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SHiP: Search for Hidden Particles

Mitesh Patel (Imperial College London)

PPAP Meeting

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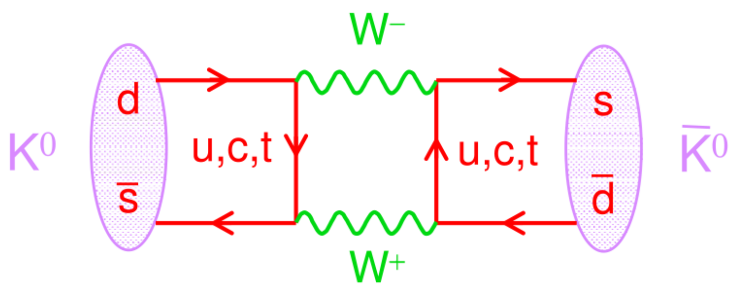
On behalf of,

Bristol, Imperial, RAL, Warwick, UCL

Introduction

- No signs of New Physics seen in direct searches at LHC

- Nothing seen in loop processes



(charged LFV, electron EDM …)

Scale of strongly coupled new physics, Λ, well above the reach of accelerators : **$\Lambda > 10^3$-10^4 TeV**

- Still have the shortcomings of the SM e.g. :
  - Pattern of neutrino masses & oscillations
  - Excess of matter over antimatter in the Universe
  - The nature of non-baryonic Dark Matter

A hidden sector … ?

- Rather than being **heavy**, could new particles be light but *very* weakly interacting?

- Get such particles in a very wide range of theories e.g.
  - SUSY → light sgoldstinos associated with sym. breaking
  - Extra-dimensions → Axion Like Particles (ALPs) at Fermi scale
  - "Hidden sector" Models → new particles at Fermi scale which are singlets wrt gauge group of the SM
    - Can still get production (and decay) by mixing hidden sector particle with some SM "portal particle"

In all cases, interactions can be sufficiently weak so as to evade precision flavour and electroweak constraints

Exploring Hidden Sectors with SHiP

- Several possibilities for so-called portal operators :
  - **Vector portal** – new U(1) $B_{\mu\nu}$ – mixing with photon → $\varepsilon B_{\mu\nu}F^{\mu\nu}$
  - **Higgs portal** – new scalar field χ → $(\mu\chi+\lambda\chi^2)H'H$
  - **Axial portal** – new axial-vector a → $(a/F)G_{\mu\nu}G^{\mu\nu}$, $(\delta_\mu a/F)\psi'\gamma_\mu\gamma_5\psi$
  - **Neutrino portal** – new heavy neutral leptons (HNL) → $YH^TN'L$

[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] experiment is intended to hunt for new physics in the largely unexplored domain of very weakly interacting particles with masses below the [illegible] scale, inaccessible to the LHC experiments, and to study tau neutrino physics. The same proton beam setup can be used [illegible] $\to 3\mu$ and to search for weakly-interacting sub-GeV dark matter candidates. We discuss the evidence for physic[illegible] interactions between new particles and four different *portals* — scalars, vectors, fermions or axion-like particles. We discuss motivations for different

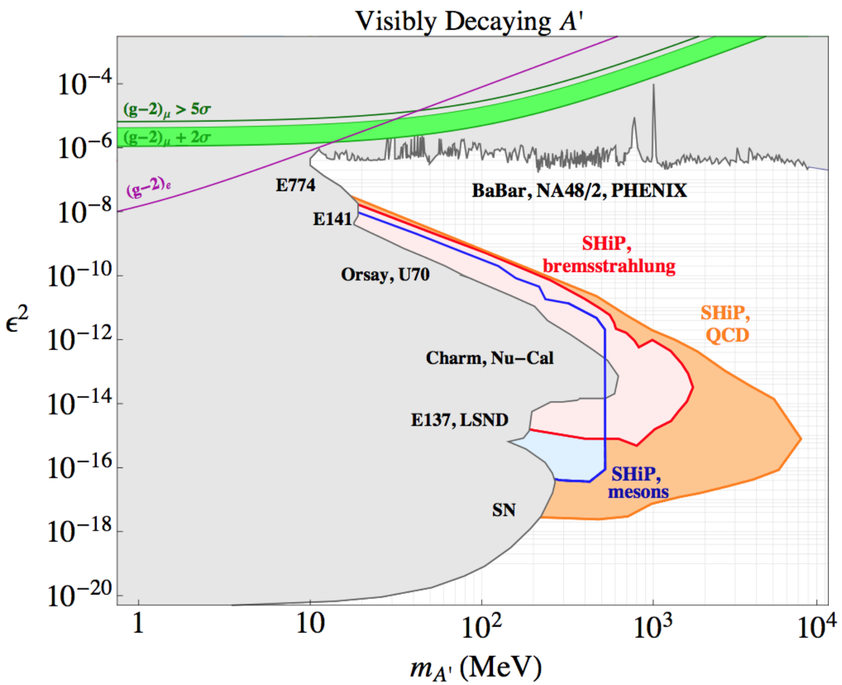
SHiP will make world-beating and model independent searches in of all of these areas

- Diverse physics programme…
- Weak mixing → (v.) long lifetime
- Require very large number of intn. → **fixed-target experiment**

Vector Portal

- New vector boson ("dark photon") at O(GeV) scale motivated by range of astrophysical observations
  - e.g. positron excess, excess annihilation in the galactic centre (see e.g. arXiv:0810.0713)

- Can produce γ in target, mixes into a dark photon ($\sim\varepsilon$), dark photon mixes back into a SM photon ($\sim\varepsilon$) then decays into l^+l^-, $\pi^+\pi^-$ etc.

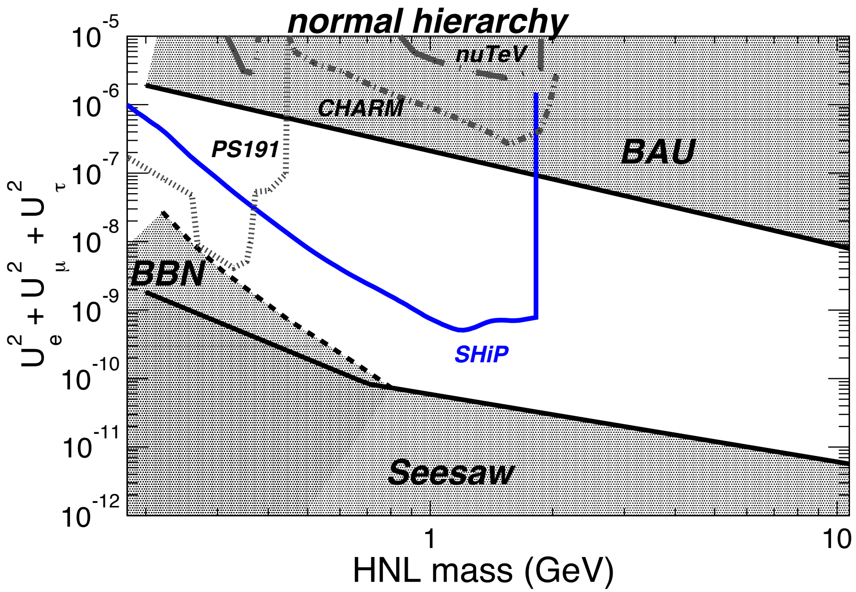


- As dark photon has no other interactions with SM particles can fly through material : "light-shining-through-a-wall"

Neutrino Portal

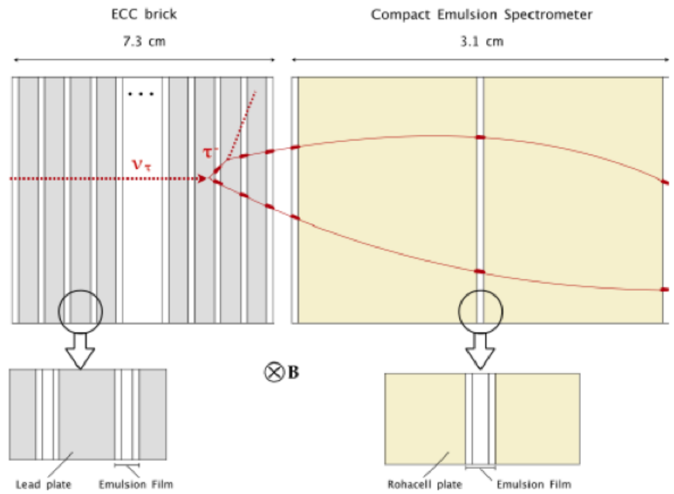
- The **neutrino Minimal Standard Model** (**νMSM**) adds three right-handed, Majorana, Heavy Neutral Leptons (HNL) to the SM particles
  - **N_1** – mass in keV region, (warm) dark matter candidate
  - **$N_{2,3}$** – mass in 100 MeV – GeV region – generate neutrino masses via see-saw mech. (Seesaw) and produce baryon asymmetry of the Universe (BAU) – **$N_{2,3}$** can decay into $\mu\pi$

- Theoretical constraints [Seesaw, BAU and Big Bang Nucleosynthesis (BBN)] suggest that interesting region has only been explored below the m_K

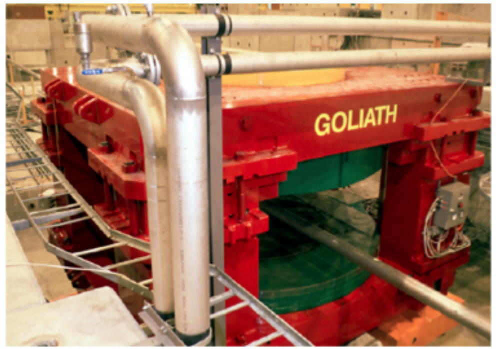


Tau neutrino physics

- Large flux of ν_τ produced as a by-product of interactions in target → ~6700 (3400) ν_τ ($\bar{\nu}_\tau$) intn(*)



- Use dedicated detector to observe $\bar{\nu}_\tau$ for first time, measure both ν_τ and $\bar{\nu}_\tau$ cross-sections in terms of all structure functions



- Improve on the OPERA concept :
  - ν_e : e producing EM-shower in emulsion
  - $\nu_\mu/\bar{\nu}_\mu$: use dedicated muon spectrometer
  - $\nu_\tau/\bar{\nu}_\tau$: ν interaction and τ decay vertices in emulsion target

(*) cf. DONUT@Fermilab 9 candidates, OPERA@LNGS 5 candidates (from oscillations)

Experimental design

- Propose a beam dump experiment at the CERN SPS with a total of **~2×10^{20} protons on target** (POT)
  - more than **10^{17} D mesons** ($D\to\mu\nu$, ν mixes into HNL)
  - more than **10^{20} brem.** γ @ 1 GeV (γ mixes into γ')
  - …

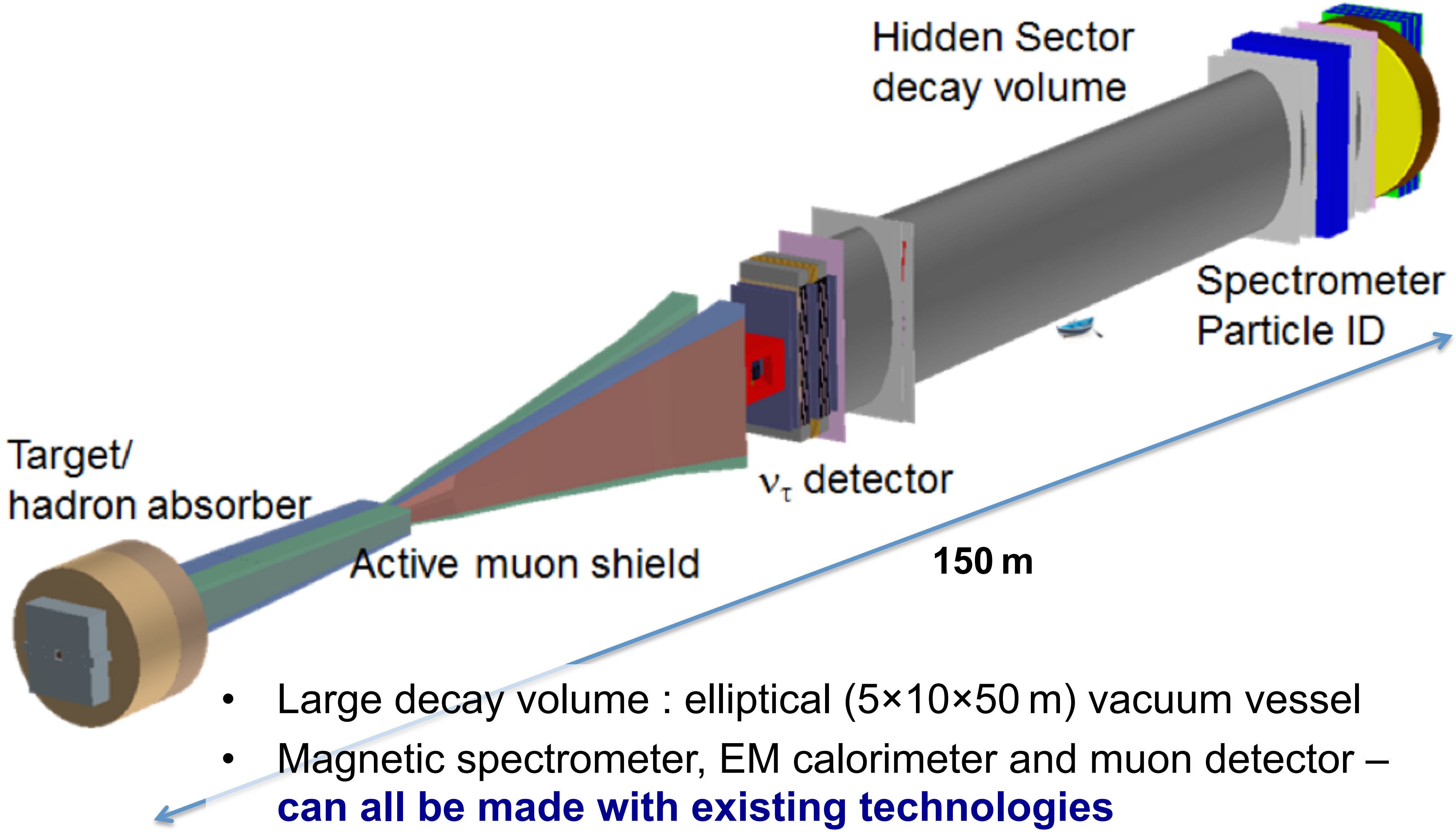
→ **O(10000) improvement over any previous searches**

- Crucial expt design parameters: **residual ν and μ fluxes** - (can produce e.g. $\mathbf{K^0_L}$ decays that mimic signal events)
  - Neutrinos from light meson decays

    → **dense target/hadron absorber**
  - Short-lived resonances generate **10^{10}** μ /spill

    → **active muon shield – essential to viability of the expt**

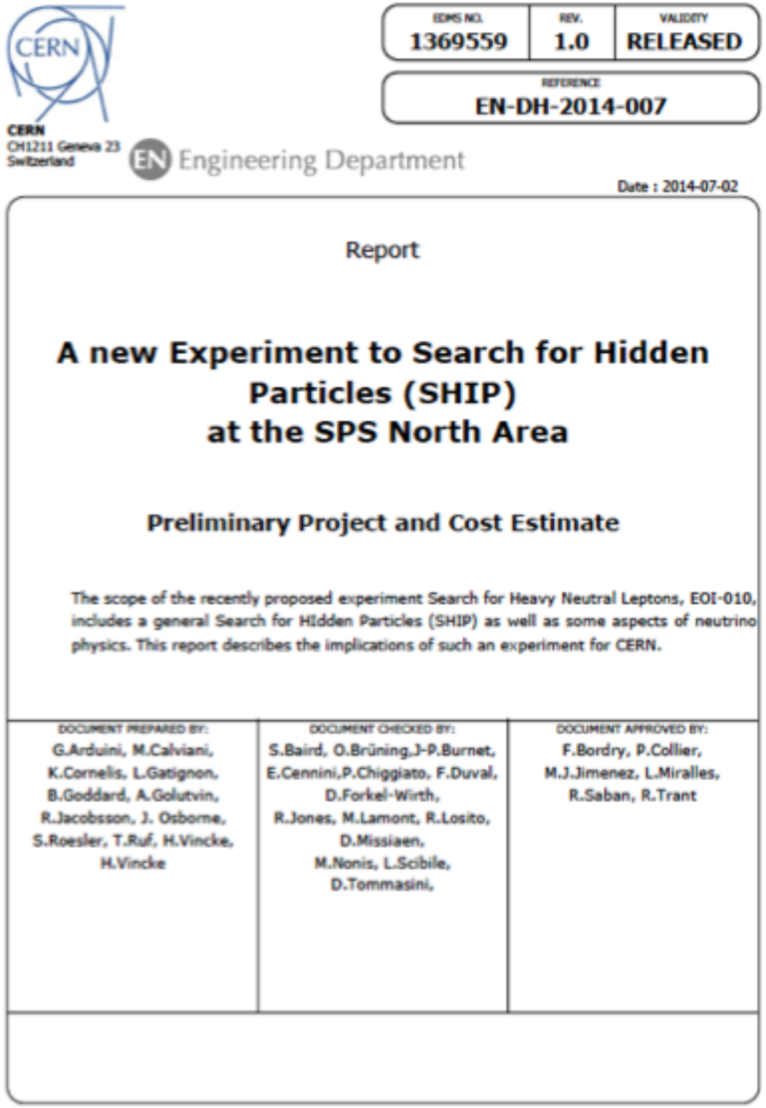
The SHiP experiment



- 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**

CERN task force

- Great enthusiasm for the project at CERN
- Relevant divisions have made detailed assessments of :
  - Target design
  - Radiological aspects
  - Civil engineering
  - Site selection
  - Costs and manpower
- Task Force report published and discussed with directorate



CERN
CH1211 Geneva 23
Switzerland

EN Engineering Department

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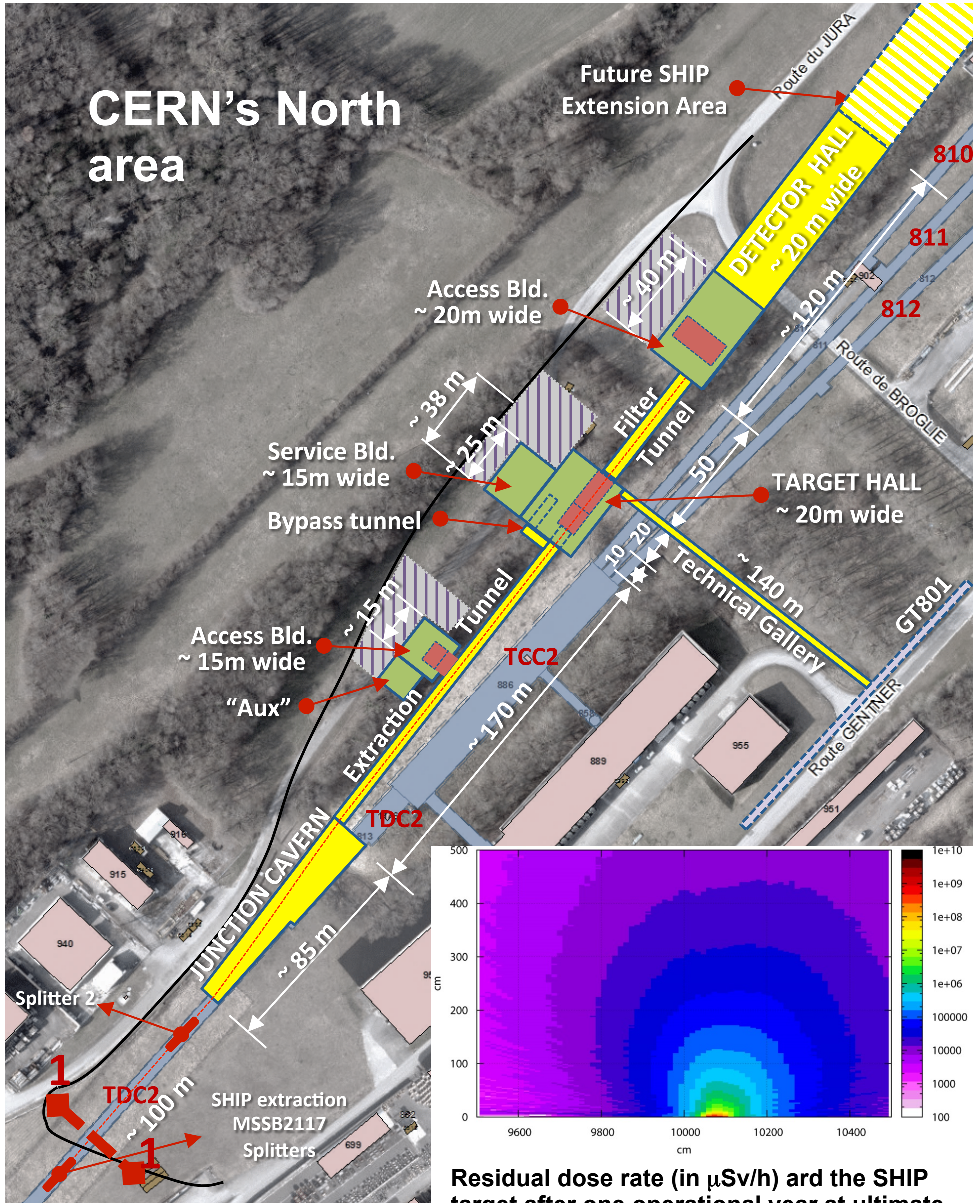
Report

A new Experiment to Search for Hidden Particles (SHIP) at the SPS North Area

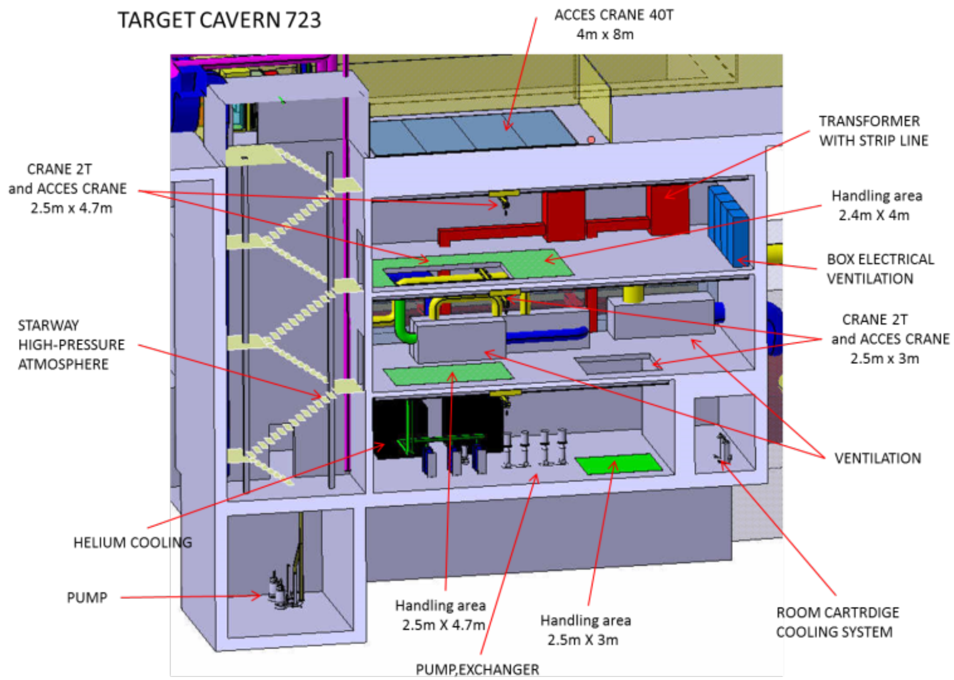
Preliminary Project and Cost Estimate

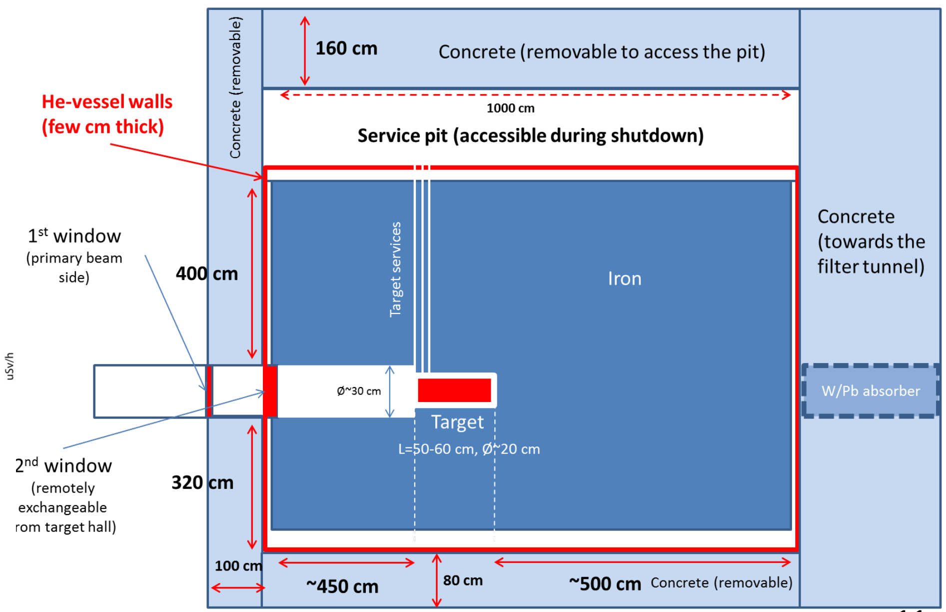
The scope of the recently proposed experiment Search for Heavy Neutral Leptons, EOI-010, includes a general Search for Hidden Particles (SHIP) as well as some aspects of neutrino physics. This report describes the implications of such an experiment for CERN.

DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:	DOCUMENT APPROVED BY:
G.Arduini, M.Calviani, K.Cornelis, L.Gatignon, B.Goddard, A.Golutvin, R.Jacobsson, J. Osborne, S.Roesler, T.Ruf, H.Vincke, H.Vincke	S.Baird, O.Brüning,J-P.Burnet, E.Cennini,P.Chiggiato, F.Duval, D.Forkel-Wirth, R.Jones, M.Lamont, R.Losito, D.Missiaen, M.Nonis, L.Scibile, D.Tommasini,	F.Bordry, P.Collier, M.J.Jimenez, L.Miralles, R.Saban, R.Trant



Residual dose rate (in μSv/h) ard the SHIP target after one operational year at ultimate intensity and 1 month of cooling time





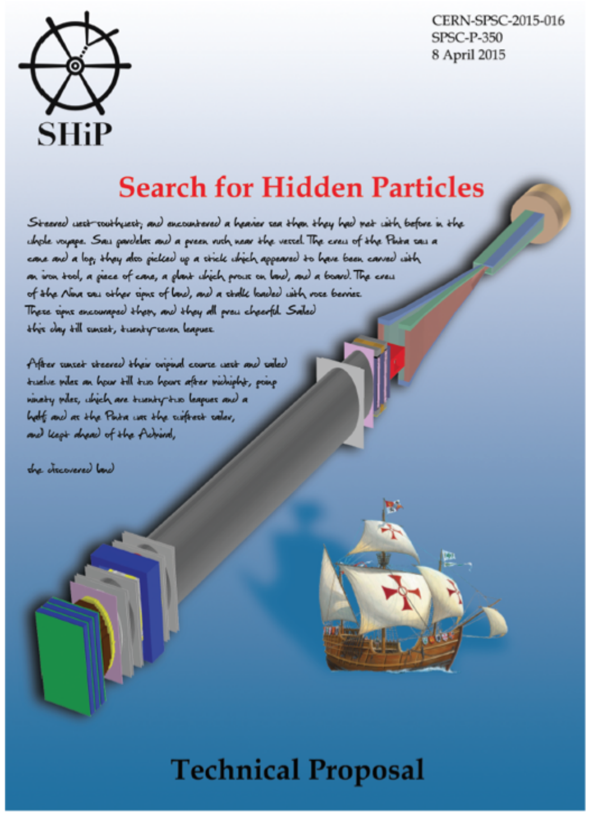
Status of the proposal

- Submitted our EoI in Oct 2013 [arXiv:1310.1762]

- SPSC discussed proposal in Jan 2014 and asked for a Technical Proposal

- Produced TP in Apr 2015, positive response from SPSC referees – just finished addendum to TP

- Discussion on-going about use of new facility beyond SHiP experiment



- Collaboration now 243 members from 45 institutes in 14 countries, admission of additional institutes pending

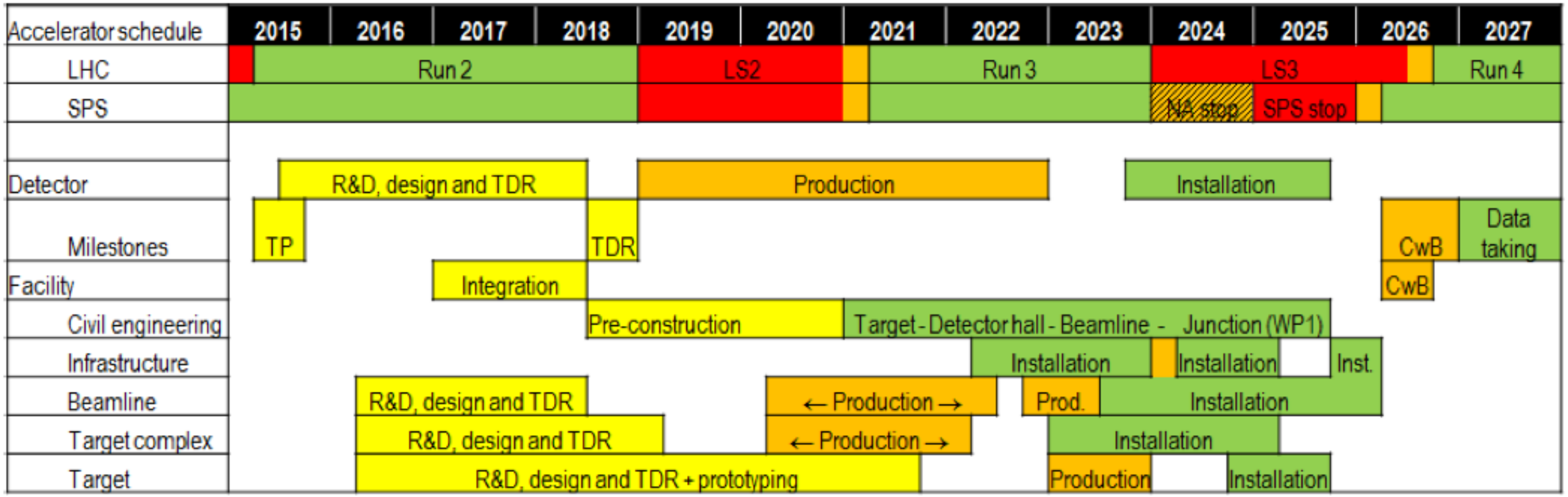
SHiP UK

- UK physicists initiated the SHiP project
  → significant influence / leadership
  - Spokesperson
  - Convenor 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 '15 roadmap : "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"
- UK-SoI for R&D considered Apr '15 – received with much interest. Decision pending commitment from CERN (Expected spring '16)

Schedule

- Revised schedule takes into account latest understanding of LHC shutdowns, allows request for significant funds from CERN to be delayed until 2020



  - **Given growth of collaboration and central nature of muon-shield work package, if the UK wishes to maintain its leadership then resources will be needed for R&D**

Conclusions

- SHIP will search for new, very weakly interacting particles which can solve significant problems of the SM
  - Can improve sensitivity by O(10000) wrt previous experiments
- Experiment also has a unique ν_τ programme
  - Sensitivity improvement O(200) for ν_τ physics, first direct observation $\bar{\nu}_\tau$
- Detector is challenging but based on existing technologies
- UK physicists initiated the SHiP project and are playing a leading role in its development

Backup

Cost and Resources

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

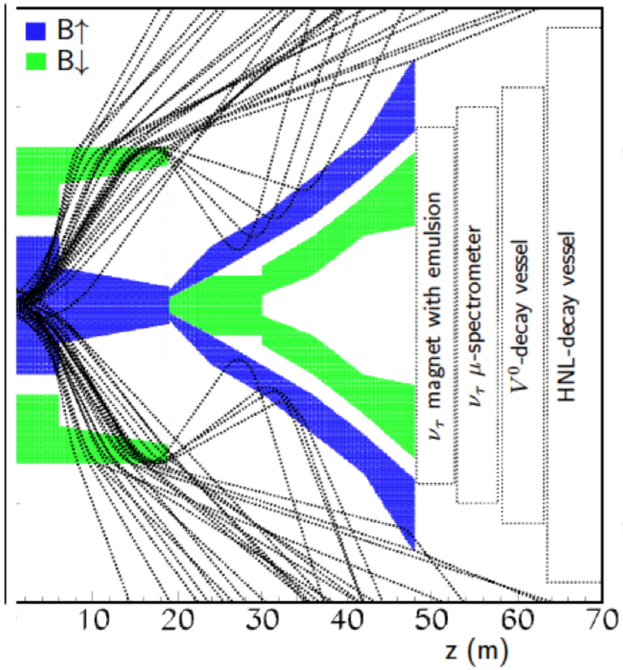
Item	Cost (MCHF)	
Facility		**135.8**
Civil engineering	57.4	
Infrastructure and services	22.0	
Extraction and beamline	21.0	
Target and target complex	24.0	
Muon shield	11.4	
Detector		**58.7**
Tau neutrino detector	11.6	
Hidden Sector detector	46.8	
Computing and online system	0.2	
Grand total		**194.5**

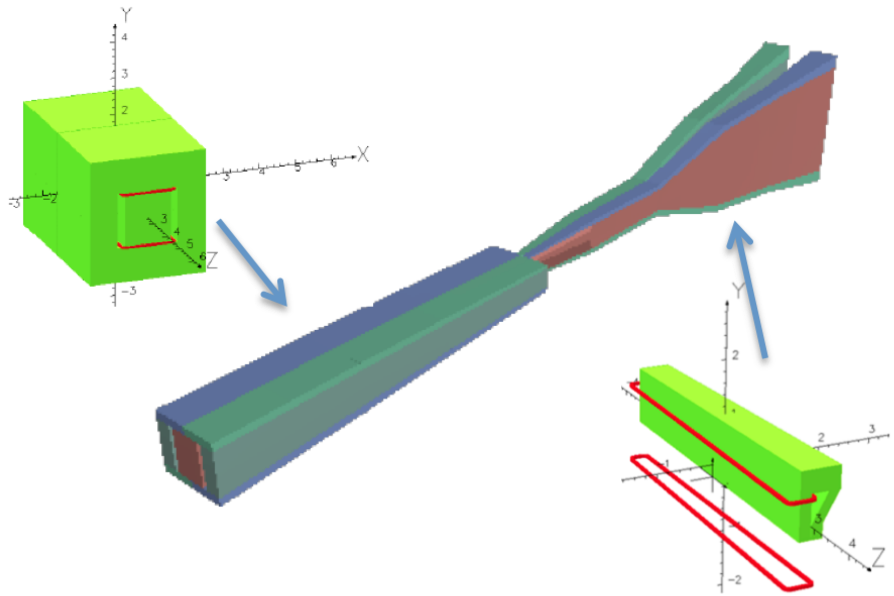
- CERN manpower for preparation of entire facility and installation: 103 FTEs - Fellows (6.3 MCHF) included in cost
- CERN resource requirements for TDR phase (3years) excluding integration and CE : ~3.2 MCHF and 12.5 FTEs
- CE preparatory cost (integration, design, EIA, permit, tendering, 2.5 years)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

Active muon shield

- Muon flux limit driven by Hidden Sector backgrounds and emulsion-based neutrino detector
- Magnetic sweeper with field integral B_y=86.4 Tm
- Realistic design of sweeper magnets performed by UK groups
  - Challenges: flux leakage, constant field profile

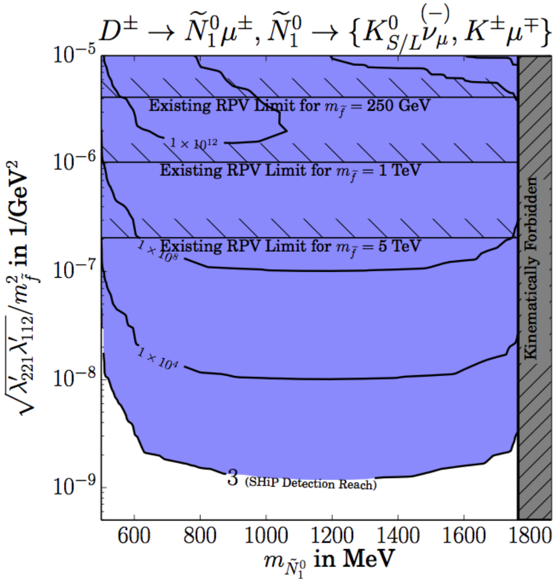
→ < 7k muons /spill (E_μ > 3 GeV)



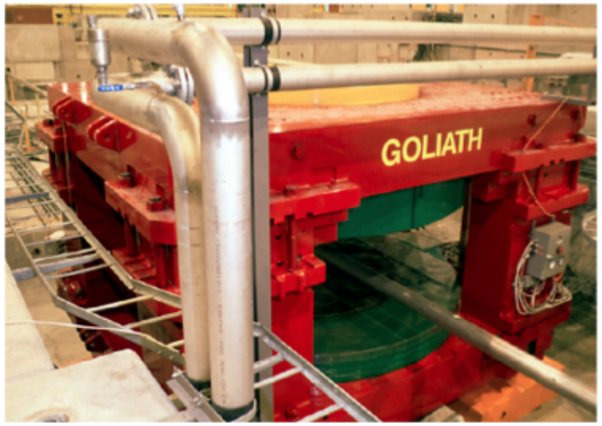


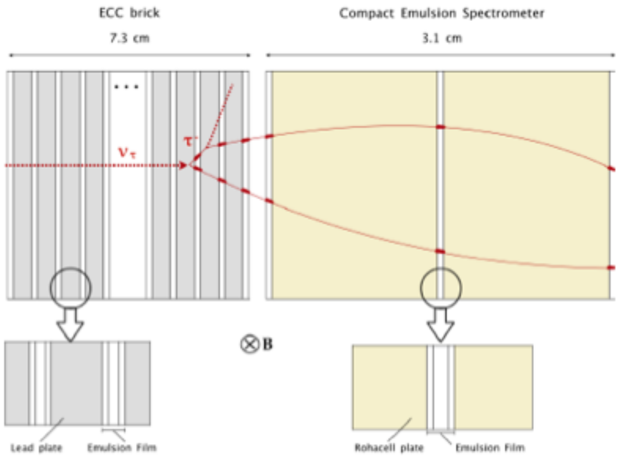
Other BSM physics

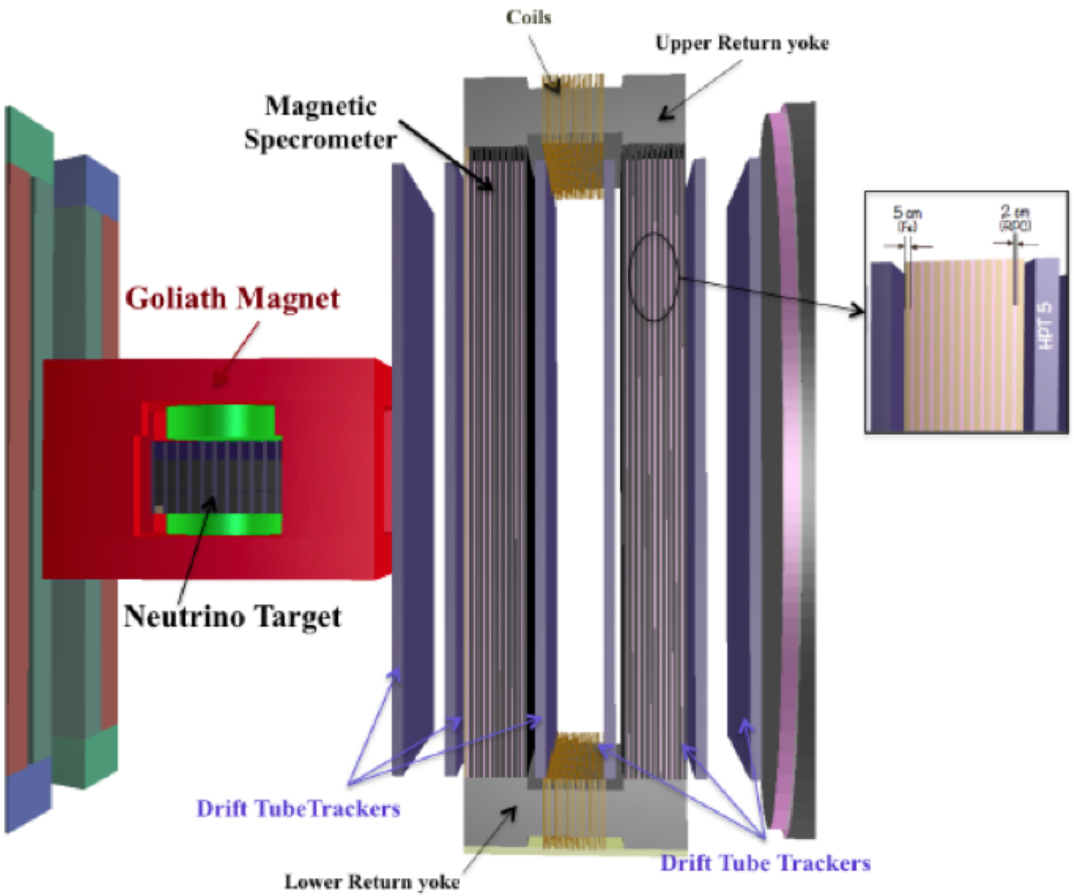
- Can make searches for other light, very weakly interacting new particles :
  - Light superpartners of goldstino in SUSY models e.g. **D→πX, X→l⁺l⁻**
    [see e.g. Gorbunov (2001)]
  - R-parity violating neutralinos in SUSY models e.g. **D→lX, X→l⁺l⁻ν**
    [see e.g. A.Dedes, H.K Dreiner, P Richardson (2001)]
  - Massive paraphotons (in secluded dark matter models) e.g. **Σ→lX, X→l⁺l⁻**
    [see e.g. M.Pospelov, A. Ritz, M.B. Voloshin (2008)]



ν_τ detector

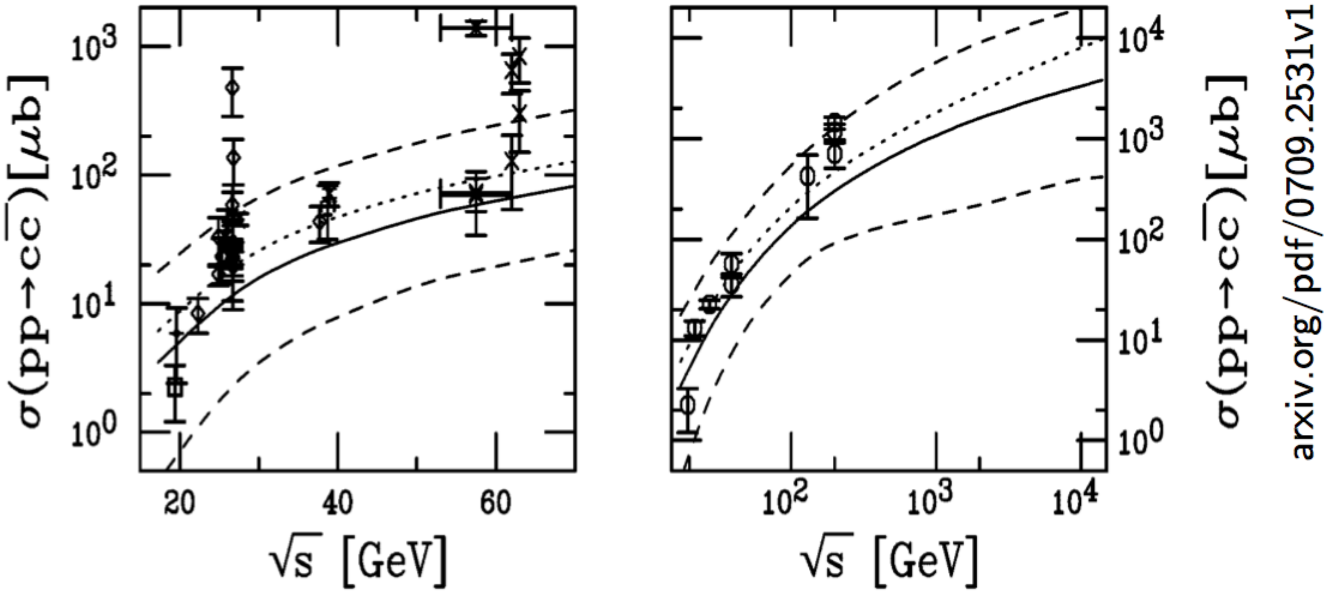






Where to produce charm?

- $c\bar{c}$ cross-section :

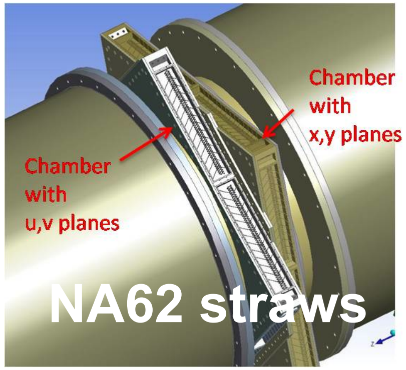


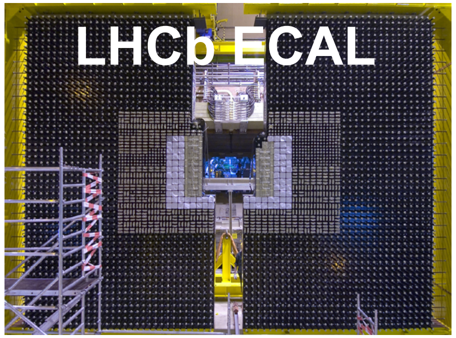
  - LHC ($\sqrt{s}$ = 14 TeV): with 1 ab^{-1} (i.e. 3-4 years): ~ 2×10^{16} in 4π
  - SPS (400 GeV p-on-target (pot) $\sqrt{s}$ = 27 GeV): with 2×10^{20} pot (i.e. 3-4 years): ~ 2×10^{17}
  - Fermilab: 120 GeV, 10× smaller σ_{cc}, 10×pot by 2025 for LBNE
- Note B-decays produced with 20-100 smaller cross-section and dominant semi-leptonic decay would be $D\mu\nu$ i.e. still limited to 3 GeV

Detector Technologies

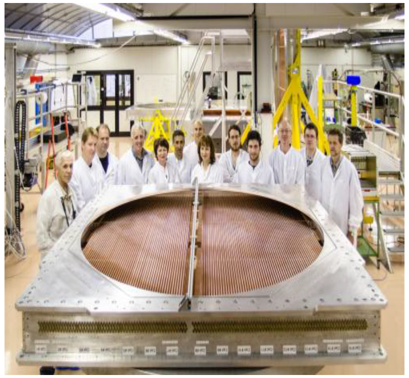
- **Dipole magnet**
  - Magnet similar to LHCb design required, but with ~40% less iron and 3× less power dissipated
  - Free aperture of ~16 m^2 and field integral ~ 0.5 Tm over 5 m length

- **Vacuum tank and straw tracker**
  - NA62 has 10^{-5} mbar pressure cf. 10^{-2} mbar required here
  - Have demonstrated gas tightness of straw tubes with **120 μm spatial resolution** and **0.5% X_0/X** material budget in long term tests



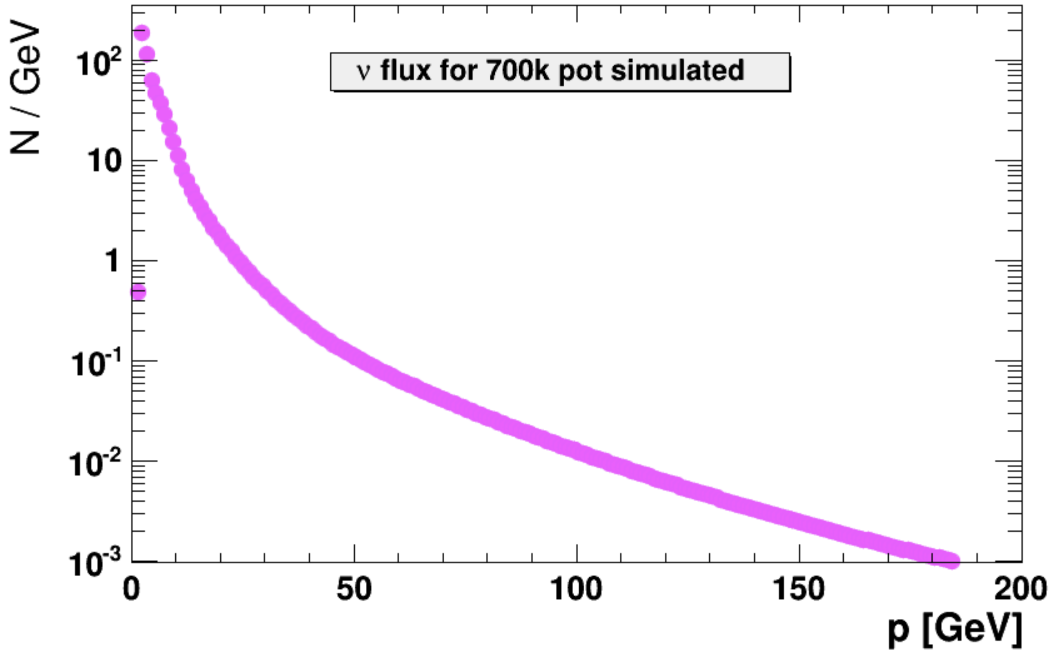


- **Electromagnetic calorimeter**
  - Shashlik technology used in LHCb would provide economical solution with good energy and time resolution



Residual neutrino flux

- Momentum spectrum of the neutrino flux after the muon shield



- At atmospheric pressure expect **2×10^4** neutrino interactions in the decay volume per **2×10^{20} pot**

  → **becomes negligible at 0.01 mbar**

Other facilities

- Have considered if could perform experiment elsewhere
- Fermilab
  - 120 GeV proton beam, 4×10^{19} POT
    - factor ten lower event yield than in the proposed SPS experiment
  - 800 GeV proton beam, 1×10^{19} POT
    - Lower POT would be approximately compensated by higher charm cross-section
    - Would require much longer muon shield → loss of acceptance
- KEK
  - 30 GeV proton beam, 1×10^{21} POT
    - large uncertainty due to the poor knowledge of the charm cross-section at low energy
    - Estimate factor 1.5-2 lower signal yields
- Colliding beam experiment at LHC, 1000 fb^{-1}, 14 TeV
  - Assuming experiment located 60m away from the interaction region and 50 mrad off-axis to avoid LHC beams – factor 200 worse than proposal