Universität Zürich[UZH]

SHiP
Search for Hidden Particles

Status of the SHiP experiment at CERN

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PASCOS 2019, Manchester

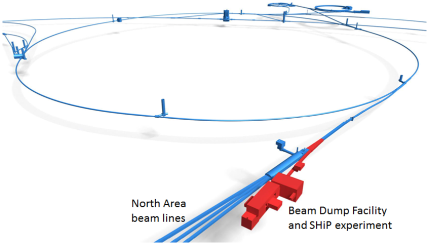
July 2, 2019

Setting the stage

- LHC and other experiments have not seen anything beyond the standard model + neutrino oscillations
- Yet, there remain several unsolved problems indicating the existence of particles beyond the standard model
  - Dark matter
  - Baryon asymmetry of the universe
  - Origin of the neutrino masses

Why look for new physics at a beam dump facility?

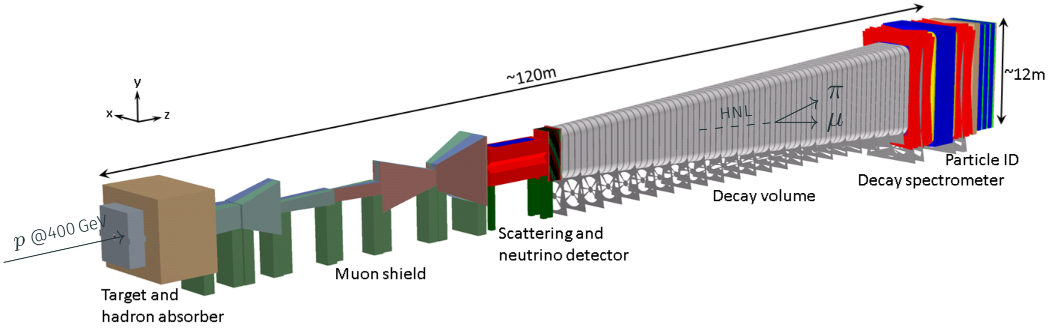
- Why haven't we seen any new particles?
  - Higher masses (→future colliders?) and/or
  - Too weakly coupled to be seen at existing experiments → intensity
- The beam dump facility (BDF) at the CERN SPS is a unique facility, complementing existing and future collider experiments:
  - 400 GeV
  - 5 years of BDF @ SPS (2×10^{20} protons on target):
    - 10^{18} charm mesons
    - 10^{14} beauty mesons
    - 10^{16} τ leptons
- No conflict with HL-LHC data taking
- BDF could also host τFV parasitically upstream of SHiP



[JINST 14 (2019) no.03, P03025]
[CERN-PBC-REPORT-2018-001]

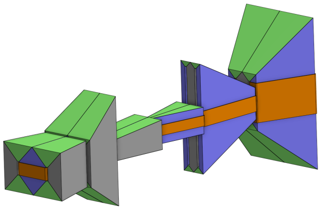
SHiP

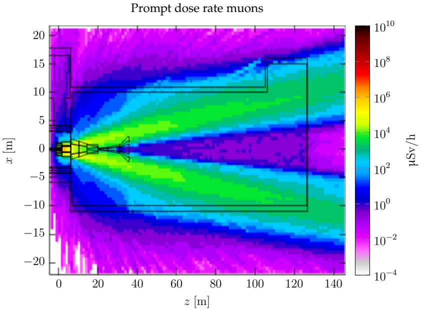
[SPSC-SR-248, CERN-SPSC-2015-016, CERN-SPSC-2015-040, Rept.Prog.Phys. 79 (2016) no.12, 124201, JINST 14 (2019) no.03, P03025]



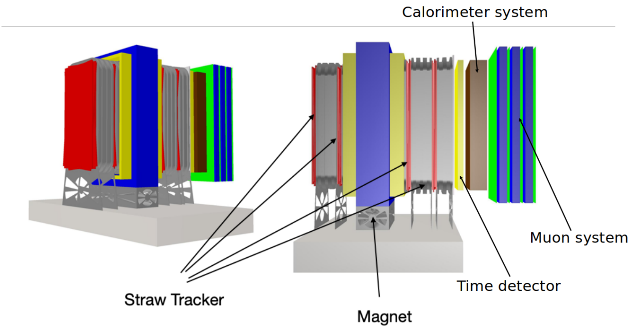
- Designed for **discovery and measurement** of super-weakly interacting new particles
- Decay and scattering signatures give complementary access to new physics models
- Ultra-low background environment for hidden sector decays

- Heavy target $(12X_0)$
  - Fully absorbs the beam
  - Reabsorbs pions and kaons before decay
  - Enhances production of heavy flavour through a cascade of interactions ($\times 2.3$ for D, $\times 1.7$ for B)
- Magnetised hadron absorber separates muon polarities
- Muon shield bends muons out of experimental acceptance $10^{11} \rightarrow 25 \times 10^{3}$ [JINST 12 (2017) no.05, P05011]
  - Optimised using machine learning
  - Expected muon flux validated using dedicated experiment in 2018



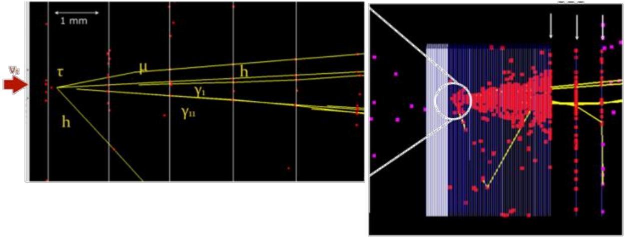


- Background tagger surrounding entire decay volume
- Decay volume under vacuum to control neutrino background
- Timing detector to reject combinatorial background
- SplitCal can reconstruct $\gamma\gamma$ vertices with σ_θ of $\mathcal{O}(\mathrm{mrad})$



- 0 background events expected → 2 candidates needed for discovery
- Can measure decay vertex, invariant mass, impact parameter of signal candidate
  - mass, charge and flavour of new particles measurable
  - redundant background rejection (+background tagger, timing,...)

Scattering and Neutrino Detector



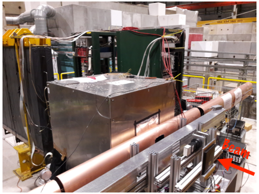
	$\langle E \rangle$ /GeV	# CC DIS
ν_e	59	1.1×10^6
ν_μ	42	2.7×10^6
ν_τ	52	3.2×10^4
$\bar{\nu}_e$	46	2.6×10^5
$\bar{\nu}_\mu$	36	6.0×10^5
$\bar{\nu}_\tau$	70	2.1×10^4

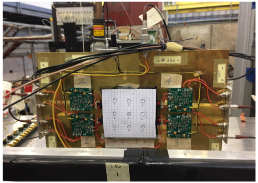
- 10 t of lead instrumented with emulsion and SciFi trackers
- Can distinguish all neutrino flavours, their charge
  - First direct observation of $\bar{\nu}_\tau$
  - Precision neutrino physics (e.g. form factors, ν_τ...)
- Also ideal for scattering of hidden sector particles, e.g. light dark matter

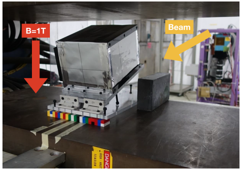
Detector and infrastructure R&D

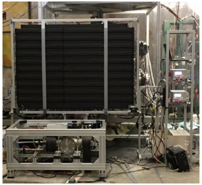
- BDF very mature, developed by a dedicated CERN team [CERN-PBC-REPORT-2018-001]
  - CERN Machine Development runs in summer 2018 with an instrumented target [SPS-LJ-EC-0012]
  - Detailed engineering plans for target bunker and experimental hall
- During comprehensive design study (2016–2019), all subdetectors underwent [SPSC-SR-248]
  - Extensive R&D, simulation studies, concretisation of engineering designs (CAD, FEA)
  - Phase 1 prototyping
  - Dedicated tests with and without beam
- Phase 2 prototyping ongoing, several beam tests planned for 2019–2021, including another dedicated experiment at the SPS

Prototypes & test beams





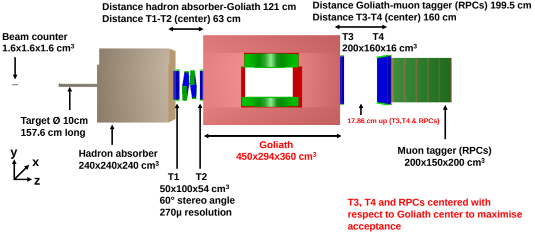




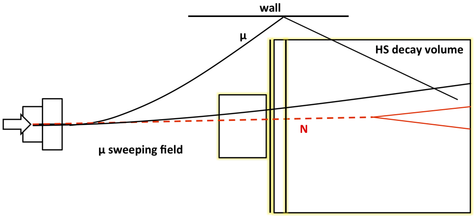
+...

- Mature software framework using PYTHIA6, PYTHIA8, GENIE, GEANT4
  - Cascade production of heavy flavour implemented [CERN-SHiP-NOTE-2015-009]
  - Validation of simulation with data from NA62 and HYPERON [SPSC-SR-248]
- Validated using 2 dedicated experiments in summer 2018 at SPS
  - Muon flux measurement with target replica accumulated 10^{11} protons on target →
  - Charm cross-section measurement with an instrumented target (prototype for longer measurement after LS2 [SPSC-EOI-017]

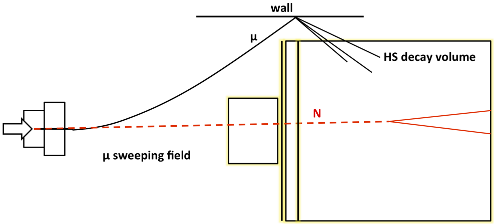
[SPSC-EOI-016]



Ultra-low background

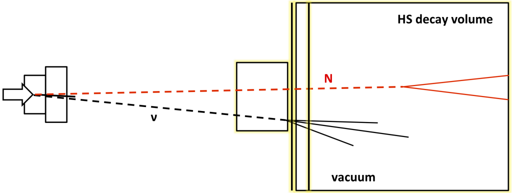


Muon combinatorial



Deep inelastic

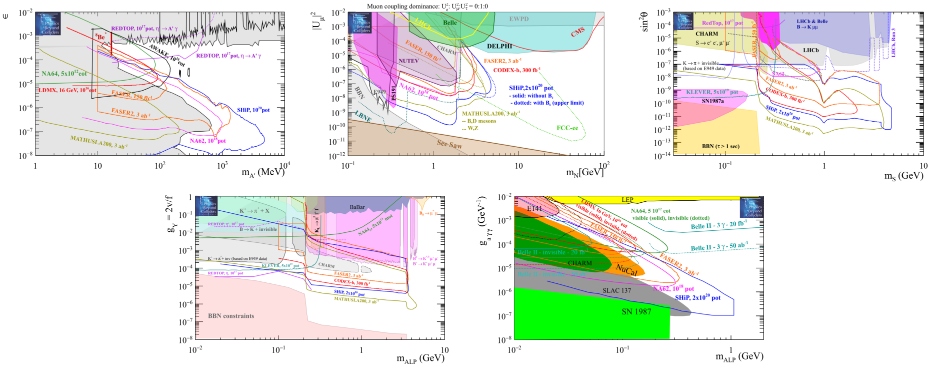
Background source	Expected events
Neutrino background	< 1
Muon DIS (factorisation)	$< 6 \times 10^{-4}$
Muon Combinatorial	4.2×10^{-2}



Neutrino interactions

Backgrounds **redundantly** shown to be < 1, even for **partially reconstructed signal**

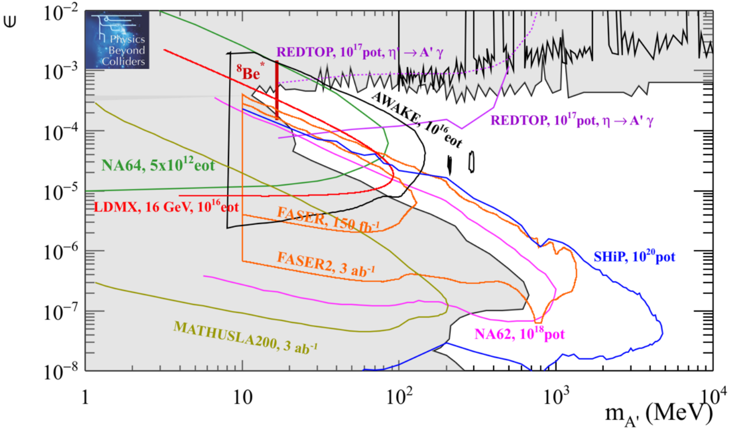
[CERN-PBC-REPORT-2018-007]



- Selection redundantly suppresses background while maintaining high signal efficiency
- In case of discovery, final state can be fully reconstructed (mass, charge, flavour) to identify particular models

Vector portal

- Production taken into account via:
  - Bremsstrahlung
  - Meson decay
  - QCD
- $\mathcal{O}(10^{20})$ photons of sufficient energy during SHiP run



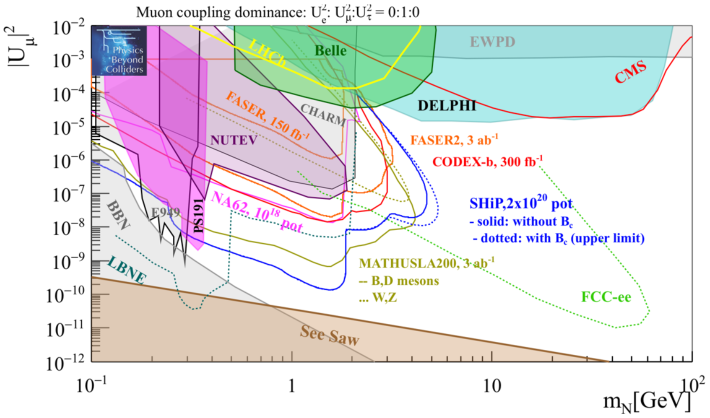
[dedicated paper in preparation]

Neutrino portal

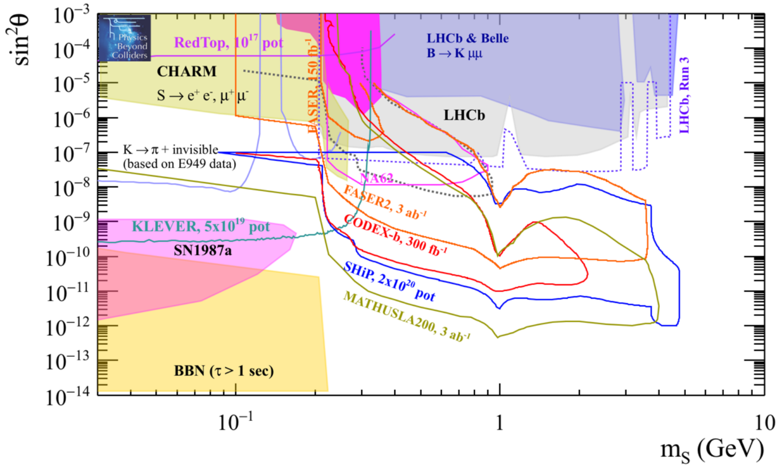
- Showing case

$$U_e^2 : U_\mu^2 : U_\tau^2 = 0 : 1 : 0$$

- Tools and data files **publicly available** to calculate the sensitivity to **arbitrary patterns of flavour mixing**
- B_c-contribution not known; showing upper and lower limits

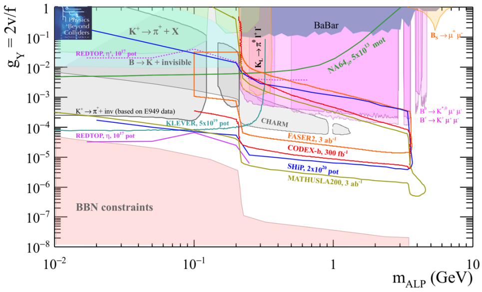


Dedicated paper: [JHEP 1904 (2019) 077]

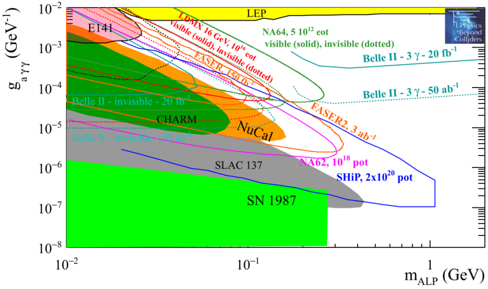


Mainly produced in B and K FCNC decays due to coupling to Higgs

ALP→$f\,f$



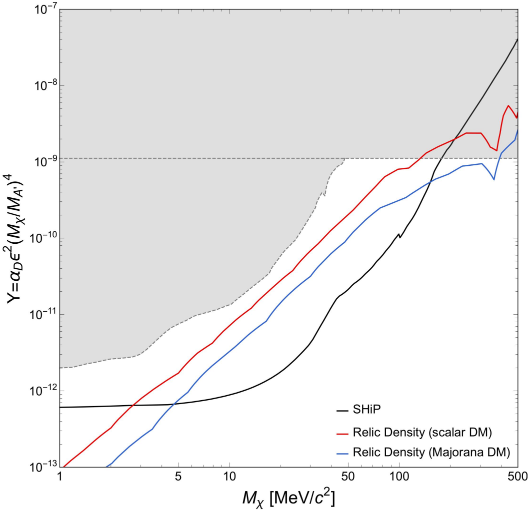
ALP→$\gamma\gamma$



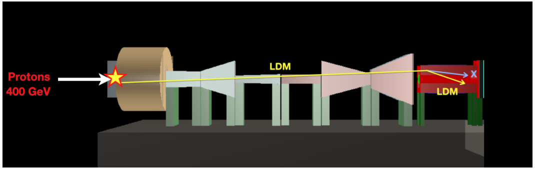
Sensitive to fermion and $\gamma\gamma$ final states due to SplitCal

Invisible decays

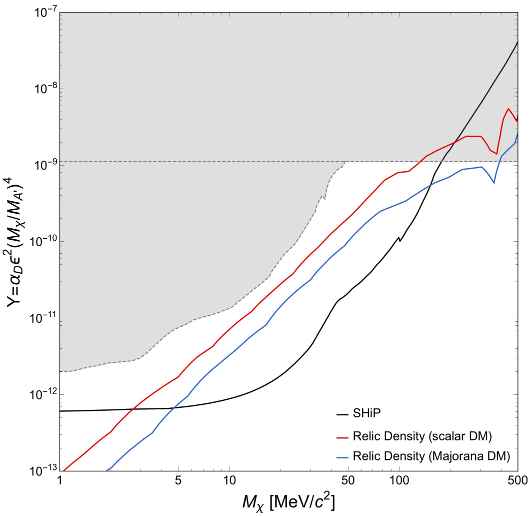
- While WIMP remains dominant paradigm, interest in light dark matter growing
- If LDM exists, the mediator is probably light as well →
  SHiP can look for mediator & LDM simultaneously combining searches in both detectors
- Complementary to missing energy searches for LDM:
  - different systematics
  - less model dependent...
  - ...but ϵ^4 vs. ϵ^2



[dedicated paper in preparation]



- Produce $A' \to \chi\chi$ (or other mediator)
- Detect $\chi e \to \chi e$
- Background from neutrino interactions, reducible using kinematics and additional activity around the vertex
- In case of excess, bunched beam and time of flight can confirm light dark matter signal
- $\chi^* \to \chi A' (\to \ell\ell)$ can leave signal in HSD



[dedicated paper in preparation]

Conclusion

- We don't know the scale of new physics: **complementarity of searches crucial**
- SHiP designed to discover super-weakly interacting new particles:
  - High intensity beam dump facility gives access to couplings $\mathcal{O}(10^{-10})$ for masses up to $\mathcal{O}(10\,\mathrm{GeV})$
  - Redundant background rejection for ultra-low background environment
  - Full reconstruction of final state
  - Complementary decay and scattering signatures
- Strong collaboration: 290 authors, 53 Institutes, 18 countries
- Completed Comprehensive design study including detailed sensitivity studies, good progress towards TDR [SPSC-SR-248]