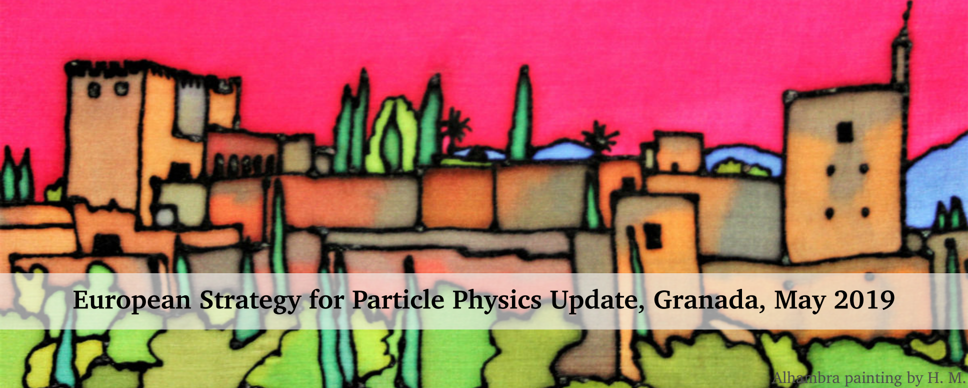
Dark Sector searches with proton beams

E. Graverini for the **SHiP** collaboration



European Strategy for Particle Physics Update, Granada, May 2019

Alhambra painting by H. M.

New Physics hunt in beam dump

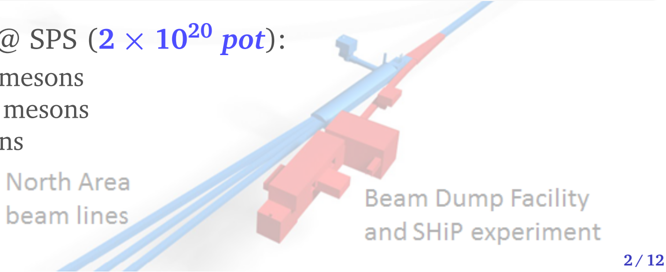
- LHC runs I+II heritage: need to probe much weaker couplings
- giving existing facilities and reliables technologies a new challenge: **intensity**
- long tradition of beam dump searches with far (CHARM, NuTeV) and near detectors (PS191)

The SPS provides a unique high-intensity beam of 400 GeV protons: ideal setting for a CERN-based **Beam Dump Facility** (BDF)

[CERN-PBC-REPORT-2018-001, see M. Lamont's talk]

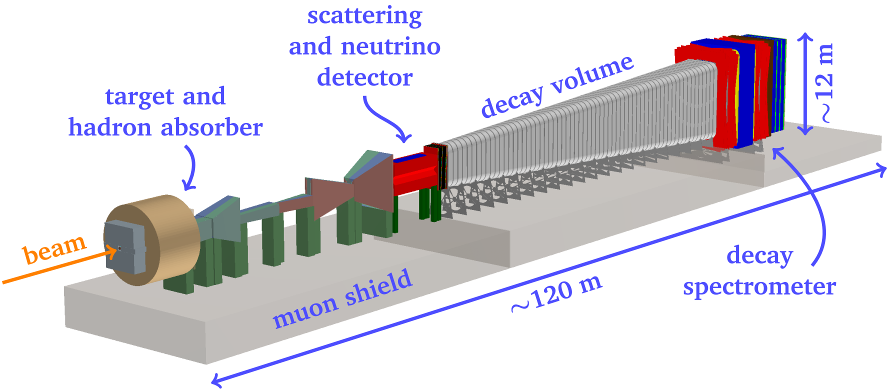
5 years of BDF @ SPS ($\mathbf{2 \times 10^{20}}$ ***pot***):

- 10^{18} charm mesons
- 10^{14} beauty mesons
- 10^{16} τ leptons



SHiP

[ins-det:1504.04956, JINST 14(2019)03 P03025, CERN-SPSC-2019-010]

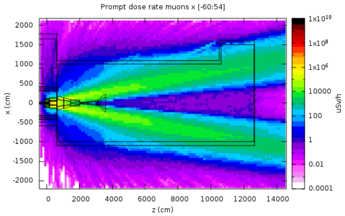


- **a discovery machine for weakly coupled LLPs**, with a complementary detector for ν physics and LDM scattering signatures
- large geometrical acceptance: long volume close to dump
- zero background with spectrometry, PID and VETO taggers

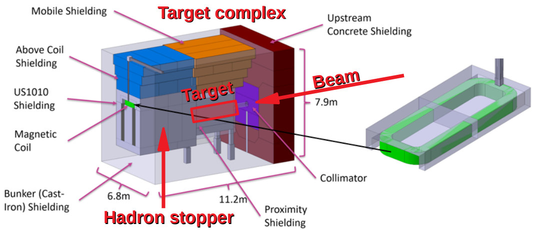
Target and shielding

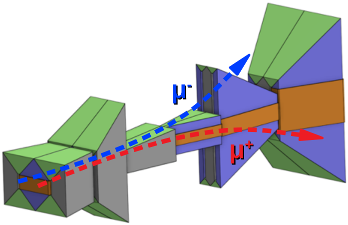
[JINST 12(2017)05 P05011]

- heavy target to absorbe πs before decay
- magnetized hadron stopper: immediately separate $\mu^{\pm}$
- ideal muon shield configuration optimised with machine learning
  $\Longrightarrow$ μ rate reduced to $\sim$ 25 kHz



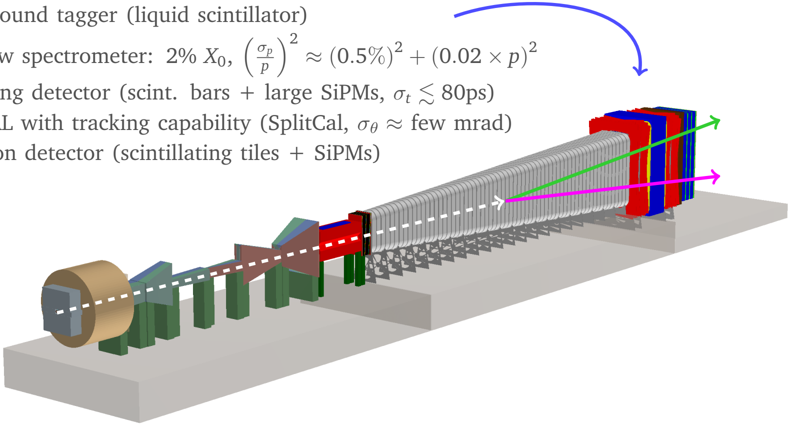
- μ spectrum validated with dedicated experiment in 2018





Decay Spectrometer

- surround tagger (liquid scintillator)
- straw spectrometer: 2% X_0, $\left(\frac{\sigma_p}{p}\right)^2 \approx (0.5\%)^2 + (0.02 \times p)^2$
- timing detector (scint. bars + large SiPMs, $\sigma_t \lesssim 80\text{ps}$)
- ECAL with tracking capability (SplitCal, $\sigma_\theta \approx$ few mrad)
- muon detector (scintillating tiles + SiPMs)

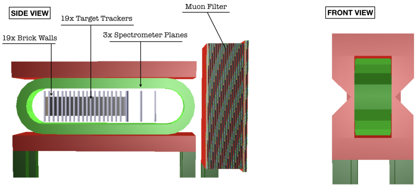


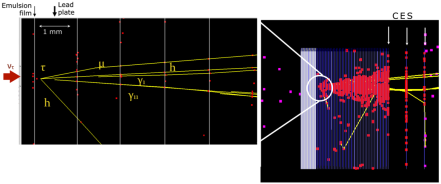
- 0 background $\Longrightarrow$ 2 candidates are a discovery
- mass, charge, flavour information available at observation
  $\Longrightarrow$ narrow down physics models

Scattering and Neutrino Detector

- distinguish ν_e, ν_μ, ν_τ and hadrons
  - measure charge
- ν_f cross sections measurements relevant for flavour anomalies
- first $\bar{\nu}_\tau$ observation
- Target (emulsion chambers + target tracker) + Downstream spectrometer + Muon filter

	$\bar{E}$ [GeV]	CC DIS int.
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

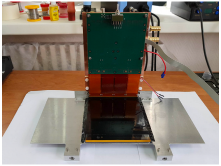




- ideal laboratory also for Light Dark Matter scattering signatures!

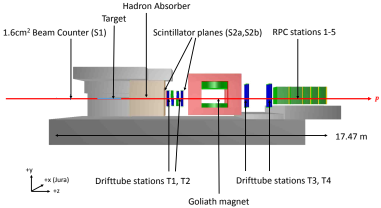
Detector and infrastructure development

- beam facility is being developed by the CERN BDF team (see M. Lamont's talk)
- all detector subsystems have undergone:
  - simulation studies, requirements definition, R&D
  - phase 1 prototyping (small scale, single modules)
  - off and on-beam testing (2017–2018)
- phase 2 prototyping ongoing, beam tests planned for 2019-2021



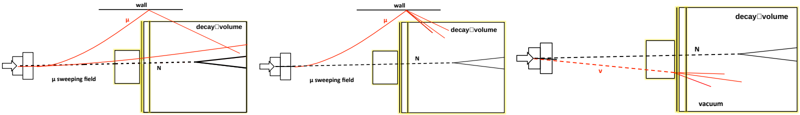
Simulation and validation

- Simulation tuned on data (Pythia8 + Genie + Geant4)
- μ spectrum validated using data from Hyperon and NA62
- two dedicated measurements in July 2018:
  - μ flux, critical for dark sector searches: $\sim 6 \times 10^{11}$ *pot*
  - charm production cross-section, for dark sector and ν physics



- repeat χ_{cc} measurement after LS2, collecting $> 10^7$ *pot*

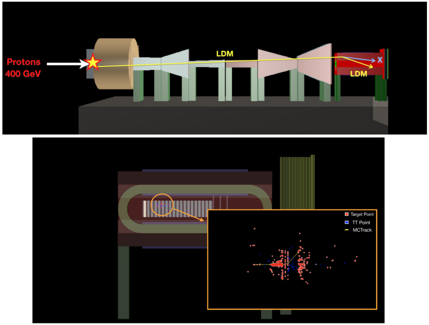
SHiP is a 0 background LLP experiment

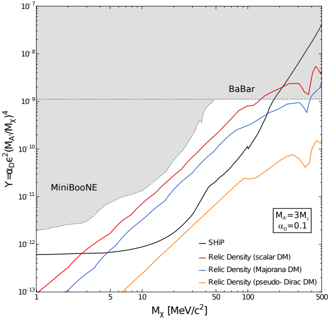


- **Muon combinatorial:**
  - $10^{16} \xrightarrow{\text{selection}} 10^{9} \xrightarrow{\text{timing}} 10^{-2}$ candidates in 5 years @ $90\% CL$
  - ML used to generate large sample of dangerous μ
- **Muon inelastic:**
  - 5 years of SHiP simulated
  - ~~correlation~~ between VETO and selection: $< 6 \times 10^{-4}$ @ $90\% CL$
- **ν interactions:**
  - 10 years of SHiP simulated, increasing to 100
  - ν-air: $< 10^{-2}$ with pressure ~ 1 mbar
  - ν-material: $5 \times 10^{5} \begin{cases} \xrightarrow{\text{cuts (fully reco)}} 0 \\ \xrightarrow{\text{cuts (part. reco)}} 2 \xrightarrow{\text{opening angle}} 0 \end{cases}$ @ $90\% CL$

Physics performance: invisible decays

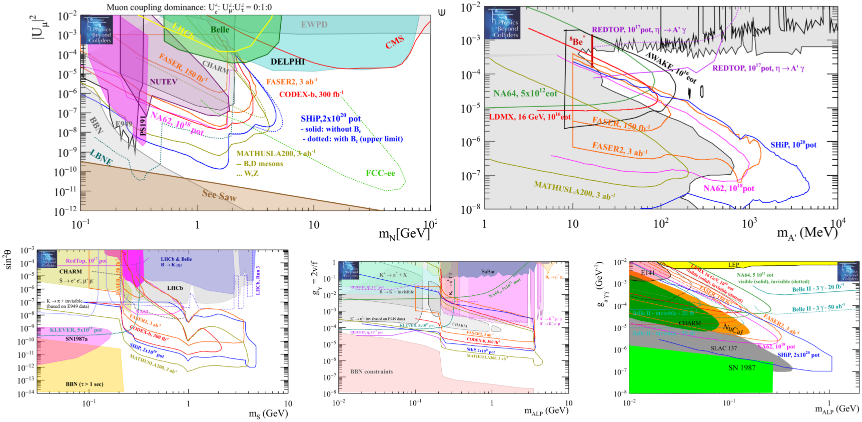
- benchmark: $\gamma' \to \chi\chi$, $\chi e \to \chi e$ scattering in the emulsion target
- expect single EM shower w/o associated tracks
  - $\bar{\nu}_e N \to eX$ background reduced by tagging extra activity at the vertex
  - $\nu_e e \to \nu_e e$ slightly kinematically different
  - if excess is observed $\Longrightarrow$ can switch to bunched beam and use TOF
  - excess observed in real time using target tracker (R&D ongoing)





- $\chi_2 \to \chi_1\gamma' (\to \ell\ell)$ can be searched with the Decay Spectrometer

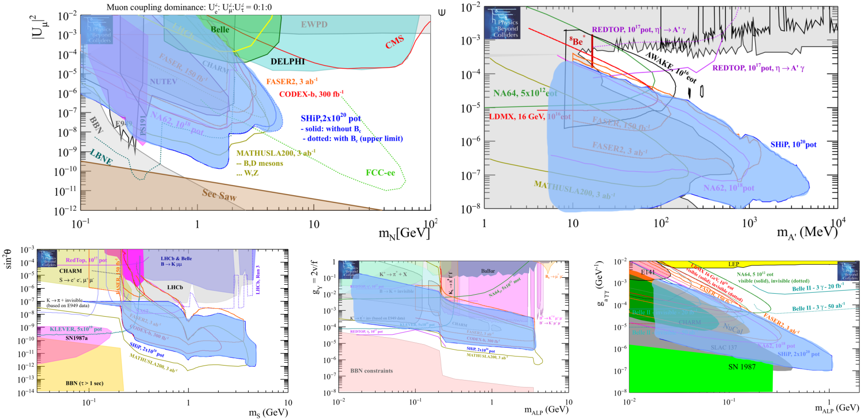
Physics performance: visible decays



[1504.04956, 1504.04855, 1811.00930, 1901.09966]

- from top left: HNL (heavy meson decays), dark photon (decays + bremsstrahlung + QCD), scalar (K and B decays), ALPs coupled to fermions, ALPs coupled to photons
- event selection: high signal efficiency + redundant BG suppression

Physics performance: visible decays



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- **in case of discovery** $\Longrightarrow$ full reconstruction and PID allows identifying models and measuring parameters

Conclusions

- scale of NP after LHC run II = **?** $\Rightarrow$ diversifying is key
- high intensity SPS beam allows probing couplings $\mathcal{O}\left(10^{-10}\right)$
  - with minimal modifications to existing facilities
- BDF can fit other experiments after SHiP or at the same time
  - tauFV can run in parallel and could give a spin to flavour anomalies
- SHiP enters the game as a discovery experiment
  - with large acceptance, spectrometry, PID
  - with reliable **zero-background** expectations
  - and with a complementary neutrino physics / scattering programme
- Physics performance guaranteed by redundant VETO system and event selection
- project in very good shape, moving fast towards TDR

Spare slides

Cost and schedule

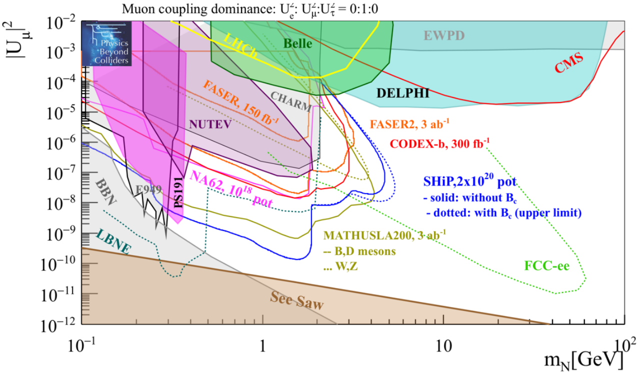
- all sub-detector's phase 1 prototypes constructed and tested with beam, with nice results
  - schedule driven by SPS/LHC schedule: installation LS3
  - phase 2 prototyping ongoing
  - 3 years for TDRs
  - construction of BDF $\sim$5 years (see M. Lamont's talk)
  - detector production, installation, commissioning $\sim$6-7 years (in parallel to BDF construction)
  - aiming for operation in Run 4 (as early as possible)
  - project mature and no showstoppers
- $^{+10-30\%}_{-10-20\%}$ cost estimate produced for the Technical Proposal
- major design changes since TP, but cost stable
  - revised costing together with updated project plan is being prepared for the detector Comprehensive Design Study (November 2019)

Comparison with previous beam dump experiments

Experiment	PS191	NuTeV	CHARM	SHiP
Proton energy (GeV)	19.2	800	400	400
Protons on target ($\times 10^{19}$)	0.86	0.25	0.24	20
Decay volume (m^3)	360	1100	315	1780
Decay volume pressure (bar)	1 (He)	1 (He)	1 (air)	10^{-6} (air)
Distance to target (m)	128	1400	480	80-90
Off beam axis (mrad)	40	0	10	0

Table: Comparison of the experimental conditions for HNL search experiments [SHiP Tech. Prop. 1504.04956].

Physics performance: HNL [hep-ph/1811.00930] [PBC-REPORT-2018-007]



- HNL production and decay $\mathcal{B}$'s revised [JHEP11(2018)032]
- cascade production of charm and beauty [SHiP-NOTE-2015-009]
- flavour-independent sensitivity matrix including B_c contribution
- HNL identification and discovery reach close to seesaw limit
- great sensitivity also in U_τ^2-enhanced scenario

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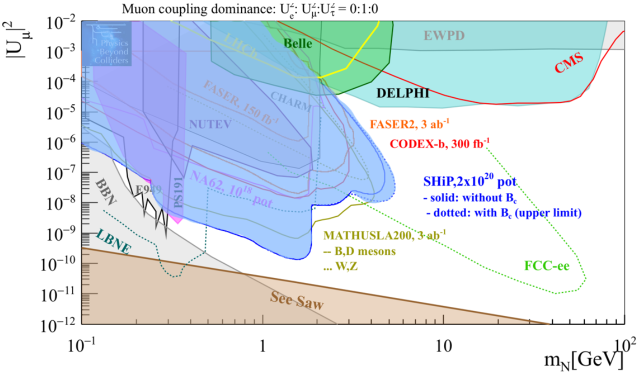

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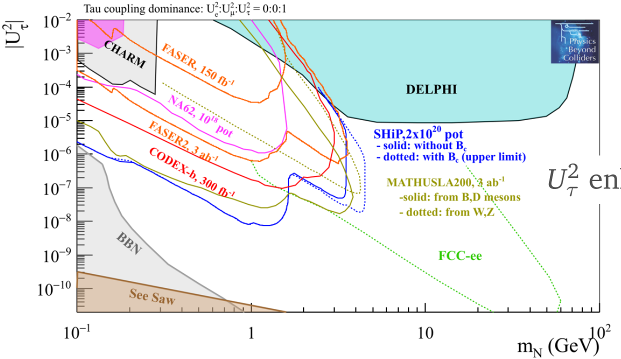

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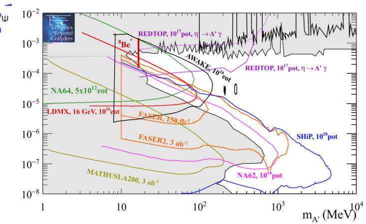
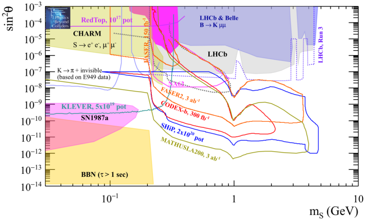
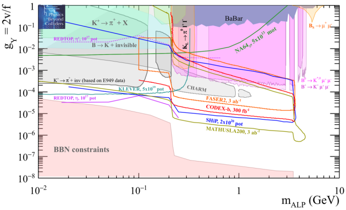
Benchmark models for visible d

- **Dark photon:**
  - meson decays, proton bremsstrahlung, $qq \to \gamma'$
  - expect improvements at low mass from:
    - cascade production
    - EM showers
- **Dark scalar:**
  - couple to Higgs in FCNC K and B decays
- **Axion-like particles:**
  - couple to fermions and to photons
  - SplitCal developed for $ALP \to \gamma\gamma$







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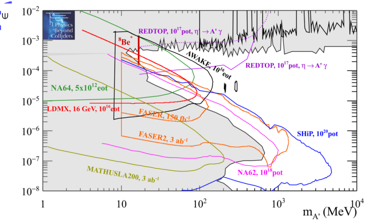
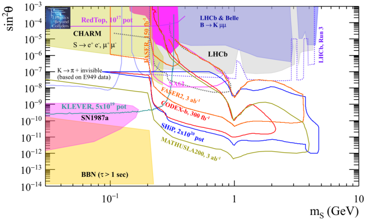
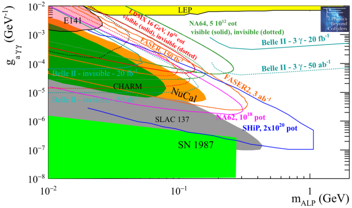
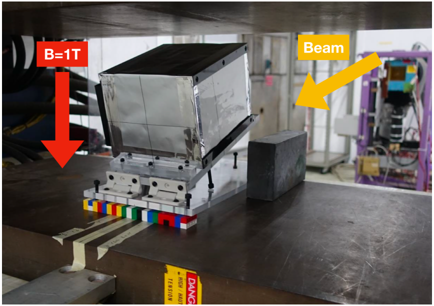






Scattering Spectrometer: status

- CES tested at CERN PS in 2017
- μ-RWELL or SciFi for tracking, both tested on beam (2018)
- μ ID system: RPC tested in CERN H4 in summer 2018



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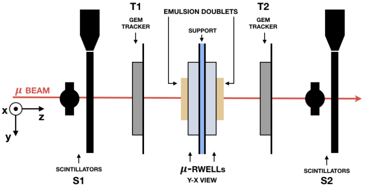
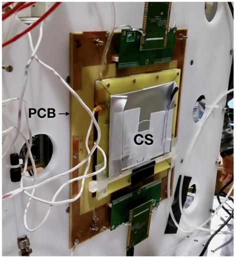
RWELL test beam





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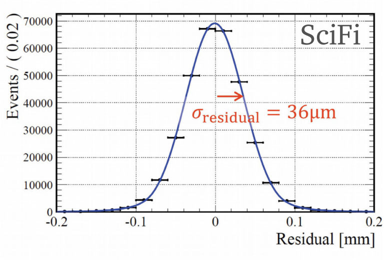
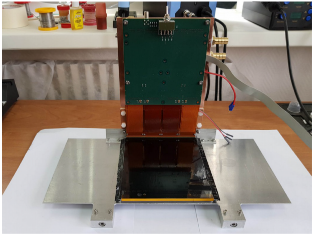


(a)



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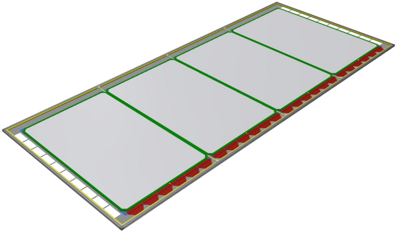

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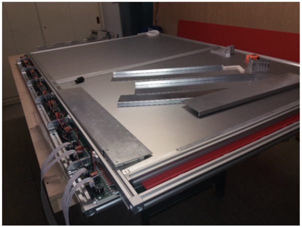

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ECAL SplitCal with 3 high-res layers for $ALP \to \gamma\gamma$ ($\sigma_\theta \sim$ few mrad)

- measure barycentre at 3 depths with MPGDs; $>$ 1 m lever arm

MUON move to scintillating tiles with SiPM readout. Beam test Oct. 2018, aim at $\sigma_t < 200$ps

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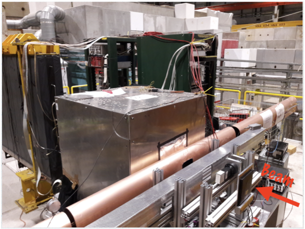

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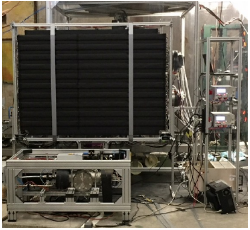

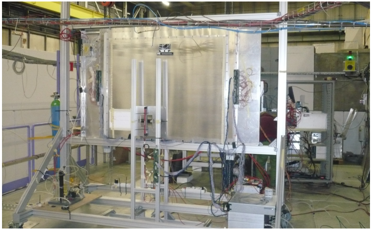

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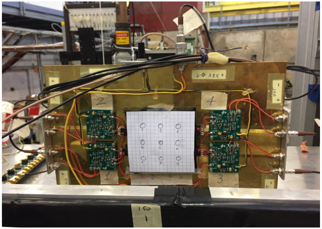


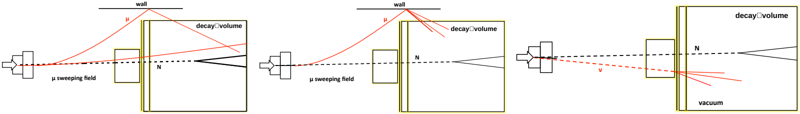
Hidden sector: physics performance

- setup ideally suited for *any* weakly interacting LLP

Cut	Value
Track momentum	$> 1.0\text{GeV}/c$
Children distance of closest approach	< 1 cm
Decay vertex position	(> 5 cm from inner wall)
IP w.r.t. target (fully reconstructed)	< 10 cm
IP w.r.t. target (partially reconstructed)	< 250 cm

- event selection: high signal efficiency + redundant BG suppression
- common selection (model independent search)
- redundancy cuts:
  - associated activity in VETO systems
  - PID cuts
  - time coincidence (suppress combinatorial background)
  - opening angle (reject events from γ conversions in the material)

Hidden sector: backgrounds



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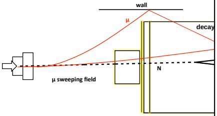
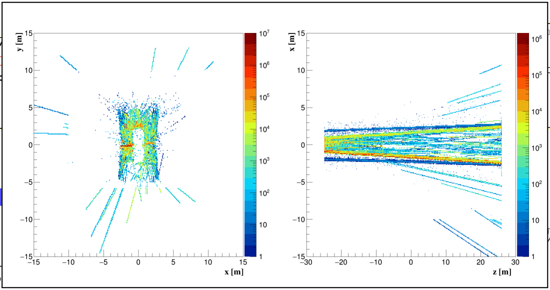
  - 10 years of SHiP simulated, increasing to 100
  - ν-air: $< 10^{-2}$ in 5 years with pressure ~ 1 mbar
  - ν-material: $5 \times 10^{5} \begin{cases} \xrightarrow{\text{cuts (fully reco)}} 0 \\ \xrightarrow{\text{cuts (part. reco)}} 2 \xrightarrow{\text{opening angle}} 0 \end{cases}$ @ $90\% CL$

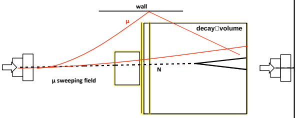
Hidden sector: backgrounds

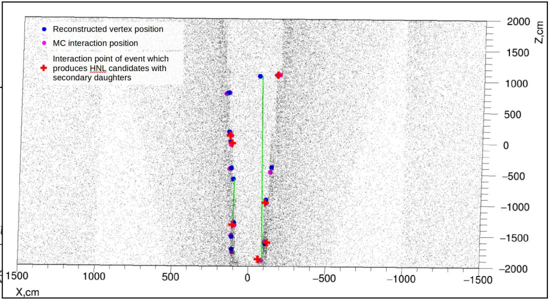




- **Muon combinat**
  - $10^{16} \xrightarrow{\text{selection}}$ … %CL
  - ML used to g…
- **Muon inelastic:**
  - 5 years of SHiP operation simulated
  - ~~correlation~~ between VETO and selection: $< 6 \times 10^{-4}$ @ 90%CL
- **ν interactions:**
  - 10 years of SHiP simulated, increasing to 100
  - ν-air: $< 10^{-2}$ in 5 years with pressure ~ 1 mbar
  - ν-material: $5 \times 10^5 \begin{cases} \xrightarrow{\text{cuts (fully reco)}} 0 \\ \xrightarrow{\text{cuts (part. reco)}} 2 \xrightarrow{\text{opening angle}} 0 \end{cases}$ @ 90%CL

Hidden sector: backgrounds



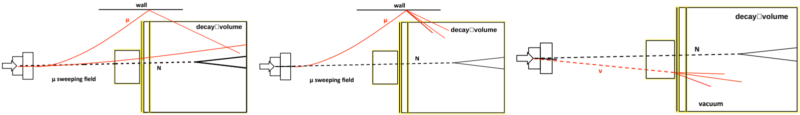


- **Muon combinatorial:**
  - $10^{16} \xrightarrow{\text{selection}} 10^{9} \xrightarrow{\Delta}$
  - ML used to generate

- **Muon inelastic:**
  - 5 years of SHiP operation simulated
  - ~~correlation~~ between VETO and selection: $< 6 \times 10^{-4}$ @ $90\% CL$

- **ν interactions:**
  - 10 years of SHiP simulated, increasing to 100
  - ν-air: $< 10^{-2}$ in 5 years with pressure ~ 1 mbar
  - ν-material: $5 \times 10^{5} \begin{cases} \xrightarrow{\text{cuts (fully reco)}} 0 \\ \xrightarrow{\text{cuts (part. reco)}} 2 \xrightarrow{\text{opening angle}} 0 \end{cases}$ @ $90\% CL$

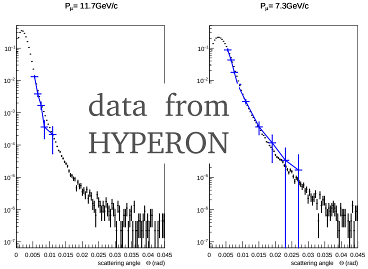
Hidden sector: backgrounds

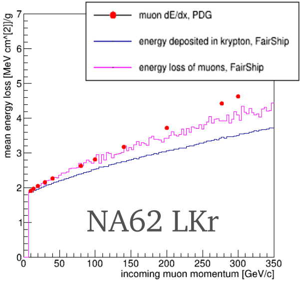


- **Muon combinatorial:**
  - $10^{16} \xrightarrow{\text{selection}} 10^{9} \xrightarrow{\Delta t < 340\text{ps}} 10^{-2}$ candidates in 5 years @ $90\% CL$
  - ML used to generate large sample of dangerous μ
- **Muon inelastic:**
  - 5 years of SHiP operation simulated
  - ~~correlation~~ between VETO and selection: $< 6 \times 10^{-4}$ @ $90\% CL$
- **ν interactions:**
  - 10 years of SHiP simulated, increasing to 100
  - ν-air: $< 10^{-2}$ in 5 years with pressure ~ 1 mbar
  - ν-material: $5 \times 10^{5} \begin{cases} \xrightarrow{\text{cuts (fully reco)}} 0 \\ \xrightarrow{\text{cuts (part. reco)}} 2 \xrightarrow{\text{opening angle}} 0 \end{cases}$ @ $90\% CL$

SHiP simulation / validation

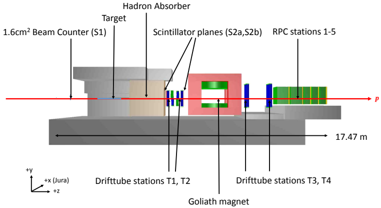
- based on FairRoot, uses:
  - Pythia8 for p-on-target collisions, tuned to include production of c, b mesons from secondaries
  - Geant4 for propagation through the target and detector material. $V^0 \to \mu\mu$, $\gamma \to \mu\mu$, $ee \to \mu\mu$ activated and boosted
  - Genie for neutrino interactions
- several HS models added/extended (HNL, γ', S, RPV $\tilde{\chi}^0$...)
- 1.8×10^9 / 6.5×10^{10} *pot* simulated with $E_{th} = 1$ / 10 GeV
- μ MS and catastrophic energy loss validated with existing data





Charm / μ flux measurements (July 2018)

- replica of BDF target + drift tube spectrometer + RPC μ tagger
- $\sim 6 \times 10^{11}$ *pot* recorded, analysis ongoing



- measure of charm production essential for HS and ν_τ studies
- lead target + emulsions. 1.6×10^{6} *pot* + 10$\times$ run after LS2