SHiP experiment at CERN SPS

Dmitry Gorbunov

Institute for Nuclear Research of RAS, Moscow

on behalf of the **SHiP collaboration**

Search for **Hi**dden **P**articles

SHiP

QFTHEP-2015

Samara, Russia

Outline

1. At QFTHEP-2013 . . .
2. Building the sketch of the SHiP
3. Physics at SHiP
   - Elusive NP: portals to a hidden World
   - Elusive NP: exotic SUSY
   - Elusive SM physics: neutrinos
4. Summary

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Searches for GeV-scale sterile neutrinos with CERN SPS proton beam

Dmitry Gorbunov

Institute for Nuclear Research of RAS, Moscow

XXIst International Workshop on Quantum Field Theory and High Energy Physics, St.-Petersburg, Repino, 26.06.2013

Phenomenological problems of the Standard Model

Gauge fields (interactions) – γ, $W^{\pm}$, Z, g

Three generations of matter: $L = \binom{\nu_L}{e_L}$, e_R; $Q = \binom{u_L}{d_L}$, d_R, u_R

- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe
  - Neutrino oscillations : active neutrino masses via mixing
  - Dark matter (Ω_{DM}) : sterile neutrino as DM
  - Baryon asymmetry : leptogenesis via sterile neutrino decays or oscillations

- Sterile neutrinos explain the oscillations
- and the cosmological problems

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Sterile neutrinos: NEW ingredients

One of the optional physics beyond the SM:

sterile: new fermions uncharged under the SM gauge group
neutrino: explain observed oscillations by mixing with SM (active) neutrinos

Attractive features:

- possible to achieve within renormalizable theory
- only $N = 2$ Majorana neutrinos needed
- baryon asymmetry via leptogenesis
- dark matter (with $N \geq 3$ at least)
- light(?) sterile neutrinos might be responsible for neutrino anomalies. . . ?

Disappointing feature:

Major part of parameter space is UNTESTABLE

Seesaw mechanism: $M_N \gg 1$ eV (Type I)

With $m_{active} \lesssim 1$ eV we work in the seesaw (type I) regime:

$$\mathscr{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.}$$

When Higgs gains $\langle H \rangle = v/\sqrt{2}$ we get in neutrino sector

$$\mathscr{V}_N = v\,\frac{f_{\alpha I}}{\sqrt{2}}\,\overline{\nu}_\alpha N_I + \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.} = \left(\overline{\nu}_1, \ldots \overline{N}_1^c \ldots\right) \begin{pmatrix} 0 & v\,\frac{\hat{f}}{\sqrt{2}} \\ v\,\frac{\hat{f}^\dagger}{\sqrt{2}} & \hat{M}_N \end{pmatrix} \left(\nu_1, \ldots N_1 \ldots\right)^{\mathrm{T}}$$

Then for $M_N \gg \hat{M}^D = v\,\frac{\hat{f}}{\sqrt{2}}$ we find the eigenvalues: seesaw at work

$$\simeq \hat{M}_N \quad \text{and} \quad \hat{M}^\nu = -\hat{M}^{D\dagger}\frac{1}{\hat{M}_N}\hat{M}^D \propto f^2\,\frac{v^2}{M_N} \propto \theta^2 M_N \lll M_N$$

Mixings: flavor state $\nu_\alpha = U_{\alpha i}\nu_i + \theta_{\alpha I} N_I$

active-active mixing: $U^\dagger \hat{M}^\nu U = diag\,(m_1, m_2, m_3)$

active-sterile mixing: $\theta_{\alpha I} \propto \frac{(M^D)^\dagger_{\alpha I}}{M_N} = \hat{f}^\dagger\,\frac{v}{M_N} \ll 1$

Sterile neutrinos: M_{N_I} violate lepton symmetry

Most general renormalizable with 2(3...) right-handed neutrinos N_I ?

$$\mathscr{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.}$$

Parameters to be determined from experiments

9(7): active neutrino sector

2 Δm_{ij}^2: oscillation experiments

3 θ_{ij}: oscillation experiments

1 CP-phase: oscillation experiments

2(1) Majorana phases: $0\nu ee$, $0\nu\mu\mu$

1(0) m_ν: ${}^3\text{H} \to {}^3\text{He} + e + \bar{\nu}_e$, cosmology, ...

11: $N = 2$ sterile neutrinos (works if $m_\nu = 0$!!!)

2: Majorana masses M_{N_I}

9: New Yukawa couplings $f_{\alpha I}$ which form

2: Dirac masses $M^D = f\langle H\rangle$

3+1: mixing angles

2+1: CP-violating phases

4 new parameters in total
help with leptogenesis

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both BAU and DM are possible

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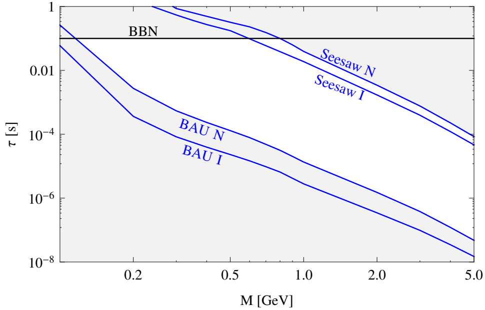
νMSM: 2 GeV-scale & 1 keV-scale neutrinos

T.Asaka, S.Blanchet, M.Shaposhnikov (2005)

2 GeV-scale seesaw neutrinos

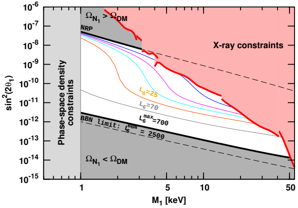
- give masses and mixing to active neutrinos — need two!
- violate CP — need two!
  out-of-equilibrium oscillations $\nu_a \leftrightarrow N_{2,3}$
  need very small mixing $\theta^2_{\alpha I} \lll 1$
  in the early Universe redistribute lepton charge
  need degeneracy: $\Delta M_{N_{2,3}} \ll M_{N_2}, M_{N_3}$



DM: 1-50 keV

mixing with active neutrinos:

- $\tau_{N_1} > \tau_U \rightarrow$
  little contribution to m_ν
- signature in X-rays
  $N_1 \rightarrow \gamma\nu_a$
- produced in early Universe in plasma
  needs strong fine-tuning

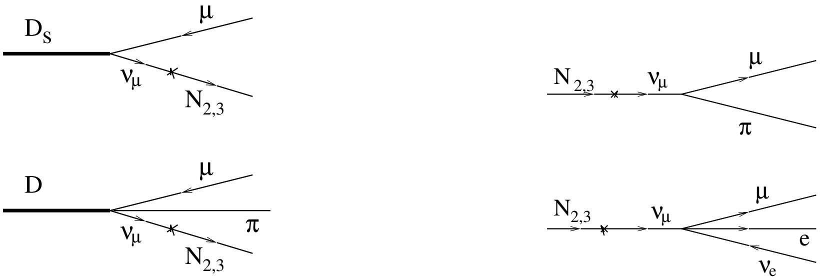


easily produced by inflaton *XNN*

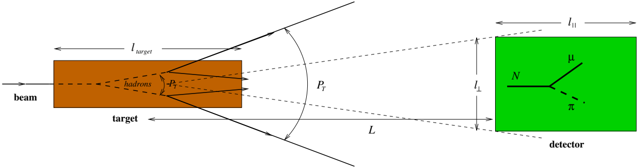
M.Shaposhnikov, I.Tkachev (2006),
F.Bezrukov, D.G. (2009)

Direct searches for sterile neutrinos: 2 approaches

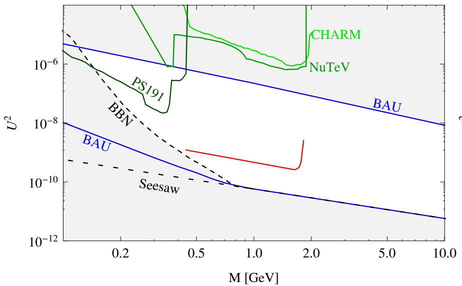
Weak decays due to mixing

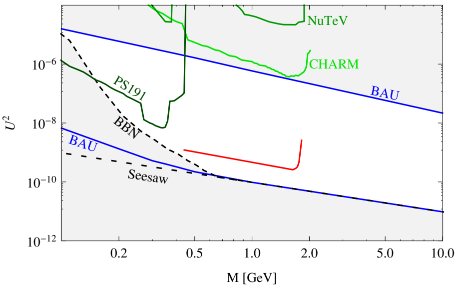


Production in beam-dump experiments



νMSM parameter space $\qquad \theta^2_{\nu N} \propto U^2$





D.G, M.Shaposhnikov (2007)

L.Canetti, M.Drewes, M.Shaposhnikov (2012)

$$\mathrm{Br}\,(D \to lN) \lesssim 2\cdot 10^{-8}$$

$$\mathrm{Br}\,(D_s \to lN) \lesssim 3\cdot 10^{-7}$$

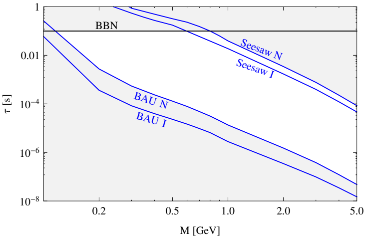
$$\mathrm{Br}\,(D \to KlN) \lesssim 2\cdot 10^{-7}$$

$$\mathrm{Br}\,(D_s \to \eta lN) \lesssim 5\cdot 10^{-8}$$

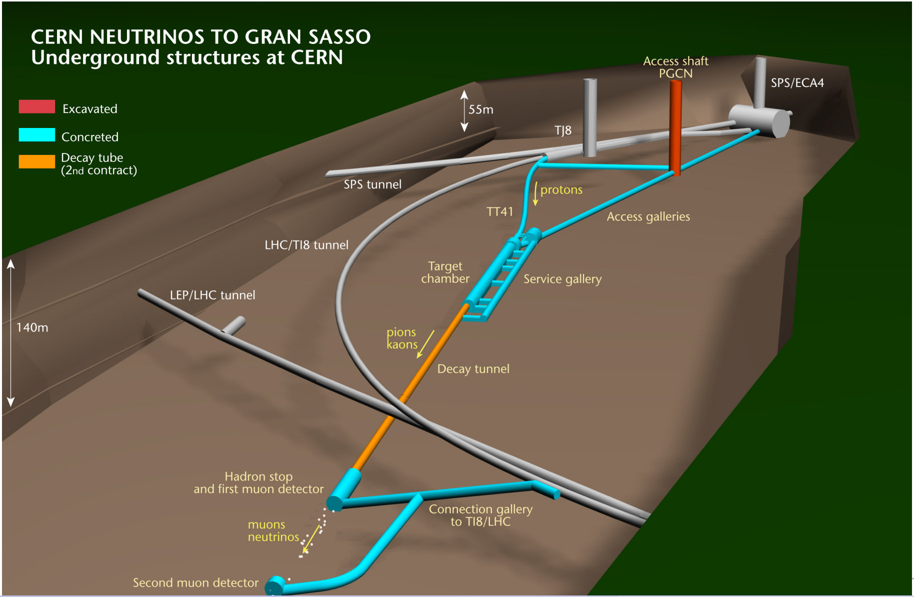
$$\mathrm{Br}\,(D \to K^* lN) \lesssim 7\cdot 10^{-8}$$

$$\mathrm{Br}\,(B \to D^* lN) \lesssim 4\cdot 10^{-7}$$

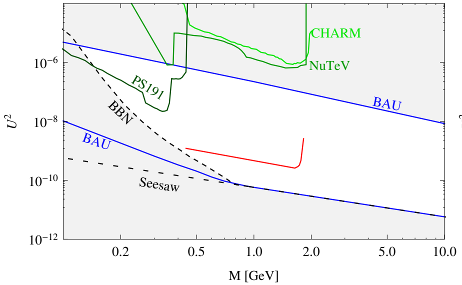
$$\mathrm{Br}\,(B_s \to D_s^* lN) \lesssim 3\cdot 10^{-7}$$

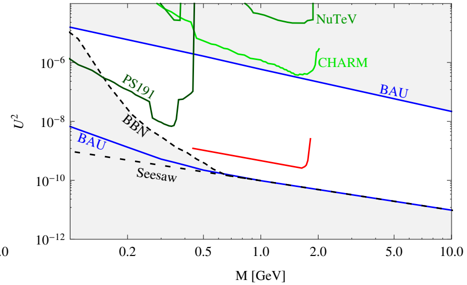


CNGS site is free after OPERA



νMSM parameter space for $M_N < 2\,\mathrm{GeV}$



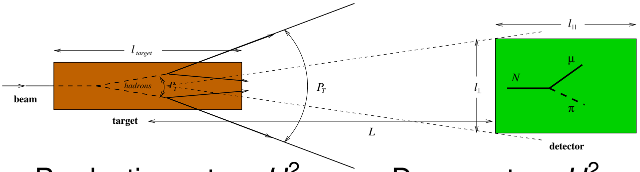


D.G, M.Shaposhnikov (2012)

L.Canetti, M.Drewes, M.Shaposhnikov (2012)

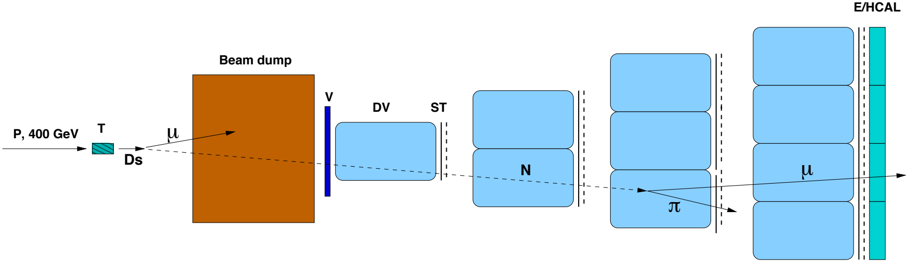
S.Gninenko, D.G, M.Shaposhnikov (2012)

L=100 m $\quad l_\perp \sim 5$ m $\quad l_{||} \sim 100$ m



Production rate $\propto U^2$, Decay rate $\propto U^2$

To fully explore the region $M_N < 2\,\text{GeV}$



$$N_{\text{PoT}} \simeq 10^{20}\,, \qquad l_{\text{total}} \simeq 3\,\text{km}$$

multisectional detector (presumably on surface)

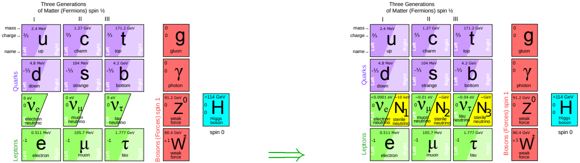
Sterile neutrinos: dedicated experiment is needed

- Most economic explanation of neutrino oscillations within renormalizable approach: $N = 2$ Majorana neutrinos
- Capable of explaining baryon asymmetry of the Universe even with $\delta_{CP} = 0$
- One more neutrino can serve as (naturally Warm) dark matter

νMSM

direct searches are feasible for $M_N < 2\,\text{GeV}$ (5 GeV)

- 100-m length detector at SNGS site operated on upgraded SPS beam allows to cover major part of paramater space
- 3-km scale detector is needed to fully explore the model



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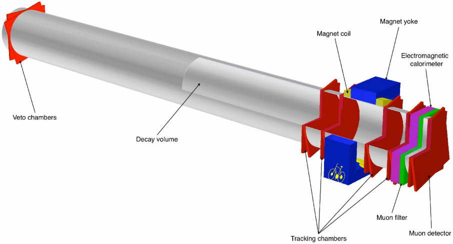
3 Physics at SHiP
- Elusive NP: portals to a hidden World
- Elusive NP: exotic SUSY
- Elusive SM physics: neutrinos

4 Summary

Under the name. . . Search for Hidden Particles

- νMSM: T.Asaka, S.Blanchet, M.Shaposhnikov (2005), T.Asaka, M.Shaposhnikov (2005), see also review A. Boyarsky, O. Ruchayskiy, M.Shaposhnikov (2009)
- direct tests of νMSM: D.G., M.Shaposhnikov (2007)
- searches for dark matter A. Boyarsky, O. Ruchayskiy, M.Shaposhnikov, I.Tkachev, etc...
- proposal for direct searches submitted to European Strategy Group, 2012 D.G., M.Shaposhnikov
- sketch of realistic experiment S.Gninenko, D.G., and M.Shaposhnikov (2013)
- Expression Of Interests: Proposal to Search for Heavy Neutral Leptons at the SPS W. Bonivento et al, 1310.1762



At the crossroads

What we have at present

- We certainly need NP
  – neutrino oscillations
  – dark matter
  – baryon asymmetry of the Universe
- Any NP contribute to the Higgs boson mass, which is 126 GeV
- No clear signal of NP (no SUSY) at 8 TeV

Logically possible ways out

- NP is right at 13-14 TeV
  (why hidden so well at 8 TeV ?)
  (why no hints in flavor ?)
  Energy frontier: LHC, ILC, . . .
- NP is
  at the gravity (Planck) scale
  Theory frontier: quantum gravity applied for black holes, early Universe, . . .
- NP is below EW scale
  Intensity frontier:
  beam-target experiments

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Evaluation of the proposal by SPSC

Outcome of the 112th SPSC (Spring 2014):

”The Committee **received with interest** the response of the proponents to the questions raised in its review of EOI010. The SPSC **recognises** the interesting physics potential of searching for heavy neutral leptons and investigating the properties of neutrinos. Considering the large cost and complexity of the required beam infrastructure as well as the significant associated beam intensity, such a project should be designed as a general purpose beam dump facility with the broadest possible physics programme, including maximum reach in the investigation of the hidden sector. To further review the project the Committee **would need an extended proposal** with further developed physics goals, a more detailed technical design and a stronger collaboration. . . ”

Step by step towards the SHiP

Physics goals

To cover as much Physics as possible

- Any BSM
  with light,
  only tiny coupled to SM,
  relatively long-lived new particles
- Physics of τ-neutrino (largest statistics we had so far)

Technical proposal

To be as close to target as possible

- Great challenge:
  get rid of the background from a host of muons
- New beam-pipe and detector hall: construction schedule must be adjusted to LHC(SPS) shutdowns

Stronger collaboration

To be as open as possible

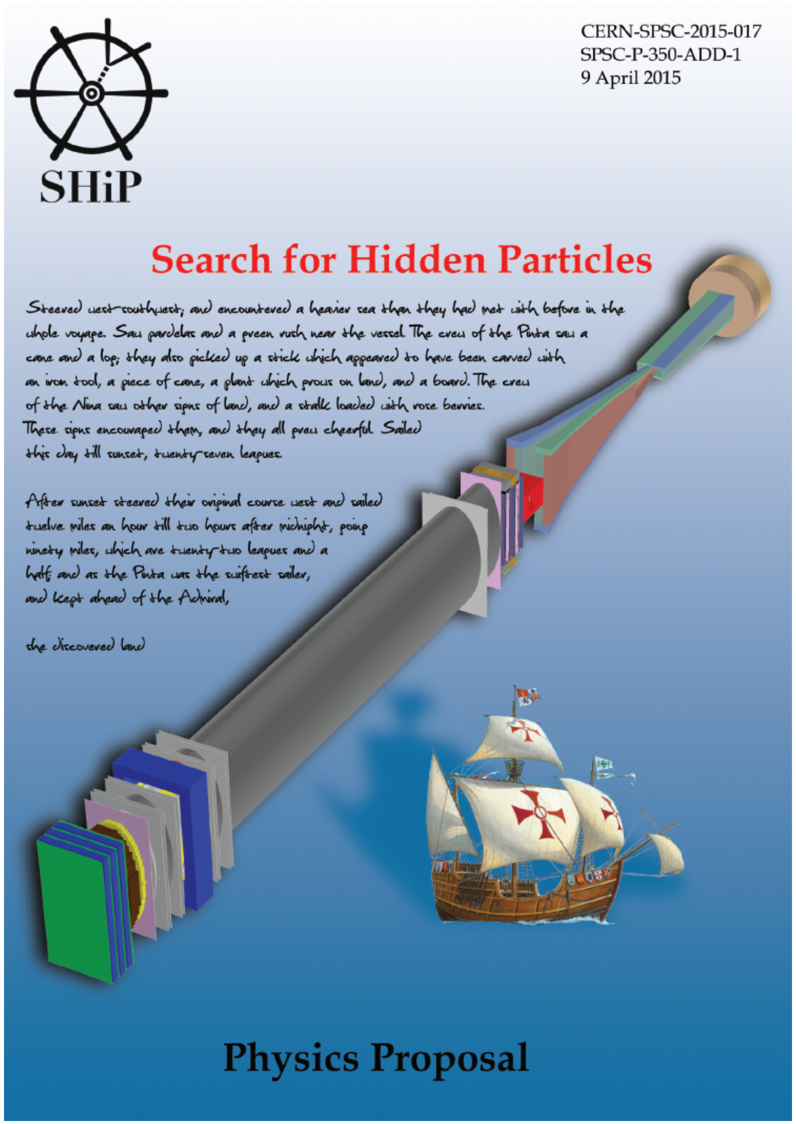
- No direct support at beginning
- Original group members are involved in LHCb, ...
- CERN departments always help wherever relevant

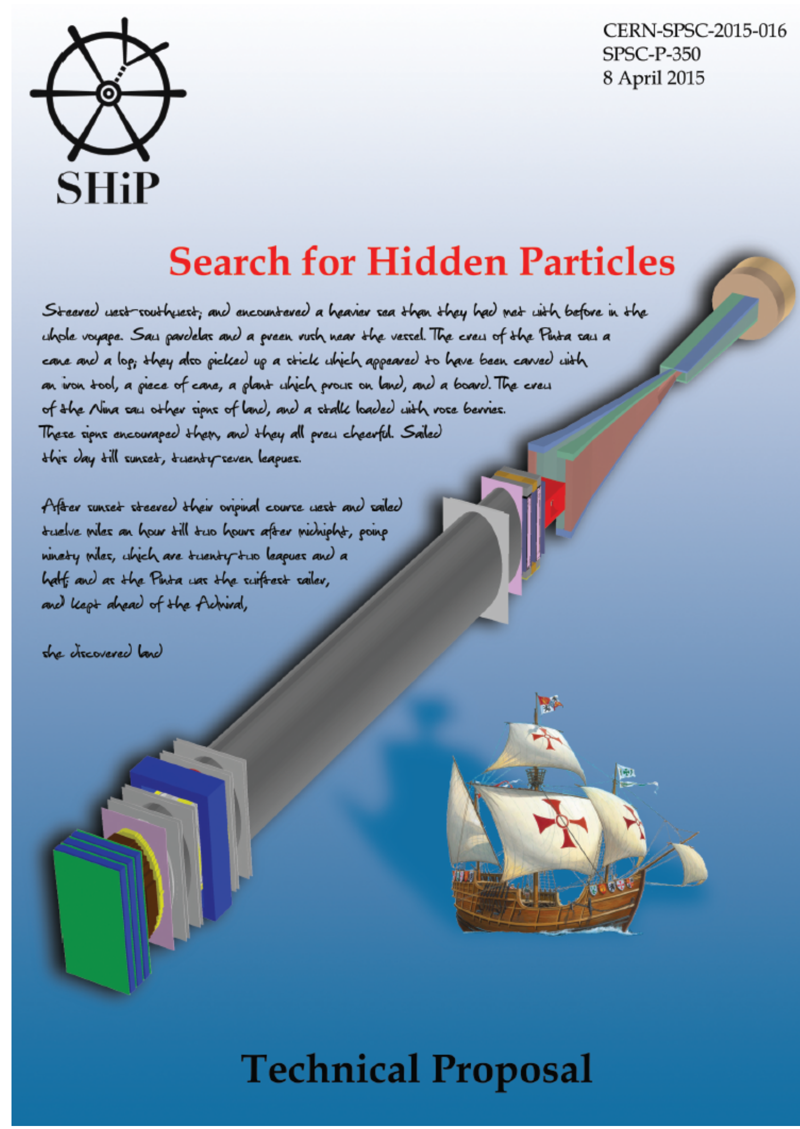
http://ship.web.cern.ch/ship/

On behalf of the SHiP collaboration

Mikhail Shaposhnikov
EPFL, Lausanne

Andrey Golutvin
Imperial College London





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 (*Search for Hidden Particles*) experiment is intended to hunt for new physics in the largely unexplored domain of very weakly interacting particles with masses below the Fermi scale, inaccessible to the LHC experiments, and to study tau neutrino physics. The same proton beam setup can be used later to look for decays of tau-leptons with lepton flavour number non-conservation, $\tau \to 3\mu$ and to search for weakly-interacting sub-GeV dark matter candidates. We discuss the evidence for physics beyond the Standard Model and describe interactions between new particles and four different *portals* — scalars, vectors, fermions or axion-like particles. We discuss motivations for different models, manifesting themselves via these interactions, and how they can be probed with the SHiP experiment and present several case studies. The prospects to search for relatively light SUSY and composite particles at SHiP are also discussed. We demonstrate that the SHiP experiment has a unique potential to discover new physics and can directly probe a number of solutions of beyond the Standard Model puzzles, such as neutrino masses, baryon asymmetry of the Universe, dark matter, and inflation.

*Editor of the paper
§Convener of the Chapter

Technical Proposal

A Facility to Search for Hidden Particles (SHiP) at the CERN SPS

Abstract

A new general purpose fixed target facility is proposed at the CERN SPS accelerator which is aimed at exploring the domain of hidden particles and make measurements with tau neutrinos. Hidden particles are predicted by a large number of models beyond the Standard Model. The high intensity of the SPS 400 GeV beam allows probing a wide variety of models containing light long-lived exotic particles with masses below $\mathcal{O}(10)$ GeV/c^2, including very weakly interacting low-energy SUSY states. The experimental programme of the proposed facility is capable of being extended in the future, e.g. to include direct searches for Dark Matter and Lepton Flavour Violation.

The SHiP Collaboration

M. Anelli[14], S. Aoki[17], G. Arduini[33(BE)], J.J. Back[40], A. Bagulya[24], W. Baldini[11], A. Baranov[30], G.J. Barker[40], S. Barsuk[4], M. Battistin[33(EN)], J. Bauche[33(TE)], A. Bay[35], V. Bayliss[41], L. Bellagamba[9], G. Bencivenni[14], M. Bertani[14], O. Bezshyyko[44], D. Bick[7], N. Bingefors[32], A. Blondel[34], M. Bogomilov[1], A. Boyarsky[44], D. Bonacorsi[9,b], D. Bondarenko[23], W. Bonivento[10], J. Borburgh[33(TE)], T. Bradshaw[41], R. Brenner[32], D. Breton[4], N. Brook[43], M. Bruschi[9], A. Buonaura[12,e], S. Buontempo[12], S. Cadeddu[10], A. Calcaterra[14], M. Calviani[33(EN)], M. Campanelli[43], C. Capoccia[14], A. Cecchetti[14], A. Chatterjee[34], J. Chauveau[5], A. Chepurnov[29], M. Chernyavskiy[24], P. Ciambrone[14], C. Cicalo[10], G. Conti[33], K. Cornelis[33(BE)], M. Courthold[41], M. G. Dallavalle[9], N. D'Ambrosio[13], G. De Lellis[12,e], M. De Serio[8,a], L. Dedenko[29], A. Di Crescenzo[12], N. Di Marco[13], C. Dib[2], J. Dietrich[6], H. Dijkstra[33], D. Domenici[14], S. Donskov[26], D. Druzhkin[25,g], J. Ebert[7], U. Egede[42], A. Egorov[27], V. Egorychev[22], M.A. El Alaoui[2], T. Enik[21], A. Etenko[25], F. Fabbri[9], L. Fabbri[9,b], G. Fedorova[29], G. Felici[14], M. Ferro-Luzzi[33], R.A. Fini[8], M. Franke[6], M. Fraser[33(TE)], G. Galati[12,e], B. Giacobbe[9], B. Goddard[33(TE)], L. Golinka-Bezshyyko[44], D. Golubkov[22], A. Golutvin[42], D. Gorbunov[23], E. Graverini[36], J-L Grenard[33(EN)], A.M. Guler[37], C. Hagner[7], H. Hakobyan[2], J.C. Helo[2], E. van Herwijnen[33], D. Horvath[33(EN)], M. Iacovacci[12,e], G. Iaselli[8,a], R. Jacobsson[33], I. Kadenko[44], M. Kamiscioglu[37], C. Kamiscioglu[38], G. Khaustov[26], A. Khotjansev[23], B. Kilminster[36], V. Kim[27], N. Kitagawa[18], K. Kodama[16], A. Kolesnikov[21], D. Kolev[1], M. Komatsu[18], N. Konovalova[24], S. Koretskiy[25,g], I. Korolko[22], A. Korzenev[34], S. Kovalenko[2], Y. Kudenko[23], E. Kuznetsova[27], H. Lacker[7], A. Lai[10], G. Lanfranchi[14], A. Lauria[12,e], H. Lebbolo[5], J.-M. Levy[5], L. Lista[12], P. Loverre[15,f], A. Lukiashin[29], V.E. Lyubovitskij[2,h], A. Malinin[25], M. Manfredi[33(GS)], A. Perillo-Marcone[33(EN)], A. Marrone[8,a], R. Matev[1], E.N. Messomo[34], P. Mermod[34], S. Mikado[19], Yu. Mikhaylov[26], J. Miller[2], D. Milstead[31], O. Mineev[23], R. Mingazheva[24], G. Mitselmakher[45], M. Miyanishi[18], P. Monacelli[15,f], A. Montanari[9], M.C. Montesi[12,e], G. Morello[14], K. Morishima[18], S. Movtchan[21], V. Murzin[27], N. Naganawa[18], T. Naka[18], M. Nakamura[18], T. Nakano[18], N. Nurakhov[25], B. Obinyakov[25], K. Ocalan[37], S. Ogawa[20], V. Oreshkin[27], A. Orlov[25,g], J. Osborne[33(GS)], P. Pacholek[33(EN)], J. Panman[33], A. Paoloni[14], L. Paparella[8,a], A. Pastore[8], M. Patel[42], K. Petridis[39], M. Petrushin[25,g], M. Poli-Lener[14], N. Polukhina[24], V. Polyakov[26], M. Prokudin[22], G. Puddu[10,c], F. Pupilli[14], F. Rademakers[33], A. Rakai[33(EN)], T. Rawlings[41], F. Redi[42], S. Ricciardi[41], R. Rinaldesi[33(EN)], T. Roganova[29], A. Rogozhnikov[30], H. Rokujo[18], A. Romaniouk[28], G. Rosa[15,f], I. Rostovtseva[22], T. Rovelli[9,b], O. Ruchayskiy[35], T. Ruf[33], G. Saitta[10,c], V. Samoylenko[26], V. Samsonov[28], A. Sanz Ull[33(TE)], A. Saputi[14], O. Sato[18], W. Schmidt-Parzefall[7], N. Serra[36], S. Sgobba[33(EN)], M. Shaposhnikov[35], P. Shatalov[22], A. Shaykhiev[23], L. Shchutska[45], V. Shevchenko[25], H. Shibuya[20], Y. Shitov[42], S. Silverstein[31], S. Simone[8,a], M. Skorokhvatov[28,25], S. Smirnov[28], E. Solodko[33(TE)], V. Sosnovtsev[28,25], R. Spighi[9], M. Spinetti[14], N. Starkov[24], B. Storaci[36], C. Strabel[33(DGS)], P. Strolin[12,e], S. Takahashi[17], P. Teterin[28], V. Tioukov[12], D. Tommasini[33(TE)], D. Treille[33], R. Tsenov[1], T. Tshchedrina[24], A. Ustyuzhanin[25,30], F. Vannucci[5], V. Venturi[33(EN)], M. Villa[9,b], Heinz Vincke[33(DGS)], Helmut Vincke[33(DGS)], M. Vladymyrov[24], S. Xella[3], M. Yalvac[37], N. Yershov[23], D. Yilmaz[38], A. U. Yilmazer[38], G. Vankova-Kirilova[1], Y. Zaitsev[22], A. Zoccoli[9,b]

Project organization: cost and resources

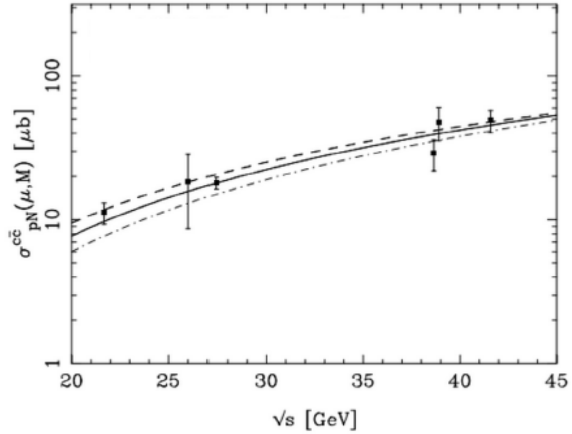
SHiP Collaboration at the time of TP:

- *243 members from 45 institutes in 14 countries*
- *Admission of several institutes pending*

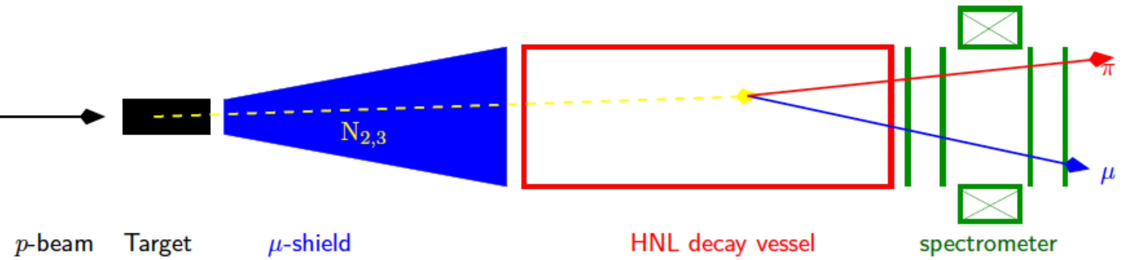
Current commitments for preparation of TP and TDR

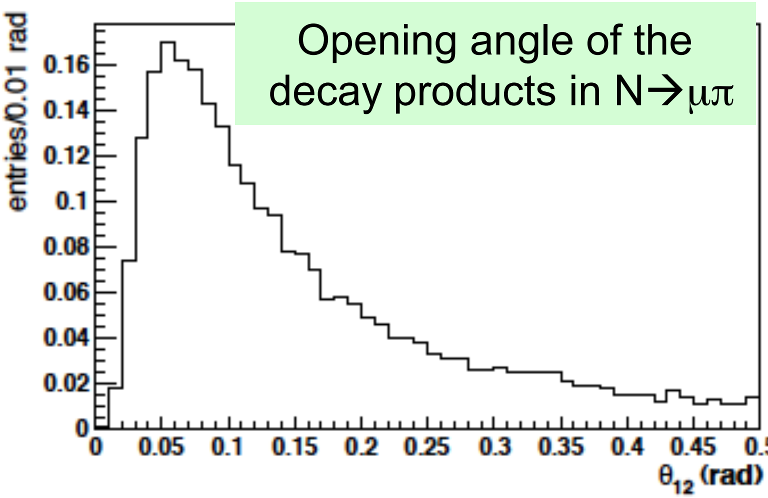
Component	Countries	Institutes
Beamline and target	CERN	CERN
Infrastructure	CERN	CERN
Muon shield	UK	RAL, Imperial College, Warwick
HS vacuum vessel	Russia	NRC KI
Straw tracker	Russia, CERN	JINR, MEPhI, PNPI, CERN
HS spectrometer magnet		
ECAL	France, Italy, Russia	ITEP, Orsay, IHEP, INFN-Bologna
HCAL	Italy, Russia, Sweden	ITEP, IHEP, INFN-Bologna, Stockholm
Muon	Italy, Russia	INFN-Bologna, INFN-Cagliari, INFN-Lab. Naz. Frascati,
		INFN-Ferrara, INR RAS, MEPhi
Surrouding background tagger	Germany, Russia	Berlin, LPNHE, MEPhI
Timing detector and upstream veto	France, Italy, Russia, Switzerland	Zurich, Geneva, INFN-Cagliari, Orsay, LPNHE
Tau neutrino emulsion target	Italy, Japan, Russia, Turkey	INFN-Naples, INFN-Bari, INFN-Lab. Naz. Gran Sasso,
		Nagoya, Nihon, Aichi, Kobe, Moscow SU,
		Lebedev, Toho, Middle East Technical University, Ankara
Tau neutrino tracker (GEM)	Italy, Russia	NRC KI, INFN-Lab. Naz. Frascati
Tau neutrino detector magnet	Italy	INFN-Lab. Naz. Frascati, INFN-Bari, INFN-Naples,
		INFN-Roma
Tau neutrino tracking (RPC)	Italy	INFN-Lab. Naz. Frascati, INFN-Bari,
		INFN-Lab. Naz. Gran Sasso, INFN-Naples, INFN-Roma
Tau neutrino tracker (drift tubes)	Germany	Hamburg
Online computing	Denmark, Russia, Sweden, UK, CERN	Niels Bohr, Uppsala, UCL, YSDA, LPHNE, CERN
Offline computing	Russia, CERN	YSDA, CERN
MC simulation	Bulgaria, Chile, Germany, Italy, Russia,	Sofia, INFN-Cagliari, INFN-Lab. Naz. Frascati,
	Switzerland, Turkey, UK, Ukraine,	INFN-Napoli, Zurich, Geneva and EPFL Lausanne,
	USA, CERN	Valparaiso, Berlin, PNPI, NRC KI, SINP MSU, MEPhI,
		Middle East Technical University, Ankara, Bristol, YSDA,
		Imperial College, Florida, Kyiv, CERN

General experimental requirements



- ✓ *Search for HS particles in Heavy Flavour decays*
- ✓ *HS produced in charm decays have significant P_T*

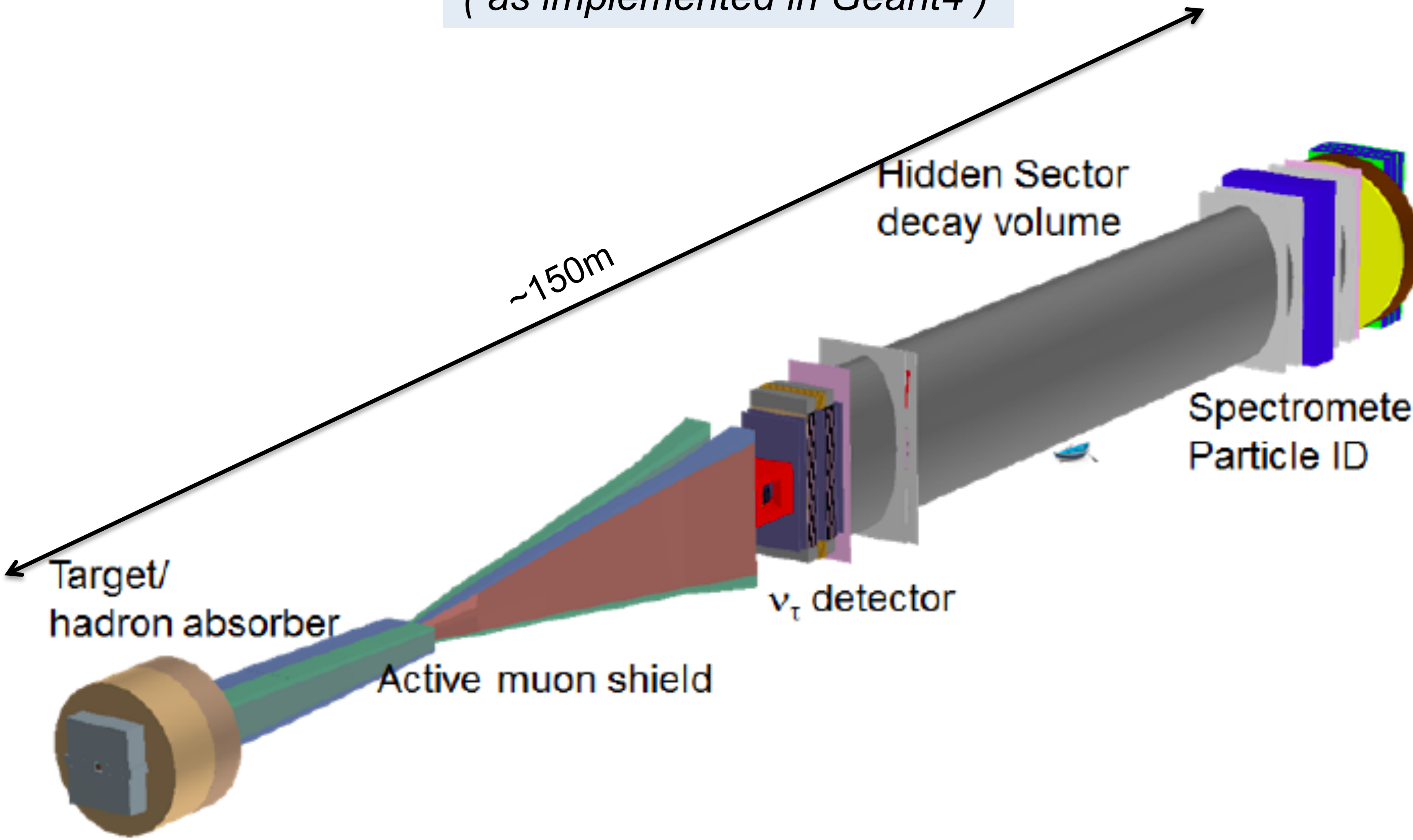




Detector must be placed close to the target to maximize geometrical acceptance → compromise between HS life time and production angle

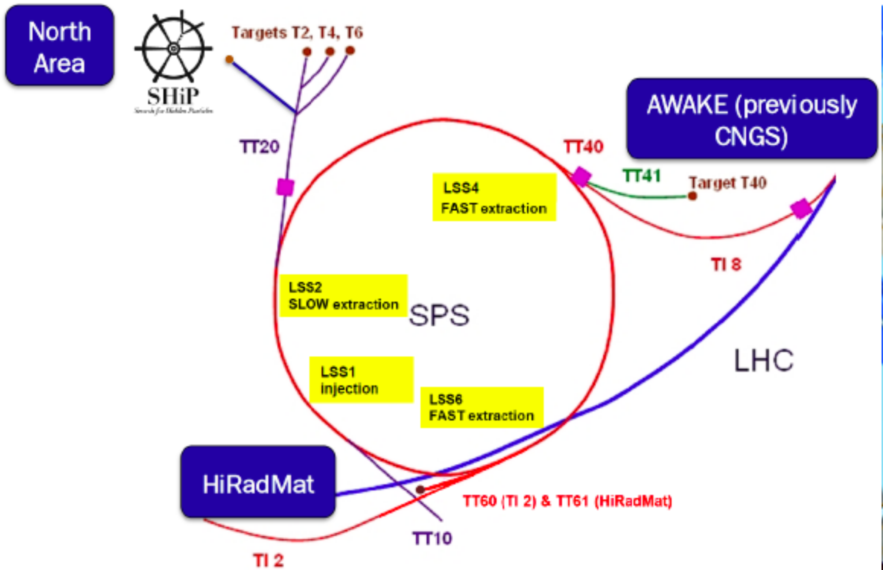
Effective (and "short") muon shield is essential to reduce muon-induced backgrounds

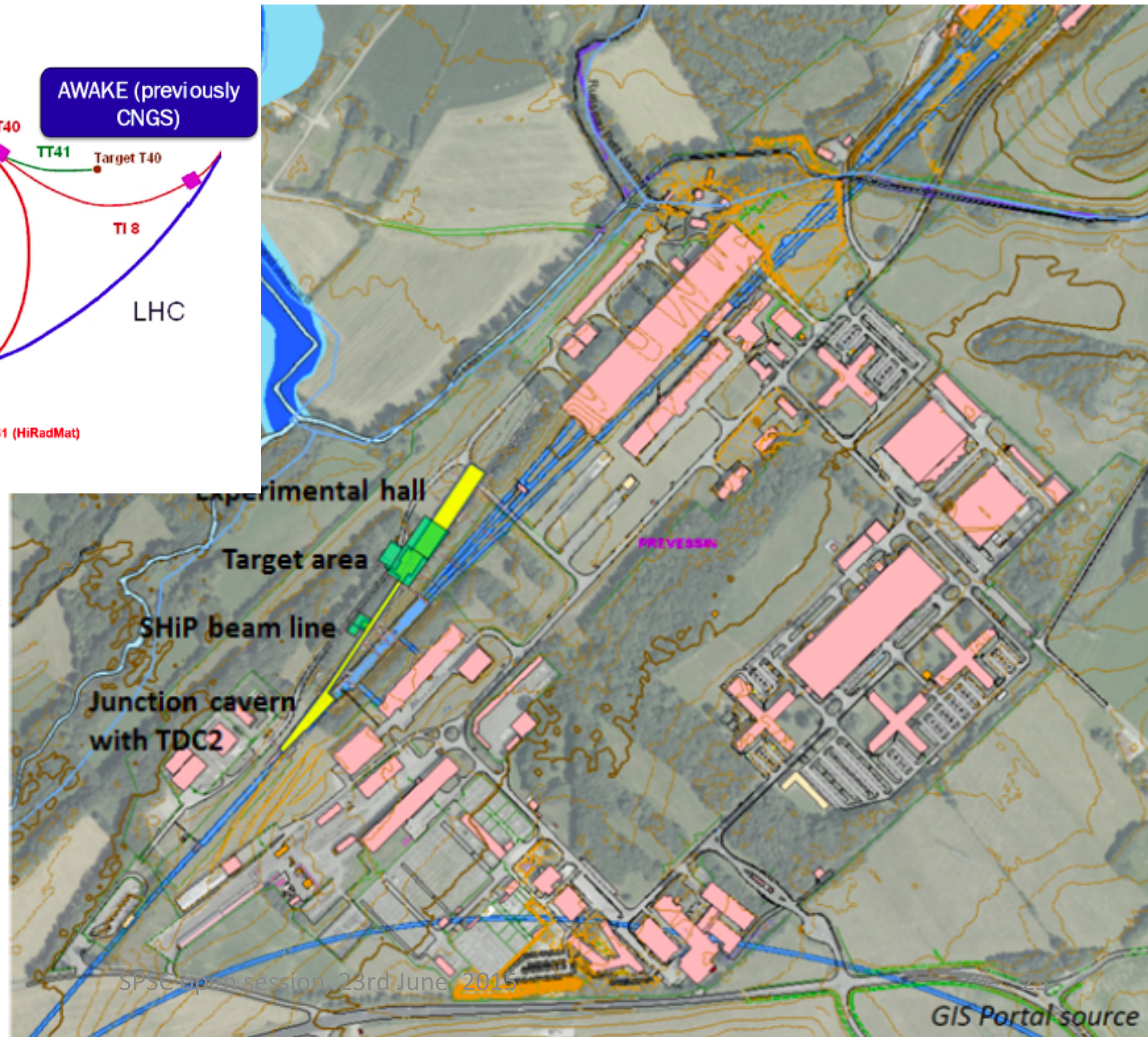
The SHiP experiment
(as implemented in Geant4)



The Fixed-target facility at the SPS (Prevessin North Area site)

Proposed implementation is based on minimal modification to the SPS complex





The SHiP facility is located on the North Area and shares the TT20 transfer line, and slow extraction, with the fixed target programmes

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Outline for New Physics with Vacuum vessel

- New unstable neutral particles of GeV-scale mass

  Why no hints recognized at this scale?

- couplings to the SM fields are tiny
- which probably implies not a GUT-like new physics (all is $\propto g$)
  other than gauge couplings are involved
- hence coupling to new gauge singlets
  usually nonrenormalizable interactions. . .
  however, there are exceptions. . . so called portals
- terms which mildly violates some symmetries
  – supersymmetry
  – R-parity
  – scale-invariance
  – . . .
- signatures: two- and three-body decays with two charged particles in a final state
  $X \to l^+ l^-$, $X \to \pi^+ l^-$, $X \to l^+ l^- \nu$, etc

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Three Portals to the hidden World

Renormalizable interaction including SM field and new (hypothetical) fields singlets with respect to the SM gauge group

Attractive feature: couplings are insensitive to energy in c.m.f., hence low energy experiments (intensity frontier) are favorable

- Scalar portal: SM Higgs doublet H and hidden scalar S — the simplest dark matter, inflaton field

$$\mathscr{L}_{\text{scalar portal}} = -\beta\, H^\dagger H S^\dagger S$$

- Spinor portal: SM lepton doublet L, Higgs congugate field $\tilde{H} = \epsilon H^*$ and hidden fermion N — sterile neutrino !!

$$\mathscr{L}_{\text{spinor portal}} = -y \bar{L} \tilde{H} N$$

- Vector portal: SM gauge field of $U(1)_Y$ and gauge hidden field of abelian group $U(1)'$

$$\mathscr{L}_{\text{vector portal}} = -\frac{\epsilon}{2} B_{\mu\nu}^{U(1)_Y} B_{\mu\nu}^{U(1)'}$$

Scalar portal: phenomenology

Typical Lagrangian:

$$(\alpha_1 S + \alpha S^2) H^\dagger H + L_{SM} + L_{hidden}$$

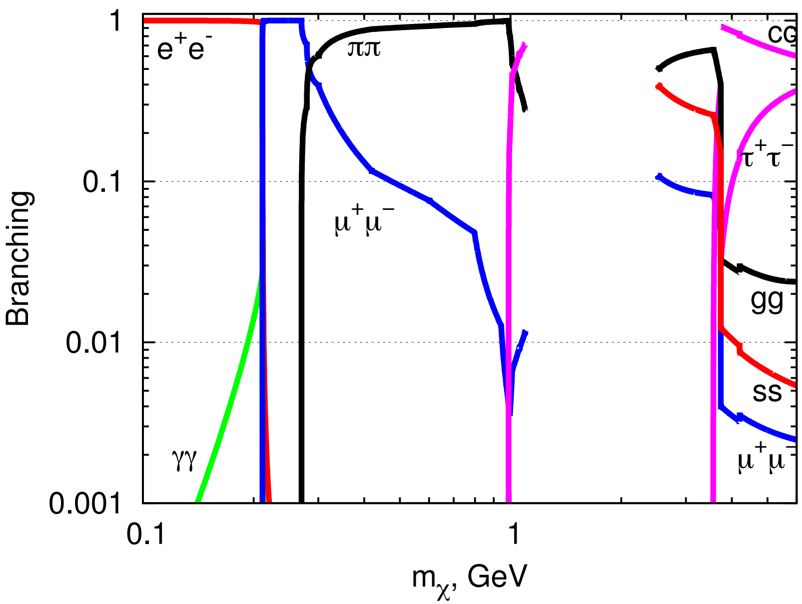
Production

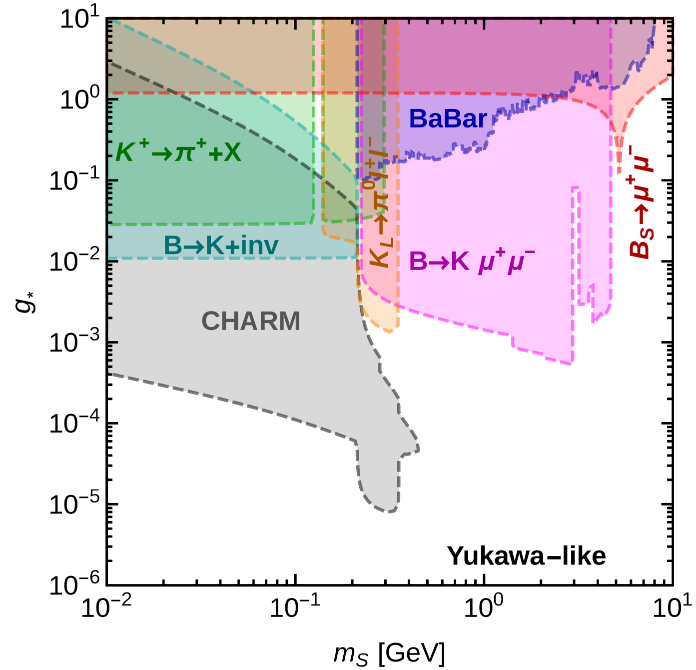
- Direct production $p + \mathbf{target} \to S + \ldots$
- Production via intermediate (hadronic) state

  $p + \mathbf{target} \to \mathbf{mesons} + \ldots$, and then $\mathbf{hadron} \to S + \ldots$.

Decays

- Subsequent decay of S to SM particles





Through mixing with Higgs

Example of constraints,

$$g_* = \alpha_1 V / m_h^2$$

Sensitivity to hidden scalars
(mixing with the SM Higgs with $\sin^2\Theta$)

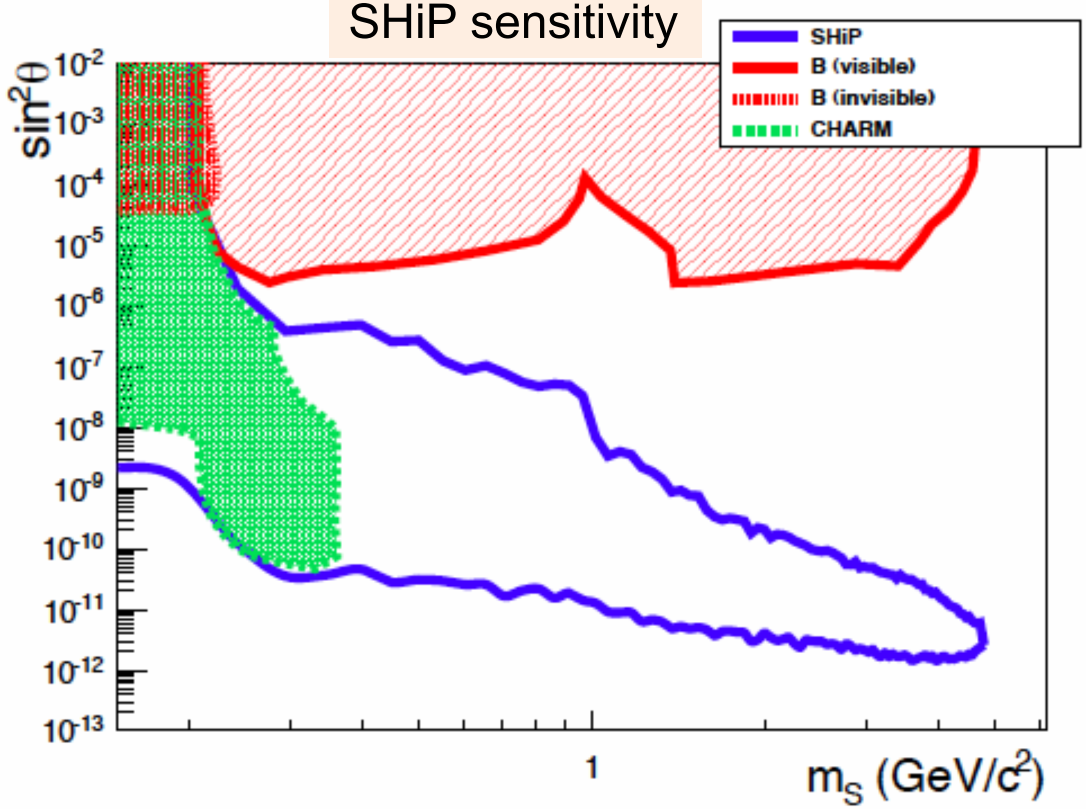
✓ ***Production:***

- mostly penguin-type decays of B and K decays (D decays are strongly suppressed by CKM)

✓ ***Decay***

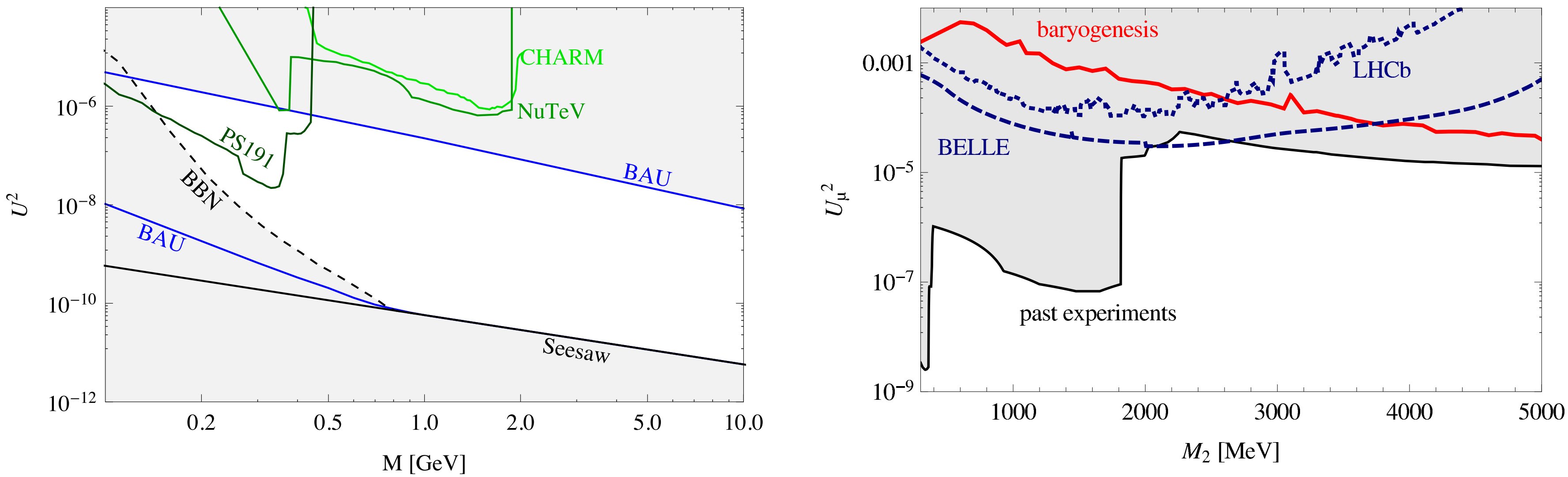
into $\underline{e^+e^-, \mu^+\mu^-, \pi^+\pi^+}$*,* $\eta\eta$*, KK,* $\tau\tau$*, DD, …*

SHiP sensitivity



SHiP probes unique range of couplings and masses, thus complementing existing limits from CHARM and B-factories

Neutrino portal: cosmological and experimental constraints



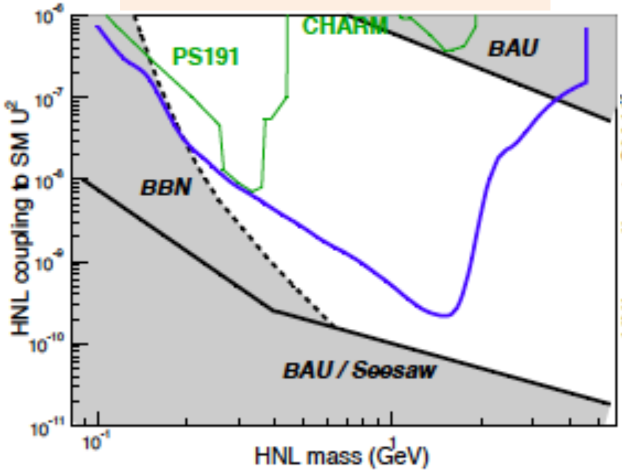
Constraints on mixing angle U^2 coming from the baryon asymmetry of the Universe, from the see-saw formula, from the big bang nucleosynthesis and experimental searches.

Left panel - normal hierarchy, 2HNL+1 DM HNL; right panel - 3 HNL .

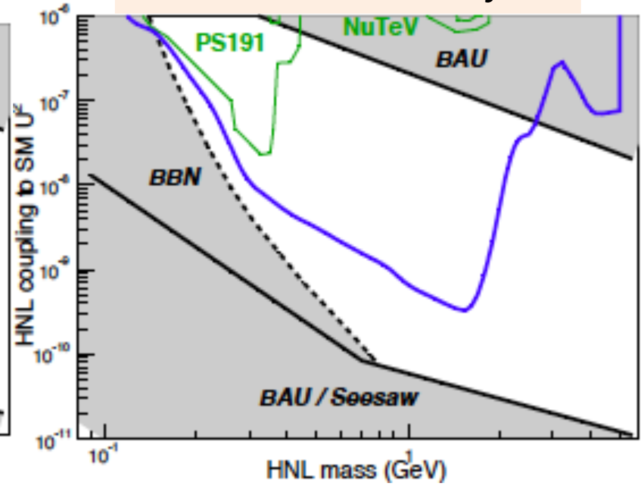
Sensitivity to HNLs for representative scenarios

(moving down to ultimate see-saw limit)

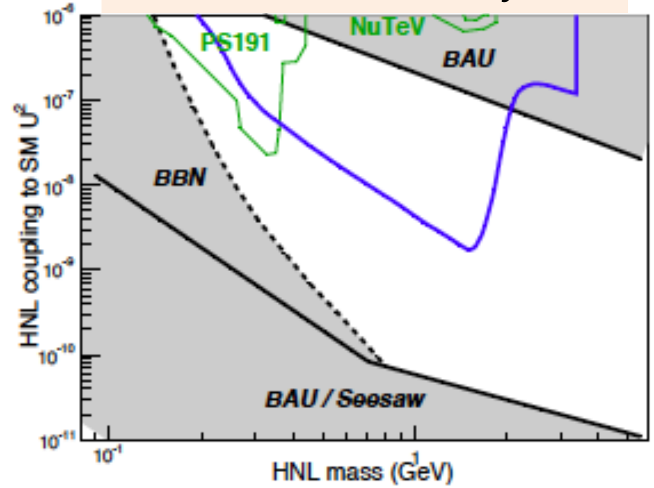
U^2_e: U^2_μ: U^2_τ~52:1:1
Inverted hierarchy



U^2_e: U^2_μ: U^2_τ~1:16:3.8
Normal hierarchy

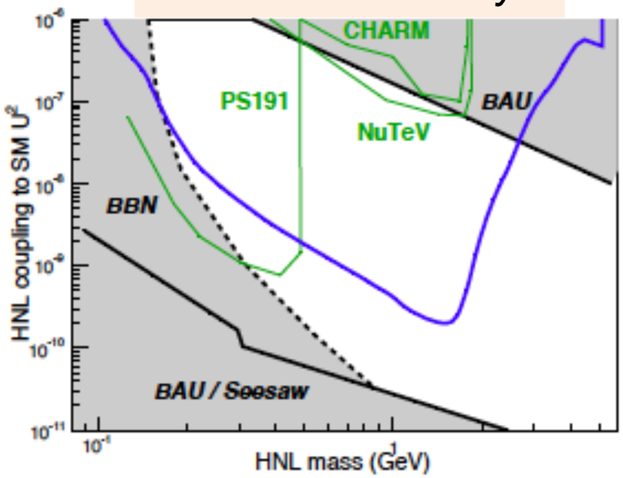


U^2_e: U^2_μ: U^2_τ~0.061:1:4.3
Normal hierarchy

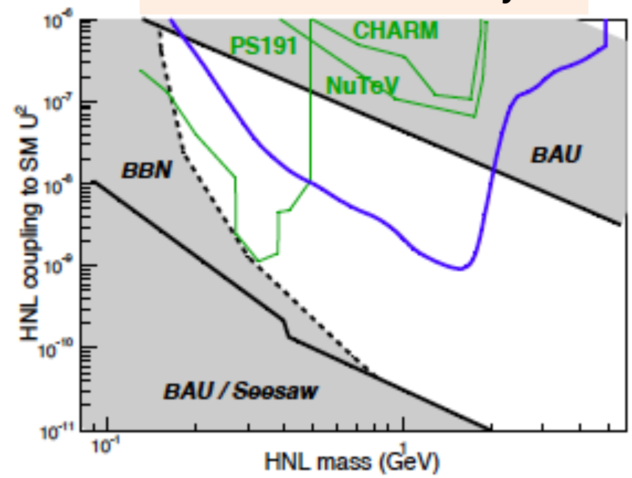


Scenarios for which baryogenesis was numerically proven

U^2_e: U^2_μ: U^2_τ~48:1:1
Inverted hierarchy

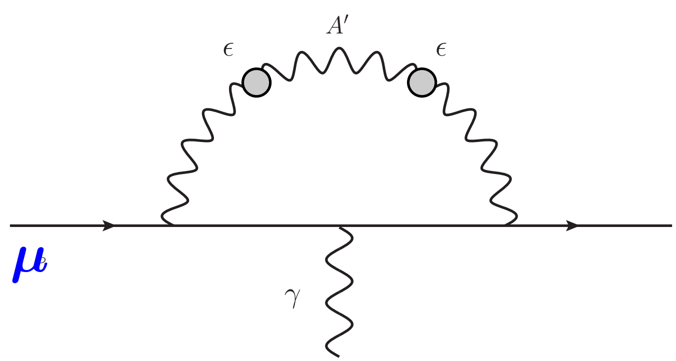


U^2_e: U^2_μ: U^2_τ~1:11:11
Normal hierarchy

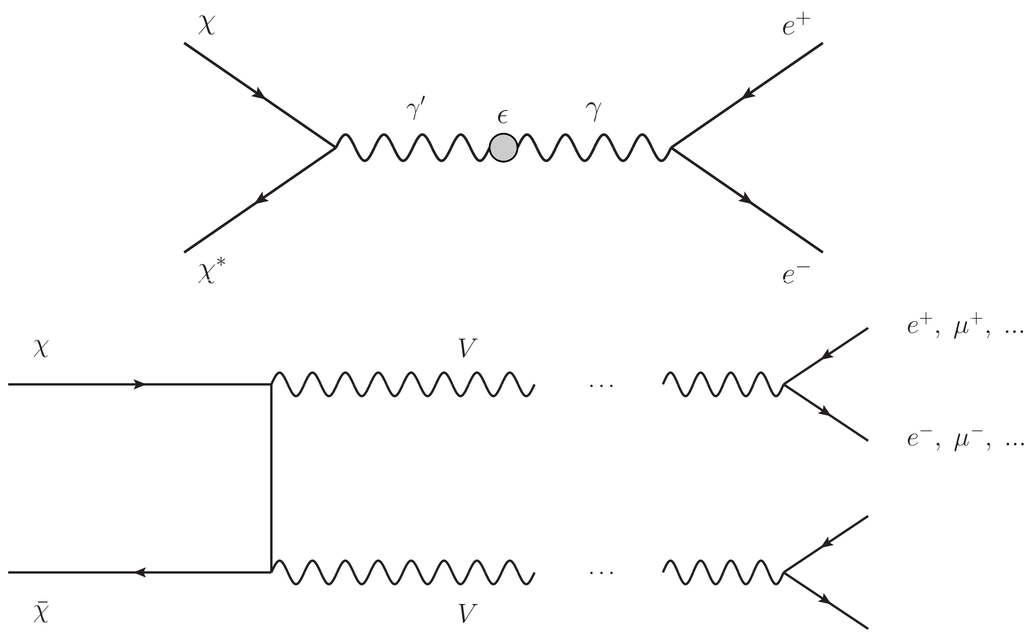


New vector particles: motivations

- Structure of the SM gauge group SU(3)×SU(2)×U(1) may descend from a larger (e.g. GUT) group, and low energy theory symmetric under SU(3)×SU(2)×$[U(1)]^n$ is possible. Examples: gauging of the $B - L$ "accidental" global symmetry of the SM; messenger between left and right mirror particles (spontaneous parity breaking)
- Possible solution of muon $g - 2$ discrepancy



- Mediator of interaction with Dark matter
  - Light dark matter with M as small as few MeV: increase of annihilation cross-section of
    DM particles. Used for DM explanations of the positron excess;



  - Self-interacting dark matter: core-cusp problem in dwarf galaxies, too-big-to-fail problem (excess of massive sub-halos in N-body simulations of Milky Way type galaxies)

Vector portal: phenomenology

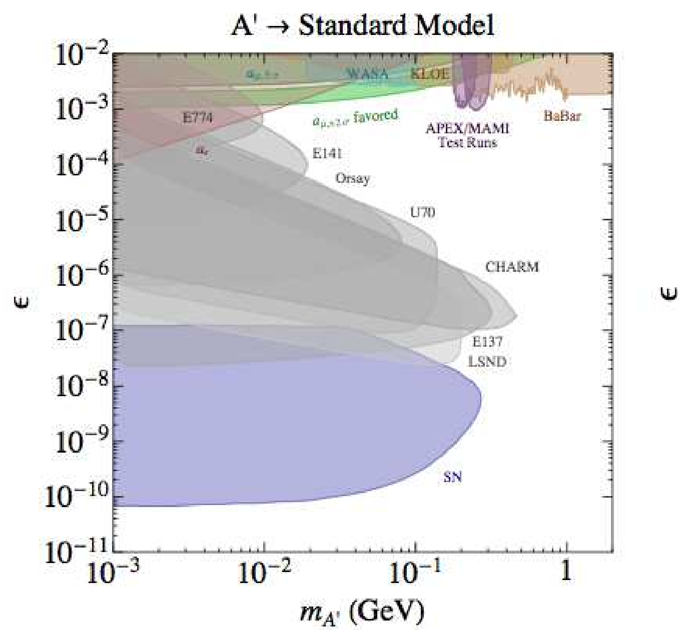
Production

- Meson decays, such as $\eta,\ \rho,\ \pi, \ldots \to \gamma A'$; Bremsstrahlung processes $pp \to ppA'$; Direct QCD production $q\,\bar{q} \to A',\ q\,g \to A'\,q$

Decays

- $A' \to l^+l^-,\ \ A' \to \mathbf{hadrons},\ \ A' \to \chi\bar{\chi}$

Example of constraints



Sensitivity to dark photons

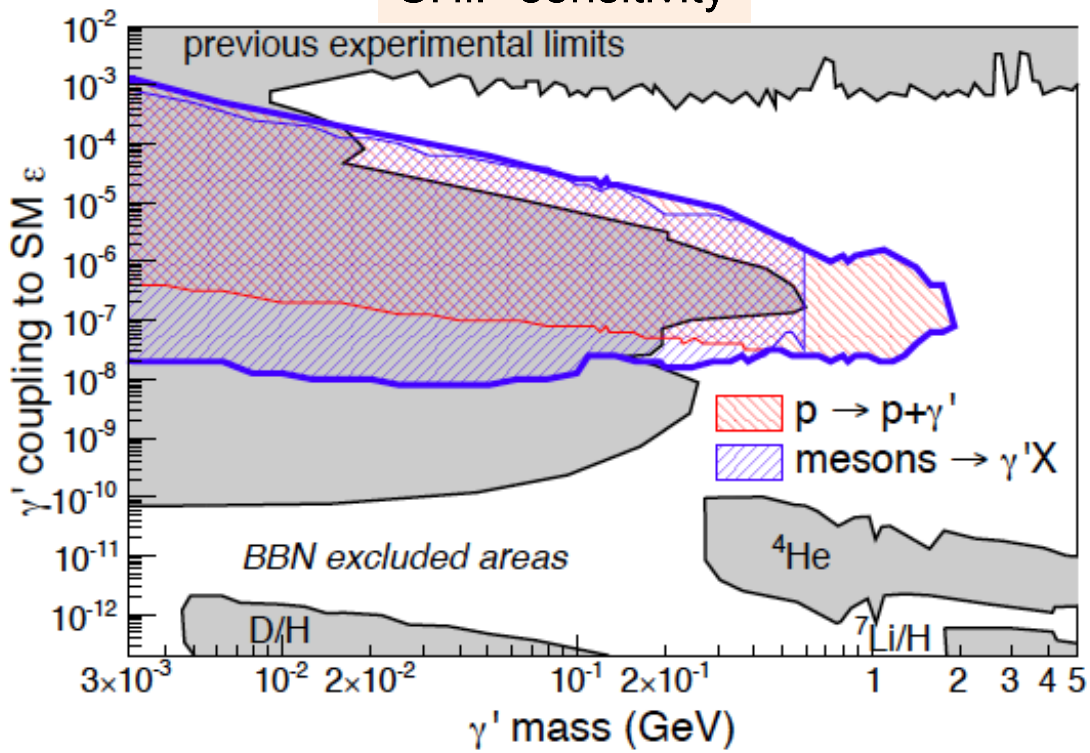
✓ **Production:**

- mainly decays of $\pi^0 \rightarrow \gamma'\gamma$, $\eta \rightarrow \gamma'\gamma$, $\omega \rightarrow \gamma'\pi^0$ and $\eta' \rightarrow \gamma'\gamma$
- a la proton bremsstrahlung (above Λ_{QCD} one should consider parton bremsstrahlung, currently is approximated by the form factor)

✓ **Decay**

into a pair of SM particles by mixing again with the SM photon

SHiP sensitivity



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Light SUSY particles: motivations

SUSY: general framework for addressing hierarchy problem and Grand Unification. The prejudice that SUSY particles are heavy comes from the minimal models such as MSSM or CMSSM

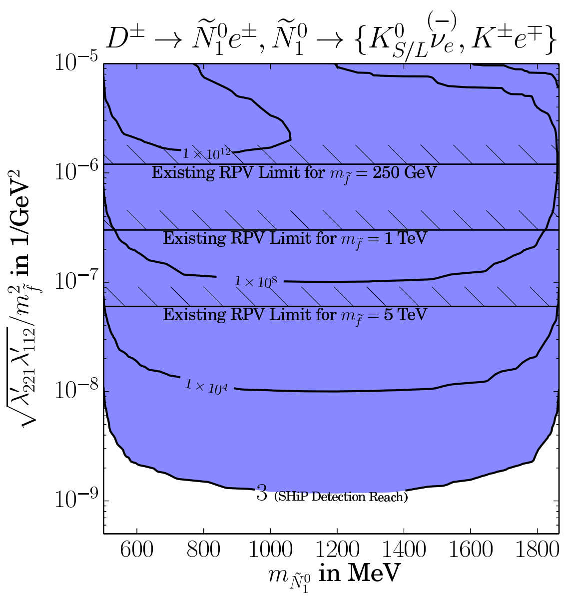
- Unstable neutralino in models with R-parity breaking (then DM candidates - axino or axion)
- Scalar and pseudoscalar sgoldstinos coming from SUSY breaking (e.g. no-scale SUGRA)
- Pseudo Dirac gauginos χ_1, χ_2: dark matter candidate χ_1
- SUSY partners of axion: axino and saxion
- SUSY partners of dark photons: hidden photinos $\tilde{\gamma}, \tilde{\gamma}', ...$ (string theory compactifications)

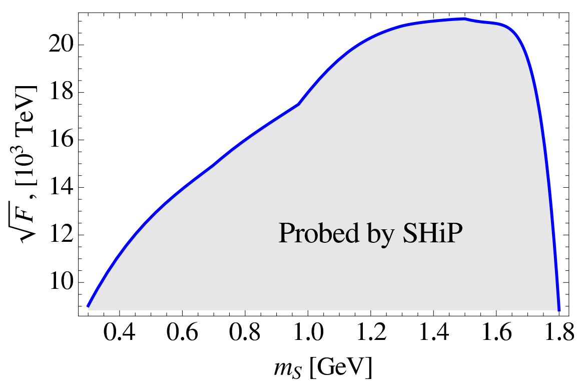
Examples of constraints

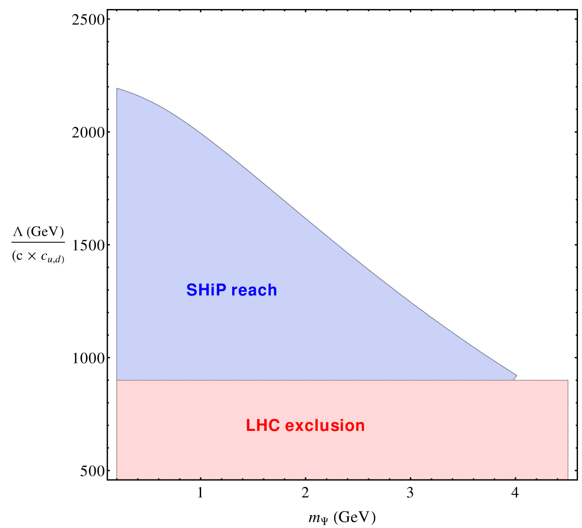
SUSY breaking scale

as a function of

sgoldstino mass







RPV neutralinos

$\boldsymbol{\lambda}$- amplitude of RPV

Pseudo-Dirac fermion

$\mathbf{1/\Lambda^2}$ - interaction

with SM fields

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Outline for New Physics with ν_τ-detector

- Discovery of $\bar{\nu}_\tau$
- measurement of ν_τ cross section (few thousands of events)
- Determination DIS structure functions F_4 and F_5 of ν_τ, $\bar{\nu}_\tau$ (contributions proportional to charged lepton mass)
- Update of ν_μ ($\sim 2 \times 10^6$ events) and ν_e ($\sim 10^6$ events) DIS
- EW parameters, e.g. $\sin^2\theta_W$
- Magnetic moment of ν_τ (scattering on electrons)
- ...
- NP: Exotics produced by neutrinos and decaying within few meters

  E.g., sterile neutrinos with dipole transition moments

  (suggested to explain MiniBooNe),

  ...

Outline

1. At QFTHEP-2013 . . .
2. Building the sketch of the SHiP
3. Physics at SHiP
   - Elusive NP: portals to a hidden World
   - Elusive NP: exotic SUSY
   - Elusive SM physics: neutrinos
4. Summary

Summary: intensity frontier

- We definitely need New Physics
- There are arguments in favour of NP below EW scale. . .
- Then above GeV scale we can test it with LHC
- While at GeV scale a fixed-target experiment is much more sensitive

new project SHiP proposed at CERN

- Physical Paper and Technical Proposals have been submitted to SPSC in April 2015

final decision by Spring 2016 . . . ?

The physics is complimentary to what we have at LHC:
very weakly interacting particles of 0.1-10 GeV mass

- If smth fundamental is at(above) TeV-scale,
  SHiP will hunt for the light renegates: Pseudo-Nambu-Goldstone bosons,. . .
- If the only NP is at GeV-scale,
  SHiP will explore the DM, BAU and Neutrino oscillations origin.
- Also physics of ν_τ and $\bar{\nu}_\tau$

http://ship.web.cern.ch/ship/

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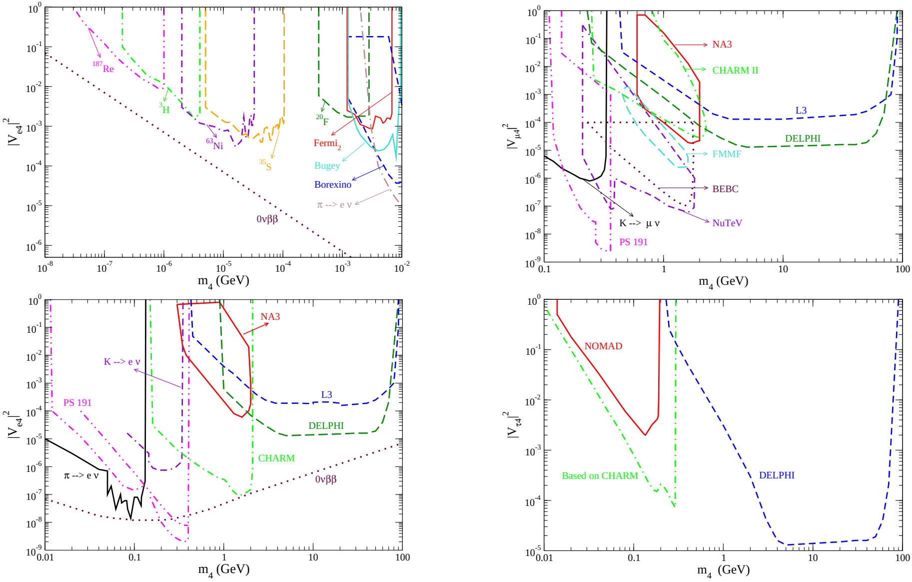
Backup slides

Present limits

0901.3589: 1) $0\nu\beta\beta$-bound is stronger by 10, 1205.3867 2) limits from LHCb and CMS

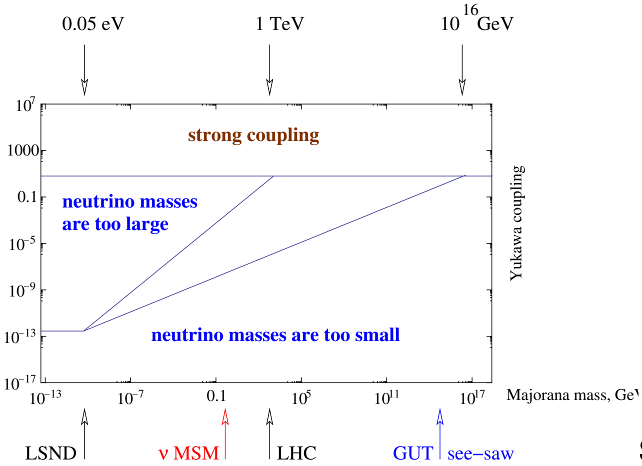


Sterile neutrino mass scale: $\hat{M}_\nu = -v^2 \hat{f}^T \hat{M}_N^{-1} \hat{f}$

NB: With fine tuning in $\hat{M}_N$ and $\hat{f}$ we can get a hierarchy in sterile neutrino masses, and 1 keV and even 1 eV sterile neutrinos

$L_e - L_\mu - L_\tau$ or discrete symmetries
Froggatt-Nielsen mechanism

Extended seesaw



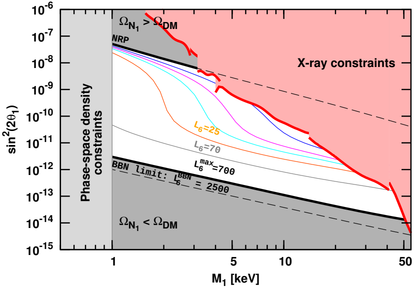
Seesaw diagram

Lightest sterile neutrino N_1 as Dark Matter

Non-resonant production
(active-sterile mixing) is ruled out

Resonant production (lepton asymmetry) requires $\Delta M_{2,3} \lesssim 10^{-16}$ GeV

arXiv:0804.4542, 0901.0011, 1006.4008



Dark Matter production
from inflaton decays in plasma at $T \sim m_\chi$

Not seesaw neutrino!

M.Shaposhnikov, I.Tkachev (2006)

$$M_{N_I} \bar{N}_I^c N_I \leftrightarrow f_I X \bar{N}_I N_I$$

Can be "naturally" Warm ($250\,\text{MeV} < m_\chi < 1.8\,\text{GeV}$)

F.Bezrukov, D.G. (2009)

$$M_1 \lesssim 15 \times \left(\frac{m_\chi}{300\ \text{MeV}}\right) \text{keV}$$

Light sgoldstinos in SUSY models

SUSY is spontaneously broken (no scalar electron with mass of 510 keV !!)

breaking of $SU(2)_W \times U(1)_Y$ by the $\langle H \rangle = v$

Goldstones bosons couple to all massive fields

(Goldberger–Treiman formula like for pion)

$$\mathscr{L} = \frac{1}{v} J^{\mu}_{SU(2)_W \times U(1)_Y} \partial_\mu H$$

Higgs mechanism: three modes of H are eaten giving masses to Z, $W^\pm$

breaking of SUSY by $\langle F_\varphi \rangle = F$

Goldstone fermion: goldstino

$$\mathscr{L}_\psi \propto \frac{1}{F} J^{\mu}_{SUSY} \partial_\mu \psi$$

Super-Higgs mechanism: goldstino is eaten giving mass to gravitino

ψ — goldstino $\xrightarrow{SUGRA}$ longitudinal gravitino

Physics of Goldstino supermultiplet: (boson φ (sgoldstino), fermion ψ (goldstino))

~~SUSY~~ $\longleftrightarrow$ $F \equiv \langle F_\varphi \rangle \neq 0$ $\qquad \Phi = \varphi + \sqrt{2}\theta\psi + F_\varphi \theta\theta$ $\qquad \frac{1}{\sqrt{2}}\left(\varphi + \varphi^\dagger\right) \equiv S$ — scalar

sgoldstino: $\mathscr{L}_{S,P} \propto \frac{M_{soft}}{F}$ $\qquad F \sim$ (~~SUSY~~ scale)^2 $\qquad \frac{1}{i\sqrt{2}}\left(\varphi - \varphi^\dagger\right) \equiv P$ — pseudoscalar

M_{soft}: MSSM soft terms

superpartner masses and trilinear couplings,

massless at tree level

naturally may be light...

gauginos:

$$M_\lambda \lambda\lambda \longrightarrow \frac{M_\lambda}{F} S F_{\mu\nu} F^{\mu\nu}, \quad \frac{M_\lambda}{F} P F_{\mu\nu} \tilde{F}^{\mu\nu}$$

squarks, sleptons:

$$A_{ij} h_u \tilde{q}_i \tilde{u}_j \longrightarrow \frac{A_{ij}}{F} S h_u q_i u_j, \quad \frac{A_{ij}}{F} P h_u q_i u_j$$

R-parity violating neutralinos in SUSY models

Superpotential (SUSY-invariant part) gives Yukawa-like couplings for SM fermions

$$W_{\not R} = \lambda_{ijk} L_i^a \varepsilon_{ab} L_j^b \bar{E}_k + \lambda'_{ijk} L_i^a \varepsilon_{ab} Q_j^b \bar{D}_k + \lambda''_{ijk} \bar{U}_i^\alpha \varepsilon_{\alpha\beta\gamma} \bar{D}_j^\beta \bar{D}_k^\gamma$$

Yet the proton is stable if $\lambda'' = 0$ (baryon parity), or $\lambda, \lambda' = 0$ (lepton parity) and proton is lighter than LSP: $R_p = (-1)^{(3B+L+2S)}$

But LSP is unstable in these models, so no problems with overproduction (but we need another candidate to be dark matter. . .)

Nevertheless cosmology and astrophysics exclude

BBN: $0.1\,\text{s} < \tau_{\text{LSP}}$ cosmic γ-rays (FERMI): $\tau_{\text{LSP}} < 10^{18}\,\text{yr}$

hence, the allowed range:

$$3 \times 10^{-23} < (\lambda, \lambda', \lambda'') < 3 \times 10^{-10}$$

Direct searches at LHC (and TeVatron) probe:

$$(\lambda, \lambda', \lambda'') > 10^{-6}$$

otherwise LSP decays outside ATLAS and CMS

Massive vectors (paraphotons)

Vector portal to a secluded sector: e.g. with Dark matter Ψ

one more $U(1)'$ gauge group [spontaneously broken] in secluded sector: mixing with $U(1)_Y$ is naturally expected and unsuppressed by high energy scale 0711.4866

$$\mathscr{L}_{\text{DM+mediator}} = \bar{\Psi}\left(i\gamma^\mu \partial_\mu - e'\,\gamma^\mu A'_\mu - m_\Psi\right)\Psi - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{m^2_{\gamma'}}{2}A'_\mu A'^\mu + \varepsilon A'_\mu \partial_\nu B^{\mu\nu}$$

when $m_\Psi > m_{\gamma'} \sim 1\,\text{GeV}$

Cosmology:

- Limits from BBN:

$$\tau_V < 1\,\text{s}\,, \implies \varepsilon^2\left(\frac{m_{\gamma'}}{1\,\text{GeV}}\right) \gtrsim 10^{-21}$$

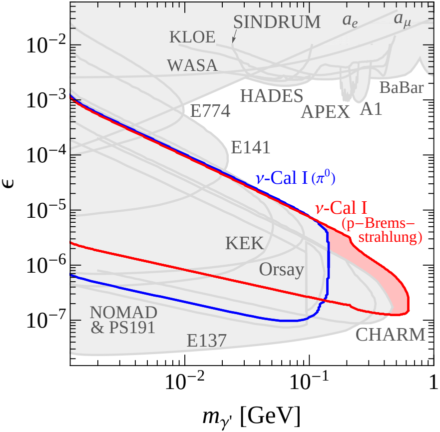
- For DM particles to be in thermal equilibrium in primordial plasma:

$$\varepsilon^2\left(\frac{m_{\gamma'}}{1\,\text{GeV}}\right) \gtrsim 10^{-11}\times\left(\frac{m_\Psi}{500\,\text{GeV}}\right)^2$$

Production by virtual photon $\sigma \propto \varepsilon^2$

Decay through virtual photon, $\Gamma \propto \varepsilon^2$

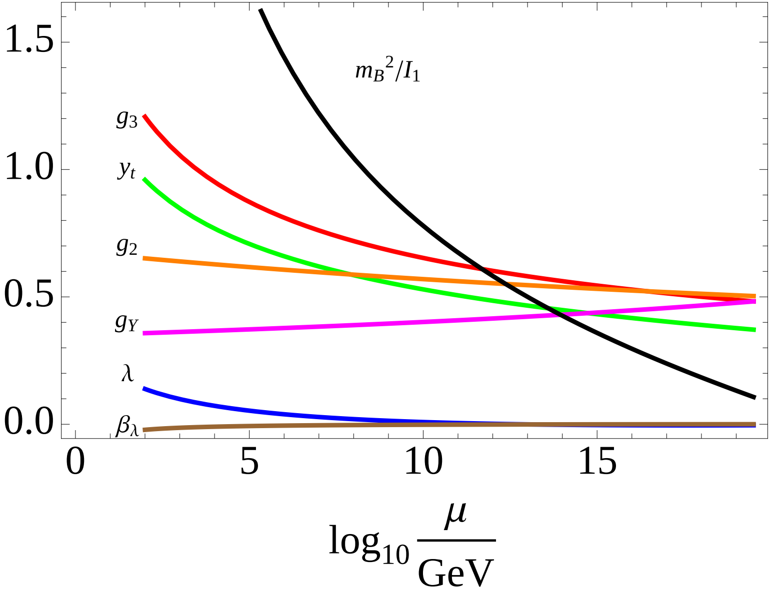
$V \to e^+e^-\,,\ \mu^+\mu^-\,,$ etc



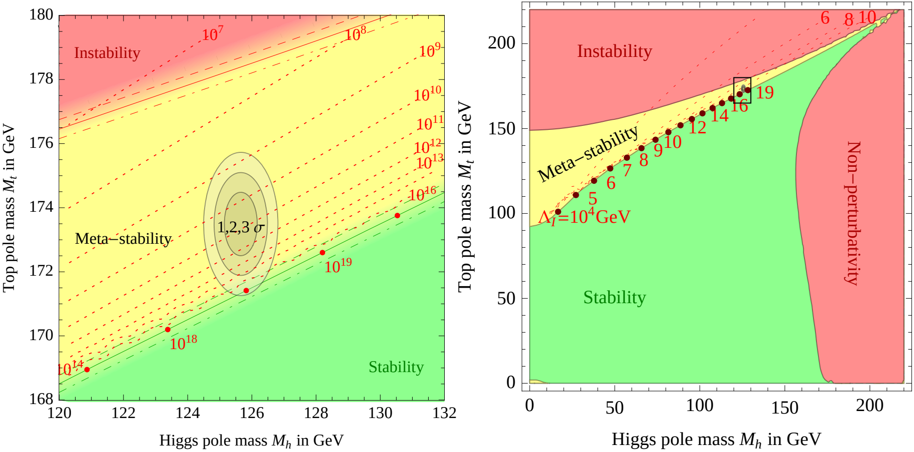
1311.5104

RG evolution of the SM couplings

1305.7055



How “natural” the 126 GeV. . .



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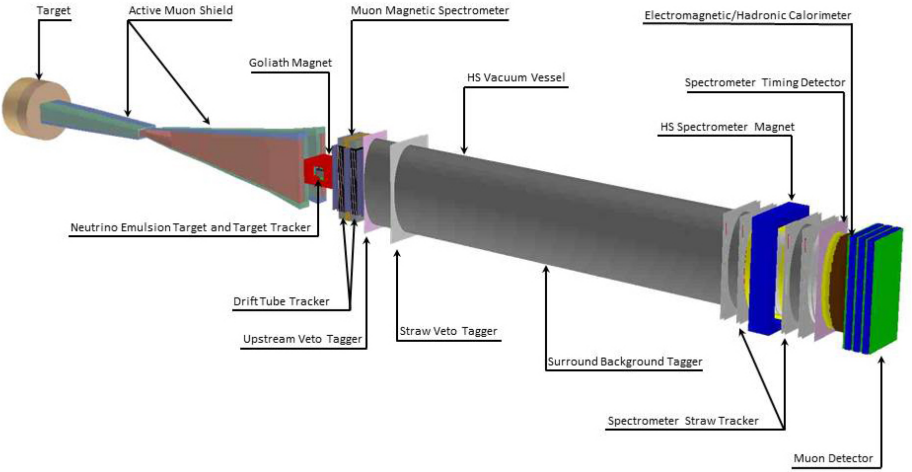
The SHiP detector



Active neutrino masses without new fields

Dimension-5 operator $\Delta L = 2$

$$\mathscr{L}^{(5)} = \frac{F_{\alpha\beta}}{4\Lambda} \bar{L}_\alpha \tilde{H} H^\dagger L^c_\beta + \text{h.c.}$$

L_α are SM leptonic doublets, $\alpha = 1,2,3$, $\tilde{H}_a = \varepsilon_{ab} H^*_b$, $a, b = 1,2$; in a unitary gauge $H^T = \left(0, (v+h)/\sqrt{2}\right)$ and

$$\mathscr{L}^{(5)}_{\nu\nu} = \frac{v^2 F_{\alpha\beta}}{4\Lambda} \times \frac{1}{2} \bar{\nu}_\alpha \nu^c_\beta + \text{h.c.} = m_{\alpha\beta} \times \frac{1}{2} \bar{\nu}_\alpha \nu^c_\beta + \text{h.c.}$$

where

Λ is the scale of new dynamics

$F_{\alpha\beta}$ is the strength of new dynamics

only their ratio is fixed by the scale of active neutrino masses

Perturbative regime for model parameters

$$F_{\alpha\beta} \lesssim 1 \qquad \Longrightarrow \qquad \Lambda \lesssim 3\times 10^{14}\,\text{GeV} \times \left(\frac{3\times 10^{-3}\,\text{eV}^2}{\Delta m^2_{\text{atm}}}\right)^{1/2}$$

The model has to be UV-completed at the scale Λ $\rightarrow$ New physics

- The scale is certainly below the Planck (string) scale, and hence is most probably at (below) EW scale
- Why no hints recognized at this scale?

  couplings to the SM fields are tiny
- which probably implies not a GUT-like new physics (all is $\propto g$)

  hence coupling to new gauge singlets
- that is usually nonrenormalizable interactions. . . however, there are exceptions. . .

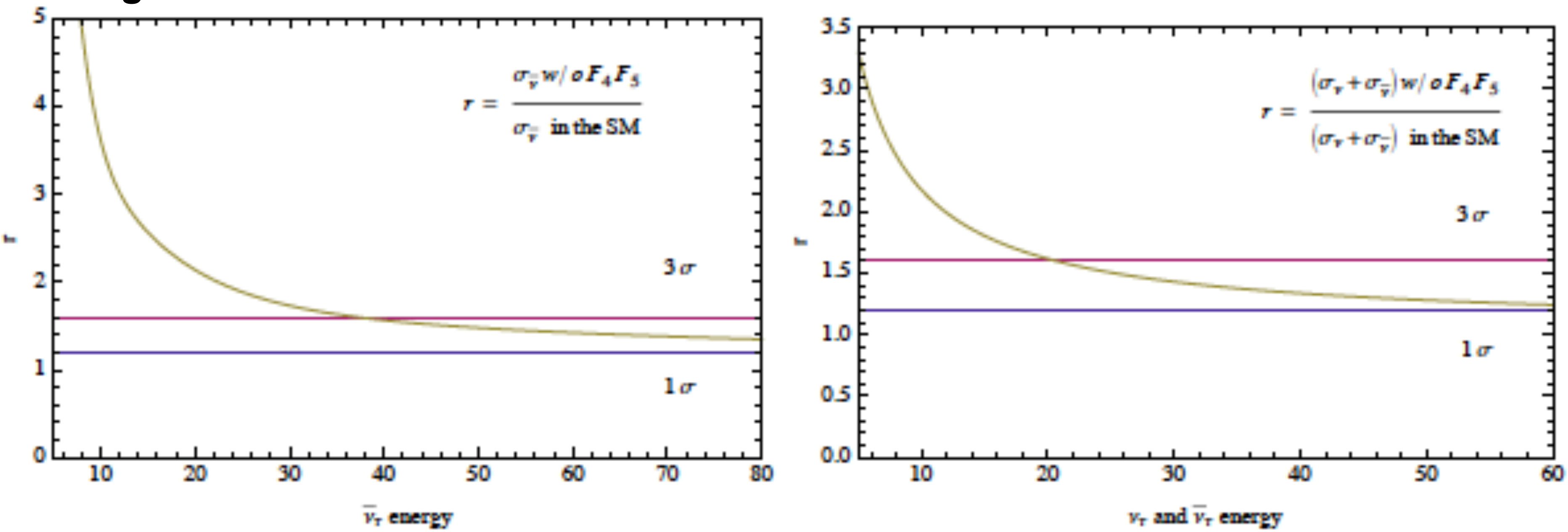
  thus we arrive at the portals

Structure functions F_4 and F_5

F_4 and F_5 , neglected in muon neutrino interactions, give significant contribution to the tau neutrino cross-section:

$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\Bigg((y^2x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})\right]F_2 \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4 - \frac{m_\tau^2}{E_\nu M}F_5\Bigg),$$

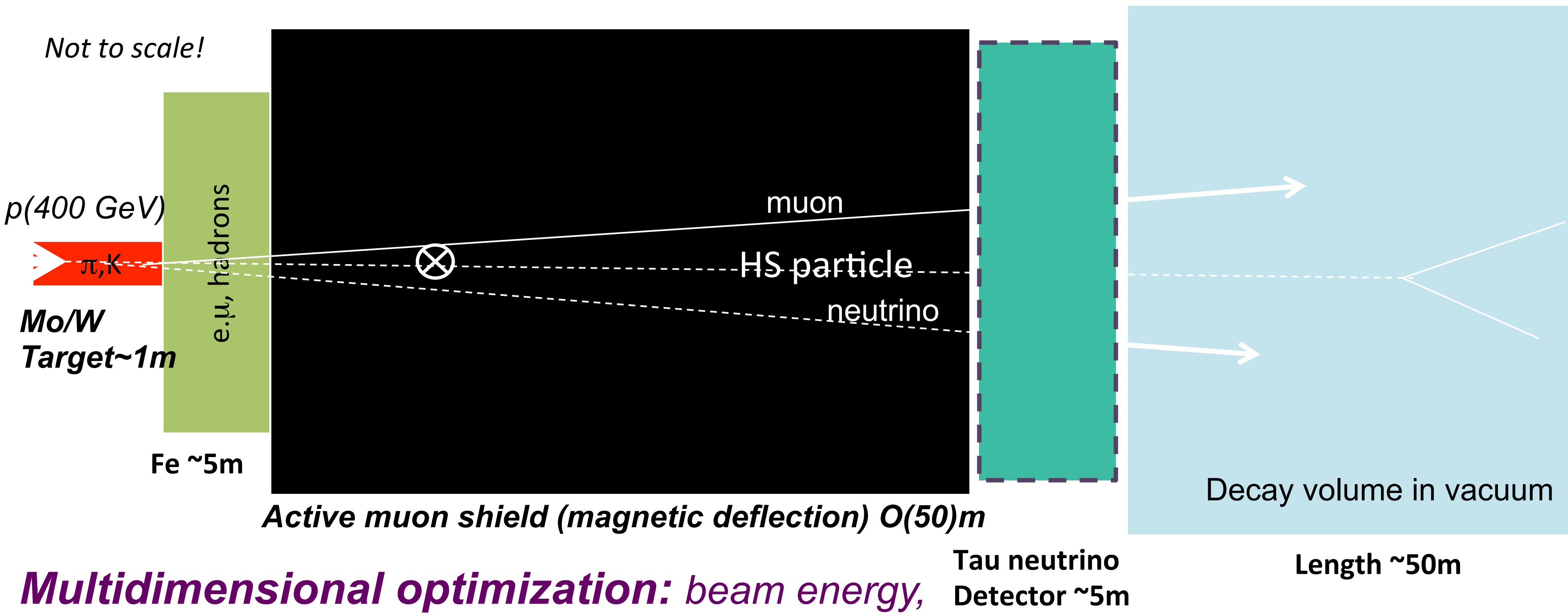
SHiP will provide 3σ evidence for non-zero F_5 (F_4 is ~1% of F_5) for neutrino energies below 20 GeV



SHiP beam-line
(incompatible with conventional neutrino facility)

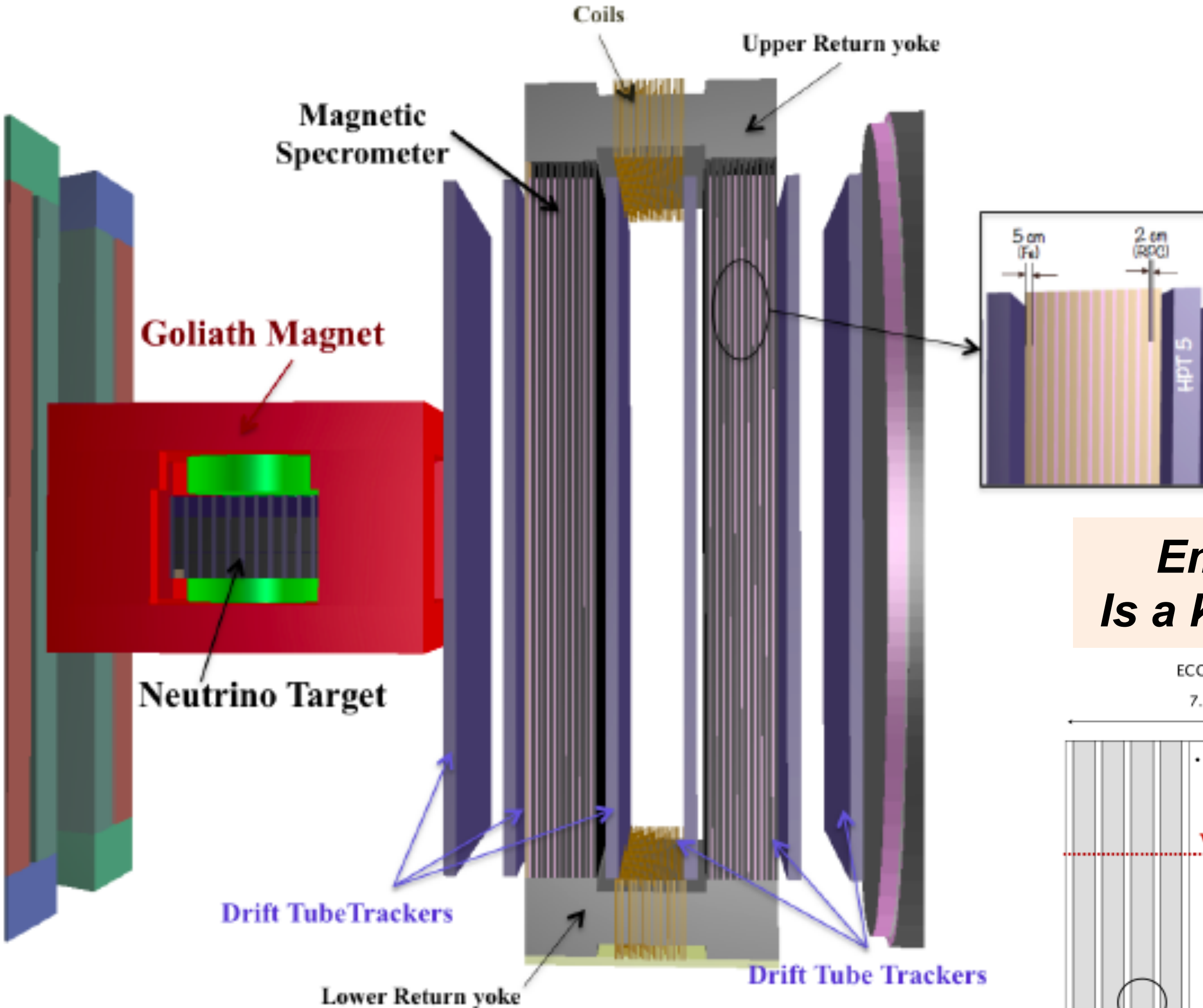
Initial reduction of beam induced backgrounds

- *Heavy target to minimize neutrinos from $\pi/K \rightarrow \mu\nu$ decays*
- *Hadron absorber*
- *Effective muon shield (without shield: muon rate ~10^{10} per spill of 5×10^{13} pot)*
- *Slow (and uniform) beam extraction ~1s to reduce occupancy in the detector*

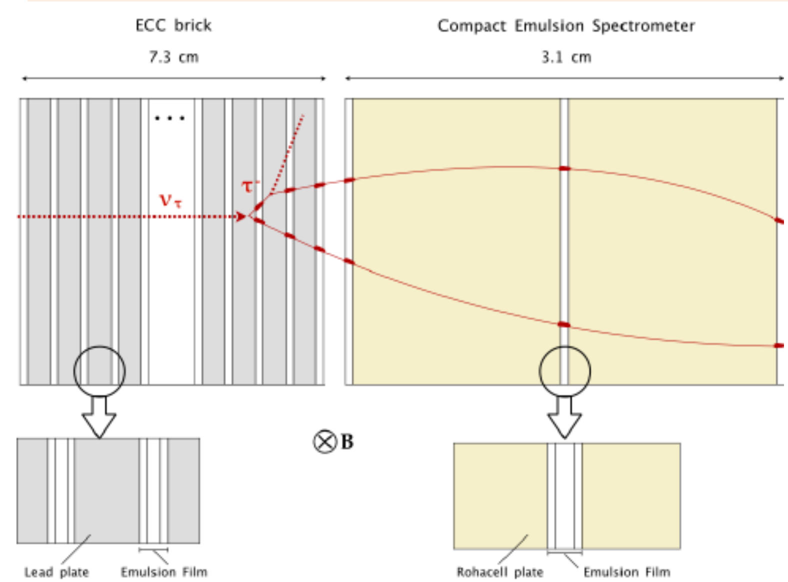


Multidimensional optimization: *beam energy, beam intensity, background conditions and detector acceptance*

ν_τ detector follows the concept of OPERA



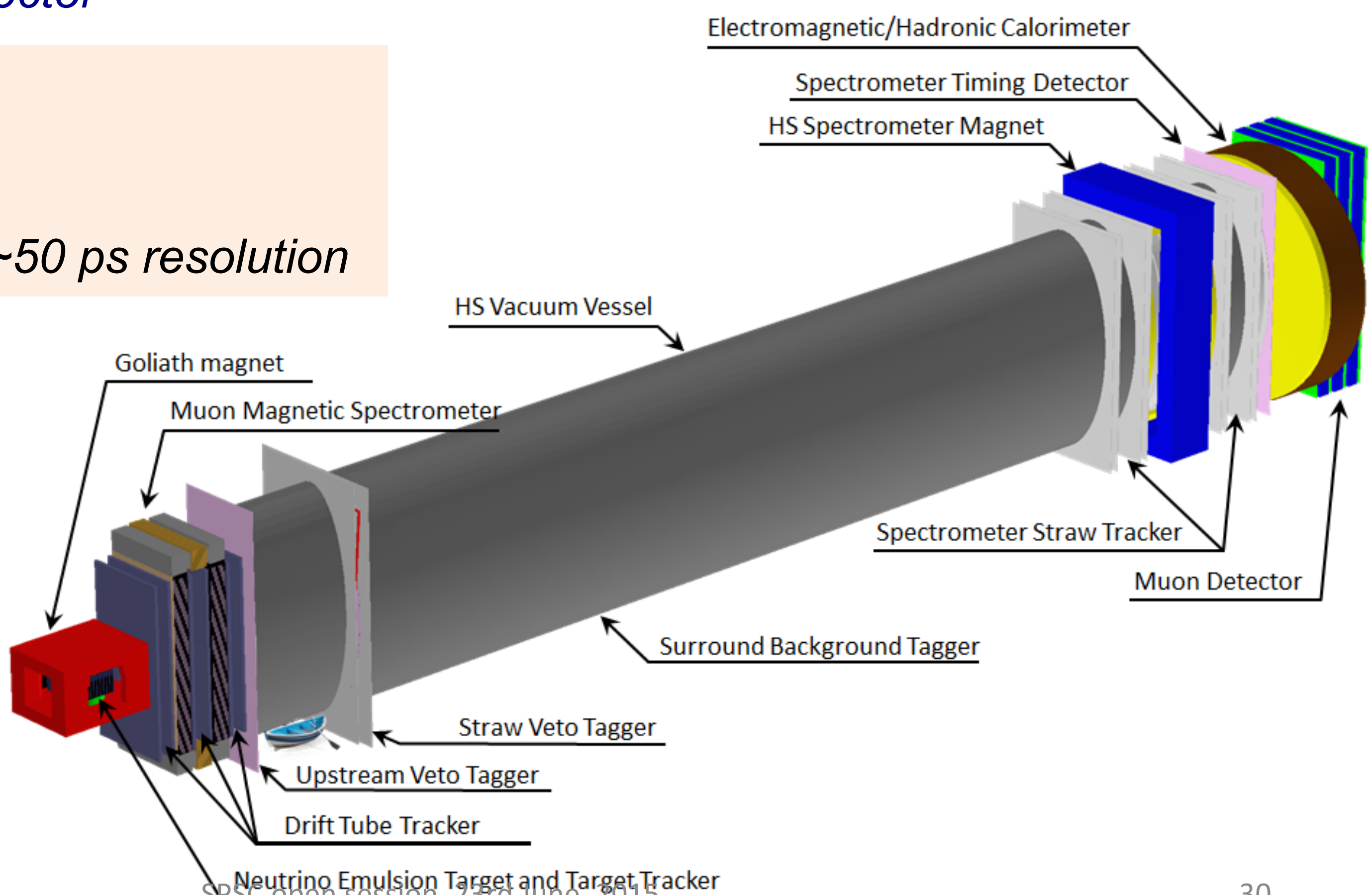
Emulsion Cloud Chamber Is a key element of ν_τ detection



HS detector concept
(based on existing technologies)

✓ Reconstruction of the HS decays in various final states
Long decay volume protected by various Veto Taggers, Magnetic Spectrometer followed by the Timing Detector, and Calorimeters and Muon systems.
All heavy infrastructure is at distance to reduce neutrino / muon interactions in proximity of the detector

Challenges:
- Large vacuum vessel
- 5 m long straw tubes
- Timing detector with ~50 ps resolution



Decay volume and spectrometer magnet

- ✓ ***Estimated need for vacuum: < 10^{-3} mbar***

- ✓ ***Vacuum vessel***
  - *10 m x 5 m x 60 m*
  - *Walls thickness: 8 mm (Al) / 30 mm (SS)*
  - *Walls separation: 100 mm;*
  - *Liquid scintillator (LS) volume (~120 m^3) readout by WLS optical modules (WOM) and PMTs*
  - *Vessel weight ~ 480 t*

- ✓ ***Magnet designed with emphasis on low power***
  - *Power consumption < 1 MW*
  - *Field integral: 0.65Tm over 5m*
  - *Weight ~800 t*
  - *Aperture ~50 m^2*