Opportunities with the SHiP experiment at the CERN SPS Beam Dump Facility

R. Jacobsson

on behalf of the SHiP Collaboration of 38 institutes from 15 countries and CERN

Future physics prospects

~10% of LHC+HL-LHC data recorded - still no sign of "New Physics"

Why do we assume there must be "New Physics" beyond Standard Model, i.e. possible new particles and interactions?

Experimental evidence of unexplained phenomena

1. Flavour mixing and mass of neutrinos
2. Matter/antimatter asymmetry of the Universe
   - → Measurements from BBN and CMB $\eta = \left\langle \frac{n_B}{n_\gamma} \right\rangle_{T=3K} \sim \left\langle \frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \right\rangle_{T \gtrsim 1\, GeV} \sim 6 \times 10^{-10}$
   - → Current measured CP violation in quark sector ➔ $\eta \sim 10^{-20}$!!
3. Dark Matter – Non-baryonic, neutral and stable or long-lived
4. Dark Energy

➔ *No prejudice on mass scale of the "new physics" required to solve these!*

Theoretical "evidence" – "prejudice"

1. Mass of the Higgs
2. Structure of Standard Model
3. Unification of interactions
4. Description of gravity
5. Inflation
6. ….

➔ *Some preference for new particles with large masses….*

So where is it...?

- ➔ For the first time, no definitive unambiguous guidance from experiments or theory!
- ➔ New Physics should either be very heavy OR interact very feebly to have escaped detection!
- ➔ Possible guidance from cosmology and astrophysics!

Limited theoretical guidance is not new…

Nucl. Phys. B106 (1976)

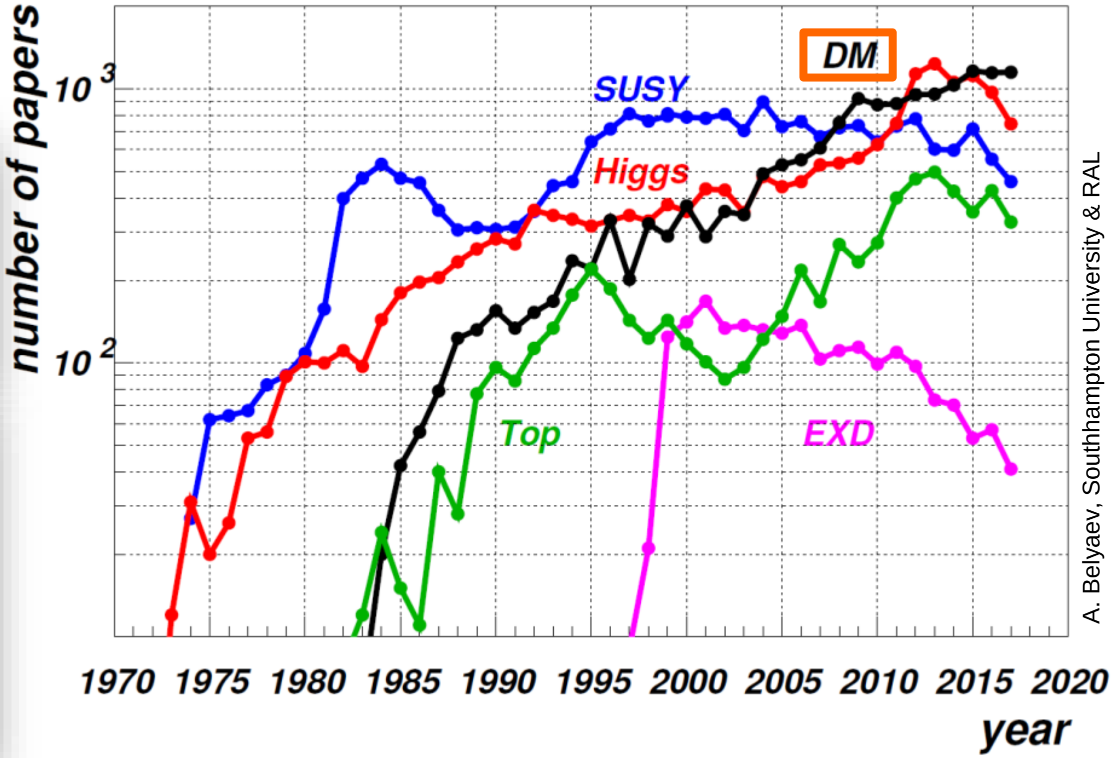
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

334 *J. Ellis et al. / Higgs boson*

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.



A. Belyaev, Southhampton University & RAL

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

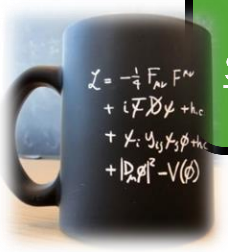
- *Exploration of Feebly Interacting Particles* up to now mainly as by-product of experiments built for other purposes – post-analyses, data mining, often limited to exclusion capability

- Enough reasons to build a dedicated accelerator-based 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!
  - Essential complementarity with projects in launch/commissioning on the cosmofrontier
  - One of the main objectives of HL-LHC (and FCC) will be exploring FIPs…

Theory of a Hidden Sector?

- *Standard Model gives us tools to implement Hidden Sector with well-defined phenomenology*

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



Visible Sector
Standard Model

"Portal interaction"

Hidden Sector
"Dark standard model"

Options for "portals" = correspondence to all *neutral* features of Standard Model

- ➔ Dark Photons
- ➔ Dark Higgses
- ➔ *Heavy Neutrinos*
- ➔ Axion-Like Particles
- ➔ also some SUper-SYmmetric "portals"…

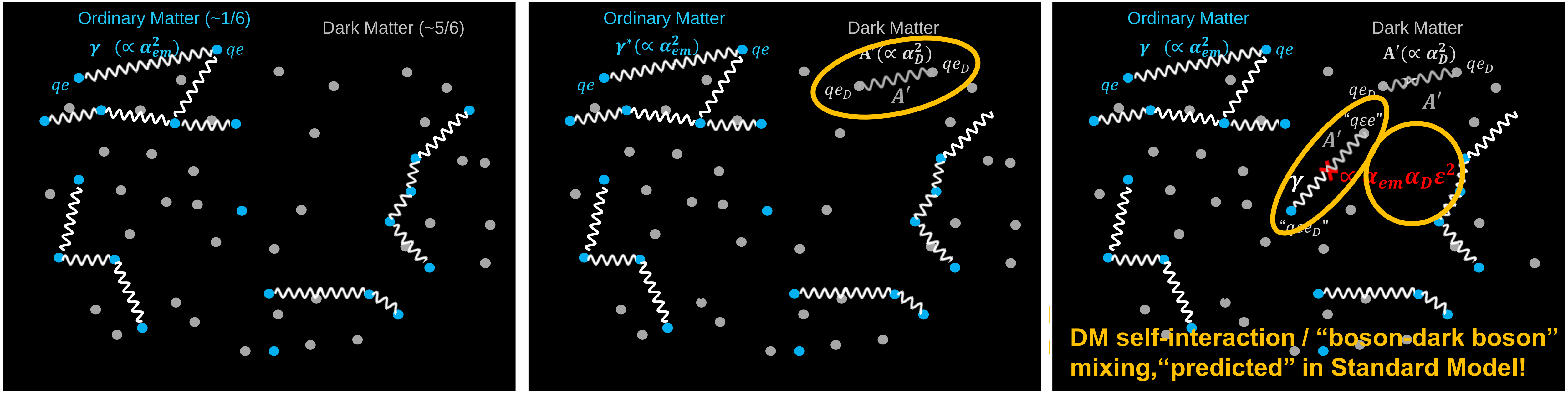
Portal interactions may "drive" dynamics observed in the Visible Sector!

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

Portal interactions under the microscope

Example of FIP physics case

What if…?!



Profiting from "portal" coupling at accelerator!

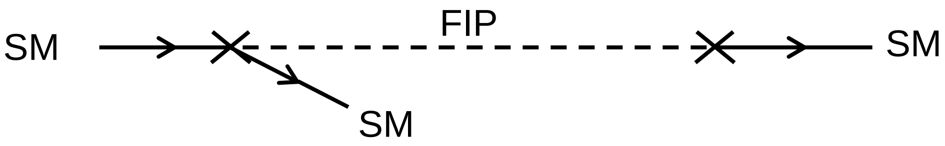
- Typical coupling at 10^{-6} - 10^{-10}…
- Long-lived with $c\tau$ ~ metres-kilometres….

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

for all types of FIPs

Production

Detection by decay or by scattering



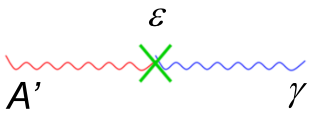
New Physics prospects in Hidden Sector

Composite operators as "portals":

D = 2: Vector portal

- Kinetic mixing with massive dark/secluded/paraphoton A' : $\frac{1}{2}\varepsilon F^{SM}_{\mu\nu} F^{\mu\nu}_{HS}$

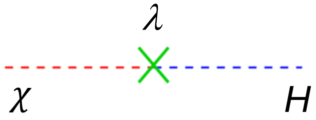
➔ Motivated in part by idea of "mirror world" restoring L/R symmetry, dark matter, g-2 anomaly, …



D = 2: Scalar portal

- Mass mixing with dark singlet scalar χ : $(g\chi + \lambda\chi^2)H^\dagger H$

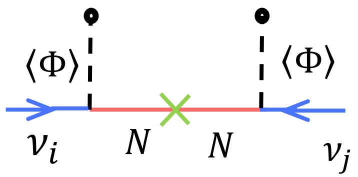
➔ Mass to Higgs boson and mass generation in dark sector, inflaton, dark phase transitions BAU, dark matter,…



D = 5/2: Neutrino portal

- Mixing with right-handed neutrino N (Heavy Neutral Lepton): $Y_{I\ell} H^\dagger \bar{N}_I L_\ell$

➔ Neutrino oscillation and mass, baryon asymmetry, dark matter

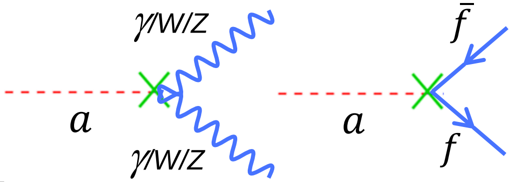


D = 4: Axion portal

- 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

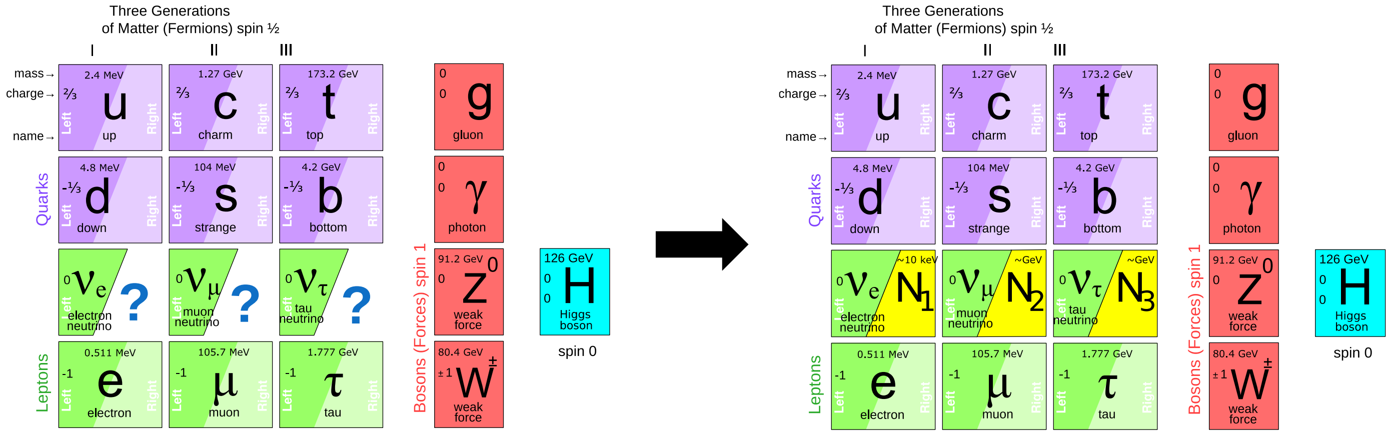
➔ Extended Higgs, SUSY breaking, dark matter, possibility of inflaton,…

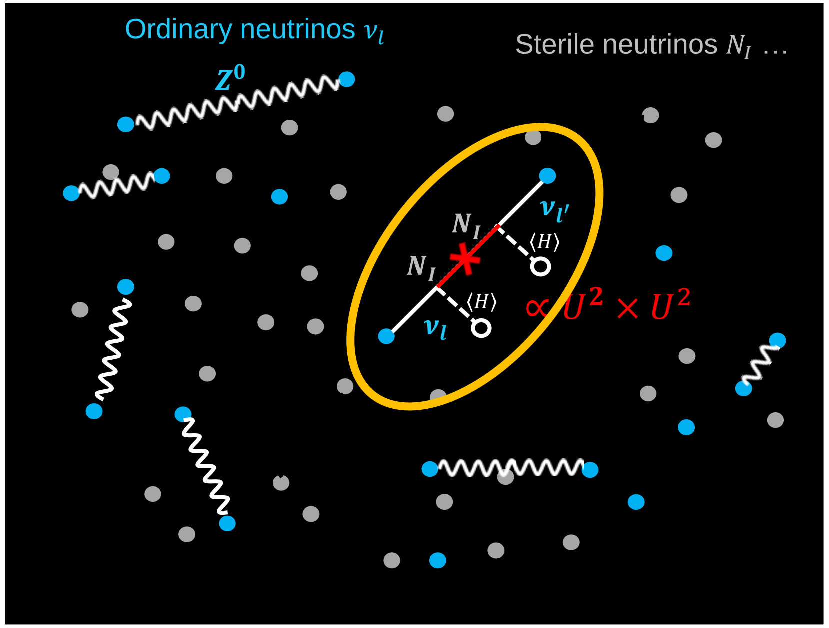


Also light SUSY (Neutralino, sgoldstino, axino, saxion, hidden photinos…)

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

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{\substack{I=1,2,3;\\ \ell=1,2,3(e,\mu,\tau)}} i\bar{N}_I \partial\!\!\!/_\mu \gamma^\mu N_I - Y_{I\ell} H^\dagger \bar{N}_I L_\ell - M_I^R \bar{N}_I N_I^c + h.c$$

$M_I^R \bar{N}_I N_I^c$ → $\mathcal{L}_{Majorana\ mass}$

$Y_{I\ell} H^\dagger \bar{N}_I L_\ell$ → 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

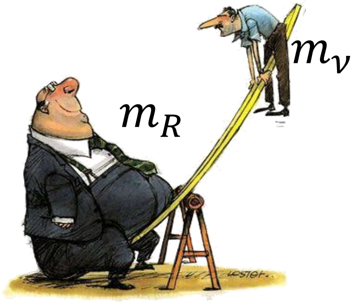
$$\mathcal{L}_{mass} = \frac{y_i\langle H\rangle}{\sqrt{2}}(\overline{\nu_L}N_R + \overline{N_R}\nu_L) + m_L^M\overline{N_L^c}N_L + m_R^M\overline{N_R^c}N_R + h.c. \quad = [\overline{\nu_L}, \overline{N_R^c}]\begin{bmatrix} m_L^M & m_D \\ m_D & m_R^M \end{bmatrix}\begin{bmatrix} \nu_L \\ N_R^c \end{bmatrix}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

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

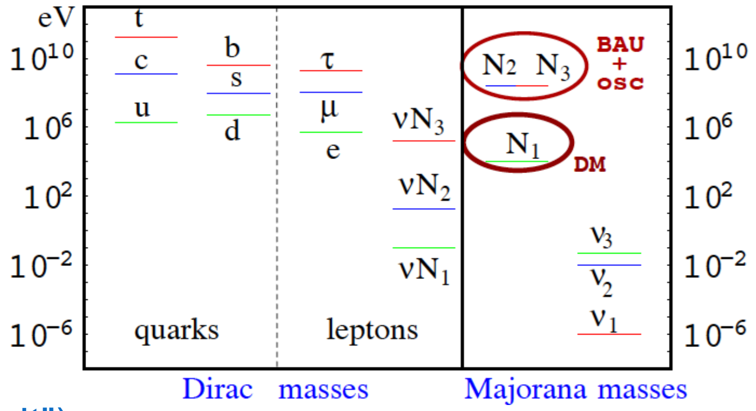
➔ Active neutrino mass $\tilde{m}_1 \sim = \frac{(Y_{I\ell}v)^2}{M_I^R} = \frac{m_D^2}{M^R} \sim m_\nu$

➔ 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!



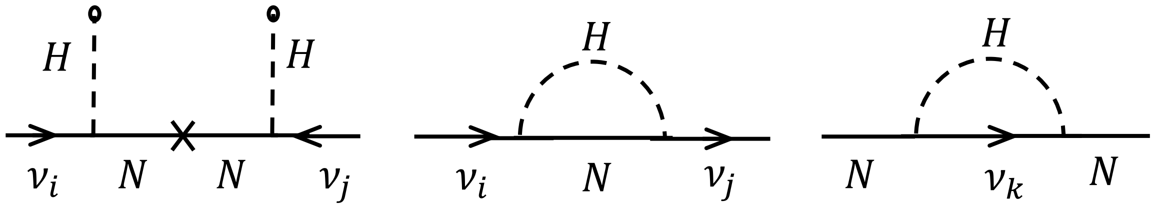
- Effective mixing between N_I and active neutrino $\mathcal{U}_{I\ell} = \frac{Y_{I\ell}v}{M_I^R} \sim \frac{m_D}{M^R}$

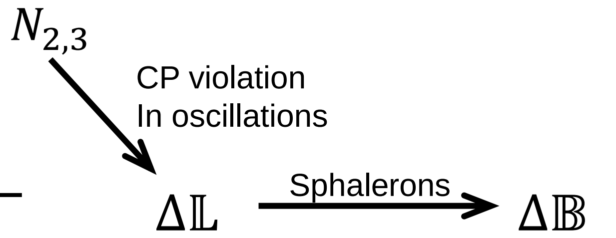
➔ Total coupling $\mathcal{U}^2 = \sum_{\substack{I=1,2,3 \\ \ell=1,2,3(e,\mu,\tau)}} \frac{v^2|Y_{\ell I}|^2}{{m_I^R}^2} \sim \mathcal{O}\left(\frac{m_\nu}{M_N}\right) > 5\times10^{-11}\ /M_N[GeV]$ (“seesaw limit”)

Intriguing possibility with HNLs in “νMSM”

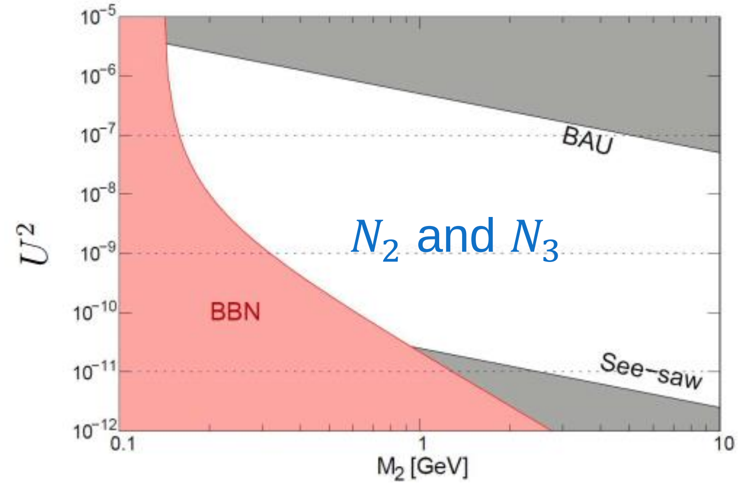
hep-ph/0503065
hep-ph/0505013
hep-ph/0605047
arXiv:0804.4543v2

- 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*



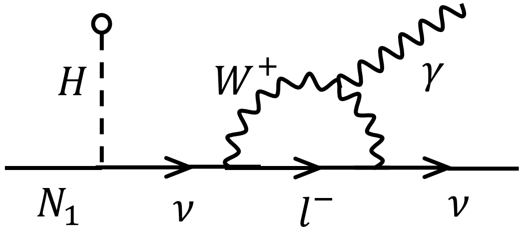


e.g. Phys.Rev D, Vol. 42, 10 (1990)
e.g. arXiv:1006.0133v3

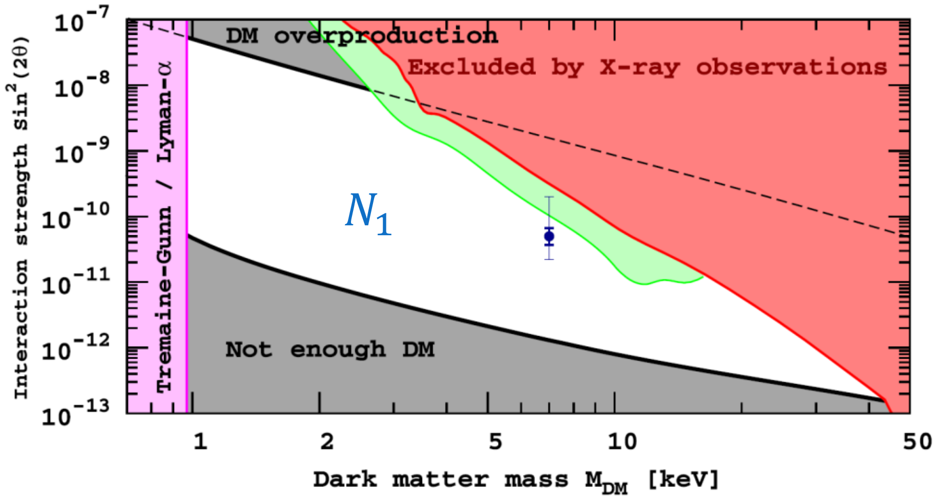


- N_1 with very small coupling and a mass of $\mathcal{O}$(keV) as Dark Matter!

Subdominant radiative decay



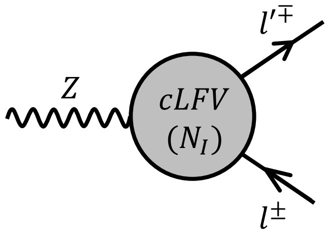
$$E_\gamma = \frac{M_{N_1} c^2}{2}$$



Observational consequences of HNLs (accelerators)

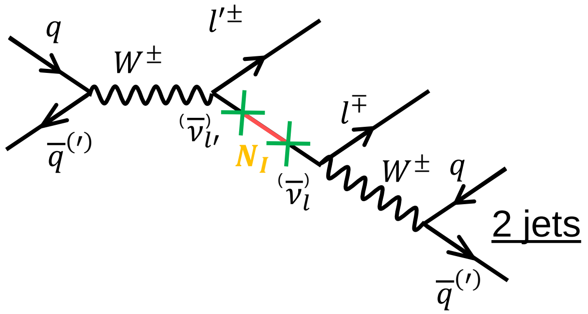
- Indirect observables
  - PMNS matrix unitarity violation
  - Deficit in Z «invisible» width
  - LNV and cLFV
  - Modification of Fermi constant ➔ Electroweak precision observables

$$G_\mu^2 \approx G_F^2(1-|\mathcal{U}_e|^2)(1-|\mathcal{U}_\mu|^2)$$

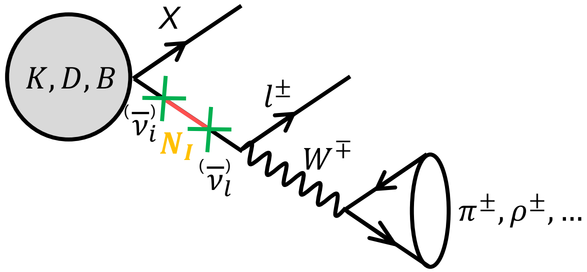


- Direct observables:
  - Visible decays $N \to lW, \nu Z$ in detectors with displaced vertices, lepton and charge identification
  - Production in
    - Kaon, charm and beauty hadron leptonic/semi-leptonic decays
    - Higgs, Z, W, visible exotic decays with LFV and LNV

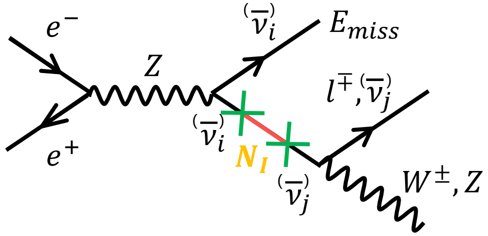
Ex. Proton-proton colliders (LHC)



Ex. Proton beam dump (Near future!)



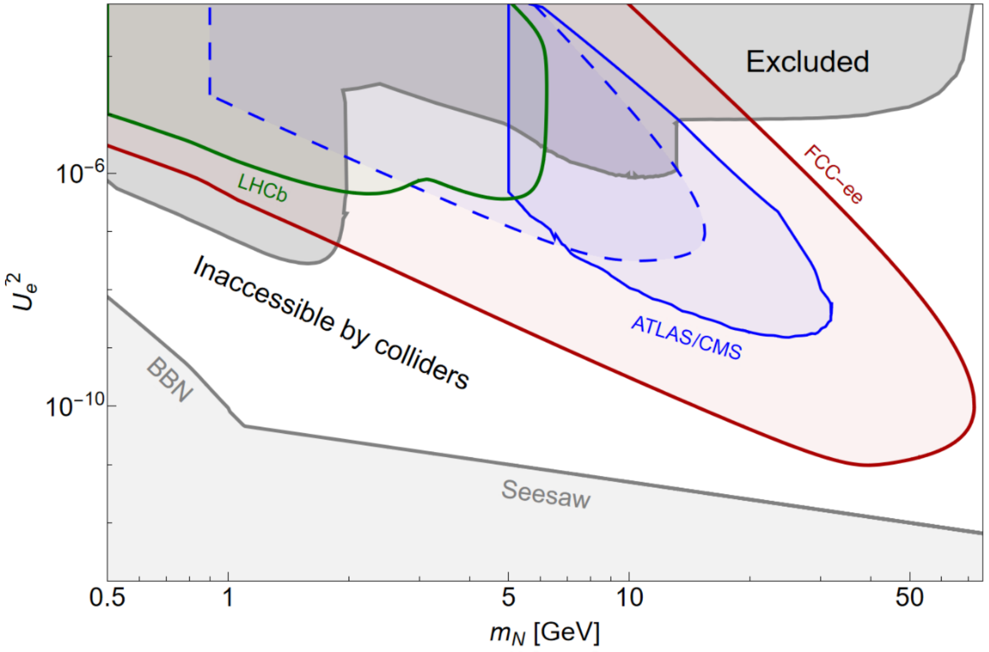
Ex. Electron-electron colliders (future)



Why SHiP?

- 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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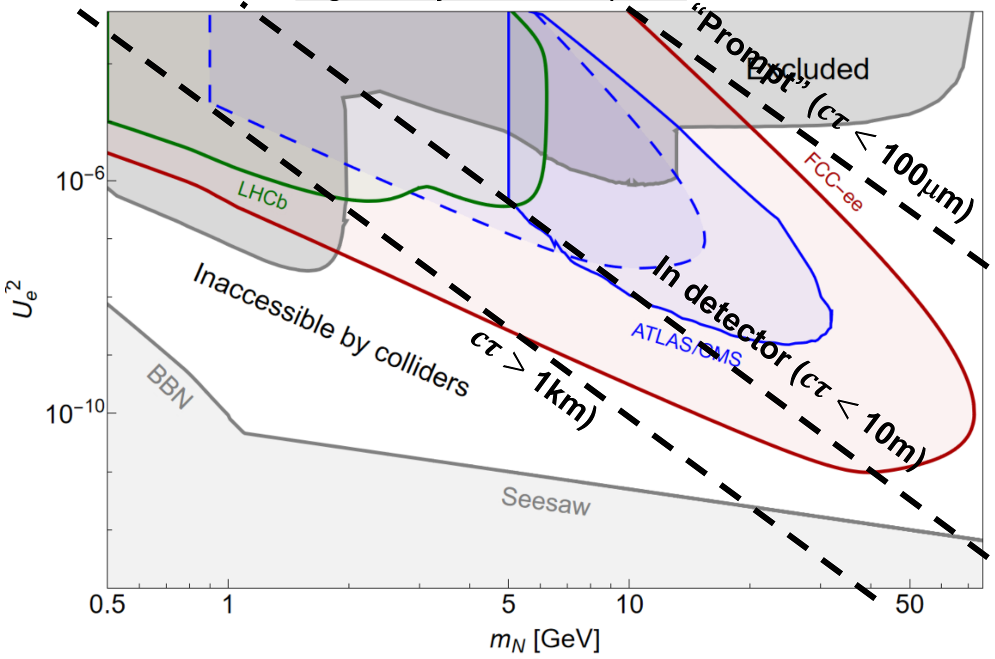

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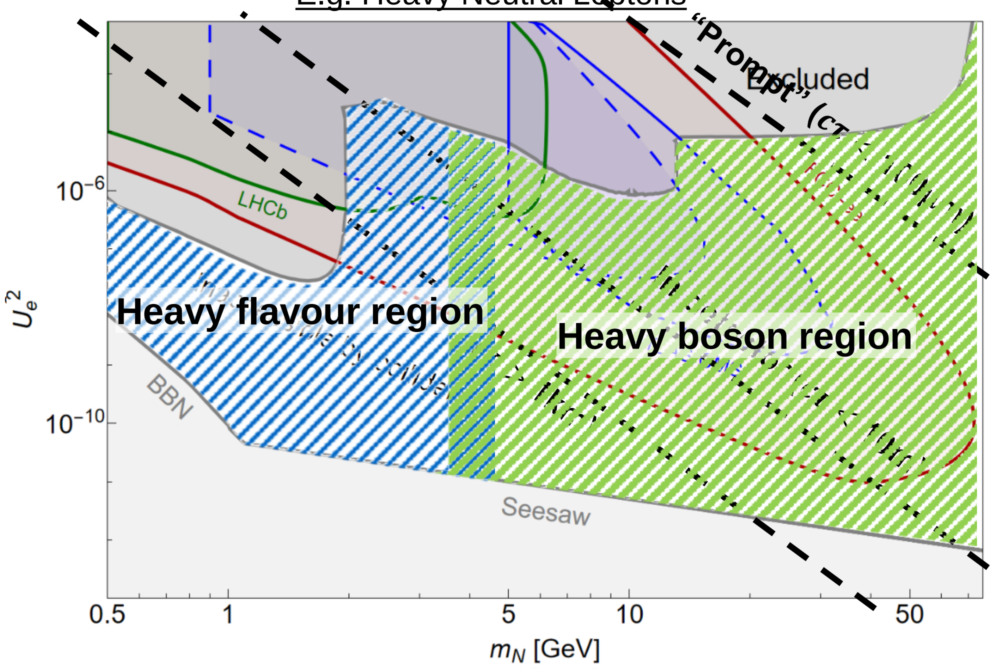

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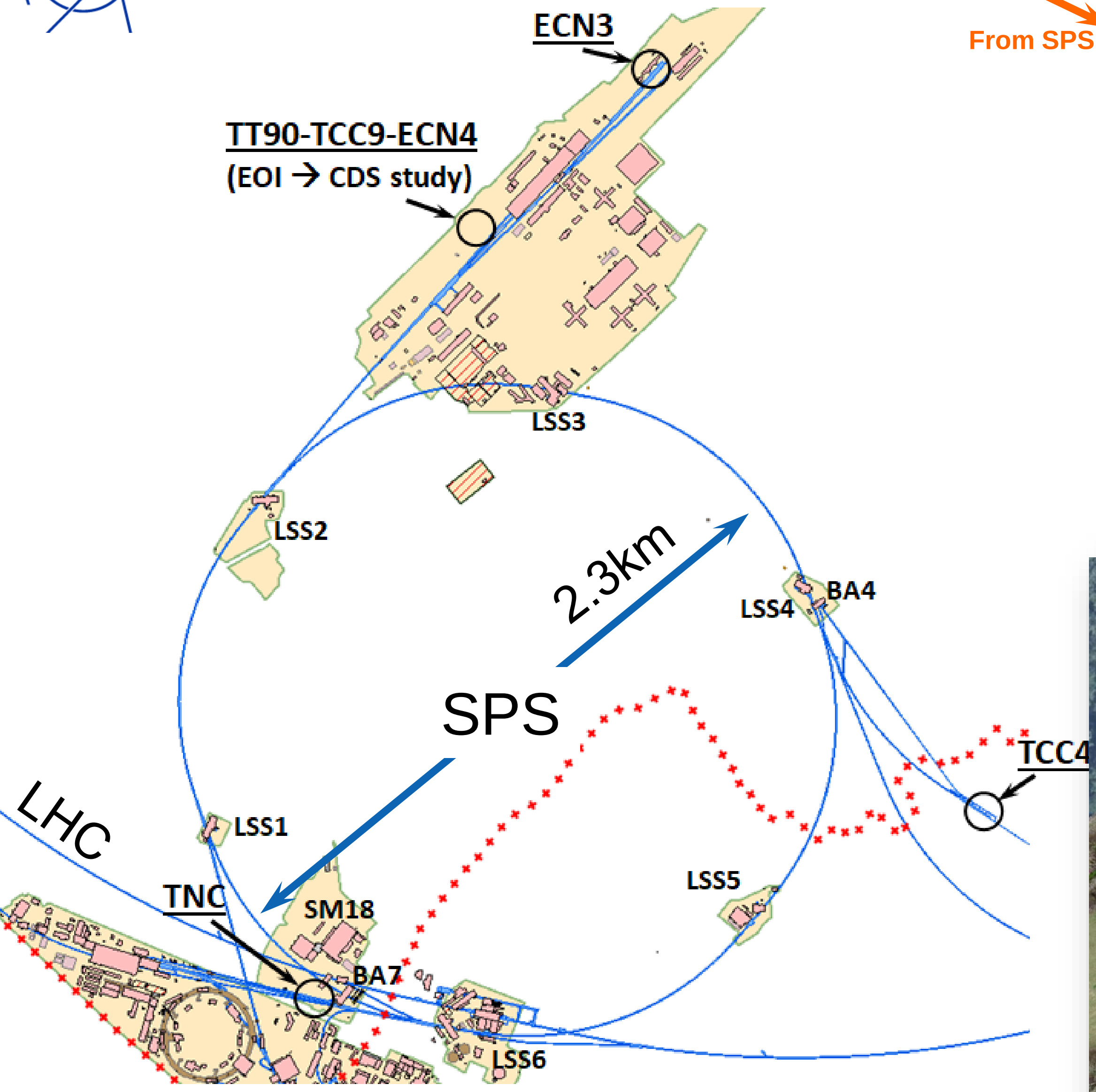
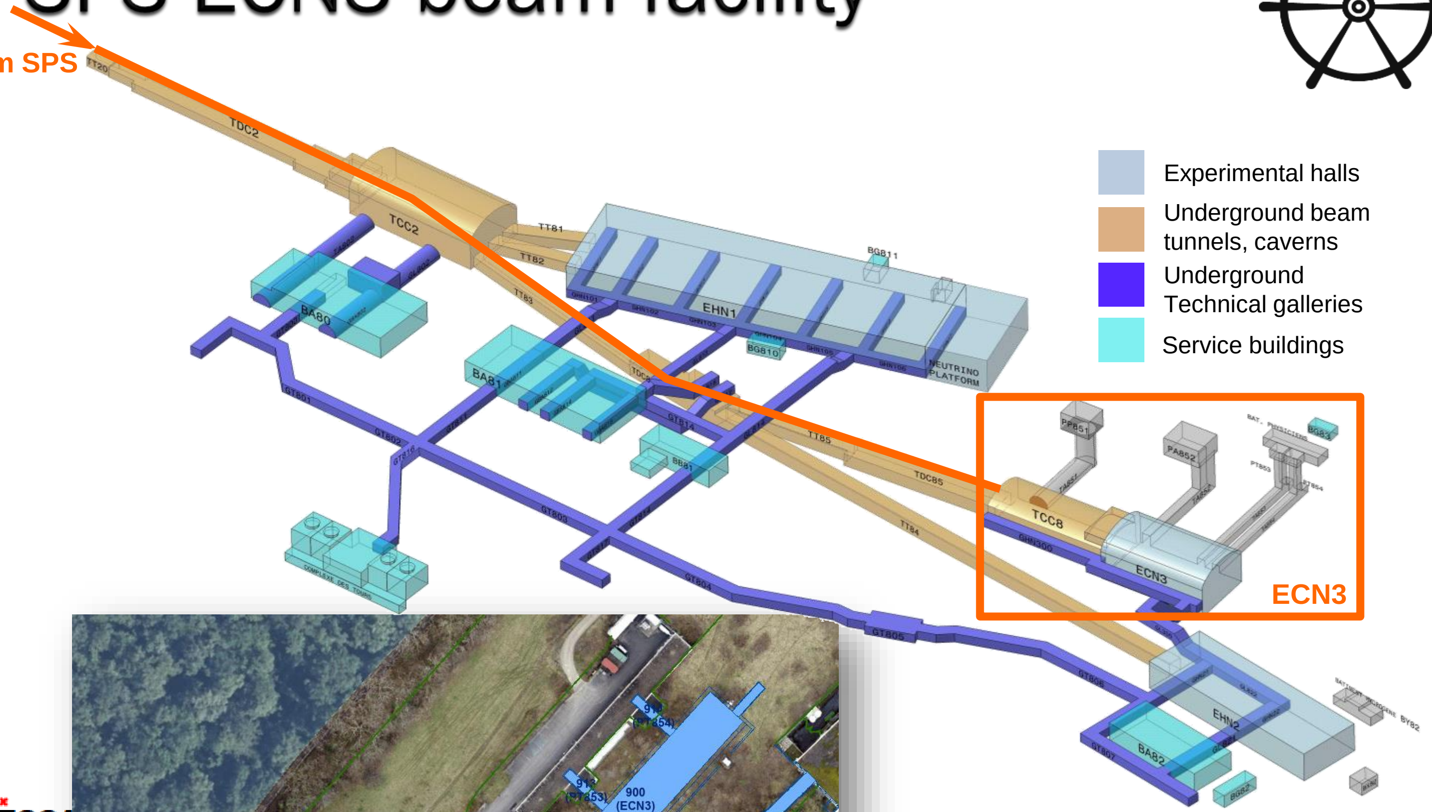
SHiP @ SPS ECN3 beam facility

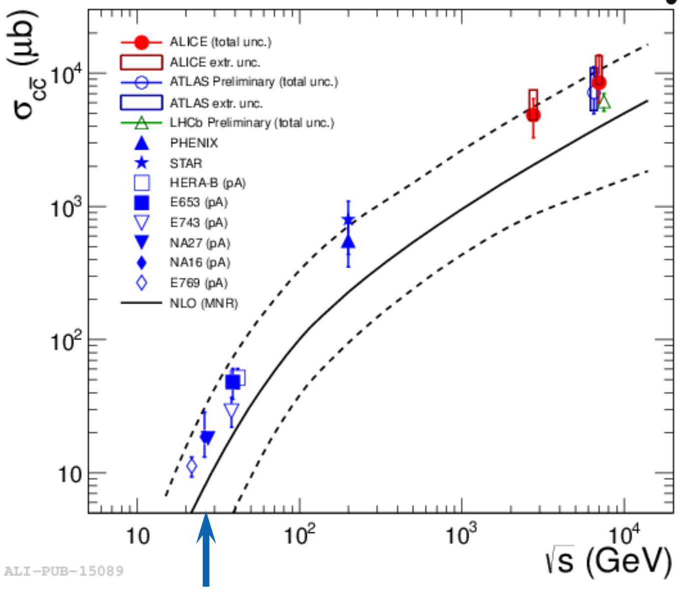




4x10^{19} protons per year available

BDF/SHiP optimization of physics reach

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



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

➔ BDF luminosity with the optimised target and $4\text{x}10^{19}$ protons on target per year *currently available* in the SPS

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

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

➔ 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:

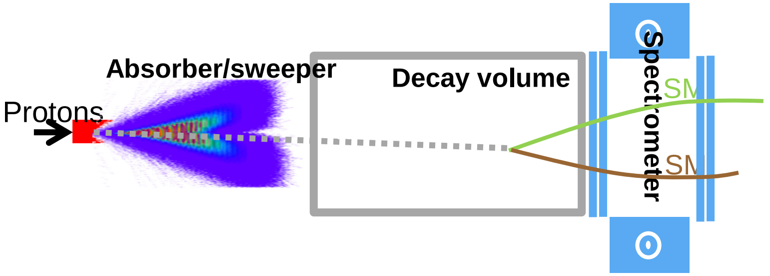
  $3500\ \nu_\tau + \bar{\nu}_\tau$ *per year*, and 2×10^5 $\nu_e + \bar{\nu}_e$ / 7×10^5 $\nu_\mu + \bar{\nu}_\mu$ despite target design

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

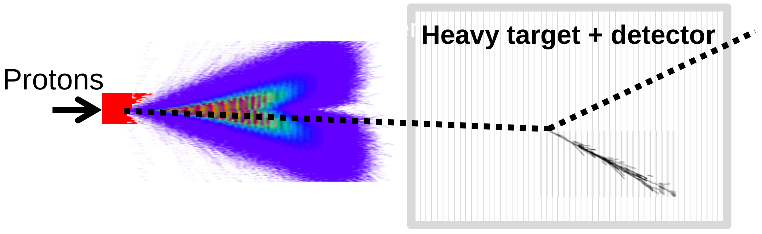
BDF/SHiP experimental techniques

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

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**

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

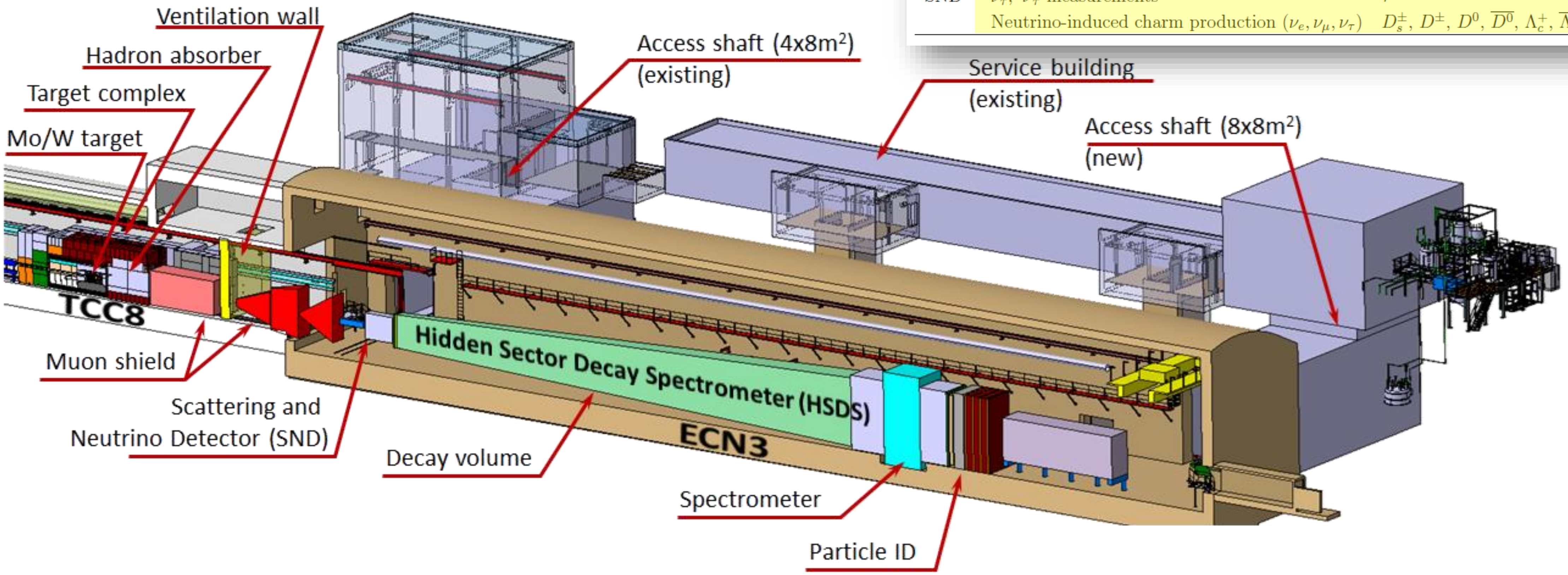
➔ **Rich "bread and butter" neutrino interaction physics with unique access to tau neutrino**

BDF/SHiP in ECN3

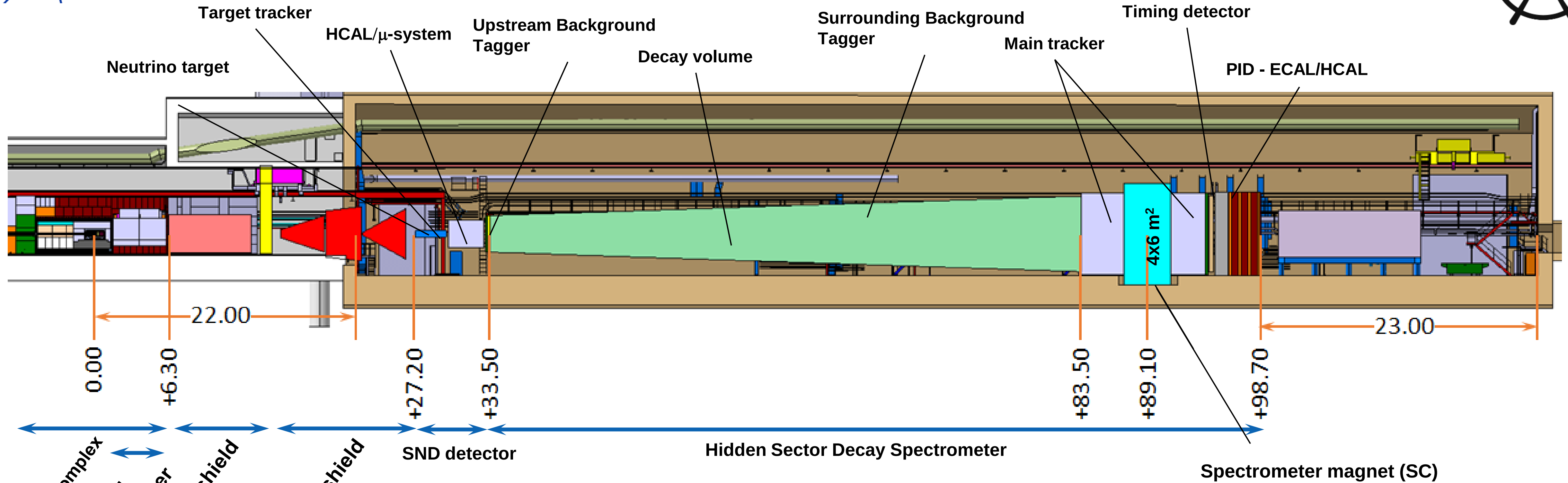
Two separate detector systems: “SND” and “HSDS”

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



SHiP detector in more detail

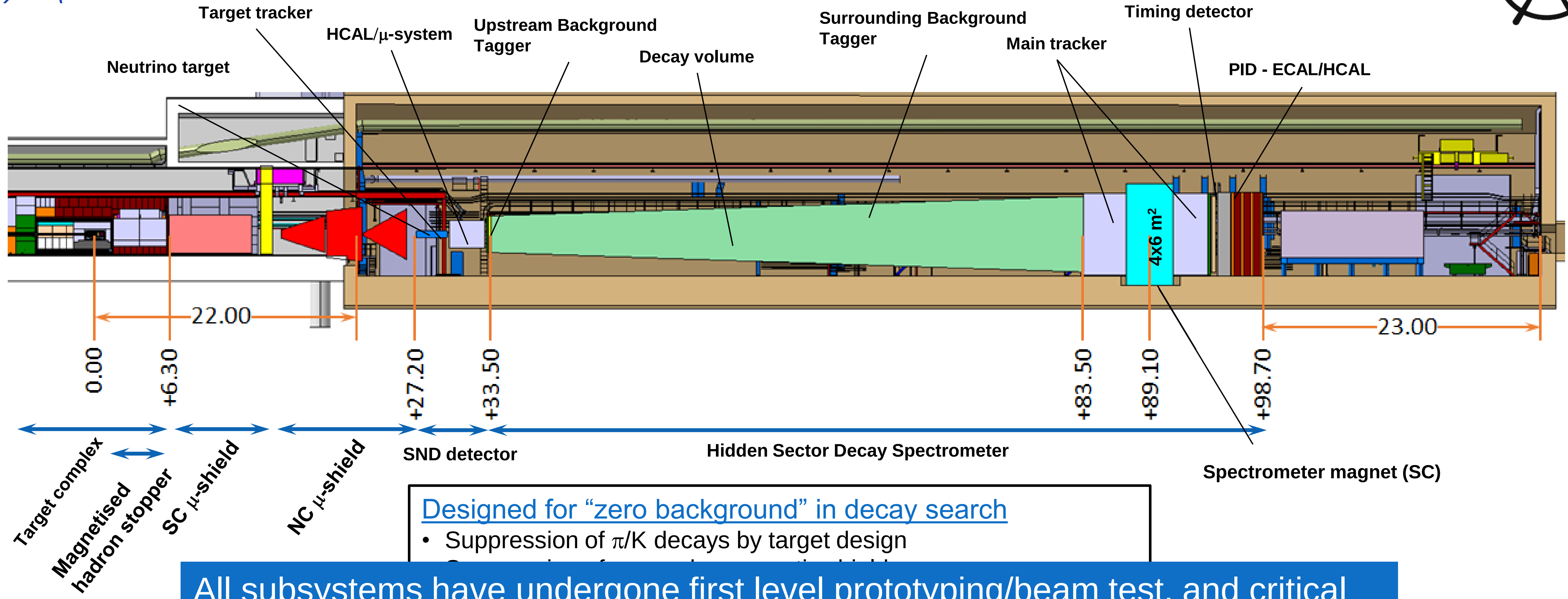


Designed for "zero background" in decay search

- Suppression of π/K decays by target design
- Suppression of muons by magnetic shield
- Suppression of neutrino by decay volume under low air pressure
- Background veto taggers
- Momentum and decay vertex information } by main tracker
- Impact parameter at target
- Coincidence timing

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

SHiP detector in more detail



Designed for "zero background" in decay search
- Suppression of π/K decays by target design
- Momentum and decay vertex information
- Impact parameter at target
- Coincidence timing

} by main tracker

- Invariant mass
- Particle identification

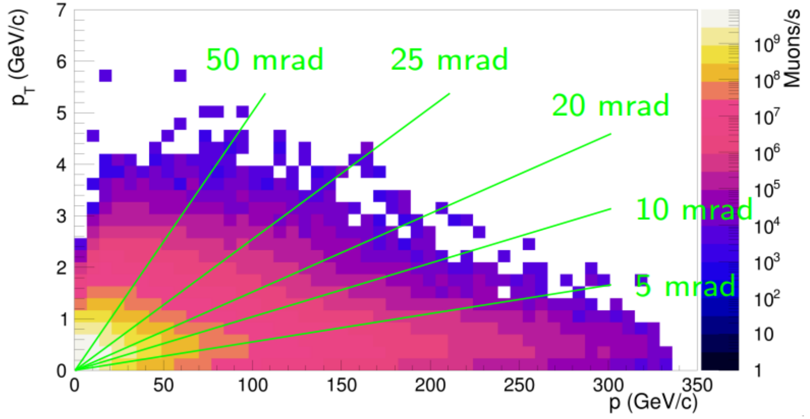
} Not currently used in background suppression

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

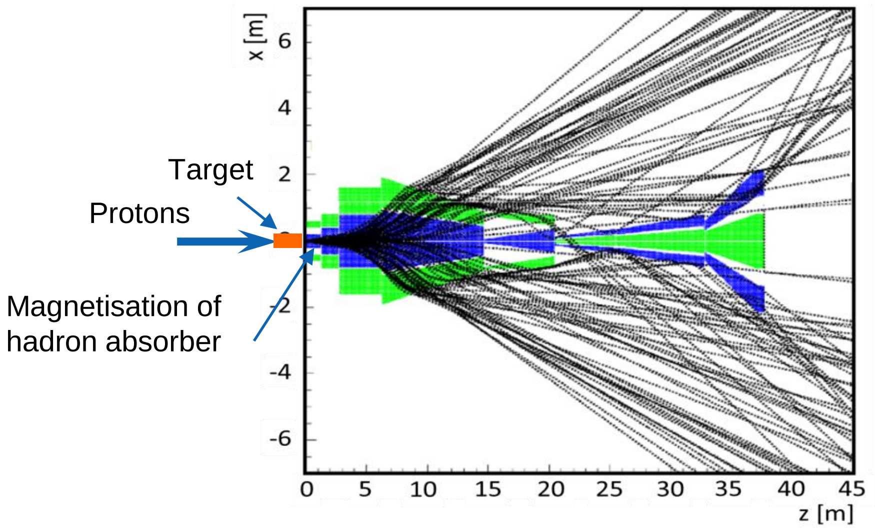
Beam-induced background

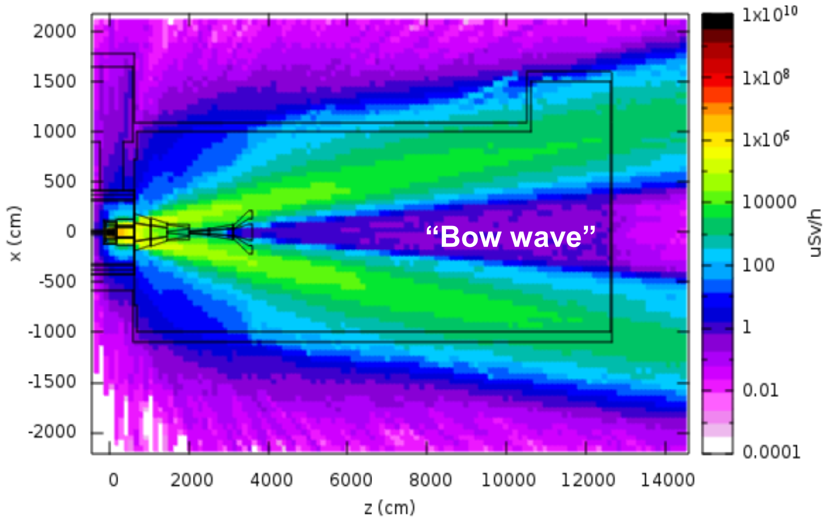
Background and detector optimisation studied with complete experimental setup implemented in GEANT (FairShip)

- Critical muon shield optimised for muon spectrum



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

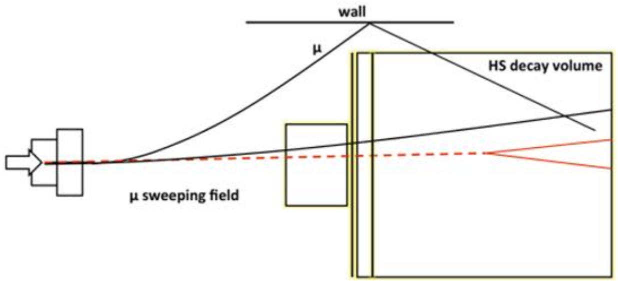




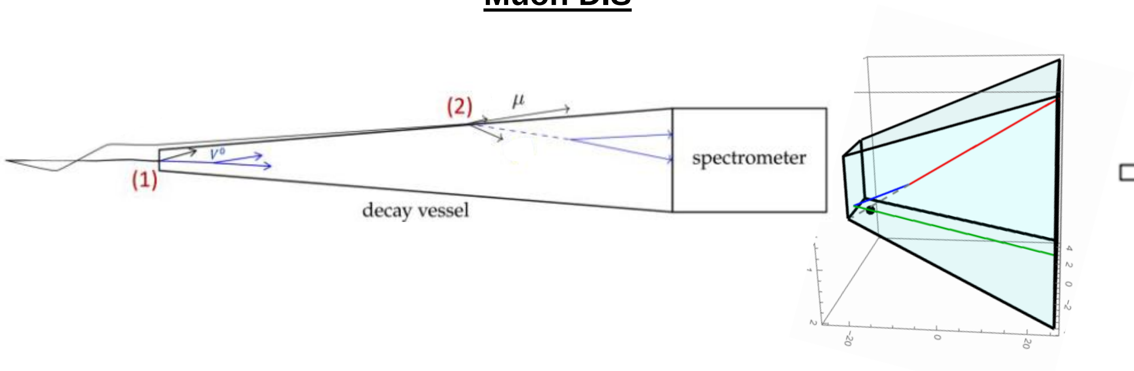
HSDS: FIP decay search background evaluation

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

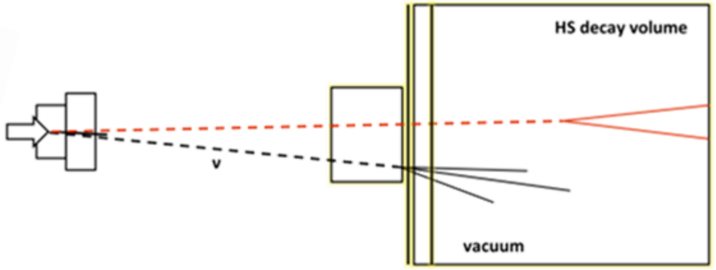
Muon combinatorial



Muon DIS



Neutrino DIS



- Backgrounds from muon and neutrino DIS are dominated by random combinations of secondaries, not by V^0s

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

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

Selection

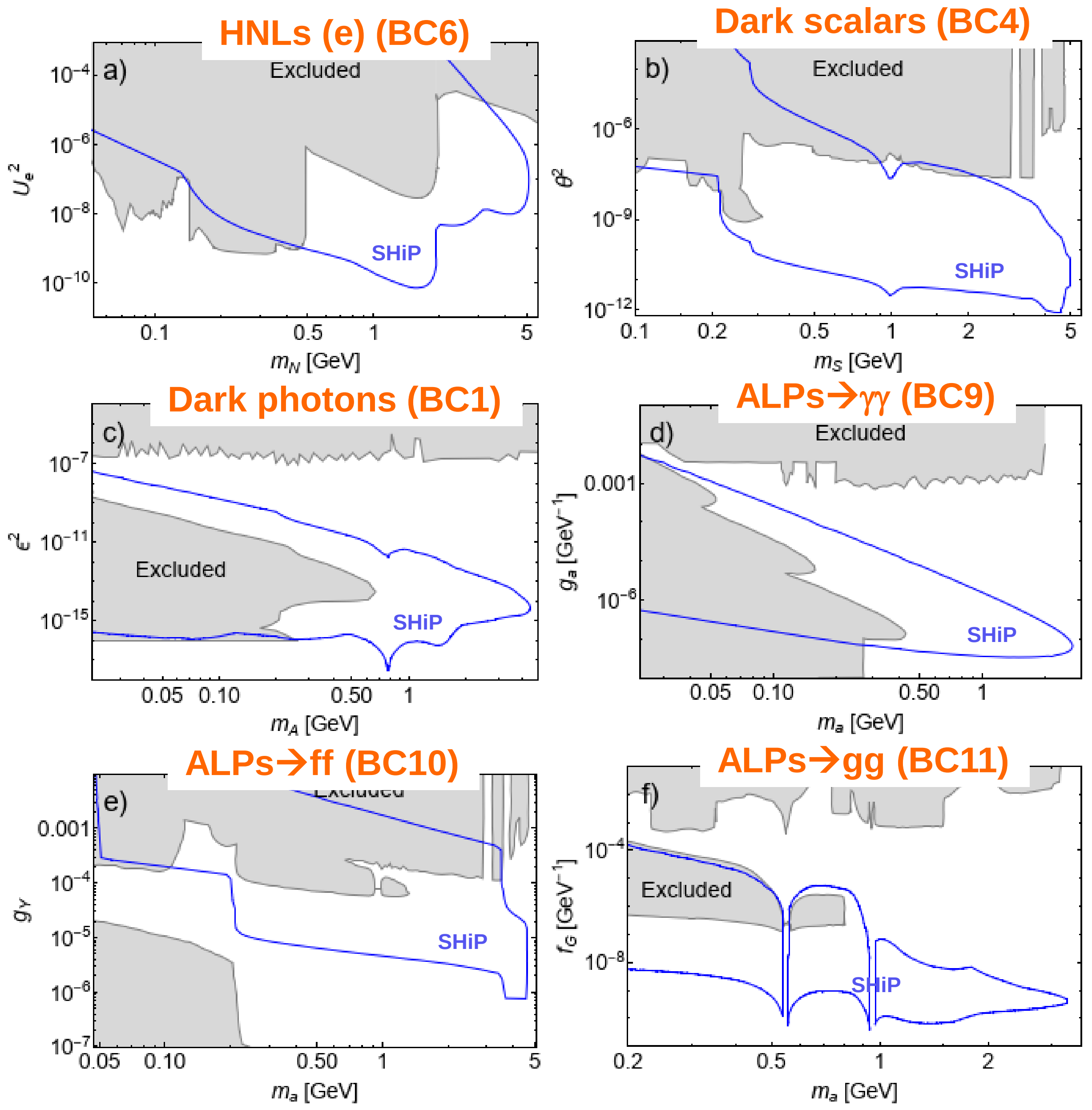
Criterion	Requirement
Track momentum (and track quality)	$> 1.0\,\mathrm{GeV}/c$
Vertex quality (distance of closest approach)	$< 1\,\mathrm{cm}$
Track pair vertex position in decay volume	$> 5\,\mathrm{cm}$ from inner wall $> 100\,\mathrm{cm}$ from entrance (partially)
Impact parameter w.r.t. target (fully reconstructed)	$< 10\,\mathrm{cm}$
Impact parameter w.r.t. target (partially reconstructed)	$< 250\,\mathrm{cm}$

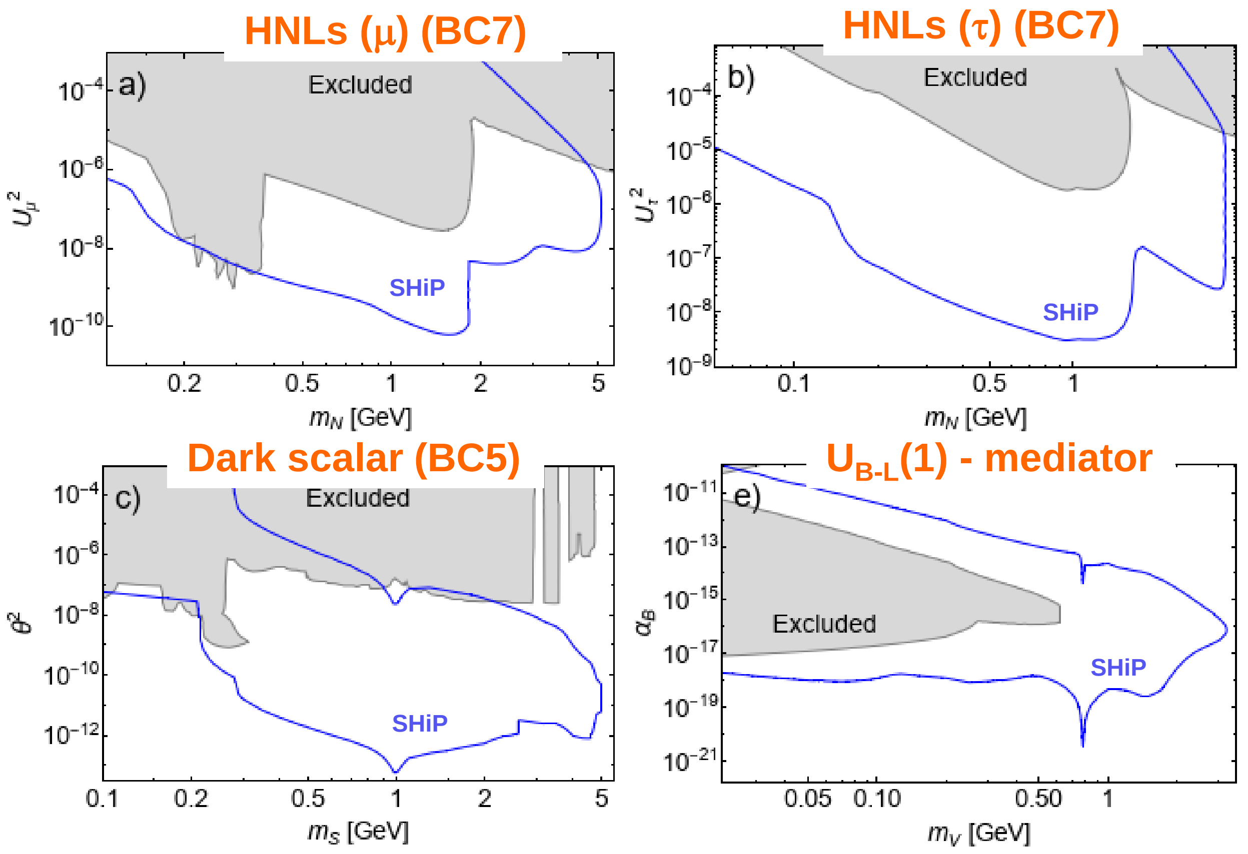
+ Time coincidence + UBT/SBT

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)*	$< 5\times10^{-3}$ (fully) / $<$ 0.2(partially)
Muon combinatorial	$(1.3\pm2.1)\times10^{-4}$

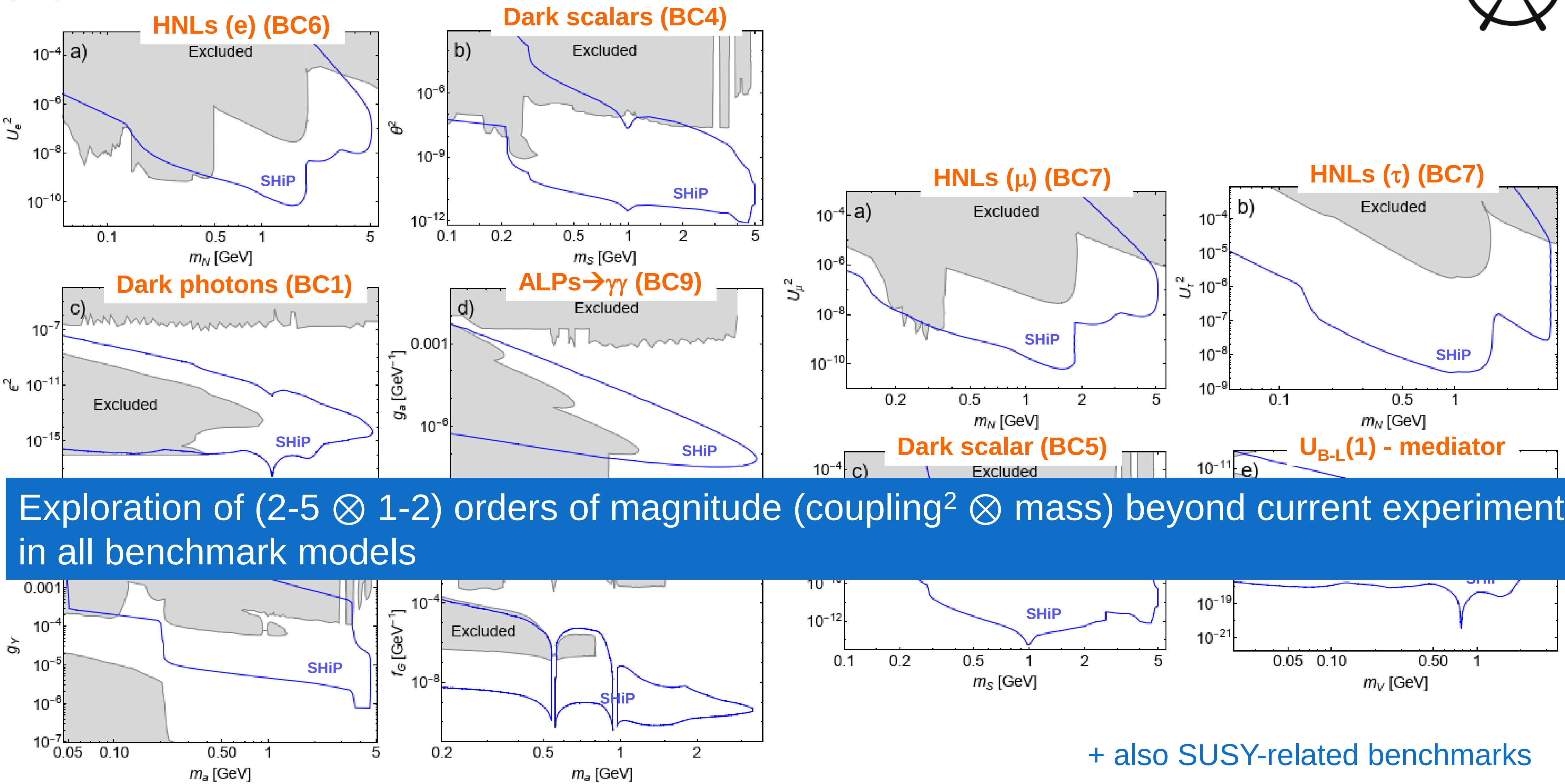
HSDS: FIP decay search performance, all benchmarks





+ also SUSY-related benchmarks

HSDS: FIP decay search performance, all benchmarks

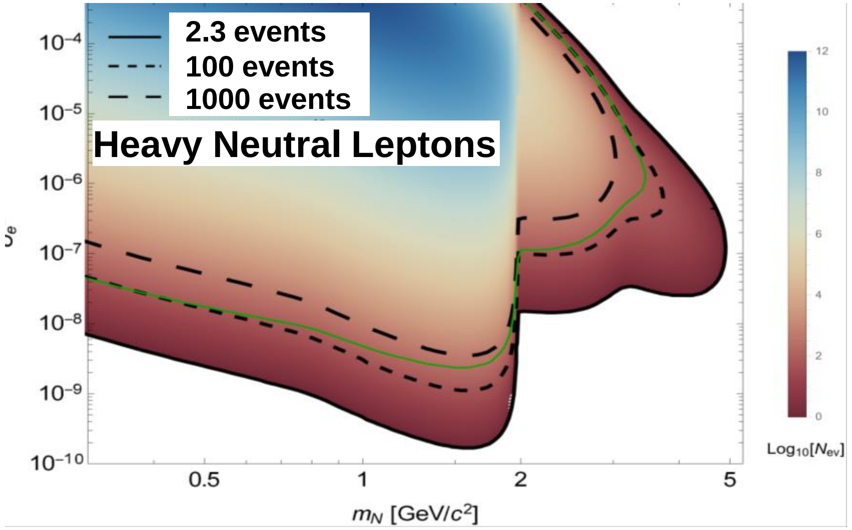


Exploration of (2-5 ⊗ 1-2) orders of magnitude (coupling^2 ⊗ mass) beyond current experiments in all benchmark models

+ also SUSY-related benchmarks

Physics sensitivities – FIPs cont'd

Experiment aimed at discovery and measurements ➔ Number of signal events (6×10^{20} pot)

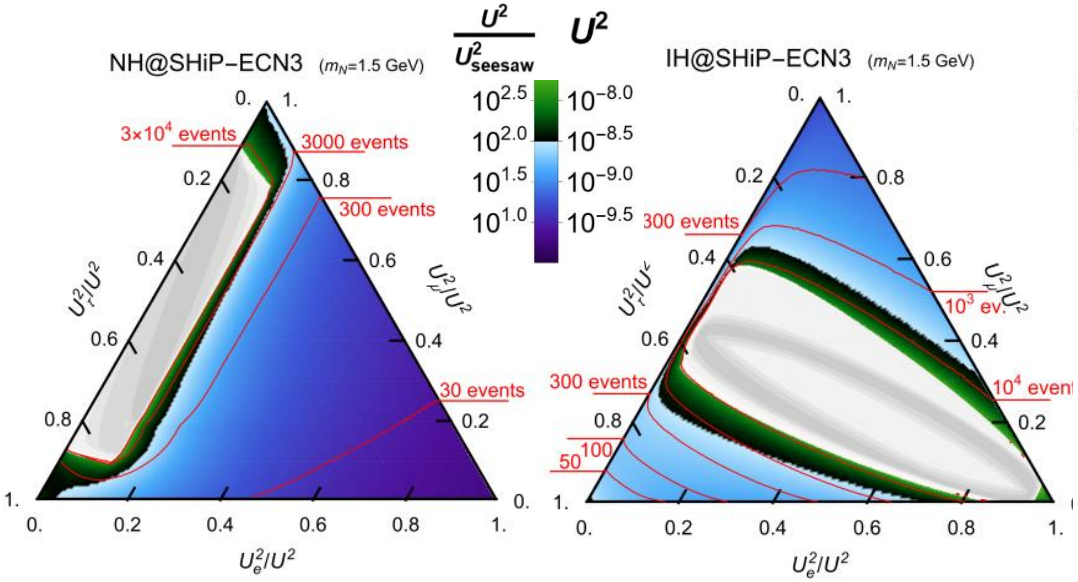


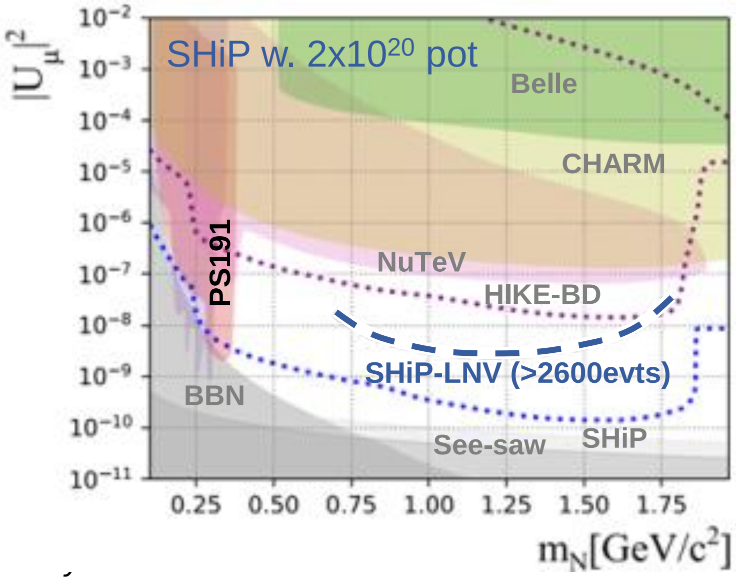
- Step 1: Characterise new object - precise mass, branching ratios, spin: $\mathcal{O}(10)$ evts

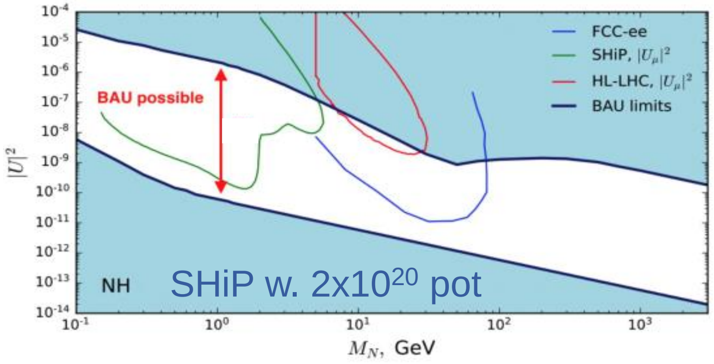
- Step 2: Test compatibility with hypothesis addressing SM issues: $\mathcal{O}(100-1000)$ evts

O. Mikulenko (Leiden Univ.) et al., "New physics at the Intensity Frontier, how much can we learn and how?", to be submitted

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

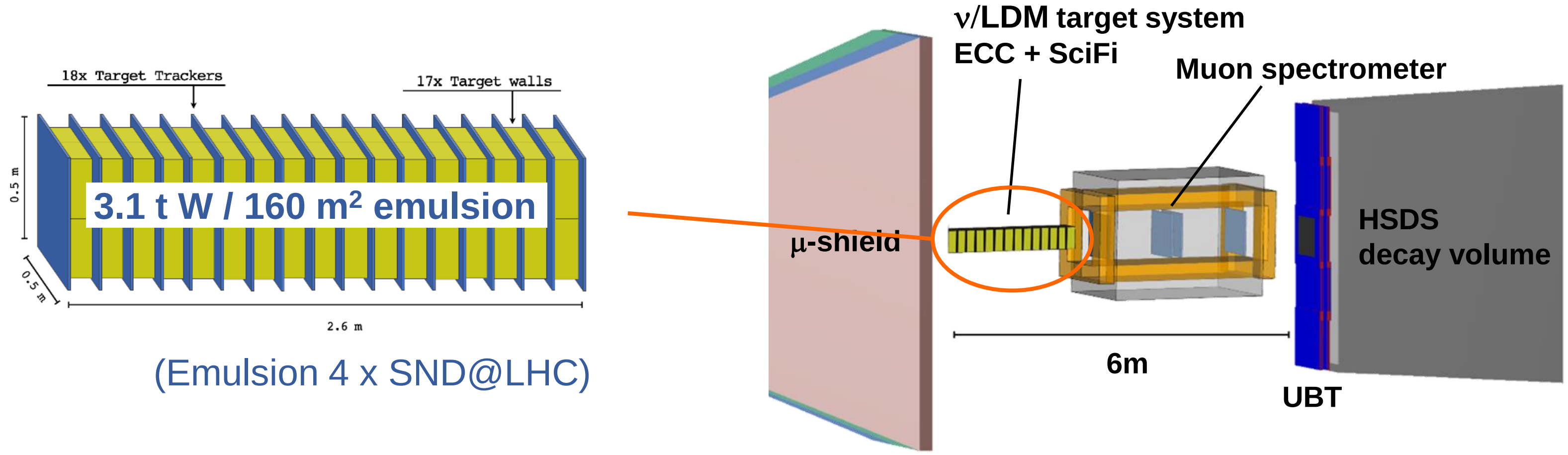


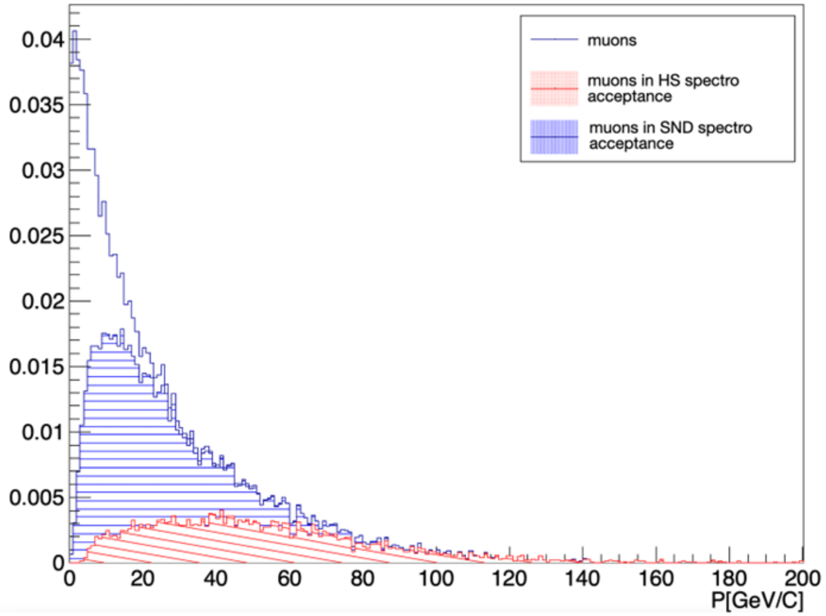




LDM scattering and neutrino detector (SND)

- 3 tonne LDM/neutrino W-target instrumented with layers of emulsion films
  - Micrometric accuracy is crucial for detecting tau neutrino by tau lepton decay vertices, and detecting neutrino-induced charm
  - Reconstruct electron and muon neutrino flavour from identification of electromagnetic showers and muons
  - Magnetised muon system for charge determination





- Neutrino energy from determination of electromagnetic/hadronic energy in target and muon momentum
  - Muon momentum range covered by both SND muon system and HSDS spectrometer (25% of total flux)

➔ Purely electronic techniques under investigation in the context of SND@LHC upgrade to replace emulsion

LDM scattering and neutrino detector (SND)

- 3 tonne LDM/neutrino W-target instrumented with layers of emulsion films
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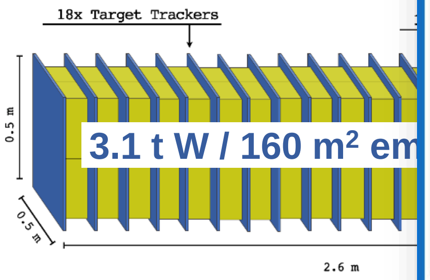
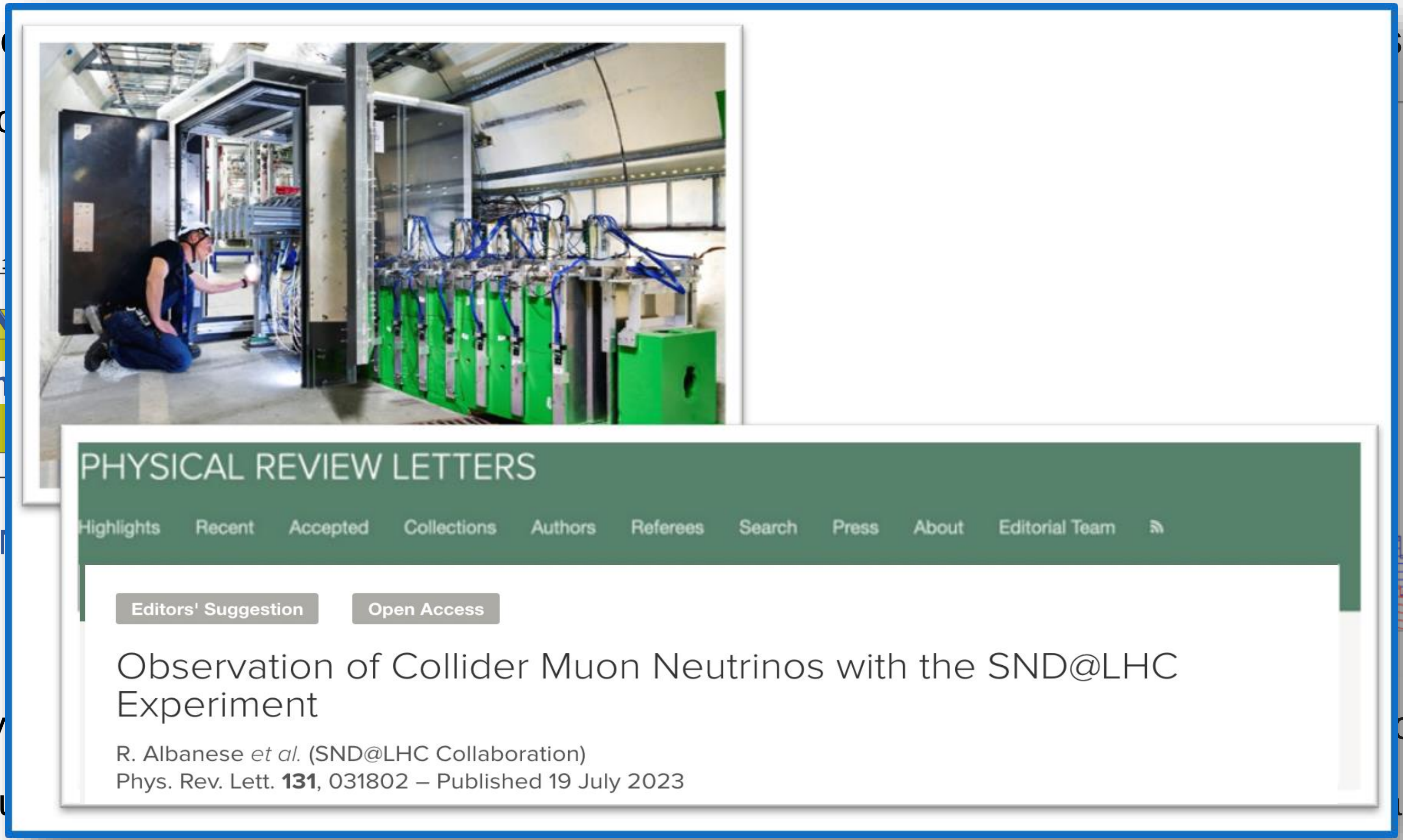
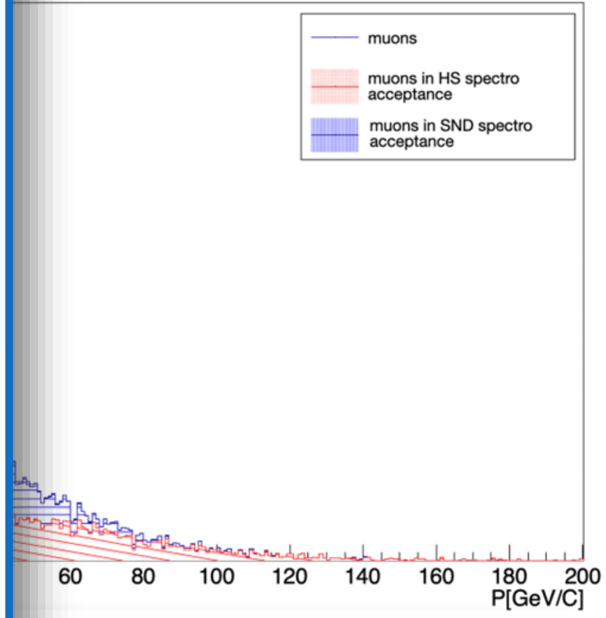
  - Magnetised muc …



(Emulsion 4 x SI …



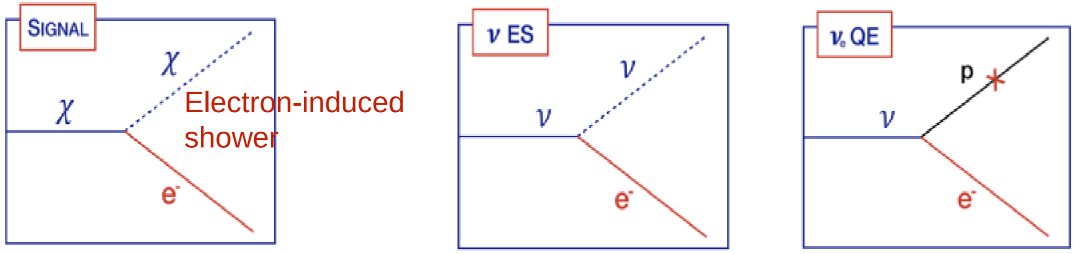


- Neutrino energy … omentum
  - Muon momentu … l flux)

➔ Purely electronic techniques under investigation in the context of SND@LHC upgrade to replace emulsion

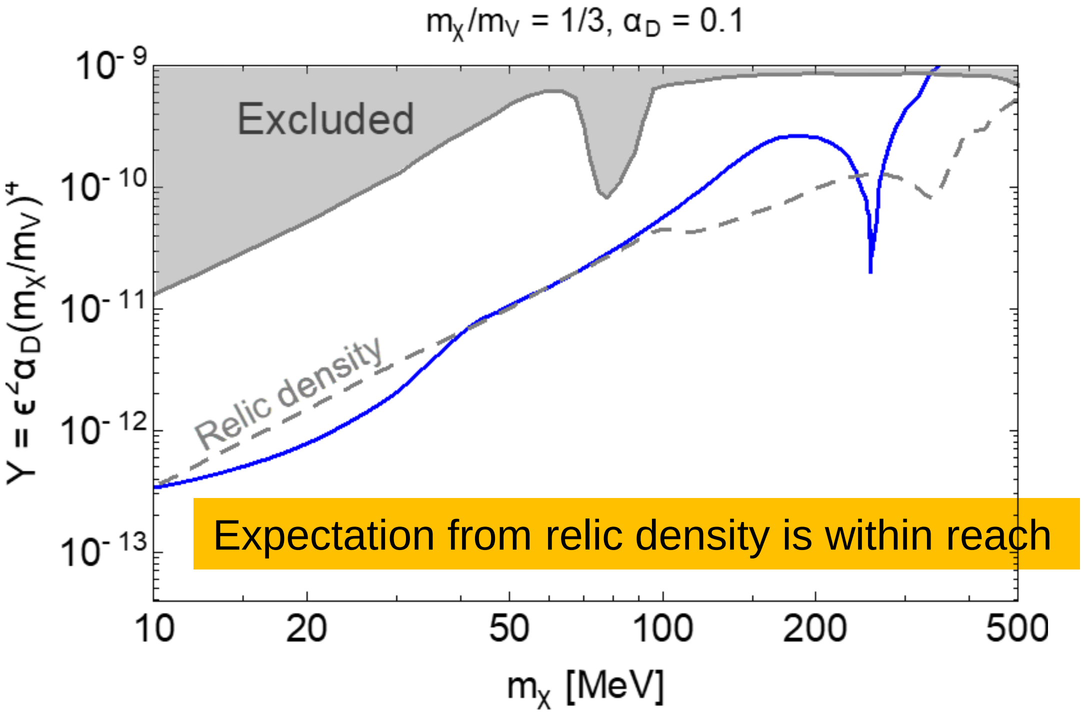
SND: "Direct" light dark matter search

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



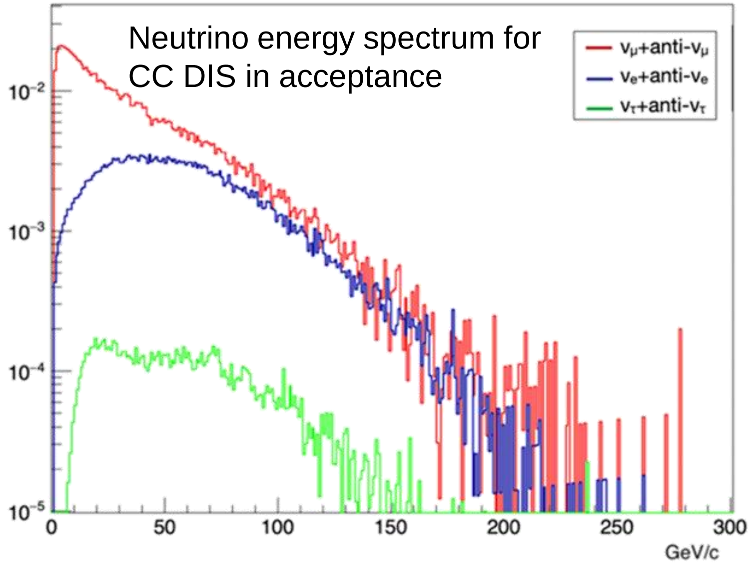
➔ Background is dominated by neutrino elastic and quasi-elastic scattering, for 6 $\times 10^{20}$ PoT

6 $\times$10²⁰	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 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	$\overline{\nu}_\tau$
$\tau \to \mu$	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	

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 $\sigma_{\nu-CC\ DIS}$

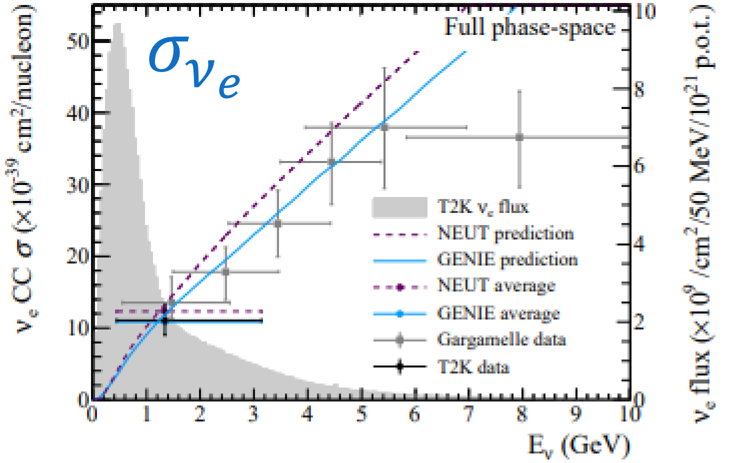
- Never measured, only accessible with tau neutrinos, realistically at <10% [C.Albright and C.Jarlskog, NP B84 (1975)]

➔ Exotics, …

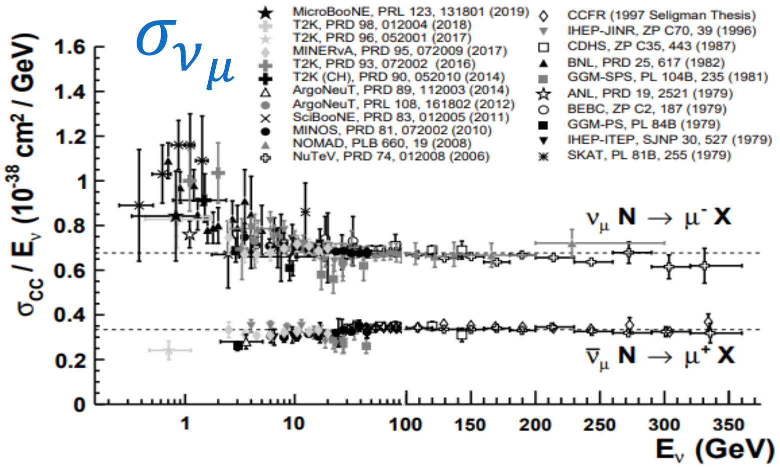
$$\frac{\sigma(\nu_e)}{\sigma(\nu_\mu)} = \frac{(\nu_e \text{ events observed})}{(\nu_\mu \text{ events observed})} \frac{\int E_{\nu_\mu}(\nu_\mu \text{ flux})dE}{\int E_{\nu_e}(\nu_e \text{ flux})dE} = 1.09 \pm 0.17 .$$

➔ 15%!

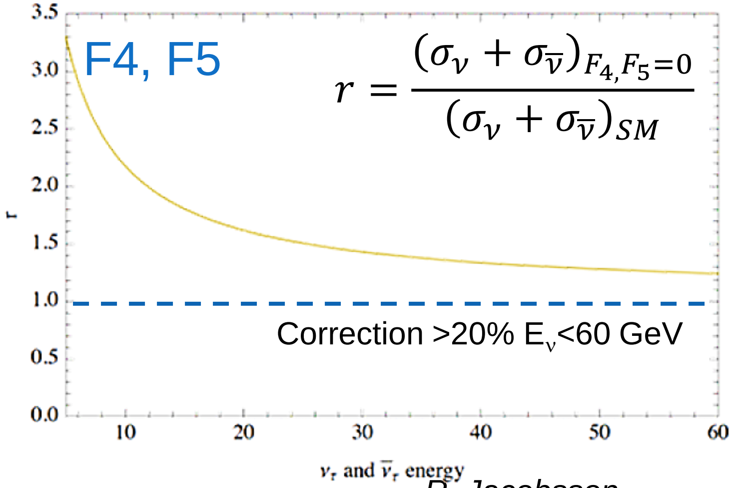
Phys.Rev. D41, 2653 (1990)



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



PDG



Rep. Prog. Phys. 79 (2016)124201

SND: Neutrino interaction physics (3)

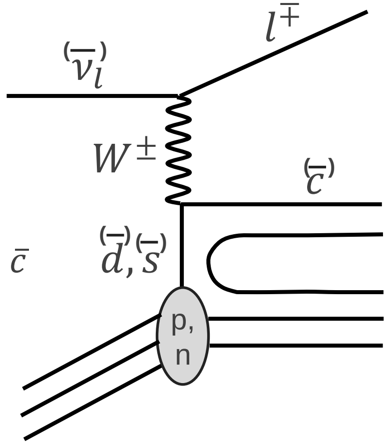
Neutrino-induced charm production programme

- 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

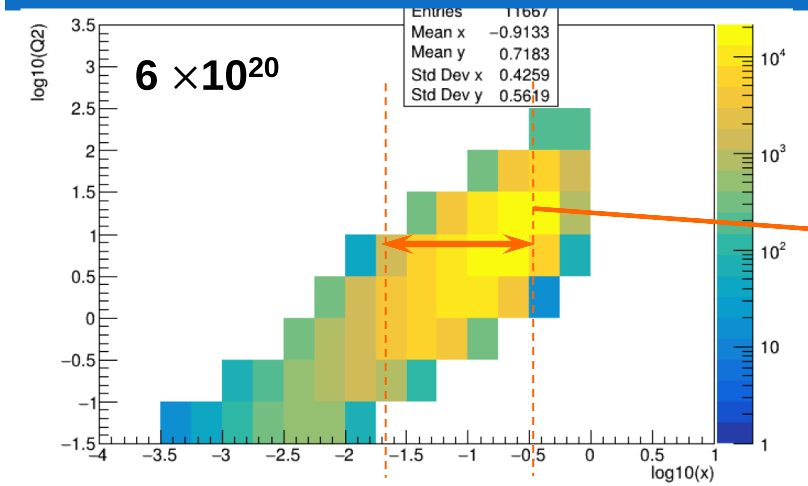
	<E> (GeV)	CC DIS with charm prod
N_{ν_μ}	57	3.5×10^5
N_{ν_e}	71	1.7×10^5
$N_{\overline{\nu}_\mu}$	50	0.7×10^5
$N_{\overline{\nu}_e}$	60	0.3×10^5
total		6.2×10^5

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

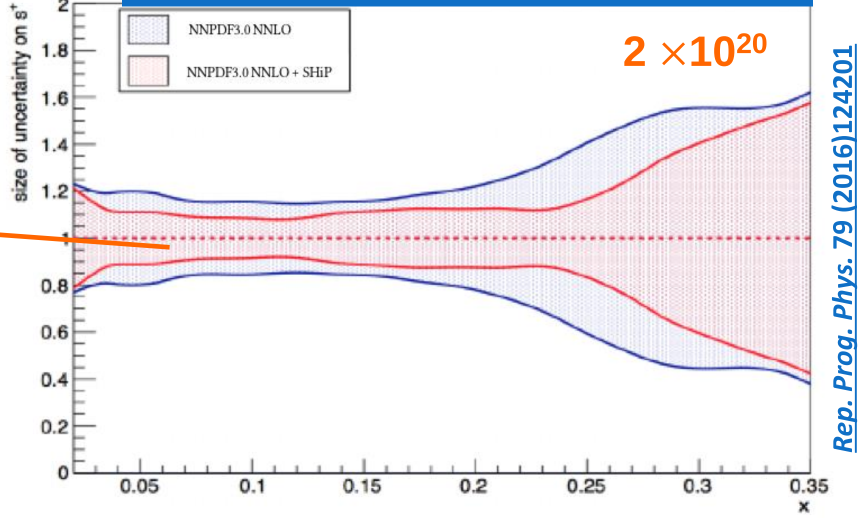


No charm candidate from ν_e and ν_τ interactions ever reported

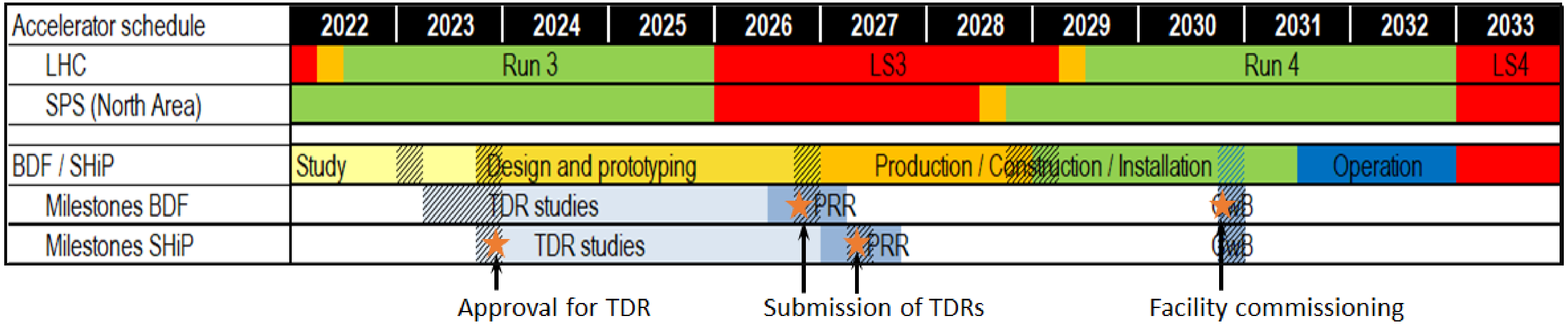
Large data samples at SHiP will greatly improve current measurements up to high values of x



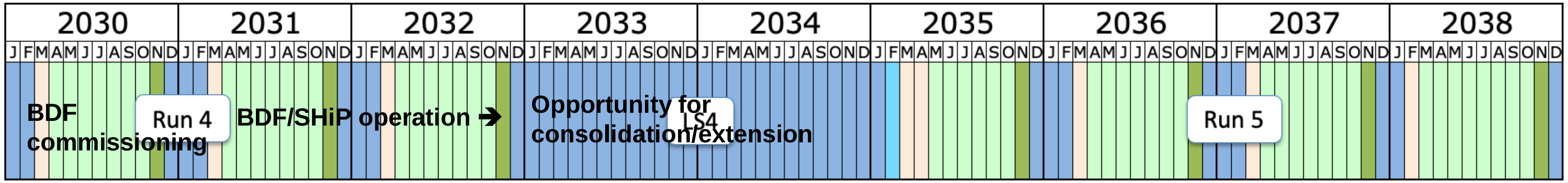
SHiP sensitivity to PDF for x < 0.35
(evaluated in [Prog. Phys. 79 (2016) 124201)]



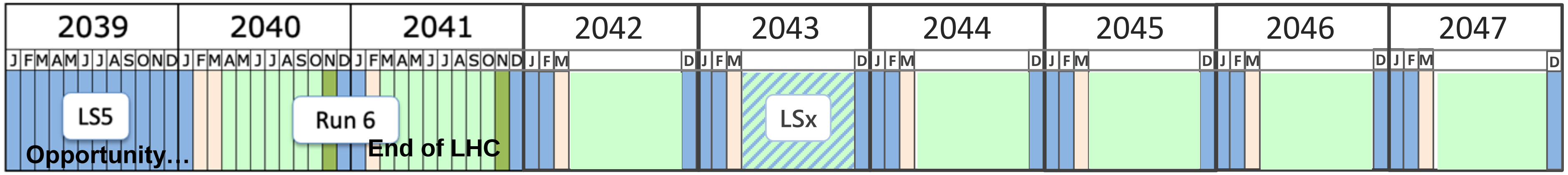
BDF/SHiP tentative schedule



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



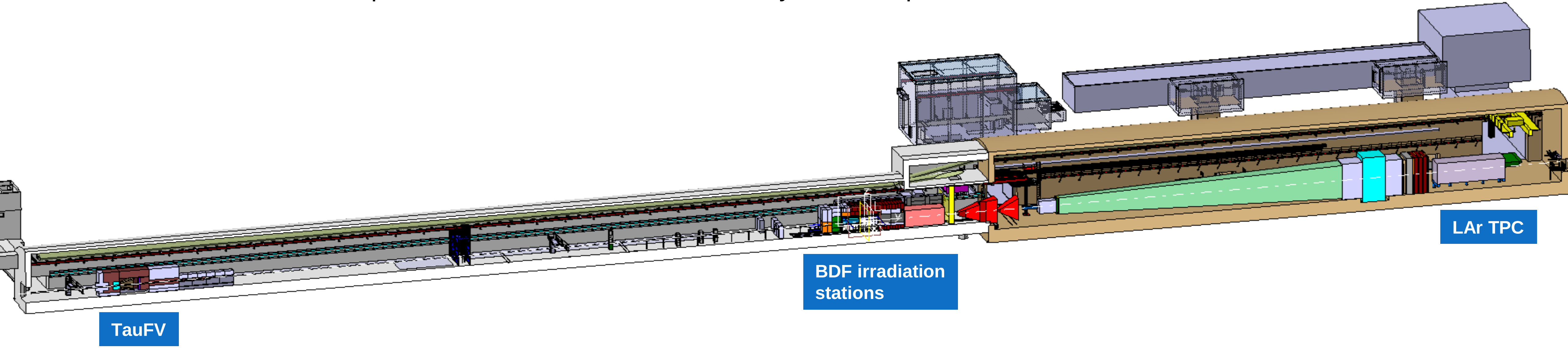
SPS decoupled from injector role in 2042, fully dedicated to proton/ion FT physics



Last update: April 2023

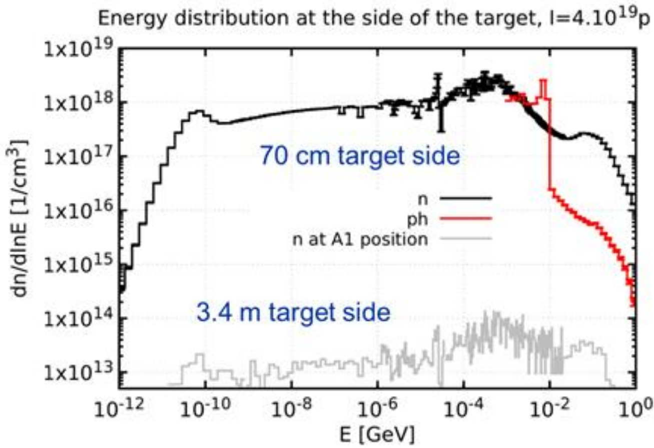
Overview of BDF extensions

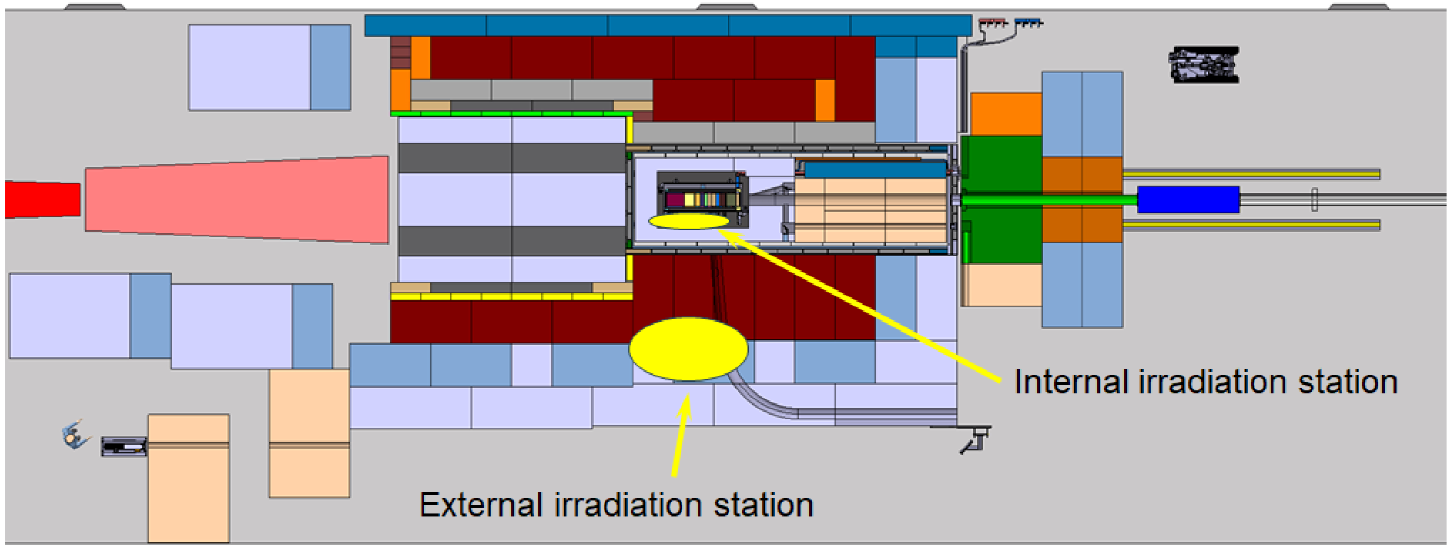
- Preliminary studies of opportunities to extend BDF's physics programme *synergetically with SHiP*:
  - Irradiation stations (nuclear astrophysics and accelerator / material science applications)
  - LArTPC to extend search for FIPs using different technology
  - TauFV to search for lepton flavour violation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

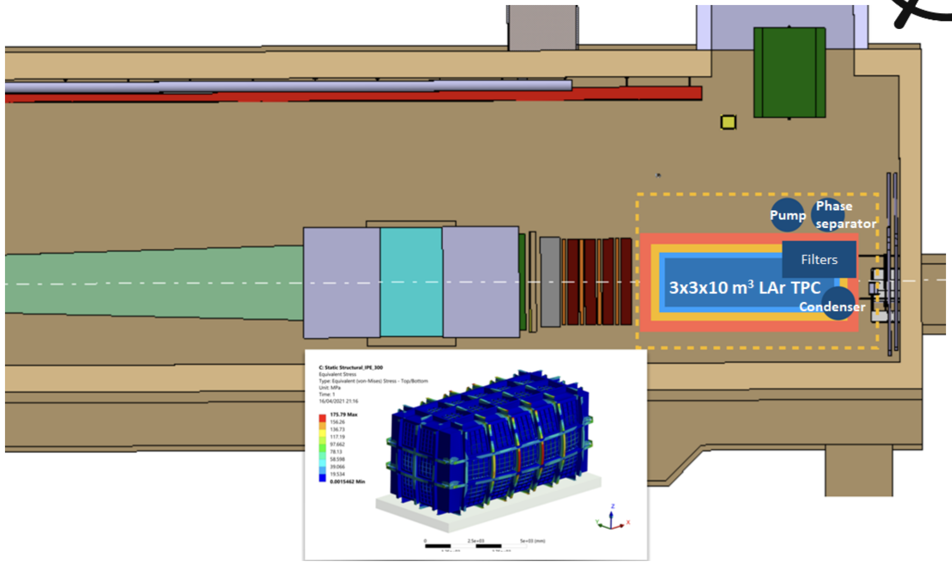
Extensions: FIP searches with LAr TPC detector

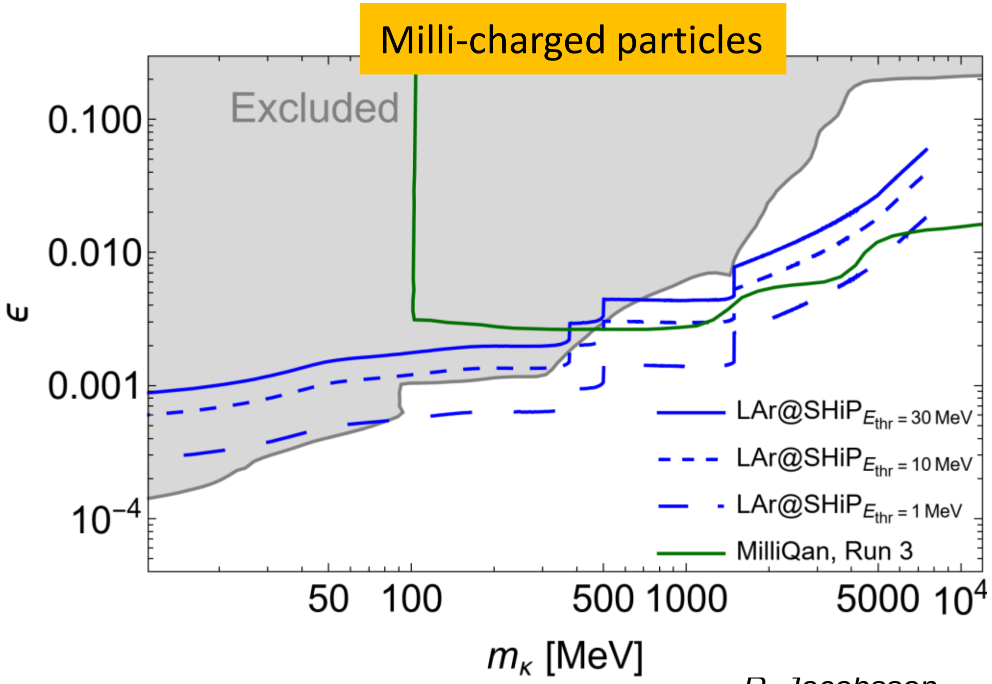
LArTPC technology is currently used in neutrino and cosmic Dark Matter search experiments

- 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

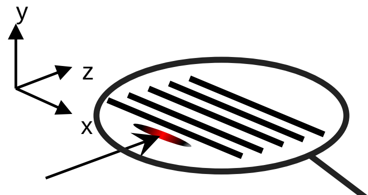




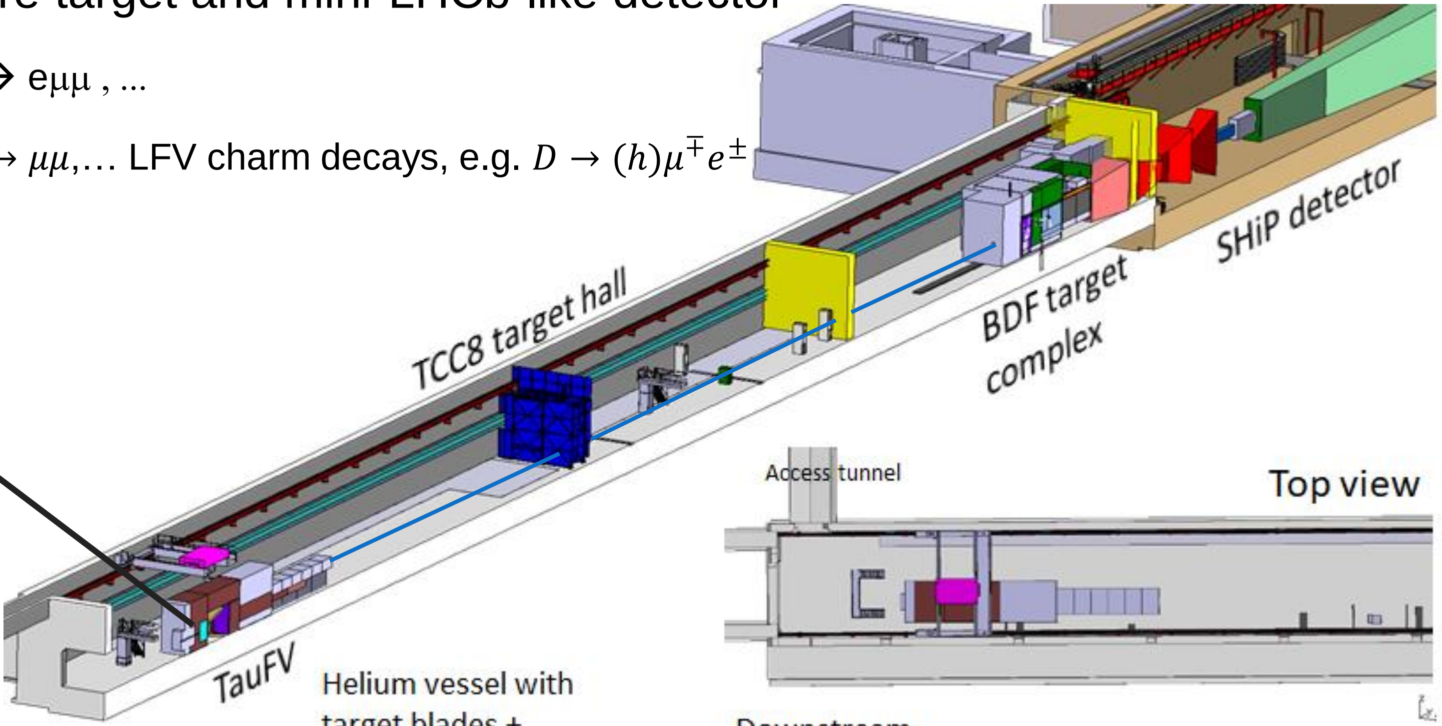
Extensions: Tau flavour violation experiment

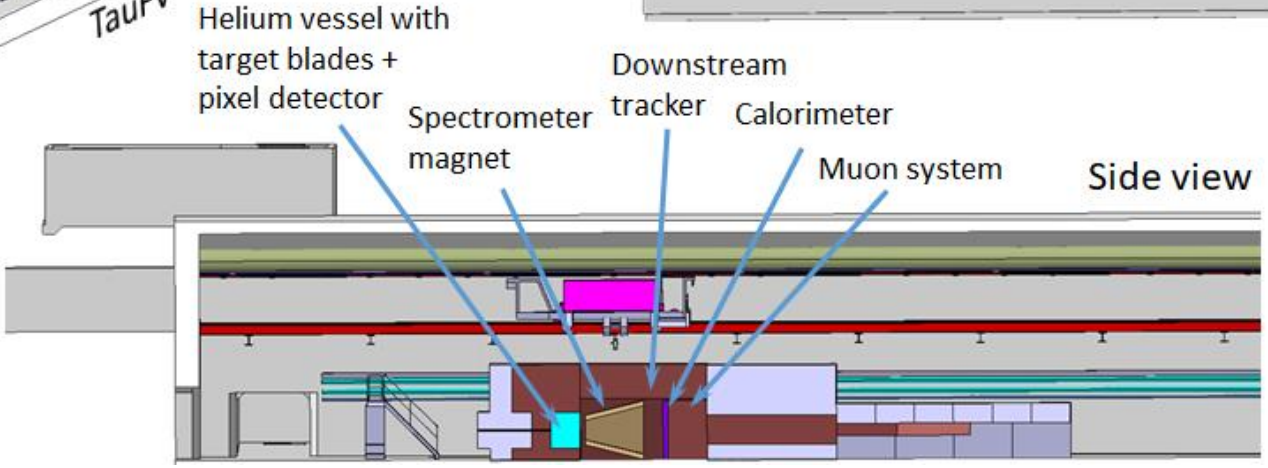
Intercepting 1-2% of protons in BDF line with wire target and mini-LHCb-like detector

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



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





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

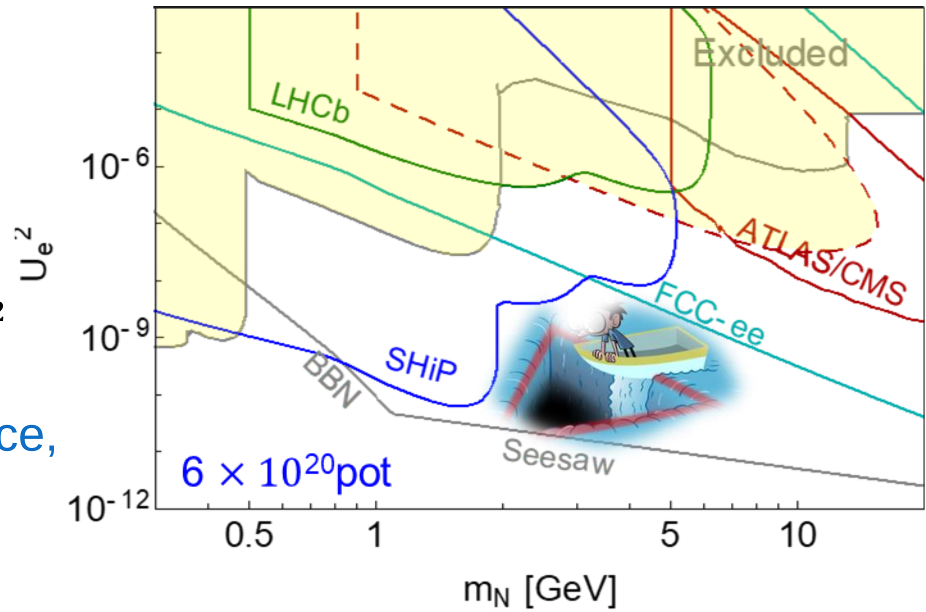
Experiment	PoT / $\int \mathcal{L}dt$	Yield
TauFV	4×10^{18}	800
Belle II	$50\,\mathrm{ab}^{-1}$	1
LHCb Upgrade I	$50\,\mathrm{fb}^{-1}$	14
LHCb Upgrade II	$300\,\mathrm{fb}^{-1}$	84

Summary

- Unique physics potential of SPS to explore *"Coupling Frontier"* with synergy between accelerator-based searches and searches in astrophysics/cosmology
  - First hints might come with breadth of modern earth/space-based telescopes

- "New Physics (NP)" = "ν Physics (νP)" !?...
  - ➔ Search for "*no new scale*" very feebly interacting physics highly justified
  - ➔ HNLs with masses in $keV < m_N < m_{W,Z}$ provide very interesting possibilities as a minimal SM extension (ν mass and oscillation, BAU, DM)
  - ➔ Theoretical calculations in some models may give input on preferred m_N%$|\mathcal{U}|^2$

- 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.

Acknowledgement

Huge thanks for the support from the ATS sector and HSE, and in particular the BDF WG

The SHiP Collaboration wishes to thank the Castaldo company (Naples, Italy) for their contribution to the development studies of the decay vessel. The support from the National Research Foundation of Korea with grant numbers of 2018R1A2B2007757, 2018R1D1A3B07050649, 2018R1D1A1B07050701, 2017R1D1A1B03036042, 2017R1A6A3A01075752, 2016R1A2B4012302, and 2016R1A6A3A11930680 is acknowledged. The support from the FCT - Fundação para a Ciencia e a Tecnologia of Portugal with grant number CERN/FIS-PAR/0030/2017 is acknowledged. The support from the TAEK of Turkey are acknowledged.

We are greatly indebted to the support of the Beam Dump Facility Working Group (below).

Outside of the SHiP collaboration and the BDF WG, we acknowledge in particular, for their contribution to:
- magnetisation of hadron stopper: V. Bayliss, J. Boehm, G. Gilley,
- muon shield superconducting magnet: B. Cure, M. Mentink, A. Milanese, E. Todesco,
- superconducting spectrometer magnet: H. Bajas, D. Tommasini,
- BDF irradiation station: S. Danzeca, A. Mengoni, N. Pacifico, F. Ravotti, R. Garcia Alia,
- LAr TPC: F. Resnati,
- TauFV: P. Collins, G. Wilkinson,
- and to the development of the SHiP detectors: M. Andreini, H. Danielsson.

BDF Working Group[30]

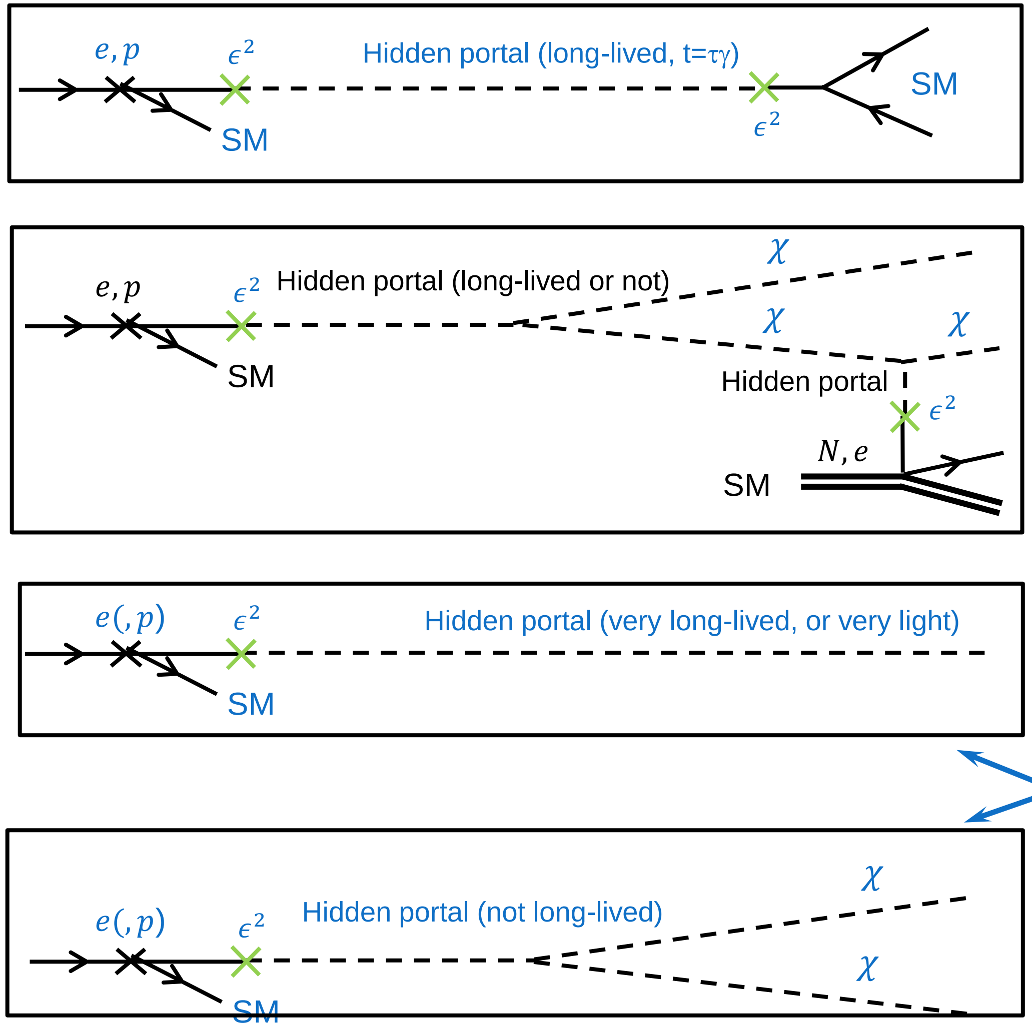
O. Aberle, C. Ahdida, P. Arrutia, K. Balazs, M. Calviani, Y. Dutheil, L.S. Esposito, R. Franqueira Ximenes, M. Fraser, F. Galleazzi, S. Gilardoni, J.-L. Grenard, T. Griesemer, R. Jacobsson, V. Kain, L. Krzempek, D. Lafarge, S. Marsh, J.M. Martin Ruiz, G. Mazzola, R.F. Mena Andrade, Y. Muttoni, A. Navascues Cornago, P. Ninin, J. Osborne, R. Ramjiawan, F. Sanchez Galan, P. Santos Diaz, F. Velotti, H. Vincke, P. Vojtyla

SPARE SLIDES

Experimental techniques

Production | Detection

Direct



Indirect

Decay signature ("displaced vertex")
Probability $\propto \epsilon^4$
Model independent
+
Reconstruction of decay: mass, PID
→ Distinguish models
→ Measurement of properties

MATHUSLA
ANUBIS
CODEX-b

NA62
NA64
FASER
SHiP

Dark matter scattering
Model-dependent interpretation
Recoil against electron or nuclei
Probability $\propto \epsilon^4$

SHiP
SND@LHC

Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

Cannot be directly distinguished
→ Model-dependent interpretation

If $m_{HP} > 2m_{DM}$
Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

NA64
LDMX

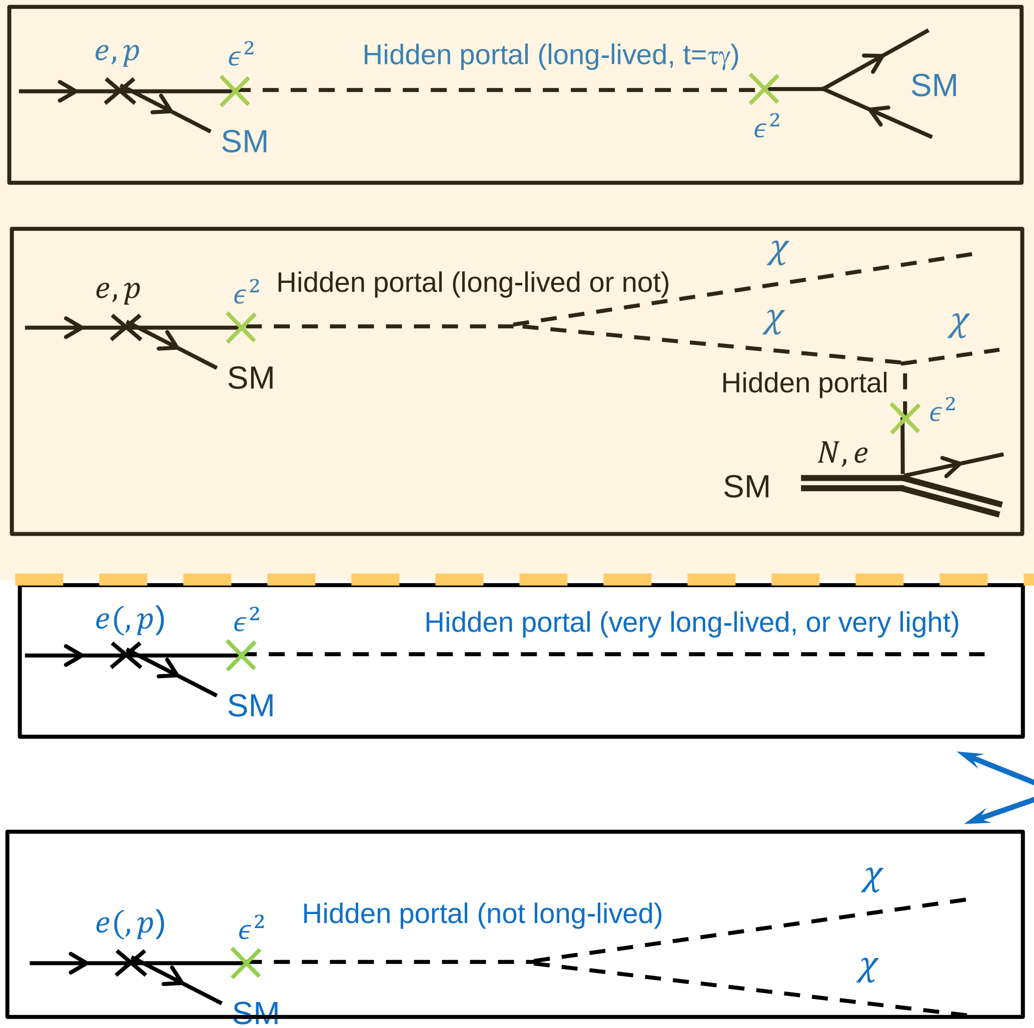
→ Background situation very different in the different techniques!!

Use of electrons limits search to Dark Photon mediator (&ALPs)

SHiP experimental technique

Production — Detection

Direct



Decay signature ("displaced vertex")
Probability $\propto \epsilon^4$
Model independent
+
Reconstruction of decay: mass, PID
→ Distinguish models
→ Measurement of properties

MATHUSLA, ANUBIS, CODEX-b
NA62, NA64, FASER, SHiP

Dark matter scattering
Model-dependent interpretation
Recoil against electron or nuclei
Probability $\propto \epsilon^4$

SHiP, SND@LHC

SHiP with protons

Indirect

Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

Cannot be directly distinguished
→ Model-dependent interpretation

If $m_{HP} > 2m_{DM}$
Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

NA64, LDMX

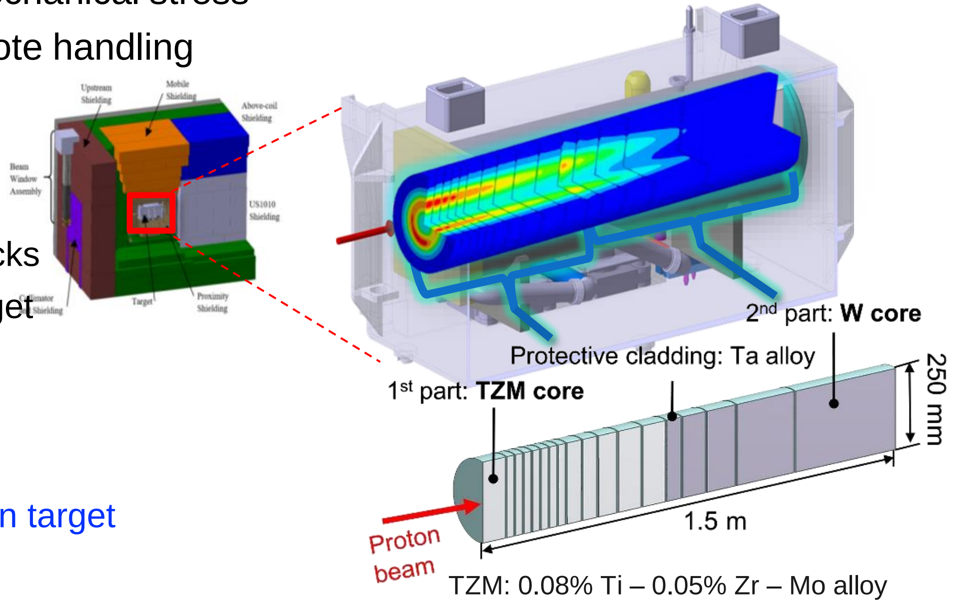
Use of electrons limits search to Dark Photon mediator (&ALPs)

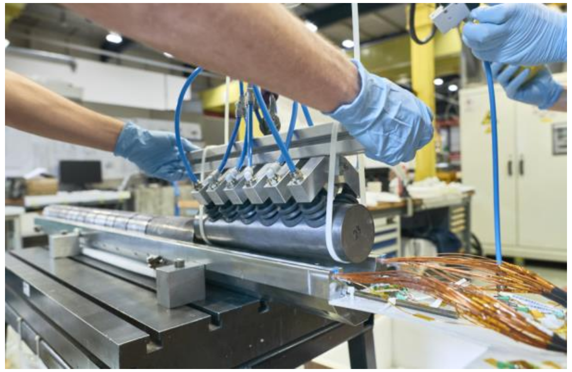
➔ Background situation very different in the different techniques!!

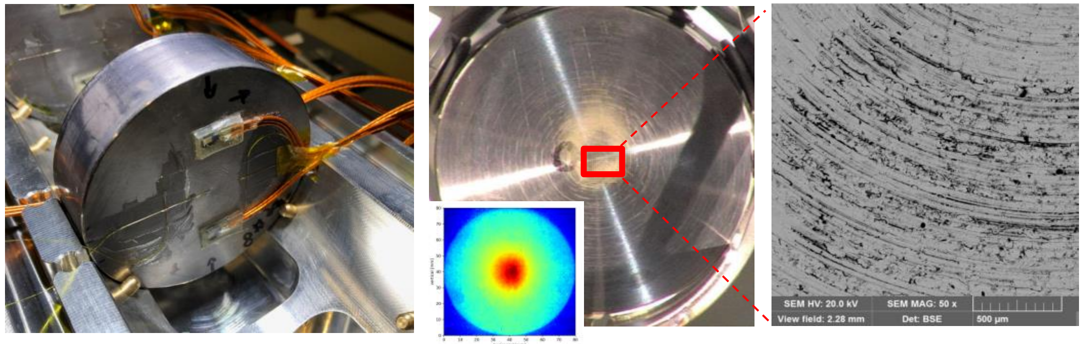
BDF/SHiP Target

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

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



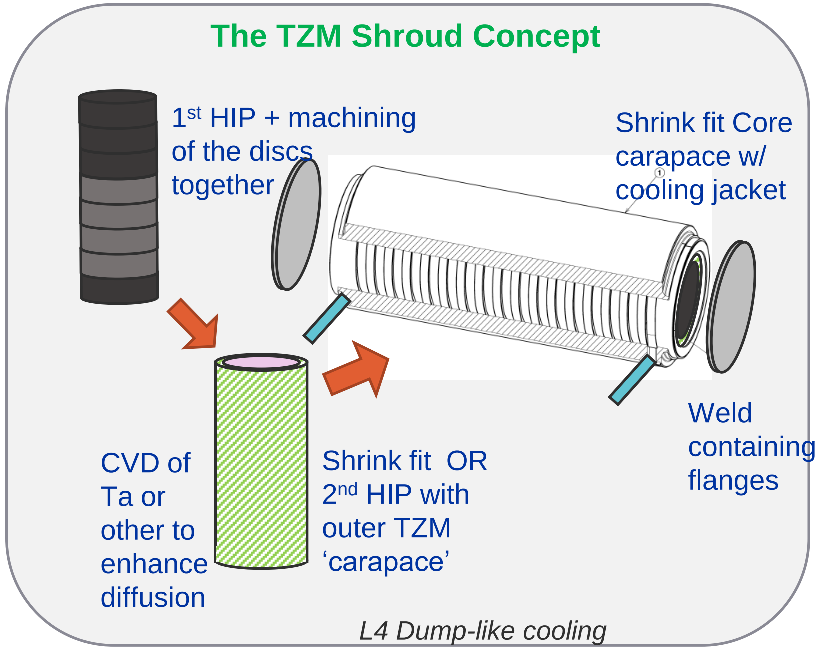


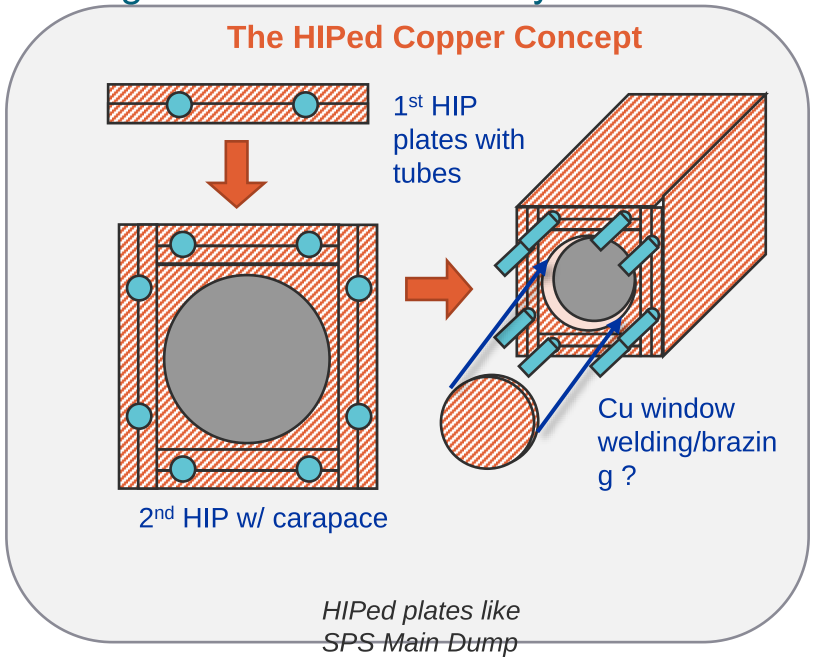


Prototype instrumentation. Visual and optical microscopy inspections during the PIE.

BDF/SHiP target – new ideas

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



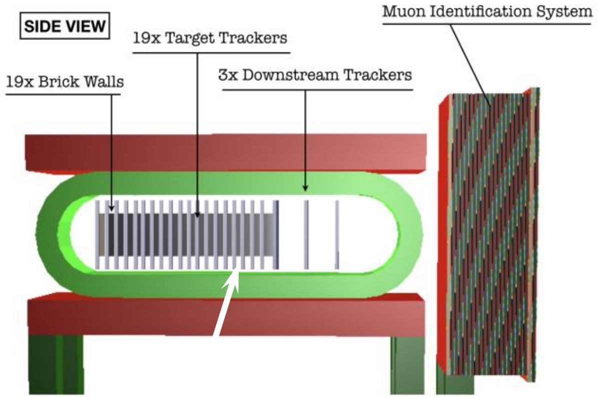


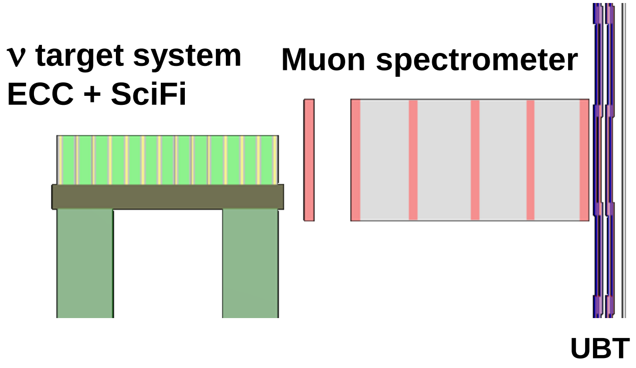
L4 Dump-like cooling serpentine jackets (welded beforehand)

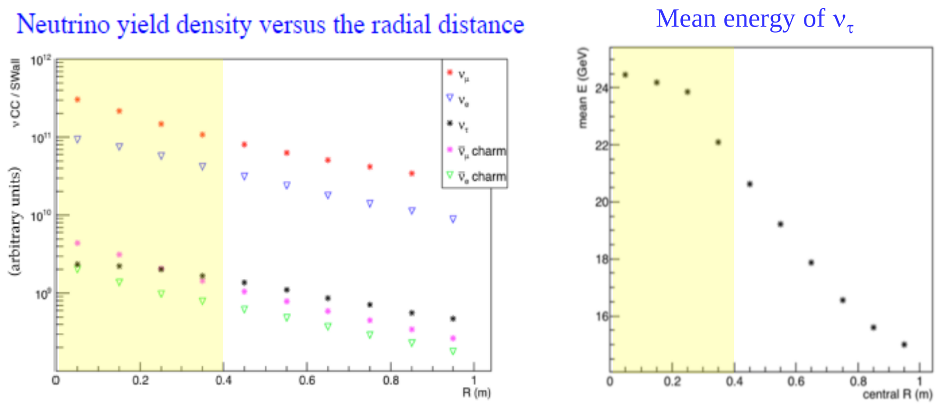
HIPed plates like SPS Main Dump TIDVG5

Scattering and neutrino detector

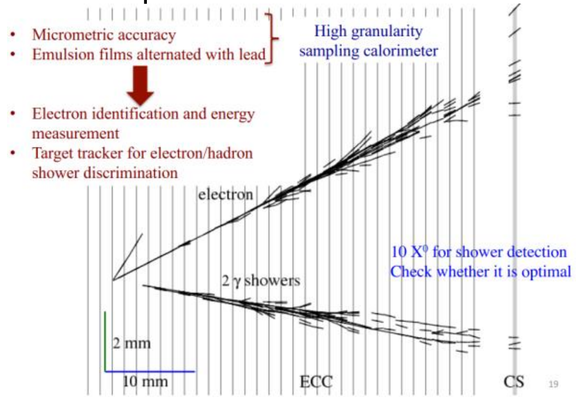
- Revised configuration
  - Magnetisation of muon system (ECN3) instead of target system (ECN4)







ν_e event in Opera



ECN3/ECN4 ν yield and track density of up to $6\times10^5/cm^2$ from SND@LHC experience:

- ECN4 (CDS): 8 tonnes with 2 replacements per year
- ECN3 closer setup: 3.1 tonnes with 2 to 4 replacements per year → on average less emulsions

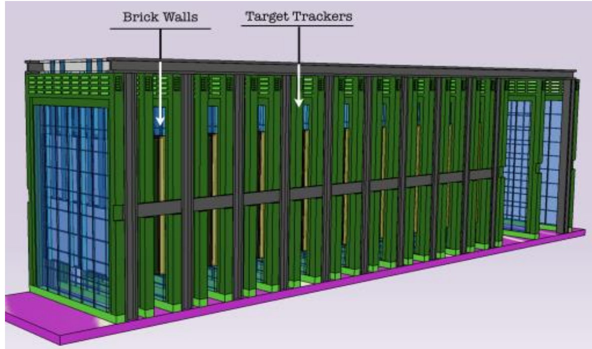
SND ECC + Target tracker

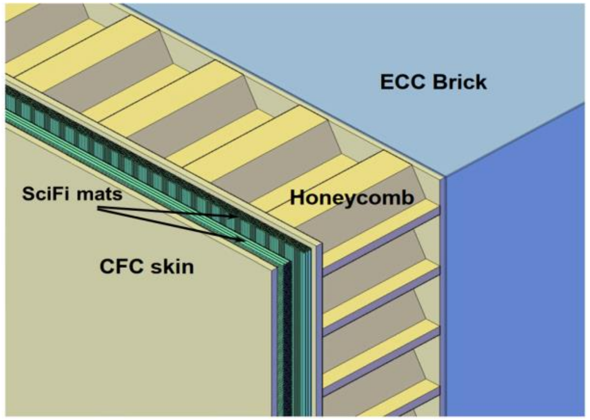
- Purpose: Neutrino/LDM vertex detector and neutrino energy with hadrons and electrons

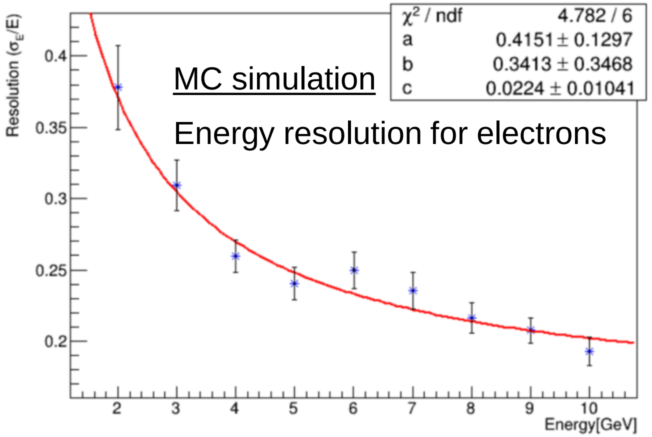
- Emulsion Cloud Chamber brick characteristics
  - Bricks of 40x40 cm^2
  - Thickness ~8 cm (57 films/lead plates → ~10 X_0)
  - Weight ~100 kg
  - Scanning speed 200 cm^2/h, 10x faster than Opera

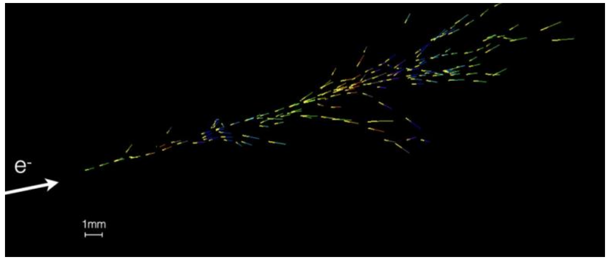
- SciFi target tracker characteristics
  - $\sigma_{x,y}$~30-50 μm resolution
  - Six scintillating fibre layers, total 3mm thickness ~ 0.05 X_0
  - Multi-channel SiPM at one end, ESR foils as mirrors on other
  - Time resolution <0.5ns
  - Extended with silicon (study in SND@HL-LHC)?

- Emulsion + TT beam test at DESY in 2019
  - Emulsion: electron identification and directionality
  - Emulsion + TT: Electron energy and time resolution



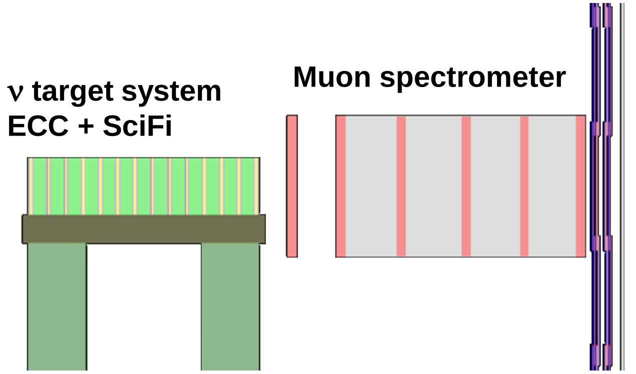


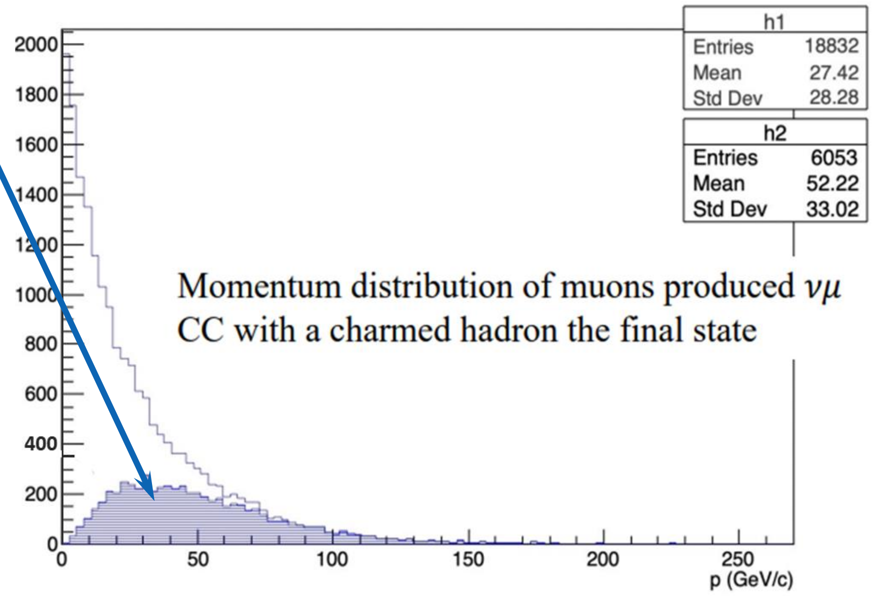




SND Muon spectrometer

- Purpose: Track and identify muons, measure charge/momenta
- Magnetised air/iron over ~3m with ~1 T
- Momentum coverage split in two/three momentum ranges
  - Position resolution of ~100 μm
  - Hidden sector acceptance is about 1/3 and correlated with high energy muons



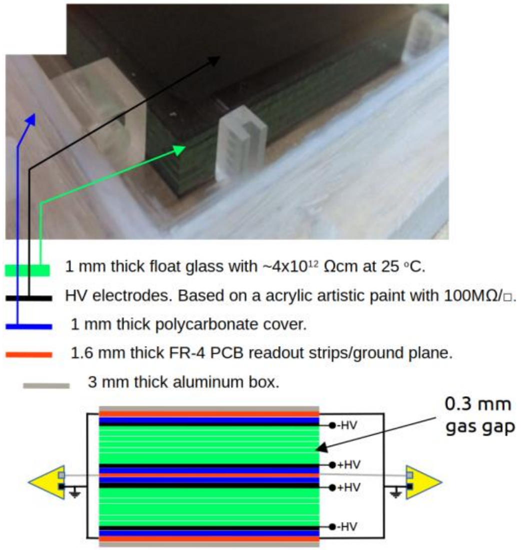


➔ Possible detector options with drift tubes or SciFi

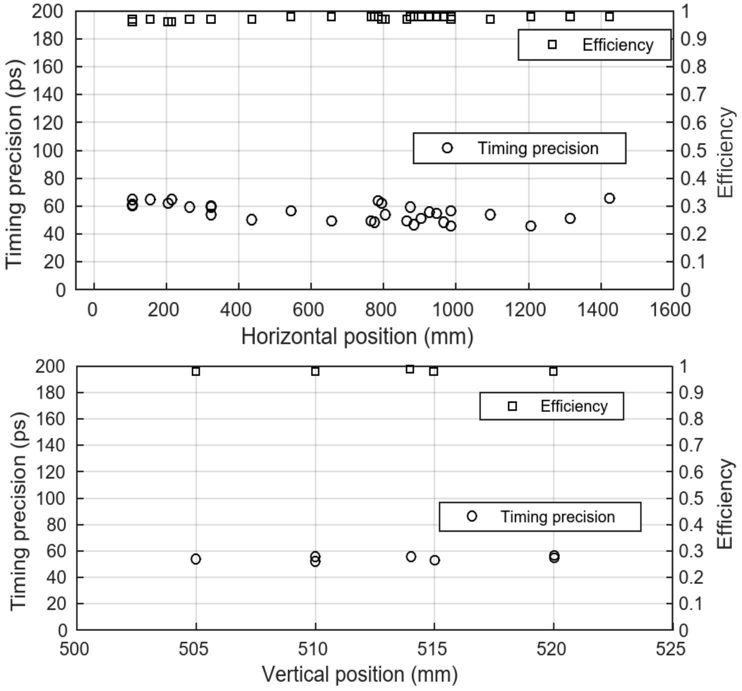
Upstream Background Tagger

- Purpose: Veto in front of decay volume
  - ➔ High efficiency, <100ps resolution, ~cm resolution

- Characteristics with 3-layer MRPC
  - 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



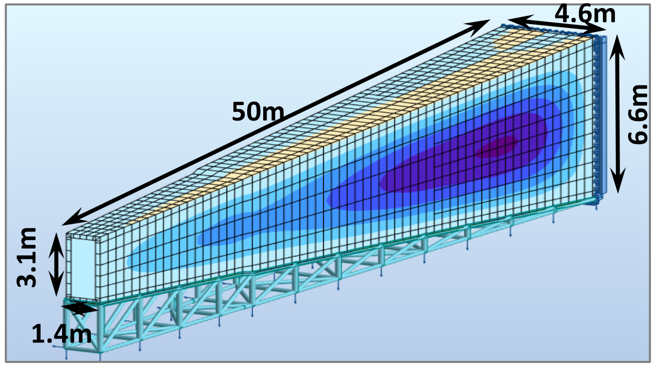
Decay volume and SBT

Per spill of $4x10^{13}$ protons

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

➔ Evacuated to ~mbar air – ~bar He

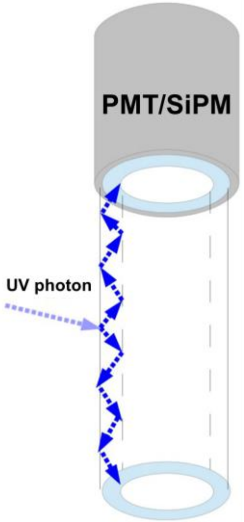
➔ Liquid scintillator veto in surrounding compartments

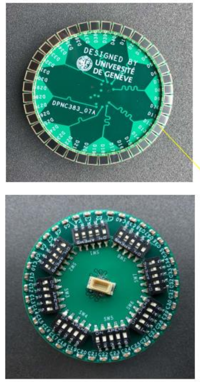


~2000 cells,
~80 x ~80 cm,
thickness ~20cm

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

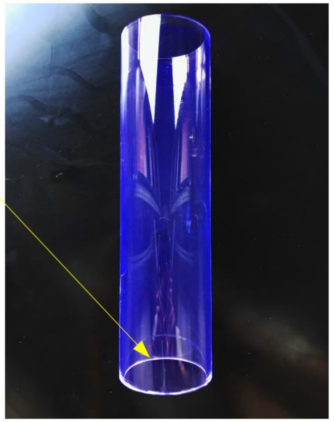
- Characteristics
  - Liquid scintillator based: linear alkylbenzene (LAB) together with 2.0 g/l diphenyl-oxazole (PPO) as the fluorescent
  - WOMs with SiPM readout Hamamatsu S14160-3050PE (40x 3x3mm²) and surrounded by PMMA vessel

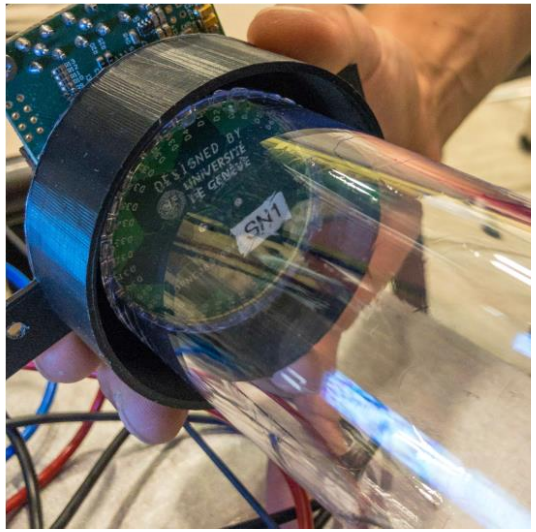


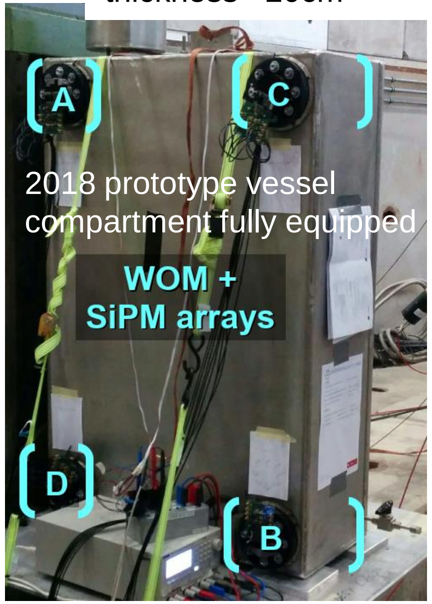


40-SiPMs array
built by Geneva

WOM w/o lightguide

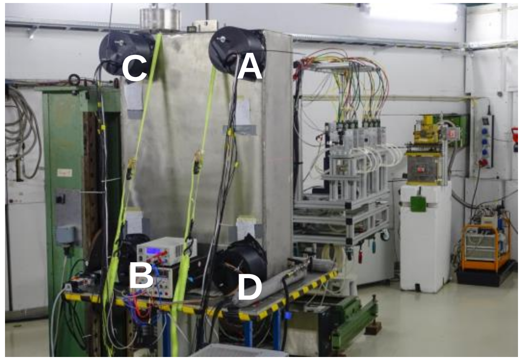


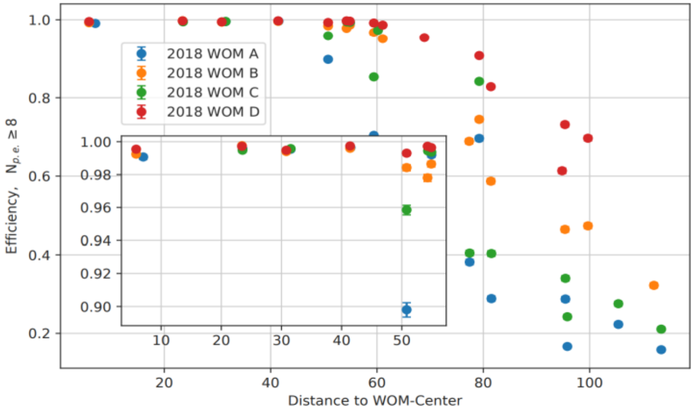


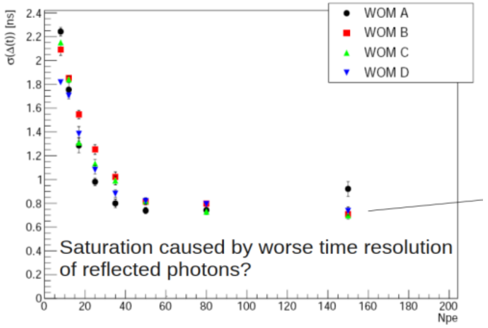


HS Surrounding Background Tagger

‘Prototype 0’: 2018 test beam results







➔ >99% efficiency (>45 MeV deposited), time resolution of 1 ns

'Prototype 1':

- 240 litre cell: Corten steel
- $BaSO_4$ reflective coating
- LHS prototype
- Improved mechanical & optical coupling
- 2 WOMs (SiPM readout)

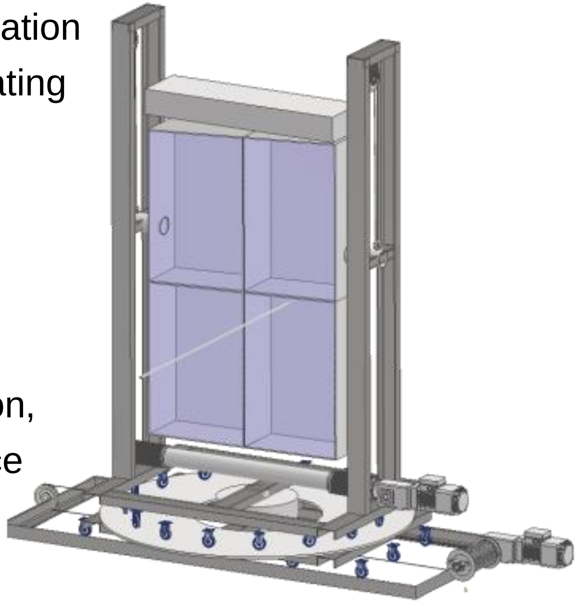
➔2022 DESY: e-

‘Module 0’ – 4-cell demonstrator

- LS handling system
- Improved mechanical integration
- Optimised cell reflective coating
- Updated readout & DAQ
- Multi-dimensional event reconstruction:

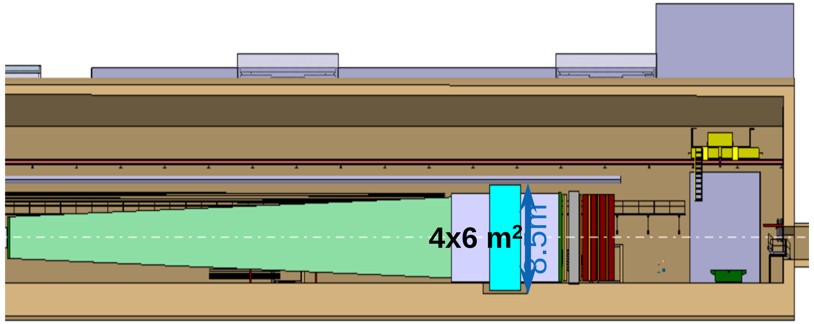
➔CERN test beam: 2023-Q4

- Light yield, energy deposition,
- spatial information, incidence angle...

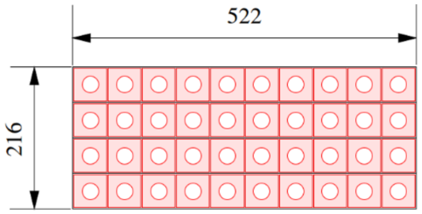


SHiP spectrometer section

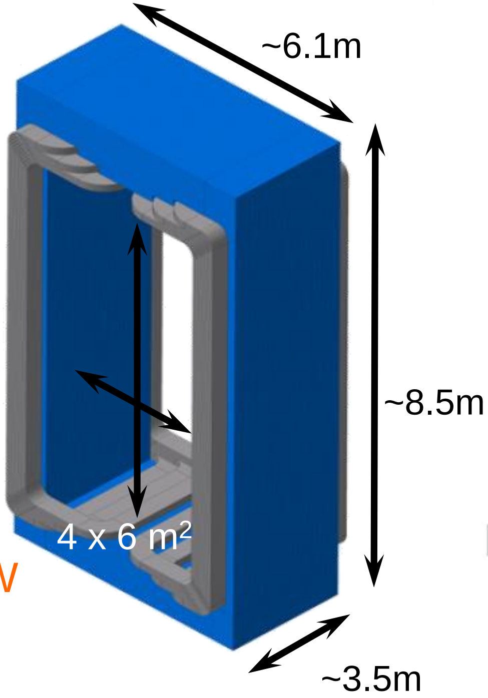
- Initial studies with aperture 5x10m^2 ➔ now 4x6m^2
  - H. Bajas, D. Tommasini, EDMS 2440157 (21 April 2020)
  - P. Wertelaers, CERN-SHiP-INT-2019-008

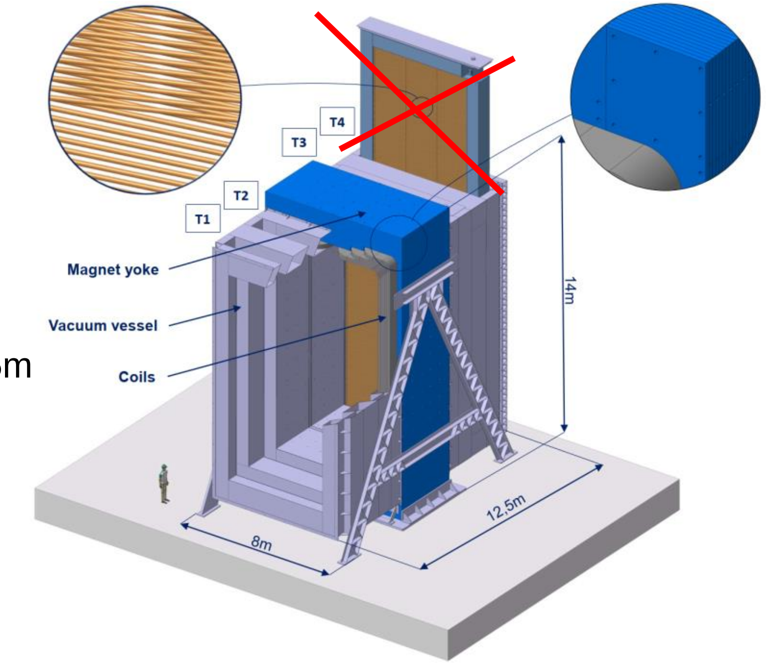


- Requirements:
  - Physics aperture 4 x 6 m^2
  - Bending field 0.6-0.7 Tm , nominal on axis ~0.15T
  - Integration of vacuum chamber



Coil's cross-section
Aluminium hollow conductor



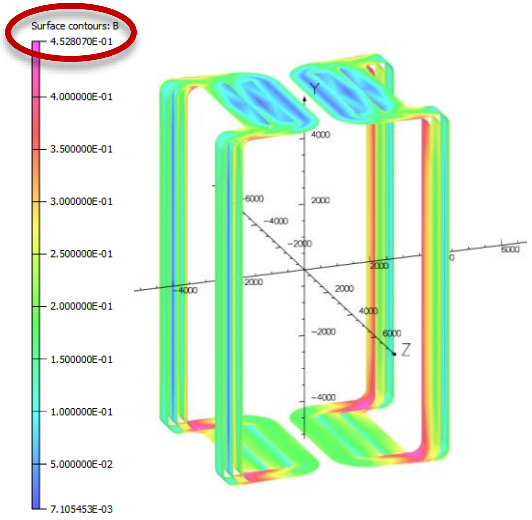


- Resistive baseline option 0.5 MW

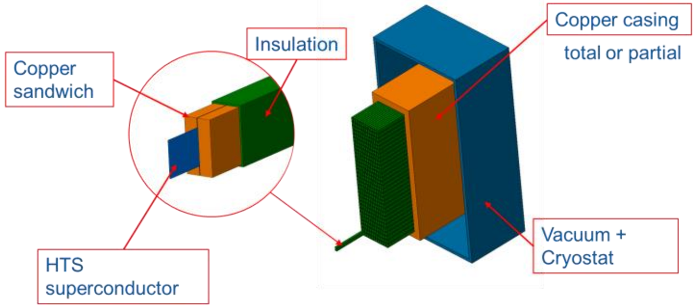
- What about superconductive with coil of same dimensions?

"Super-copper"

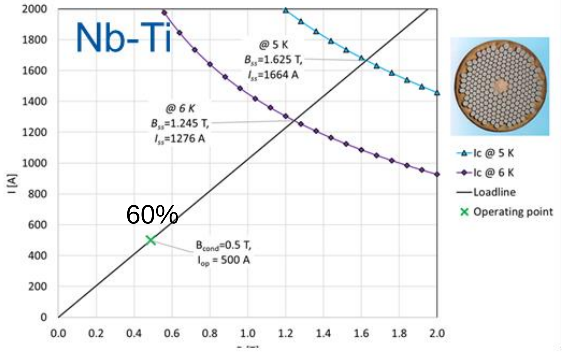
- H. Bajas, D. Tommasini, EDMS 2440157 (21 April 2020) - study of NbTi or Nb3Sn or MgB2 or ReBCO

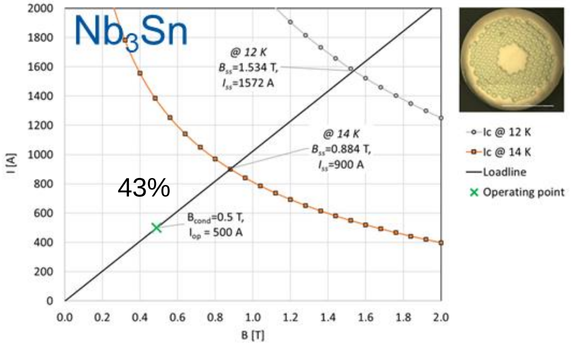


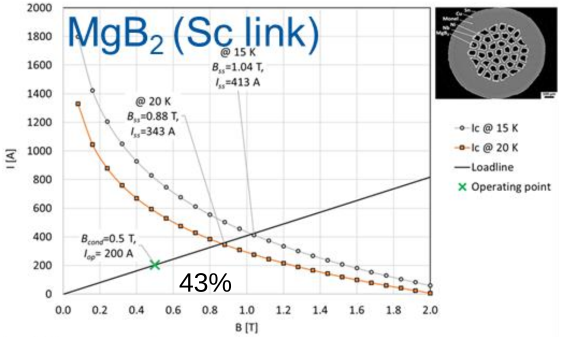
B_{peak} of 0.5 T ➔ NI_{tot} = 360 kA.turn

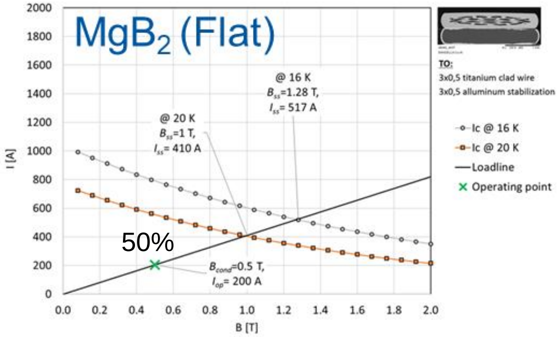


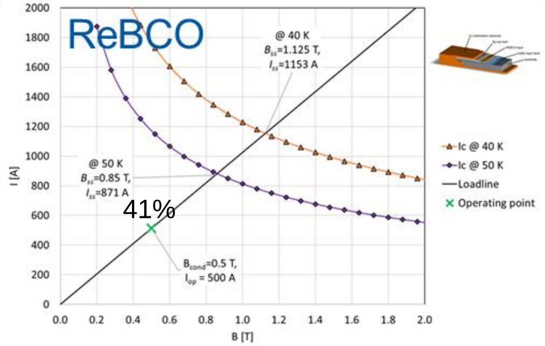
Courtesy Philip Schwarz, April 2019







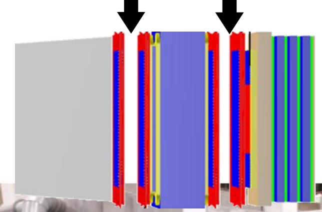


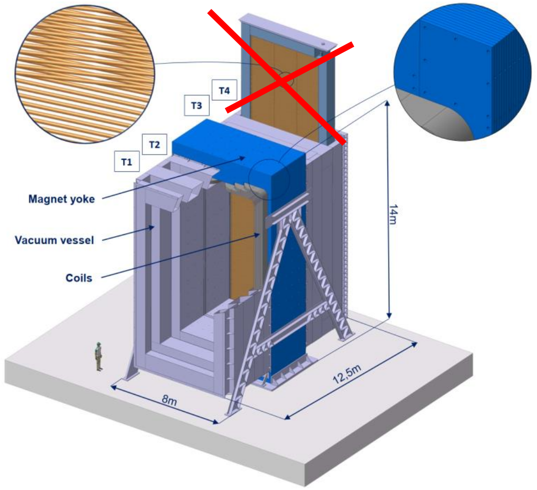


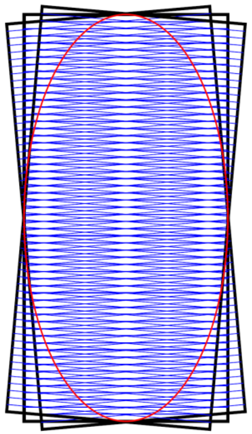
- Existing and future spectrometer magnets with large apertures will be required for many years to come!

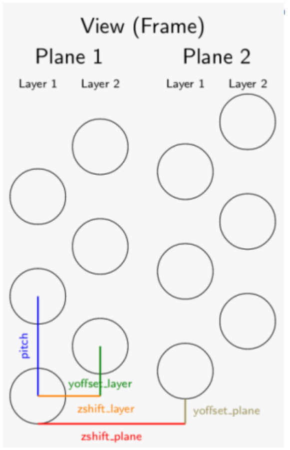
HS Straw Tracker

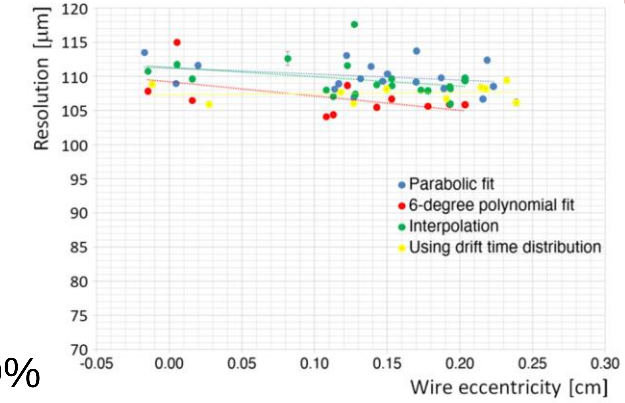
- Purpose: Track reconstruction and momentum, reconstruction of origin of neutral particle candidate. Match hits in timing detector
- Technology developed for the NA62 experiment
  - ➔ SHiP strategy: decoupling supporting frames from vacuum envelope
  - ➔ Horizontal orientation of tubes ➔ mechanical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





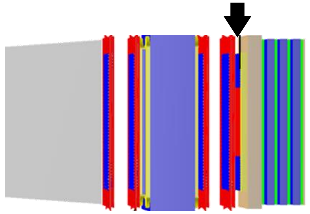




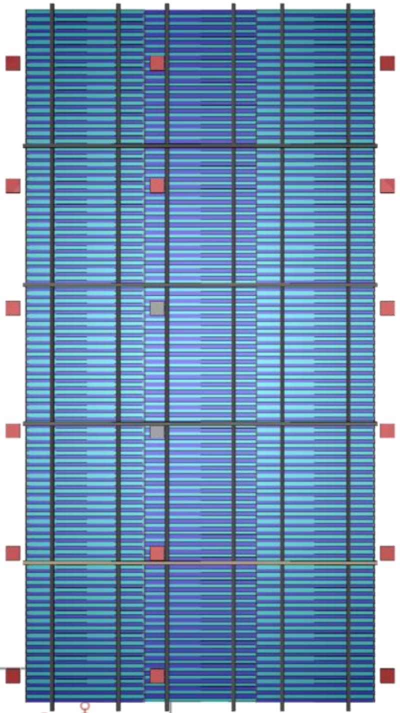


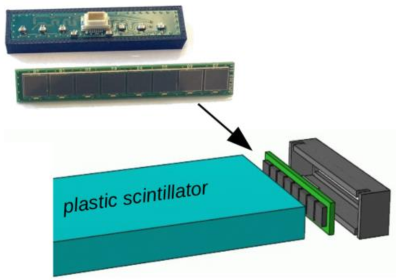
Test beams confirm 120μm hit resolution with hit efficiency >99%

HS Timing Detector

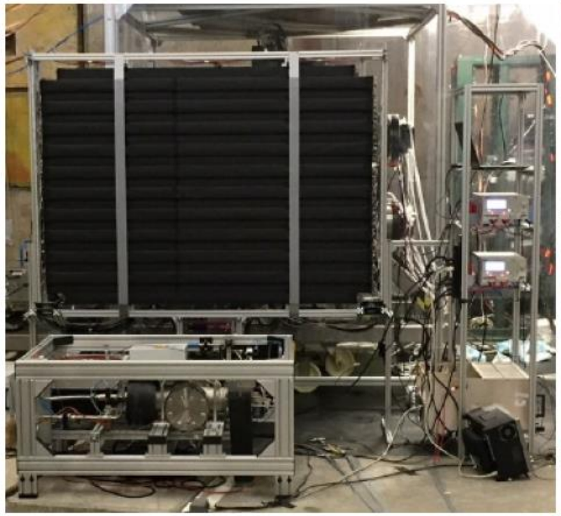


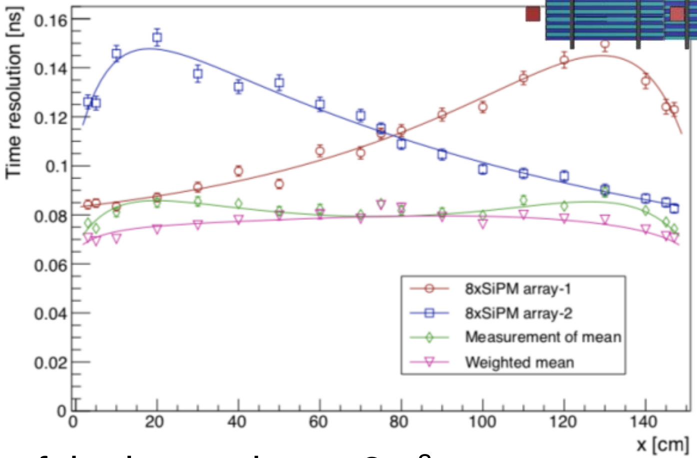
- Purpose: Provide precise timing (<100 ps) of each track to reject combinatorial background
- Plastic scintillator characteristics
  - Three-column setup with EJ200 plastic bars of 135cm × 6cm × 1cm, providing 0.5cm overlap
  - Readout on both ends by array of eight 6×6 mm^2 SiPMs, 8 signals are summed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





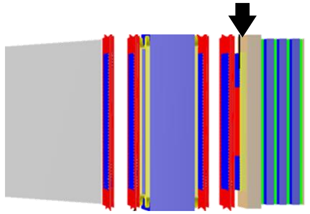
22x 168cm bar (44 channels) prototype tested at PS





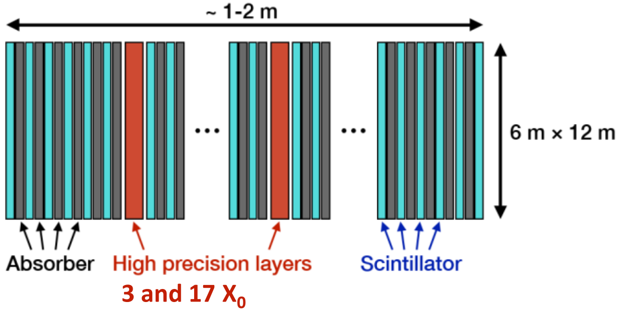
Resolution demonstrated to be ~80 ps along the whole length of the bar and over 2m^2 prototype

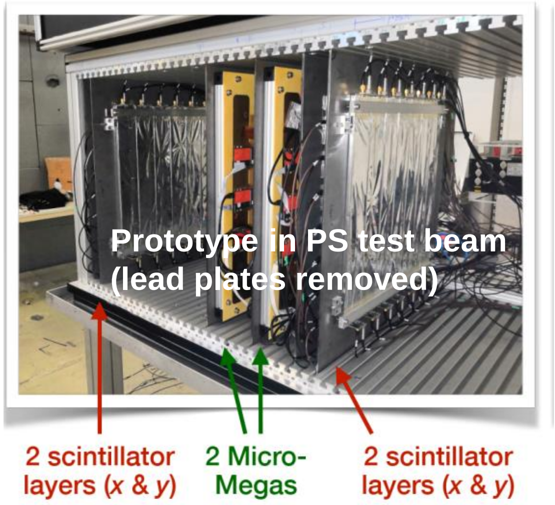
HS ECAL (“SplitCal”)

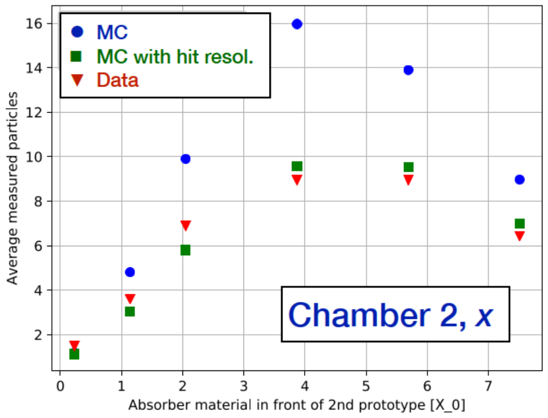


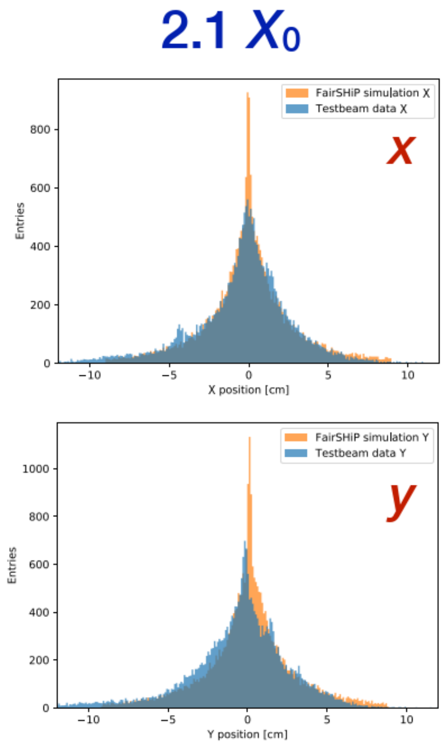
- Purpose: e/γ identification, π^0 reconstruction, photon directionality ~5mrad for ALP$\rightarrow \gamma\gamma$ (coincidence timing)
- Characteristics
  - 25 X_0 longitudinally segmented calorimeter with coarse and fine space resolution active layers
  - Coarse layers: 40-50 planes of scintillating bar readout by WLS + SiPM (0.28cm / 0.5X_0 lead + 0.56 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





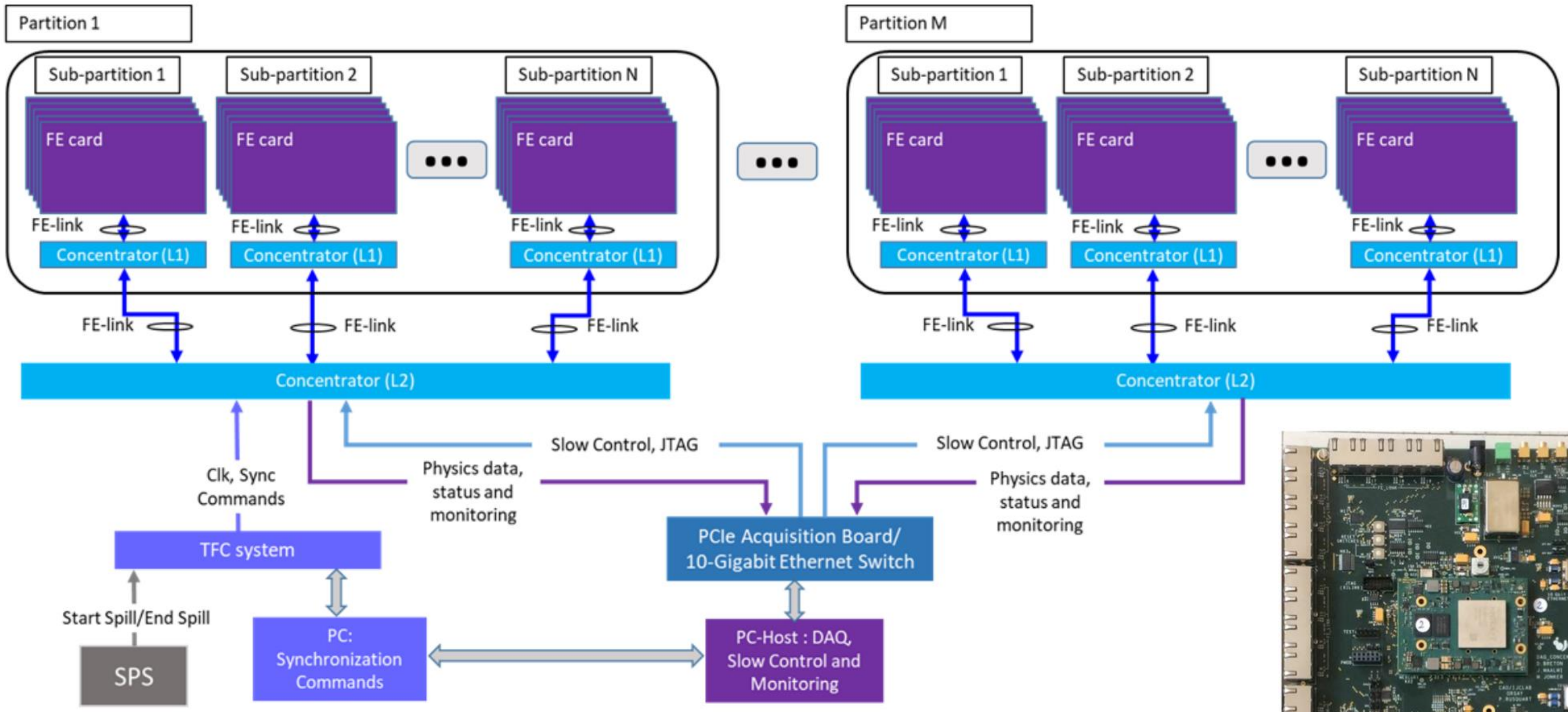




Reconstruction challenge: satellite showers in the long transverse tails

Electronics and readout

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



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