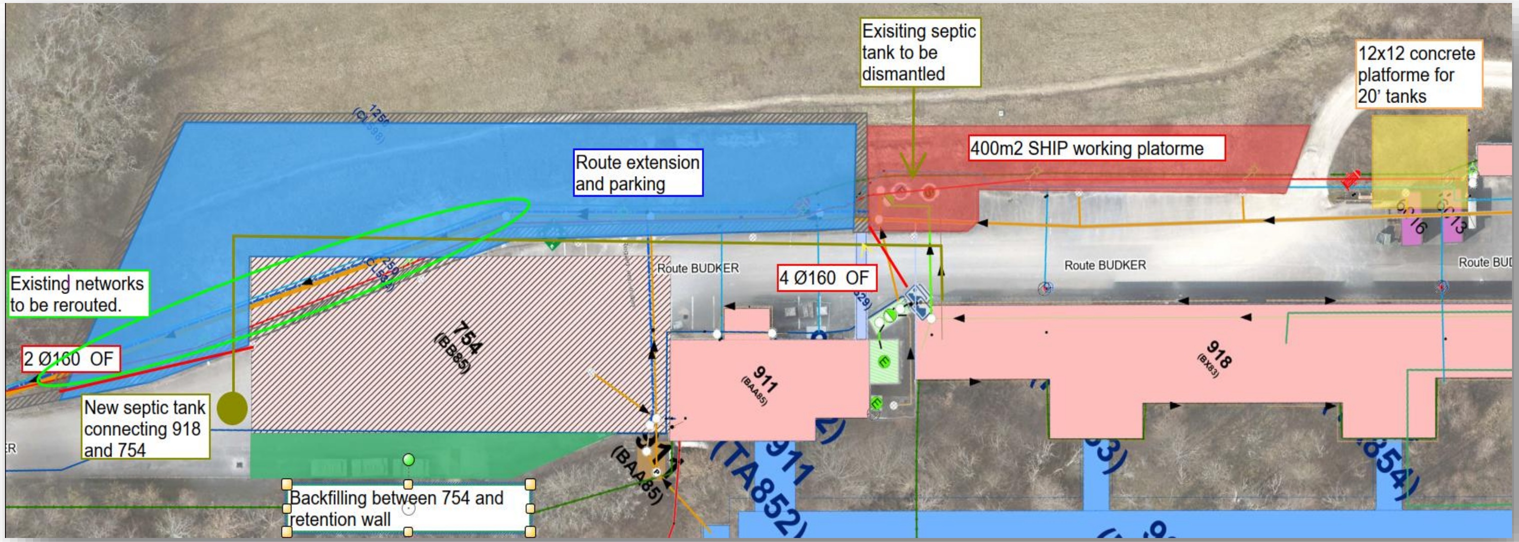
Civil engineering

May - July 2025: Ground-breaking at ECN3 for BDF/SHiP:
Rerouting of service trench to make space for the construction of the new BDF target complex service building 754 and installation of new access door to 911

June – Sep 2025: Ground-breaking at TT7:
Recovery of 600t of iron shielding blocks from the PS neutrino facility, operated in the early 80's, to be reused for shielding at BDF/SHiP

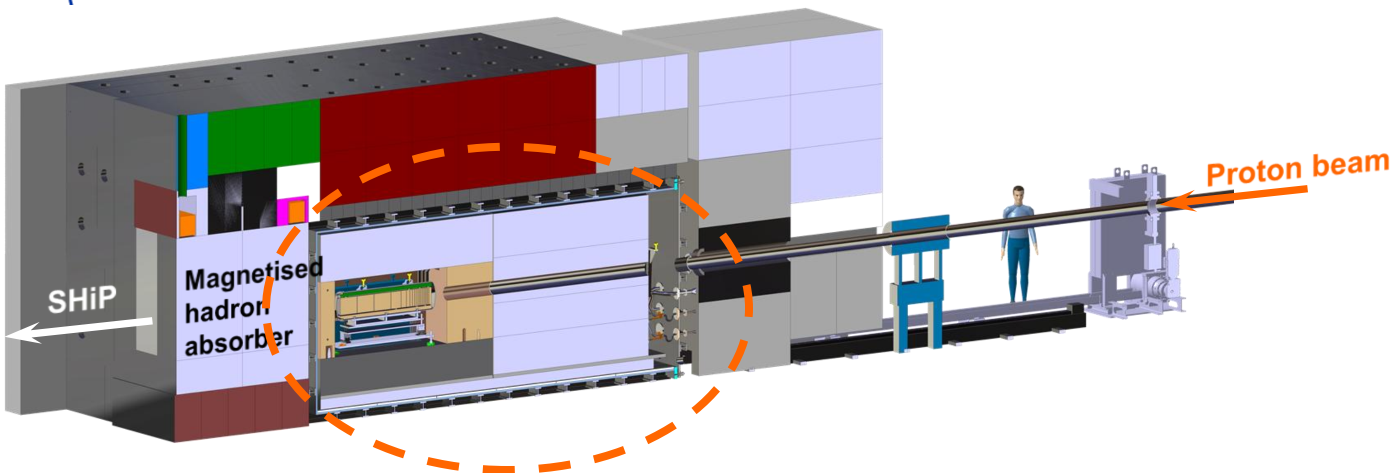
Civil engineering procurement start Q2-2026

- **Oct 2025: Civil engineering project approval**
- B754 to house facility able to handle, maintain and decommission BDF target: collaboration with RWM to treat legacy CERN waste in the long-term
- Design Study of Service Cell by external contractor returned and being integrated into procurement of CE

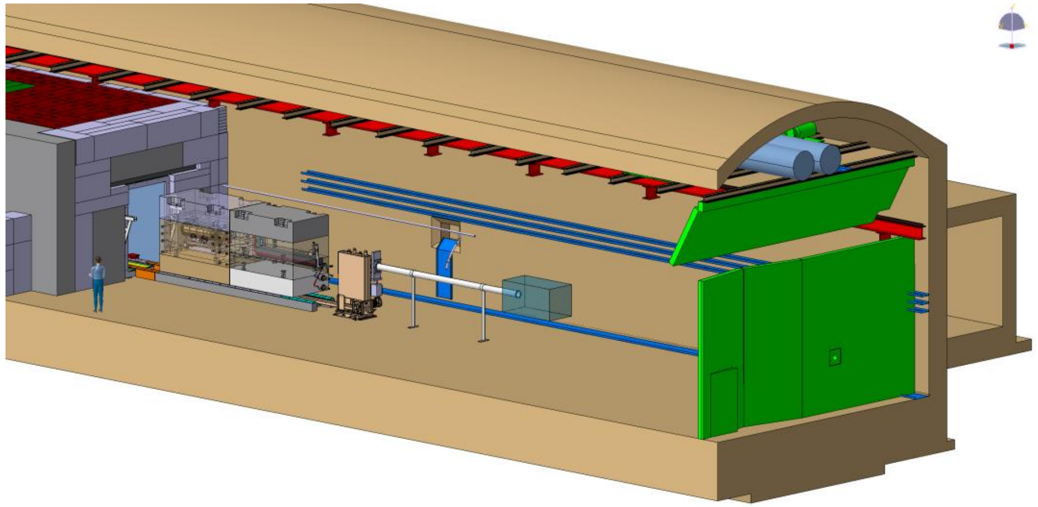


Target complex and service building

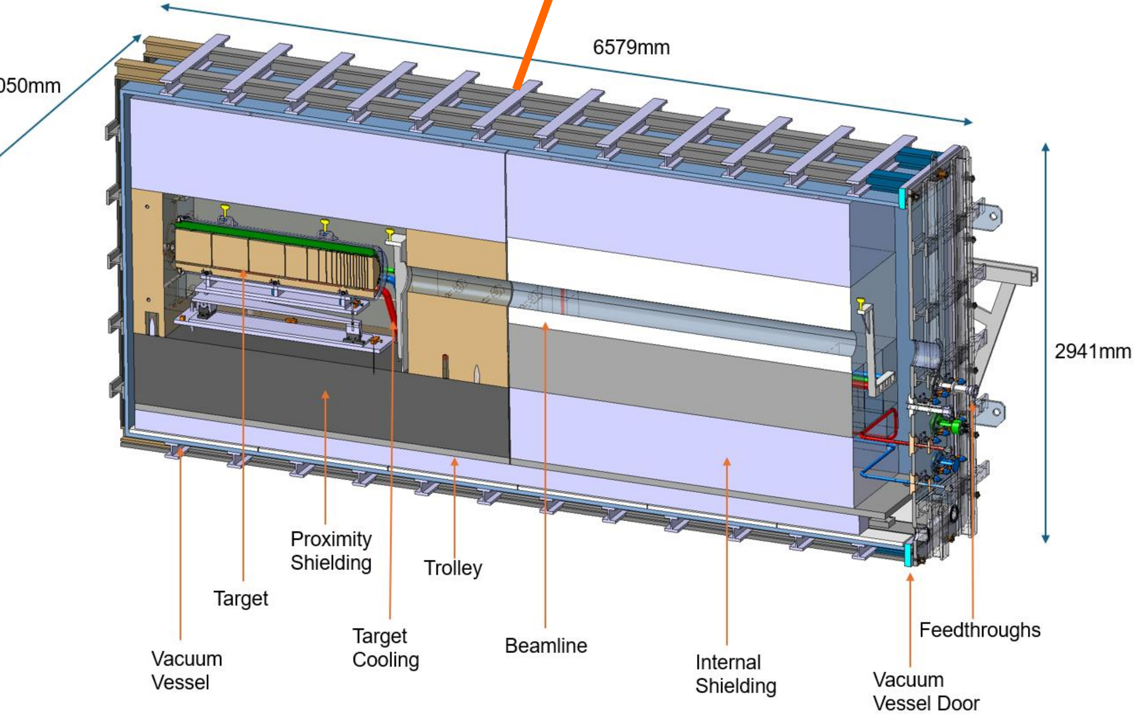
HI-ECN3



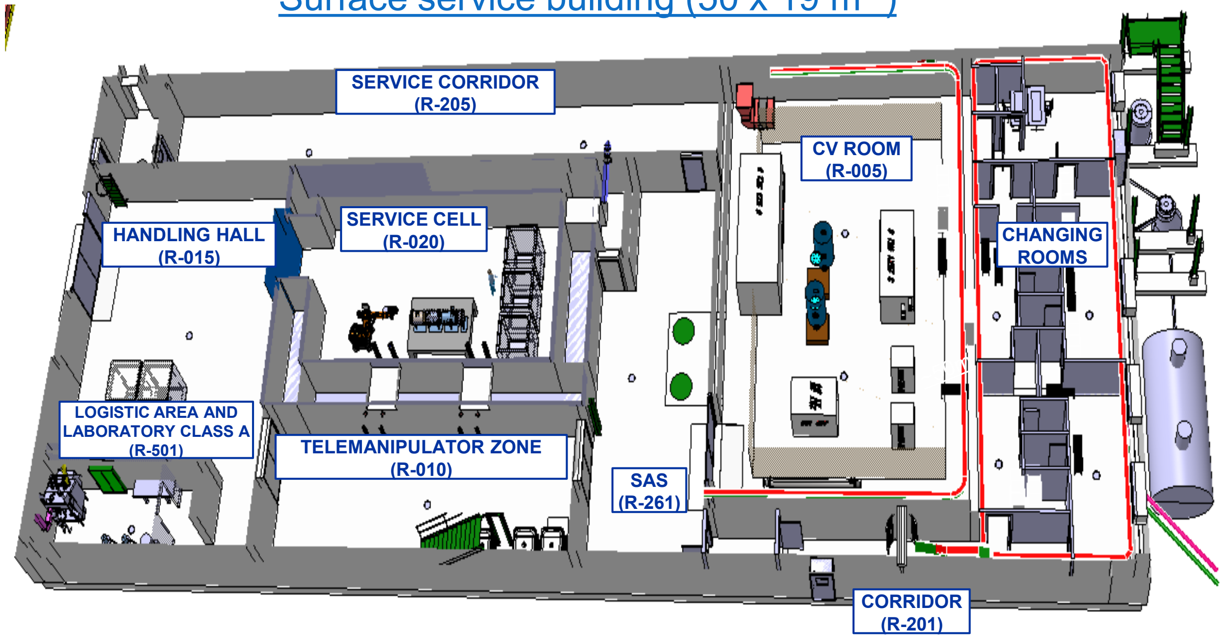
"Target trolley"



Proximity shielding embedded in vacuum vessel (~10^{-3} mbar)

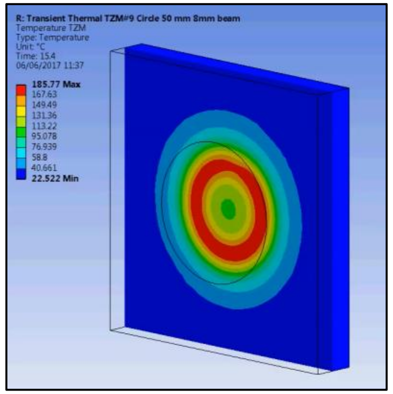


Surface service building (50 x 19 m^2)



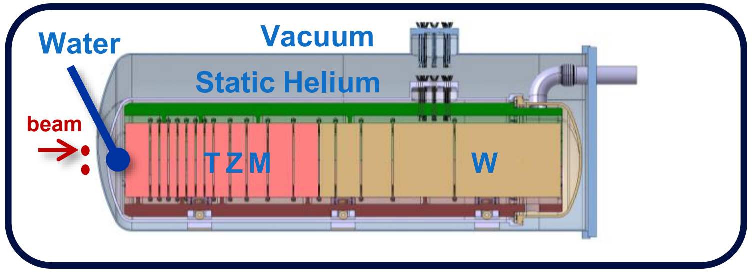
BDF target system

Parameter	Value	Unit
Proton momentum	400	GeV/c
Nominal beam intensity	4e13	POT/spill
Total cycle length	7.2	s
Spill duration	1.0	s
Circular dilution radius	50	mm
Beam sigma (H,V) [10]	16,16	mm
Thermal power deposited in target	305	kW
Expected target lifetime	2e20	POT

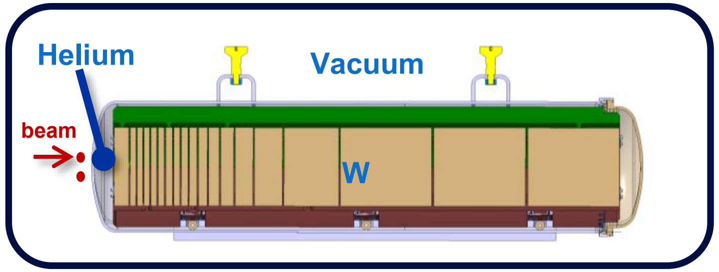


Long high-A/Z target = beam dump

Water cooled



Helium cooled



https://doi.org/10.1103/PhysRevAccelBeams.22.113001

Water Cooling

- Inner vessel with circulated water (~ 22 bar)
- Outer vessel with static Helium (~ 1 bar)

Dimensions and materials

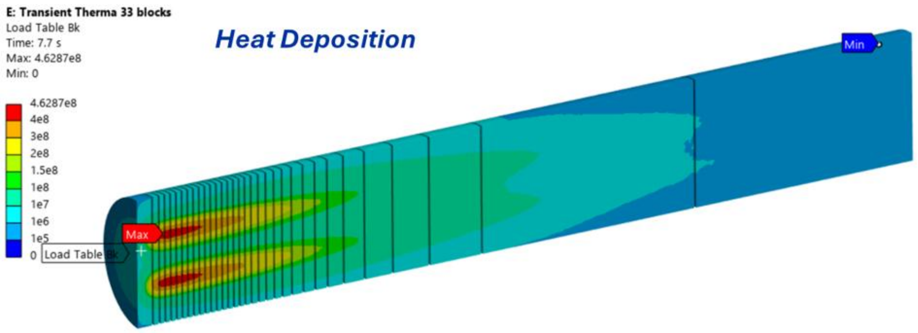
- Mass: ~2 tons (~0.9 tons of blocs)
- TZM and W Blocks all clad in Ta2.5W
- If chosen, design would be increased in length.

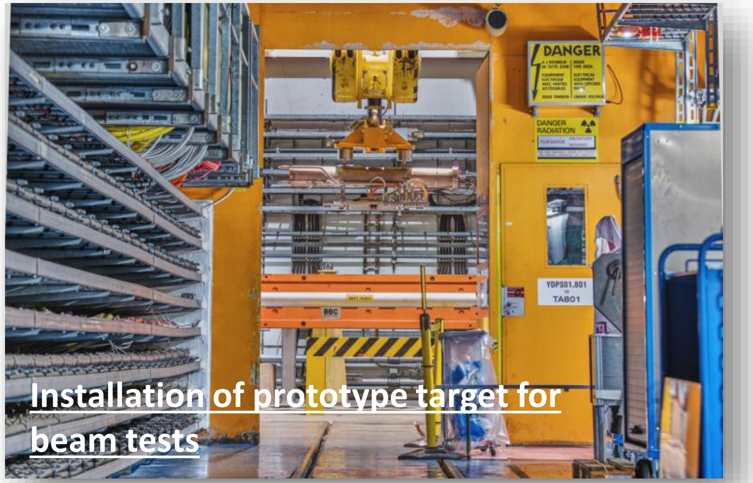
Helium Cooling

- Vessel with circulated helium (~ 16 bar, 25/200 °C)

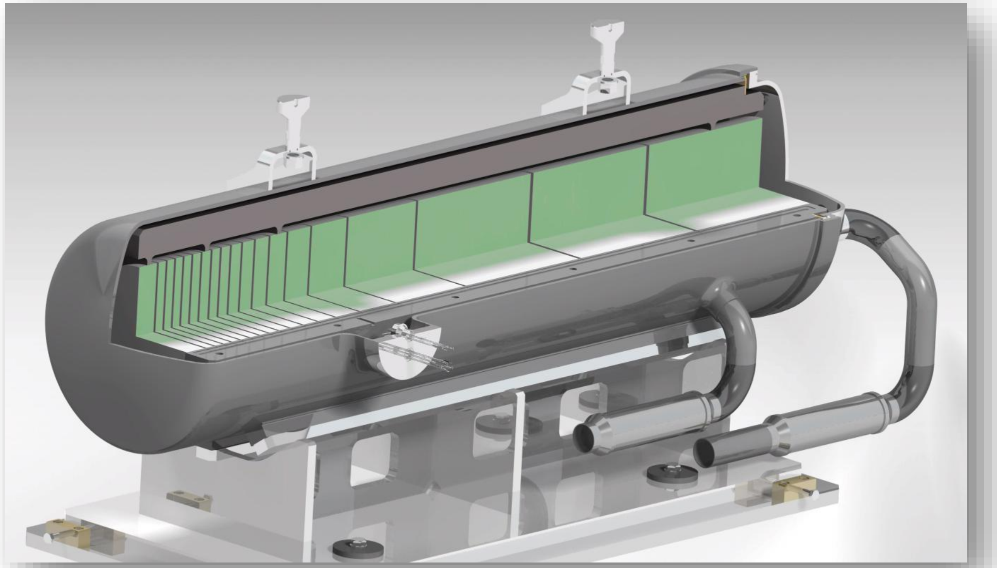
Dimensions and materials

- Total mass: ~2.3 tons (~1.3 tons of blocs)
- W blocks, maybe clad Ta or Nb or other

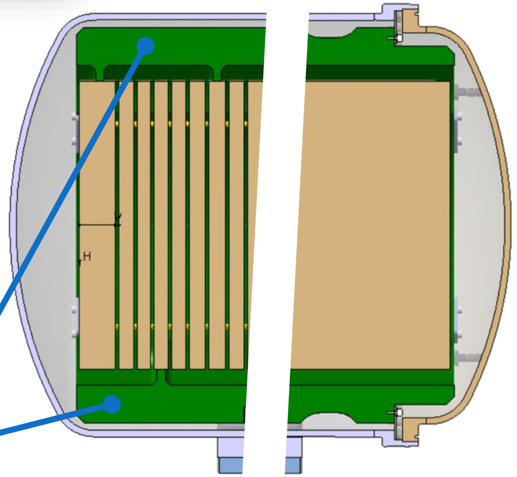


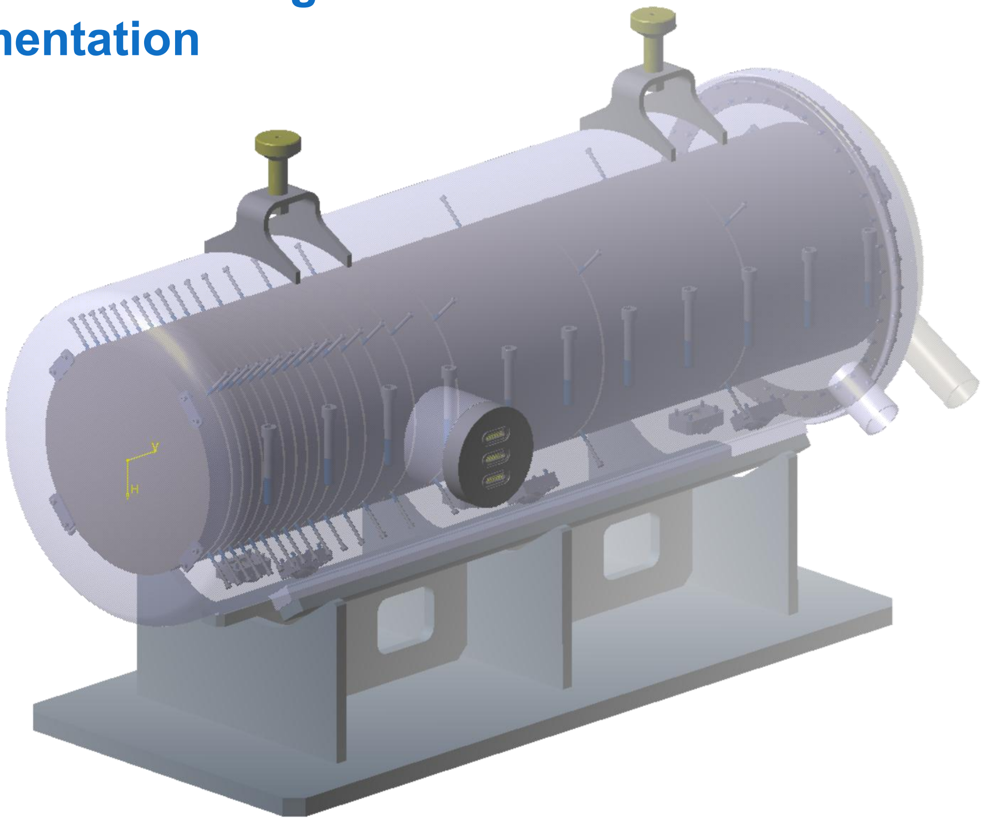


Helium vessel for W target



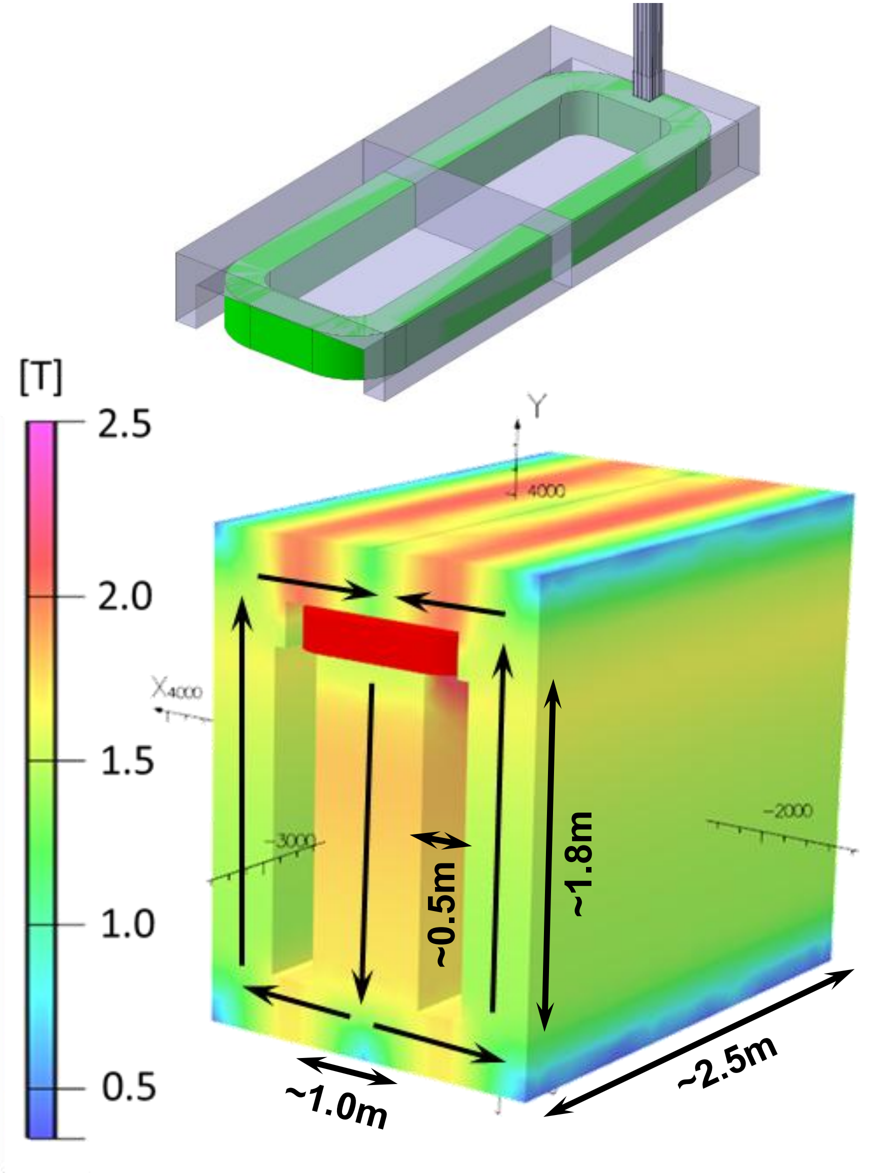
16 bar helium vessel containing target and instrumentation

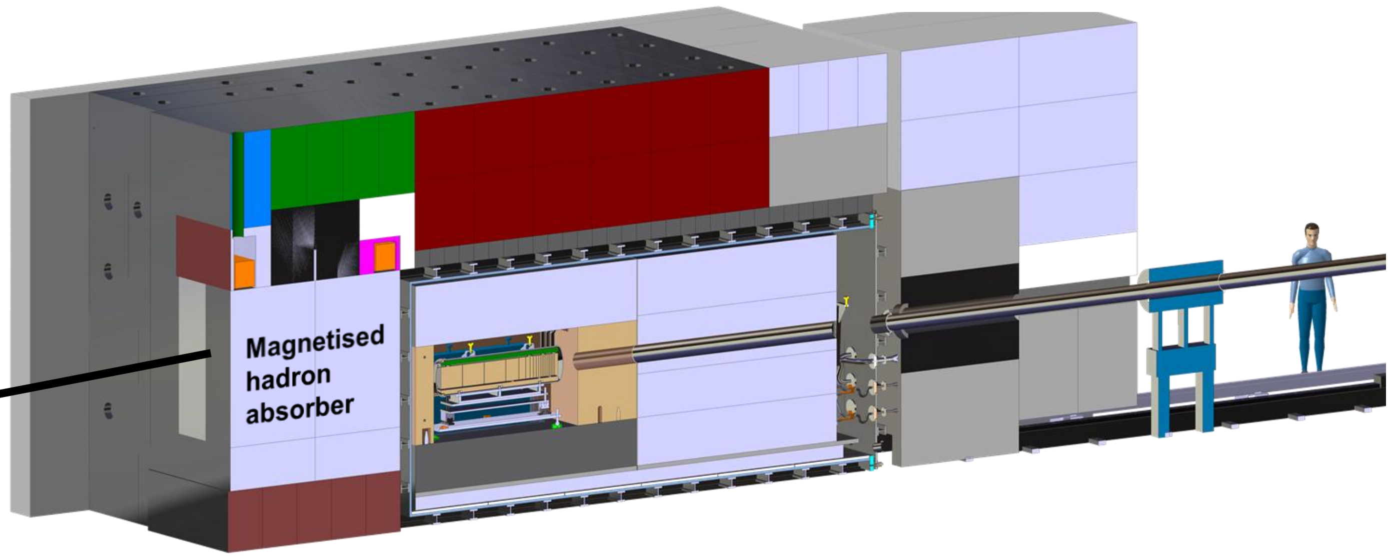




Clam-shell manifold includes machined helium flow-path

Magnetisation of downstream shielding



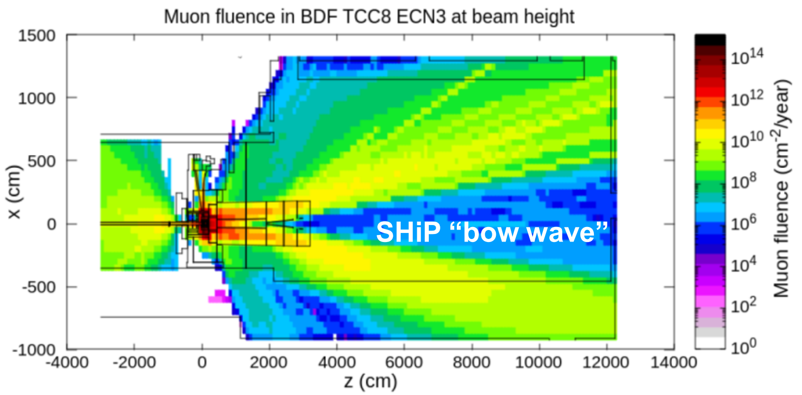


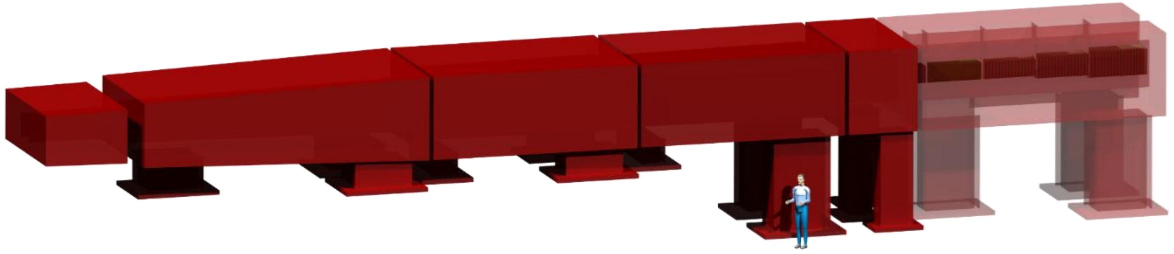
- Single resistive coil providing $\int_{-L/2}^{L/2} B_y(z)dz = 1.5T\ x\ 2.5m$
  - Water-cooled copper coil
  - Core field defined by stainless steel walls
- Main challenges
  - Service connections
  - Handling

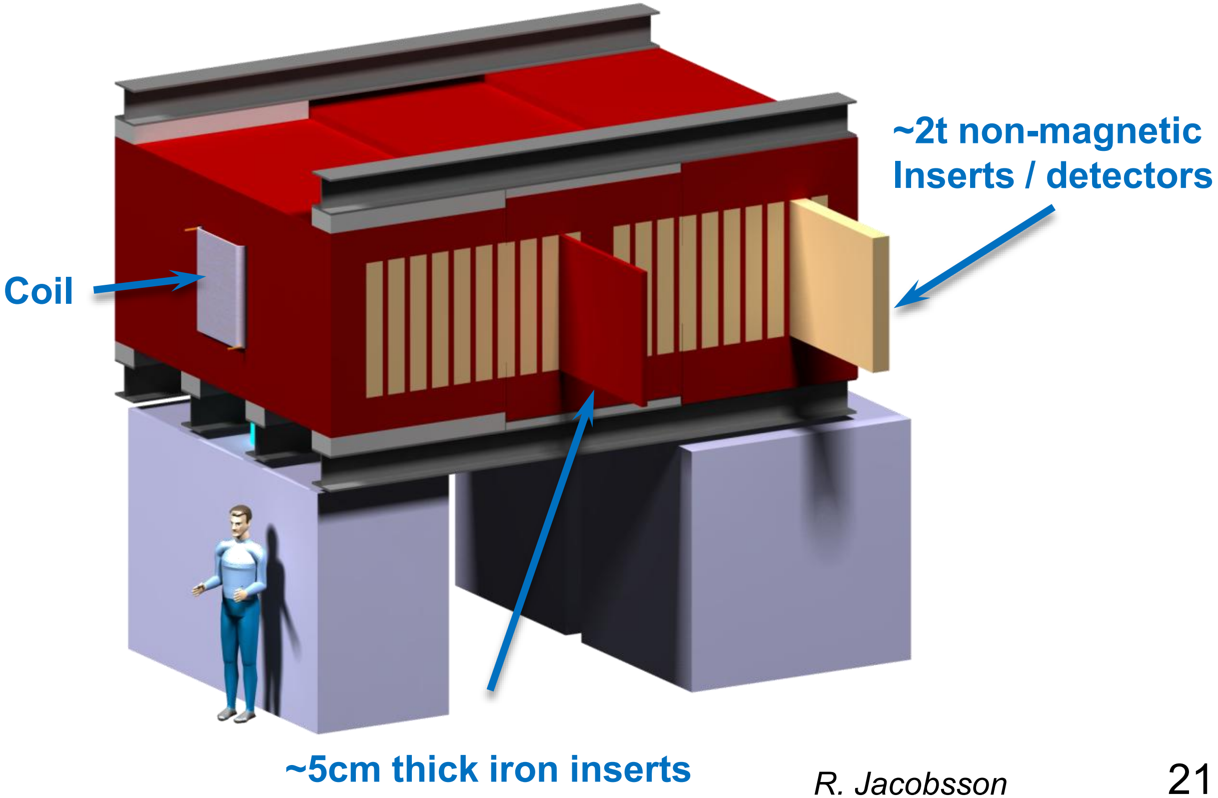
Free-standing muon shield

Muon shield is one of the most critical components of the experiment

➔ Guarantee low-background environment: 10^{11} muons/ proton spill / s ➔ max 100 kHz in detector

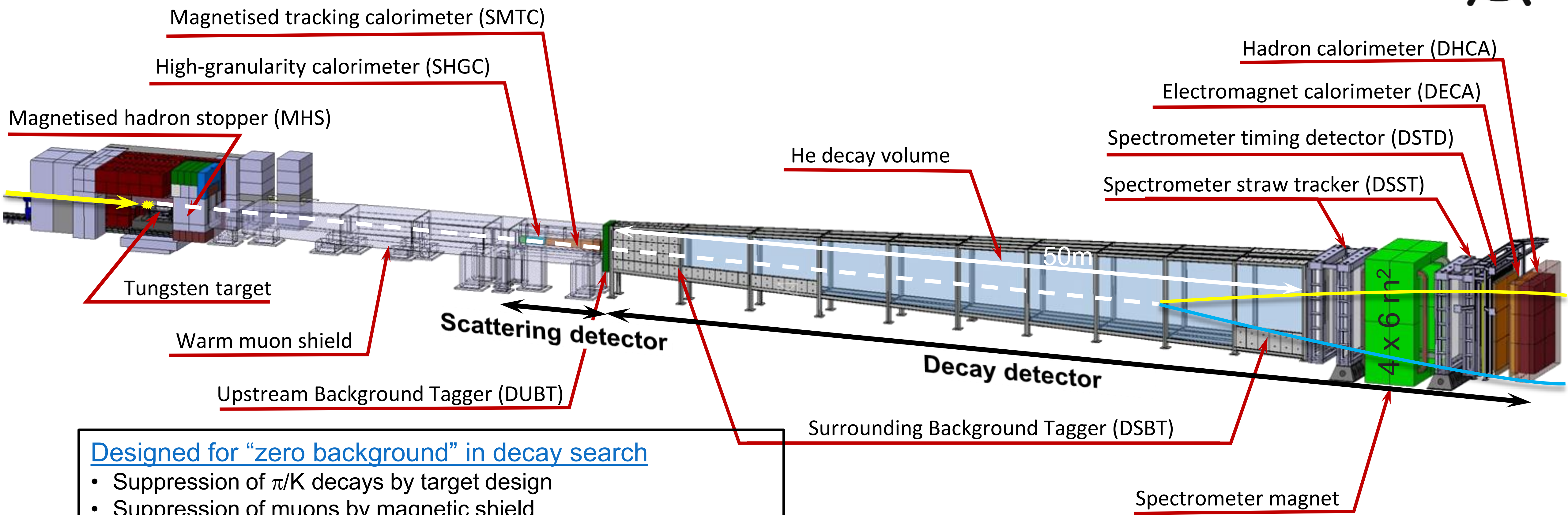






- A generic concept has been developed for the tapered-shaped muon shield magnets. 5 or 6 very similar units are to be manufactured and assembled inside the ECN3 cavern and the TCC8 tunnel.
- The yoke is made of ~130t of forged blocks or hot-rolled plates of low-carbon steel (AISI 1006) per magnet to obtain a 1.9T magnetic field in the core region.
- Coil of water-cooled copper conductor for a 500A maximum current and ampere-turns (NI) of ≈22000.
- Lateral magnetic/non-magnetic inserts to allow "tuning" return field and inserting muon monitoring system.
- Alignment system for the ~230t magnet required as part of design.

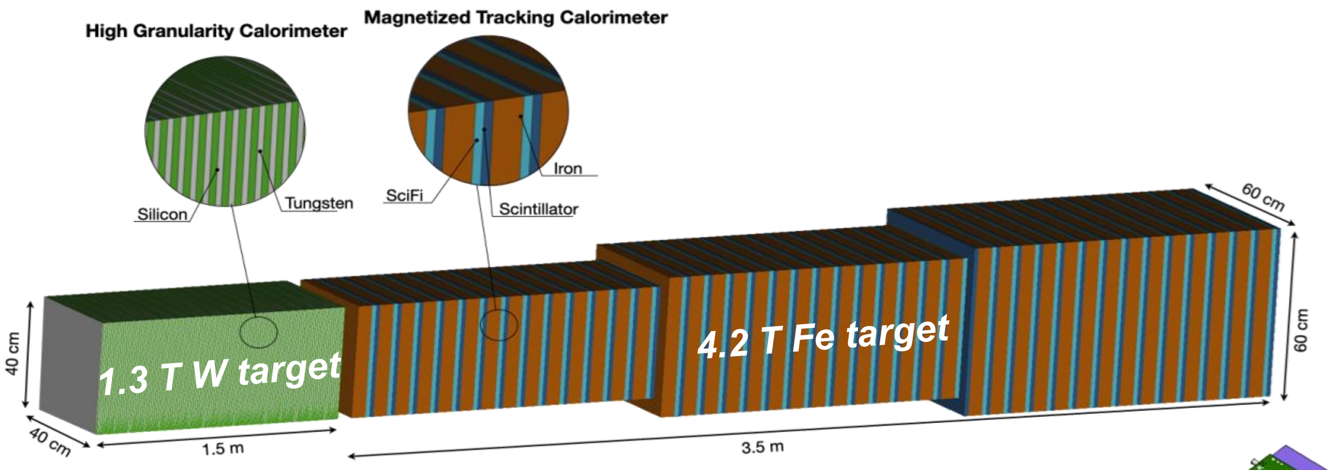
Overview of SHiP detector

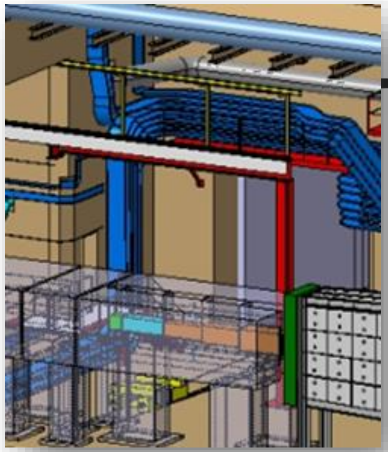


Designed for "zero background" in decay search

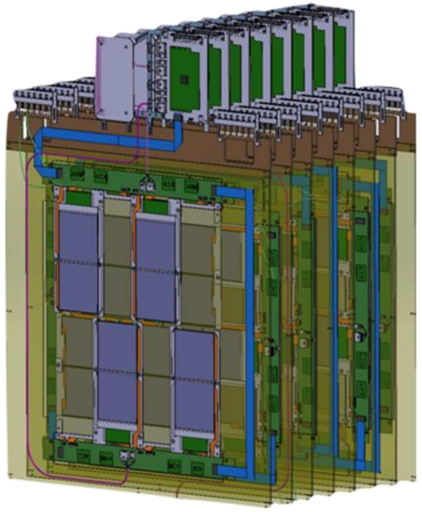
- Suppression of π/K decays by target design
- Suppression of muons by magnetic shield
- Suppression of neutrino by decay volume by evacuating air
- Background taggers
- Momentum and decay vertex information } by main tracker
- Impact parameter at target } by main tracker
- Coincidence timing
- Invariant mass } Not currently used in background suppression
- Particle identification } Not currently used in background suppression

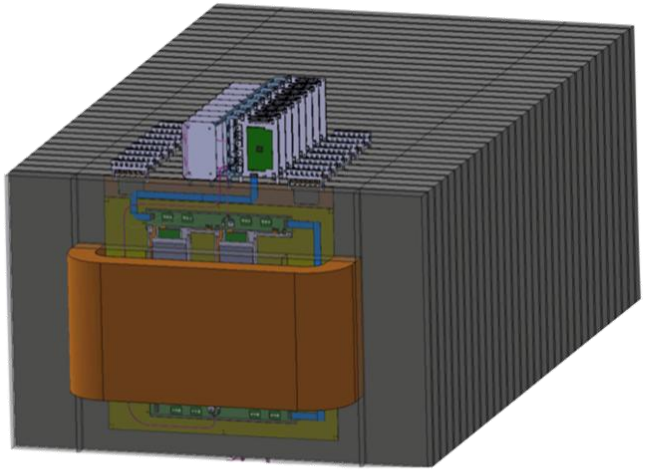
Scattering detector technologies

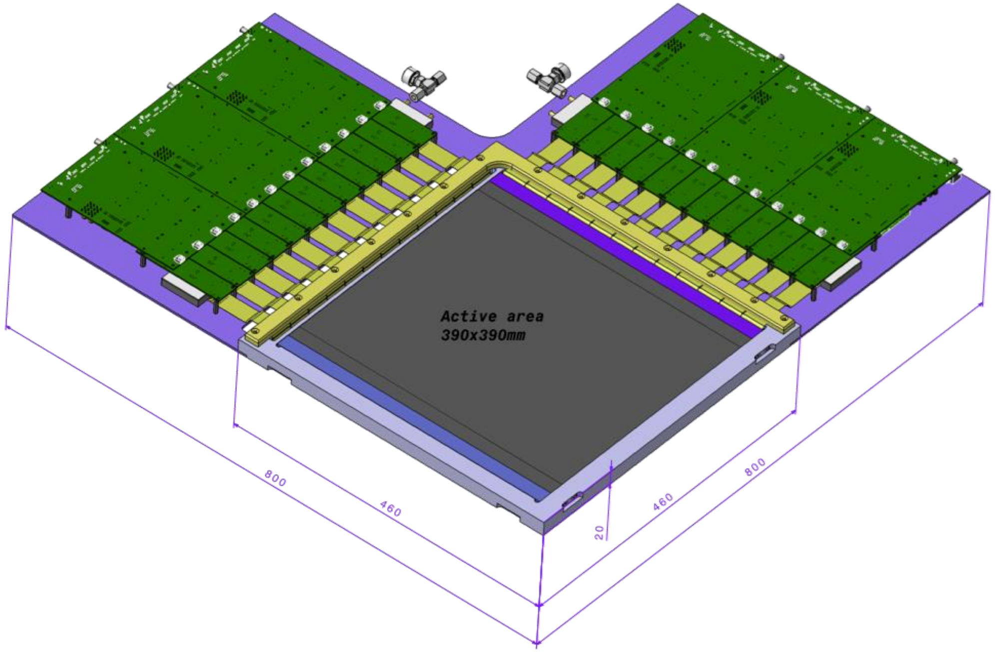




Silicon detector prototyping in the context of the SND@LHC experiment upgrade





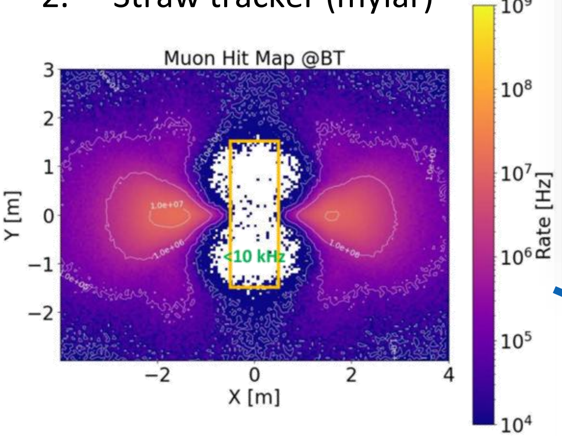


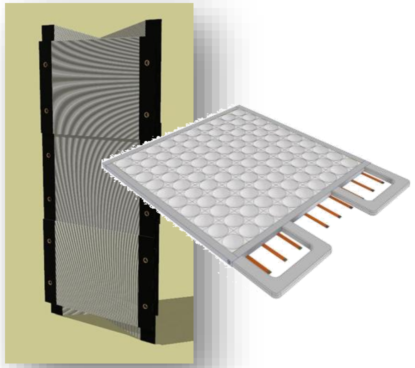
Decay detector technologies

Upstream Background Tagger (eff >99%)

- σ_{space} ~100 μm, σ_{time} ~200 ps

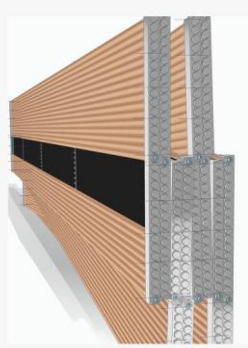
1. Scintillating tiles + SiPM
2. Straw tracker (mylar)





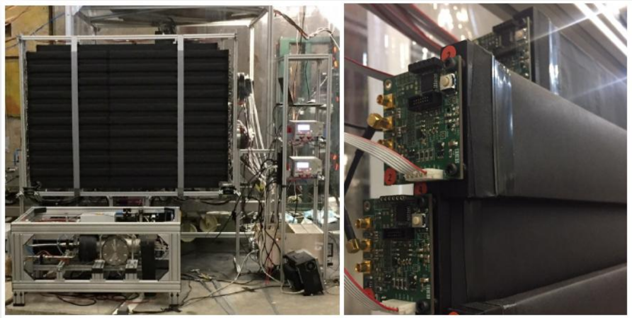
Spectrometer Straw Tracker

- σ_{space} ~120 μm
- Mylar straws



Spectrometer Timing Detector

- <100 ps
- Scintillating bars + SiPM



Decay volume

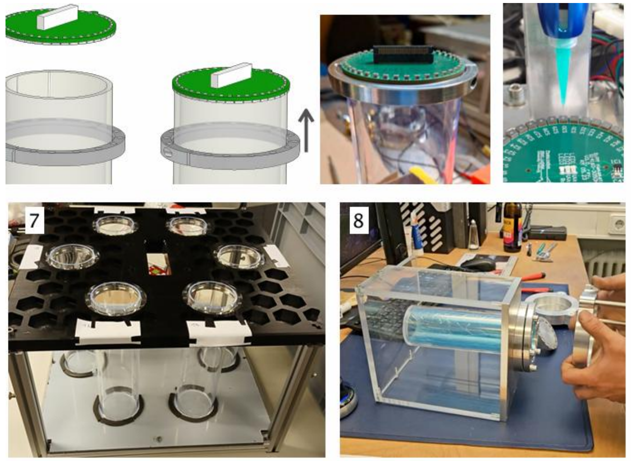
- He balloon

Hadron calorimeter

- PID
- Scintillating bars/tiles

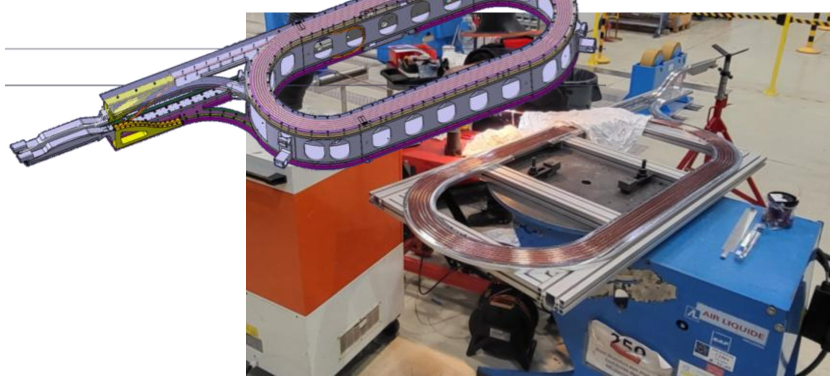
Surrounding Background Tagger

- σ_{space} ~$\mathcal{O}$(cm), σ_{time} < ns ps
- Liquid scintillator + WLS optical modules



Spectrometer magnet

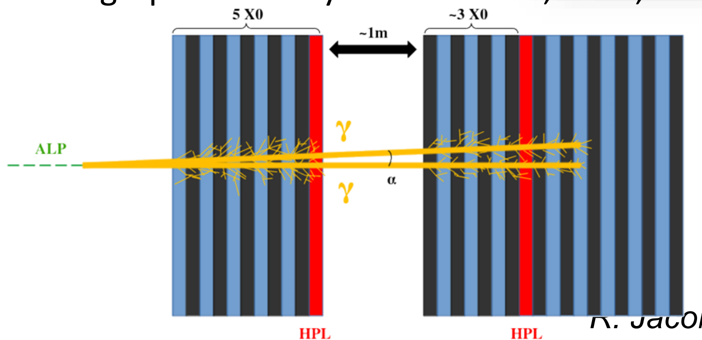
- 4m x 6m, 0.6 – 0.7 Tm
- HTS technology (MgB_2)



Electromagnet Calorimeter

- PID + shower axis <5mrad

1. Scintillating tiles/bars
2. High-precision layer with GEMs, RPCs, or SciFi



Opportunities for industrial return in summary

Among others:

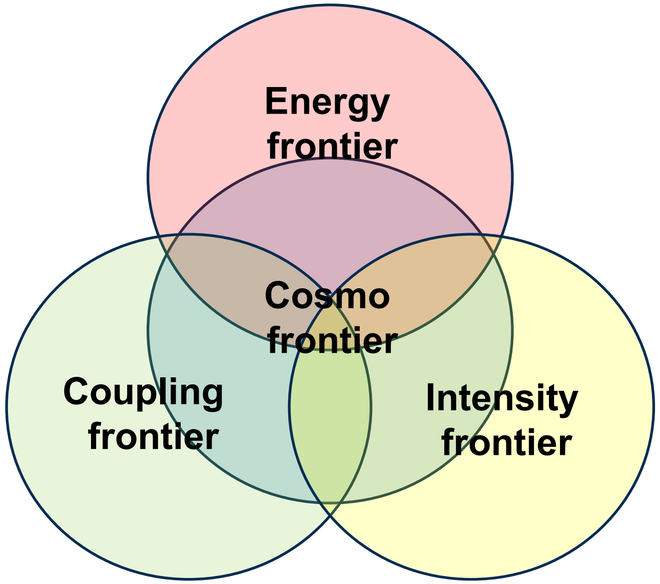
- Magnet systems, normal conducting and high-temperature superconducting, and instrumentation
- Magnet yoke material (iron and stainless steel)
- Small-scale and large-scale mechanics (steel, aluminium, carbon fibre)
- Helium gas bag, helium purification
- Detector components
- Cooling systems
- LV/HV power systems
- Control and monitoring
- Electronics
- Cabling
- Tooling for transport and handling
- Computing infrastructure (switches, routers, data processing, storage, control computers)
- General building infrastructure
- Waste management
- …

Conclusions

SHiP is a dedicated accelerator-based facility to explore *"Coupling Frontier"*

- Unique physics potential with the SPS
- SHiP is complementary to Hidden Sector searches at HL-LHC and Future Circular Collider
- Essential complementarity with projects in launch/commissioning on the cosmofrontier

- Cost estimates
  - Experimental facility: ~60 MCHF
  - Full baseline detector cost: ~50 MCHF
  - Initial detector configuration: ~30 – 35 MCHF



⦿ Many scientific and technological challenges ahead!

➔ Many opportunities for Swedish researchers **and** industry!

➔ My hope is to establish SHiP in Sweden and the other Nordic countries