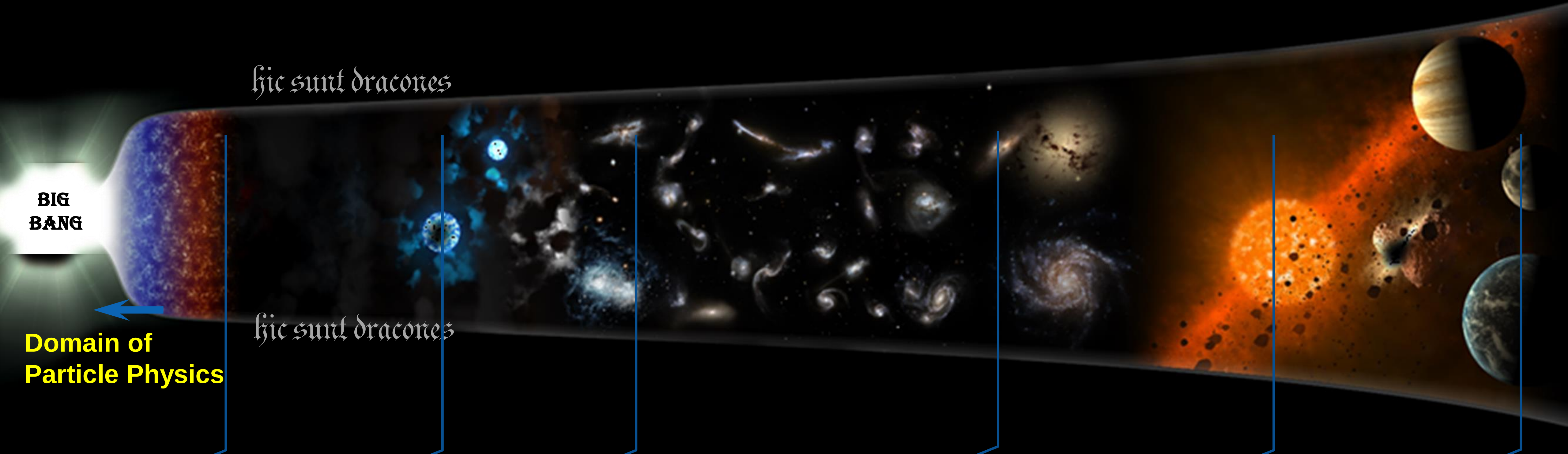
Challenges at the Hidden Physics Frontier with the SHiP(NA67) experiment at the SPS Beam Dump Facility

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

➔ Now in Technical Design Report (TDR) phase

R. Jacobsson

13 800 000 000 (billion) years in the making



Universe becomes transparent

380 000 y.
T= 3000 ºC
Size 1/1000

First stars light up

100 million y.
T= 20 ºC
Size 1/100

Galaxies form

500 million y.
T= -255 ºC
Size 1/6

Expansion rate of the Universe starts to accelerate

~5 billion y.
T=-264 ºC
Size 1/3

Birth of the Solar system

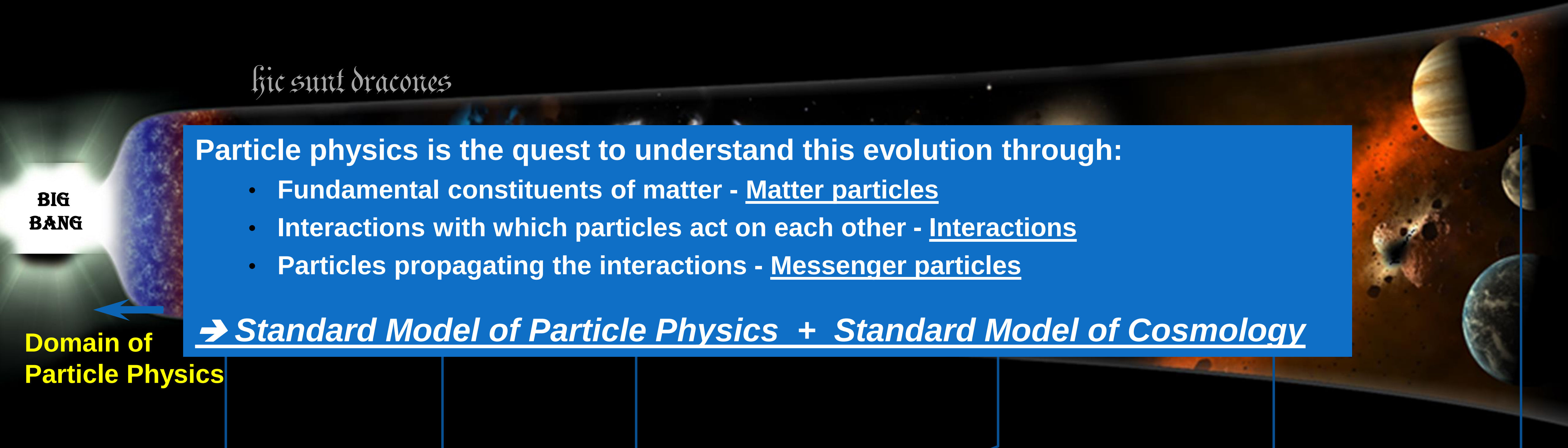
9 billion y.
T=-267 ºC
Size 1/2

5 July 2024

13.7 billion y.
T=-270 ºC
Size 1/1

Time ~zero
T= 100 000 000 000 000 000 000 000 000 000 000 ºC
Size 0.000 000 000 000 000 000 000 000 000 000 000 010 m

13 800 000 000 (billion) years in the making



Particle physics is the quest to understand this evolution through:

- **Fundamental constituents of matter - <u>Matter particles</u>**
- **Interactions with which particles act on each other - <u>Interactions</u>**
- **Particles propagating the interactions - <u>Messenger particles</u>**

➔ Standard Model of Particle Physics + Standard Model of Cosmology

Domain of Particle Physics

Universe becomes transparent

First stars light up

Galaxies form

Expansion rate of the Universe starts to accelerate

Birth of the Solar system

5 July 2024

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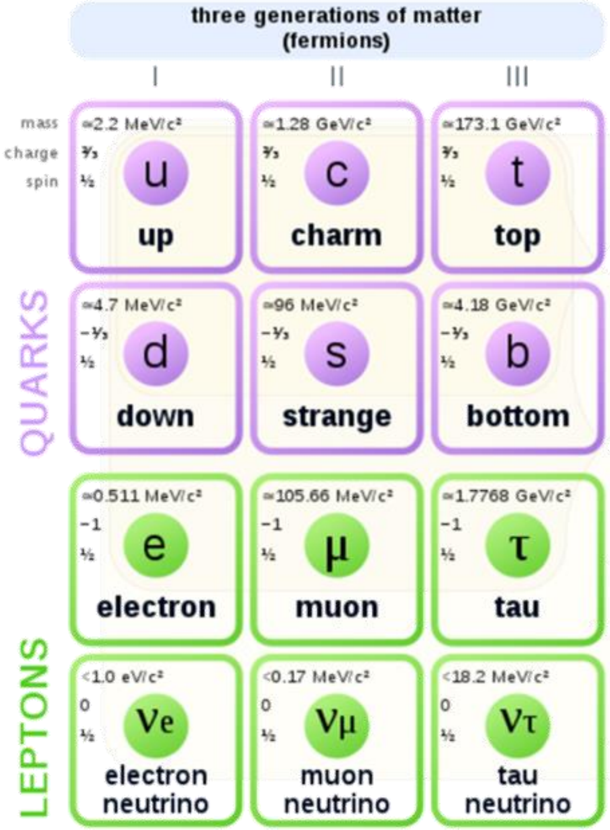
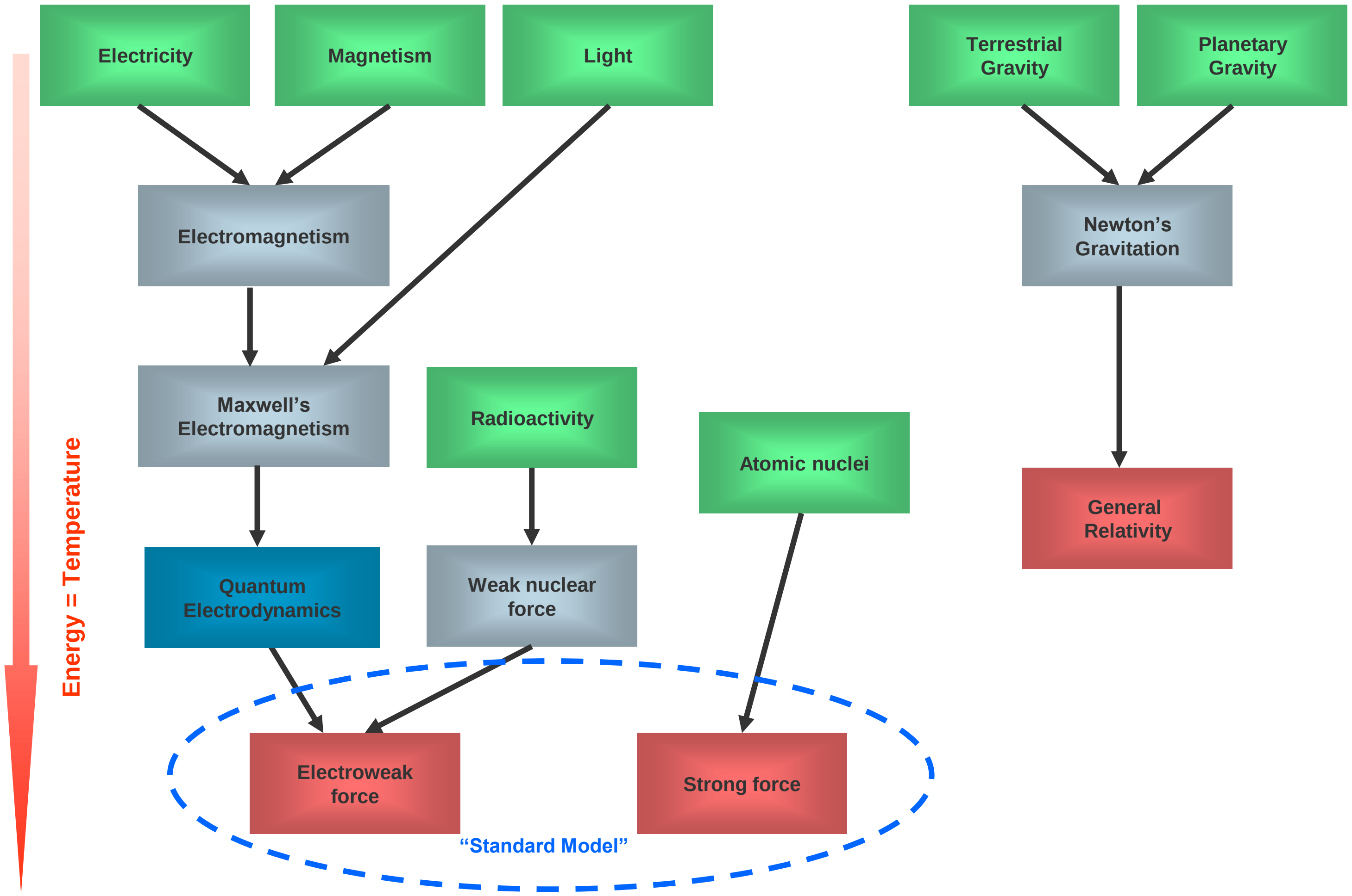
Standard Model of particle physics looking great!

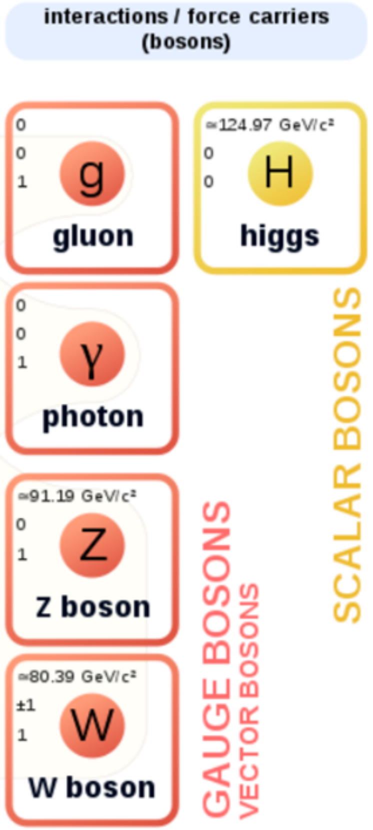
Matter



Interactions (~forces)



Interaction mediators

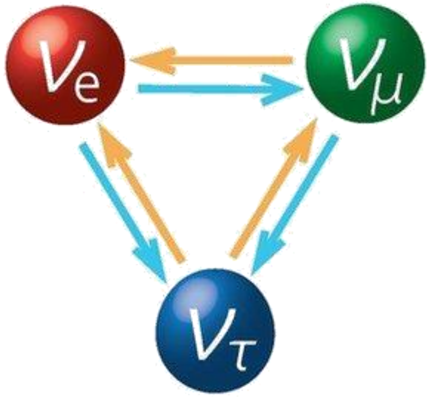


… but …

Experimental evidence of unexplained phenomena – not accommodated in Standard Model

1. **Mass of neutrinos** (“neutrino flavour oscillations”)
2. **Matter/antimatter imbalance** of the Universe – totally dominated by matter
3. **Dark Matter** – ~6 times more than ordinary matter, sourcing of additional gravity

Neutrino flavour oscillation



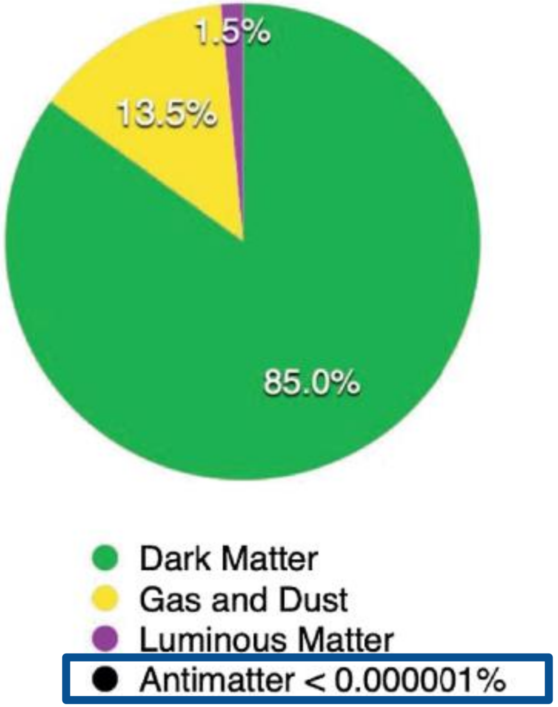
In Universe :

~1 proton/m^3

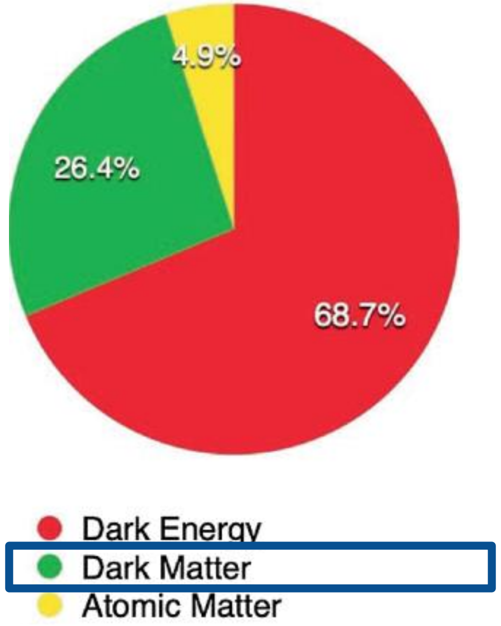
~10x10^9 photons/m^3 (Cosmic Microwave Background 2.725 K)

~0.33x10^9 neutrinos/m^3 (Cosmic ν Background 1.95 K)

Total matter in Universe



Energy balance in Universe



➔ ***There must be “New Physics” beyond Standard Model, i.e. new particles and interactions***

Where is New physics?

~10% of LHC + HL-LHC data recorded - no sign of “New Physics” up to now

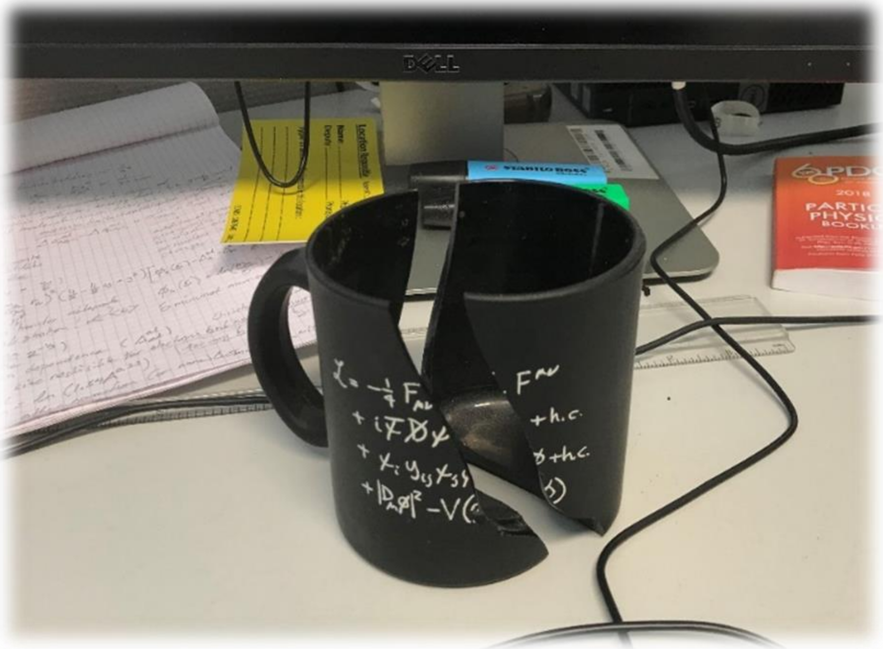
Standard Model has given us successful formalism to implement particles, interaction and mediators

- SM not only successful, we discovered what it predicted
- SM describes both what we observe and what we do **not** observe directly

Standard Model “equation of motion”

$$\mathcal{L}_{effective\,SM} = \mathcal{L}_{SM} + \sum_{d>4} \frac{Coupling^{(d)}}{Energy\ scale_{NP}^{d-4}} Operator^{(d)}$$

“Indirect effect” from New Phenomena on Standard Model



Why am I late to work?

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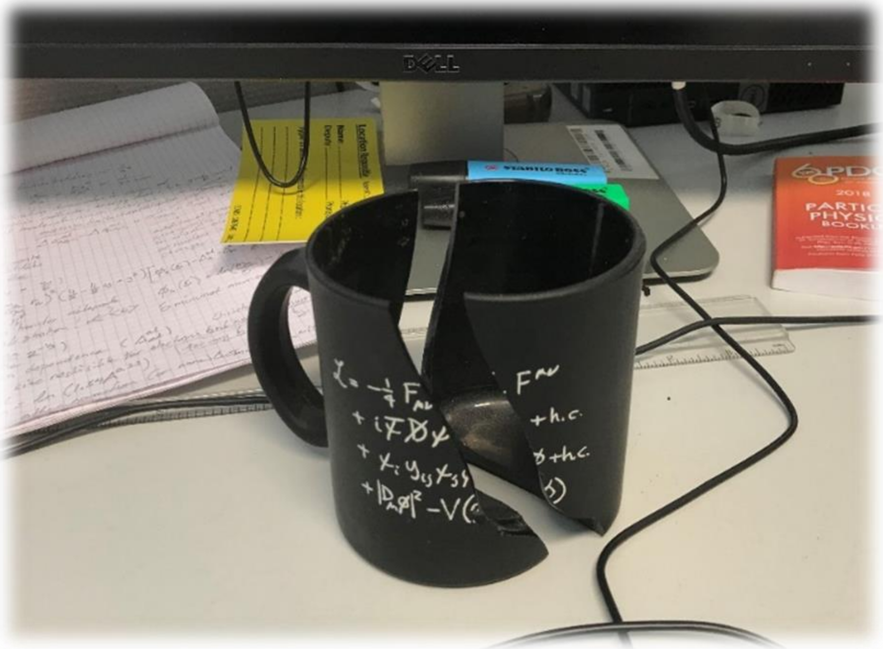
Public Transport "equation of motion"

$$\mathcal{L}_{effective\ PT} = \mathcal{L}_{PT} + \sum_{d>4} \frac{Risk^{(d)}}{Impact_{NP}^{d-4}} Delay^{(d)}$$

"Indirect effects" from "New Phenomena"
influencing chances of getting to work on time!



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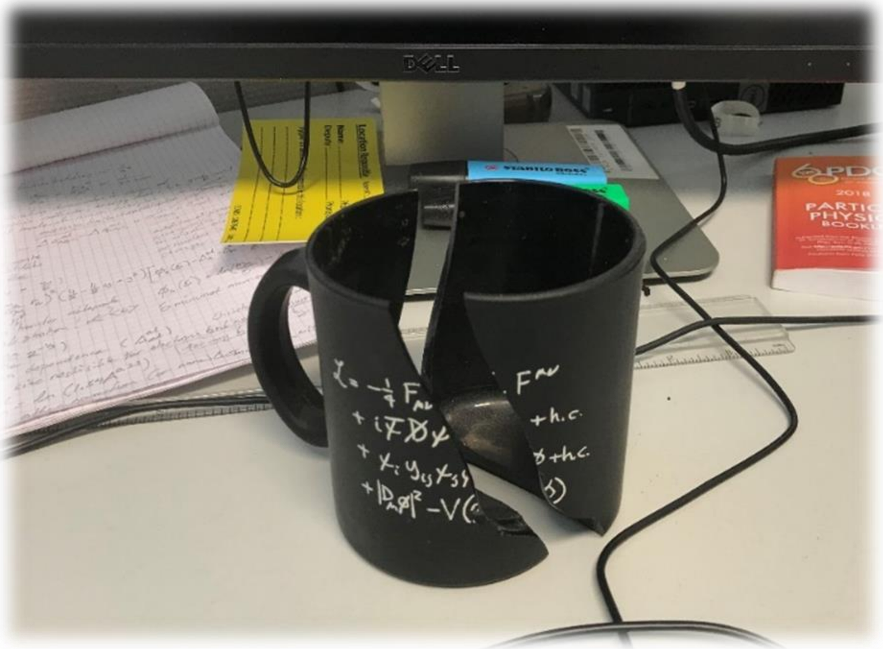
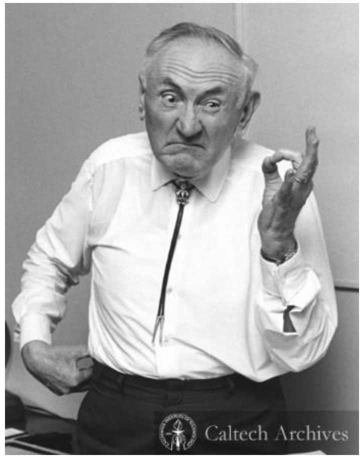


➔ *"New Physics"* should either be very heavy OR interact very feebly to have escaped detection!

Our dawn on Dark Matter

- Observation of cluster of “nebulae”: F. Zwicky (1933)



Helvetica Physica Acta, 6, 110, 1933

Die Rotverschiebung von extragalaktischen Nebeln
von F. Zwicky.
(16. II. 33.)

§ 5. Bemerkungen zur Streuung der Geschwindigkeiten im Coma-Nebelhaufen.

Rotverschiebung extragalaktischer Nebel. 125

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

The Redshift of extragalactic Nebulae

5. Comments on the velocity dispersion in the Coma cluster of Nebulae

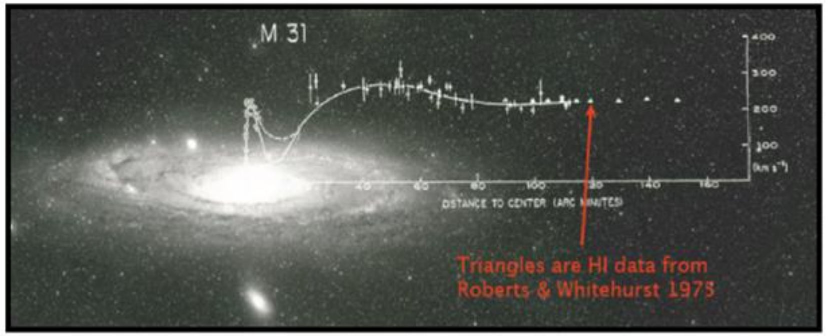
In order to obtain, as observed, a medium-sized Doppler effect of 1000 km/s or more, the average density in the Coma system would have to be at least 400 times greater than that derived on the basis of observations of luminous matter [A. Einstein and W. De Sitter, Proc. of the Nat. Acad. Sci. Vol. 18, S.213, 1932]. If this should be verified, it would lead to the surprising result that dark matter exists in much greater density than luminous matter.

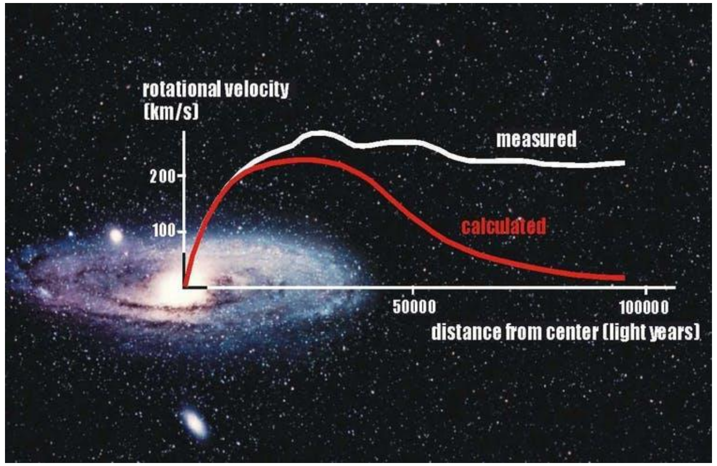
- Galaxy rotation curves: V. Rubin (1970)

70

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡





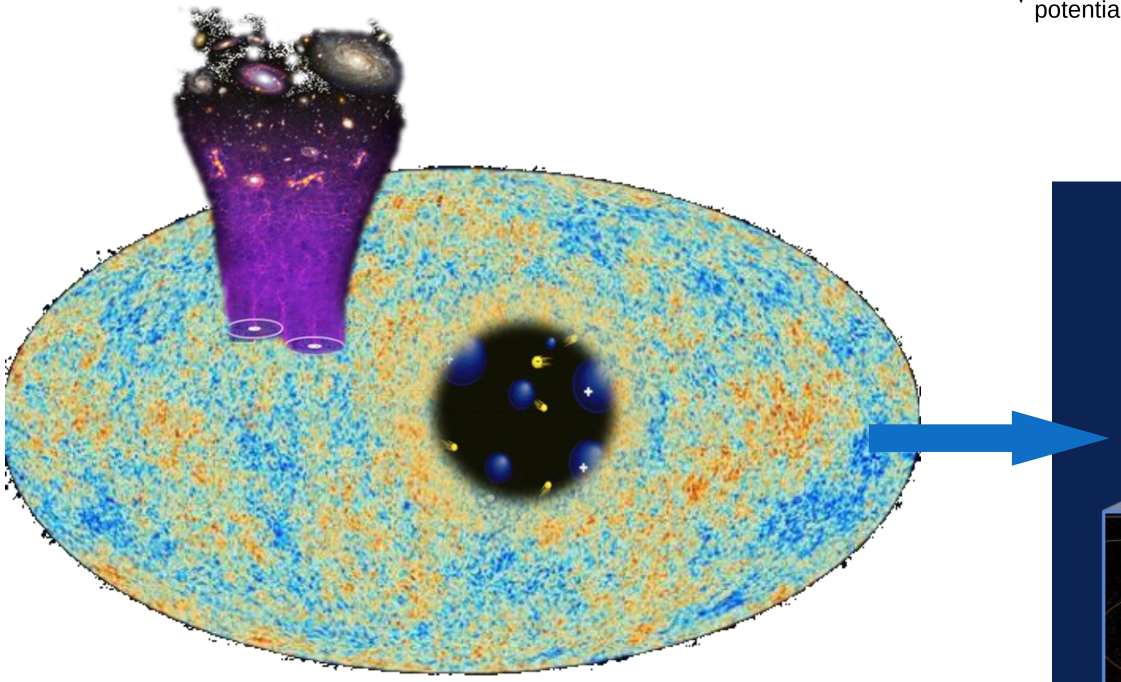
➔ Dark Matter is (at least almost) non-interacting, except through gravity!

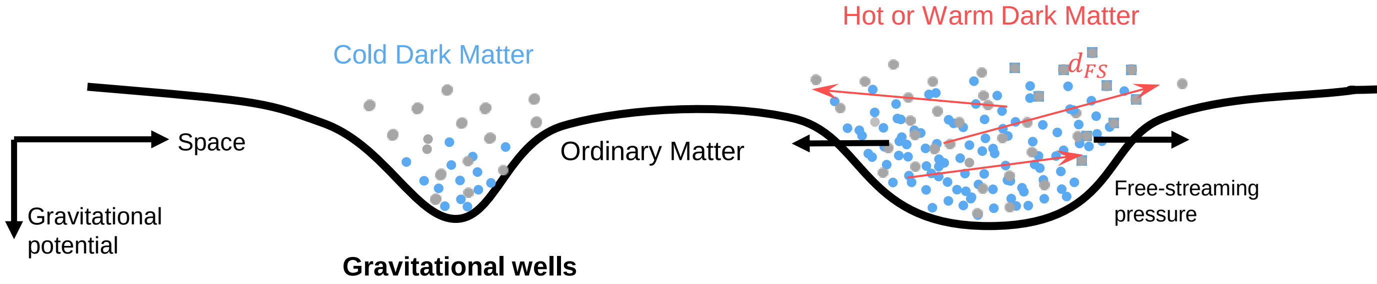
Role of Dark Matter in the Universe?

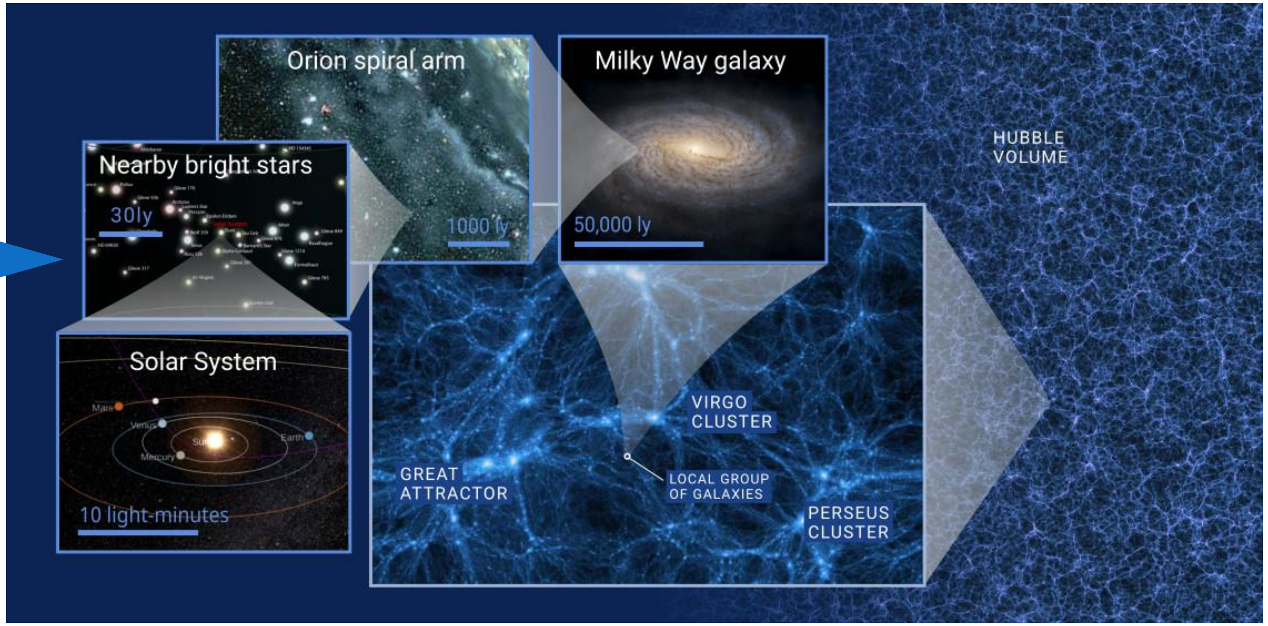
➔ *Dark Matter is critical ingredient to **realise structure formation** in the Universe with help of gravity*

Photo of Universe at age of 380 000 years

➔ *Density variations at the level of 10^{-5} form stars and galaxies*







➔ *~100 million years for first stars*

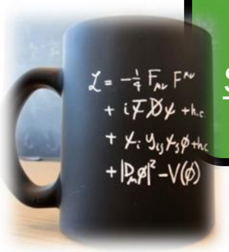
➔ *1000 million years for first galaxies*

Theory of a Hidden Sector with Dark Matter?

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

In the Standard Model language

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



Visible Sector
Standard Model

"Portal interaction"

Hidden Sector
"Dark standard model"

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
- ….

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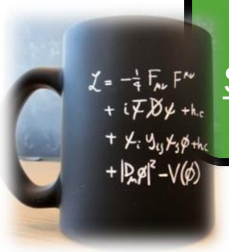

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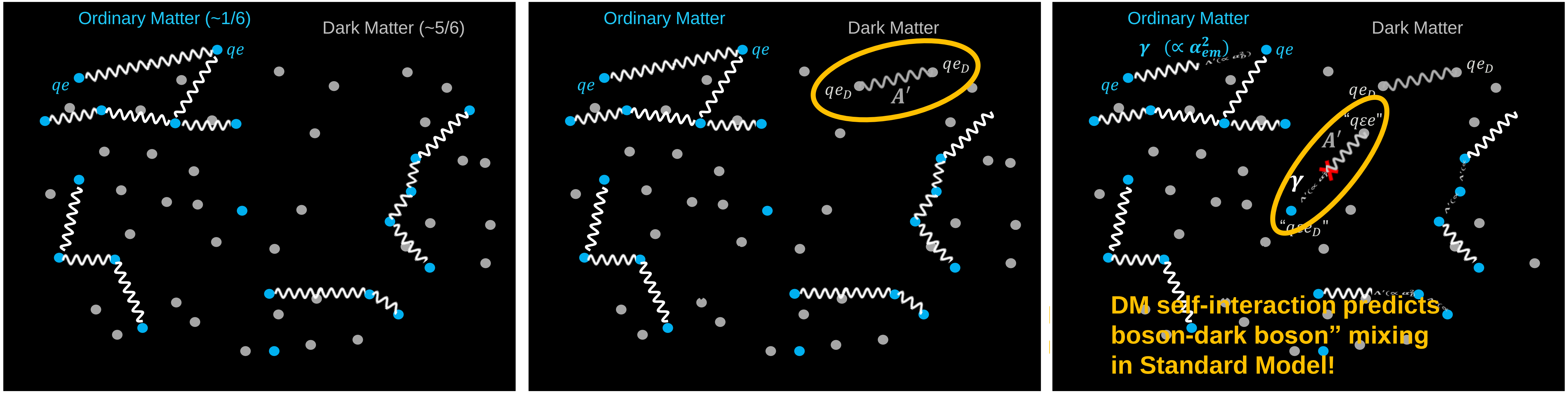
➔ $\mathcal{O}(1000)$ *scientific theory papers developing ideas around this since the 90's !*

➔ 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

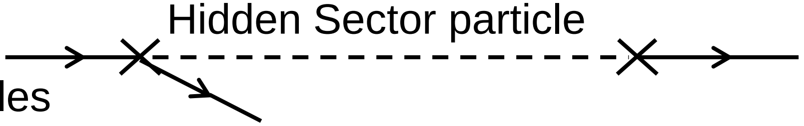


Profiting from "portal" coupling at accelerator!

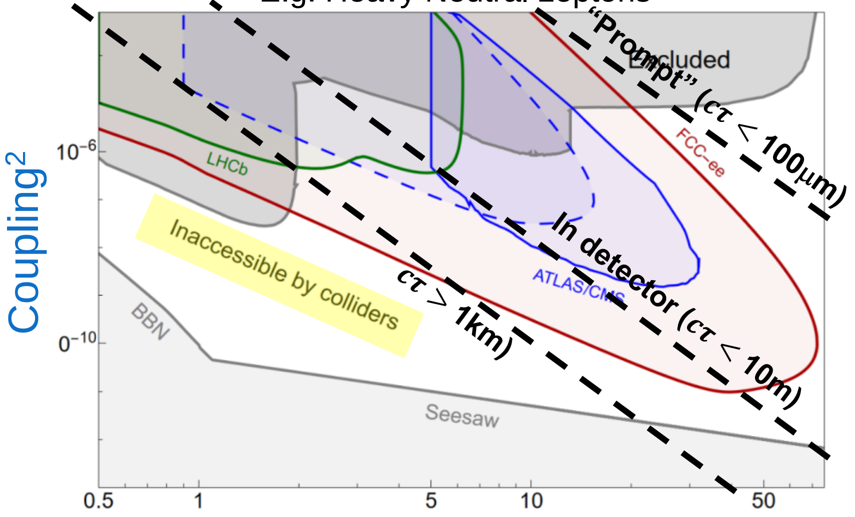
➔ Light Hidden Sector particles are long-lived, travel metres-kilometres

Production

Detection



E.g. Heavy Neutral Leptons



Seminal work leading up to SHiP

CERN-SPSC-2013-024 / SPSC-EOI-010
October 8, 2013

Proposal to Search for Heavy Neutral Leptons at the SPS

W. Bonivento[1,2], A. Boyarsky[3], H. Dijkstra[2], U. Egede[4], M. Ferro-Luzzi[2], B. Goddard[2], A. Golutvin[4], D. Gorbunov[5], R. Jacobsson[2], J. Panman[2], M. Patel[4], O. Ruchayskiy[6], T. Ruf[2], N. Serra[7], M. Shaposhnikov[6], D. Treille[2 (‡)]

[1] *Sezione INFN di Cagliari, Cagliari, Italy*
[2] *European Organization for Nuclear Research (CERN), Geneva, Switzerland*
[3] *Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands*
[4] *Imperial College London, London, United Kingdom*
[5] *Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia*
[6] *Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
[7] *Physik-Institut, Universität Zürich, Zürich, Switzerland*
(‡) *retired*

Executive Summary

A new fixed-target experiment at the CERN SPS accelerator is proposed that will use decays of charm mesons to search for Heavy Neutral Leptons (HNLs), which are right-handed partners of the Standard Model neutrinos. The existence of such particles is strongly motivated by theory, as they can simultaneously explain the baryon asymmetry of the Universe, account for the pattern of neutrino masses and oscillations and provide a Dark Matter candidate.

Cosmological constraints on the properties of HNLs now indicate that the majority of the interesting parameter space for such particles was beyond the reach of the previous searches at the PS191, BEBC, CHARM, CCFR and NuTeV experiments. For HNLs with mass below 2 GeV, the proposed experiment will improve on the sensitivity of previous searches by four orders of magnitude and will cover a major fraction of the parameter space favoured by theoretical models.

The experiment requires a 400 GeV proton beam from the SPS with a total of 2×10^{20} protons on target, achievable within five years of data taking. The proposed detector will reconstruct exclusive HNL decays and measure the HNL mass. The apparatus is based on existing technologies and consists of a target, a hadron absorber, a muon shield, a decay volume and two magnetic spectrometers, each of which has a 0.5 Tm magnet, a calorimeter and a muon detector. The detector has a total length of about 100 m with a 5 m diameter. The complete experimental set-up could be accommodated in CERN's North Area.

The discovery of a HNL would have a great impact on our understanding of nature and open a new area for future research.

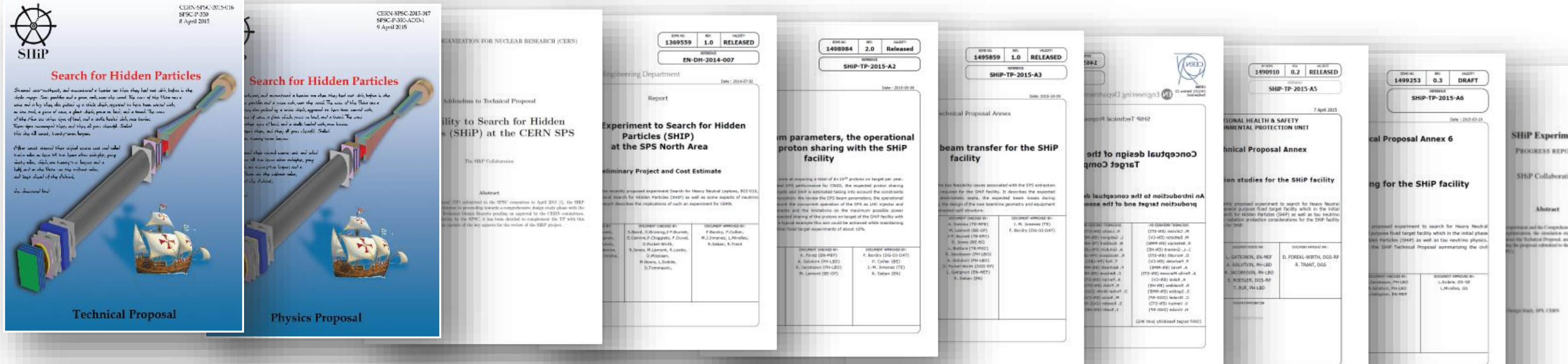
1 Introduction

The new scalar particle with mass $M_H = 125.5 \pm 0.2_{stat}\ ^{+0.5}_{-0.6}{}_{syst}$ GeV (ATLAS) [1], $M_H = 125.7 \pm 0.3_{stat} \pm 0.3_{syst}$ GeV (CMS) [2], recently found at the LHC, has properties consistent with those of the

1

BDF/SHiP development history

- 2013 Oct: EOI with SHiP@SPS North Area as a new high intensity facility
  ...following brainstorming SHiP@LHCb, SHiP@CNGS, SHiP@WANF, SHIP@ECN3



- 2014 Jan: Form collaboration and launch of TP phase
- 2015 Apr: TP submission
- 2016 Jan: Recommendation by SPSC to proceed to Comprehensive Design Study (CDS)
- 2016 Apr: CERN management launch of Beyond Collider Physics study group
- 2018 Dec: EPPSU contribution submitted by SHiP and BDF, and SHiP Progress Report to SPSC
- 2019 Dec: CDS reports on BDF (Yellow Book) and SHiP submitted to SPSC
- 2020 Sep: CERN launches continued BDF/SHiP R&D towards implementation in existing area
  ➔ Location and layout optimization study recommending ECN3
- 2023 Mar: Provisional approval of High Intensity ECN3 project
- 2024 Mar/Jun: Approval of SHiP for implementation in ECN3 -TDR phase

First media reactions…

B B C

Home News Sport Business Innovation Culture Travel Earth Video Live

Cern: Scientists search for mysterious ghost particles

25 March 2024

Share

Pallab Ghosh
Science correspondent

Artwork: Ghost particles can't currently be detected

Some physicists have long suspected that mysterious 'ghost' particles in the world around us could greatly advance our understanding of the true nature of the Universe.

euro news.

…ch News

Hunting for 'ghost particles': How CERN plans to search for a better understanding of the Universe

Copyright Laurent Gillieron/Keystone via AP, file

By Anna Desmarais
Published on 26/03/2024 - 12:28 GMT+1 • Updated 03/04/2024 - 12:45 GMT+2

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CERN is launching a project that researchers say could help them prove the existence of hidden particles that make up the fabric of the Universe.

INDUSTRInyheter.se

Svensk forskare projektleder bygget av experimentet SHIP vid CERN

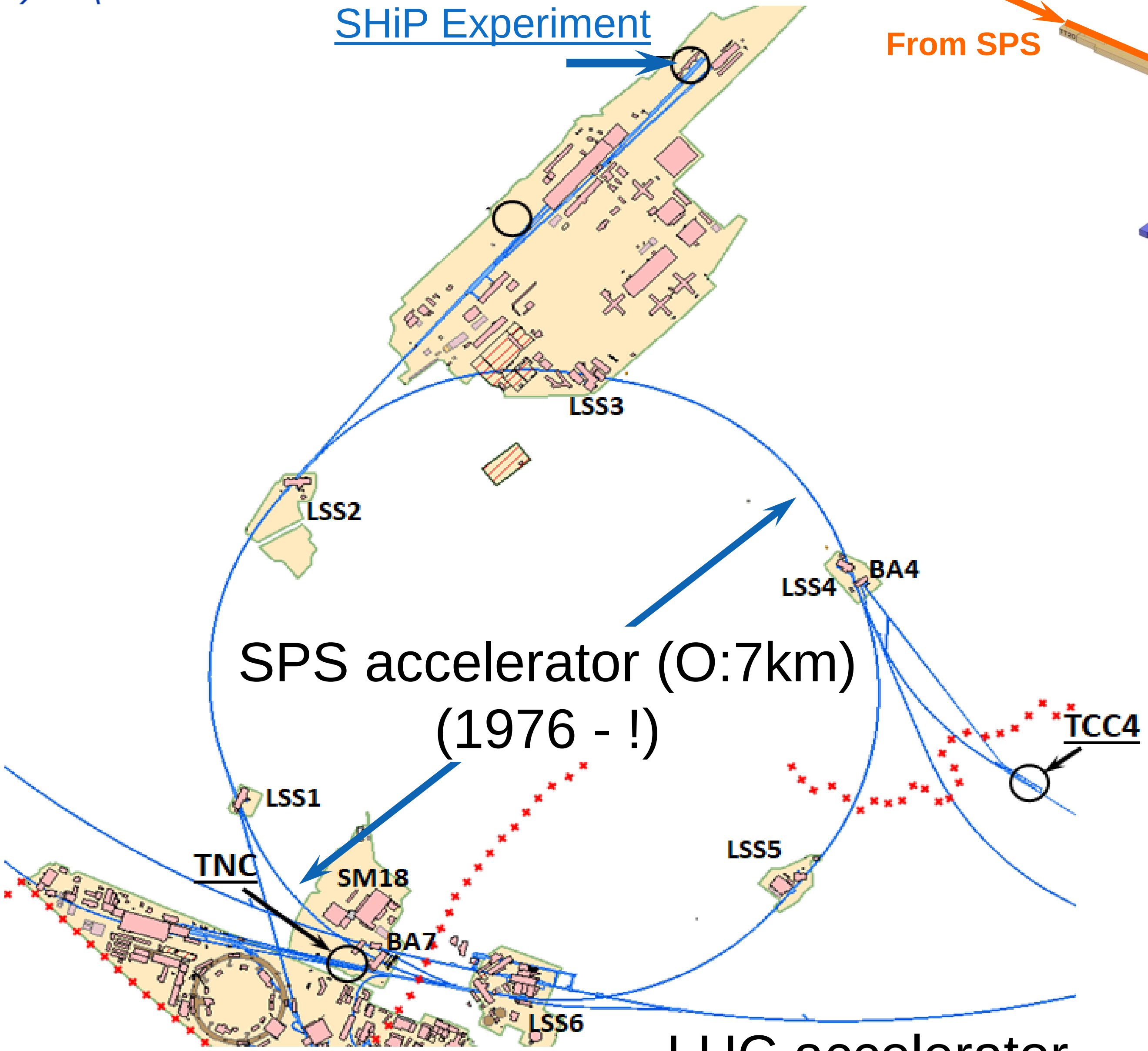
Flygbild över CERN. Foto: Brücke-Osteuropa/Wikimedia Commons

Publicerad av
simon matthis - 26 mar, 2024

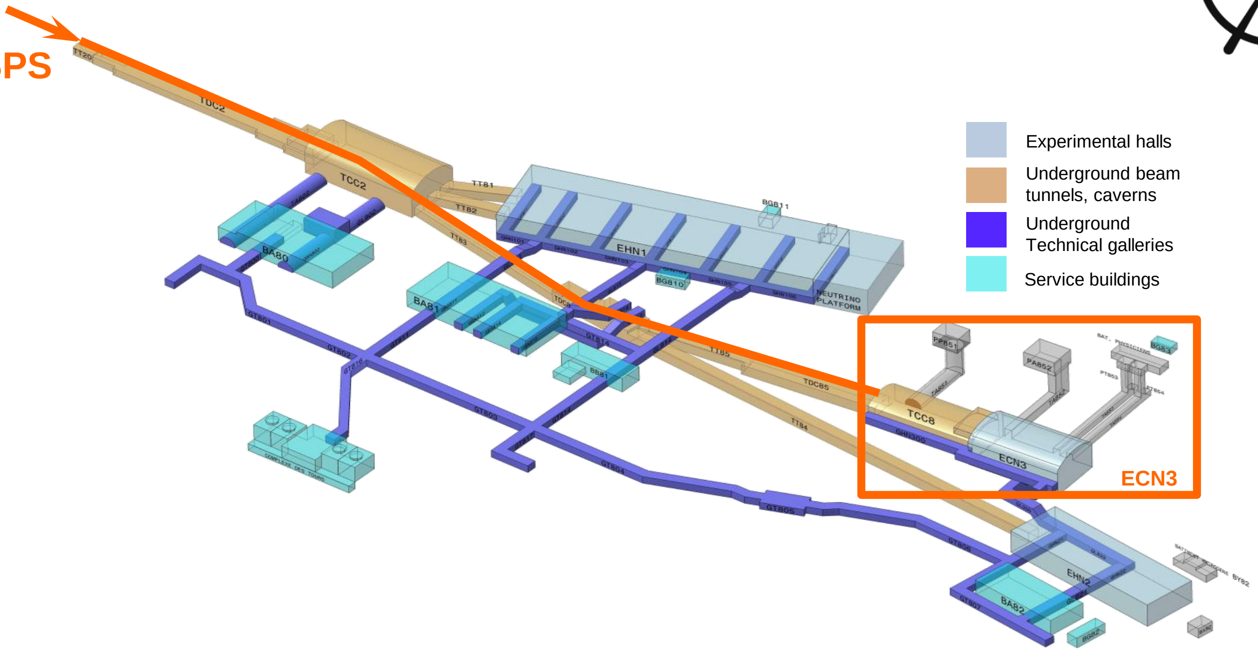
Partikelfysiklaboratoriet CERN i Schweiz har tagit beslut om att bygga experimentet SHiP (Search for Hidden Particles) som projektleds av Richard Jacobsson, svensk senior fysiker vid CERN. SHiP är ett experiment för att söka efter "dolda" partiklar vilka som kan förklara till exempel mörk materia, neutrinoscillationer och ursprunget till baryonasymmetrin i universum.

BDF/SHiP @ SPS

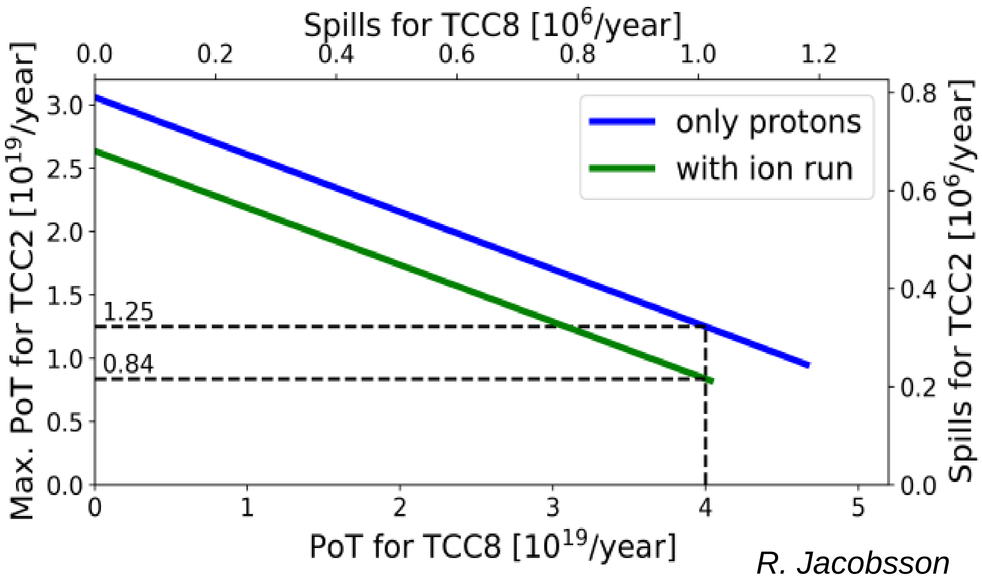
SHiP Experiment



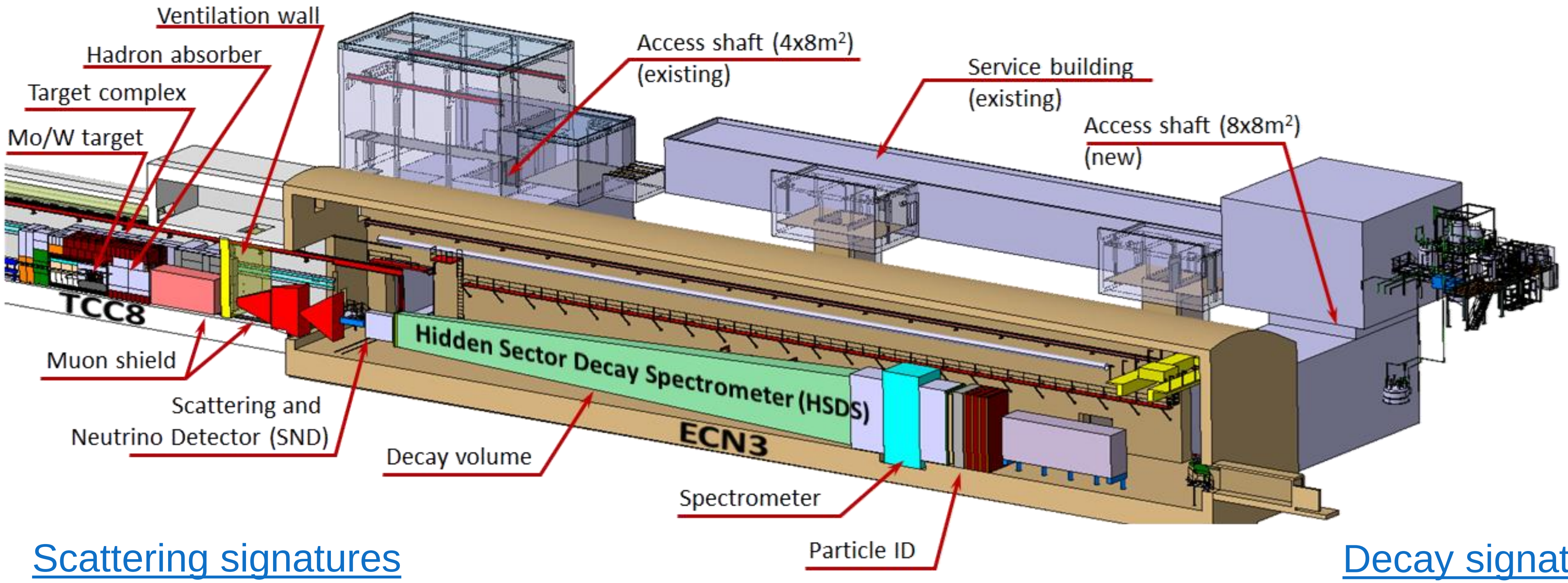
LHC accelerator



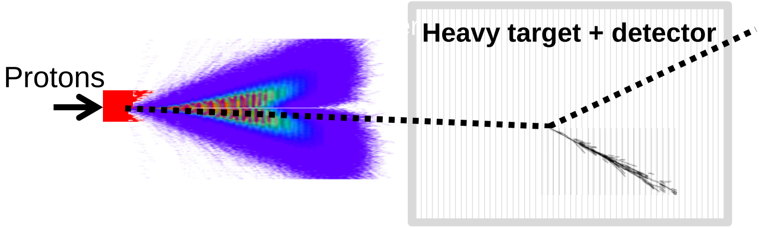
4x10^{19} protons per year available in SPS



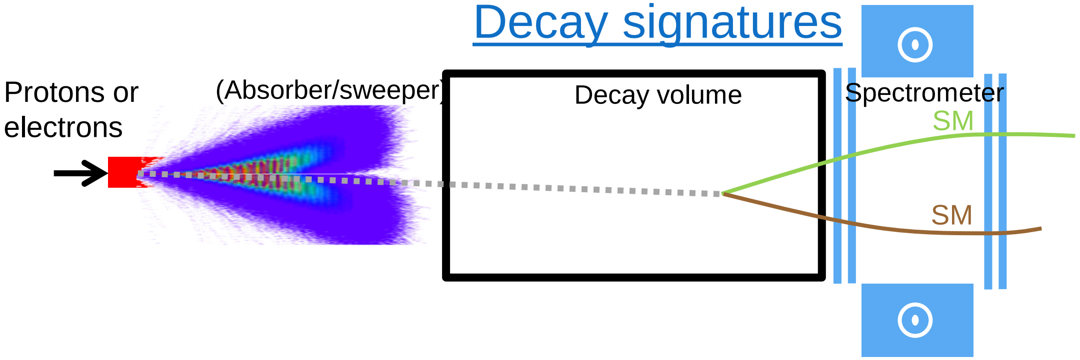
SHiP: two-in-one detector



Scattering signatures



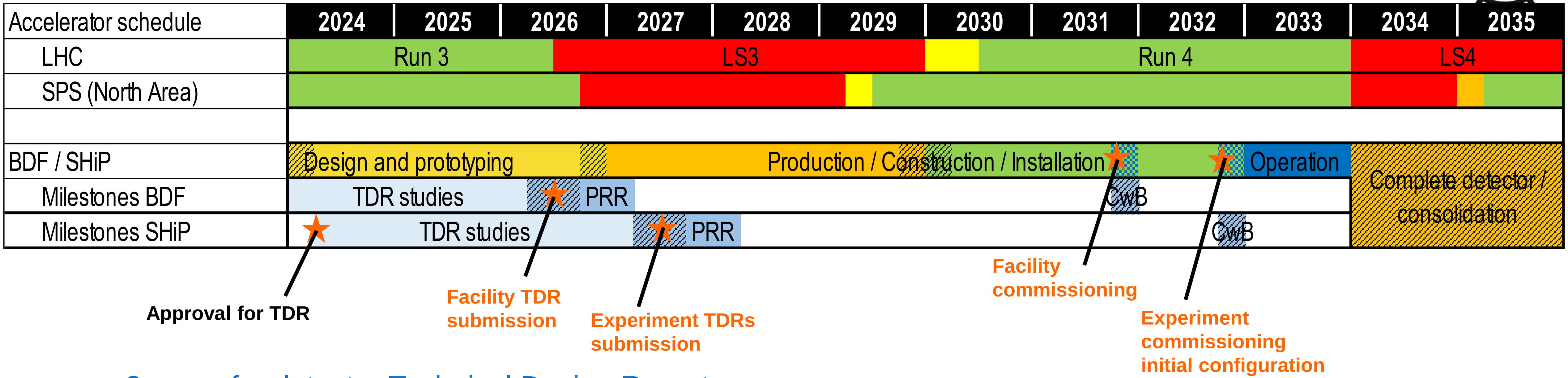
Decay signatures



- ➔ BDF luminosity with the optimised target and $4\text{x}10^{19}$ protons on Mo 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)

BDF/SHiP schedule



- ~3 years for detector Technical Design Reports
- Facility implementation starting in Long Shutdown 3 of CERN's accelerator complex
- Important to start data taking in 2032, ~2 year before Long Shutdown 4

➔ Complete detector at the latest in LS4 with initial configuration operating in 2032-2033

→ Initial configuration built from critical systems in full scale and full physics capability towards signal and background measurements

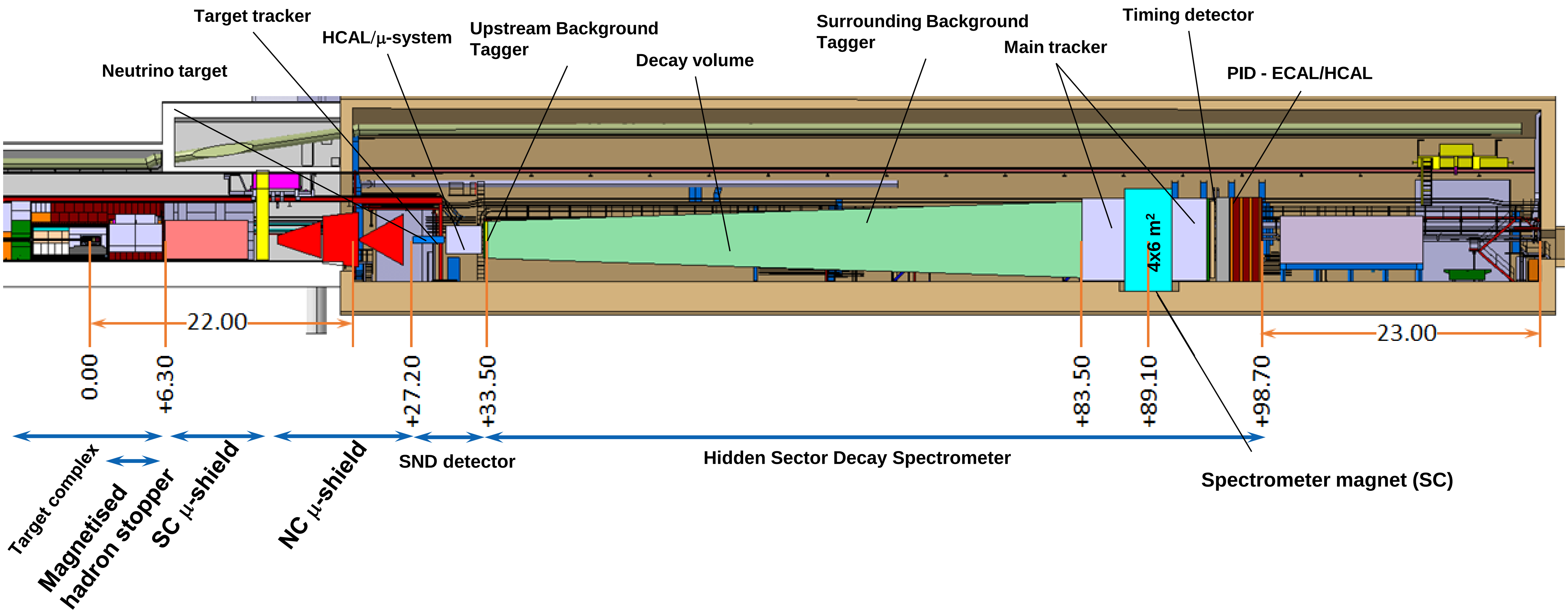
→ Decide and design with upgrade path in mind

→ Prototypes may fill "holes" in 2032-2033

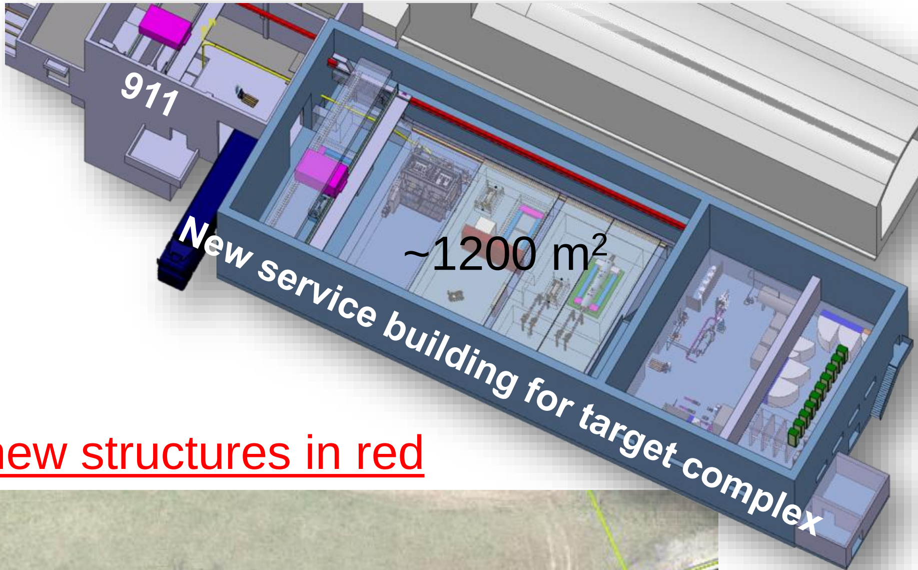
➔ 15 years of physics exploration

Walk-through of the SHiP project
- Facility and detector -

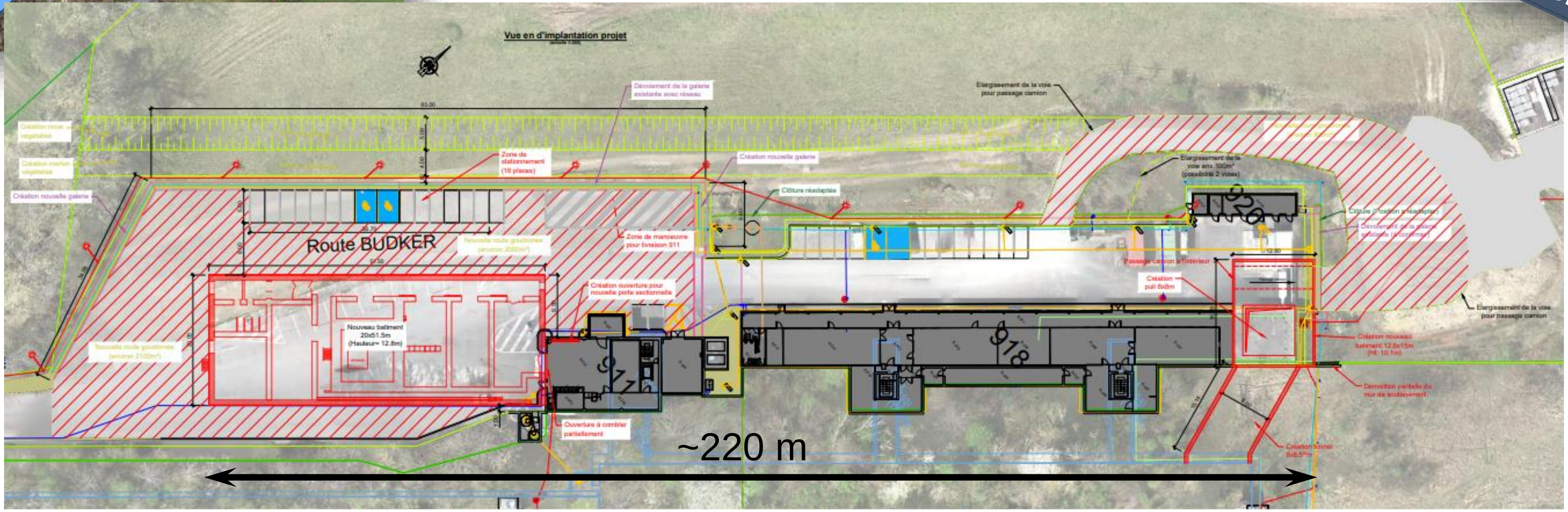
SHiP detector in more detail



Site works for BDF/SHiP

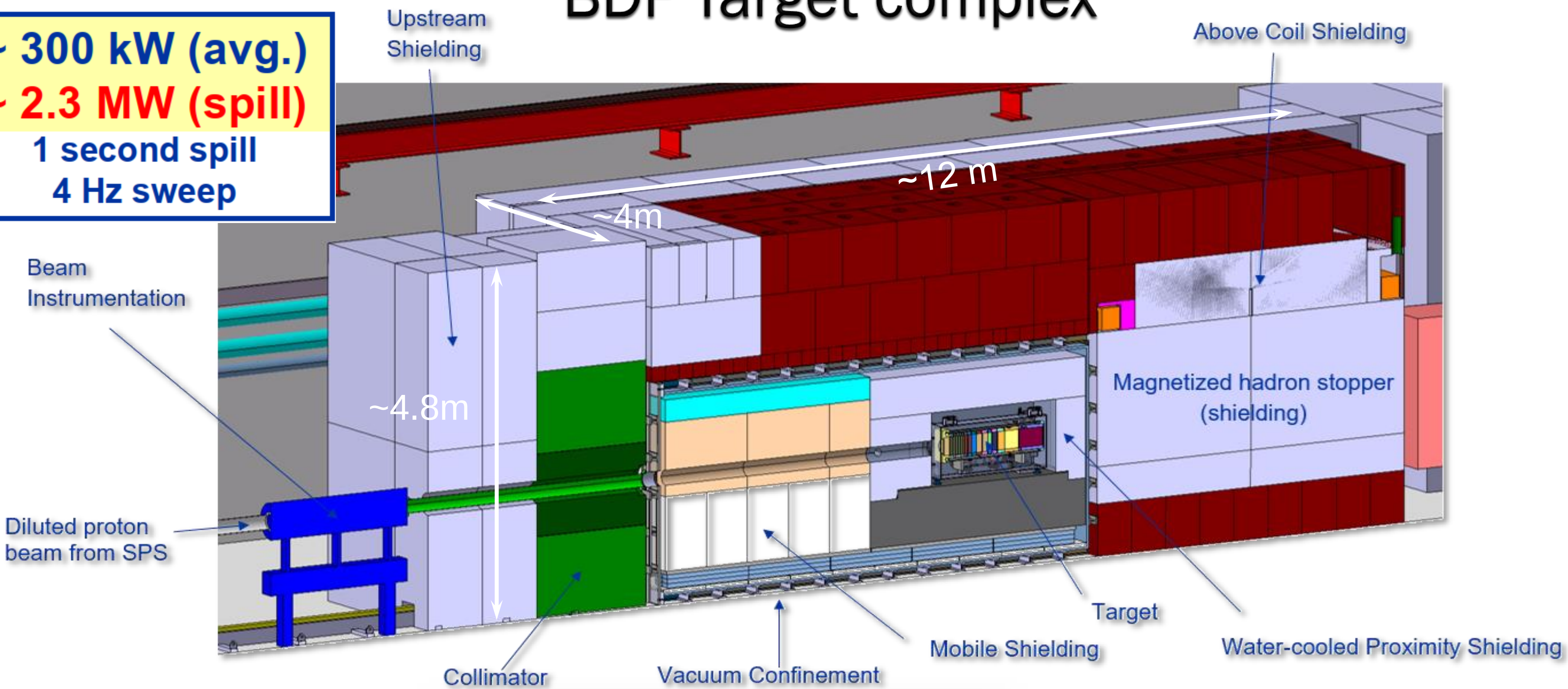


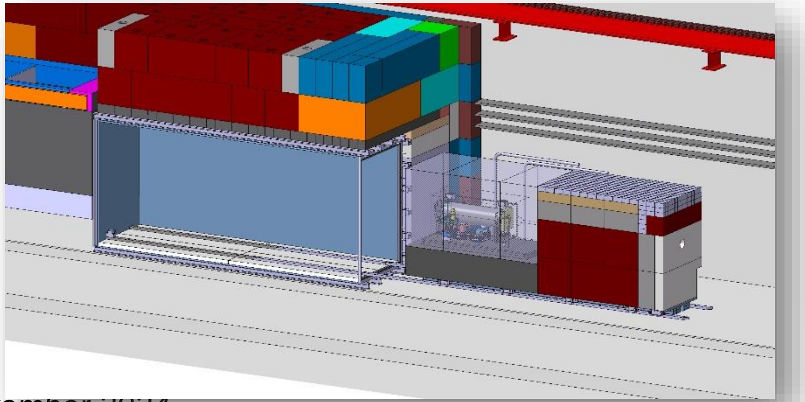
Civil engineering modifications /new structures in red



BDF Target complex

~ 300 kW (avg.)
~ 2.3 MW (spill)
1 second spill
4 Hz sweep

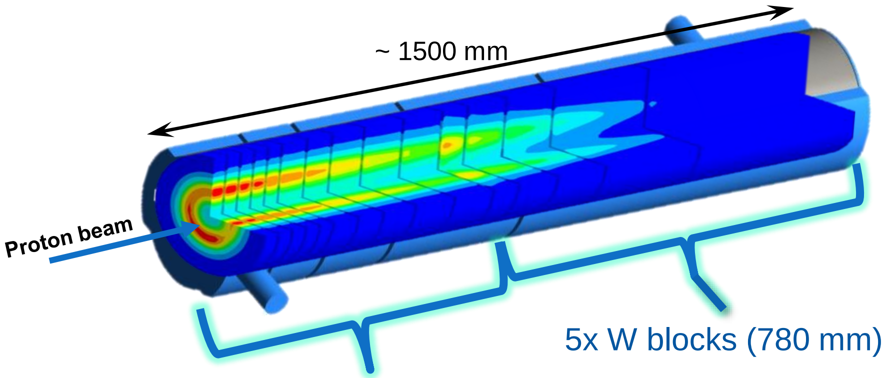




BDF/SHiP target

Baseline design

- Water-cooled, Mo & W blocks (cladded with Ta)
- Tested with beam in 2018, 2.4 x10^{16} protons on target



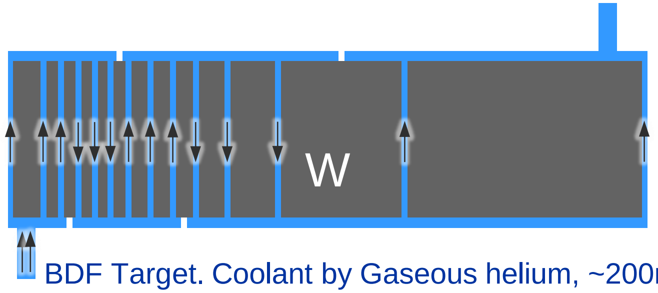
Baseline beam parameters of the BDF Target operation
https://doi.org/10.23731/CYRM-2020-002

Proton momentum (GeV/c)	400
Beam intensity (p$^+$/cycle)	4×10^{13}
Cycle length (s)	7.2
Spill duration (s)	1.0
Beam dilution pattern	Circular
Beam sweep frequency (turns/s)	4
Dilution circle radius (mm)	50
Beam sigma (H, V) (mm)	(8, 8)
Average beam power (kW)	356
Average beam power deposited in target (kW)	305
Average beam power during spill (MW)	2.3

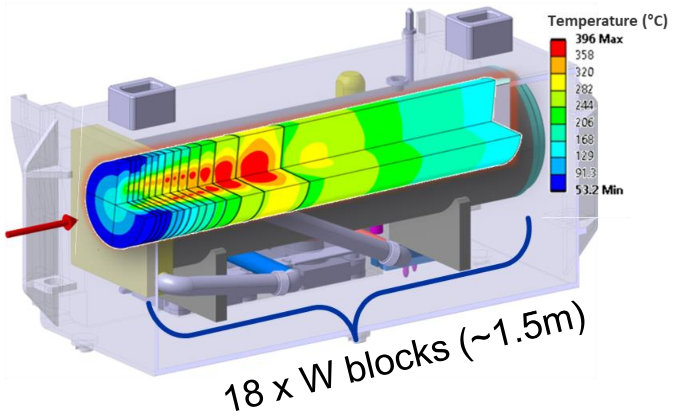
~ 4.0×10^{19} p$^+$/y

TDR phase aimed at improving CDS design:

- Moving towards a target entirely made from tungsten
- Alternatives to water cooling to avoid cladding and production of radicals
- Investigating helium rather than water cooling to simplify and improve safety & reliability, in synergy with other international laboratories

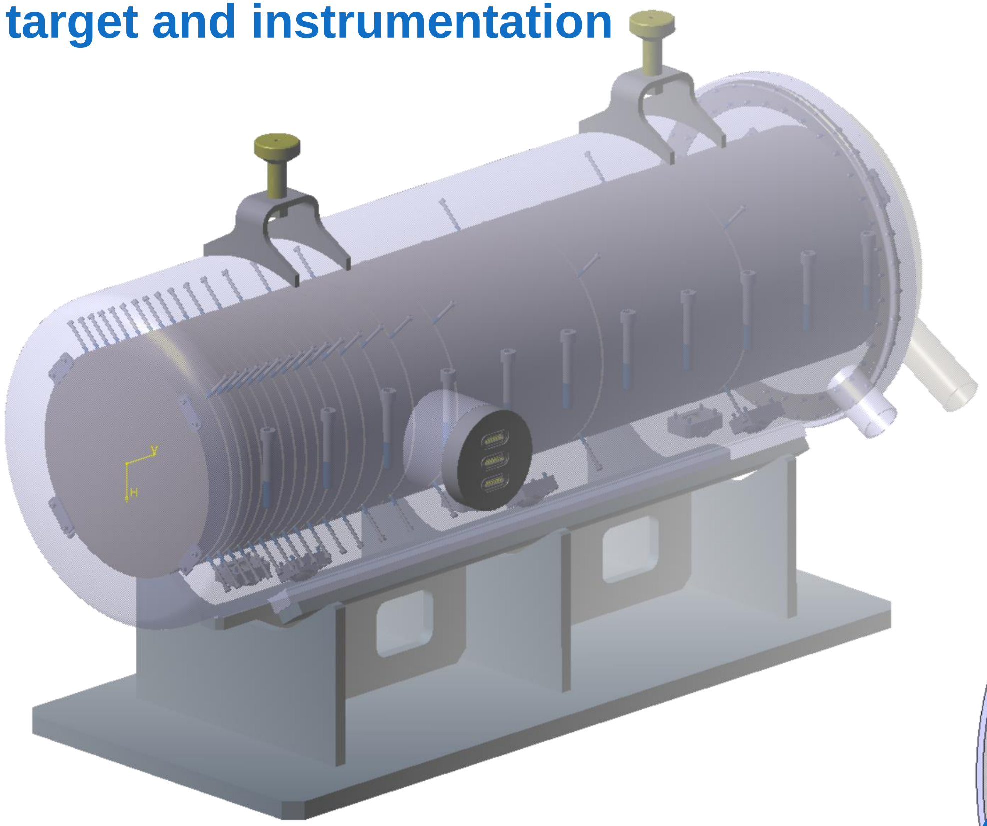


BDF Target. Coolant by Gaseous helium, ~200m/s.
3 or 4 channels in parallel.

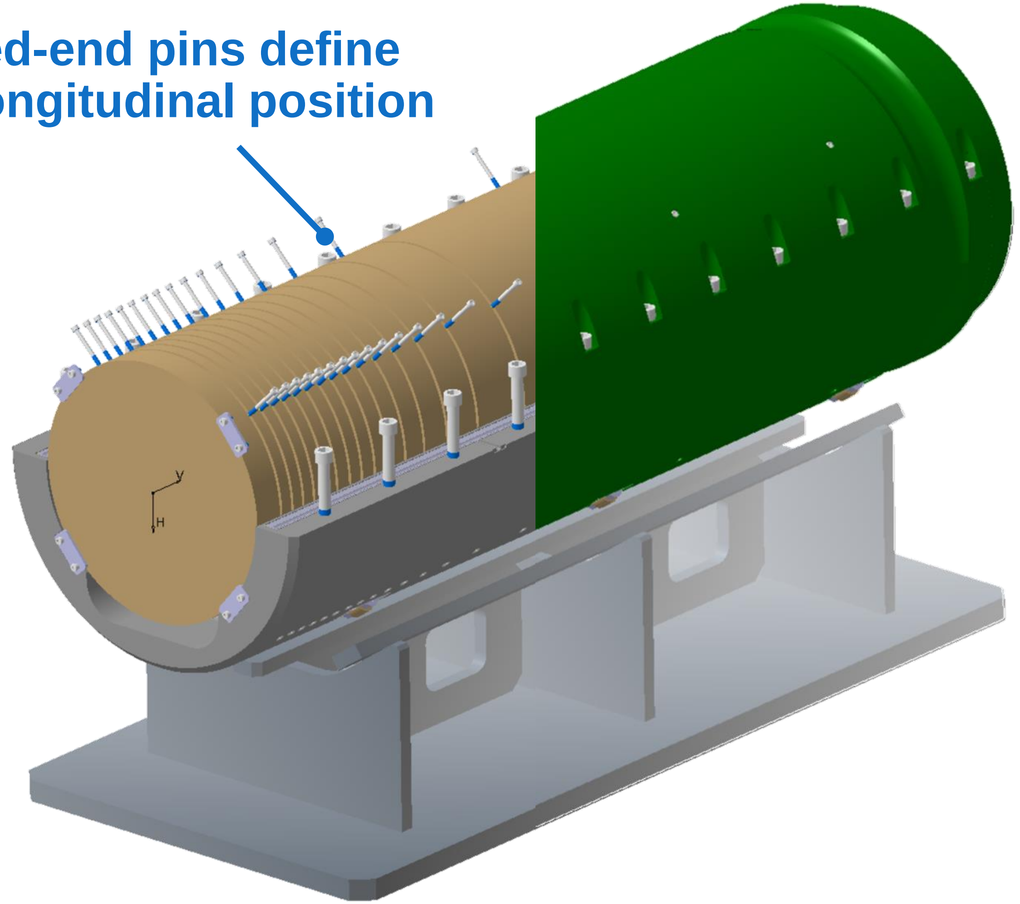


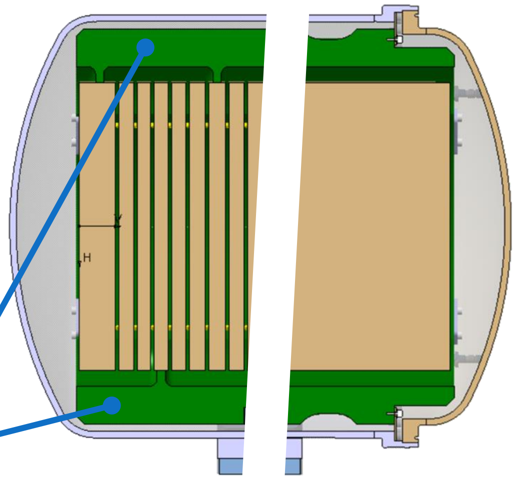
Helium cooling vessel for W target

16bar helium vessel containing target and instrumentation



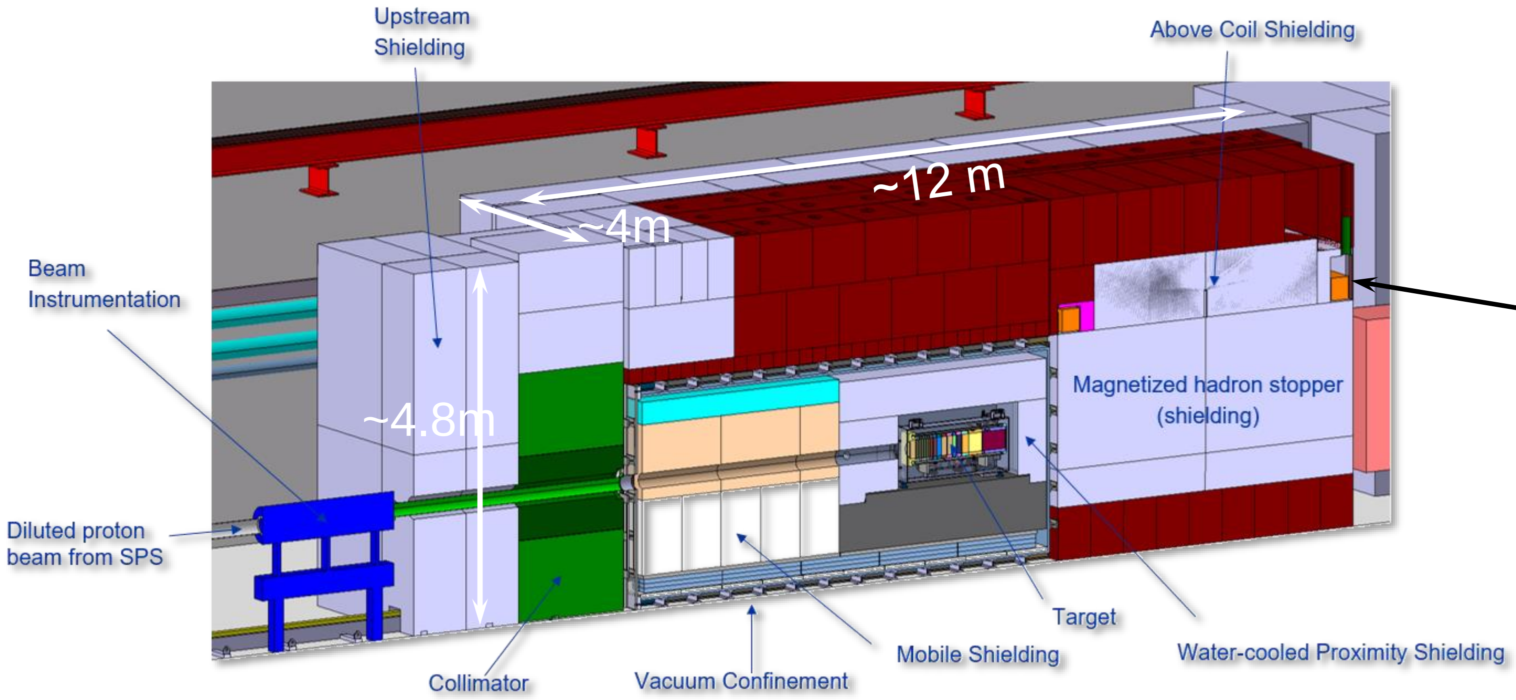
Machined-end pins define plates longitudinal position

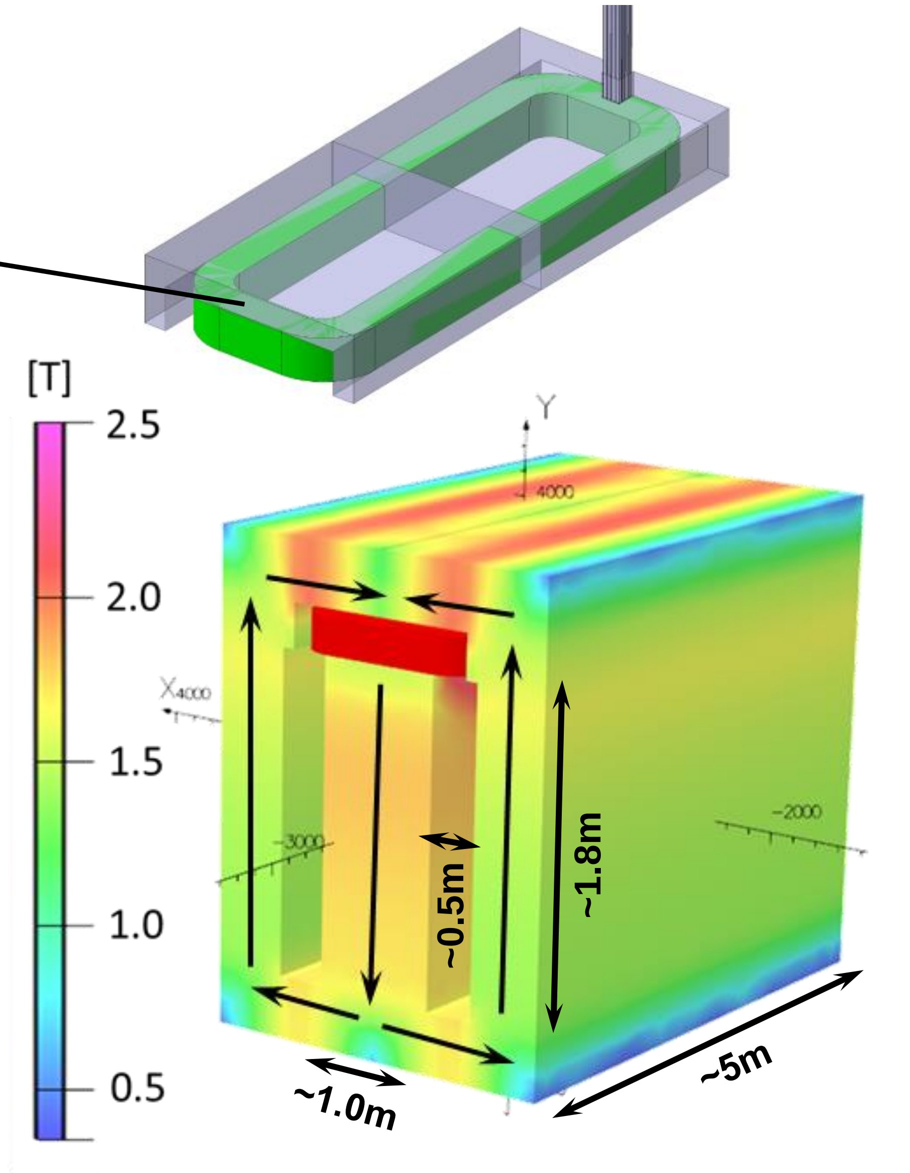




Clam-shell manifold includes machined helium flow-path

Magnetisation of downstream shielding

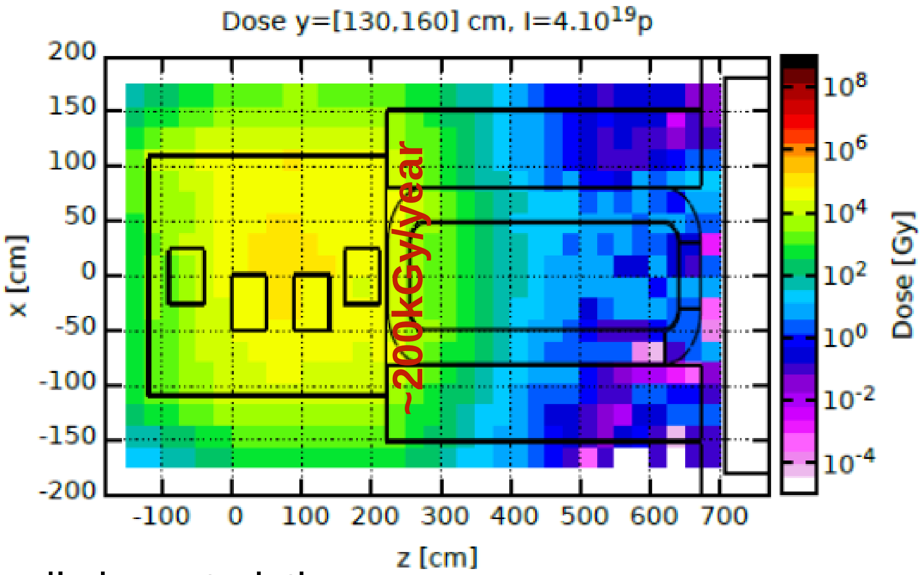




- Single resistive coil providing $\int_{-L/2}^{L/2} B_y(z)dz = 1.5T\ x\ 5m$
  - Both Al- and Cu-based solution investigated
  - Gaseous cooling
  - Core field defined by stainless steel walls
- Main challenges
  - Service connections
  - Handling

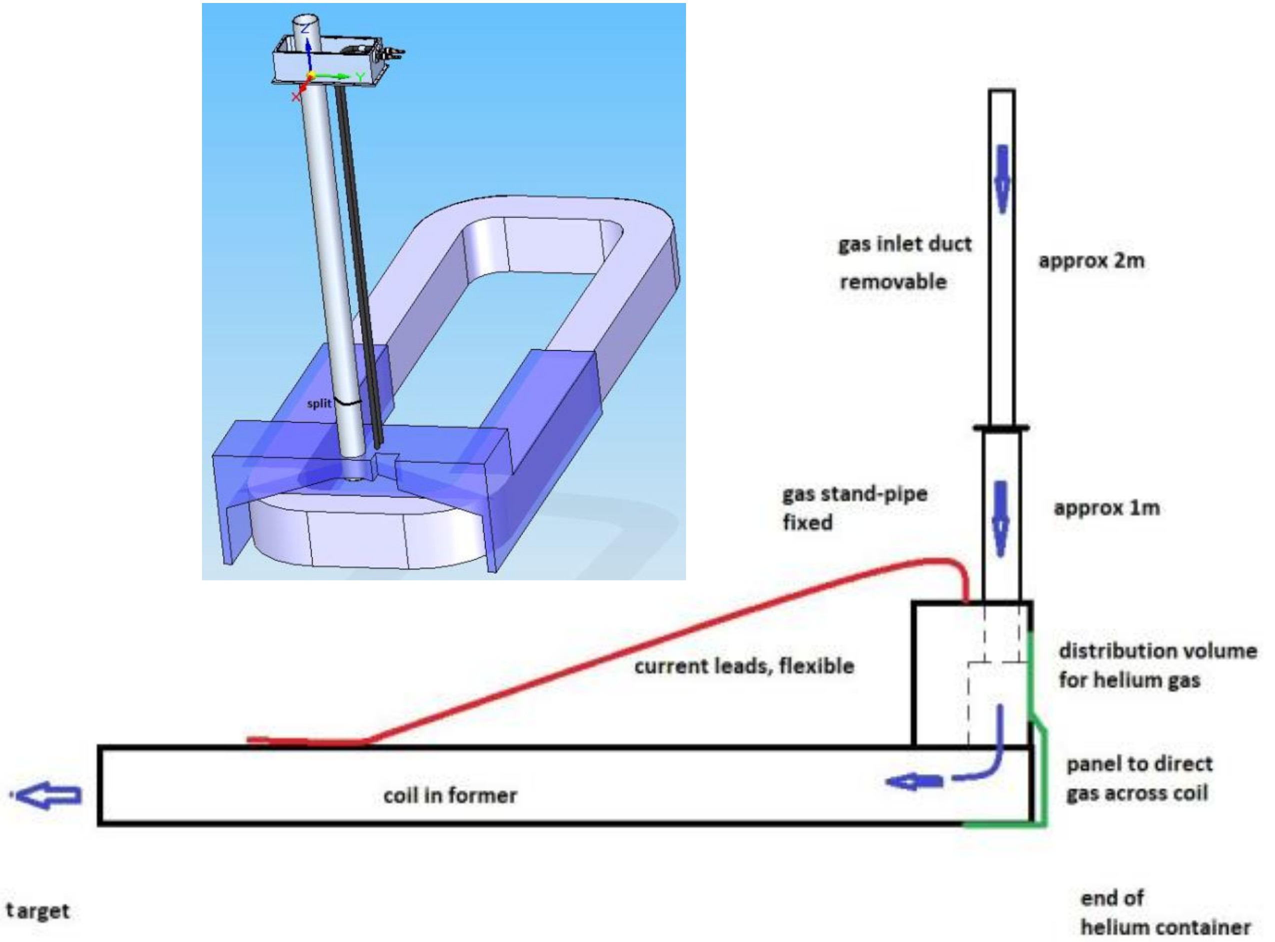
Hadron stopper magnetisation

Dose/year:



Preliminary coil characteristics:

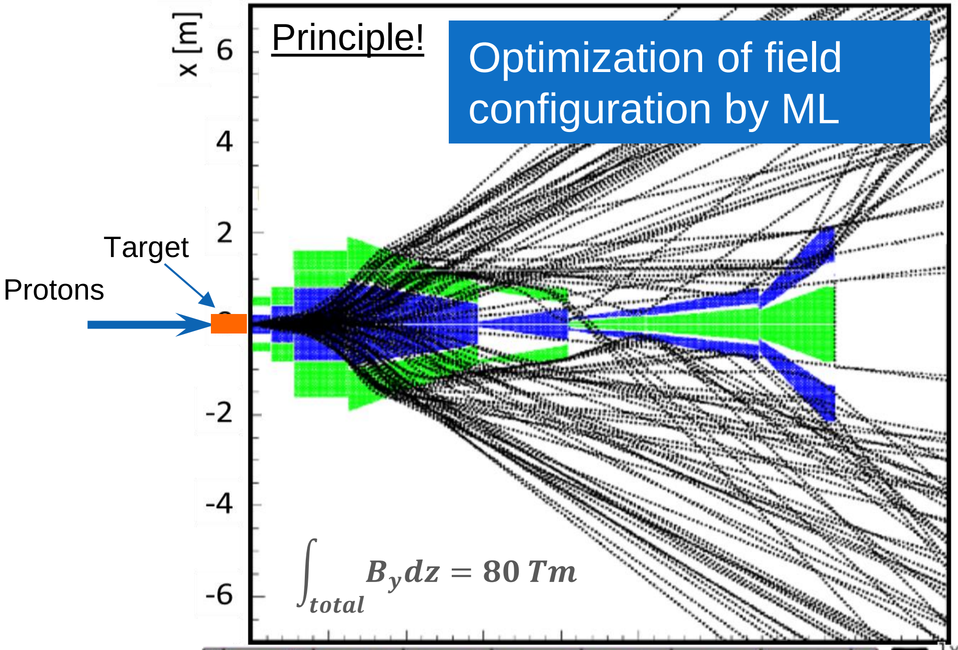
Material	Aluminium	
External dimensions	4.48 x 2.07 x 0.3	m
Cross section	0.26 x 0.30	m^2
Coil surface	13 (approx.)	m^2
Strip dimensions	1 x 300	mm^2
Packing fraction	0.9	
Total length of strip	2560	m
Potting agent	None	
Mass	2700 (approx.)	kg
Electrical resistivity ρ (at RT)	2.82×10^{-8}	Ohm-m
Thermal conductivity	205 (in the plane of the strip)	W/mK
Current	135	A
Current density (strip)	0.45	A/mm^2
Current density (engineering)	0.41	A/mm^2
Amp-turns	32,000	A
Resistance	0.24 @ 20°C, 0.27 @ 50°C	Ohm
Voltage	33 @20°C, 36.2 @ 50°C	V
Power	4.43 @ 20°C, 4.90 @ 50°C	kW

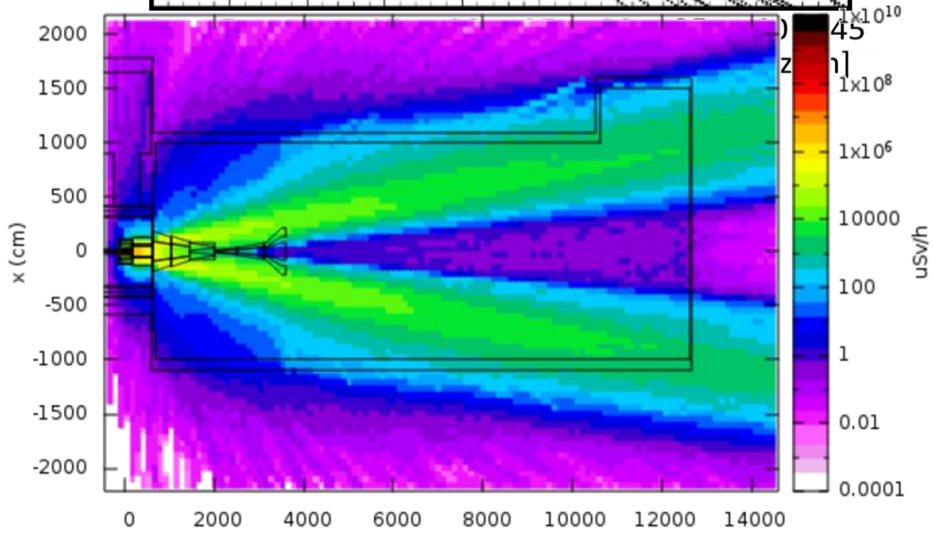


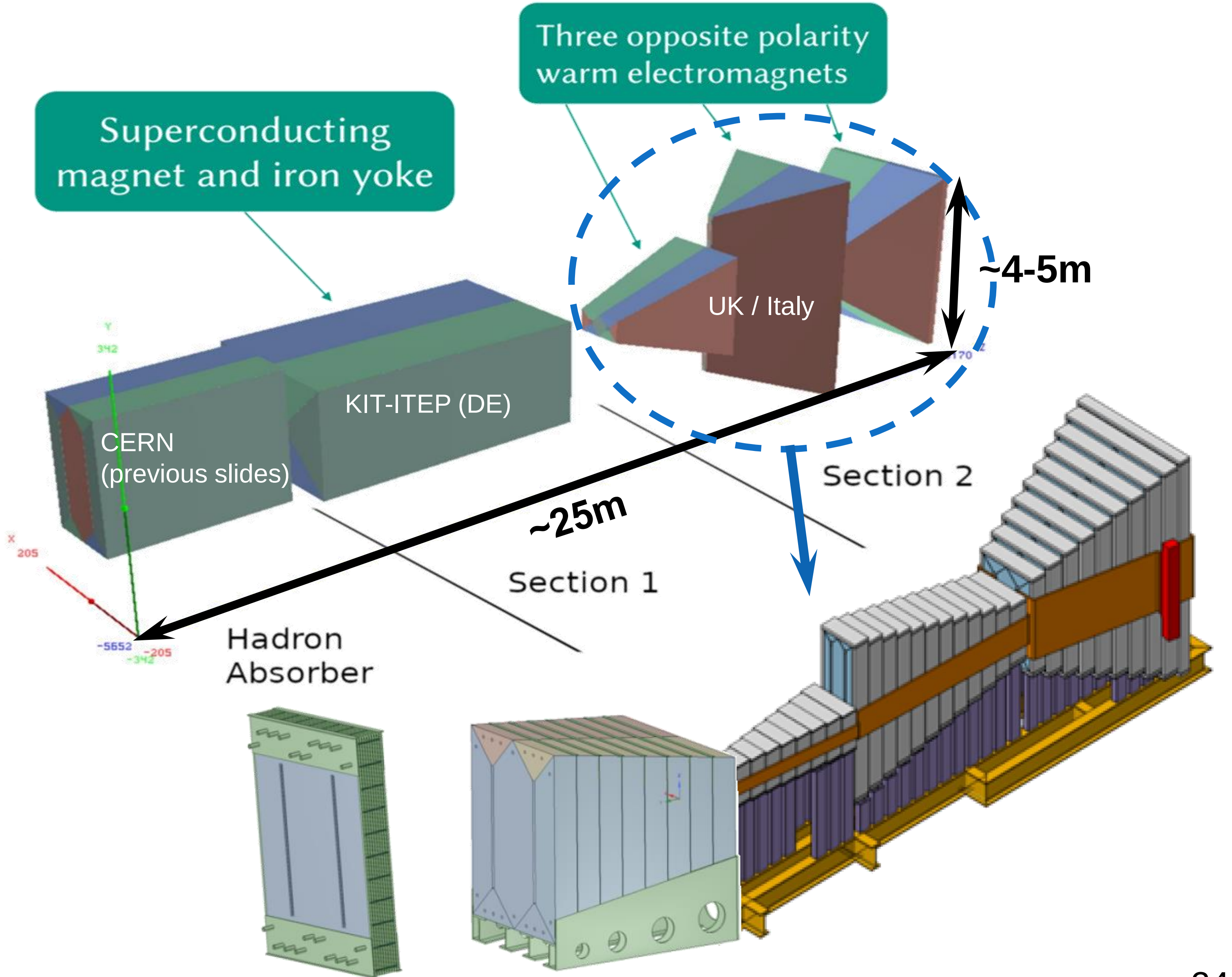
To be developed in close collaboration with Target Complex project and SHiP

Magnetic deflector of muons ("muon shield")

Suppress beam-induced muon flux by ~6 orders of magnitude by *magnetic sweeper system*

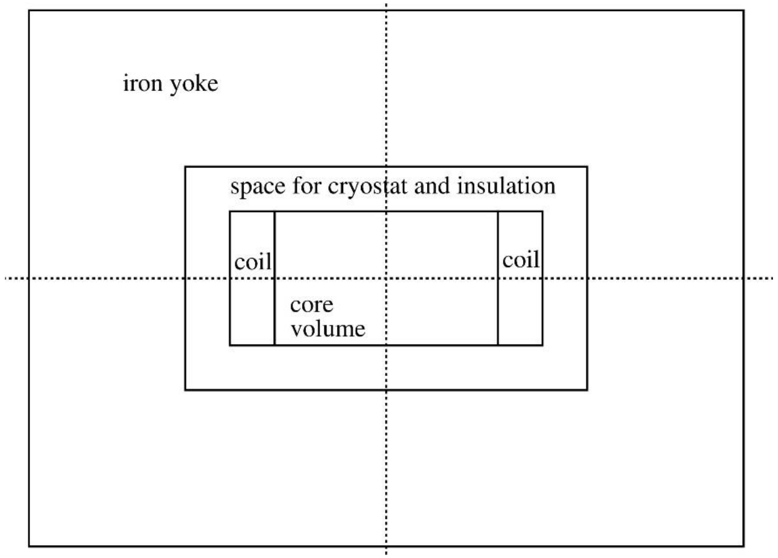




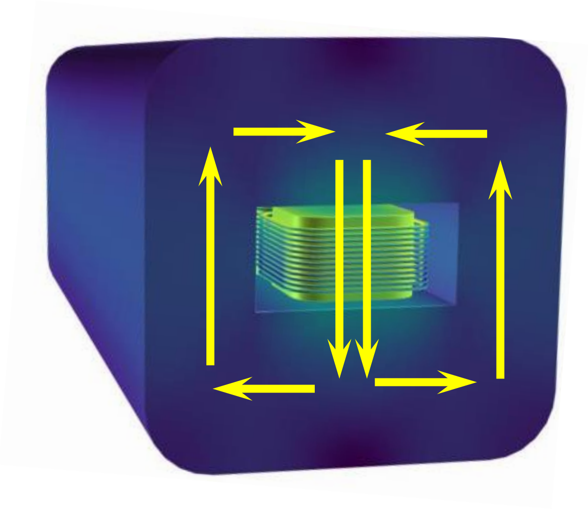


Muon Shield HTS magnet for Section 1

- Requirements
  - Along z-axis: $\int_0^L B_y(z)dz = \sim 35$ T m
    - B_y on z-axis: 4 – 5 T ⇒ Length: 7 – 8.8 m
    - Field-homogenity not required
  - Core cross section: 0.9 – 1m × 0.5 – 0.6 m
    - The core may be filled with iron
  - Gap space: 0.2 m surround for cryostat and insulation
  - Surround iron yoke thickness: 0.7 m–1.2 m
  - Stray field at 4 m distance: $B \sim \mathcal{O}(10)$ mT
  - Stable operation
  - ➔ Low beam-related heating (muons)



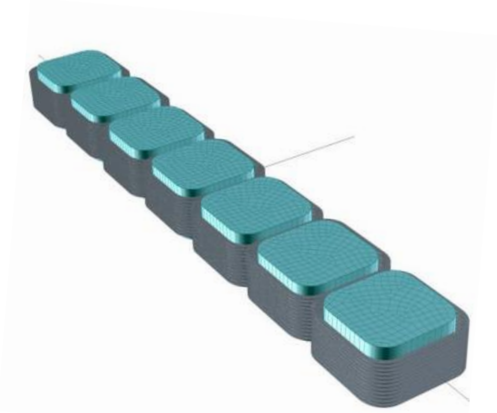
- Assumptions for the base design with 2G-HTS
  - Single-wound ReBCO tape
    - Width: 12 mm
    - Total thickness: 0.1 mm
  - No-insulation winding technique
  - Epoxy impregnated
  - Operating temperature of 30 K
    - Closed-cycle neon-refrigeration system
    - Cooling tubes run thoughout the magnet system

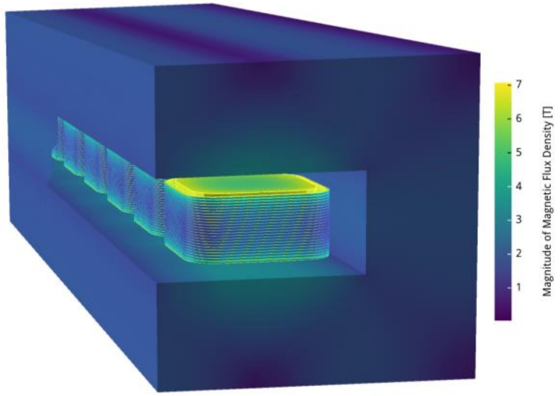


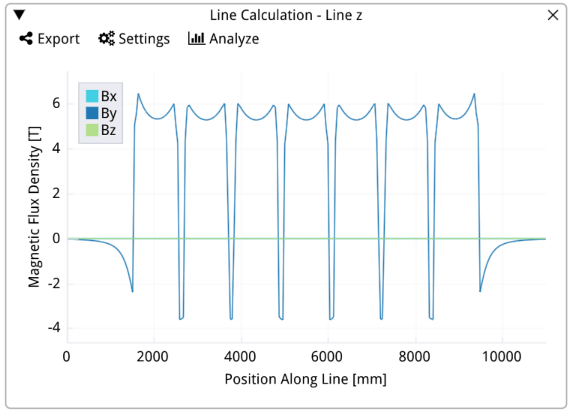
Muon Shield HTS magnet

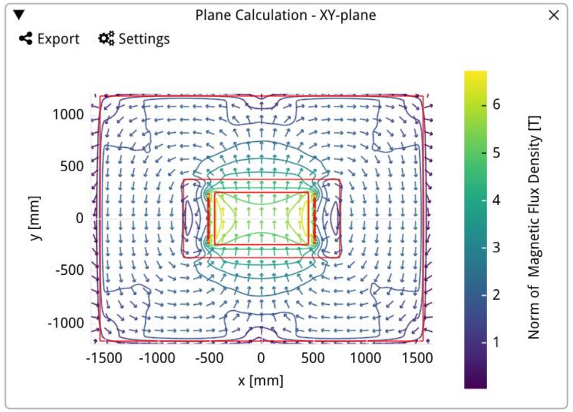
Proposal: Array of square coils with inner and outer iron yoke

- Coil inner dimensions: 1000 mm x 1000 mm
- Radial coil thickness: 20 mm
- Winding turns per pancake coil: 200 (no insulation)
- Coil bending radius: 200 mm
- Operating current: 649 A
- Number of coils: 168 coils
- Total tape length: 126 km (750 m per coil)
- Magnetic energy: 68.6 MJ
- Total inductance: 365 H
- Iron core dimensions: 900 mm x 500 mm x 900 mm (7 blocks)
- Outer iron yoke
- Inner cross-section: 1500 mm x 750 mm
- Thickness: 800 mm, Length: 7800 mm
- Outer cross-section: 3100 mm x 2350 mm
- Stray B-field at 4 m: about 14 mT
- Mass estimate: 450 tonnes









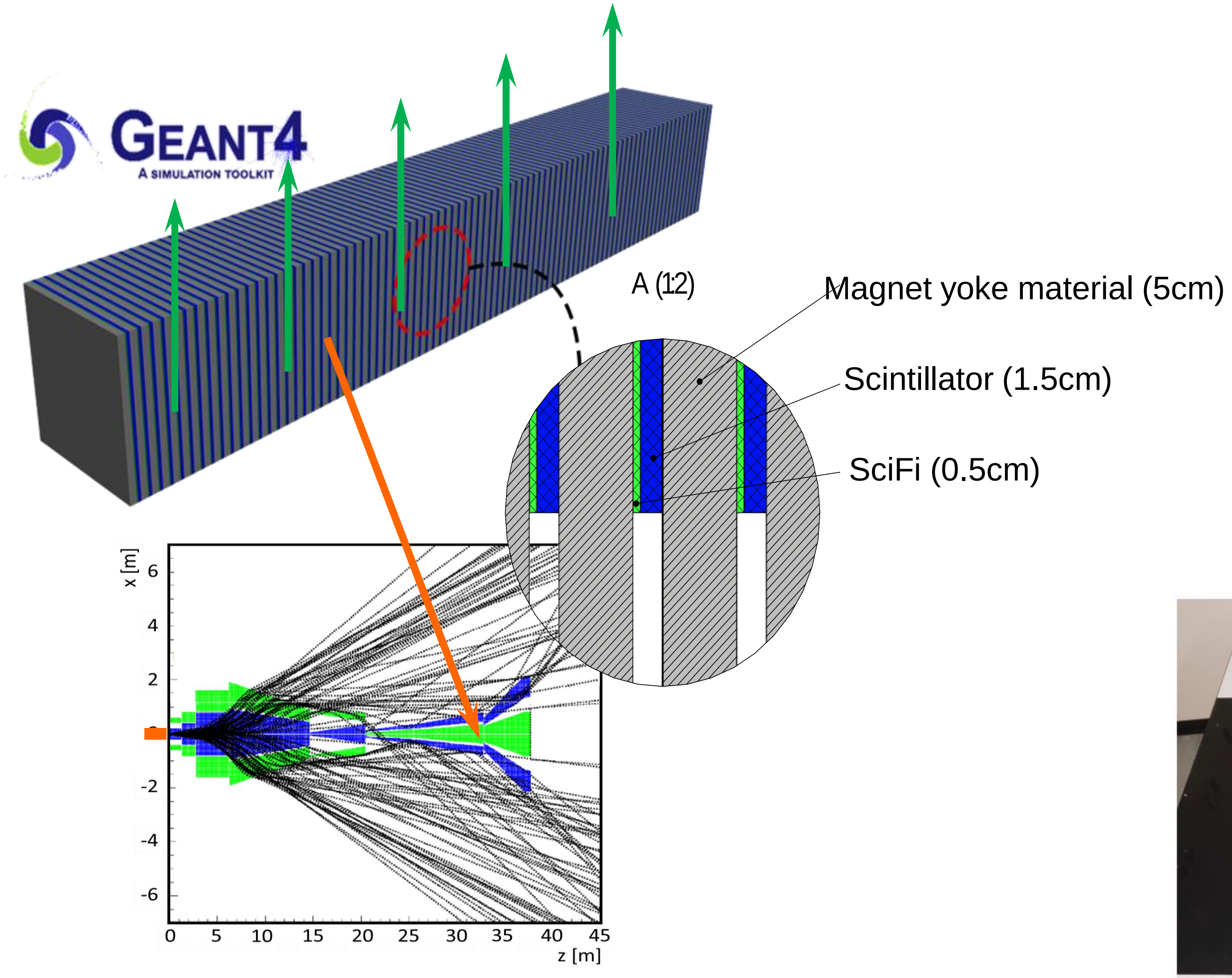
- ⦿ Alternative solution with Elliptical Pancake Tilted Solenoid

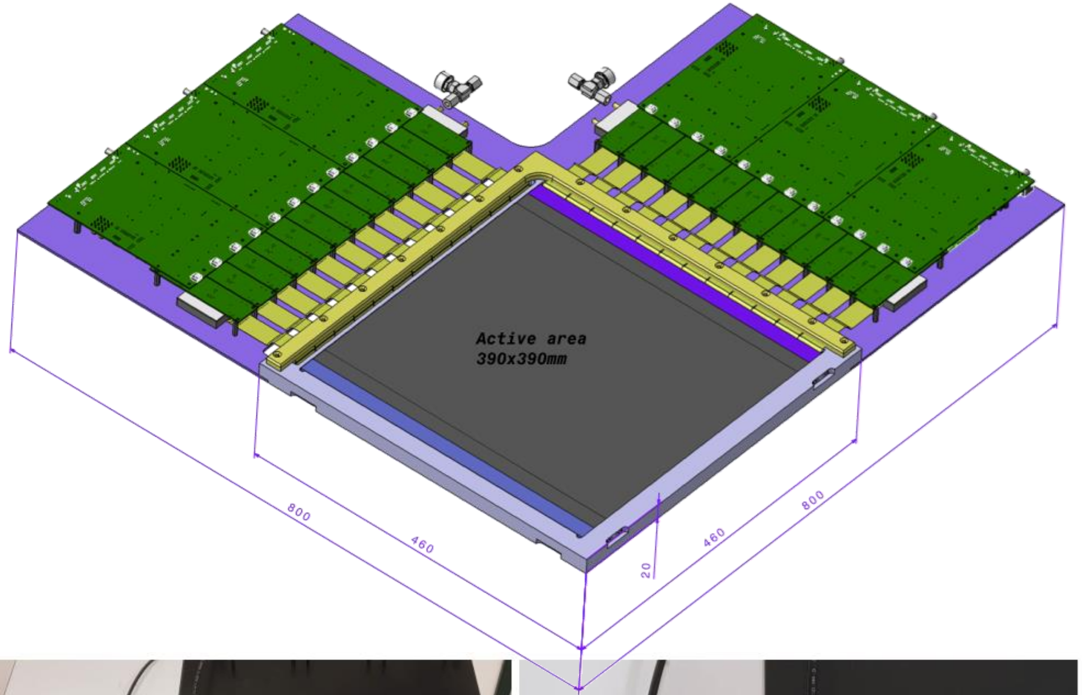
➔ Programme of feasibility defined, initially focussing on winding process and coil characterisation

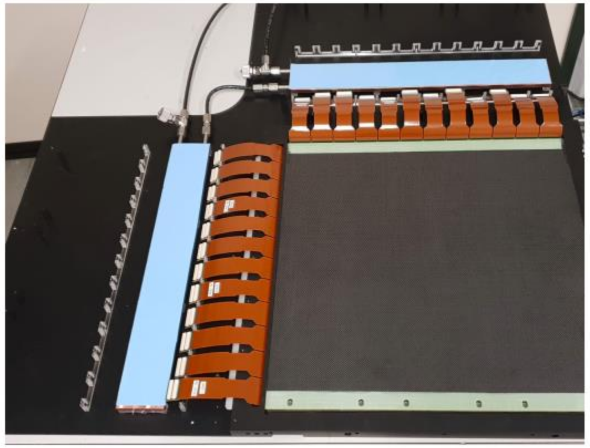
➔ Magnet protection?

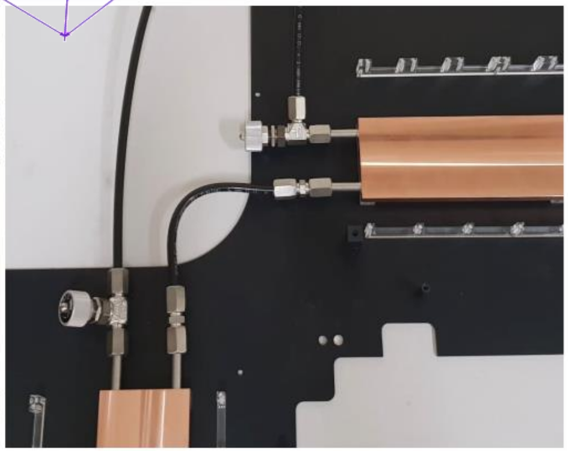
Dark Matter scattering and neutrino detector

Integrated into muon shield to use the return magnetic field for particle charge determination

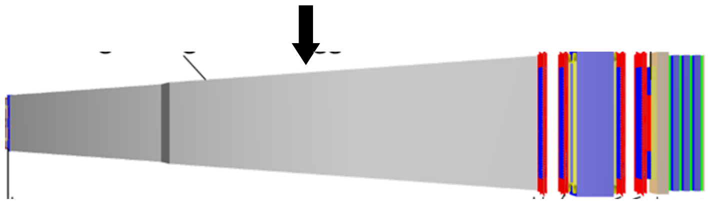






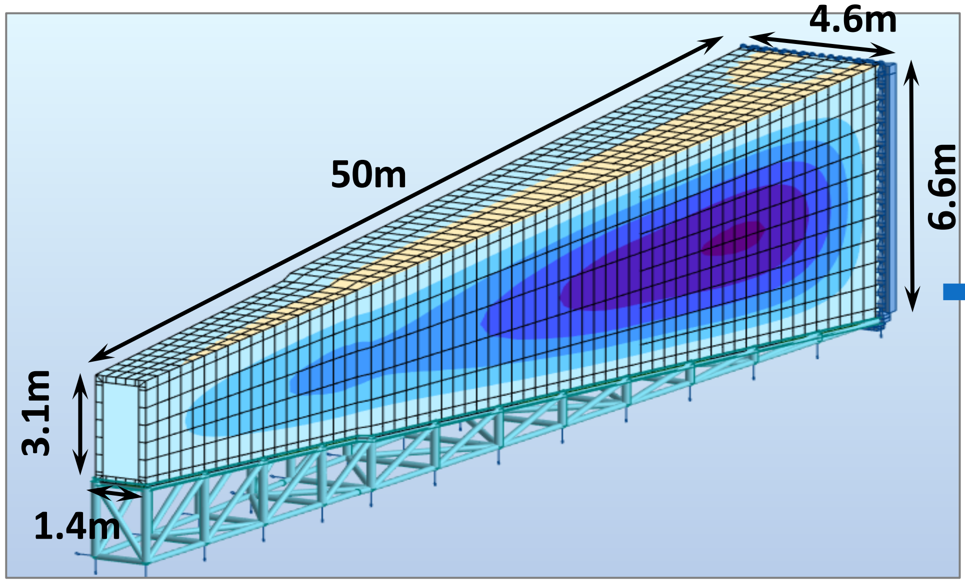


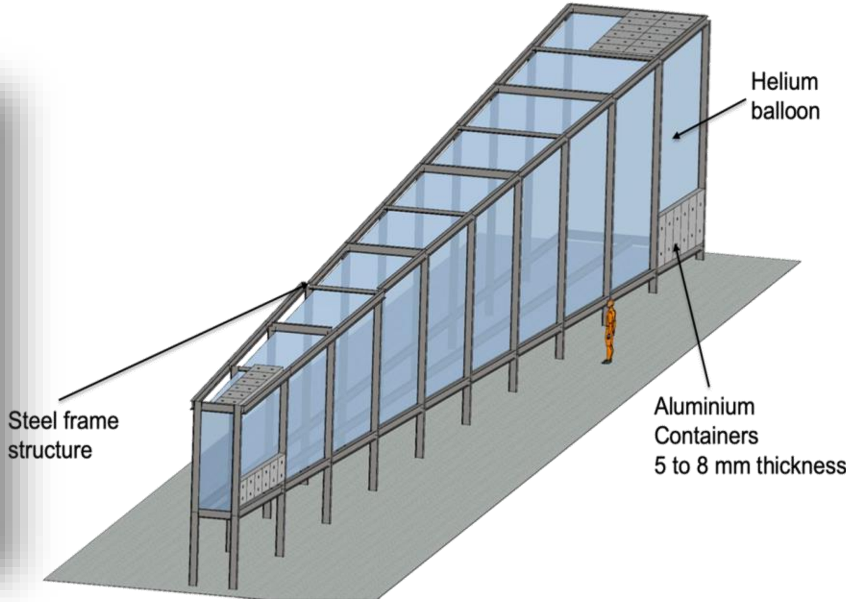
Decay volume



10^{18} neutrinos and anti-neutrinos through SHiP's fiducial volume, potentially producing background

1. Suppress to <10 interactions in ~550 m^3 decay volume (~700 m^2 membrane) by evacuating air
2. Reject interactions in decay volume structure by surrounding scintillator veto system

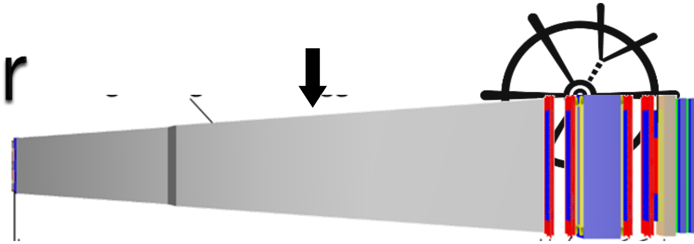




➔Helium gas bag at 1atm sufficient instead of vacuum at 1mbar (upgrade path) held in place by a frame structure of aluminium profiles

➔ Need for a large-volume helium circulation and purification system (>99%)

Surrounding Background Tagger



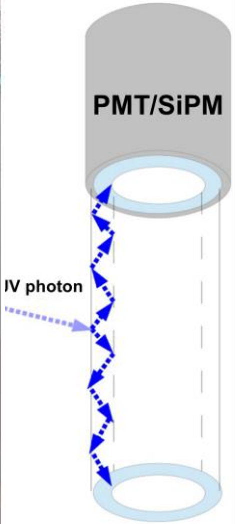
- Purpose: Tagging charged particles entering decay volume
  - ➔ >99% efficiency, O(10)cm spatial resolution and ~1ns time resolution

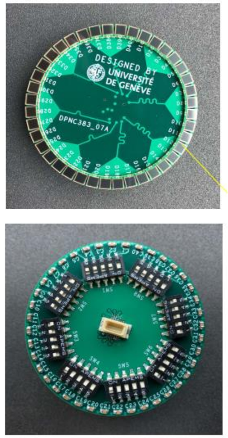
- Characteristics

  In critical areas
  - Liquid scintillator based: linear alkylbenzene (LAB) together with 2.0 g/l diphenyl-oxazole (PPO) as the fluorescent
  - WOMs with SiPM readout and surrounded by PMMA vessel

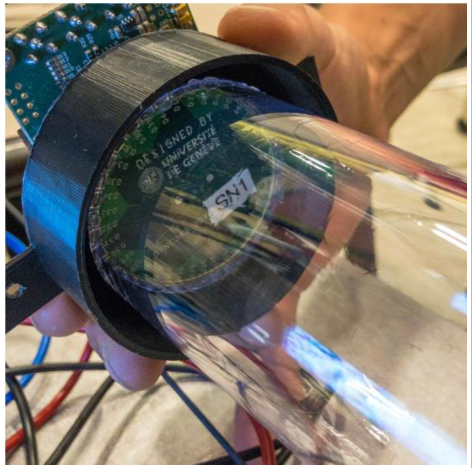
  Complemented with
  - Plastic scintillator staves and SiPM readout

Liquid scintillator system

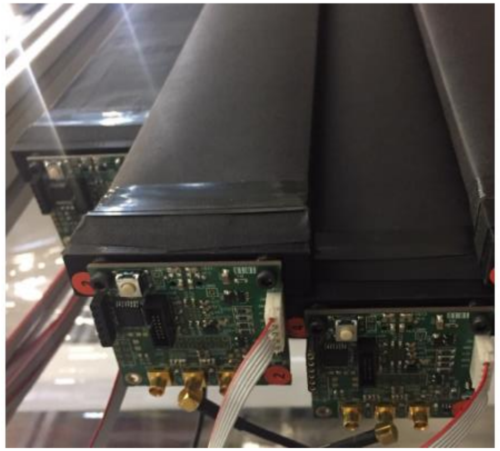


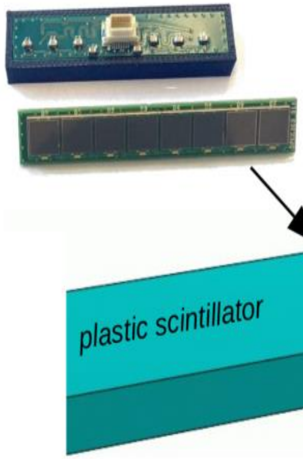


40-SiPMs array built by Geneva

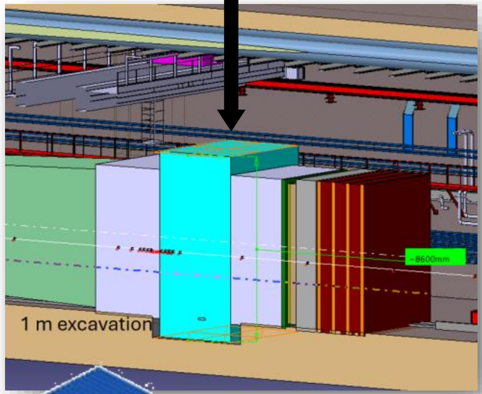


Plastic scintillator system



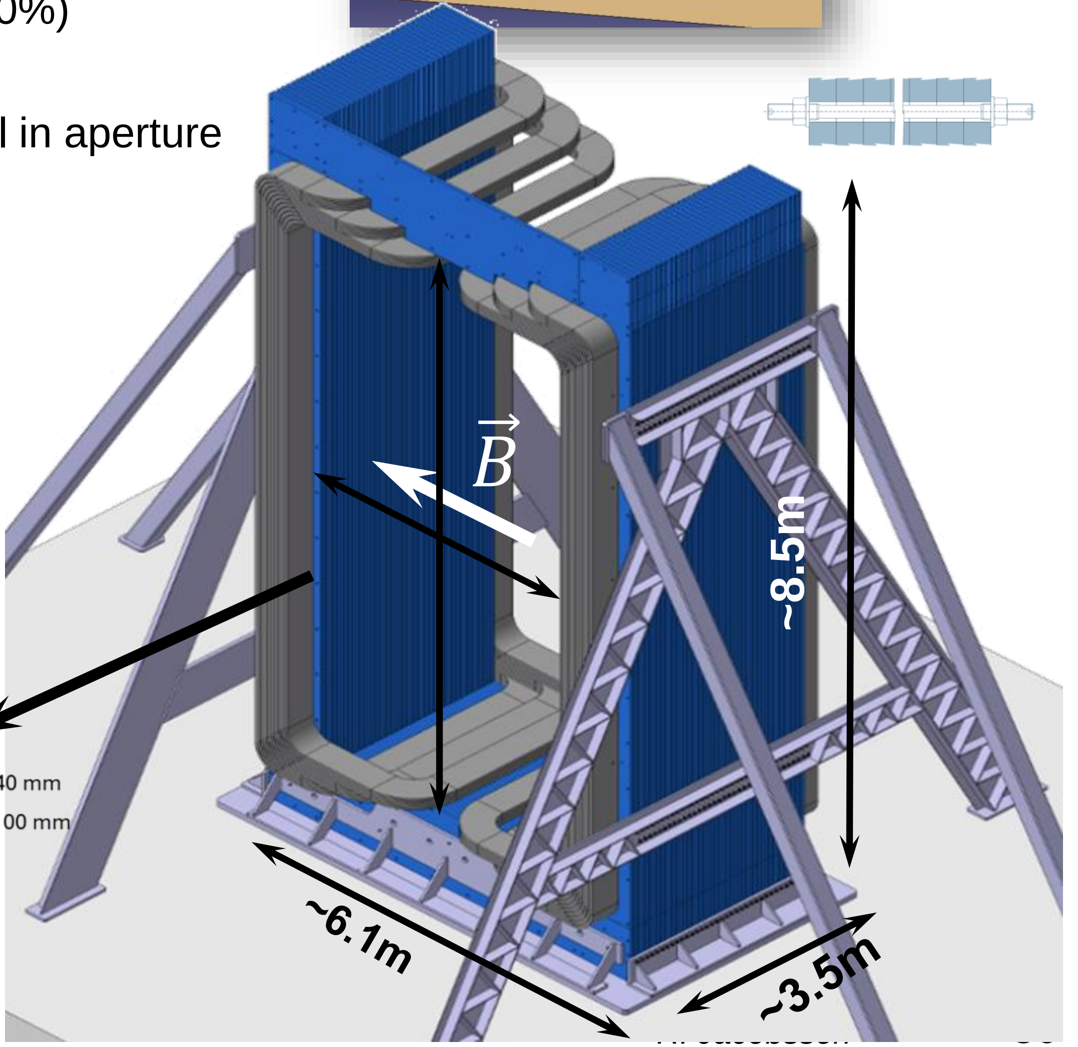


Spectrometer magnet

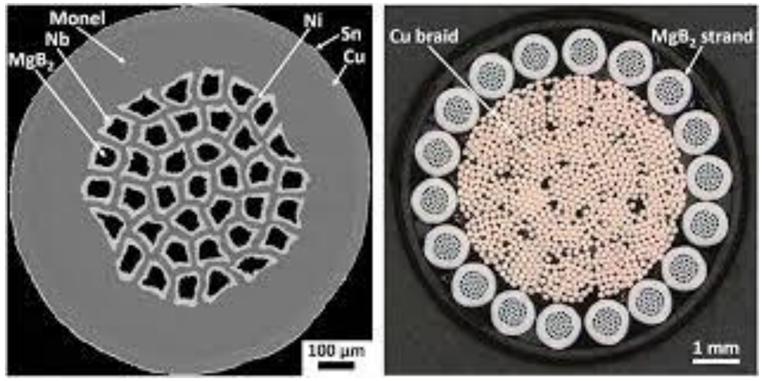


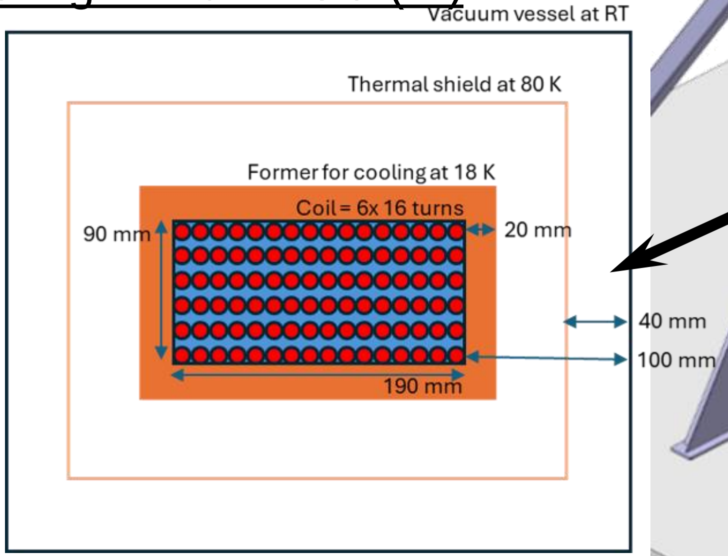
- Spectrometer requirements :
  - Physics aperture 4 x 6 m^2
  - Bending field ~0.6-0.8 Tm , nominal on axis ~0.15T
  - Integrated field uniformity more important than field uniformity (~5-10%)
  - Field mapping in-situ important
  - Design allowing future upgrade where yoke supports vacuum vessel in aperture

➔ Exploratory study of NbTi / Nb_3Sn / MgB_2 / ReBCO



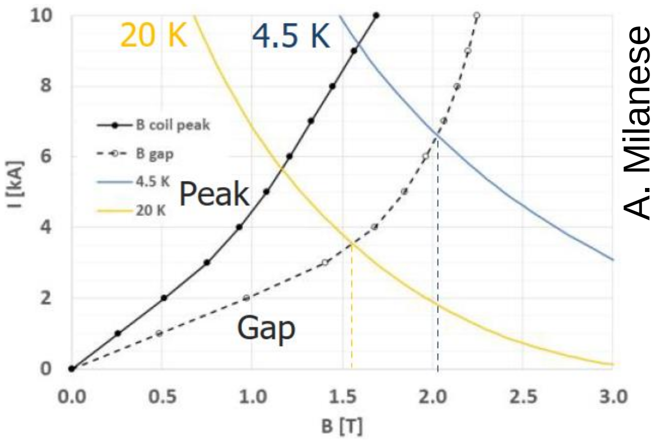
HL-LHC superconducting link sub-cable MgB2 from ASG (IT)





“Energy-Efficient Superferric Dipole”

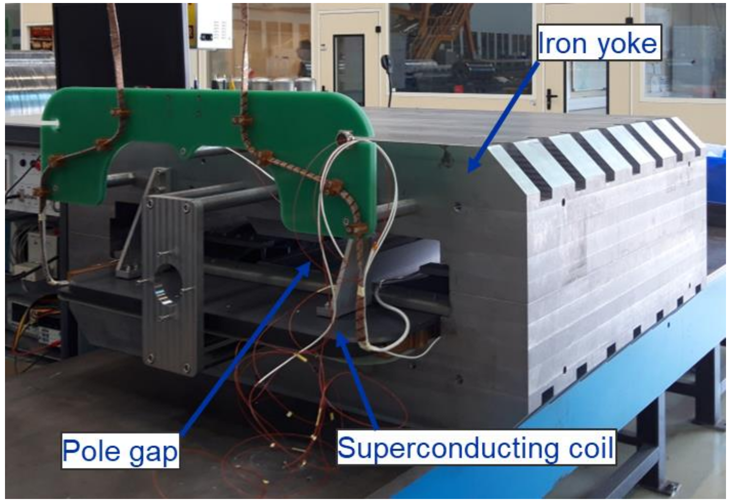
- Proposal
  - Design with MgB_2 sub-cables from HL-LHC WP6a, operate with gaseous helium at 20K with cryocoolers (HFM WP 4.6)



A. Milanese

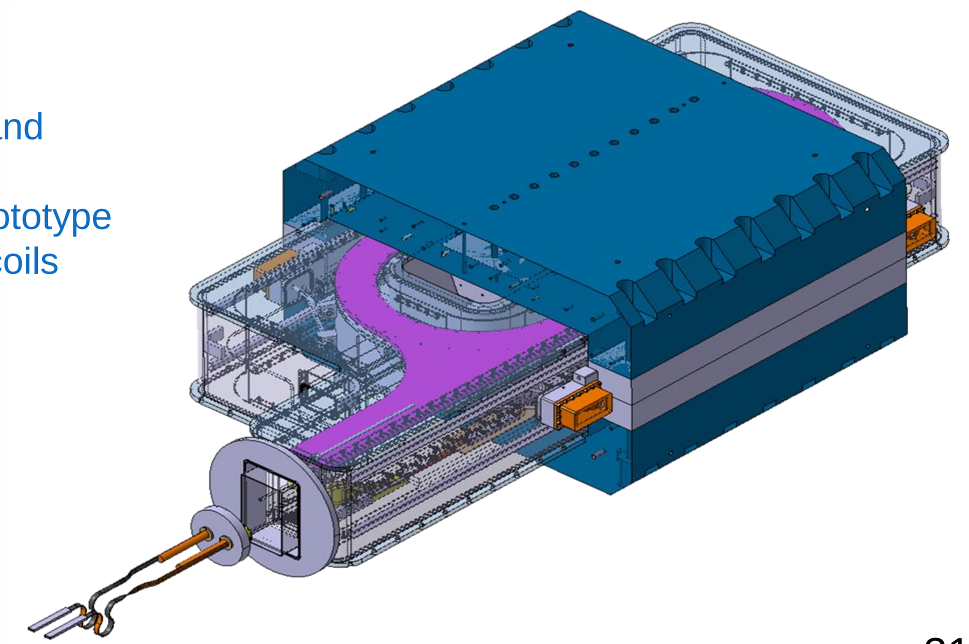
- Under investigation with demonstrator
  - ✓ Prototype phase 1 (LHe@4.5K) and 2(Ghe@20-30K) : thermal cycling, no training, no performance change after quench test
  - ➔ Phase 3 (preparation ongoing): Test with warm yoke and coil at 20 K integrated in dedicated cryostat with indirect cooling
  - ➔ Next steps: optimisation of cooling configuration and current leads, and study of final coil configuration and support

Prototype for phase 1 and 2 (2023-24)

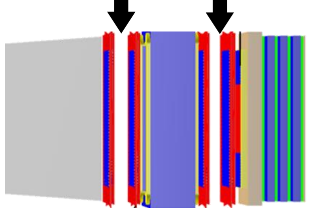


To optimize cryostat design and transfer of Lorentz loads, electromagnetic design of prototype includes two racetrack-type coils

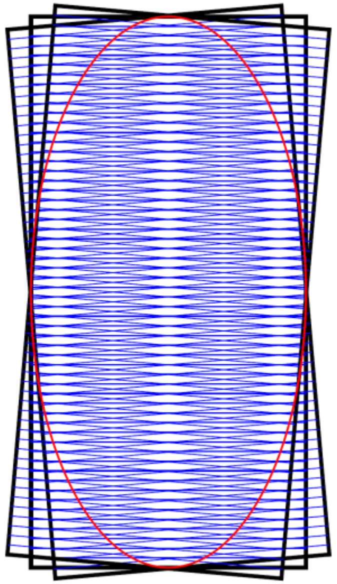
Prototype for phase 3 (2025)

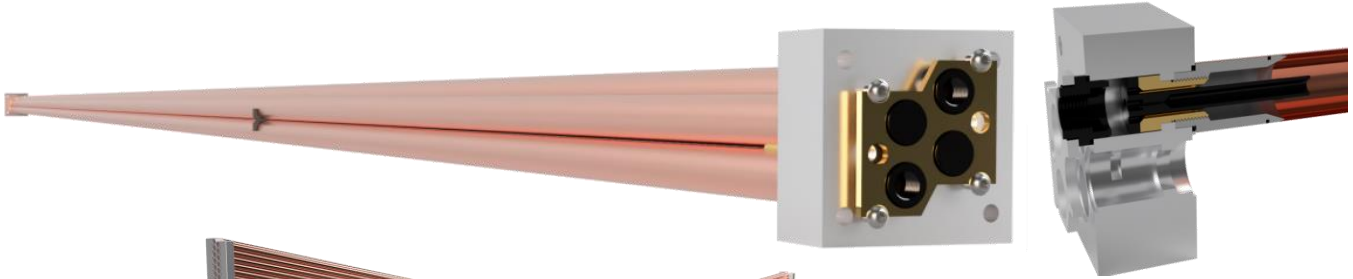


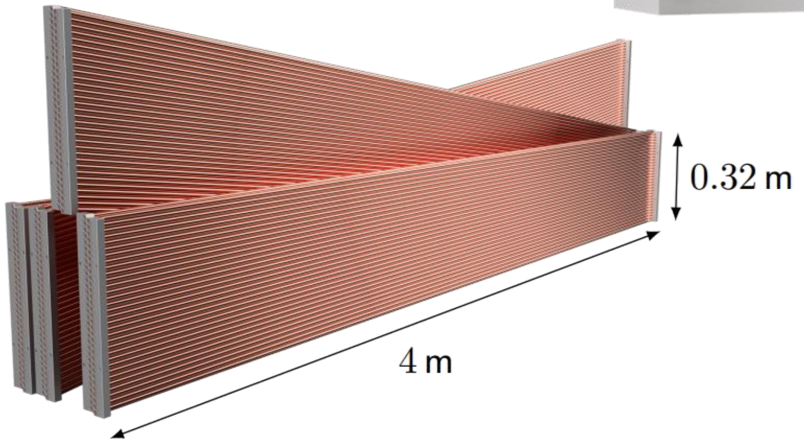
Straw Tracker



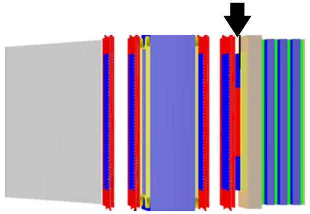
- Purpose: Track reconstruction and momentum, match hits in timing detector
- Technology developed for the NA62 experiment
  - ➔ Horizontal orientation of tubes ➔ mechanical challenge
  - ➔ Lower rate allows increasing straw diameter (highest rate ~10 kHz)
- Characteristics
  - 4 x 6 m^2 sensitive area
  - Baseline:4m long 20mm diameter 36μm thick PET film coated with 50nm Cu and 20nm Au operated at 1 bar Ar/CO_2 mix,
  - Alternative: ~100μm aluminium straws
  - Four stations, each with four views Y-U-V-Y, ~9600 straws





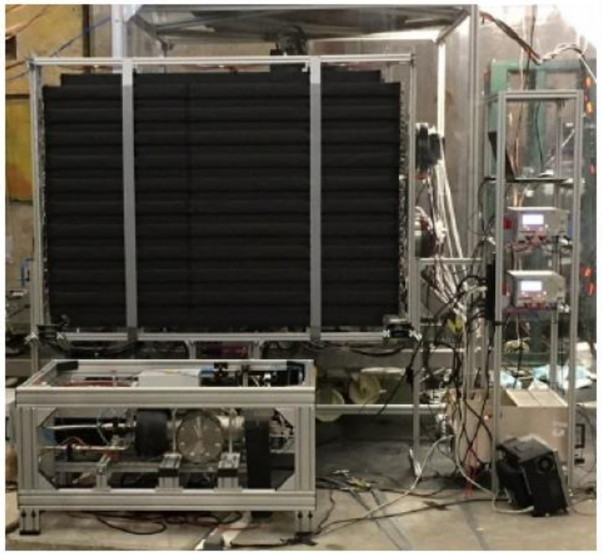


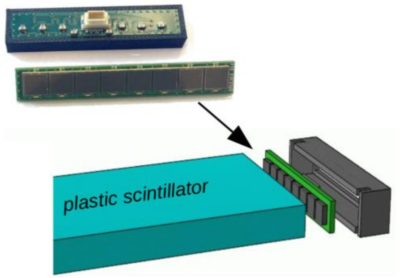
Timing Detector

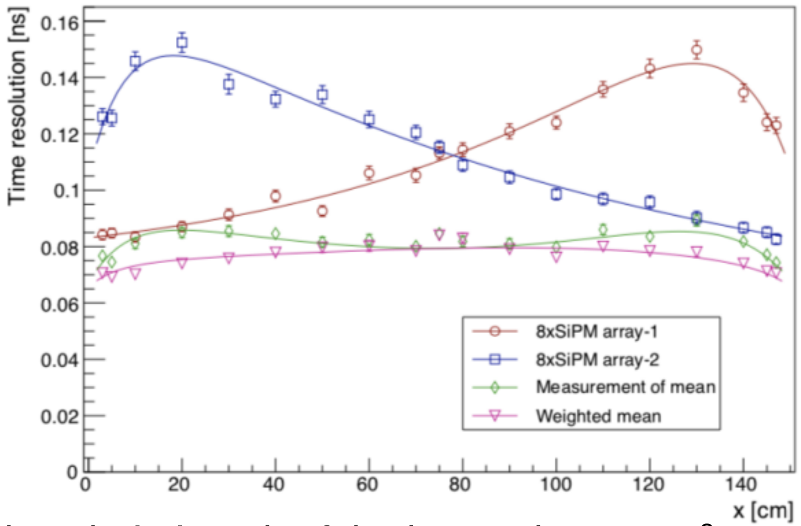


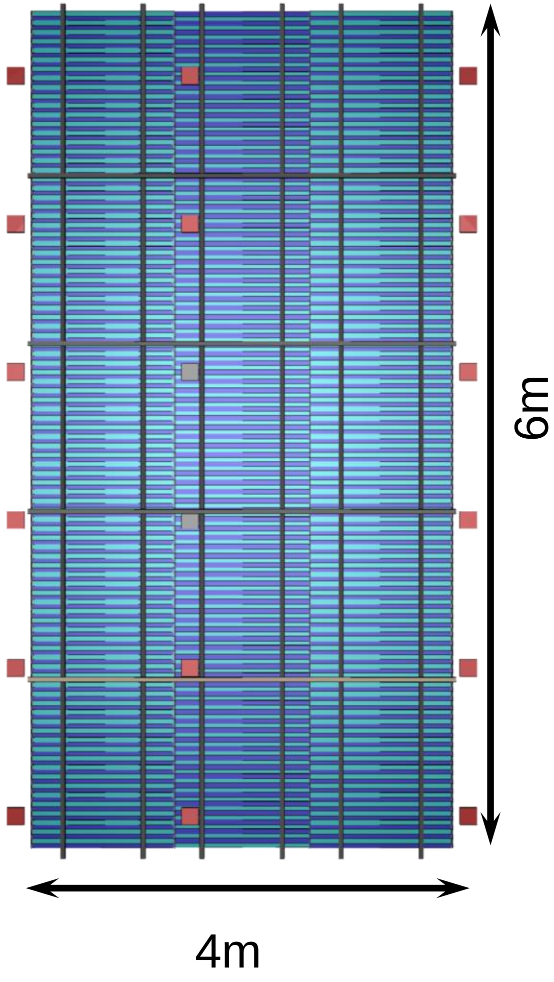
- Purpose: Provide precise timing (<100 ps) of each track
- Plastic scintillator characteristics
  - Three-column setup with EJ200 plastic bars of 135cm × 6cm × 1cm, providing 0.5cm overlap
  - Readout on both ends by array of eight 6×6 mm^2 SiPMs, 8 signals are summed
  - 330 bars and 660 channels

22x 168cm bar (44 channels) prototype tested at PS



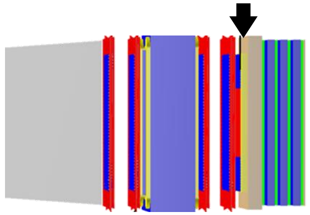




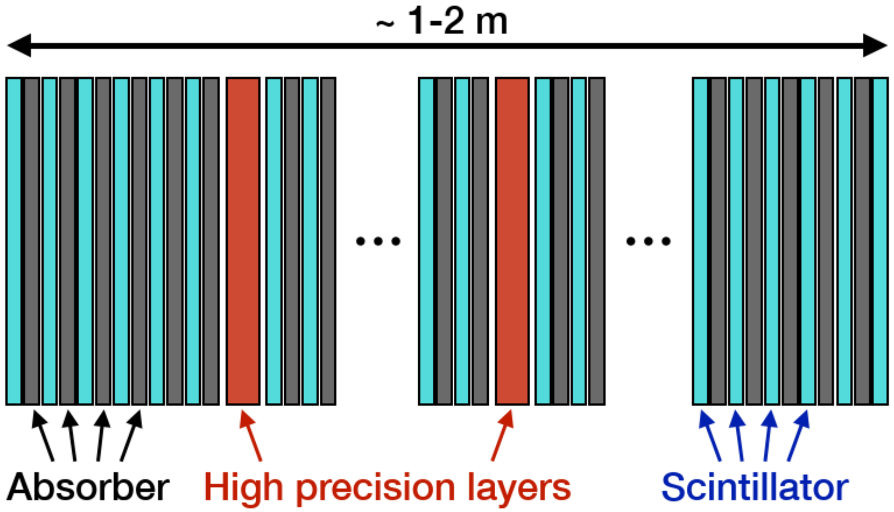


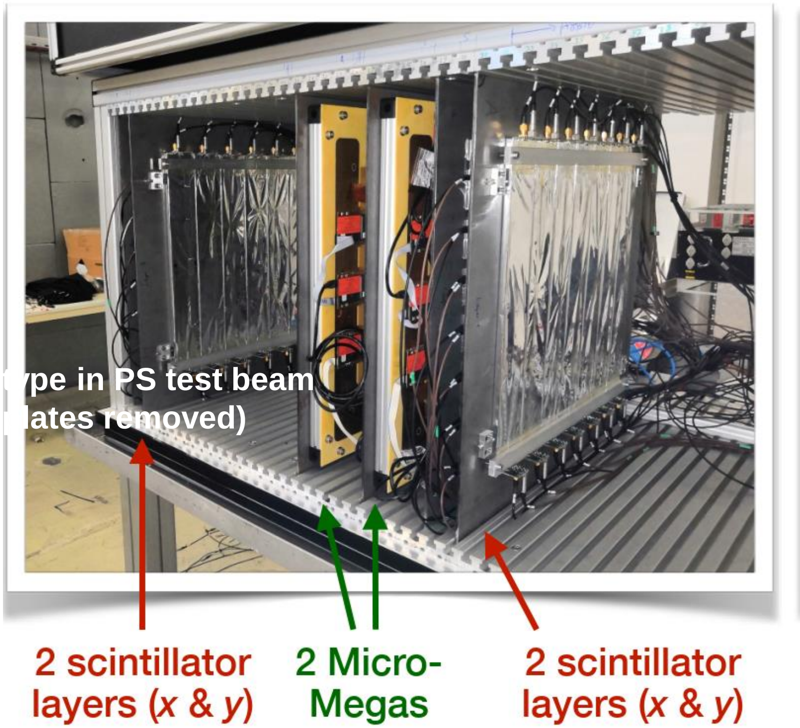
Resolution demonstrated to be ~80 ps along the whole length of the bar and over 2m^2 prototype

Calorimeters



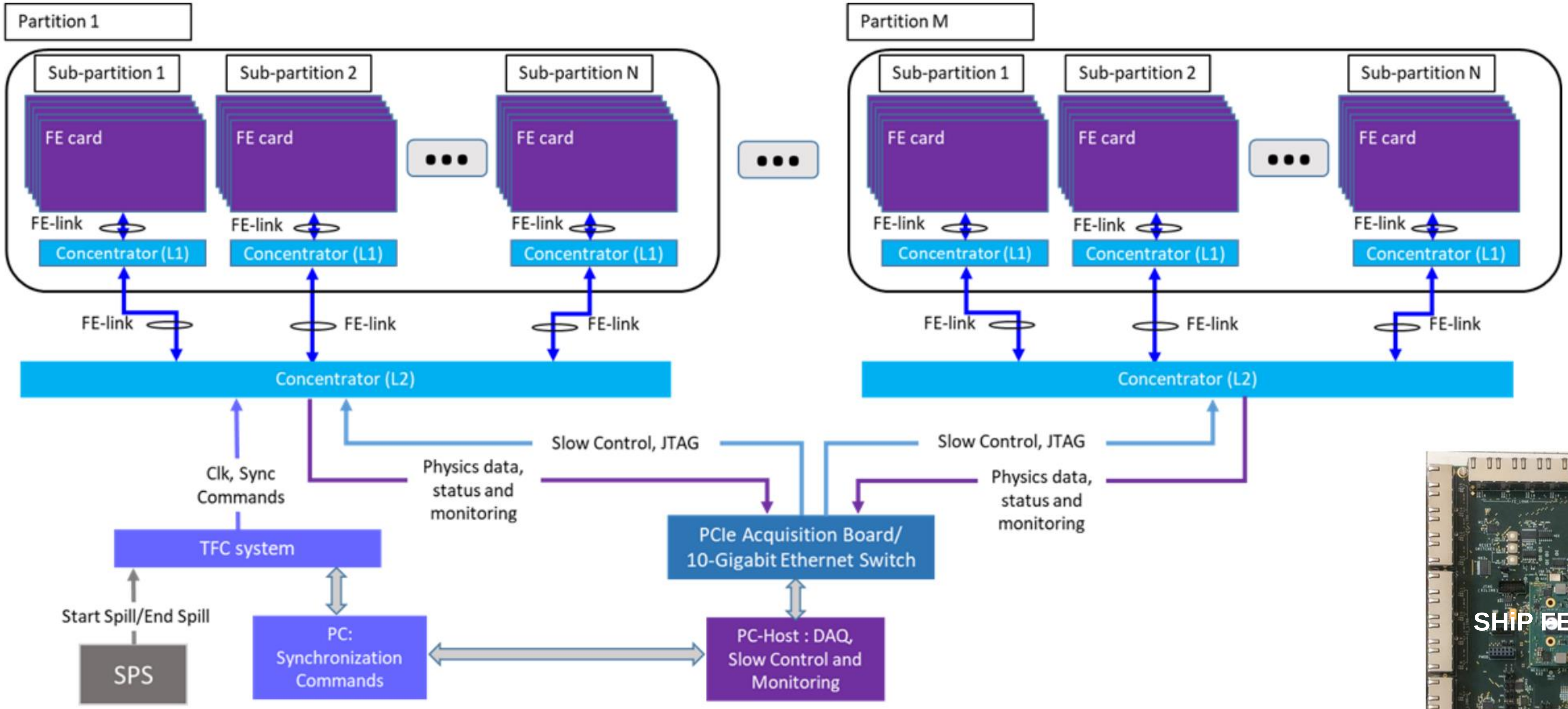
- Purpose: e/γ identification, π^0 reconstruction, photon directionality ~5mrad
- Characteristics
  - 20 X_0 longitudinally segmented calorimeter with coarse and fine space resolution active layers
  - Coarse layers: 60 planes of scintillating bar readout by WLS + SiPM (0.58cm / 0.3X_0 iron + 1 cm plastic)
  - Fine resolution layers: 3 layers (1.12cm thick), first at 3X_0, and two layers at shower maximum to reconstruct transverse shower barycentre, with resolution of ~200μm micro-pattern or SciFi detectors

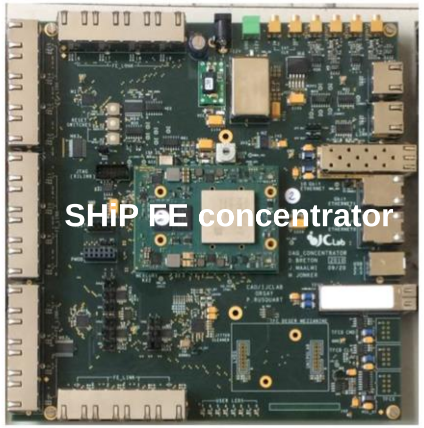




Electronics and readout

- Subsystem architecture – aiming for common electronics





- Relatively low data rates, but very spread out, no radiation, easy access….
- Custom electronics in Front-End, COTS network and computer readout in back-end

+ Computing infrastructure for control, data processing, and storage and data bases

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)
- Detector components (e.g. plastic scintillators)
- Cooling systems (CO_2)
- Helium gas bag, helium purification and
- Tooling for transport and handling
- LV/HV power systems
- Control and monitoring
- Electronics
- Cabling
- Computing infrastructure (switches, routers, data processing, storage, control computers

Status of Collaboration (2023) and Detector Cost

Sub-projects	Main lead	Involved groups
Muon shield		
Muon shield*	CERN[30]	RAL(UK)[38], CERN[30], ++
SND		
Emulsion system	Naples(IT)	LNGS(IT)[17], Naples(IT)[16,c], Aichi(JP)[18], Kobe(JP)[19], Nagoya(JP)[20], Nihon(JP)[21], Toho(JP)[22], Gyeongsang(KR)[23], Gwangju(KR)[24], Seoul(KR)[25], Gyeong Gi-do(KR)[26], METU(TR)[33]
Target tracker	Lausanne(CH)	Lausanne(CH)[31], Siegen(DE)[12]
Muon spectrometer	Naples(IT)	Bari(IT)[13,a], Naples(IT)[16,c]
HSDS		
Decay vacuum vessel + caps*	Naples(IT)	Naples(IT)[c], CERN[30]
Spectrometer vacuum vessel*	CERN[30]	CERN[30]
Spectrometer magnet*	CERN[30]	CERN[30], ++
Upstream background tagger	Lisbon(PT)	Lisbon(PT)[28]
Surrounding background tagger	Berlin(DE)	Berlin(DE)[7], Freiburg(DE)[8], Juelich(DE)[10], Mainz(DE)[11], Kiev(UA)[39]
Spectrometer tracker	Hamburg(DE)	Hamburg(DE)[9], Juelich(DE)[10], Kiev(UA)[39], CERN[30]
Timing detector	Zurich(CH)	Zurich(CH)[32]
Particle identification detectors		Mainz(DE)[11], Bologna(IT)[14], Cagliari(IT)[15,b], Bristol(UK)[35], ICL(UK)[36], UCL(UK)[37]
Online + offline		
Common electronics and online(*)	Orsay(FR)	Orsay(FR)[6], CERN[30]
Computing		CERN[30], Copenhagen(DK)[5]
Subdetector infrastructure, engineering, electronics		Sofia(BG)[1], SAPHIR(CL)[2], UNAB-Santiago(CL)[3], ULS-Serena(CL)[4], Copenhagen(DK)[5], Siegen(DE)[12], Leiden(NL)[27], Belgrade(RS)[29], Ankara(TR)[34]

Item	Production material cost [kCHF]	
Muon Shield		**11 100**
Hadron stopper magnetisation	included in facility cost	
Muon shield - SC section*	7 000	
Muon shield - NC section*	4 100	
Scattering and Neutrino Detector		**5 300**
Emulsion system, inc. facility tooling	2 400	
Target tracker	1 500	
Muon spectrometer magnet	1 200	
Muon detector	200	
Hidden Sector Decay Spectrometer		**30 300**
Decay volume vacuum vessel + caps*	4 700	
Spectrometer vacuum vessel*	3 900	
Spectrometer magnet*	6 400	
Upstream background tagger	200	
Surrounding background tagger	4 700	
Spectrometer tracker	4 400	
Timing detector	700	
Particle identification detectors	5 300	
Infrastructure		**2 000**
Online + offline		**2 200**
Common electronics and online(*)	1 200	
Computing	1 000	
Total		**50 900**

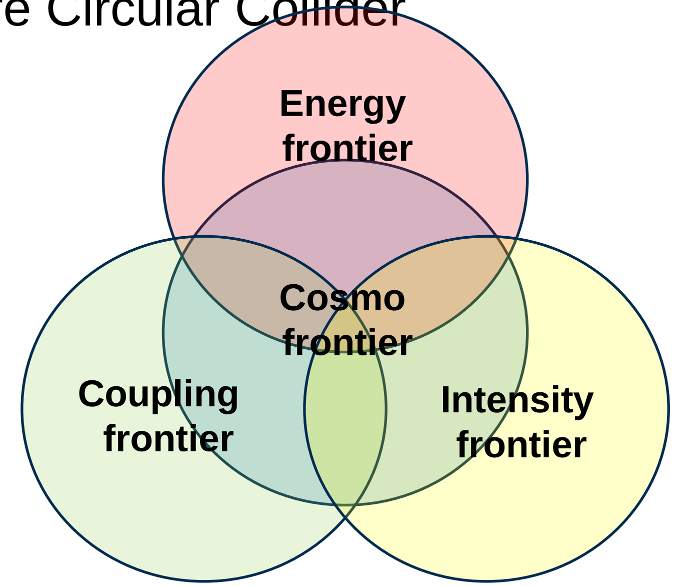
➔ 2024: 40 institutes from 18 countries and CERN

- Currently interest from 7 new groups in Austria, Italy, Netherlands, UK
- In contact with groups in Finland, France, **and I hope Sweden! ➔ Facilitate procurement!**

Conclusions

Strong reasons for a dedicated accelerator-based facility to explore *“Coupling Frontier”*

- We are sharing the Universe already with feebly coupled and not-understood neighbours!
- Light Hidden Sector can provide solutions to well-established problems!
- Essential complementarity with projects in launch/commissioning on the cosmofrontier
- Unique physics potential of SPS with the SHiP experiment
- SHiP is complementary to Hidden Sector searches at HL-LHC and Future Circular Collider



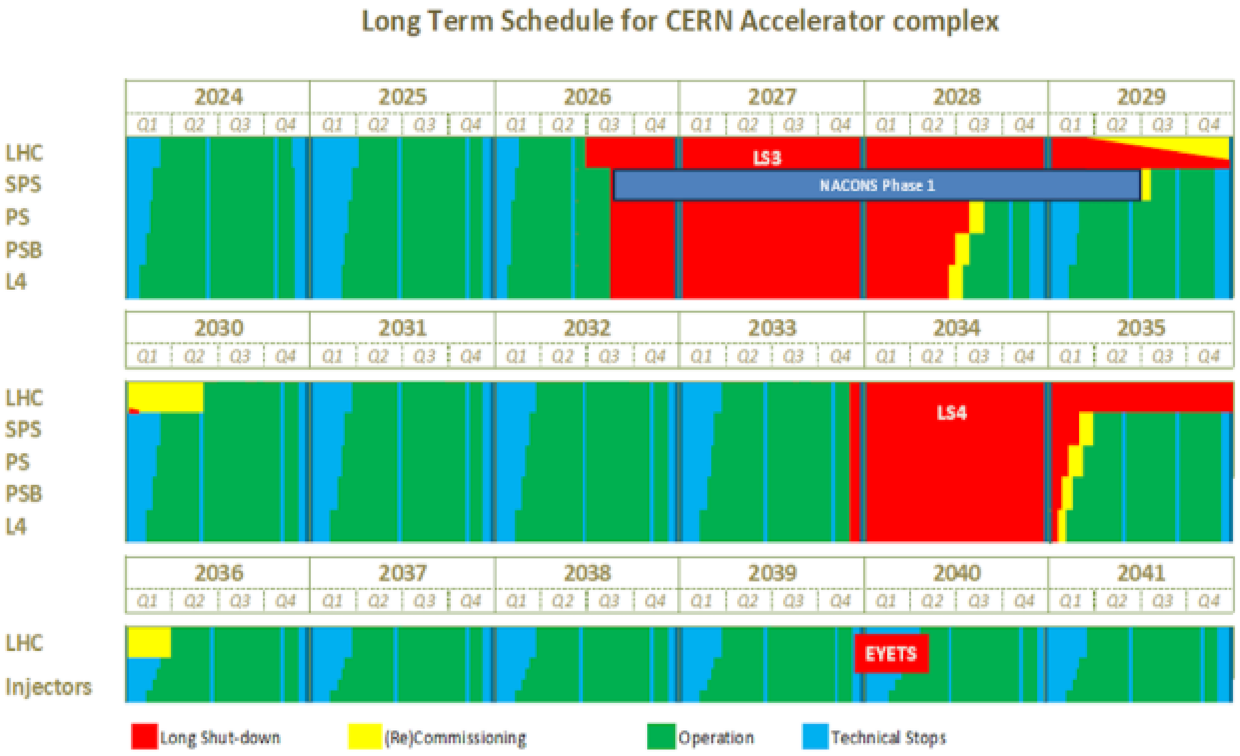
⊙ Many scientific and technological challenges ahead!

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

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

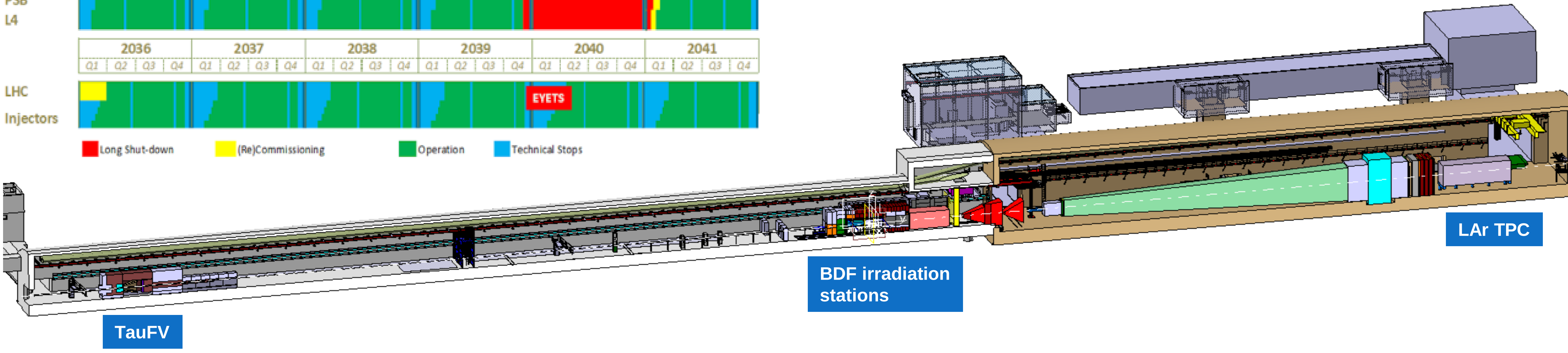
Overview of extensions of research facility

➔ SHiP physics exploration stretches over 15 years



Preliminary studies of opportunities to extend physics programme *synergetically with SHiP*:

1. Irradiation stations (nuclear astrophysics and accelerator / material science applications)
2. LArTPC to extend search for FIPs using different technology
3. TauFV to search for lepton flavour violation and rare decays of tau leptons and D-mesons



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26c. High-Intensity ECN3 (Experimental facility for SHiP)

Goal	To continue to fully exploit CERN's world-leading role in high-energy fixed-target physics, the High-Intensity ECN3 (HI-ECN3) project aims to extend the physics reach of the SPS North Area. The project will allow the full potential of the SPS to be realised by increasing the intensity transferred to the ECN3 underground cavern by over an order of magnitude. This will allow ECN3 to house a beam dump facility (BDF) capable of meeting the challenging requirements of the Search for Hidden Particles (SHiP) experiment. The project builds on the sustained research and development that was presented in the *SPS BDF Comprehensive Design Study* (CDS) published in 2020 and has subsequently been pursued through the recent PBC Study Group's efforts on *Post-LS3 Experimental Options in ECN3*. This work culminated in the decision to approve the SHiP experiment, as presented to the SPC and the Council in March 2024. In synergy with the NA-CONS project, the planned schedule for BDF/SHiP aims to have first beam on target to start the commissioning of the SHiP detector systems in the second half of Run 4, with the experimental physics programme starting before LS4.
Approval	Presented to the CERN Council in 2024
Start date	31 July 2023 (appointment of Project Leader of ECN3 High-Intensity Study by ATS Director, EDMS #2921486).
Costs	The material cost to completion of the HI-ECN3 project is 58.5 MCHF, complemented by 4.2 MCHF of dedicated consolidation under the North Area consolidation project
Competitiveness	There is strong and growing evidence from both particle physics and astrophysical observations for the existence of physics beyond the Standard Model (BSM) that has so far evaded direct discovery in high-energy colliders. The BDF at SPS will allow the SHiP experiment to search directly for new, low-mass feebly interacting particles (FIPs) at a luminosity some three orders of magnitude higher than that of the HL-LHC, in a parameter range not accessible to the LHC experiments.
Risks	The schedule for the completion of BDF/SHiP is constrained on the critical path by the timeline of the required civil engineering activities. To minimise the risk of delay to the construction activities, prompt communication to SCE of clear design requirements during the TDR phase is planned. Furthermore, the timely dismantling of the NA62 experiment and its related infrastructure and beamline in ECN3 and TCC8 at the start of LS3 must be guaranteed. The HI-ECN3 project strongly depends on the progress of the North Area consolidation project (NA-CONS). There is a risk of delaying the HI-ECN3 project and increasing its cost to completion if key NA-CONS milestones for the inclusion of HI-ECN3 requirements are missed. To mitigate this risk, the two projects are structured to guarantee synergy and communication, and a common Steering Committee has been established to ensure that the projects stay aligned. The impact of longer-term NA-CONS infrastructure consolidation planned in LS4 is deemed acceptable for the operation of HI-ECN3. Regarding safety, the project is fully committed to addressing and minimising all risks associated with BDF/SHiP and to designing a state-of-the-art high-power target facility according to best practices and in compliance with the applicable CERN Safety Rules and Regulations. The project is collaborating closely with the Occupational Health and Safety and Environmental Protection (HSE) unit, with relevant DSOs and other safety officers and with the Experimental Physics Department Safety Office to address all risks associated with the facility, including any necessary mitigation. For example, the radiological risks are thoroughly taken into consideration in a sustainable facility design consistent with the radiation protection and environmental legislation and with ALARA

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equipped 400 MHz 1- and 2-cell cavity prototypes will follow for high-power system tests in a horizontal cryostat. Similar tests of a 5-cell 800 MHz cavity prototype are also planned as part of an international collaboration. In parallel, a complete 400 MHz prototype cryomodule for four 2-cell cavities will be built and cold-tested, as well as an 800 MHz prototype cryomodule.

The **Efficient Particle Accelerators (EPA) project** aims at modernising the operation of the CERN accelerator complex using advanced automation techniques based on artificial intelligence and machine learning. The final goal is to increase efficiency, reproducibility, flexibility, performance, and sustainability and to minimise human errors and operation delays. Work packages include dynamic beam scheduling, automated LHC filling, automated parameter control and optimisation, hysteresis compensation, automated equipment testing, etc. The project, which is time-bounded as improvements need to be ready for Run 4, has two phases: prototyping and first operational tests during Run 3; and full implementation during LS3 and sequential commissioning during Run 4. A review is planned at the end of 2025. Funding is provided in this MTP, as discussed in Section 4.2 below.

2.3. The SHiP experiment

In March 2024, the Research Board approved the SHiP beam-dump experiment for operation at the upgraded ECN3 facility, with beam intensities of up to 4×10^{19} protons-on-target (POT)/year. The upgrade will be implemented during LS3 and SHiP is expected to start operation in 2031 and to provide unique results in the search for feebly-interacting particles.

The core cost of the complete SHiP detector, including infrastructure and services, is estimated to be 51 MCHF. In addition to the provision of the beam facility, CERN's contribution during the R&D and construction phases will be primarily focused on the muon spectrometer magnet and on the interfaces between the experimental area and the detector, as part of the host lab responsibility. The magnet is based on a new configuration of superconducting technology for large-scale, low-field magnets, with the aim of significantly reducing power consumption compared to normal-conducting magnets. Given the emphasis on developing and constructing all detector components outside CERN except for the magnet, significant effort will be required from CERN in terms of coordination, design support, and integration. This is particularly important for the decay volume and the straw tracker.

The Research Board recommended that, as only a fraction of the required funding is currently available, the detailed layout of the experiment for the initial configuration will need to be developed in consultation with the funding agencies and CERN. In parallel, a staged/descoped detector scenario should be developed as a risk mitigation strategy, which would only be implemented if the gap between the needed and the available resources could not be bridged. The baseline layout, along with the staged/descoped scenario, should be developed on a time scale of about a year and be reviewed by the SPSC.

The current timeline provides for an R&D and TDR phase covering the period 2024-2027, followed by the construction phase in the years 2027-2030, and operation as of 2031.