SHiP
Search for Hidden Particles

Overview of BDF/SHiP at the SPS ECN3 beam facility

R. Jacobsson

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

Principal review documents:

- ***Proposal, BDF/SHiP at the ECN3 high-intensity beam facility, to be submitted Oct. 2023***
- ***Letter of Intent, BDF/SHiP at the ECN3 high-intensity beam facility, CERN-SPSC-2022-032***
- ***Study of alternative locations for the SPS Beam Dump Facility, CERN-SPSC-2022-009***
- ***SHiP Experiment - Comprehensive Design Study, CERN-SPSC-2019-049***
- ***SPS Beam Dump Facility - Comprehensive Design Study, (2019), arXiv:1912.06356***
- ***The SHiP Physics Case, Rep. Prog. Phys. 79 (2016)124201***

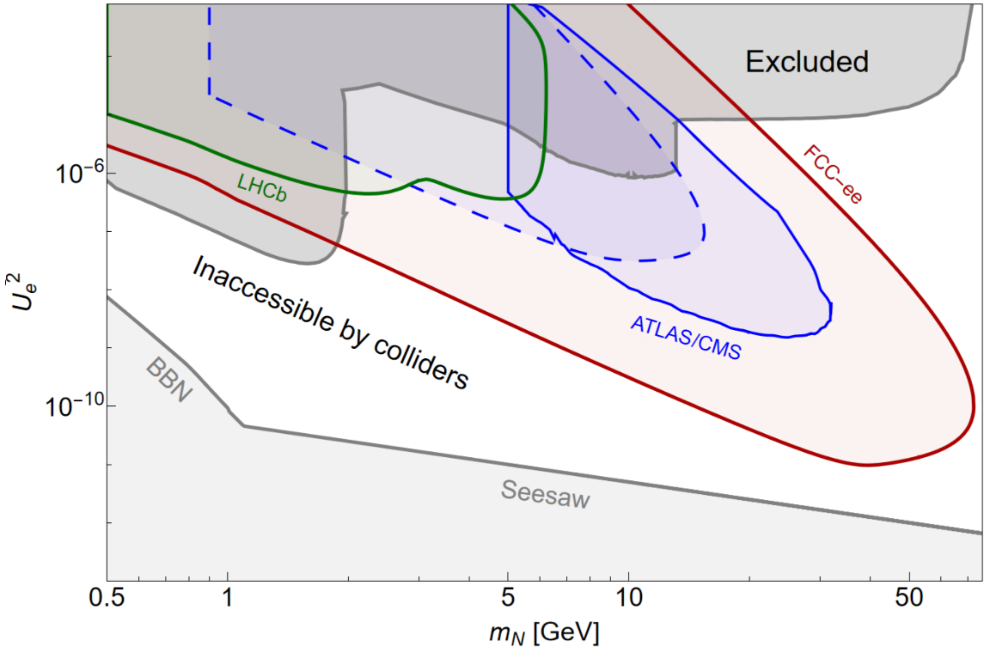
BDF/SHiP strategy

- Initiative to
  - return SPS to full exploitation of unique physics potential made available with termination of CNGS
  - Identify rich and relevant physics programme, going beyond LHC, bridging gap to next collider

  ➔ Documented in “SHiP Physics Proposal” compiled and signed by a collaboration of 80 theorists: *Rep. Prog. Phys.* **79** (2016)124201

➔ SPS suitability to explore *Light Dark Matter and associated mediators, and ν mass generation* – FIPs generically

E.g. Heavy Neutral Leptons



➔ Region that can *only* be explored by optimised beam-dump experiment

➔ Production modes in limited forward cone – large lifetime acceptance

➔ SPS energy and intensity provide huge production of charm, beauty and electromagnetic processes

➔ Unique *direct discovery potential in the world in the heavy flavour region,* capable of reaching “physical/technical floor”

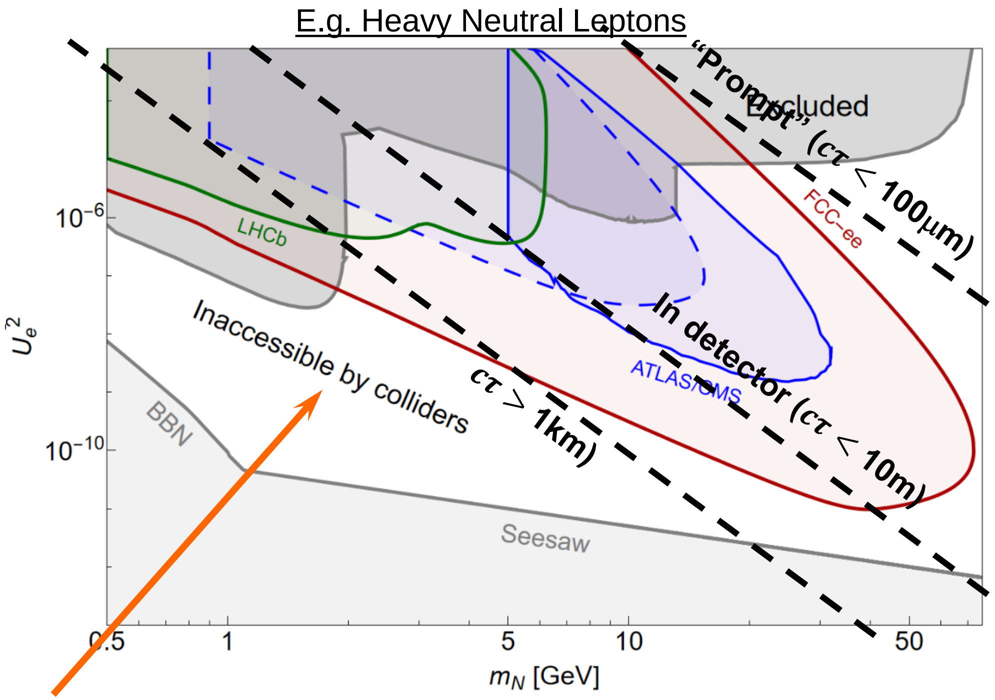
BDF/SHiP strategy

- Initiative to
  - return SPS to full exploitation of unique physics potential made available with termination of CNGS
  - identify rich and relevant physics programme, going beyond LHC, bridging gap to next collider

  ➔ Documented in “SHiP Physics Proposal” compiled and signed by a collaboration of 80 theorists: *Rep. Prog. Phys.* **79** (2016)124201

➔ SPS suitability to explore *Light Dark Matter and associated mediators, and ν mass generation* – FIPs generically

E.g. Heavy Neutral Leptons



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

for all types of FIPs

➔ Region that can *only* be explored by optimised beam-dump experiment

➔ Production modes in limited forward cone – large lifetime acceptance

➔ SPS energy and intensity provide huge production of charm, beauty and electromagnetic processes

➔ Unique *direct discovery potential in the world in the heavy flavour region,* capable of reaching “physical/technical floor”

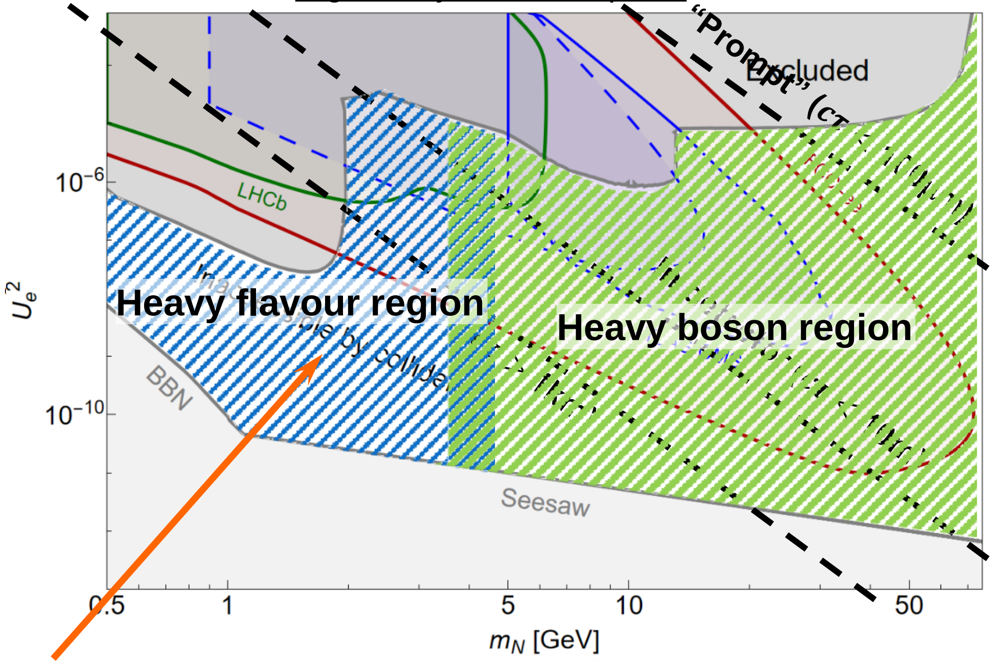
BDF/SHiP strategy

- Initiative to
  - return SPS to full exploitation of unique physics potential made available with termination of CNGS
  - identify rich and relevant physics programme, going beyond LHC, bridging gap to next collider

    ➔ Documented in "SHiP Physics Proposal" compiled and signed by a collaboration of 80 theorists: *Rep. Prog. Phys.* **79** (2016)124201

  ➔ SPS suitability to explore *Light Dark Matter and associated mediators, and ν mass generation* – FIPs generically

E.g. Heavy Neutral Leptons



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

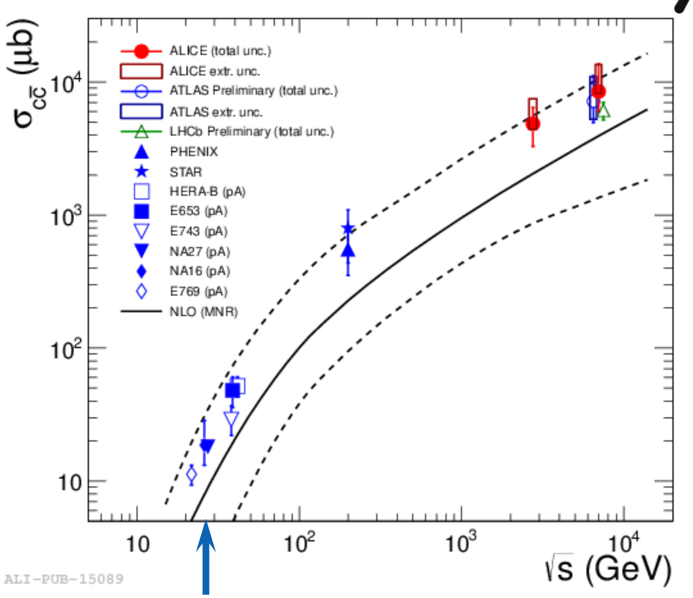
for all types of FIPs

➔ Region that can *only* be explored by optimised beam-dump experiment

- ➔ Production modes in limited forward cone – large lifetime acceptance
- ➔ SPS energy and intensity provide huge production of charm, beauty and electromagnetic processes
- ➔ Unique *direct discovery potential in the world in the heavy flavour region,* capable of reaching "physical/technical floor"

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 4x10^{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/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

σ(pp→ssbar X)/σ(pp→X) ~ 0.15
σ(pp→ccbar X)/σ(pp→X) ~ 2x10^{-3}
σ(pp→bbbar X)/σ(pp→X) ~ 1.6 x10^{-7}
Cascade effect, e.g. >2 for charm

- Large number of neutrinos *detected* with 3t-W ν-target:

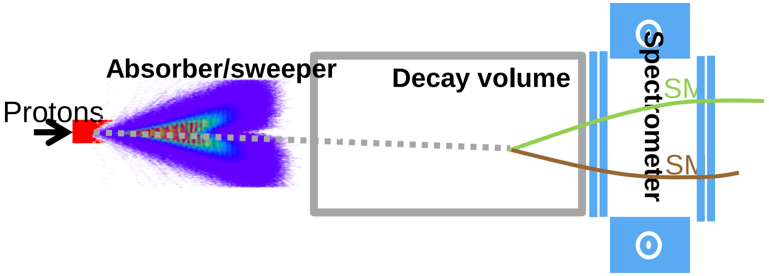
  $3500\ \nu_\tau + \bar{\nu}_\tau$ *per year*, and 2×10^5 $\nu_e + \bar{\nu}_e$ / 7×10^5 $\nu_\mu + \bar{\nu}_\mu$ despite target design

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

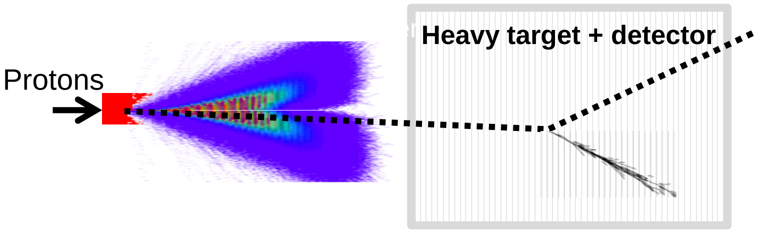
BDF/SHiP experimental techniques

➔ 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

- Acceptance optimisation of both techniques described in arXiv:2304.02511, accepted by EPJ

- Designed for exhaustive search by aiming at model-independent detector setup
  - Full reconstruction and identification of as many final states as possible of both fully and partially reconstructible modes
    ➔Sensitivity to partially reconstructed modes also proxy for the unknown
  - **In case of discovery ➔ precise measurements to discriminate between models / test compatibility with hypothetical signal**

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

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

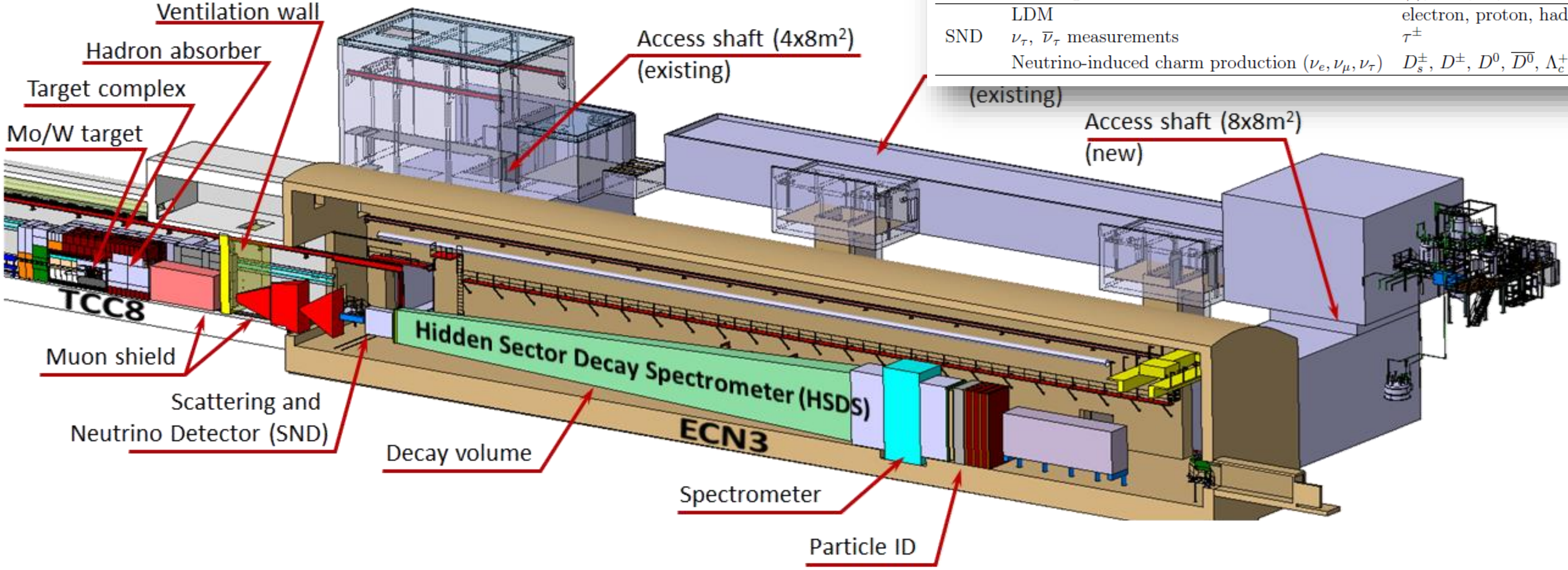
BDF/SHiP in ECN3 proposal

➔ TCC8/ECN3 ideal location in all aspects

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^+, $\overline{\Lambda_c}^-$



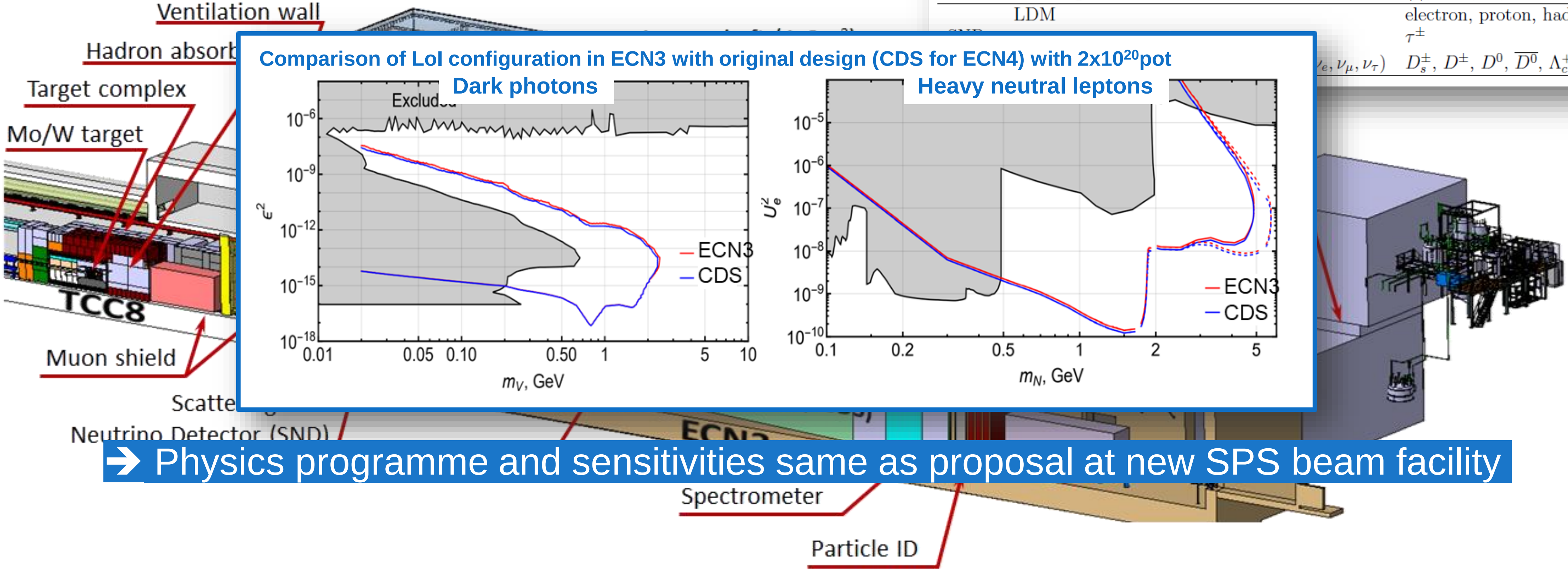
BDF/SHiP in ECN3 proposal

➔ TCC8/ECN3 ideal location in all aspects

Two separate detector systems: "SND" and "HSDS"

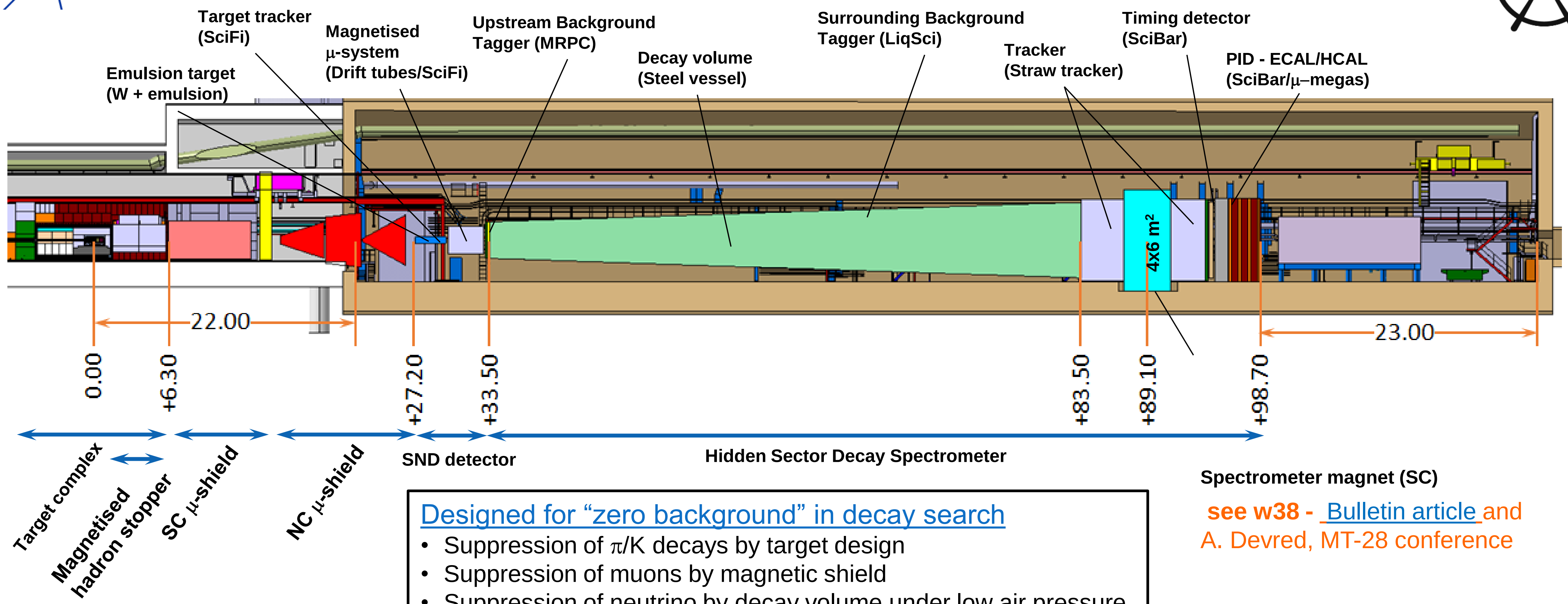
Examples of primary final states:

	Physics model	Final state
	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)	$\ell^+\ell^-, 3\pi, \eta\pi\pi, q\bar{q}$
HSDS	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	$\gamma\gamma, \ell^+\ell^-, 2\pi, 2K$
	LDM	electron, proton, hadronic shower
		$\tau^\pm$
	…ν_e, ν_μ, ν_τ)	$D_s^\pm$, $D^\pm$, D^0, $\overline{D^0}$, Λ_c^+, $\overline{\Lambda_c}^-$



➔ Physics programme and sensitivities same as proposal at new SPS beam facility

SHiP detector in more detail



see w38 - Bulletin article and A. Devred, MT-28 conference

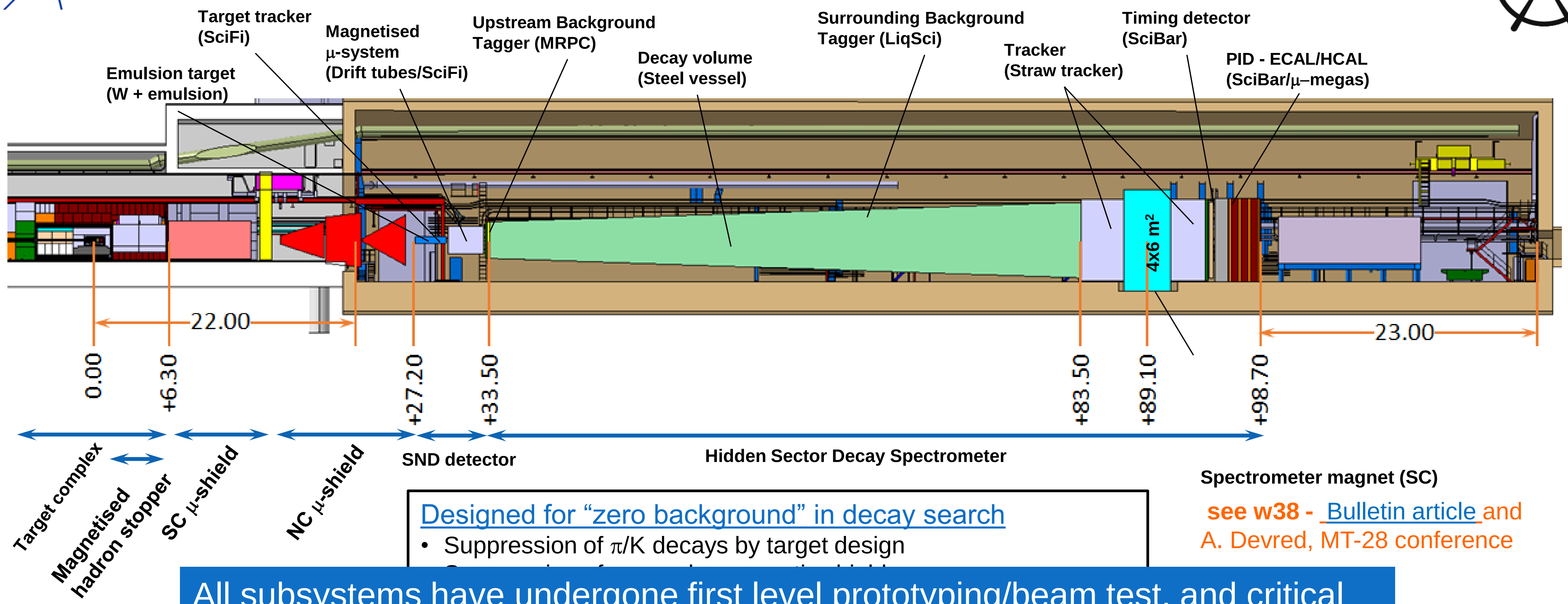
Designed for "zero background" in decay search

- 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

- Spare slides with details on subdetector systems
- SHiP detector seminar October 13

SHiP detector in more detail



see w38 - Bulletin article and A. Devred, MT-28 conference

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

details on subdetector systems
- SHiP detector seminar October 13

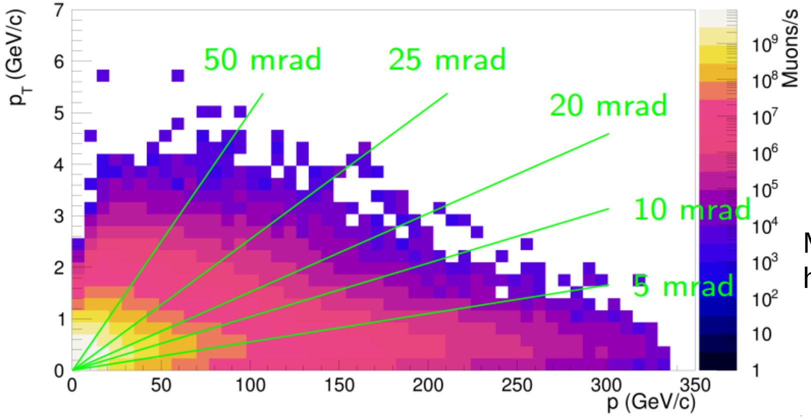
Background evaluation

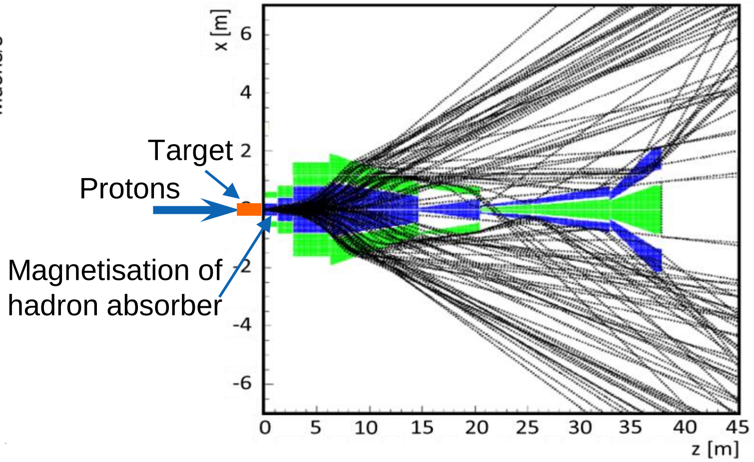
Background and detector optimisation studied with complete experimental setup implemented in GEANT (FairShip)

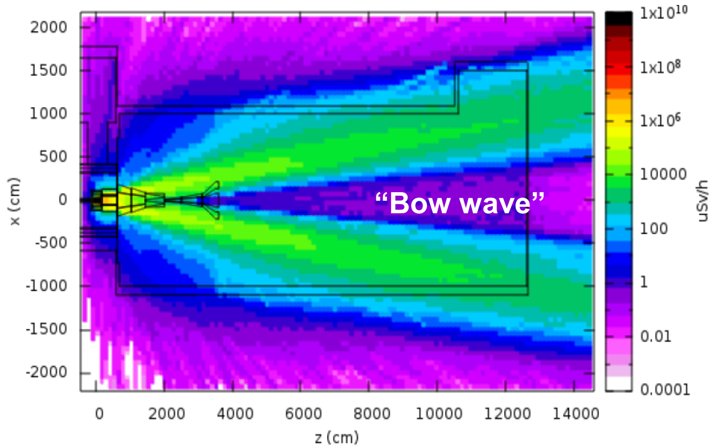
- Pythia6/GENIE used to generate muon/neutrino DIS events in material
  ➔ Boost statistics by forcing each muon and neutrino to interact according to the material distribution
- Simulation tuned with detector performance parameters measured in test beam on prototype
- Muon spectrum validated with actual measurements at SPS with BDF/SHiP prototype target - agreement within 30%

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

⦿ Critical muon shield optimised for muon spectrum (illustrations of principle from earlier studies)







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

Muon shield in ECN3

- Option 1: Robust option with purely normal conducting (NC) magnets
  - Total length ~25m : Acceptable rate of muons of ~70 kHz in the main tracker

- Option 2: Hybrid superconducting (SC) / NC configuration
  - Optimisation converges at 18 – 21m length

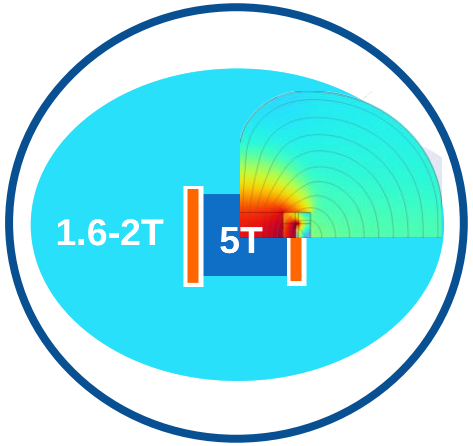
➔ Conservative starting parameters for SC magnet:

- Core aperture in range 0.5 x 0.5 – 1.0 x 1.0 m^2
- Iron/air core field 5T over 4 – 8m with NbTi @ 4.5K or HTS (~50 A/mm^2)
- Low beam-related heating (muons) - Fluka

➔ Challenge in assembly

➔ Al-stabilized co-extrusion production line must be re-established for NbTi option

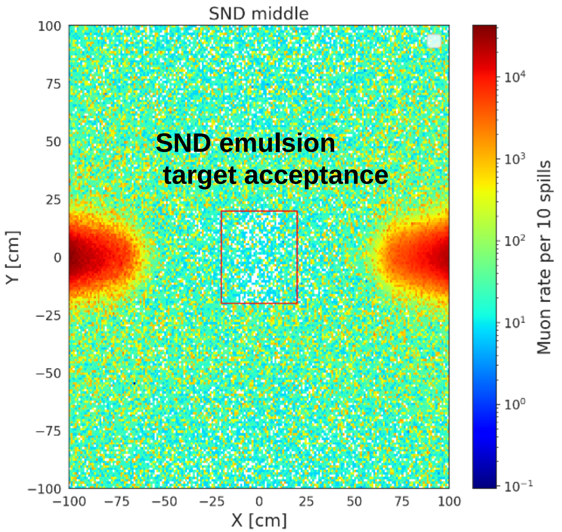
➔ **"Generous" requirements make magnet attractive and realistic as test bench for HTS (T. Arndt, KIT)**

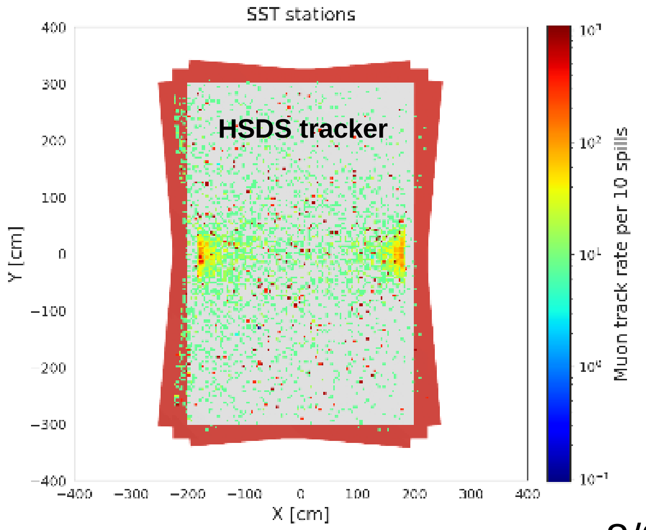


➔ Low rates of residual muons

- ~10 kHz in the HSDS tracker with hybrid option

- Both options provide acceptable rate in SND at O(Hz/cm^2)

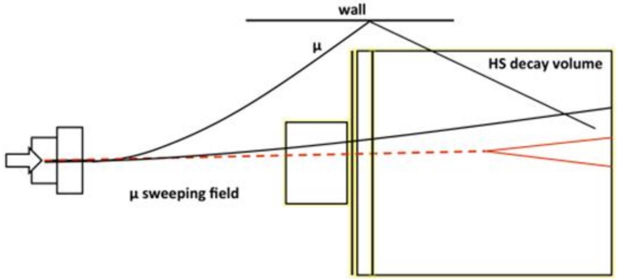




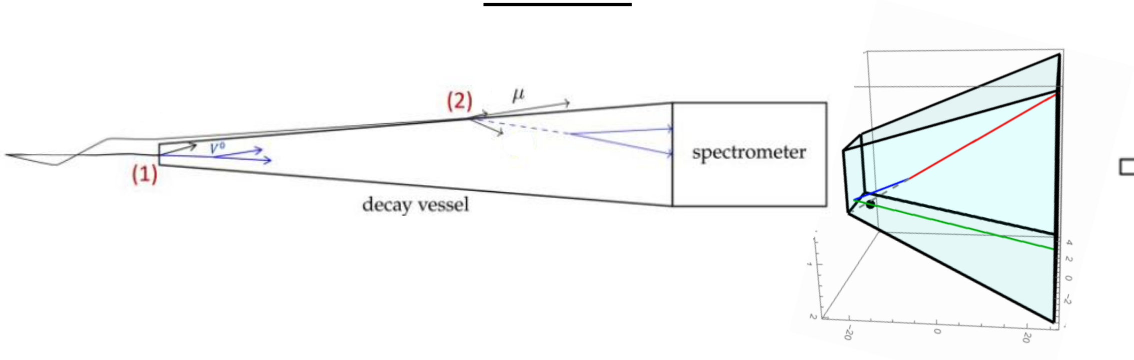
HSDS: FIP decay search background evaluation

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

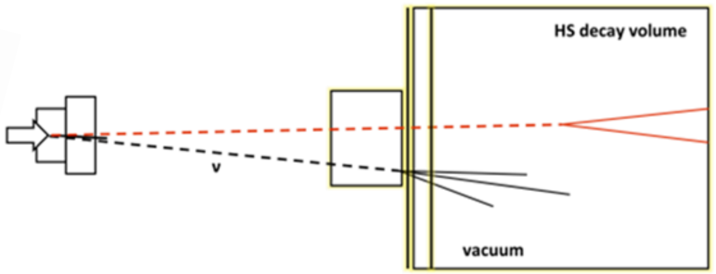
Muon combinatorial



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)	$< 250\,\mathrm{cm}$

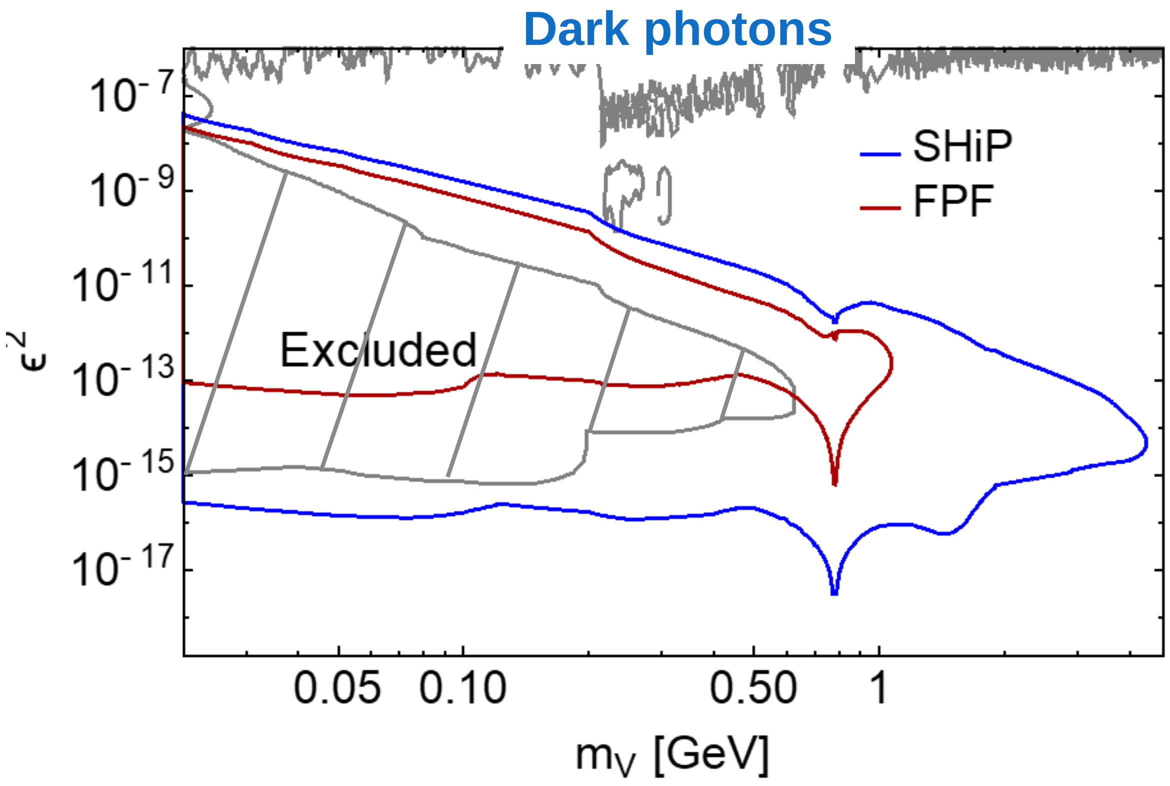
+ Time coincidence + UBT/SBT

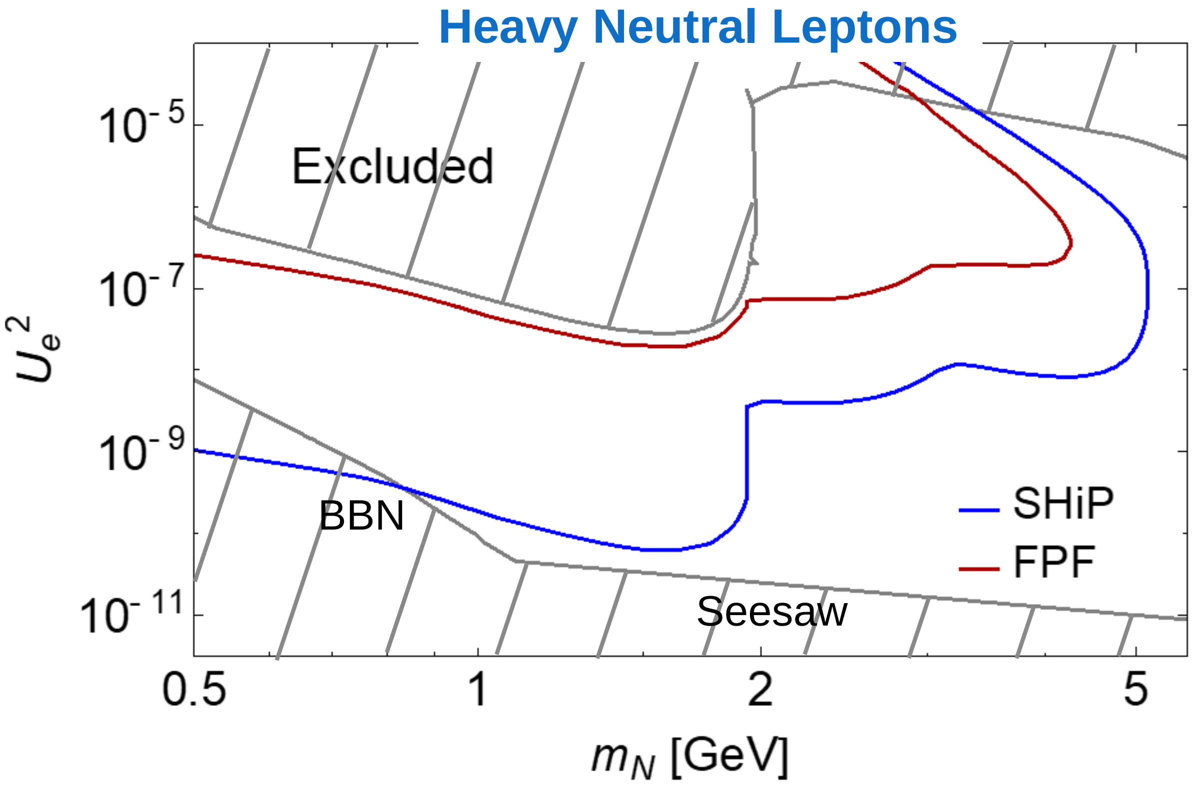
Expected background is <1 event for 6×10^{20} pot (15 years of operation)

Background source	Expected events
Neutrino DIS	< 0.1 (fully)/$<$ 0.3(partially)
Muon DIS (factorisation)*	$< 5\times10^{-3}$ (fully) / $<$ 0.2(partially)
Muon combinatorial	$(1.3 \pm 2.1)\times10^{-4}$

HSDS: FIP decay search performance

➔ SHiP sensitivity is not limited by backgrounds in 6 x 10^{20} PoT

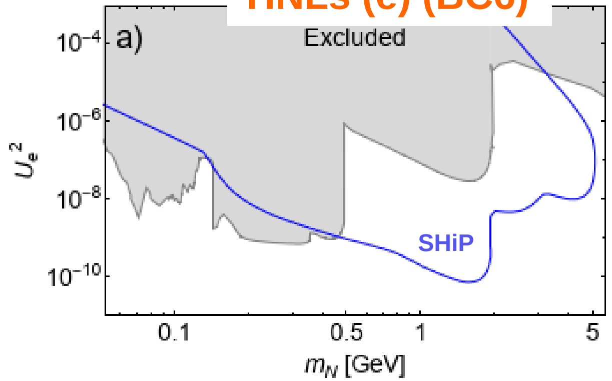




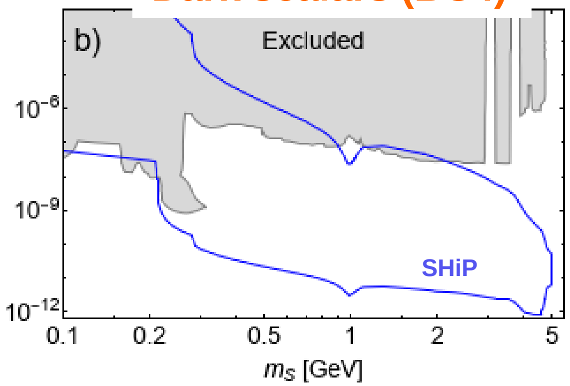
SHiP sensitivities to FIPs are orders of magnitude better than competing projects, including Forward Physics Facility

HSDS: FIP decay search performance, all benchmarks

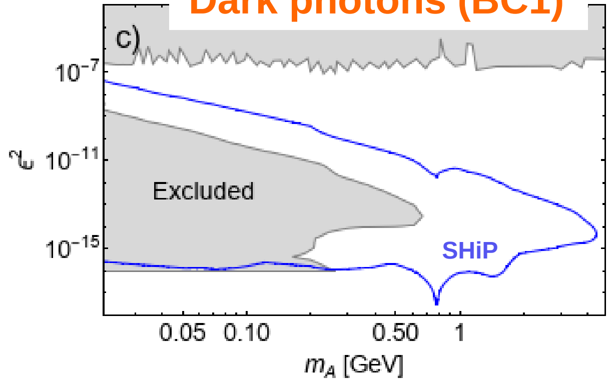
HNLs (e) (BC6)



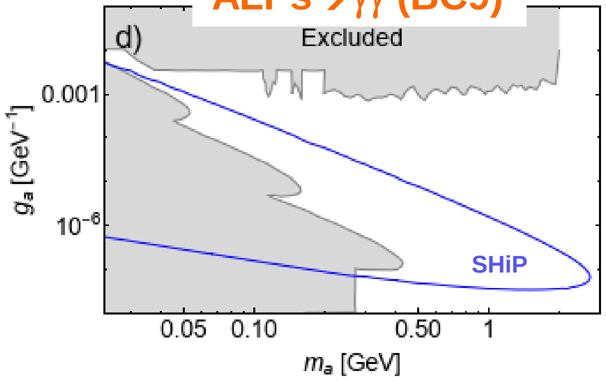
Dark scalars (BC4)



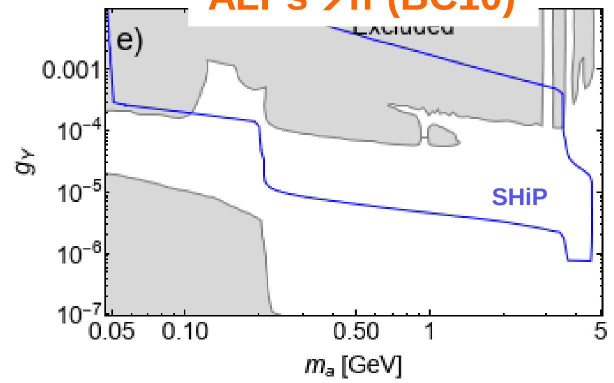
Dark photons (BC1)



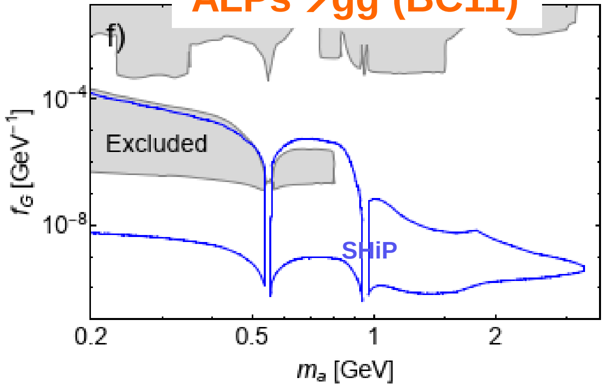
ALPs→γγ (BC9)



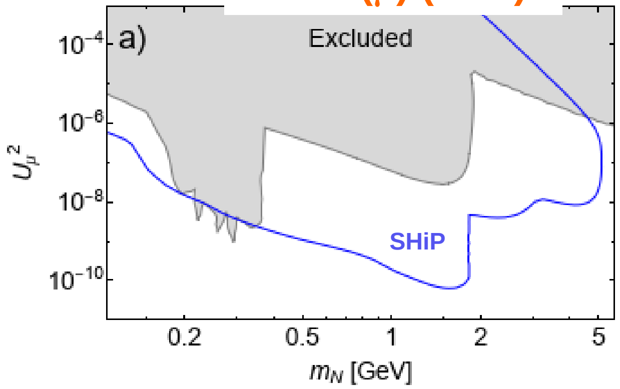
ALPs→ff (BC10)



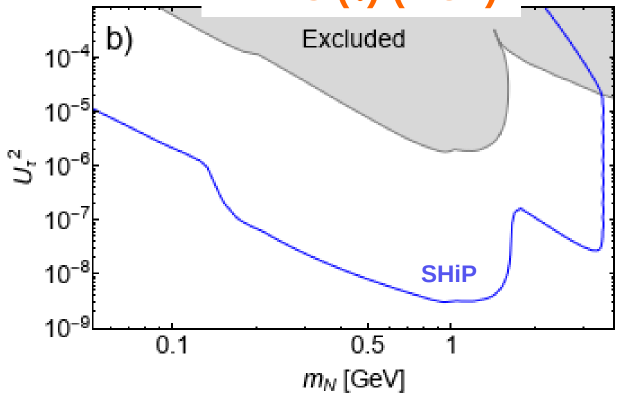
ALPs→gg (BC11)



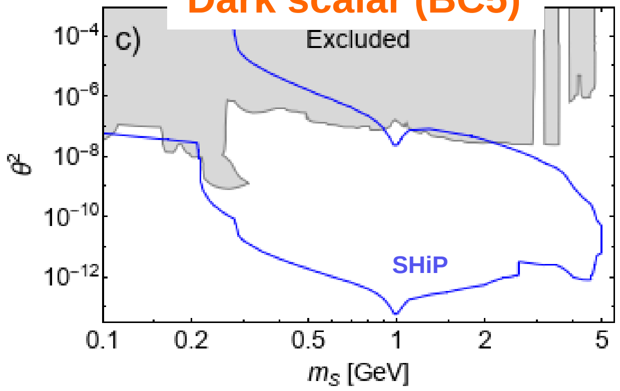
HNLs (μ) (BC7)



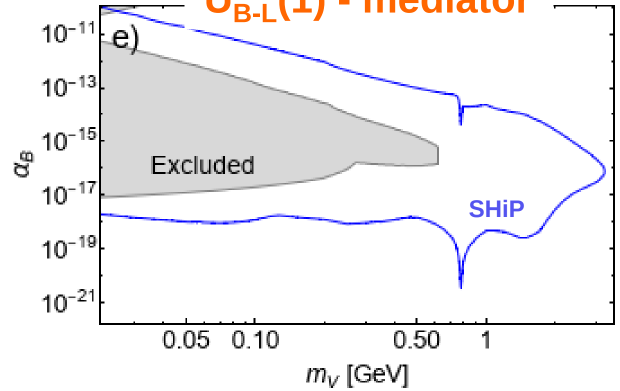
HNLs (τ) (BC7)



Dark scalar (BC5)

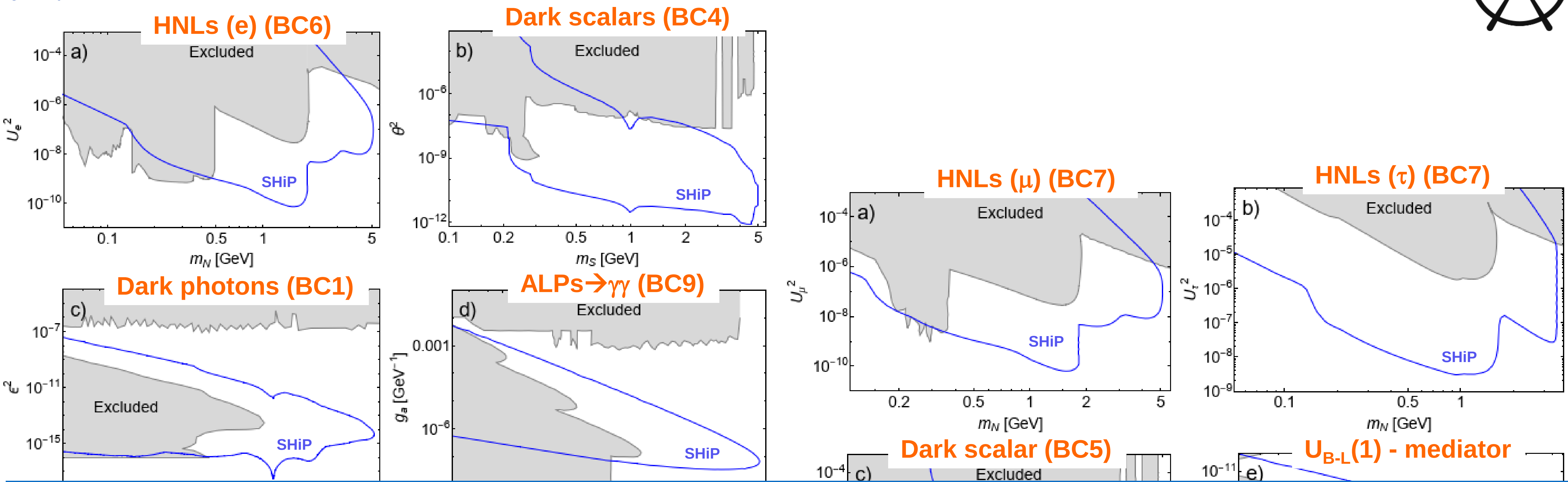


$U_{B-L}(1)$ - mediator

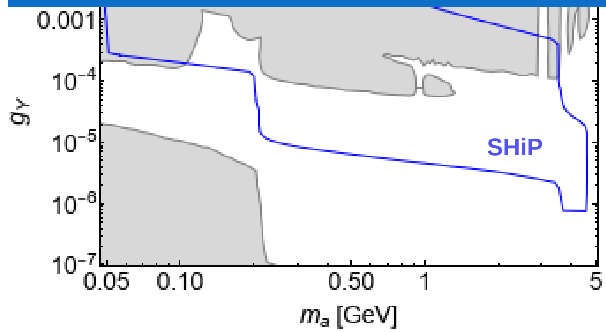


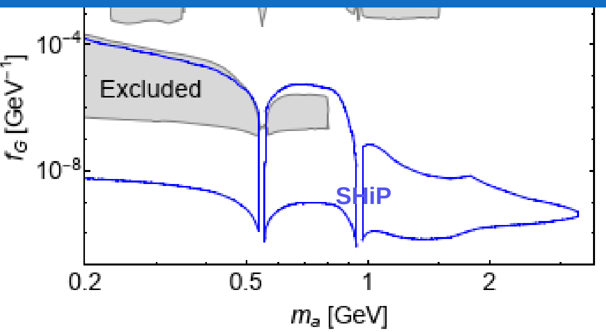
+ also SUSY-related benchmarks

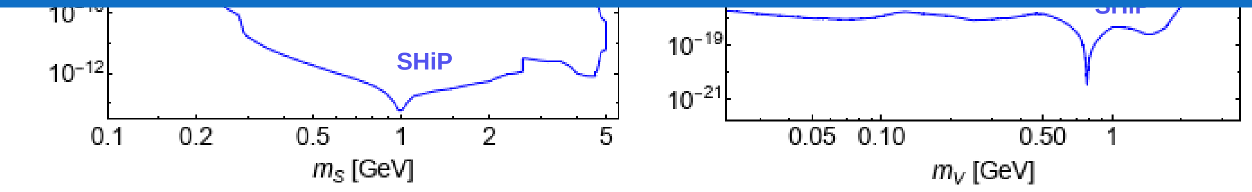
HSDS: FIP decay search performance, all benchmarks



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



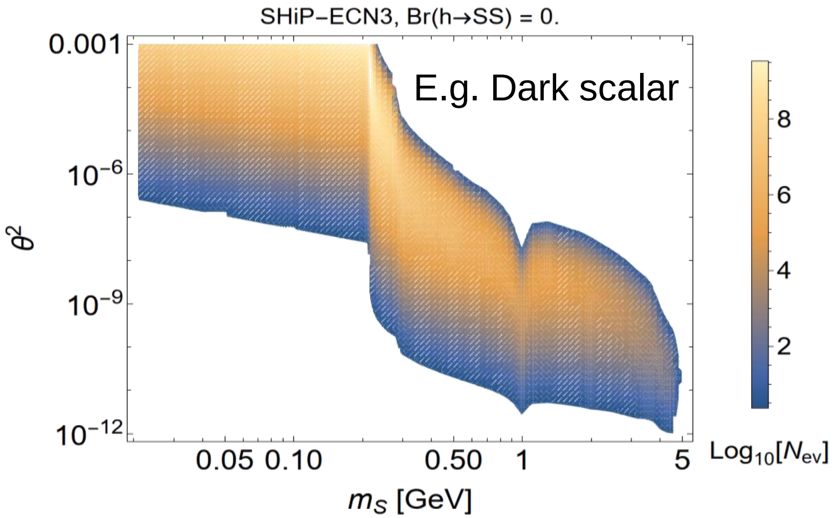




+ also SUSY-related benchmarks

Physics sensitivities – FIPs cont'd

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

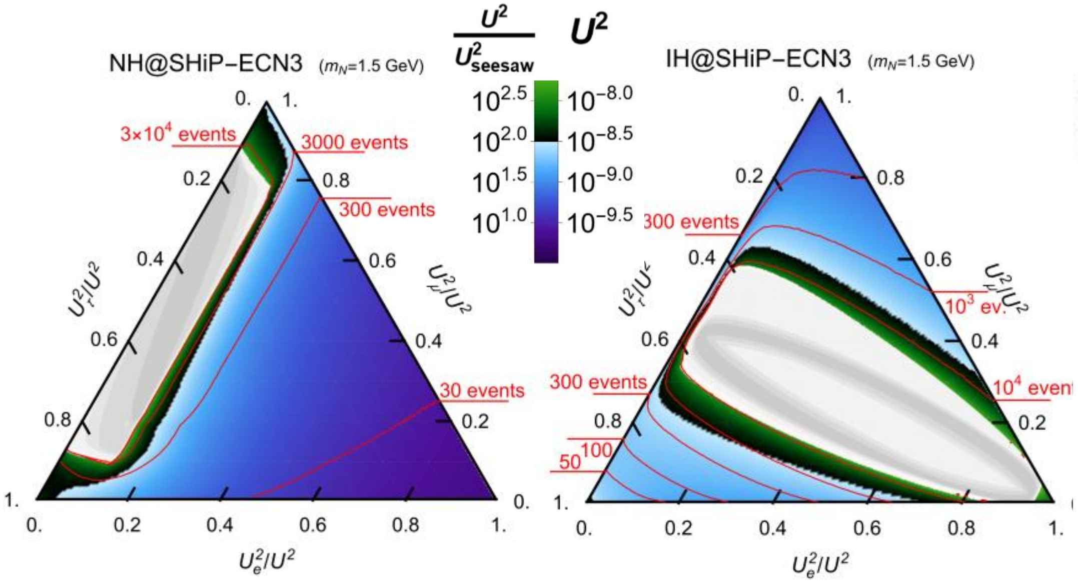


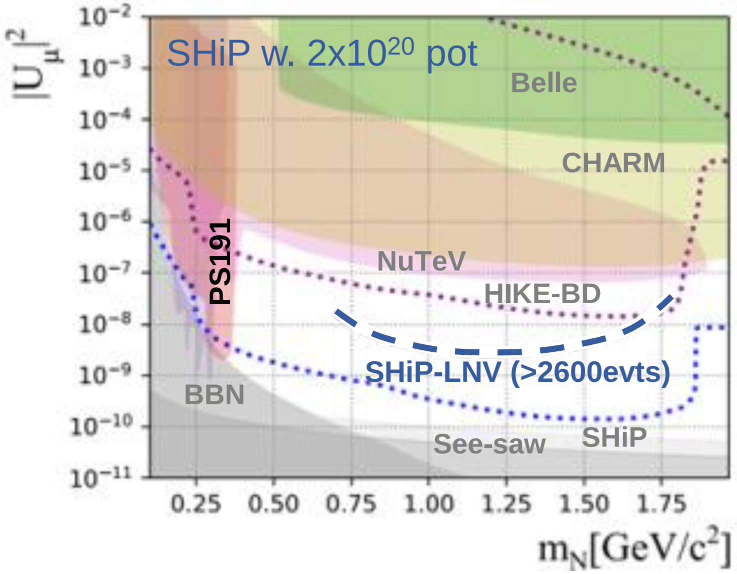
- Step 1: Characterise new object - precise mass, branching ratios, spin: $\mathcal{O}(10)$ evts

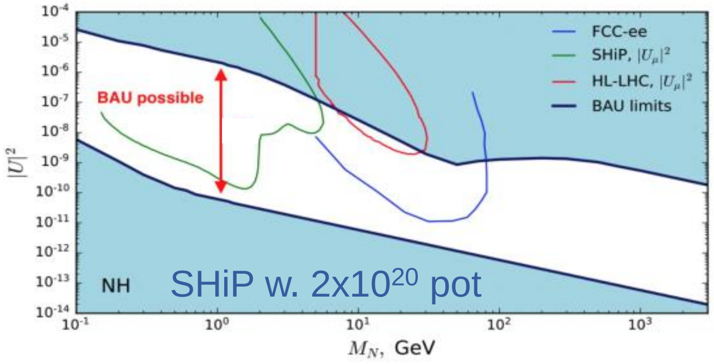
- Step 2: Test compatibility with hypothesis addressing SM issues: $\mathcal{O}(100 - 1000)$ evts

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*

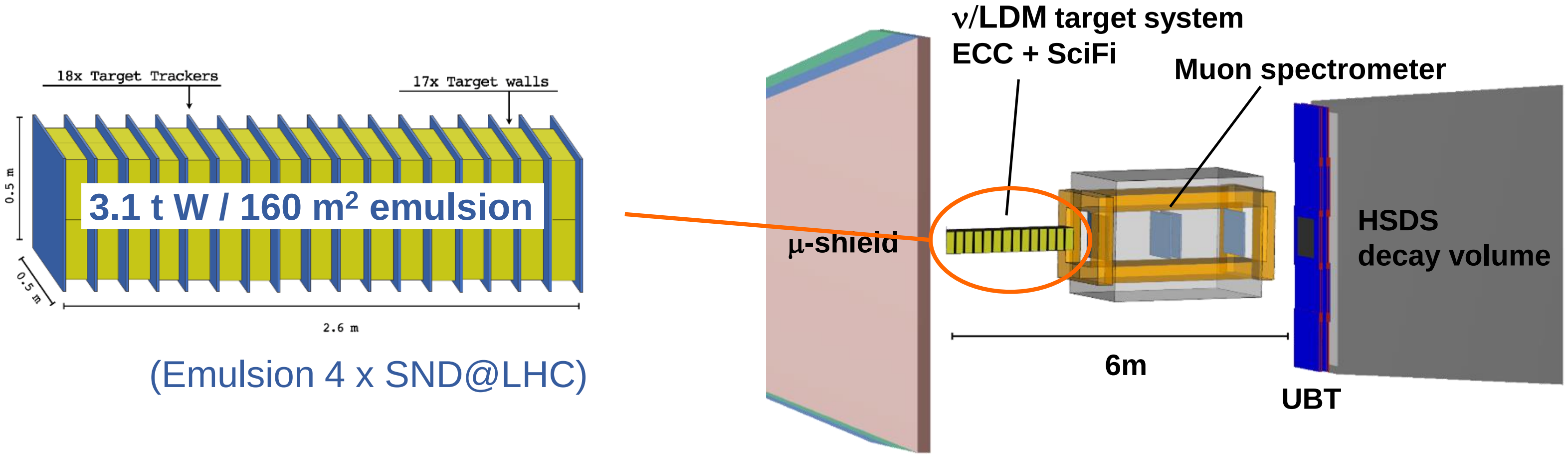


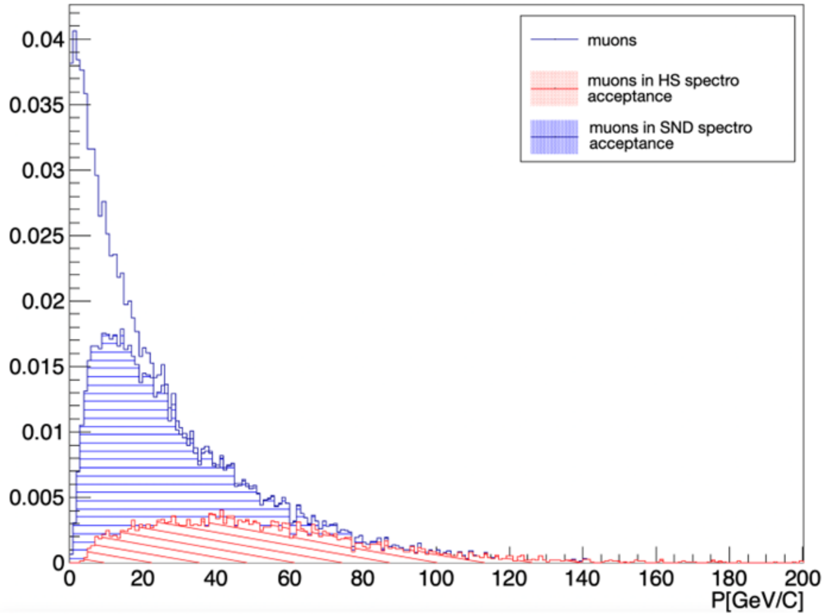




LDM scattering and neutrino detector (SND)

- 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



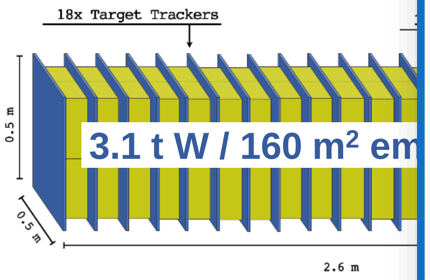


  - Neutrino energy from determination of electromagnetic/hadronic energy in target and muon momentum
    - Muon momentum range covered by both SND muon system and HSDS spectrometer (25% of total flux)

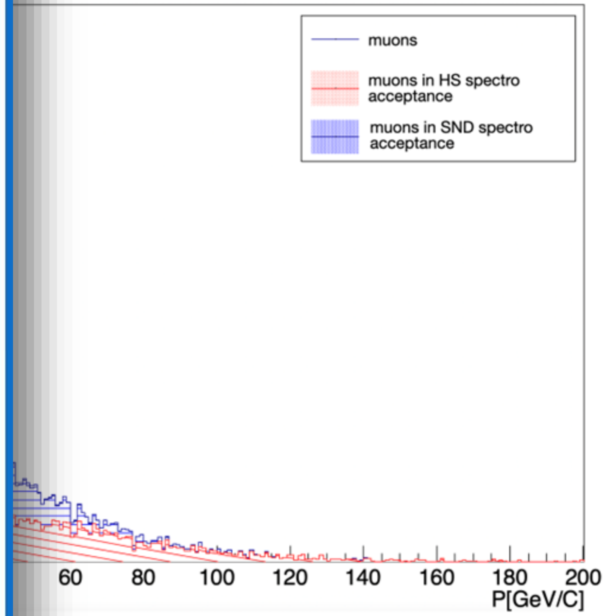
➔ Purely electronic techniques under investigation in the context of SND@LHC upgrade to replace emulsion

LDM scattering and neutrino detector (SND)

- 3 tonne LDM/neutrino W-target instrumented with layers of emulsion films
  - Micrometric accuracy is crucial for detecting tau neutrino by tau lepton decay vertices, and detecting neutrino-induced charm
  - Reconstruct ele… and muons
  - Magnetised mu…



(Emulsion 4 x SI…

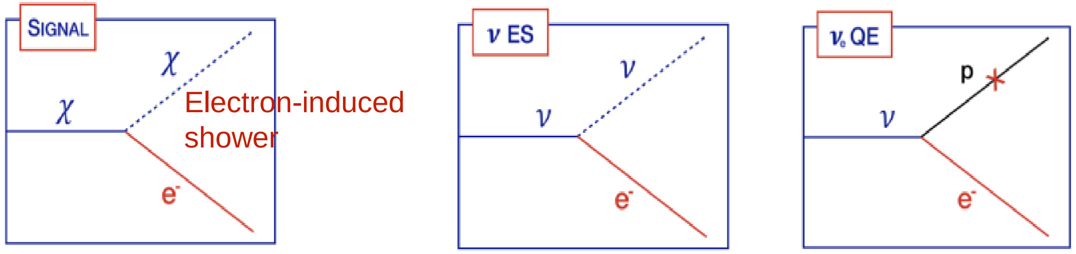


  - Neutrino energy… omentum
    - Muon momentu… l flux)

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

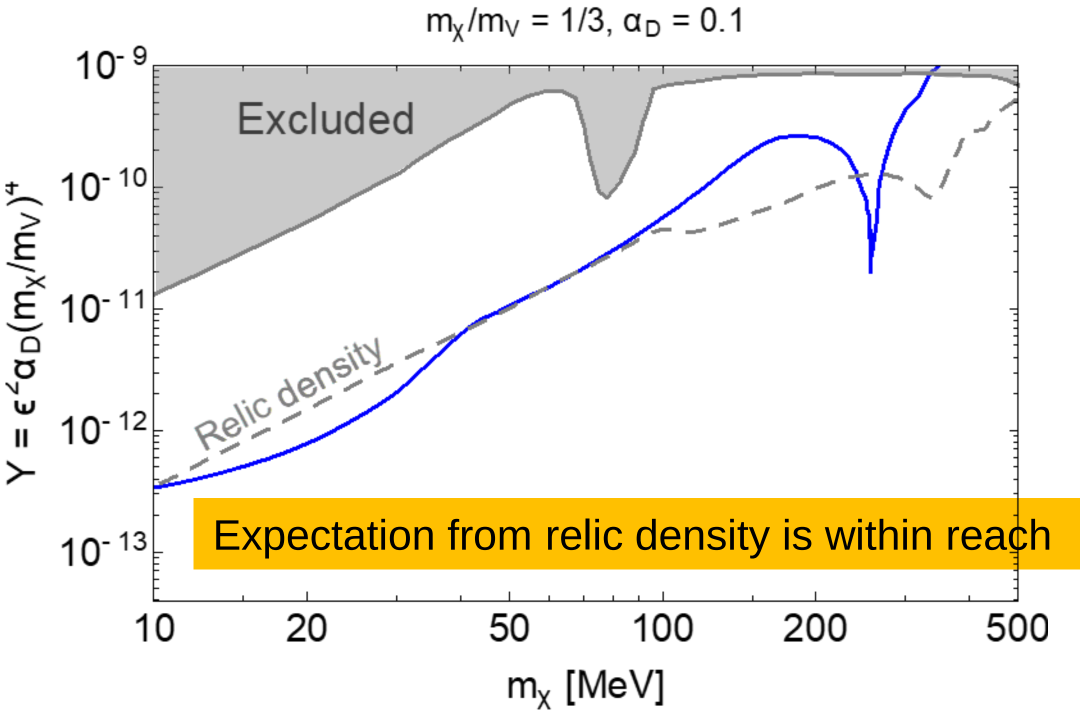
SND: “Direct” light dark matter search

- *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 ×10^20 PoT

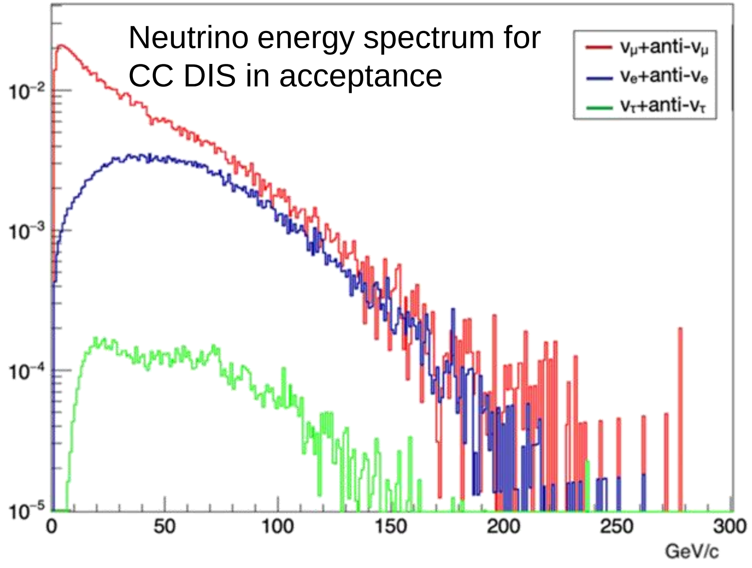
6 ×10^20	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	156	81	192	126	555
Quasi - elastic scattering	-	27			27
Resonant scattering	-	-			-
Deep inelastic scattering	-	-			-
Total	156	108	192	126	582



SND: Neutrino interaction physics (1)

Comes (almost) for free!

- 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
  - Measure kinematic variables in both CC and NC DIS
  - $\sigma_{stat} < 1\%$ for all neutrino flavours



	<E>[GeV]	Beam dump	<E>[GeV]	CC DIS interactions
N_{ν_e}	6.3	4.1×10^{17}	63	2.8×10^6
N_{ν_μ}	2.6	5.4×10^{18}	40	8.0×10^6
N_{ν_τ}	9.0	2.6×10^{16}	54	8.8×10^4
$N_{\overline{\nu}_e}$	6.6	3.6×10^{17}	49	5.9×10^5
$N_{\overline{\nu}_\mu}$	2.8	3.4×10^{18}	33	1.8×10^6
$N_{\overline{\nu}_\tau}$	9.6	2.7×10^{16}	74	6.1×10^4

Incl. reconstruction efficiencies

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

Systematic uncertainty from knowledge of ν_τ flux

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

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

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

SND: Neutrino interaction physics (2)

➔ Measurement of neutrino DIS cross-sections up to 100 GeV
- E_ν< 10 GeV as input to accelerator-based neutrino oscillation programme
- ν_τ cross-section input to atmospheric oscillations and cosmic neutrino studies
- $\sigma_{stat+syst}$~5%

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

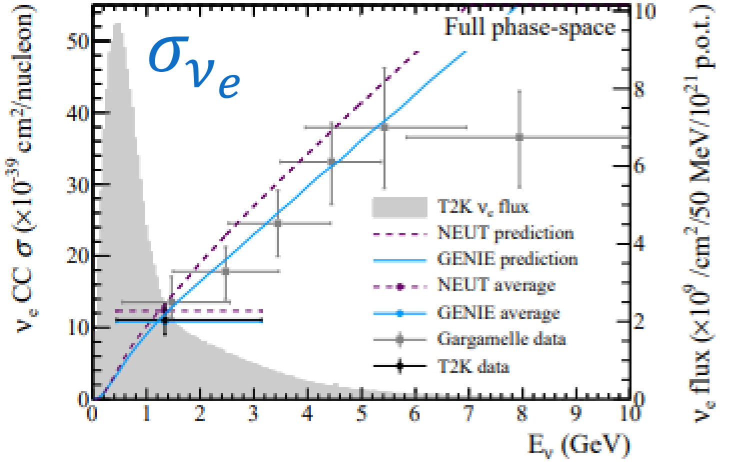
➔ Test of F_4 and F_5 ($F_4 \approx 0,\ F_5 = F_2/2x$ with $m_q \to 0$) structure functions in $\sigma_{\nu-CC\ DIS}$
- Never measured, only accessible with tau neutrinos, realistically at <10%
  [C.Albright and C.Jarlskog, NP B84 (1975)]

➔ Exotics, …

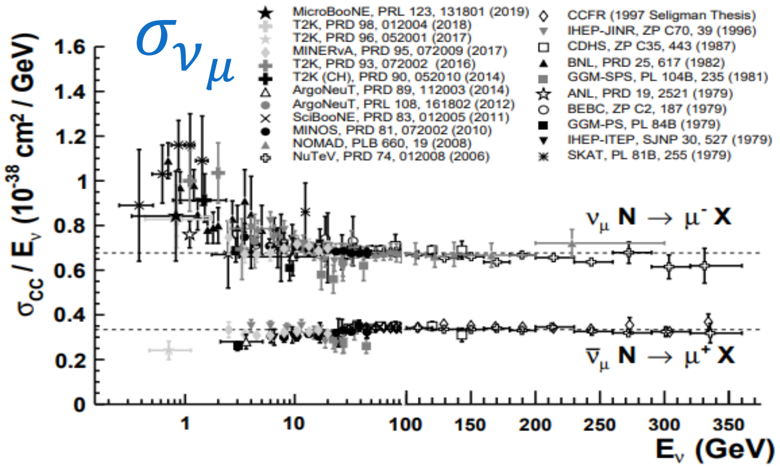
$$\frac{\sigma(\nu_e)}{\sigma(\nu_\mu)} = \frac{(\nu_e \text{ events observed})}{(\nu_\mu \text{ events observed})} \frac{\int E_{\nu_\mu}(\nu_\mu \text{ flux})dE}{\int E_{\nu_e}(\nu_e \text{ flux})dE} = 1.09 \pm 0.17 .$$

➔ 15%!

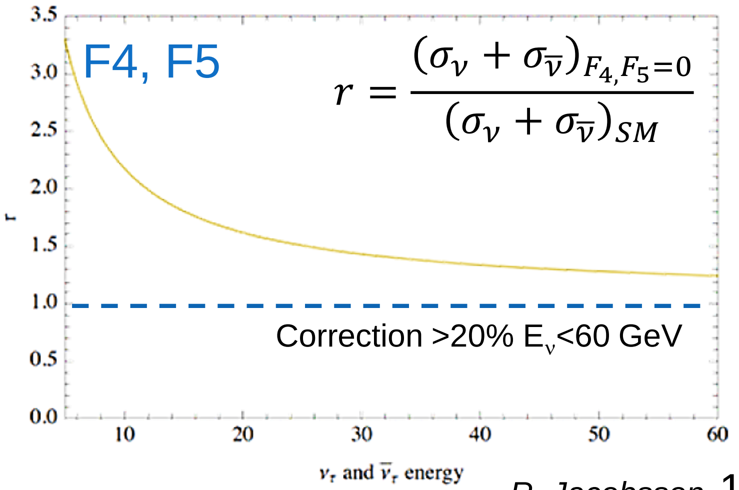
Phys.Rev. D41, 2653 (1990)



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



PDG



Rep. Prog. Phys. 79 (2016)124201

SND: Neutrino interaction physics (3)

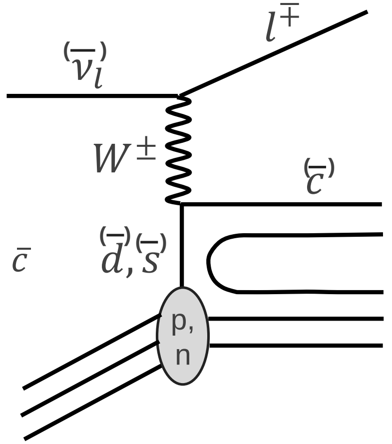
Neutrino-induced charm production programme

- 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

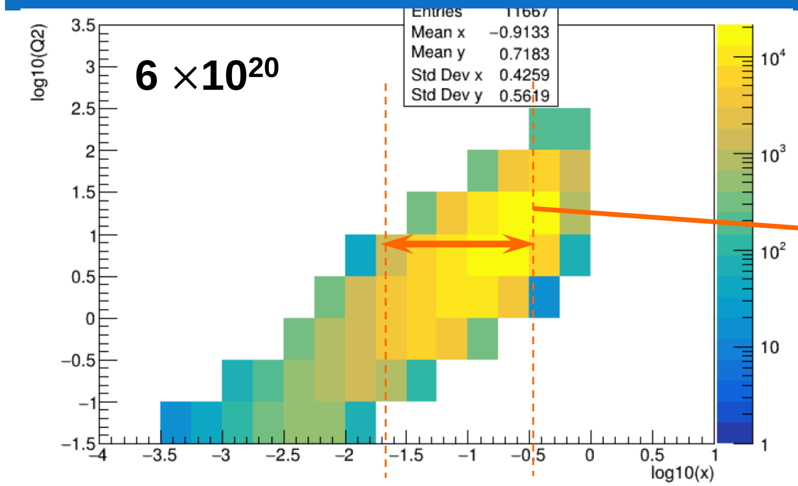
	<E> (GeV)	CC DIS with charm prod
N_{ν_μ}	57	3.5×10^5
N_{ν_e}	71	1.7×10^5
$N_{\overline{\nu}_\mu}$	50	0.7×10^5
$N_{\overline{\nu}_e}$	60	0.3×10^5
total		6.2×10^5

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

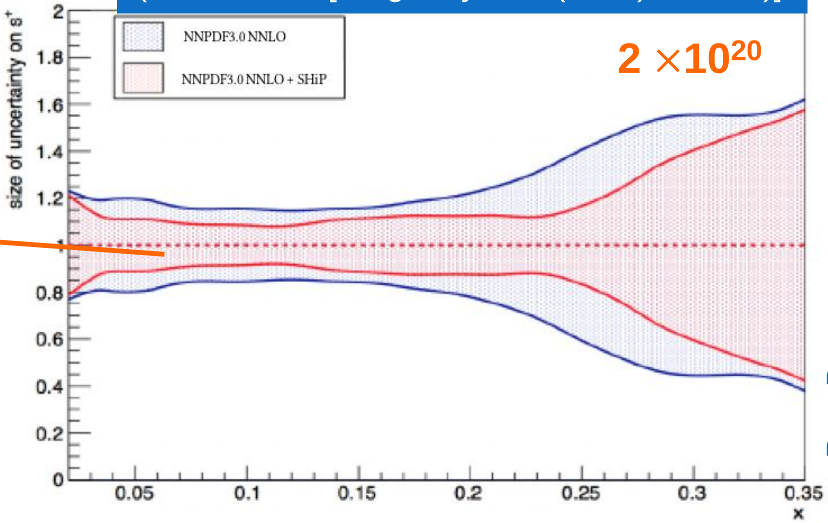


No charm candidate from ν_e and ν_τ interactions ever reported

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])



Rep. Prog. Phys. 79 (2016)124201

SND: Neutrino interaction physics (3)

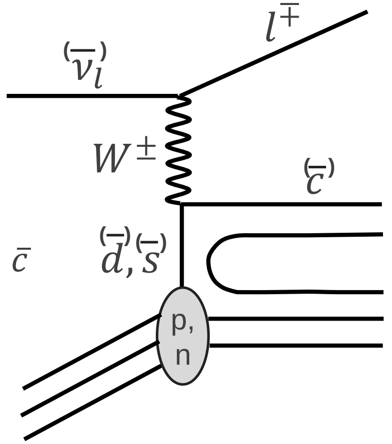
Neutrino-induced charm production to probe PDF

- 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 proton (~90%)
  - Understanding of nucleon strangeness is critical for precision tests of SM at LHC

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

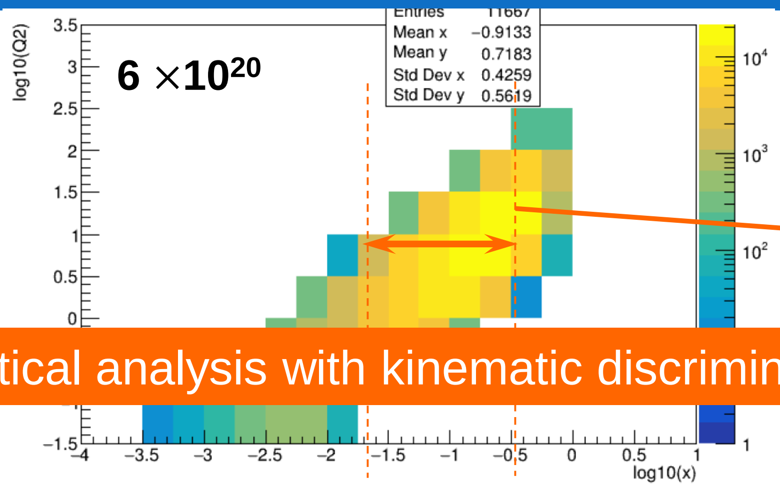
	<E> (GeV)	CC DIS with charm prod
N_{ν_μ}	57	3.5×10^5
N_{ν_e}	71	1.7×10^5
$N_{\overline{\nu}_\mu}$	50	0.7×10^5
$N_{\overline{\nu}_e}$	60	0.3×10^5
total		6.2×10^5

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

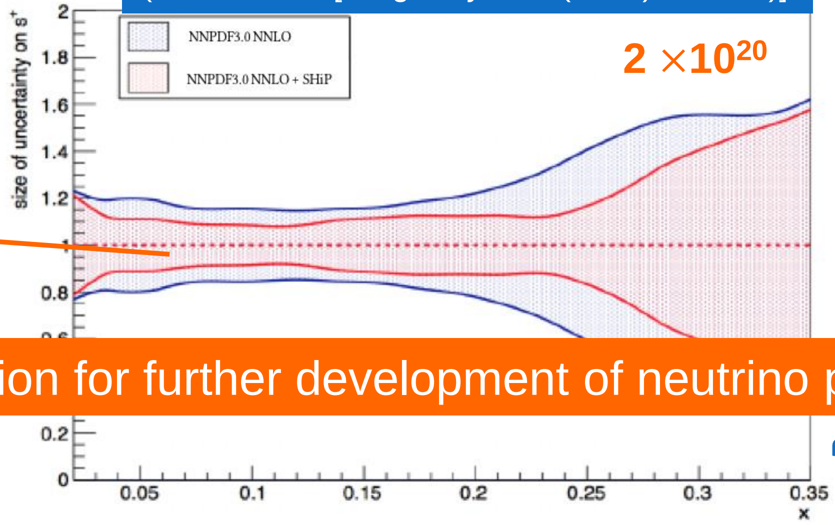


No charm candidate from ν_e and ν_τ interactions ever reported

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

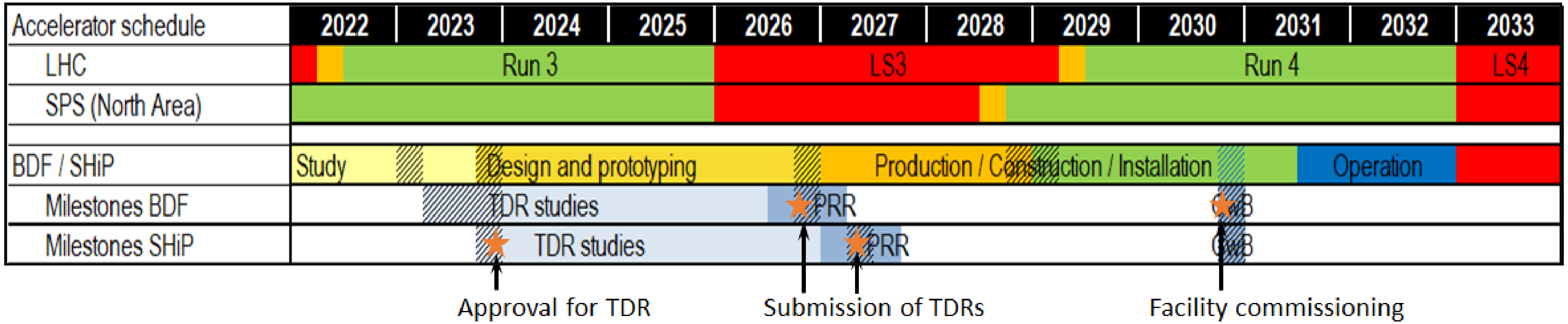


SHiP sensitivity to PDF for x < 0.35
(evaluated in [Prog. Phys. 79 (2016) 124201])

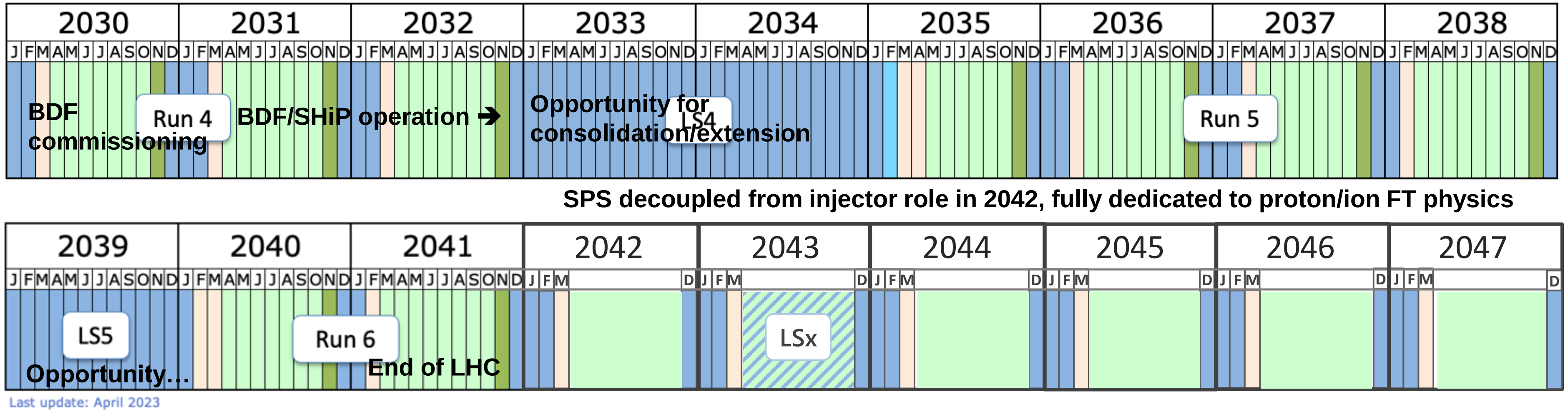


Use of statistical analysis with kinematic discrimination for further development of neutrino programme

BDF/SHiP preliminary schedule

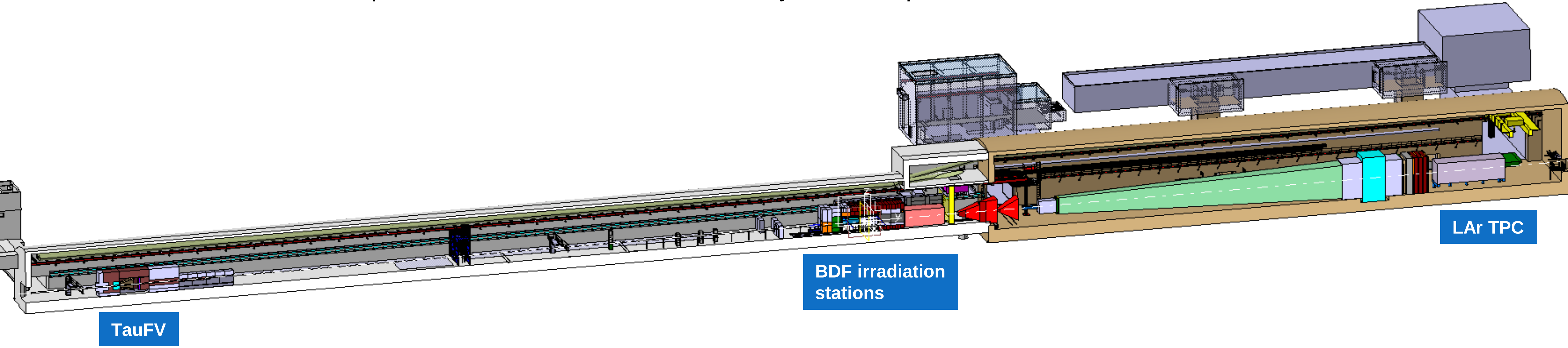


- ~3 years for detector TDRs (approval in 2023 is critical to ensure timely funding)
- Construction / installation of facility and detector is decoupled from NA operation
- Availability of test beams challenging
- Important to start data taking >1 year before LS4
- Several upgrades/extensions of the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



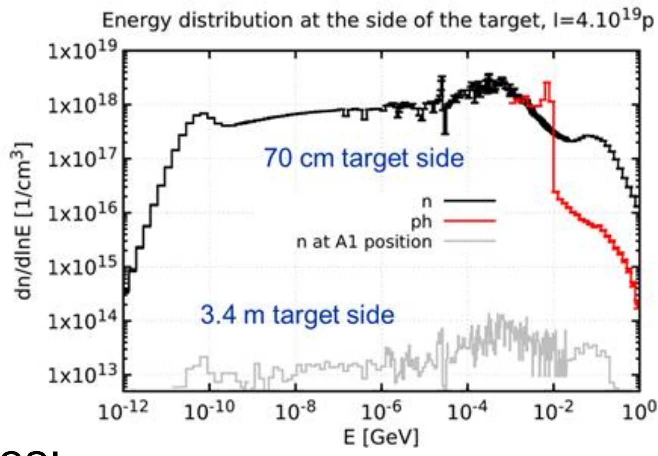
Overview of BDF extensions

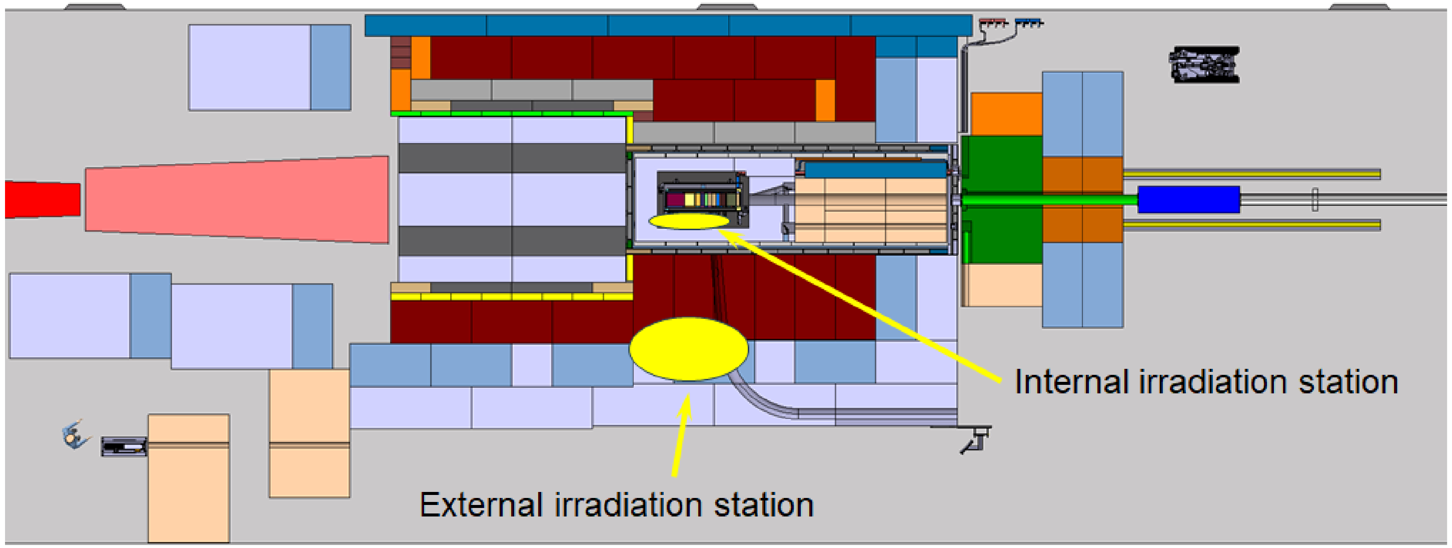
- Preliminary studies of opportunities to extend BDF's physics programme *synergetically with SHiP*:
  - Irradiation stations (nuclear astrophysics and accelerator / material science applications)
  - LArTPC to extend search for FIPs using different technology
  - TauFV to search for lepton flavour violation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

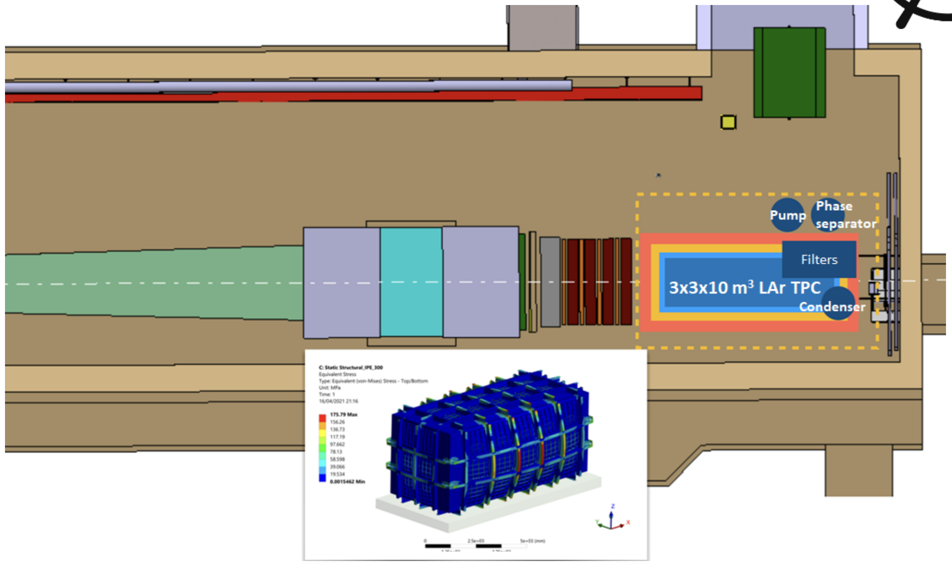
Extensions: FIP searches with LAr TPC detector

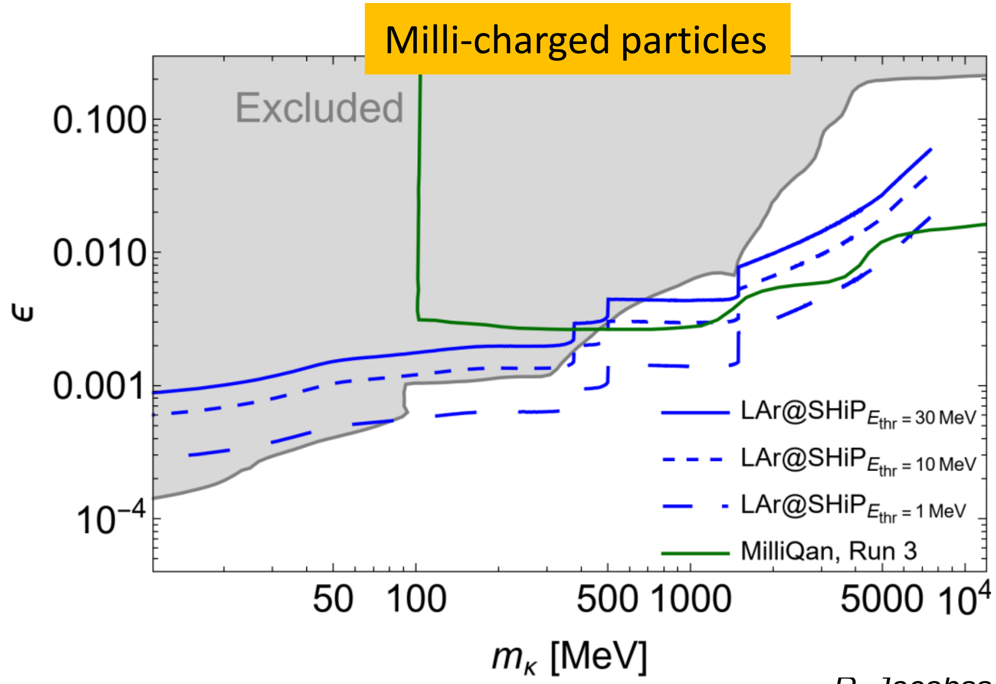
LArTPC technology is currently used in neutrino and cosmic Dark Matter search experiments

- 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

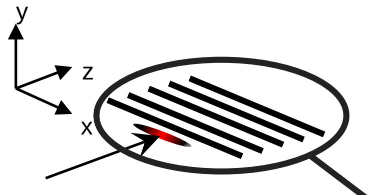


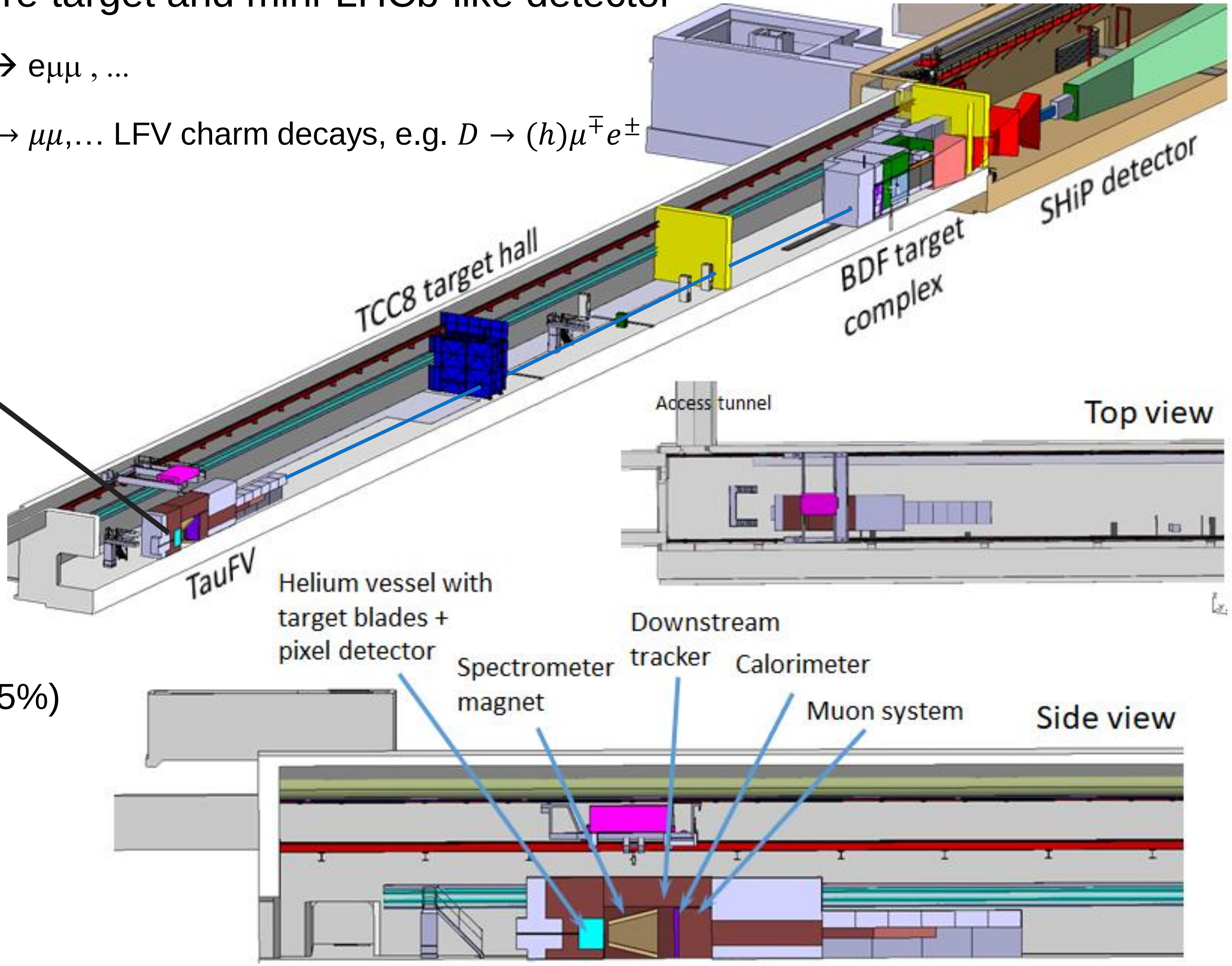


Extensions: Tau flavour violation experiment

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. $D \rightarrow (h)\mu^{\mp}e^{\pm}$





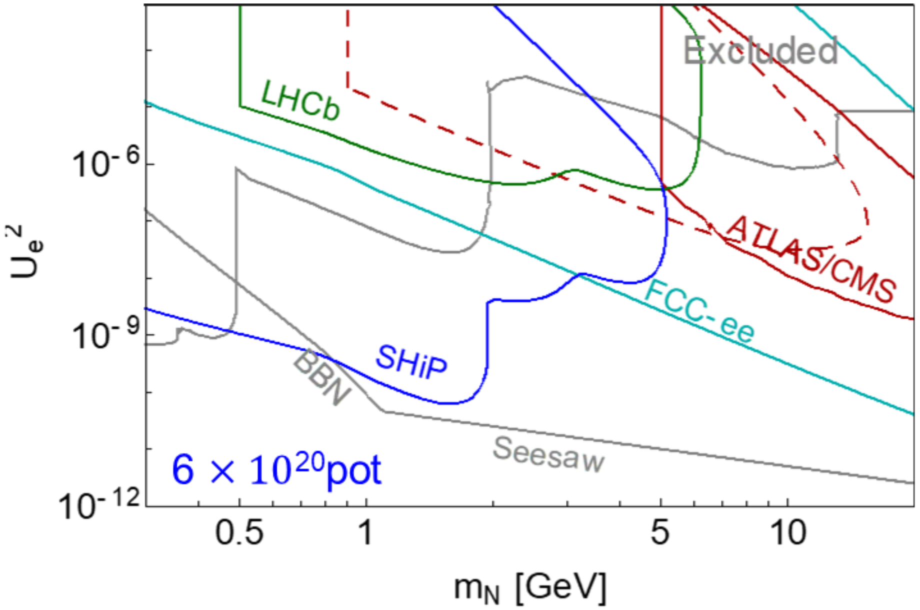
➔ $\tau \rightarrow \mu\mu\mu$ yields with *5 years* of operation and assuming branching ratio 10^{-10}
(TauFV acceptance * preselection efficiency = 5%)

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

- 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

Acknowledgements

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, A. Ballarino, A. Devred, A. Milanese, D. Tommasini,
- BDF irradiation station: S. Danzeca, S. Fiore, G. Lerner, 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, L. Di Giulio.

BDF Working Group[30]

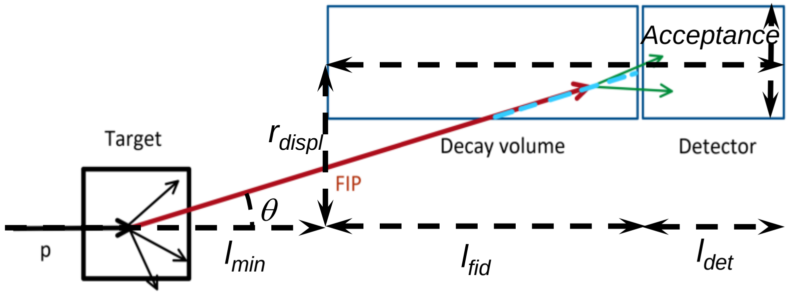
O. Aberle, C. Ahdida, P. Arrutia, K. Balazs, M. Calviani, Y. Dutheil, L.S. Esposito, R. Franqueira Ximenes, M. Fraser, F. Galleazzi, S. Gilardoni, J.-L. Grenard, T. Griesemer, R. Jacobsson, V. Kain, L. Krzempek, D. Lafarge, S. Marsh, J.M. Martin Ruiz, G. Mazzola, R.F. Mena Andrade, Y. Muttoni, A. Navascues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

Spare slides

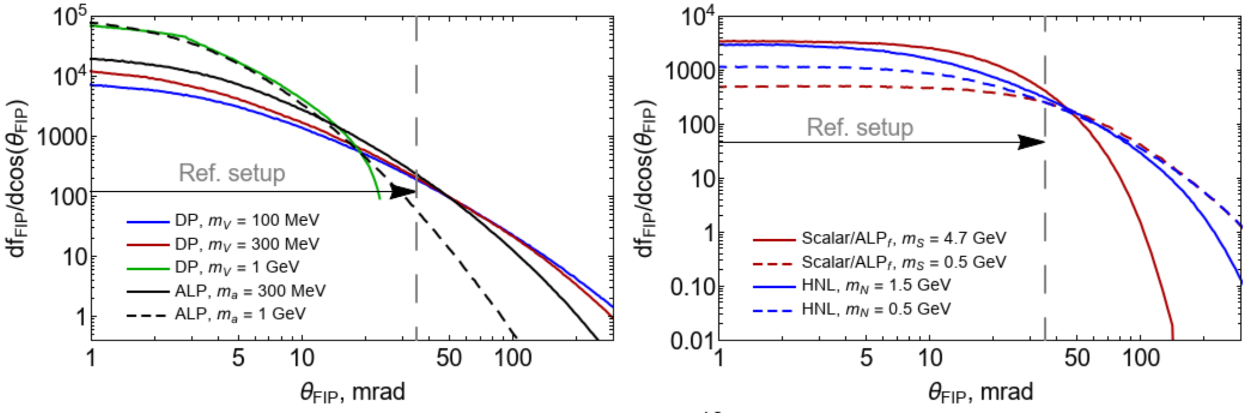
Optimisation of a proton beam dump experiment for FIPs

[arXiv:2304.02511](https://arxiv.org/abs/2304.02511)

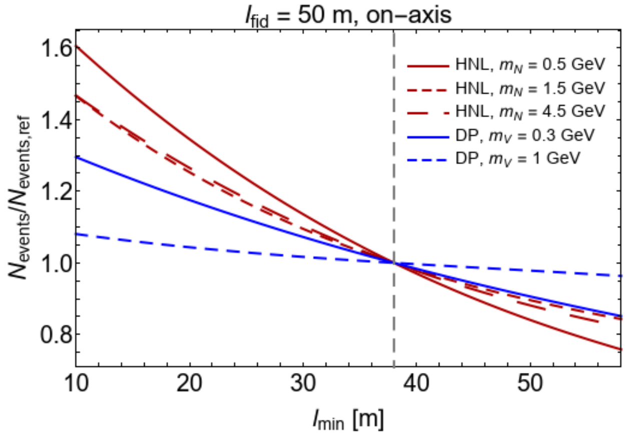
Generic setup



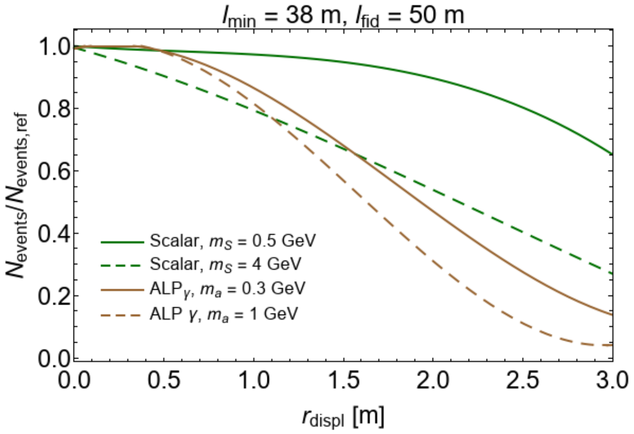
Differential acceptance



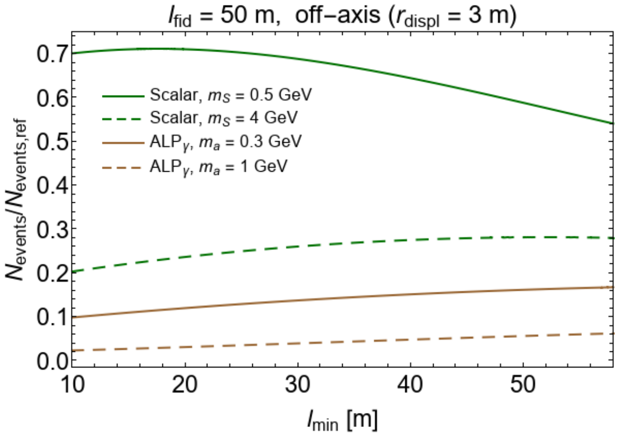
Varying distance to target



Varying offset

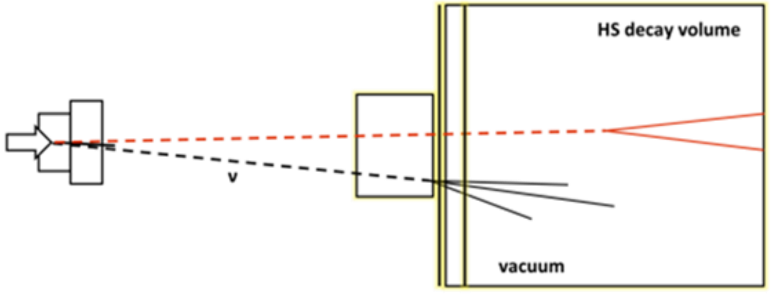


Varying distance to target with offset



Backgrounds in FIP decay search

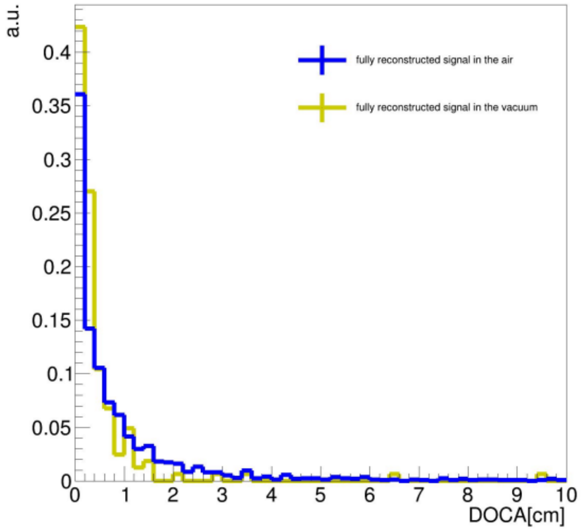
- Neutrino DIS background
  - Similar to muon DIS, dominated by interactions in the proximity of the decay volume
    - MC sample used equivalent to 35 years of SHiP data
  - Sources of neutrino DIS background:
    - SND ~ 11%
    - Inner wall of the decay volume ~52%
    - Liquid scintillator ~26%
    - Outer wall of the decay volume ~4%
    - Others ~7%

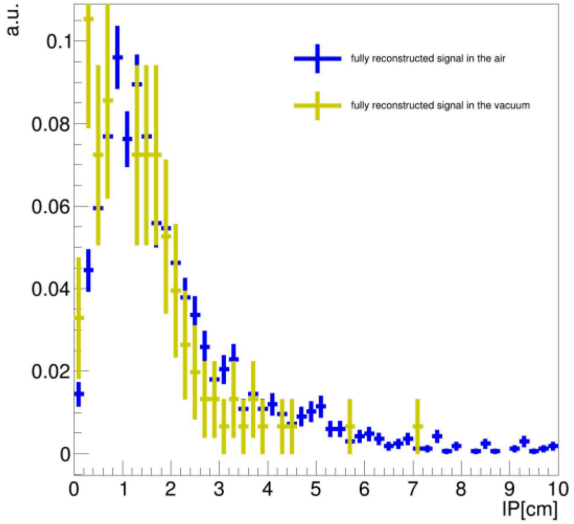


  - Background so low that He @ 1atm being considered in decay volume

➔ Needs further study

Check of signal resolution air vs vacuum





Current status of the Collaboration

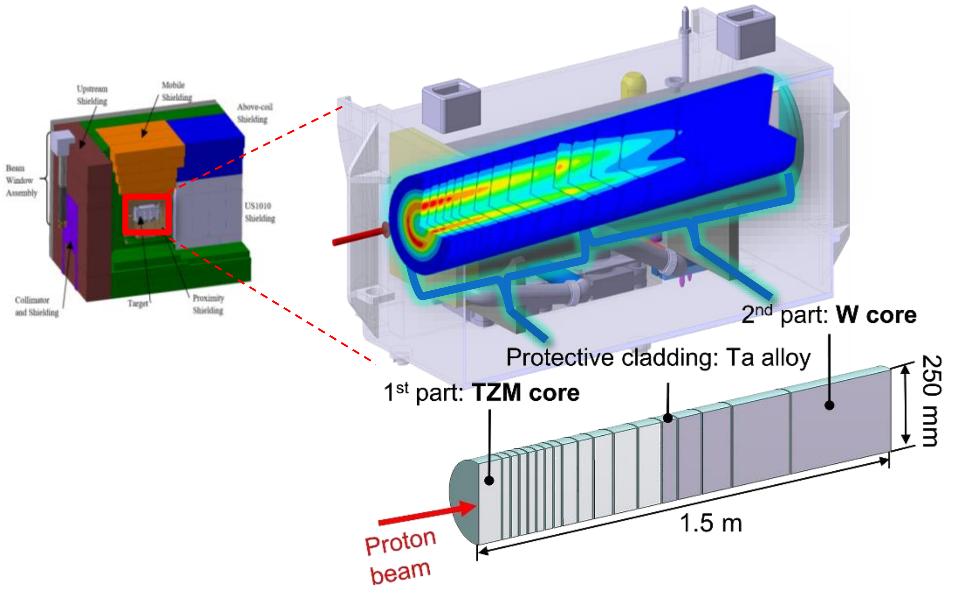
- Key competencies covered (PID main lead is being discussed)
- CF projects have main lead identified
- Final sharing of responsibilities to be discussed with funding agencies after approval
- Significant number of groups from various countries (including Germany, France, Italy, Netherlands, Sweden and UK) expressed interest pending the approval of the TDR phase

Sub-projects	Main lead	Involved groups
Muon shield		
Muon shield*	CERN[30]	RAL(UK)[38], CERN[30], ++
SND		
Emulsion system	Naples(IT)	LNGS(IT)[17], Naples(IT)[16,c], Aichi(JP)[18], Kobe(JP)[19], Nagoya(JP)[20], Nihon(JP)[21], Toho(JP)[22], Gyeongsang(KR)[23], Gwangju(KR)[24], Seoul(KR)[25], Gyeong Gi-do(KR)[26], METU(TR)[33]
Target tracker	Lausanne(CH)	Lausanne(CH)[31], Seigen(DE)[12]
Muon spectrometer	Naples(IT)	Bari(IT)[13,a], Naples(IT)[16,c]
HSDS		
Decay vacuum vessel + caps*	Naples(IT)	Naples(IT)[c], CERN[30]
Spectrometer vacuum vessel*	CERN[30]	CERN[30]
Spectrometer magnet*	CERN[30]	CERN[30], ++
Upstream background tagger	Lisbon(PT)	Lisbon(PT)[28]
Surrounding background tagger	Berlin(DE)	Berlin(DE)[7], Freiburg(DE)[8], Juelich(DE)[10], Mainz(DE)[11], Kiev(UA)[39]
Spectrometer tracker	Hamburg(DE)	Hamburg(DE)[9], Juelich(DE)[10], Kiev(UA)[39], CERN[30]
Timing detector	Zurich(CH)	Zurich(CH)[32]
Particle identification detectors		Mainz(DE)[11], Bologna(IT)[14], Cagliari(IT)[15,b], Bristol(UK)[35], ICL(UK)[36], UCL(UK)[37]
Online + offline		
Common electronics and online(*)	Orsay(FR)	Orsay(FR)[6], CERN[30]
Computing		CERN[30], Copenhagen(DK)[5]
Subdetector infrastructure, engineering, electronics		Sofia(BG)[1], Zurich(CH)[32], SAPHIR(CL)[2], UNAB-Santiago(CL)[3], ULS-Serena(CL)[4], Copenhagen(DK)[5], Siegen(DE)[12], Leiden(NL)[27], Belgrade(RS)[29], Ankara(TR)[34]

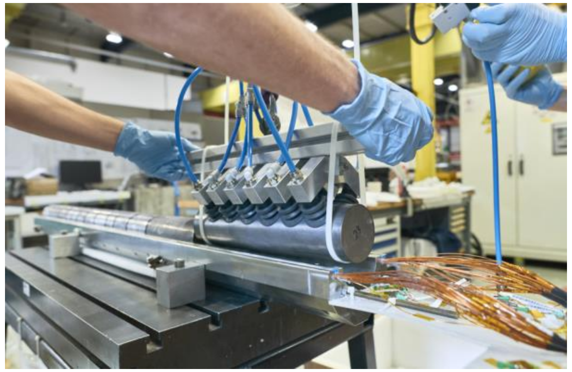
BDF/SHiP Target

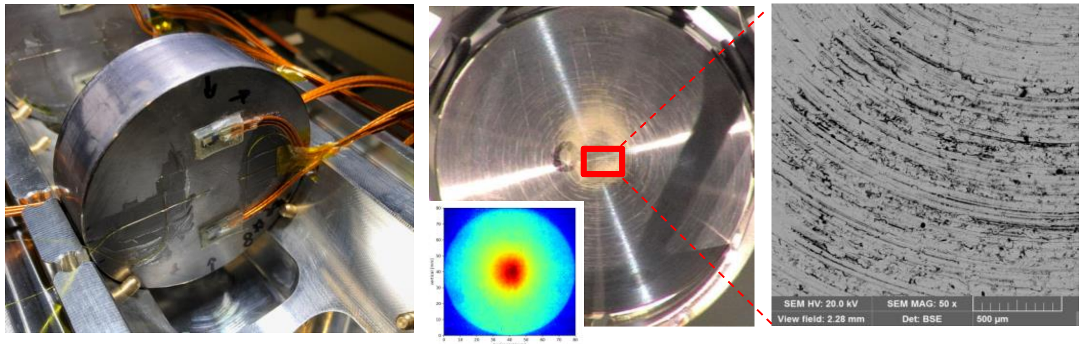
- Challenges
  - High A/Z target with high beam power of up to 2.56 MW during the 1 s spill and 320 kW on average
  - ➔ High-A/Z material resilience to high flow of cooling water
  - ➔ Target block cladding behaviour under thermo-mechanical stress
  - ➔ Integrated design of target assembly for fully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



TZM: 0.08% Ti – 0.05% Zr – Mo alloy

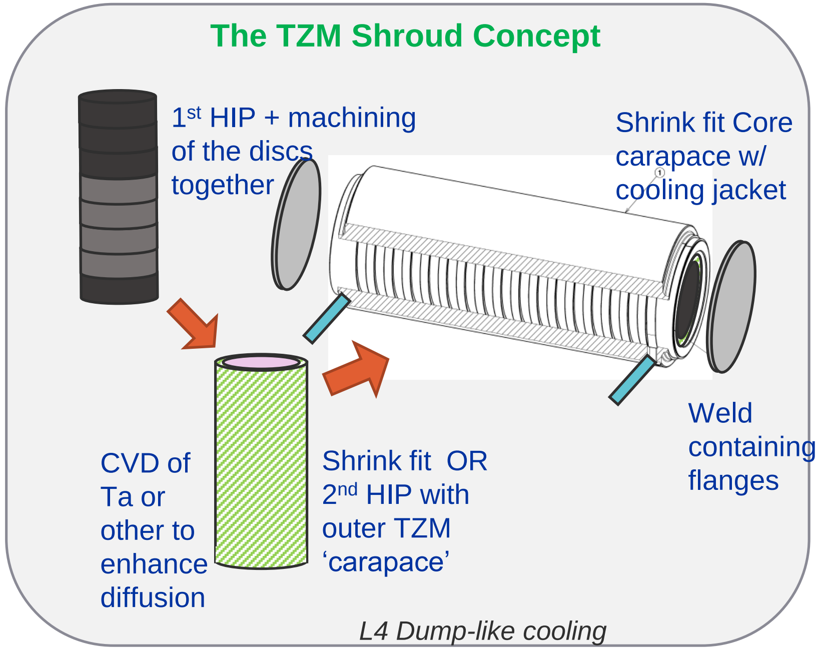


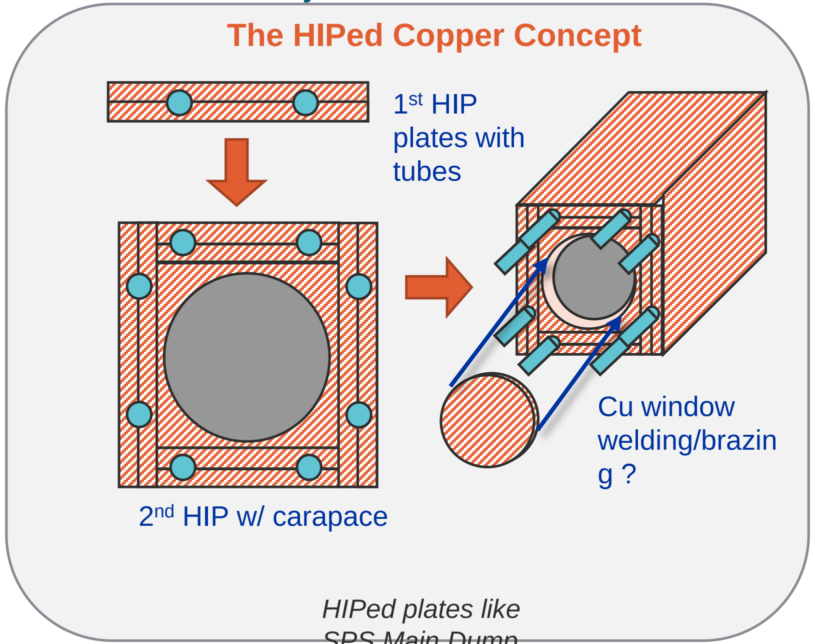


Prototype instrumentation. Visual and optical microscopy inspections during the PIE.

BDF/SHiP target – further optimisation

- 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

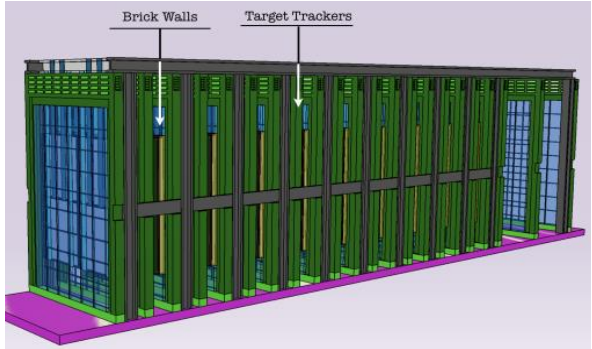
SND ECC + Target tracker

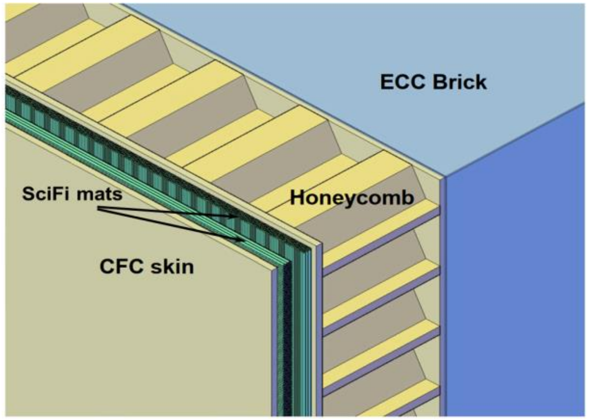
- Purpose: Neutrino/LDM vertex detector and neutrino energy with hadrons and electrons

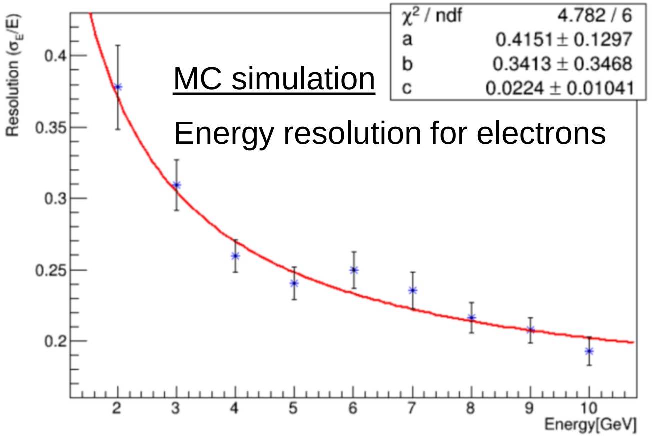
- Emulsion Cloud Chamber brick characteristics
  - Bricks of 40x40 cm^2
  - Thickness ~8 cm (57 films/lead plates → ~10 X_0)
  - Weight ~100 kg
  - Scanning speed 200 cm^2/h, 10x faster than Opera

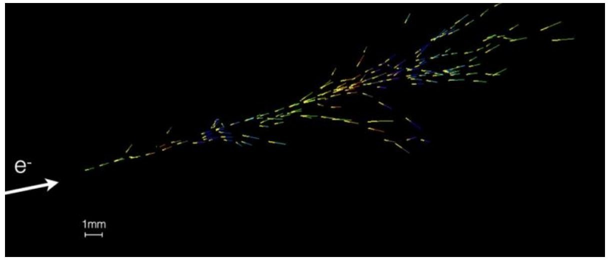
- SciFi target tracker characteristics
  - $\sigma_{x,y}$~30-50 μm resolution
  - Six scintillating fibre layers, total 3mm thickness ~ 0.05 X_0
  - Multi-channel SiPM at one end, ESR foils as mirrors on other
  - Time resolution <0.5ns
  - Extended with silicon (study in SND@HL-LHC)?

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

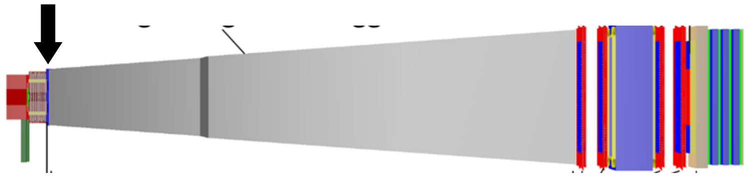






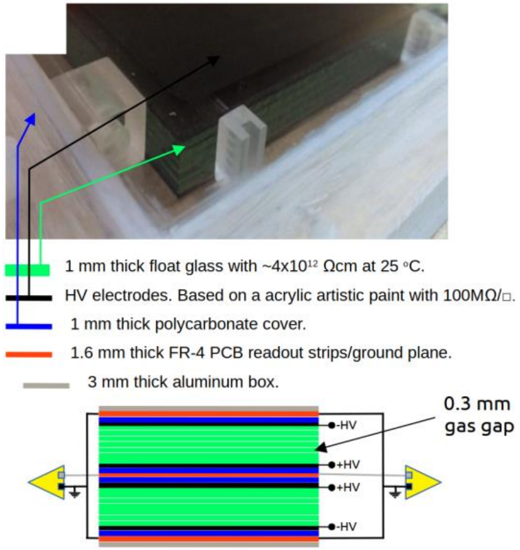


Upstream Background Tagger

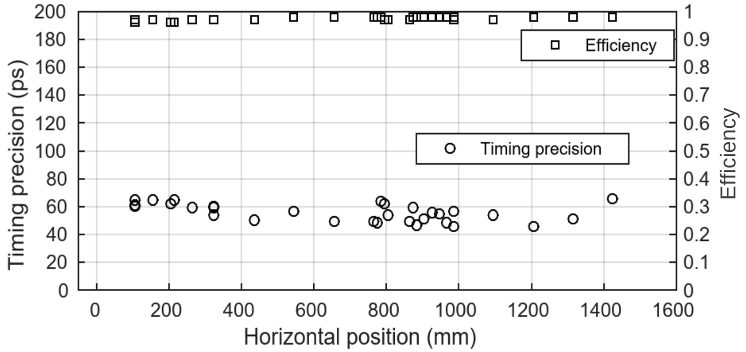


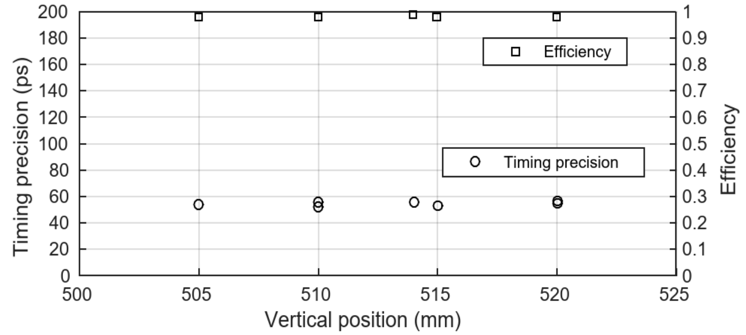
- Purpose: Veto in front of decay volume
  - ➔ High efficiency, <100ps resolution, ~cm resolution

- 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



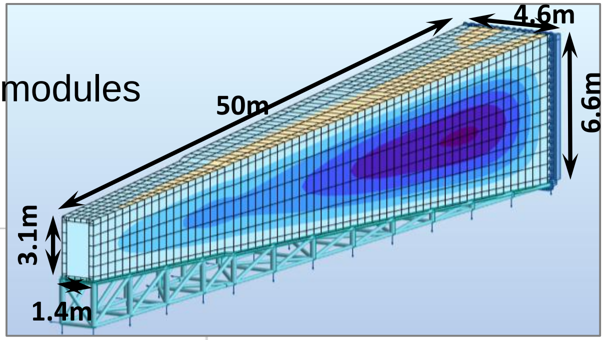
$2m^2$ prototype in beam test at PS

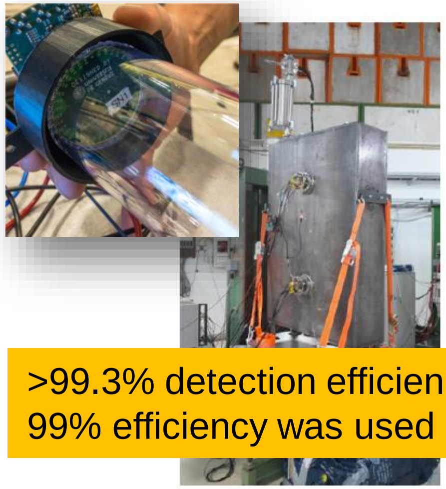


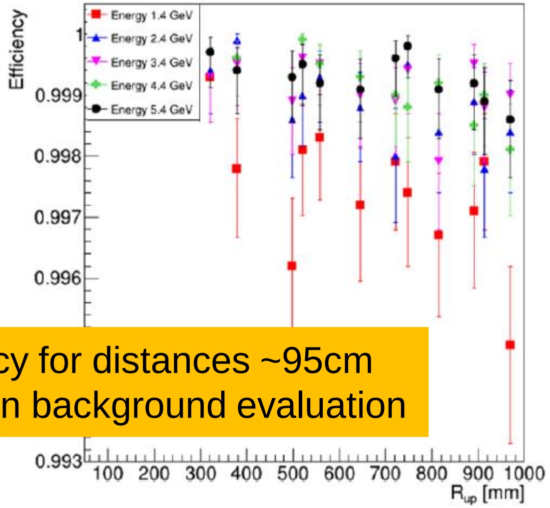


Surrounding background tagger (SBT)

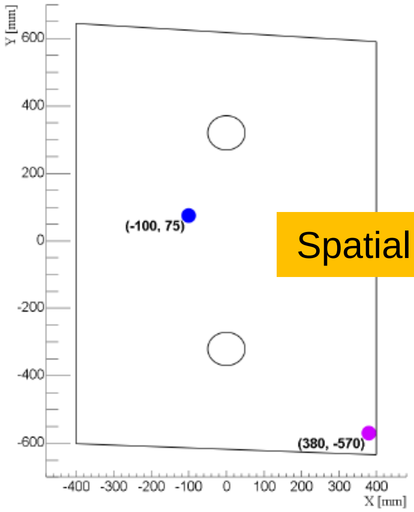
- Residual muons, muon and neutrino DIS tagged by veto system around decay volume
  - SBT based on liquid-scintillator (LS) technology → provides high veto efficiency at reasonable cost
  - SBT LS cells integrated into the wall structure of decay vessel with readout by wave-length-shifting optical modules
  - ➔ Performance demonstrated with beam test of large-scale prototype

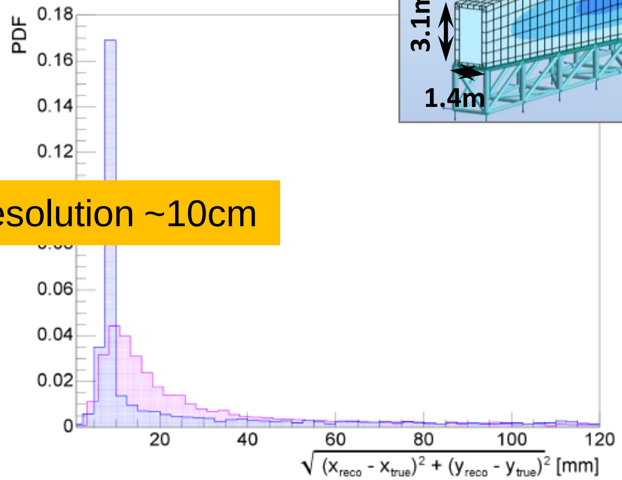




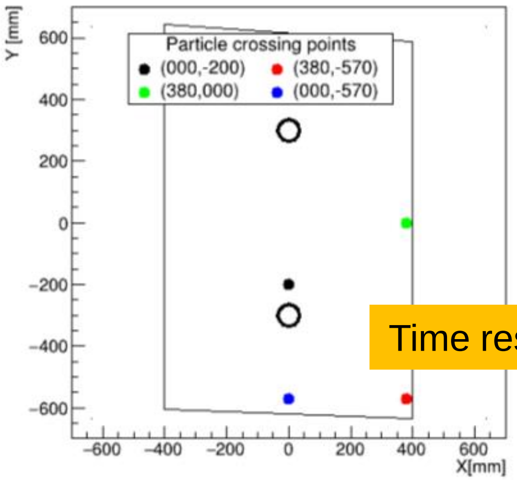


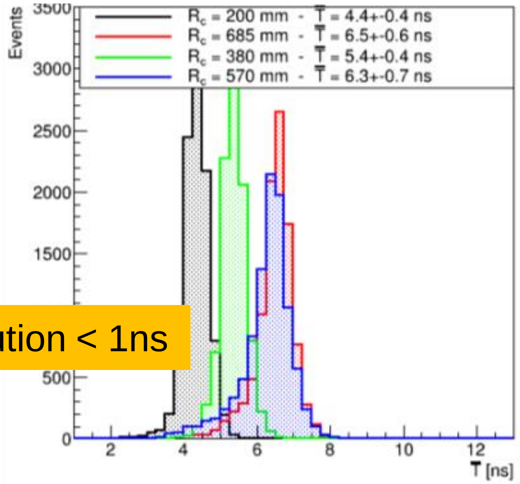
>99.3% detection efficiency for distances ~95cm
99% efficiency was used in background evaluation





Spatial resolution ~10cm





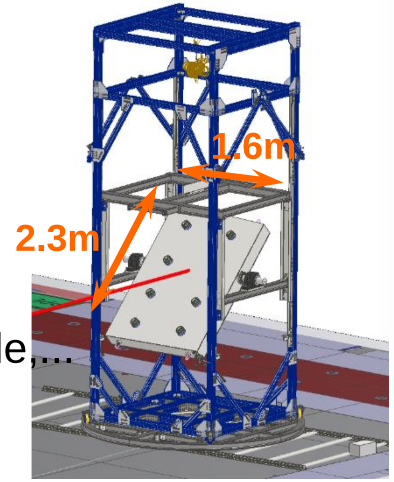
Time resolution < 1ns

2023 prototype

CERN test beam: 2023-Q4

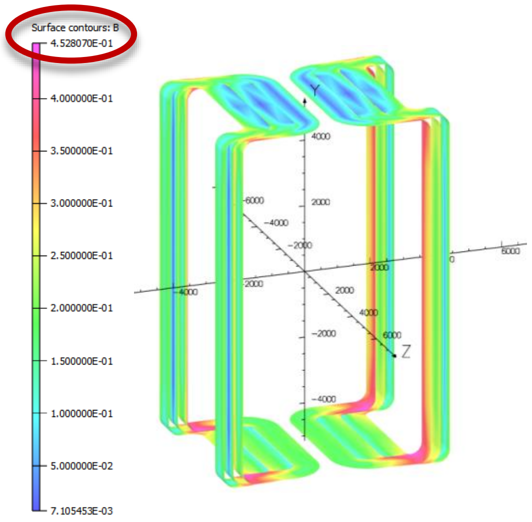
Light yield, energy deposition,

spatial information, incidence angle,…

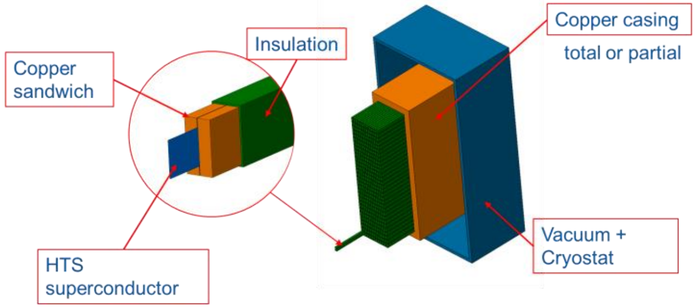


"Super-copper"

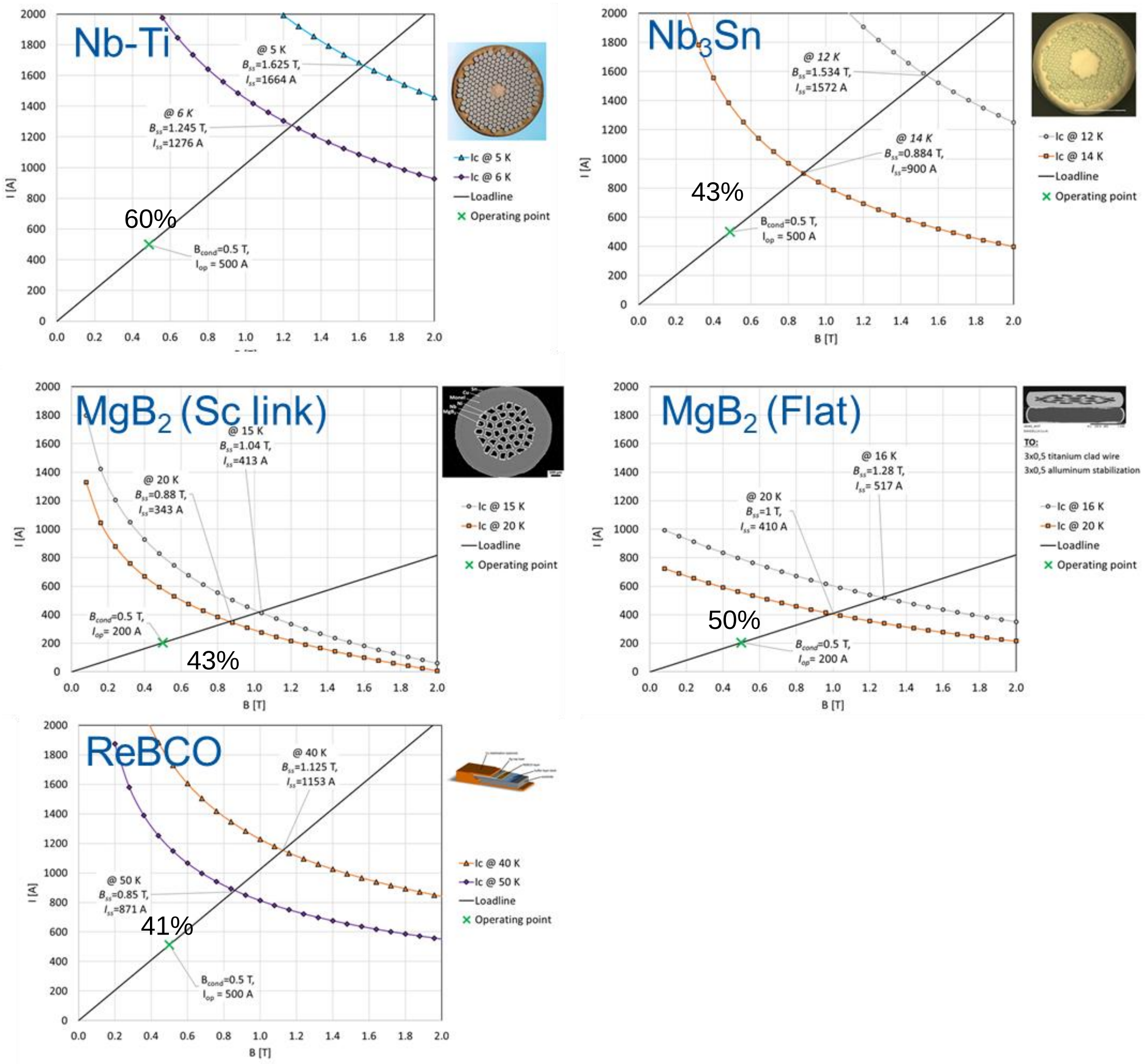
- H. Bajas, D. Tommasini, EDMS 2440157 (21 April 2020) - study of NbTi or Nb3Sn or MgB2 or ReBCO



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



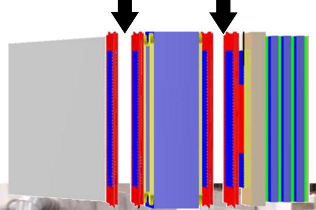
Courtesy Philip Schwarz, April 2019

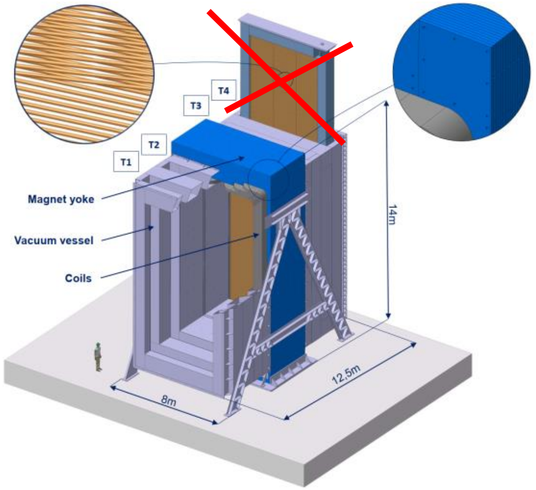


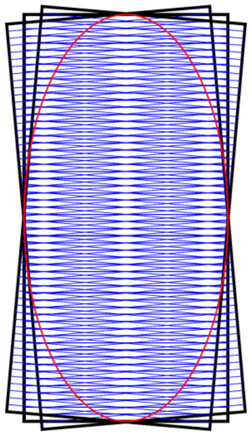
- Existing and future spectrometer magnets with large apertures will be required for many years to come!

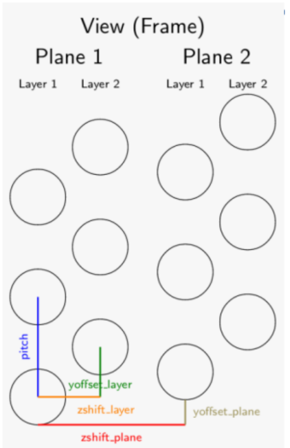
HS Straw Tracker

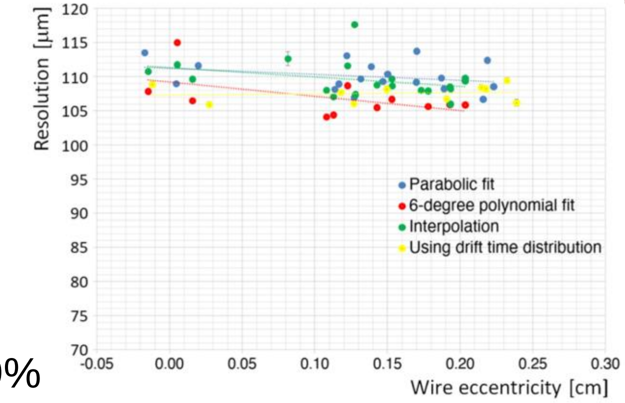
- Purpose: Track reconstruction and momentum, reconstruction of origin of neutral particle candidate. Match hits in timing detector
- Technology developed for the NA62 experiment
  - ➔ SHiP strategy: decoupling supporting frames from vacuum envelope
  - ➔ Horizontal orientation of tubes ➔ mechanical challenge
  - ➔ Lower rate allows increasing straw diameter (rate <100 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





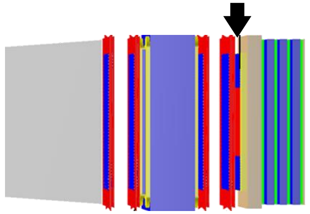




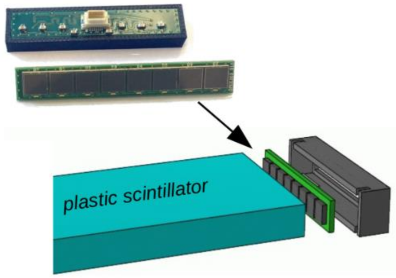


Test beams confirm 120µm hit resolution with hit efficiency >99%

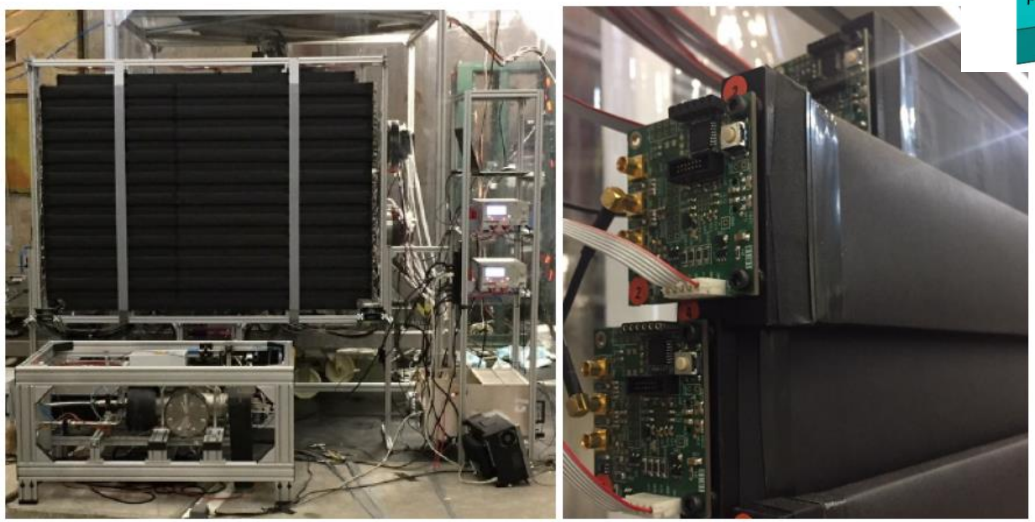
HS Timing Detector

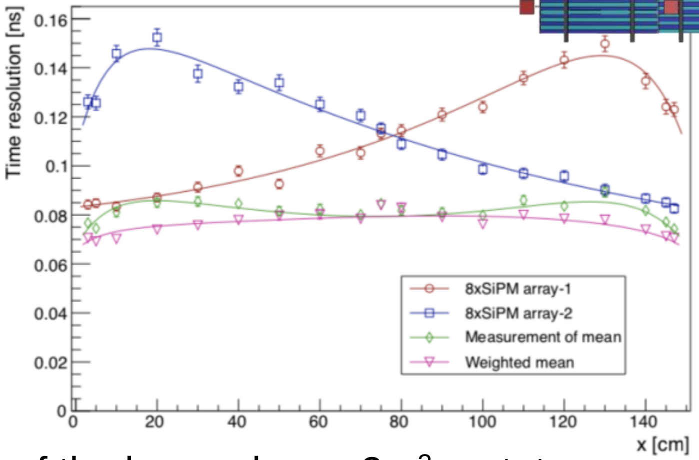


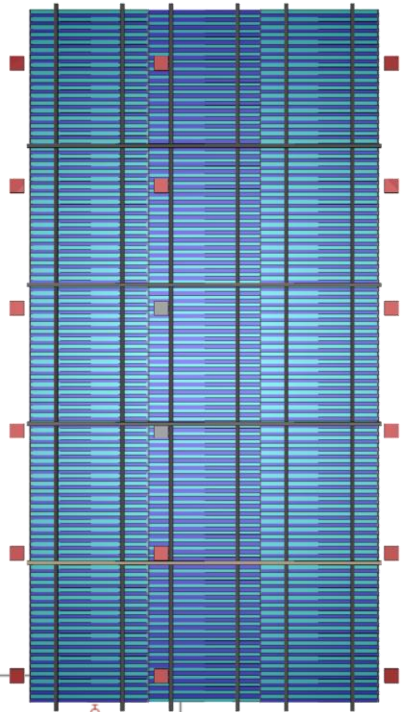
- Purpose: Provide precise timing (<100 ps) of each track to reject combinatorial background
- Plastic scintillator characteristics
  - Three-column setup with EJ200 plastic bars of 135cm × 6cm × 1cm, providing 0.5cm overlap
  - Readout on both ends by array of eight 6×6 mm^2 SiPMs, 8 signals are summed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



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

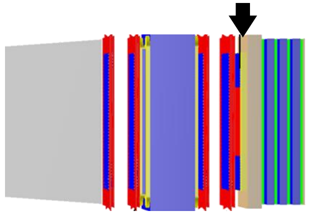


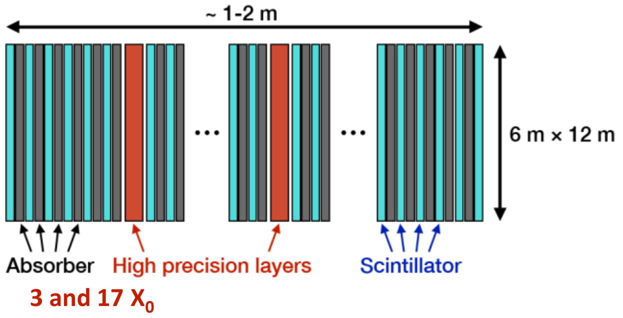




Resolution demonstrated to be ~80 ps along the whole length of the bar and over 2m^2 prototype

HS ECAL ("SplitCal")

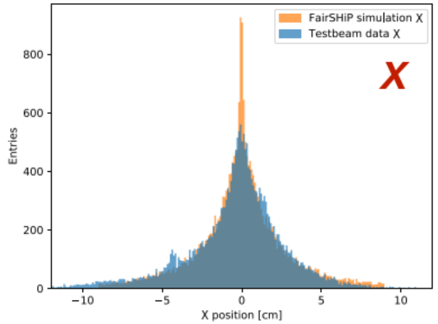


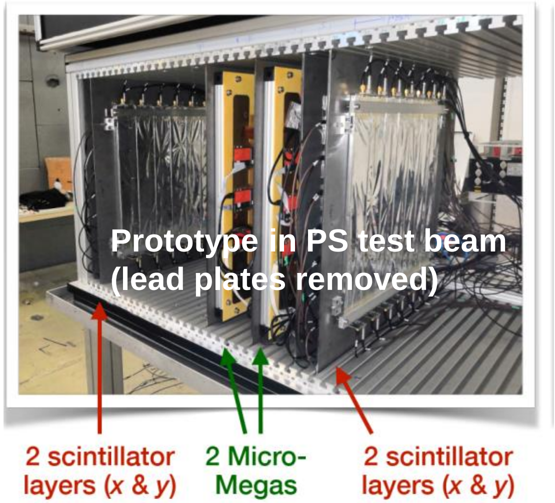


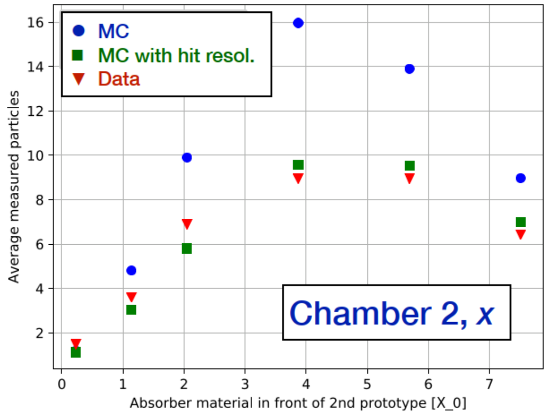
- Purpose: e/γ identification, π^0 reconstruction, photon directionality ~5mrad for ALP→ $\gamma\gamma$ (coincidence timing)
- Characteristics
  - 25 X_0 longitudinally segmented calorimeter with coarse and fine space resolution active layers
  - Coarse layers: 40-50 planes of scintillating bar readout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

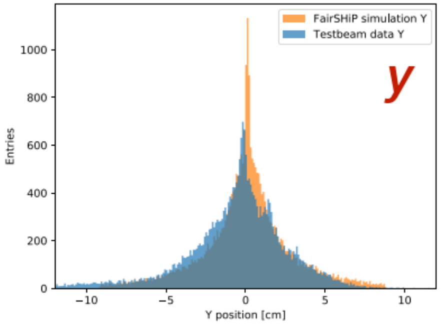
  ➔ 3 mrad for 20 GeV, 5 mrad for 10 GeV and 9 mrad for 6 GeV photons

2.1 X_0





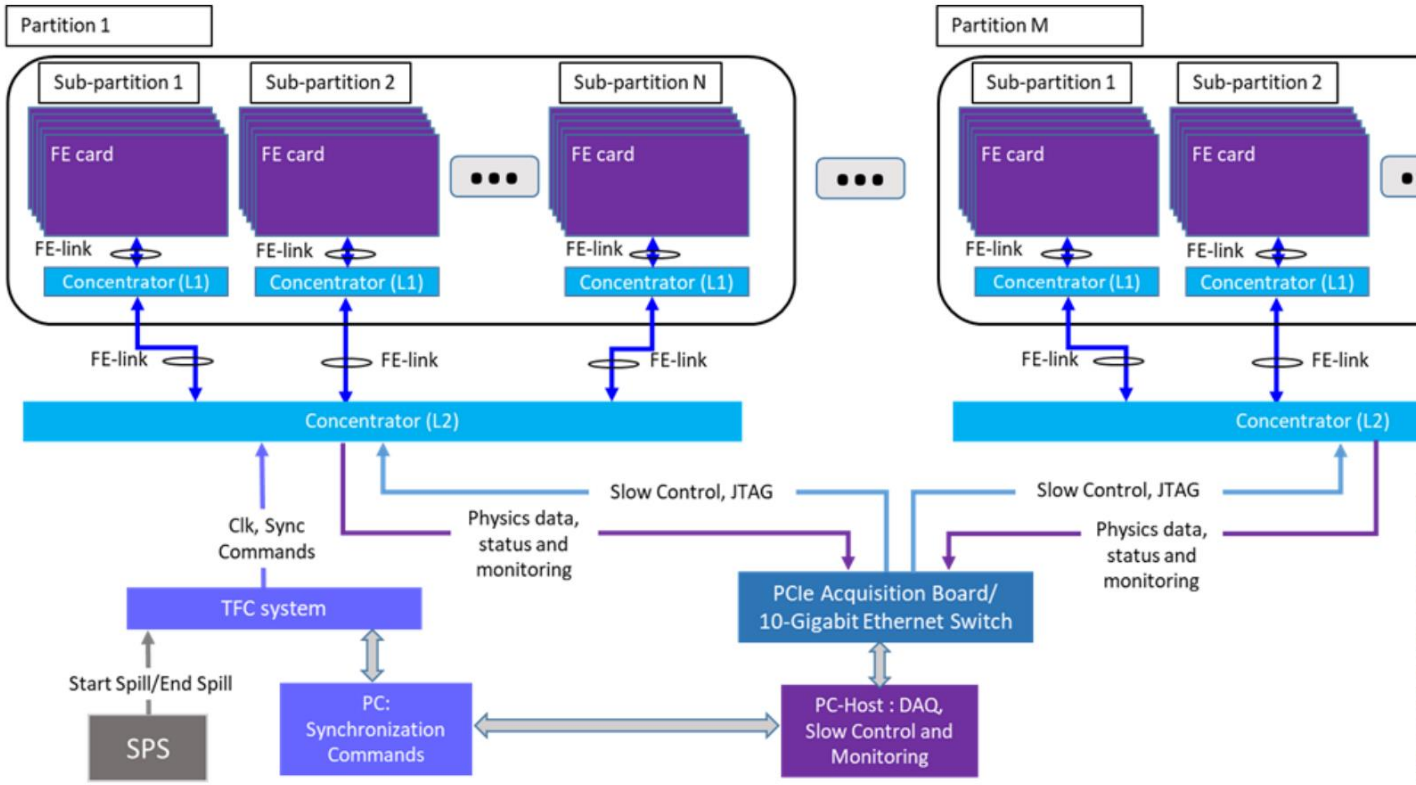


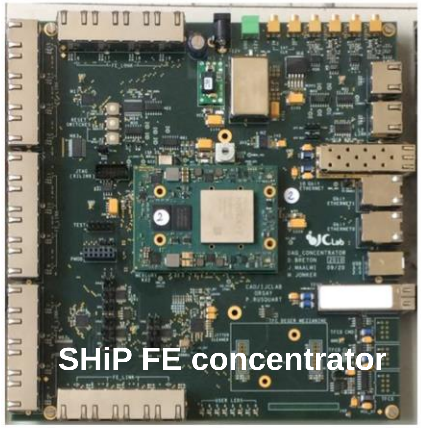


Reconstruction challenge: satellite showers in the long transverse tails

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.