SHiP project as a new facility at intensity frontier

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NRC «Kurchatov Institute»

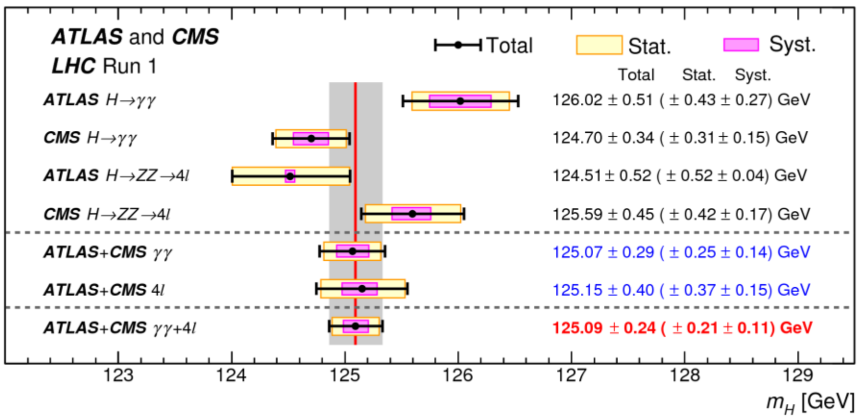
on behalf of the SHiP collaboration

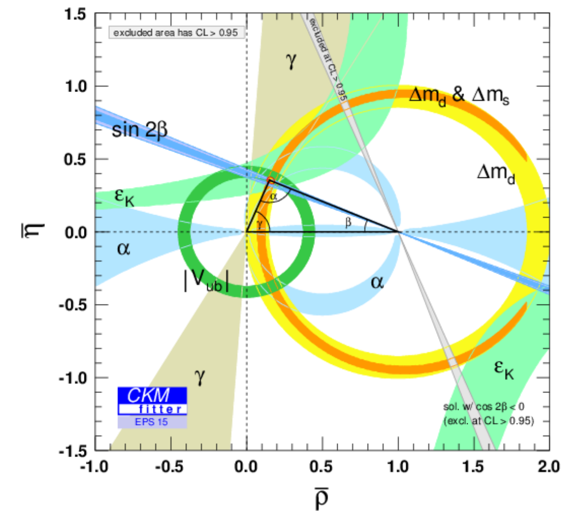
QUARKS-2018

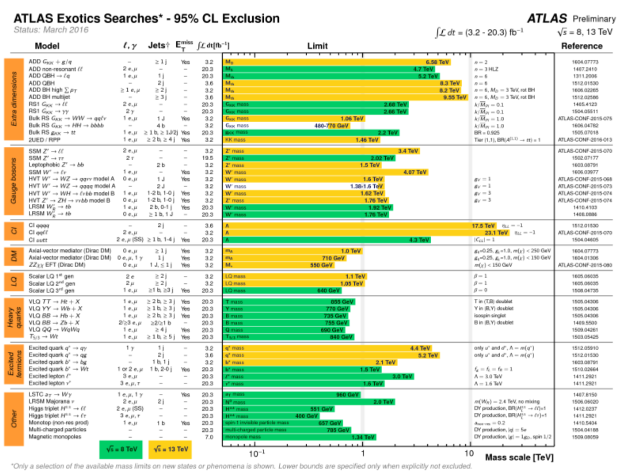
31 May 2018

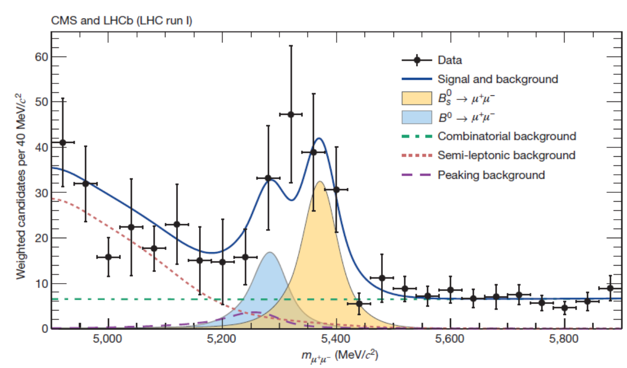
Present status

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**:

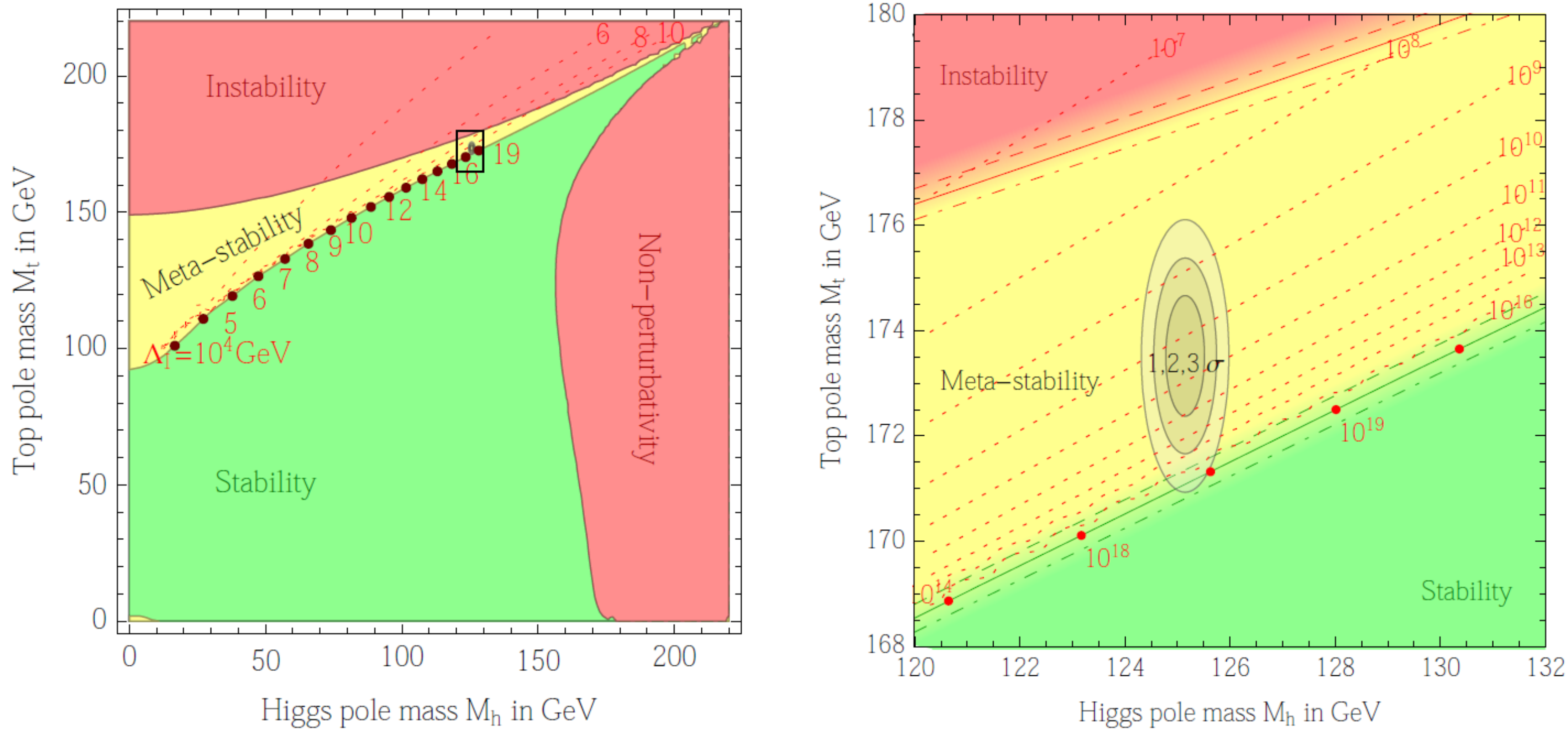
- Neutrino masses and oscillations
- Dark matter
- Baryon asymmetry of the Universe
- ...

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?
- ...

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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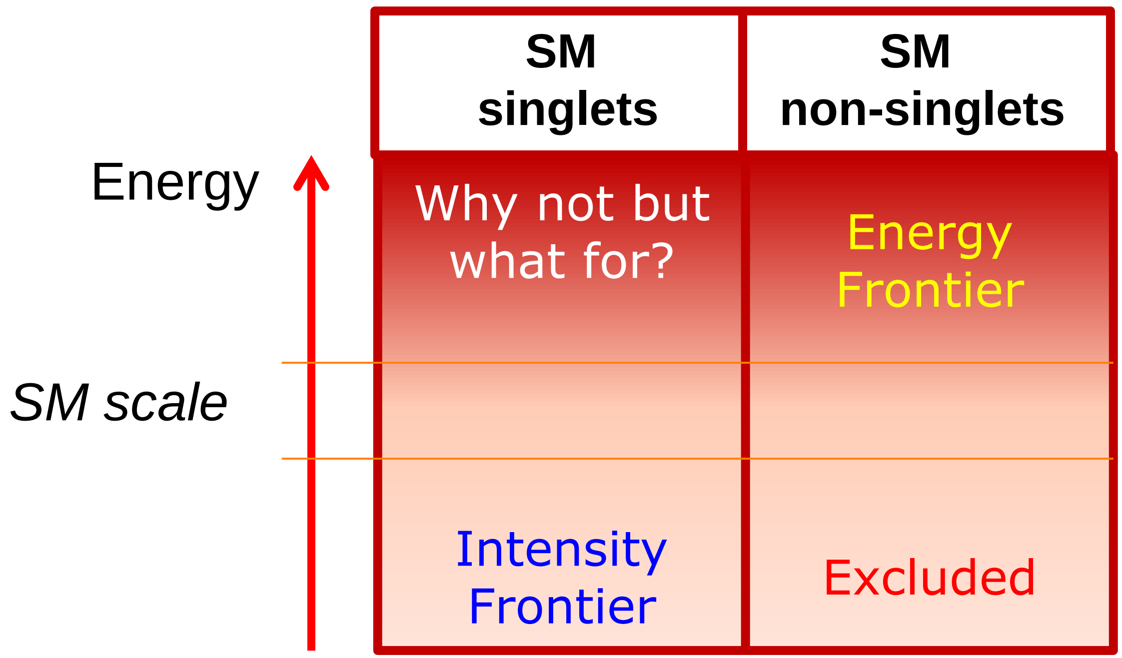
Abstract

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.

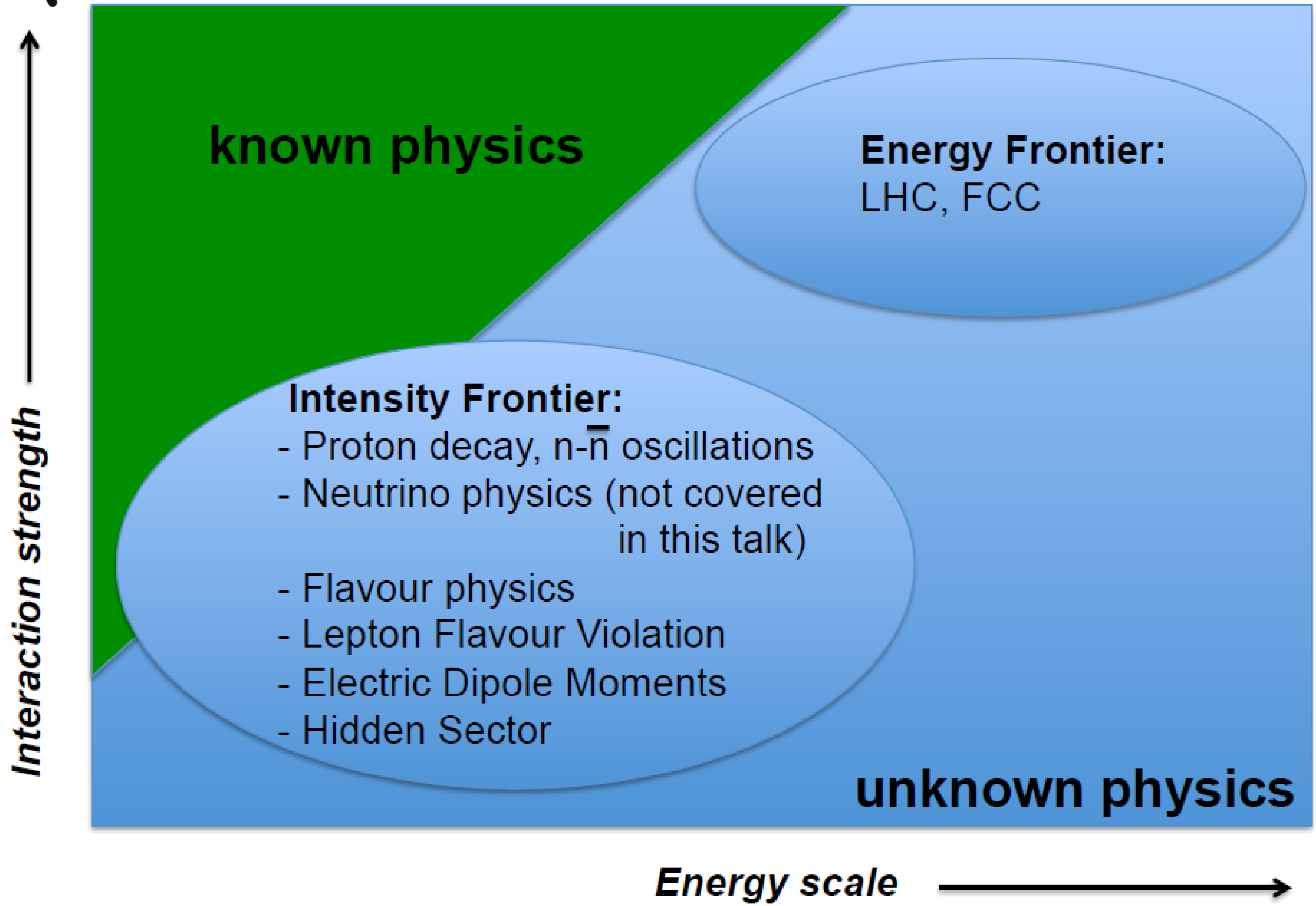
Perhaps it is more useful to think not about New Physics that could solve theoretical problems of the **SM**, but about NP that could explain observed effects beyond **SM**.

In hope that theory will settle things anyway..

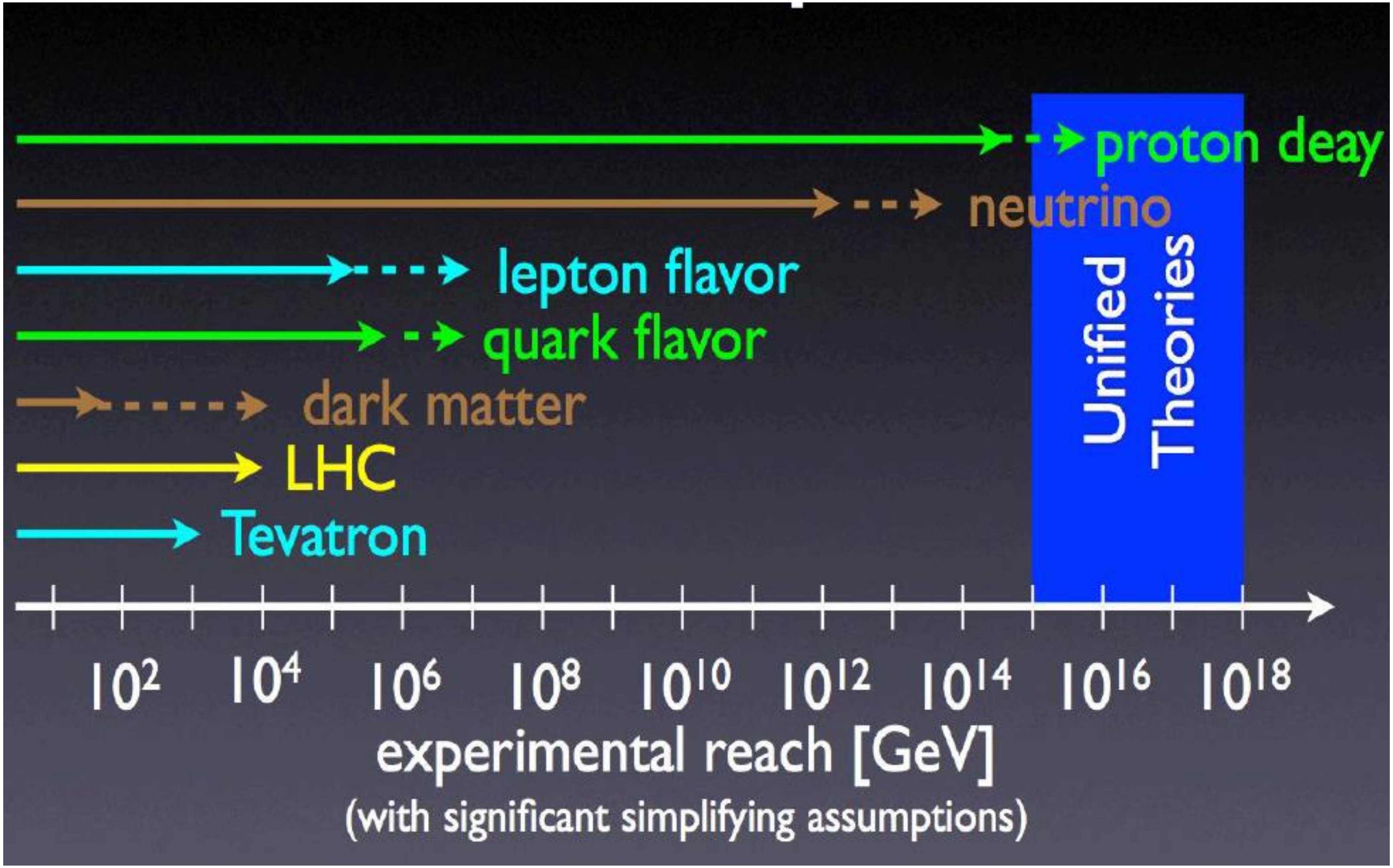
What could the new degrees of freedom be?



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



Intensity frontier physics reach



(picture of Z.Ligeti)

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»**

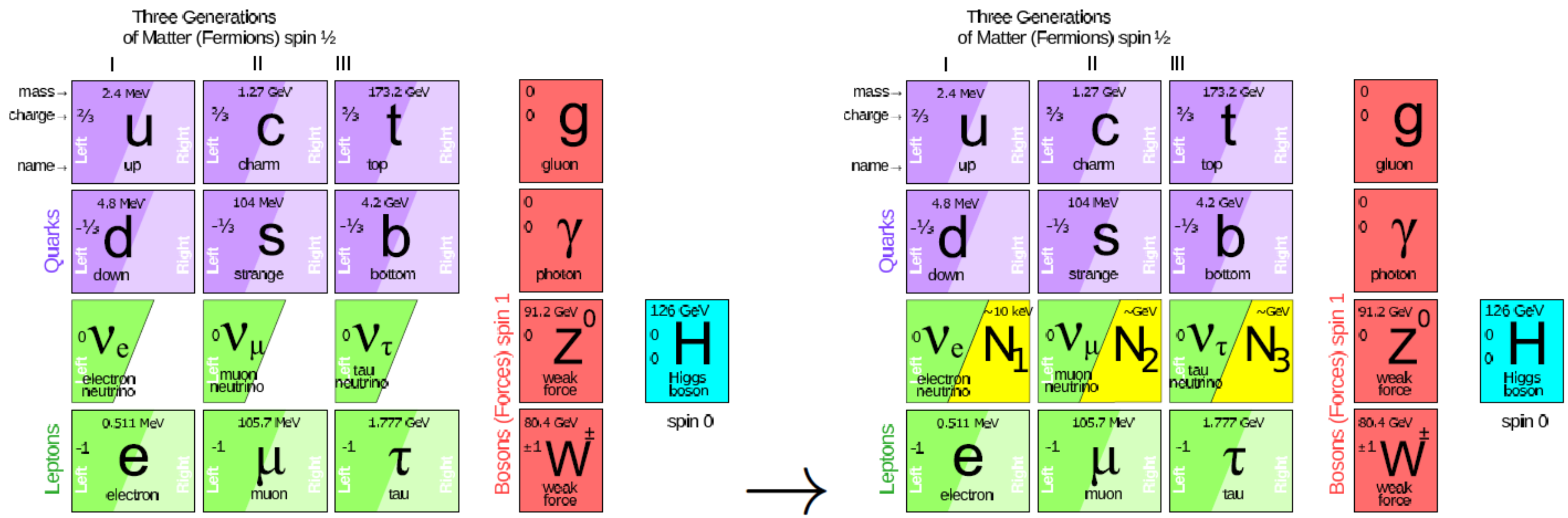
$$\mathcal{L}_{\text{Scalar portal}} = (\lambda_i S_i^2 + g_i S_i)(\Phi^\dagger \Phi)$$

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

νMSM *(T.Asaka, M.Shaposhnikov, 2005)*

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

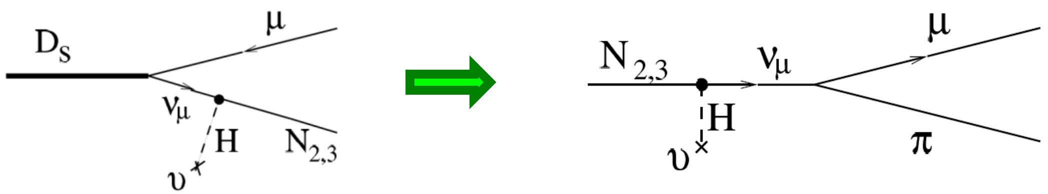
$$L = L_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\Phi \bar{N}_I L_\alpha - \frac{M_I}{2}\bar{N}_I^c N_I + \text{h.c.}$$



N_1 with mass $\mathcal{O}$(keV) – dark matter

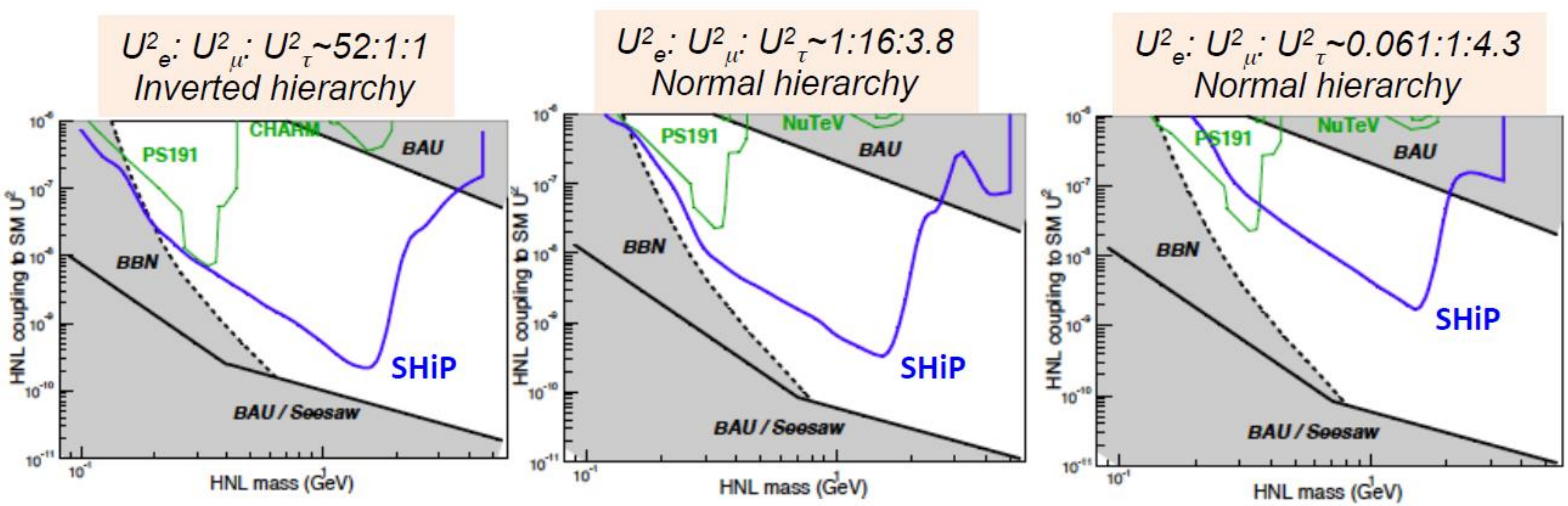
N_2 , N_3 with mass $\mathcal{O}$(GeV) – neutrino masses and BAU

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	$\pi^0\pi^0$



General requirements

to fixed-target (beam dump like) experiment

- Maximize number of particles on target

SPS@CERN: 4×10^{13} protons @ 400 GeV

- Preference to slow beam extraction

SPS@CERN: 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

A bit of history

Proposal to Search for Heavy Neutral Leptons at the SPS

W. Bonivento, A. Boyarsky, H. Dijkstra, U. Egede, M. Ferro-Luzzi, B. Goddard, A. Golutvin, D. Gorbunov, R. Jacobsson, J. Panman, M. Patel, O. Ruchayskiy, T. Ruf, N. Serra, M. Shaposhnikov, D. Treille

(Submitted on 7 Oct 2013)

EoI (16 auth.)
October 2013

CERN
CH1211 Geneva 23
Switzerland

EN Engineering Department

EDMS NO.	REV.	VALIDITY
1369559	1.0	RELEASED

REFERENCE
EN-DH-2014-007

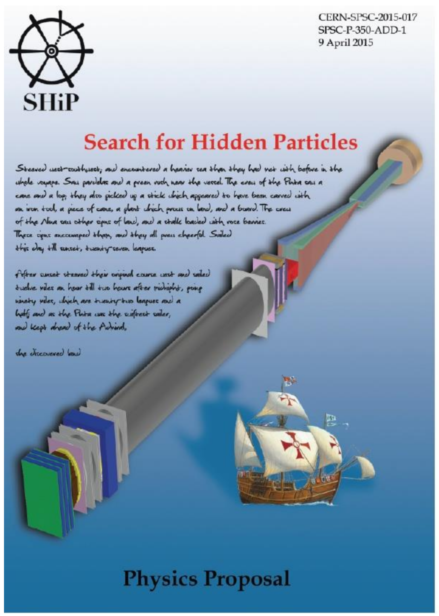
Date : 2014-07-02

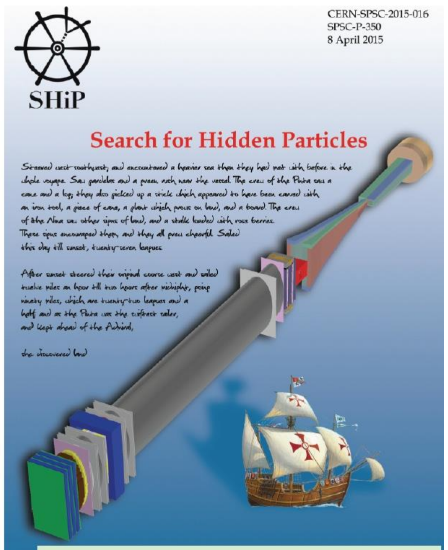
Report

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

Preliminary Project and Cost Estimate

Task force report for
Beam Dump Facility
July 2014

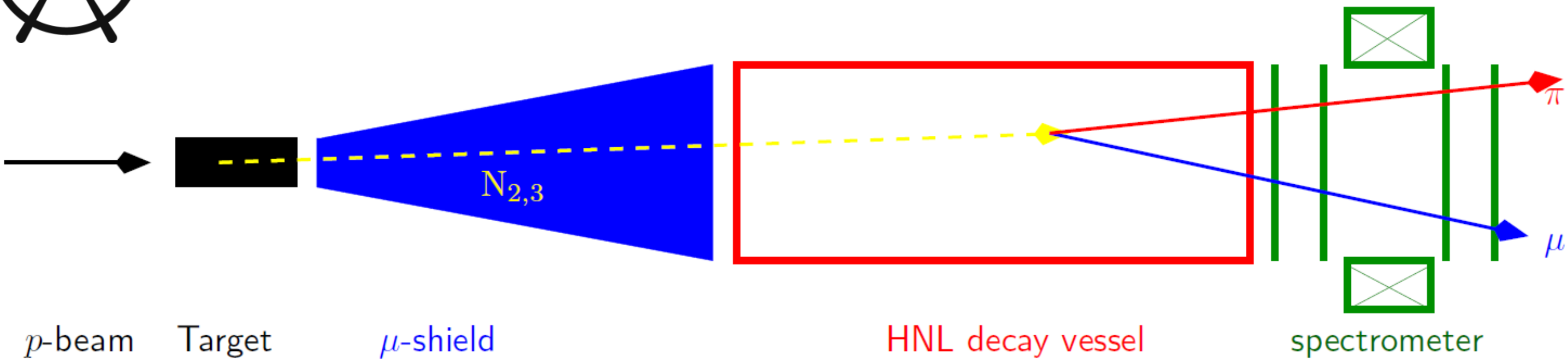


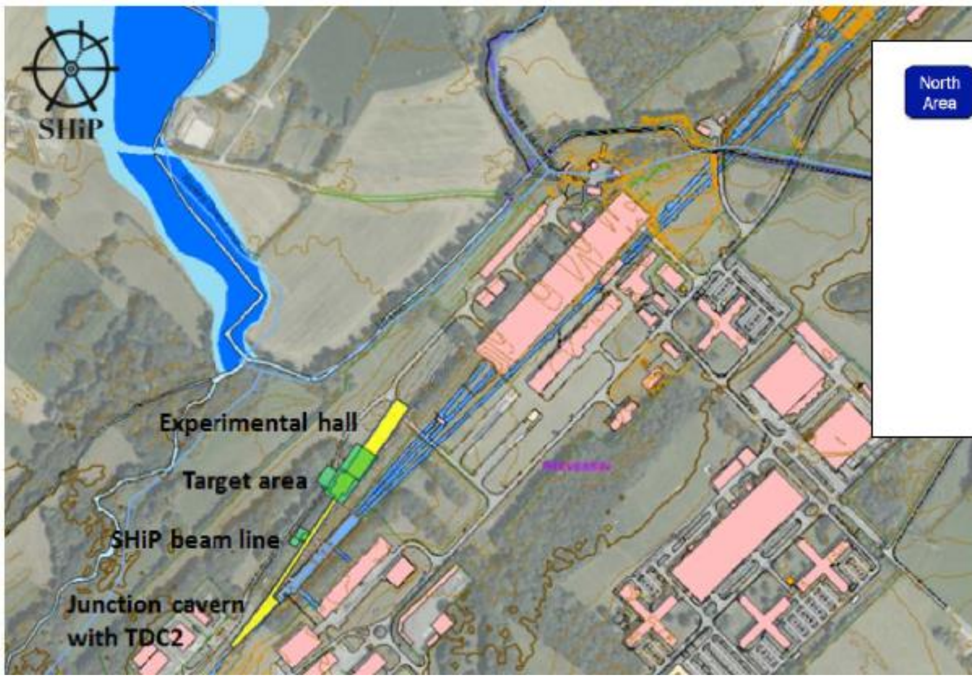


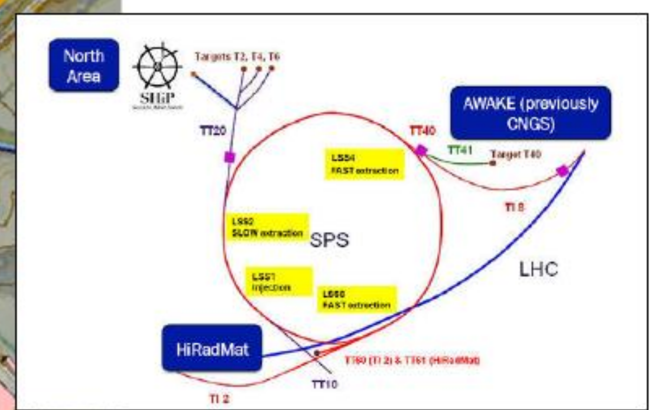
SHiP Technical Proposal: arXiv 1504.04956
SHiP Physics Paper: arXiv 1504.04855

SHiP Technical Proposal (250 auth.)
SHiP Physics Paper (85 auth.)
April 2015

Principle layout of the experiment

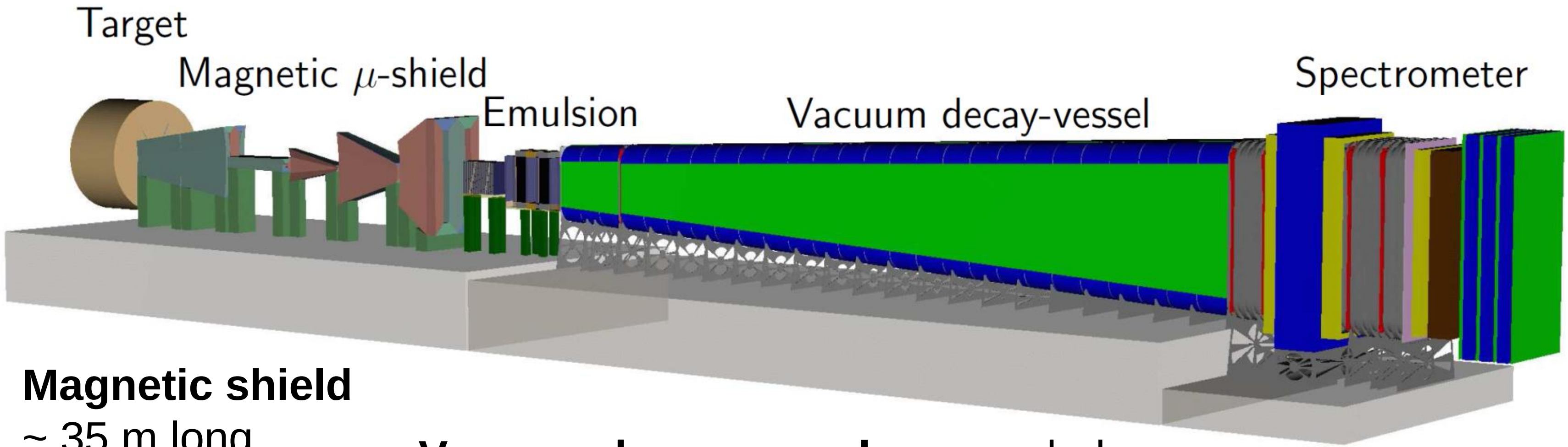






$$\frac{N(HNL)\,@\,SHiP}{N(HNL)\,@\,CHARM} \sim 10000$$

Current layout (optimized with respect to TP)



Magnetic shield
~ 35 m long
1.8 T magnets

Vacuum decay vessel surrounded by liquid or plastic scintillator veto system

Target
13 TZM+5 W blocks

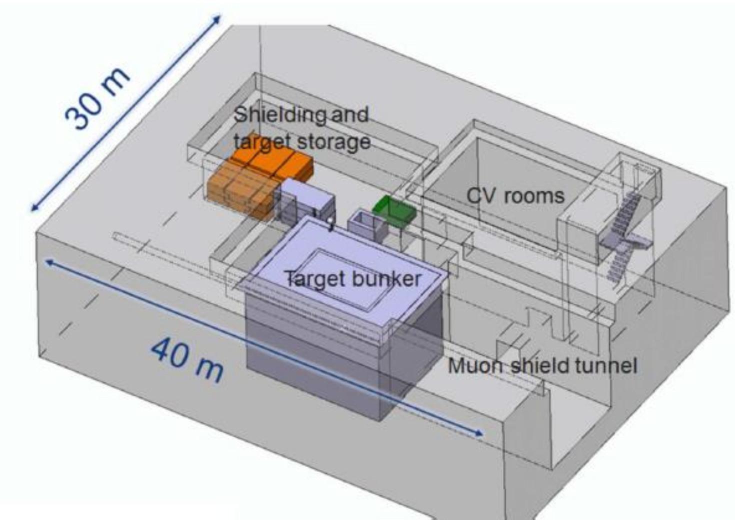
Emulsion detector
LDM scatters on e/nuclei
tau-neutrino physics

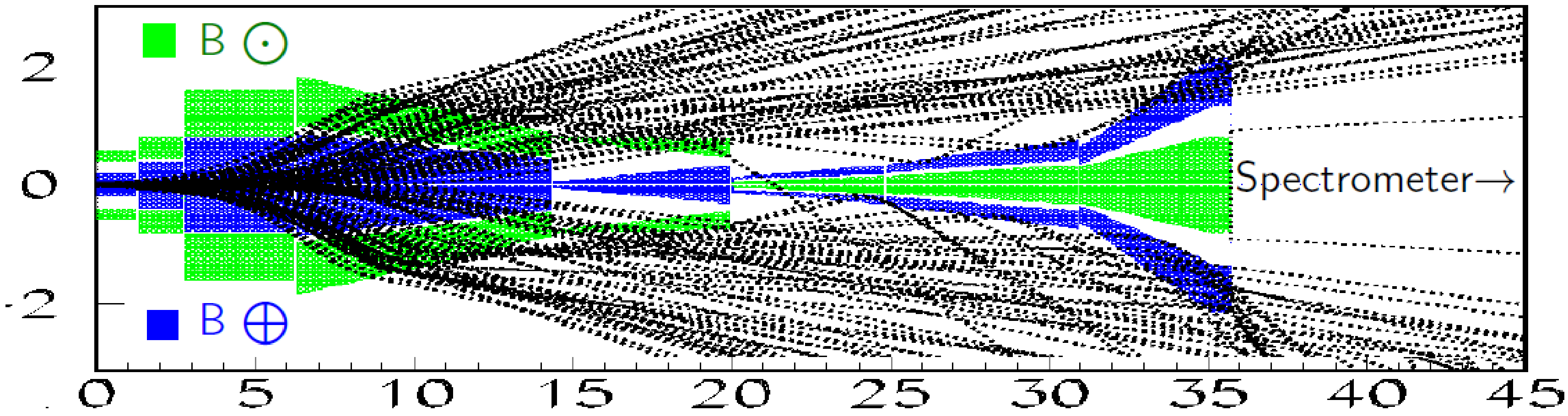
Spectrometer
Tracker
Magnet
Calorimeter
Muon detector

400 GeV p-beam from SPS, 2 × 10^{20} pot in 5 years
Peak power – 2.6 MW, 10^{11} muons/sec

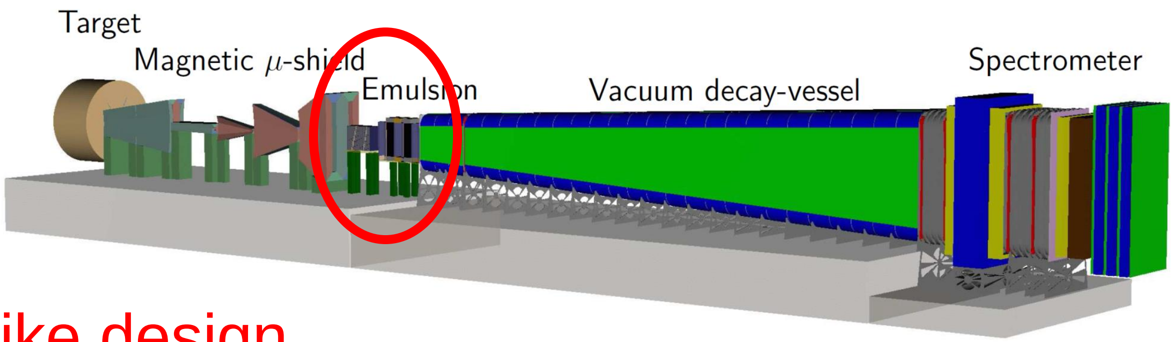
Target and active muon shield

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





ν_τ / iSHiP detector subsystem



OPERA-like design

- Tau-neutrino is the least known particle in the **SM**, first observation by DONUT in 2001.

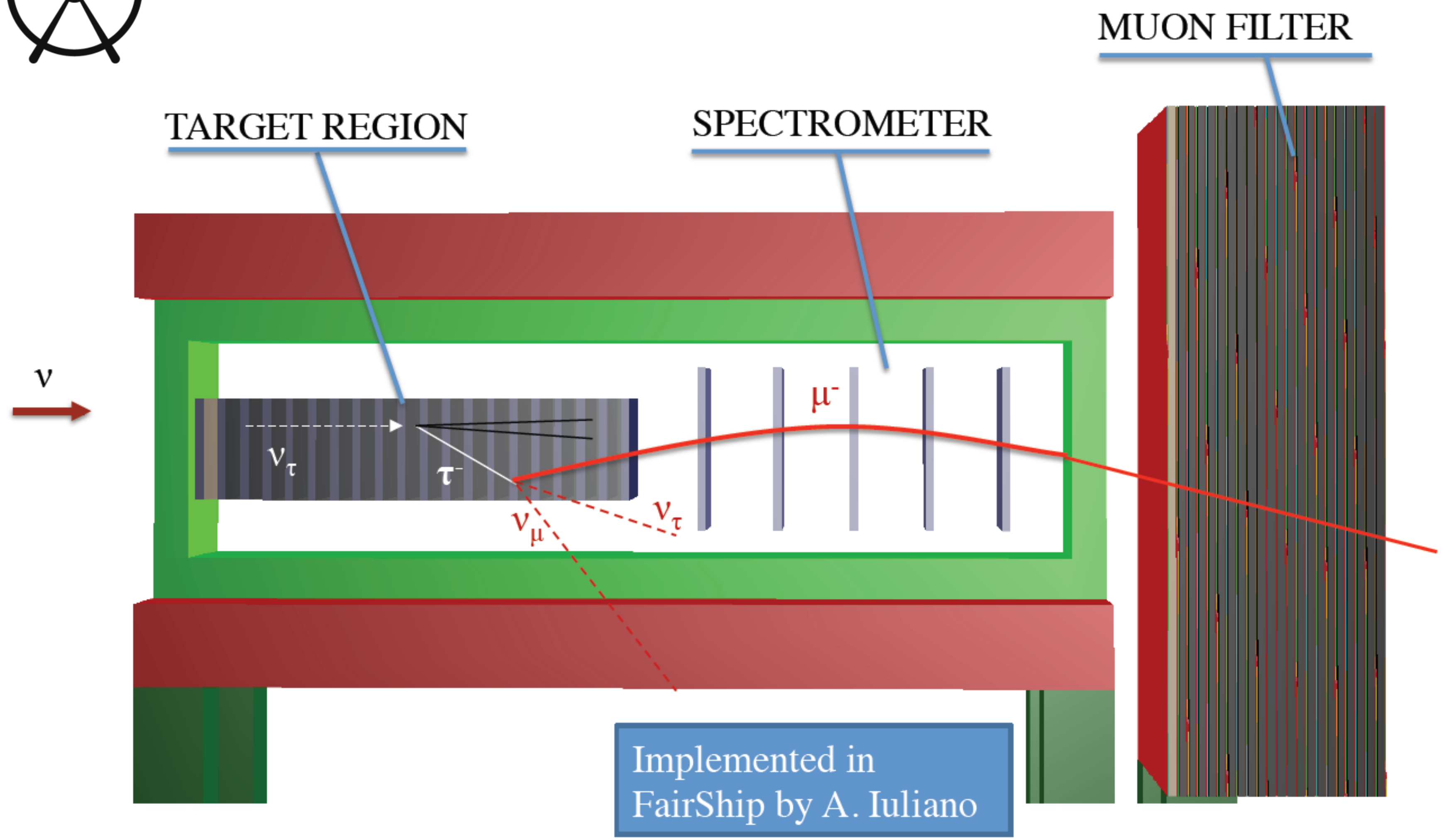
- **10** ν_τ candidates in total recently reported by OPERA

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

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

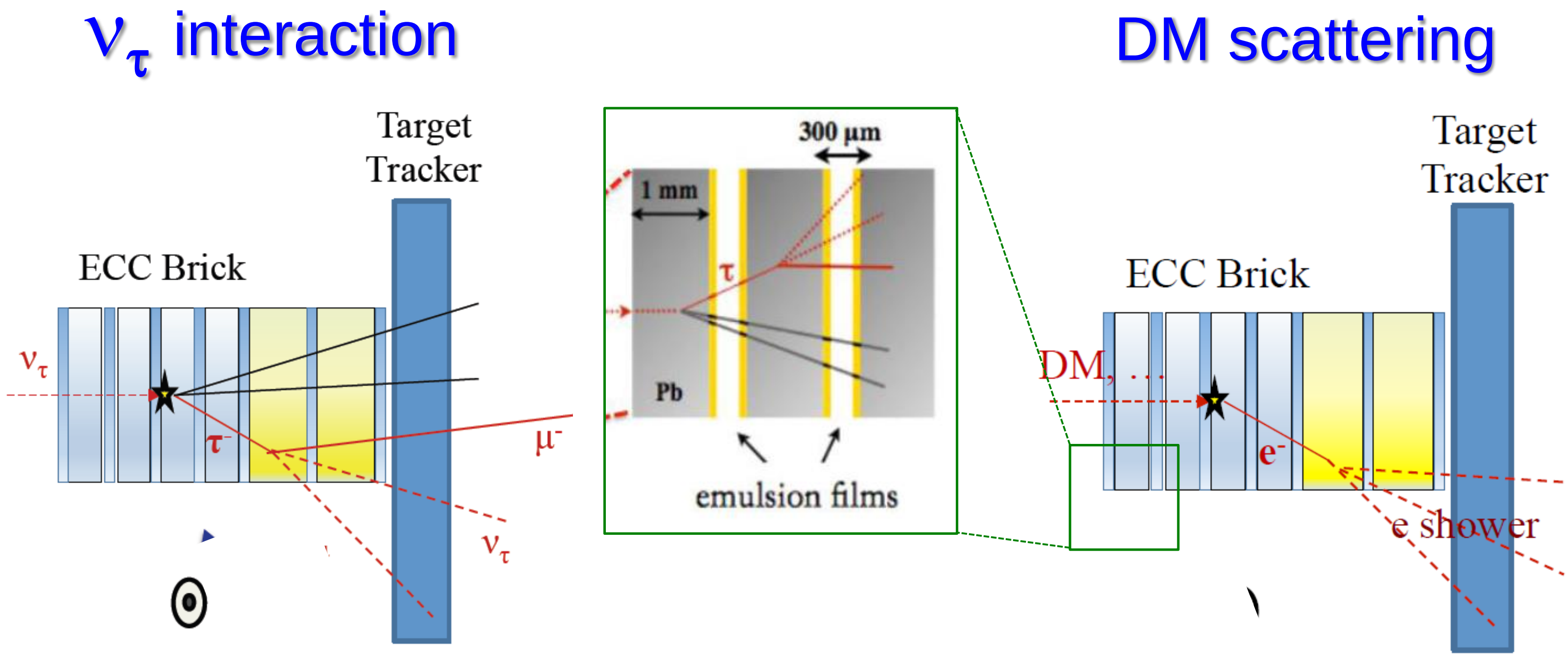
$$N_{\nu_\tau} \simeq 6.7 \times 10^3 \qquad N_{\overline{\nu}_\tau} \simeq 3.4 \times 10^3$$

ν_τ / iSHiP detector subsystem



(picture by G.DeLellis)

Main ν_τ / iSHiP processes

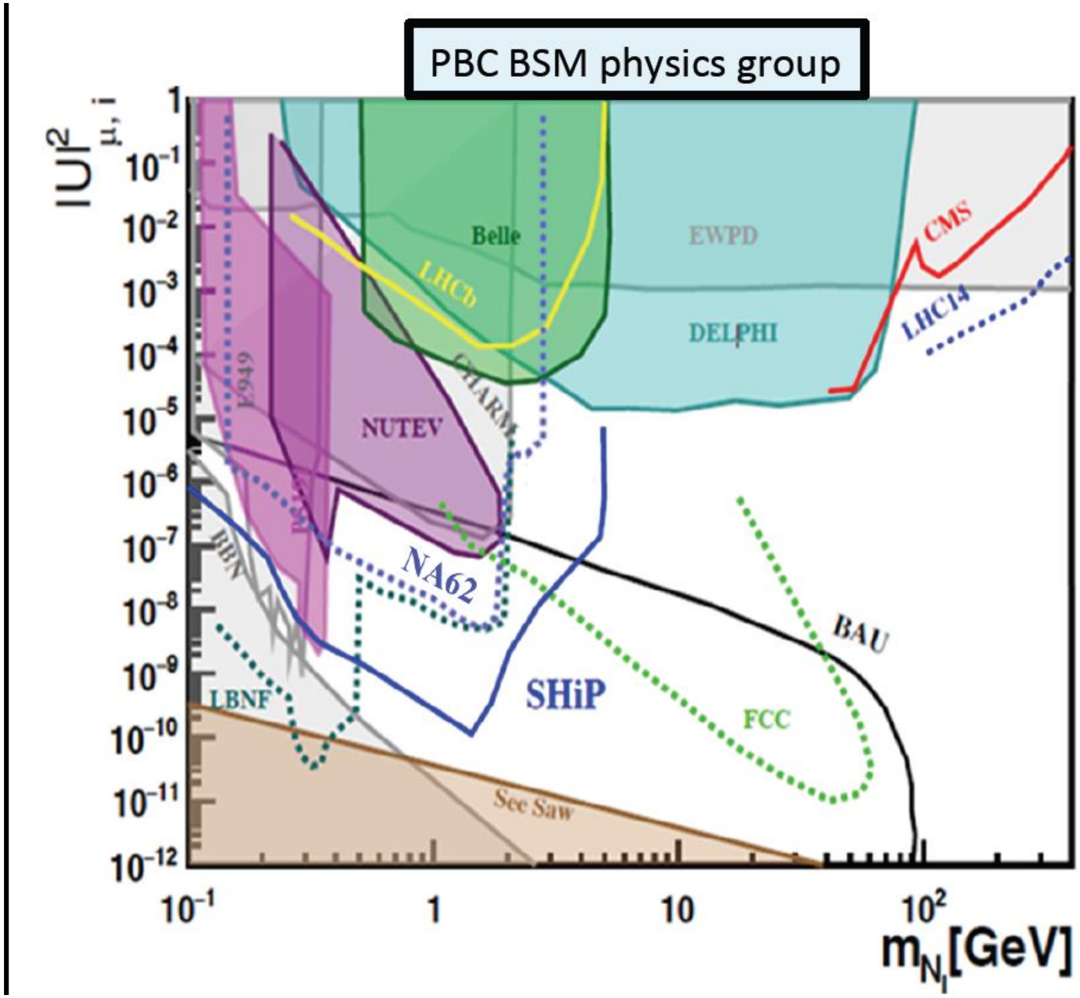


$$N_{\nu_\tau+\bar{\nu}_\tau} = 4N_{pot}\frac{\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} \mathrm{Br}(D_s \to \tau) = 2.85 \times 10^{-5} N_{pot}$$

- Emulsion Cloud Chamber (ECC): passive material (lead) - massive target
- Main tracking device – nuclear emulsion, high (a few μm) resolution
- Target SciFi tracker planes ~ 2×1 m², provide time stamp

SHiP sensitivity to HNL

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

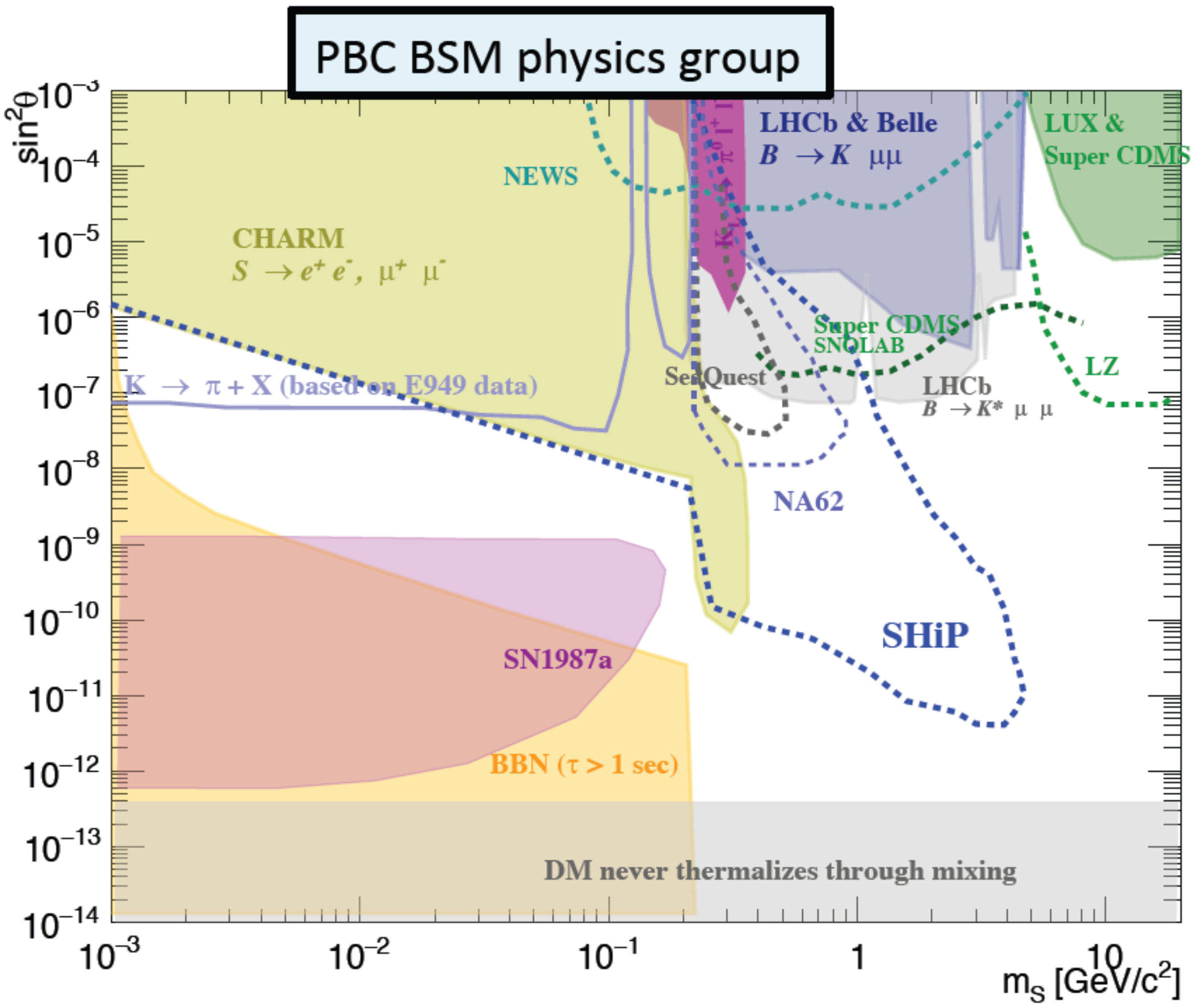


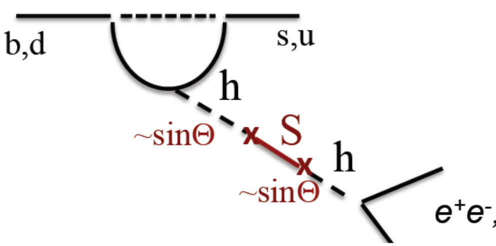
$M_{HNL} < M_B$:
SHiP will have much better sensitivity than LHCb & Belle-II

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

$M_{HNL} < M_Z$:
HL-HE LHC

SHiP sensitivity to scalars

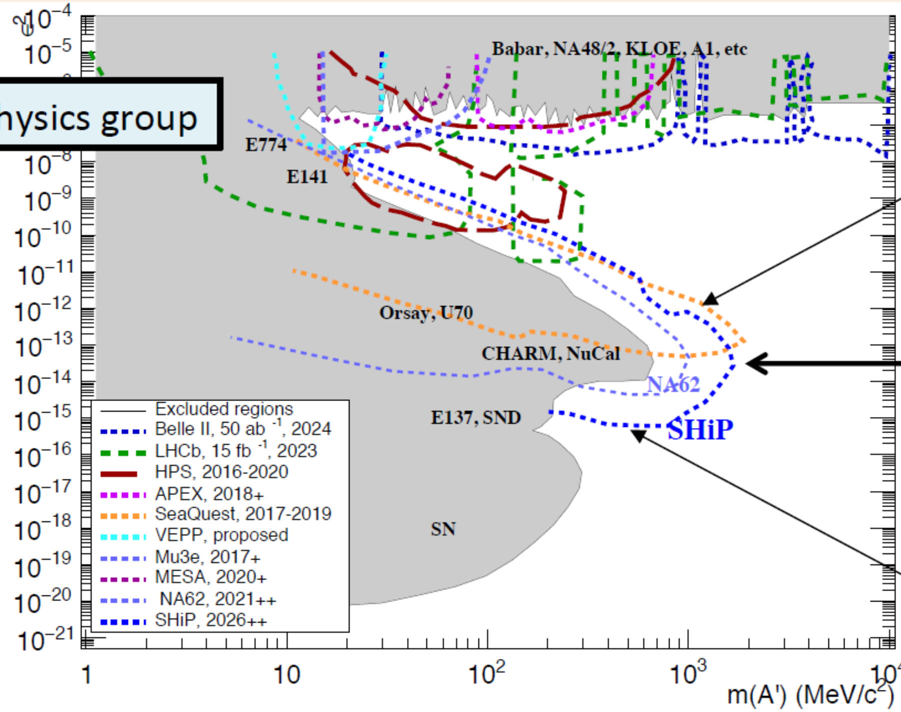




SHiP sensitivity to dark photons

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

PBC BSM physics group

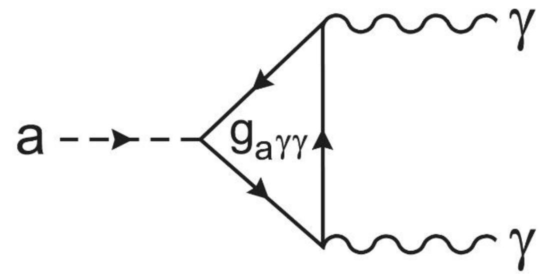


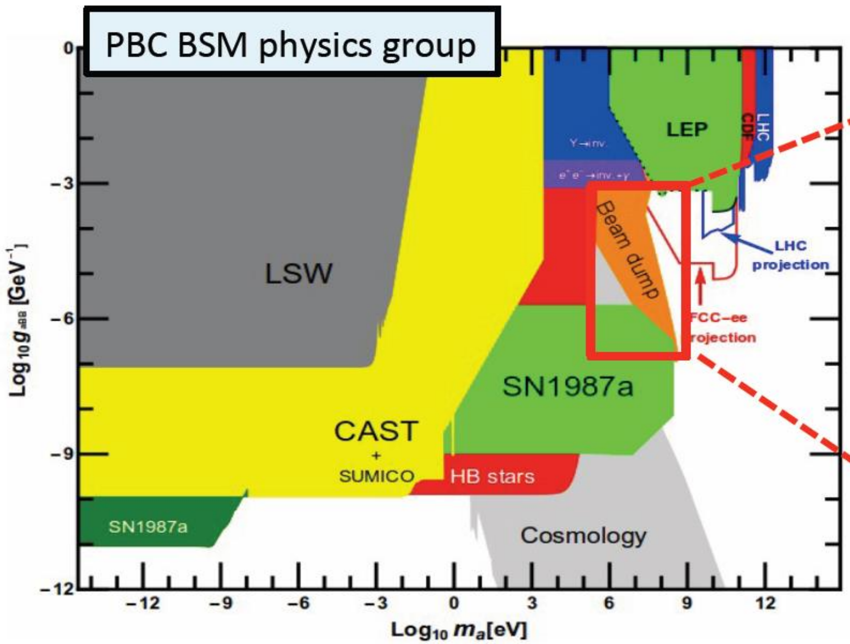
Decay before reaching detector $N \sim \exp(-\epsilon^2 m^2/p)$

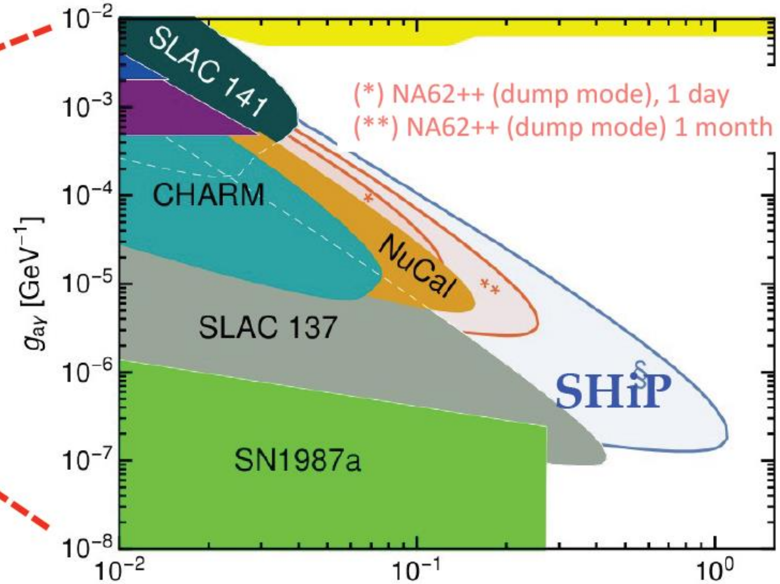
Kinematic limit

Lifetime too large: $N \approx (\epsilon)^4$

SHiP sensitivity to light axion

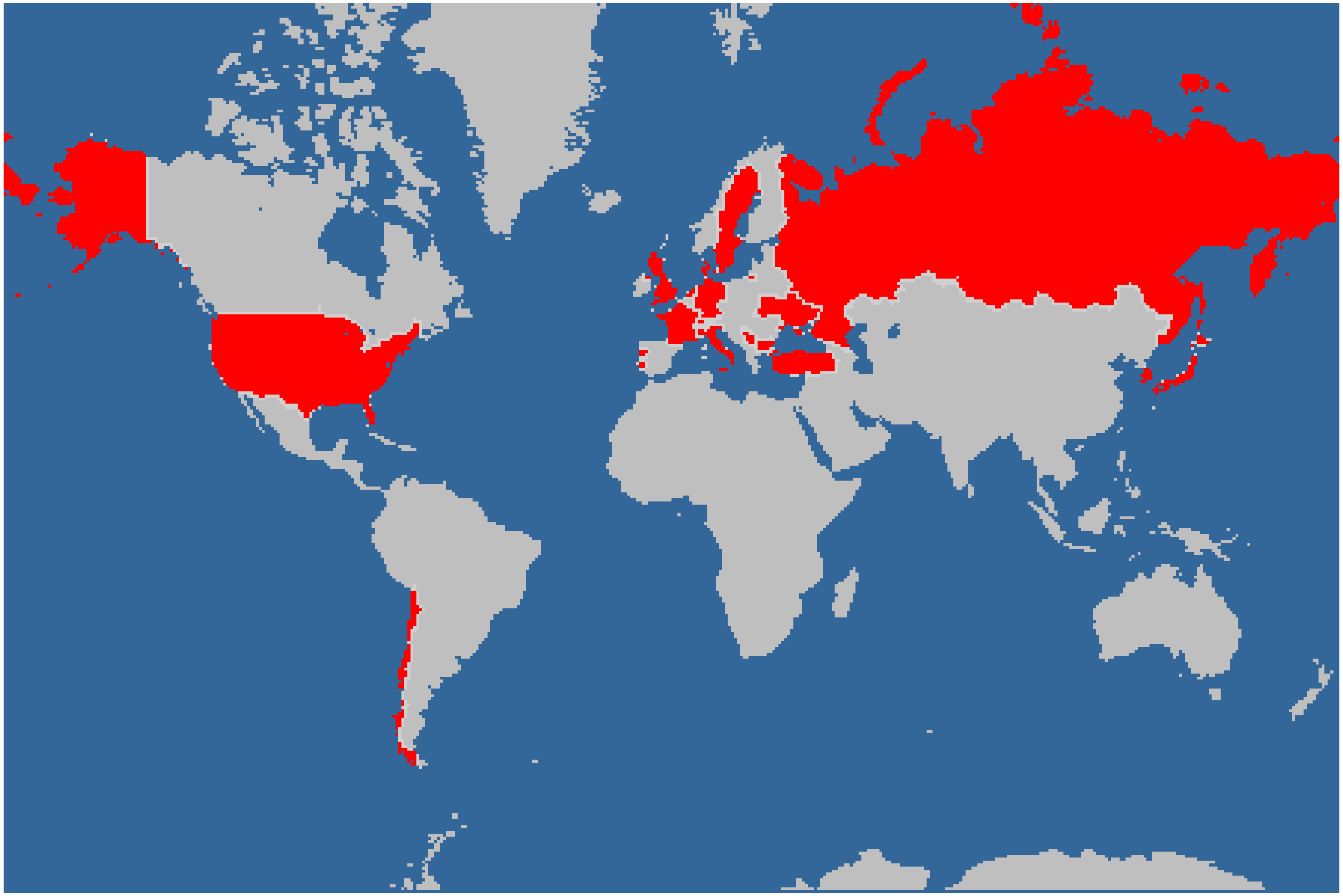




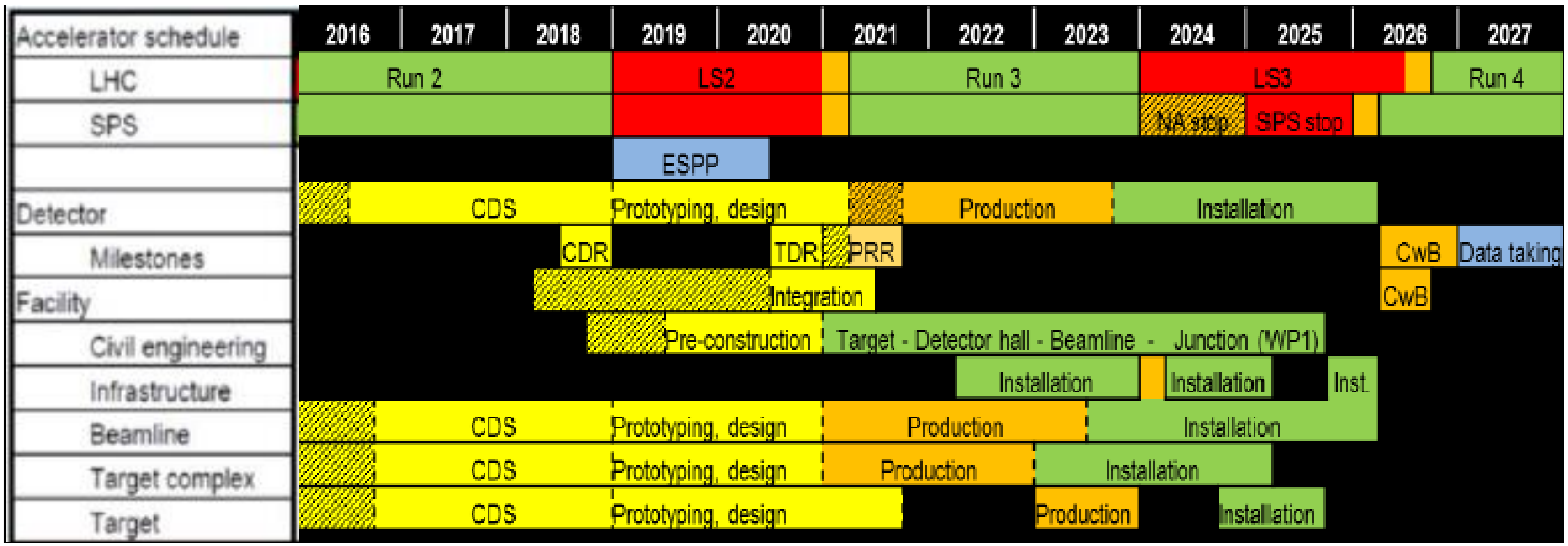


SHiP Collaboration – 2018

17 countries; 52 institutes; >250 members



SHiP current status & planning



Planning is aligned with:

- Comprehensive Design Study by **2018**
- Update of European Strategy for Particle Physics **2019/2020**
- Production Readiness Review **2020**
- Data taking **2026**

Summary

- Strong hints to «no NP at the energy frontier» motivate studies (both theoretical and experimental) of perspectives at the intensity frontier
- **S**earch for **Hi**dden **P**articles (SHiP) experiment is proposed to search for NP 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

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

Proton beam dump experiments: the past

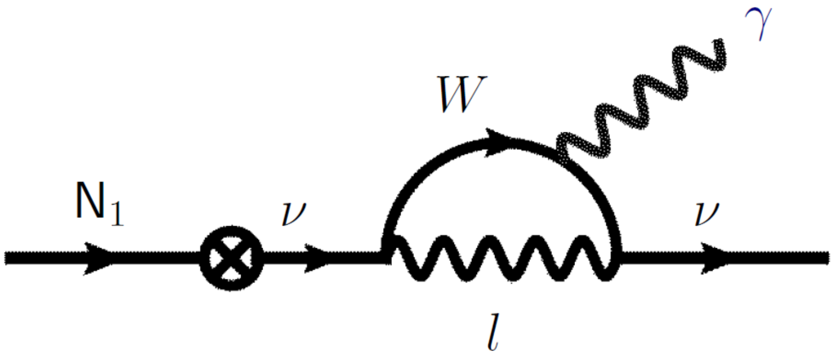
Experiment	Location	approx. Date	Amount of Beam (10^{20} POT)	Beam Energy (GeV)	Target Mat.	Ref.
CHARM	CERN	1983	0.024	400	Cu	[16]
PS191	CERN	1984	0.086	19.2	Be	[17, 18]
E605	Fermilab	1986	4×10^{-7}	800	Cu	[19]
SINDRUM	SIN,PSI					
ν-Cal I	IHEP Serpukhov	1989	0.0171	70	Fe	[20–22]
LSND	LANSCE	1994-1995 1996-1998	813 882	0.798	H20, Cu 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 2005-2012 2013-2014	6.27 11.3 1.86	8.9	Be Be Steel	[27] [28] [29]
+ DONUT	FNAL		3.6×10^{-3}	800	W	

(from W.Bonivento)

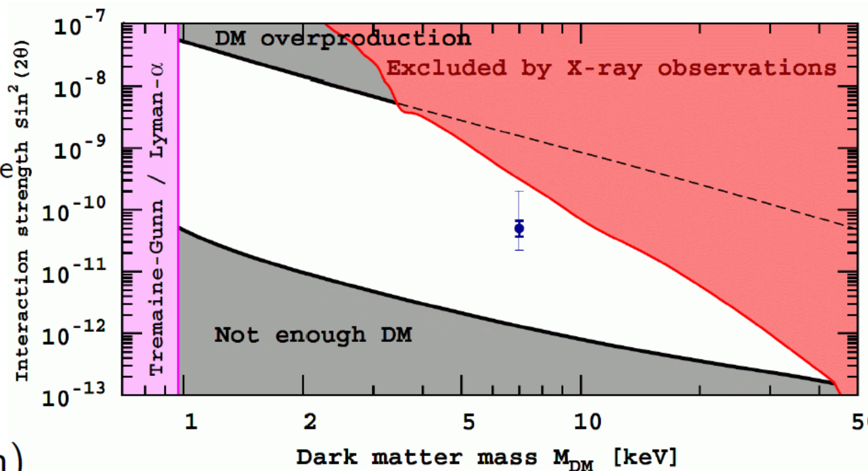
νMSM: closer look at N_1

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

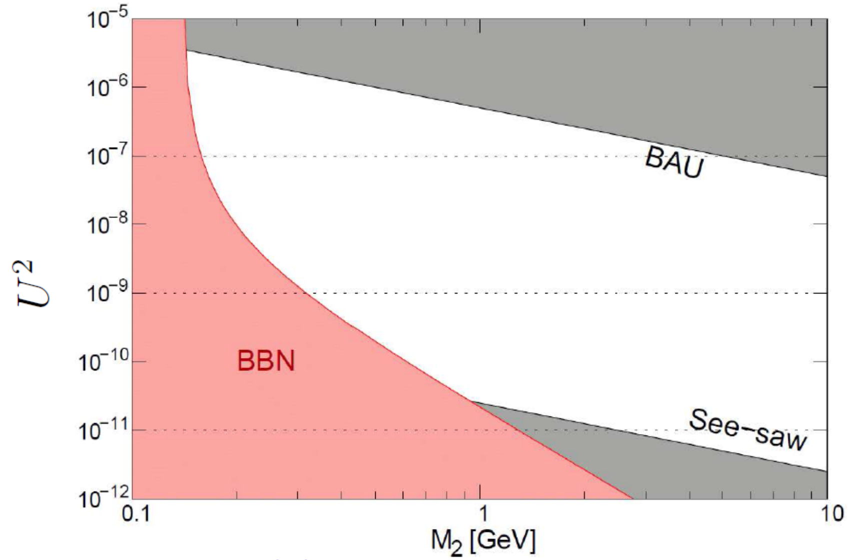
SHiP

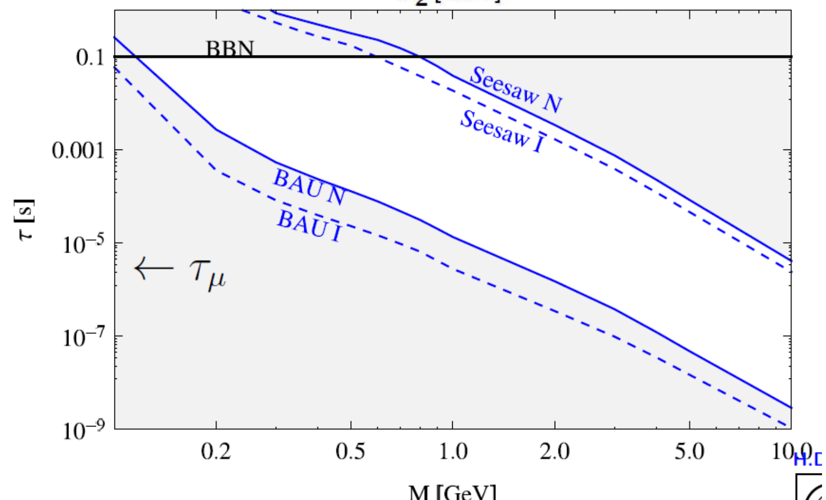
$\mathbf{N}_{2,3}$

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

- ν 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 N_2 nearly degenerate with 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!





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

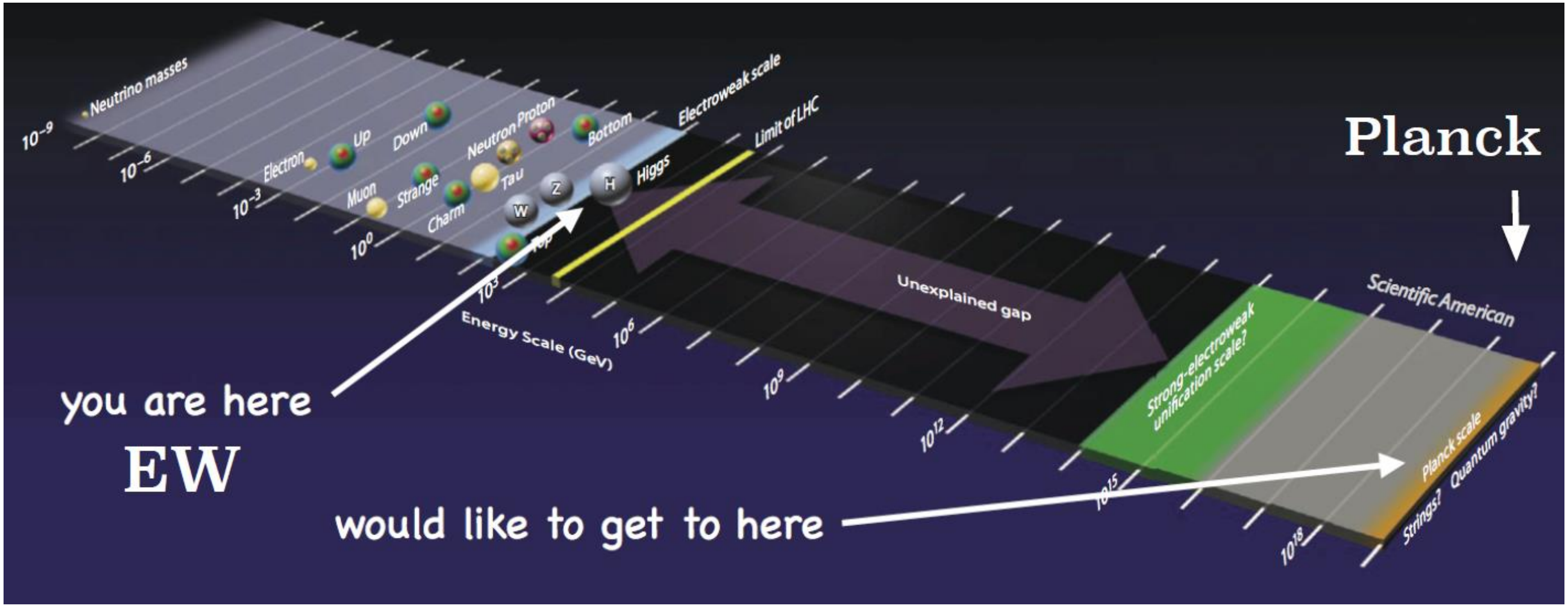
$$U^2 = U_e^2 + U_\mu^2 + U_\tau^2$$

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

is detector acceptance for all HNL final (visible) states

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

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 ?)