BDF/SHiP @CERN: **S**earch for **Hi**dden **P**articles at a dedicated **B**eam **D**ump **F**acility

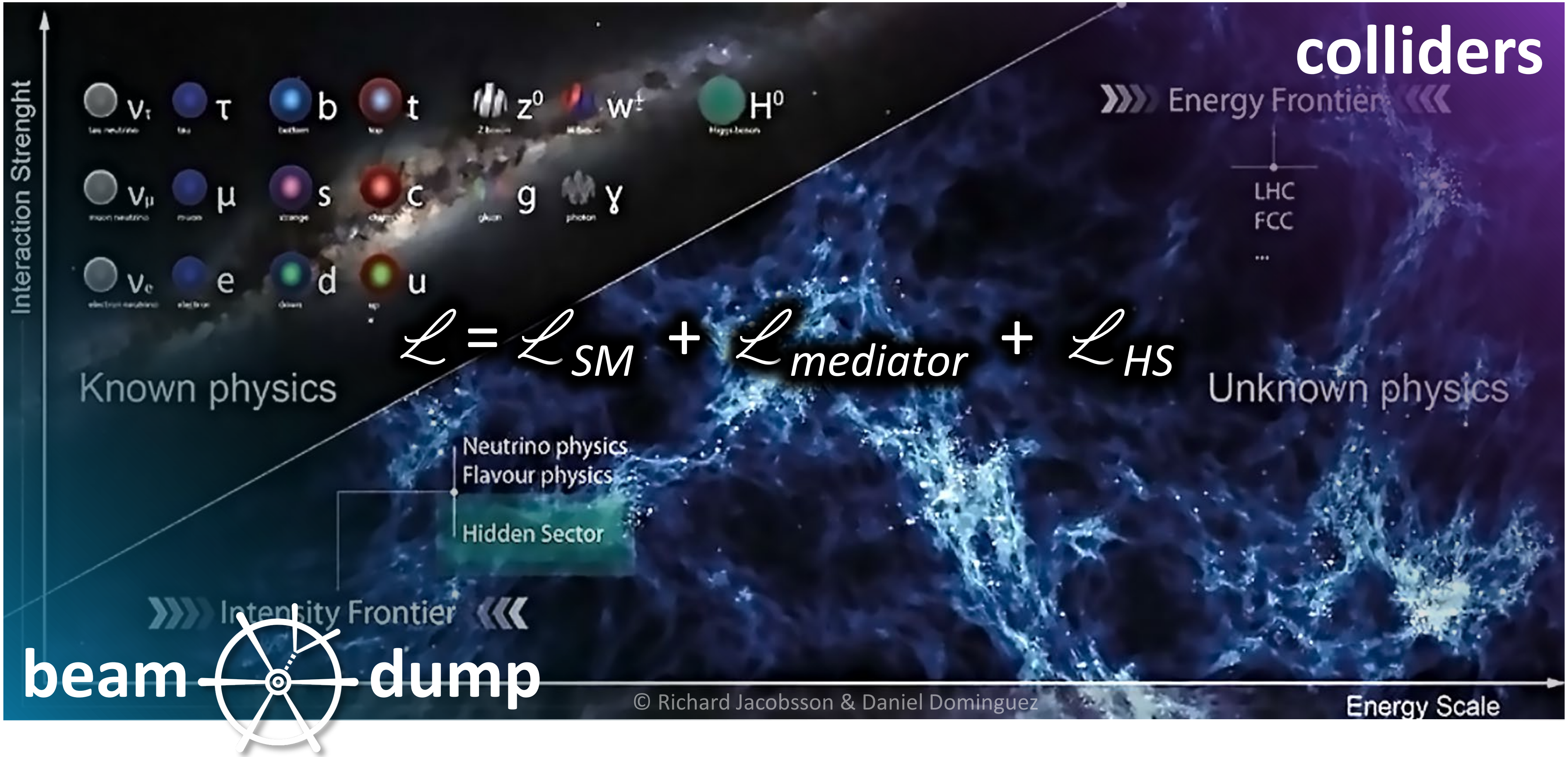
Annika Hollnagel on behalf of the **SHiP Collaboration**

annika.hollnagel@uni-mainz.de
Johannes Gutenberg-Universität Mainz, ETAP

Introduction:
(Un)Charted Territory

Exploring the Hidden Sector

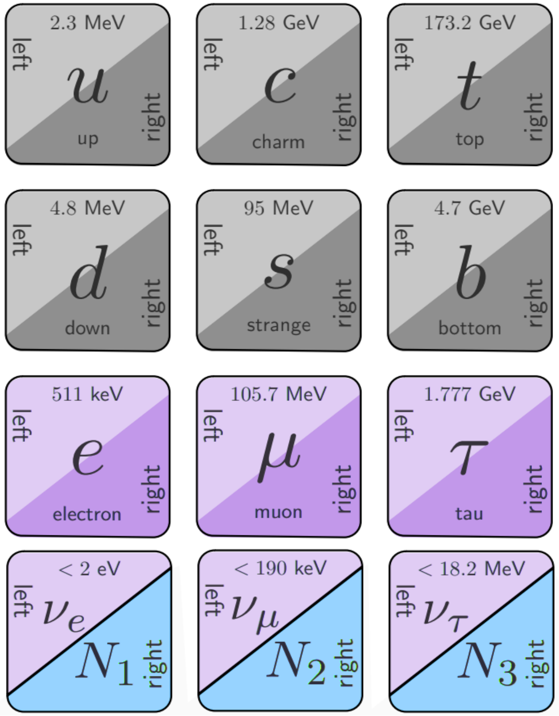
Hidden Sector (HS): HNL / ALPs / dark photons / dark scalars / …



$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{mediator} + \mathcal{L}_{HS}$$

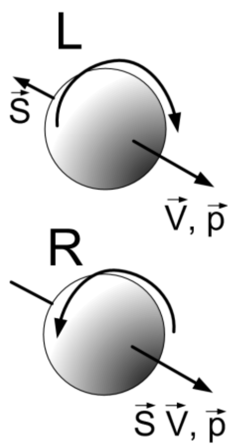
Mediators (Portals) to Visible Sector: Fermion / axial / vector / Higgs / …

Heavy Neutral Leptons & νMSM



Neutrino Minimal Standard Model (νMSM): Type I See-Saw

extension of the SM by 3 right-handed (Majorana) Heavy Neutral Leptons (HNL)



Light N_1 : Mass $\mathcal{O}$ (10keV)

- **Dark Matter** candidate

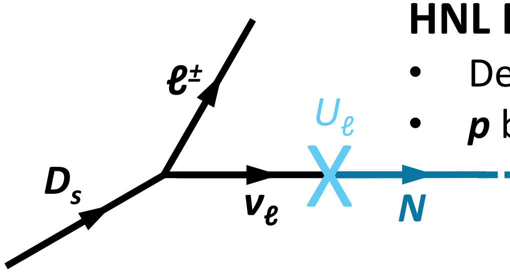
▶ To be studied by **X-ray telescopes** in space

Heavy N_2 , N_3: Mass $\mathcal{O}$ (1GeV)

- Origin of **neutrino masses**
- **Leptogenesis** & **baryon asymmetry** of the Universe

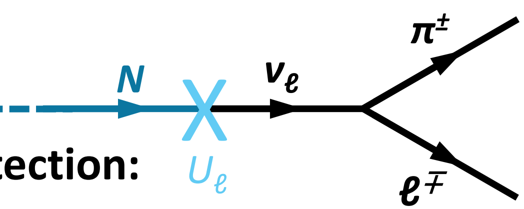
▶ Accessible at **colliders** (*m* > 3GeV, energy frontier) or **beam dump facilities** (m < 3GeV, intensity frontier)

[CERN-SPSC-2015-017, **Physics Letters B 631 (2005) 151–156, M. Shaposhnikov Neutrino2024**]



HNL Production:

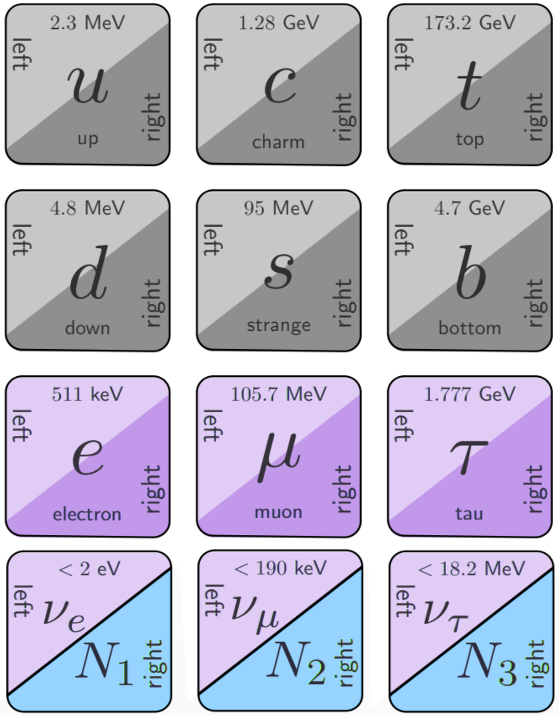
- Decays of ***D* *(charm)* & *B* (beauty) mesons**
- ***p*** bremsstrahlung



HNL Detection:

- **Visible decays** into charged leptons, *p*, *γ* ...

Heavy Neutral Leptons & νMSM



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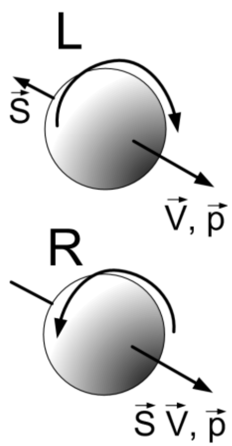

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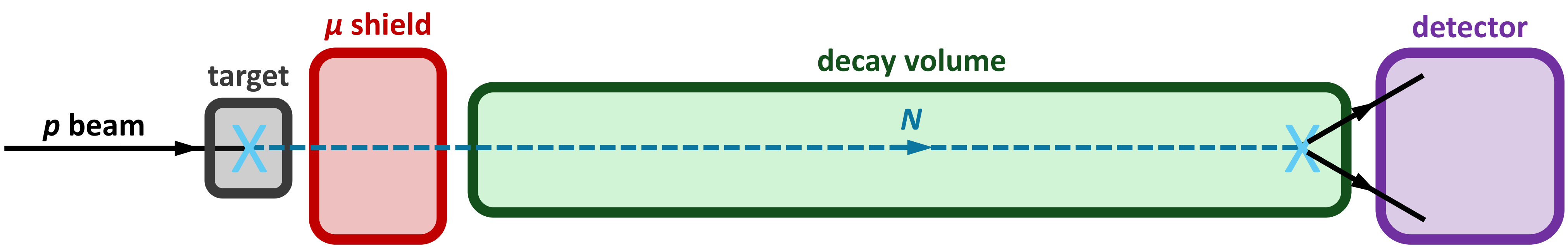


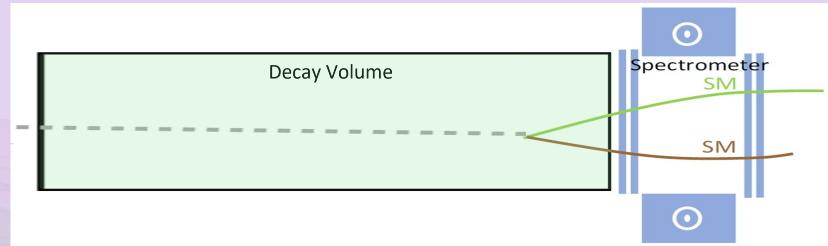
BDF/SHiP @CERN

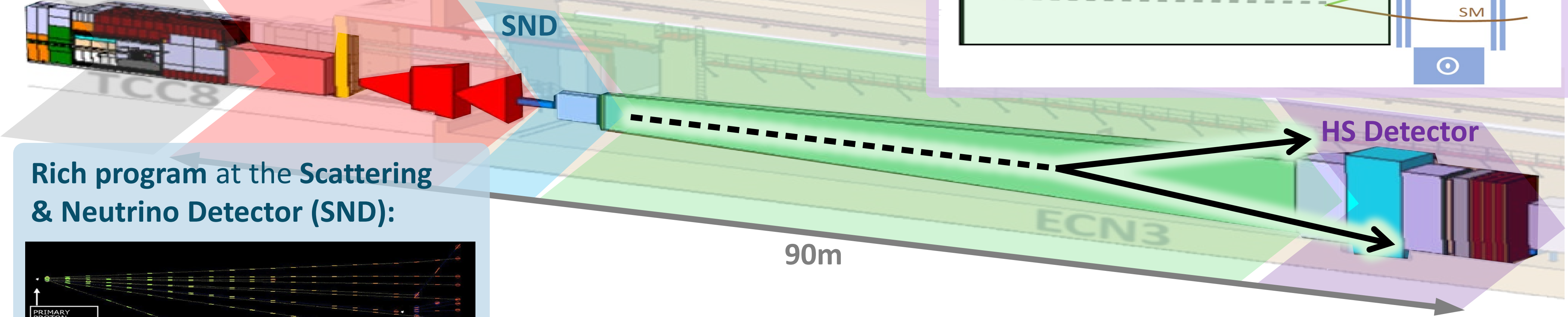
BDF/SHiP: Search for Hidden Particles

Search for Hidden Particles (SHiP) at a dedicated **Beam Dump Facility (BDF):**

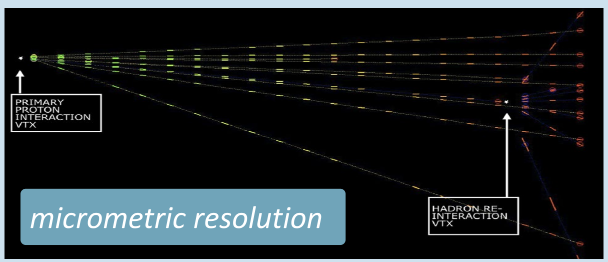
- High-Intensity (HI) upgrade of **CERN SPS 400GeV proton facility**
- General-purpose **beam dump facility**
- **Dedicated beam** to ECN3

Search for **Feebly-Interacting Particles** with the **Hidden Sector Decay Spectrometer (HSDS):**





Rich program at the **Scattering & Neutrino Detector (SND):**



- **Original Proposal (2013):** Developed for new cavern EHN4
- ▶ Refined Proposal (2023): **Adaptation to existing ECN3 facility**

[CERN-SPSC-2013-024, CERN-SPSC-2022-032 / SPSC-I-258, **CERN-SPSC-2023-033 / SPSC-P-369**]

Baseline intensity: 4.0×10^{13} *p*/spill → 4.0×10^{19} p.o.t./yr

→ **6.0×10^{20} p.o.t.** after **15 years**

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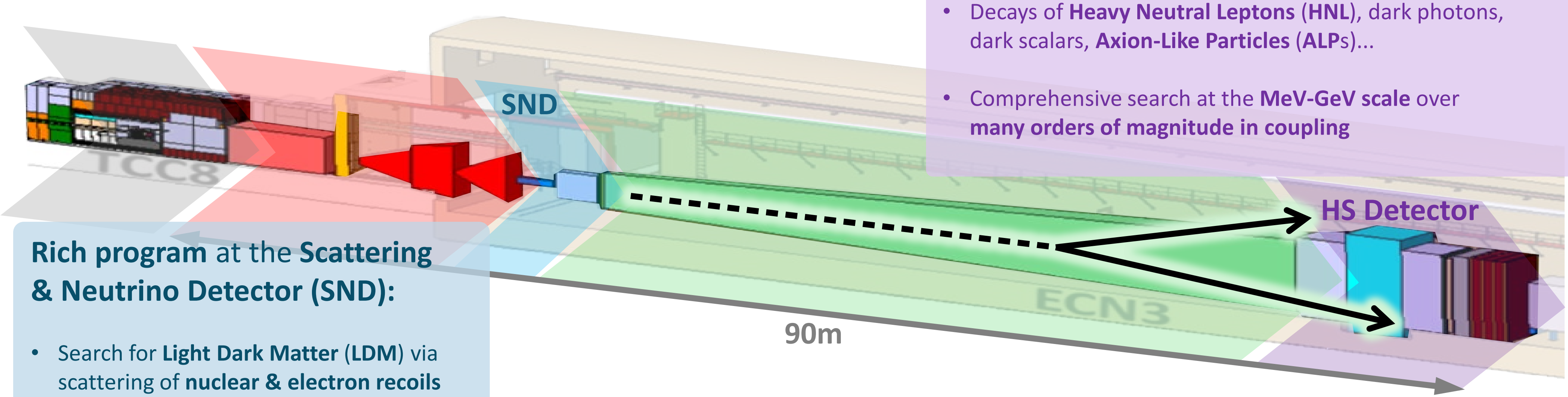
Search for **Feebly-Interacting Particles** with the **Hidden Sector Decay Spectrometer (HSDS):**

- Decays of **Heavy Neutral Leptons** (**HNL**), dark photons, dark scalars, **Axion-Like Particles** (**ALPs**)...
- Comprehensive search at the **MeV-GeV scale** over **many orders of magnitude in coupling**



Rich program at the **Scattering & Neutrino Detector (SND):**

- Search for **Light Dark Matter** (**LDM**) via scattering of **nuclear & electron recoils**
- ν_τ **physics**, ν interactions, ν-induced **charm production**...

- **Original Proposal (2013):** Developed for new cavern EHN4

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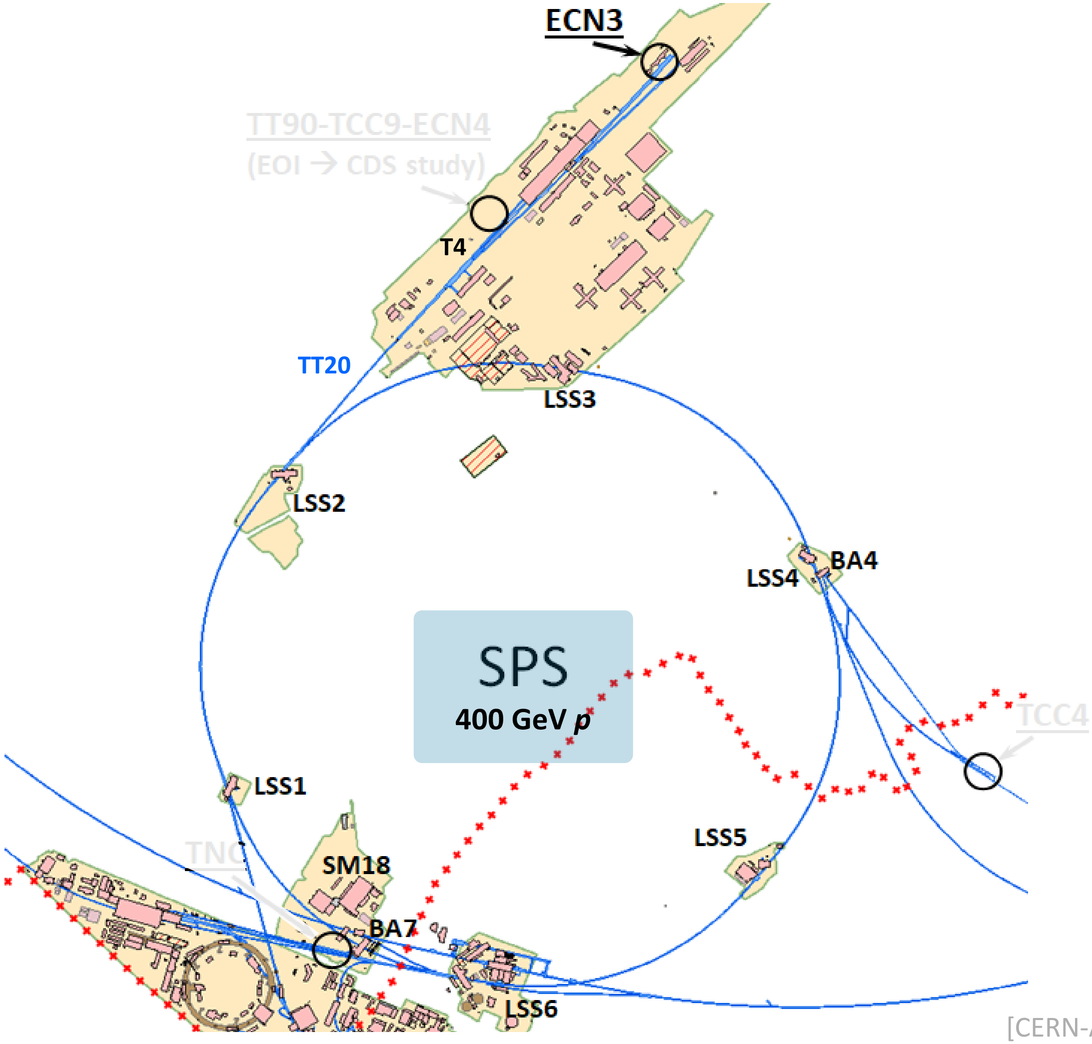
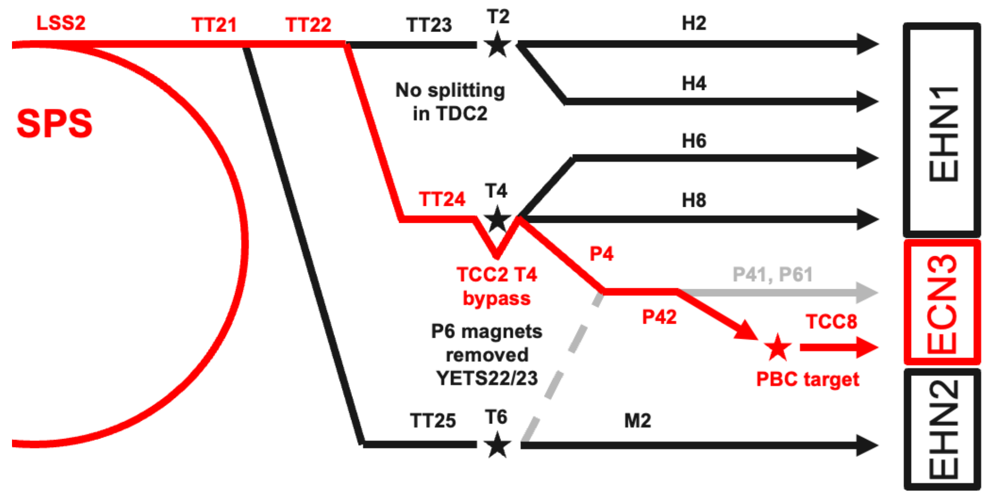
SPS North Area
& beam delivery to
ECN3

SPS Beam Delivery to ECN3

New dedicated operational scenario (T4 bypass):

beam transported through TT20 and TCC2 and delivered exclusively onto experimental target





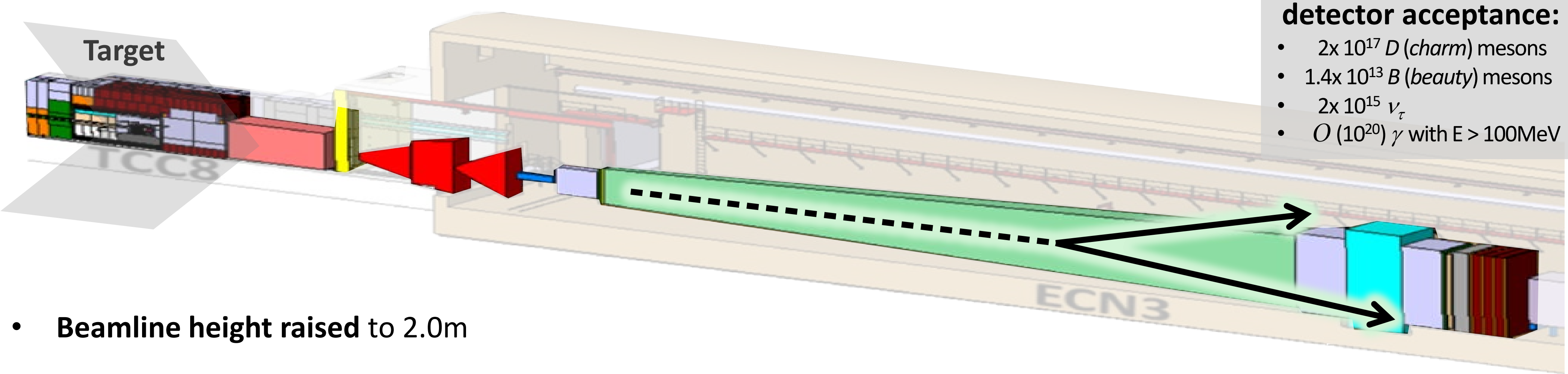
ECN3 scenario	SPS p^+ Intensity [p/spill] [pot/yr]	ECN3 p^+ Intensity [p/spill] [pot/yr]	Spills [ECN3/day] [NA/day]	Spill Length [s]	Repetition period [s]
Dedicated T4 bypass	$\leq 4.2 \times 10^{13}$ $\leq 5 \times 10^{19}$	$\leq 4.0 \times 10^{13}$ $\leq 4.0 \times 10^{19}$	≤ 5000 ≤ 6250	≥ 1.0	≥ 7.2

[CERN-ACC-NOTE-2022-0009, CERN-PBC-REPORT-2023-001, CERN-PBC-REPORT-2023-003]

SHiP Detector Technology

BDF/SHiP: Facility & Detector Technology

Target & Hadron Stopper

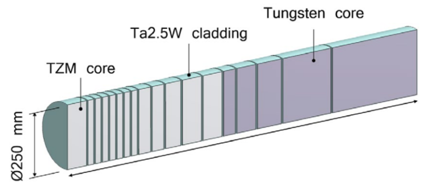


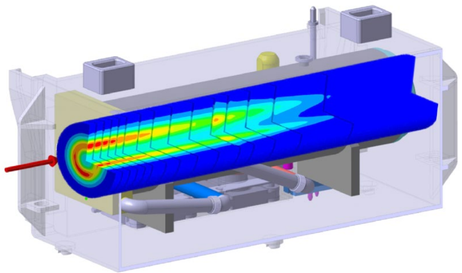
Annual yields within detector acceptance:

- 2×10^{17} *D* (*charm*) mesons
- 1.4×10^{13} *B* (*beauty*) mesons
- 2×10^{15} ν_τ
- $\mathcal{O}(10^{20})$ γ with E > 100MeV

- **Beamline height raised** to 2.0m

[CERN-SPSC-2019-049 / SPSC-SR-263, CERN-PBC-Notes-2021-005, CERN-PBC-REPORT-2023-003, **CERN-SPSC-2023-033 / SPSC-P-369**]

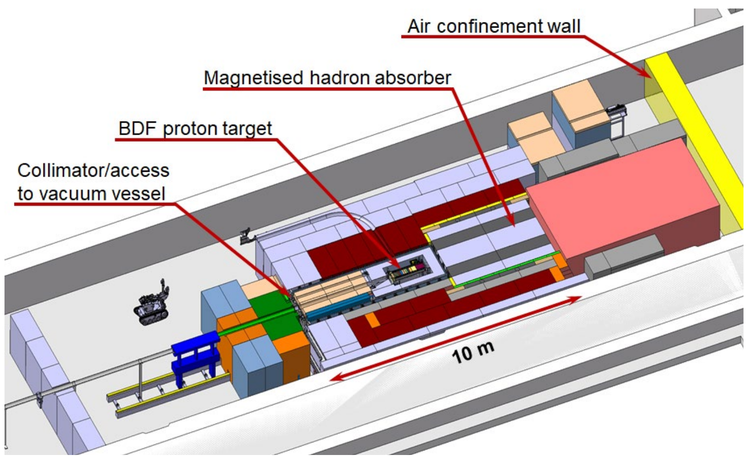




- **High-density proton target:** 12λ
  Ti-Zr-Mo (TZM) + **W blocks**, clad by Ta

► **Optimised for heavy meson production**

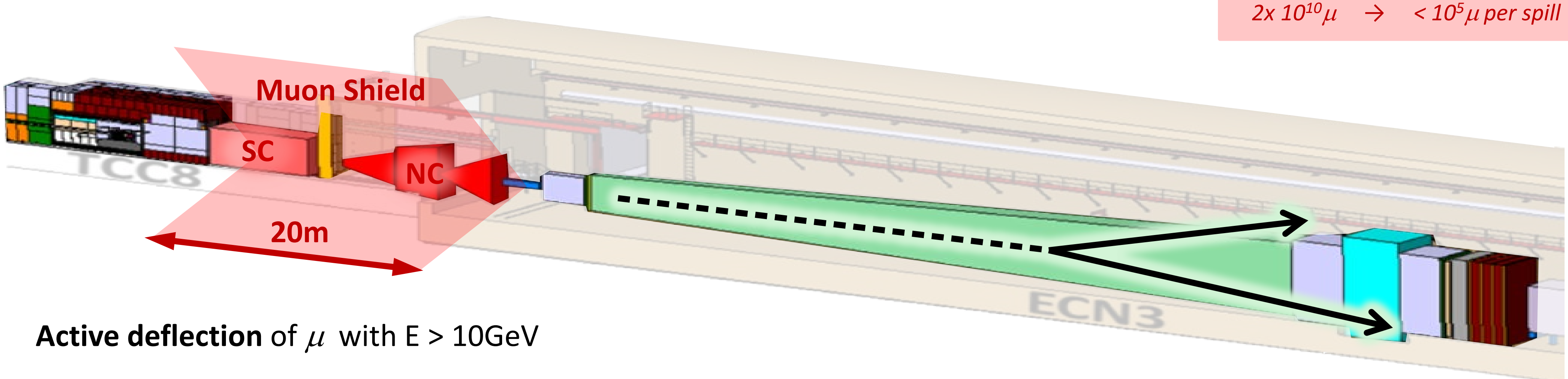
- **Shielding:** Cast iron & concrete, water-cooled & vacuum-confined
- 5m-long magnetised hadron stoppper



BDF/SHiP: Facility & Detector Technology

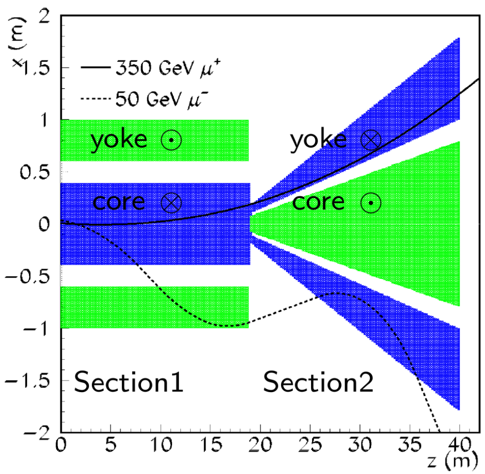
(Superconducting) Magnetic Muon Shield

Reduction of μ rate:
2x $10^{10}\mu$ → < $10^{5}\mu$ per spill



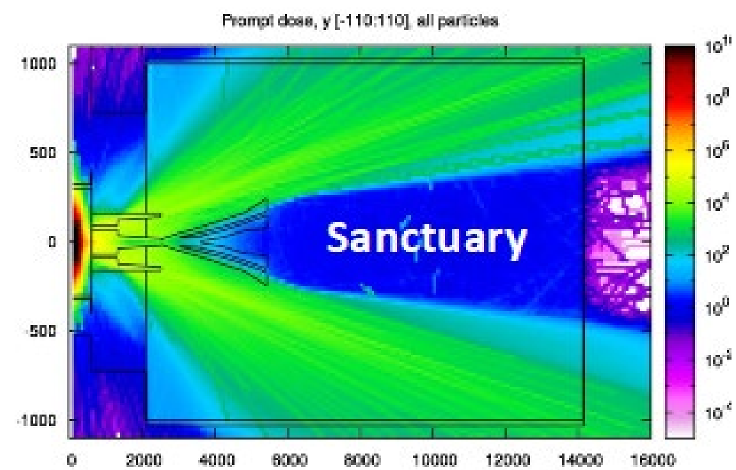
- **Active deflection** of μ with E > 10GeV

[CERN-SHiP-NOTE-2016-005, 2017 JINST-12-P05011, CERN-SPSC-2019-049 / SPSC-SR-263, **EPJC-80(2020)3-284**, **CERN-SPSC-2023-033 / SPSC-P-369**]



- **Alternate-polarity scheme:**
  Split of **positive & negative** μ to **left & right** of decay volume
- **ECN3 optimisation (hybrid SC / NC):** 5.1T
  Shortened, preserving experiment sensitivity
- **Initial (& fallback) design (NC):** 1.7T

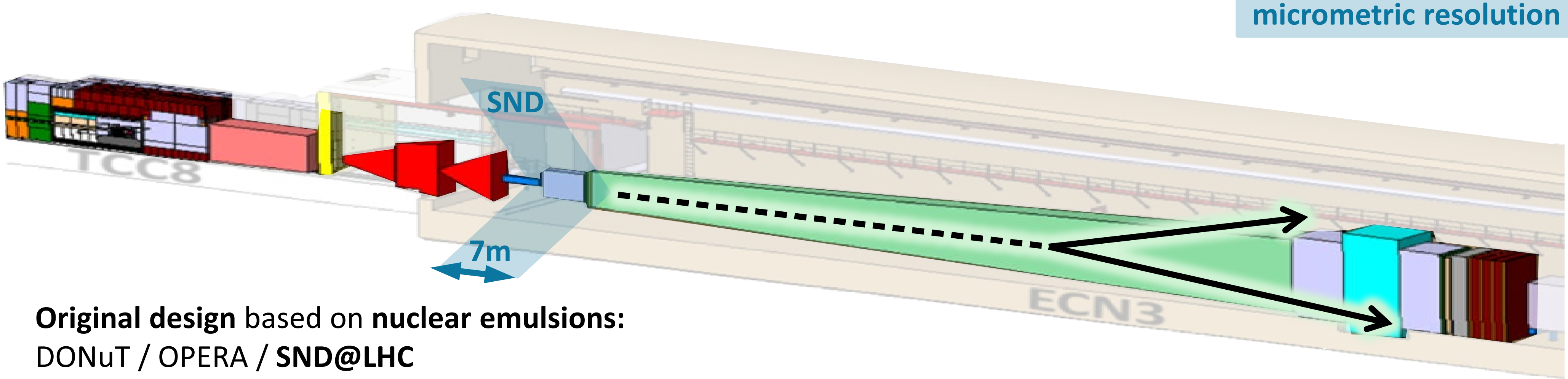
▶ Ongoing **ML-assisted optimisation campaign**



BDF/SHiP: Facility & Detector Technology

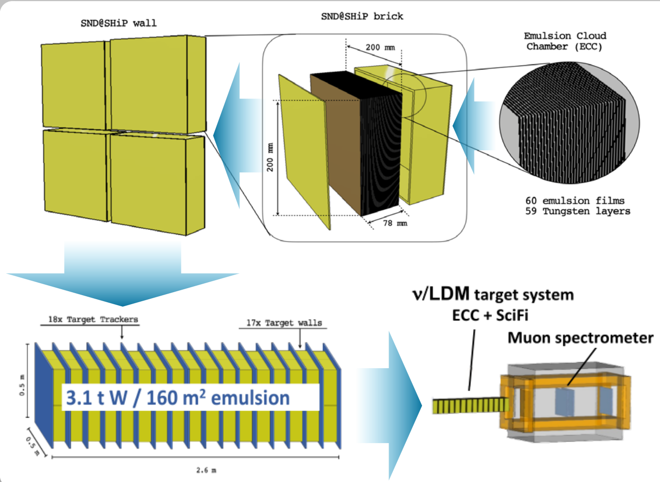
BDF/SHiP: Scattering & Neutrino Detector (SND)

Particle tracking with **micrometric resolution**



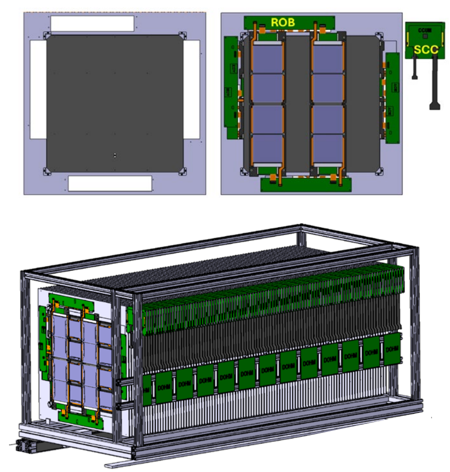
- **Original design** based on **nuclear emulsions:**
  DONuT / OPERA / **SND@LHC**

[CERN-SPSC-2019-049 / SPSC-SR-263, CERN-LHCC-2020-002, **CERN-SPSC-2023-033 / SPSC-P-369, EPJC(2024)84:562, CERN-LHCC-2024-007 / LHCC-I-040**]



- **Emulsion Cloud Chamber (ECC) bricks:**
  AgBr nuclear emulsions interleaved with **W**
- **Target Tracker (TT):** 18 layers of **SciFi**
- **μ spectrometer:** Drift tubes (4 stations)
- **Air core dipole magnet:** 1 T

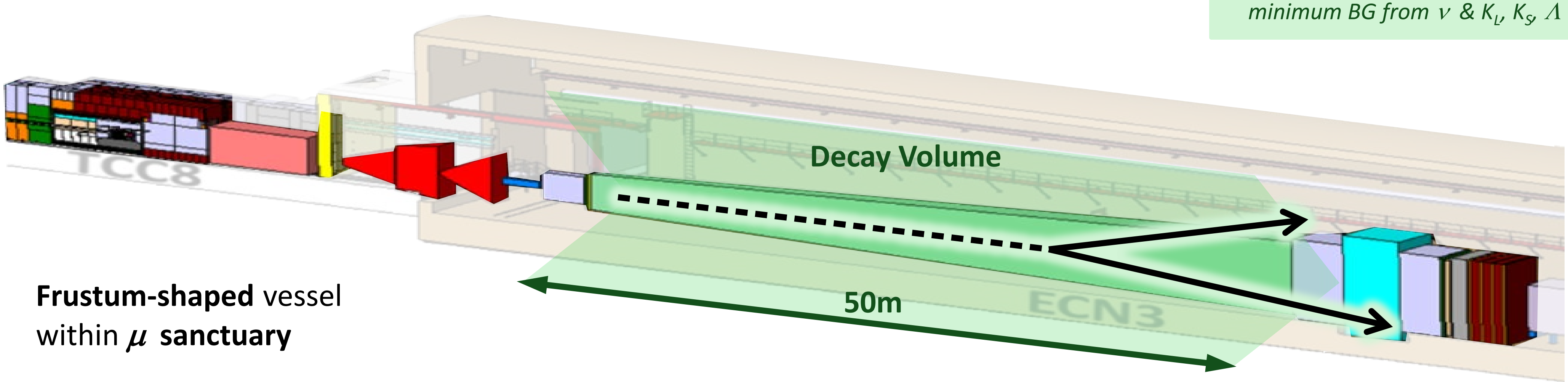
► **Re-optimisation study** for **realtime readout** using **CMS TOB silicon modules (AdvSND)**



BDF/SHiP: Facility & Detector Technology

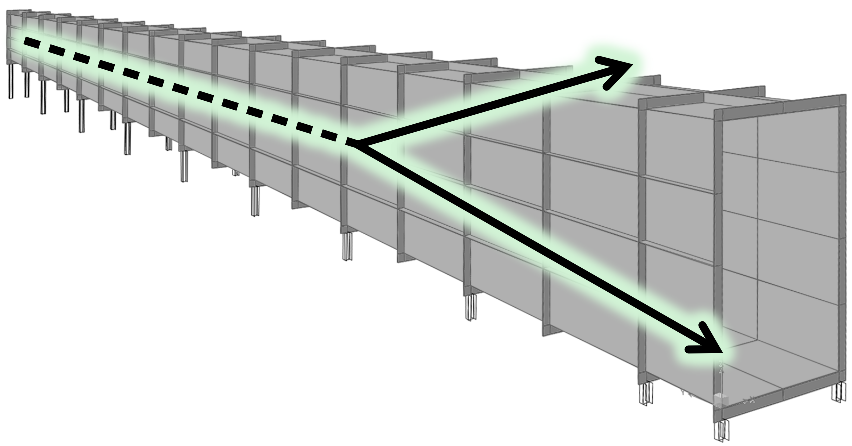
Hidden Sector (HS) Decay Volume

50m-long decay volume:
minimum BG from ν & K_L, K_S, Λ



- **Frustum-shaped** vessel within μ **sanctuary**

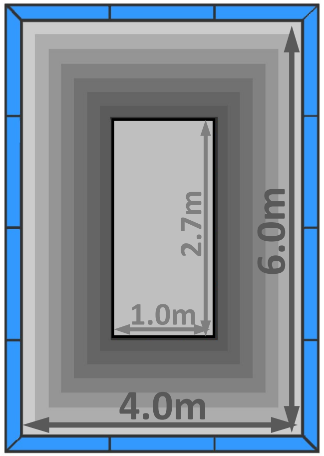
[CERN-SPSC-2019-049 / SPSC-SR-263, ACME (2021) 21:3, CERN-STUDENTS-Note-2023-122, **CERN-SPSC-2023-033 / SPSC-P-369**]



- **He** at **atmospheric pressure**
  Initial design: Evacuated vessel at < 10^{-2} bar

▶ **Lightweight structure** (**Al** / stainless steel)
▶ Low material budget to **minimise μ** and **ν interactions**

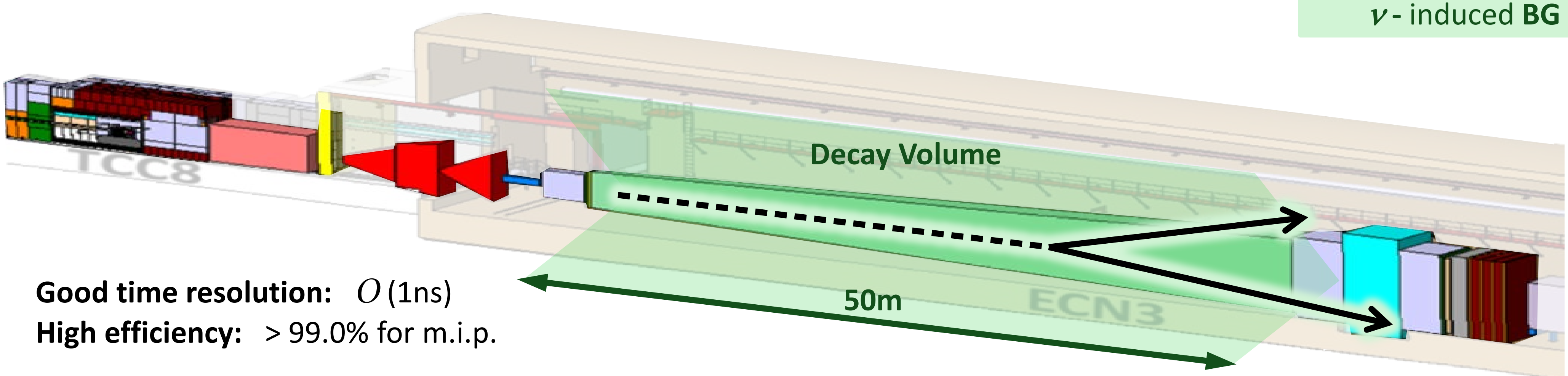
\+ **Support** for **LS-SBT** integration



BDF/SHiP: Facility & Detector Technology

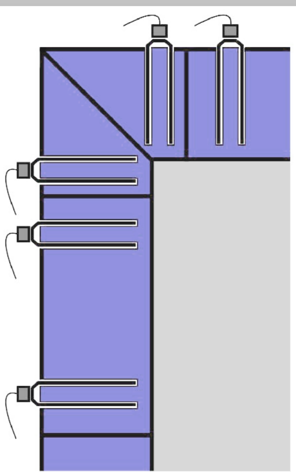
Liquid Scintillator-Surrounding Background Tagger (LS-SBT)

Tagging of μ **-** and ν **-** induced **BG**

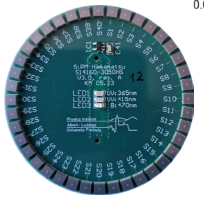


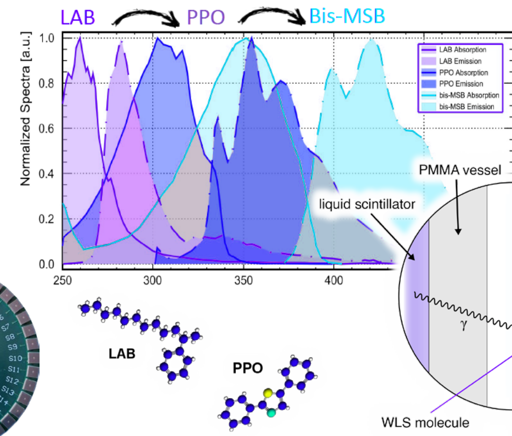
- **Good time resolution:** $\mathcal{O}$(1ns)
- **High efficiency:** > 99.0% for m.i.p.

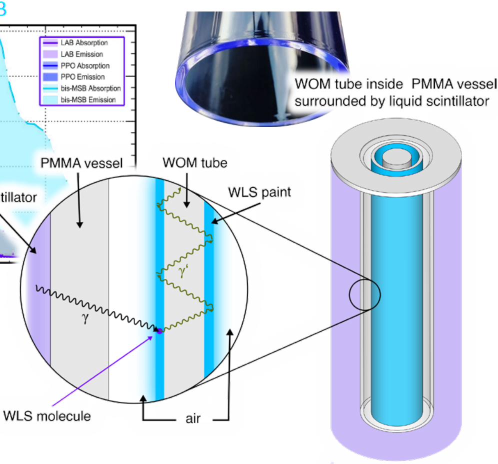
[CERN-SPSC-2019-049 / SPSC-SR-263, **JINST 14 P03021**, CERN-SPSC-2023-033 / SPSC-P-369, **JINST 19 05 P05024**]



- **Segmented geometry:** 850 cells
- Filled with **145 000l** state-of-the-art Liquid Scintillator (LS) made from LAB + PPO
- Instrumented with 1 500 Wavelength-Shifting Optical Modules (WOMs)
- Read out by circular arrays of SiPMs



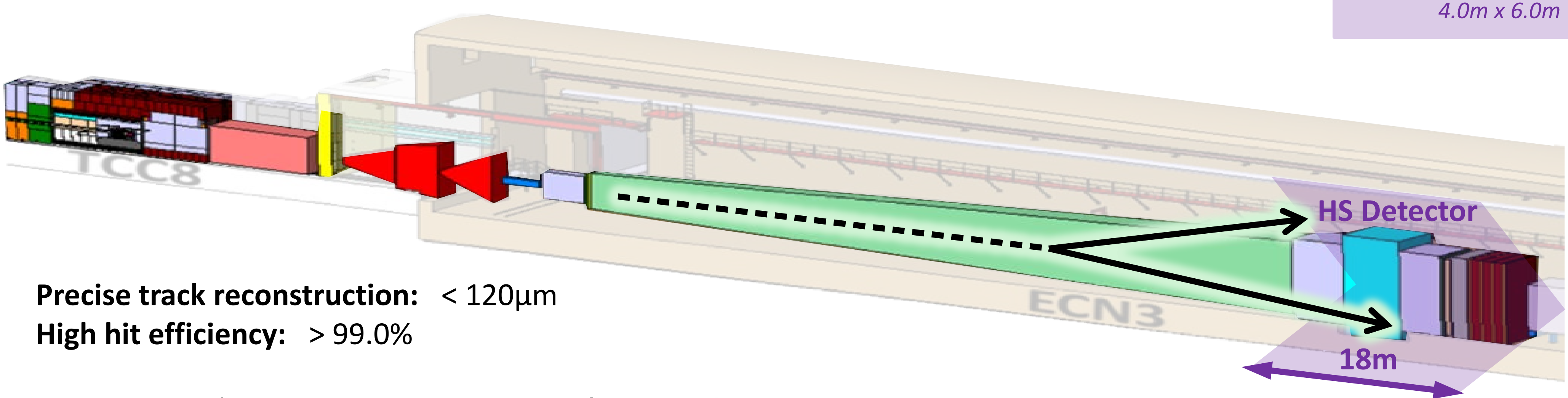




BDF/SHiP: Facility & Detector Technology

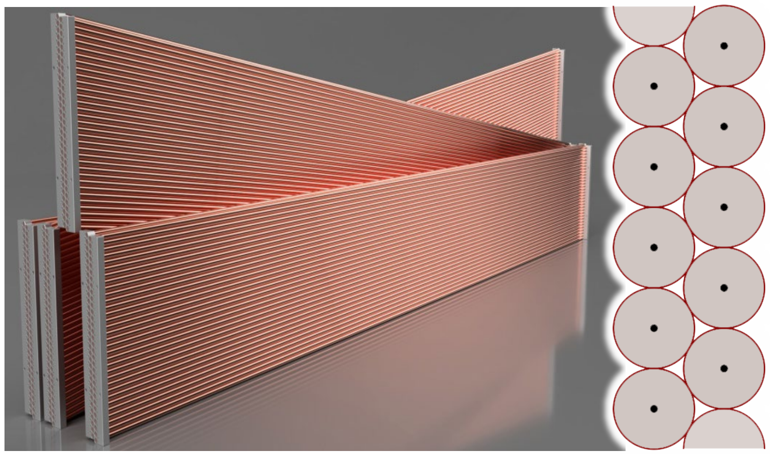
HS Detector: Spectrometer Straw Tracker (SST) & Magnet

Large aperture:
4.0m x 6.0m

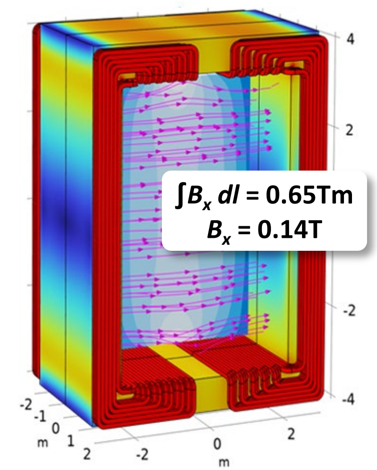


- **Precise track reconstruction:** < 120µm
- **High hit efficiency:** > 99.0%

[CERN-SPSC-2019-049 / SPSC-SR-263, **CERN-SPSC-2023-033 / SPSC-P-369**]



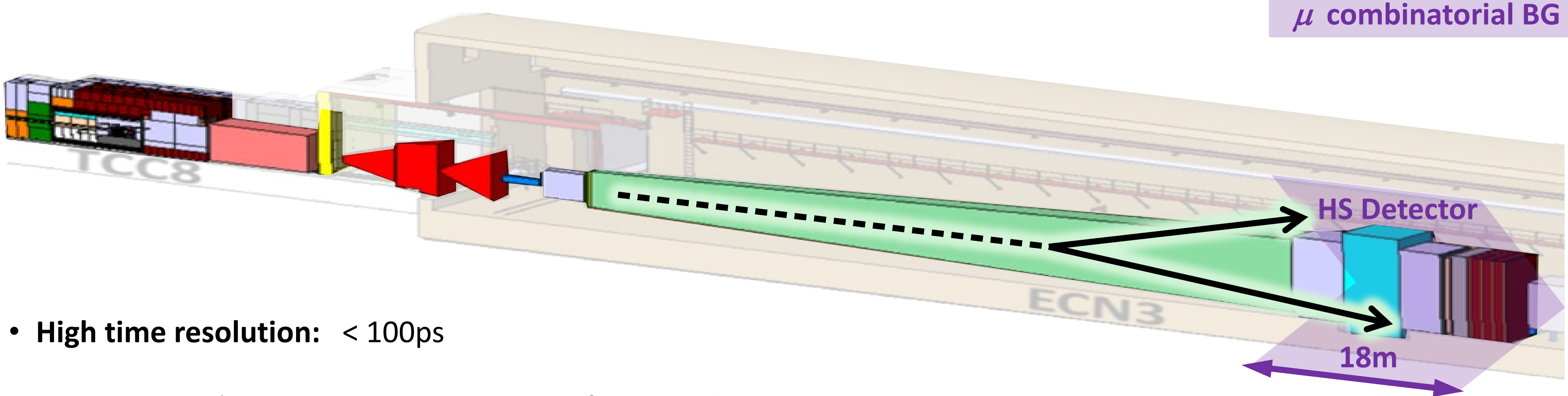
- **Cu/Au-coated Mylar drift tubes (NA62 design):** 4m length, 2cm diameter, 36µm wall thickness, Ar:CO_2 mixture (70:30)
  - ▶ **Low material budget**
- 2x 2 stations of 4 double layers at 10° stereo angle, **10 000 channels altogether**
- **Magnet (NC baseline):** 0.65Tm / 0.15T
  SC options being studied (MgB_2)



BDF/SHiP: Facility & Detector Technology

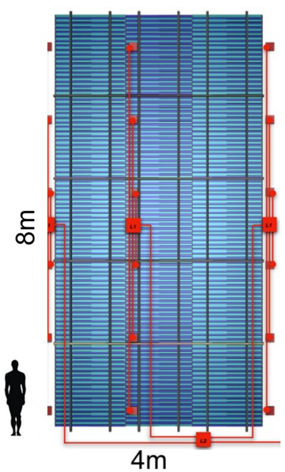
HS Detector: Timing Detector (TD)

Suppression of μ combinatorial BG



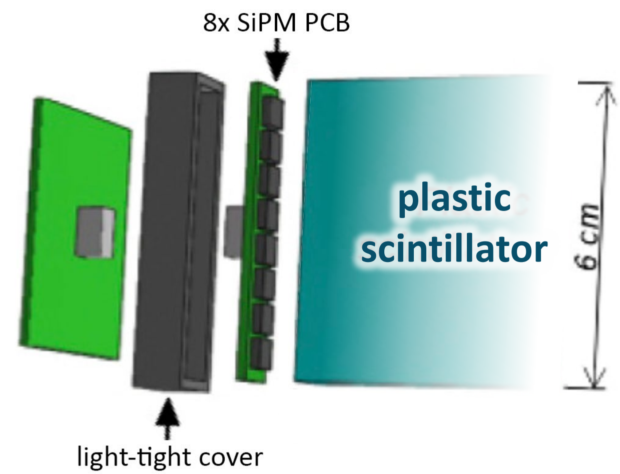
- **High time resolution:** < 100ps

[CERN-SPSC-2019-049 / SPSC-SR-263, **CERN-SPSC-2023-033 / SPSC-P-369**]



- **EJ200 plastic scintillator bars:**
  135cm x 6cm x 1cm
- **Readout** at both ends by **SiPM arrays**
- 3 columns of 111 vertically staggered bars (5mm overlap), **666 channels altogether**

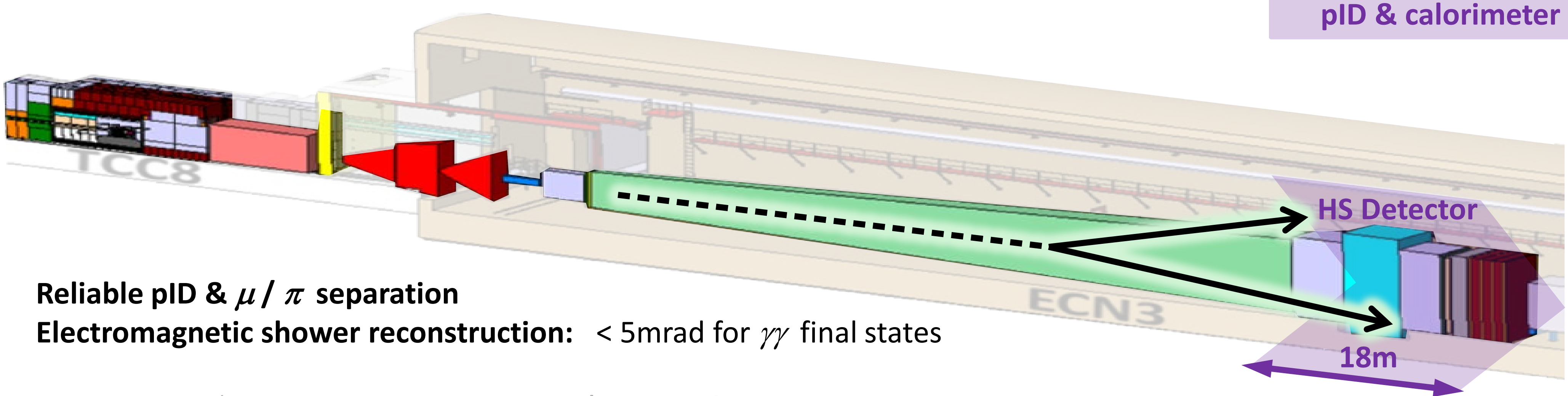
▶ **Timestamp** for SST
▶ **ToF identification** of particle decay products



BDF/SHiP: Facility & Detector Technology

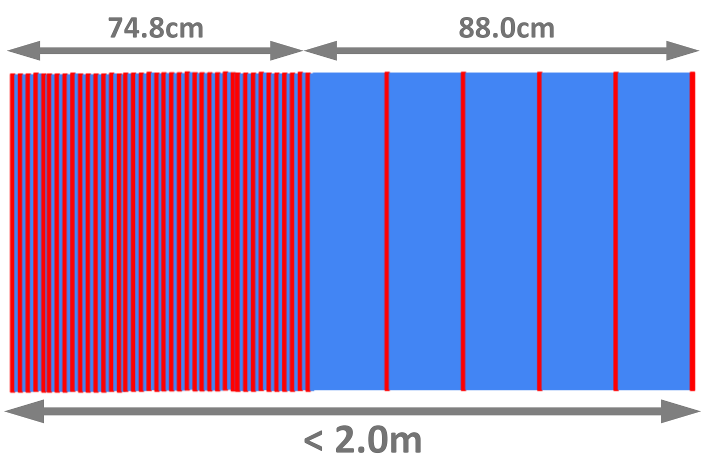
HS Detector: Particle Identification (pID) & Calorimeter (ECal / HCal)

Integrated system of pID & calorimeter



- **Reliable pID & μ / π separation**
- **Electromagnetic shower reconstruction:** < 5mrad for $\gamma\gamma$ final states

[CERN-SPSC-2019-049 / SPSC-SR-263, **CERN-SPSC-2023-033 / SPSC-P-369**]



- **Electromagnetic sampling calorimeter (ECal):**
  40 layers of **thin Fe absorbers** (1/20λ each) & **plastic scintillators**
- **Compact hadron sampling calorimeter (HCal):**
  5 layers of **thick Fe absorbers** (1λ each) & **plastic scintillators**

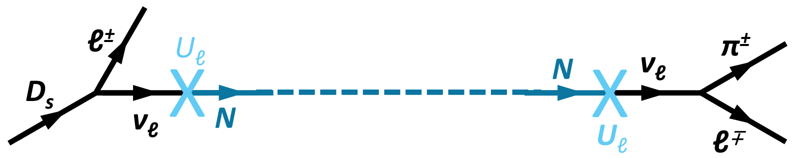
▶ **Total length:** 7λ (> 99.5% π interaction probability)

\+ **1 – 3 MicroMeGaS high-precision layers**
\+ Possible 1m-air gap for **additional μ stations**

SHiP Physics Reach:
Hidden **S**ector **D**ecay **S**pectrometer

Signal vs Background

FIP decay search:



Fully / partially* reconstructed signal events:

Physics model	Final state
HNL	$\ell^+\ell'^-\nu$, $\pi\ell$, $\rho\ell$, $\pi^0\nu$, $q\bar{q}'\ell$
ALPs (fermion coupling)	$\ell^+\ell^-$, 3π , $\eta\pi\pi$, $q\bar{q}$
ALPs (gluon coupling)	$\pi\pi\gamma$, 3π , $\eta\pi\pi$, $\gamma\gamma$
ALPs (photon coupling)	$\gamma\gamma$
Dark photon	$\ell^+\ell^-$, 2π , 3π , 4π , KK , $q\bar{q}$, $D\bar{D}$
Dark scalar	$\ell\ell$, $\pi\pi$, KK , $q\bar{q}$, $D\bar{D}$, GG
SUSY neutralino	$\ell^{\pm}\pi^{\mp}$, $\ell^{\pm}K^{\mp}$, $\ell^{\pm}\rho^{\mp}$, $\ell^+\ell^-\nu$
SUSY sgoldstino	$\ell\gamma$, $\ell^+\ell^-$, 2π , $2K$
Axino	$\ell^+\ell^-\nu$

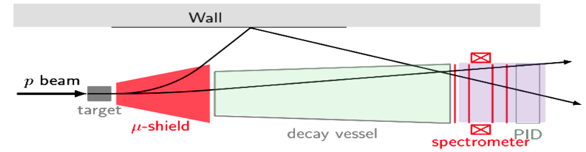
*) Wider distribution of impact parameters

Tracker > Decay vertex of charged particles
Calorimeter > Neutral particles & invariant mass
pID > Model distinction

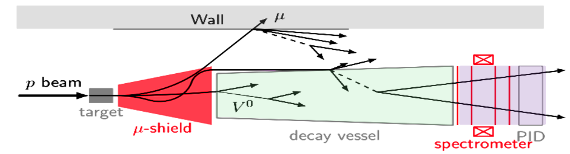
[CERN-SPSC-2023-033 / SPSC-P-369]

BG sources & rejection:

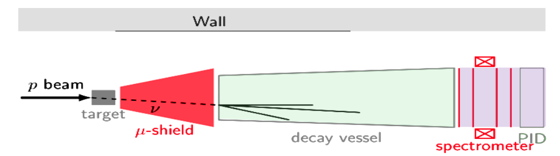
- **μ combinatorial**



- **μ DIS**



- **ν DIS**



> **μ Shield**
> **UBT & SBT**
> **Timing detector**

Remaining expected BG (6x 10^{20} p.o.t.):

BG source	Expected BG events to partially rec. events	fully rec. events
μ combinatorial	(1.3 ± 2.1)x 10^{-4}	
μ DIS	< 0.2	5x 10^{-3}
ν DIS (vacuum)	< 0.3	< 0.1
ν DIS (helium)	~ 1.0	~ 0.6

HSDS Physics Reach: ALPs

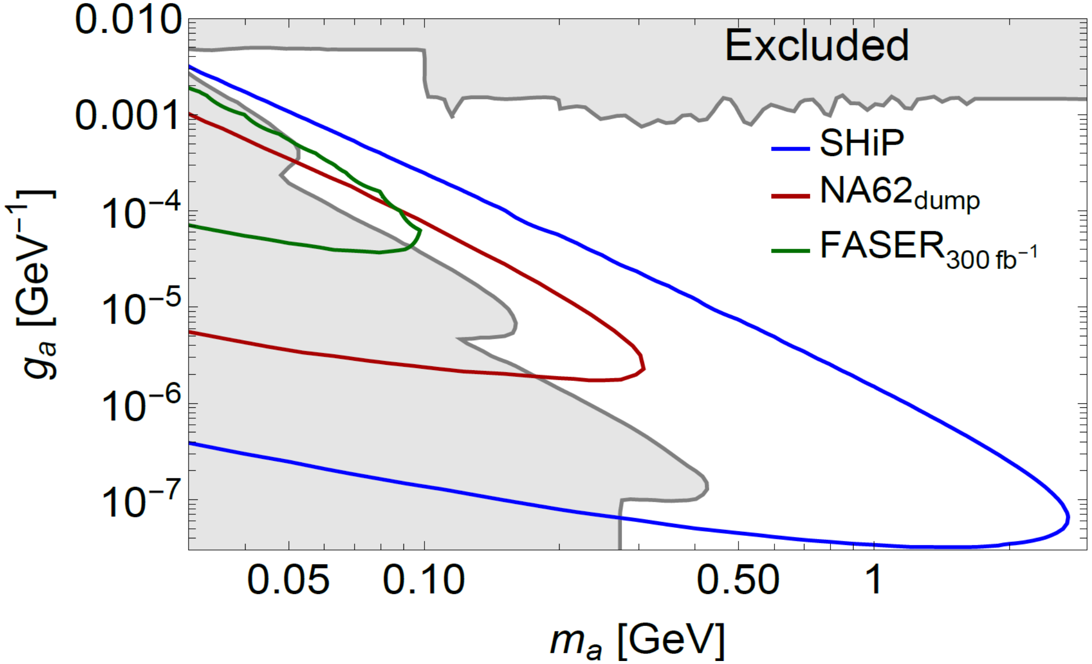
Sensitivity to Axion-Like Particles (ALPs):

90% CL, assuming 6x 10^{20} p.o.t.

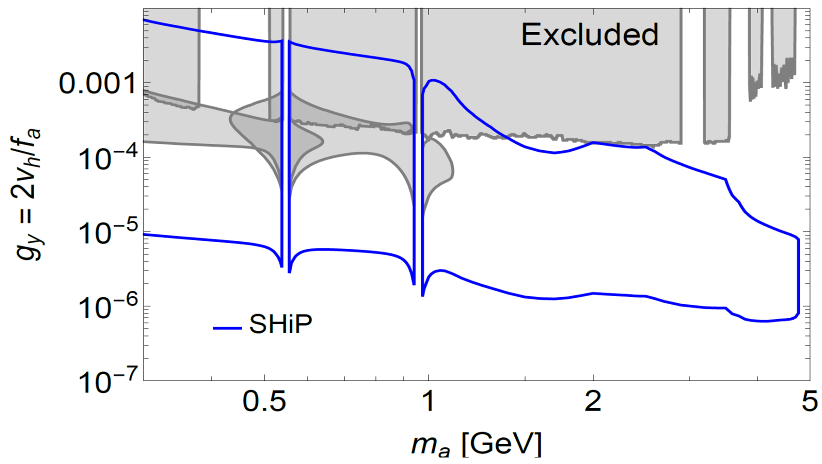
- **SensCalc computation** & **FairSHiP simulation**
- **Production processes:** *B* meson decays, pseudoscalar mixing, Primakoff scattering

[, CERN-SPSC-2022-032 / SPSC-I-258, **CERN-SPSC-2023-033 / SPSC-P-369**]

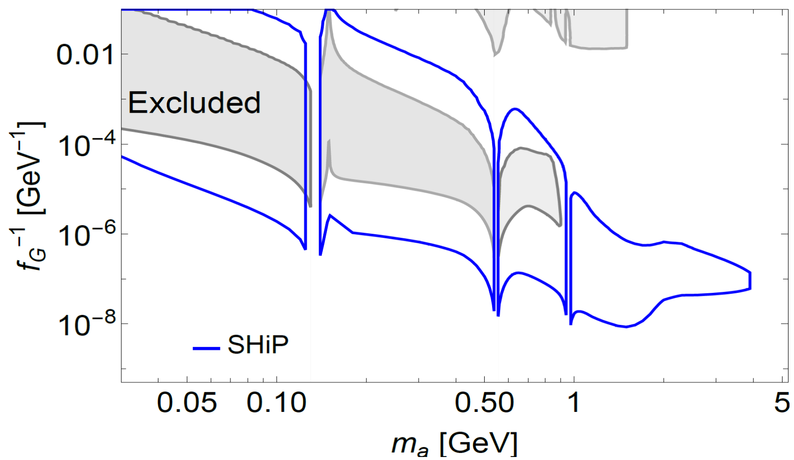
g_a (BC9): Exclusive photon coupling



g_y (BC10): Exclusive fermion coupling



f_G (BC11): Exclusive gluon coupling



HSDS Physics Reach: HNL

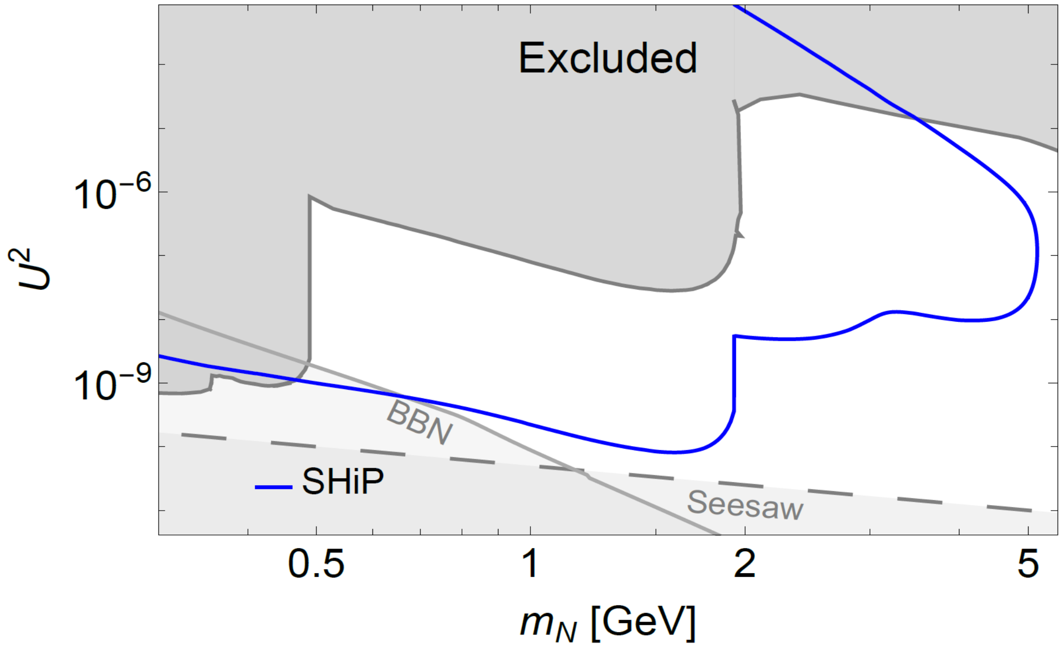
Sensitivity to Heavy Neutral Leptons (HNL):

90% CL, assuming 6x 10^{20} p.o.t.

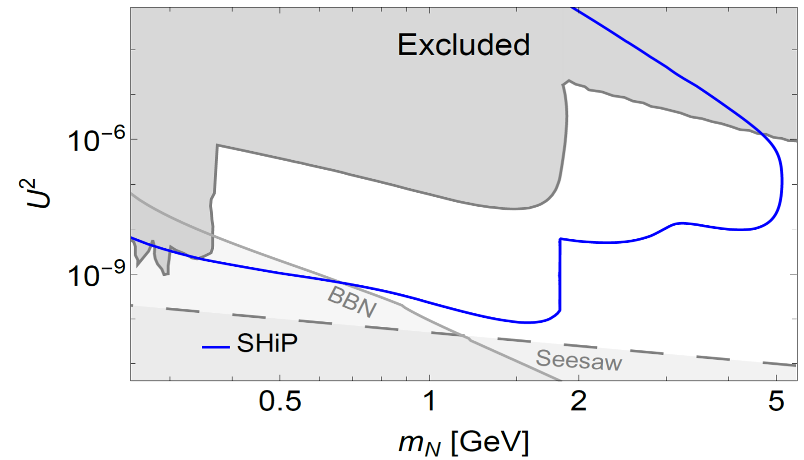
- **SensCalc computation** & **FairSHiP simulation**
- **Production processes:** *D* & *B* mesons decays

[**JHEP04(2019)077**, CERN-SPSC-2022-032 / SPSC-I-258, **CERN-SPSC-2023-033 / SPSC-P-369**]

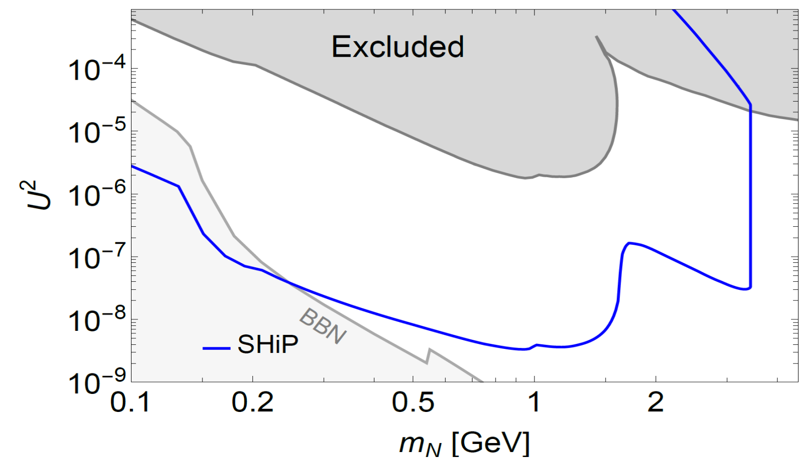
***U_e^2* (BC6):**



***U_μ^2* (BC7):**



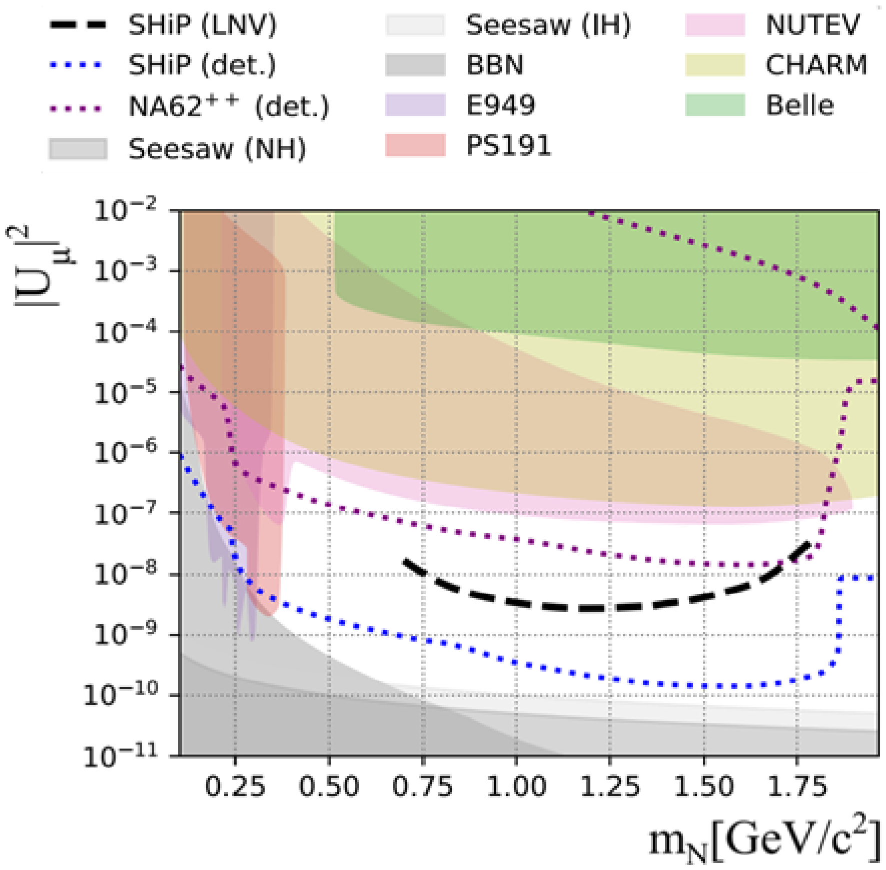
***U_τ^2* (BC8):**



HSDS Physics Reach

HNL & Lepton Number Violation (LNV):

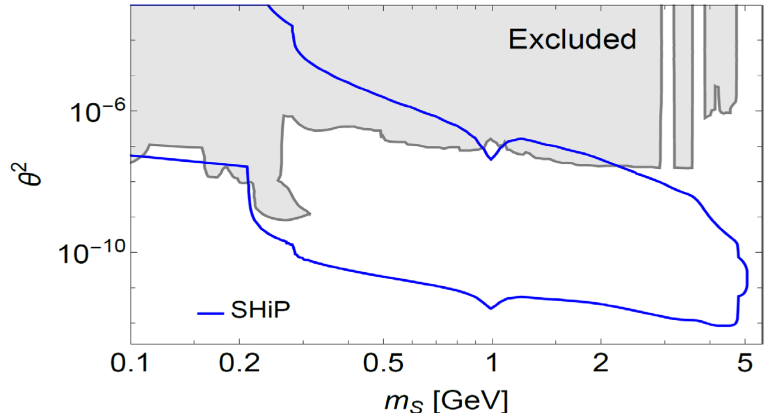
distinguish between Majorana- and Dirac-type HNL in significant fraction of parameter space



[**JHEP04(2020)005**, CERN-SPSC-2022-032 / SPSC-I-258, **CERN-SPSC-2023-033 / SPSC-P-369**]

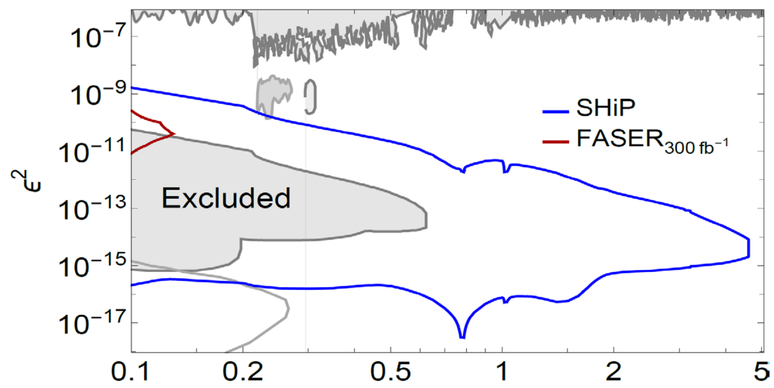
Sensitivity to dark scalars: θ^2 (BC4)

90% CL, assuming 6x 10^{20} p.o.t., Higgs portal



Sensitivity to dark photons: ε^2 (BC1)

90% CL, assuming 6x 10^{20} p.o.t., vector portal



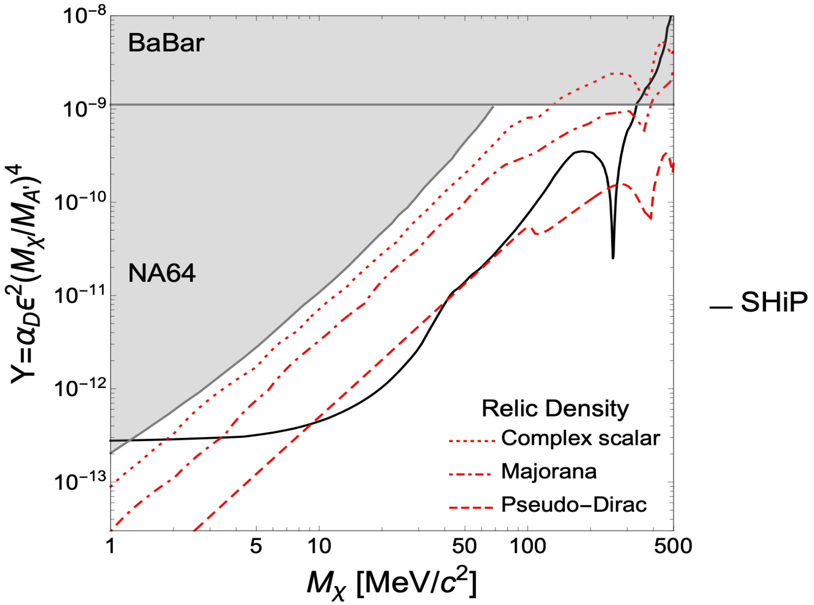
[**EPJC(2021)81:451**]

SHiP Physics Reach:
Scattering & **N**eutrino **D**etector

SND Physics Reach

Direct Search for Light Dark Matter (LDM):

90% CL, assuming 6x 10^{20} p.o.t.



- **Expected BG:** ν elastic & QE scattering

	ν_e	$\overline{\nu}_e$	ν_μ	$\overline{\nu}_\mu$	Total
elastic (*e*)	156	81	192	126	**555**
QE	-	27	-	-	**27**
RES	-	-	-	-	**-**
DIS	-	-	-	-	**-**
Total	156	108	192	126	582

[CERN-SPSC-2022-032 / SPSC-I-258, **CERN-SPSC-2023-033 / SPSC-P-369**]

Neutrino physics performance:

assuming 6x 10^{20} p.o.t.

- **Expected CC DIS interactions:**

	<E> [GeV]	CC DIS interactions	CC DIS charm production
N ν_e	63	2.8x 10^6	1.7x 10^5
N ν_μ	40	8.0x 10^6	3.5x 10^5
N ν_τ	54	8.8x 10^4	
N $\overline{\nu}_e$	49	5.9x 10^5	0.3x 10^5
N $\overline{\nu}_\mu$	33	1.8x 10^6	0.7x 10^5
N $\overline{\nu}_\tau$	74	6.1x 10^4	

- **Expected observed ν_τ ($\overline{\nu}_\tau$) signal events:**

Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to e$	8 000	
$\tau \to \mu$	4 000	3 000
$\tau \to h$	27 000	
$\tau \to 3h$	11 000	
Total	53 000	

SND Physics Reach

High-statistics ν_τ physics:

- ν_τ **cross section**
- First **direct measurement of $\bar{\nu}_\tau$**
- ν_τ **magnetic moment**

DIS structure functions:

measurement of F_4 and F_5 in ν_τ / $\bar{\nu}_\tau$ interactions

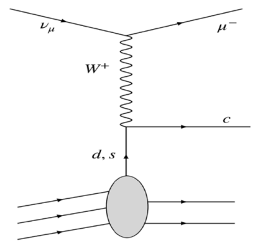
$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\Bigg((y^2 x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})\right] F_2 \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right] F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x} F_4 - \frac{m_\tau^2}{E_\nu M} F_5\Bigg),$$

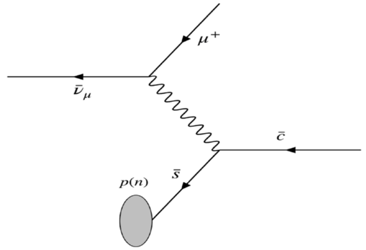
negligible in ν_μ interactions,
but **accessible for ν_τ interactions**
(LO / NLO)

[CERN-SPSC-2015-017, **CERN-SPSC-2023-033 / SPSC-P-369**]

Neutrino-induced charm production:

limited ν_μ / $\bar{\nu}_\mu$ statistics so far, no charm from ν_e yet…





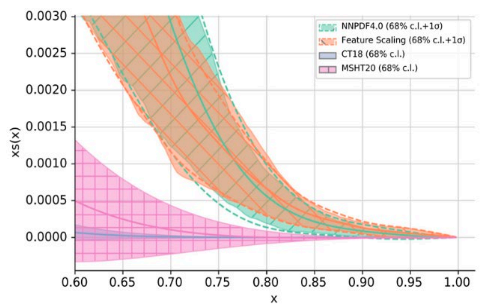
CKM precision measurement: $|V_{cd}|$

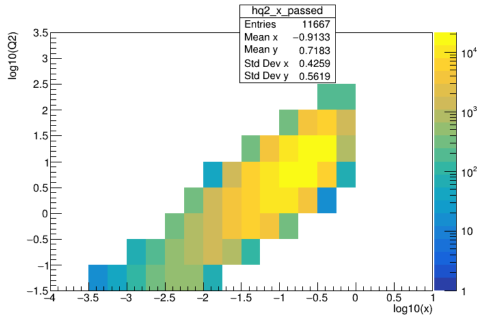
tagging of inclusive c / $\bar{c}$ production in μ / $\bar{\mu}$ DIS

- Independent of knowledge of **branching fractions**

Parton distribution functions:

s -> c & $\bar{s}$ -> $\bar{c}$ transitions





Summary & Outlook

Summary & Timeline: BDF/SHiP @ECN3

State-of-the-art general-purpose intensity-frontier beam-dump facility:

a diverse programme complementary to the energy frontier

- Take ***full** advantage* of the **4×10^{19} p.o.t./year** at **400 GeV** offered by the **CERN SPS**
- Search for **FIPs** in a **region of mass & coupling** that is ***only*** accessible with a dedicated **beam-dump** configuration
- Search for new physics via ***both*** **decay and scattering** signatures
- ***Comprehensive*** **neutrino physics program**

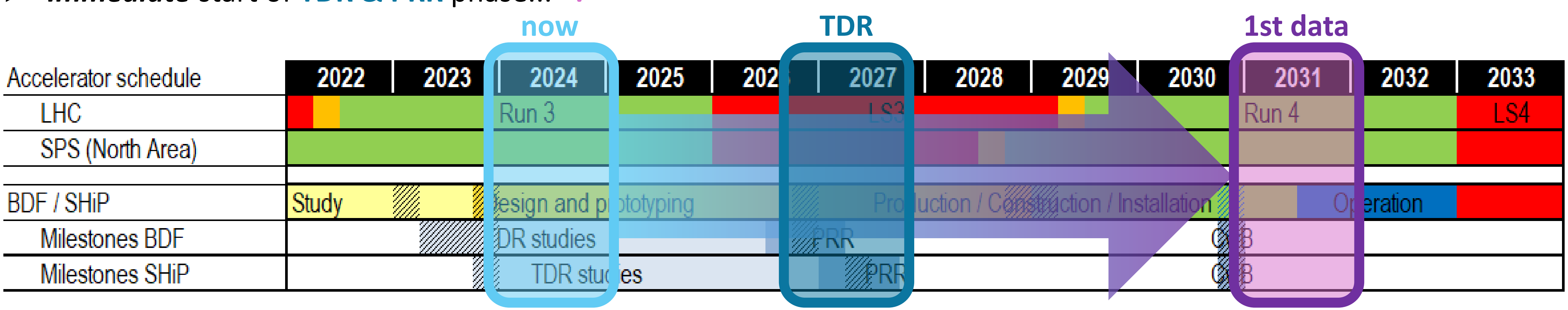
Early 2023: Experiment-***agnostic*** SPSC **recommendation for ECN3 High-Intensity facility** ✓

► Advanced beam delivery studies and refined experiment proposals ✓

Early 2024: Experiment-***specific*** SPSC recommendation & CERN Research Board **decision for BDF/SHiP** ✓

► Go-ahead for ECN3 High-Intensity facility in **2024 – 2028 CERN Medium-Term Plan** ✓

► ***Immediate*** start of **TDR & PRR** phase... !



The reward of work well done…

is more work

[38 institutes from 15 countries & CERN]

…come join the crew!