# Imperial College London



# Search for new physics with the SHiP experiment at CERN

Oliver Lantwin on behalf of the SHiP Collaboration. EPS-HEP 2017

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#### ~250 scientific authors

Search for Hidden Particles

17 member countries: Bulgaria, Chile, Denmark, France, Germany, Italy, Japan, Korea, Portugal, Russia, Serbia, Sweden, Switzerland, Turkey, United Kingdom, Ukraine, United States of America + CERN, DUBNA 49 member institutes: Sofia, Valparaiso, Niels Bohr Institute Corenhagen, LAL Orsay, LPNPE Paris, Berlin, Humbold University Hamburg.

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5 associated institutes: Jeju, Gwangju, Chonnam, National University of Science and Technology "MISIS" Moscow, St. Petersburg Polytechnic University

Technical Proposal: [CERN-SPSC-2015-016] Physics Proposal: [CERN-SPSC-2015-017]

# The state of particle physics



"We know there is new physics,..."

- ► There is experimental evidence for new physics beyond the standard model (sm):
  - 1. Neutrino masses and their origin
  - 2. Dark Matter
  - 3. Baryon asymmetry of the universe

 $\rightarrow$  these problems could be solved by new particles that are coupled to the standard model (if very weakly)

► And of course there are plenty of theoretical criticisms of the standard model...

# New physics?

- "... We don't know where it is..."
- ► We do not know at which energy new physics will show up.
- New physics could have eluded us so far in two ways:
  - new physics is at a higher energy scale
  - new physics is too weakly coupled to be detected at the current generation of experiments



"... We need to be as broad as possible in our exploratory approach"

— Fabiola Gianotti

### I will focus on the second option: Super-weakly coupled new physics with $m_{\rm NP} < \mathcal{O}(10 \, {\rm GeV})$ .



# Hidden sectors & portals



If there is super weakly coupled new physics, there generally is a portal that mediates between the standard model and one or more hidden particles, i.e. the hidden sector (HS):

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

There are four possible types of portal:

- Scalar (e.g. dark scalar, dark Higgs)
- ► Vector (e.g. dark photon)
- ► Fermion (e.g. heavy neutral lepton (HNL))
- ► Axion-like particle (ALP)

### Consider example of the fermion portal here: HNL

See our physics proposal [CERN-SPSC-2015-017] for an overview of the many other models we can test!

 $(H^{\dagger}H)\phi$   $\epsilon F_{\mu\nu}F'_{\mu\nu}$   $H^{\dagger}\overline{N}L$  $aF^{\mu\nu}\tilde{F}^{\mu\nu}$ 

### Example: Fermion portal/HNL of the $\nu$ MSM

A model with a minimal number of additional particles that can solve all of the experimental problems is the neutrino minimal standard model ( $\nu$ MSM) [arXiv:hep-ph/0505013]

- ► Add three right-handed Majorana neutrinos N<sub>i</sub>:
  - ▶ Light  $N_1$  with mass  $\mathcal{O}(10 \text{ keV})$ , essentially decoupled from  $N_{2,3}$ 
    - Dark matter candidate
  - ▶ Heavy  $N_{2,3}$  with masses  $\mathcal{O}(1\,\mathrm{GeV})$ , weakly coupled to standard model  $\rightarrow$  HNL
    - Set active neutrino masses
    - Create baryon asymmetry of the universe via leptogenesis and sphaelerons
    - Produced in charm decays; detectable via visible decays:







### Two signatures:

- 1. Via decay to visible particles in hidden sector spectrometer
- 2. Via scattering in nuclear emulsion

Generic signatures predicted by many new physics models

<sup>\*</sup>see talk by Marilisa De Serio in the Neutrino Physics track

# Crucial challenges



### Maximise intensity and mass reach

- ► Intense proton beam from the SPS @400 GeV at the new beam dump facility (BDF) in the North Area
- Very dense target of  $12 \times \lambda_{int}$ 
  - abundant production of heavy flavour
  - reduced neutrino production from  $\pi$  and K decays
- Number of protons per cycle similar to CNGS, but slow instead of fast extraction
- Operation in parallel with LHC, other beam-lines at the SPS



# Crucial challenges



[2017 JINST 12 P05011]



### Zero background

- Passive hadron absorber
- Active muon shield that has to reduce muon flux by at least 6 orders of magnitude
- kinematic range of muons up to  $p\sim$  350 GeV
- kinematic range of muons up to  $p_T \sim 8 \, {\rm GeV}$

# The muon shield is the critical component to optimise to maximise the experimental acceptance

► A measurement of the muon spectrum for the SHiP target at the H4 test-beam at CERN'S SPS is planned for 2018

# Crucial challenges

Zero background Background taggers for any visible particles entering or exiting the decay vessel	Evacuated decay vessel to reduce the background from neutrino interactions to negligible levels $\mu$	PID to suppress background guish signal final states:	Timing <sup>†</sup> combin backgrc muons Tracking vertexir impact measur and disti	Timing <sup>†</sup> to suppress <sup>vived</sup> , for Hidden Paridee combinatorial background from muons Tracking for vertexing and impact parameter measurement		
			Particle	Final states		
		HNL, NE	$\ell^{\pm}\pi^{\mp}$ , $\ell^{\pm}K^{\mp}$ , $\ell^{\pm}\rho^{\mp}$			
		Vector, scalar, axion portals; g	$\ell^{\pm}\ell^{\mp}$			
		HNL, neutralir	$\ell^{\pm}\ell^{\mp}\nu_{\ell}$			
		Axion portal, sg	oldstino	$\gamma\gamma$		
A	im for redundancy to suppress	background sg	oldstino	$\pi^0\pi^0$		

## Status

- ► Expression of interest
- ► Technical proposal (TP) & physics proposal (PP)
- SPSC and CERN research board recommended we continue to a comprehensive design study (CDS) phase → Re-optimisation of the entire experiment
- Part of the CERN Physics beyond colliders (PBC) working group and will be an input to the European strategy meeting (ESPP) in 2019/2020

Accelerator schedule	2015	2016	2017	2018	2019	2020		2021	2022	2023	2024	2025		2026	2027
LHC		F	Run 2		L	S2			Run 3			LS3			Run 4
SPS											NA stop	SPS sto	op 🛛		
					ESPF	<b>&gt;</b>									
Detector			CD	S	Prototyping	, design			Product	ion	Insta	llation			
Milestones	TP							PRR						CwB	Data taking
Facility						Integ	ratio	n						CwB	
Civil engineering					Pre-c	onstruction	Т	arget - I	Detector hall	- Beamline	- Junction	ו (WP1)			
Infrastructure									Inst	allation	Installati	on	Inst.		
Beamline			CD	S	Prototyping	, design		P	roduction		Installa	ation			
Target complex			CD	S	Prototyping	, design		Proc	duction	Inst	allation				
Target			CD	S	Prototyping	, design				Production	Ins	tallation			



Now

# Sensitivity: HNL



Figure: HNL sensitivity at SHiP for  $\nu \rm MSM$  with  $U_e^2:U_{\tau}^2:U_{\tau}^2=1:16:3.8$  and a normal neutrino mass hierarchy.

### NB: Before re-optimisation



- ► Best sensitivity up to charm kinematic limit
- ► Significant contribution from *B*-decays

Theoretical limits from:

- ► Baryon asymmetry of the universe (BAU)
- ► Big bang nucleosynthesis (ввN)
- Model-independent limit for any Seesaw model

# Sensitivity: Dark Scalars



Figure: Dark scalar sensitivity at SHiP.

### NB: Before re-optimisation

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- ► For short lifetimes *B*-factories and LHCb best
- SHiP covers unique parameter space complementing other experiments
- ► Large contribution from *B*-decays at SHiP
- "Hole" at cτ ~ O(m), where lifetime is too short for SHiP and too long for B-experiments

# Sensitivity: Dark Photons





- Based on  $> 10^{20}\gamma$  at SHiP over 5 years
- Visible decays of dark photons
- Produced in QCD, bremsstrahlung and meson decays
- $\blacktriangleright$  No production via EM showers yet  $\rightarrow$  Work in progress
- Complementary to regions studied by other experiments
- Top-right edge of sensitivity determined by short lifetime

NB: Before re-optimisation

# Sensitivity: Light Dark Matter



Figure: Light dark matter sensitivity at SHiP for  $\frac{m_{A'}}{m_{\chi}}=3.$ 

#### NB: Before re-optimisation Oliver Lantwin (Imperial College London) EPS-HEP 2017

 For dark matter lighter than WIMPs "direct detection" experiments quickly lose sensitivity.



### Two approaches:

- missing mass/energy searches ( $\propto U^2$ )
- scattering/recoil (  $\propto U^4$  )

SHiP: Indirect detection via electron and nuclear recoil in nuclear emulsion:

- ► Main background for electron recoil from v<sub>e</sub> scattering, but differences in the kinematics can be exploited.
- ► Preliminary; cascade production not yet implemented → already best sensitivity for scattering

LDMX@SLAC:

missing energy at electron beam

# Conclusion



- ► Plenty of room for new physics to hide in the dark sector!
- ► SHiP is sensitive to many different final states in decay and scattering
- SHiP is currently undergoing a re-optimisation to improve physics performance while respecting cost constraints
- Sensitivities and backgrounds are being updated for new configurations, additional production and decay channels are being added in collaboration with theorists

"We have to leave all this spectrum of possibilities open and just enjoy this extremely fascinating science."

— Carlo Rubbia