Search for Hidden Particles

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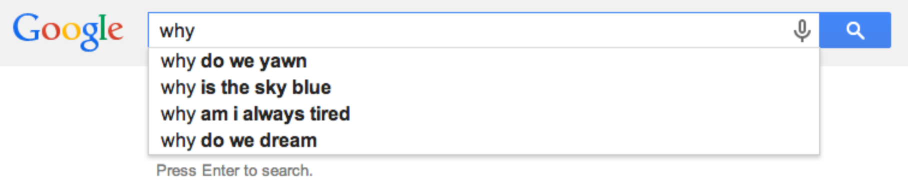
Important questions

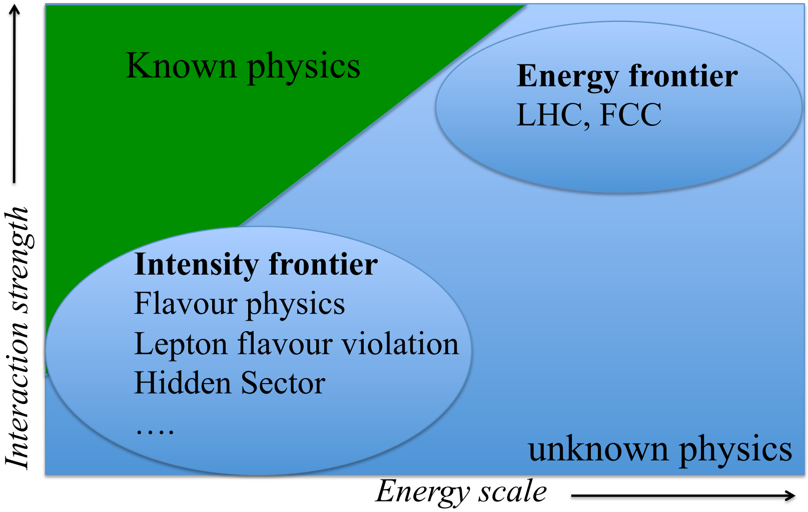


- What is the origin of dark matter?
- What is the origin of CP violation in the universe?
- What is the origin of neutrino masses
- Why is there a hierarchy of fermion masses?
- Why do elements of the CKM matrix have a large spread?

The Standard Model (SM) for all its success has no answers to these

Not clear what the scale of New Physics is and what is the coupling strength of NP to the SM

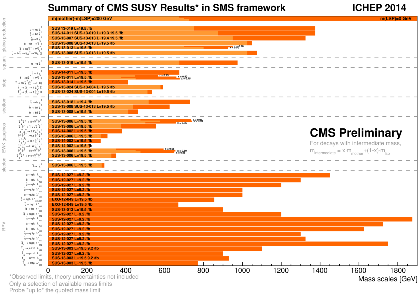
How do we search for new physics?

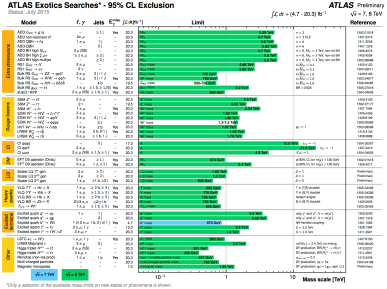


The picture of new physics

SHiP
Search for Hidden Particles

- Large number of direct searches resulting in no new physics at scales up to ~ 5TeV





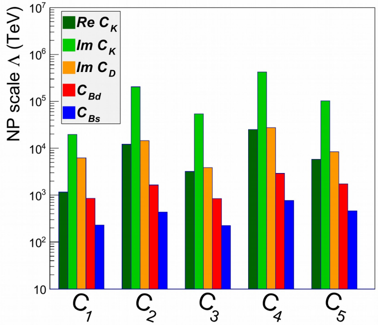
- Notable anomalies in $\gamma\gamma$ excess (maybe) but no smoking gun...

The picture of new physics

- Even more stringent constraints through indirect flavour measurements

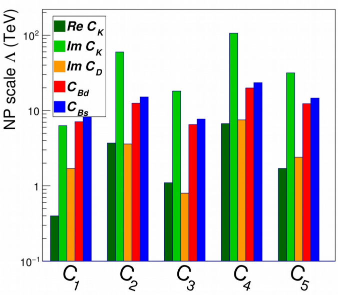
[Silvestrini 2016]

Bounds from $\Delta F=2$ processes, generic flavour structure



$\Delta F=2$ processes scale as $1/\Lambda^2$

Bounds from $\Delta F=2$ processes, CKM-like flavour structure



$\Delta F=2$ processes scale as $1/\Lambda^2$

- Notable anomalies in $b \to c\ell\nu$ and $b \to s\ell\ell$ but no smoking gun...

A Hidden Sector

SHiP
Search for Hidden Particles

- New particles are light (rather than heavy) and interact very weakly with SM particles (through portals)

$$\mathcal{L}_{\text{World}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{portal}} + \mathcal{L}_{\text{HS}}$$

- Such particles found in very wide range of theories
  - SUSY $\rightarrow$ light neutralino with RPV/light goldstinos associated with symmetry breaking
  - Extra-dimensions $\rightarrow$ Axion Like Particles at Fermi Scale
  - Hidden sector models $\rightarrow$ New particles at Fermi scale which are singlets of the SM gauge group

In all these models, interactions can be sufficiently weak, evading precision flavour and electroweak constraints

Examples of portals

Physics proposal including >80 theorists

New light and weakly interacting particle:

- Scalar (via Higgs coupling): $\mathcal{L}_{\text{portal}} = (\lambda_i S_i^2 + g_i S_i) H^\dagger H$
- Vector (via mixing with photon): $\mathcal{L}_{\text{portal}} = \epsilon F'_{\mu\nu} F_{\mu\nu}$
- Axion-like (via mixing/coupling with photon/gluon/fermions): $\mathcal{L}_{\text{portal}} = \partial_\mu A \bar{\psi} \gamma^\mu \gamma^5 \psi$, $\frac{1}{2} \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma} F_{\mu\nu} A$
- Neutrino (νMSM via yukawa coupling): $\mathcal{L}_{\text{portal}} = F_{\alpha I} \bar{L}_\alpha \Phi N_I$

[arXiv:1504.04855]

A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case

Sergey Alekhin,[1,2] Wolfgang Altmannshofer,[3] Takehiko Asaka,[4] Brian Batell,[5] Fedor Bezrukov,[6,7] Kyrylo Bondarenko,[8] Alexey Boyarsky⋆,[8] Nathaniel Craig,[9] Ki-Young Choi,[10] Cristóbal Corral,[11] David Curtin,[12] Sacha Davidson,[13,14] André de Gouvêa,[15] Stefano Dell'Oro,[16] Patrick deNiverville,[17] P. S. Bhupal Dev,[18] Herbi Dreiner,[19] Marco Drewes,[20] Shintaro Eijima,[21] Rouven Essig,[22] Anthony Fradette,[17] Björn Garbrecht,[20] Belen Gavela,[23] Gian F. Giudice,[5] Dmitry Gorbunov,[24,25] Stefania Gori,[3] Christophe Grojean§,[26,27] Mark D. Goodsell,[28,29] Alberto Guffanti,[30] Thomas Hambye,[31] Steen H. Hansen,[32] Juan Carlos Helo,[11] Pilar Hernandez,[33] Alejandro Ibarra,[20] Artem Ivashko,[8,34] Eder Izaguirre,[3] Joerg Jaeckel§,[35] Yu Seon Jeong,[36] Felix Kahlhoefer,[27] Yonatan Kahn,[37] Andrey Katz,[5,38,39] Choong Sun Kim,[36] Sergey Kovalenko,[11] Gordan Krnjaic,[3] Valery E. Lyubovitskij,[40,41,42] Simone Marcocci,[16] Matthew Mccullough,[5] David McKeen,[43] Guenakh Mitselmakher ,[44] Sven-Olaf Moch,[45] Rabindra N. Mohapatra,[46] David E. Morrissey,[47] Maksym Ovchynnikov,[34] Emmanuel Paschos,[48] Apostolos Pilaftsis,[18] Maxim Pospelov§,[3,17] Mary Hall Reno,[49] Andreas Ringwald,[27] Adam Ritz,[17] Leszek Roszkowski,[50] Valery Rubakov,[24] Oleg Ruchayskiy⋆,[21] Jessie Shelton,[51] Ingo Schienbein,[52] Daniel Schmeier,[19] Kai Schmidt-Hoberg,[27] Pedro Schwaller,[5] Goran Senjanovic,[53,54] Osamu Seto,[55] Mikhail Shaposhnikov⋆,§,[21] Brian Shuve,[3] Robert Shrock,[56] Lesya Shchutska§,[44] Michael Spannowsky,[57] Andy Spray,[58] Florian Staub,[5] Daniel Stolarski,[5] Matt Strassler,[39] Vladimir Tello,[53] Francesco Tramontano§,[59,60] Anurag Tripathi,[59] Sean Tulin,[61] Francesco Vissani,[16,62] Martin W. Winkler,[63] Kathryn M. Zurek[64,65]

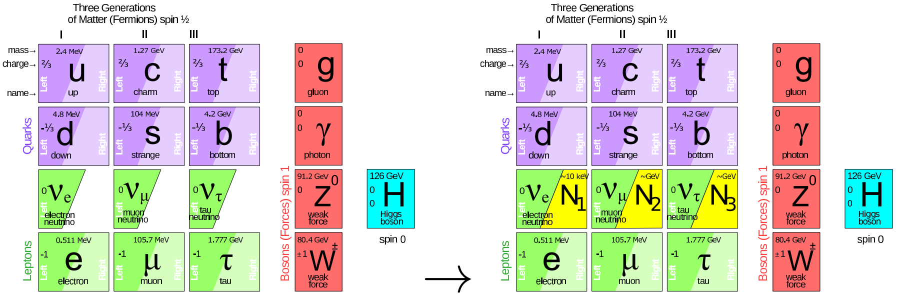
Abstract: This paper describes the physics case for a new fixed target facility at CERN SPS. The SHiP [illegible] and to search for weakly-interacting sub-GeV dark matter candidates. We discuss the evidence for phys[illegible] interactions between new particles and four different *portals* — scalars, vectors, fermions or axion-like particles. We discuss motivations for different

SHiP will make world-beating and model independent searches in of all of these areas

Concrete example: the νMSM

Asaka, Shaposhnikov [PLB620(2005)17]

- Minimally extend the SM by introducing 3 right-handed SM singlet Majorana neutrinos (Heavy Neutral Leptons)



- N_1 can provide a dark matter candidate
- $N_{1,2,3}$ can provide neutrino masses via the seesaw mechanism
- $N_{2,3}$ can induce leptogenesis $\rightarrow$ baryogenesis

Closer look at $N_{1,2,3}$ of the νMSM

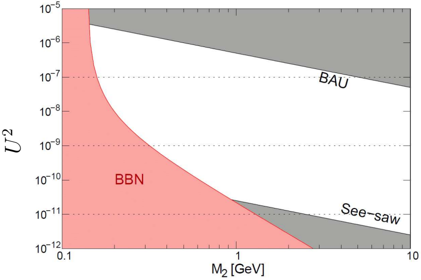
SHiP
Search for Hidden Particles

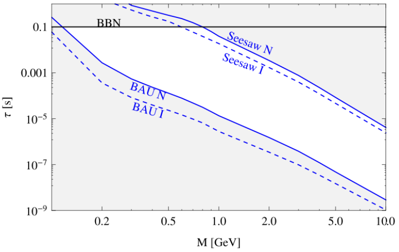
$$\delta\mathcal{L} = \bar{N}_I i\partial_\mu\gamma^\mu N_I - F_{\alpha I}\,\bar{L}_\alpha N_I \Phi - \frac{M_I}{2}\,\bar{N}_I^c N_I + h.c.$$

- Both Dirac ($M_D = F\langle\Phi\rangle$) and Majorana ($M_I$) mass terms included and are $\leq M_{\mathrm{EWK}}$ No additional energy scale required
- See-saw mechanism for ν masses constrains yukawa coupling (U) and $M_{N_{2,3}}$ since $m_\nu = \frac{M_D^2}{M_N} \sim \frac{U^2\langle H\rangle^2}{M_N}$
  $\rightarrow$ Since $M_N \leq M_{\mathrm{EWK}}$ have small U in order to satisfy m_ν

Closer look at $N_{1,2,3}$ of the νMSM cont'd

- N_1 provides DM candidate if sufficiently stable
  $\rightarrow 1 < M_{N_1} < 5$keV to satisfy cosmological constraints
  $\rightarrow$ very weak mixing parameters with other leptons
  $\rightarrow$ one active neutrino with $m_\nu \sim 10^{-5}$eV
- Baryogenesis: $M_{N2} \sim M_{N3} = M_N$, CP phases from F_{al} tuned to explain Baryon Asymmetry of Universe
- Big Bang Nucleosynthesis: $M_N > 1$GeV and $\tau_N < 0.1$s to maintain $H1/He4 \sim 75/25\%$





Closer look at $N_{1,2,3}$ of the νMSM cont'd

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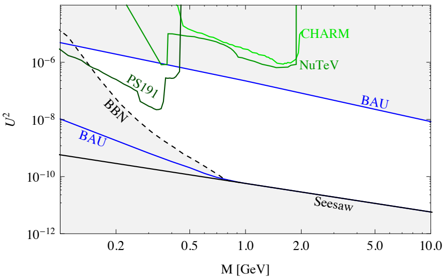
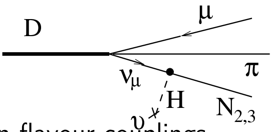


- Very small fraction of relevant parameter space has been explored

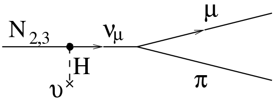
Searching for $N_{2,3}$

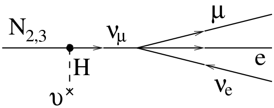
- Produce through semileptonic hadron decays
  $\rightarrow K \rightarrow \mu\nu$, $D \rightarrow \mu\nu X$, $B \rightarrow \mu\nu X$
- For $M_N > 1$GeV need decays of charm and beauty
- Very weak $N_{2,3} \rightarrow \nu$ mixing (U^2) $\rightarrow N_{2,3}$ very long lived
  $\rightarrow$ For $M_N \sim 1$GeV, $c\tau \sim \mathcal{O}(10)$km



Branching fractions depend on flavour couplings

- $\mathcal{B}(D \rightarrow \pi \ell N)$: $(10^{-12} - 10^{-8})$
- $\mathcal{B}(N \rightarrow \mu/e\pi)$: $(0.1 - 50)\%$
- $\mathcal{B}(N \rightarrow \mu/e\rho)$: $(0.5 - 20)\%$
- $\mathcal{B}(N \rightarrow \nu\mu e)$: $(1 - 10)\%$

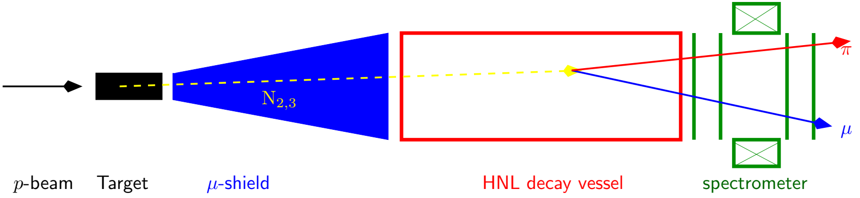




Experimental requirements

Charm production

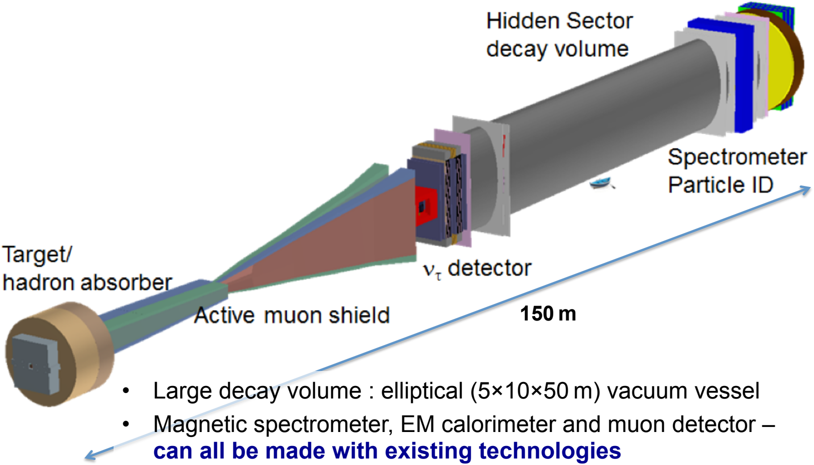
- LHC ($\sqrt{s} = 14$TeV 1ab^{-1}): $\sim 2 \times 10^{16}$ in 4π
- SPS (400GeV fixed target $\sqrt{s} = 27$GeV 2×10^{20}pot): $\sim 8 \times 10^{17}$



- Heavy Target (Mo+W)
  $\rightarrow$ Minimise $\pi, K \rightarrow \mu\nu_\mu$ / Maximise heavy flavour production
- Detector placed as close to target as background allows
  $\rightarrow$ Maximise signal acceptance / Minimise μ flux
- Decay vessel in vacuum $\rightarrow$ Avoid ν-interactions
- Magnetic spectrometer $\rightarrow$ Reconstruct HNL mass

SHiP layout

As implemented in Geant4



- Large decay volume : elliptical (5×10×50 m) vacuum vessel
- Magnetic spectrometer, EM calorimeter and muon detector – **can all be made with existing technologies**
- **Design to suppress hidden sector backgrounds to ~zero**

The SHiP Technical Proposal

- Technical Proposal and Physics Proposal submitted April 2015 → 9 months review with SPS committee [arXiv:1504.04956]
- Collaboration: ∼ 250 members from 45 institutes in 14 countries, admission of additional institutes pending

Very positive response from SPSC

*The SPSC **has reviewed** the proposal for "A Facility to Search for Hidden Particles (SHiP) at the CERN SPS" (Technical Proposal P-350 and Physics case P-350-ADD-1), submitted in April 2015 following an earlier submission of the Expression of Interest EoI-010 in October 2013. The review included several lists of questions sent to the proponents, which were all answered including submission of a proposal addendum P-350-ADD-2 in October 2015.*

*In the review process the Committee **was impressed** by the dedication of the SHiP proponents and their responsiveness to the Committee's requests. In particular significant progress has been made since the EoI, along the lines of the SPSC112 recommendations, including optimisation of the proton beam dump design, broadening of the physics case and adaptation of the SHiP scheduling to external constraints. The CERN SPS offers a unique opportunity for the proposed programme and the SHiP proponents have the potential strength to build the proposed detector setup.*

The main physics motivation of SHiP is to explore the domain of hidden particles, searching in particular for new scalar, fermionic and vector particles. These would be produced in a proton beam dump at 400 GeV, either directly or from decays of charm or beauty particles. The experiment would be sensitive to a hitherto unexplored region of parameter space, spanning masses from a few hundred MeV to a few GeV and over two orders of magnitude in squared couplings. The main experimental signature involves two charged decay tracks, and will be complemented by decays to neutral particles. The experiment is also proposed to be equipped with an emulsion target, which would allow for unprecedented tau neutrino and antineutrino measurements and valuable QCD studies. Furthermore it would extend the hidden sector search to scattering of dark matter particles. The facility could accommodate additional detectors extending the range of dark matter searches. The SPSC supports the motivation for the search for hidden particles, which will explore a domain of interest for many open questions in particle physics and cosmology, and acknowledges the interest of the measurements foreseen in the neutrino sector. SHiP could therefore constitute a key part of the CERN Fixed Target programme in the HL-LHC era.

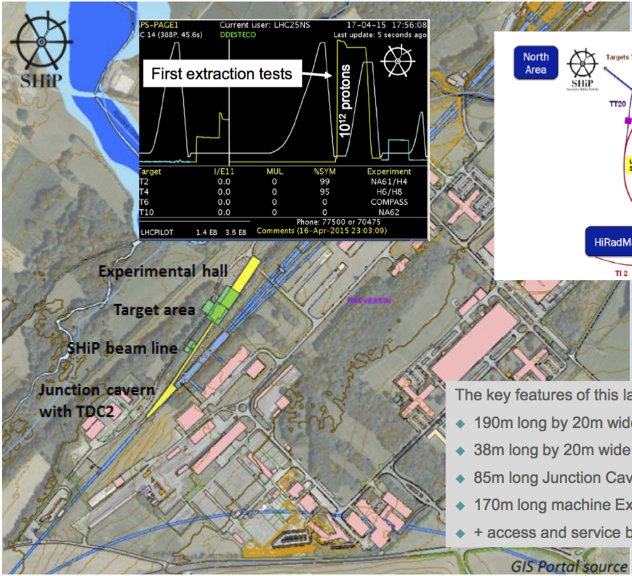
*The SPSC **supports** the updated SHiP schedule, which takes into account the HL-LHC preparation constraints during LS2, and defers any significant civil engineering investments for SHiP to the period following full approval of SHiP. The SPSC **notes** that, in this updated schedule, the time scale for the SHiP comprehensive design study, required for a final decision, coincides with the expected revision of the EU HEP strategy. The Committee **also notes** the plans of the incoming CERN Management to set up a working group to prepare the future of the CERN Fixed Target programme after LS2, as input to the next EU strategy update. In this context the SPSC **recommends** that the SHiP proponents proceed with the preparation of a Comprehensive Design Report (CDR), and that this preparation be made in close contact with the planned Fixed Target working group.*

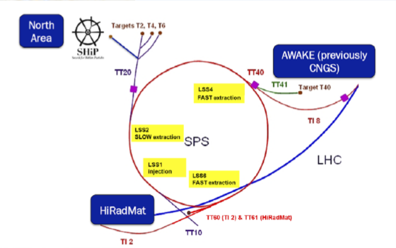
The fixed target facility

- Requirements: 400GeV protons $4 \times 10^{13} p$/spill (1s spill every 7s)
- Expect 2×10^{20}pot in 5 years of running
  $\rightarrow$ 60% of SPS super-cycle (a-la CNGS) compatible with operation of both the LHC and North Area facilities (as currently implemented)
- High intensity demands new dedicated beam line connected to existing TT20 transfer line
- Constraint in the planning: 1.5 years shutdown of North Area operation (best done in LS2 and has been endorsed as fully compatible)

The fixed target facility cont'd

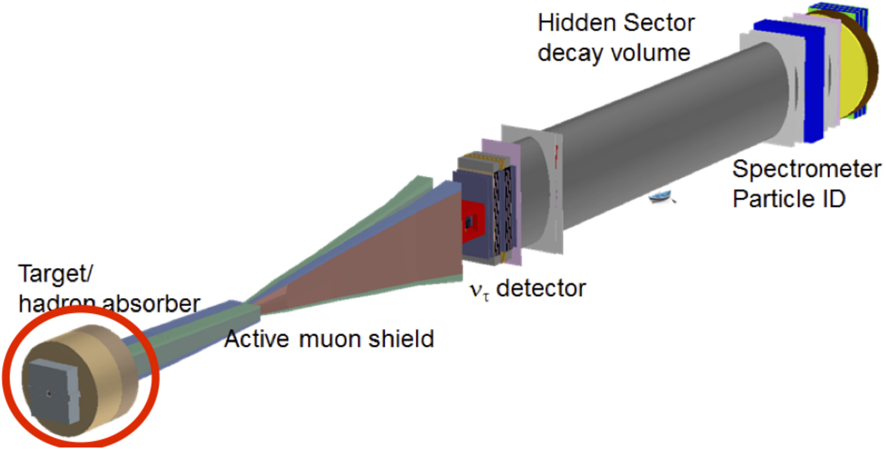
[Courtesy T. Ruf]





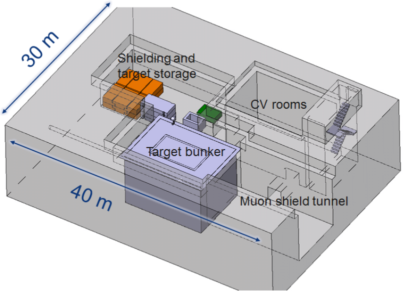
The key features of this layout are:

- 190m long by 20m wide Experimental Hall
- 38m long by 20m wide Target Area
- 85m long Junction Cavern in the TDC2 line
- 170m long machine Extraction Tunnel (4m wide by 4m high)
- + access and service buildings

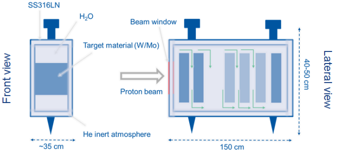

Hidden Sector
decay volume
Spectrometer
Particle ID
ν_τ detector
Target/
hadron absorber
Active muon shield

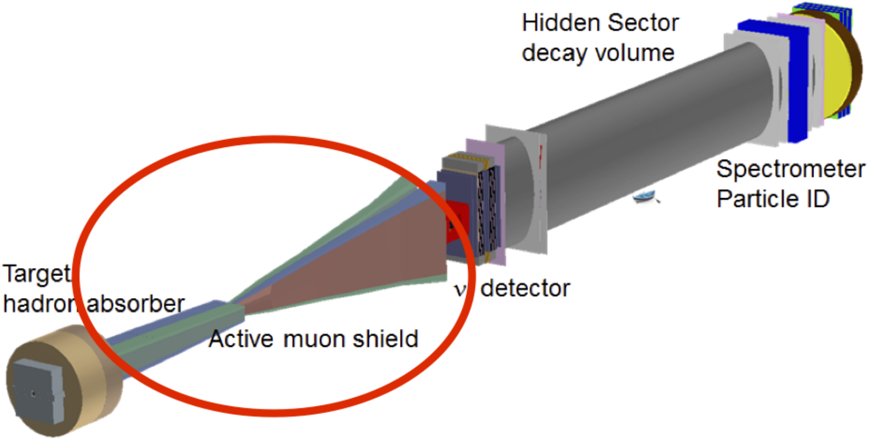
The target

- Detailed engineering design study performed by dedicated CERN task force
- 2.6MJ on target during 1s every 7s (kinetic energy of 100kg at 800km/h)
- Challenges due to radiation and mechanical stresses
  $\rightarrow$ Remote handling, helium atmosphere and cooling required
- Results of simulations: Molybdenum alloy and tungsten water cooled
- Designed for multi-purpose exchange of target and shielding configurations for alternative uses



	DONUT [1)]	CHARM [2)]	SHiP
Target material	W-alloy	Cu (variable ρ)	TZM + pure W
Momentum (GeV/c)	800	400	400
Intensity	$0.8*10^{13}$	$1.3*10^{13}$	**$4*10^{13}$**
Pulse length (s)	20	$23*10^{-6}$	1
Rep. rate (s)	60	~10	7.2
Beam energy (kJ)	1020	830	2560
Avg. beam power (spill) (kW)	51	$3.4*10^{7}$ (fast)	2560
Avg. beam power (SC) (kW)	17	69	355
POT	Few 10^{17}	Few 10^{18}	**$2*10^{20}$**

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decay volume
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ν detector
Active muon shield

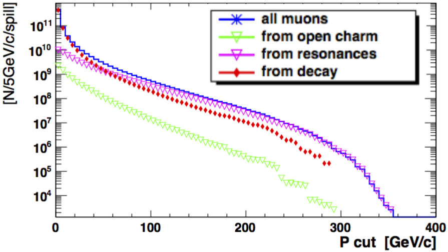
Muon shield

The problem: Muons can interact with surroundings and produce V^0's decaying to pair of displaced charged tracks mimicking signal.

- Monumental rate of muons even after target/hadron absorber
- Hidden particles from D and B decays have significant p_{T}

  $\rightarrow$ Detector as close as possible to target

  $\rightarrow$ Need compact, efficient and cost effective way to shield against these muons
- Aim: reduce muon induced V^0 production at level less than the neutrino induced background

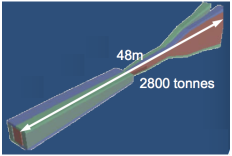


Solution: Magnetic sweeping of muons

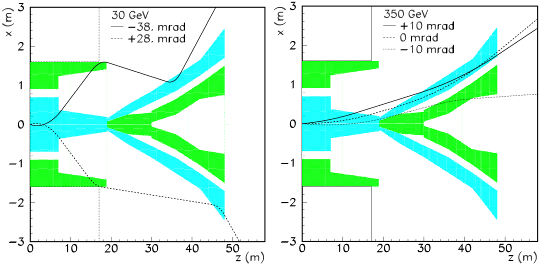
Active muon shield

- Sweep away muons with momenta up to 350GeV

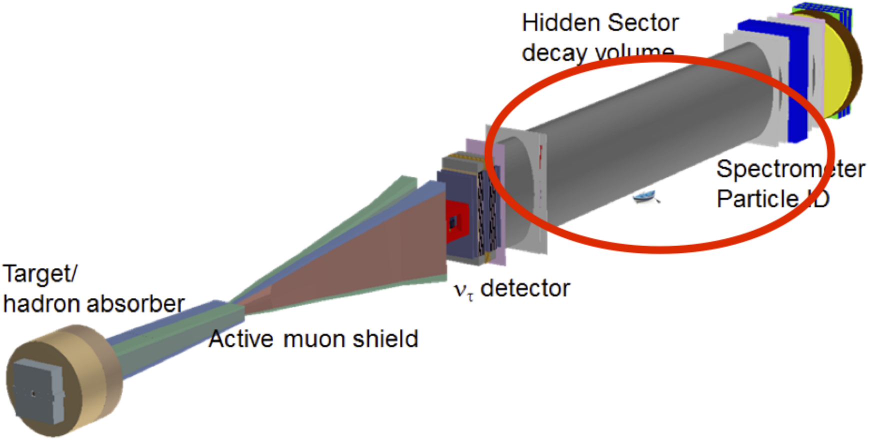
  → Require 30Tm to deflect 350GeV muons
- Cost effective: Dipole magnets with saturated iron $B_{\max} = 1.8$T in a special arrangement



- Detailed engineering design performed at RAL
  → Using grain oriented steel
  → Field strength and configuration not an issue



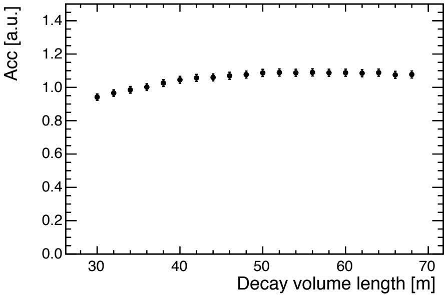
- Left with $\sim 5 \times 10^4$ muons per spill with large p_T e.g from J/ψ and Υ

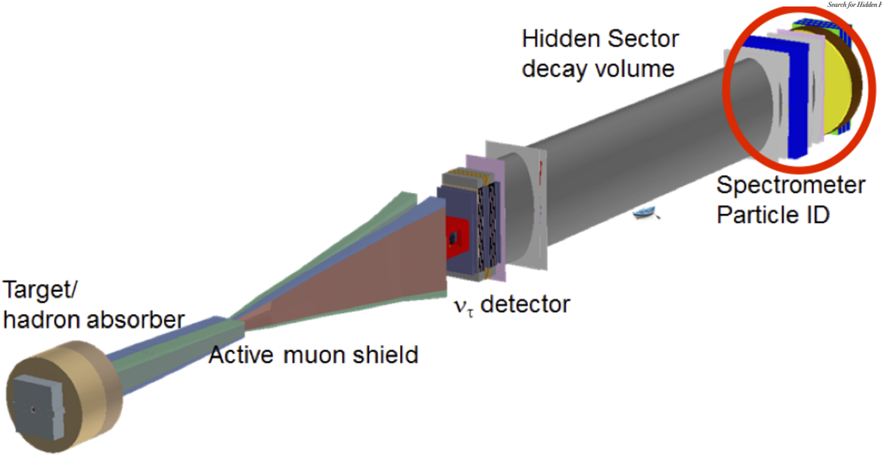

Hidden Sector
decay volume
Spectrometer
Particle ID
Target/
hadron absorber
Active muon shield
ν_τ detector

Hidden sector decay volume

- Minimise neutrino interactions in decay volume
  → Decay volume at 10^{-6}bar pressure
  → <1 neutrino interaction in 5 years
  → Pressure requirements could be relaxed in the future as can use topology of interaction products to reject background

- Decay volume: Elliptical 10m×5m×60m
- Following optimisation procedure maximising acceptance while allocating necessary space for sweeping magnet
- Veto detectors in front and surrounding the volume
- Tracking stations inside the vacuum
- Dipole magnet 0.65Tm





Hidden Sector
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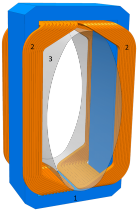
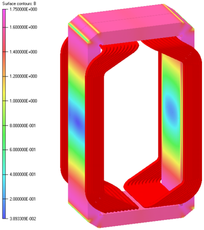
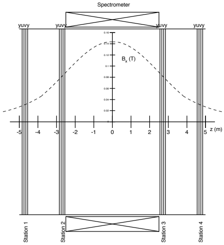
Hidden sector spectrometer

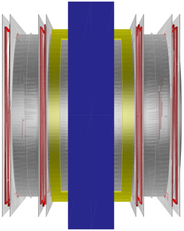
- Dipole magnet of length 5m with 0.65Tm, similar to LHCb design
- Aperture 50m^2, power dissipation $\sim$ 1MW ($3\times$ less than LHCb)
- Field computations performed with Opera-3d





- Two tracking stations in front and two behind



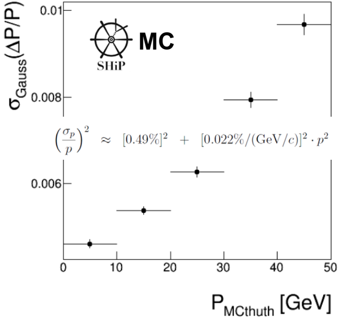


Hidden sector spectrometer cont'd

- Straw tracker: Similar technology to NA62 but instead 5m straws at 1μb (cf 2m at 0.01μb)
- 0.5% X/X_0 with 120μm spatial resolution
- Demonstrated to work in vacuum

- Implemented in simulation and R&D is ongoing

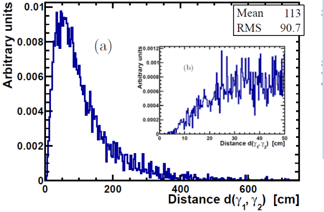
Momentum resolution in simulation

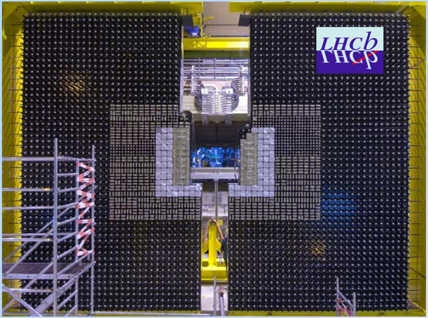


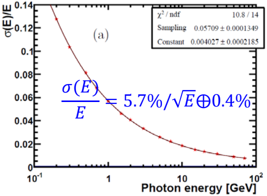
Electromagnetic calorimeter

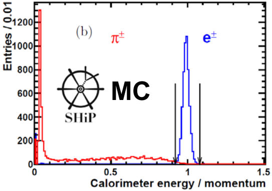
Courtesy T. Ruf

- LHCb Shashlik
  - $6.3 \times 7.8\ \text{m}^2$
  - $\frac{\sigma(E)}{E} < 10\%/\sqrt{E} \oplus 1.5\%$
- For $\mathbf{N} \rightarrow \boldsymbol{\mu^+\rho^-(\pi^-\pi^0(\gamma\gamma))}$,





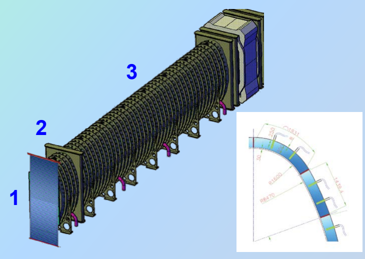




Veto systems

- Residual backgrounds arising from muons surviving shield, cosmic muons, neutrino interactions reduced by a set of veto counters

1. Upstream Veto Tagger in front of the vacuum vessel
   - Plastic scintillator bars ϵ 99.9%
2. Straw Veto Tagger 5m from the entrance window
   - Same technology as tracking systems
3. Surround Background Tagger around the decay volume
   - Liquid scintillator $120m^3$+1800 Wavelength-shifting Optical Modules (IceCube)



Estimating backgrounds

Or lack thereof...

Signature	Physics	Backgrounds
$\pi^-\mu^+$,$K^-\mu^+$	HNL,NEU	RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$
$\pi^-\pi^0\mu^+$	HNL($\to \rho^-\mu^+$)	$K_L^0 \to \pi^-\mu^+\nu_\mu(+\pi^0)$, $K_L^0 \to \pi^-\pi^+\pi^0$
π^-e^+,K^-e^+	HNL, NEU	$K_L^0 \to \pi^-e^+\nu_e$
$\pi^-\pi^0e^+$	HNL($\to \rho^-e^+$)	$K_L^0 \to \pi^-e^+\nu_e$, $K_L^0 \to \pi^-\pi^+\pi^0$
μ^-e^++p^{miss}	HNL,Higgs Portal (HP)($\to \tau\tau$)	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e$
$\mu^-\mu^+$+p^{miss}	HNL,HP($\to \tau\tau$)	RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$
$\mu^-\mu^+$	DP,PNGB,HP	RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$
$\mu^-\mu^+\gamma$	Chern-Simons	$K_L^0 \to \pi^-\pi^+\pi^0$, $K_L^0 \to \pi^-\mu^+\nu_\mu(+\pi^0)$
e^-e^++p^{miss}	HNL,HP	$K_L^0 \to \pi^-e^+\nu_e$
e^-e^+	DP,PNGB,HP	$K_L^0 \to \pi^-e^+\nu_e$
$\pi^-\pi^+$	DP,PNGB,HP	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e$, $K_L^0 \to \pi^-\pi^+\pi^0$,$K_L^0 \to \pi^-\pi^+$
$\pi^-\pi^+$+p^{miss}	DP,PNGB, HP($\to \tau\tau$), HSU,HNL($\to \rho^0\nu$)	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e$, $K_L^0 \to \pi^-\pi^+\pi^0$, $K_L^0 \to \pi^-\pi^+$,$K_S^0 \to \pi^-\pi^+$,$\Lambda \to p\pi$
K^+K^-	DP,PNGB, HP	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e K_L^0 \to \pi^-\pi^+\pi^0$, $K_L^0 \to \pi^-\pi^+$,$K_S^0 \to \pi^-\pi^+$,$\Lambda \to p\pi$
$\pi^+\pi^-\pi^0$	DP,PNGB,HP, HNL($\eta\nu$)	$K_L^0 \to \pi^-\pi^+\pi^0$
$\pi^+\pi^-\pi^0\pi^0$	DP,PNGB,HP	$K_L^0 \to \pi^-\pi^+\pi^0(+\pi^0)$
$\pi^+\pi^-\pi^0\pi^0\pi^0$	PNGB($\to \pi\pi\eta$)	–
$\pi^+\pi^-\gamma\gamma$	PNGB($\to \pi\pi\eta$)	$K_L^0 \to \pi^-\pi^+\pi^0$
$\pi^+\pi^-\pi^+\pi^-$	DP,PNGB,HP	–
$\pi^+\pi^-\mu^+\mu^-$	Hidden Susy (HSU)	–
$\pi^+\pi^-e^+e^-$	Hidden Susy	–
$\mu^+\mu^-\mu^+\mu^-$	Hidden Susy	–
$\mu^+\mu^-e^+e^-$	Hidden Susy	–

HNL=Heavy Neutral Lepton, NEU=neutralino
DP=Dark Photon, PNGB=Pseudo-Nambu Goldston Boson
Background: RDM=random di-muons from the target

Background suppression

Goal: Zero background experiment over 5 year lifetime

Background sources:

1. μ interactions in decay volume or surrounding material
2. ν interactions in decay volume or surrounding material
3. Combination of μ from different *p*-Target interactions (pile-up)

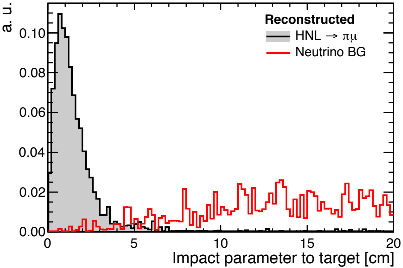
Tools:

- Muon shield
  $\rightarrow 10^6$ rejection
- Veto detectors including timing information with $3\sigma = 340$ps
  $\rightarrow 10^2$ rejection per muon, 10^4 rejection for pile-up muons
- Decay volume in vacuum
  $\rightarrow 10^6$ rejection
- Decay topology e.g vertexing and pointing to *p*-target
  $\rightarrow \geq 10^4$ rejection for ν and pile-up muons

Background suppression cont'd

Left: Impact parameter extrapolated 100m to target (example plot of decay topology info)

Right: Background yields after all selections



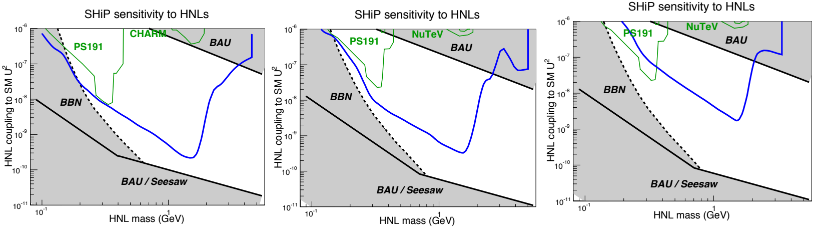
Background source	Stat. weight	Expected background (UL 90% CL)
ν-induced		
$2.0 < p < 4.0$ GeV/c	1.2	1.9
$4.0 < p < 10.0$ GeV/c	1.8	1.3
$p > 10$ GeV/c	3.8	0.6
$\bar{\nu}$-induced		
$2.0 < p < 4.0$ GeV/c	0.24	9.5
$4.0 < p < 10.0$ GeV/c	0.5	4.9
$p > 10$ GeV/c	0.65	3.5
Muon inelastic	0.5	4.6
Muon combinatorial	–	0.1
Cosmics		
$p < 100$ GeV/c	2.0	1.2
$p > 100$ GeV/c	1600	0.002

- As rate calculations and choice of cuts using Pythia8+Geant4, use CHARM geometry and compare to CHARM measured rates as cross-check
- More sophisticated optimisation underway

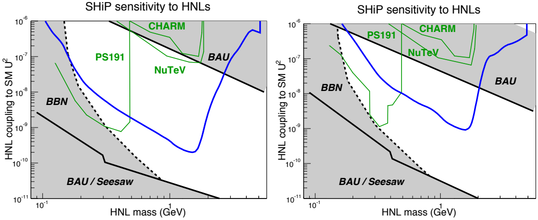
Physics reach: νMSM

- Sensitivity to 5 benchmarks depending on couplings to SM lepton flavours.

$U_e^2 : U_\mu^2 : U_\tau^2$ = Left: IH 52:1:1, Middle: NH 1:16:3.8, Right: NH 0.06:1:4.3



$U_e^2 : U_\mu^2 : U_\tau^2$ = Left: IH 48:1:1, Right: NH 1:11:11

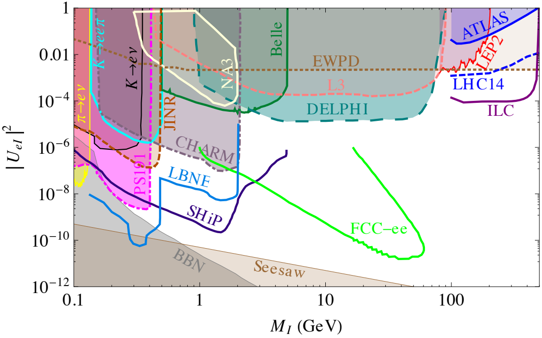


- Pushing towards cosmologically allowed limit

Physics reach: νMSM

Considering other facilities

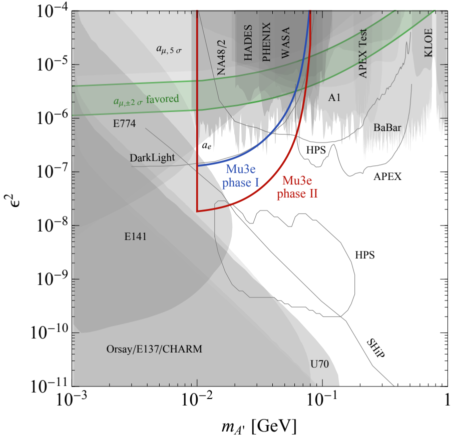
- LBNF performance assumes five year program fully devoted to Hidden sector searches with optimised detector
- JPARC 5×10^{-3} less charm produced
- FCC offers complementary reach



Physics reach: Dark Photons

- Hidden vector particle mixing with photon (vector portal)
- Produce $> 10^{20}$ brem γ at 1 GeV for dark photon to mix with
- Dark photon decays to $\ell^+\ell^-$, $\pi^+\pi^-$ etc

- SHiP probes unique parameter space
- Assuming LBNF dedicated to HS searches, similar dark photon yield for 0 background
- JPARC similar sensitivity to dark photons



Physics reach: SUSY

Example RPV Neutralinos (many more in Physics proposal)

- Benchmark models to study sensitivity of SHiP from de Vries, Dreiner, Scheier [arXiv:1511.07436]
- Model used previously to explain the NuTeV dimuon event excess through neutralino production from B-meson decays Dedes, Dreiner, Richardson [arXiv:hep-ph/0106199]
- Complementary to LHC SUSY searches as such models allow to probe sfermion masses up to $\mathcal{O}(10)$TeV

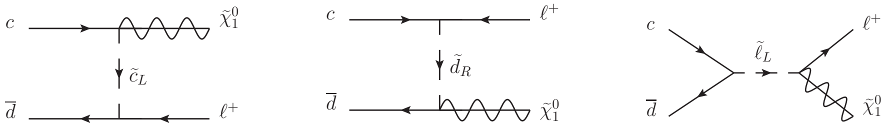


FIG. 1. Relevant Feynman Diagrams for $D^+ \to \tilde{\chi}_1^0 + \ell^+$

- Production and decay similar to νMSM

Physics reach: SUSY

Example RPV Neutralinos (many more in Physics proposal)

- Benchmark models to study sensitivity of SHiP from de Vries, Dreiner, Scheier [arXiv:1511.07436]
- Model used previously to explain the NuTeV dimuon event excess through neutralino production from B-meson decays Dedes, Dreiner, Richardson [arXiv:hep-ph/0106199]
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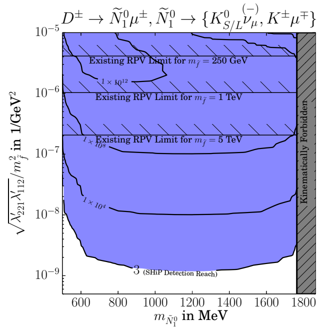
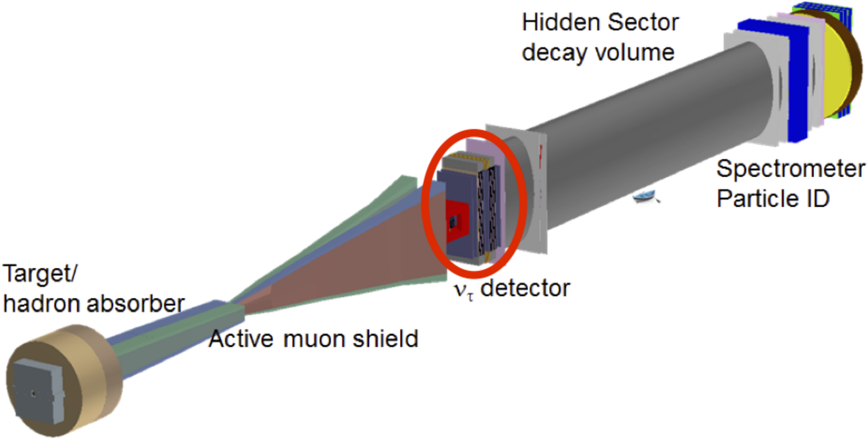
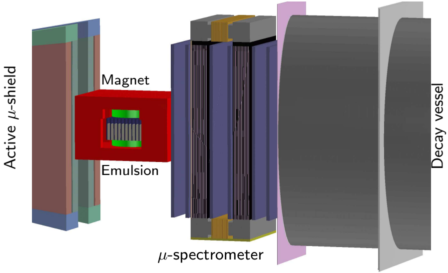
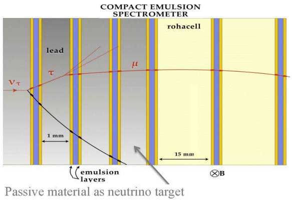



Hidden Sector
decay volume
Spectrometer
Particle ID
Target/
hadron absorber
Active muon shield
ν_τ detector

Tau neutrino physics

- Large flux of ν_τ produced from p-target (decays of τs and D_ss)
- Expect $\sim$6700 ($\sim$3400) ν_τ ($\overline{\nu}_\tau$) interactions cf DONUT 9, OPERA 5 candidates
- Observe $\overline{\nu}_\tau$ for the first time and measure production cross-sections of ν_τ, $\overline{\nu}_\tau$ (access to additional structure functions)



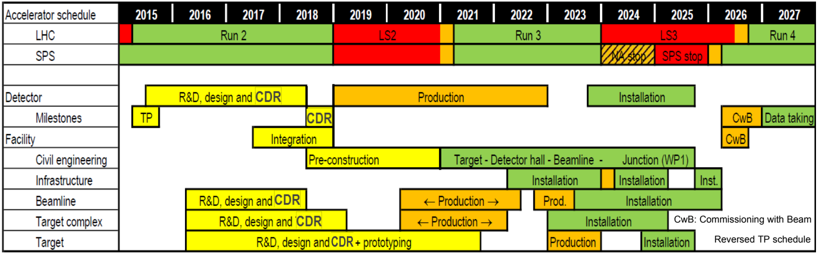


- Pb/Emulsion: $\sim$ 10k, 340k, 2.4M CC ν_τ, ν_e, ν_μ interactions $\rightarrow$ rich ν-physics program.
- B-field in emulsion and muon-filters in μ-spectrometer: distinguish ν_τ from $\bar{\nu_\tau}$.

- Emulsion+muon spectrometer enable τ decay vertex reconstruction and separation of ν_τ over ν_e and ν_μ interactions

Schedule

Takes into accound latest understanding of shutdowns, allows request for significant funds from CERN to be delayed by 2020



SHiP UK

- UK physicists initiated the SHiP project

  → Significant influence and leadership
  - Spokesperson
  - Convener of muon-shield group

- UK activities focused on muon-shield:
  - Simulation of particles in target (Warwick)
  - Design of shield, magnetic modelling (Bristol/ICL/RAL)
  - Residual muon studies (Bristol/ICL)
  - Consequences for DAQ/trigger (UCL)

- PPAP roadmap 2015: "There is considerable UK leadership and emerging interest in SHiP, which potentially has high physics reward. This should be evaluated further and be reviewed should the project go ahead internationally"

Conclusions

- The SHiP experiment will explore the unknown territory of very weakly interacting long-lived particles
  - Well motivated particularly given ATLAS/CMS and flavour measurements
  - Offer answers to DM, BAU, m_ν
- Also offers unique opportunity to perform ν_τ-physics

- Major technological and engineering challenges of the SHiP facility have been addressed (help from CERN departments)
  - Including beam-line, target, infrastructure, muon-shield etc
- SHiP Detector design relies on existing technologies

- Technical Proposal reviewed by SPSC and received positive response. Work has started towards a Comprehensive Design Report

- First civil engineering planned in LS2 (2019-2020)
- First data taking 2026

Backup

Costs

Detector

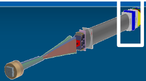
Item		Cost (MCHF)
Tau neutrino detector		**11.6**
Active neutrino target	6.8	
Fibre tracker	2.5	
Muon magnetic spectrometer	2.3	
Hidden Sector detector		**46.8**
HS vacuum vessel	11.7	
Surround background tagger	2.1	
Upstream veto tagger	0.1	
Straw veto tagger	0.8	
Spectrometer straw tracker	6.4	
Spectrometer magnet	5.3	
Spectrometer timing detector	0.5	
Electromagnetic calorimeter	10.2	
Hadronic calorimeter	4.8	
Muon detector	2.5	
Muon iron filter	2.3	
Computing and online system		**0.2**
Total detectors		**58.7**

Facility

Item		Cost (MCHF)
Facility		**135.8**
Civil engineering	57.4	
Infrastructure and services	22.0	
Extraction and beamline	21.0	
Target and target complex	24.0	
Muon shield	11.4	
Detector		**58.7**
Tau neutrino detector	11.6	
Hidden Sector detector	46.8	
Computing and online system	0.2	
Grand total		**194.5**

- CERN manpower for preparation of entire facility and installation: 103 FTEs - Fellows (6.3 MCHF) included in cost
- CERN resource requirements for TDR phase (3years) excluding integration and CE : ~3.2 MCHF and 12.5 FTEs
- CE preparatory cost (integration, design, EIA, permit, tendering, 2.5 years) → 2.5 MCHF and 12.5 FTEs

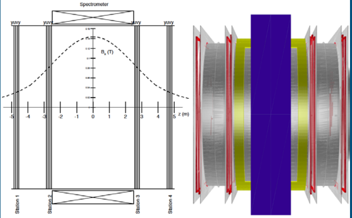
HS tracking system



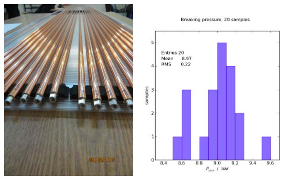
- NA62-like straw detector

Parameter	Value
Straw	
Length of a straw	5 m
Outer straw diameter	9.83 mm
Straw wall (PET, Cu, Au)	
PET foil thickness	36 μm
Cu coating thickness	50 nm
Au coating thickness	20 nm
Wire (Au-plated Tungsten)	
diameter	30 μm
Straw arrangement	
Number of straws in one layer	568
Number of layers per plane	2
Straw pitch in one layer	17.6 mm
Y extent of one plane	$\sim$ 10 m
Y offset between straws of layer 1&2	8.8 mm
Z shift from layer 1 to 2	11 mm
Number of planes per view	2
Y offset between plane 1&2	4.4 mm
Z shift from plane 1 to 2	26 mm
Z shift from view to view	100 mm
Straw station	
Number of views per station	4 (Y-U-V-Y)
Stereo angle of layers in a view Y,U,V	0, 5, -5 degrees
Z envelope of one station	$\sim$ 34 cm
Number of straws in one station	9088
Straw tracker	
Number of stations	4
Z shift from station 1 to 2 (3 to 4)	2 m
Z shift from station 2 to 3	5 m
Number of straws in total	36352

Horizontal orientation of 5m straws



First production of 5m straws at JINR

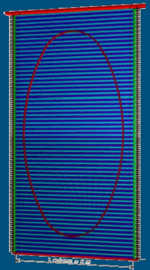


- Straws in test beam 2016
  - Study sagging effects and compensation
  - Read out of signal, attenuation / two-sided readout
- Upstream straw veto may be based on same technology

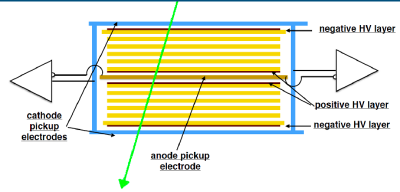
JINR Dubna (NA62, SHiP): Straws
St Petersburg (CMS, SHiP): Infra

Timing detector

- Critical task: Coincidence of decay products
- Two options: scintillating bars (NA61/SHINE, COMPASS) and MRPC (ALICE)



120 bars x 11cm (1cm overlap) = 12m

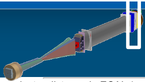


120 cm long strips, 3 cm wide pitch
Actual intrinsic time resolution ~20ps

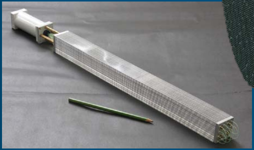
- Main challenges (< 100 ps resolution) requiring R&D
  - Long scintillating bars with large attenuation length
  - Read out by SiPM arrays
  - Embed SiPM arrays throughout scintillator along bar length to improve timing and position resolution
  - Time alignment

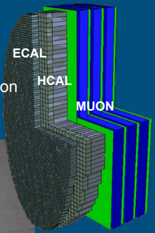
Seminar at TUM, Munich, Germany, February 5, 2016 *R. Jacobsson (CERN)* 53

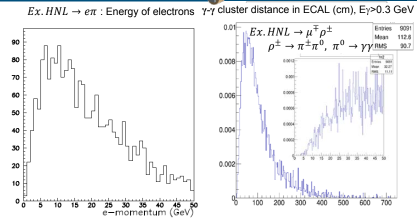
PID: ECAL/HCAL



- Critical tasks
  - Identify e, γ, π^0
  - Discriminate e/π
  - Improve μ/π discrimination
- Shashlik type designs







- ECAL design
  - Dimensions 6x6 cm^2
  - Radiation thickness 22.5 X_0
  - Energy resolution 5.7%/√E ⊕ 0.3%
  - Overall dimension (TP) W:5m x H:10m x D:50cm

  ➔ 2876 modules and 11504 cells (readout channels)

- HCAL design
  - Dimensions 24x24 cm^2
  - Interaction thickness 1.7λ / 4.5λ
  - Overall dimension (TP) W:5m x H:10m

  ➔ 1512 modules/cells (readout channels)

- Main challenge is ECAL calibration
  - 2 x 10^9 μ /day (MIP) and 1.3 x 10^6 e /day (from μ➔e)

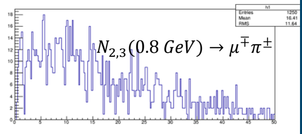
  ➔ Equalization on MIP, energy scale with E/p for electrons per cell

  ➔ $\mathcal{O}(100)$ electrons/cell/day ➔ ~1% calibration accuracy in a week

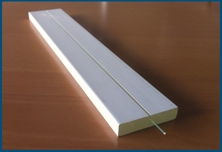
Protvino (COMPASS, SHiP): ECAL, HCAL
ITEP (LHCb, SHIP): ECAL, HCAL

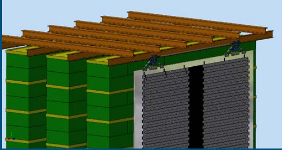
PID: MUON

- Critical tasks: μ and π identification with high efficiency
- Challenge
  - ➔ Tough as pions decay in flight before PID system
  - 20% of the pions at 2GeV, 10% at 5GeV, 4% at 30GeV



- 4 stations based on x-y plans of scintillating bars with WLS fibres and SiPM readout



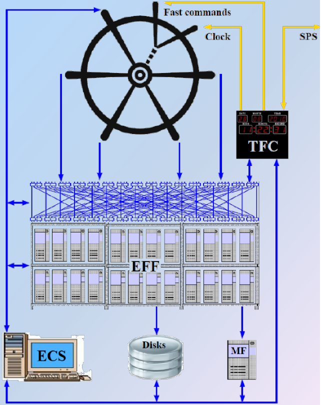


- MUON design
  - Bar dimensions: 5 x 300 x 2 cm^3
  - Number of bars: 3840
  - WLS length: 23 km
  - Overall dimension (TP): W:6m x H:12m
  - Iron filter weight: ~1000 tonnes
  - ➔ 2876 modules and 11504 cells (readout channels)

INR (ν-physics, SHiP): MUON

Trigger and Online System

- Trigger-less readout system: sub-detectors are continuously readout
- No radiation issues, can use commercial solutions for the network
- Event building of zero-suppressed data executed on small computer farm
  - Control system: ECS
  - Fast Control (TFC): generates clock
  - Data transmitted via Ethernet
  - Event Filter Farm (EFF): selects interesting events and sends to storage



$0\nu\beta\beta$ comparison

- Under the assumption that seesaw generated through mechanism other than HNL as ν and N contributions cancel

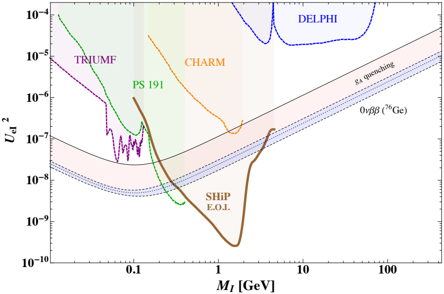


Figure 4.13: Bounds on the mixing between the electron neutrino and a **single** heavy neutrino from the combination of bounds obtained with Ge $0\nu\beta\beta$ experiments [498] using the representation introduced in [599]. This limit *is not valid for seesaw HNLs* because of the different cancellations discussed in Sec. 4.5.2. The bands correspond to the uncertainties discussed in the text. The dashed contours indicate the mass regions excluded by some of the accelerator experiments considered in [313]: CHARM (90% C. L., [587]), DELPHI (95% C. L., [551]), PS 191 (90% C. L., [578]), TRIUMF (90% C. L., [542, 544]).

[1504.04855]