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

Future physics prospects

- No definitive unambiguous guidance on New Physics from experiments or theory!

- SM describes both what we observe and what we do **not** observe directly

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

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

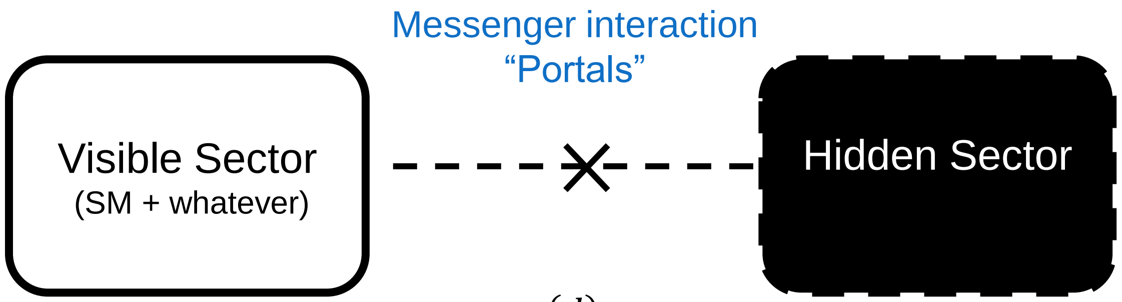
- New Physics should either be very heavy *OR* interact very feebly to have escaped detection!
  ➔ Neutrino and Dark Matter…..possible guidance from cosmology and astrophysics!

- Exploration of Feebly Interacting Particles (FIPs) up to now mainly as by-product of experiments built for other purposes – post-analyses, data mining, often limited to exclusion capability

- Enough reasons to build a dedicated accelerator-based general-purpose facility to explore FIPs
  - We are sharing the Universe already with feebly coupled and not-understood neighbours!
  - Light feebly coupled sector can provide solutions to well-established problems!
  - Essential complementarity with projects in launch/commissioning on the cosmofrontier
  - One of the main objectives of HL-LHC will be exploring FIPs…

Feebly interacting particles

Hidden Sector may have their own (hidden/dark) charges and interactions



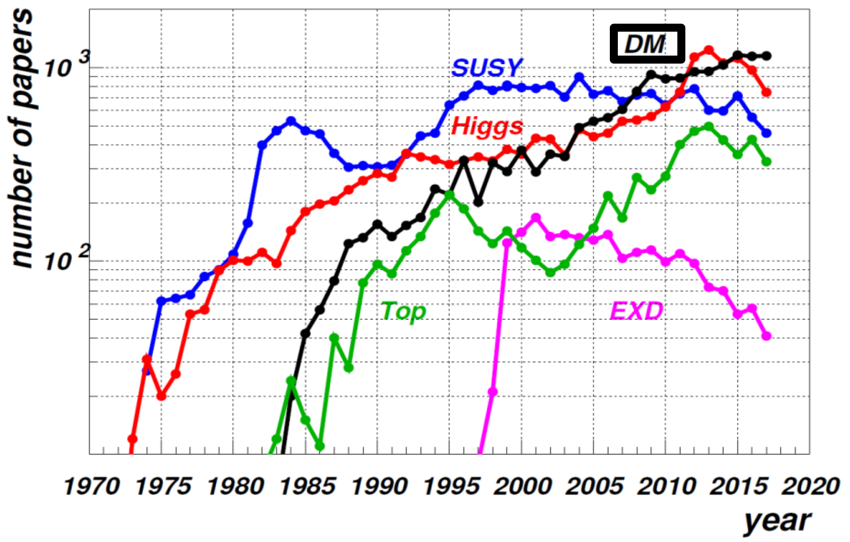
$$\mathcal{L} = \mathcal{L}(\psi_{SM}, A_{SM}, H_{SM})_{dim\leq 4} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda_{NP}^{d-4}} \mathcal{O}^{(d)} + \mathcal{L}(\psi_{HS}, A_{HS}, H_{HS}) + \mathcal{L}_{portal}$$

Lowest dimension makes up "portals" between visible and Hidden Sector

Portals may "drive" dynamics observed in the Visible Sector!

- Dark Matter (trivial)
- Neutrino mass and oscillations
- Matter-Antimatter asymmetry
- Higgs mass
- Structure formation
- Inflation and Dark Energy
- ….

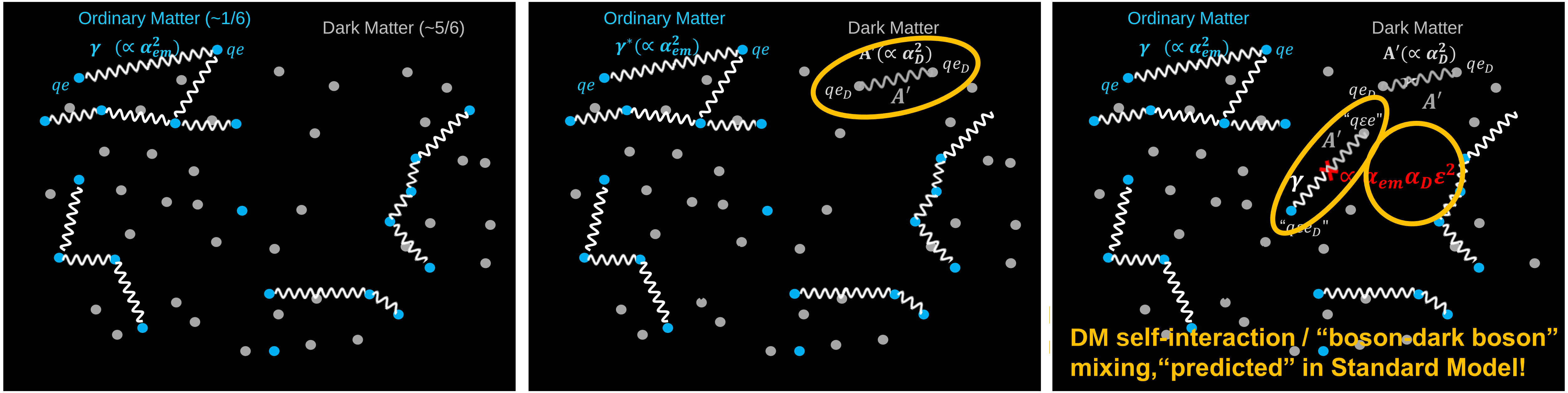
➔ Plethora of alternative SM extensions!



Portal interactions under the microscope

<u>***Example*** of FIP physics case</u>

What if…?!



Profiting from "portal" coupling at accelerator!

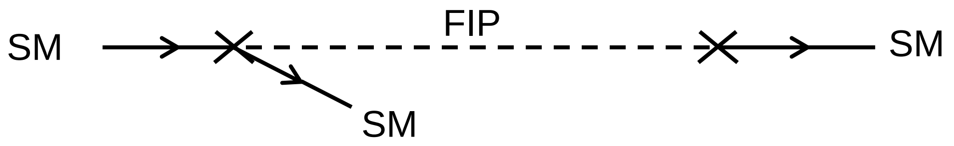
- ➔ Typical coupling at 10^{-6} - 10^{-10}…
- ➔ Long-lived with cτ ~ metres-kilometres….

Similar behaviour $\tau_{FIP} \propto \frac{1}{\epsilon_{FIP}^{x} m_{FIP}^{y}}$

for all types of FIPs

<u>Production</u>

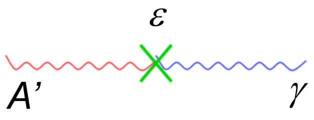
<u>Detection by decay or by scattering</u>



New Physics prospects in Hidden Sector

Composite operators as "portals" :

- **D = 2: Vector portal**
  - Kinetic mixing with massive dark/secluded/paraphoton A' : $\frac{1}{2}\varepsilon F^{SM}_{\mu\nu} F^{\mu\nu}_{HS}$
  - ➔ Motivated in part by idea of "mirror world" restoring L/R symmetry, dark matter, g-2 anomaly, …



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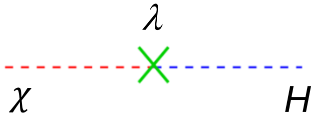
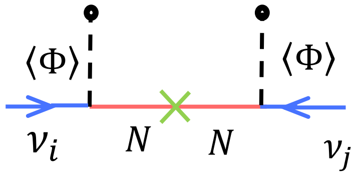
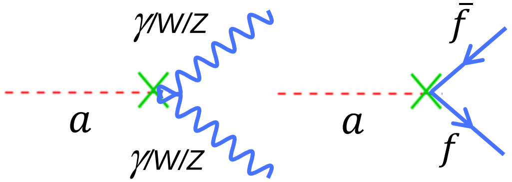


- ***D = 5/2: Neutrino portal***
  - Mixing with right-handed neutrino N (Heavy Neutral Lepton): $\mathrm{Y_{I\ell} H^\dagger \overline{N}_I L_\ell}$
  - ➔ Neutrino oscillation and mass, baryon asymmetry, dark matter

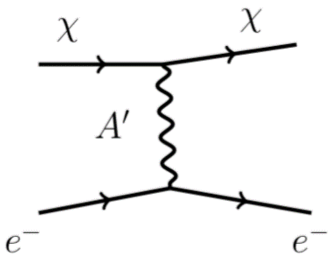


- **D = 4: Axion portal**
  - Mixing with Axion Like Particles, pseudo-scalars pNGB : $\frac{a}{F} G_{\mu\nu}\tilde{G}^{\mu\nu}$, $\frac{\partial_\mu a}{F}\bar{\psi}\gamma_\mu\gamma_5\psi$, etc
  - ➔ Generically light pseudo-scalars arise in spontaneous breaking of approximate symmetries at a high mass scale F
  - ➔ Extended Higgs, SUSY breaking, dark matter, possibility of inflaton,…



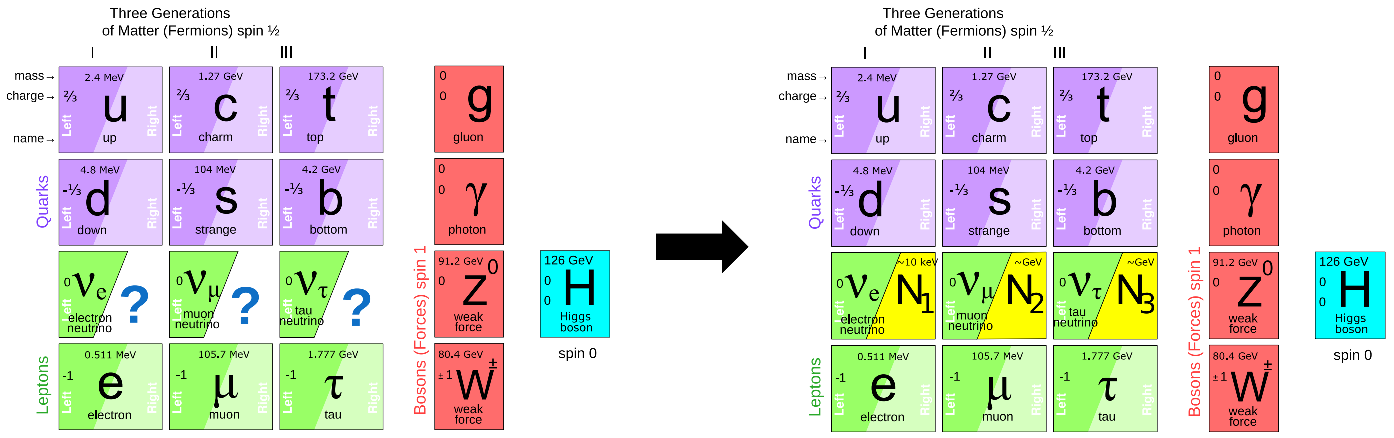
- **Also light SUSY** (Neutralino, sgoldstino, axino, saxion, hidden photinos…)

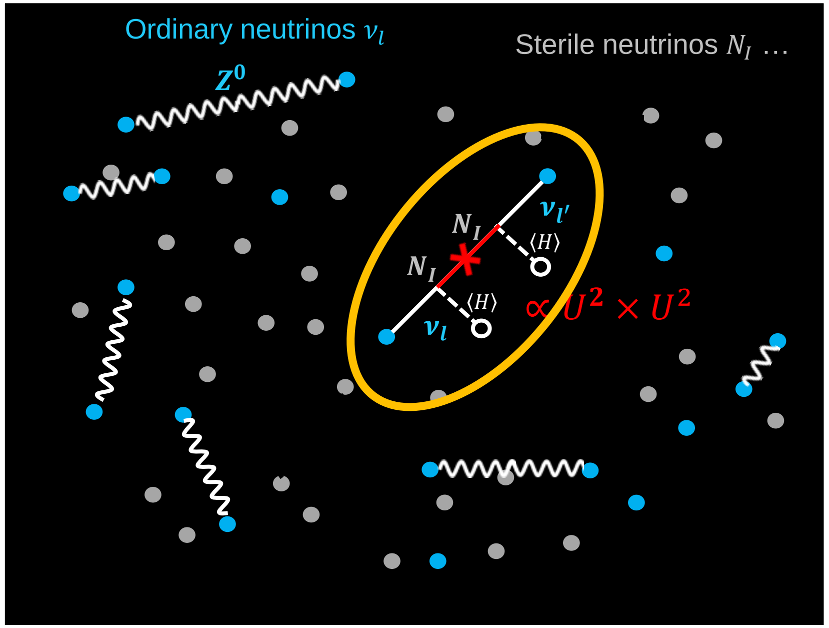
- **Light dark matter χ interpretation of scattering signatures**



Making neutrinos count!

- Introduce three right-handed Majorana fermions N_I with mass $M_I^R \equiv$ "Heavy Neutral Leptons (HNL)"
  - Make the leptonic sector 'similar' to the quark sector
  - No electric, strong or weak charges ➔ "sterile"





- "Portal" through neutrino Yukawa coupling with right-handed neutrinos

Minkowski 1977
Yanagida 1979
Gell-Mann, Ramond, Slansky 1979
Glashow 1979

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{\substack{I=1,2,3;\\ \ell=1,2,3(e,\mu,\tau)}} i\bar{N}_I \not{\partial}_\mu \gamma^\mu N_I - Y_{I\ell} H^\dagger \bar{N}_I L_\ell - M_I^R \bar{N}_I N_I^c + h.c$$

$\mathcal{L}_{Majorana\ mass}$

cmp $\mathcal{L}_{Dirac\ mass} = \frac{y_f \langle H\rangle}{\sqrt{2}}(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$, $\langle H\rangle = v \sim 174\ GeV$

where L_ℓ are the lepton doublets, H is the Higgs doublet, and $Y_{I\ell}$ are the corresponding new Yukawa couplings

➔ Lepton flavour violating term results in mixing between N_I and SM active neutrinos

NOTE: Discovery of Higgs vital for this extension!

Making neutrinos count!

- Neutrino mass matrix with both Dirac and Majorana masses

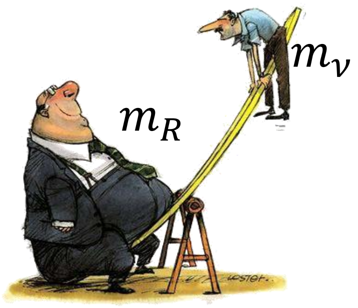
$$\mathcal{L}_{mass} = \frac{y_i\langle H\rangle}{\sqrt{2}}(\overline{\nu_L}N_R + \overline{N_R}\nu_L) + m_L^M\overline{N_L^c}N_L + m_R^M\overline{N_R^c}N_R + h.c. \quad = [\overline{\nu_L}, \overline{N_R^c}]\begin{bmatrix} m_L^M & m_D \\ m_D & m_R^M \end{bmatrix}\begin{bmatrix} \nu_L \\ N_R^c \end{bmatrix} + h.c.$$

- With Majorana mass scale M^R >> $m_D(= Y_{I\ell}v)$ obtain mass eigenstates

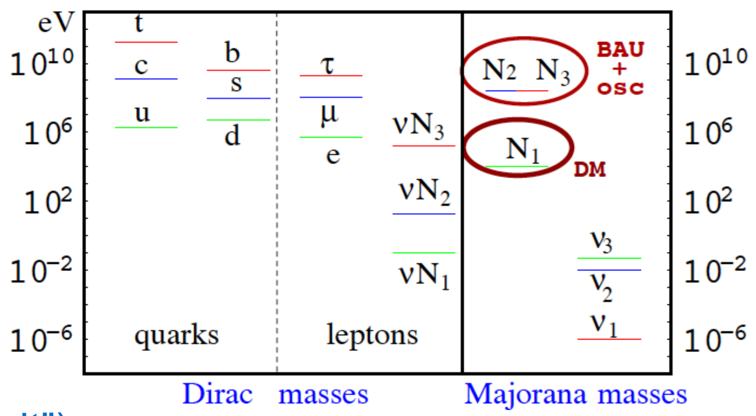
➔ Active neutrino mass $\tilde{m}_1 \sim = \frac{(Y_{I\ell}v)^2}{M_I^R} = \frac{m_D^2}{M^R} \sim m_\nu$

➔ Heavy singlet fermion mass $\tilde{m}_2 \sim M^R\left(1 + \frac{m_D^2}{M^{R^2}}\right) \sim M^R \sim M_N$

➔ See-saw mechanism



No new energy scale!



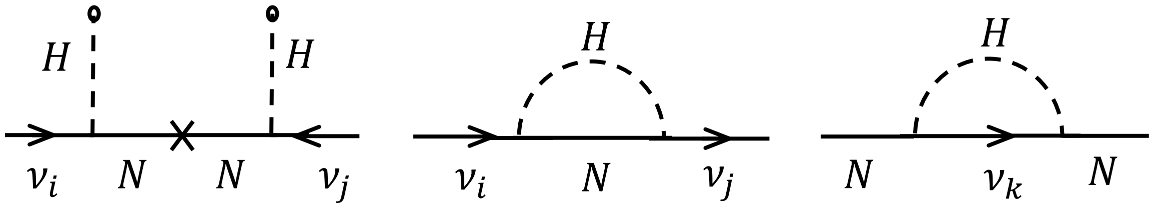
- Effective mixing between N_I and active neutrino $\mathcal{U}_{I\ell} = \frac{Y_{I\ell}v}{M_I^R} \sim \frac{m_D}{M^R}$

➔ Total coupling $\mathcal{U}^2 = \sum_{\substack{I=1,2,3 \\ \ell=1,2,3(e,\mu,\tau)}} \frac{v^2|Y_{\ell I}|^2}{m_I^{R^2}} \sim \mathcal{O}\left(\frac{m_\nu}{M_N}\right) > 5 \times 10^{-11}\ /M_N[GeV]$ ("seesaw limit")

Intriguing possibility with HNLs in "νMSM"

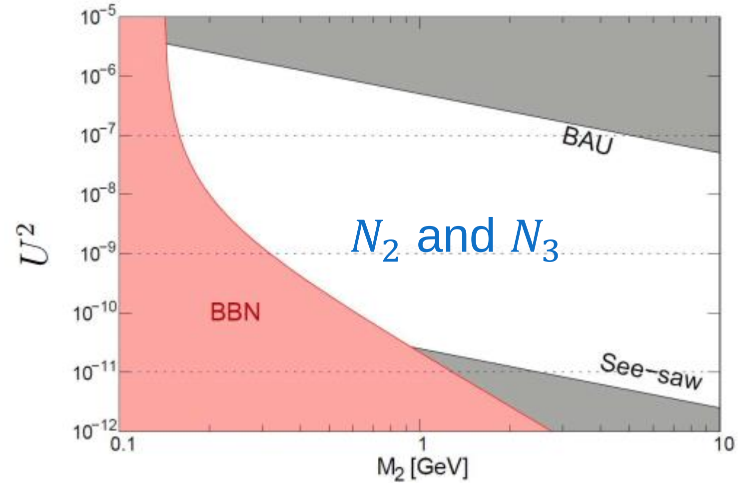
hep-ph/0503065
hep-ph/0505013
hep-ph/0605047
arXiv:0804.4543v2

- N_2 and N_3 with degenerate mass of $\mathcal{O}(m_q/m_{l^\pm})$ (100 MeV – GeV) responsible for neutrino oscillation and tiny masses and extra CP violation through interference in oscillation leading to leptogenesis → baryogenesis



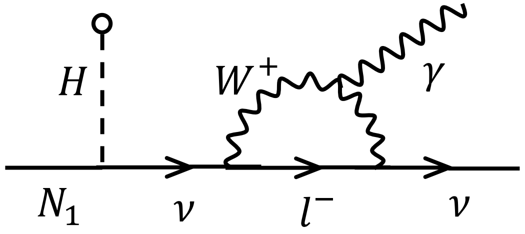
$N_{2,3}$ $\xrightarrow{\text{CP violation In oscillations}}$ $\Delta\mathbb{L}$ $\xrightarrow{\text{Sphalerons}}$ $\Delta\mathbb{B}$

e.g. Phys.Rev D, Vol. 42, 10 (1990)
e.g. arXiv:1006.0133v3

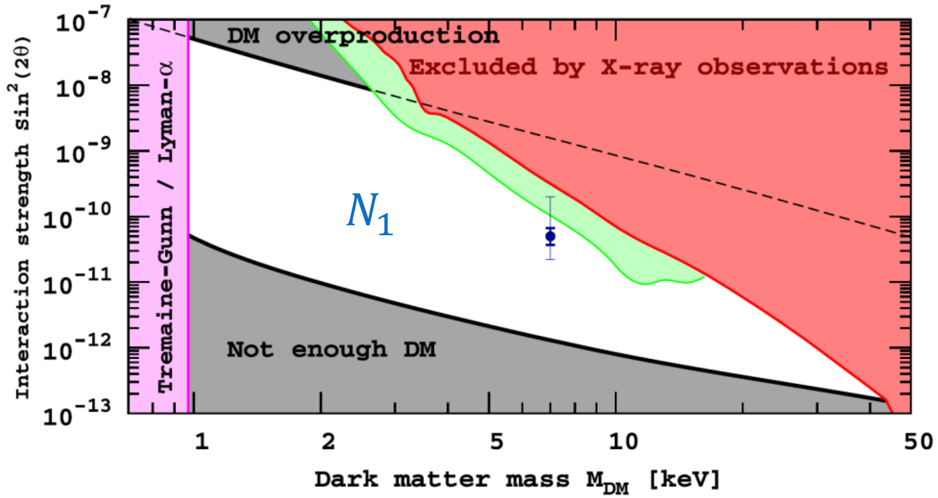


- N_1 with very small coupling and a mass of $\mathcal{O}$(keV) as Dark Matter!

Subdominant radiative decay



$$E_\gamma = \frac{M_{N_1} c^2}{2}$$



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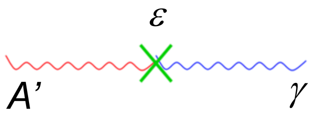

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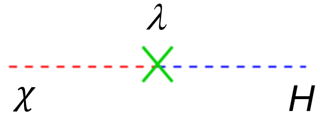

Bottom line: We need large production of $\gamma, q/g, c, b, W, Z, H$!

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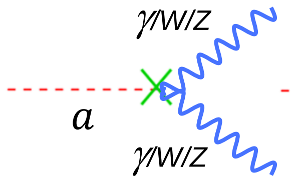

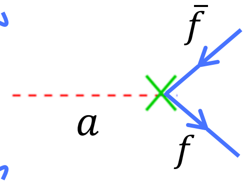

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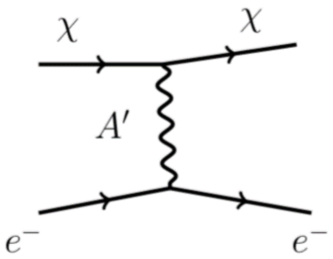
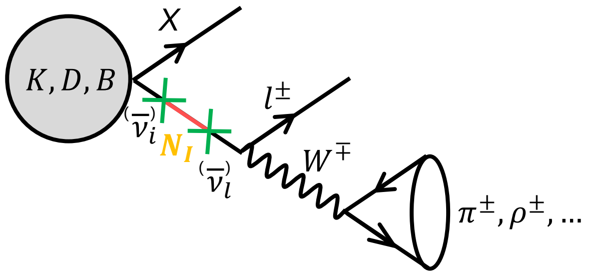
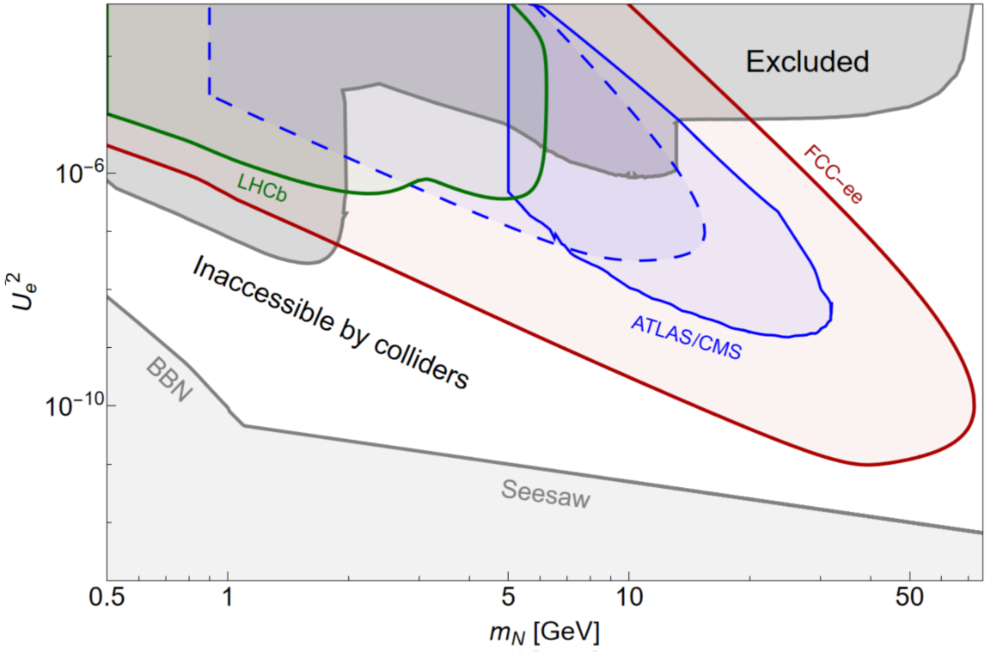


SHiP raison d'être

- 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
  - ➔ SPS energy and intensity provide huge production of charm, beauty and electromagnetic processes
  - ➔ Large lifetime acceptance - production modes in limited forward cone



E.g. Heavy Neutral Leptons



- Return CERN SPS accelerator to full exploitation of unique physics potential
  - ➔ SHiP Physics Proposal compiled and signed by a collaboration of 80 theorists: *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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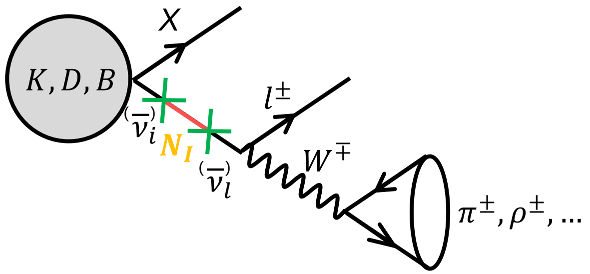

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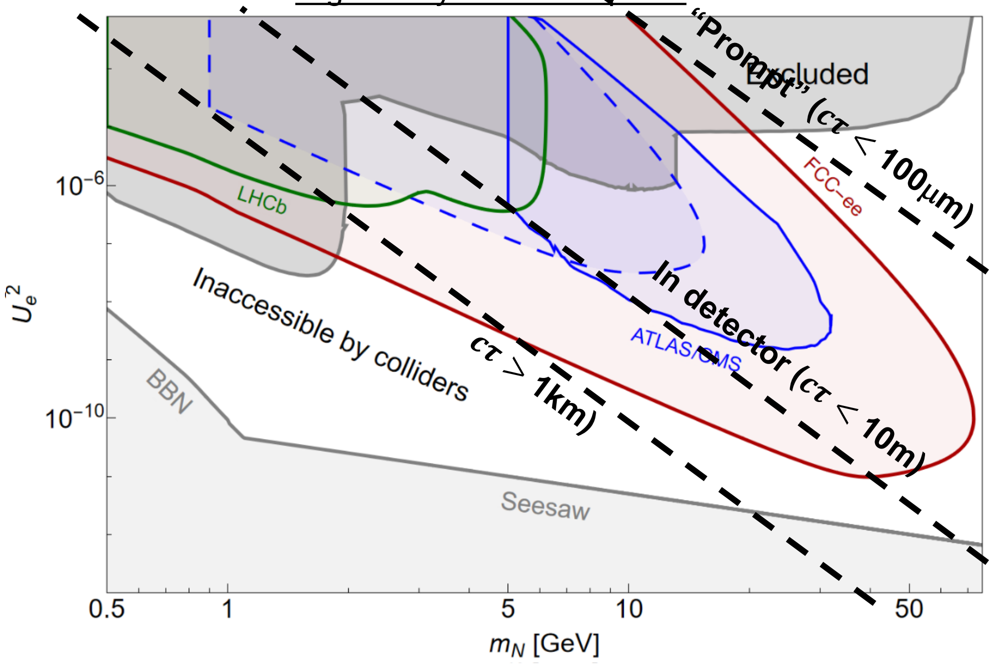

Similar behaviour $\tau_{FIP} \propto \frac{1}{\epsilon_{FIP}^{x} m_{FIP}^{y}}$

for all types of FIPs

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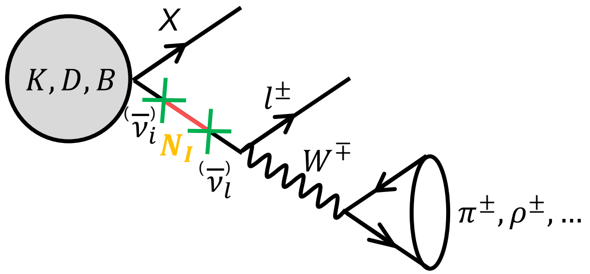

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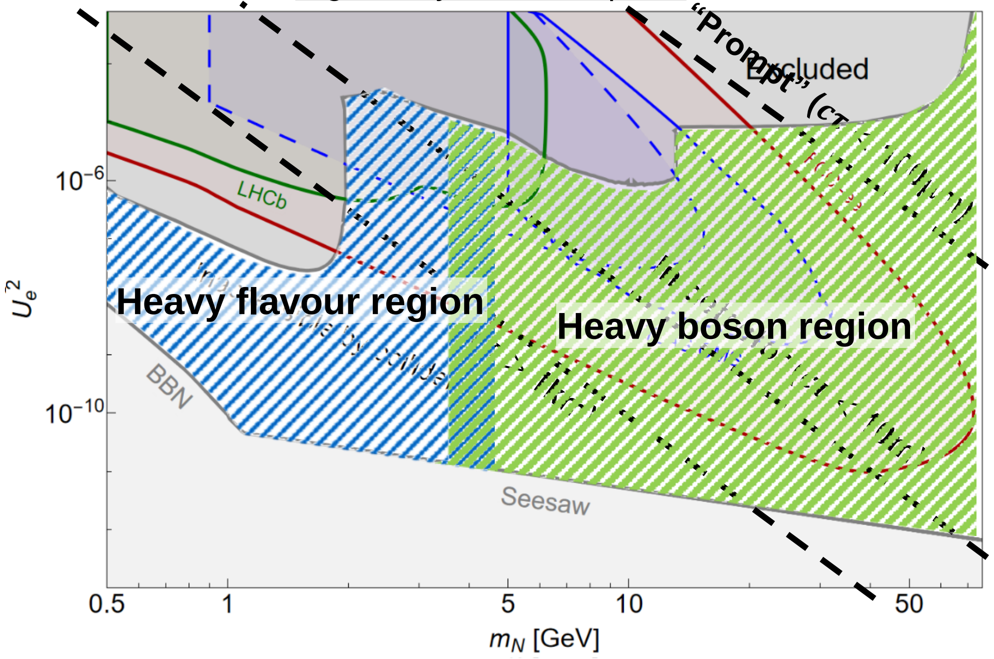

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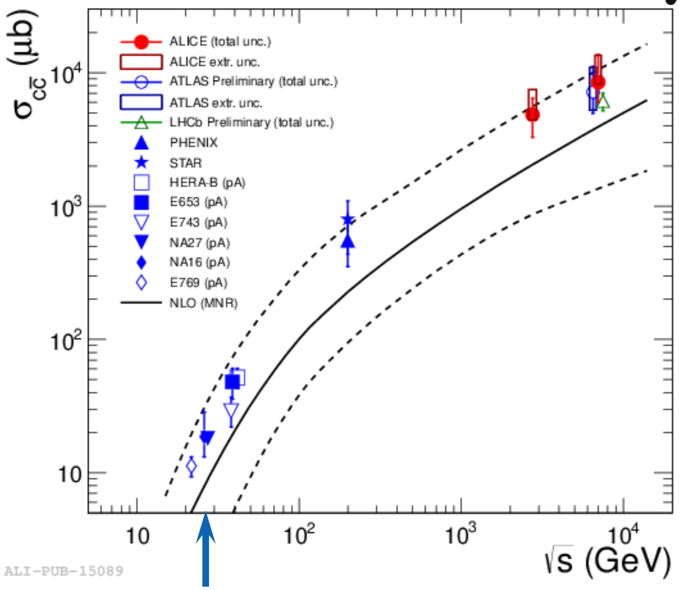
Generic physics reach

- 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 luminosity with the optimised target and 4×10^{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 @ $\sqrt{s} = 27\ GeV$

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

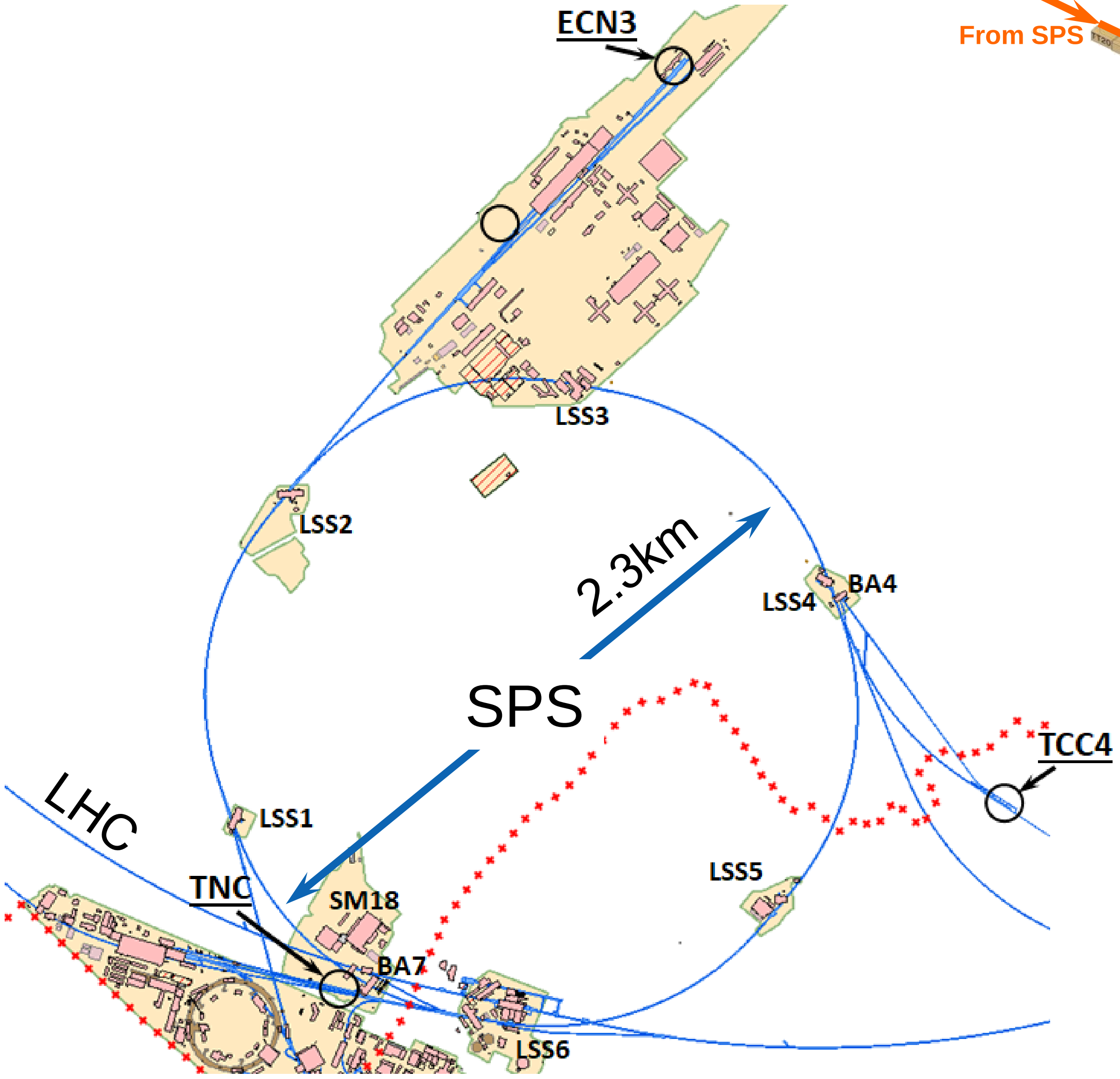
- ~ 2×10^{17} charmed hadrons (>10 times the yield at HL-LHC)
- ~ 2×10^{12} beauty hadrons
- ~ 2×10^{15} tau leptons
- $\mathcal{O}(10^{20})$ photons above 100 MeV
- Large number of neutrinos *detected* with 3t-W ν-target:

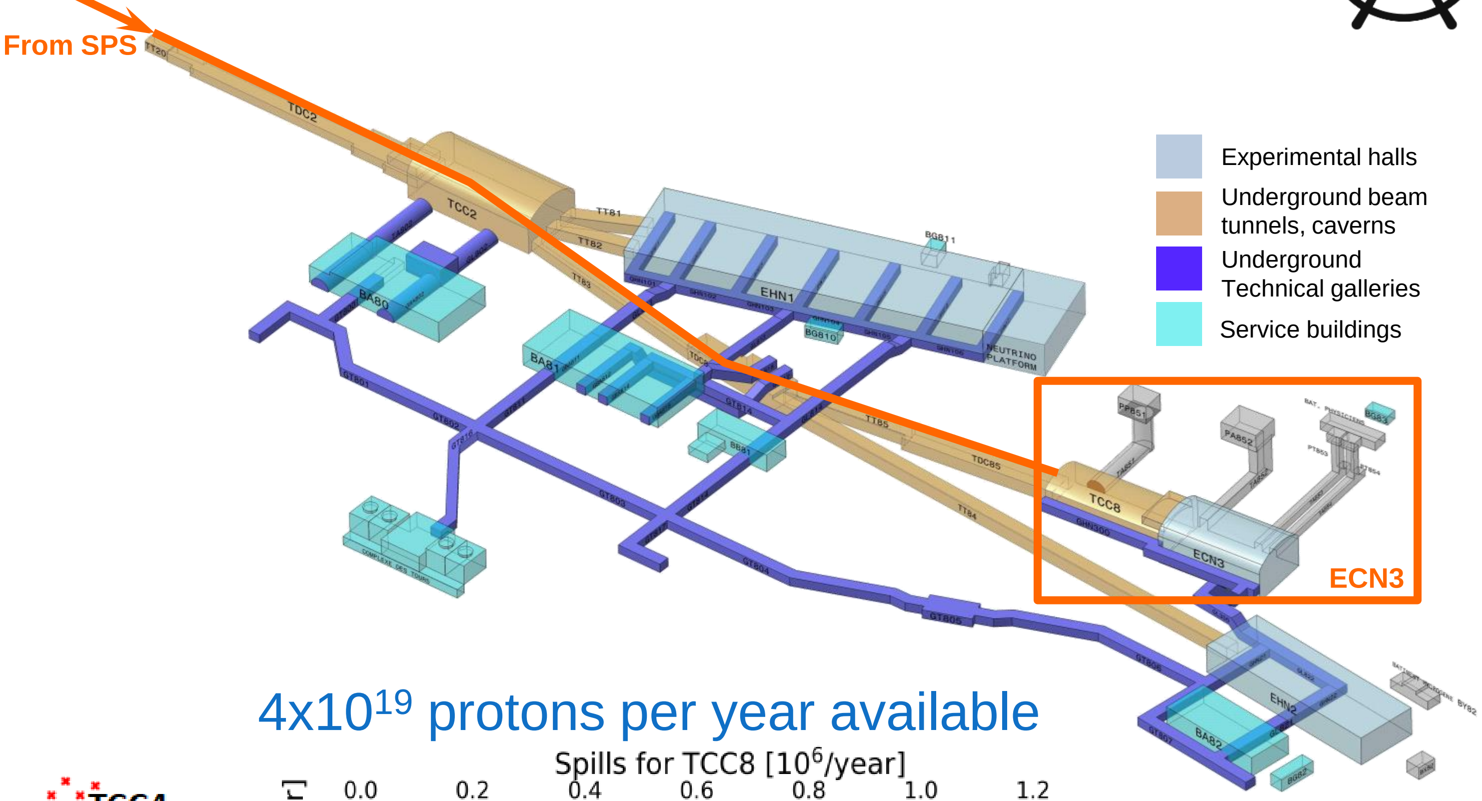
  $3500\ \nu_\tau + \bar{\nu}_\tau$ *per year*, and 2×10^5 $\nu_e + \bar{\nu}_e$ / 7×10^5 $\nu_\mu+\bar{\nu}_\mu$ despite target design

σ(pp→ssbar X)/σ(pp→X) ~ 0.15
σ(pp→ccbar X)/σ(pp→X) ~ $2\text{x}10^{-3}$
σ(pp→bbbar X)/σ(pp→X) ~ 1.6 $\text{x}10^{-7}$
Cascade effect, e.g. >2 for charm

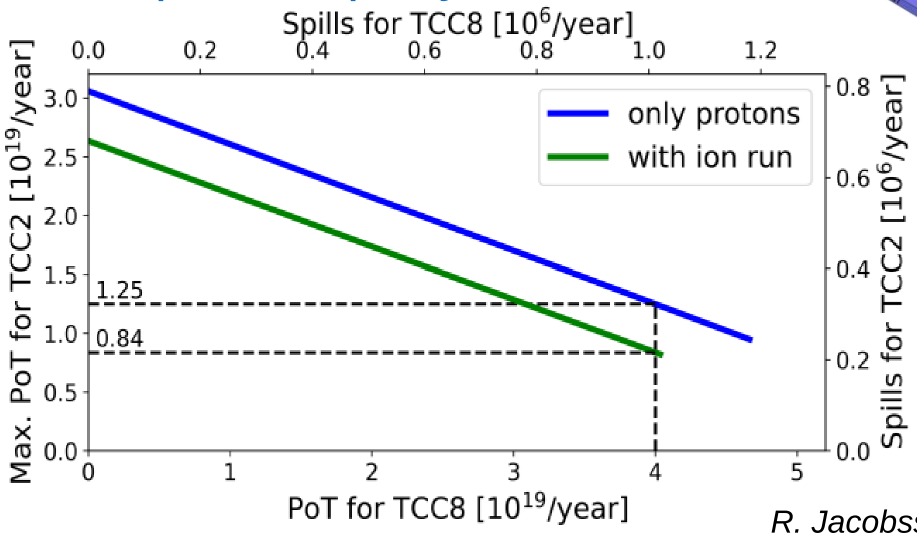
- No technical limitations to operate beam and facility with 4×10^{19} protons/year for 15 years

SHiP @ SPS ECN3 beam facility

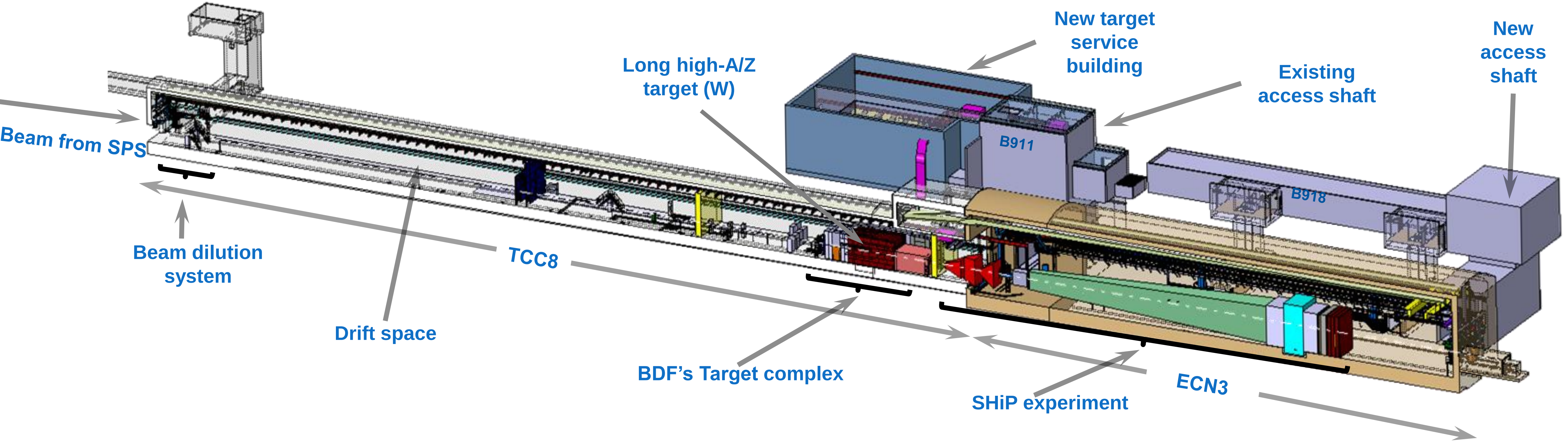




4×10^{19} protons per year available



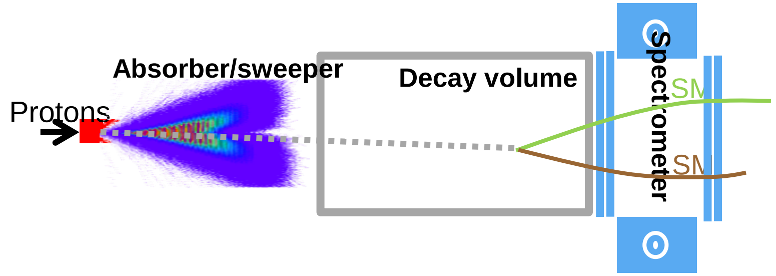
Overview of BDF/SHiP @ SPS ECN3



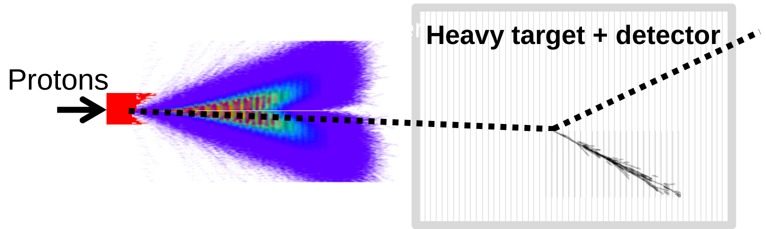
BDF/SHiP experimental techniques

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

Decay signatures



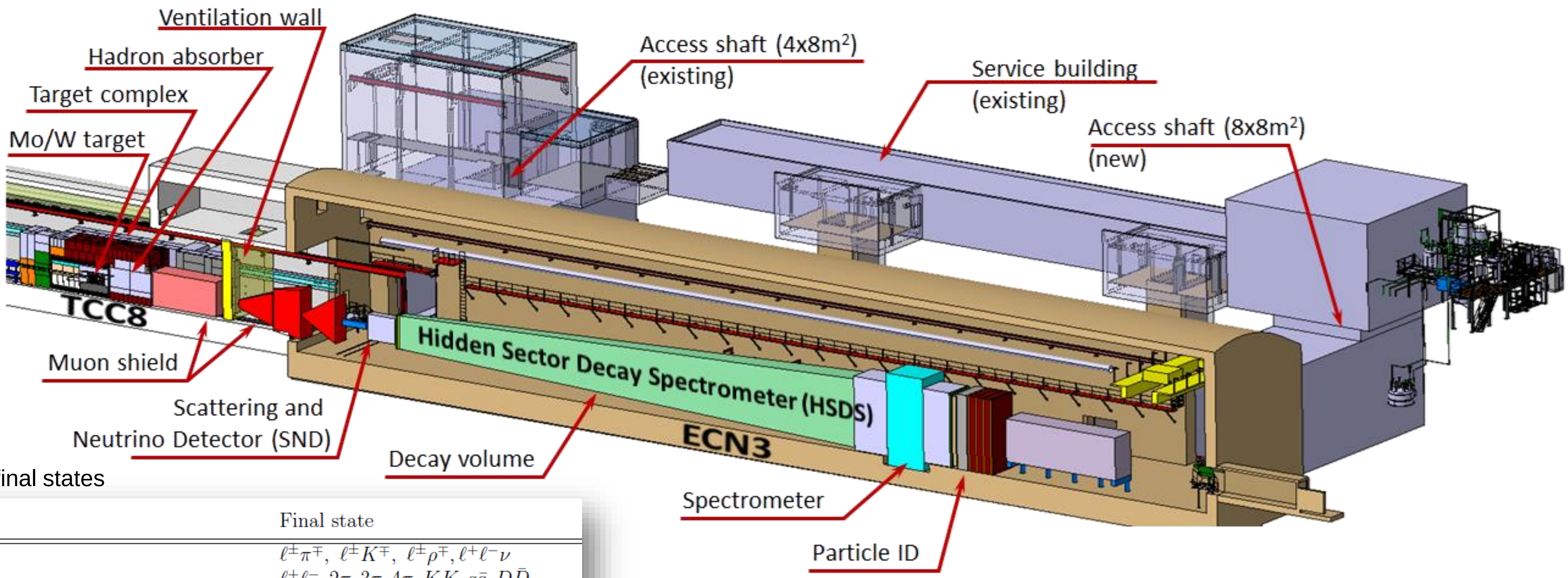
Scattering signatures



Also suitable for neutrino interaction physics with all flavours

- Design 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**

Overview of BDF/SHiP @ SPS 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)	$D_s^\pm,\ D^\pm,\ D^0,\ \overline{D^0},\ \Lambda_c^+,\ \overline{\Lambda_c}^-$

Dual detection technique: scattering and decay signature

Background challenge

Optimization and background challenges studied with complete experimental setup implemented in GEANT (FairShip)

➔ Simulation tuned with detector performance parameters measured in test beam on prototypes

- Rates of neutrinos and muons partly suppressed by high-A&Z target, but further suppression needed

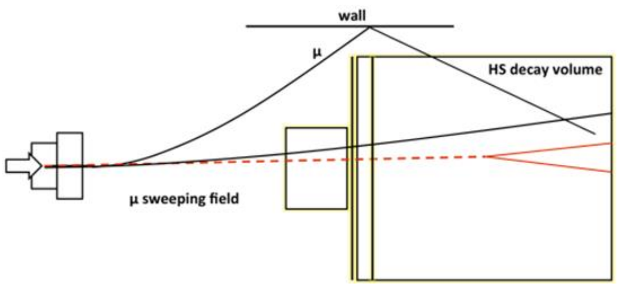
➔ Per spill of $4\text{x}10^{13}$ protons

- 1.5×10^{12} neutrinos and anti-neutrinos through SHiP's fiducial volume
- $\mathcal{O}(10^{11})$ muons above 1 GeV/c (spectrum validated in measurement at SPS with prototype target - agreement within 30%)

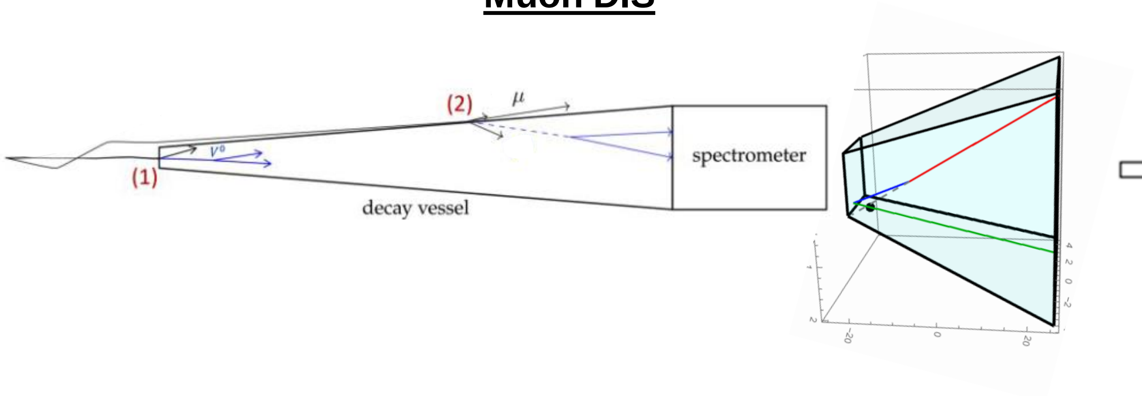
(Eur. Phys. J. C 80 (2020) 284)

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

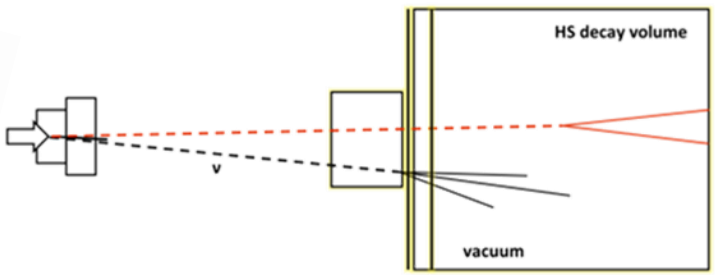
Muon combinatorial



Muon DIS

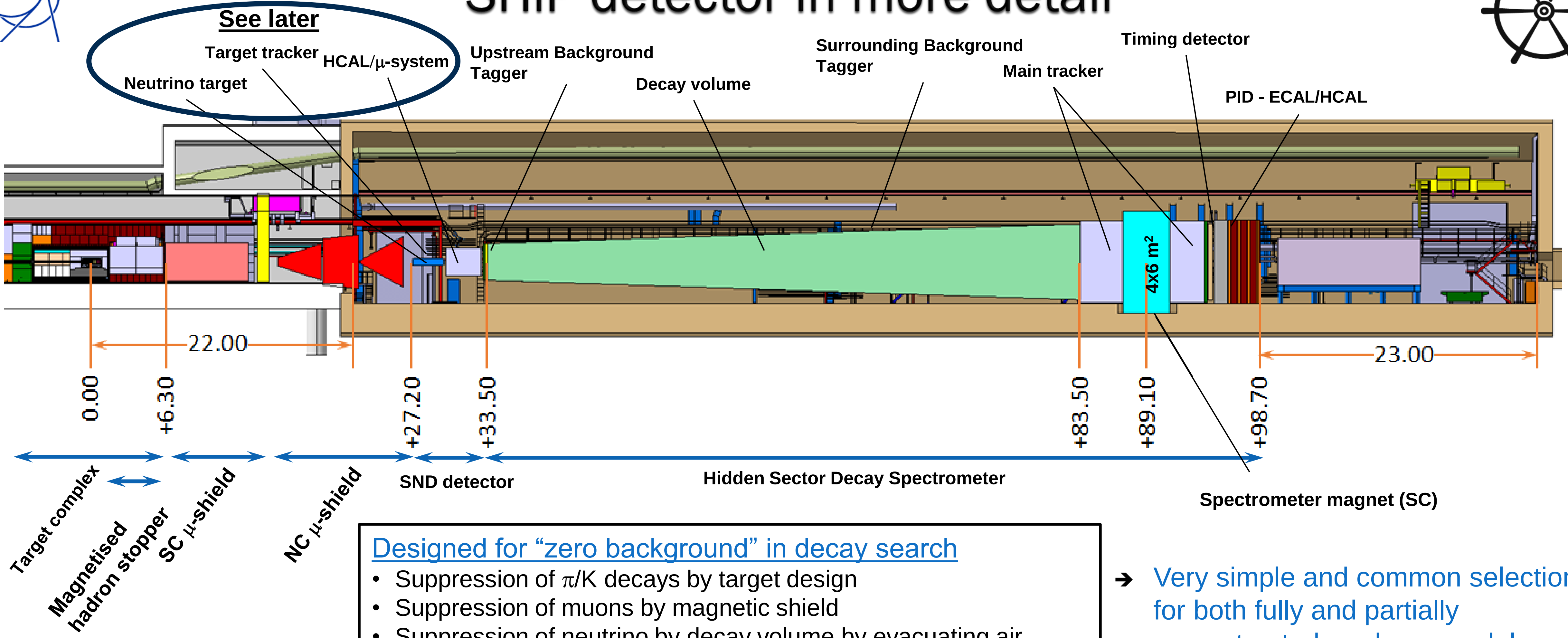


Neutrino DIS



- Most "dangerous" signal-type muons are produced in charm and beauty decays, and in QED resonance decays (e.g. $\rho \to \mu\mu$).

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 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

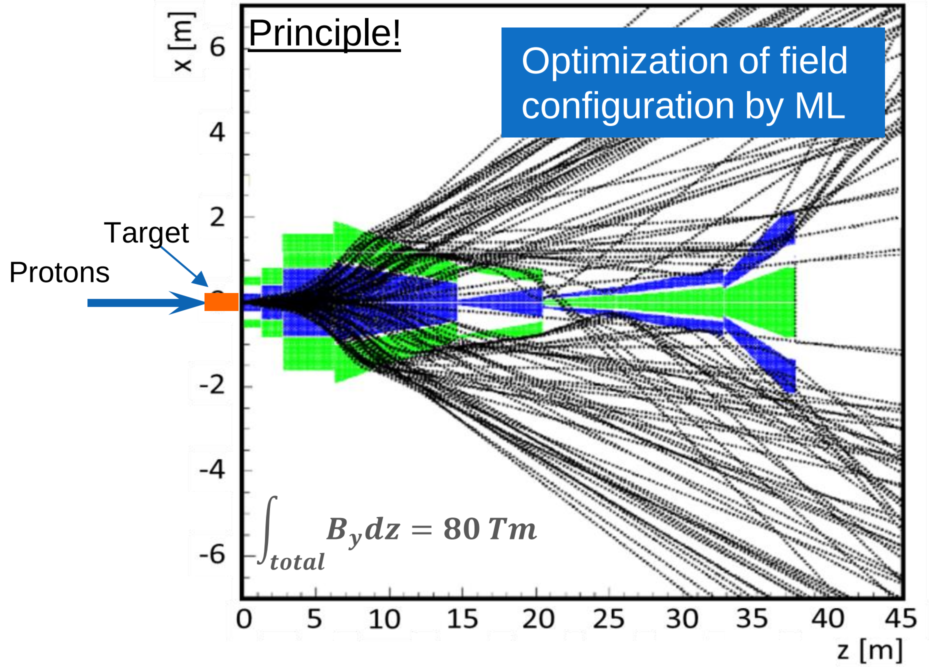
➔ Very simple and common selection for both fully and partially reconstructed modes – model independence

➔ Redundant selection- Possibility to measure background with data by relaxing suppression techniques

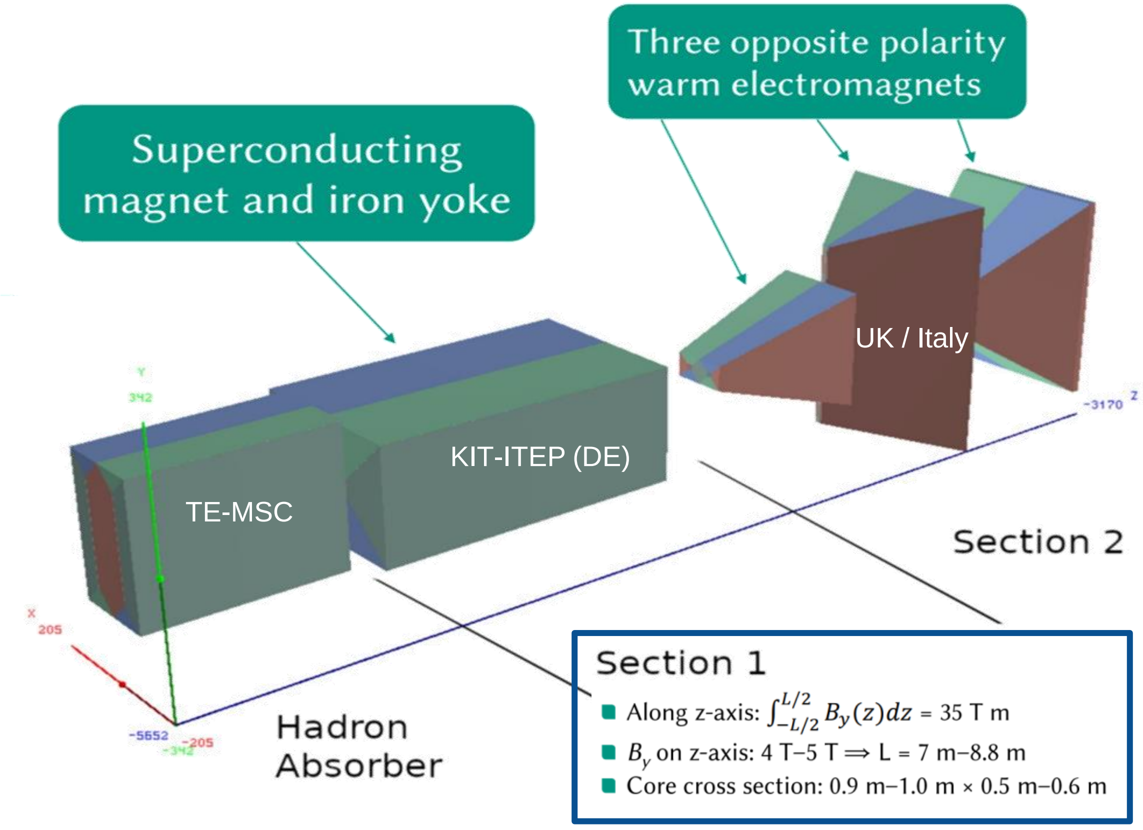
Muon shield

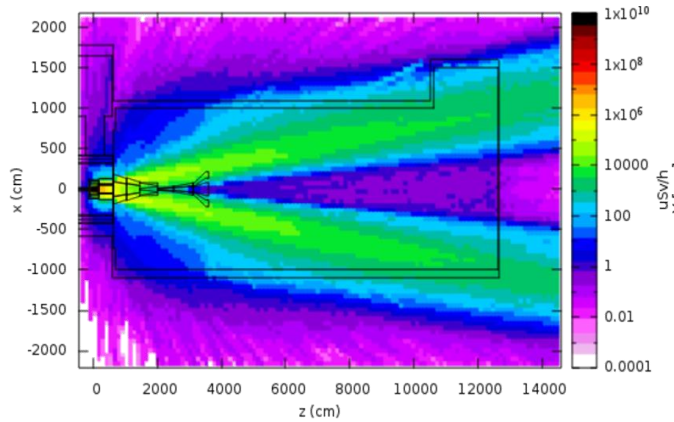
M. Ferro-Luzzi, CERN

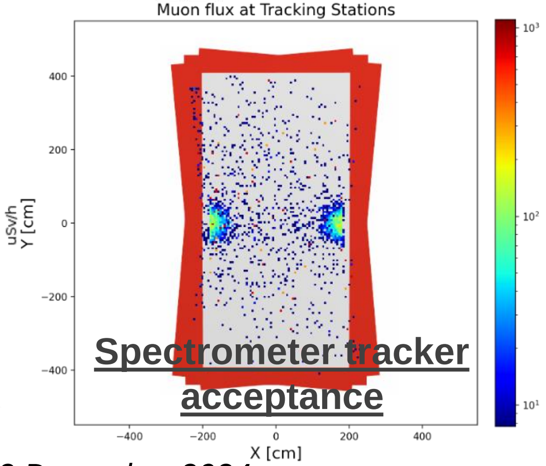
Magnetic sweeper system



➔ Fully warm magnet configuration developed but now exploring hybrid configuration with SC magnet in Section 1





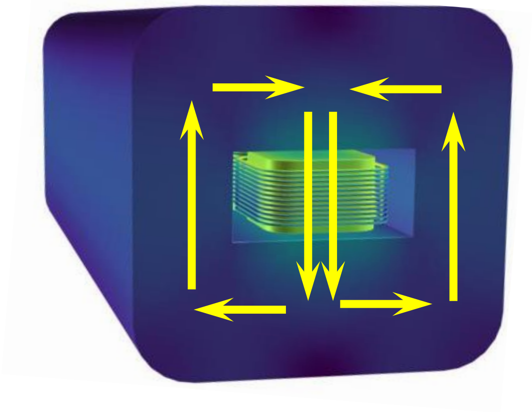


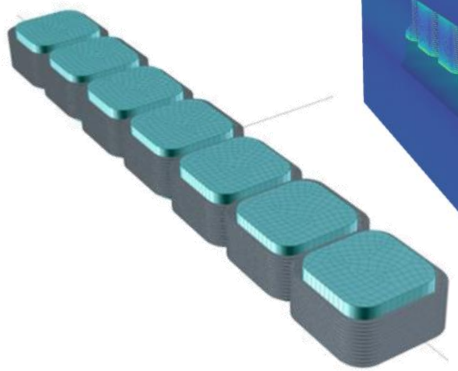
Muon Shield HTS magnet

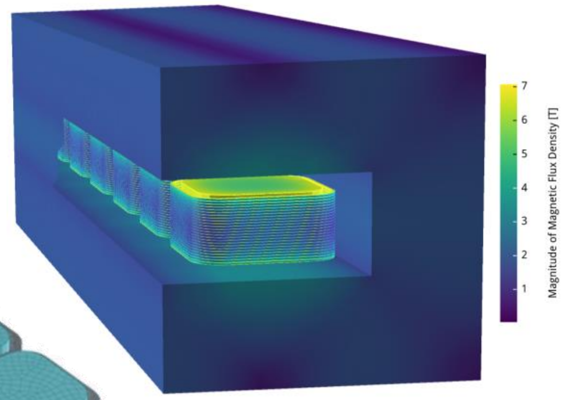
T. Arndt, M. Dam (KIT)

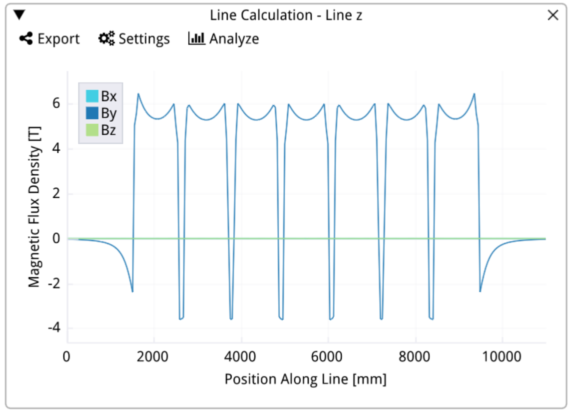
Proposal 1: Array of square coils with inner and outer iron yoke

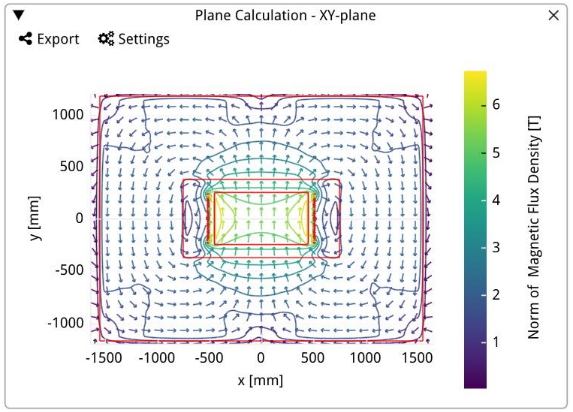
- Coil inner dimensions: 1000 mm x 1000 mm
- Radial coil thickness: 20 mm
- Winding turns per pancake coil: 200 (no insulation)
- Coil bending radius: 200 mm
- Operating current: 649 A
- Number of coils: 168 coils
- Total tape length: 126 km (750 m per coil)
- Magnetic energy: 68.6 MJ
- Total inductance: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











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

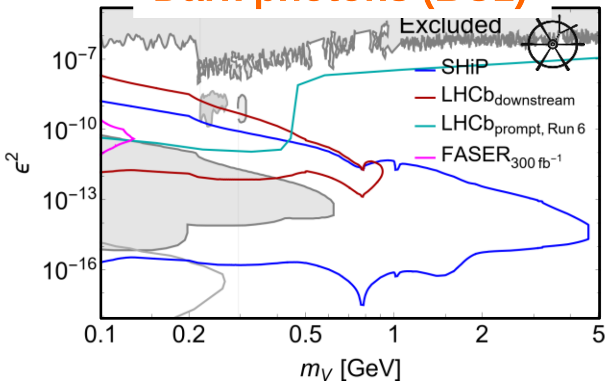
Procurement of HTS tape in collaboration with TE-MSC

HSDS: FIP decay search performance, benchmarks

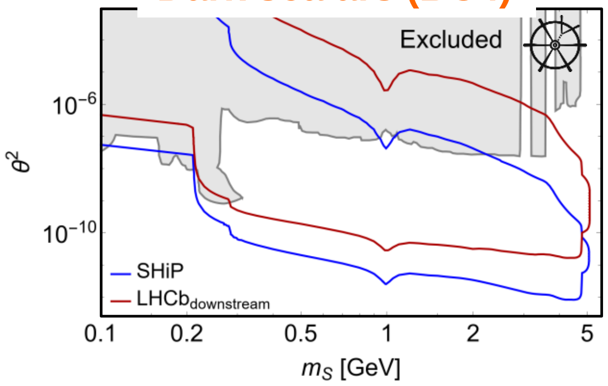
Expected background is <1 event for 6×10^{20} pot (15 years of operation)

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	$(1.3 \pm 2.1) \times 10^{-4}$

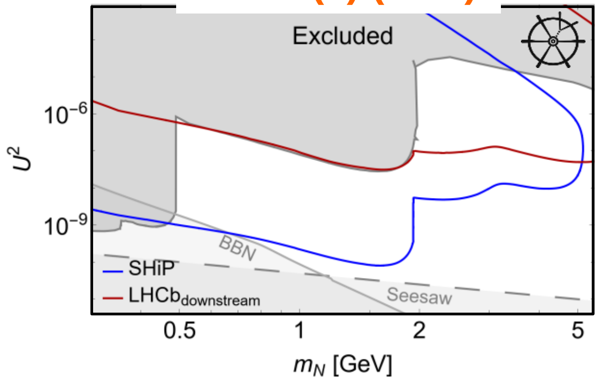
Dark photons (BC1)



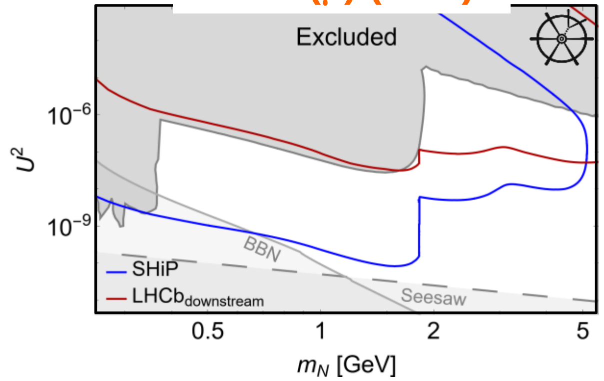
Dark scalars (BC4)



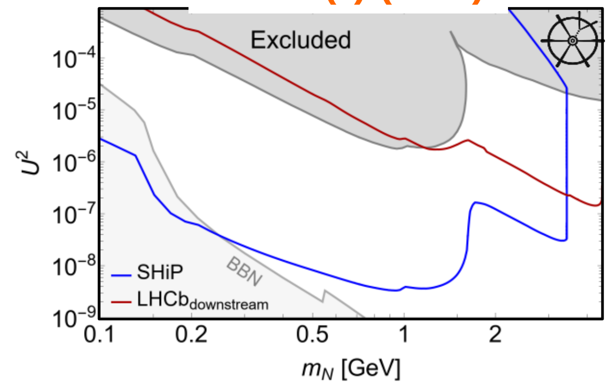
HNLs (e) (BC6)



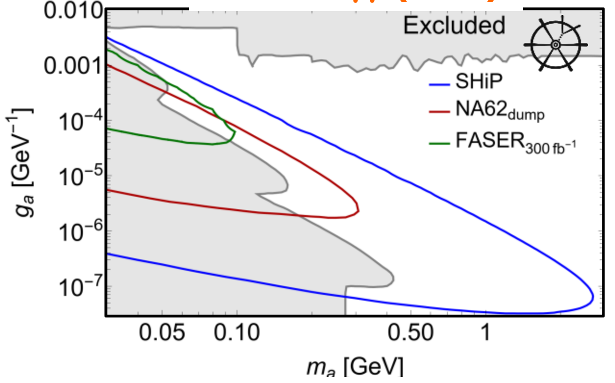
HNLs (μ) (BC7)



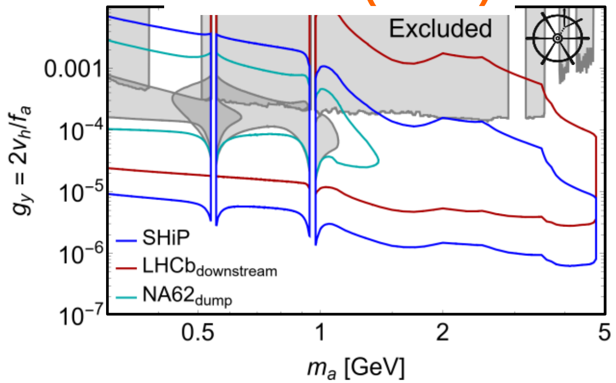
HNLs (τ) (BC7)



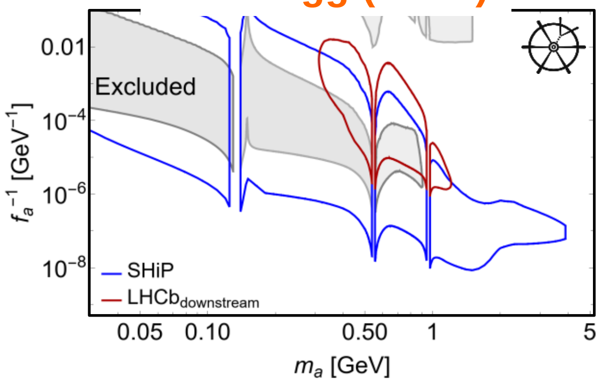
ALPs→γγ (BC9)



ALPs→ff (BC10)



ALPs→gg (BC11)



+ also SUSY-related benchmarks

HSDS: FIP decay search performance, benchmarks

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

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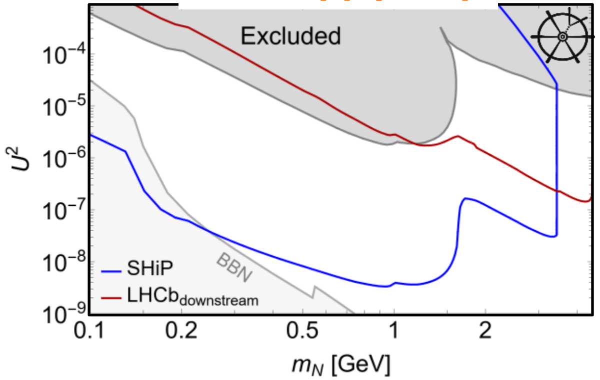
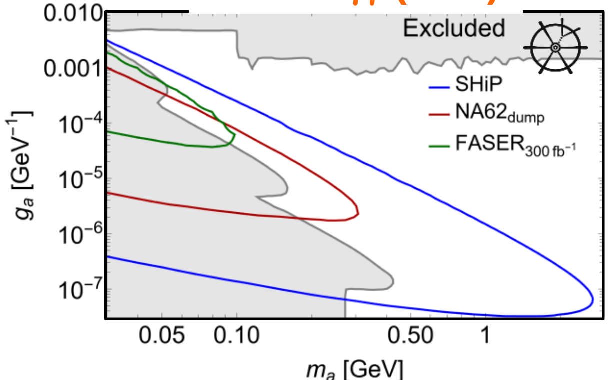
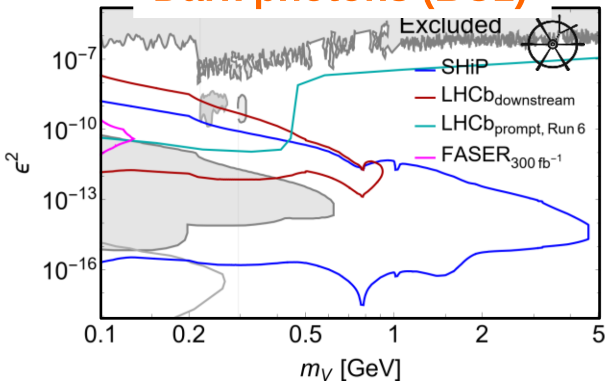
HNLs (τ) (BC7)



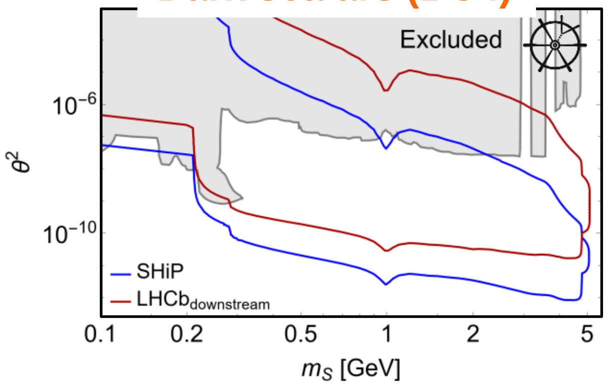
ALPs→γγ (BC9)



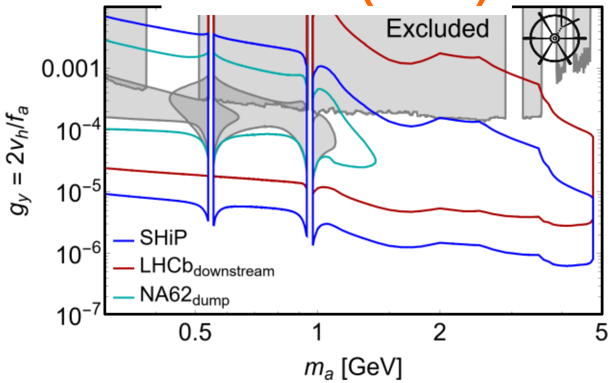
Dark photons (BC1)



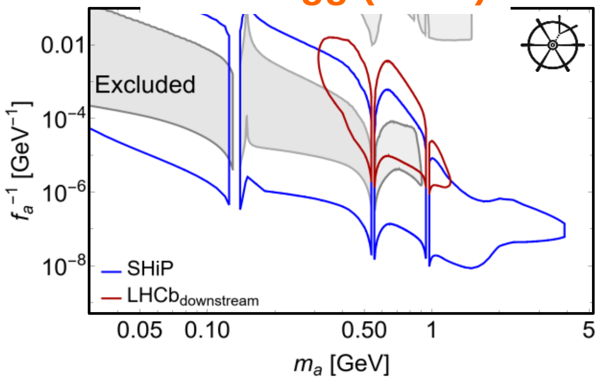
Dark scalars (BC4)



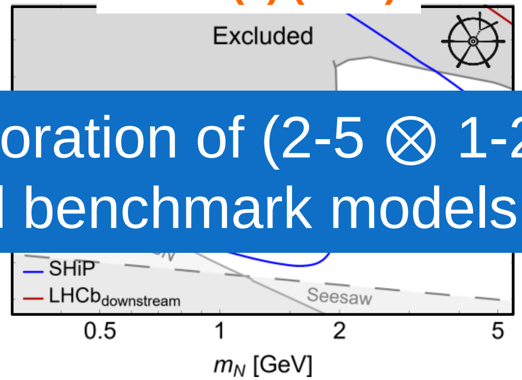
ALPs→ff (BC10)



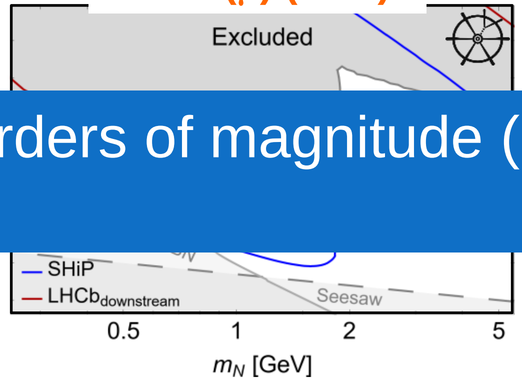
ALPs→gg (BC11)



HNLs (e) (BC6)

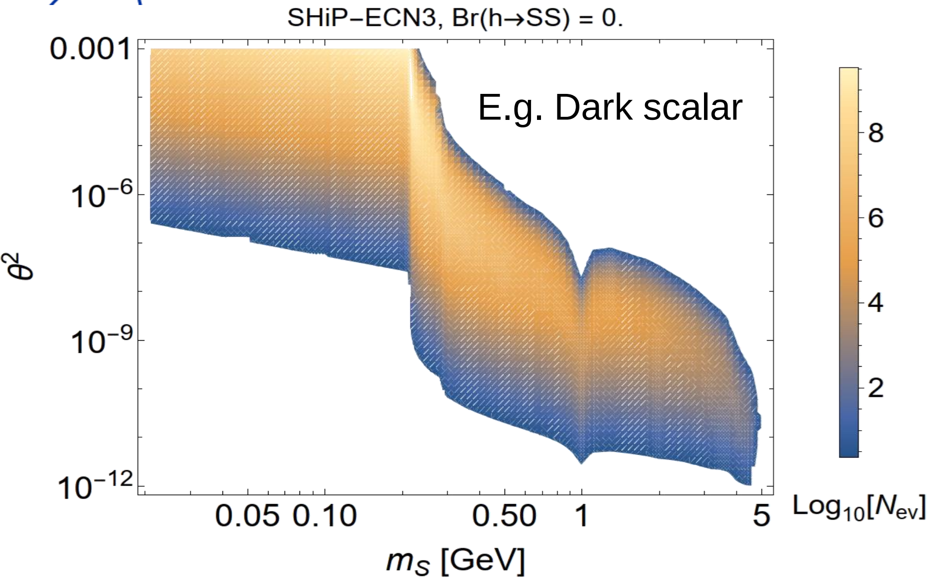


HNLs (μ) (BC7)



Exploration of (2-5 ⊗ 1-2) orders of magnitude (coupling^2 ⊗ mass) beyond current experiments in all benchmark models

Physics sensitivities – FIPs cont'd

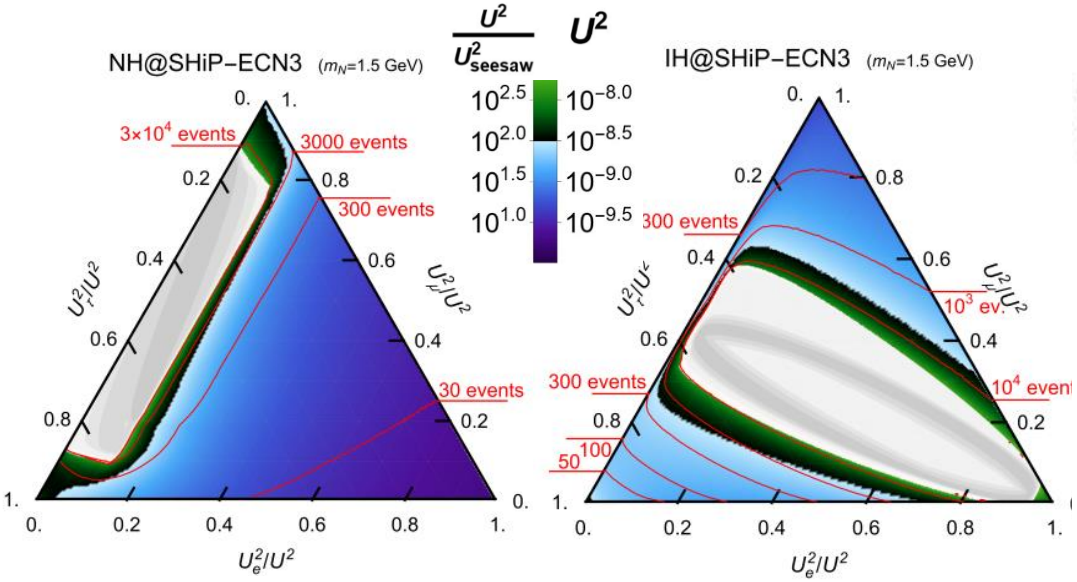


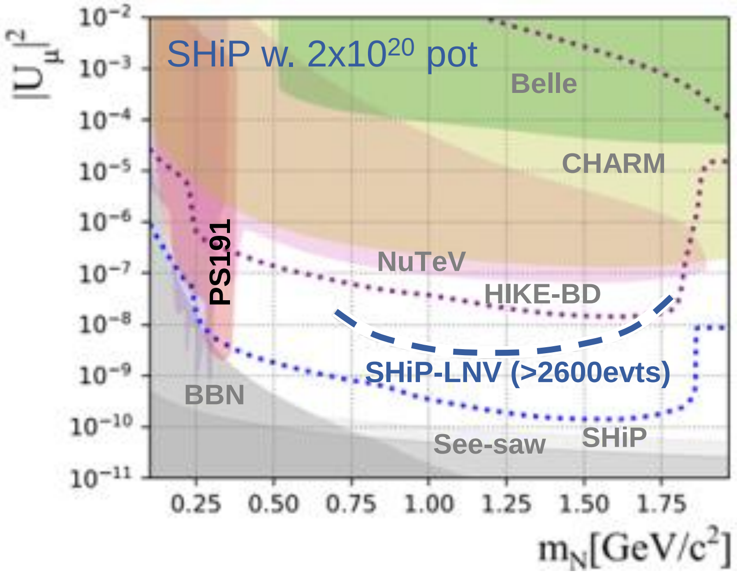
- Step 1: Characterise new object - precise mass, branching ratios, spin: $\mathcal{O}(10)$ evts

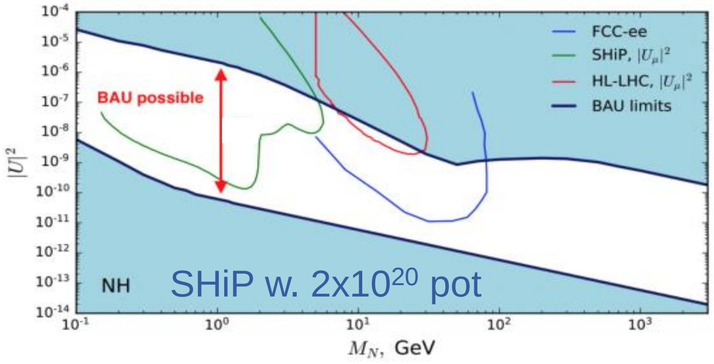
- Step 2: Test compatibility with hypothesis addressing SM issues: $\mathcal{O}(100-1000)$ evts

https://arxiv.org/abs/2312.00659
https://arxiv.org/abs/2312.05163

➔ *E.g. check if HNL mixing pattern fits neutrino flavour oscillations, and lepton number violation and BAU*







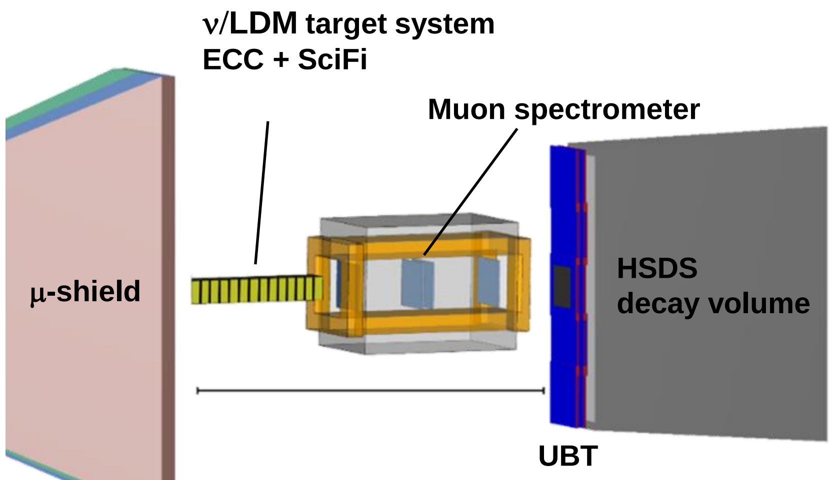
LDM scattering and neutrino detector (SND)

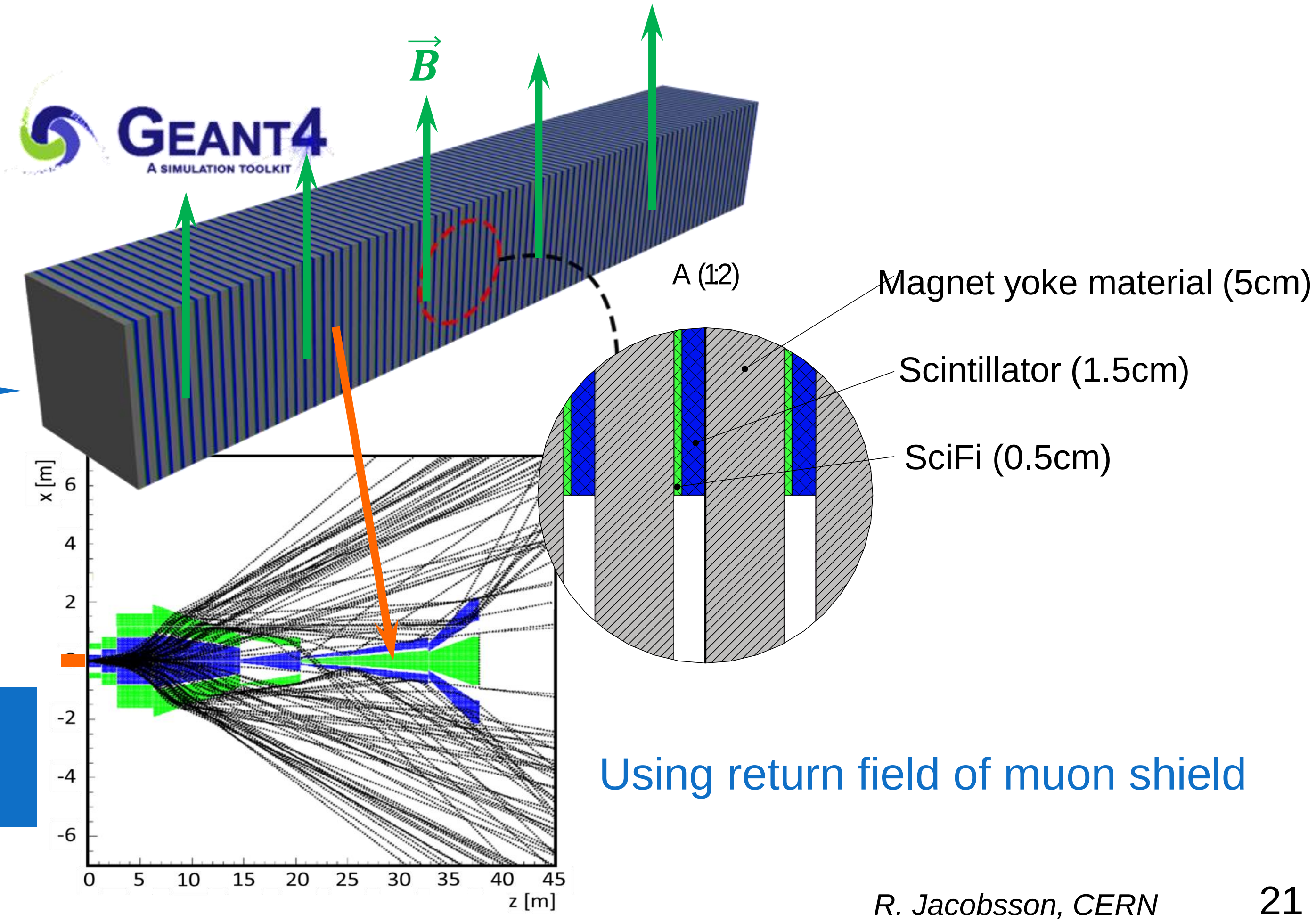
- Neutrino flavour identification, energy, and muon momentum and charge measurement

➔ Ongoing revision to build SND detector only from electronic detectors integrated into SHiP μ-shield

➔ Missing p_T efficient for ν_τ at SPS ➔ Tracker / fine-segmented HCAL with magnetised absorber

➔ Clean vertex and accurate e.m. shower reconstruction for LDM ➔ Silicon/Fe or W



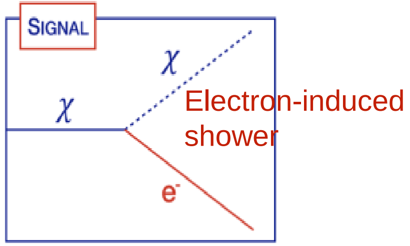


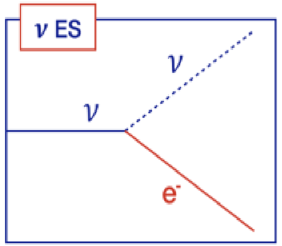
Possibly two detectors with different configuration/optimisation

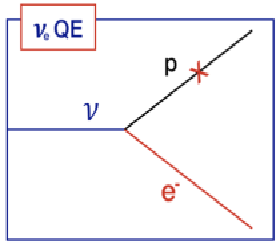
Using return field of muon shield

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

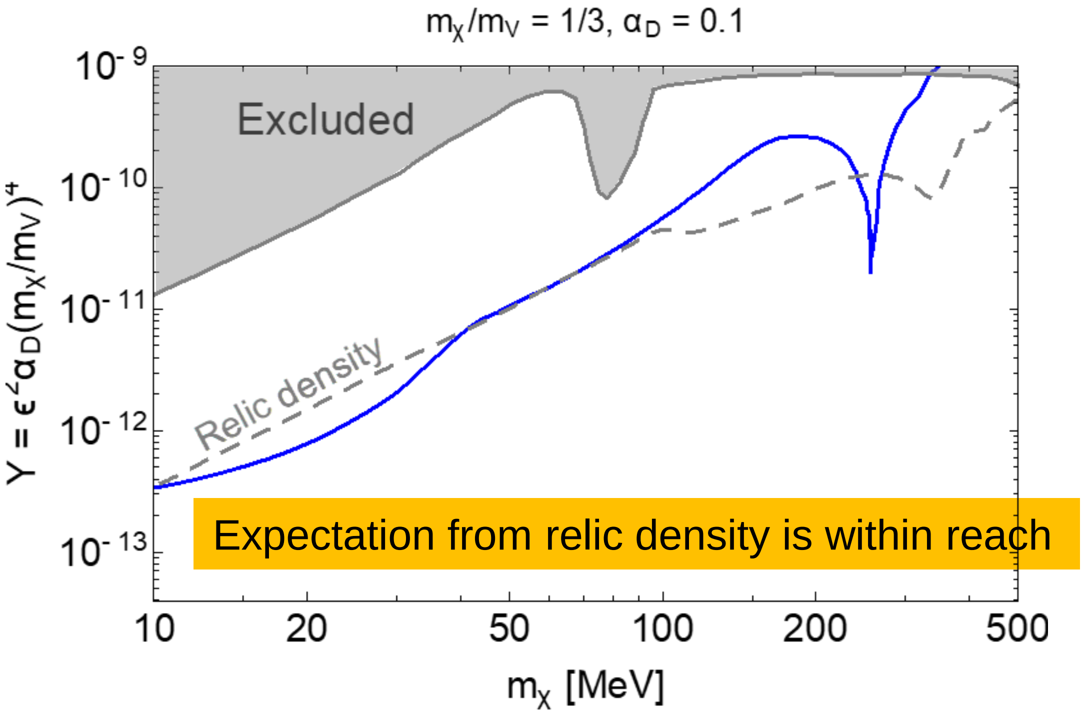






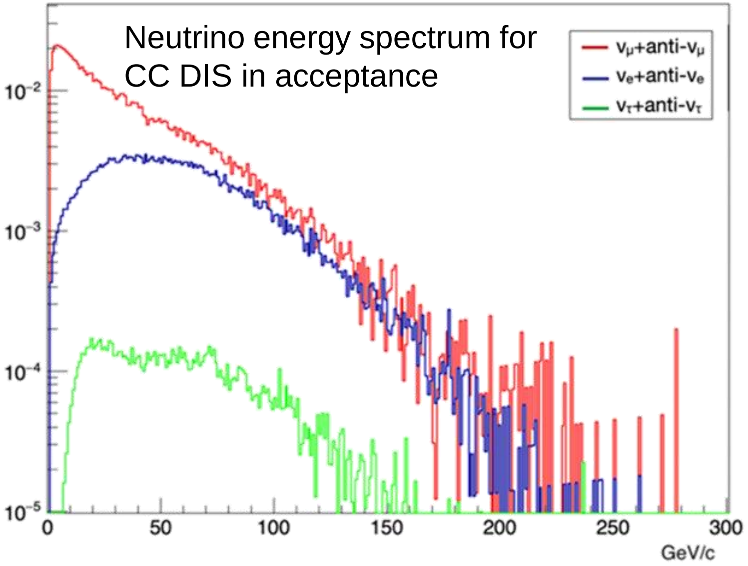
➔ Background is dominated by neutrino elastic and quasi-elastic scattering, for 6×10^{20} PoT

6×10^{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



SND: Neutrino yields

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



Incl. reconstruction efficiencies

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

	<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

Systematic uncertainty from knowledge of ν_τ flux

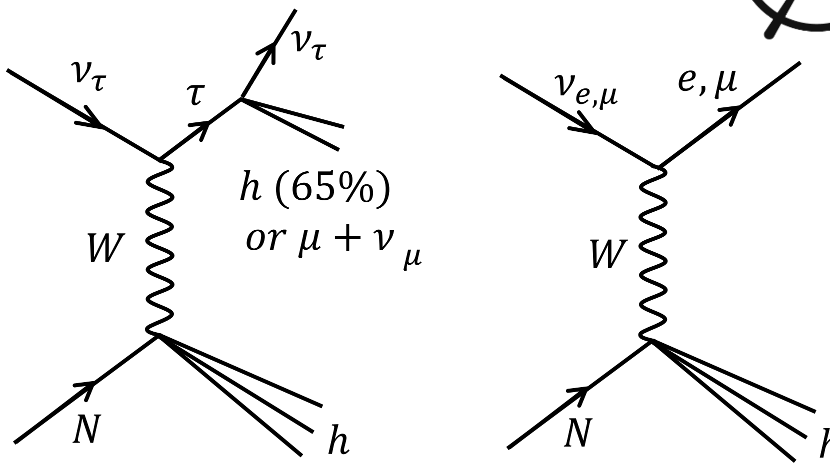
1. D_s production cross-section at SPS
   - Currently 10%, but NA65 expects to reconstruct ~1000 events
2. BR($D_s \rightarrow \tau\nu_\tau$) ~3-4%
3. Cascade production of charm in thick target
   - SHiP plans dedicated experiment to measure J/ψ and charm production using muons in targets of variable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

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

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

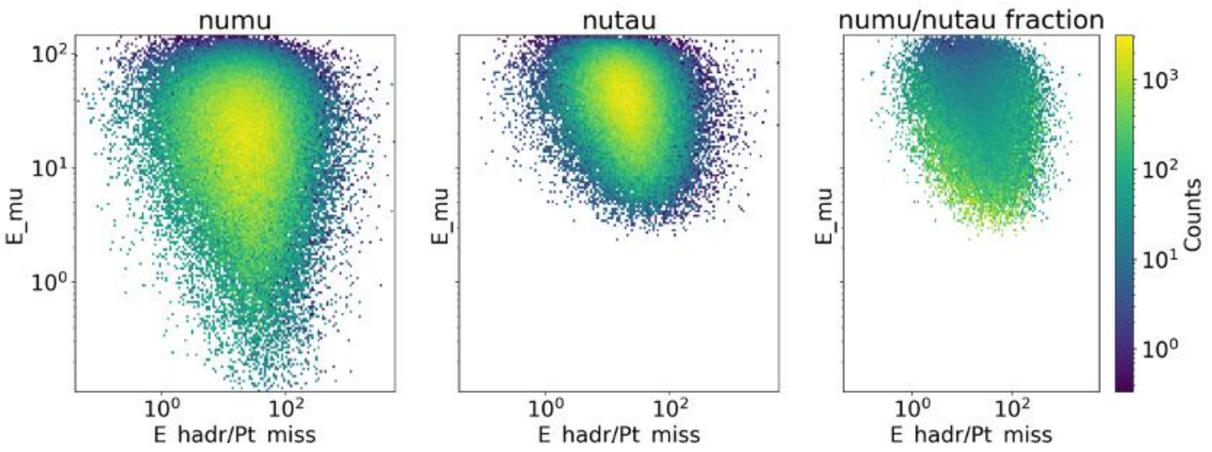
Neutrino reconstruction

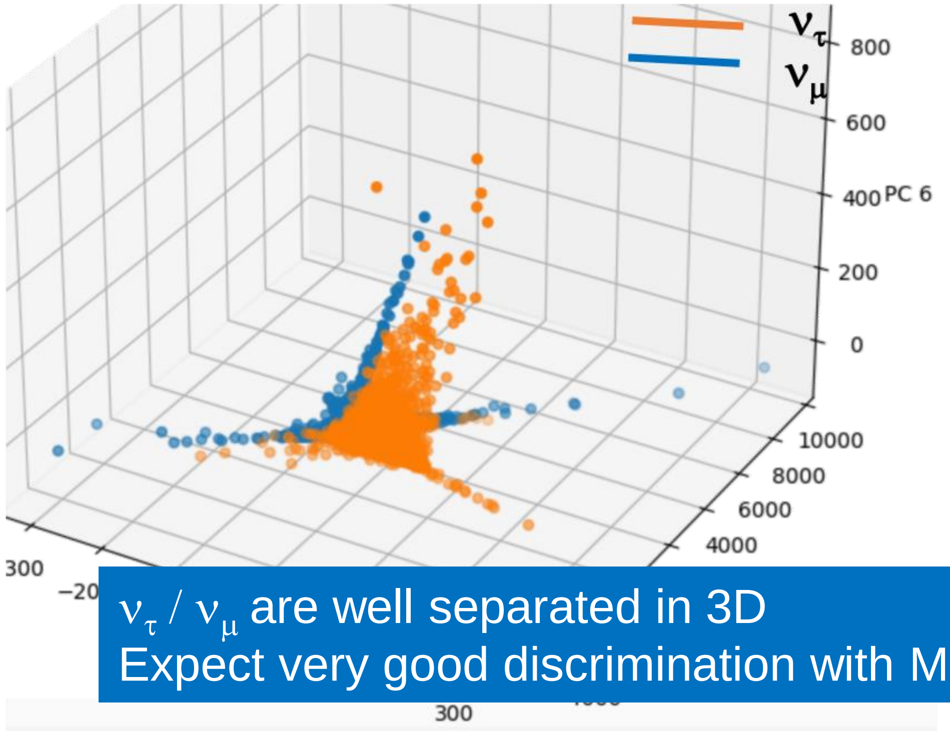
- Experimental signature of tau neutrino:
  - Topological: "double-kink" signature resulting from ν_τ-interaction and τ-decay
  - Statistical: Missing P_t carried away by two neutrinos from t-decay



➔ Kinematical variables

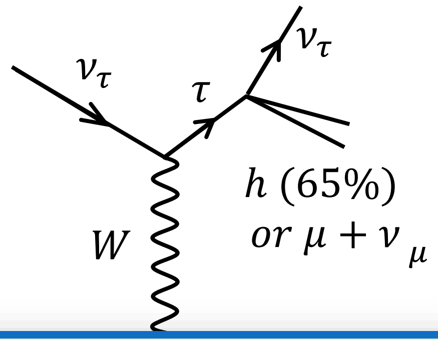
- Missing momentum wrt ν_τ direction-of-flight
- Muon momentum
- Energy of hadrons
- Additional use of impact parameter with silicon

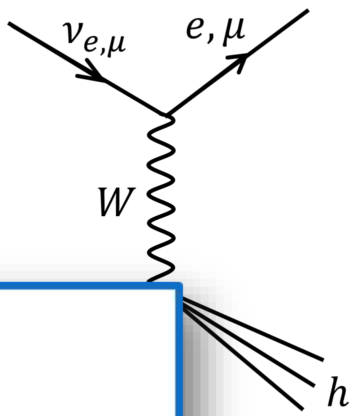




ν_τ / ν_μ are well separated in 3D
Expect very good discrimination with ML

Neutrino reconstruction





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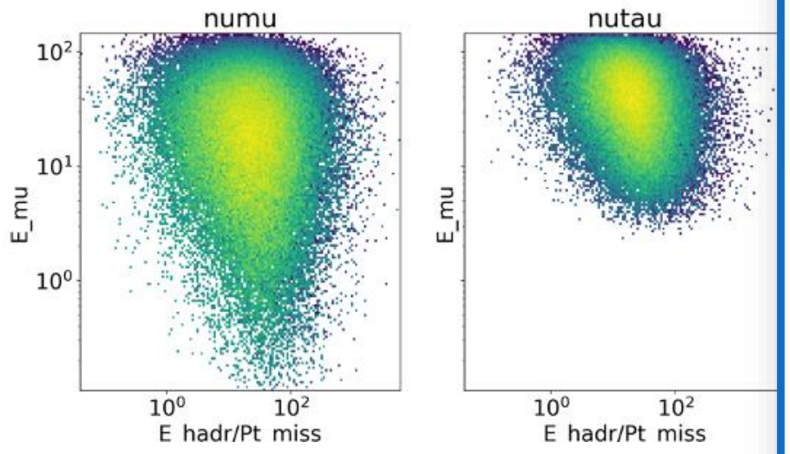
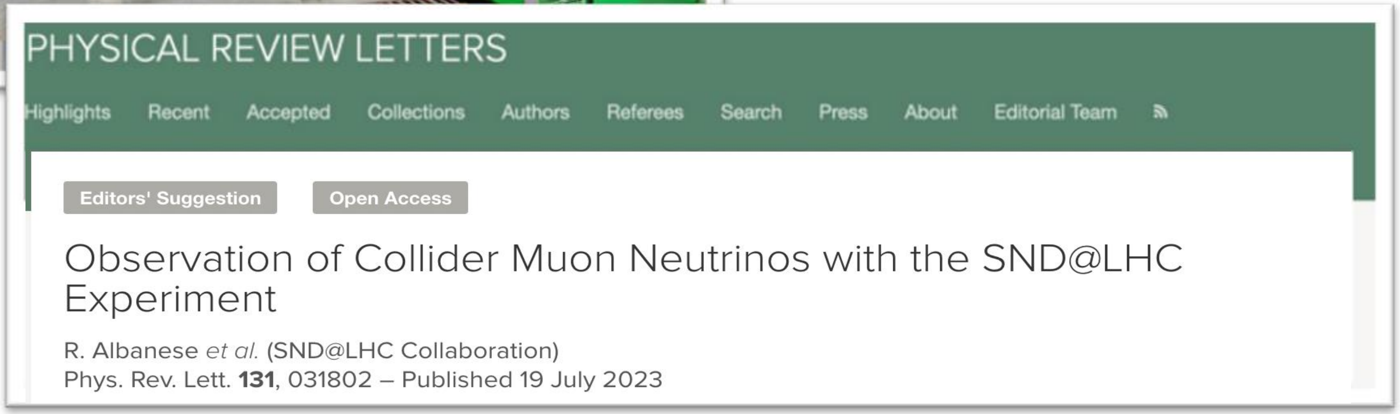
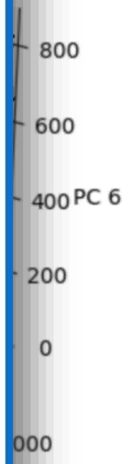




Observation of Collider Muon Neutrinos with the SND@LHC Experiment

R. Albanese *et al.* (SND@LHC Collaboration)
Phys. Rev. Lett. **131**, 031802 – Published 19 July 2023



with ML

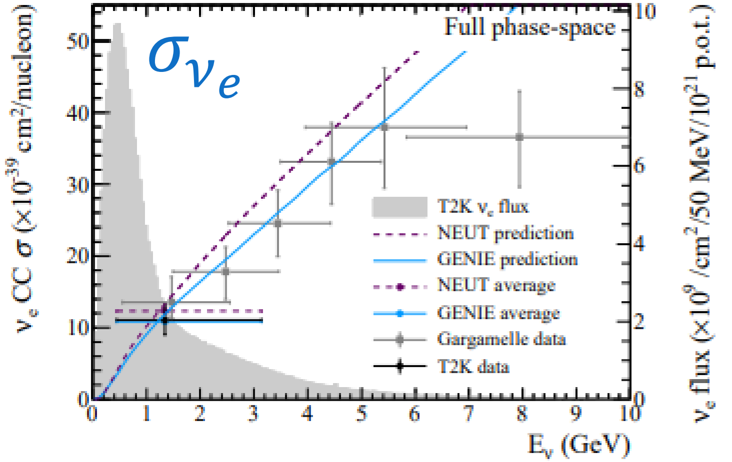
SND: Neutrino interaction physics

- 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

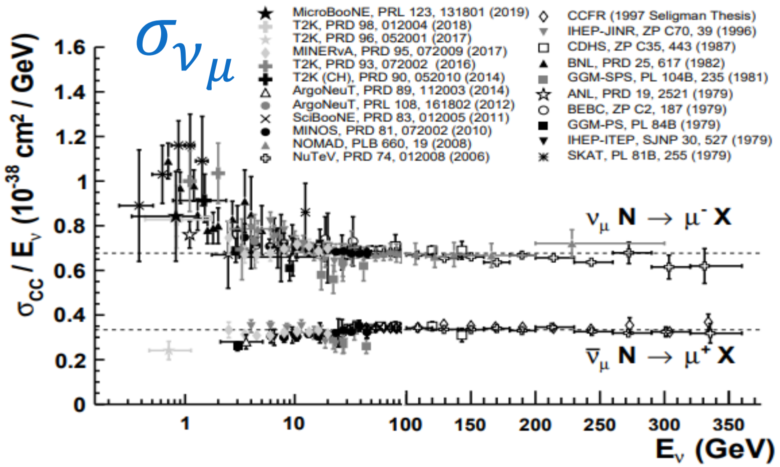
$$\frac{\sigma(\nu_e)}{\sigma(\nu_\mu)} = \frac{(\nu_e \text{ events observed})}{(\nu_\mu \text{ events observed})} \frac{\int E_{\nu_\mu}(\nu_\mu \text{ flux})dE}{\int E_{\nu_e}(\nu_e \text{ flux})dE} = 1.09 \pm 0.17\ .$$

➔ 15%!

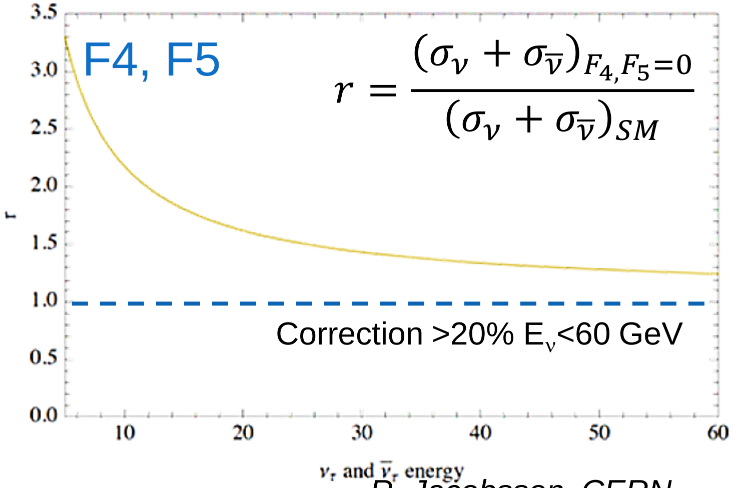
Phys.Rev. D41, 2653 (1990)



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



PDG



Rep. Prog. Phys. 79 (2016)124201

SND: Neutrino interaction physics

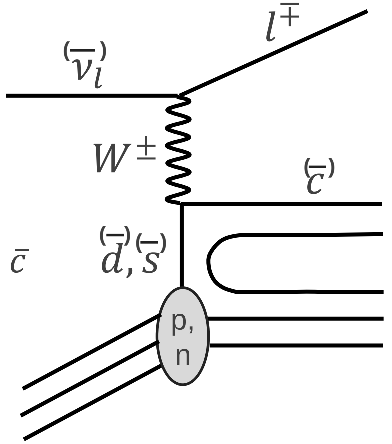
Neutrino-induced charm production programme

- 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

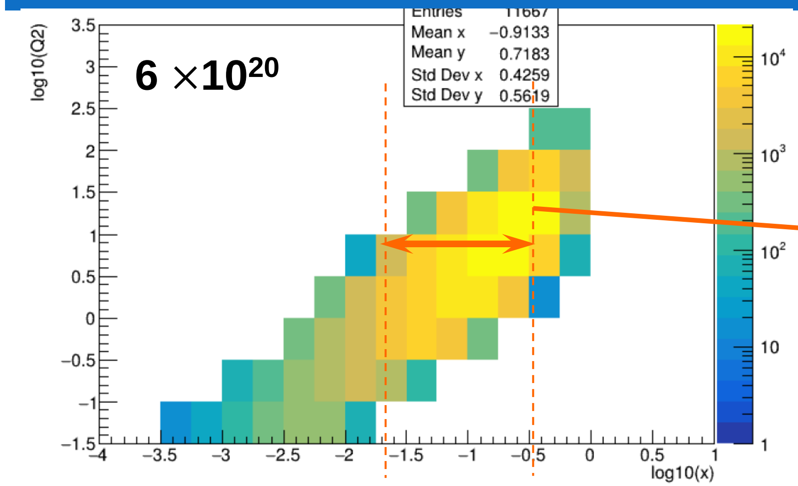
	<E> (GeV)	CC DIS with charm prod
N_{ν_μ}	57	$3.5\ \times10^5$
N_{ν_e}	71	$1.7\ \times10^5$
$N_{\overline{\nu}_\mu}$	50	0.7×10^5
$N_{\overline{\nu}_e}$	60	$0.3\ \times10^5$
total		$6.2\ \times10^5$

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

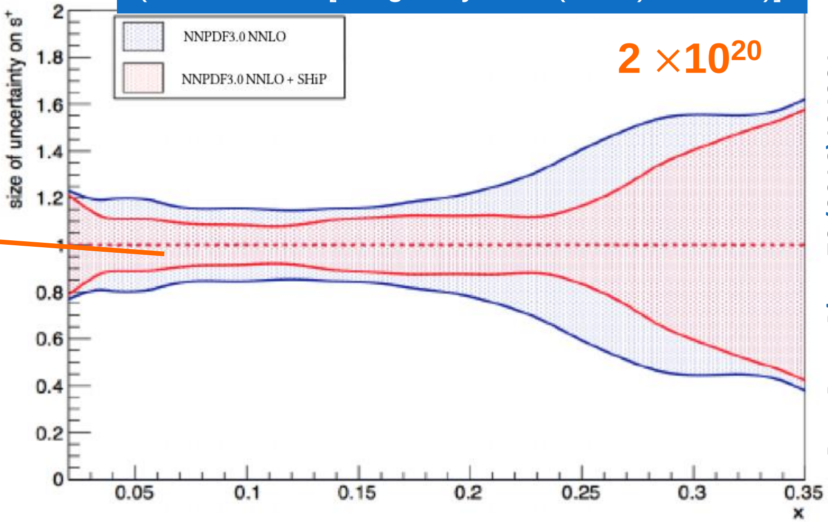


No charm candidate from ν_e and ν_τ interactions ever reported

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

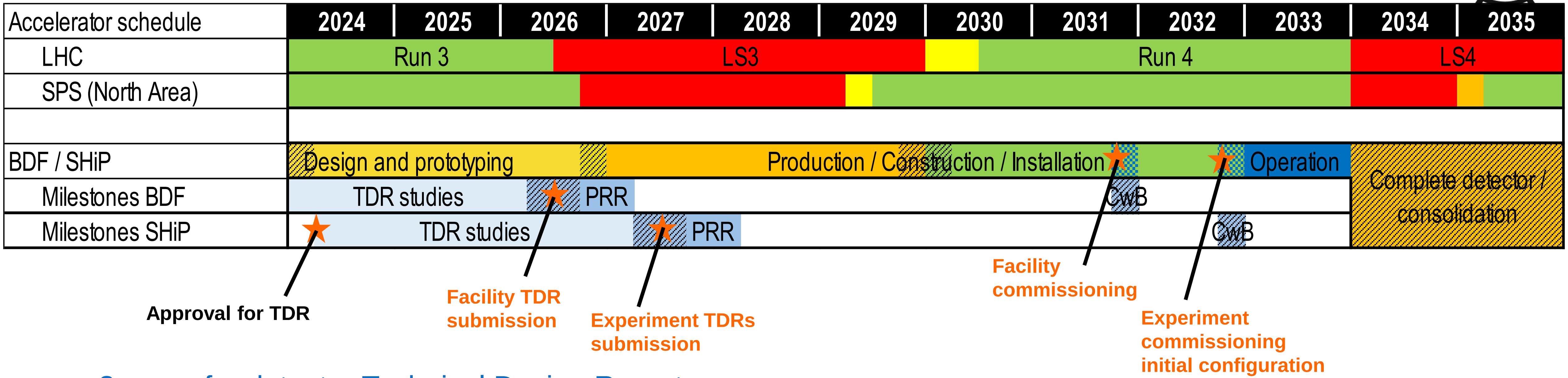


SHiP sensitivity to PDF for x < 0.35
(evaluated in [Prog. Phys. 79 (2016) 124201)]



Rep. Prog. Phys. 79 (2016)124201

BDF/SHiP schedule



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

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

→ Objectives: commissioning facility/detector, performance, background measurements, physics in nominal conditions

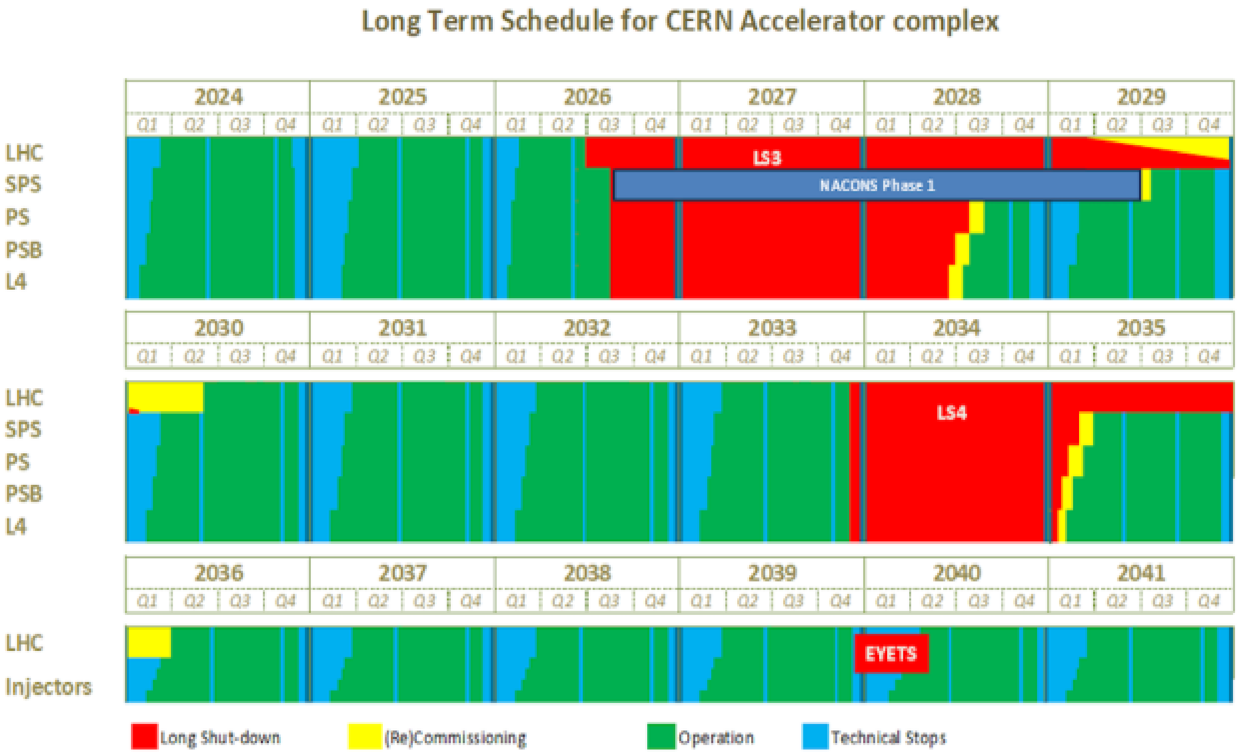
→ Critical systems in full scale and full physics capability

→ Prototypes may fill "holes" in 2032-2033

➔ 15 years of physics exploration

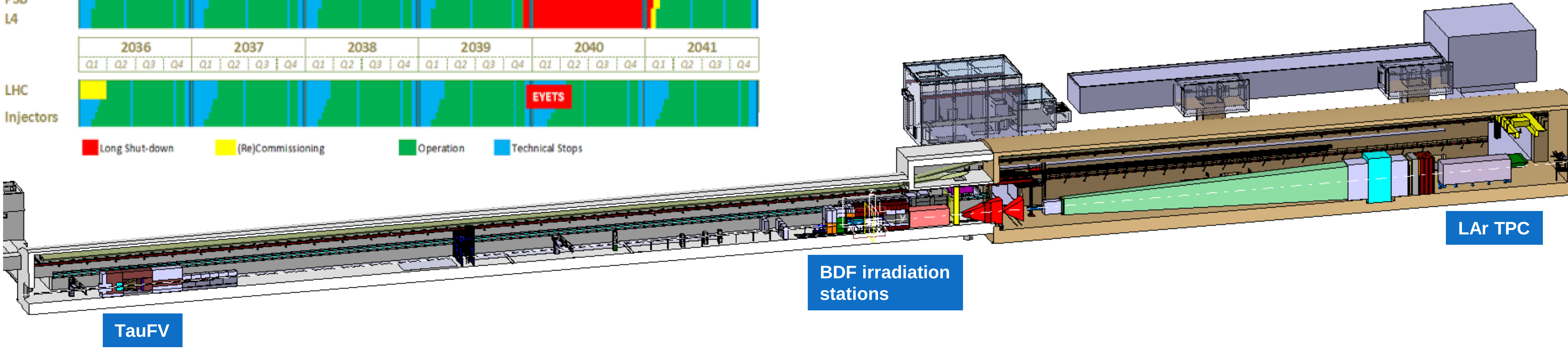
Overview of extensions of research facility

➔ SHiP physics exploration stretches over 15 years



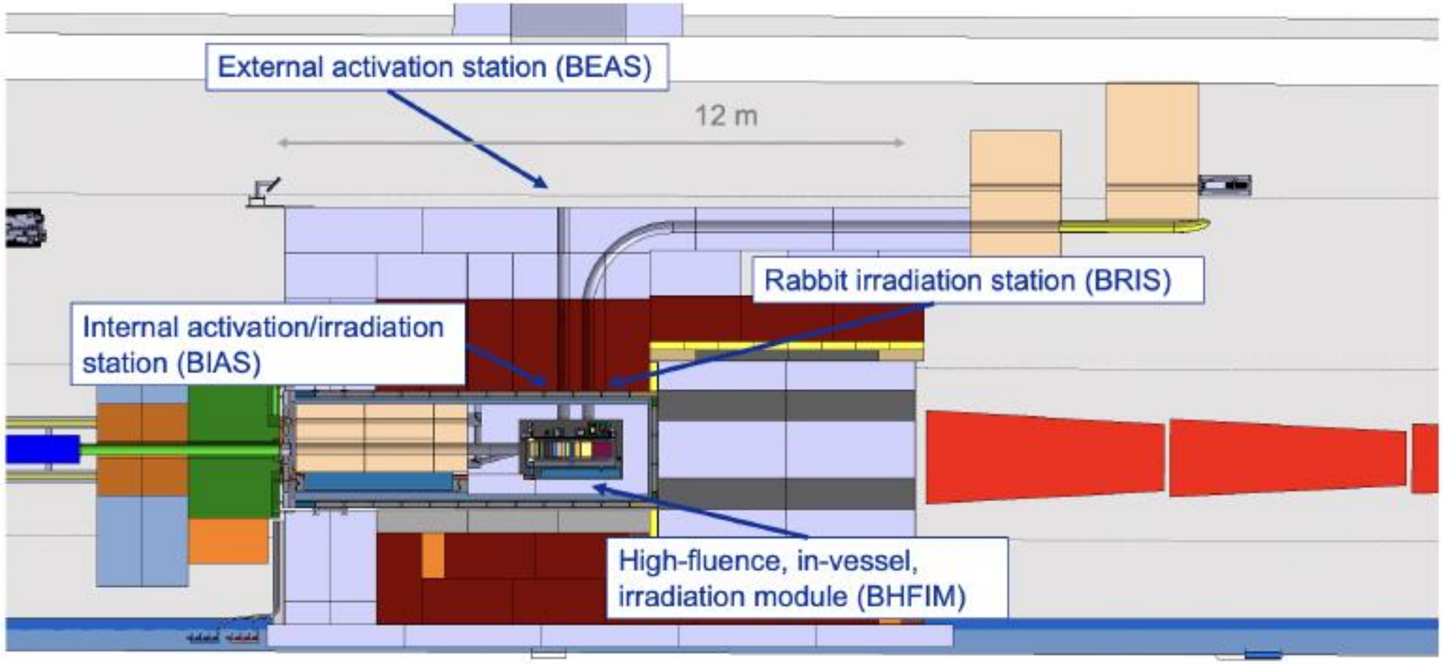
Preliminary studies of opportunities to extend physics programme *synergetically with SHiP*:

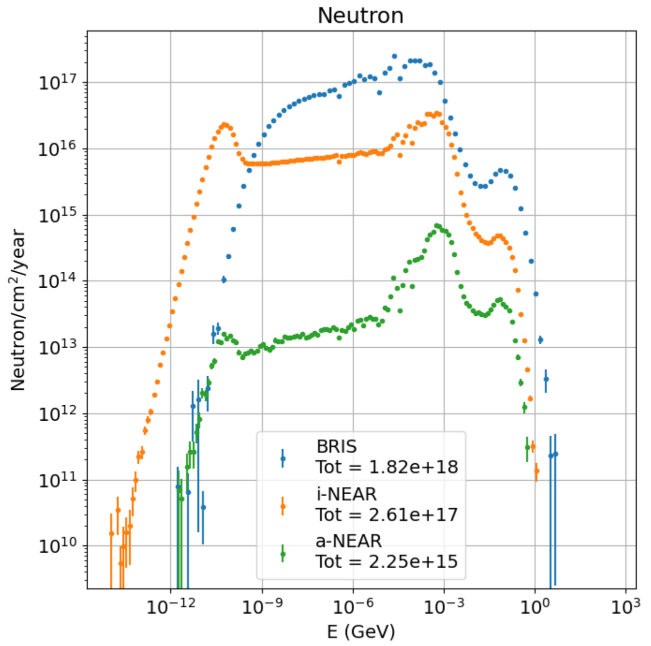
1. Irradiation stations (nuclear astrophysics and accelerator / material science applications)
2. LArTPC to extend search for FIPs using different technology
3. TauFV to search for lepton flavour violation and rare decays of tau leptons and D-mesons



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





Flux 3-4 orders of magnitudes higher than at present n_TOF NEAR

- Nuclear physics
- Radiation tolerance test of materials and electronic components at extreme conditions expected at FCC

Neutron Activation Station at the SPS Beam Dump Facility

CERN-SPSC-2024-027 / SPSC-EOI-023

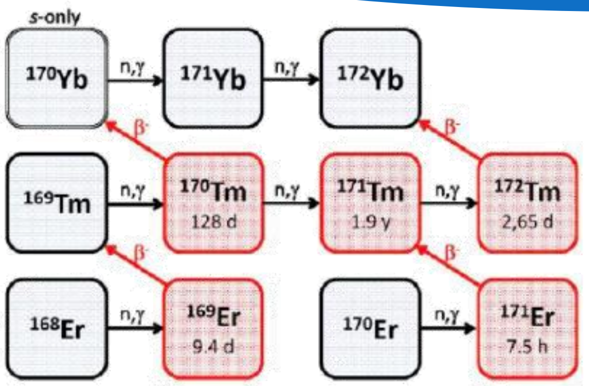
Claudia Lederer-Woods

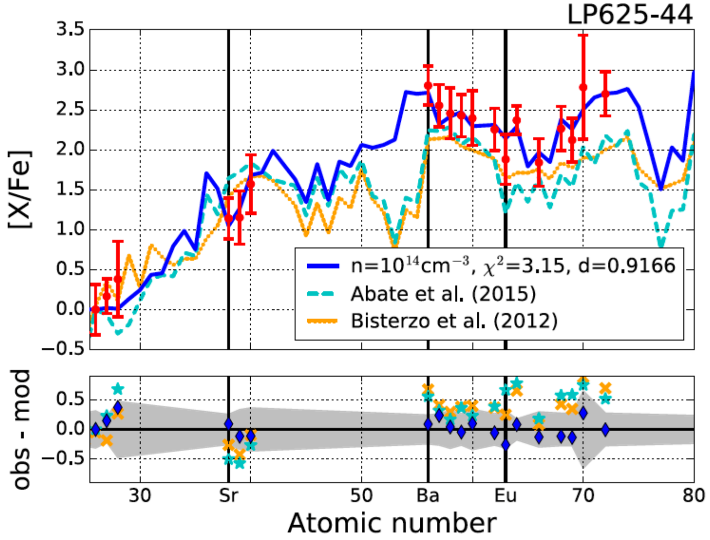
nTOF

Science examples:

Measurements to determine neutron densities and temperature in stellar interiors e.g. (n,γ) on ^{94}Nb, ^{147}Pm, ^{163}Ho and ^{171}Tm

Measurements to explain peculiar abundances in old stars e.g. (n,γ) on ^{125}Sb, ^{137}Cs, ^{144}Ce





Measurements for next generation fission and fusion reactors e.g. (n,2n) on ^{109}Ag, ^{151,153}Eu

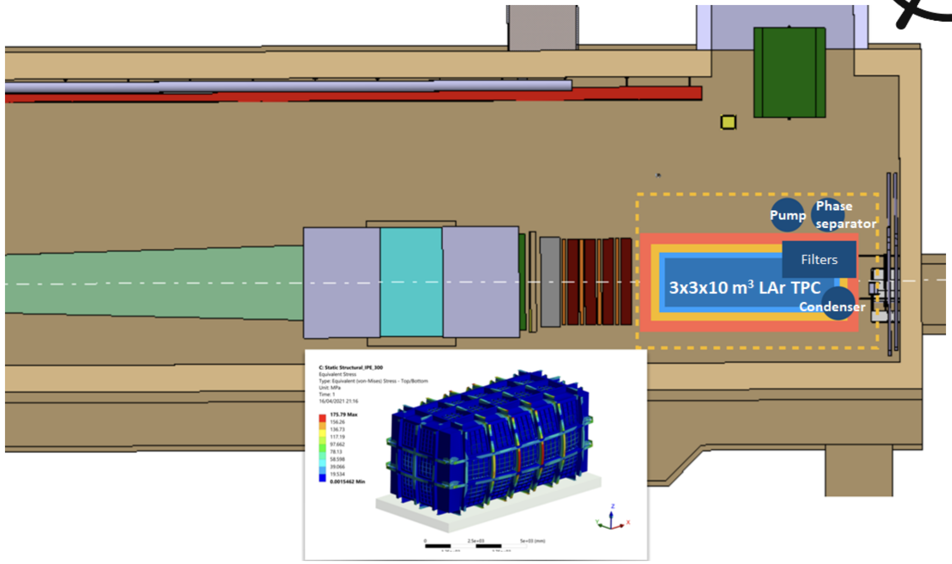
Extensions: FIP searches with LAr TPC detector

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

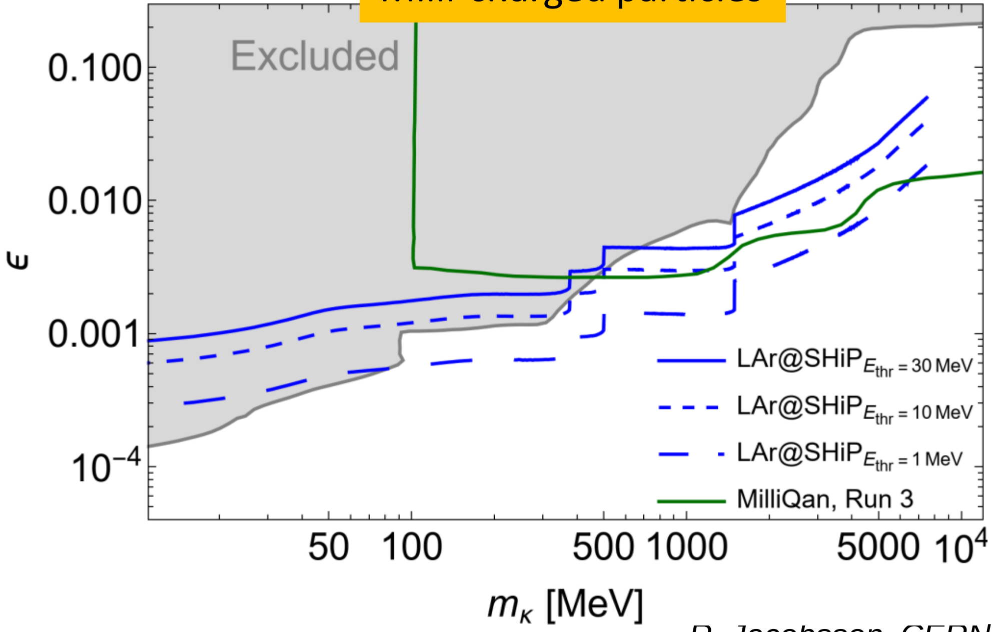
- Large experience at CERN with building 700 t detectors for DUNE
- Space available behind SHiP allows installation of LArTPC with an active volume ~3×3×10 m³ (~130 t) and associated infrastructure

➔ Extends SHiP's physics reach using different technology

New opportunities with LAr@SHiP,
A. De Roeck et al, arXiv:2312.14868



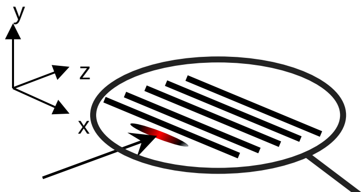
Milli-charged particles



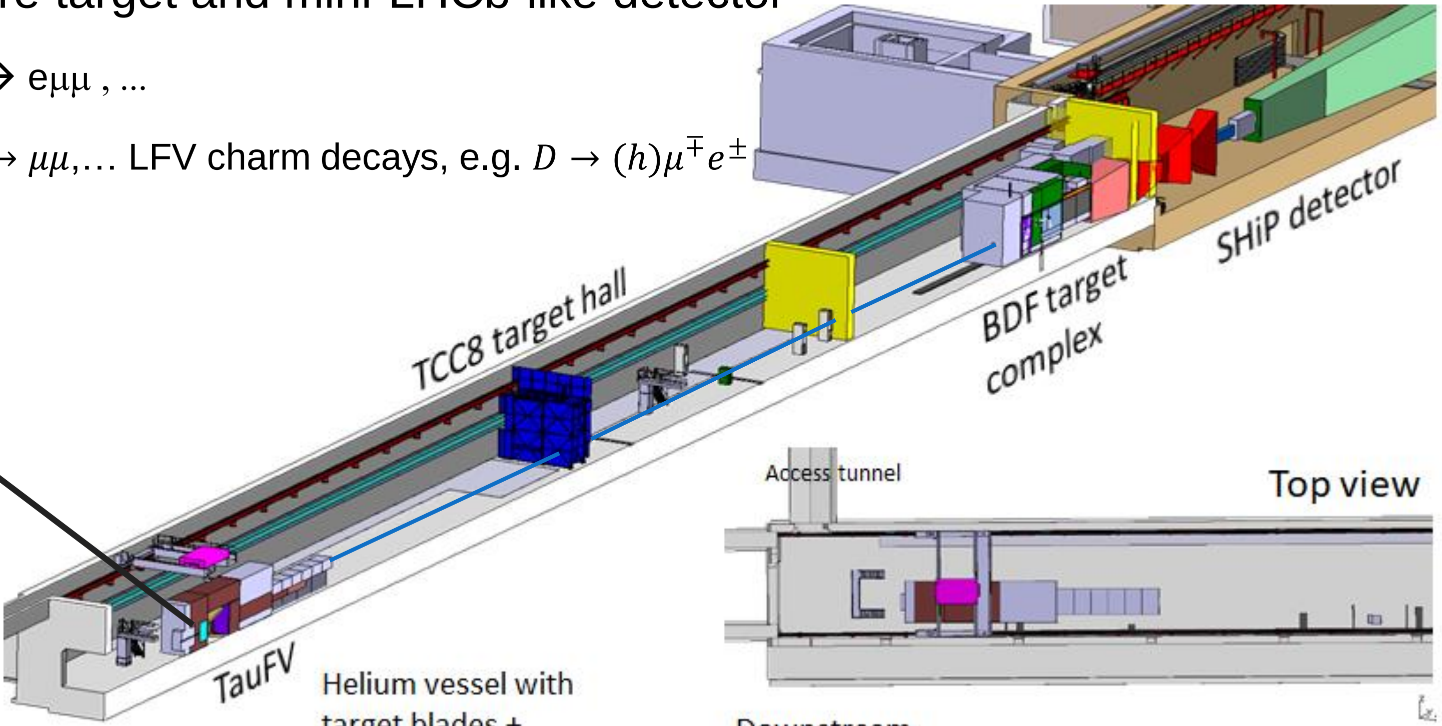
Extensions: Tau flavour violation experiment

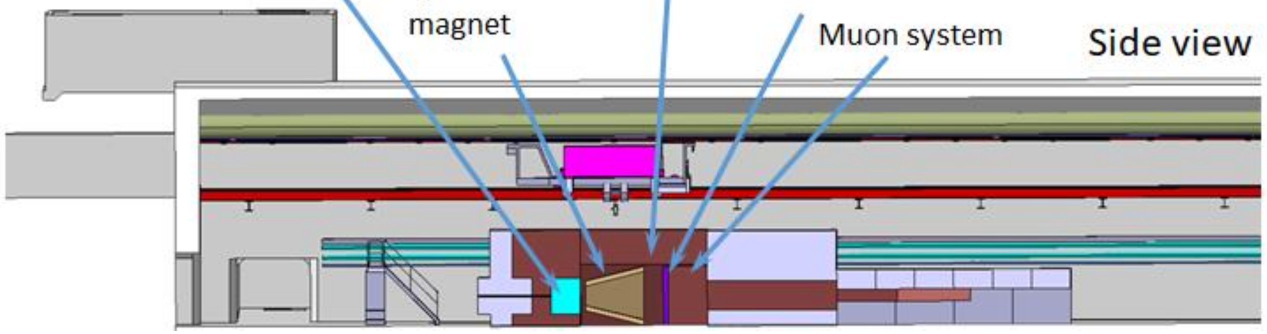
Intercepting 1-2% of protons in BDF line with wire target and mini-LHCb-like detector

- 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 $D \to \mu\mu,\ldots$ LFV charm decays, e.g. $D \to (h)\mu^{\mp}e^{\pm}$



~5 x (0.4mm x 2mm) tungsten wires (actually “blades”)





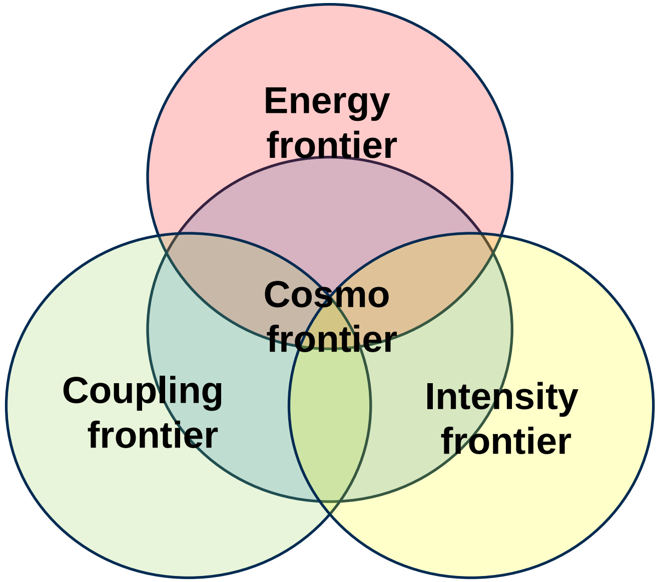
➔ $\tau \to \mu\mu\mu$ yields with *5 years* of operation and assuming branching ratio 10^{-10}
(TauFV acceptance * preselection efficiency = 5%)

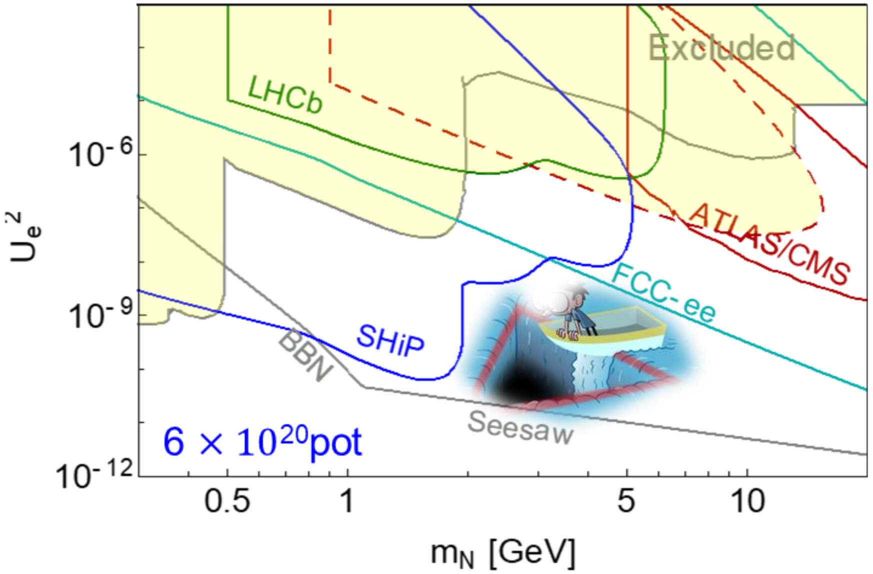
Experiment	PoT / $\int \mathcal{L}dt$	Yield
TauFV	4×10^{18}	800
Belle II	$50\,\mathrm{ab}^{-1}$	1
LHCb Upgrade I	$50\,\mathrm{fb}^{-1}$	14
LHCb Upgrade II	$300\,\mathrm{fb}^{-1}$	84

Conclusion

- Unique physics potential of SPS to explore *“Coupling Frontier”* with synergies with collider 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





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

➔ With approval, SHiP is now seeking to extend collaboration

CERN Medium Term Plan 2025 - 2029

https://cds.cern.ch/record/2908145/files/English.pdf

CERN/SPC/1236/Rev.
CERN/FC/6812/Rev.
CERN/3829

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

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

CERN Medium Term Plan 2025 - 2029

https://cds.cern.ch/record/2908145/files/English.pdf

CERN/SPC/1236/Rev.
CERN/FC/6812/Rev.
CERN/3829

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

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

2.3. The SHiP experiment

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

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

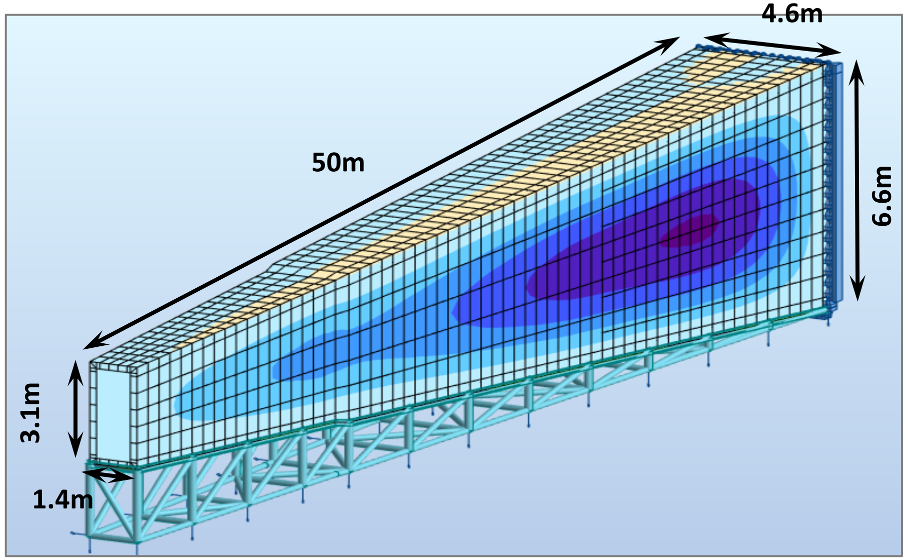
The Research Board recommended that, as only a fraction of the required funding is currently available, the detailed layout of the experiment for the initial configuration will need to be developed in consultation with the funding agencies and CERN. In parallel, a staged/descoped detector scenario should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

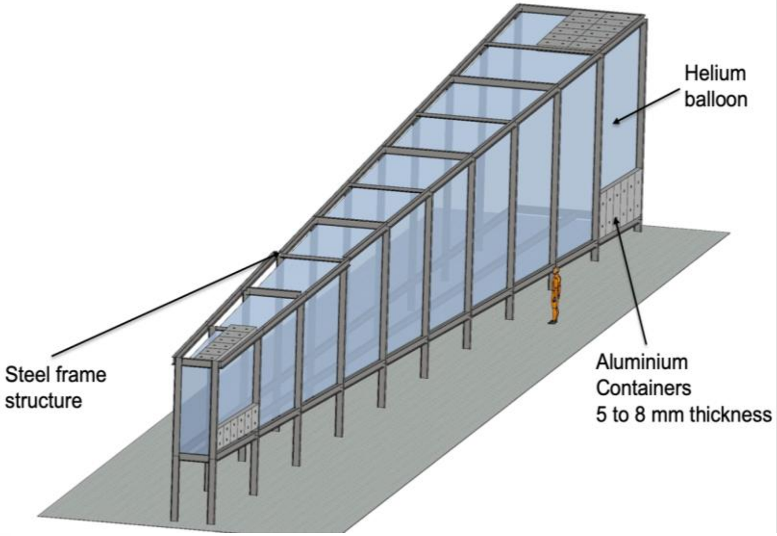
The current timeline provides for an R&D and TDR phase covering the period 2024-2027, followed by the construction phase in the years 2027-2030, and operation as of 2031.

Decay volume

Per spill of 4×10^{13} protons: 1.5×10^{12} neutrinos and anti-neutrinos through SHiP's fiducial volume

1. Suppress to <10 interactions in ~550 m^3 decay volume
2. Reject interactions in decay volume structure by surrounding scintillator system





➔ Conclusion from October Collaboration meeting: Helium at 1atm sufficient instead of vacuum at 1mbar

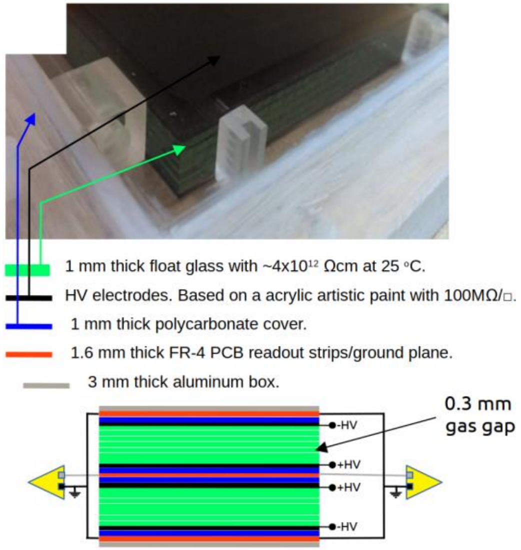
- Steel vacuum vessel replaced by soft liner ("balloon") held in place by a frame structure of aluminium
- Need for a large-volume helium circulation and purification system (~99%)

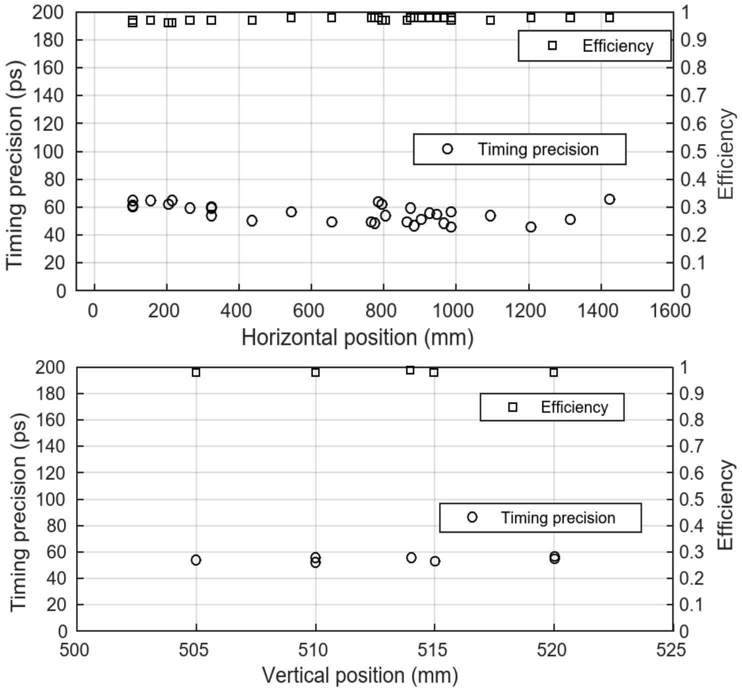
HS Upstream Background Tagger

- Purpose: Veto in front of decay volume
  - ➔ High efficiency >99%, <100ps resolution, ~cm resolution, rate capability O(100) kHz

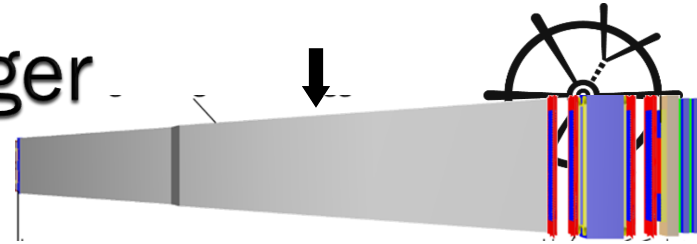
- Characteristics with 3-layer MRPC (option with SciFi under investigation)
  - Multi-gap RPC structure: six gas gaps defined by seven 1 mm thick float glass electrodes of about 1550 × 1250 mm^2, separated by 0.3 mm nylon mono-filaments
  - Two identical sensitive modules sandwiched with a plane of pick-up electrodes, consisting of 1600×30 mm^2 Cu strips

2m^2 prototype in beam test at PS



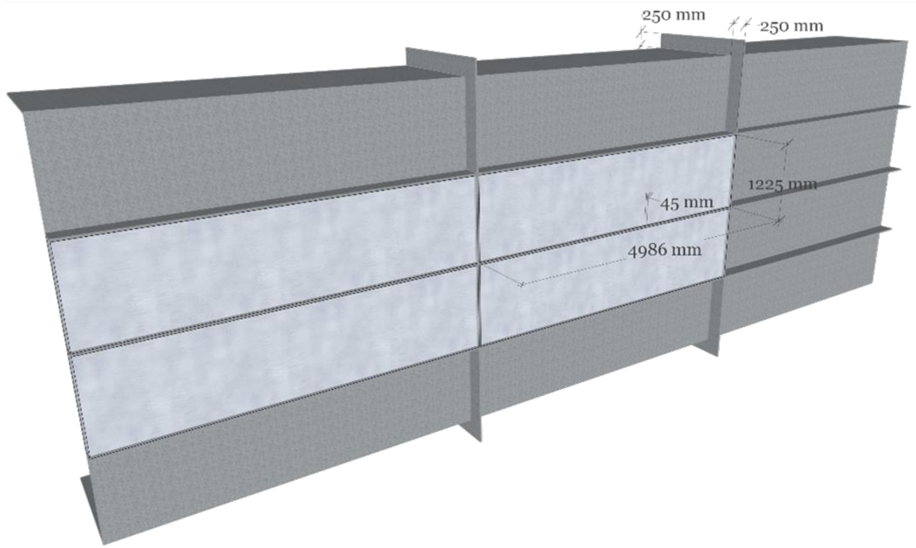


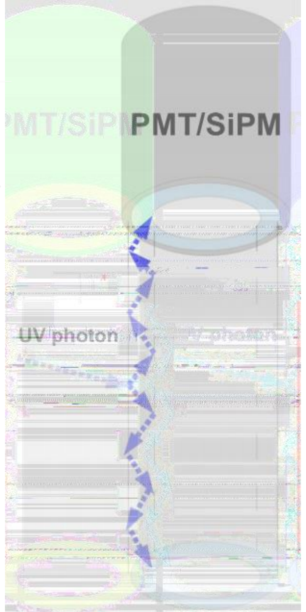
HS Surrounding Background Tagger



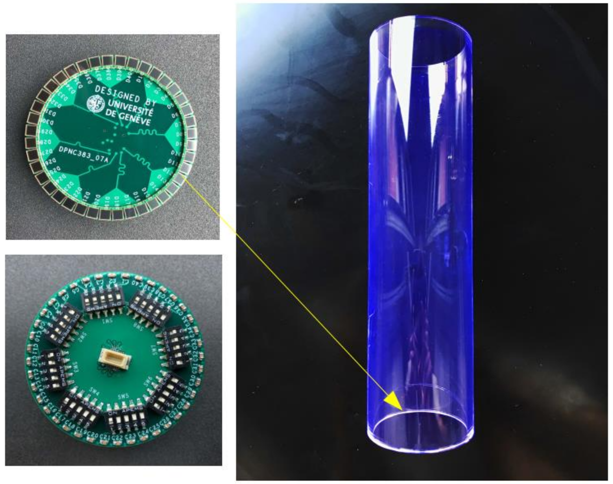
- Purpose: Tagging charged particles entering decay volume and tagging ν and μ interactions in the vacuum chamber walls
  - ➔ >99% efficiency and ~1ns time resolution
  - ➔ Combined system of liquid scintillator compartments and staves of plastic scintillators in different regions

- Characteristics of LiSci system
  - 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 3x3mm^2) and surrounded by PMMA vessel
  - Thickness 20cm
  - Total quantity 160 m^3 / 130 tonnes

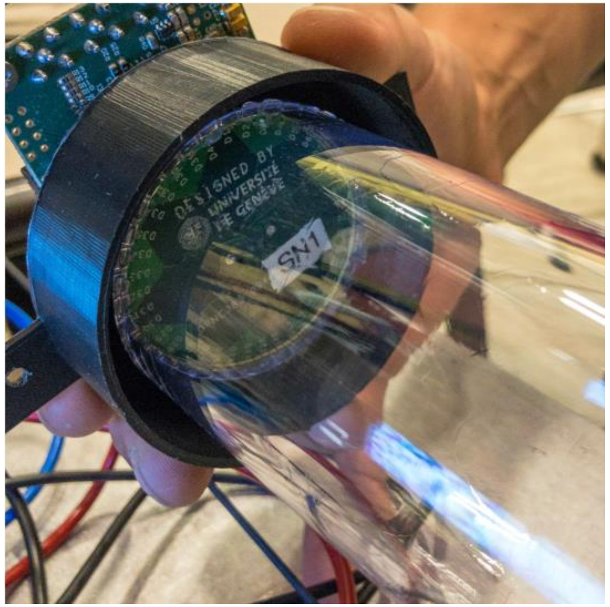




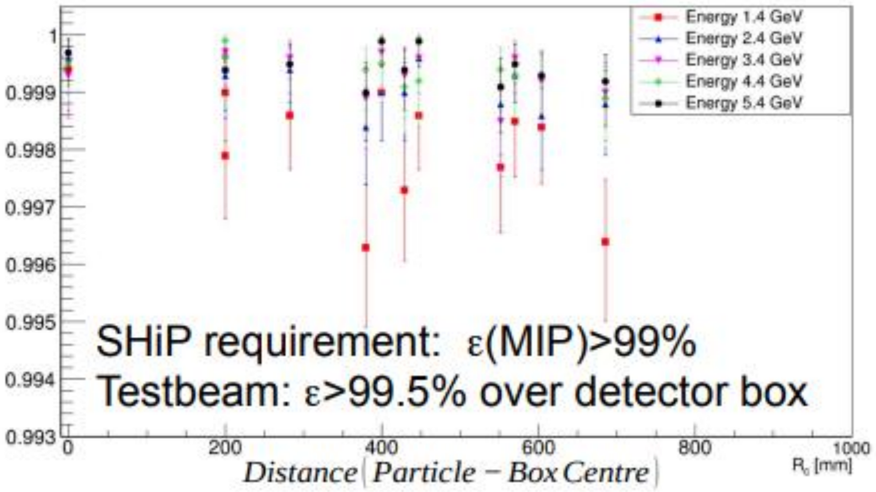
WOM w/o lightguide

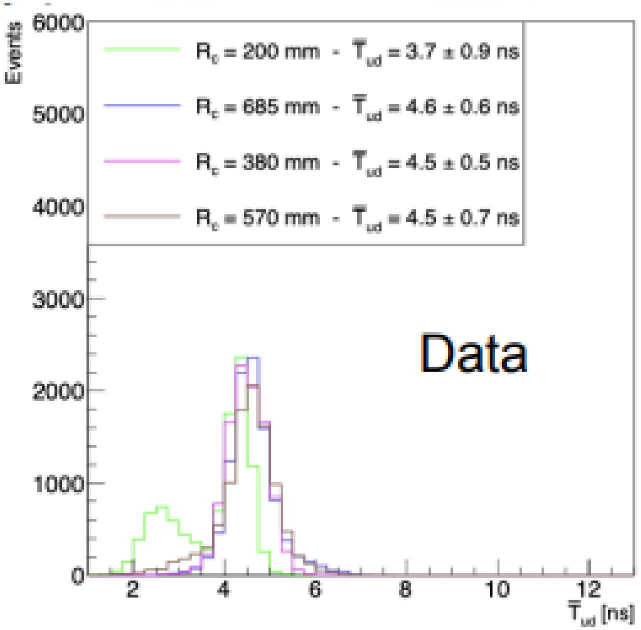


40-SiPMs array
built by Geneva



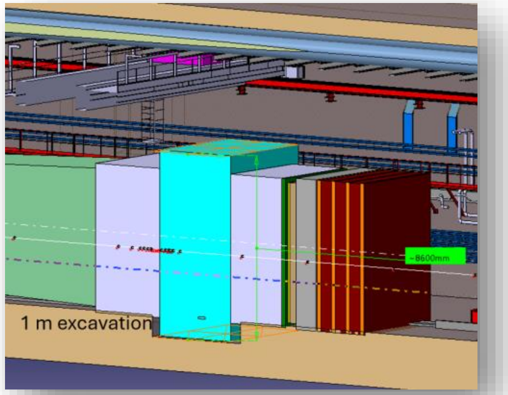
HS Surrounding Background Tagger





With a decay volume under helium, complementing with plastic scintillator system becomes an option

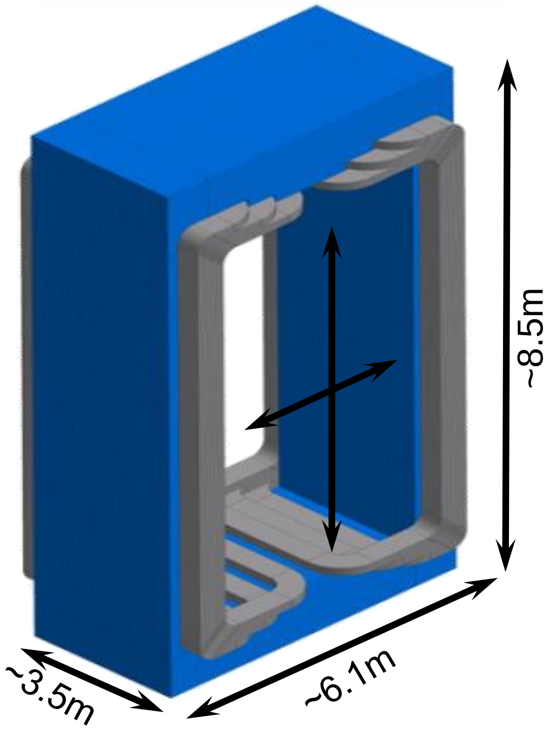
Spectrometer magnet



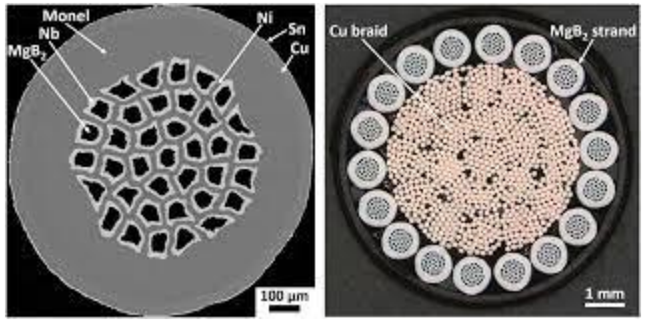
- Spectrometer requirements (cmp. LHCb magnet):
  - Physics aperture 4 x 6 m^2
  - Bending field ~0.6-0.8 Tm , nominal on axis ~0.15T
  - Integrated field uniformity more important than field uniformity (~5-10%)
  - Field mapping in-situ important
  - Design allowing future upgrade where yoke supports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

- Initial conceptual studies
  - P. Wertelaers, CERN-SHiP-INT-2019-008 ➔ Resistive version ~1 MW
  - H. Bajas, D. Tommasini, EDMS 2440157 (21 April 2020)

    ➔ Exploratory study of NbTi / Nb_3Sn / MgB_2 / ReBCO



HL-LHC superconducting link sub-cable

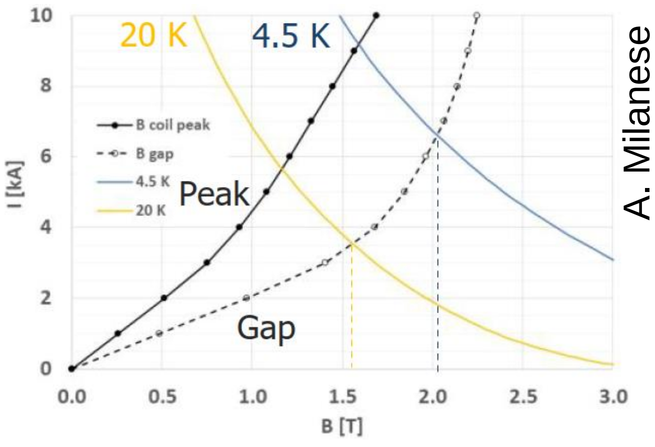


"Energy-Efficient Superferric Dipole"

A. Devred, L. Baudin

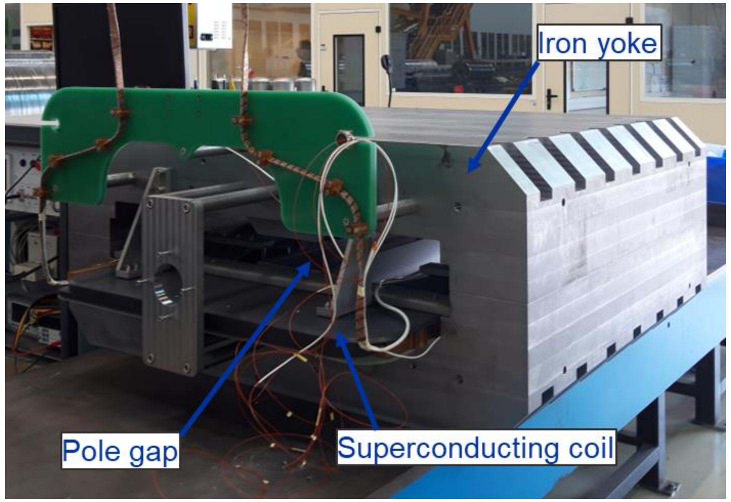
- Proposal from TE-MSC
  - Design with MgB_2 sub-cables from HL-LHC WP6a, operate with gaseous helium at 20K with cryocoolers (HFM WP 4.6)

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



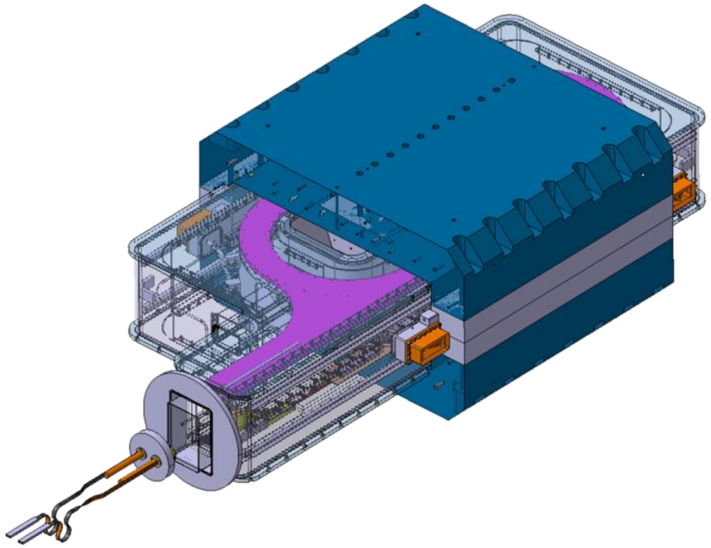
A. Milanese

Prototype for phase 1 and 2 (2023-24)

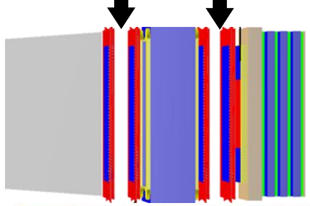


To optimize cryostat design and transfer of Lorentz loads, electromagnetic design of prototype includes two racetrack-type coils

Prototype for phase 3 (2025)



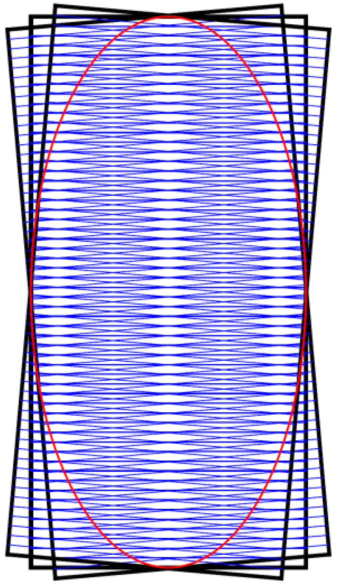
HS Straw Tracker

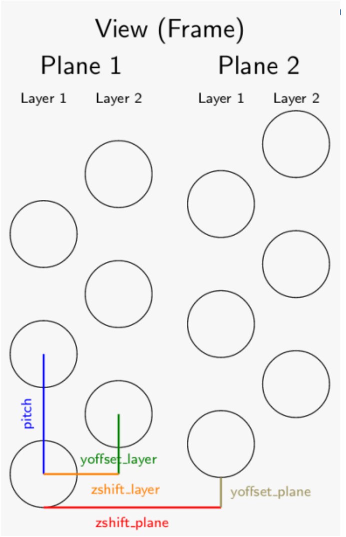


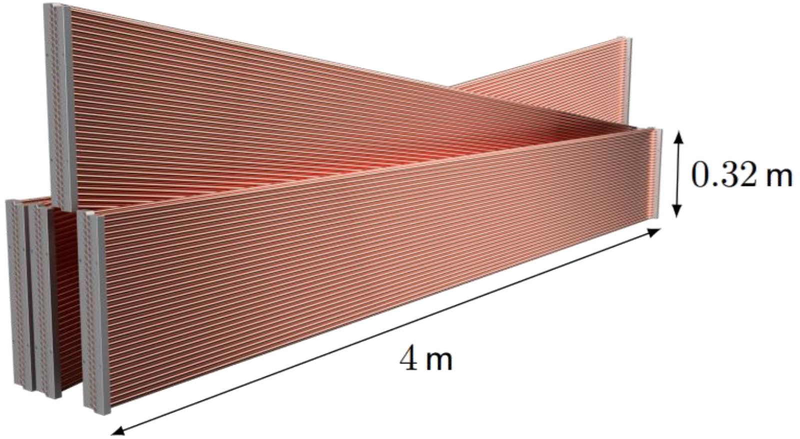
- Technology developed for the NA62 experiment, also proposed for near-detector at DUNE
- Characteristics at SHiP
  - Horizontal orientation of tubes ➔ mechanical challenge
  - Lower rate allows increasing straw diameter (highest rate $\mathcal{O}(10)$ kHz)
  - 4 x 6 m^2 sensitive area

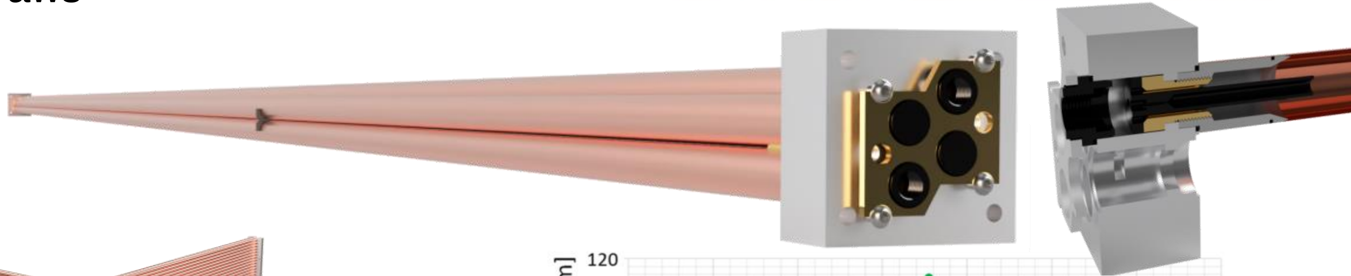
➔ 4m long 20mm diameter 36μm thick PET film coated with 50nm Cu and 20nm Au operated at 1 bar, produced and tested (option with Al tubes under investigation)

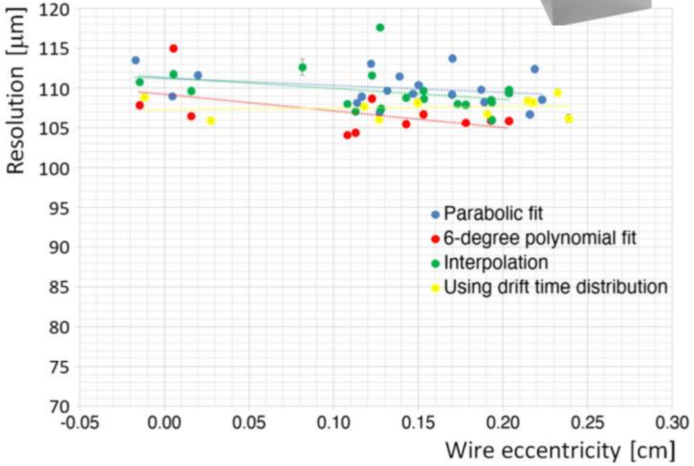
➔ Four stations, each with four views Y-U-V-Y, ~9600 straws





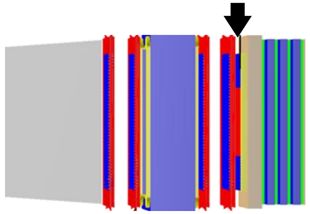




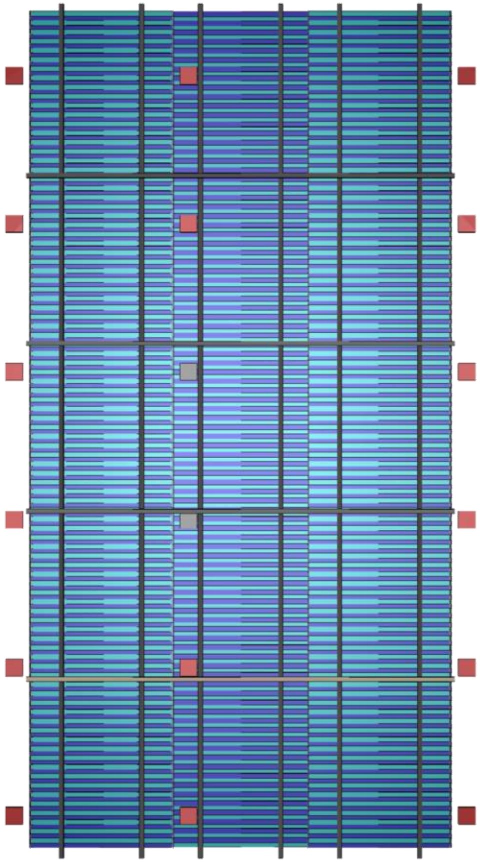


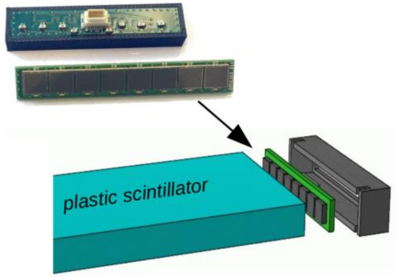
Test beams confirm 120μm hit resolution with hit efficiency >99%

HS Timing Detector

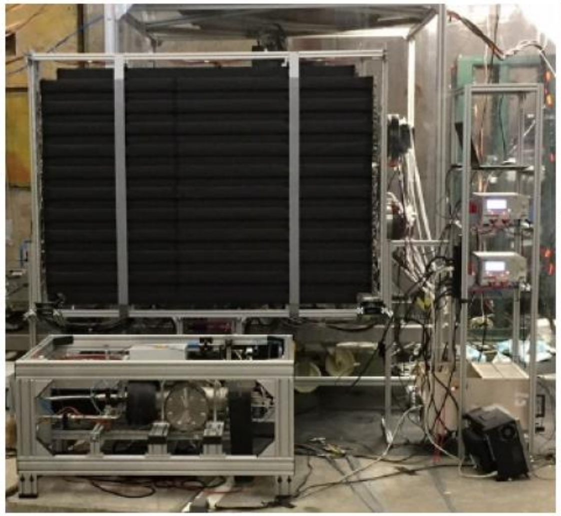


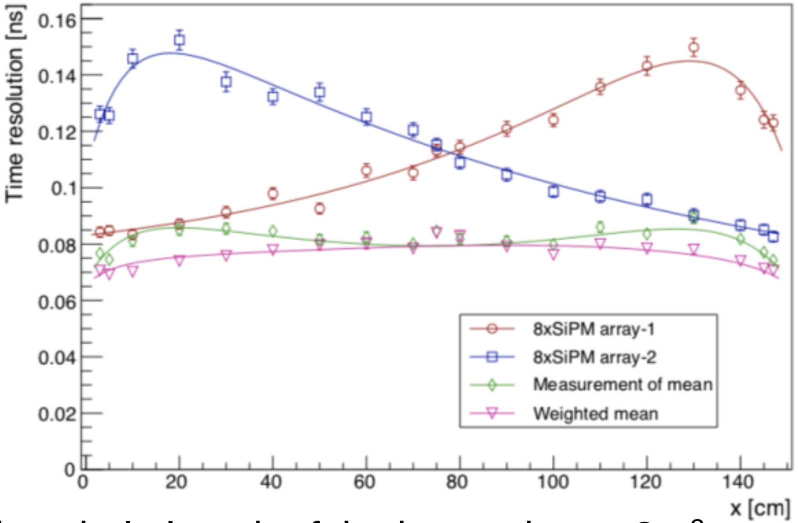
- Purpose: Provide precise timing (<100 ps) of each track to reject combinatorial background
- Plastic scintillator characteristics
  - Three-column setup with EJ200 plastic bars of 135cm × 6cm × 1cm, providing 0.5cm overlap
  - Readout on both ends by array of eight 6×6 mm^2 SiPMs, 8 signals are summed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





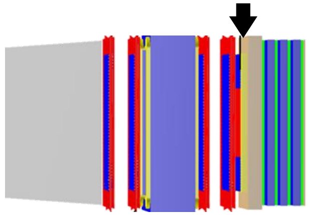
22x 168cm bar (44 channels) prototype tested at PS

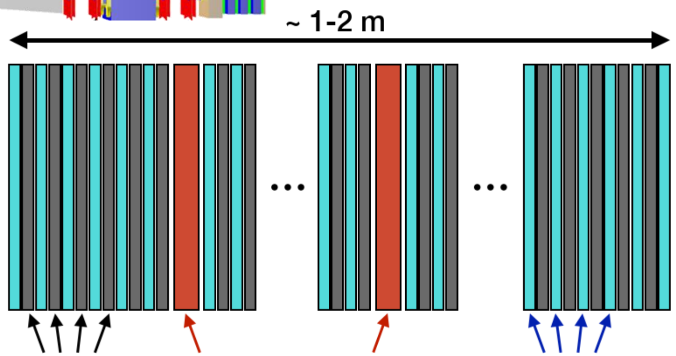




Resolution demonstrated to be ~80 ps along the whole length of the bar and over 2m^2 prototype

HS ECAL (“SplitCal”) and HCAL

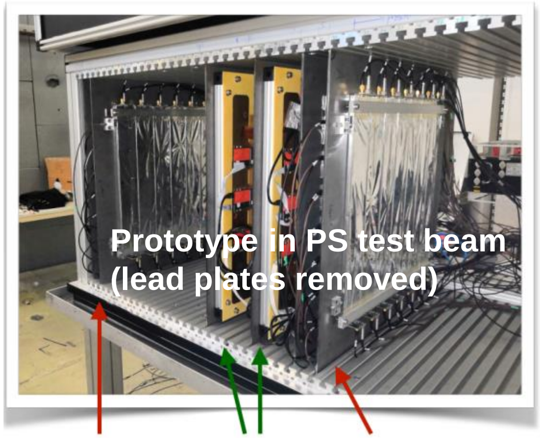


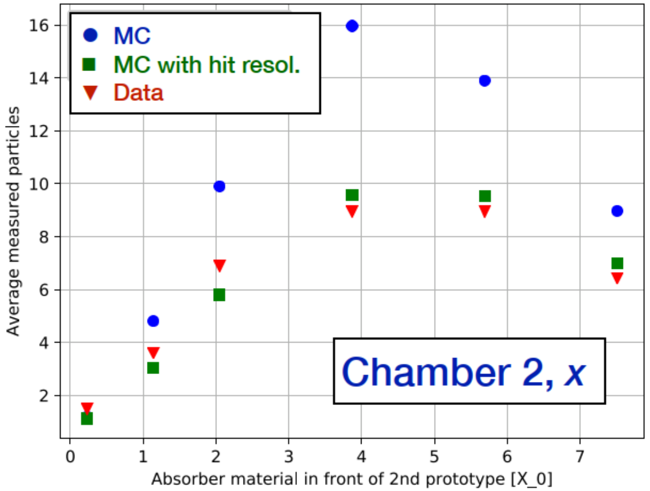


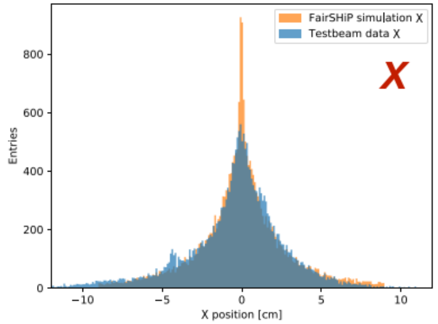
- Purpose: e/γ identification, π^0 reconstruction, photon directionality ~5mrad for ALP→ $\gamma\gamma$ (coincidence timing)
- Characteristics
  - 20 X_0 longitudinally segmented calorimeter with coarse and fine space resolution active layers
  - Coarse layers: 60 planes of scintillating bar readout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

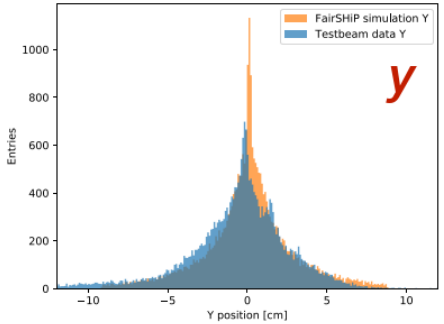
  ➔ 3 mrad for 20 GeV, 5 mrad for 10 GeV and 9 mrad for 6 GeV photons

2.1 X_0





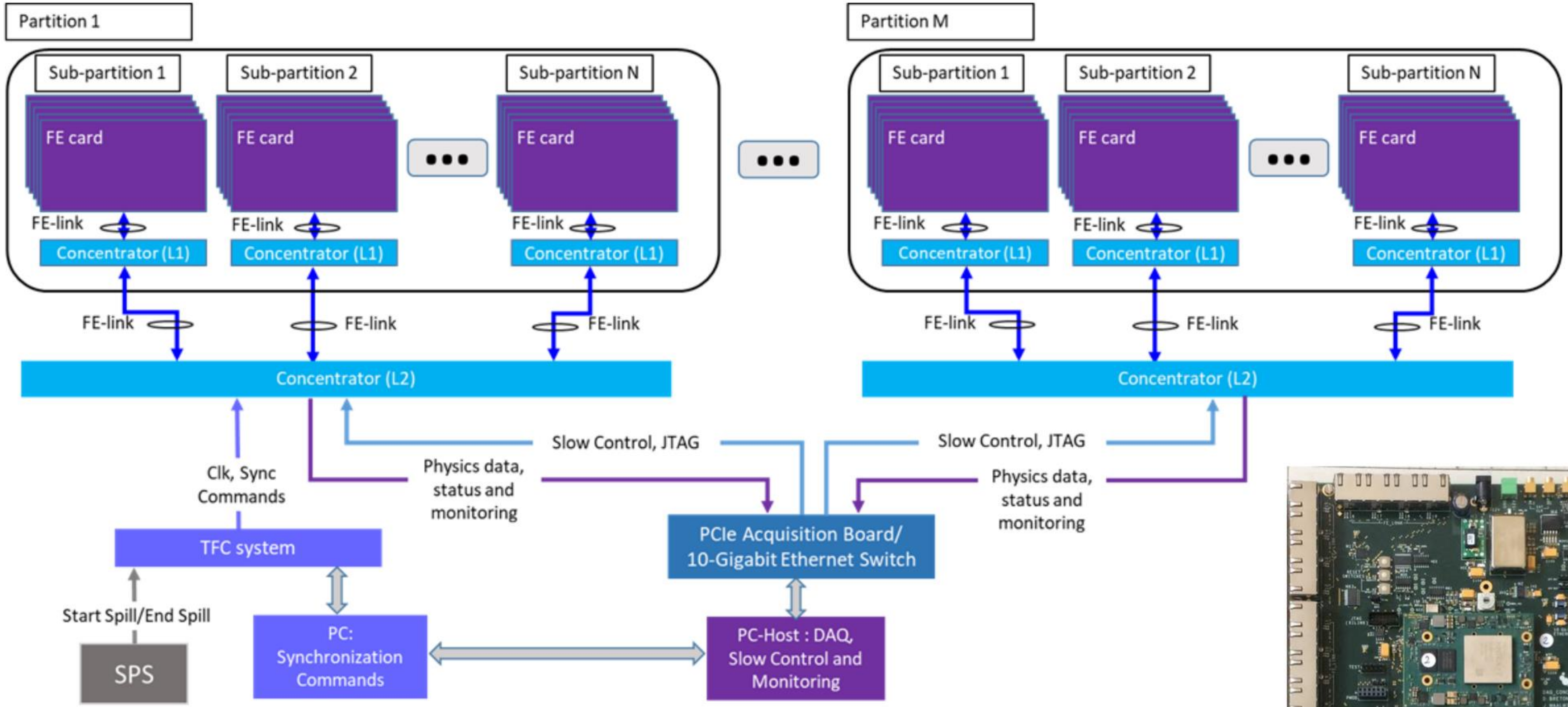


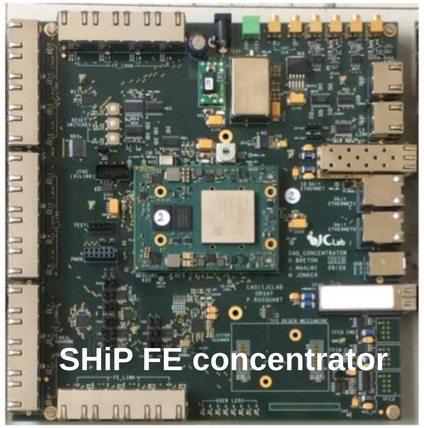


Reconstruction challenge: satellite showers in the long transverse tails

Electronics and readout

- Subsystem architecture – aiming for common electronics




SHiP FE concentrator

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