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BDF/SHiP @ ECN3 Proposal

on behalf of the SHiP collaboration of 33 institutes from 15 countries and CERN

→ Attention is given to changes since LoI [CERN-SPSC-2022-032]

OUTLINE:

- *New configuration of the muon shield with SC section*
- *Modified geometry of SHiP*
- *Re-evaluation of backgrounds*
- *Physics performance (FIPs and neutrino programme)*
- *Possible future upgrades and extensions of BDF*
- *Road map and cost estimate*
- *Status of collaboration*
- *Summary*

Brief summary of the LoI configuration

- ✓ ***Muon shield is made of Normal Conducting (NC) magnets***

  - total length ~25m, shorter than in CDS by 5m

  The muon shield was not optimised, but simply shortened to adapt to ECN3 dimensions while respecting an acceptable rate of passing muons

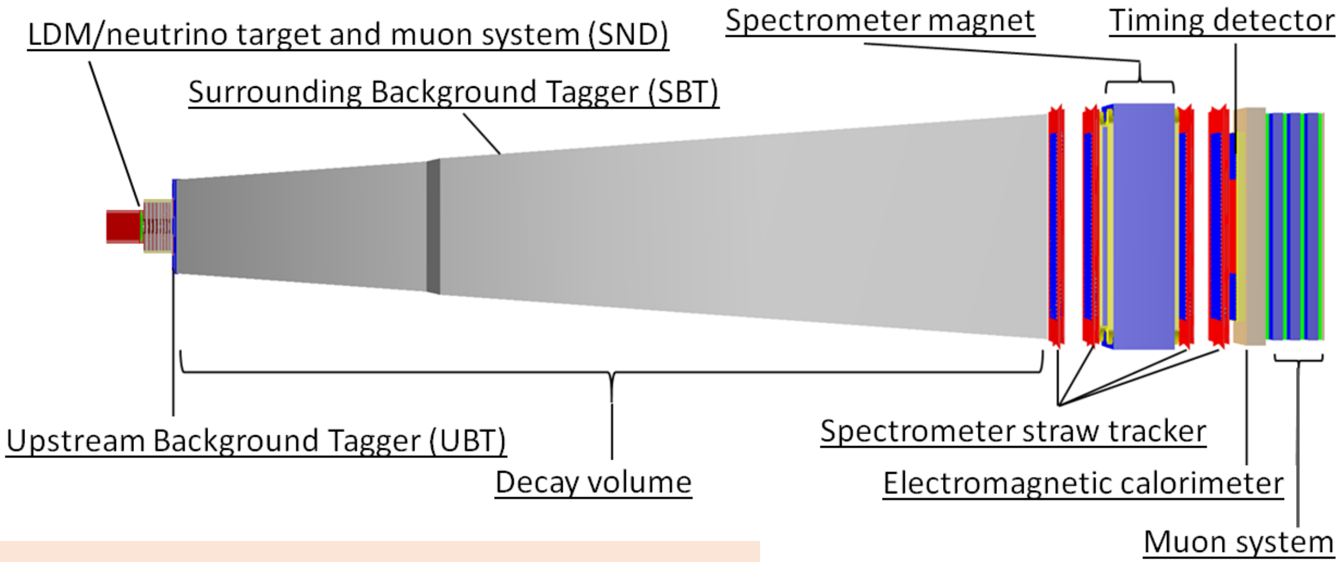
  - 154 kHz in the main tracker

  - 4 Hz/cm^2 in SND

  After LoI, an optimisation of the NC muon shield was completed. Rates reduced down to

  - 67 kHz in the main tracker

  - 2 Hz/cm^2 in SND
- ✓ ***SND shorter by 3m***
- ✓ ***HSDS spectrometer re-dimensioned for ECN3, has the same length as in CDS, but located closer to the SHiP target by 8m***

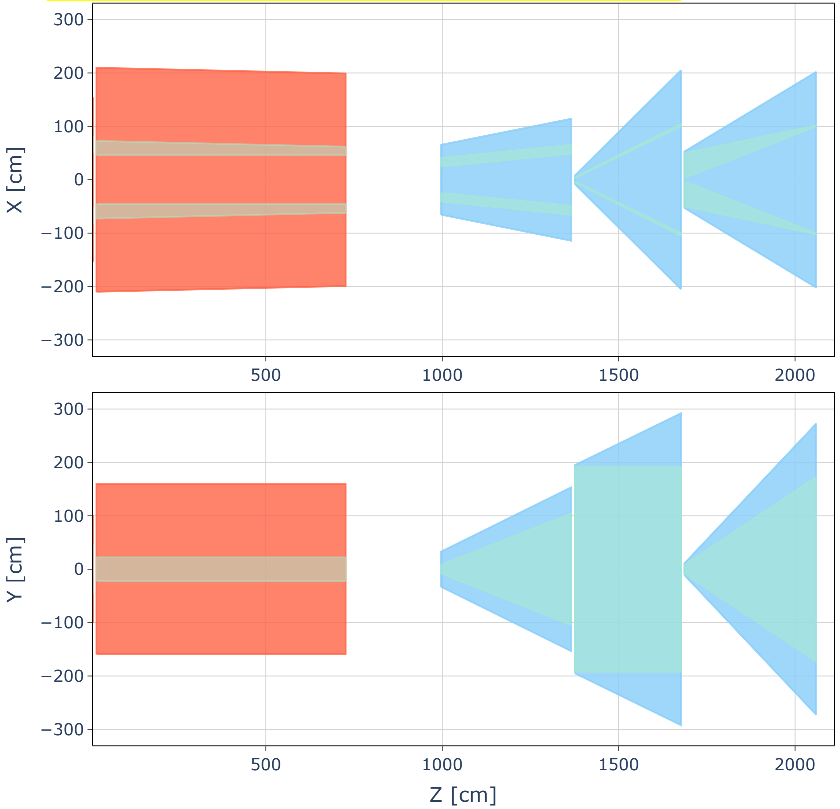


- ***Robust NC option of the muon shield at ECN3 confirmed***
- ***SHiP sensitivity is similar to CDS***

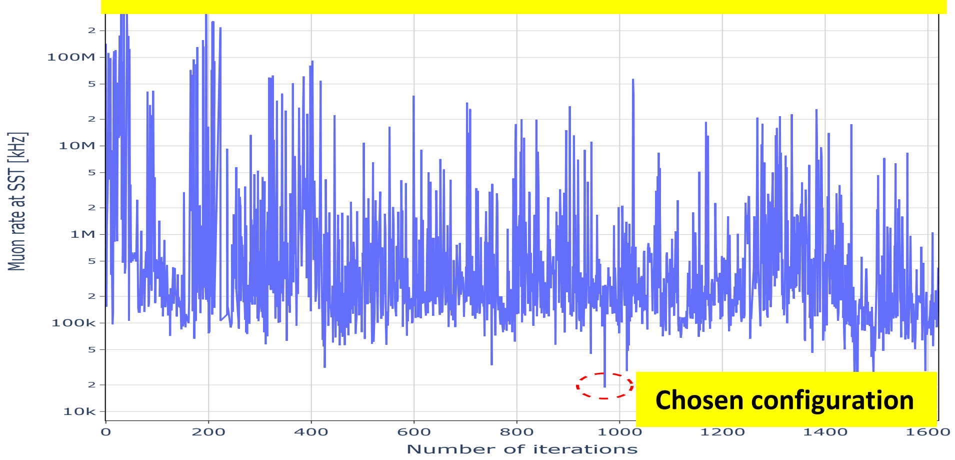
New configuration of the muon shield

- ✓ *Consider using superconducting (SC) technology to reduce the length of the muon shield*
  → hybrid option with 1st section SC and 2nd section NC
- ✓ *Optimisation provides numerous solutions with acceptable rates in SND and the HS tracker*

Hybrid option of the muon shield



Optimisation finds many local minima in rates



Chosen configuration

Final configuration will be further optimised including more engineering details

- ✓ *The length of the hybrid option is reduced by 5m compared to LoI → the SHiP decay volume is closer to the target by 13m compared to CDS design*
- ✓ ***Low rates of passing muons: 12 kHz in the HS tracker, ~1 Hz/cm^2 in SND***
- ✓ ***Hybrid option is in FairShip for background evaluation***

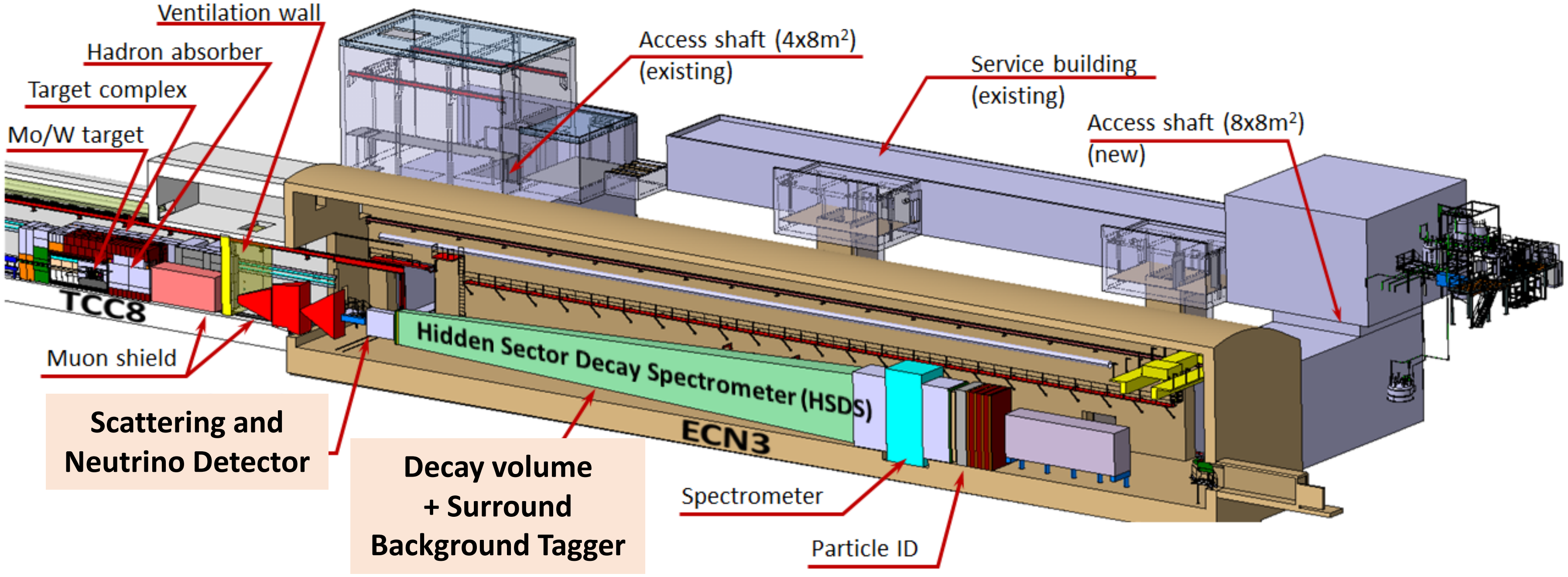
Modified SHiP geometry
(compared to LoI)

- ✓ ***Hybrid muon shield***

- ✓ ***New layout of SND***
  SND is at closer distance and sees higher flux of neutrinos → more compact detector (145 m^2 of emulsion, just three times more than at SND@LHC)

- ✓ ***SBT with reduced thickness of Liquid Scintillator (20cm)***
  Good spatial and time resolution demonstrated with prototypes

- ✓ ***Single PID system**, merging ECAL and Muon detectors*



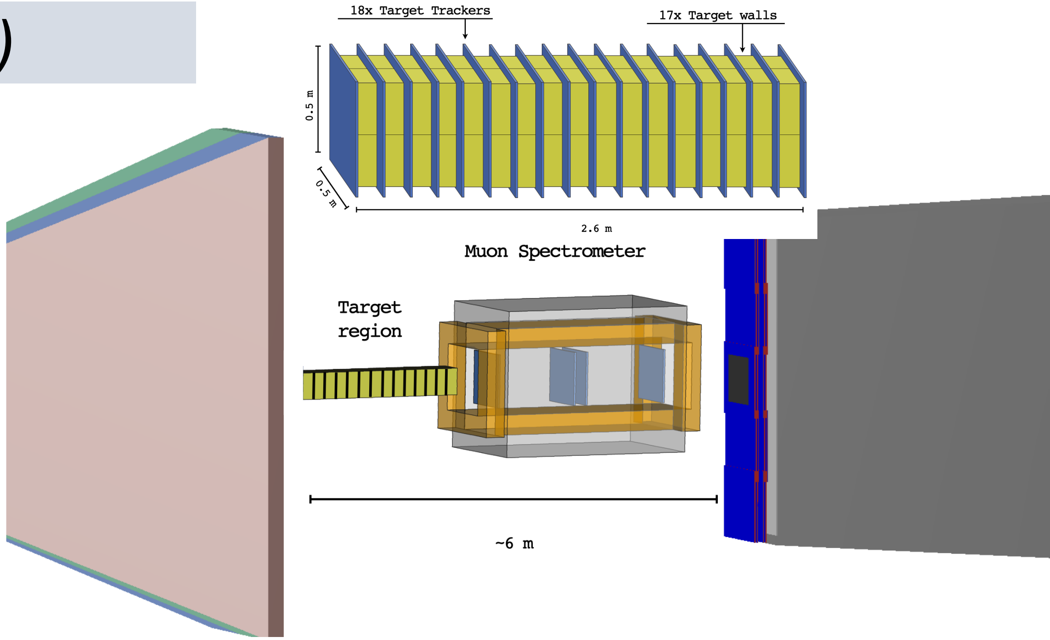
Scattering and Neutrino Detector

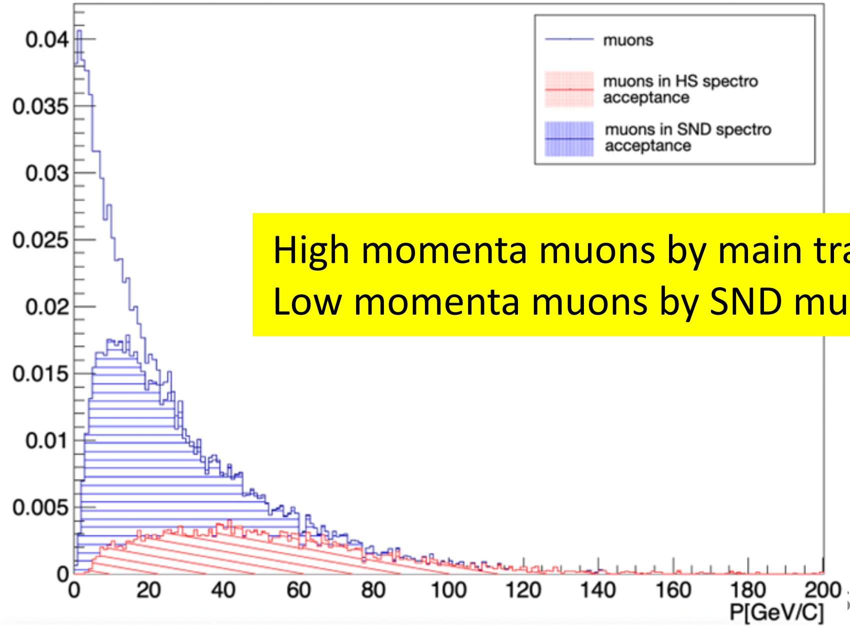
Decay volume + Surround Background Tagger

Modified SHiP configuration implemented in FairShip as an alternative to the LoI configuration

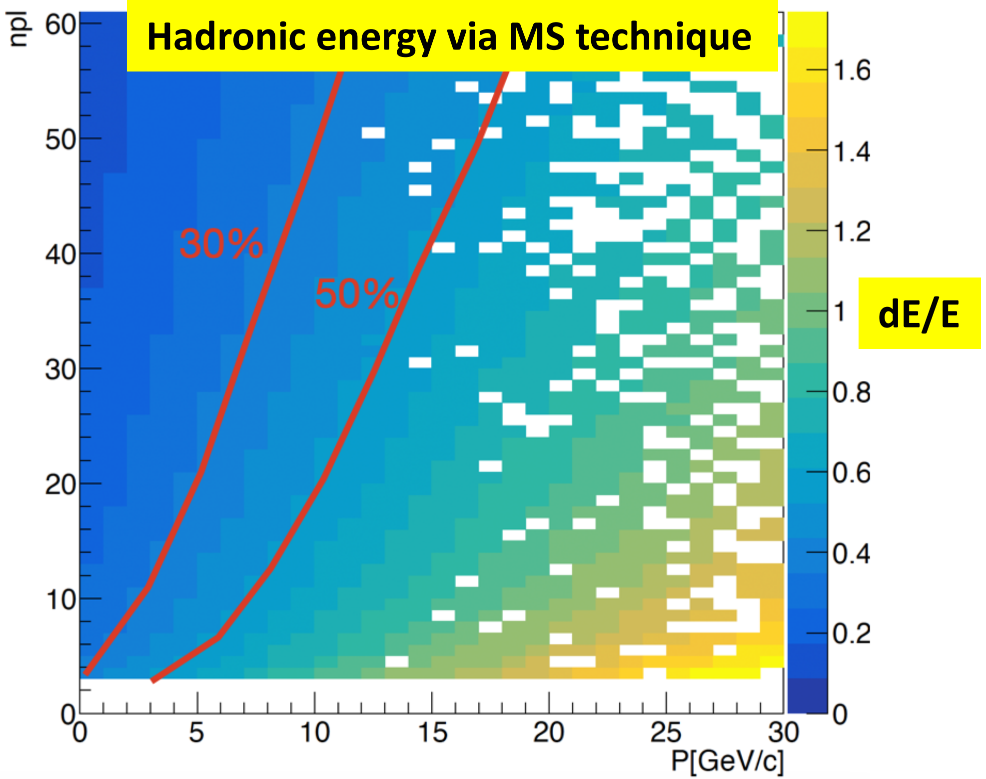
Scattering Neutrino Detector (SND)

- ✓ *Neutrino/LDM W-target instrumented with layers of emulsion films → micrometric accuracy is crucial for tau neutrino physics (detecting tau lepton and charm decay vertices)*
- ✓ *Target trackers provide time stamping and help reconstructing em-showers*
- ✓ *SND muon spectrometer (with the help of main tracker) measures the charge and momenta of muons (10% accuracy with 1T magnetic field over 3m and 100μm position resolution)*
- ✓ *Momenta of pions and kaons measured using their Multiple Scattering (MS) in the target (~40% accuracy for P_h < 15 GeV/c)*





High momenta muons by main tracker (~25%)
Low momenta muons by SND muon spectrometer



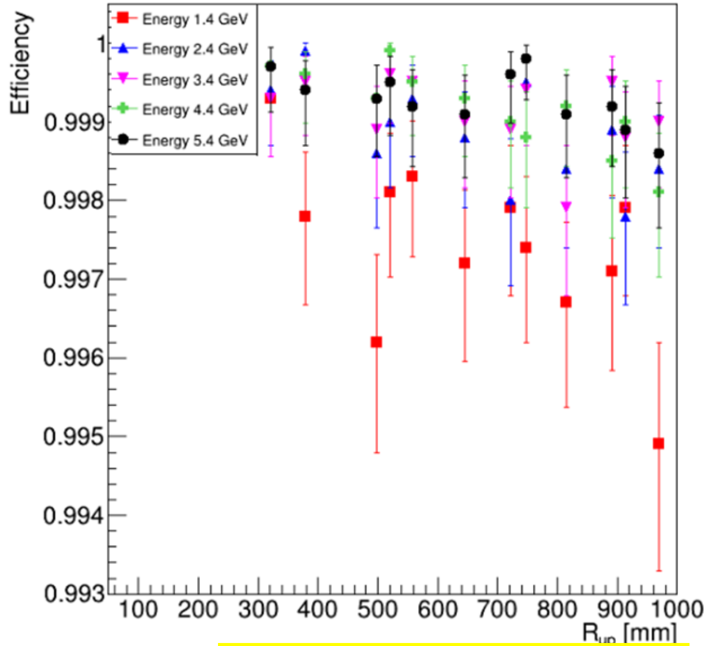
Hadronic energy via MS technique

dE/E

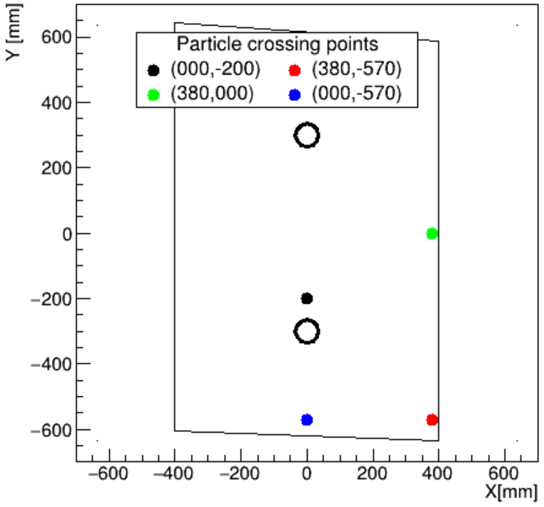
*Surrounding **B**ackground **T**agger (**SBT**)*

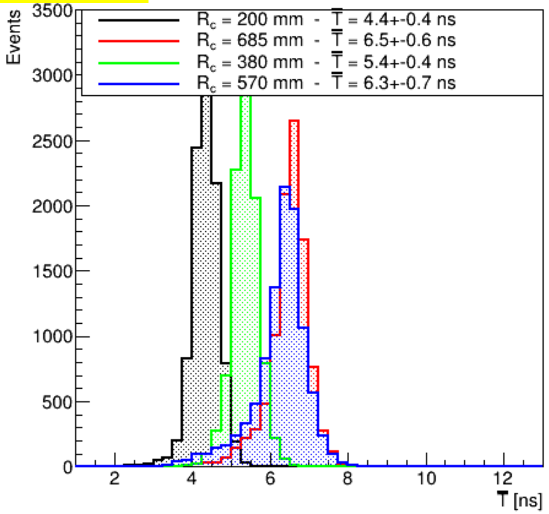
- ✓ *SBT based on Liquid Scintillator (LS) technology → provides high veto efficiency at reasonable cost*
- ✓ *SBT LS cells integrated into the wall structure of decay vessel*
- ✓ *Scintillating light is readout by wave-length-shifting optical modules*

Beam test of large scale prototype demonstrated >99.3% detection efficiency for distances ~95cm
99% efficiency was used in background evaluation

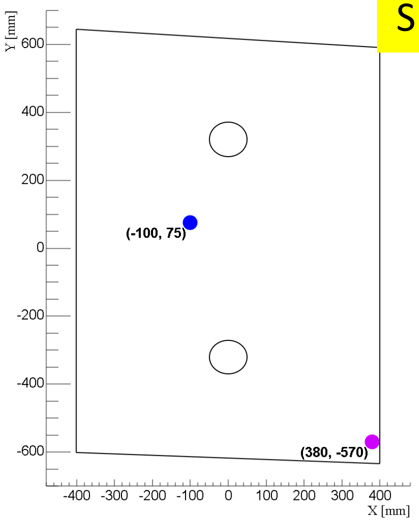


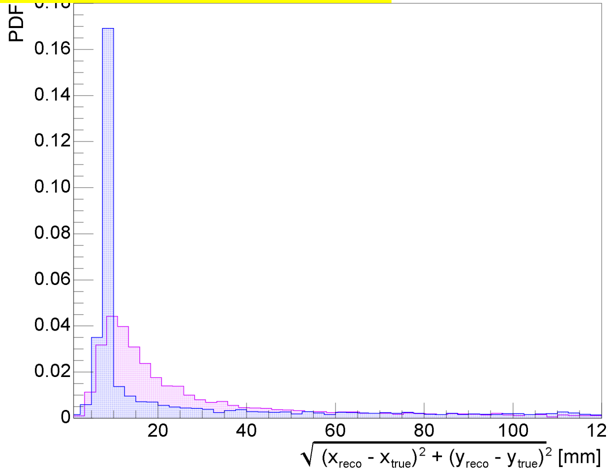
Time resolution < 1ns





Spatial resolution ~10cm





Excellent time and position resolutions demonstrated with prototypes
Have not been used so far → will potentially improve veto performance

Evaluation of backgrounds
(for hybrid muon shield)

✓ ***Background estimation is based on full GEANT-based MC, FairShip, updated with the complete geometry of the ECN3 complex and revised muon shield (hybrid SC/NC option) and detectors.***

✓ ***Critical points in background evaluation:***

- *Use PYTHIA6 for muon DIS and GENIE for neutrino interactions*
- *Generate dedicated samples of charm and beauty hadrons known to produce muons and neutrinos with kinematics similar to the signal events*
- *Backgrounds from muon and neutrino DIS are dominated by random combinations of secondaries but NOT by the V^0s*
- *Use very simple selection for both fully and partially reconstructed events*

Selection + **Time coincidence** + **Veto**

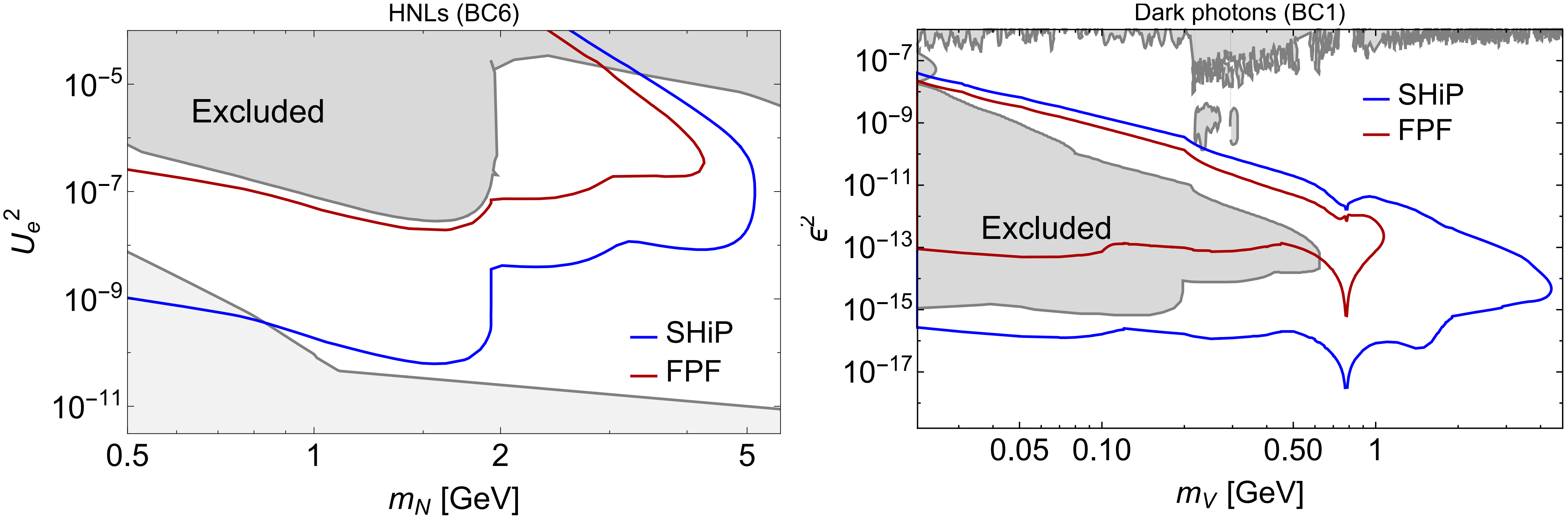
Track momentum	$> 1.0\,\mathrm{GeV}/c$
Track pair distance of closest approach	$< 1\,\mathrm{cm}$
Track pair vertex position in decay volume	$> 5\,\mathrm{cm}$ from inner wall
	$> 100\,\mathrm{cm}$ from entrance (partially)
Impact parameter w.r.t. target (fully reconstructed)	$< 10\,\mathrm{cm}$
Impact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

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

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

Sensitivity to FIPs
(decay signature)

Similar to the CDS sensitivities for the same Npot. But significant increase comes from assuming data taking for 15 years. SHiP sensitivity is not limited by backgrounds. Specialized infrastructure, required to collect 6 ×10^{20} or more, has been studied and is not a limiting factor



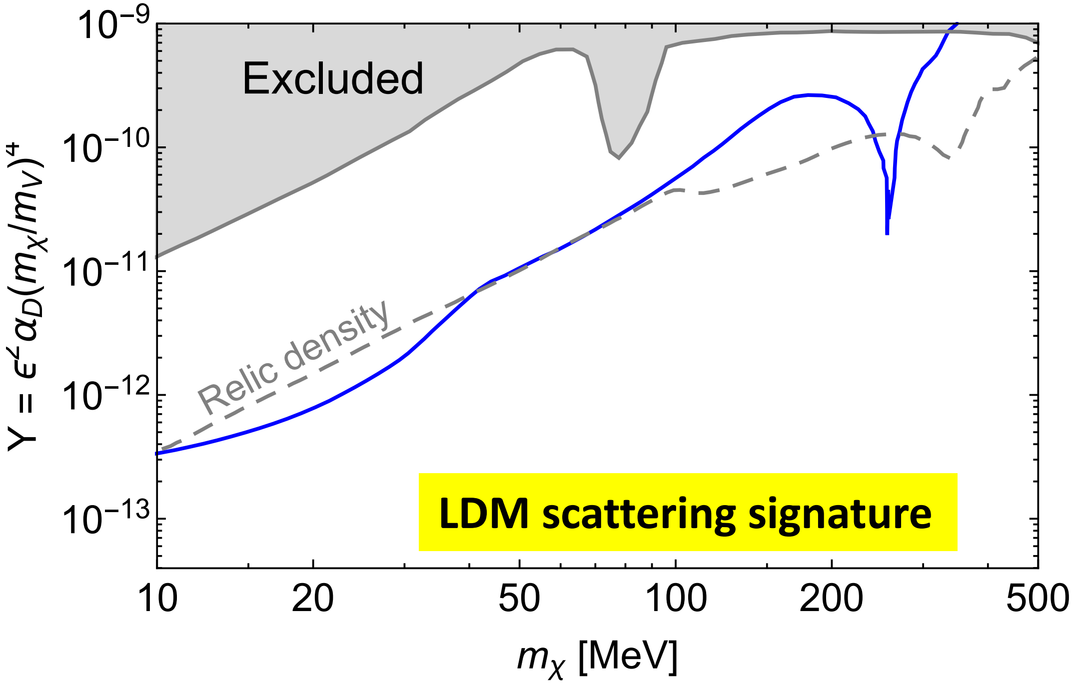
SHiP sensitivities to FIPs are orders of magnitude better than the ones for competing projects, including FPF

Sensitivity to LDM
(scattering signature)

- ✓ *Evaluation of backgrounds is now completed for the new configuration of the SND detector*
- ✓ *Background is dominated by neutrino elastic and quasi-elastic scattering, and is slightly smaller than in CDS (230 events) for the same Npot*

	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	52	27	64	42	185
Quasi - elastic scattering	-	9			9
Resonant scattering	-	-			-
Deep inelastic scattering	-	-			-
Total	52	36	64	42	194

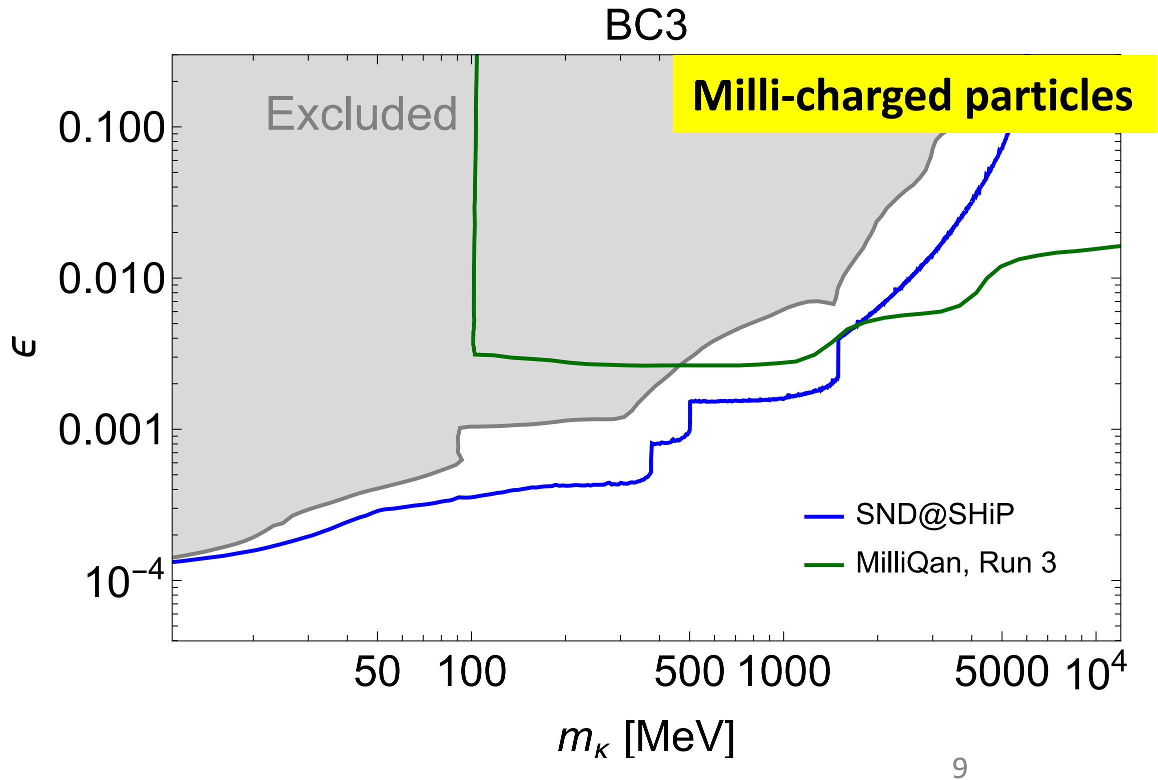
$m_\chi/m_V = 1/3$, $\alpha_D = 0.1$



LDM scattering signature

Expectation from relic density is in reach

BC3

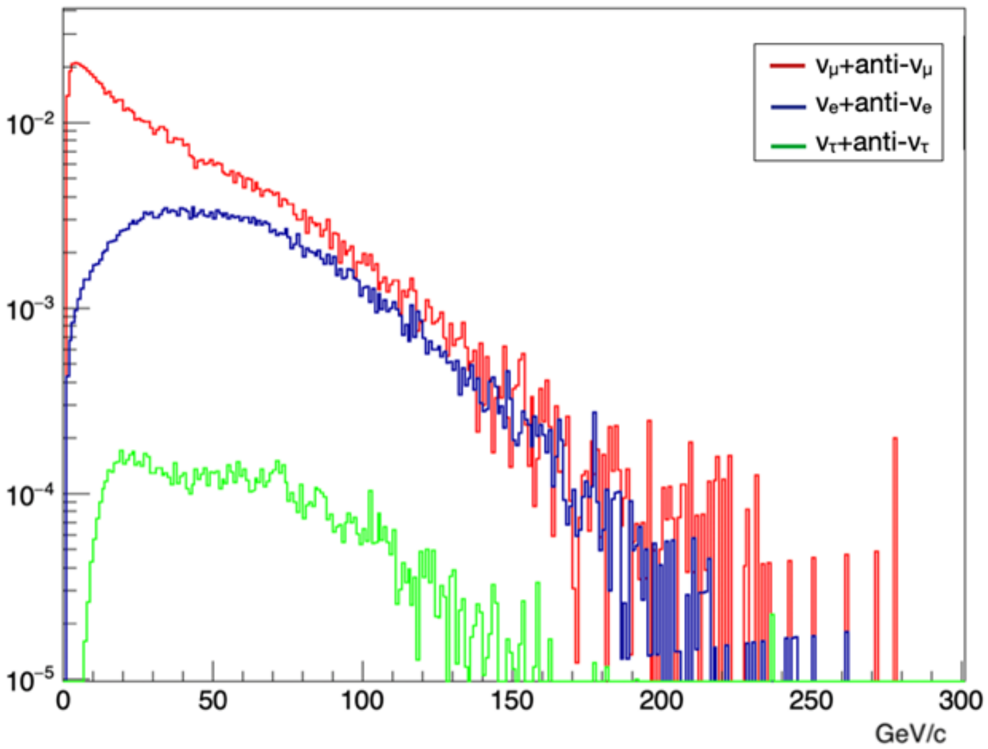


Milli-charged particles

Neutrino interaction physics

Huge sample of tau neutrinos can be produced at SPS via $D_s \rightarrow \tau\nu_\tau$

	<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}



Uncertainty of ν_τ flux is dominated by accuracy in:

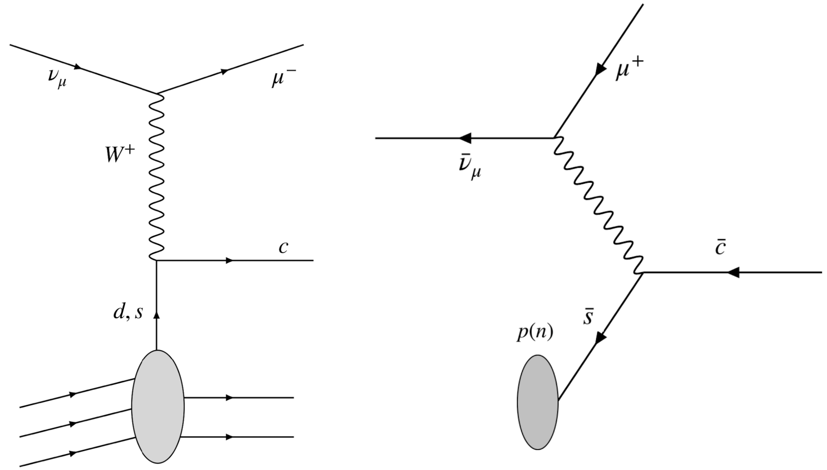
- ***D_s production cross-section at SPS,*** *currently 10%, but NA65 expect to reconstruct ~1000 events soon*
- ***BR($D_s \rightarrow \tau\nu_\tau$) ~3-4%***
- ***Cascade production of charm in thick target*** *SHiP plans a dedicated experiment in the near future to measure J/ψ and charm production using muons in targets of variable depths*

Plan to reach ≤5% uncertainty in ν_τ flux seems realistic

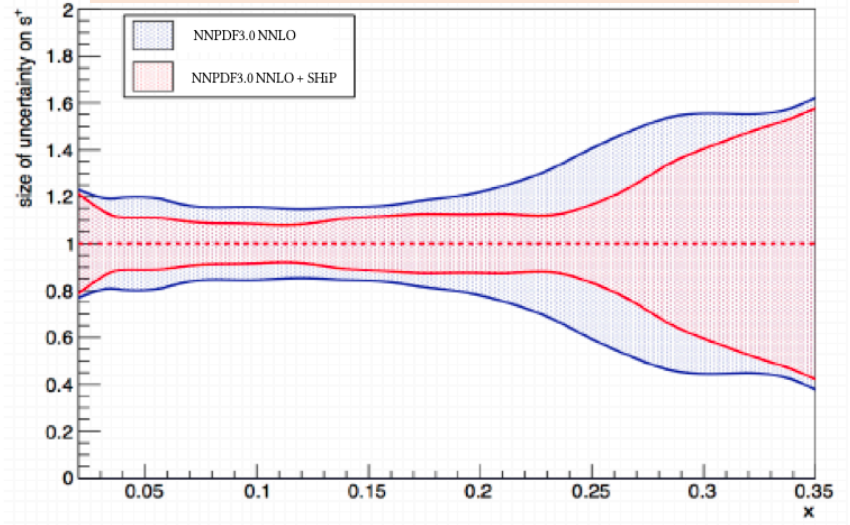
- ✓ ***Important tests of SM:***
  - *Lepton Flavour Universality in neutrino interactions (1-3% accuracy in ratios: ν_e/ν_μ, ν_e/ν_τ and ν_μ/ν_τ)*
  - *Test of F_4 ($F_4 \approx 0$) and F_5 ($F_5 = 2xF_2$) structure functions, accessible only with tau neutrinos [C.Albright and C.Jarlskog. NP B84 (1975)]*
- ✓ *Measurement of neutrino cross-sections up to 100 GeV as an input to neutrino oscillation programme*

Neutrino induced charm production

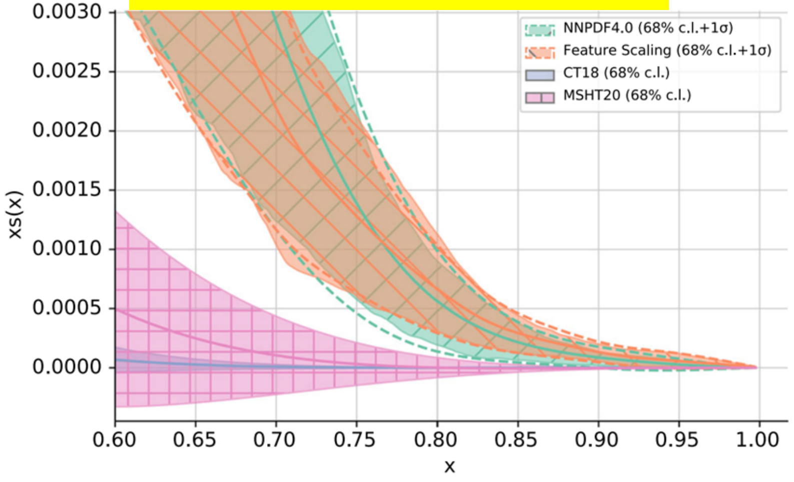
- ✓ *Expect ~6×10^5 neutrino induced charm hadrons for 6×10^{20} pot → more than an order of magnitude larger than currently available*
- ✓ *Anti-charmed hadrons are predominantly produced by anti-strange content of proton (~90%)*
- ✓ *Understanding of nucleon strangeness is critical for precision tests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



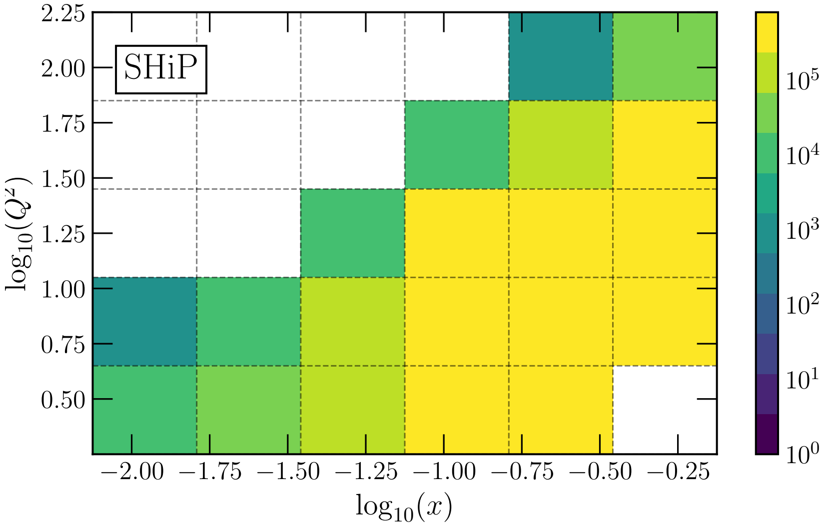
*SHiP sensitivity to PDF for x < 0.35 (already evaluated in [*Prog. Phys. 79 (2016) 124201*)]*



Current status of the proton strangeness (NuTeV/CCFR data) at high x



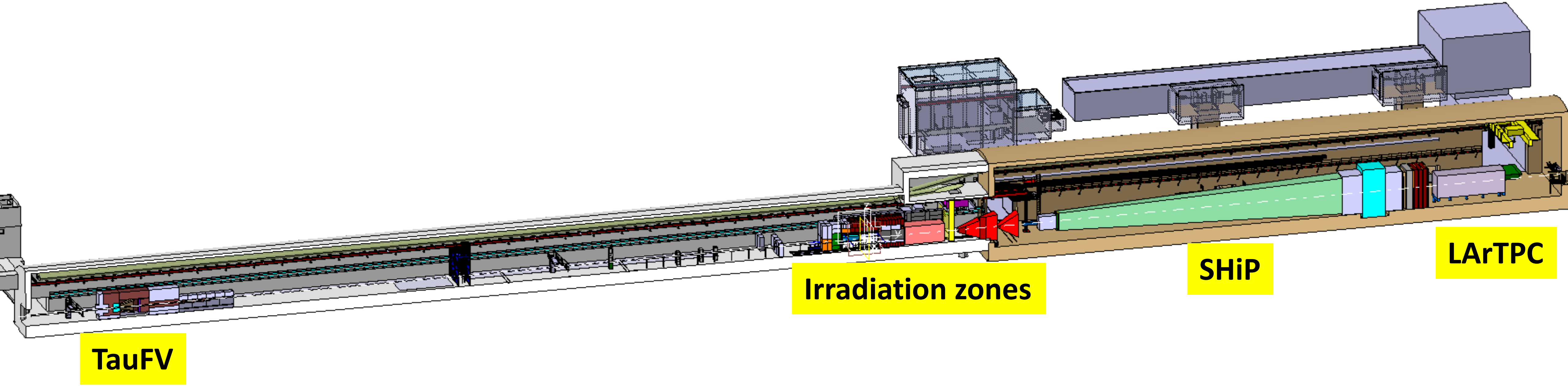
Large data samples at SHiP will greatly improve current measurements up to high values of x



Possible extensions at BDF

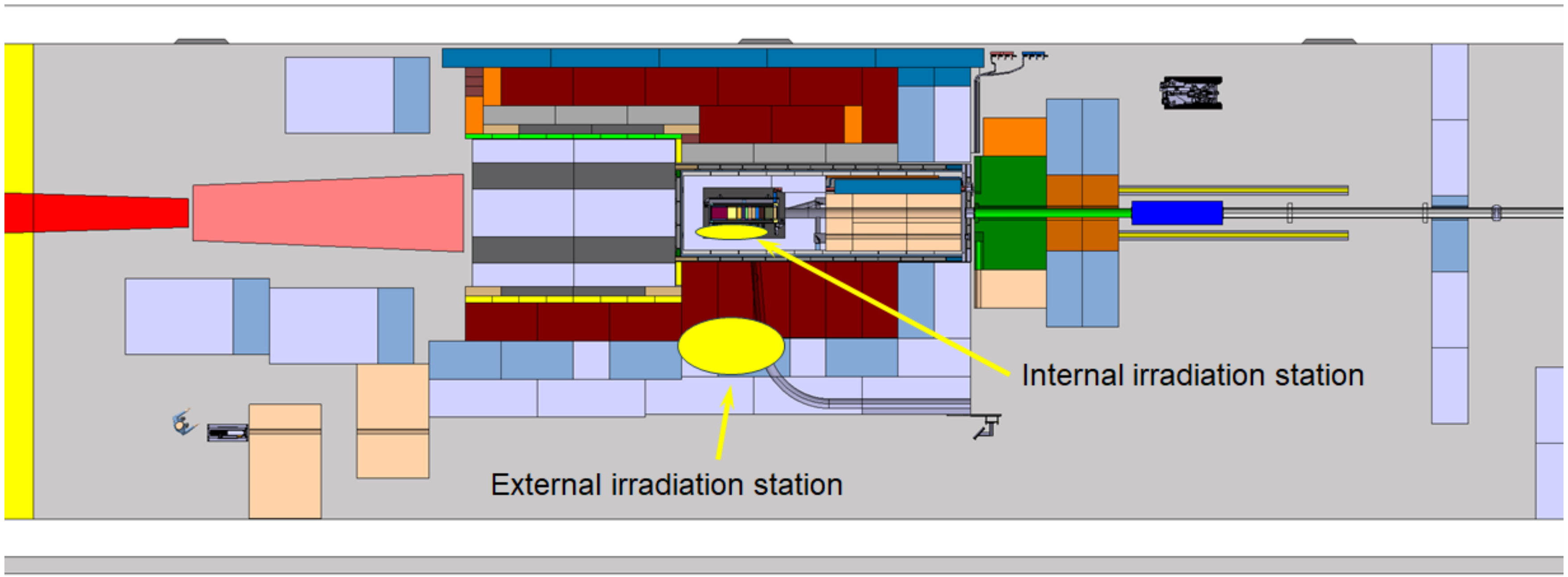
Preliminary studies of opportunities to extend BDF physics programme:

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



BDF as Irradiation Facility

- ✓ *Can be exploited synergetically with SHiP*
- ✓ *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} 1-MeV neq/cm^2 per year*



Two zones:

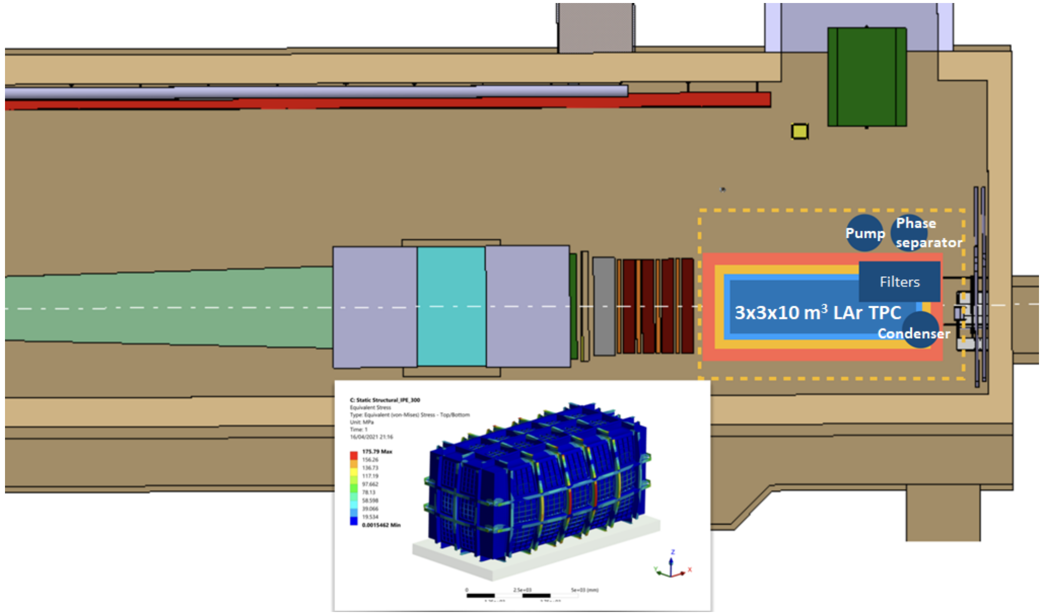
- *Internal: 100-400 MGy / year adapted for irradiation of small volumes*
- *External: Larger zone of O(m^2) with lower radiation level*

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

LAr TPC Detector

(to complement searches for FIPs)

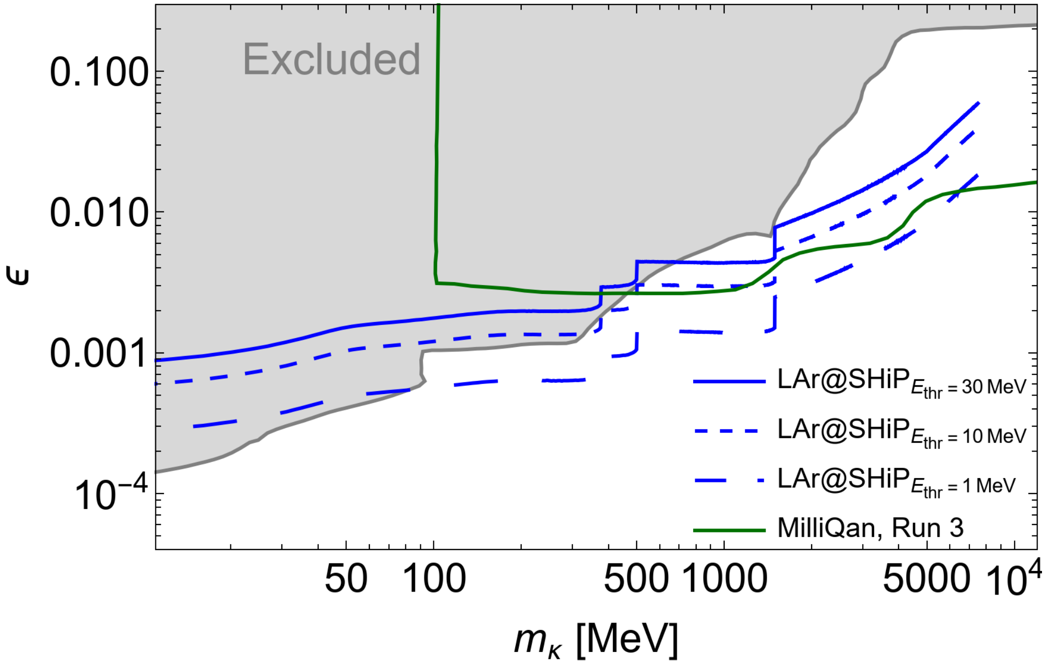
- ✓ *LArTPC technology is currently used in neutrino and DM experiments*
- ✓ *Large experience at CERN with building 700 t detectors for DUNE*
- ✓ *Space available behind SHiP would allow the installation of LArTPC with an active volume up to 3×3×10 m^3 (~130 t) and associated infrastructure*



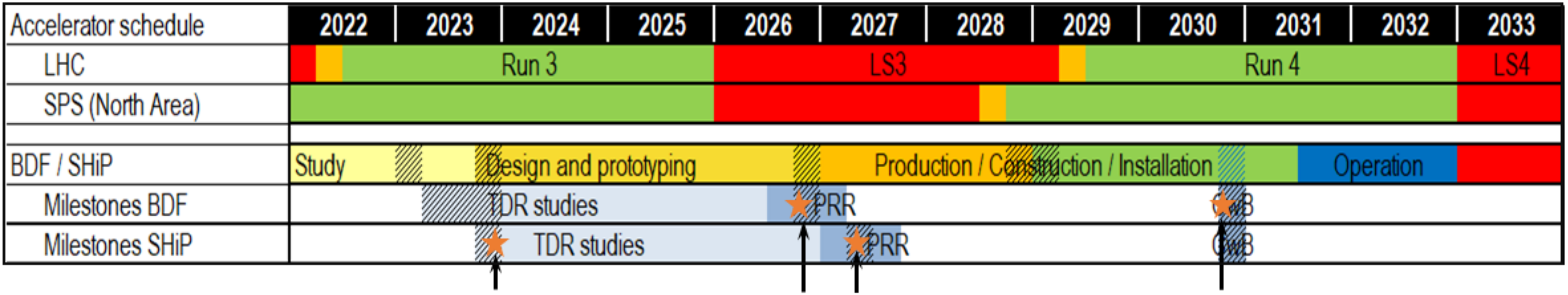
BC3

Physics reach:

- *Extends SHiP's physics reach and enables another sensitive search for Milli Charged Particles*
- *Striking confirmation of potential FIP discovery using different technology*



Roadmap



Approval for TDR

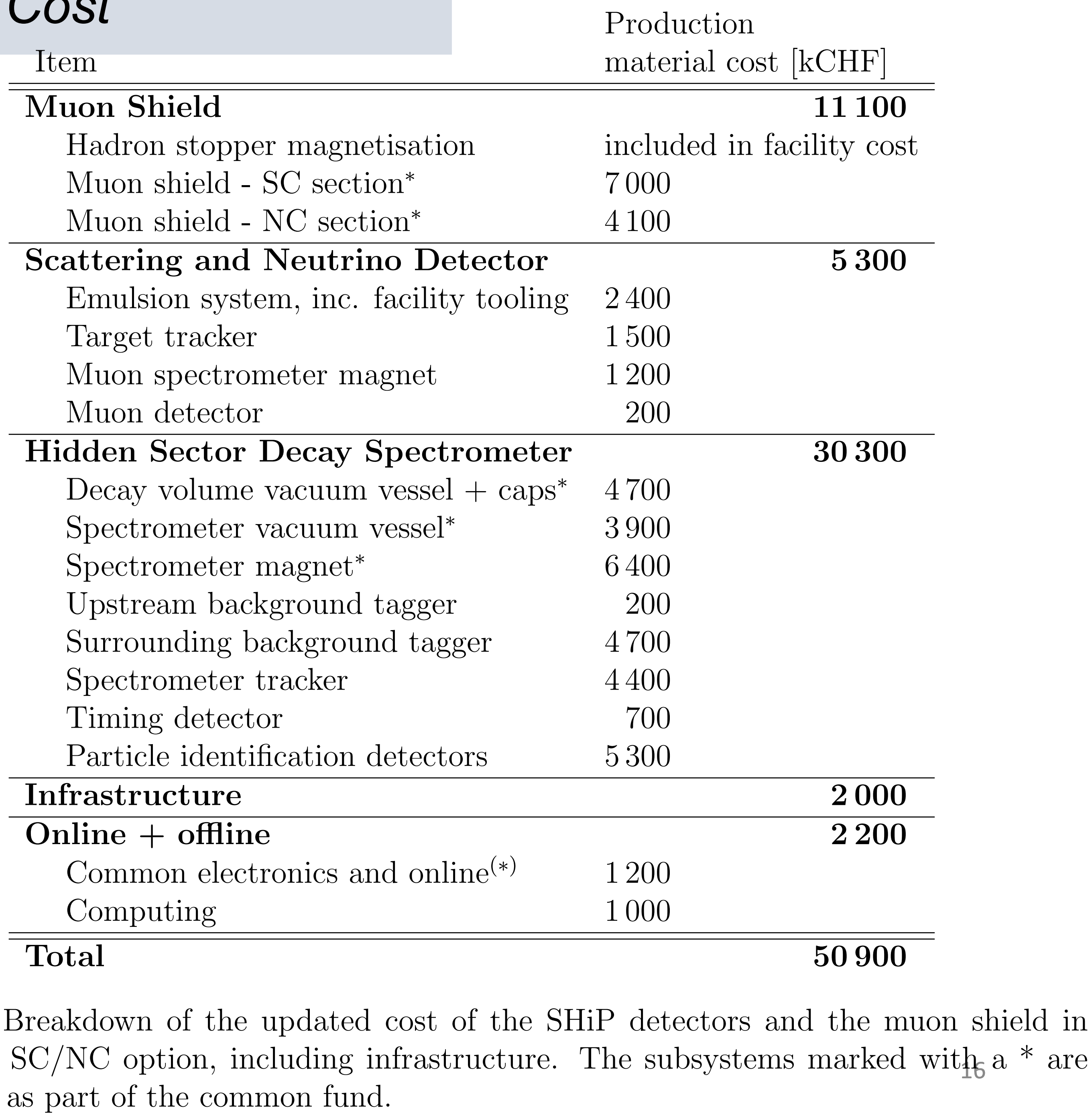
Submission of TDRs

Facility commissioning

- ✓ ***~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***

Cost

- ✓ *Cost is dominated by infrastructure and material cost (upper estimates used taking into account inflation)*
- ✓ *Uncertainty in sub-detector costs depends on the level of maturity*
- ✓ *Sub-detectors marked with (*) are considered as part of the Common Fund*
- ✓ *Staging in detector construction is possible if needed*

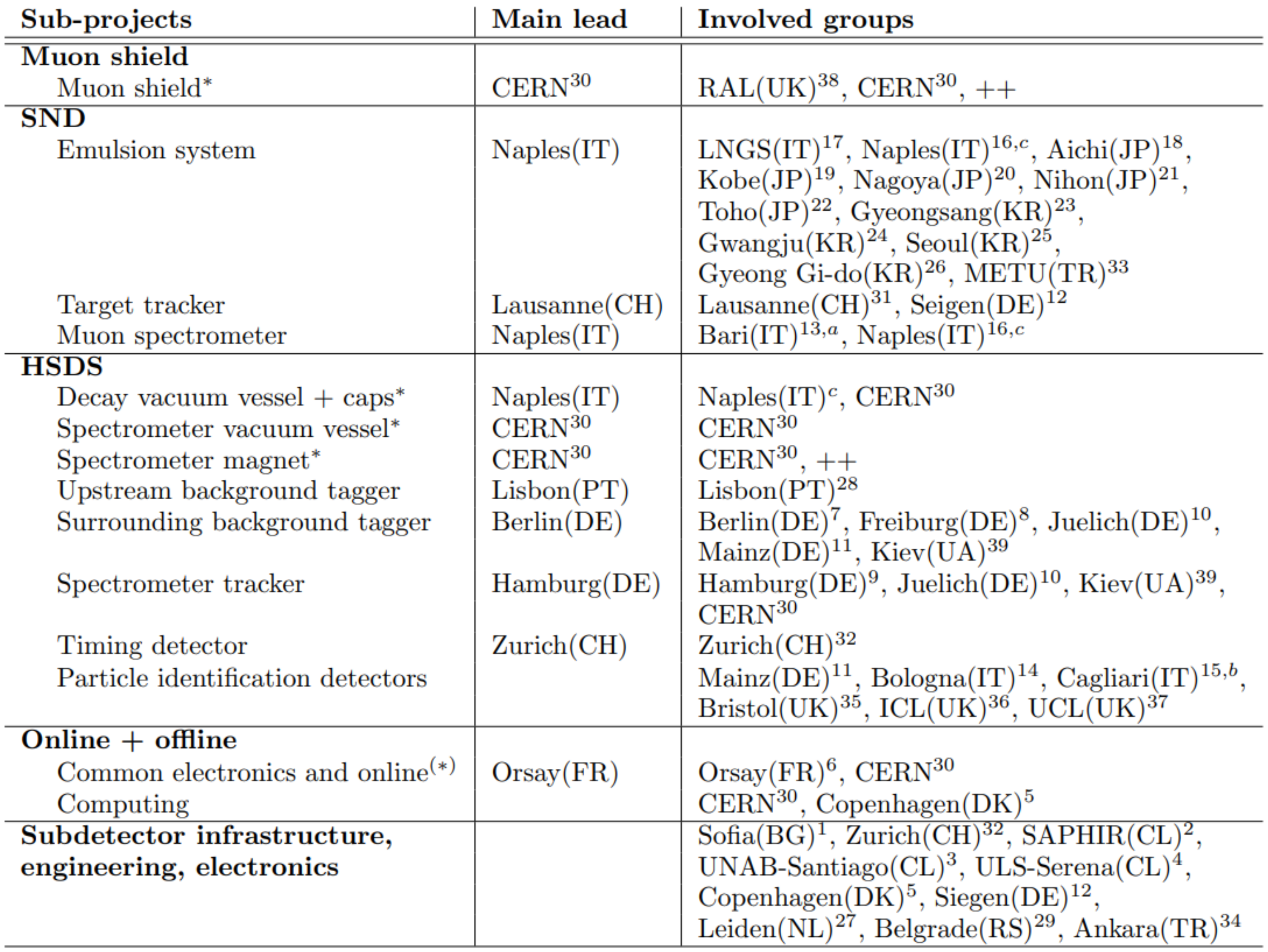


Item	Production material cost [kCHF]	
Muon Shield		**11 100**
Hadron stopper magnetisation	included in facility cost	
Muon shield - SC section*	7 000	
Muon shield - NC section*	4 100	
Scattering and Neutrino Detector		**5 300**
Emulsion system, inc. facility tooling	2 400	
Target tracker	1 500	
Muon spectrometer magnet	1 200	
Muon detector	200	
Hidden Sector Decay Spectrometer		**30 300**
Decay volume vacuum vessel + caps*	4 700	
Spectrometer vacuum vessel*	3 900	
Spectrometer magnet*	6 400	
Upstream background tagger	200	
Surrounding background tagger	4 700	
Spectrometer tracker	4 400	
Timing detector	700	
Particle identification detectors	5 300	
Infrastructure		**2 000**
Online + offline		**2 200**
Common electronics and online$^{(*)}$	1 200	
Computing	1 000	
Total		**50 900**

Table 11: Breakdown of the updated cost of the SHiP detectors and the muon shield in the hybrid SC/NC option, including infrastructure. The subsystems marked with a * are considered as part of the common fund.

Preliminary status of the collaboration
(will be updated for the SPSC meeting in November)

- ✓ *All 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*

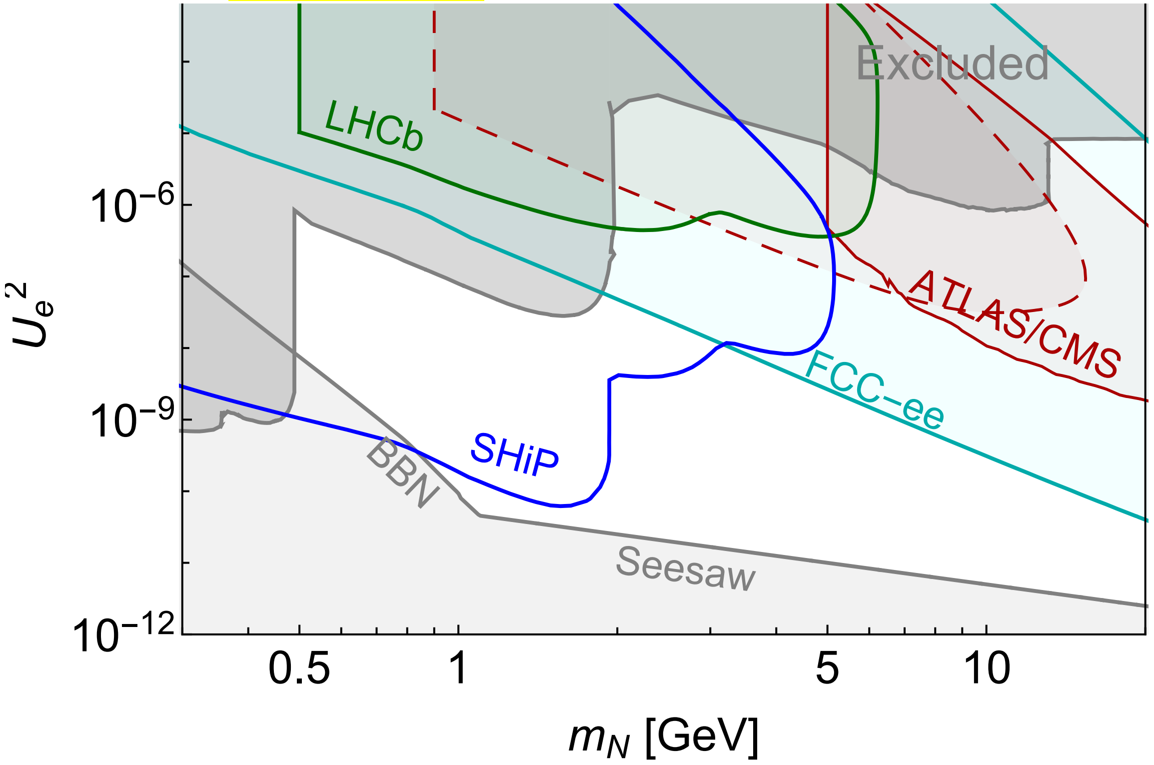


Sub-projects	**Main lead**	**Involved groups**
Muon shield		
Muon shield*	CERN[30]	RAL(UK)[38], CERN[30], ++
SND		
Emulsion system	Naples(IT)	LNGS(IT)[17], Naples(IT)[16,c], Aichi(JP)[18], Kobe(JP)[19], Nagoya(JP)[20], Nihon(JP)[21], Toho(JP)[22], Gyeongsang(KR)[23], Gwangju(KR)[24], Seoul(KR)[25], Gyeong 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]

Summary

- ✓ ***BDF/SHiP provides a clear opportunity to discover FIPs in the decays of heavy quarks (or to close this "topic" experimentally).*** *This is complementary to the FIP searches at HL-LHC and future e+e⁻ - collider (where FIPs can be searched in boson decays)*

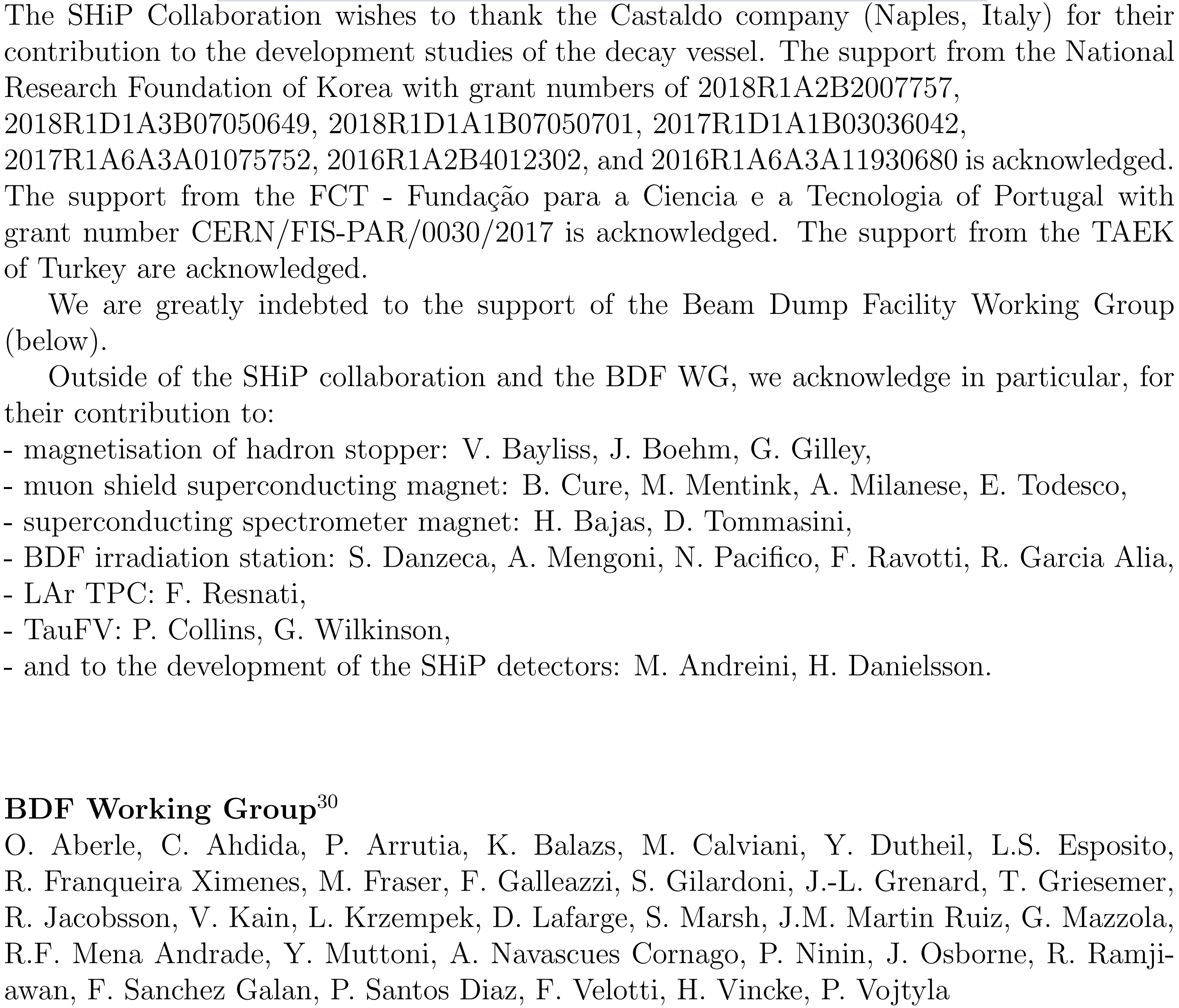
6×10^{20}pot



See-saw limit is almost in reach below charm mass

- ✓ ***Robust "bread-and-butter" neutrino physics programme, including fundamental tests of SM in tau neutrino interactions.*** *Synergy with neutrino programme at LHC*

Acknowledgments



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- 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