# SHiP: a new facility with a dedicated detector to search for new neutral particles and studying tau neutrino properties

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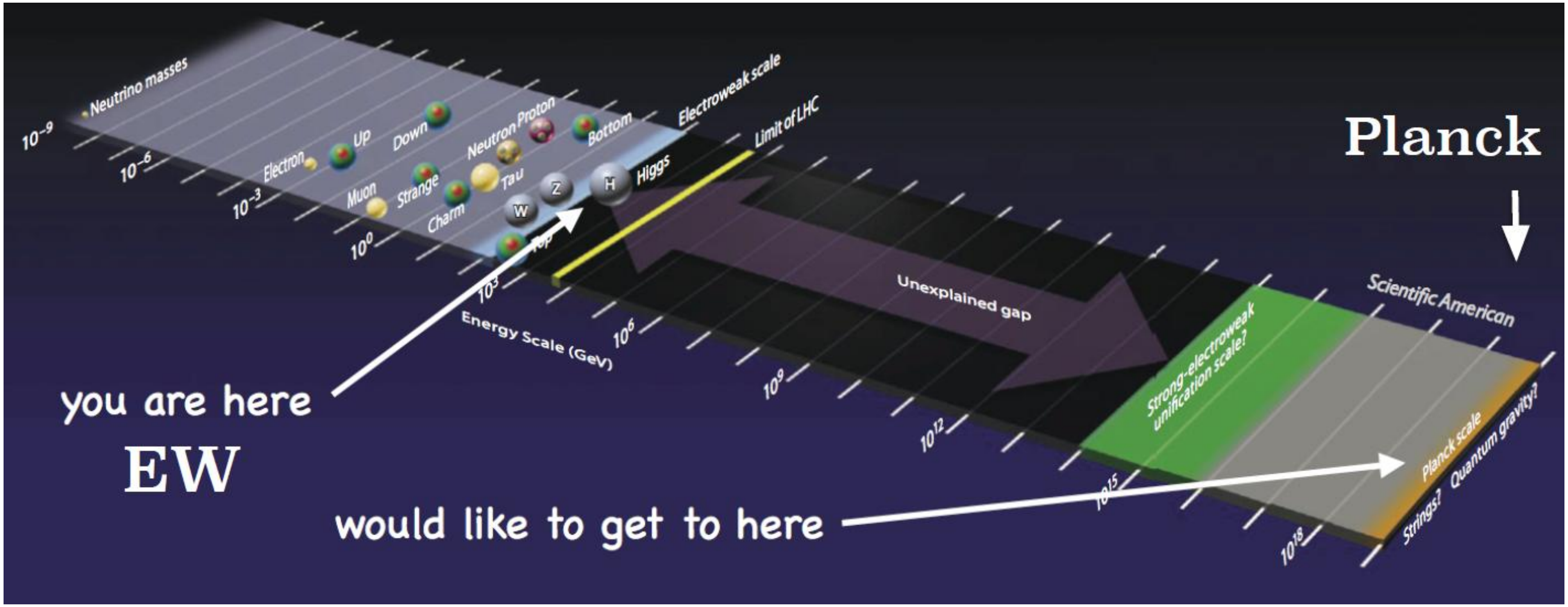
on behalf of the SHiP collaboration

**ICNFP–2016**
**Kolymbari, Crete, Greece**
**13 July 2016**

# Expectations before LHC

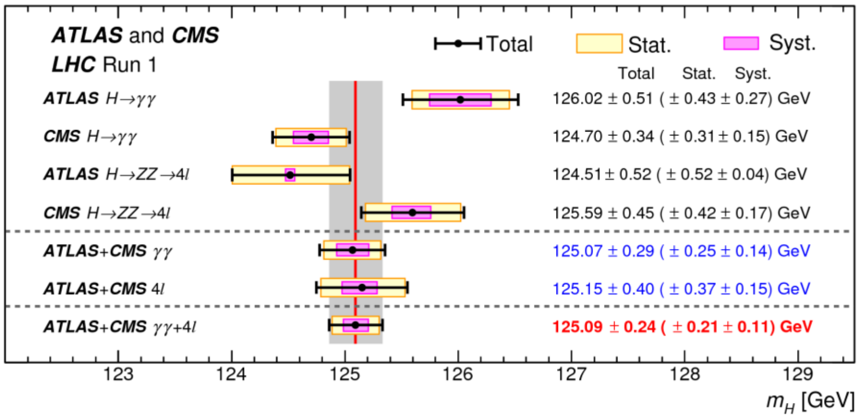


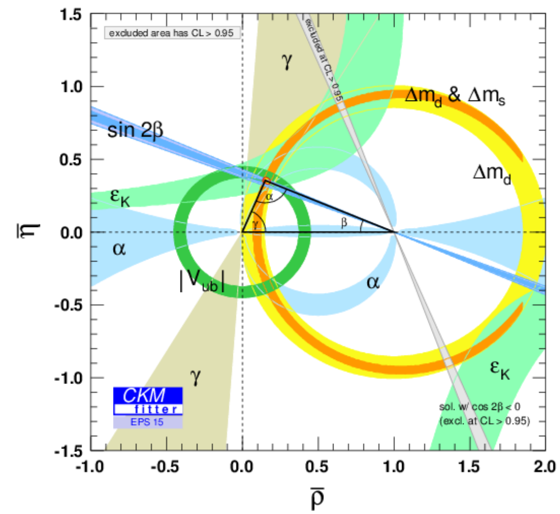

*(from C.Quigg )*

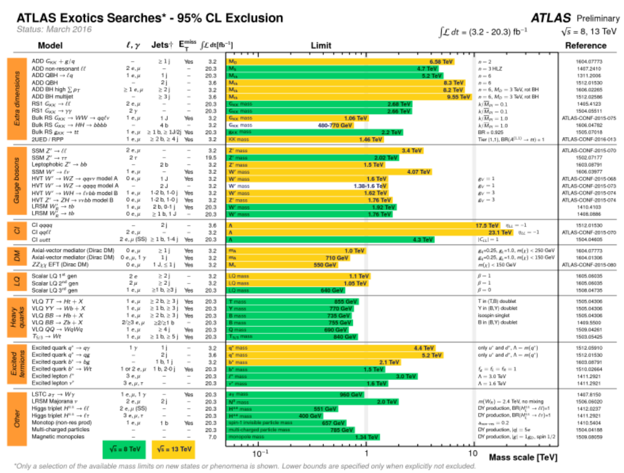
- Higgs boson or strong interaction of vector bosons («guaranteed discovery»)
- New physics in TeV ballpark (SUSY particles ?; extra dimensions ?; compositeness ?)

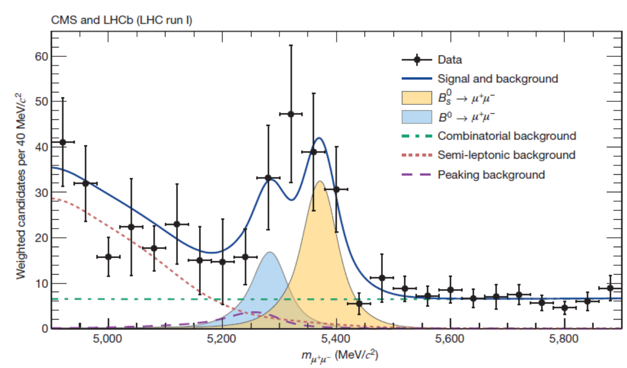
# Present status

**Triumph** of the Standard Model: Higgs boson, flavour physics, rare decays and **nothing beyond..**



We know however (not from LHC) that
***there is physics*** beyond the **SM**:

- Neutrino masses and oscillations
- Dark matter
- Baryon asymmetry of the Universe
- ...

Besides that, there are many «why» and «how» in the **SM**:

- How is EW scale so smaller than UV scale?
- Why hierarchy between **SM** scales?
- Why are lefts doublets and rights singlets?
- Why 3 generations? Why CKM hierarchy & CP?
- ...

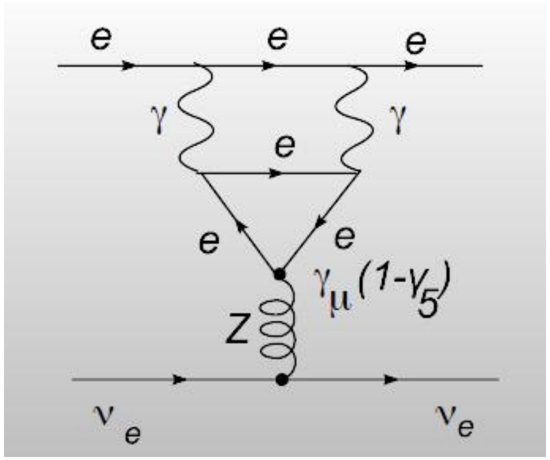
# Is the SM a consistent field theory?

Generally, NO ⇒

- Landau pole
- Anomalies
- Naturalness

but the things are arranged in such a tricky way, that (almost) all is cured…

Example: cancellation of anomalies.




Links quarks and leptons!

$$TrY^3 = \; = \; 3\left[(\frac{1}{3})^3 + (\frac{1}{3})^3 - (\frac{4}{3})^3 - (-\frac{2}{3})^3\right] + (-1)^3 + (-1)^3 - (-2)^3 = 0$$

$$\uparrow \; colour \quad \uparrow \; u_L \quad \uparrow \; d_L \quad \uparrow \; u_R \quad \uparrow \; d_R \quad \uparrow \; \nu_L \quad \uparrow \; e_L \quad \uparrow \; e_R.$$

# Physical scales and coincidences

There are many various scales and small numbers in the **SM** with intricate relations between them…

- Couplings $\alpha_{em} = (137.035999679)^{-1}$ $\alpha_s(m_Z) = (8.503)^{-1}$

$$\frac{m_e}{m_t} \sim 3 \times 10^{-6} \qquad \lambda = |V_{us}| = 0.22 \qquad 1/9 = 1/3^2$$

- Mass scales $\frac{m_{u,d}}{\Lambda_{QCD}} = (0.5 \div 2)\%$ $G_F m_p^2 = 1 \cdot 10^{-5}$

$$G_N m_p^2 = 6 \cdot 10^{-39}$$

*And even more mysterious things..*

Koide relation

$$m_e + m_\mu + m_\tau = \frac{2}{3}(\sqrt{m_e} + \sqrt{m_\nu} + \sqrt{m_\tau})^2$$

Zeldovich-Bjorken relation

$$\rho_{crit} \sim H \cdot \Lambda_{QCD}^3$$

$$10^{-29}\,\mathrm{g} \cdot \mathrm{cm}^{-3} \sim 10^{-26}\,\mathrm{m}^{-1} \cdot (10^8\,\mathrm{eV})^3$$

# How is UV scale related to physical ones?

By UV-regularization we put external and artificial information into theory

$$\int \mathcal{D}\phi(k) \to \int\limits_{k<\Lambda} \mathcal{D}\phi(k)$$

$$\rho \sim \Lambda^4 + \ldots + 10^{-29} \mathrm{g/cm^3}$$

$$M_H^2 \sim \Lambda^2 + (126\ \mathrm{GeV})^2$$

**We know from experiment in all these cases that Λ – terms are physically irrelevant.**

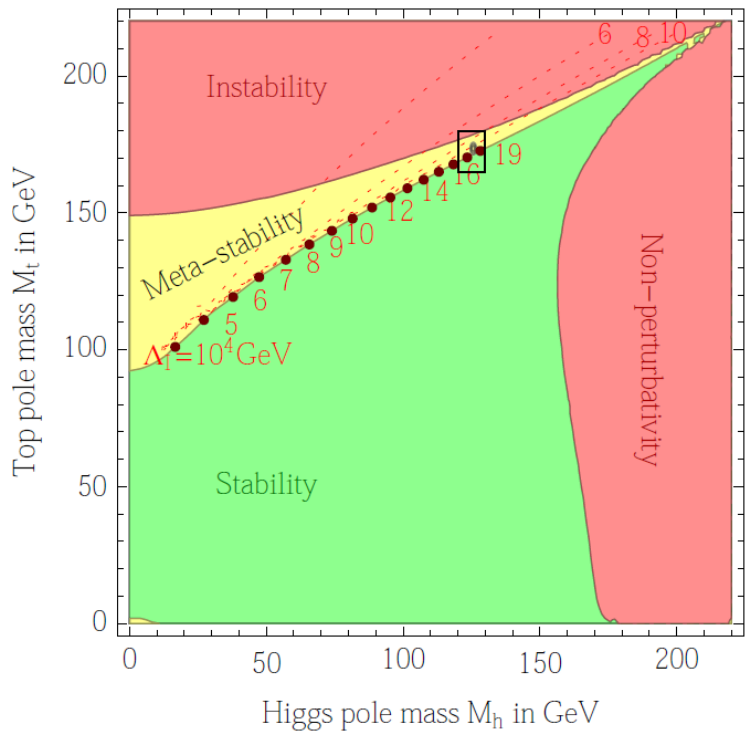
**However only in the last case we know how physical scale appears from Λ :**

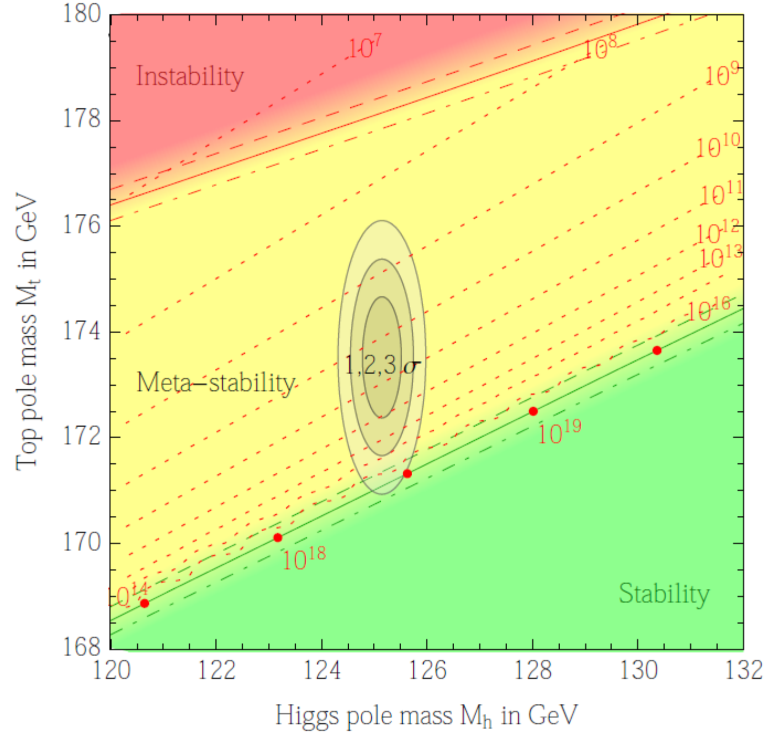
$$\langle G_{\mu\nu}^2 \rangle \sim \Lambda^4 + 0.012\ \mathrm{GeV}^4 \Longleftrightarrow \Lambda_{QCD} \sim \Lambda\, e^{-b/g^2(\Lambda)} \underset{\Lambda \to \infty}{\neq} \infty$$

Renormalizability vs naturalness. In «good» theories we need just a few numbers from the «outside» $k > \Lambda$ region to be able to work at low energy – coefficients of marginal operators, like 1/137.

# Observable Higgs mass corresponds to metastability of the SM vacuum

*(from arXiv:1307.3536)*




*(I. V. Krive, A. D. Linde, N. Cabibbo, L. Maiani, G. Parisi, R. Petronzio, M.Lindner, H.B.Nielsen, C.Froggatt, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori, A. Riotto, A. Strumia, J. R. Espinosa, M. Quiros, G.Altarelli and many others)*

Strong hint to **NO** New Physics up to the Planck scale.

# Standard Model Criticality Prediction: Top mass 173 ± 5 GeV and Higgs mass 135 ± 9 GeV.

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## Abstract

Imposing the constraint that the Standard Model effective Higgs potential should have two degenerate minima ( vacua), one of which should be - order of magnitudewise - at the Planck scale, leads to the top mass being 173 ± 5 GeV and the Higgs mass 135 ± 9 GeV. This requirement of the degeneracy of different phases is a special case of what we call the multiple point criticality principle. In the present work we use the Standard Model all the way to the Planck scale, and do not introduce supersymmetry or any extension of the Standard Model gauge group. A possible model to explain the multiple point criticality principle is lack of locality fundamentally.

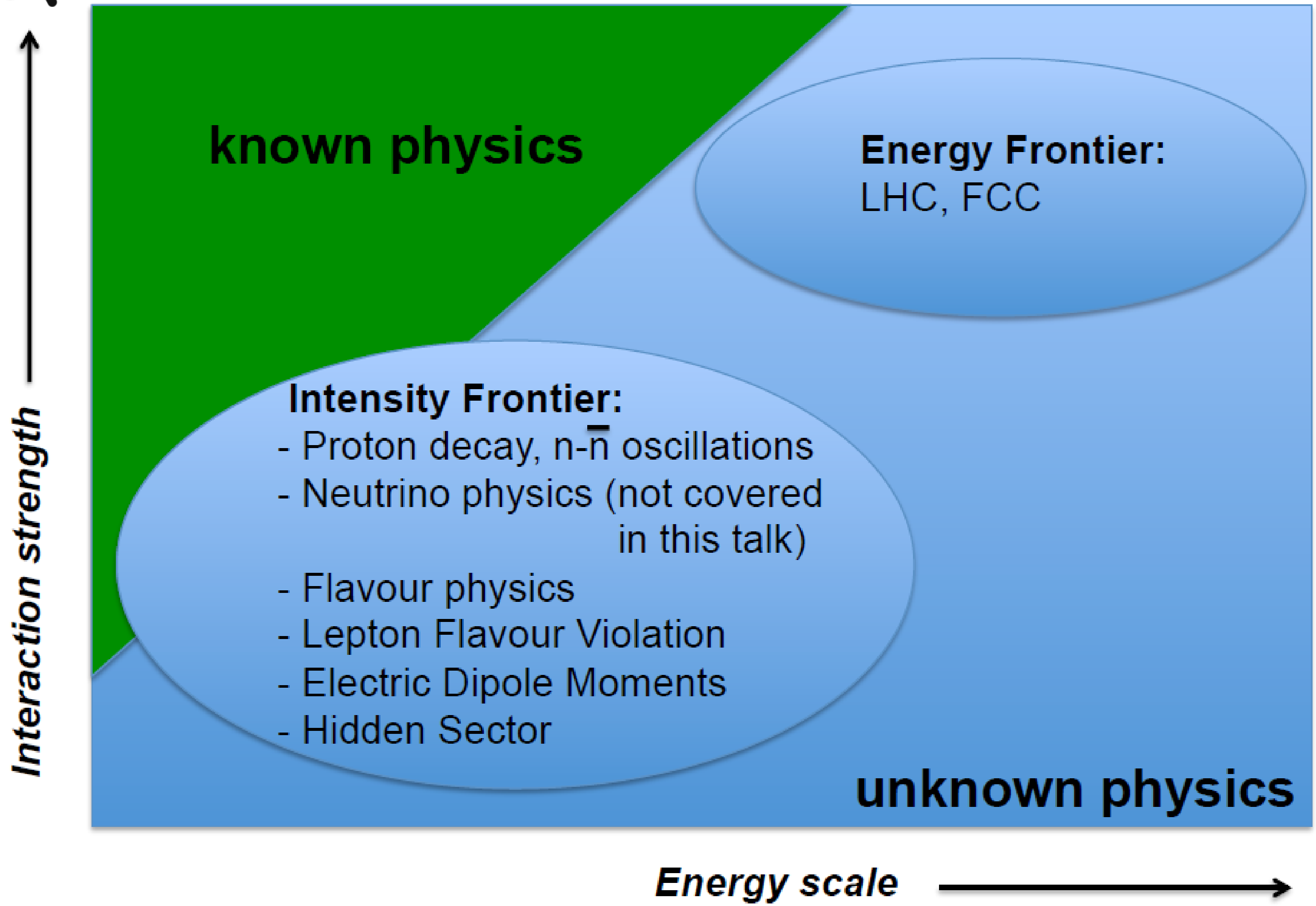
Perhaps it is more useful to think not about New Physics that could solve theoretical problems of the **SM**, but about NP that could explain observed effects beyond **SM**.

*In hope that theory will settle things anyway..*

## What could the new degrees of freedom be?

| Energy ↑ | **SM singlets** | **SM non-singlets** |
|---|---|---|
| | Why not but what for? | Energy Frontier |
| *SM scale* | | |
| | Intensity Frontier | Excluded |

$$\text{effect} \sim \frac{g^2}{M^2}$$



Light Hidden Particles → **SM**–singlets → couple to different singlet composite **SM** operators (Portals)

$$L = L_{SM} + L_{HS} + L_{portal}$$

Visible (SM) matter ⟺ Hidden Sector (HS)

**contains Dark Matter and can have very complicated structure**

Most work is on these 3 renormalizable portals in the **SM**:

$$\mathcal{L}_{\text{Vector portal}} = \epsilon F'_{\mu\nu} F^{\mu\nu}_{Y}$$ **«dark photons»**

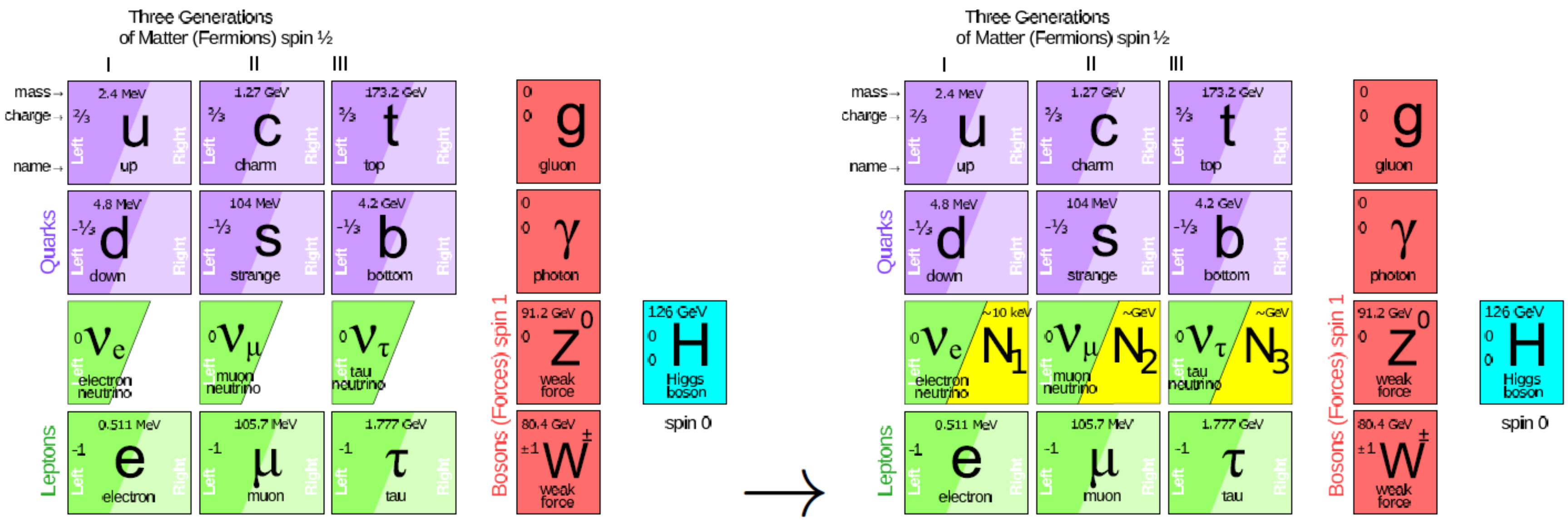
$$\mathcal{L}_{\text{Scalar portal}} = (\lambda_i S_i^2 + g_i S_i)(\Phi^\dagger \Phi)$$

$$\mathcal{L}_{\text{Neutrino portal}} = F_{\alpha I}(\bar{L}_\alpha \cdot \tilde{\Phi}) N_I$$

# $\nu$MSM *(T.Asaka, M.Shaposhnikov, 2005)*

Most general renormalizable type I see-saw Lagrangian with 3 HNLs:

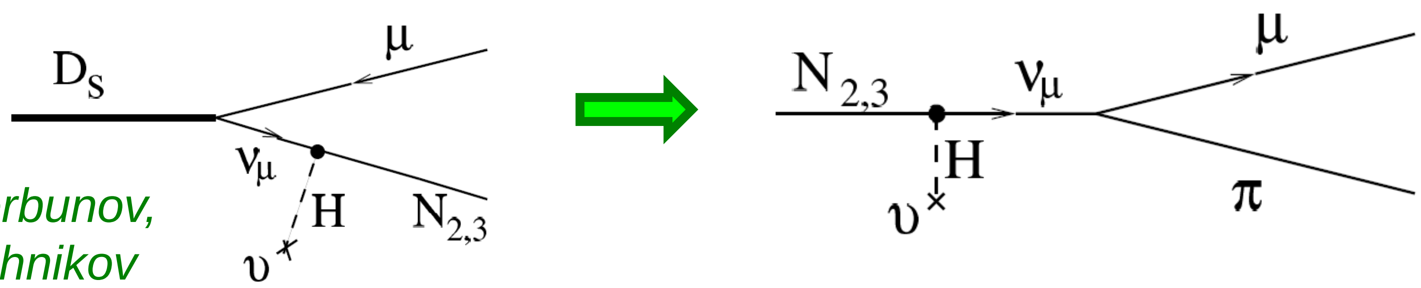
$$L = L_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I} \Phi \bar{N}_I L_\alpha - \frac{M_I}{2} \bar{N}_I^c N_I + \text{h.c.}$$




**$N_1$** with mass ***O***(keV) – dark matter

**$N_2$ , $N_3$** with mass ***O***(GeV) – neutrino masses and BAU

# How to discover?




*(see D.Gorbunov, M.Shaposhnikov hep-ph/0705.1729)*

| Models | Final states |
|---|---|
| Neutrino portal, SUSY neutralino | $\ell^\pm\pi^\mp, \ell^\pm K^\mp, \ell^\pm\rho^\mp, \quad \rho^\pm \to \pi^\pm\pi^0$ |
| Vector, scalar, axion portals, SUSY sgoldstino | $\ell^+\ell^-$ |
| Vector, scalar, axion portals, SUSY sgoldstino | $\pi^+\pi^-, K^+K^-$ |
| Neutrino portal ,SUSY neutralino, axino | $\ell^+\ell^-\nu$ |
| Axion portal, SUSY sgoldstino | $\gamma\gamma$ |
| SUSY sgoldstino | $\pi^0\pi^0$ |

- Full reconstruction and PID are essential
- Long-lived objects, travel unperturbed through **SM** matter
- Central challenge is background suppression

# Signal yield

$$N(pot) = 2 \times 10^{20}$$

$$n(HS) = N(pot) \times \chi(pp \to HS) \times \mathcal{P}_{vtx} \times \mathcal{A}_{tot}(HS \to \text{visible})$$

$$\chi(pp \to HNL) = 2 \sum_{q=c,b} \chi(pp \to q\bar{q}) \times \text{Br}(q \to HNL) \times U^2$$

where $\chi(pp \to c\bar{c}) = 1.7 \times 10^{-3}$ $\chi(pp \to b\bar{b}) = 1.6 \times 10^{-7}$

for 400 GeV protons on Molybdenum target

$\mathcal{P}_{vtx}$ is probability that HNL (of a given mass and couplings) decays in the SHiP fiducial volume

$$U^2 = U_e^2 + U_\mu^2 + U_\tau^2$$

$$\mathcal{A}_{tot}(HS \to \text{visible}) = \sum_i \text{Br}(HNL \to i) \times \mathcal{A}(i)$$

is detector acceptance for all HNL final (visible) states

Typically $\mathcal{P}_{vtx} \times \mathcal{A} \times \text{Selection} \sim 10^{-6}$

# General requirements

## to fixed-target (beam dump like) experiment

- Maximize possible number of protons on target

SPS: $4\times10^{13}$ @ 400 GeV = 500 kW

- Preference to slow beam extraction

SPS: a few seconds, to reduce detector occupancy

- Active muon shield

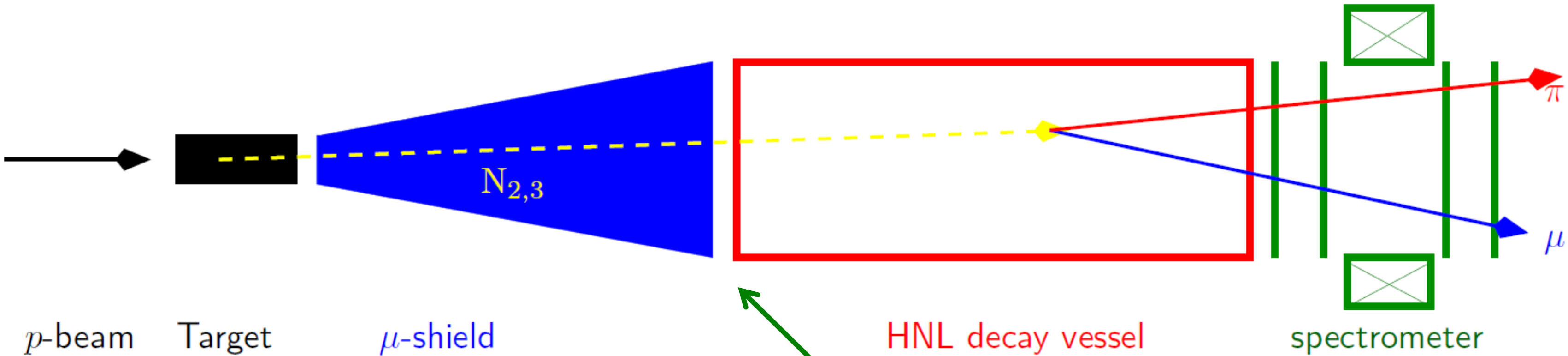
To deflect muons at short distances in order to put detector as close as possible to target (hidden particles may have large $p_T$ )

- Evacuated (or helium) and large detector volume

To reduce neutrino interactions and to give hidden particles space to fly

# Principle layout of the experiment

## «Butter physics» – hunt for HS



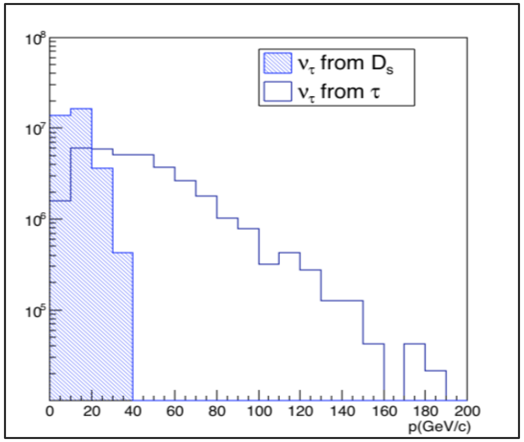

## «Bread physics» – tau neutrino detector

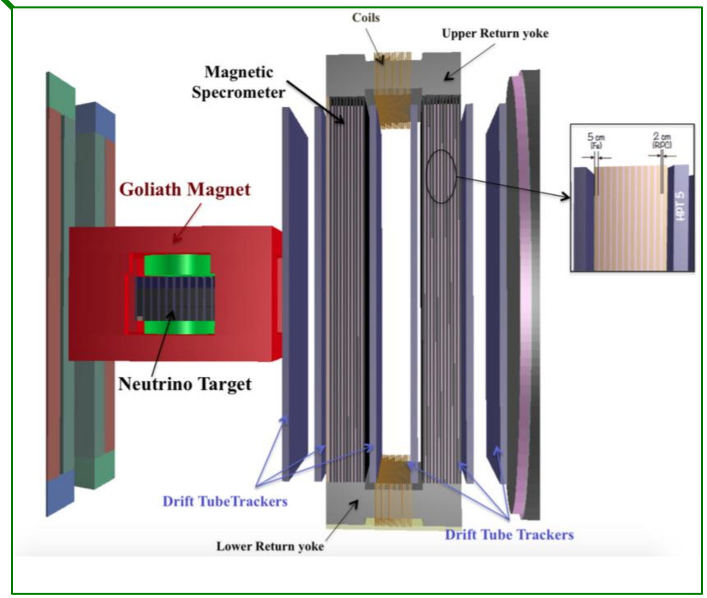
$$N_{\nu_\tau} = N_{\overline{\nu}_\tau} = 2.8 \times 10^{15}$$

at the beam dump

$$N_{\nu_\tau} = N_{\overline{\nu}_\tau} = 1.4 \times 10^{14}$$

on the detector



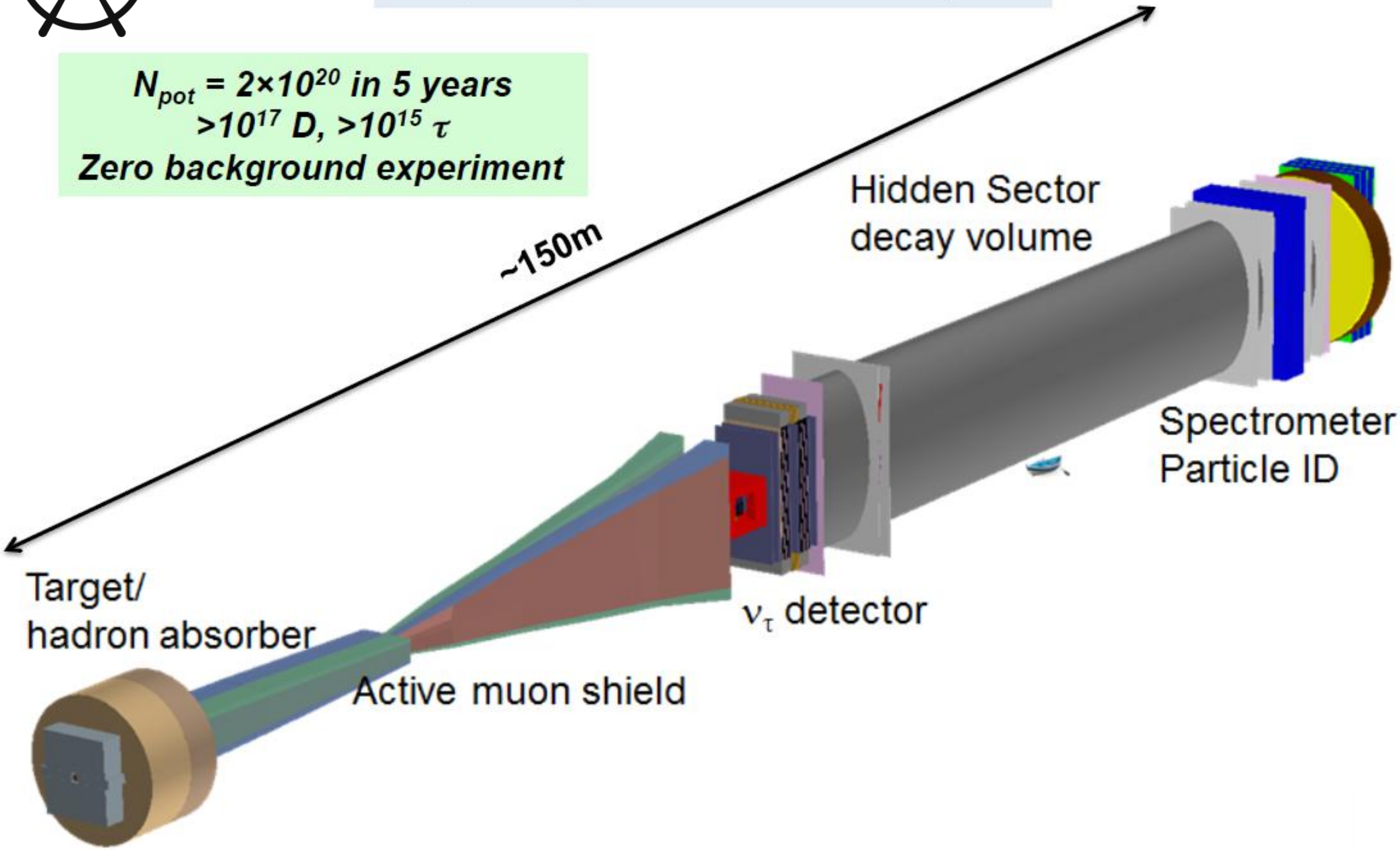
# The SHiP experiment at SPS

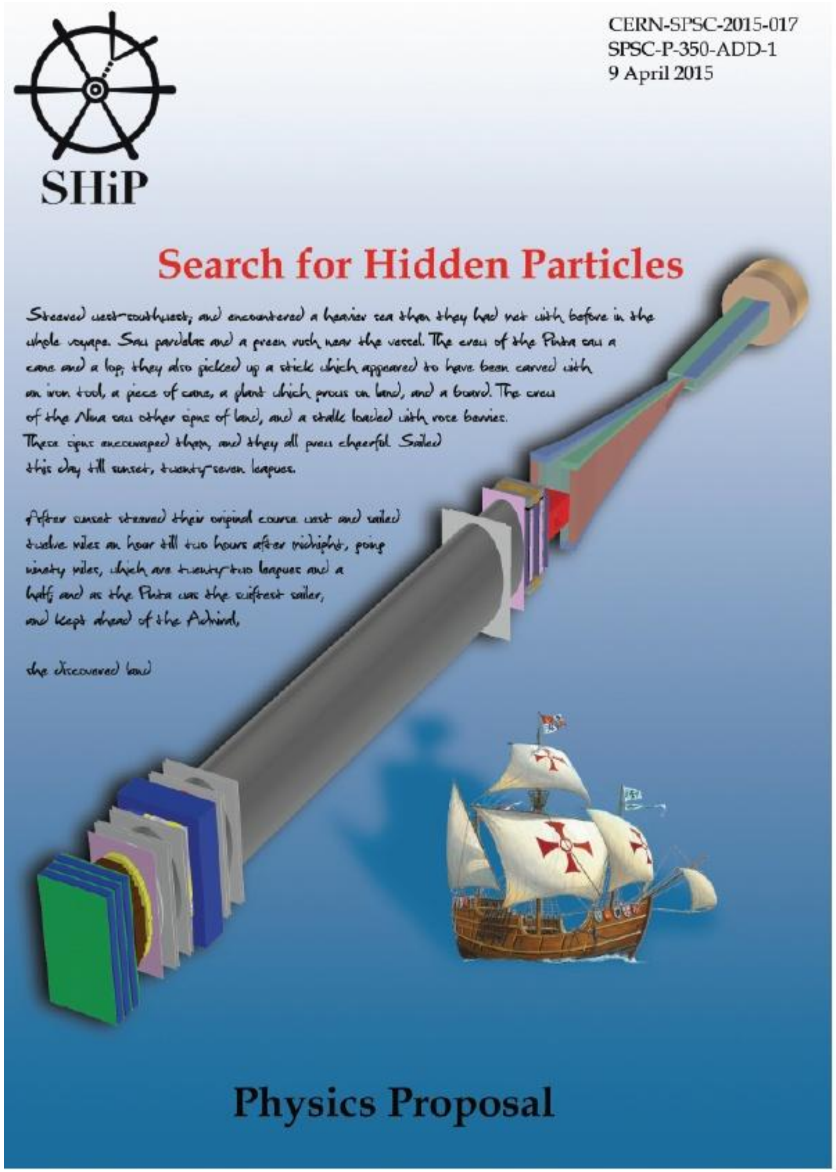
*( as implemented in Geant4 )*

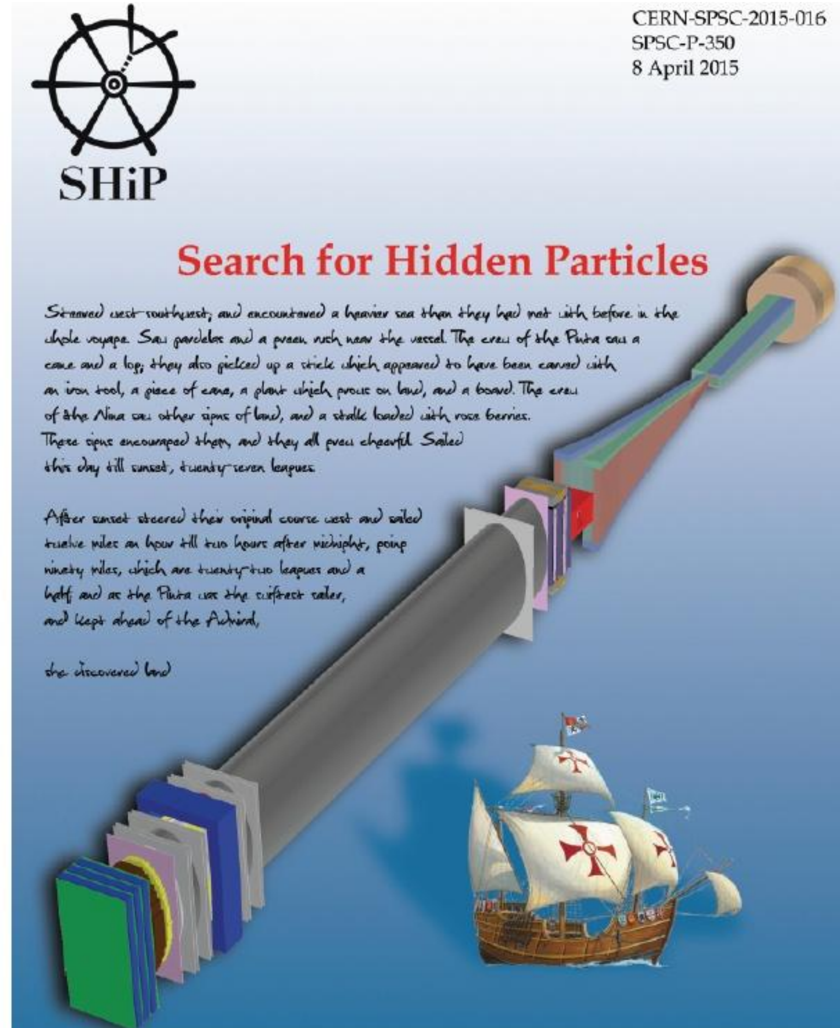
***$N_{pot} = 2\times10^{20}$ in 5 years***

***$>10^{17}$ D, $>10^{15}$ $\tau$***

***Zero background experiment***






SHiP Technical Proposal: arXiv 1504.04956
SHiP Physics Paper: arXiv 1504.04855

**85 theorists, 65 Institutes, submitted to Reviews on Progress in Physics (RPOP)**

# A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case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**Abs…** …s paper describes the physics case for a new fixed target facility at CERN SPS. The SHiP (…ch 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

SHiP

# 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.


**250 physicists, 46 Institutes, 15 countries**


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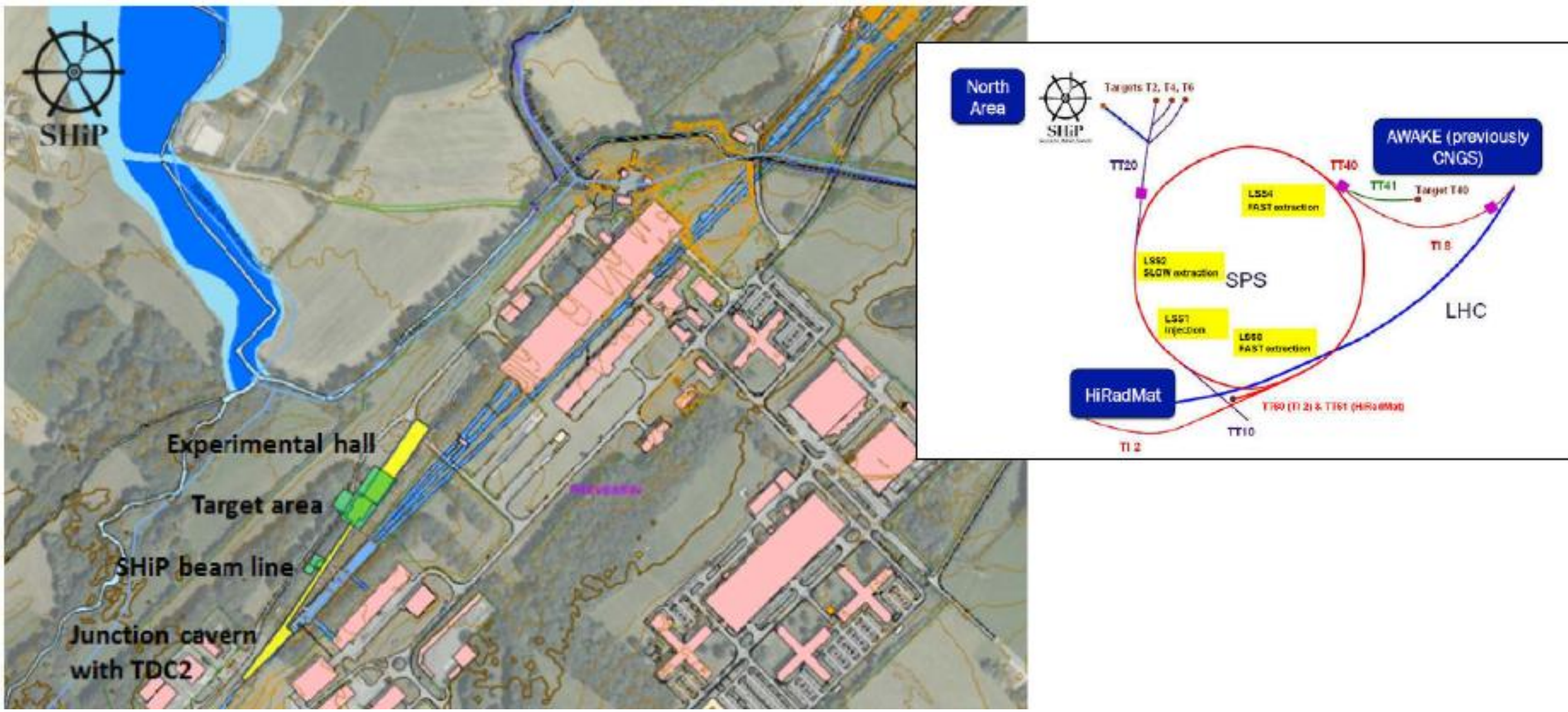
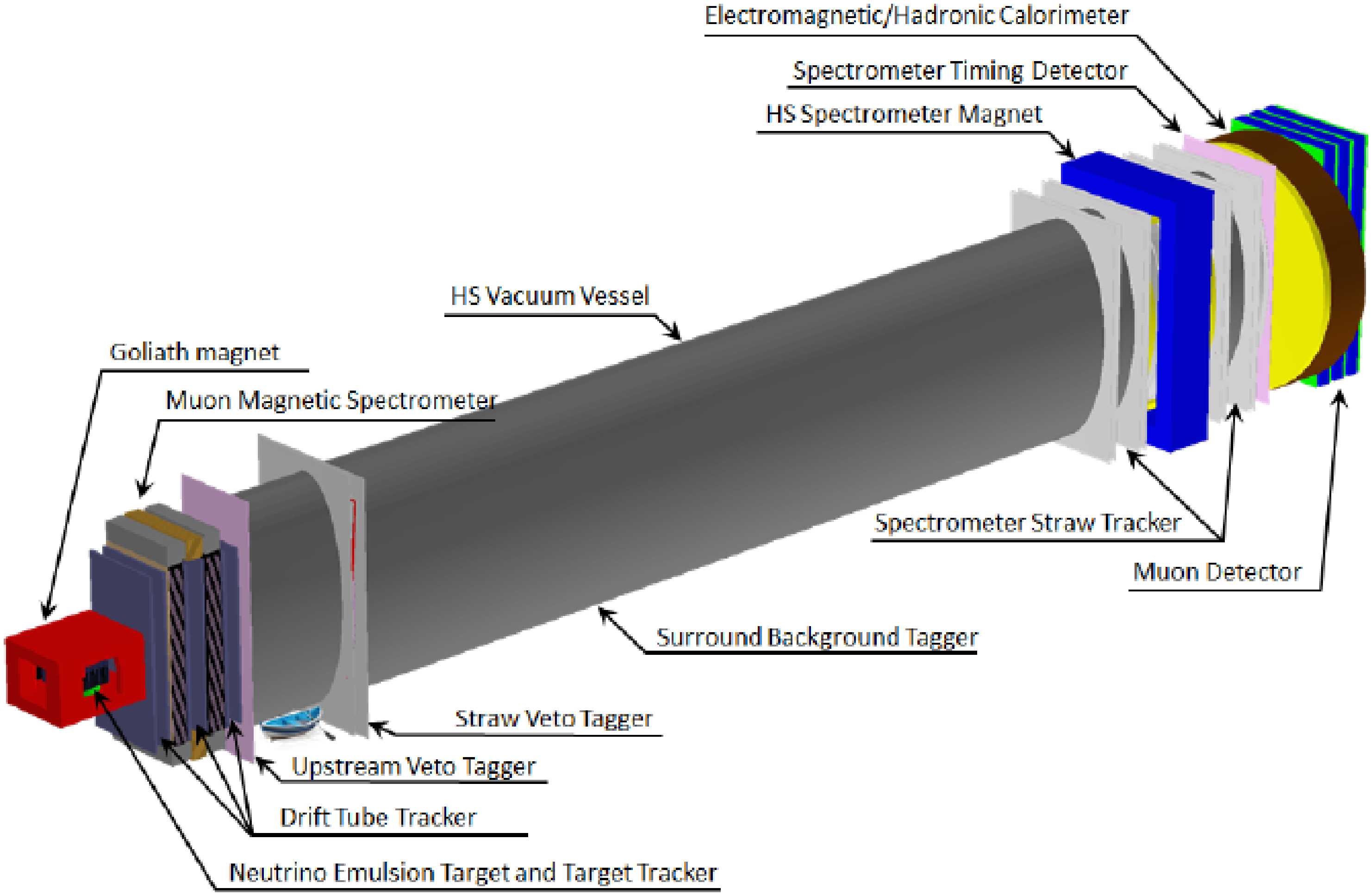
## SHiP facility is supposed to be located in the North Area and shares TT20 transfer line and the slow extraction mode with other fixed target programmes.



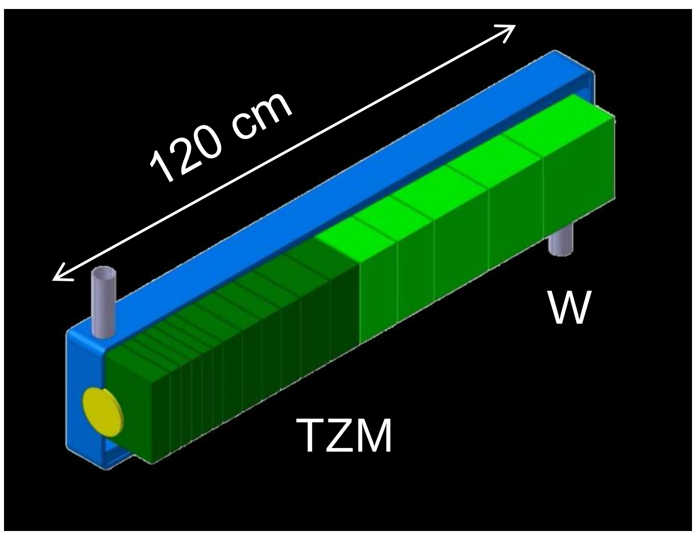

$$\frac{N(\nu_\tau)@SHiP}{N(\nu_\tau)@DONUT} \sim 600 \qquad \frac{N(HNL)@SHiP}{N(HNL)@CHARM} \sim 10000$$

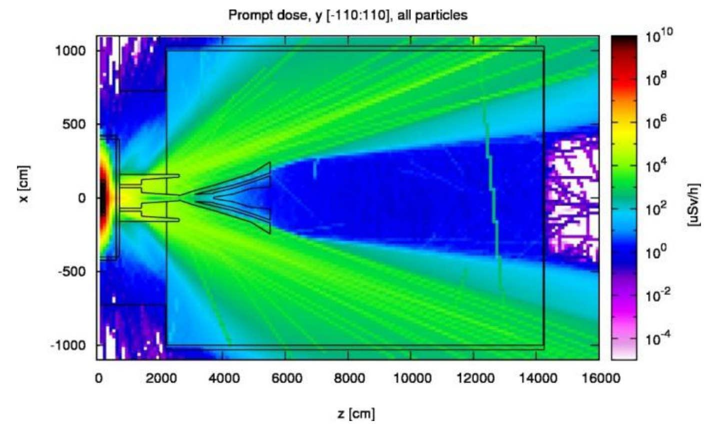
# Overview of the detector subsystems

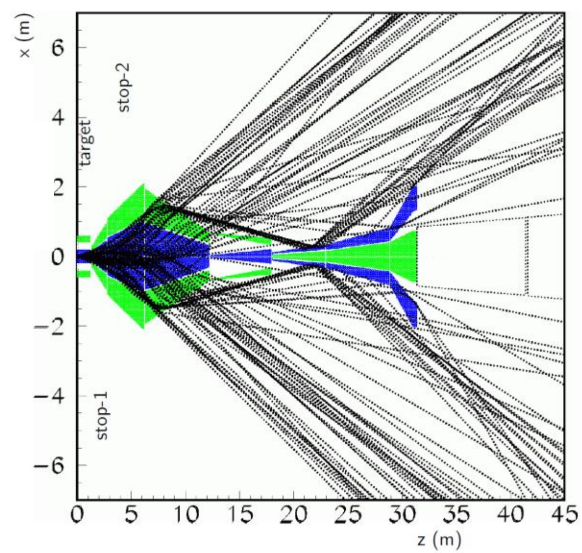


# Target and active muon shield

- **4x10$^{13}$** p / 7sec → **355** kW average, **2.56** MW during **1** sec spill – water cooled to dissipate
- Initial dose ~ **50 Sv/h**
- **10 $\lambda_{int}$** long segmented target; high-**Z** hybrid solution composed of Mo alloy (TZM, **4 $\lambda_{int}$** ) & pure W ( **6 $\lambda_{int}$** )



# Main decay vessel

## Vacuum ($10^{-3}$ mbar) vessel

Size: 10 m x 5 m x 60 m

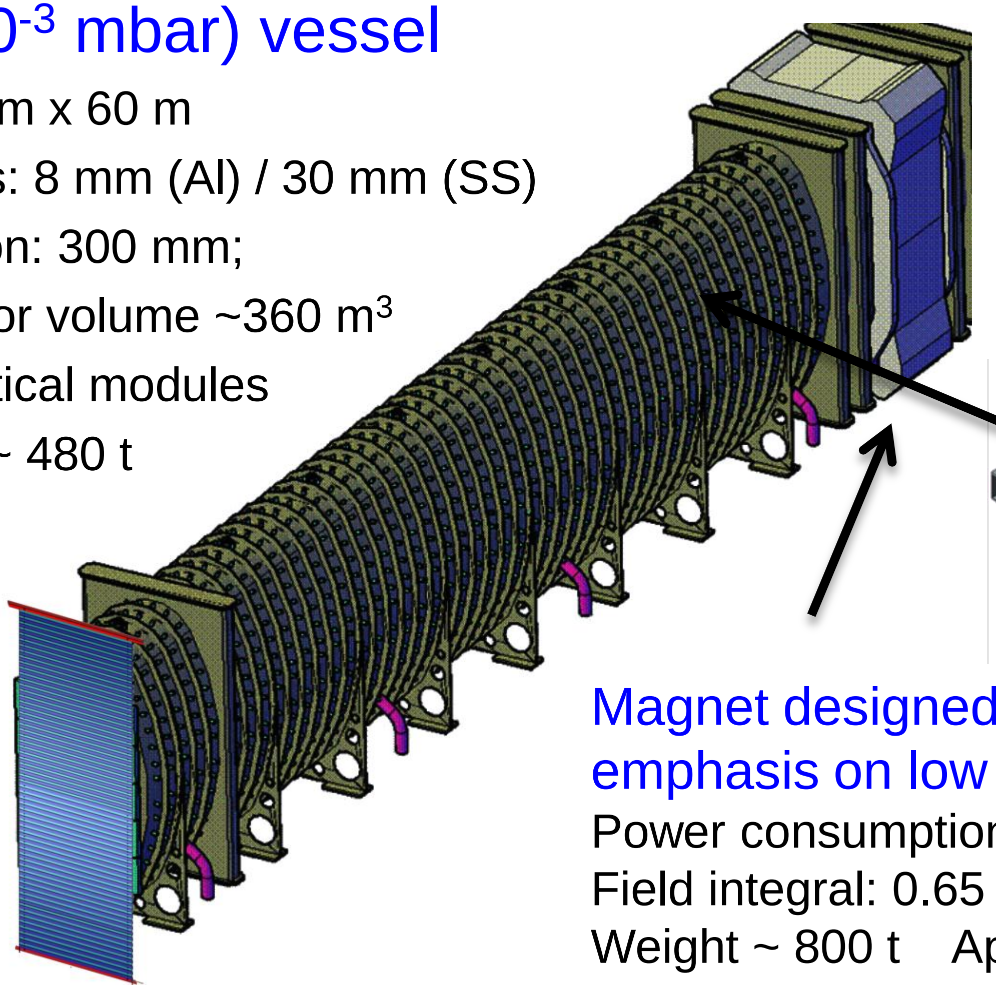
Walls thickness: 8 mm (Al) / 30 mm (SS)

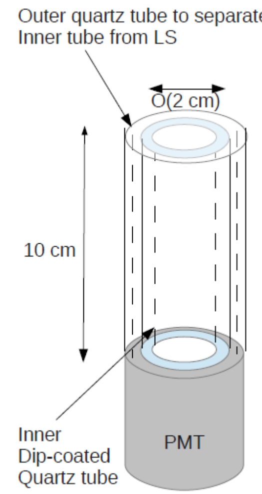
Walls separation: 300 mm;

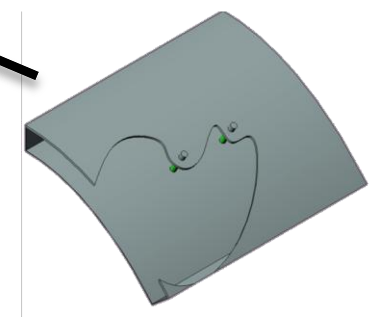
Liquid scintillator volume ~360 $m^3$

Readout by optical modules

Vessel weight ~ 480 t





## Magnet designed with an emphasis on low power

Power consumption < 1 MW

Field integral: 0.65 Tm over 5m

Weight ~ 800 t    Aperture ~ 50 $m^2$

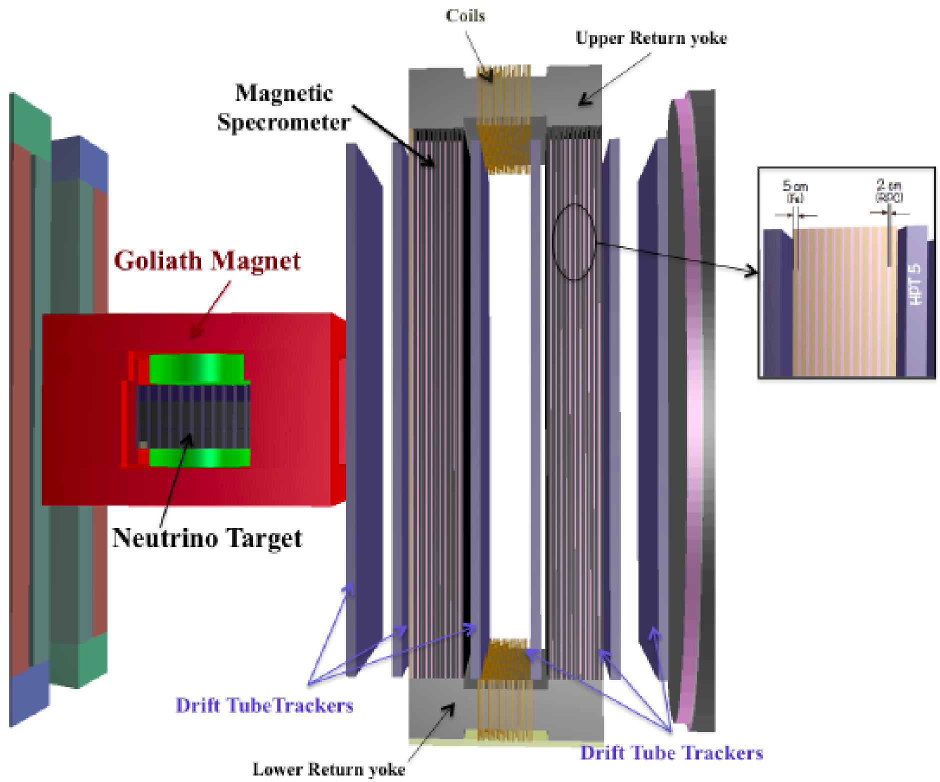
# $\nu_\tau$ detector subsystem

## OPERA-like design

- Least known particle in the **SM**, first observation by DONUT in 2001, 4 detected candidates

- 5 $\nu_\tau$ candidates were reported by OPERA for the discovery (> 5 $\sigma$ result) of $\nu_\tau$ appearance in the CNGS neutrino beam

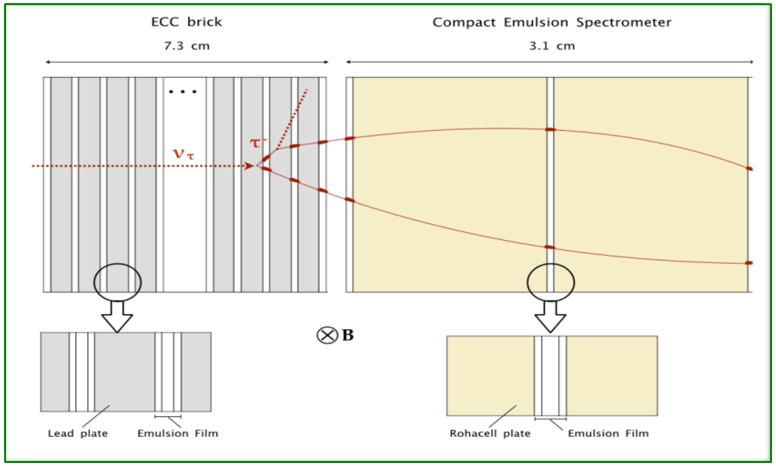
- Tau anti-neutrino is the only particle of the **SM** that has never been observed – and SHiP can do that!

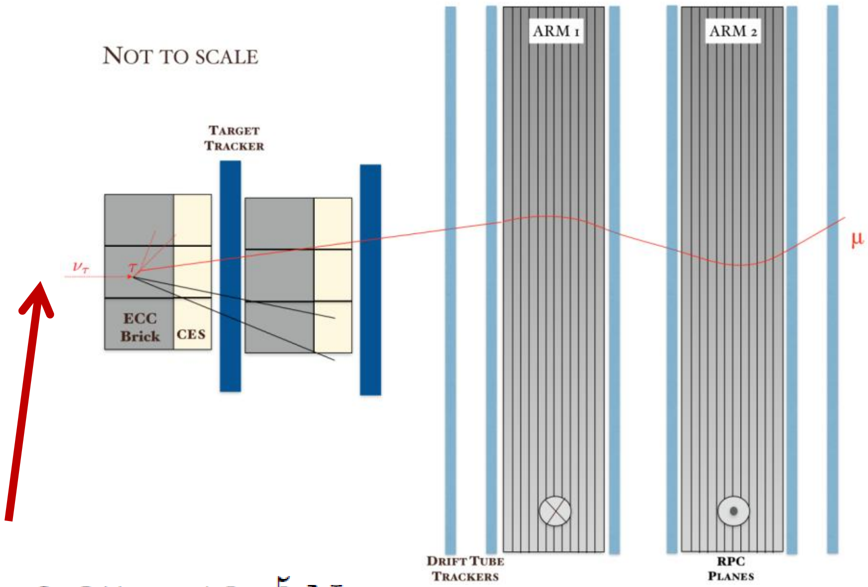



Number of interactions in 5 years run and target mass ~ 9.6 tons Pb:

$$N_{\nu_\tau} \simeq 6.7 \times 10^3 \qquad N_{\overline{\nu}_\tau} \simeq 3.4 \times 10^3$$

# General $\nu_\tau$ - detector layout




$$N_{\nu_\tau+\bar{\nu}_\tau} = 4N_{pot}\frac{\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} \mathrm{Br}(D_s \to \tau) = 2.85 \times 10^{-5} N_{pot}$$

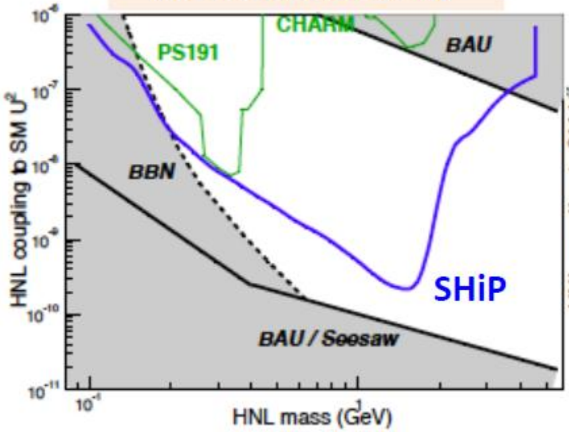
- Emulsion Cloud Chamber (ECC): passive material (lead) - massive target
- Main tracking device – nuclear emulsion, high (a few μm) resolution
- 12 target tracker planes ~ 2×1 m$^2$, first plane is for veto, provide time stamp

Scintillating Fiber Tracker option
(being worked out now for LHCb upgrade)

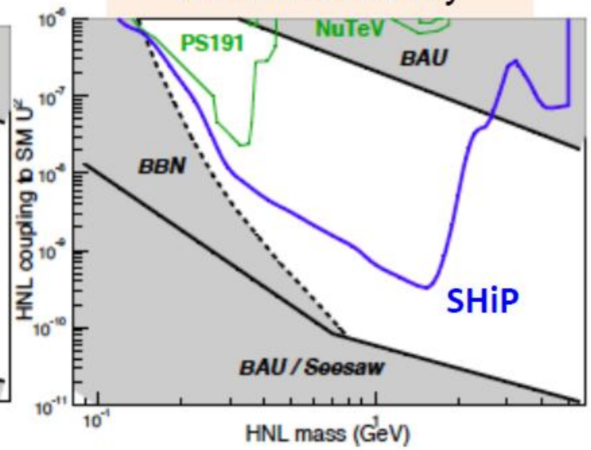
# SHiP sensitivity to HNL

## Covers most of parameter space below B-mass. Moving down towards the ultimate see-saw limit.

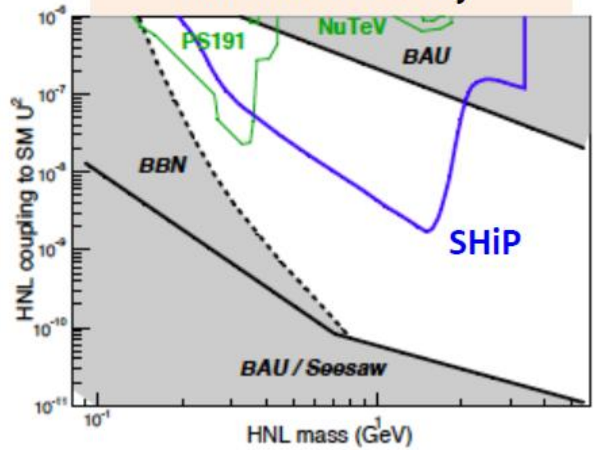
*$U^2_e : U^2_\mu : U^2_\tau \sim 52:1:1$*
*Inverted hierarchy*

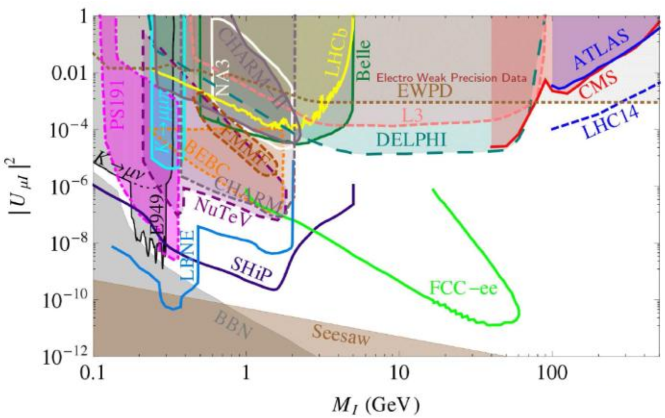



*$U^2_e : U^2_\mu : U^2_\tau \sim 1:16:3.8$*
*Normal hierarchy*




*$U^2_e : U^2_\mu : U^2_\tau \sim 0.061:1:4.3$*
*Normal hierarchy*



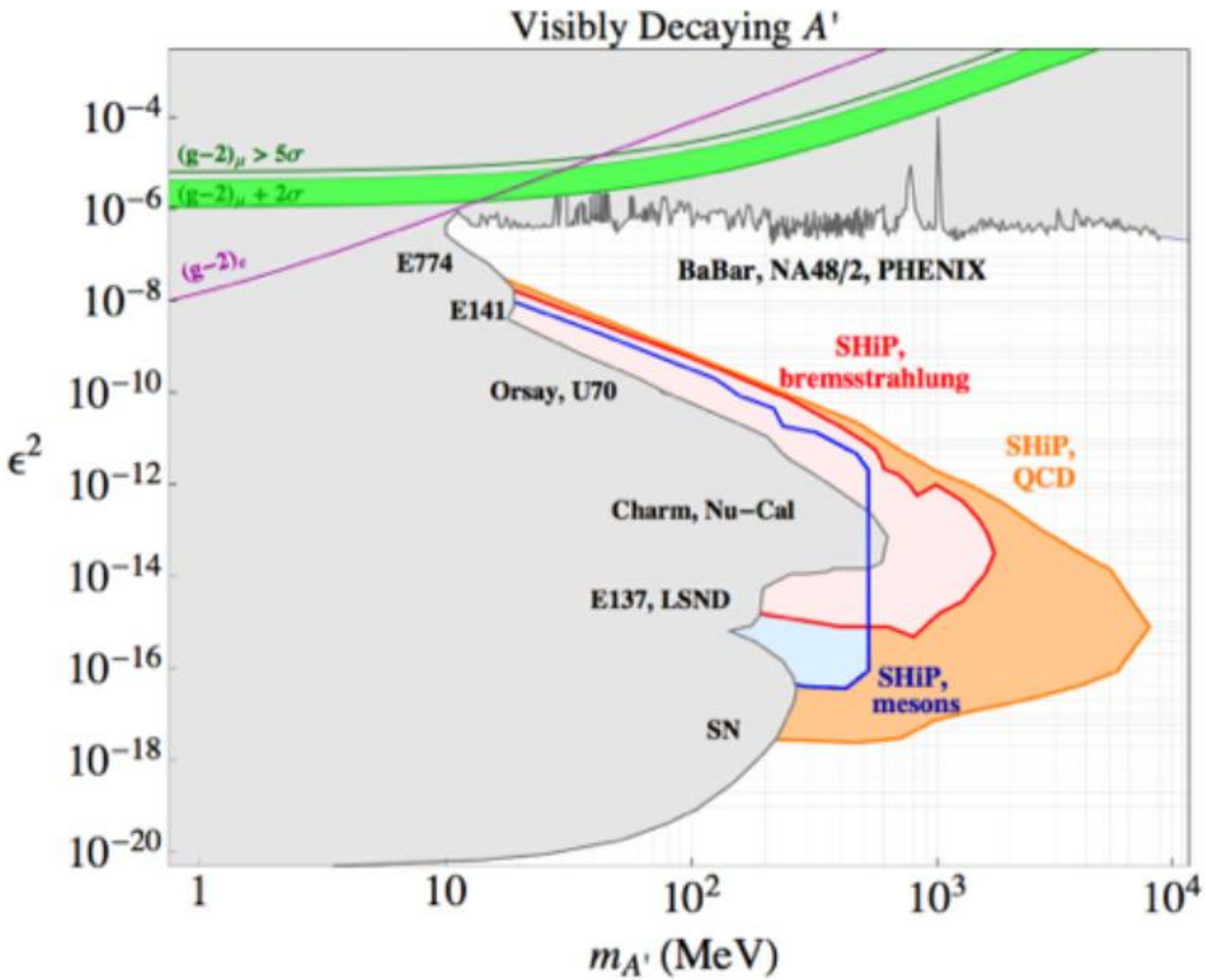




$M_{HNL} < M_B$ : SHiP will have much better sensitivity than LHCb & Belle-II

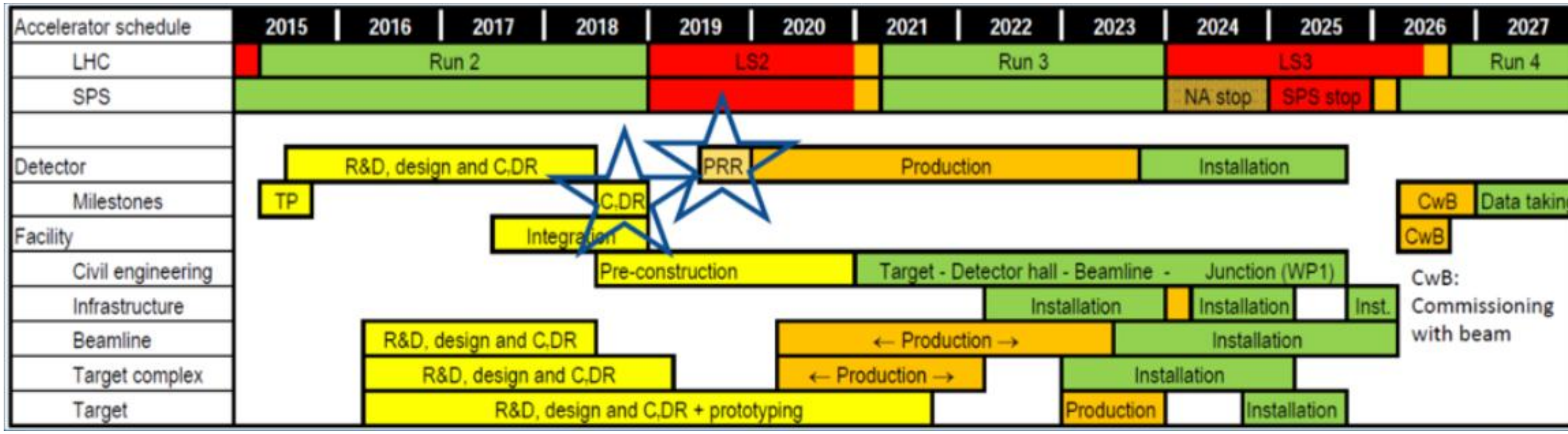
$M_B < M_{HNL} < M_Z$: FCC in ee-mode

# SHiP sensitivity to dark photons

$$\mathcal{L}_{\text{Vector portal}} = \epsilon F'_{\mu\nu} F_Y^{\mu\nu}$$



# SHiP collaboration now:
# 46 institutes from 16 countries




*«The SPSC has reviewed the proposal for "A Facility to Search for Hidden Particles (SHiP) at the CERN SPS" submitted in April 2015... The SPSC supports the motivation for the search for hidden particles, which will explore a domain of interest for many open questions in particle physics and cosmology, and acknowledges the interest of the measurements foreseen in the neutrino sector… The Research Board endorsed the recommendation from the SPSC that the collaboration should perform a CDR study, focussed on the SHiP detector … The study should be completed in time for the next update of the European Strategy for Particle Physics, on the timescale of three years, and the decision on approval will be taken following the conclusion of that update.»*

# Summary

- **S**earch for **Hi**dden **P**articles (SHiP) experiment is proposed to search for New Physics in the largely unexplored domain of new, very weakly interacting particles with masses $\mathcal{O}$(10) GeV
- Unique opportunities for tau-neutrino studies
- Sensitivity improves previous experiments by $\mathcal{O}$ ($10^4$) for Hidden Sector and by $\mathcal{O}$ ($10^2$) for neutrino physics
- The impact of the discovery of new light hidden particles is hard to overestimate

SHiP is complement to searches for New Physics at energy frontier at CERN

THERE ARE MORE THINGS IN HEAVEN AND EARTH, HORATIO, THAN ARE DREAMT OF IN YOUR PHILOSOPHY.

*W. Shakespeare,*
*Hamlet, Act 1, scene 5*

# BACKUP

# SHiP cost estimates (mid 2015)

Table 6.2: Overall cost of the SHiP facility and the detectors.

| 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** |

Table 6.3: Breakdown of the cost of the SHiP detectors.

| 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** |

Table 6.6: Interests expressed by the institutes in the construction of SHiP components.

| Component | Institutes |
|---|---|
| Beamline and target | CERN |
| Infrastructure | CERN |
| Muon shield | RAL, Imperial College, Warwick |
| HS vacuum vessel | NRC KI |
| Straw tracker | CERN, JINR, MEPhI, PNPI |
| ECAL | ITEP, Orsay, IHEP, INFN-Bologna |
| HCAL | ITEP, IHEP, INFN-Bologna, Stockholm |
| Muon | INFN-Bologna, INFN-Cagliari, INFN-Lab. Naz. Frascati, INFN-Ferrara, INR RAS, MEPhi |
| Surrounding background tagger | Berlin, LPNHE, MEPhI |
| Timing detector and upstream veto | Zürich, Geneva, INFN-Cagliari, Orsay, LPNHE |
| $\nu_\tau$ detector emulsion target, | INFN-Naples, INFN-Bari, INFN-Lab. Naz. Gran Sasso, Nagoya, Nihon, Aichi, Kobe, Moscow SU, Lebedev, Toho, Middle East Technical University, Ankara |
| $\nu_\tau$ detector tracker | NRC KI, INFN-Lab. Naz. Frascati |
| $\nu_\tau$ detector magnet | INFN-Lab. Naz. Frascati, INFN-Bari, INFN-Naples, INFN-Roma |
| $\nu_\tau$ tracking system (RPC) | INFN-Lab. Naz. Frascati, INFN-Bari, INFN-Lab. Naz. Gran Sasso, INFN-Naples, INFN-Roma |
| $\nu_\tau$ tracking system (drift tubes) | Hamburg |
| Online computing | CERN, Niels Bohr, Uppsala, UCL, YSDA, LPHNE |
| Offline computing | CERN, YSDA |
| MC simulation | CERN, Sofia, INFN-Cagliari, INFN-Lab. Naz. Frascati, INFN-Napoli, Zürich, Geneva and EPFL Lausanne, Valparaiso, Berlin, PNPI, NRC KI, SINP MSU, MEPhI, Middle East Technical University, Ankara, Bristol, YSDA, Imperial College, Florida, Kyiv |

CHAPTER VIII

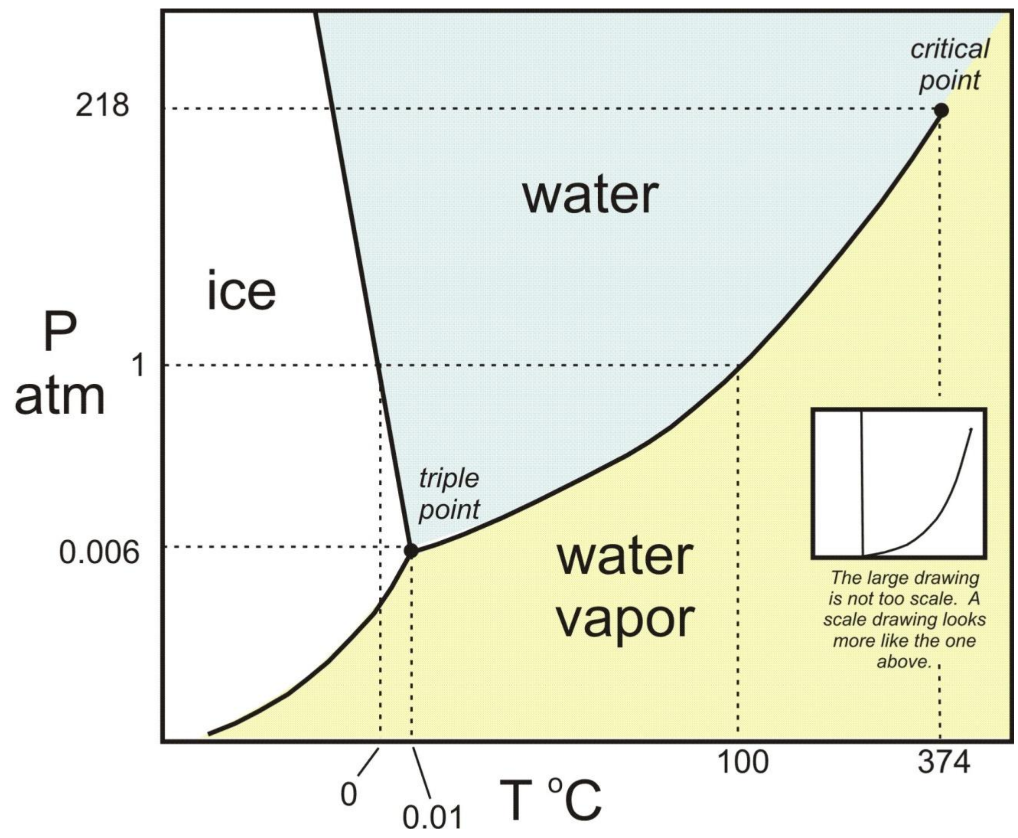
# PHASE EQUILIBRIUM

## §81. Conditions of phase equilibrium

THE (equilibrium) state of a homogeneous body is determined by specifying any two thermodynamic quantities, for example the volume $V$ and the energy $E$. There is, however, no reason to suppose that for every given pair of values of $V$ and $E$ the state of the body corresponding to thermal equilibrium will be homogeneous. It may be that for a given volume and energy in thermal equilibrium the body is not homogeneous, but separates into two homogeneous parts in contact which are in different states.

Such states of matter which can exist simultaneously in equilibrium with one another and in contact are described as different *phases*.

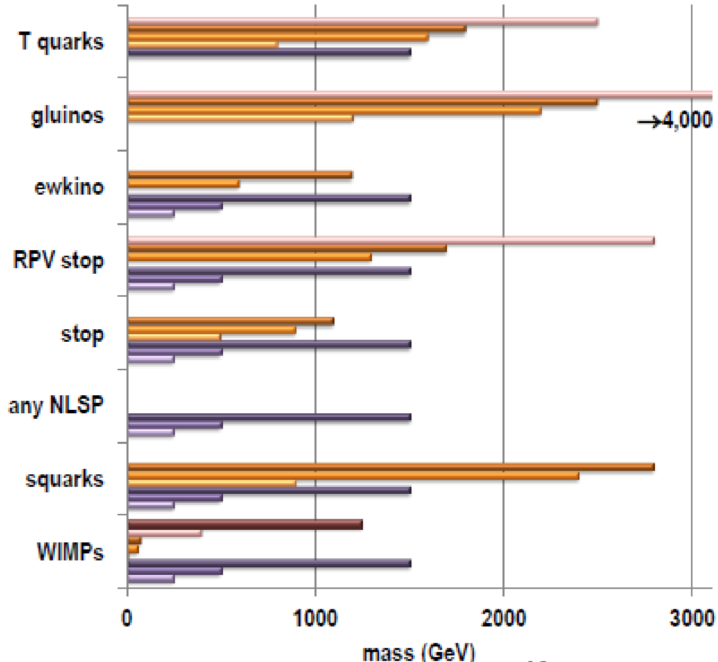
*L.D.Landau, E.M.Lifshits, Course in Theoretical Physics, volume 5*

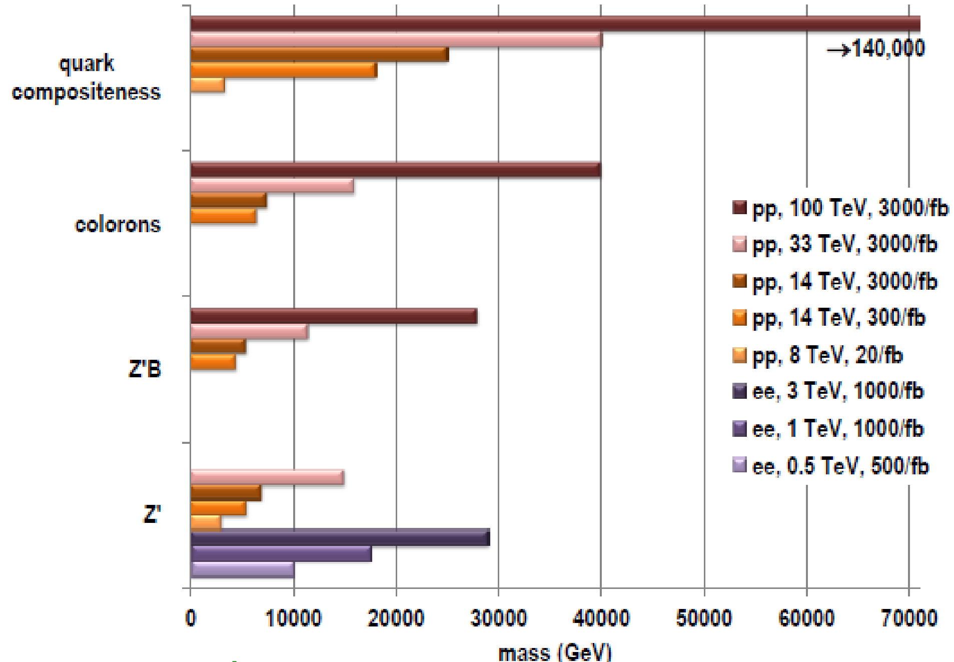



$$\frac{n_{\mathrm{H_2O}}}{V_{n_{\mathrm{H_2O}}}}\int_{0^\circ\ \mathrm{K}}^{273^\circ\ \mathrm{K}} C_{p,\mathrm{ice}}(T)dT < \rho_E < \frac{n_{\mathrm{H_2O}}}{V_{n_{\mathrm{H_2O}}}}\left(\int_{0^\circ\ \mathrm{K}}^{273^\circ\ \mathrm{K}} C_{p,\mathrm{ice}}(T)dT + (\text{molar heat of melting})\right)$$

If the initial energy happens to be in this interval, the temperature will be fine tuned to 273.15° K

# Direct search (energy frontier) reach




*(from arXiv: 1311.0299)*

**«Before LHC»**

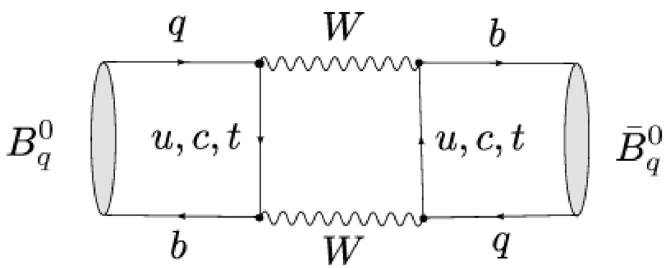
Arguments for New Physics at TeV scale

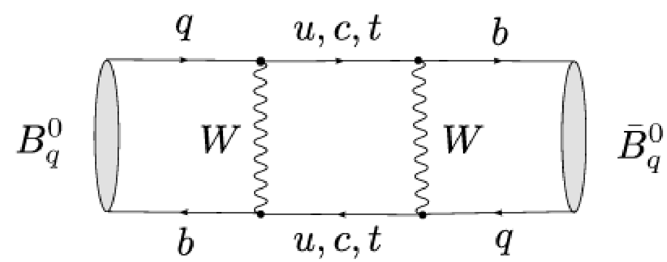
→

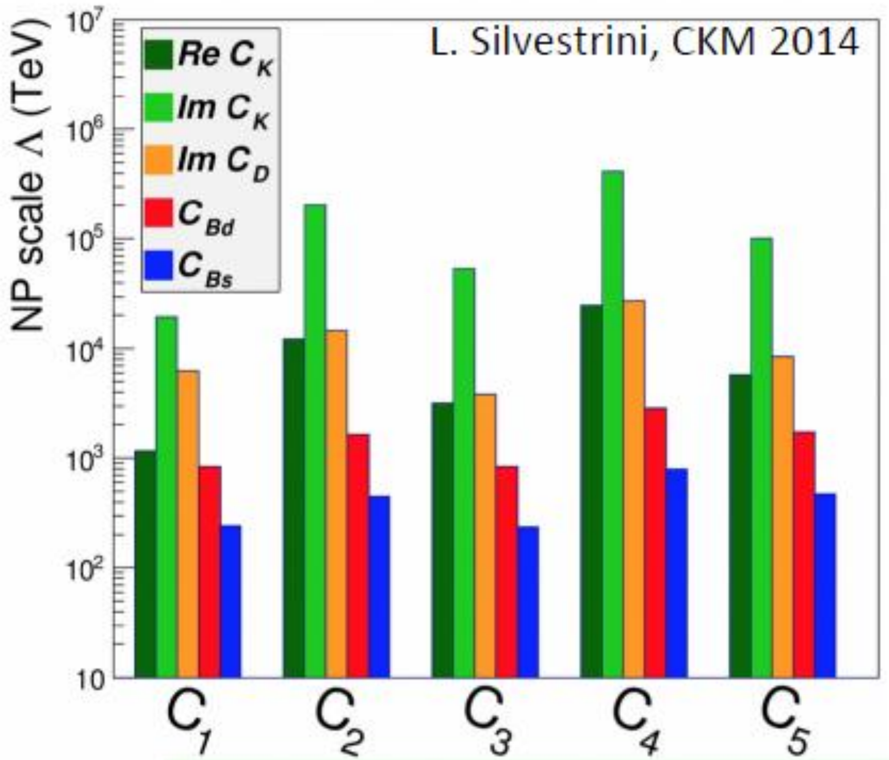
**«Now»**

No idea where next scale is

# Indirect search – loop effects and forbidden decays



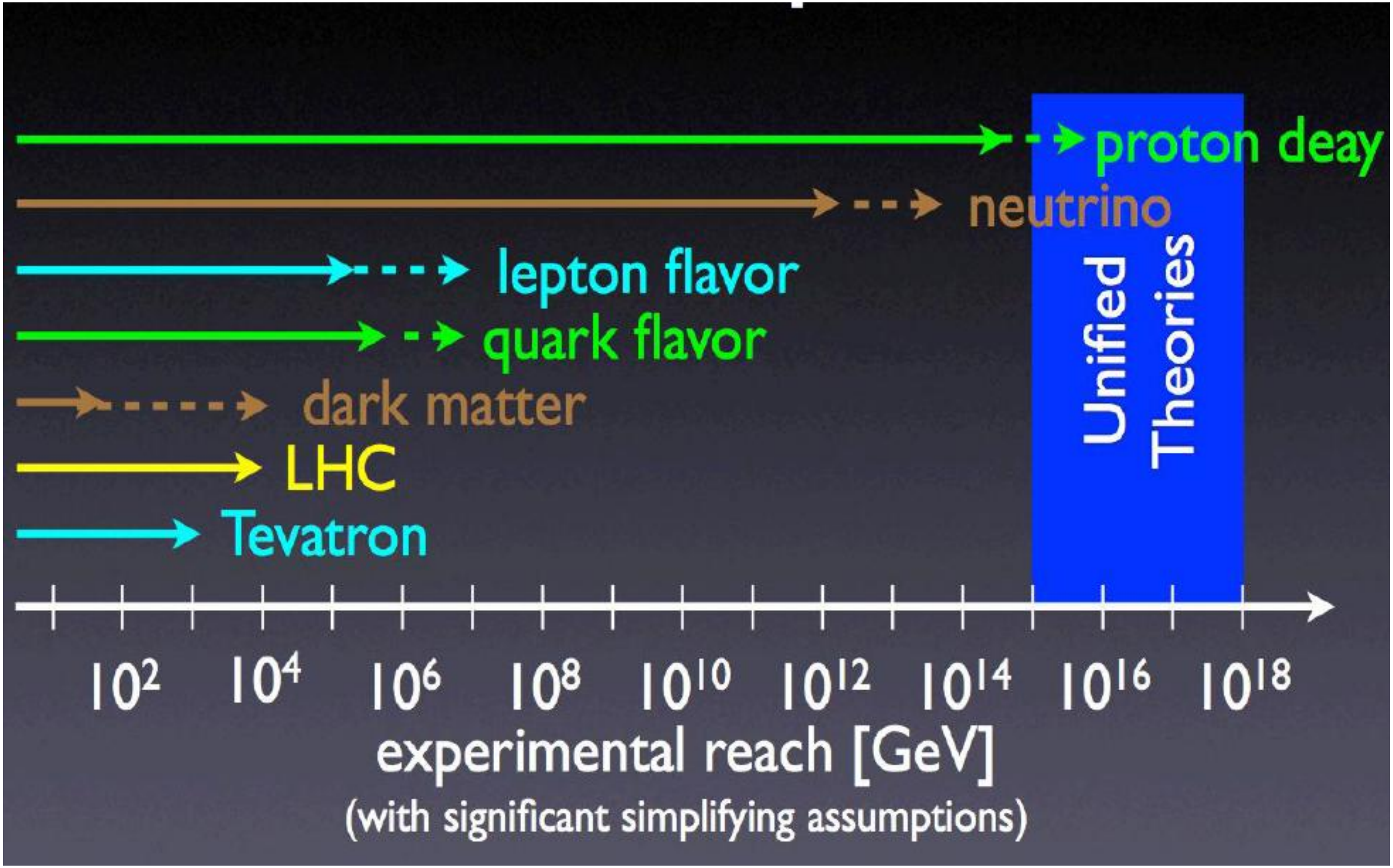

$$C_i = \frac{F_i L_i}{\Lambda^2}$$

where $F_i$ is flavor coupling while $L_i$ is loop factor.

For $F_i L_i \sim 1$

$$\Lambda \sim 10^3 - 10^5 \text{ TeV}$$

# Intensity frontier physics reach




*(picture of Z.Ligeti)*

# Proton beam dump experiments: the past

| Experiment | Location | approx. Date | Amount of Beam ($10^{20}$ POT) | Beam Energy (GeV) | Target Mat. | Ref. |
|---|---|---|---|---|---|---|
| CHARM | CERN | 1983 | 0.024 | 400 | Cu | [16] |
| PS191 | CERN | 1984 | 0.086 | 19.2 | Be | [17, 18] |
| E605 | Fermilab | 1986 | $4 \times 10^{-7}$ | 800 | Cu | [19] |
| SINDRUM | SIN,PSI | | | | | |
| $\nu$-Cal I | IHEP Serpukhov | 1989 | 0.0171 | 70 | Fe | [20–22] |
| LSND | LANSCE | 1994-1995<br>1996-1998 | 813<br>882 | 0.798 | H20, Cu<br>W,Cu | [23] |
| NOMAD | CERN | 1996-1998 | 0.41 | 450 | Be | [18, 24] |
| WASA | COSY | 2010 | | 0.550 | LH2 | [25] |
| HADES | GSI | 2011 | 0.32 pA*t | 3.5 | LH2,No,Ar+KCl | [26] |
| **MiniBooNE** | **Fermilab** | **2003-2008**<br>**2005-2012**<br>**2013-2014** | **6.27**<br>**11.3**<br>**1.86** | **8.9** | **Be**<br>**Be**<br>**Steel** | **[27]**<br>**[28]**<br>**[29]** |

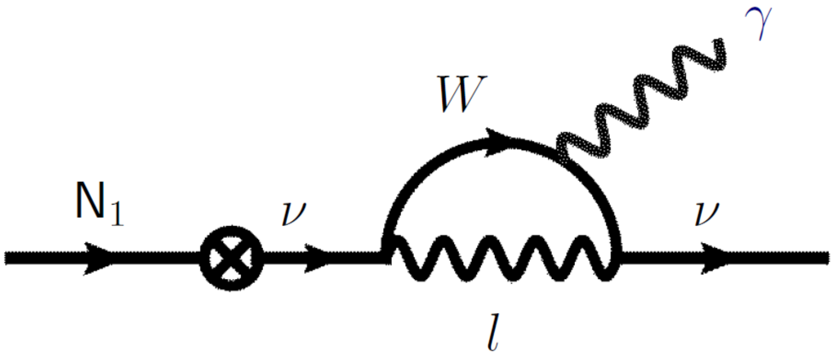
**+ DONUT** **FNAL** **$3.6 \times 10^{-3}$** **800** **W**

*(from W.Bonivento)*

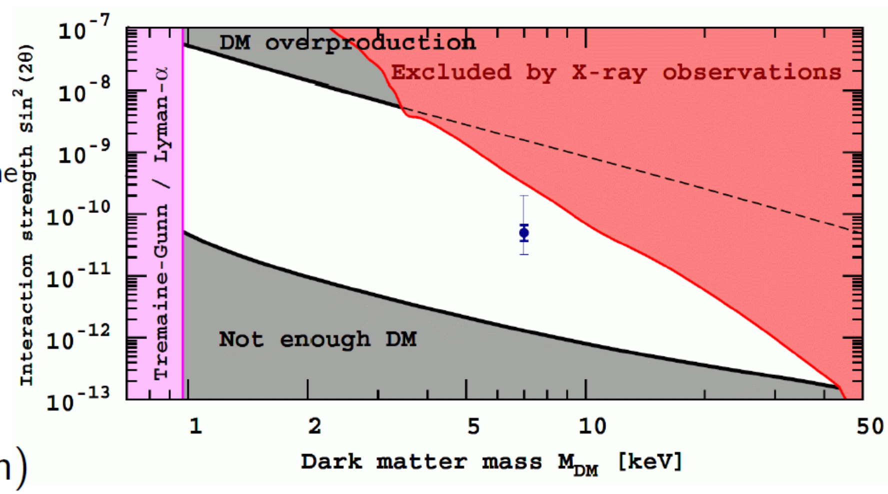
# $\nu$MSM: closer look at $N_1$

$N_1$ can provide dark matter candidate:

- very weak mixing with other leptons
- hence, stable enough for dark matter
- Seesaw: one $M_{\nu-\mathrm{active}} \sim 10^{-5}$ eV
- Radiative decay: $\tau > \tau_{\mathrm{universe}}$
- $E_\gamma = \frac{M_{N_1}}{2}$




- X-ray detection:
  - 10/2/14: arxiv.org/abs/1402.2301: Detection of an Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters
  - 17/2/14: arxiv.org/abs/1402.4119: An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster
  - Both papers refer to Astro-H (with Soft X-Ray Spectrometer, 2016 launch) to confirm/rule-out the DM origin of this signal.




arxiv.org/abs/1402.4119

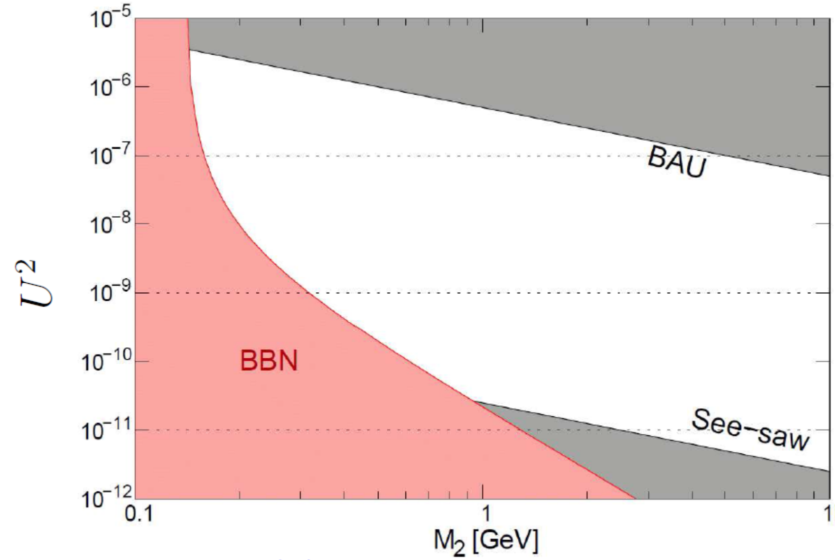
SHiP

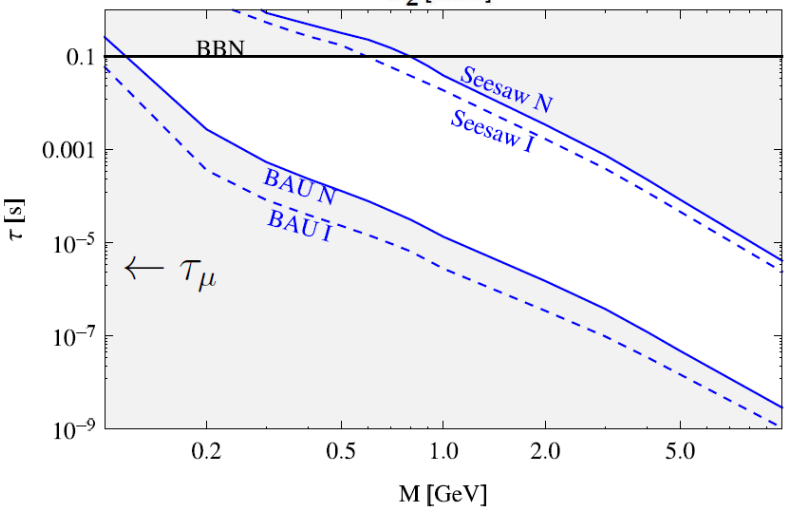
# $\mathrm{N}_{2,3}$

Use $\mathrm{N}_{2,3}$ to explain:

- $\nu$ masses:
  Seesaw constrains Yukawa coupling and $M_{\mathrm{N}_{2,3}}$, i.e. $M_\nu \propto U^2/M_{\mathrm{N}_{2,3}}$
- Baryo(Lepto)genesis: make $\mathrm{N}_2$ nearly degenerate with $\mathrm{N}_3$, and tune CPV-phases to explain baryon asymmetry of universe (BAU).
- $1/\tau_{N_{2,3}} \propto M^3_{\mathrm{N}_{2,3}}$
- $\tau_{\mathrm{N}_{2,3}} < 0.1$ s,
  otherwise Big Bang Nucleosynthesis (BBN, $\sim 75/25$ % H-1/He-4) would be affected by $\mathrm{N}_{2,3}$ decays.

These are the particles SHiP is after!



# Life Cycle of an Experiment: SHiP