Physics Opportunities with the SPS Beam Dump Facility (BDF)

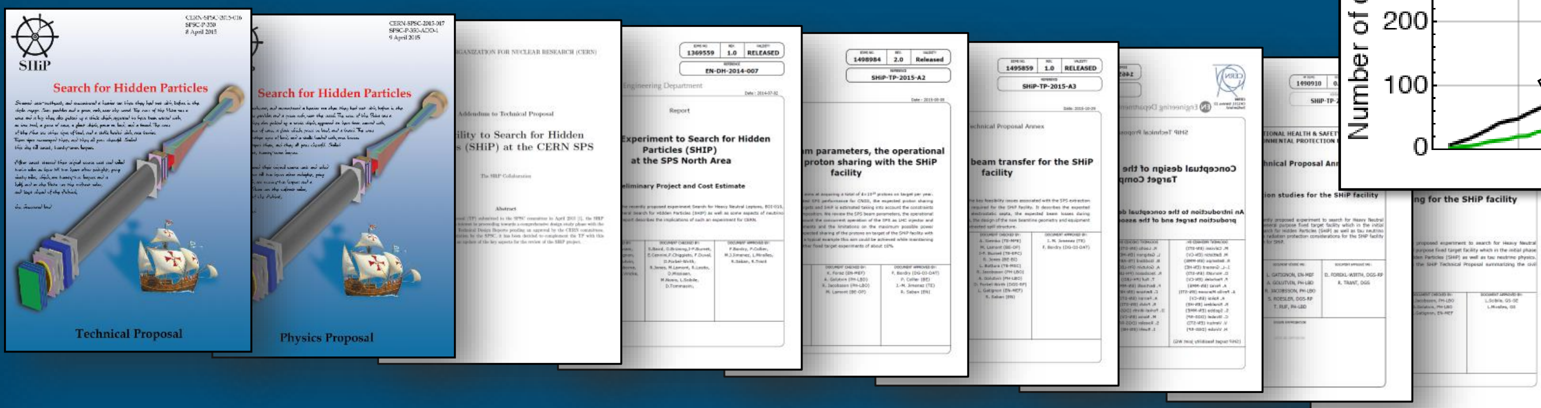
- Exploration at the Intensity Frontier –

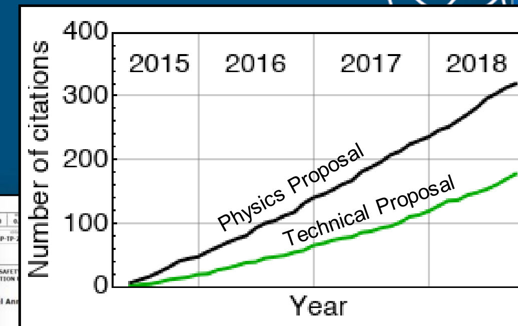
Richard Jacobsson, CERN

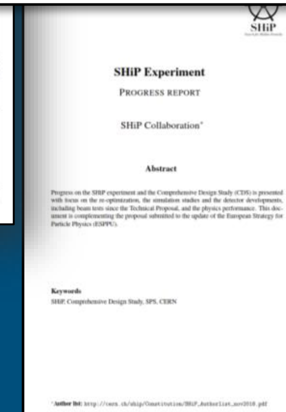
On behalf of BDF team, SHiP and TauFV collaborations

BDF/SHiP History

2013 Oct: EOI with SHiP@SPS NA
...following brainstorming SHiP@IP8, SHiP@LBD, SHiP@CNGS, SHiP@WANF







2014 Jan: Encouraged to produce TP and inter-departmental task force setup to study feasibility of proposed facility

2015 Apr: TP with ~700 pages by SHiP theorists, experimentalists, and CERN accelerator, engineering, and safety departments

2016 Jan: Recommendation by CERN SPSC to proceed to 3-year Comprehensive Design Study

2016 Apr: CERN management launch of Beyond Collider Physics study group

- SHiP experimental facility included under PBC as Beam Dump Facility

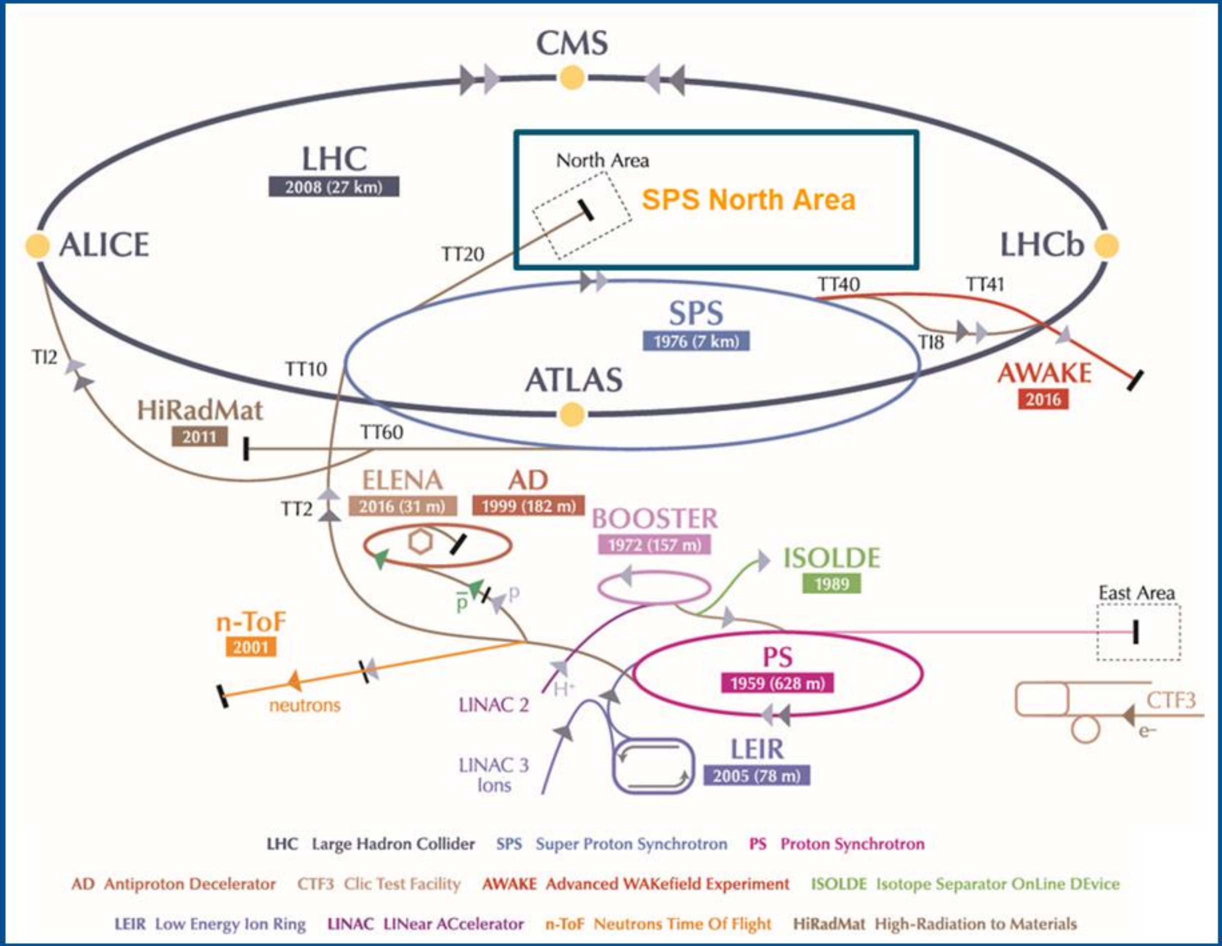
2018 Dec: EPPSU contribution submitted by SHiP and BDF, and submission of *SHiP Progress Report*

2019 Nov: Submission of Comprehensive Design Study reports

SPS Beam Dump Facility

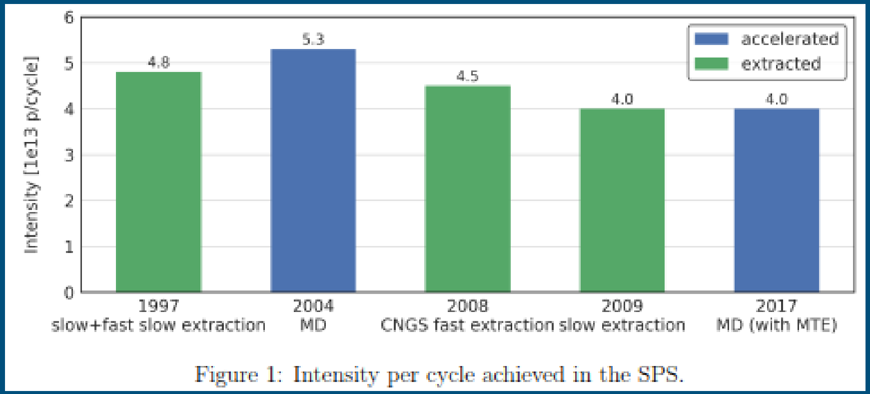
With 7% of LHC+HL-LHC data recorded still no sign of new physics

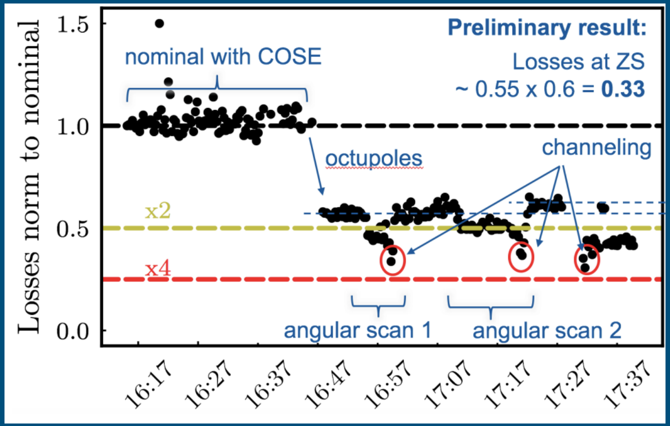
- ➔ New physics should either be very heavy or weakly coupled
- ➔ Make full use of CERN's proton complex and the SPS slow extraction for searches complementary to HL-LHC!



BDF : Proton yield

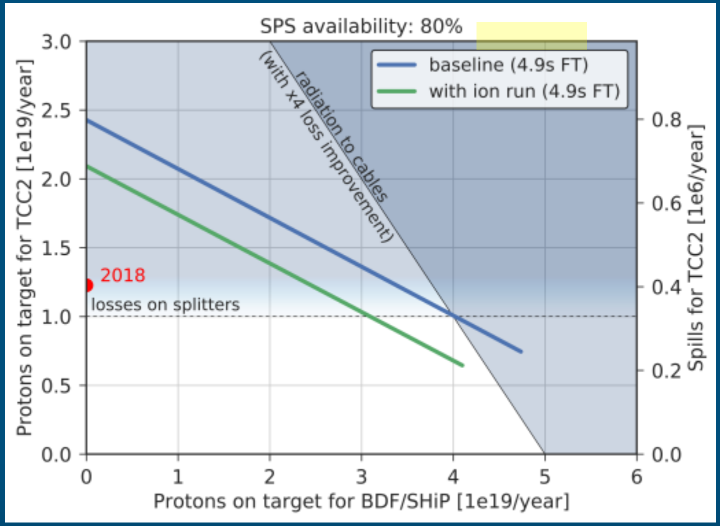
SHiP assumes current capacity of SPS, slowly extracted 1s spills with $4x10^{13}$ p / 7.2s

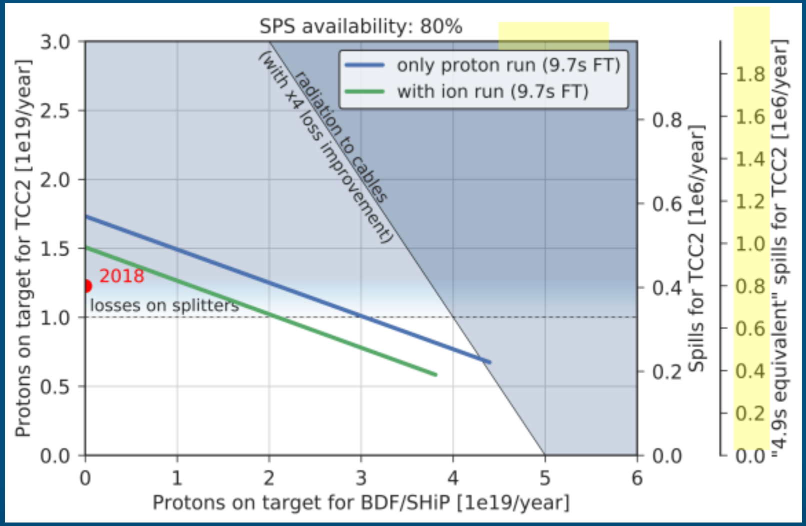




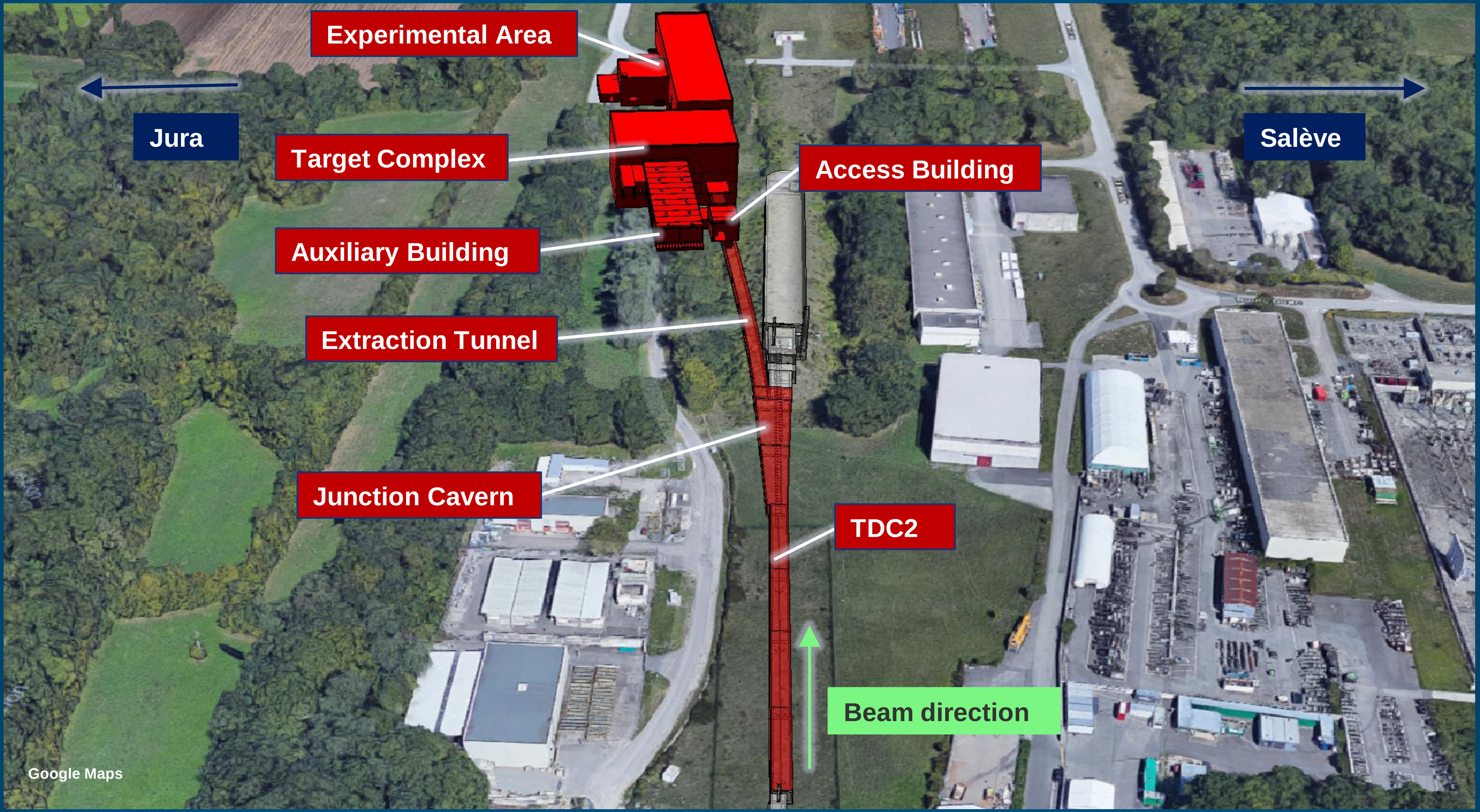
- Slow extraction of $(4 + 1) \times 10^{19}$ p/year requires reduction of losses by factor four
  - Factor of three was achieved in MDs in 2018

- Proton sharing scenarios ➔ Baseline for BDF/SHiP 3-4 x 10^{19} p.o.t/year



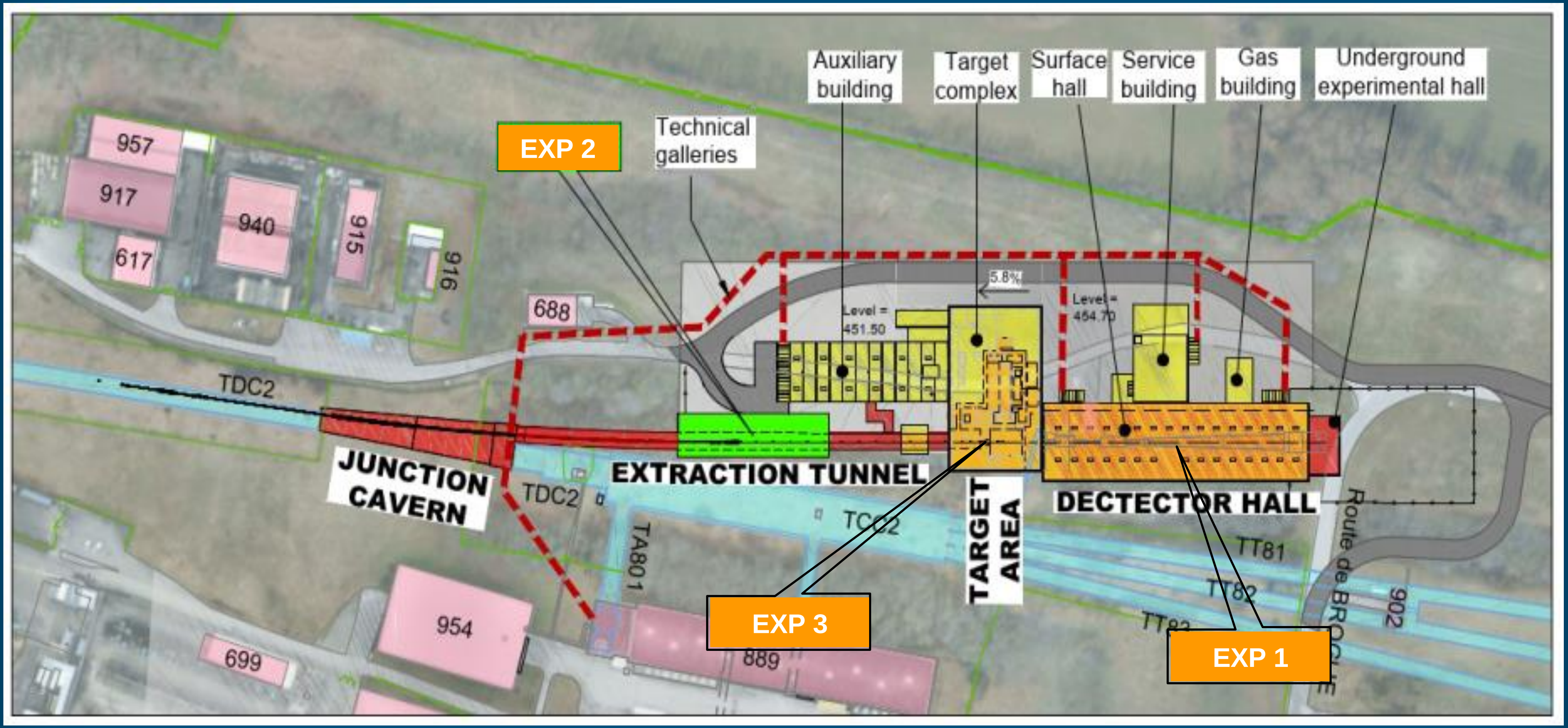


BDF/SHiP overview



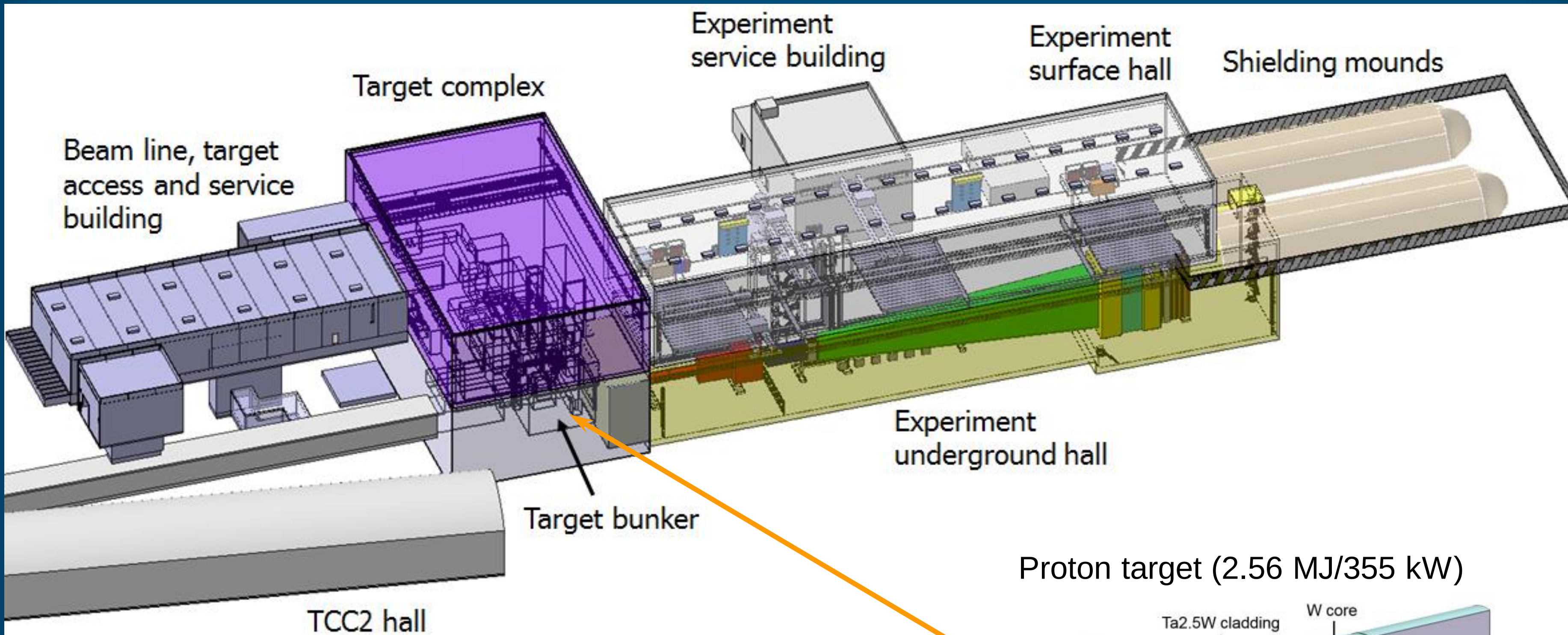
Experimental facilities

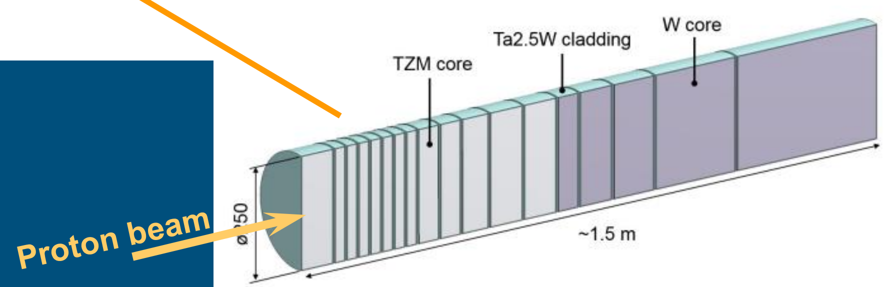
Three possible experimental facilities operating synergetically



Also taken into account possible extension of the 120m x 20m underground detector hall

SHiP@BDF





Molybdenum/tungsten target

- maximize production of heavy flavour hadrons and photons
- Stop pions and kaons before decay

➔ Beam dump

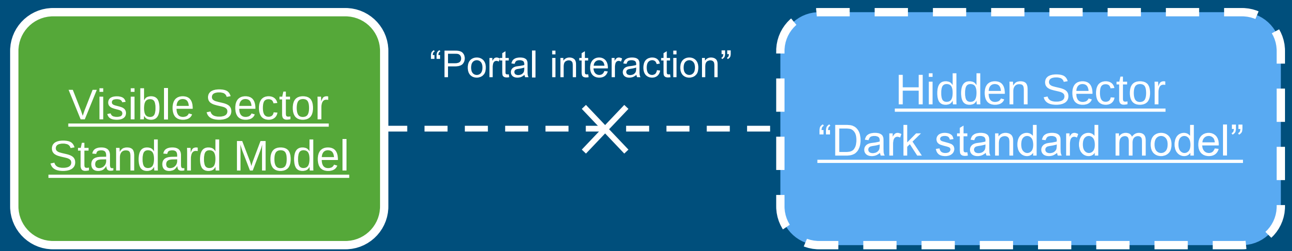
New physics prospects - Hidden Sector

"New particles" can hide in two ways: Very massive OR very weakly coupled

➔ Natural assumption: DM tells us there could be a "very feebly interacting" scale (cmp ν)

➔ SM not only successful, we discovered everything it predicted, so…
…why not dark matter self-interaction and "feeble interactions" with the visible sector

$$\mathcal{L}_{World} = \mathcal{L}_{SM} + \mathcal{L}_{mediation} + \mathcal{L}_{HS}$$



➔ Dynamics of Hidden Sector may drive dynamics of Visible Sector!

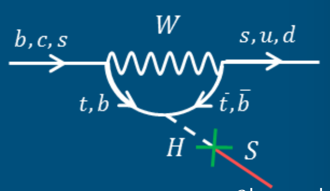
- Dark Matter (trivial!) – fermionic or scalar
- Neutrino oscillations
- Baryon asymmetry
- Higgs mass
- Dark Energy
- Inflaton
- ……

Dark versions can be considered for all (strictly neutral) SM features

FIPs: Production and principal sources

- Dark vectors ("Dark Photons")
  - Photons – Bremsstrahlung, light neutral meson decays, quark annihilation
  - Sources: electron fixed target beams, electron colliders, proton fixed heavy target
- Dark scalars ("Dark Higgses")
  - Higgses (real) or in penguin decays of K, D, B mesons
  - Proton colliders, proton fixed heavy target, electron colliders(H factory)
- Heavy neutral leptons ("sterile neutrinos")
  - Weak semi-leptonic decays of hadrons, W, Z
  - Sources: proton fixed heavy target, proton colliders, electron colliders (W, Z)
- Axion-like particles ("ALPs")
  - Possible couplings to photons, gluons and fermions
  - Proton colliders, proton heavy fixed target, space
- (Light) Dark Matter direct detection ("vWIMPs")
  - Through one of the portals or Cosmic relic

E.g. Dark scalar

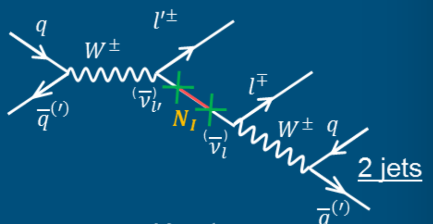


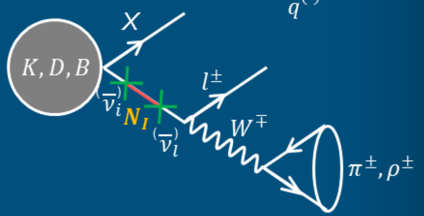
$\Gamma(K \to \pi S) \propto (m_t^2 |V_{ts}^* V_{td}|)^2$

$\Gamma(D \to \pi S) \propto (m_b^2 |V_{cb}^* V_{ub}|)^2$

$\Gamma(B \to \pi S) \propto (m_t^2 |V_{tb}^* V_{ts}|)^2$

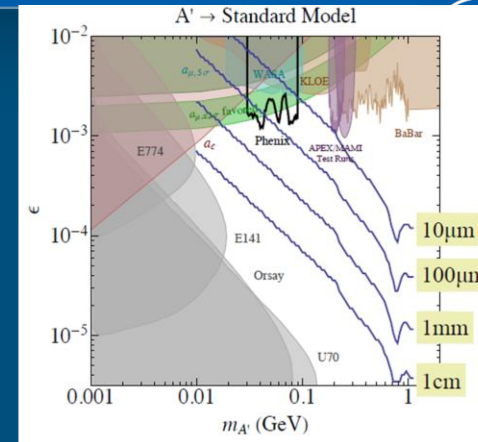
E.g. Heavy Neutral Lepton



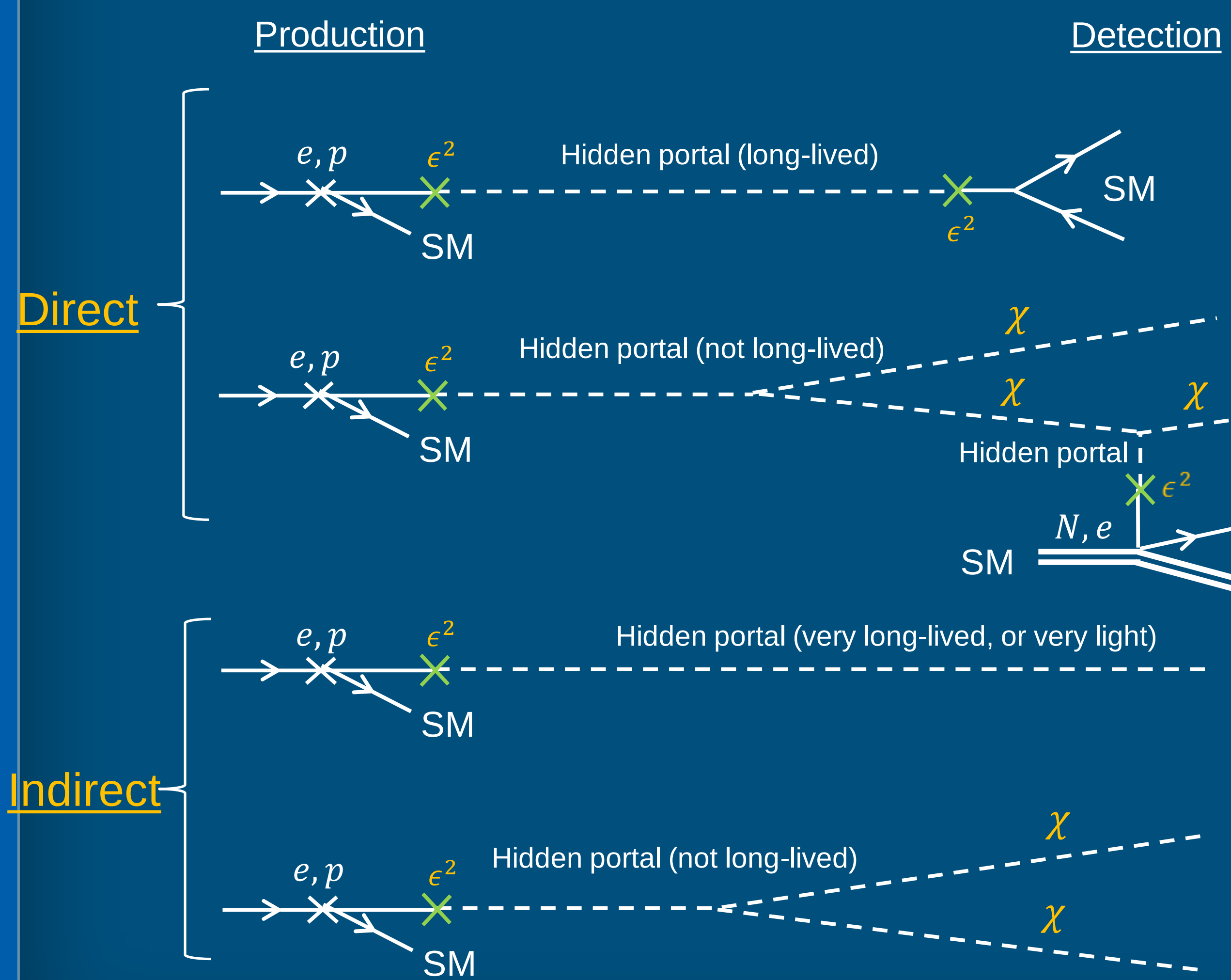


Rich variety and phenomenology requires generic and complementary search!

FIP Detection



- Weak couplings and light masses make HS particles "long-lived"



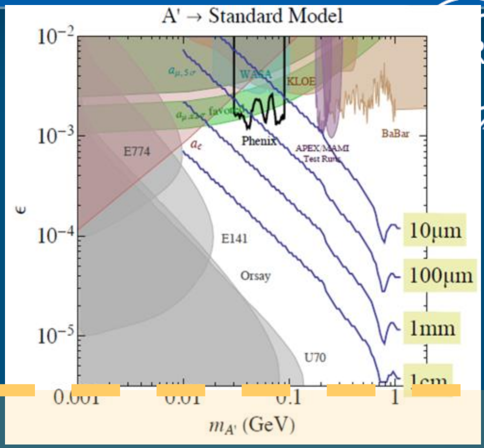
Decay signature ("displaced vertex)
Allow identification of model
Probability ∝ ϵ^4

Dark matter scattering
Recoil against electron or nuclei
Probability ∝ ϵ^4

Escape detector
Missing energy/momentum/mass
Probability ∝ ϵ^2

If $m_{HP} > 2m_{DM}$
Escape detector
Missing energy/momentum/mass
Probability ∝ ϵ^2

Detection



- Weak couplings and light masses make HS particles "long-lived"

Production — Detection

Direct

e, p — ϵ^2 — Hidden portal (long-lived) — ϵ^2 — SM; SM

Decay signature ("displaced vertex)
Allow identification of model
Probability ∝ ϵ^4

e, p — ϵ^2 — Hidden portal (not long-lived) — χ, χ — SM; χ — Hidden portal — ϵ^2 — N, e — SM

Dark matter scattering
Recoil against electron or nuclei
Probability ∝ ϵ^4

SHiP with protons

Indirect

e, p — ϵ^2 — Hidden portal (very long-lived, or very light) — SM

Escape detector
Missing energy/momentum/mass
Probability ∝ ϵ^2

e, p — ϵ^2 — Hidden portal (not long-lived) — χ, χ

If $m_{HP} > 2m_{DM}$
Escape detector
Missing energy/momentum/mass
2

Experimental challenge ➔ Intensity Frontier

BDF/SHiP experimental setup

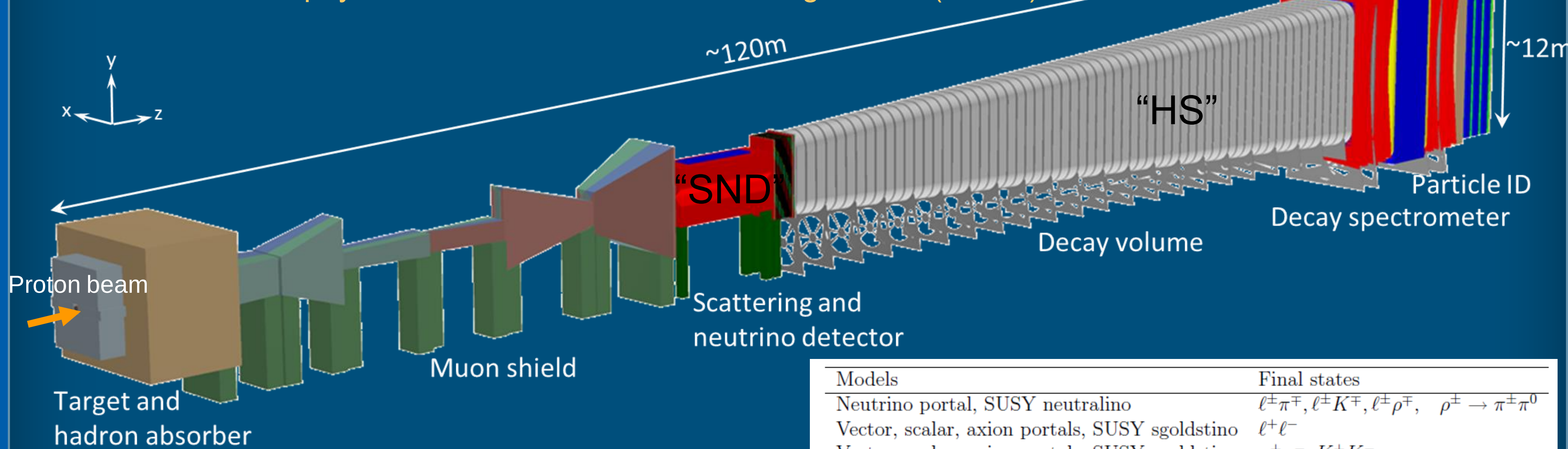
General Purpose Hidden Sector apparatus

Physics cased based on 2×10^{20} protons on target (5 years of nominal operation)

➔Signal yields from $>10^{18}$ D mesons, $>10^{16}$ τ, $>10^{21}$ photons (>100 MeV)

Dual detector system

1. Search for HS decays ("HS detector") – full reconstruction and particle identification
2. Neutrino physics and search for LDM recoil signatures ("SND")



Models	Final states
Neutrino portal, SUSY neutralino	$\ell^{\pm}\pi^{\mp}, \ell^{\pm}K^{\mp}, \ell^{\pm}\rho^{\mp}, \quad \rho^{\pm} \to \pi^{\pm}\pi^{0}$
Vector, scalar, axion portals, SUSY sgoldstino	$\ell^{+}\ell^{-}$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^{+}\pi^{-}, K^{+}K^{-}$
Neutrino portal ,SUSY neutralino, axino	$\ell^{+}\ell^{-}\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^{0}\pi^{0}$

➔ Many interesting detector development for a 3 year TDR phase (2020 – 2023)

SHiP Collaboration: ***290 authors, 52 Institutes, 17 countries***

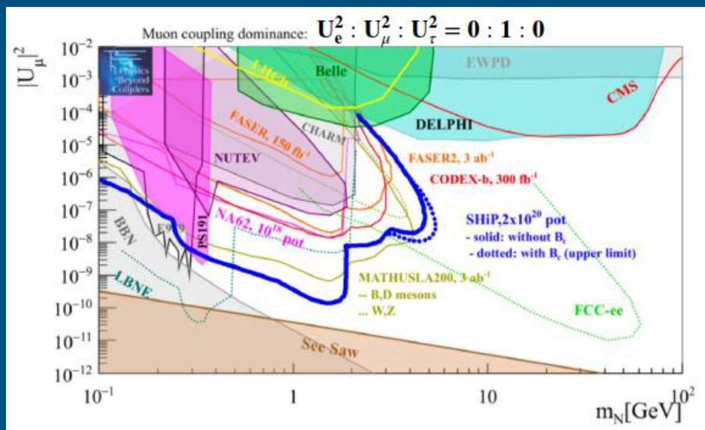
Hidden Sector performance

Main challenge is background rejection

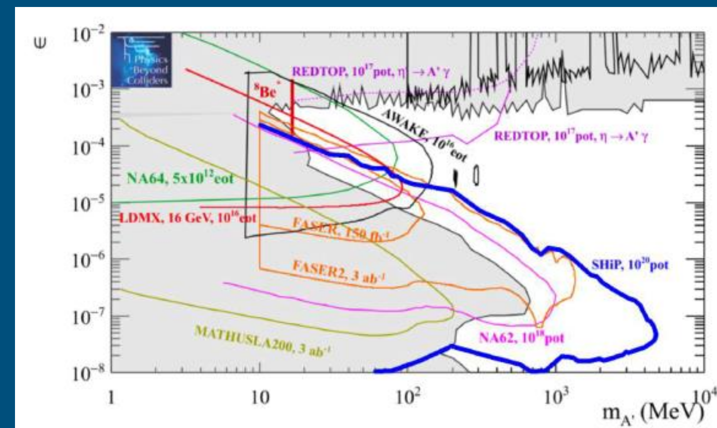
- Background estimates for 2×10^{20} p.o.t. from full simulation and validation in test beam

Background source	Expected events
Neutrino background	< 1
Muon DIS (factorisation)	$< 6 \times 10^{-4}$
Muon Combinatorial	4.2×10^{-2}

Sensitivity to HNLs and Dark Photons

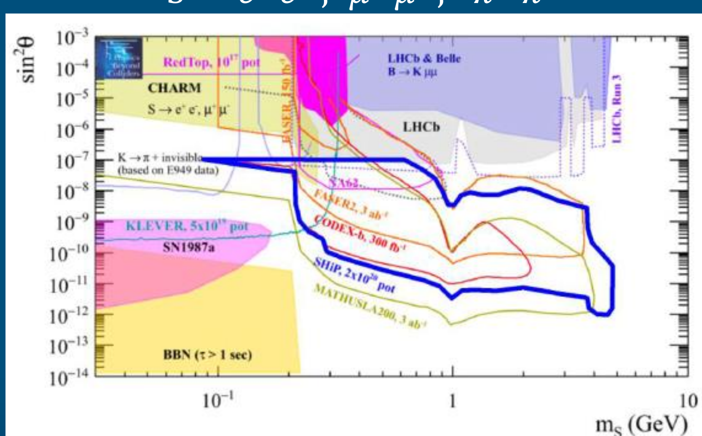


$A' \rightarrow e^+e^-,\ \mu^+\mu^-,\ \pi^+\pi^-$

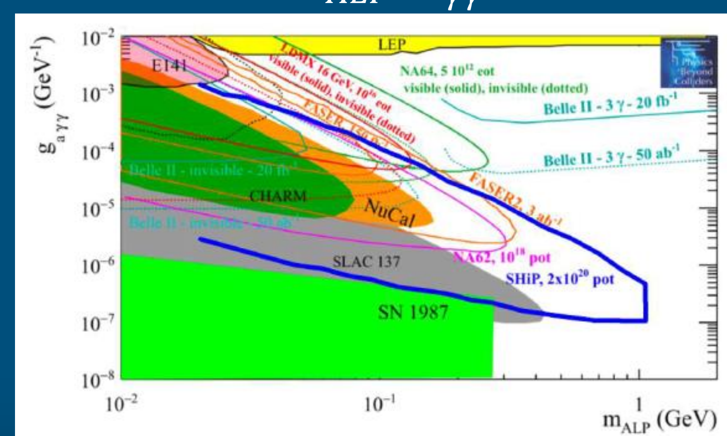


Sensitivity to Dark Scalars and ALPs

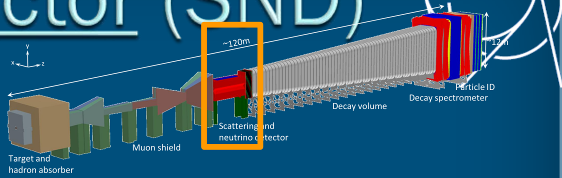
$S \rightarrow e^+e^-,\ \mu^+\mu^-,\ \pi^+\pi^-$



$ALP \rightarrow \gamma\gamma$

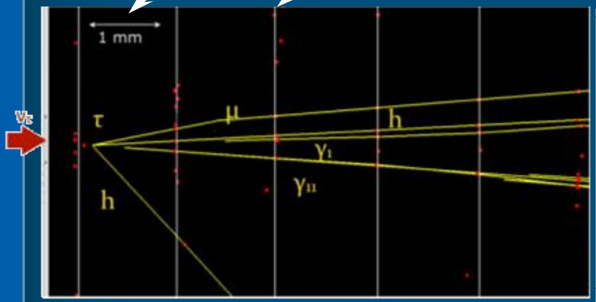


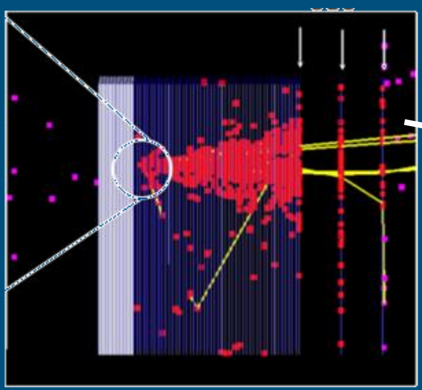
Scattering and Neutrino Detector (SND)



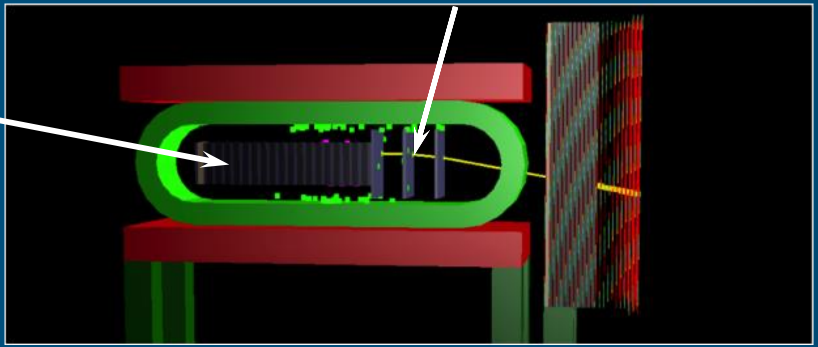
- Neutrino detection based on OPERA technique

Lead plate Emulsion film





Muon momentum measurement



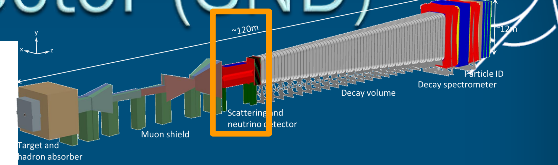
Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to \mu$	1200	1000
$\tau \to h$	4000	3000
$\tau \to 3h$	1000	700
total	6200	4700

	CC DIS interactions
N_{ν_e}	1.1×10^6
N_{ν_μ}	2.7×10^6
N_{ν_τ}	3.2×10^4
$N_{\overline{\nu}_e}$	2.6×10^5
$N_{\overline{\nu}_\mu}$	6.0×10^5
$N_{\overline{\nu}_\tau}$	2.1×10^4

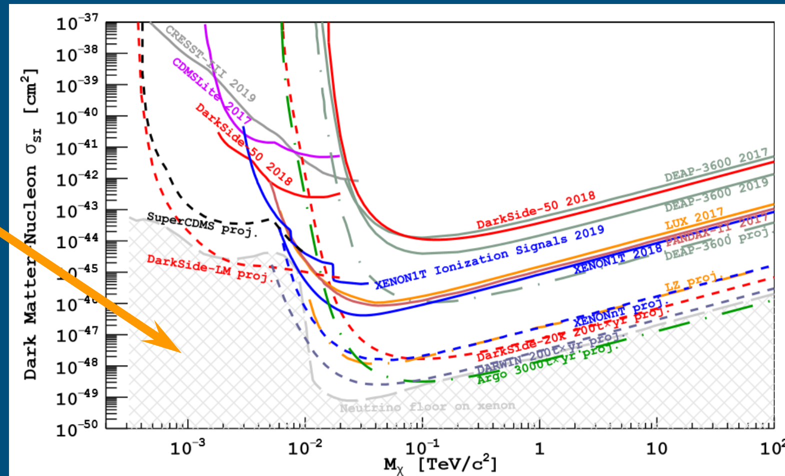
	<E> (GeV)	CC DIS with charm prod	Charm fractions (%)
N_{ν_μ}	55	1.3×10^5	4.7
N_{ν_e}	66	6.0×10^4	5.7
$N_{\overline{\nu}_\mu}$	49	2.5×10^4	4.2
$N_{\overline{\nu}_e}$	57	1.3×10^4	5.1
total		2.3×10^5	

1. First observation of $\bar{\nu}_\tau$ interaction
2. Measurement of ν_τ and $\bar{\nu}_\tau$ cross-sections
   - ➔ Extraction of F4 and F5 structure functions from charged current neutrino-nucleon DIS
   - ➔ Beyond SM
3. ν_τ magnetic moment
4. ν_e cross section at high energy
5. Testing strange quark content of nucleon
6. through charm production
7. Normalization of hidden particle search

Scattering and Neutrino Detector (SND)



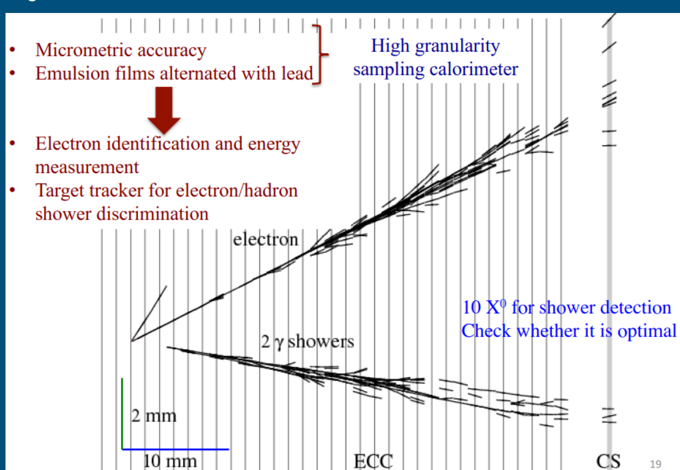
Room for accelerator-based searches

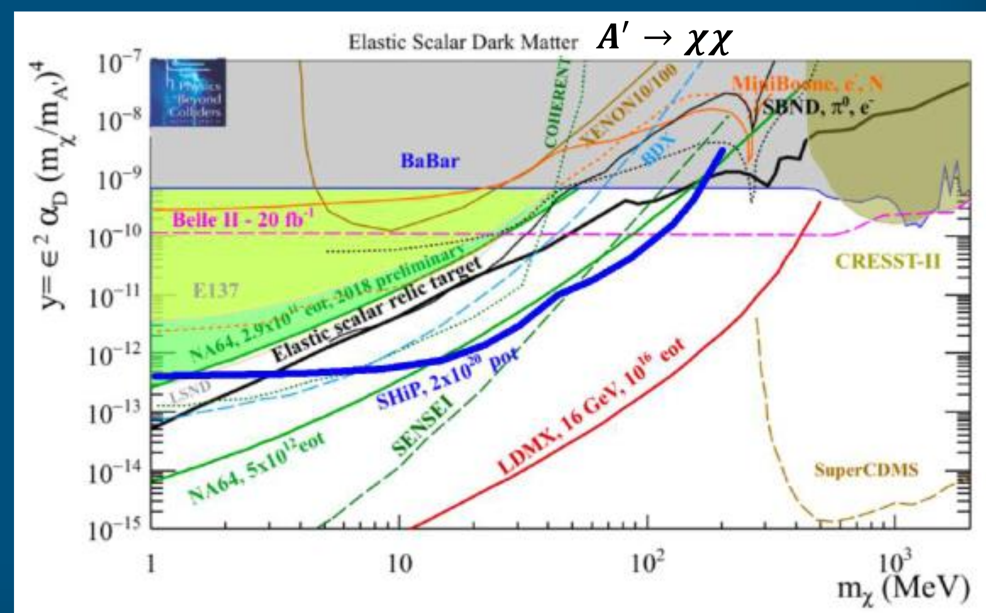


Cmp. talk by Timon Emken

- Light Dark Matter direct detection by recoil against atomic electrons
  - Detection of electromagnetic shower and reconstruction of origin by electronic Target Tracker

ν_e event in Opera



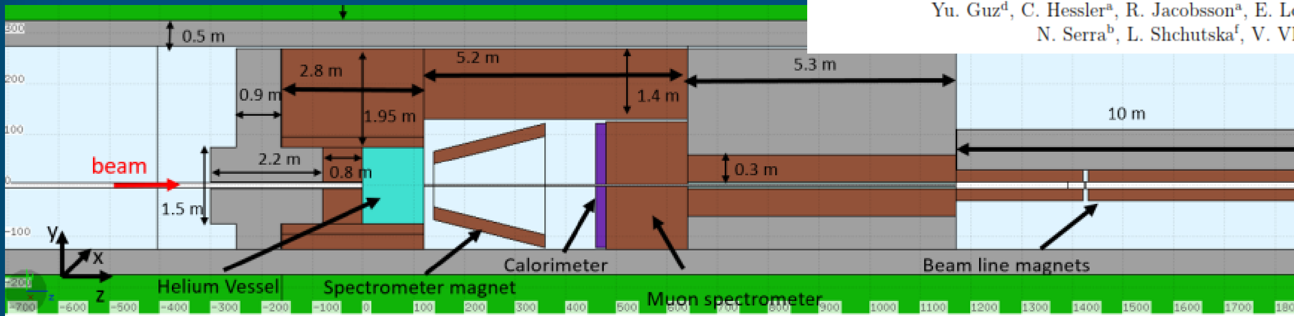


Tau flavour violation experiment

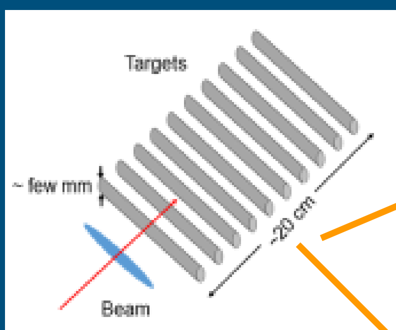
TauFV: a fixed-target experiment to search for flavour violation in tau decays

C.C. Ahdida[a], I. Bezshyiko[b], A Buonaura[b], M. Calviani[a], J.P. Canhoto Espadanal[a], M. Casolino[a], P. Collins[a], Y. Dutheil[a], B. Goddard[a], A. Golutvin[c], Yu. Guz[d], C. Hessler[a], R. Jacobsson[a], E. Lopez Sola[a], A. Milanese[a], K. Petridis[e], N. Serra[b], L. Shchutska[f], V. Vlachoudis[a], G. Wilkinson[g]

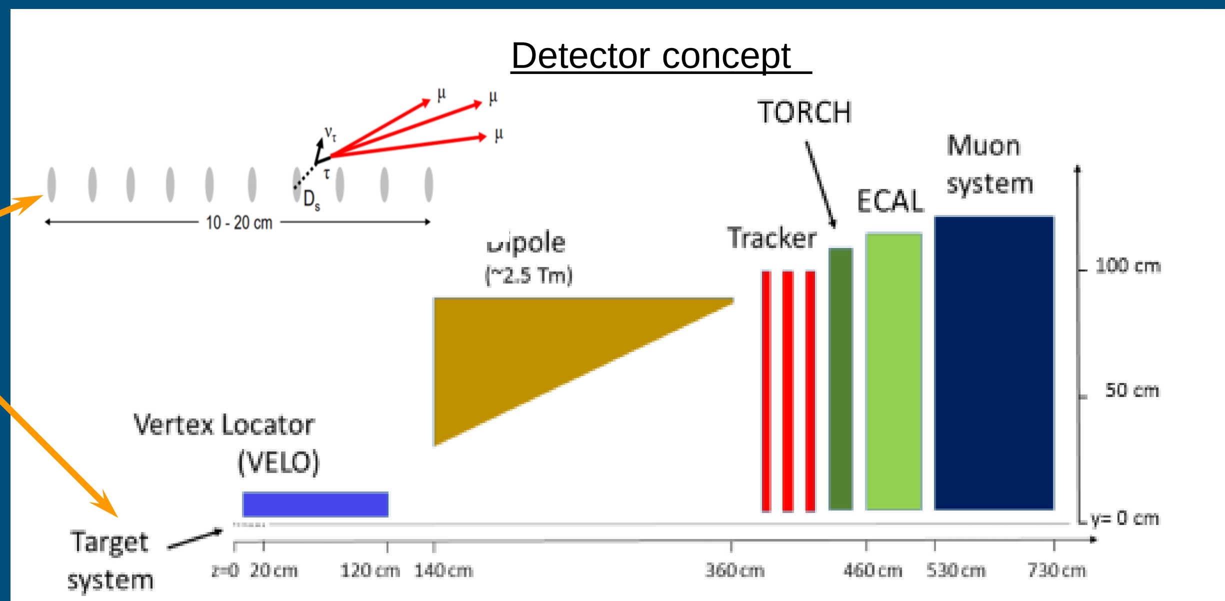
Submitted to EPPSU



➔ ~100m to SHiP target



"Tungsten" in-line target blades equivalent to 2%λ

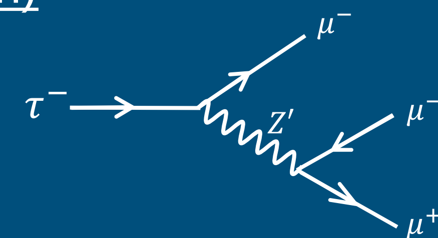


With 2mm of W, expect ~8x10^{13} $D_s \rightarrow \tau\nu$ decays and ~5x10^{15} D^0 decays

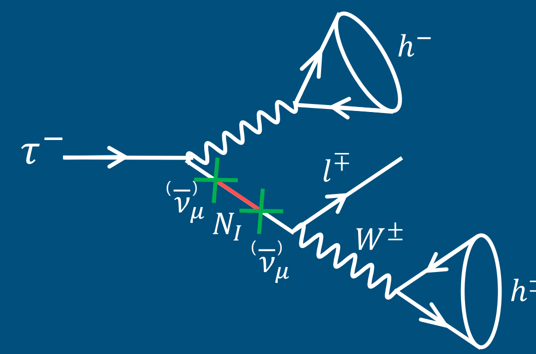
TauFV physics prospects

- Lepton flavour violation (and Lepton Number Violation)
  - **Tau decays**
    - ➔ Signal yield of $\tau \to 3\mu$ assuming BR~10^{-9} and 5 years' operation of BDF:

Experiment	PoT / $\int \mathcal{L}dt$	Yield	Source
TauFV	4×10^{18}	8000	/
Belle II	$50\,\mathrm{ab}^{-1}$	9	[2]
LHCb Upgrade I	$50\,\mathrm{fb}^{-1}$	140	[4]
LHCb Upgrade II	$300\,\mathrm{fb}^{-1}$	840	[4]



    - ➔ But also $\tau \to 3e, \tau \to ee\mu, \tau \to e\mu\mu, \tau \to hhl$



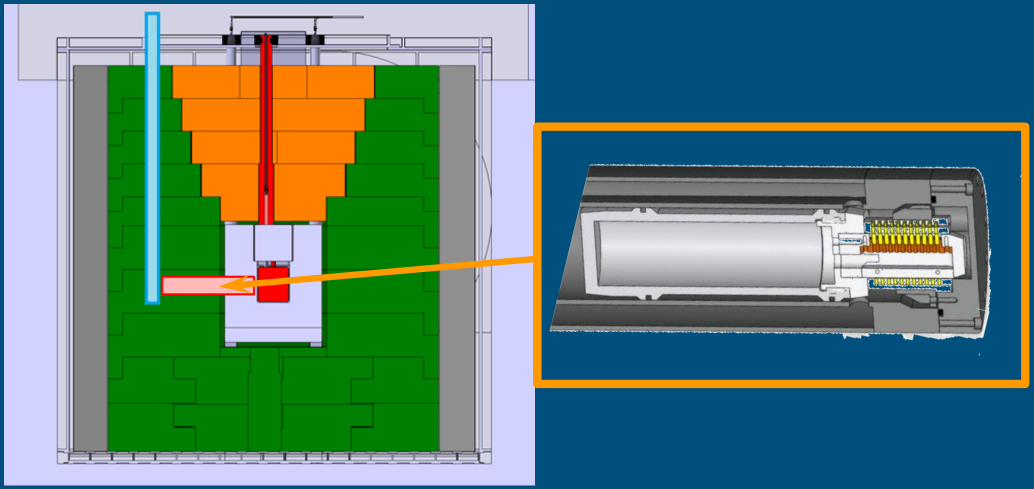
  - **Charm decays**
    - ➔ $D \to h\mu e$, $D \to hl^-l^-$
  - **Kaon decays?**
    - ➔ $K^\pm \to \pi^\pm l^+ l'^-$, $K^0 \to (\pi^0) l^+ l'^-$
    - ➔ NA62 & LHCb prospects for sensitivity of 10^{-11} – 10^{-12}
- CP violation and rare decays
  - ➔ Charm decays $D^0 \to \mu\mu, D^0 \to \gamma\gamma$

Currently studies are focusing on feasibility and physics sensitivity

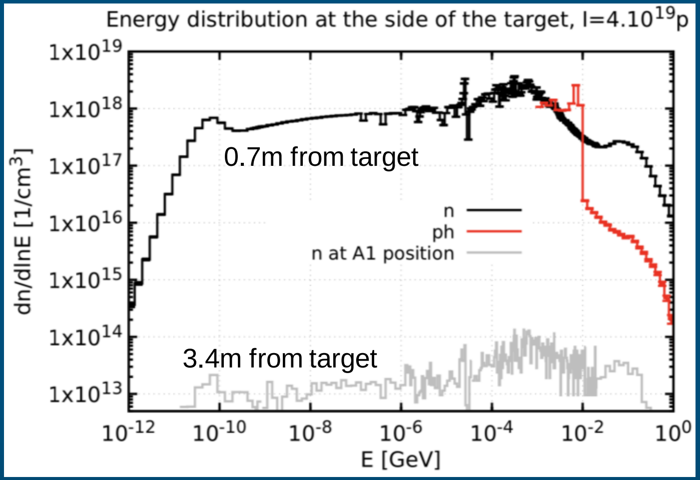
➔ Very challenging experimental conditions (HL-LHC technologies and beyond)

Other applications

- BDF could potentially be very useful for irradiation studies of materials / electronics



- Study neutron-induced reactions on short-lived isotopes, of interest for Nuclear Astrophysics
  - ➔ Proximity of the target a flux of around 10^{13}-10^{14} neutrons/cm^2/spill
  - ➔ Unique opportunity to study slow and rapid successive neutron-capture process



Physics Beyond Collider study group

THE MAIN PBC MESSAGES TO THE EPPSU

FOR CERN PROJECTS

LHC Fixed-Target opens a worldwide unique domain to both SF and QGP measurements
Requires support for full exploitation of its potential on the LHC lifetime

A SPS Beam Dump Facility would cover a worldwide unique domain for hidden sector searches complementary to high-energy colliders and non-accelerator experiments
A mid-size project now mature for an implementation decision

FOR PROJECTS OUTSIDE CERN

Support is required to fully exploit the potential of National Labs for both non-accelerator projects (e.g. IAXO) and precision physics (e.g. pEDM R&D)

The particle physics potential of the new European facilities such as ESS and DESY XFEL requires support to be fully exploited in the long term.

Claude Vallee at ECFA-EPS meeting

EPPSU Physics Briefing Book

E.g. Flavour Physics chapter:

Furthermore, from both the experimental and the theory side, a novel synergy between the searches for flavour violating decays and that for feebly interacting and dark particles is emerging. Searching for exotic signatures in flavour violating decays may have profound implications for our understanding of the Universe, and should be part of any broad program of searches for dark sectors. High-energy colliders will explore a large number of signatures and cover a large fraction of the parameter space for the high-mass range (above 10 GeV). Nevertheless fixed-target smaller-scale experiments, LHC projects dedicated to long-lived particles and beam-dump facilities may provide complementary information to explore a lower mass range (1 MeV - 10 GeV) and open new interesting research lines.

Conclusion and outlook

- *Bright future for Dark Sector*
  - Very much increased interested for Hidden Sector after LHC Run 1

- SHiP@BDF is a mature GP platform for HS exploration
  - Set up for discovery through direct detection
  - Also unique opportunity for ν_τ physics, direct Dark Matter search, flavour physics

- Facility and physics case based on the current proton injector complex and SPS

- Detector R&D and design is at an advanced level
  - ➔ But many exciting developments still and groups are more than welcome!
  - ➔ Stockholm (D. Milestead) and Uppsala (R. Brenner) already involved

- Possible timeline
  - Phase 2 prototyping ongoing
  - ~3 years for TDR, followed by preparation for construction, component production
  - Construction of BDF ~5 years
    - Civil engineering for junction cavern/first part of new transfer line during LS3 (North Area stop)
  - Detector production, installation, commissioning ~6-7 years
  - Operation in Run 4