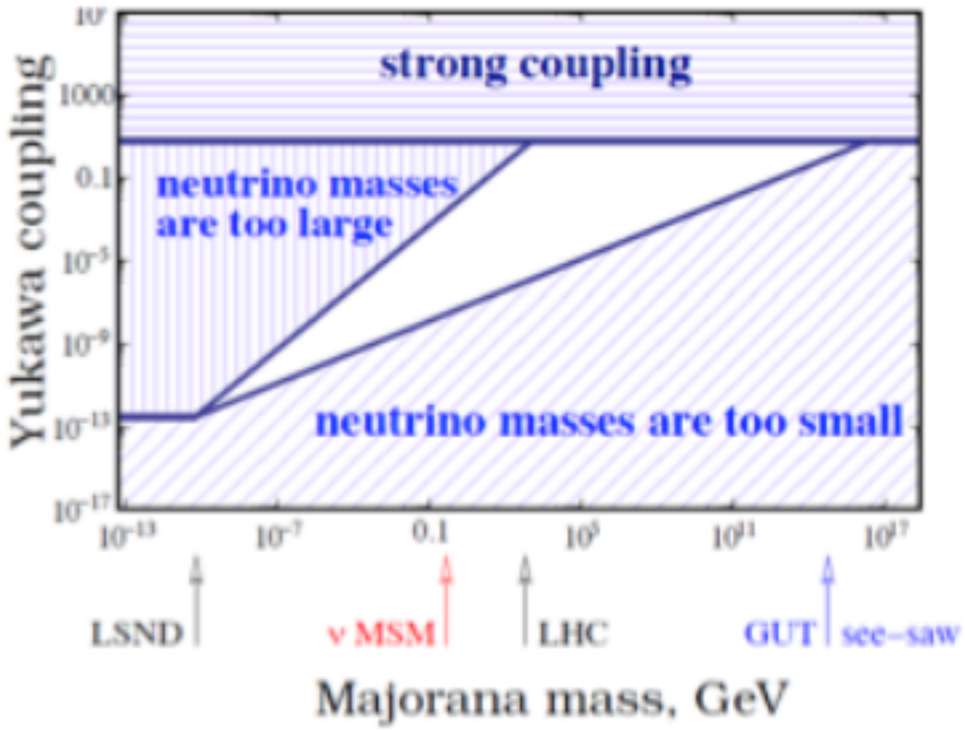
Next obvious question

Where does the ν mass come from?

—> it is clear that experimental effort (and possibly prizes…) has to be now directed in this direction!

One remarkable possibility:

see-saw mechanism (type I) with one/two/three massive and sterile Majorana-type neutrinos



$$A = \begin{pmatrix} 0 & M \\ M & B \end{pmatrix},$$

where B is taken to be much larger than M.

It has two very disproportionate eigenvalues:

$$\lambda_{\pm} = \frac{B \pm \sqrt{B^2 + 4M^2}}{2}.$$

The larger eigenvalue, λ_+, is approximately equal to B, while the smaller eigenvalue is approximately equal to

$$\lambda_- \approx -\frac{M^2}{B}.$$

Thus, $|M|$ is the geometric mean of λ_+ and $-\lambda_-$, since the determinant $\lambda_+\lambda_- = -M^2$.

If one of the eigenvalues goes up, the other goes down, and vice versa. This is the point of the name "seesaw" of the mechanism.

A matrice di massa dei neutrini, B componente di Majorana (O GUT) , M componente di Dirac O(v.e.v. EW)
—> λ- porta alla massa dei neutrini leggeri O(eV)

See-saw generation of neutrino masses

Most general renormalisable Lagrangian of SM particles (+3 singlets wrt SM gauge group):

$$L_{singlet} = i\bar{N}_I \partial_\mu \gamma^\mu N_I - Y_{I\alpha} \bar{N}_I^c \tilde{H} L_\alpha - M_I \bar{N}_I^c N_I + h.c$$

Yukawa term: mixing of N_I with active neutrinos to explain oscillations

Majorana term which carries no gauge charge

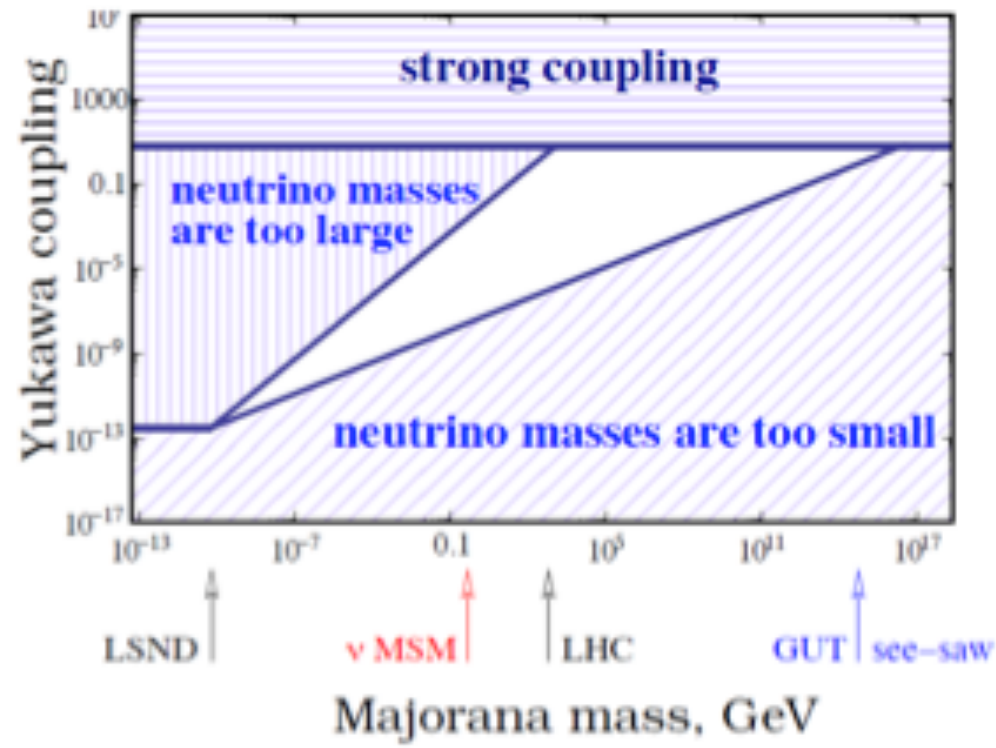
The scale of the active neutrino mass is given by the see-saw formula: $m_\nu \sim \frac{m_D^2}{M}$ **=M²/B**

where $m_D \sim Y_{I\alpha} v$ *- typical value of the Dirac mass term*

$v \sim 246$ GeV

Example:

For M ~ 1 GeV and m_ν ~ 0.05 eV it results in m_D ~ 10 keV and Yukawa coupling ~ 10^{-7}



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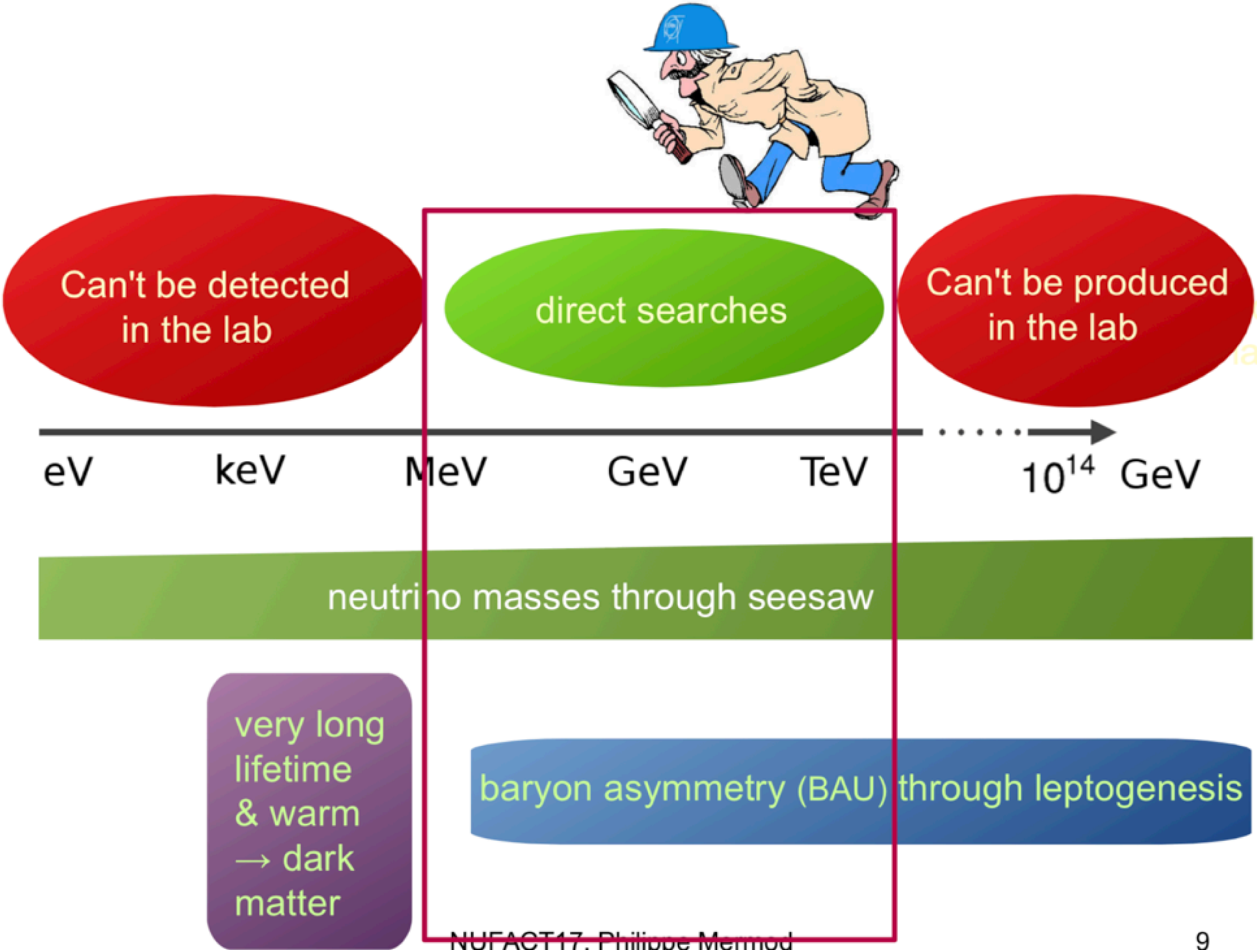

Can't be detected in the lab
direct searches
Can't be produced in the lab
eV
keV
MeV
GeV
TeV
10^{14} GeV
neutrino masses through seesaw
very long lifetime & warm → dark matter
baryon asymmetry (BAU) through leptogenesis

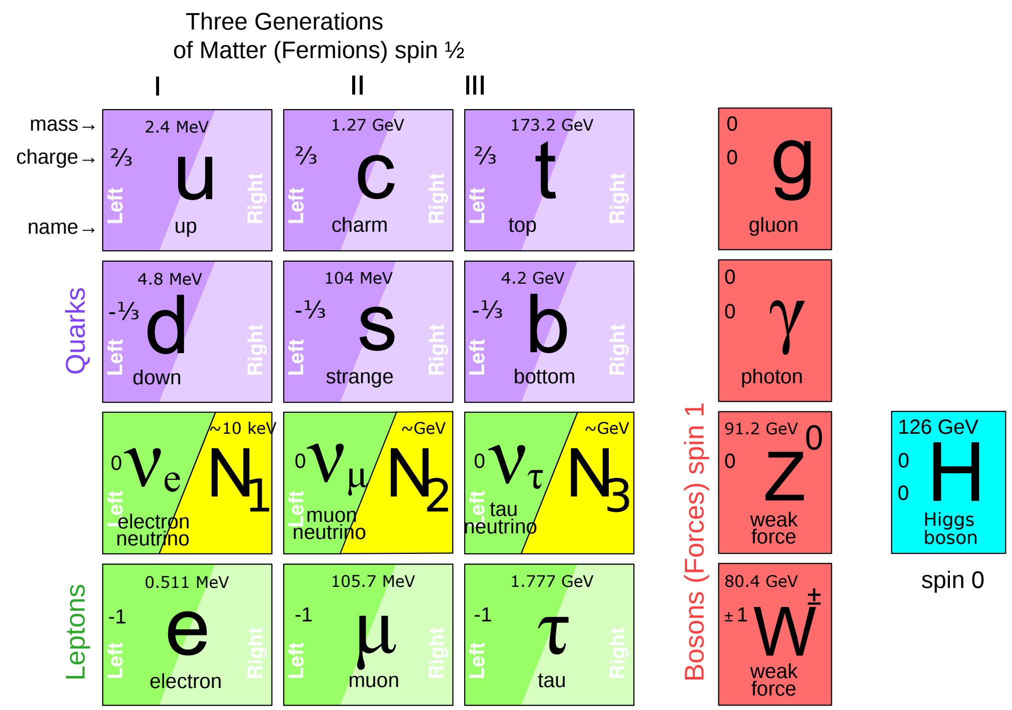
- Which observable effects allow to test such models?
  - $M >> \Lambda_{EW}$: “Non-unitarity effects” (indirect tests)
  - $M \sim \Lambda_{EW}$: On-shell heavy neutrino effects (direct tests at colliders, various promising signature processes)
  - $M < m_W$: Very sensitive searches via “displaced vertices” at colliders

The νMSM and its fellows

3 Majorana (HNL) partners of ordinary ν, with $M_N < M_W$

In a peculiar parameter space (N_2 and N_3 almost degenerate in mass and with m=O(GeV) and N_1 decoupled with m=O(keV)), νMSM explains:

neutrino masses (see-saw), baryogenesis (via lepto-genesis) and DM (N_1)! (but, in this version of the theory, DM has to be generated outside the νMSM, by e.g. the decay of an inflaton—>see Higgs portal)



***νMSM**: T.Asaka, M.Shaposhnikov PL **B620** (2005) 17*
M.Shaposhnikov Nucl. Phys. B763 (2007) 49

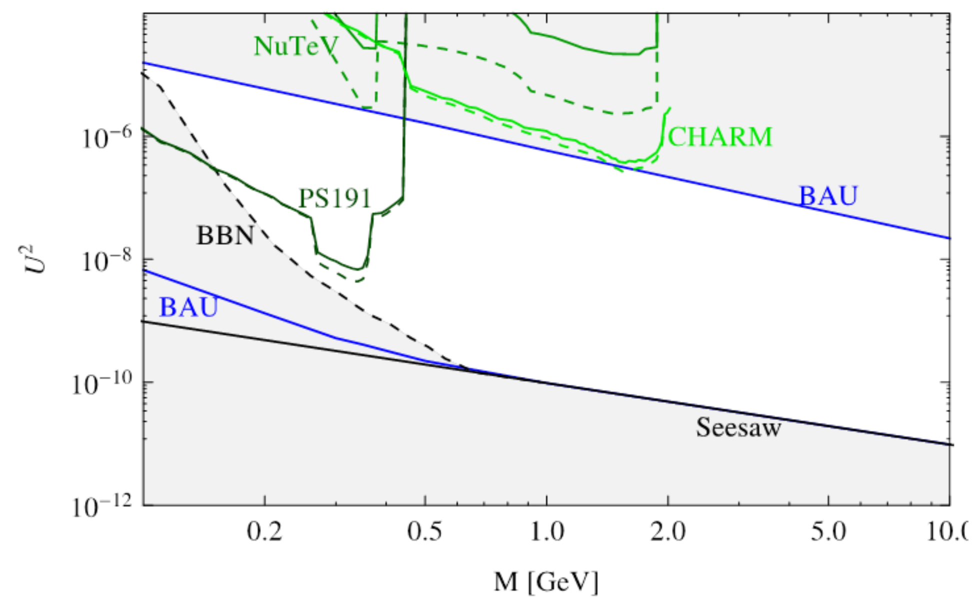
No hierarchy problem (if also the inflaton or the NP yielding N_1 has mass below EW scale)

Naturalness of the above parameter space comes from a U(1) lepton symmetry, broken at 10^{-4} level.

+ all other, less noble but less constrained, variations of this theory

$N_{2,3}$ production

inverted mass hyerarchy

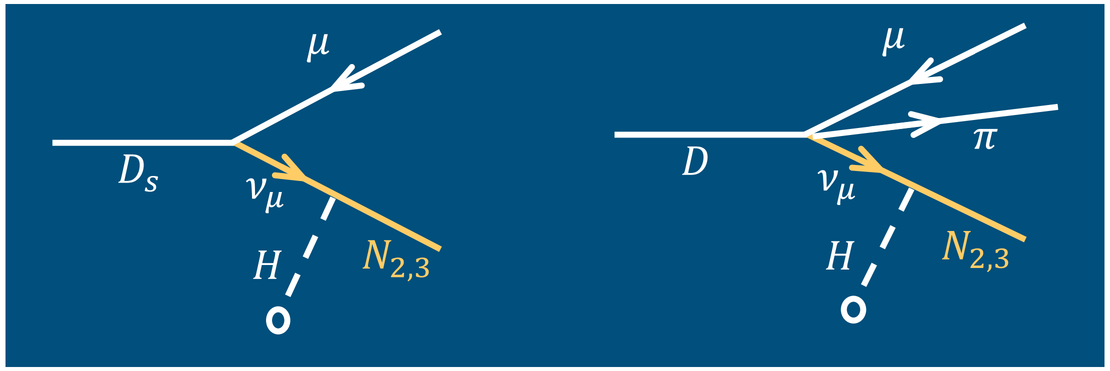


Interaction with the Higgs v.e.v. ->mixing with active neutrinos with U [2]

in the νMSM strong limitations in the parameter space (U^2,m)

a lot of HNL searches in the past but, for $m>m_K$, with a sensitivity not of cosmological interest

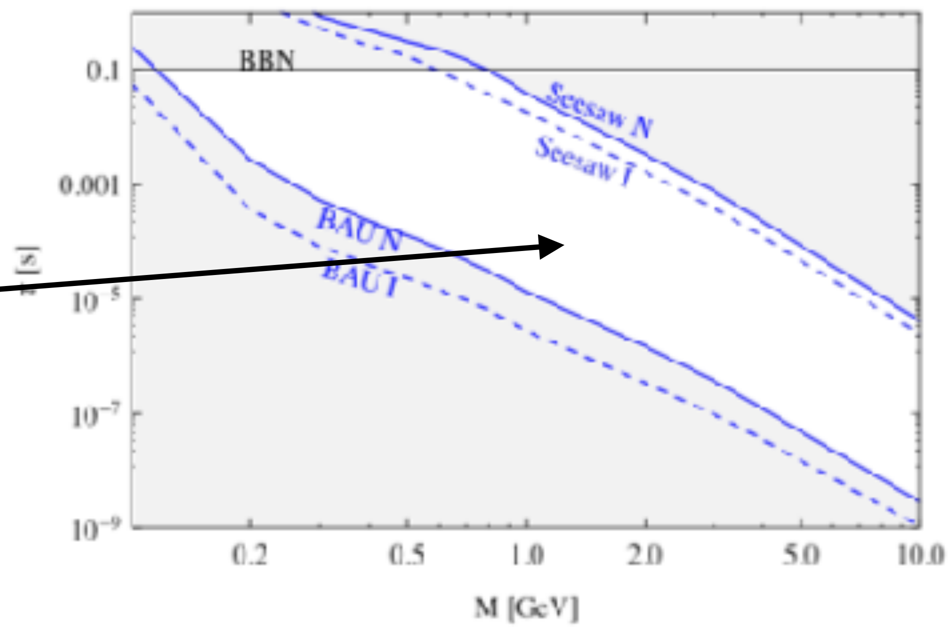
ex. meson decays —>



$N_{2,3}$ decays

Very weak HNL-active ν —>at masses below few GeV, $N_{2,3}$ have very long life-time

decay paths of O(km)!: for $U^2_\mu=10^{-7}$, $\tau_N=1.8\times10^{-5}$s

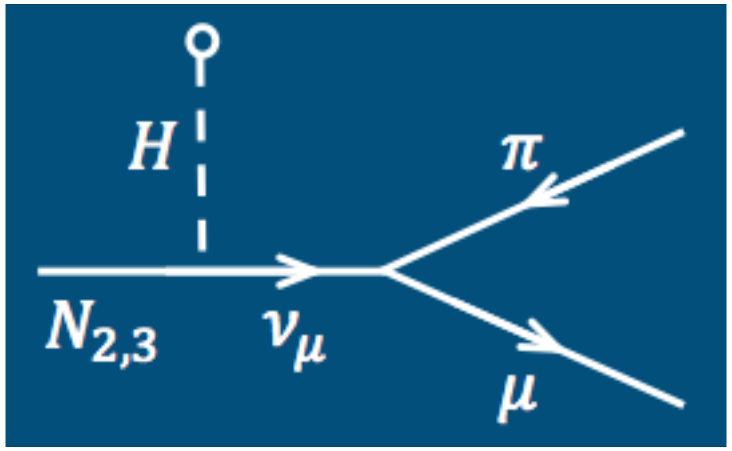


Various decay modes : the BR's depend on flavor mixing

Decay mode	Branching ratio
$N_{2,3} \to \mu/e + \pi$	0.1 - 50 %
$N_{2,3} \to \mu^-/e^- + \rho^+$	0.5 - 20 %
$N_{2,3} \to \nu + \mu + e$	1 - 10 %

The probability that $N_{2,3}$ decays within the fiducial volume of the experiment $\propto U_\mu^2$

—> number of events $\propto U_\mu^4$ if N detected

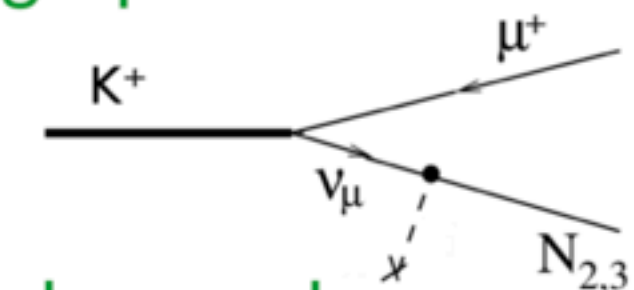


Probing hidden sectors with very small couplings to SM ⇨

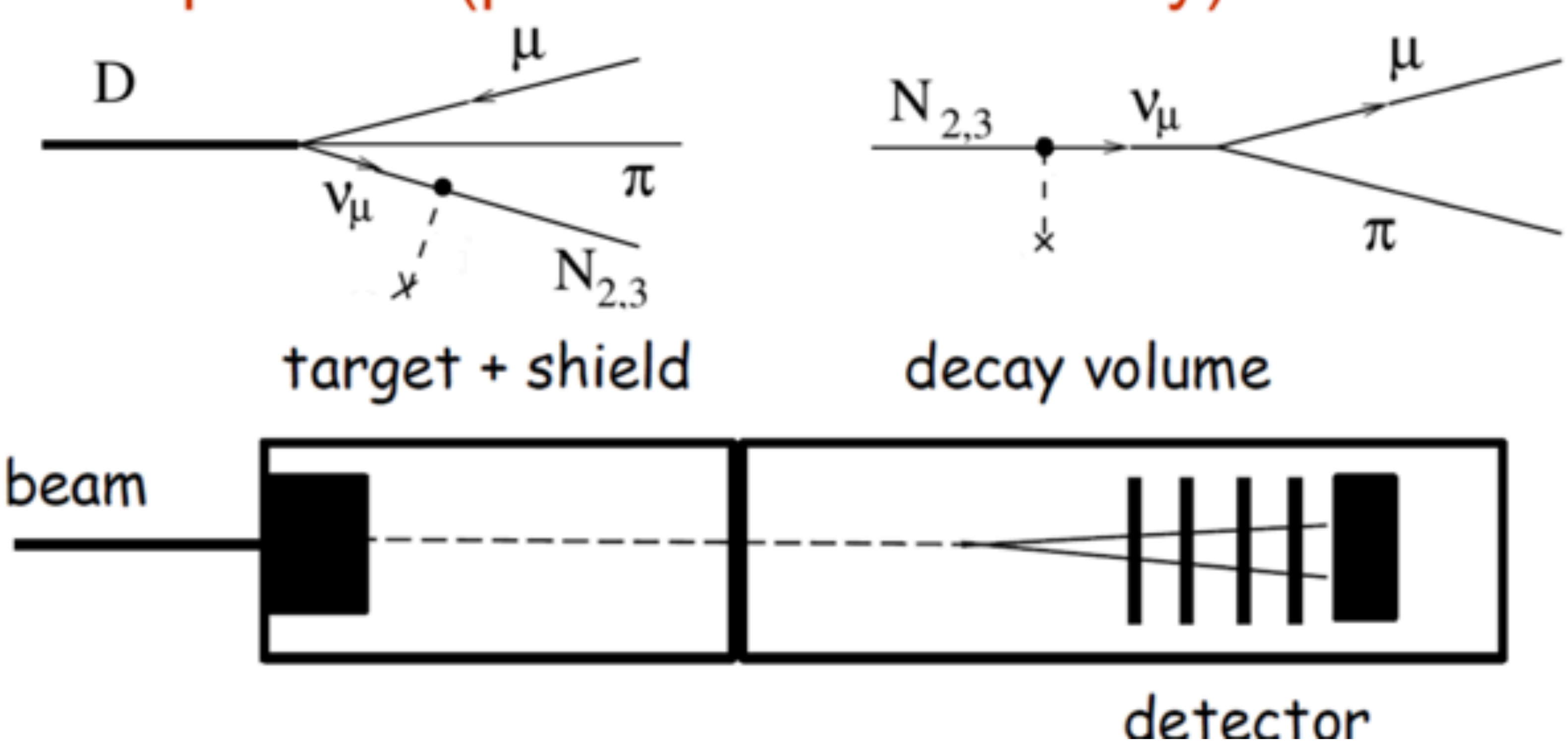
- High fluxes
- Displaced decays

Searches with proton beams

- masses up to 0.45 GeV probed through pion and kaon decays
  - → **PS191** Phys. Lett. B 203, 332 (1988)
  - → **NA62** in beam mode (production)



- masses up to 2 GeV probed through charmed meson decays
  - → **CHARM** Phys. Lett. B 166, 473 (1986)
  - → **NuTeV** Phys. Rev. Lett. 83, 4943 (1999)
  - → **NA62** in dump mode (production and decay)
  - → **SHiP**



PROTON BEAM DUMPS: 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

PROTON BEAM DUMP: (hopefully) THE FUTURE!

400GeV p, 2×10^{20}pot/5 year (already reached yearly rate with LNGS)

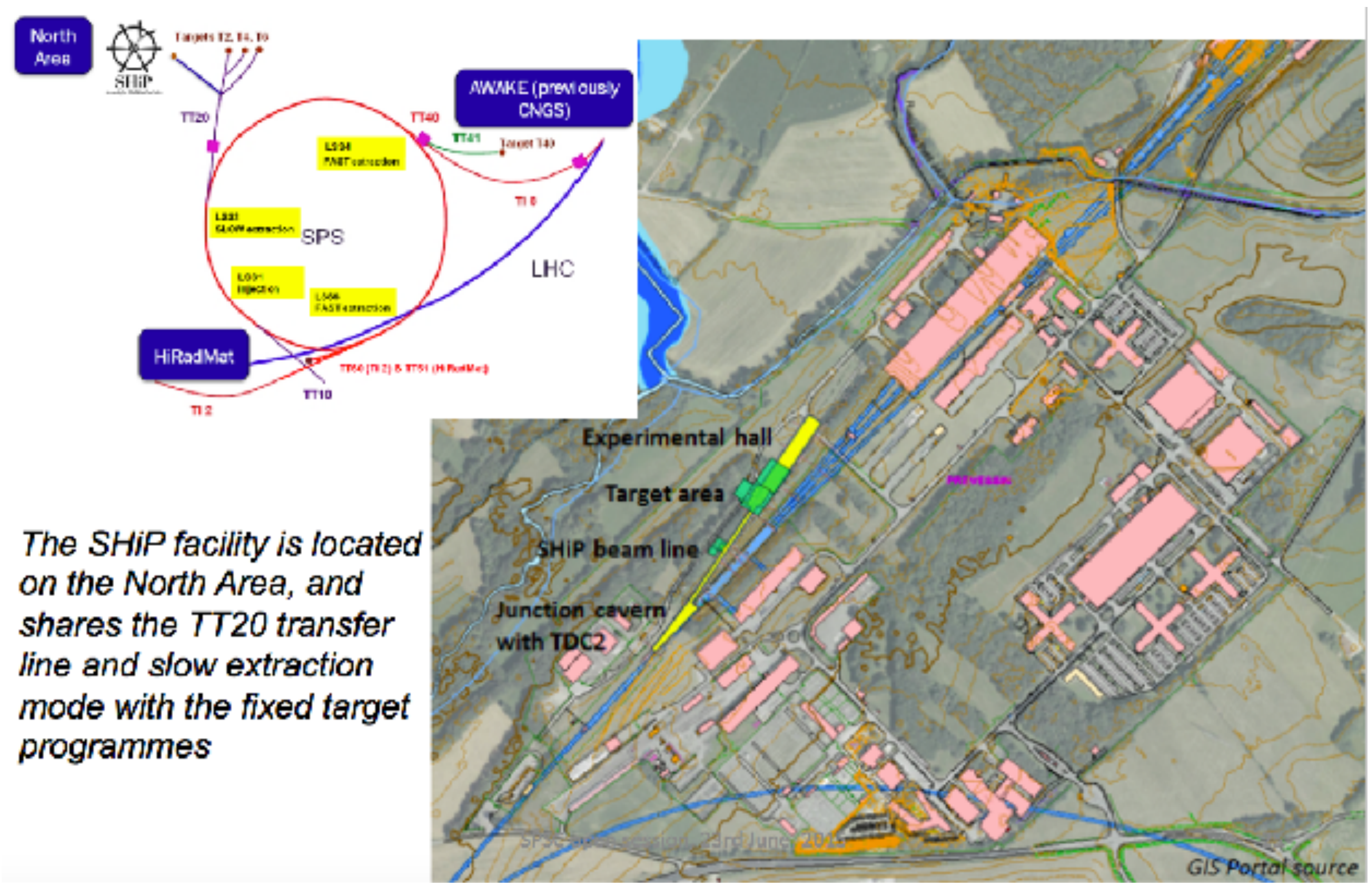


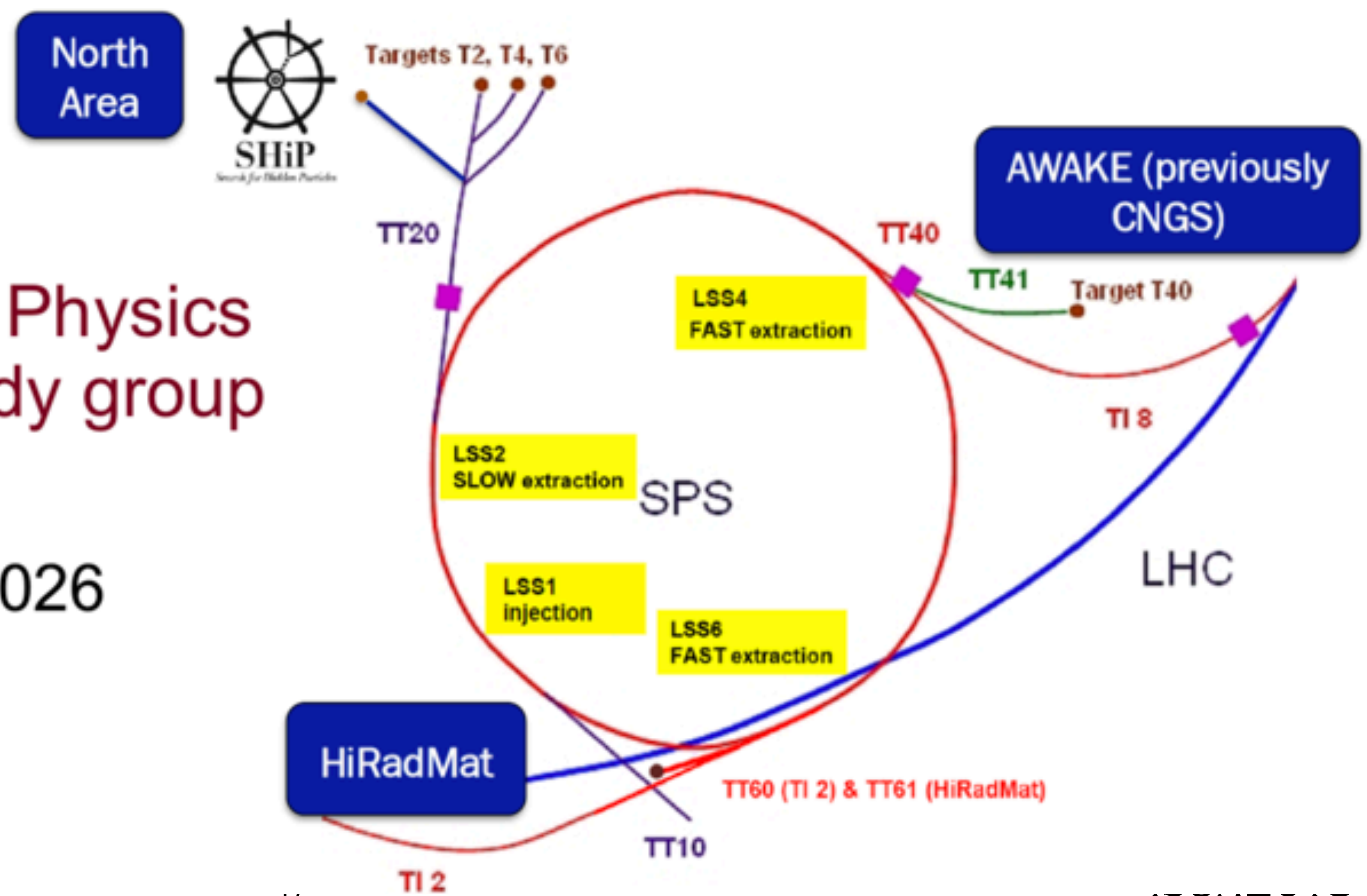
Figure of merit:

#(ν_τ)SHiP/DONUT=600

#(HNL)SHiP/CHARM=10k

Search for Hidden Particles (SHiP)

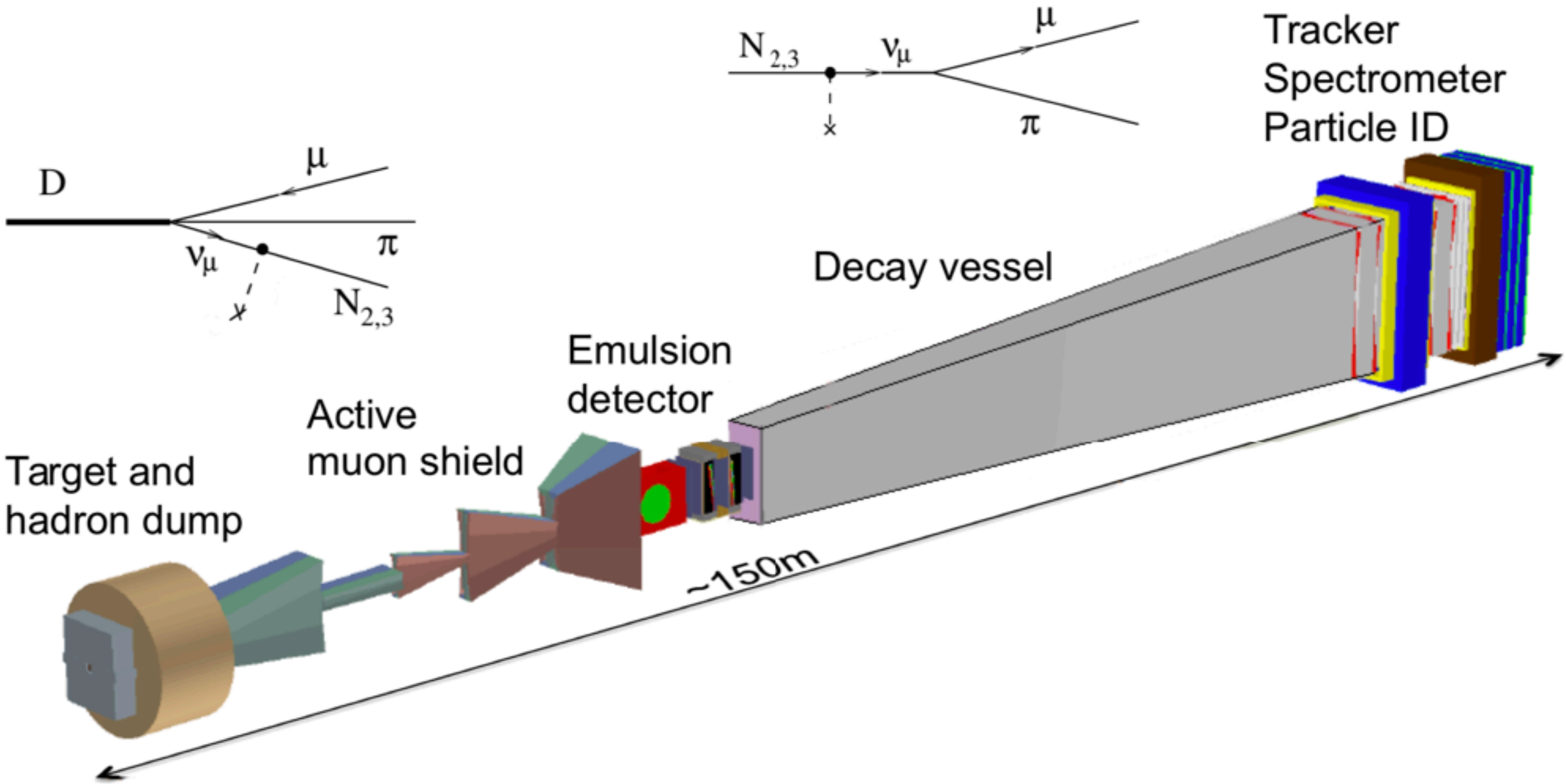
- Proposed facility: 400 GeV protons from the CERN SPS
  - New beam line and target complex
  - Aim at $2 \cdot 10^{20}$ pot in 5 years (→ ~ $5 \cdot 10^{16}$ νs from charm decays)
- Collaboration of 250 members from 46 institutes
- Technical proposal arXiv:1504.04956 (2015) Physics paper Rep. Prog. Phys. 79 (2016)



- Major actor in CERN Physics Beyond Colliders study group
  - Approval ~2020
  - Physics runs ~2026

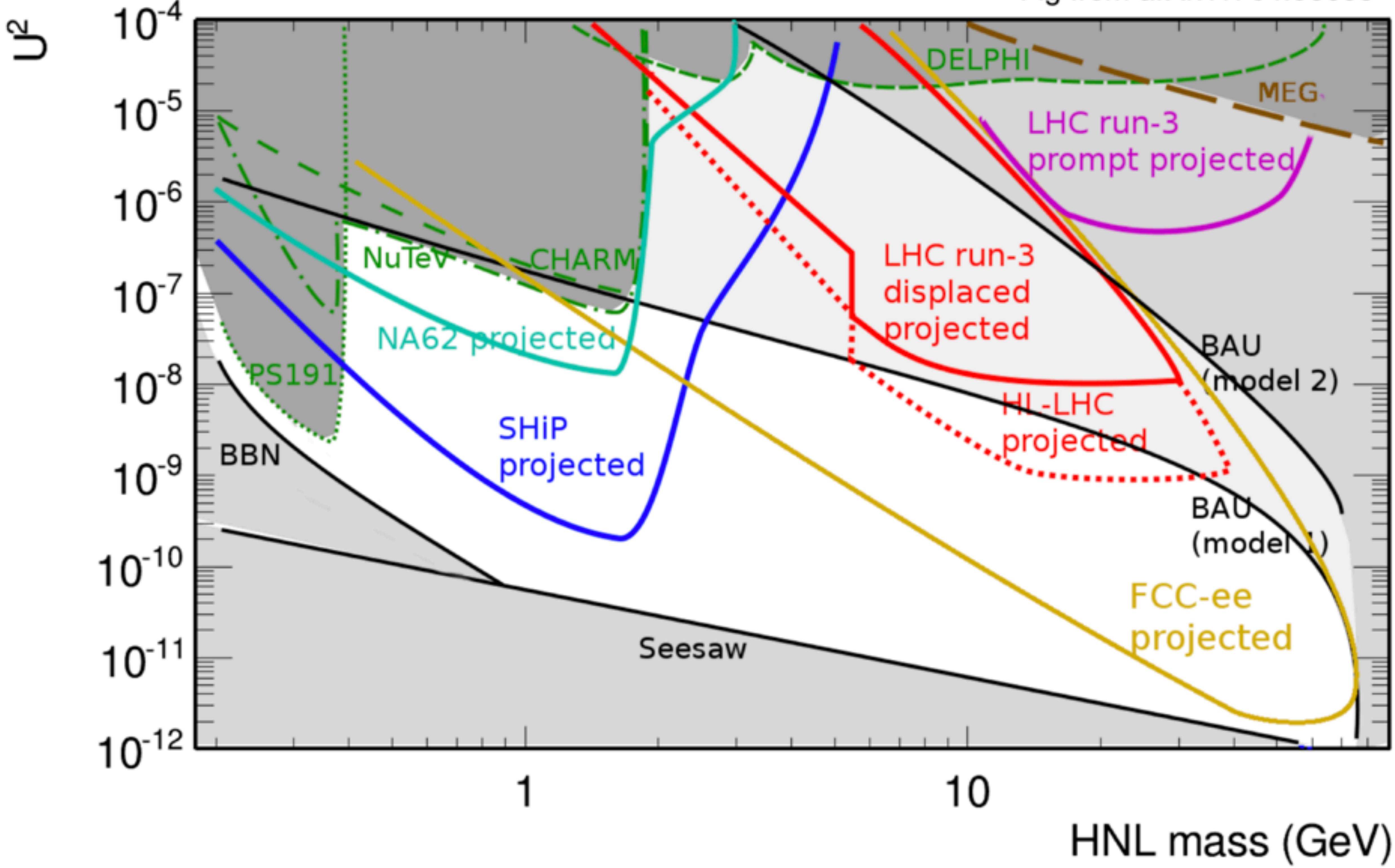
SHiP – detector

Designed for **large acceptance** and **zero backgrounds**



N at CERN in a 10-year timesecale ... and beyond

Fig from arXiv:1704.08635



The Hidden Sector

Leading SM coupling to Neutral Hidden Sector

Portals

Scalar	Right-Handed neutrino	U(1)
$\mathcal{O}_s H^\dagger H$	$L H N_R$	$B_{\mu\nu} V^{\mu\nu}$

renormalizable couplings, i.e. NOT suppressed!

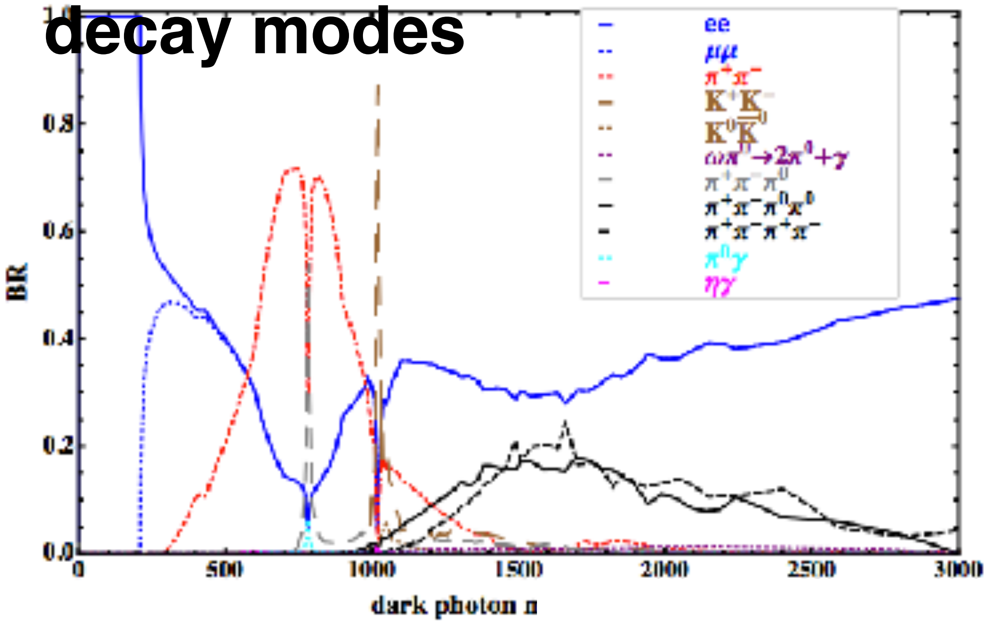
+other of higher dimensions (e.g. axion-like portal)

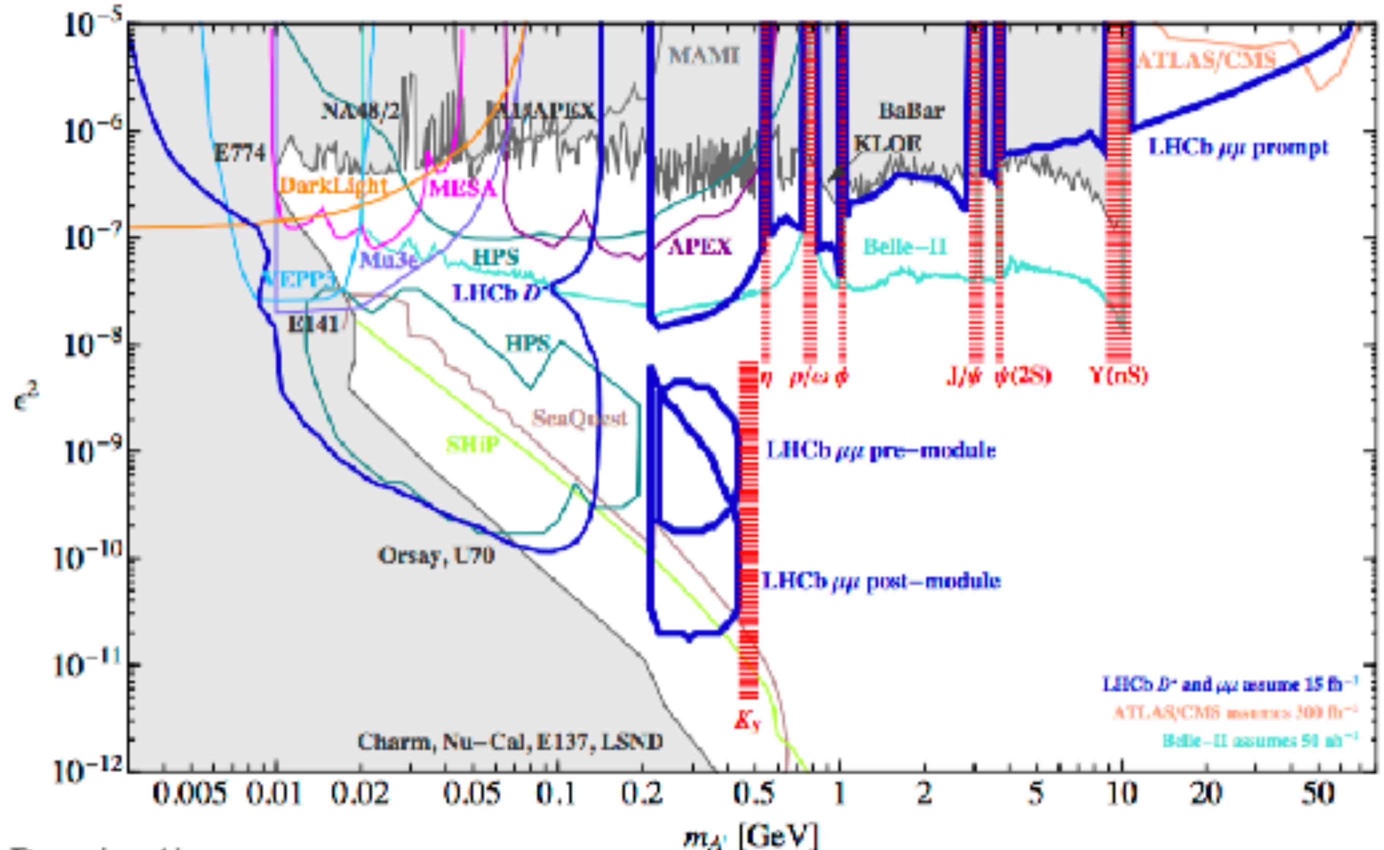
(stolen from A.Fradette, New Physics at the Intensity Frontier - Victoria, BC,Sept 2014)

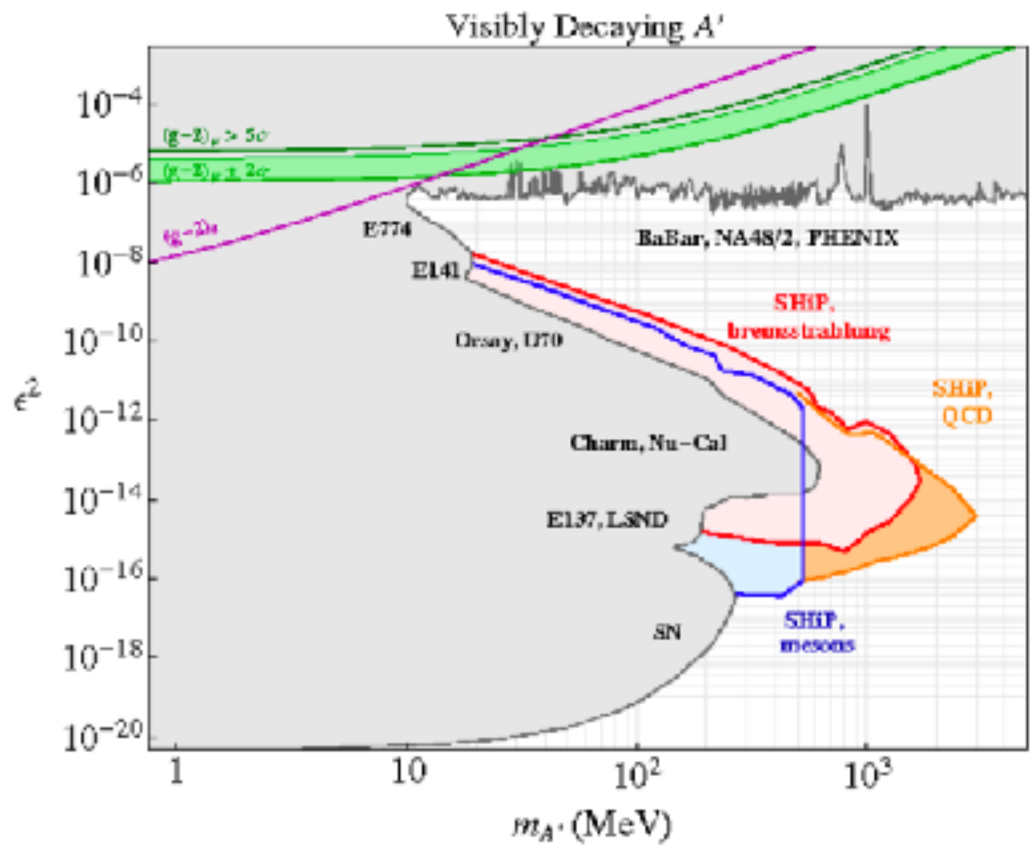
Dark photon coupling to SM particles

arXiv:1509.06765

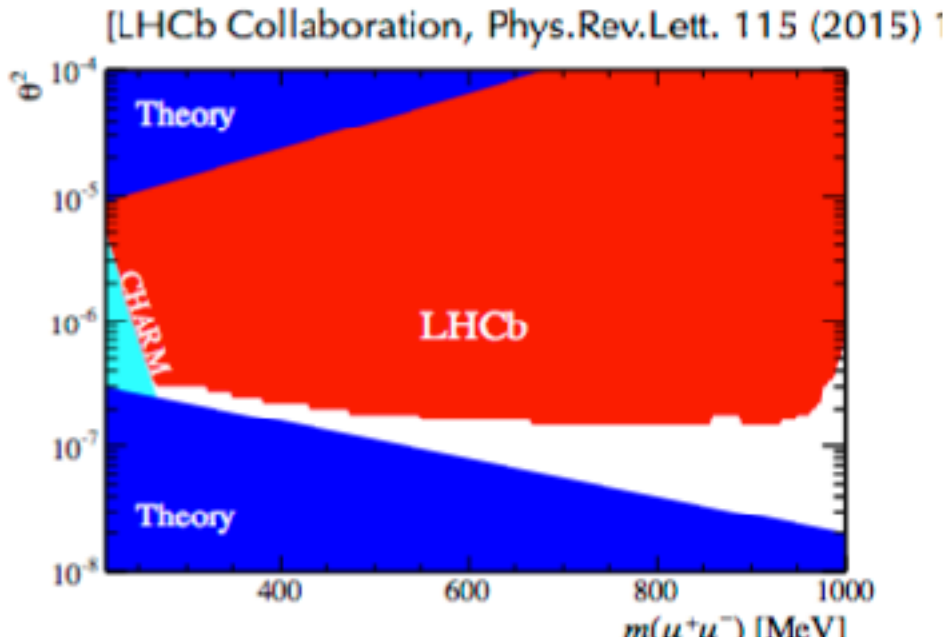
decay modes



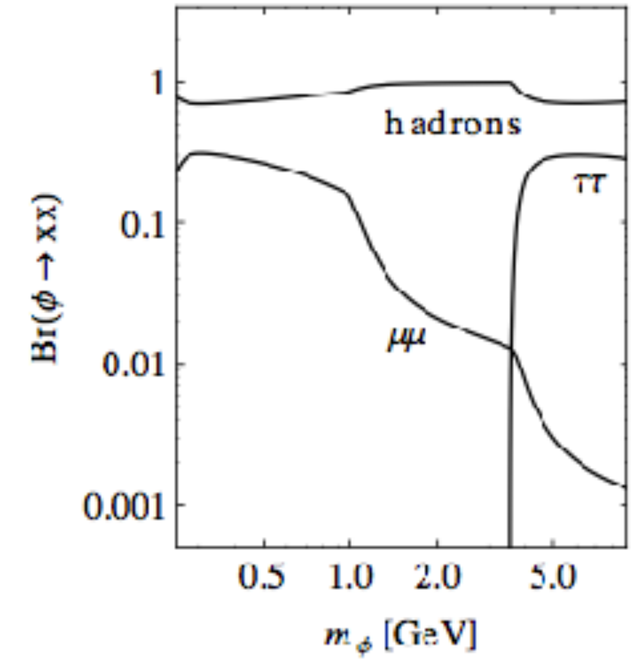


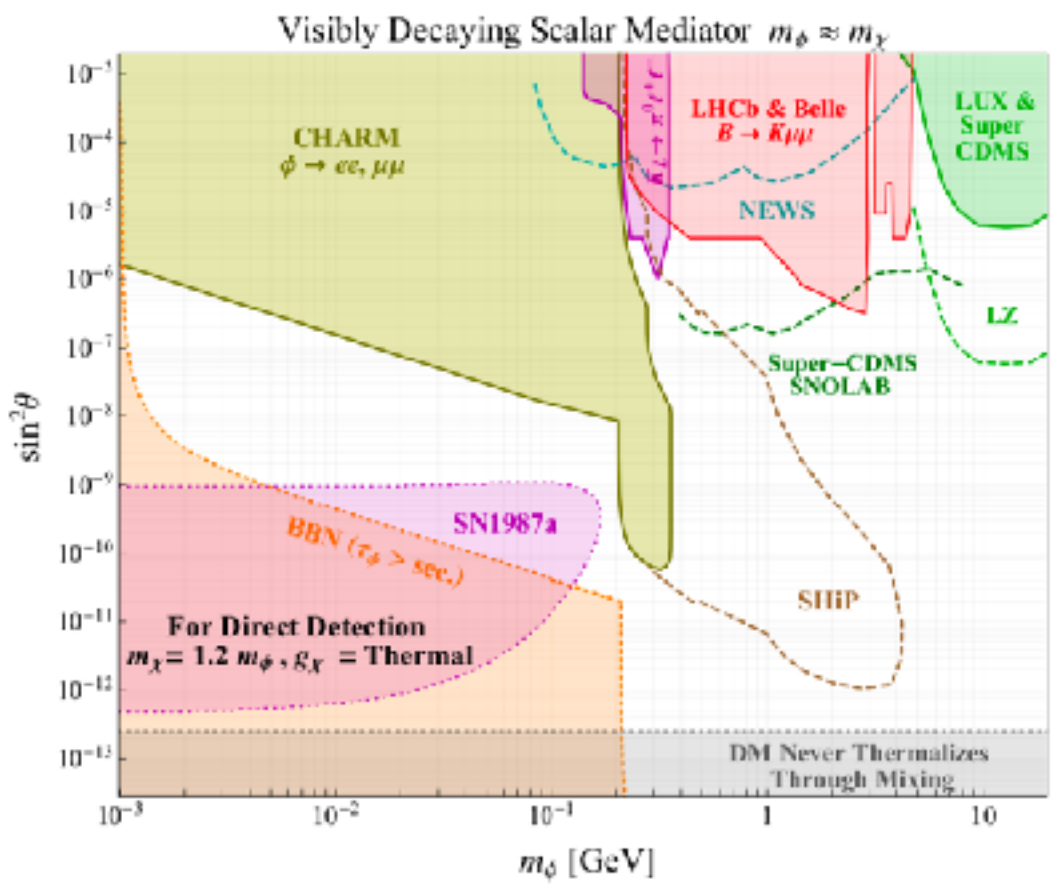


Dark Higgs

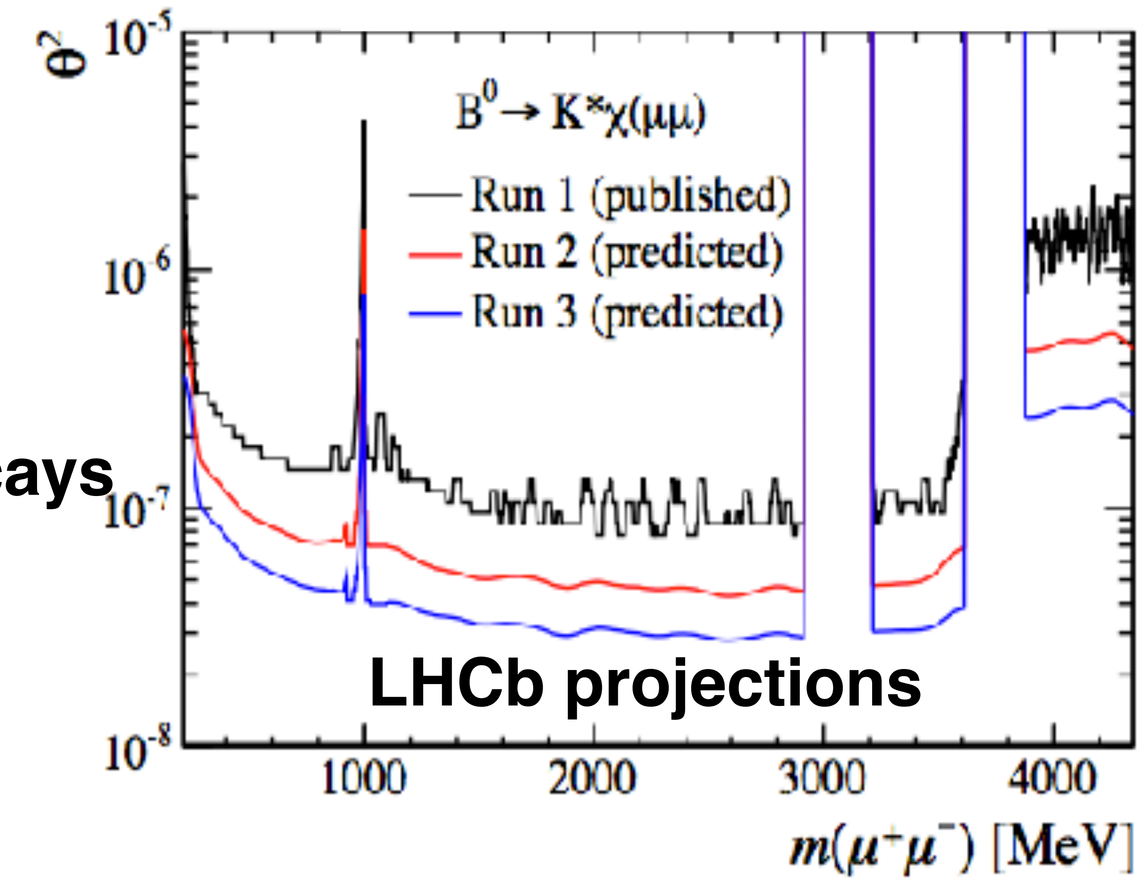


decay modes





B decays



LHCb projections

complementary!