SHiP

Search for Hidden Particles

Progress report

Comprehensive Design Report – 1 year

Richard Jacobsson

on behalf of the SHiP Collaboration

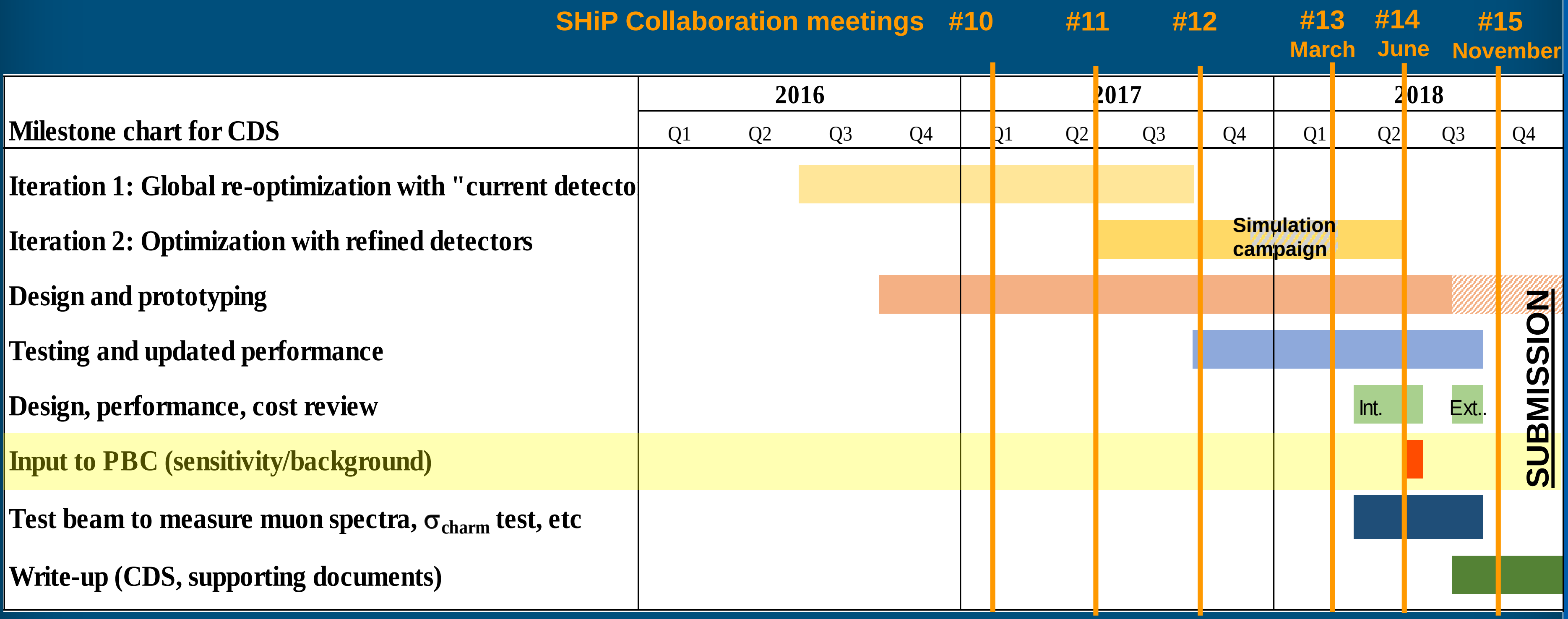
Marine glossary for the SHiP beam dump facility:

- dSHiP: Hidden Sector search through decay to SM
- νSHiP: Neutrino physics
- iSHiP: Hidden Sector search through interaction with SM matter
- τSHIP: LFV τ search

Physics Beyond Collider Workshop, CERN, 21 - 22 November 2017

Comprehensive Design Study Planning

- Developing all physics objectives of SHiP in parallel



- Detailed engineering studies going on in most subsystems
- Most effort invested in background optimization in a realistic design

➔ SHiP is aiming at exploiting maximum yield and acceptance at the proton beam dump in virtually 0-background conditions, it is not optimized for a single or sub-set of simplified models

  - Models evolve quickly

Progress on global optimization

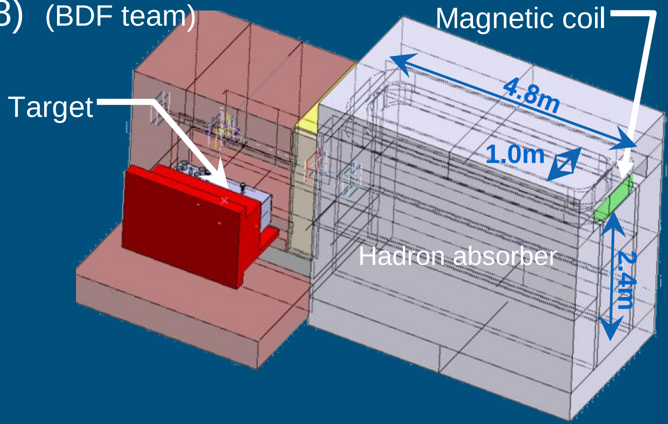
Proton target

- ⦿ Baseline 12λ TZM/W target configuration confirmed (Sep. 2018) (BDF team)
  - Key input to simulation

Muon shield: Magnetized hadron stopper

- ⦿ Concept developed by SHiP – evolved into design

➔ Very strict constraints on integration, access, thermal and magnetic stresses, cooling circuit, radio-activation within SHiP target complex

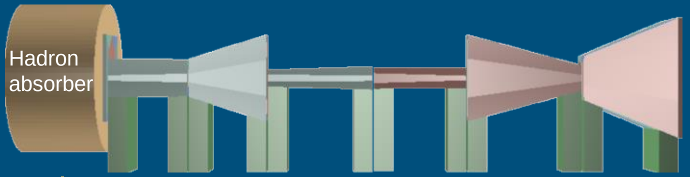


J.-L. Grenard et al.

Muon Shield

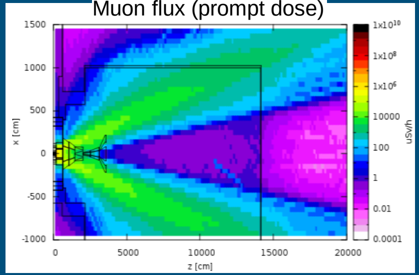
- ⦿ Hadron stopper magnetization + Bayesian optimization applied to optimize muon shield

➔ Muon shield length/weight: 35m / 1500 tonnes (TP: 50m / 2900 tonnes)



➔ Reoptimization of decay volume

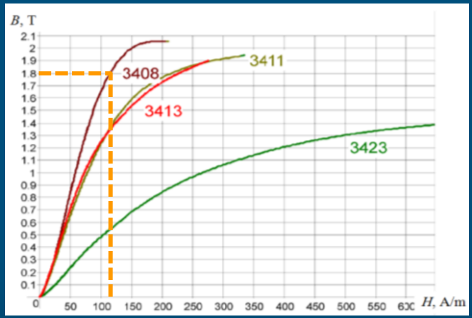
Muon flux (prompt dose)

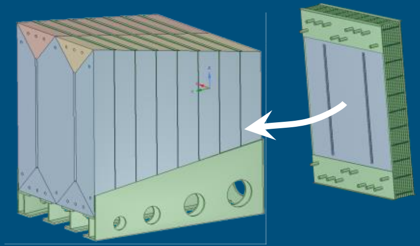


M. Casolino

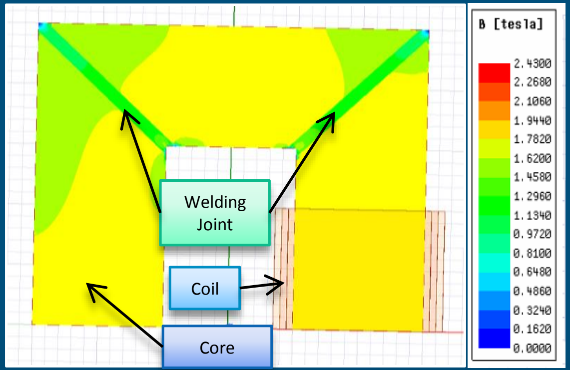
- ⦿ Studies towards engineering design with 0.3mm Grain-Oriented steel and proper field maps

➔Prototyping and test beam in 2018



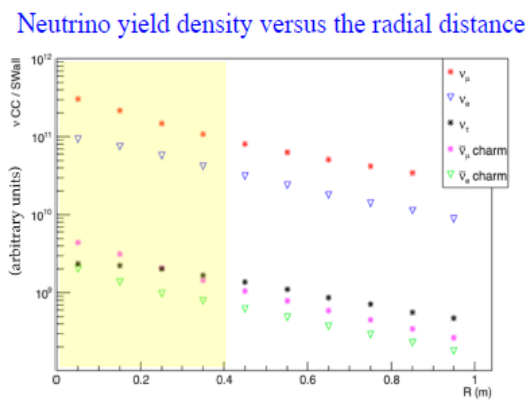


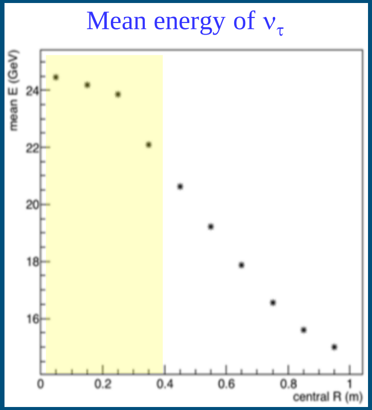
Section length - 4.5 m
Mass - 600 tons

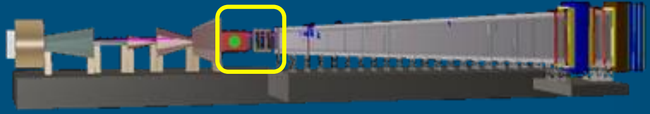


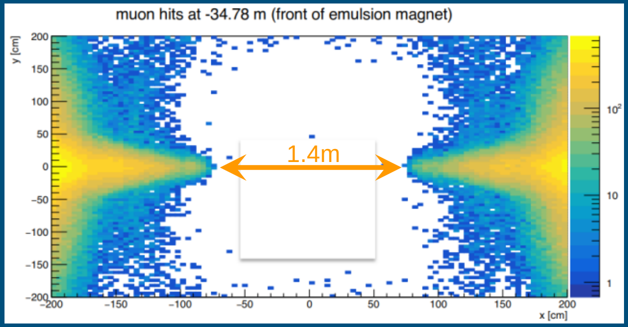
Progress on global optimization

Detector for neutrino physics and search for hidden particles through interaction ("ν/iSHiP")



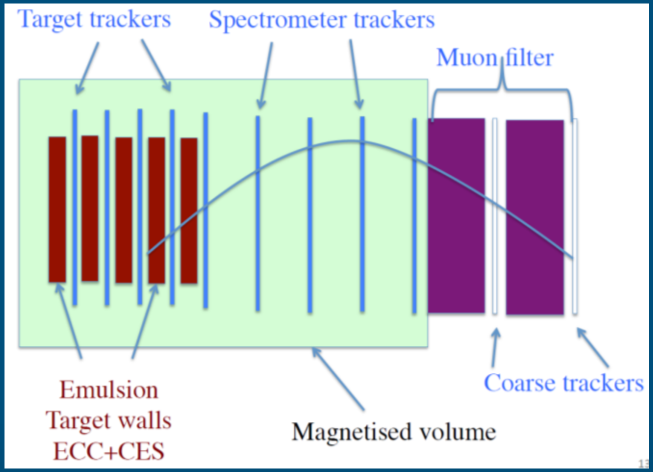




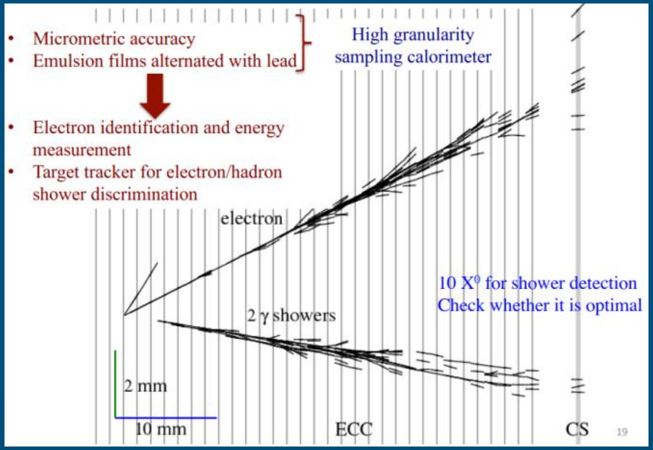


➔ Redeveloped Opera concept into long, narrow detector with single magnet

- Muon spectrometer in air
- Charge determination for muonic and hadronic modes of neutrino interactions
- Optimization of neutrino/hidden particle target with emulsion/electronic tracking



Reminder: Emulsion target concept for νWIMP search

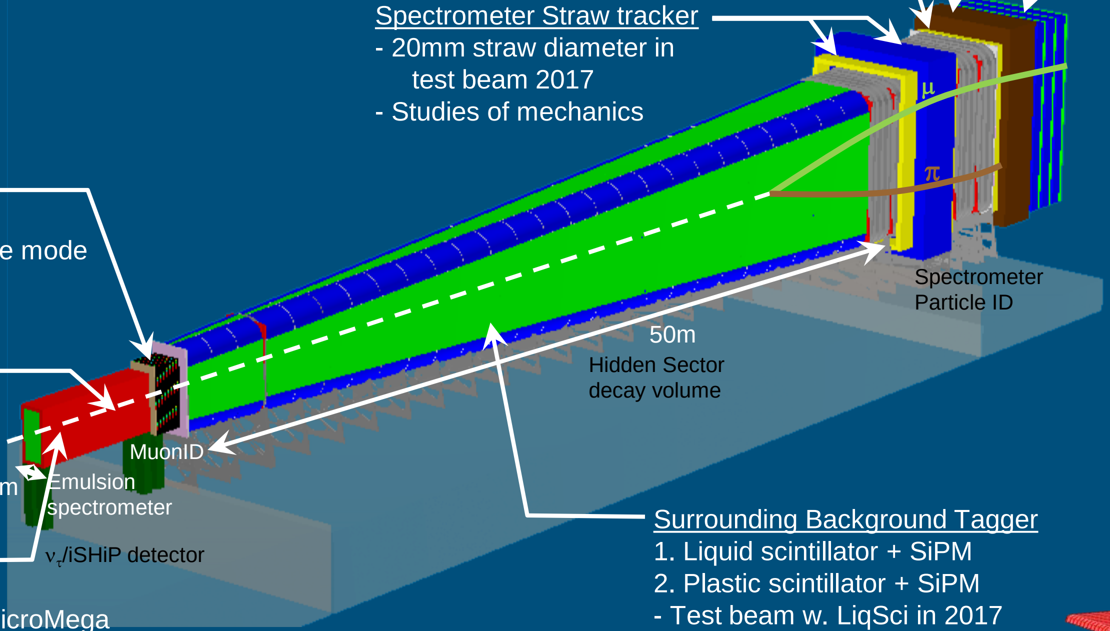


- Micrometric accuracy
- Emulsion films alternated with lead

- Electron identification and energy measurement
- Target tracker for electron/hadron shower discrimination

Detector developments

Significant progress in technology developments, e.g.



<u>ECAL/HCAL</u>
- Sandwich calorimeter w. scintillating bars+SiPM
- High-precision layers for directionality for ALP→$\gamma\gamma$
- Test beam 2018

<u>Timing Detector</u>
1. Plastic scintillator +SIPM
2. MRPC
- Test beam 2017 w. electronics
- Demonstrated σ_t<100ps

<u>MUON</u>
1. Scintilating bars+SiPM
2. Scintillatig tiles+SIPM
- Option 1 validated in test beam
- Option 2 in 2018

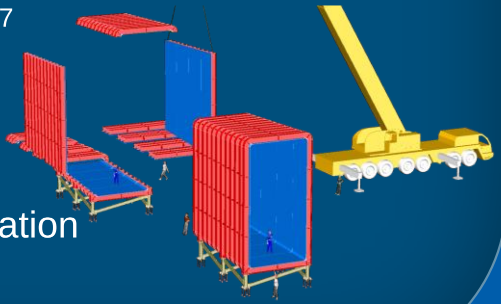
<u>Spectrometer Straw tracker</u>
- 20mm straw diameter in test beam 2017
- Studies of mechanics

<u>Upstream MuonID</u>
- RPC
- Optimized for avalanche mode

<u>Spectrometer tracker</u>
- SciFi
- Synergy with LHCb

<u>Target tracker</u>
1. SciFi
2. GEM,μRWELL, MicroMega
– μRWELL w. μTPC mode in test beam 2017
- GEM and MicroMega in earlier test beams

<u>Surrounding Background Tagger</u>
1. Liquid scintillator + SiPM
2. Plastic scintillator + SiPM
- Test beam w. LiqSci in 2017



In addition:

- Specification of infrastructure and services for assembly, installation and operation
- Evaluation of safety aspects

Background studies

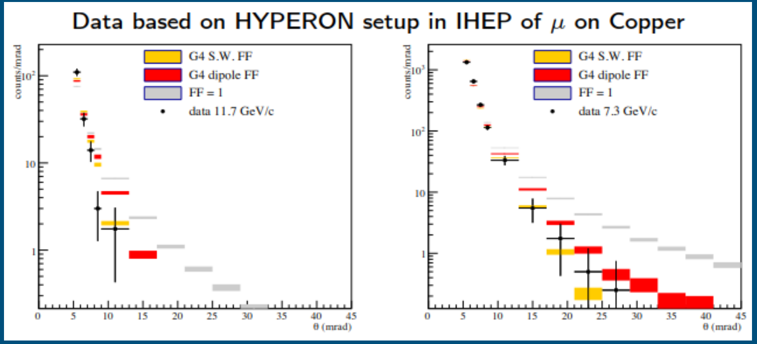
- Final pre-production (target+hadron absorber) of muon and neutrino background ongoing
  - 2 x 10^{10} p.o.t., 25ms/p: 2 months
  - Neutrino background equivalent to 2×10^{20} p.o.t. produced with Genie generator: few weeks

- iSHiP: Machine learning techniques to improve pattern recognition and measurement in emulsion

- dSHIP: residual muon induced background (combinatorial/DIS) requires techniques to boost statistics
  - Residual muons originate from rare stochastic processes, catastrophic energy loss

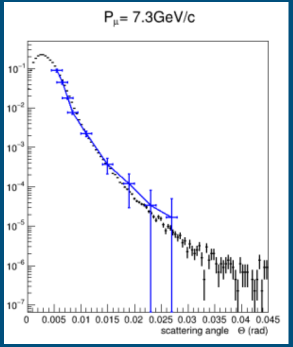
  ➔ Proper description in simulation is crucial

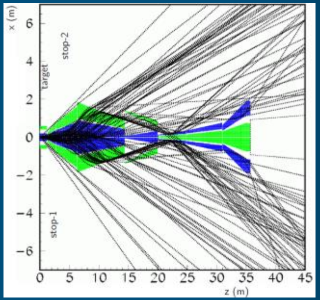
    - μ large angle coulomb scattering



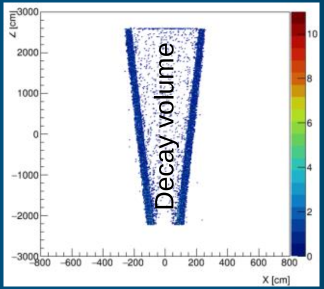
arXiv:1506.08759

GEANT4 used by SHiP





μ interaction (B_{shield}=0)



    - Verification of description of muons from γ-conversion with GEANT expert and NA64 data

  - Muon DIS studies also by switching of muon shield field
  - Neutrino background studied by relaxing cuts

  ➔ Good control of rejection of residual beam-induced background for fully reconstructed signal modes

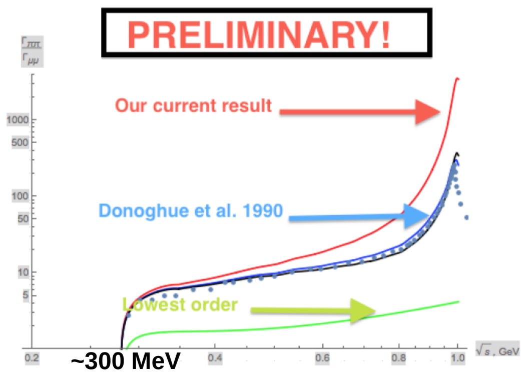
  ➔ Optimization of background rejection with partially reconstructed modes under study

➔ Re-simulating entire updated detector over coming months

SHiP Sensitivities

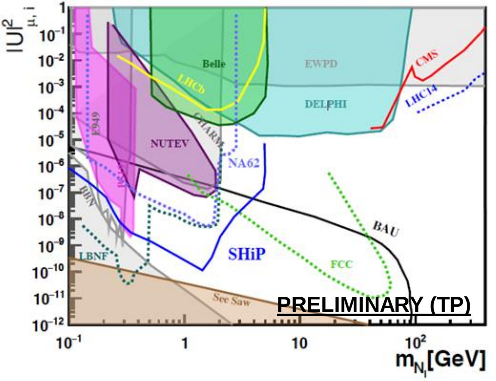
- Currently concentrating on optimization against background
- …and on updating and implementing benchmark models for sensitivity estimation
  1. HNL with recomputed BRs in full simulation
  2. Dark Photon in full simulation
     - Photon production in e.m. showers and in cascades not included, under study
  3. RPV neutralino in full simulation
  4. Scalar has been implemented in full simulation but uncertainty on hadronic BR ($S \to \pi^+\pi^-, \bar{K}K$)
     - Lowest order calculation used in many works
     - Difference may be a factor 50x
  5. ALP with gluonic coupling to be studied
- vWIMP and neutrino physics performance significant updates
  - ➔ Implementation of vWIMP models under study (see next)

➔ SHiP theory group very active

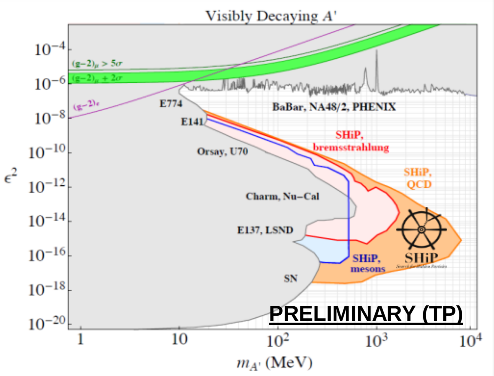


A. Boyarsky et al.

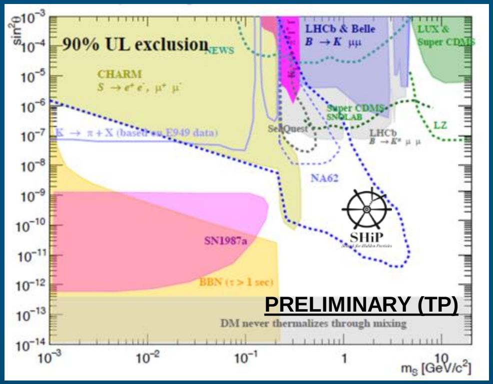
Heavy Neutral Lepton (U^2_e:U^2_μ:U^2_τ=1:16:3.8)



Dark Photon



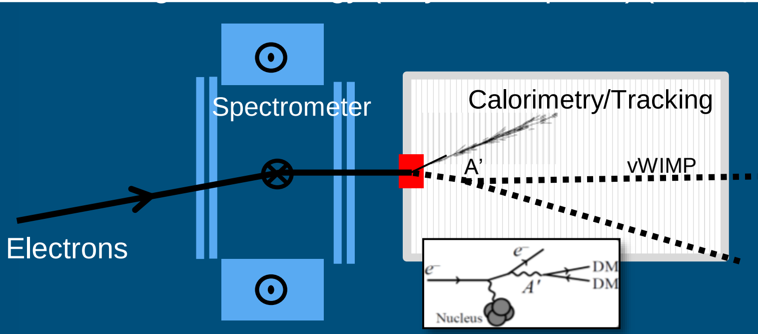
Dark Scalar



Very Weakly Interacting Massive Particles

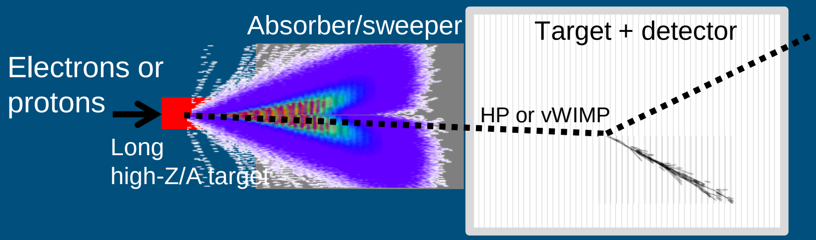
- Two search techniques for LDM or rather “vWIMP”

Indirect: Missing mass/energy (only vector portal) ($s \propto \epsilon^2/m_{A'}$)



NA64@CERN (secondary e@100, 10^{12}),
LDMX@SLAC (e@10, 10^{16}) (proposal)

Direct: Scattering off atomic electrons and nuclei ($s \propto \epsilon^4/m_{A'}$)



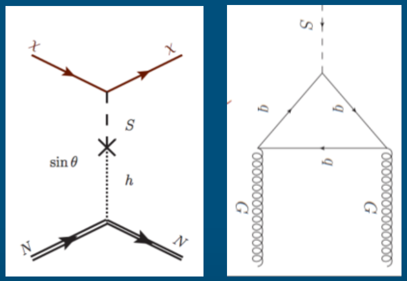
BDX@JLAB (e@11, 10^{22}),
MiniBooNE@FNAL (p@8.9, 10^{20}),
SHiP@CERN (p@400, 2×10^{20}) (proposal)

- SHiP contributes with direct search in case of vector portal
  - Best sensitivity for scattering in 20 – 200 MeV range

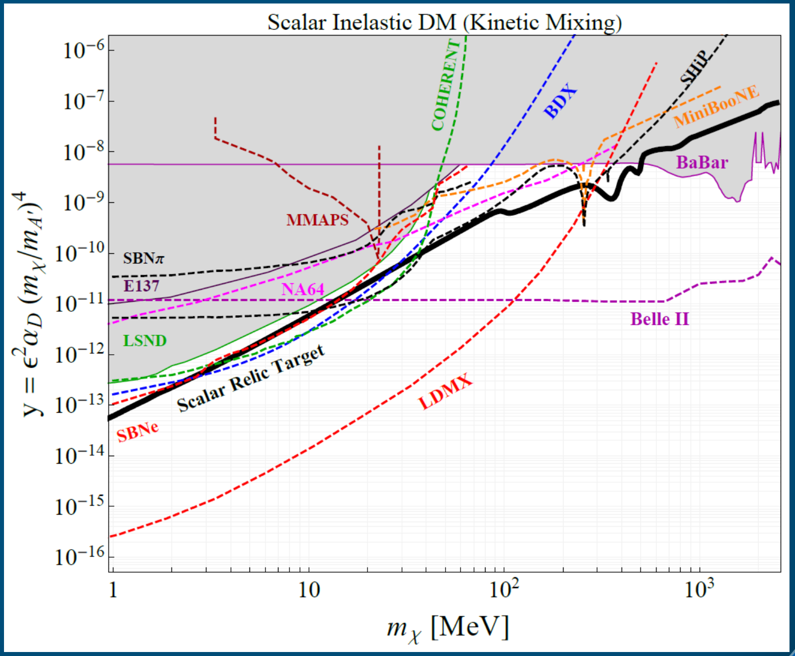
→ In addition good prospective for scalar portal scattering
  - $\mathcal{L}_{mediator-SM} = \phi \sin\theta \frac{m}{v} \bar{\psi}\psi$

  → DM-electron scattering strongly suppressed → DM-nucleon

  → Bounds from electron experiments irrelevant



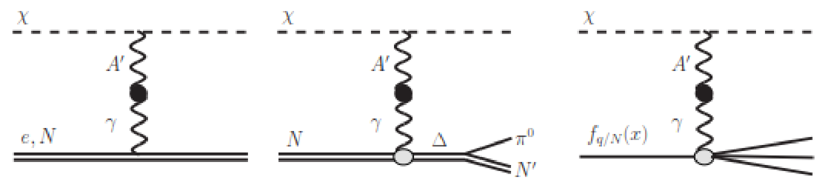
A. Boyarsky et al,

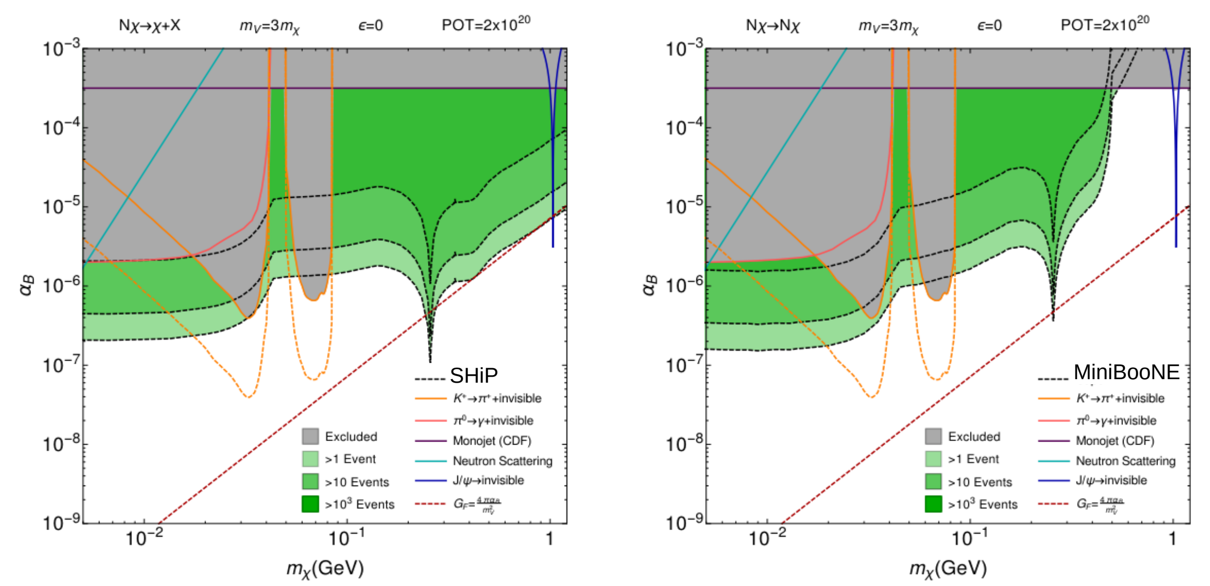


US Cosmic Visions, arXiv:1707.04591v1

Very Weakly Interacting Massive Particles

- Another example: DM with leptophobic vector mediator: DM-nucleon scattering (A. Boyarsky et al.)





SHiP(10t LAr @ 100m)
p@400, $2x10^{20}$

MiniBooNE(400t @ 500m)
p@8.9, $2x10^{20}$

arXiv:1609.01770

➔ iSHiP detector considered as generic detector for (quasi-)stable HS particles : "vWIMP"

- Model studies and detector optimization in progress

Improved background rejection for vWIMP search

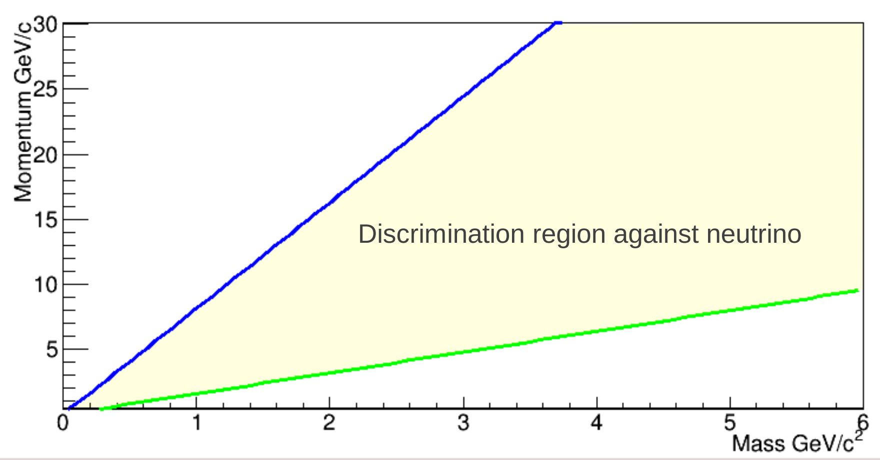
Time-of-flight discrimination against neutrino

For study: Slow extraction with bunched beam, i.e. short bunch length and ${}^{I_{bunch}}/_{I_{gap}} \rightarrow \infty$

E.g. Mu2e@FNAL

SPS 4σ bunch length/spacing of 1.5ns/25ns and 40m distance to detector target

➔ Detector time resolution: 0.5ns



- ➔ Spill scheme and cycle (BDF team)
  - ➔ SHiP spill intensity of 4×10^{13} p/25ns in 288 bunches a la LHC should be possible
  - ➔ Penalty factor of 3-4x less integrated proton yield due to longer cycle (3.6 s flat-bottom and longer ramp)

➔ A second operational mode of SHiP as another handle on neutrino background

LFV $\tau \rightarrow 3\mu$

Hints to anomalies in Lepton Flavour Universality in $b \rightarrow cl\nu_l$ and $b \rightarrow sl^+l^-$ by LHCb

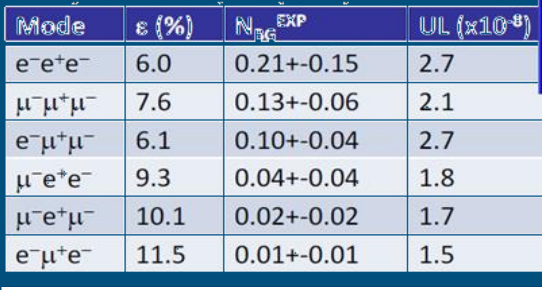
- If confirmed, hints to a NP mainly coupled to 3rd generation (G. Isidori, LHCb Implications WS 2017)
- Limits on LFV in τ decays 5 orders of magnitude weaker than in μ decays

τ decays at Belle

- Data: ~7x10^8 $\tau\tau$ – pairs
- Almost background free due to good lepton ID
- ➔ BELLE II plans to collect ~5×10^{10} $\tau\tau$ – pairs

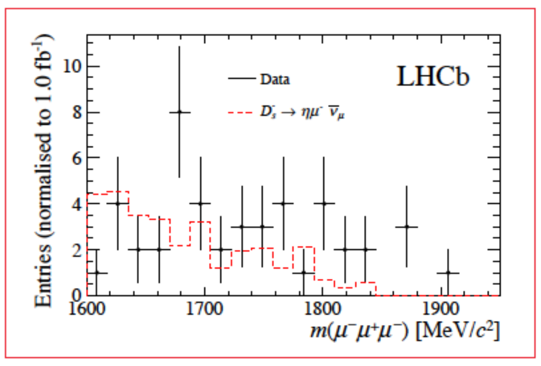
$\tau \rightarrow 3\mu$ at LHC

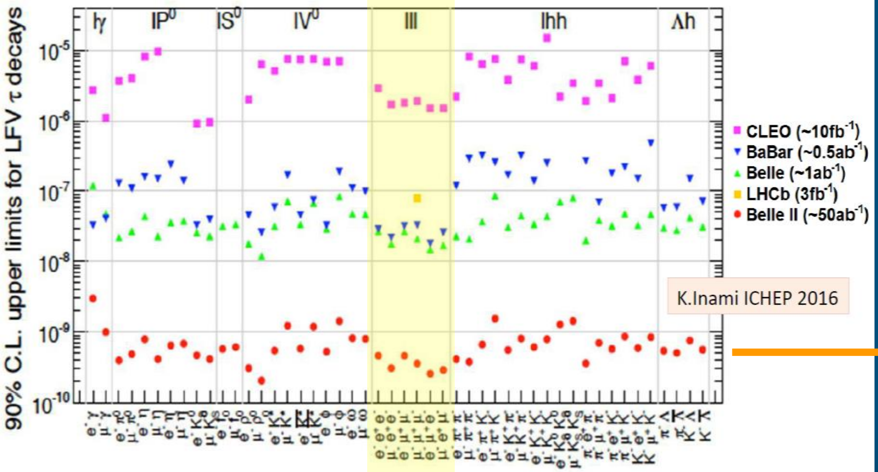
- Production mainly from D_s: ~10^{11} τ / fb^{-1}
- Most significant background from $D_s \rightarrow \eta(\mu^+\mu^-\gamma)\mu^-\nu_\mu$
- ➔ LHCb
- ➔ …or a dedicated interaction point…



Mode	ε (%)	N_{BG}^{EXP}	UL (x10^{-8})
$e^-e^+e^-$	6.0	0.21+-0.15	2.7
$\mu^-\mu^+\mu^-$	7.6	0.13+-0.06	2.1
$e^-\mu^+\mu^-$	6.1	0.10+-0.04	2.7
$\mu^-e^+e^-$	9.3	0.04+-0.04	1.8
$\mu^-e^+\mu^-$	10.1	0.02+-0.02	1.7
$e^-\mu^+e^-$	11.5	0.01+-0.01	1.5

Phys.Lett.B 687,139 (2010)





K.Inami ICHEP 2016

Few times 10^{-10} if controlling background

τ → 3μ at SHIP Facility: "τSHiP"

Resumed studies of LFV τ → 3μ at SHIP

Opportunity already explored in SHiP Physics Proposal
(Rep. Prog. Phys. 79 (2016) 124201)

➔ Parallel operation with ν/iSHiP and dSHiP most efficient!

➔ With 5x10^{13} τ decays in vacuum from 1% of 2x10^{20} pot on SHiP main target : U.L. on BR(τ → 3μ) ~ 10^{-10} or better

➔ Also opportunity for $D \rightarrow \mu\mu, \ldots$

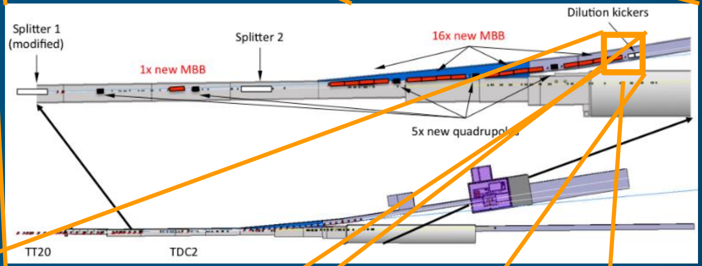
⦿ Challenges

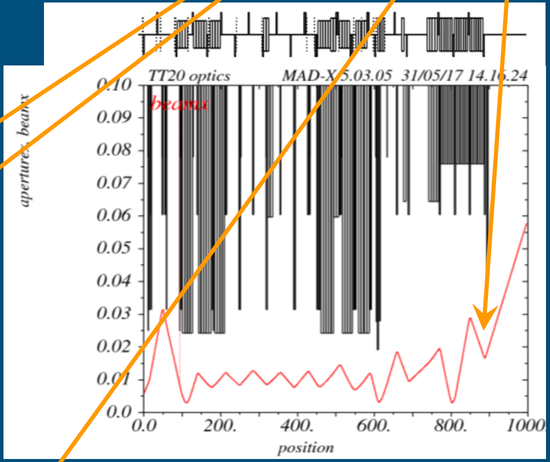
- Radiological aspects 1% beam loss
- Entire facility to be moved downstream by 20m
- Main backgrounds: $D_s \rightarrow \eta(\mu^+\mu^-\gamma)\mu^-\nu_\mu$ and combinatorial background from muons produced in η, ρ, ω decays

} Not yet subject of facility studies

➔ Very interesting and challenging technologically

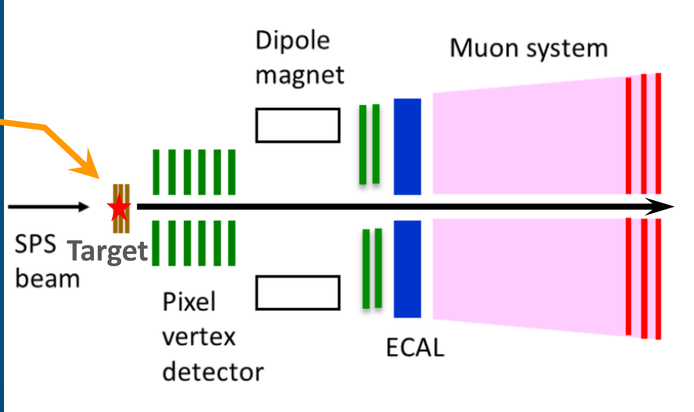
➔ Synergy with future upgrades of LHCb tracking and calorimetry





6σ beam envelope incl. 5 mm orbit deviation and 10% beta beating ➔ RMS 3mm

E.g. 1mm W (multiple) target system intercepting 1% of 2x10^{20} pot



Status of muon flux/charm measurement

1. Measurement of muon flux spectrum from SHiP target (SPSC-EOI-016)
   - Muon shield design and muon background
   - ➔ Accumulate ~10^{11} pot at H4 using the charm x-section setup in 2018
2. Associated charm production including hadronic cascade production in SHiP target (SPSC-EOI-017)
   - Hidden particle search normalization and ν_τ cross-section measurements
   - Charm yield from cascade expected 2.3x larger than prompt contribution

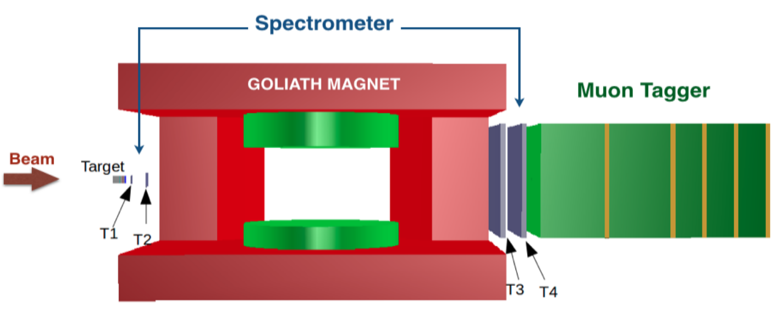
➔ DsTau collaboration: Measure 10^3 $D_s \to \tau X$ as input to σ(CC ν_τ) cross-section and testing LFU for ν_τ scattering (SPSC-P-354)

➔ SHiP to measure in addition $d^2\sigma/dEd\theta$ in long target (“tipple differential”) and branching ratios of different charm species

➔ SHiP optimization run 1/10 statistics in 2018 (one week collecting $5\text{x}10^6$ p)

➔ Four weeks in 2021 (collecting $5\text{x}10^7$ p)

➔ Request for 4 weeks in 2018 submitted to SPSC



➔ All preparations on track for July 2018

Conclusions

➔ Popularity for Hidden Sector increased significantly over last 5 years

- NA62 and NA64
- US initiatives on vector portal and LDM
- Belle II and LHC on scalar portal

➔ SHiP theorist group is in contact with relevant people

- SHiP remains unique in the neutrino portal, and can also do vector and scalar portal in 0–background conditions, both through hidden particle decay and scattering search

The Physics Seascape in 2027

The SHiP Armada (inspired by Gunnar Schnell)