SHiP
Search for Hidden Particles

Search for Hidden Particles (SHiP/NA67) experiment at the SPS Beam Dump Facility

R. Jacobsson

on behalf of the SHiP Collaboration of 39 institutes from 16 countries and CERN

Mass or coupling?

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

$$\mathcal{L}_{eff} = (\mathcal{L}_{gauge})_{dim\leq 4} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda_{NP}^{d-4}} \mathcal{O}^{(d)}$$

With sizeable couplings
$\Lambda_{NP}^{d-4} \gg$ EW scale

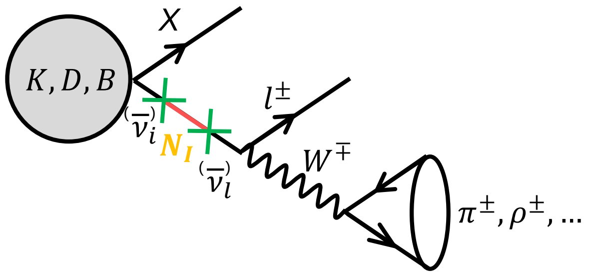
- New Physics should either be very heavy OR interact very feebly to have escaped detection!

- *New opportunities offered by the "equivalence" of mass scale and coupling scale!*
  - "Coupling Frontier" : Any Particles engaging in Feeble Interactions (FIPs) with the SM particles
  - ➔ Fair (but not necessary) starting point: *Dark Matter*
  - ➔ Another starting point: *Sterile neutrinos*

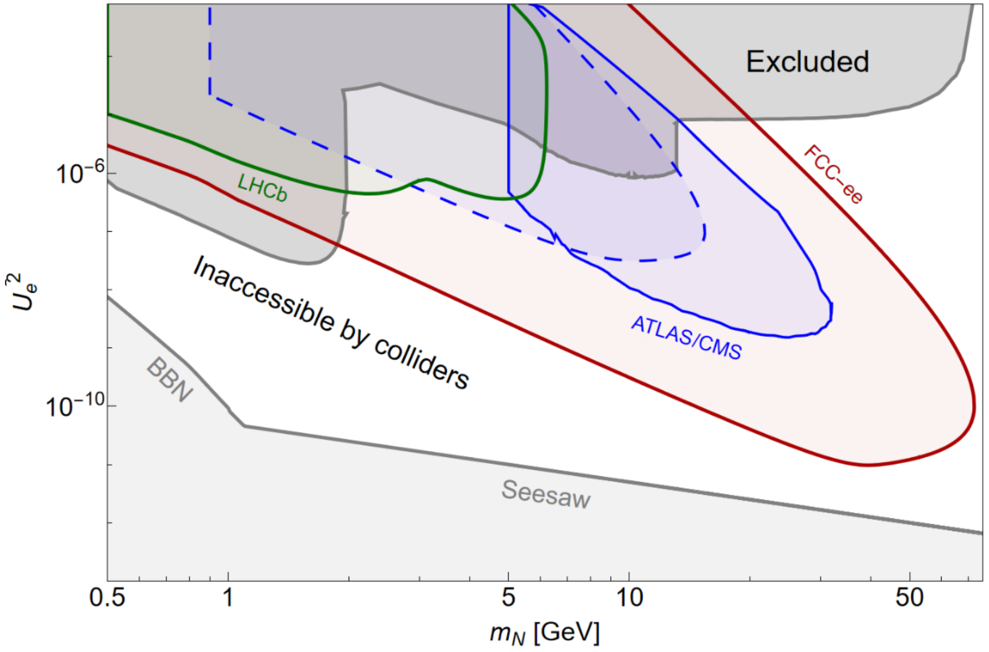
- Enough reasons to build a dedicated accelerator-based facility to explore FIPs, optimized for discovery
  - We are sharing the Universe already with feebly coupled and not-understood neighbours!
  - Light feebly coupled sector can provide solutions to well-established problems!
  - Exploration of Feebly Interacting Particles up to now mainly as by-product of experiments built for other purposes
  - Essential complementarity with projects in launch/commissioning on the cosmofrontier
  - One of the main objectives of HL-LHC (and FCC) will be exploring FIPs…

Why SHiP@SPS?

- SPS accelerator energy and intensity unique to explore *Light Dark Matter and associated mediators, and ν mass generation* – FIPs generically - Region that can *only* be explored by optimised beam-dump experiment
  - ➔ Large lifetime acceptance - production modes in limited forward cone
  - ➔ SPS energy and intensity provide huge production of charm, beauty and electromagnetic processes



E.g. Heavy Neutral Leptons



- Return CERN SPS accelerator to full exploitation of unique physics potential made available with termination of CNGS
  - ➔ "SHiP Physics Proposal" *Rep. Prog. Phys.* **79** (2016)124201
  - ➔ Unique *direct discovery potential in the world in the heavy flavour region,* capable of reaching "physical/technical floor"

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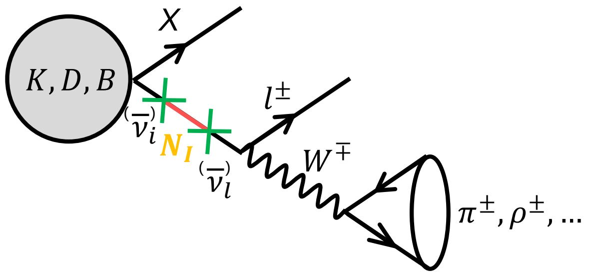

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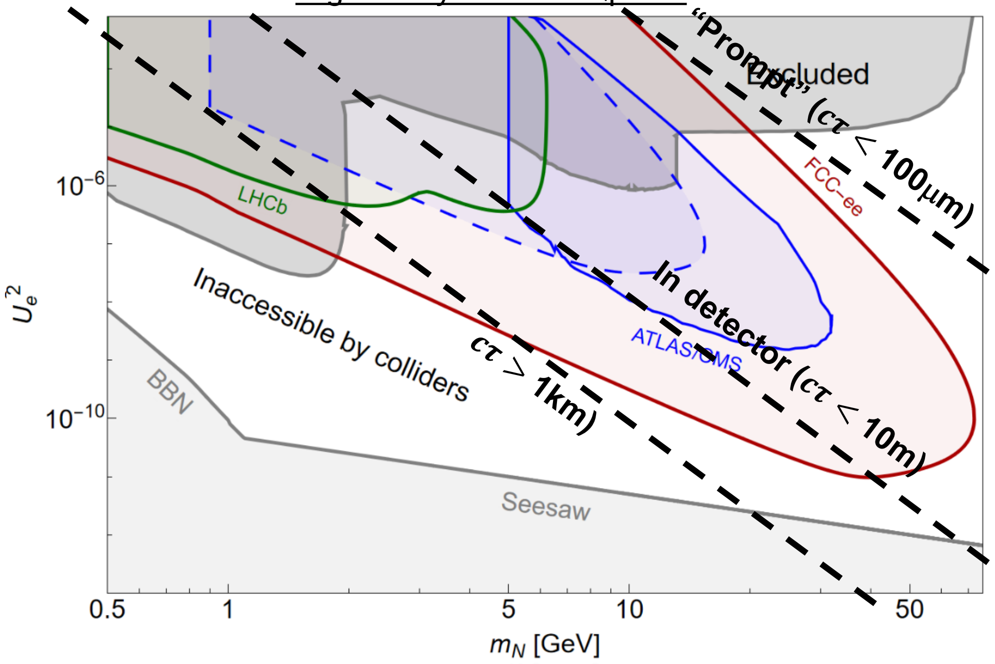

$$\tau_N \sim \frac{96\pi^2 h}{|\mathcal{U}|^2 G_F^2 M_N^5}$$

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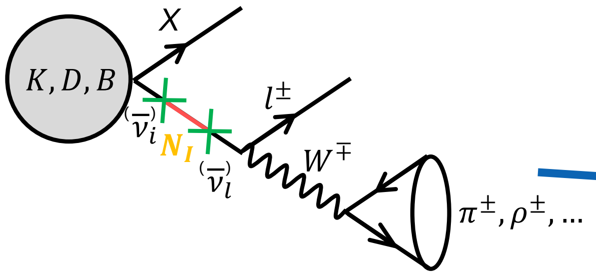

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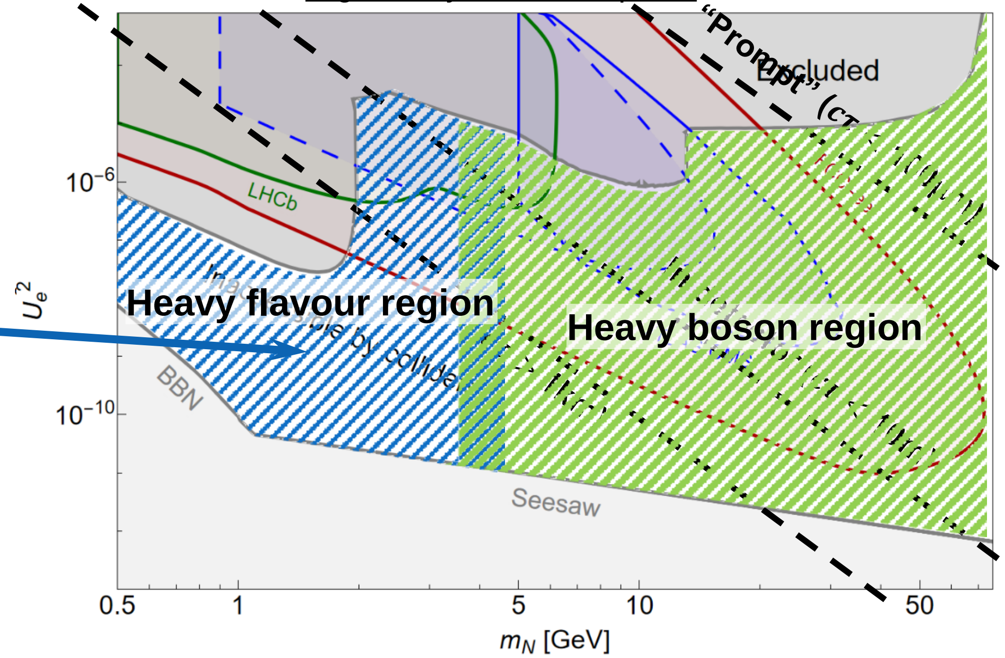

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BDF/SHiP optimization of physics reach

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

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

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

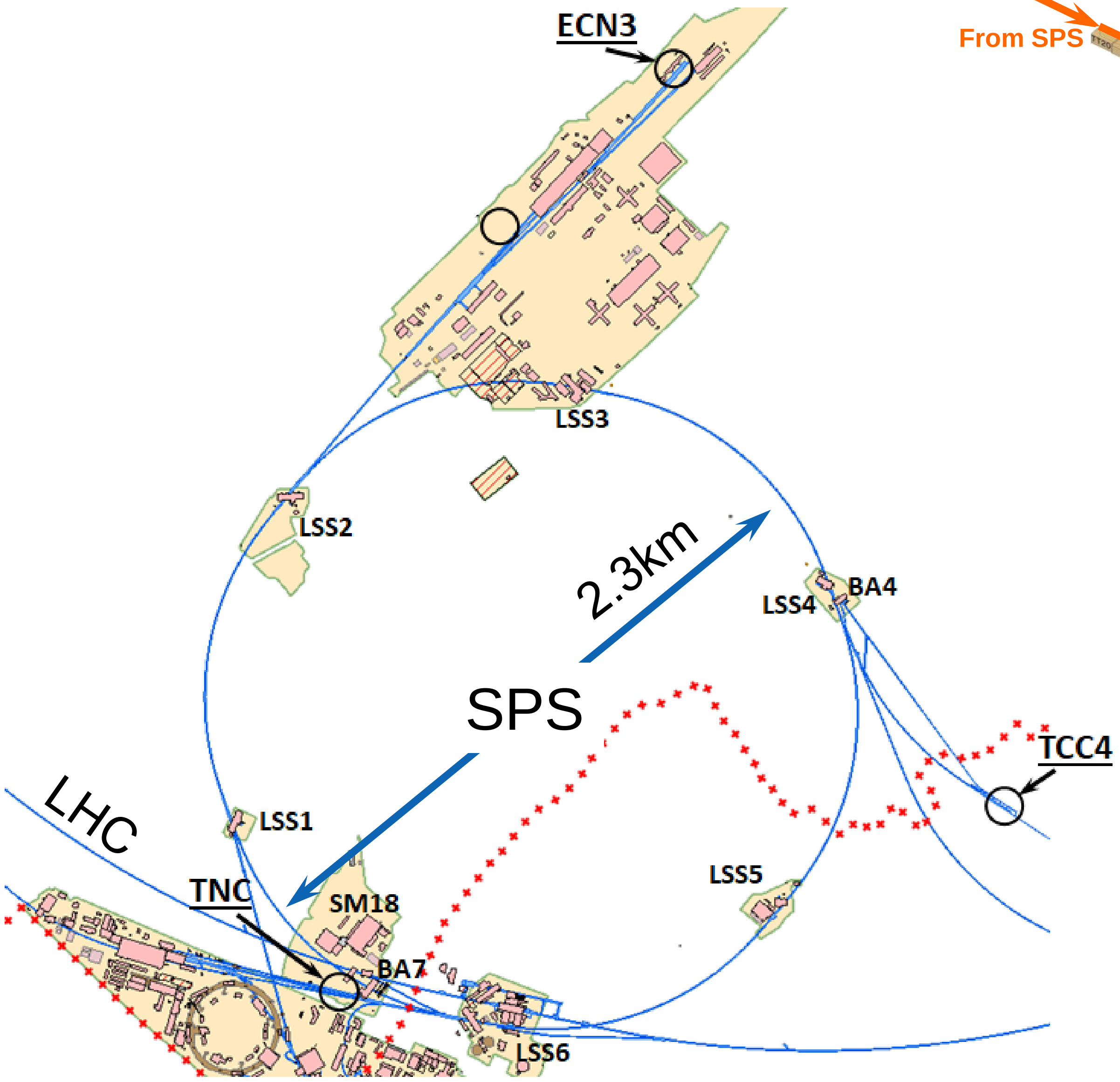
→ HL-LHC $\mathcal{L}_{int}[year^{-1}]$ = 10^{42} cm^{-2}

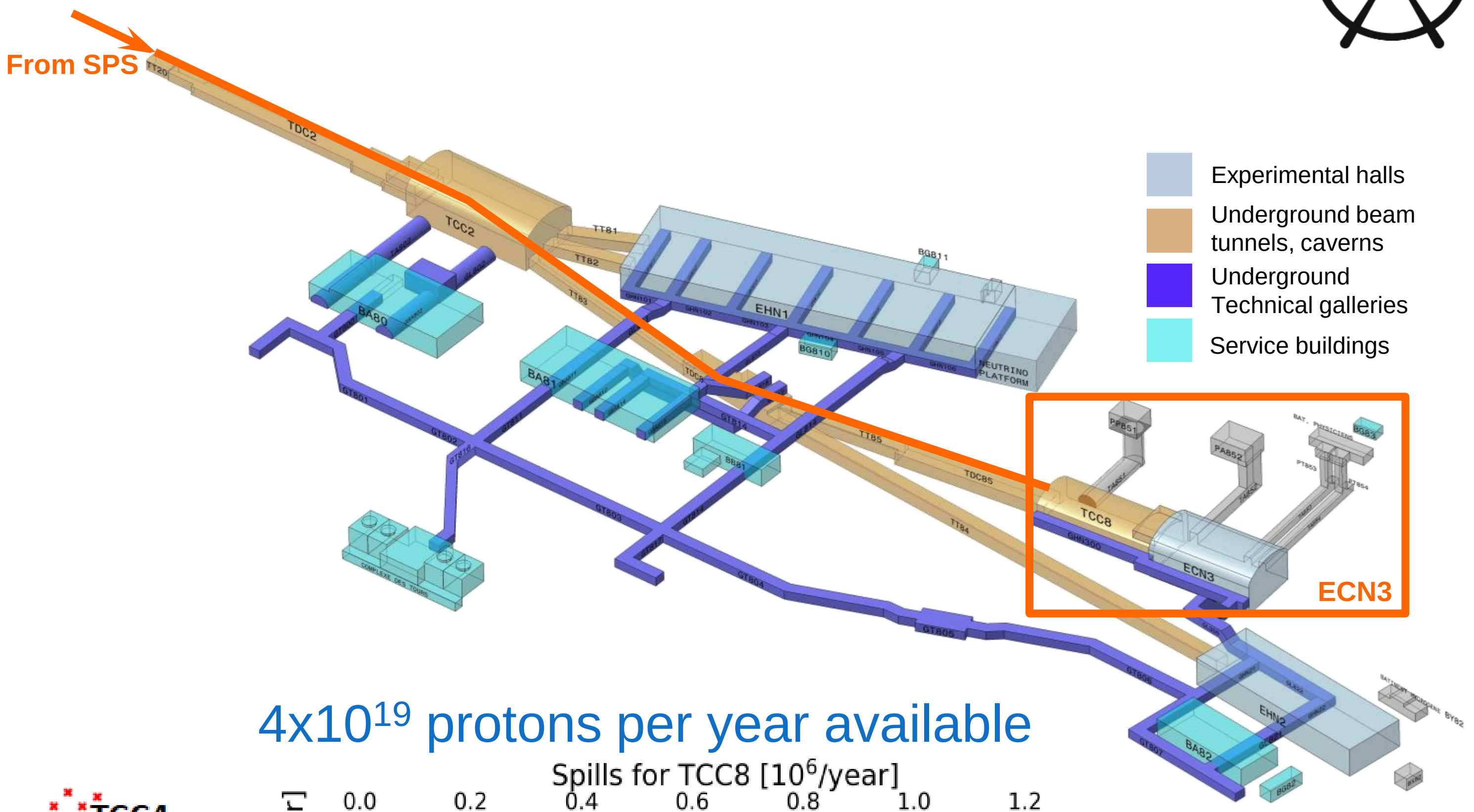
→ BDF/SHiP ***annually*** access to yields inside detector acceptance:

- ~ 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

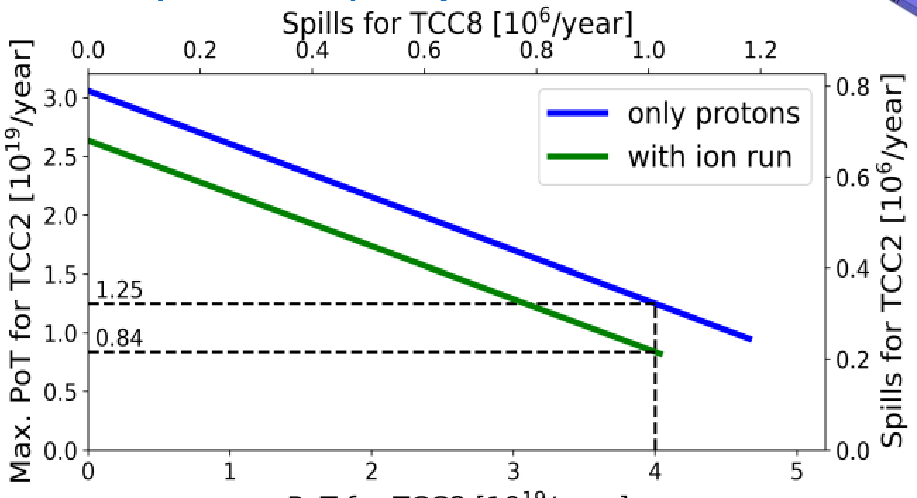
- No technical limitations to operate beam and facility with 4x10^{19} protons/year for 15 years

SHiP @ SPS ECN3 beam facility

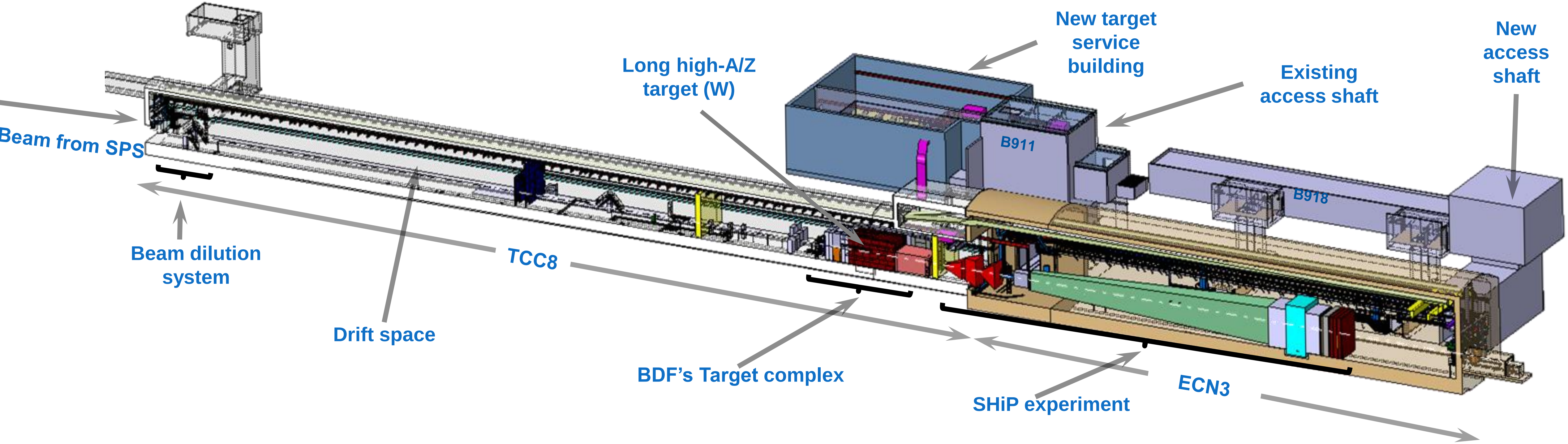




4×10^{19} protons per year available



Overview of BDF/SHiP @ SPS ECN3



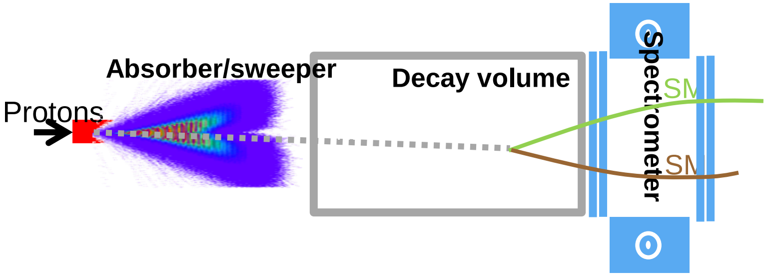
<u>Also at NBI2024:</u>

- The new ECN3 high intensity facility for the BDF/SHiP experiment and high intensity beam transfer (**Matthew Fraser**)
- Design considerations for the BDF/SHiP production target (**Rui Franqueira Ximenes**)
- BDF target station design (**Jean-Louis Grenard**)
- Radiation protection studies and considerations for the ECN3 high intensity project (**Claudia Ahdida**)

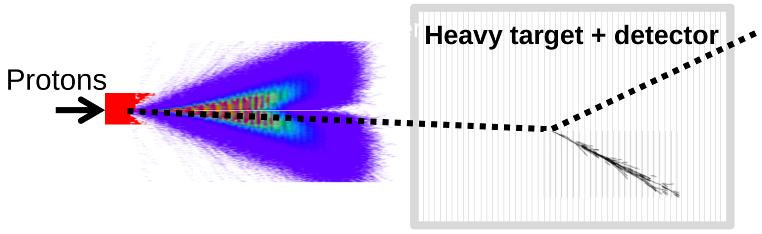
BDF/SHiP experimental techniques

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

Decay signatures



Scattering signatures



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**

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

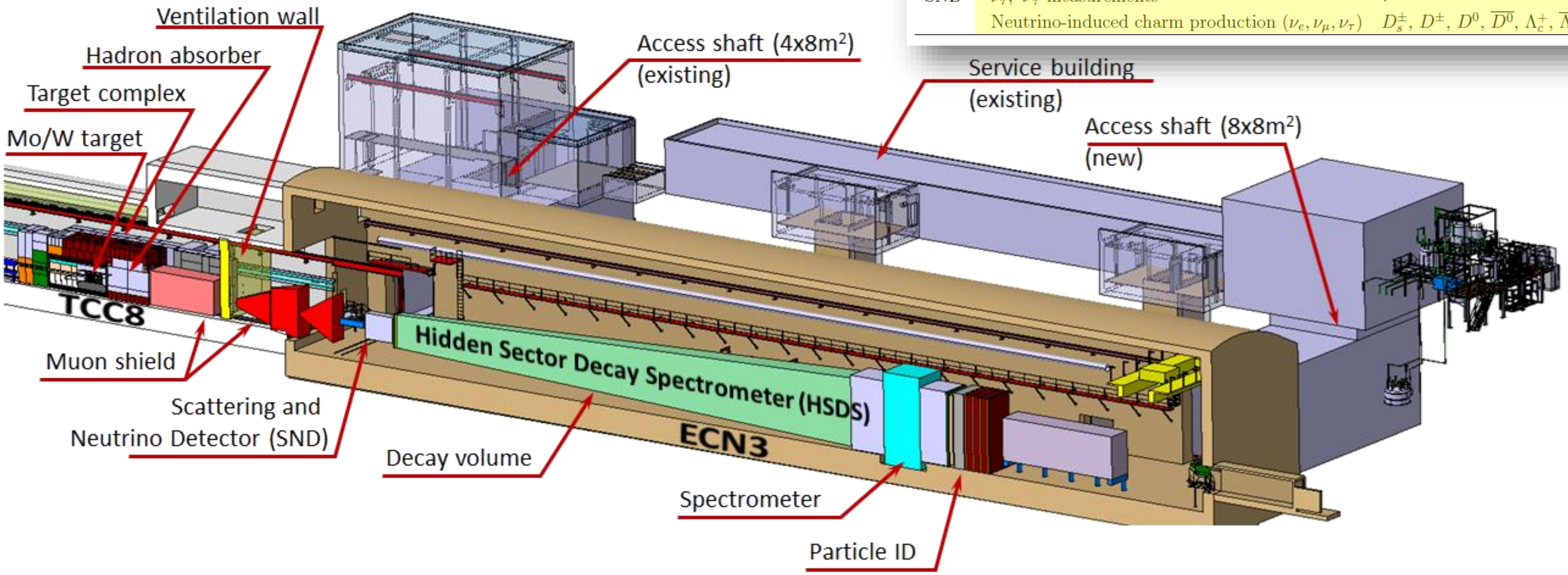
➔ **Rich "bread and butter" neutrino interaction physics with unique access to tau neutrino**

BDF/SHiP in ECN3

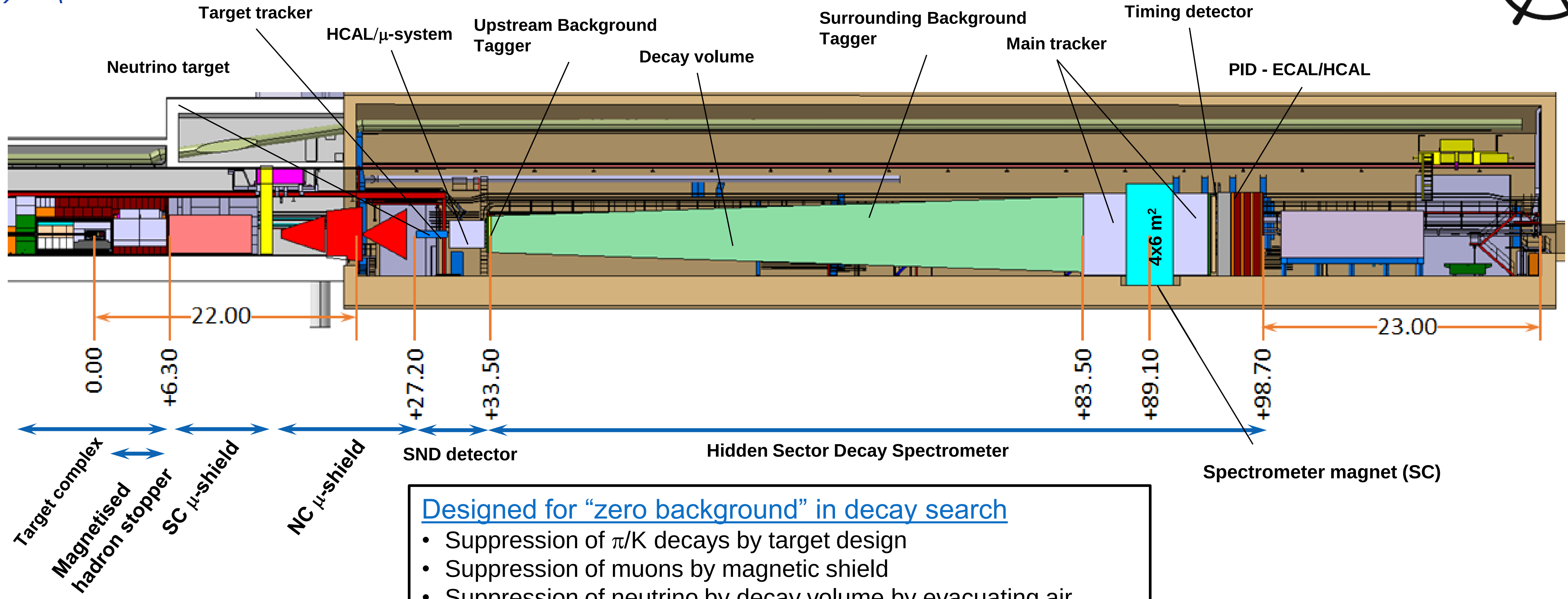
Two separate detector systems: “SND” and “HSDS”

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
	$\nu_\tau,\ \overline{\nu}_\tau$ measurements	$\tau^\pm$
	Neutrino-induced charm production (ν_e, ν_μ, ν_τ)	$D_s^\pm,\ D^\pm,\ D^0,\ \overline{D^0},\ \Lambda_c^+,\ \overline{\Lambda_c}^-$



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 by evacuating air
- Background veto taggers
- Momentum and decay vertex information } by main tracker
- Impact parameter at target } by main tracker
- Coincidence timing

- Invariant mass } Not currently used in background suppression
- Particle identification } Not currently used in background suppression

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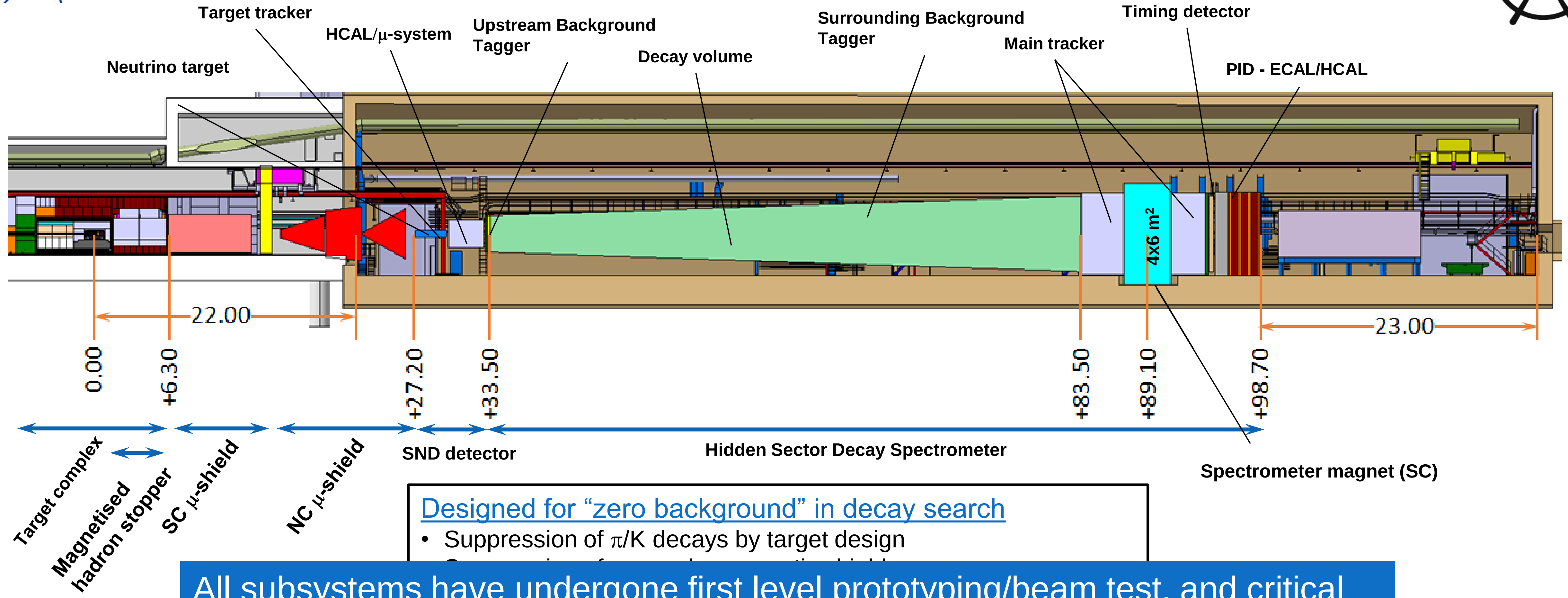

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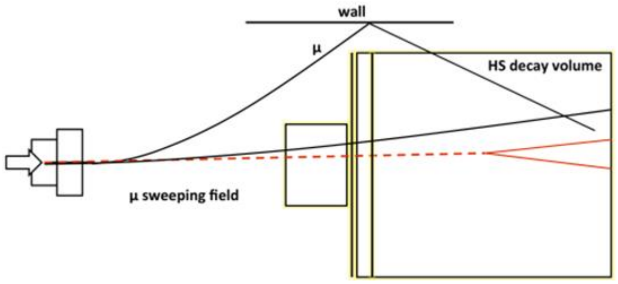
All subsystems have undergone first level prototyping/beam test, and critical components have been through large-scale prototyping

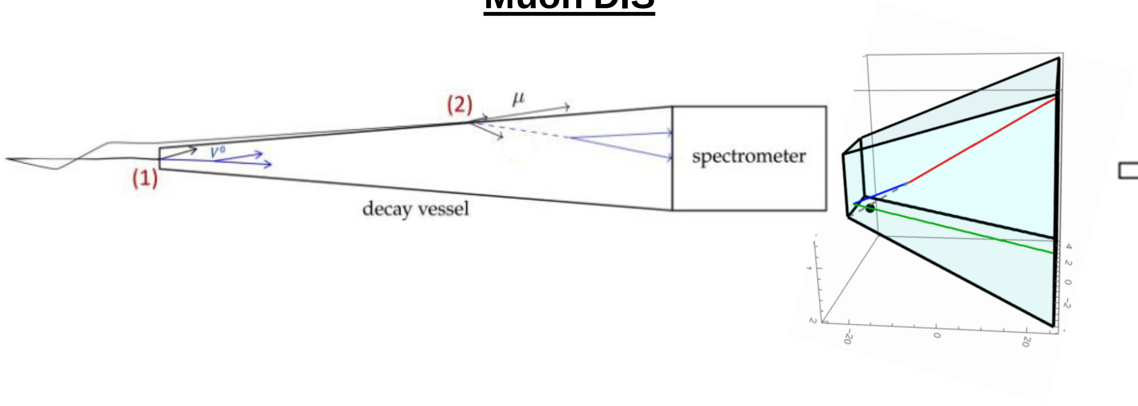
HSDS: FIP decay search background evaluation

Residual flux of muons and neutrinos lead to three categories of physics background

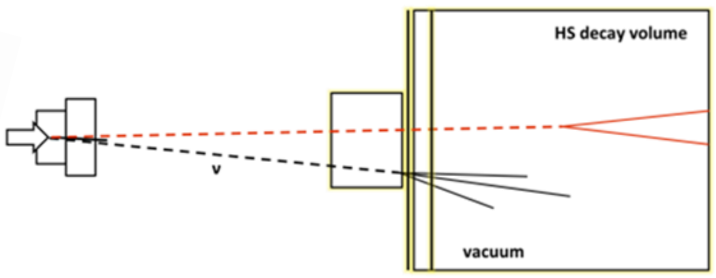
Muon combinatorial



Muon DIS



Neutrino DIS



➔ Very simple and common selection for both fully and partially reconstructed modes – model independence

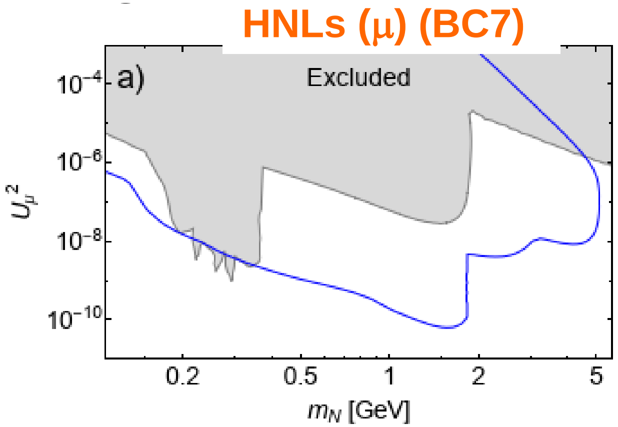
Expected background is <1 event
for 6×10^{20} pot (15 years of operation)

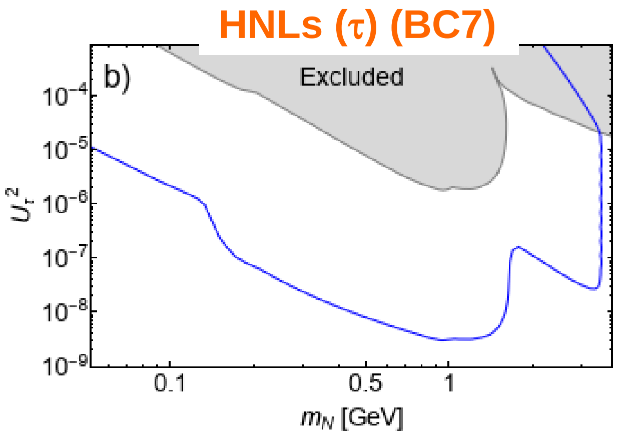
Background source	Expected events
Neutrino DIS	< 0.1 (fully)/$<$ 0.3(partially)
Muon DIS (factorisation)*	$< 5 \times 10^{-3}$ (fully) / $<$ 0.2(partially)
Muon combinatorial	$(1.3 \pm 2.1) \times 10^{-4}$

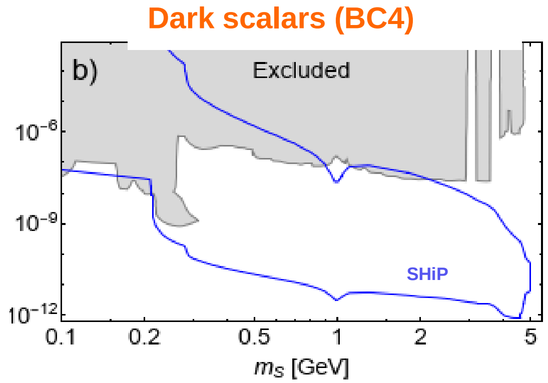
➔ Selection redundant - Possibility to measure background with data by relaxing suppression techniques

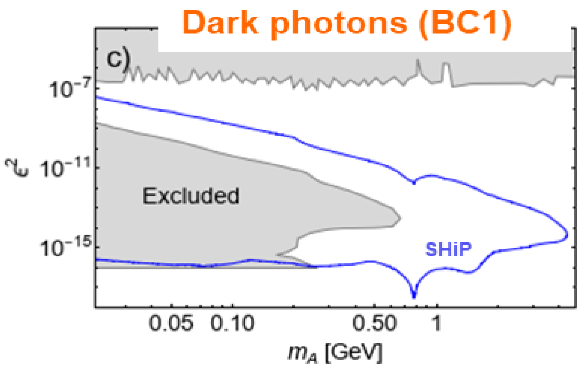
SHiP decay search performance

Benchmark examples:



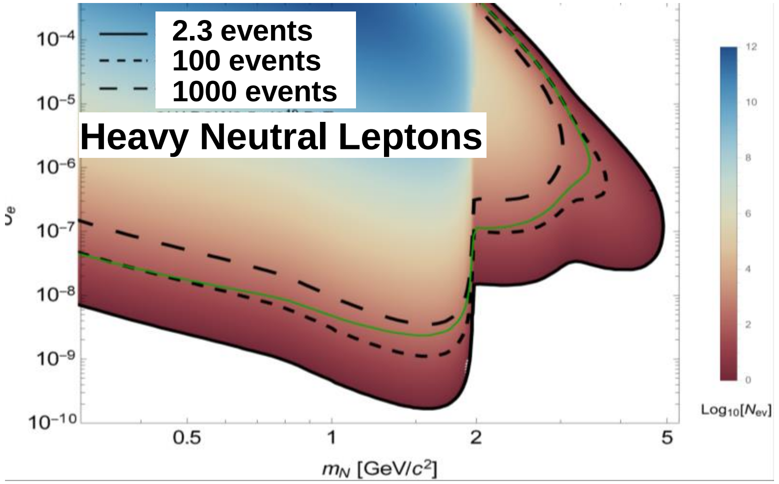






➔ Exploration of (2-5 ⊗ 1-2) orders of magnitude (coupling^2 ⊗ mass) beyond current experiments

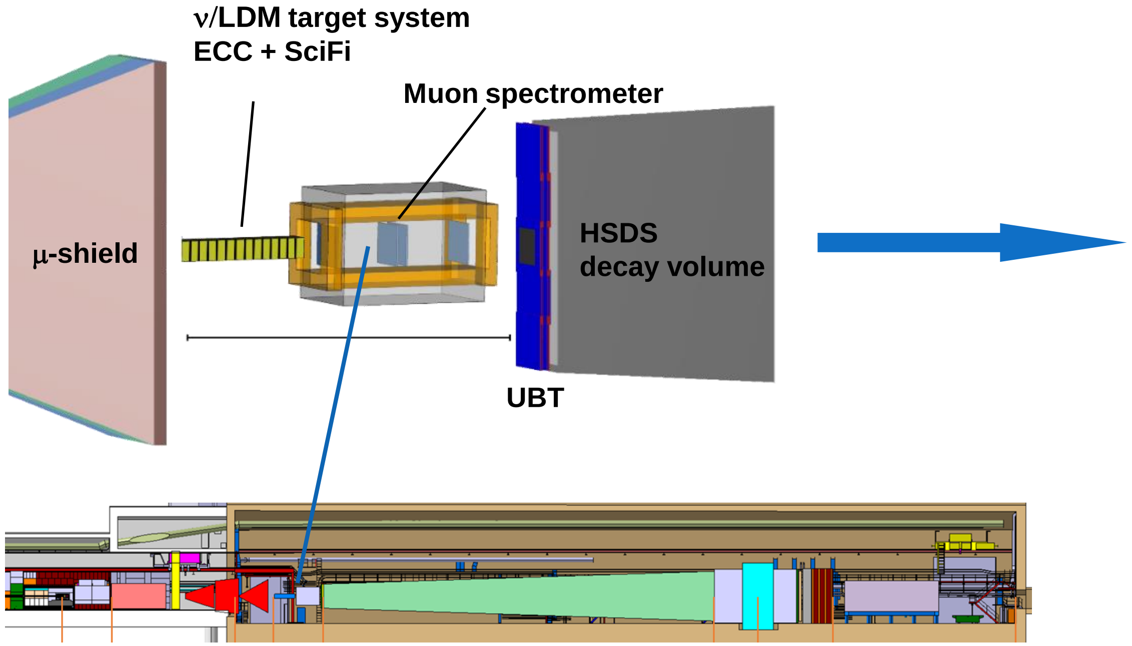
- Experiment aimed at discovery and measurements ➔ Number of signal events
  - ➔ Step 1: Characterise new object - precise mass, branching ratios, spin: $\mathcal{O}(10)$ evts
  - ➔ Step 2: Test compatibility with hypothesis addressing SM issues: $\mathcal{O}(100 - 1000)$ evts

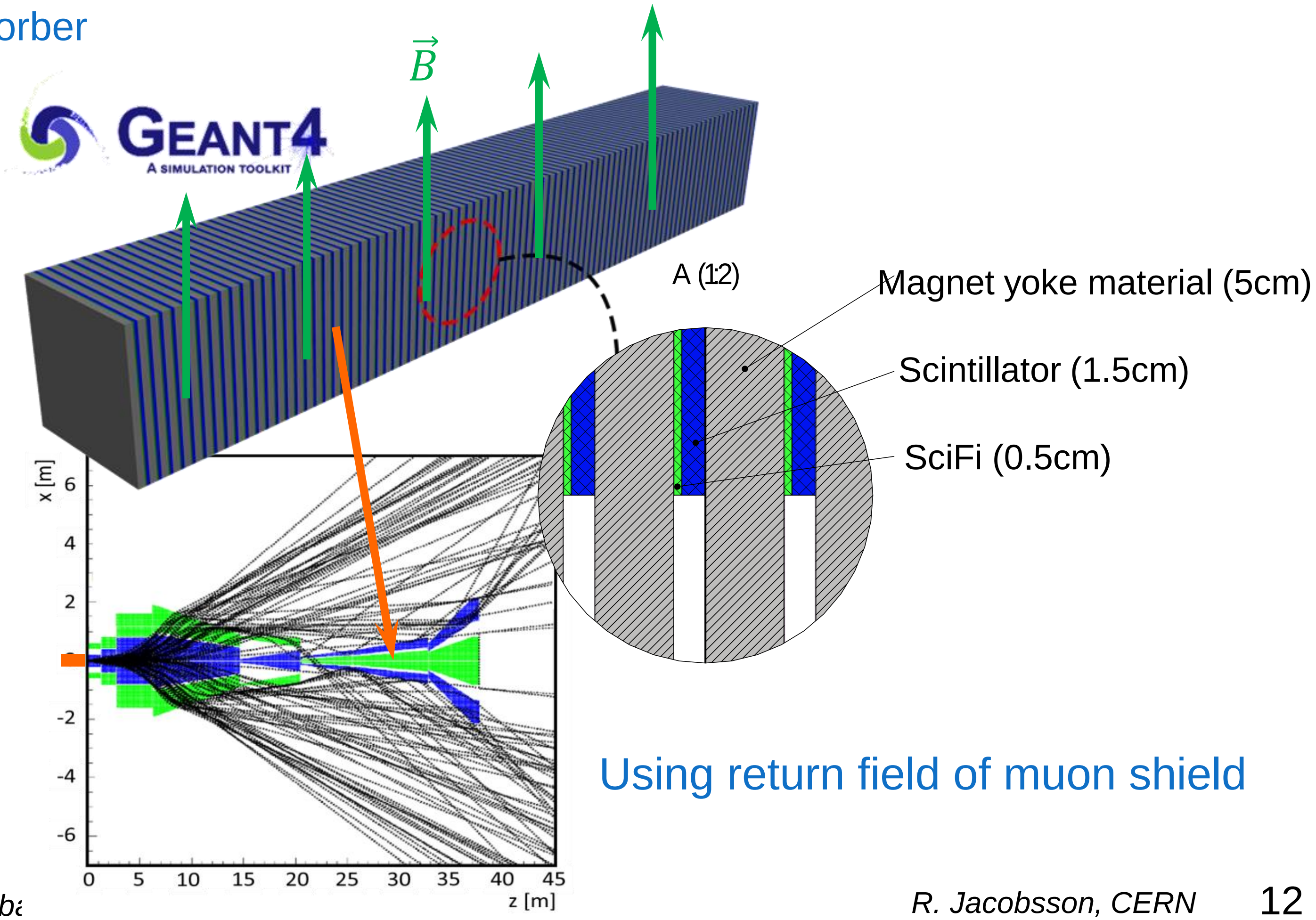


Could for instance observe oscillations between Lepton Number Violating and Conserving event rates and mass splitting between HNLs

LDM scattering and neutrino detector (SND)

- Purpose
  - Sensitivity to scattering signatures of neutrinos and light dark matter
  - ➔ Neutrino flavour identification, energy, and muon momentum and charge measurement
  - ➔ Ongoing revision to build SND detector only from electronic detectors integrated into SHiP μ-shield
  - ➔ Tracker / fine-segmented HCAL with magnetised absorber





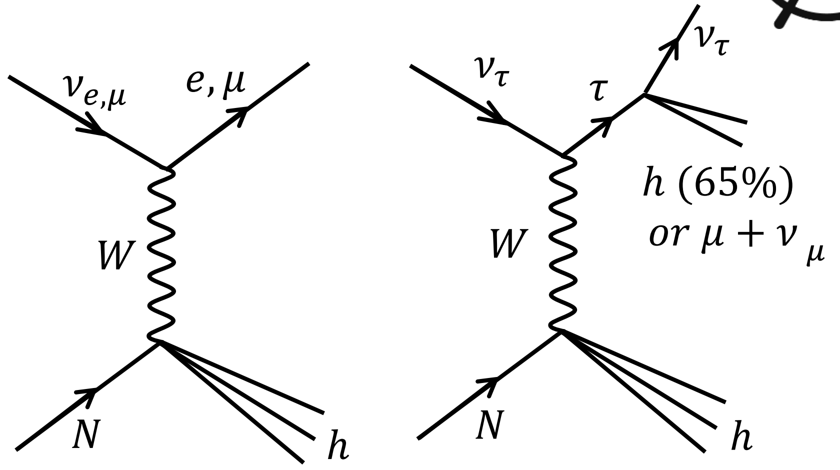
Using return field of muon shield

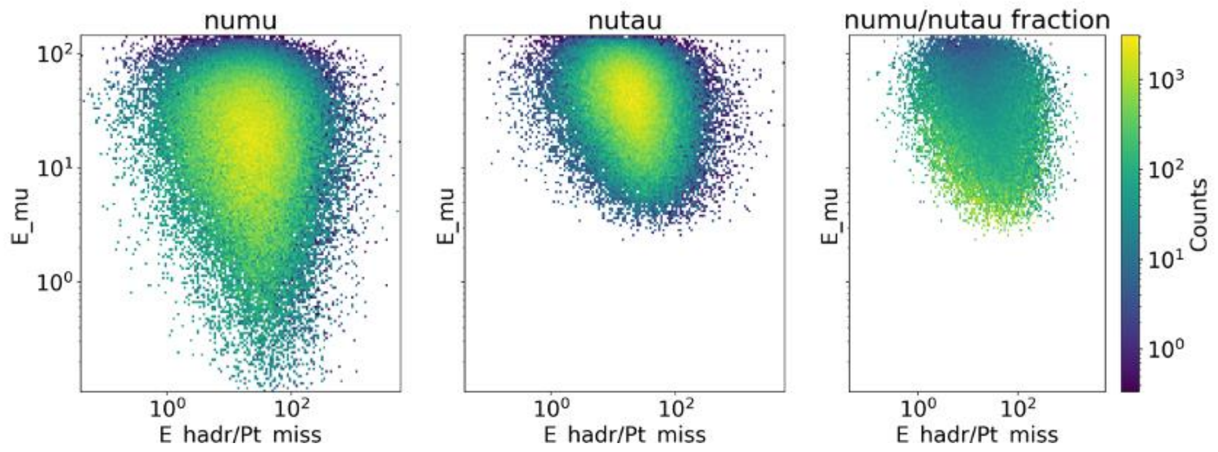
Neutrino reconstruction

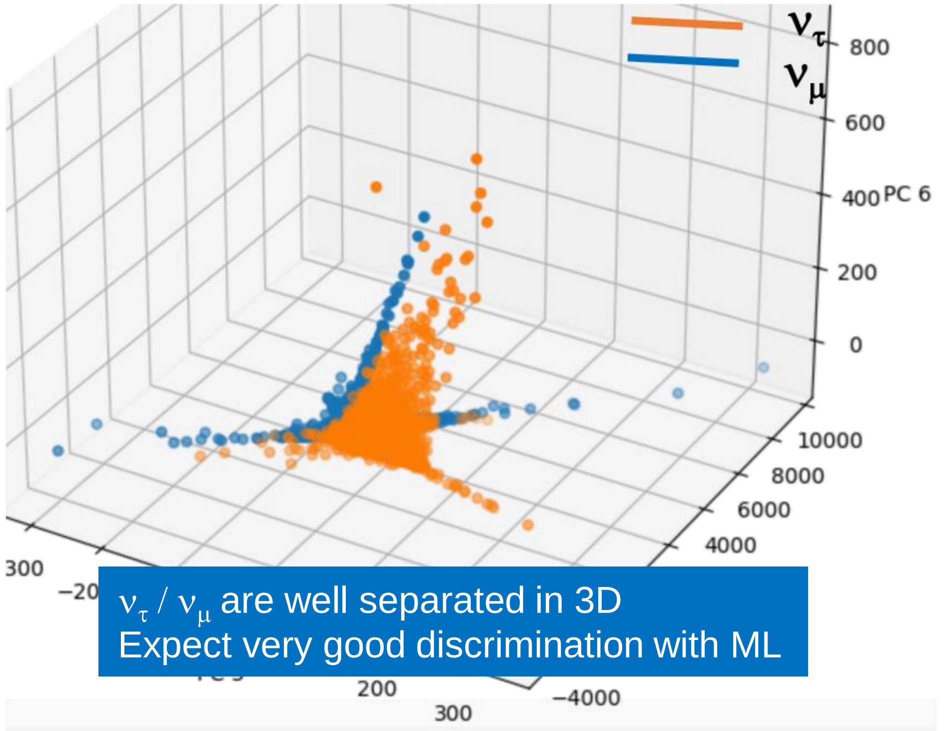
- Experimental signature of tau neutrino:
  - Topological: "double-kink" signature resulting from ν_τ-interaction and τ-decay
  - Statistical: Missing P_t carried away by two neutrinos from t-decay

    ➔ Main background from CC ν_μ interactions

  ➔ Kinematical variables
  - Missing momentum wrt ν_τ direction-of-flight
  - Muon momentum
  - Energy of hadrons
  - Additional use of impact parameter with silicon







ν_τ / ν_μ are well separated in 3D

Expect very good discrimination with ML

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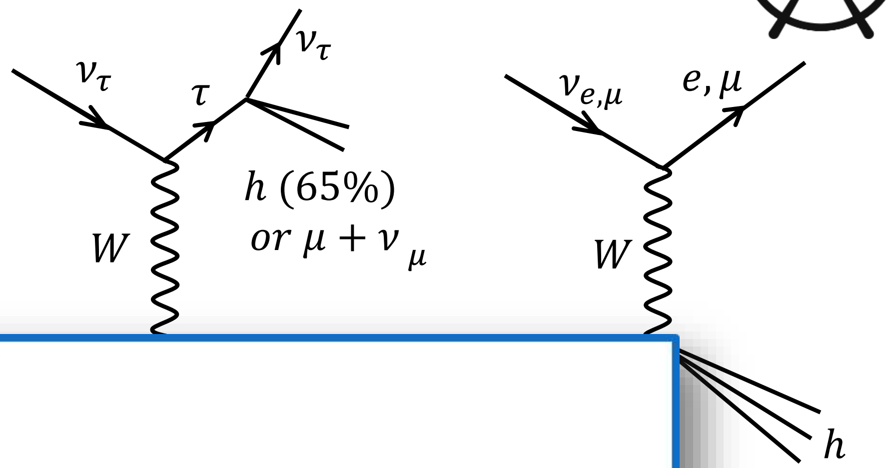
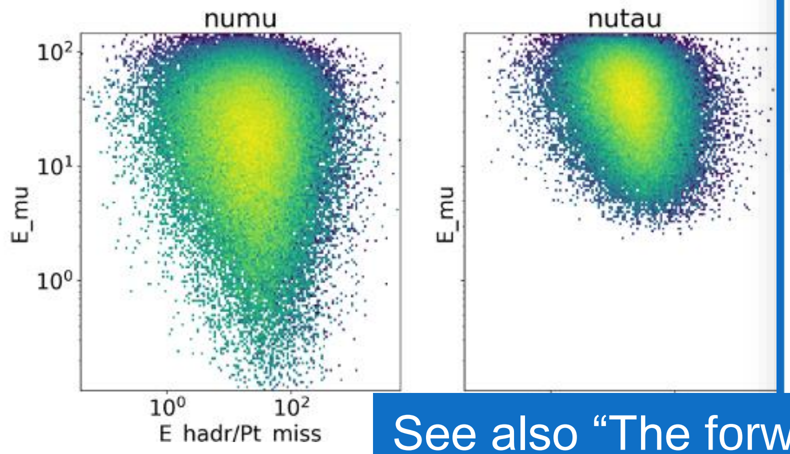
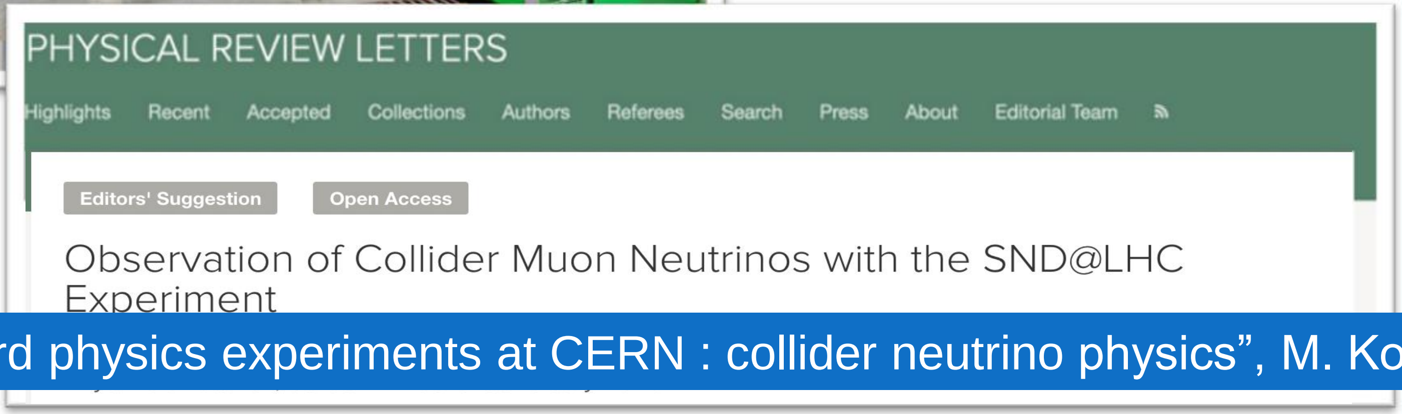


➔ Kinematical variables

- Missing momentum wrt ν_τ direction-c
- Muon momentum
- Energy of hadrons
- Additional use of impact parameter w

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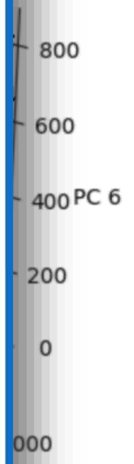
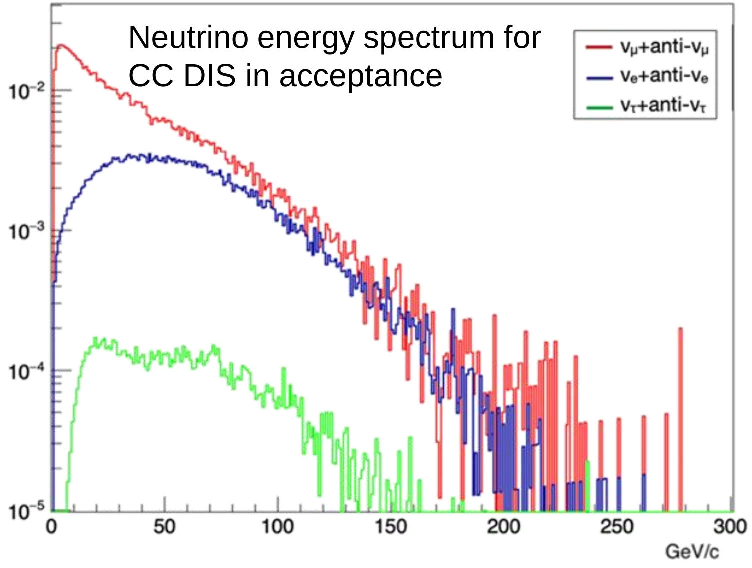
Observation of Collider Muon Neutrinos with the SND@LHC Experiment



See also “The forward physics experiments at CERN : collider neutrino physics”, M. Komatsu

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

SND: Neutrino interaction physics (2)

➔ Measurement of neutrino DIS cross-sections up to 100 GeV

- E_ν< 10 GeV as input to accelerator-based neutrino oscillation programme
- ν_τ cross-section input to atmospheric oscillations and cosmic neutrino studies
- $\sigma_{stat+syst}$~5%

➔ LFU in neutrino interactions

- $\sigma_{stat+syst}$~5% accuracy in ratios: ν_e/ν_μ , ν_e/ν_τ and ν_μ/ν_τ

➔ Test of F_4 and F_5 ($F_4 \approx 0,\ F_5 = F_2/2x$ with $m_q \to 0$) structure functions in $\sigma_{\nu-CC\ DIS}$

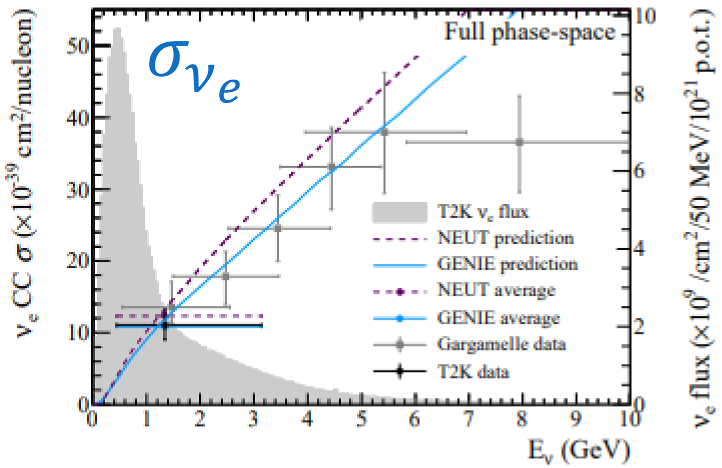
- Never measured, only accessible with tau neutrinos, realistically at <10% [C.Albright and C.Jarlskog, NP B84 (1975)]

➔ Also physics with neutrino-induced charm production

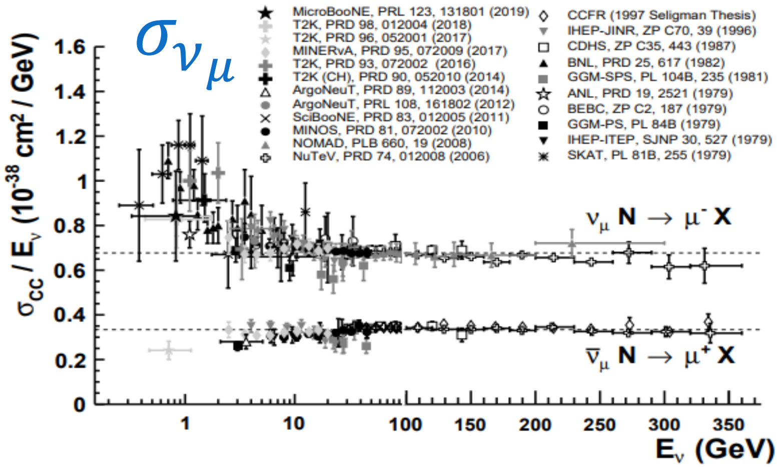
$$\frac{\sigma(\nu_e)}{\sigma(\nu_\mu)} = \frac{(\nu_e \text{ events observed})}{(\nu_\mu \text{ events observed})} \frac{\int E_{\nu_\mu}(\nu_\mu \text{ flux})dE}{\int E_{\nu_e}(\nu_e \text{ flux})dE} = 1.09 \pm 0.17 .$$

➔ 15%!

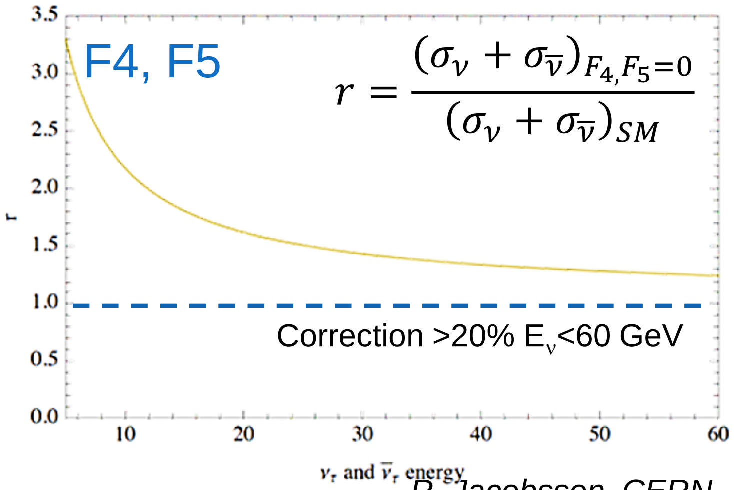
Phys.Rev. D41, 2653 (1990)



Phys.Rev.Lett 113(24). (2014)



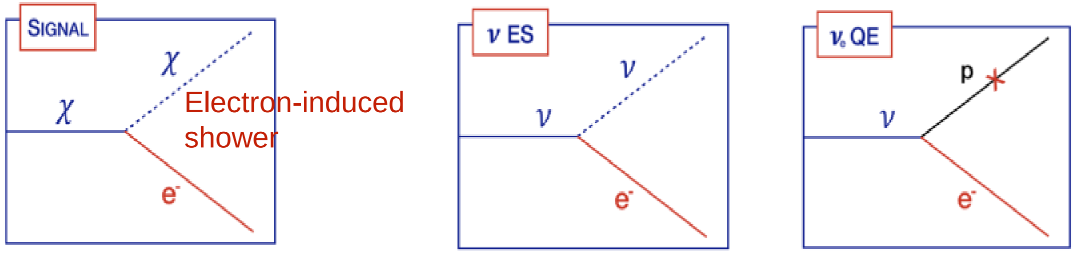
PDG



Rep. Prog. Phys. 79 (2016)124201

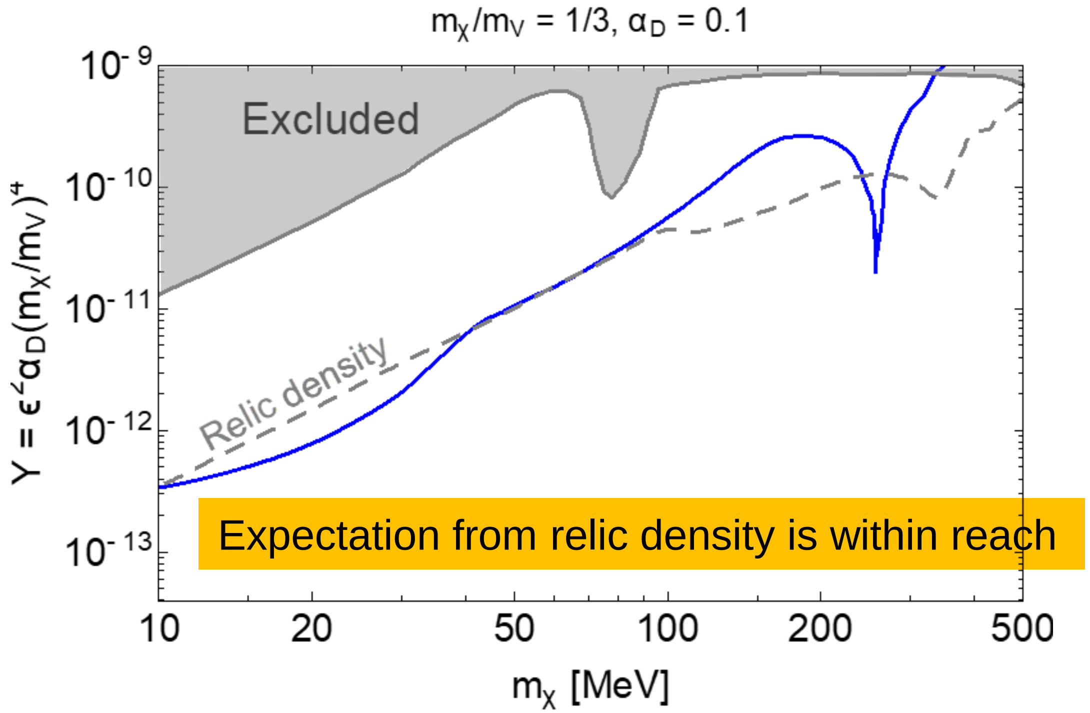
SND: "Direct" light dark matter search

- *Direct LDM search through scattering*, sensitivity to ϵ^4 instead of indirect searches ϵ^2 with missing-E technique

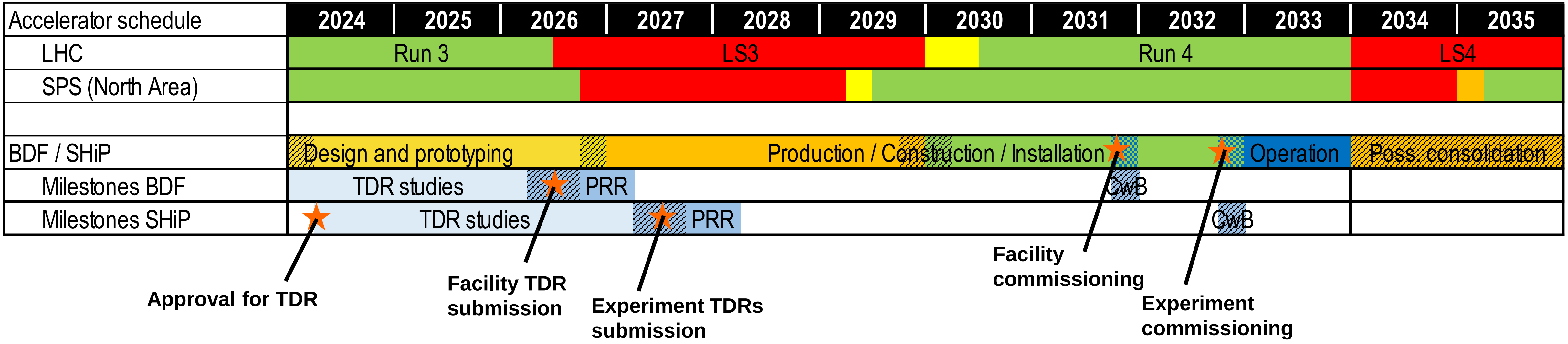


➔ Background is dominated by neutrino elastic and quasi-elastic scattering, for 6 $\times 10^{20}$ PoT

6 $\times 10^{20}$	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	156	81	192	126	555
Quasi - elastic scattering	-	27			27
Resonant scattering	-	-			-
Deep inelastic scattering	-	-			-
Total	156	108	192	126	582



BDF/SHiP schedule

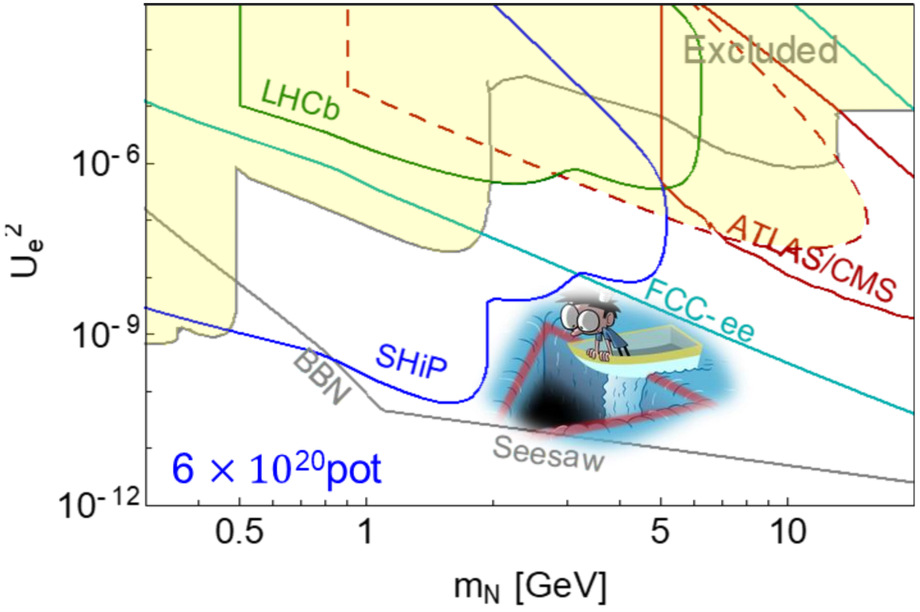


- ~3 years for detector TDRs
- Facility implementation starting in Long Shutdown 3
- Important to start data taking >1 year before LS4
- Long shutdown 4 may be used to complete detector or consolidate

Summary - "New Physics (NP)" = "ν Physics (νP)" !?...

- Unique physics potential of SPS to explore *"Coupling Frontier"* with synergy between accelerator-based searches and searches in astrophysics/cosmology

- BDF/SHiP capable of covering the heavy flavour region of parameter space, out of reach at collider experiments
  - Capability not only to establish existence but to measure properties and test compatibility with solutions to SM problems
  - Unique complementarity to FIP searches at HL-LHC and future e^+e^--collider, where FIPs can be searched in boson decays

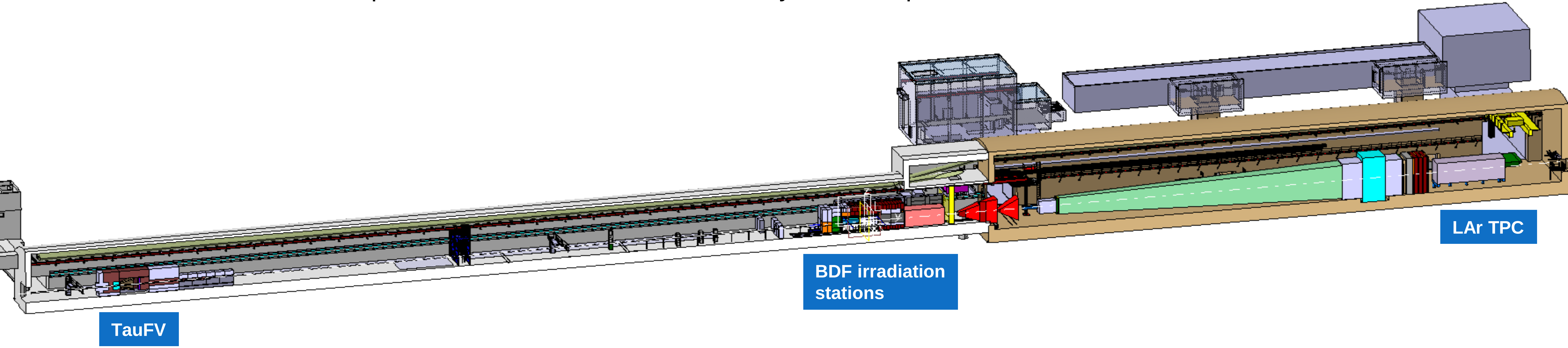


See-saw limit is almost in reach below charm mass

- Rich "biscuit'n'rhum" neutrino physics programme, including fundamental tests of SM in tau neutrino interactions
  - ➔ Synergetic and complementary to dedicated neutrino facilities

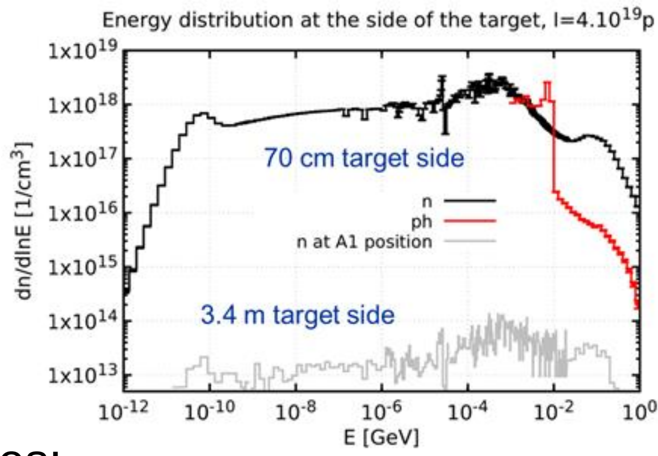
Overview of BDF extensions

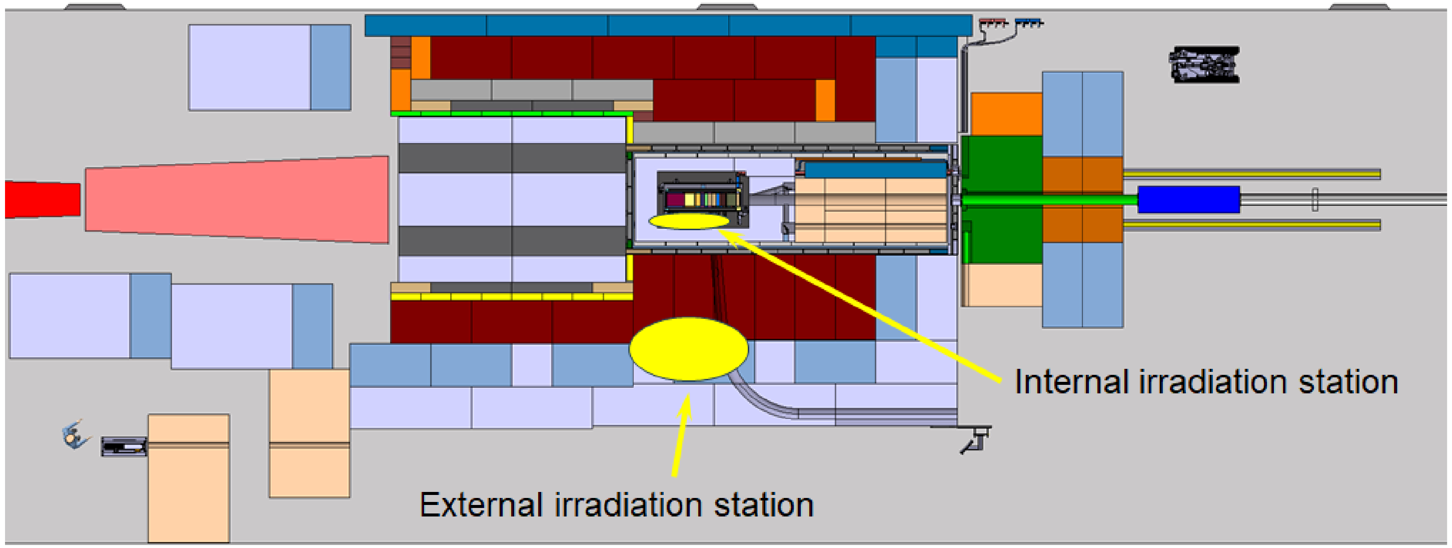
- Preliminary studies of opportunities to extend BDF's physics programme *synergetically with SHiP*:
  - Irradiation stations (nuclear astrophysics and accelerator / material science applications)
  - LArTPC to extend search for FIPs using different technology
  - TauFV to search for lepton flavour violation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



Extensions: Irradiation stations

- Can be exploited synergetically with SHiP as complementary radiation facility
  - Similar profile of radiation as at spallation neutron sources
  - A flux of ~10^{13} - 10^{14} neutrons/cm^2/pulse in the proximity of the BDF target ranging from thermal neutrons up to 100 MeV
  - Unparalleled mixed field radiation near target ~400 MGy and 10^{18} 1MeV neq/cm^2 per year





Two zones:

- Internal: 100-400 MGy / year adapted for irradiation of small volumes
- External: Larger zone of O(m^2) with lower radiation level

- Cross-sections important for nuclear astrophysics
- Radiation tolerance test of materials and electronic components at extreme conditions expected at FCC

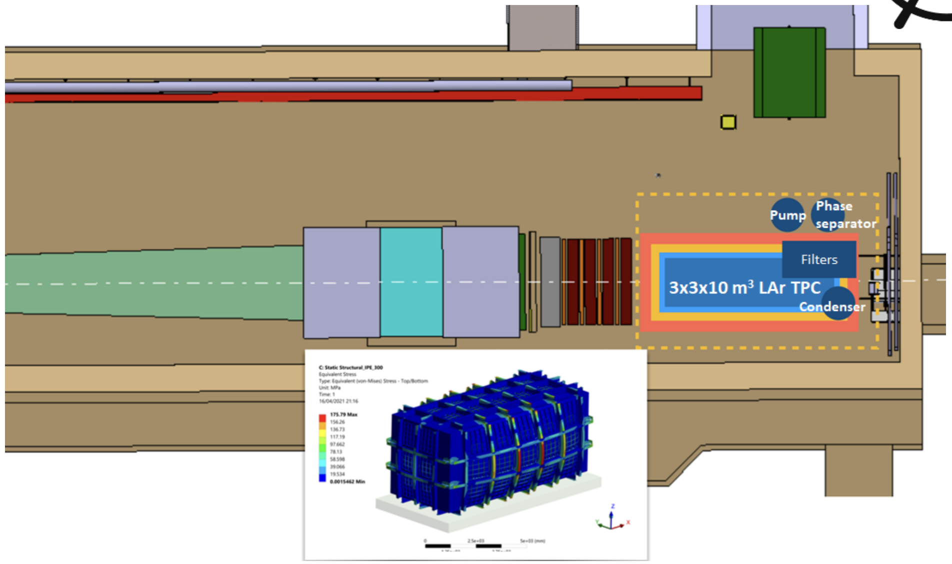
Extensions: FIP searches with LAr TPC detector

LArTPC technology is currently used in neutrino and cosmic Dark Matter search experiments

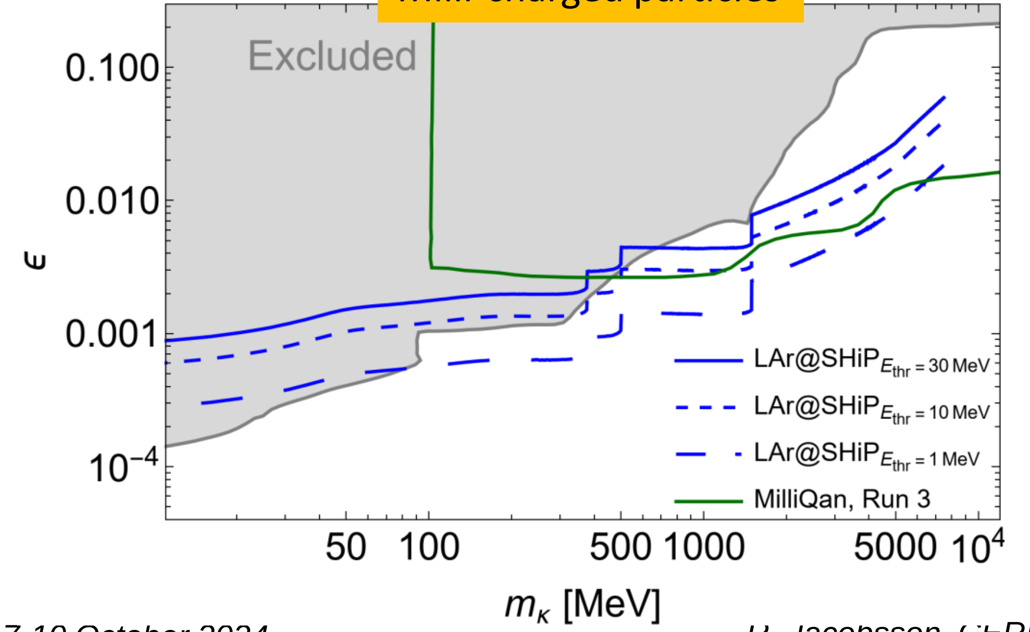
- Large experience at CERN with building 700 t detectors for DUNE
- Space available behind SHiP allows installation of LArTPC with an active volume ~3×3×10 m^3 (~130 t) and associated infrastructure

➔ Extends SHiP's physics reach using different technology

New opportunities with LAr@SHiP, A. De Roeck et al, to be submitted



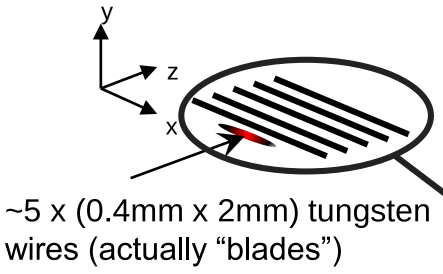
Milli-charged particles

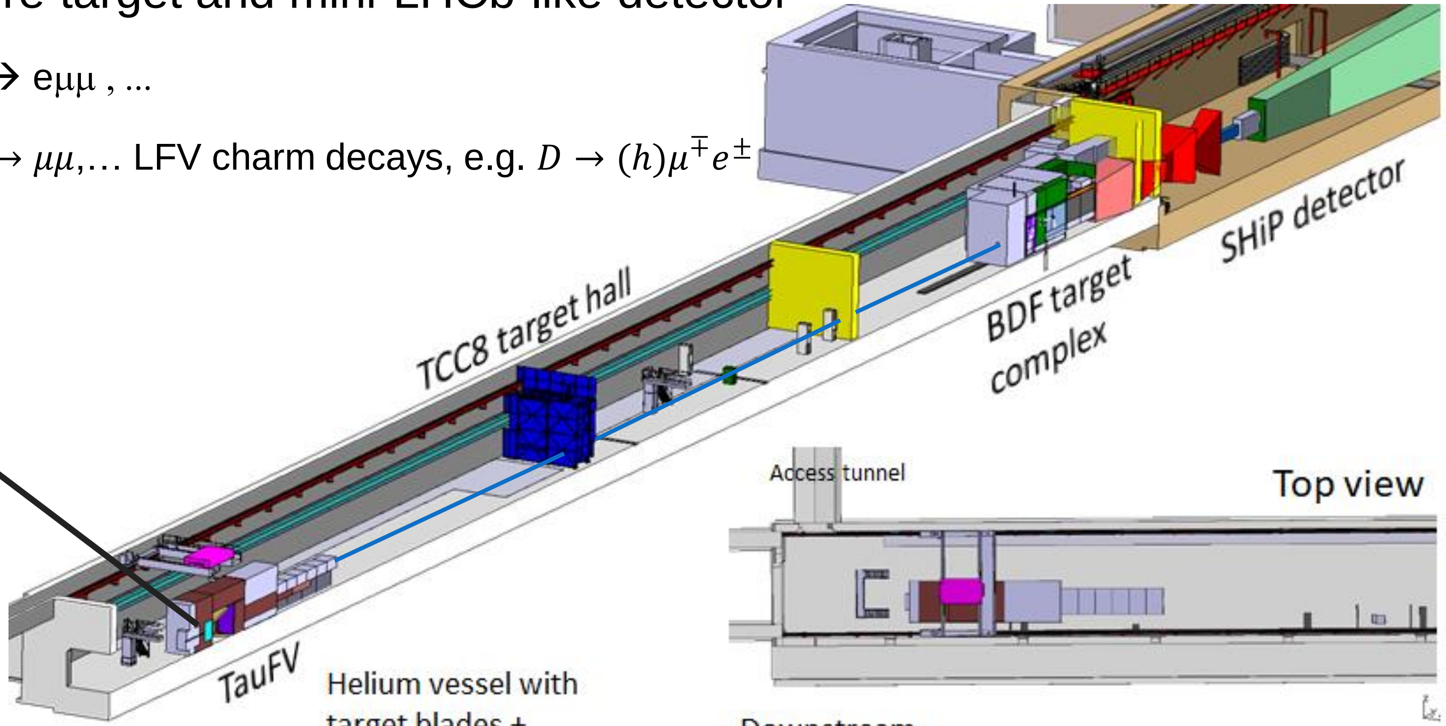


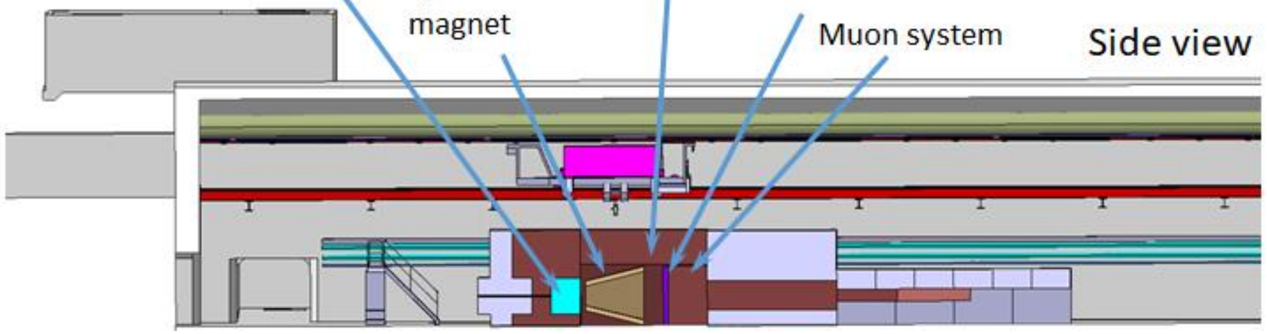
Extensions: Tau flavour violation experiment

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	$50\,\text{ab}^{-1}$	1
LHCb Upgrade I	$50\,\text{fb}^{-1}$	14
LHCb Upgrade II	$300\,\text{fb}^{-1}$	84

SND: Neutrino interaction physics (3)

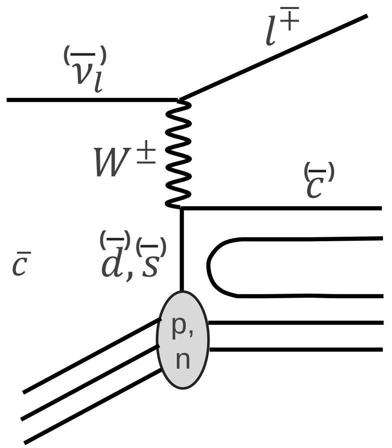
Neutrino-induced charm production programme

- Expect ~6×10^5 neutrino induced charm hadrons for 6×10^{20} pot
  - More than an order of magnitude larger than currently available
- Anti-charmed hadrons are predominantly produced by anti-strange content of the nucleon (~90%)
  - Understanding of nucleon strangeness is critical for precision tests of SM at LHC

➔ Improvement on $|V_{cd}|$ by directly identifying inclusive charm

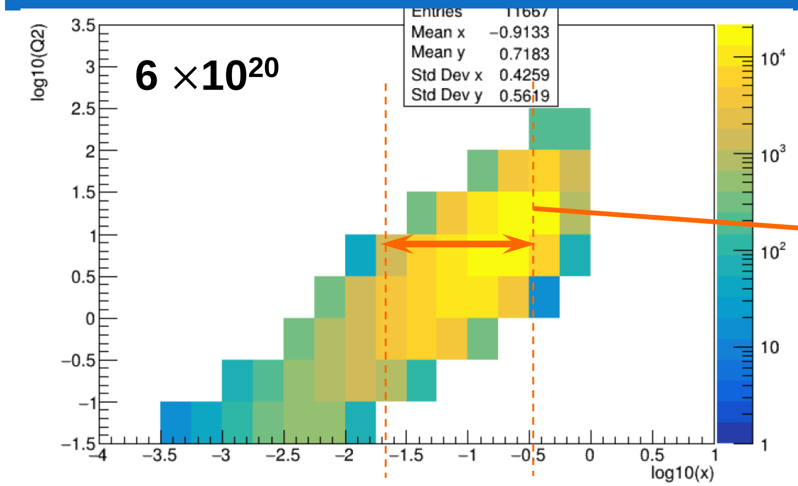
	<E> (GeV)	CC DIS with charm prod
N_{ν_μ}	57	3.5×10^5
N_{ν_e}	71	1.7×10^5
$N_{\overline{\nu}_\mu}$	50	0.7×10^5
$N_{\overline{\nu}_e}$	60	0.3×10^5
total		6.2×10^5

}90% from $\bar{s}\rightarrow\bar{c}$

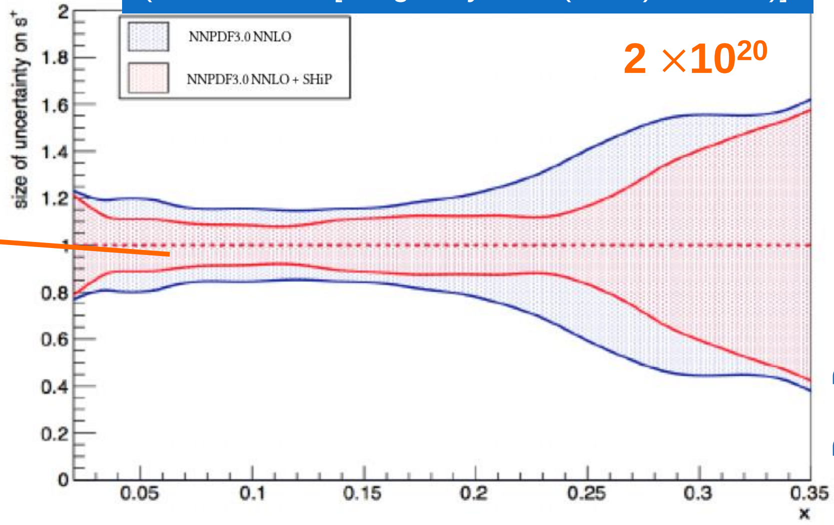


No charm candidate from ν_e and ν_τ interactions ever reported

Large data samples at SHiP will greatly improve current measurements up to high values of x



SHiP sensitivity to PDF for x < 0.35 (evaluated in [Prog. Phys. 79 (2016) 124201])



Rep. Prog. Phys. 79 (2016)124201