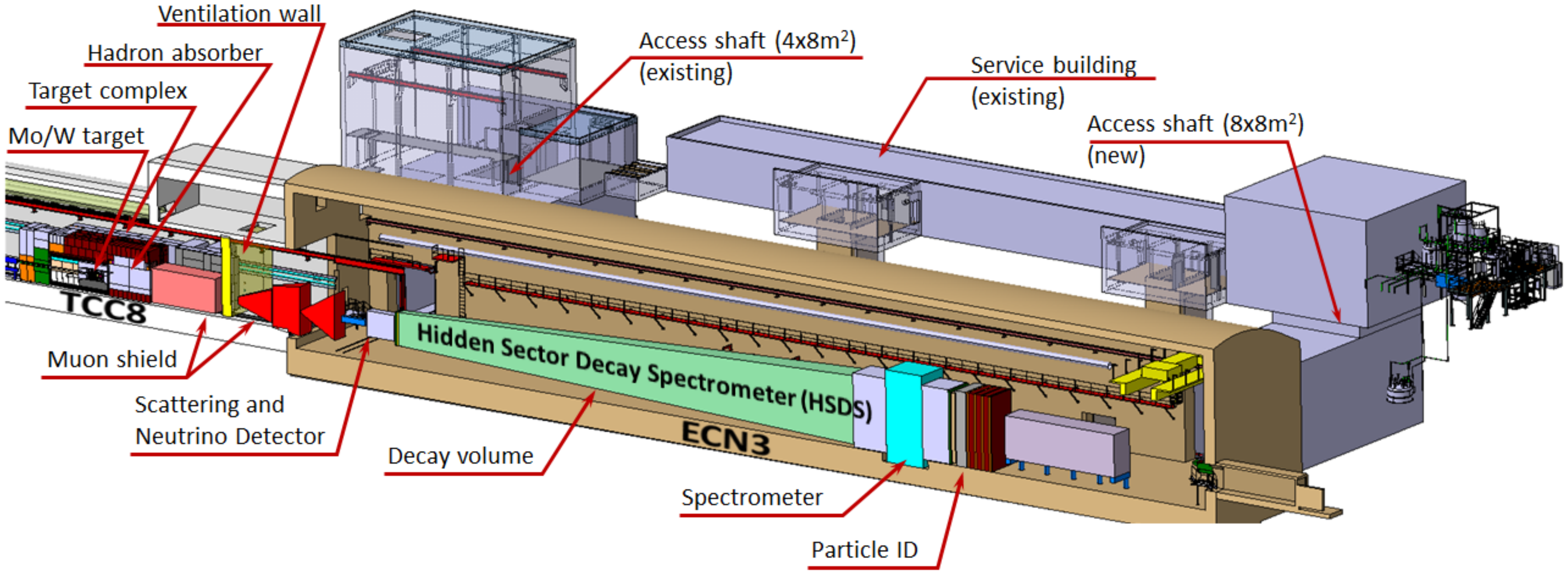
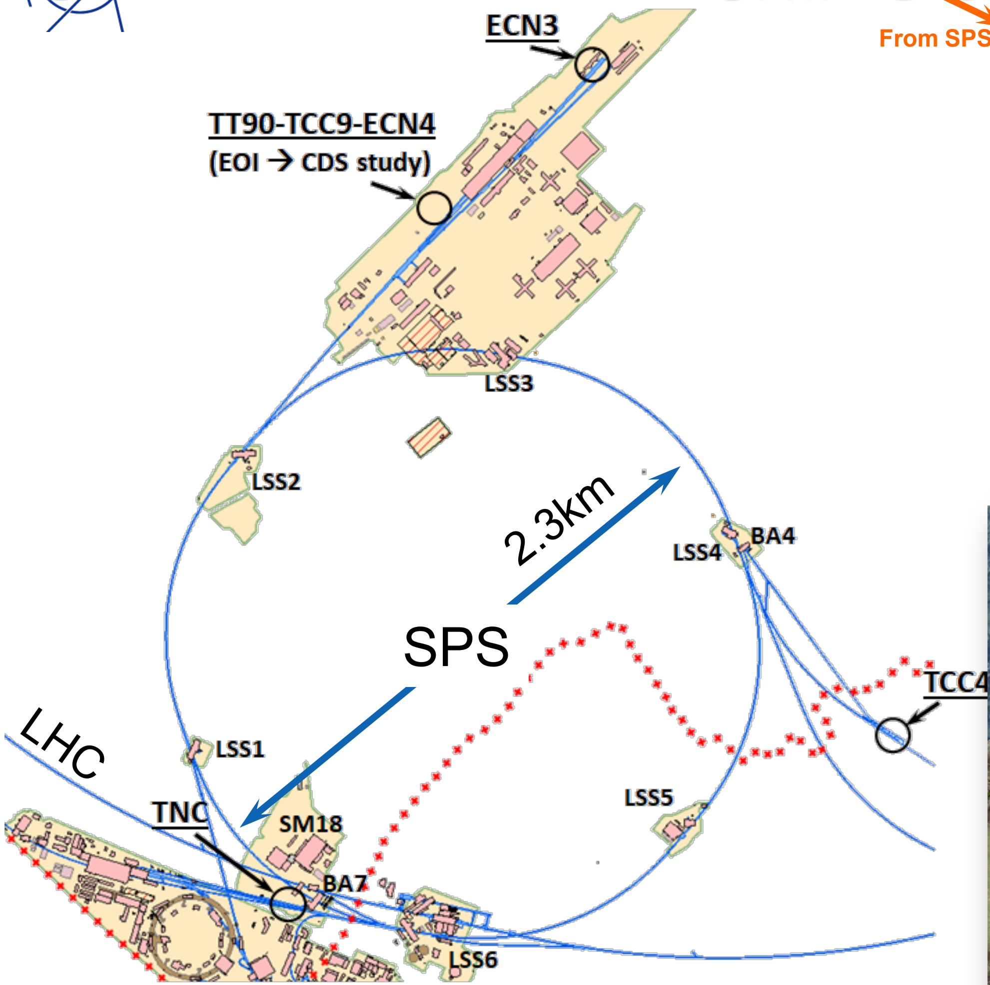
BDF e SHiP al CERN

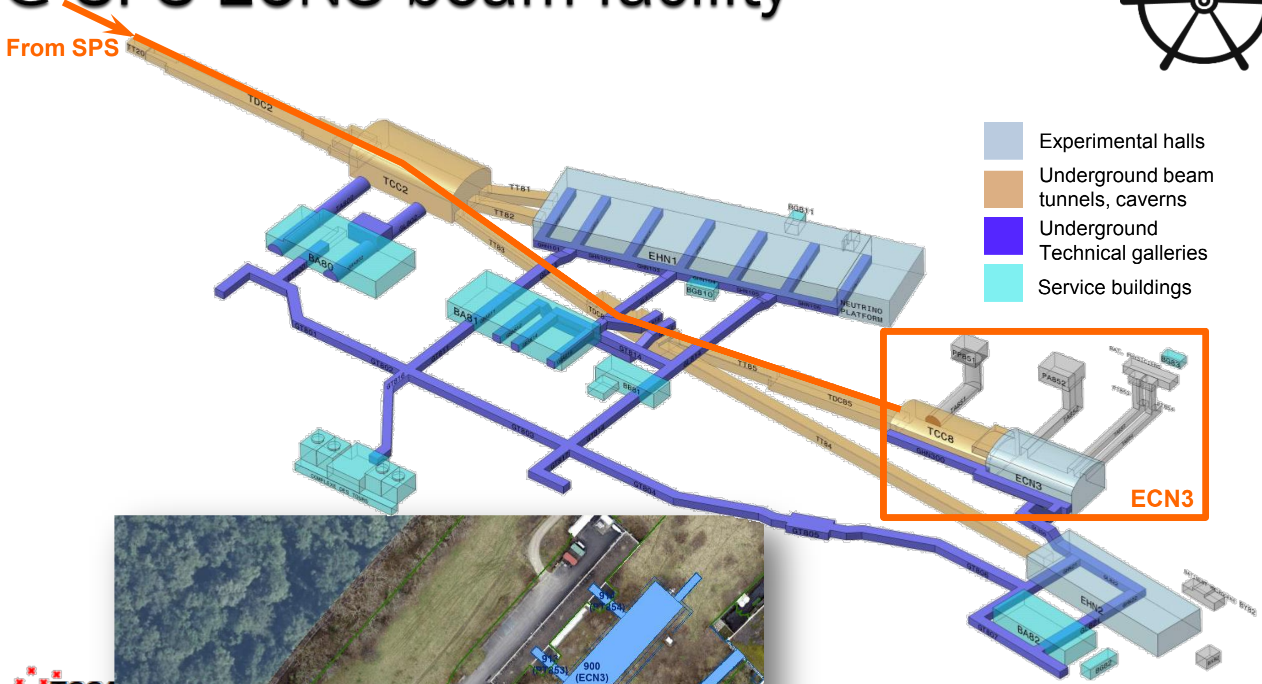
avvio della discussione per la partecipazione di ricercatori di Bologna

- costruzione, finalità e tempistiche della SPS Beam Dump Facility al CERN e dell'esperimento SHiP (Search for Hidden Particles)
    - seminario di Jacobsson a Bologna il 5 Giugno alla International Neutrino School
    - BDF/SHiP proposal a ECN3 (31 Ottobre 2023) — Green Light del CERN Apr 2024 —> TDR 2026/27
- Elementi cardine — e primi da congelare — del design:
    - target complex (interamente a carico del CERN)
    - Magnete per deflettere i muoni (doppio "kick" per evitare le traiettorie di rientro causate dal flusso di ritorno del campo) in parte finanziato dal CERN, in parte da SHiP
    - Decay Vessel e scintillatore di Veto attorno (a carico dell'esperimento SHiP)
- Rivelatori in evoluzione — TDR in 3 anni
- Collaborazione embrionale — forte gruppo CERN — in crescita, responsabilità non ancora definite : July 1-3 Collab Meet



SHiP @ SPS ECN3 beam facility

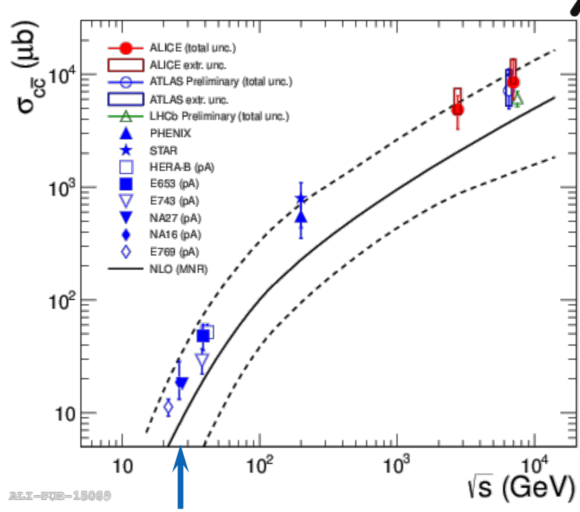




4x10^{19} protons per year available

BDF/SHiP optimization of physics reach

- Target design for signal/background optimisation:
  - Very thick → use full beam and secondary interactions (12λ)
  - High-A&Z → maximise production cross-sections (Mo/W)
  - Short λ (high density) → stop pions/kaons before decay



BDF @ $\sqrt{s} = 27\ GeV$

➔ BDF luminosity with the optimised target and 4x10^{19} protons on target per year *currently available* in the SPS

- ➔ BDF@SPS $\mathcal{L}_{int}[year^{-1}]$ = >4 x 10^{45} cm^{-2} (cascade not incl.)
- ➔ HL-LHC $\mathcal{L}_{int}[year^{-1}]$ = 10^{42} cm^{-2}

➔ BDF/SHiP ***annually*** access to yields inside detector acceptance:

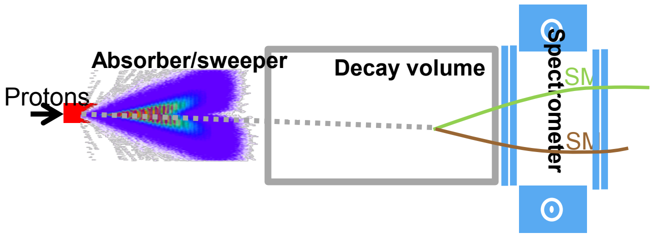
- ~ 2×10^{17} charmed hadrons (>10 times the yield at HL-LHC)
- ~ 2 × 10^{12} beauty hadrons
- ~ 2×10^{15} tau leptons
- $\mathcal{O}$(10^{20}) photons above 100 MeV
- Large number of neutrinos *detected* with 3t-W ν-target:

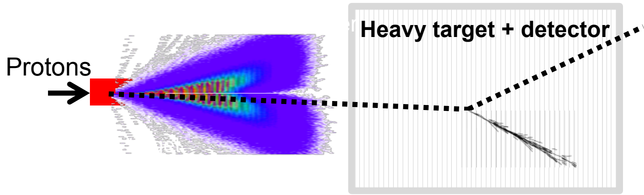
  $3500\ \nu_\tau + \bar{\nu}_\tau$ *per year*, and 2×10^5 $\nu_e + \bar{\nu}_e$ / 7×10^5 $\nu_\mu + \bar{\nu}_\mu$ despite target design

- No technical limitations to operate beam and facility with 4x10^{19} protons/year for 15 years

BDF/SHiP experimental techniques

➔ Explore Light Dark Matter, and associated mediators - generically domain of FIPs - and ν mass generation through :





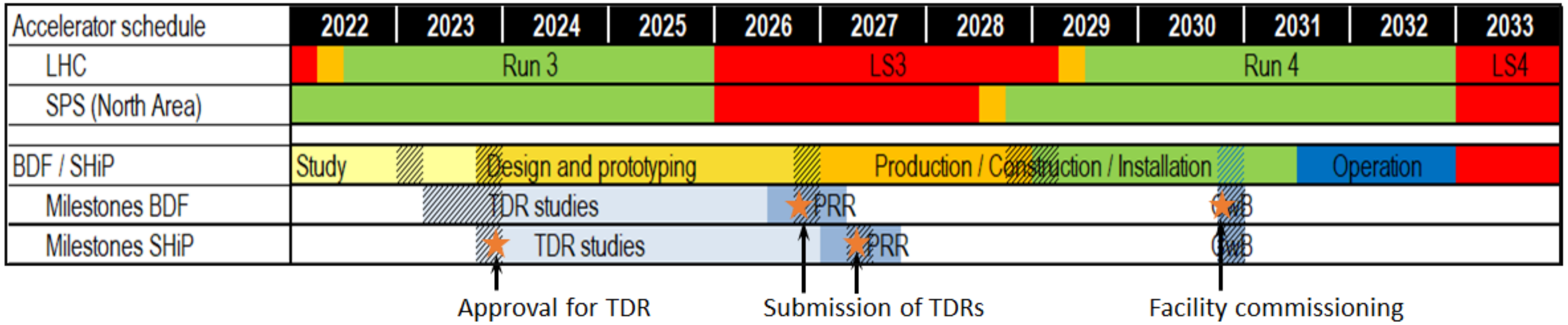
Also suitable for neutrino interaction physics with all flavours

- Designed for exhaustive search by aiming at model-independent detector setup
  - Full reconstruction and identification of as many final states as possible of both fully and partially reconstructible modes
    ➔Sensitivity to partially reconstructed modes also proxy for the unknown
  - **In case of discovery ➔ precise measurements to discriminate between models / test compatibility with hypothetical signal**

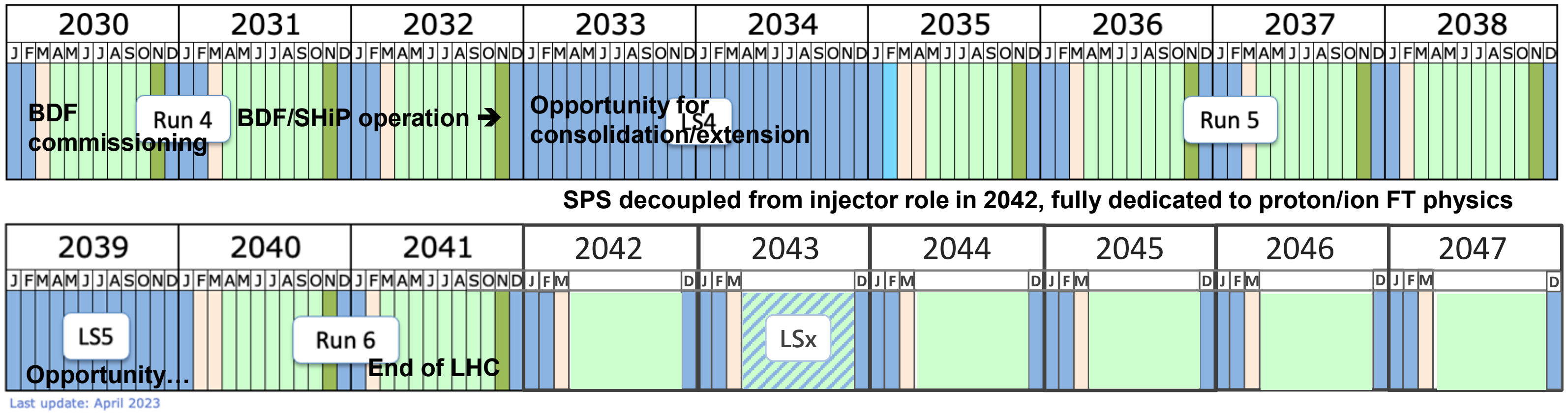
➔ **Critical with FIP decay signature search in background-free environment and LDM scattering**

➔ **Rich "bread and butter" neutrino interaction physics with unique access to tau neutrino**

BDF/SHiP tentative schedule



- ~3 years for detector TDRs (approval in 2023 is critical to ensure timely funding)
- Construction / installation of facility and detector is decoupled from NA operation
- Important to start data taking >1 year before LS4
- Several upgrades/extensions of the BDF/SHiP in consideration over the operational life

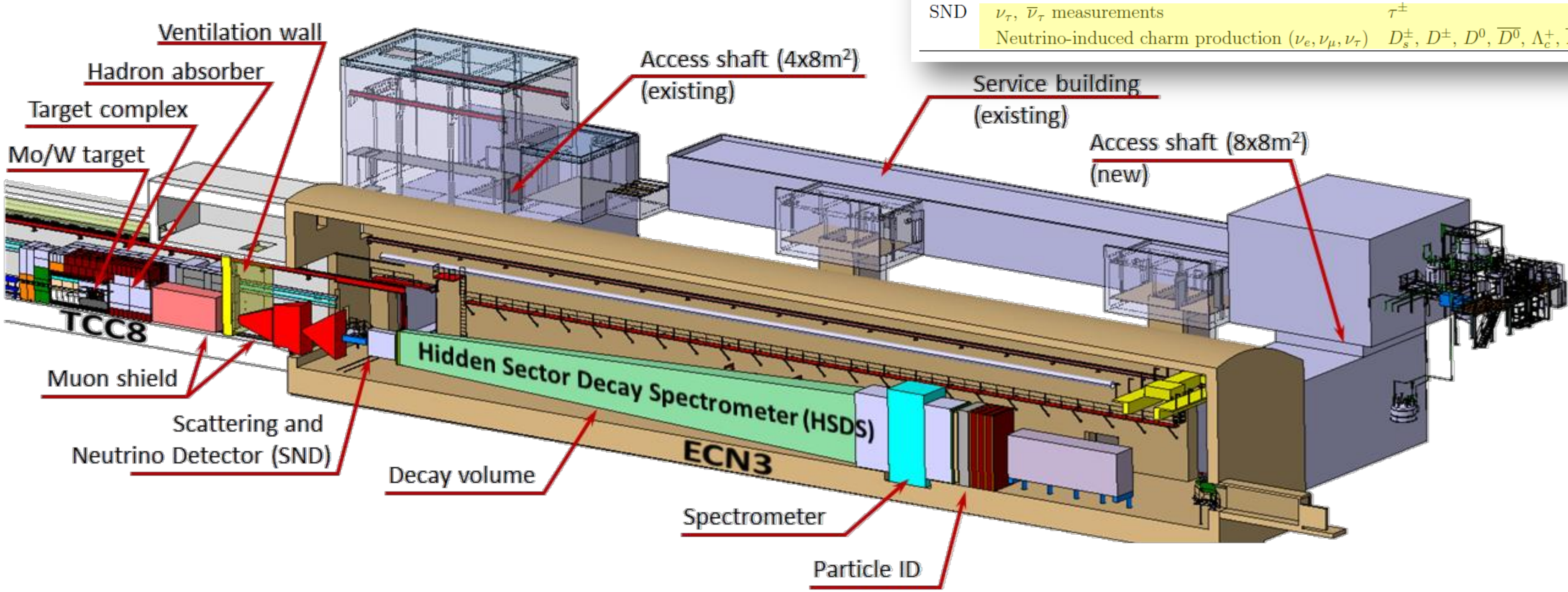


BDF/SHiP in ECN3

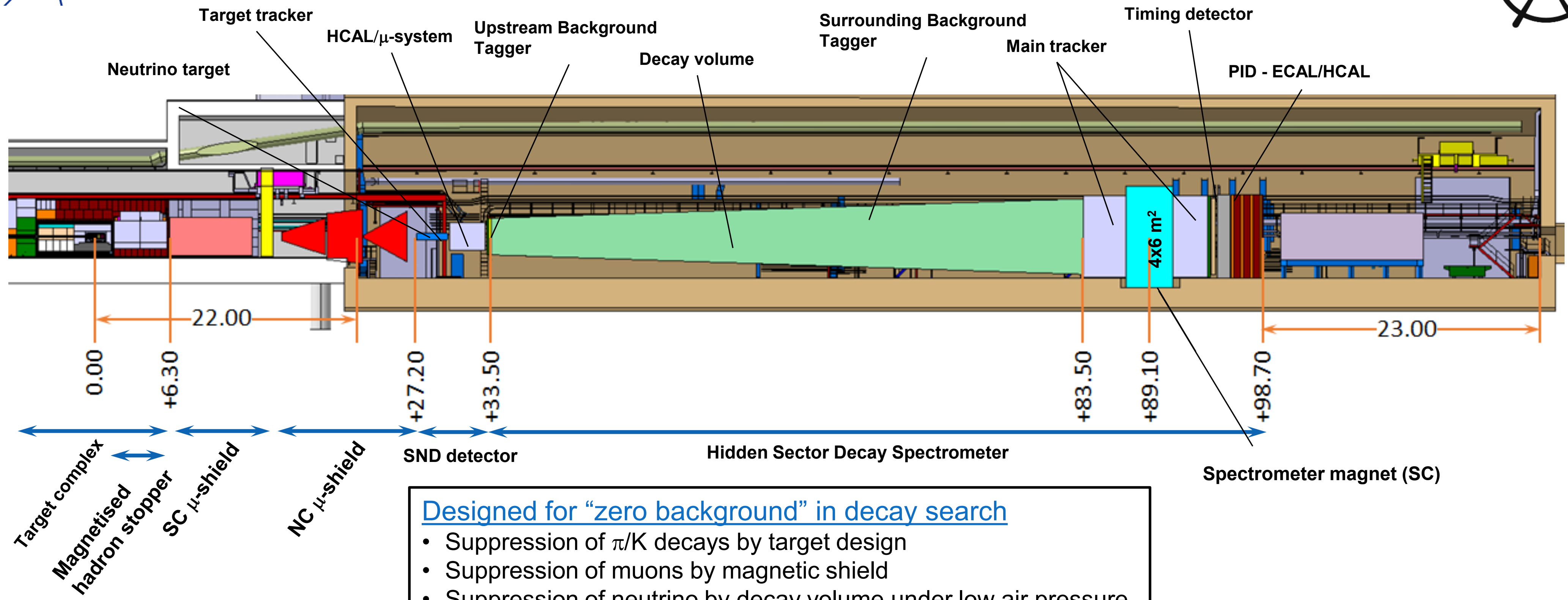
Examples of primary final states:

	Physics model	Final state
HSDS	SUSY neutralino	$\ell^\pm\pi^\mp$, $\ell^\pm K^\mp$, $\ell^\pm\rho^\mp, \ell^+\ell^-\nu$
	Dark photons	$\ell^+\ell^-, 2\pi, 3\pi, 4\pi, KK, q\bar{q}, D\bar{D}$
	Dark scalars	$\ell\ell, \pi\pi, KK, q\bar{q}, D\bar{D}, GG$
	ALP (fermion coupling)	$\ell^+\ell^-, 3\pi, \eta\pi\pi, q\bar{q}$
	ALP (gluon coupling)	$\pi\pi\gamma, 3\pi, \eta\pi\pi, \gamma\gamma$
	HNL	$\ell^+\ell^-\nu, \pi l, \rho l, \pi^0\nu, q\bar{q}'l$
	Axino	$\ell^+\ell^-\nu$
	ALP (photon coupling)	$\gamma\gamma$
	SUSY sgoldstino	$\gamma\gamma, \ell^+\ell^-, 2\pi, 2K$
SND	LDM	electron, proton, hadronic shower
	ν_τ, $\overline{\nu}_\tau$ measurements	$\tau^\pm$
	Neutrino-induced charm production (ν_e, ν_μ, ν_τ)	$D_s^\pm$, $D^\pm$, D^0, $\overline{D^0}$, Λ_c^+, $\overline{\Lambda_c}^-$

Two separate detector systems: "SND" and "HSDS"



SHiP detector in more detail

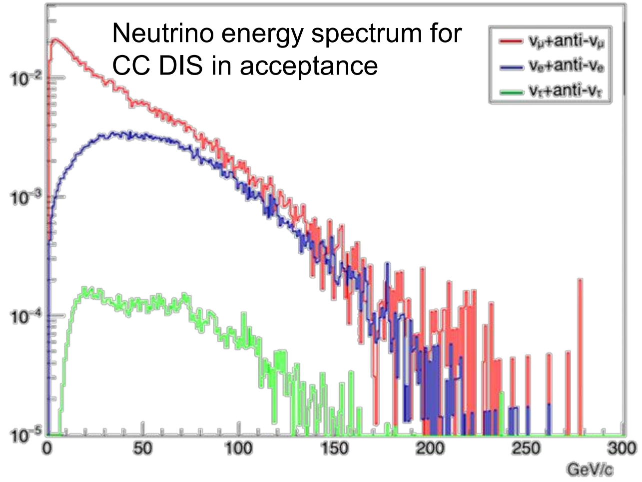


Designed for "zero background" in decay search

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

SND: Neutrino interaction physics (1)

- Huge sample of tau neutrinos available at BDF/SHIP via $D_s \rightarrow \tau\nu_\tau$
  - Despite target design to suppress pion&kaon decays, statistically valid sample of electron and muon neutrinos as well
  - $\sigma_{stat} < 1\%$ for all neutrino flavours
  - Measure kinematic variables in both CC and NC DIS



	<E>[GeV]	Beam dump	<E>[GeV]	CC DIS interactions
N_{ν_e}	6.3	4.1×10^{17}	63	2.8×10^6
N_{ν_μ}	2.6	5.4×10^{18}	40	8.0×10^6
N_{ν_τ}	9.0	2.6×10^{16}	54	8.8×10^4
$N_{\overline{\nu}_e}$	6.6	3.6×10^{17}	49	5.9×10^5
$N_{\overline{\nu}_\mu}$	2.8	3.4×10^{18}	33	1.8×10^6
$N_{\overline{\nu}_\tau}$	9.6	2.7×10^{16}	74	6.1×10^4

Incl. reconstruction efficiencies

Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \rightarrow \mu$	4×10^3	3×10^3
$\tau \rightarrow h$	27×10^3	
$\tau \rightarrow 3h$	11×10^3	
$\tau \rightarrow e$	8×10^3	
total	53×10^3	

Systematic uncertainty from knowledge of ν_τ flux

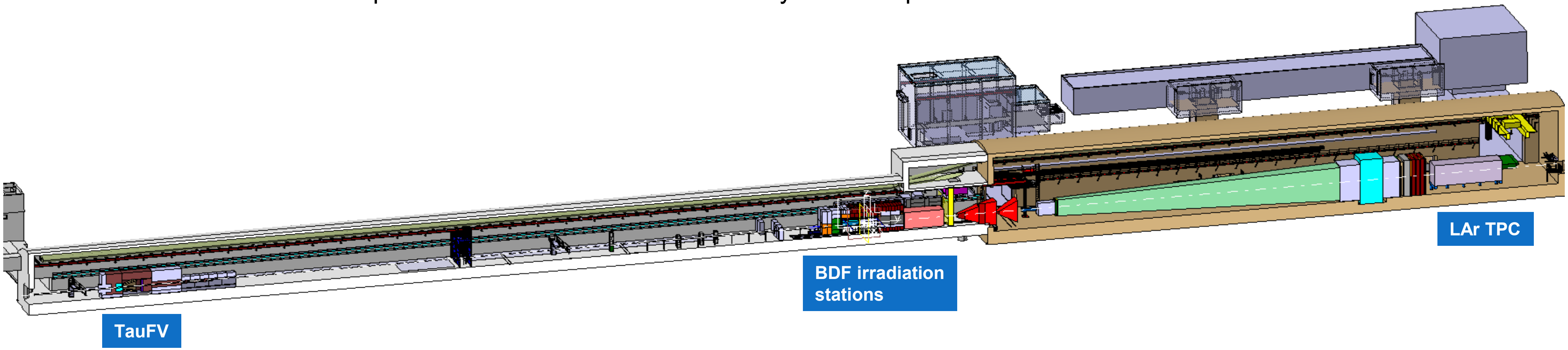
1. D_s production cross-section at SPS
   - Currently 10%, but NA65 expects to reconstruct ~1000 events
2. BR($D_s \rightarrow \tau\nu_\tau$) ~3-4%
3. Cascade production of charm in thick target
   - SHiP plans dedicated experiment to measure J/ψ and charm production using muons in targets of variable depths

➔ Plan to reach ~5% uncertainty in ν_τ flux seems realistic

➔ Also plan ~5-10% uncertainty in ν_e, ν_μ flux

Overview of BDF extensions

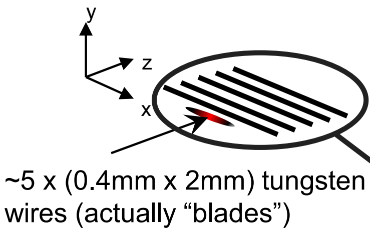
- Preliminary studies of opportunities to extend BDF's physics programme *synergetically with SHiP*:
  - Irradiation stations (nuclear astrophysics and accelerator / material science applications)
  - LArTPC to extend search for FIPs using different technology
  - TauFV to search for lepton flavour violation and rare decays of tau leptons and D-mesons

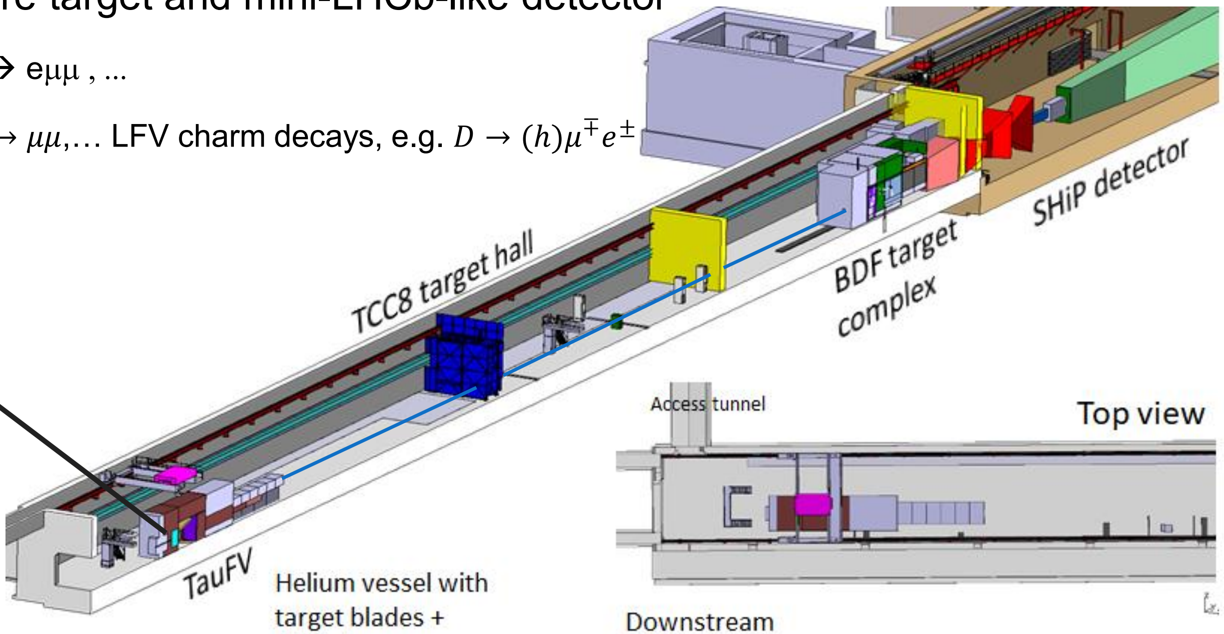


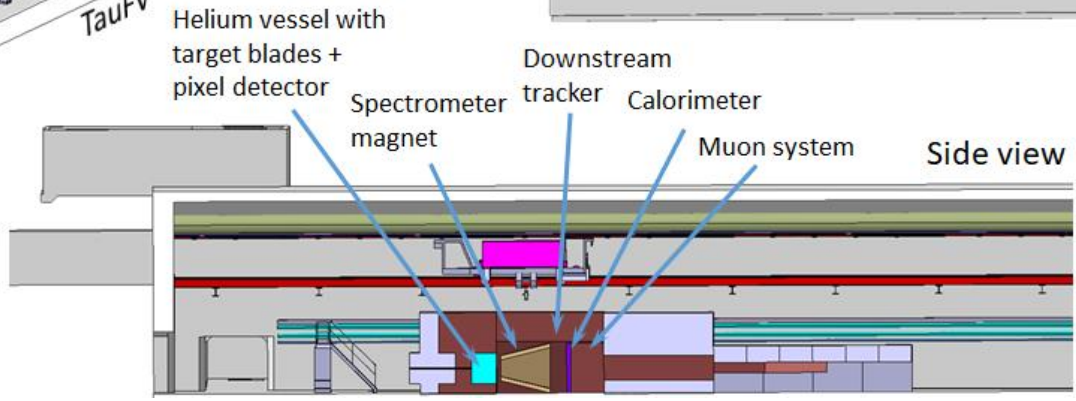
Extensions: Tau flavour violation experiment

Intercepting 1-2% of protons in BDF line with wire target and mini-LHCb-like detector

- n_τ [year^{-1}] ~ O(10^{13}) : $\tau \rightarrow 3\mu$, $\tau \rightarrow \mu\gamma$, $\tau \rightarrow ee\mu$, $\tau \rightarrow e\mu\mu$, ...
- $n_{D\ mesons}$ [year^{-1}] ~ O(10^{15}) : Also opportunity for $D \rightarrow \mu\mu, \ldots$ LFV charm decays, e.g. $D \rightarrow (h)\mu^{\mp}e^{\pm}$







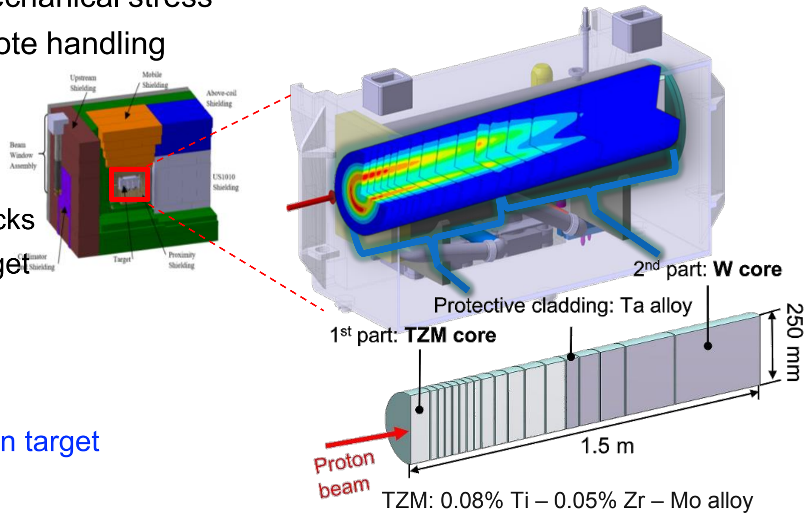
➔ $\tau \rightarrow \mu\mu\mu$ yields with *5 years* of operation and assuming branching ratio 10^{-10}
(TauFV acceptance * preselection efficiency = 5%)

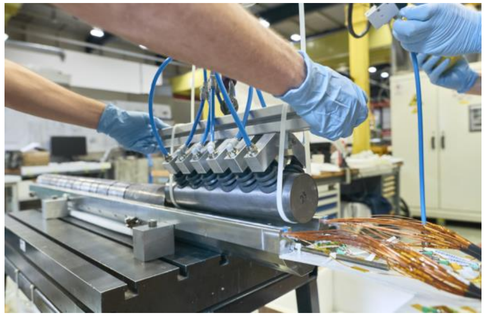
Experiment	PoT / $\int \mathcal{L}dt$	Yield
TauFV	4×10^{18}	800
Belle II	$50\,\mathrm{ab}^{-1}$	1
LHCb Upgrade I	$50\,\mathrm{fb}^{-1}$	14
LHCb Upgrade II	$300\,\mathrm{fb}^{-1}$	84

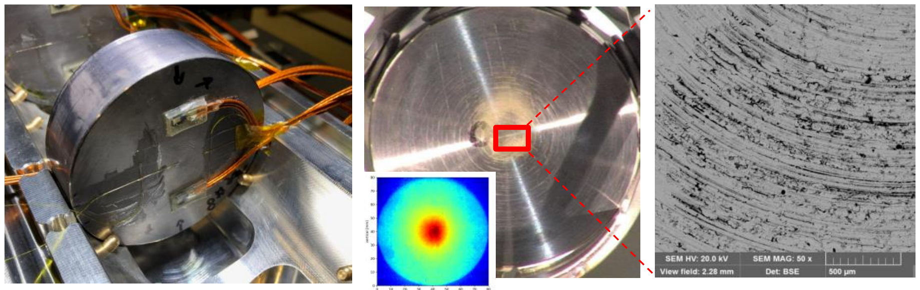
BDF/SHiP Target

- Challenges
  - High A/Z target with high beam power of up to 2.56 MW during the 1 s spill and 320 kW on average
  - ➔ High-A/Z material resilience to high flow of cooling water
  - ➔ Target block cladding behaviour under thermo-mechanical stress
  - ➔ Integrated design of target assembly for fully remote handling

- Prototyping and beam test
  - Manufacturing validation of Ta-cladded W & TZM blocks
  - Reproduce thermo-mechanical conditions of final target
  - Cross-check FEM simulations
  - Test target online instrumentation
  - Perform detailed post-irradiation examination
  - Beam tests in 2018 with a total of 2.4 x10^{16} protons on target
  - Good agreement with simulations





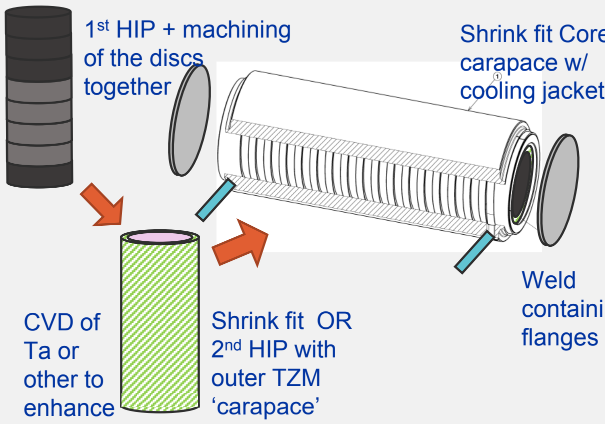


Prototype instrumentation. Visual and optical microscopy inspections during the PIE.

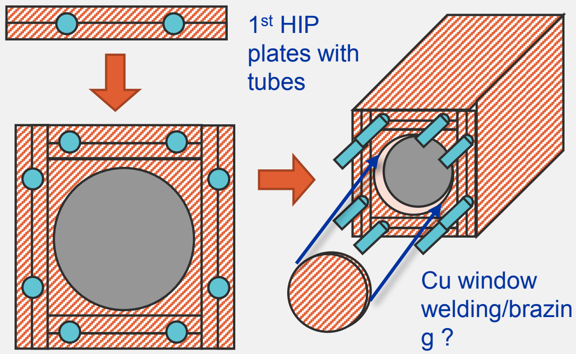
BDF/SHiP target – new ideas

- No water gaps between TZM & W blocks → Compact target
- Highly confined core, possibly increasing thermo-mechanical robustness → more W
- Manufacturing know-how already existent → Not starting from unknown territory

The TZM Shroud Concept



The HIPed Copper Concept



L4 Dump-like cooling serpentine jackets (welded beforehand)

HIPed plates like SPS Main Dump TIDVG5

Decay volume and SBT

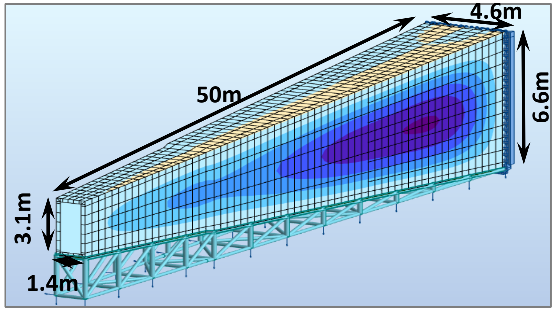
Per spill of 4x10^{13} protons

- 9 ×10^{11} and 6x10^{11} ➔ Suppress to <10 interactions per spill with decay volume under vacuum

➔ Evacuated to ~mbar air – ~bar He

➔ Liquid scintillator veto in surrounding compartments

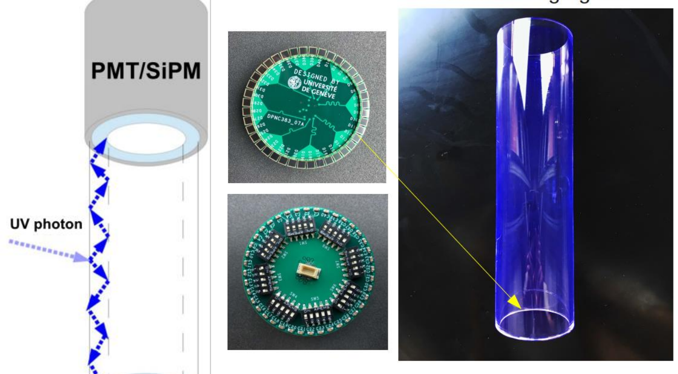
- Purpose: Tagging charged particles entering decay volume and tagging ν and μ interactions in the vacuum chamber walls
  - ➔ >99% efficiency and ~1ns time resolution



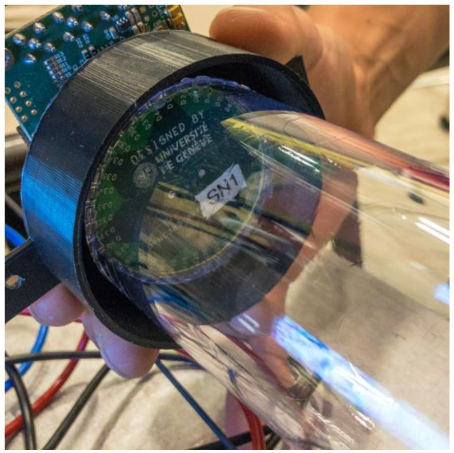
~2000 cells,
~80 x ~80 cm,
thickness ~20cm

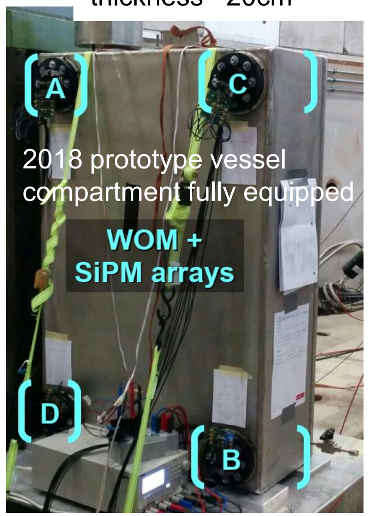
- Characteristics
  - Liquid scintillator based: linear alkylbenzene (LAB) together with 2.0 g/l diphenyl-oxazole (PPO) as the fluorescent
  - WOMs with SiPM readout Hamamatsu S14160-3050PE (40x 3x3mm²) and surrounded by PMMA vessel

WOM w/o lightguide



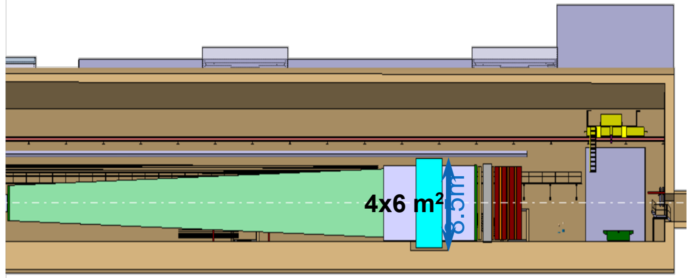
40-SiPMs array
built by Geneva



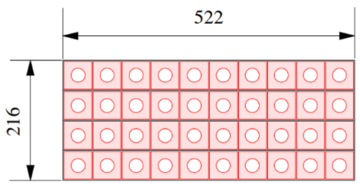


SHiP spectrometer section

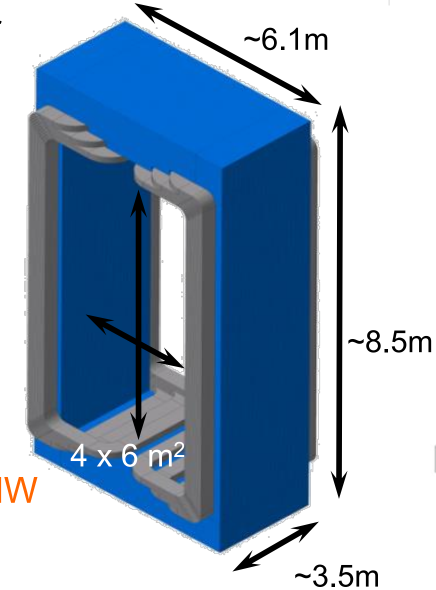
- Initial studies with aperture 5x10m^2 ➔ now 4x6m^2
  - H. Bajas, D. Tommasini, EDMS 2440157 (21 April 2020)
  - P. Wertelaers, CERN-SHiP-INT-2019-008

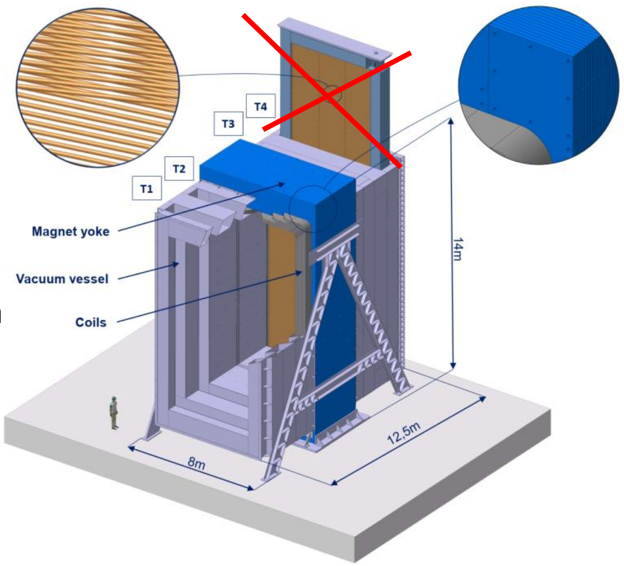


- Requirements:
  - Physics aperture 4 x 6 m^2
  - Bending field 0.6-0.7 Tm , nominal on axis ~0.15T
  - Integration of vacuum chamber



Coil's cross-section
Aluminium hollow conductor



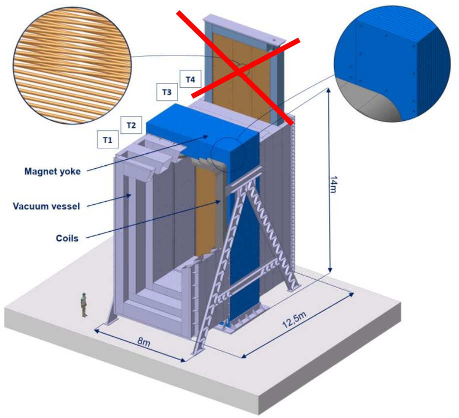


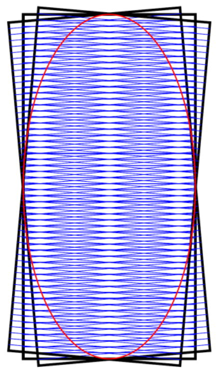
- Resistive baseline option 0.5 MW

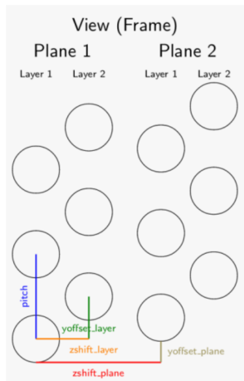
- What about superconductive with coil of same dimensions?

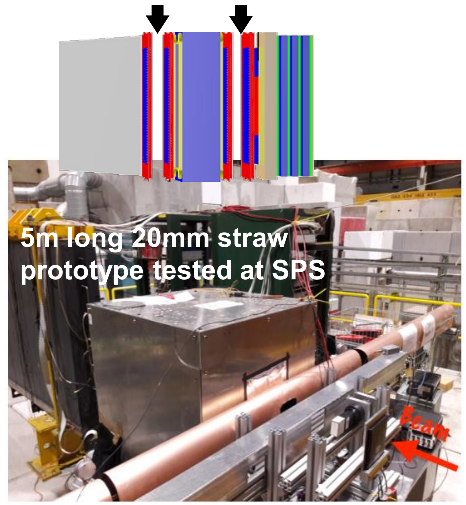
HS Straw Tracker

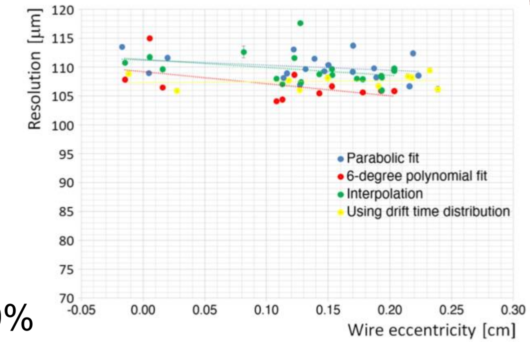
- Purpose: Track reconstruction and momentum, reconstruction of origin of neutral particle candidate. Match hits in timing detector
- Technology developed for the NA62 experiment
  - ➔ SHiP strategy: decoupling supporting frames from vacuum envelope
  - ➔ Horizontal orientation of tubes ➔ mechanical challenge
  - ➔ Lower rate allows increasing straw diameter (highest rate ~10 kHz)
- Characteristics
  - 4 x 6 m^2 sensitive area
  - 5m long 20mm diameter 36µm thick PET film coated with 50nm Cu and 20nm Au operated at 1 bar, produced and tested
  - Four stations, each with four views Y-U-V-Y, ~9600 straws





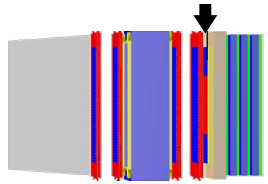


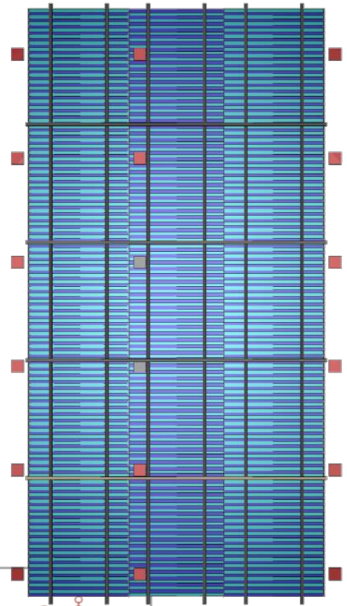




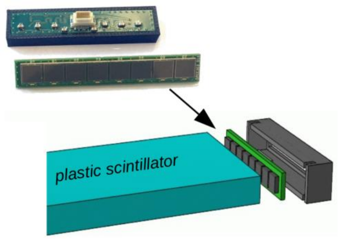
Test beams confirm 120µm hit resolution with hit efficiency >99%

HS Timing Detector

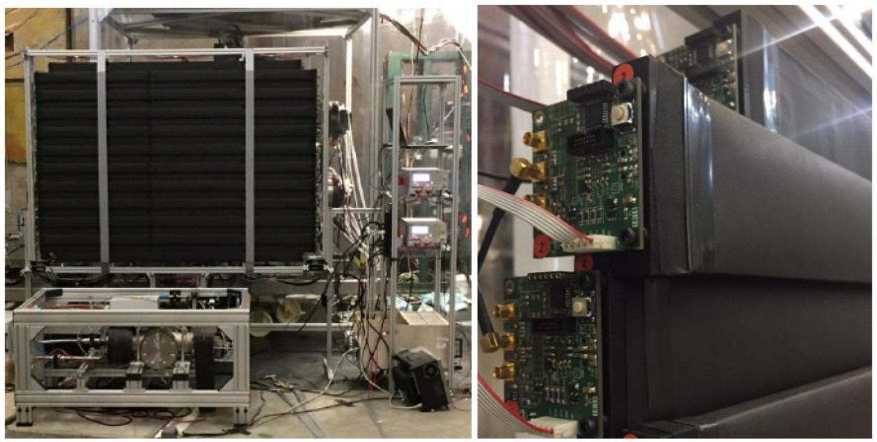


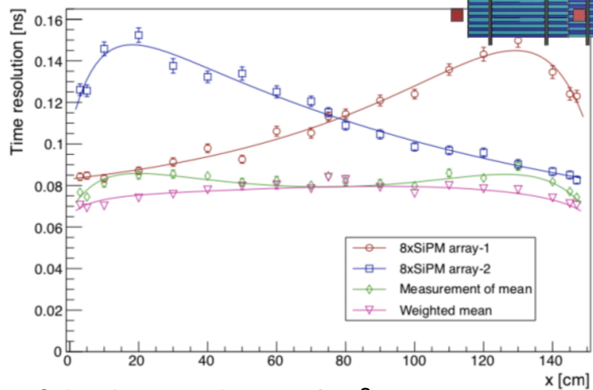


- Purpose: Provide precise timing (<100 ps) of each track to reject combinatorial background
- Plastic scintillator characteristics
  - Three-column setup with EJ200 plastic bars of 135cm × 6cm × 1cm, providing 0.5cm overlap
  - Readout on both ends by array of eight 6×6 mm^2 SiPMs, 8 signals are summed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



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

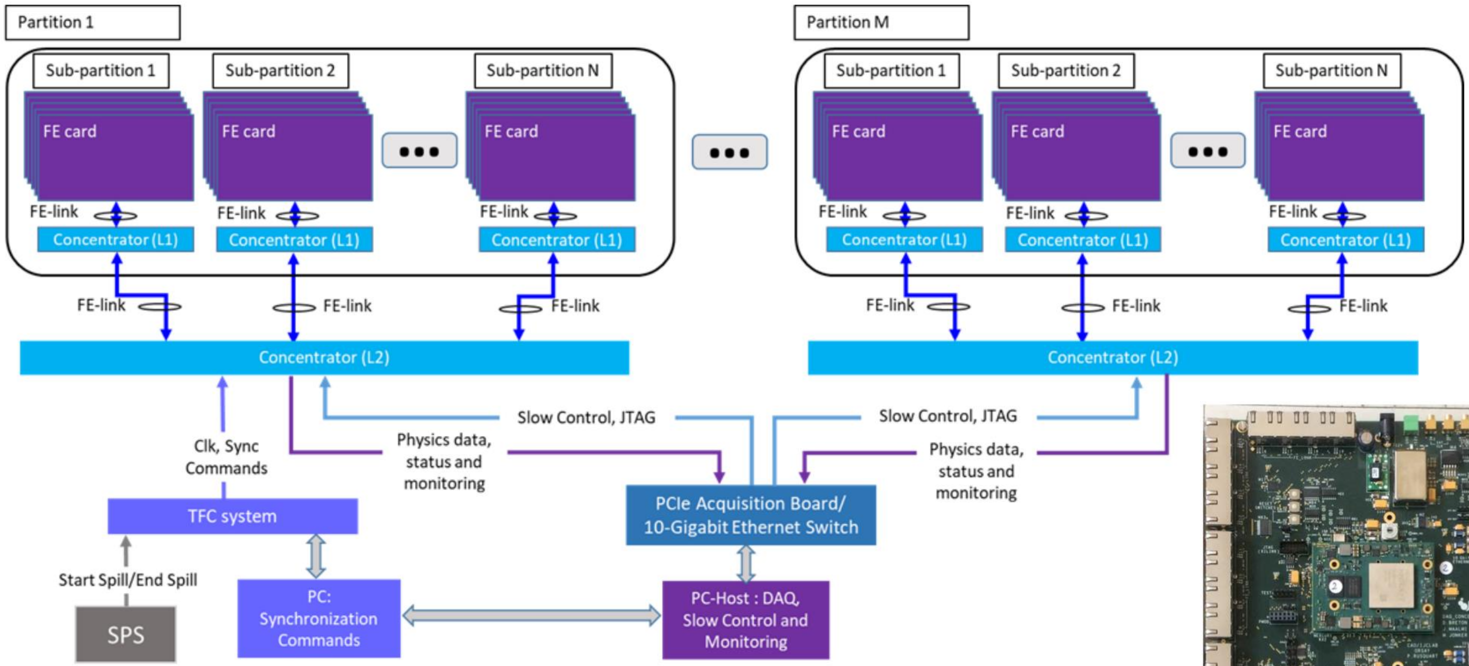


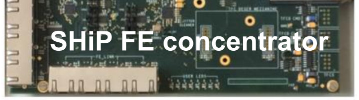


Resolution demonstrated to be ~80 ps along the whole length of the bar and over 2m^2 prototype

Electronics and readout

- Subsystem architecture – aiming for common electronics
- DAQ system simulation with proper occupancy and time distribution





- ECN4 CDS detector, it is estimated that
  - About 300 concentrator boards, 25 DAQ links, 12 FEH and 42 EFF computers.

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**

Table 11: Breakdown of the updated cost of the SHiP detectors and the muon shield in the hybrid SC/NC option, including infrastructure. The subsystems marked with a * are considered as part of the common fund.

derived in terms of direct quote from manufacturer, scaling from existing design or quote, estimate in collaboration with company, estimate in-house, and best estimate. The level of maturity in the design of the different subsystems varies.

The free-standing muon shield, the vacuum vessel, and the HSDS spectrometer magnet are critical common infrastructure items presenting major challenges. In addition, significant effort is required to determine the final configuration and design strategy for the SC magnet in the muon shield, and the viability of the SC technology for the spectrometer magnet. For these reasons, these items are attributed with relatively large uncertainties. A detailed design is only available for the vacuum vessel.

The SND emulsion target system is a well-known concept from the OPERA experiment. All additional features required by the SHiP SND detector, including operating and analysing emulsion with high occupancy, have been tested in the SPS beam test, and more importantly in the SND@LHC experiment. The SND target tracker based on SciFi and the SND muon

29th SHiP Collaboration Meeting

1 Jul 2024, 13:00 → 3 Jul 2024, 16:00 Europe/Zurich

CERN

Registration 29th SHiP Collaboration meeting

Participants Alberto Blanco Castro, Aleksandr Gorn, Alessia Brignoli, Andrei Golutvin, Annika Hollnagel, Antonio Iuliano, Christopher Betancourt, Claudia Ahdida, Claudia Caterina Delogu, Daniel Bick, Dipanwita Banerjee, Dirk Mergelkuhl, Enrico Gamberini, Fabrizio Aloschi, Federico Leo Redi, Francesca Luoni, Gerardo Vasquez, Giulia Romagnoli, Giuseppe Mazzola, Horst Fischer, Iaroslava Bezshyiko, Ixone Angulo Vaquero, James Currie, James Webb, Jong Yoon Sohn, Lesya Shchutska, Lucie Baudin, Luigi Salvatore Esposito, Maksym Ovchynnikov, Marc Schumann, Markus Brugger, Martina Ferrillo, Massimiliano de Magistris, Matthew Alexander Fraser, Mike Parkin, Nuno Leonardo, Oleg Ruchayskiy, Olin Lyod Pinto, Oliver Lantwin, Ramon Folch, Richard Jacobsson, Rui Franqueira Ximenes, Sebastian Ritter, Walter Marcello Bonivento, Wei-Chieh Lee

Questions Richard.Jacobsson@cern.ch

Monday, 1 July

13:00 → 13:25 **Opening and main goals of meeting** 25m

Speaker: Andrei Golutvin (Imperial College London)

13:30 → 15:40 **Muon shield: Muon shield 1**

Convener: Massimiliano Ferro-Luzzi (CERN)

13:30 **Muon shield status and plans** 25m

Speaker: Massimiliano Ferro-Luzzi (CERN)

14:00 **Muon rates with baseline** 20m

Speakers: Eduard Ursov, Eduard Ursov, Eduard Ursov (Humboldt-Universität zu Berlin)

14:25 **Muon shield optimisation** 20m

Speakers: Shah Rukh Qasim, Shah Rukh Qasim, Shah Rukh Qasim (University of Zurich (CH))

14:50 **Muon shield warm section status and plans** 20m

Speaker: Mitesh Patel (Imperial College (GB))

15:15 **Muon shield SC section status and plans** 20m

Speakers: Dr Magnus Dam (Karlsruhe Institute of Technology (KIT)), Tabea Arndt (Siemens AG), Prof. Tabea Arndt (KIT)

15:40 → 16:10 **Coffee** 30m

16:10 → 18:15 **Scattering and Neutrino detector 1**

Convener: Giovanni De Lellis (University Federico II and INFN, Naples (IT))

16:10 **Towards new SND configuration** 25m

Speaker: Giovanni De Lellis (University Federico II and INFN, Naples (IT))

16:40 **Use of emulsion** 20m

17:05 **LDM sensitivity** 20m

Speakers: Maksym Ovchynnikov (Leiden University (NL)), Martina Ferrillo (University of Zurich (CH))

17:30 **Neutrino physics** 20m

Speakers: Antonio Iuliano, Antonio Iuliano, Antonio Iuliano (University Federico II and INFN, Naples (IT))

17:55 **Neutrino physics with statistical analysis** 20m

Speakers: Eduard Ursov, Eduard Ursov, Eduard Ursov (Humboldt-Universität zu Berlin)

Tuesday, 2 July

09:00 → 10:30 **Decay volume: Decay volume 1**

Convener: Richard Jacobsson (CERN)

09:00 **Signal and background with helium/air** 45m

Speakers: Iaroslava Bezshyiko (University of Zurich (CH)), Maksym Ovchynnikov (Leiden University (NL)), Martina Ferrillo (University of Zurich (CH))

10:00 **Decay volume with and without SBT** 20m

10:30 → 11:00 **Coffee** 30m

11:00 → 12:10 **Decay volume: Decay volume 2**

Convener: Richard Jacobsson (CERN)

11:00 **Use of advanced SBT** 20m

11:25 **Review of requirements on SBT and UBT from physics** 20m

11:50 **Decay volume status and plans** 20m

Speakers: Andrea Miano, Dr Andrea Miano (University Federico II and INFN, Naples (IT))

12:10 → 14:00 **Lunch** 1h 50m

14:00 → 15:00 **Decay volume: Decay volume 3**

Convener: Richard Jacobsson (CERN)

14:00 **Review of SBT status** 20m

Speaker: Heiko Markus Lacker (Humboldt University of Berlin (DE))

14:25 **Alternative decay volume and SBT** 20m

15:00 → 16:20 **Spectrometer section: Spectrometer section 1**

Conveners: Daniel Bick, Daniel Bick (Universität Hamburg)

15:00 **Review of straw tracker with helium/air** 25m

Speaker: Daniel Bick (Universität Hamburg)

15:30 **Review of timing detector** 20m

Speaker: Christopher Betancourt (High Energy Accelerator Research Organization (JP))

15:55 **Signal selection** 20m

Speaker: Inar Timiryasov (University of Copenhagen)

16:20 → 16:40 **Coffee** 20m

16:40 → 17:30 **PID: PID 1**

Conveners: Walter Bonivento, Walter Marcello Bonivento (INFN Cagliari)

16:40 **Towards a PID configuration** 25m

Speakers: Walter Bonivento, Walter Marcello Bonivento (INFN Cagliari)

17:10 **PID detector technologies** 20m

17:30 → 18:45 **Collaboration Board: Collaboration Board (separate agenda: https://indico.cern.ch/event/1426988/)**

Conveners: Eric Van Herwijnen, Eric Van Herwijnen (Imperial College (GB))

17:30 **Collaboration Board** 1h 15m

https://indico.cern.ch/event/1426988/

18:45 → 21:45 **Social event: Dinner at Luigia**

Wednesday, 3 July

08:30 → 10:05 **Detector: Detector - common 1**

Convener: Richard Jacobsson (CERN)

08:30 **Spectrometer magnet status and plans** 20m

Speaker: Lucie Baudin (CERN)

08:55 **Electronics status and plans** 20m

Speakers: Mrs Jihane Maalmi, Mrs Jihane Maalmi (Université Paris-Saclay (FR))

09:20 **Survey and detector alignment** 20m

Speakers: Dirk Mergelkuhl (CERN), Dirk Mergelkuhl (CERN)

09:45 **Computing** 20m

Speaker: Oliver Lantwin (INFN Napoli)

10:05 → 10:30 **Review of backgrounds** 25m

10:35 → 10:55 **Coffee** 20m

10:55 → 11:20 **Summary of physics studies and plans** 25m

Speakers: Nicola Serra (University of Zurich (CH)), nicola serra (AdvanSiD)

11:25 → 11:45 **Status of HIECN3 - BDF** 20m

Speaker: Matthew Alexander Fraser (CERN)

11:50 → 12:15 **Detector global status and plans** 25m

Speaker: Richard Jacobsson (CERN)

12:20 → 12:40 **Report from CB** 20m

Speakers: Eric Van Herwijnen (Imperial College (GB)), Eric Van Herwijnen