Search for Hidden Particles (ShiP): an experimental proposal at the SPS

ship.web.cern.ch/ship

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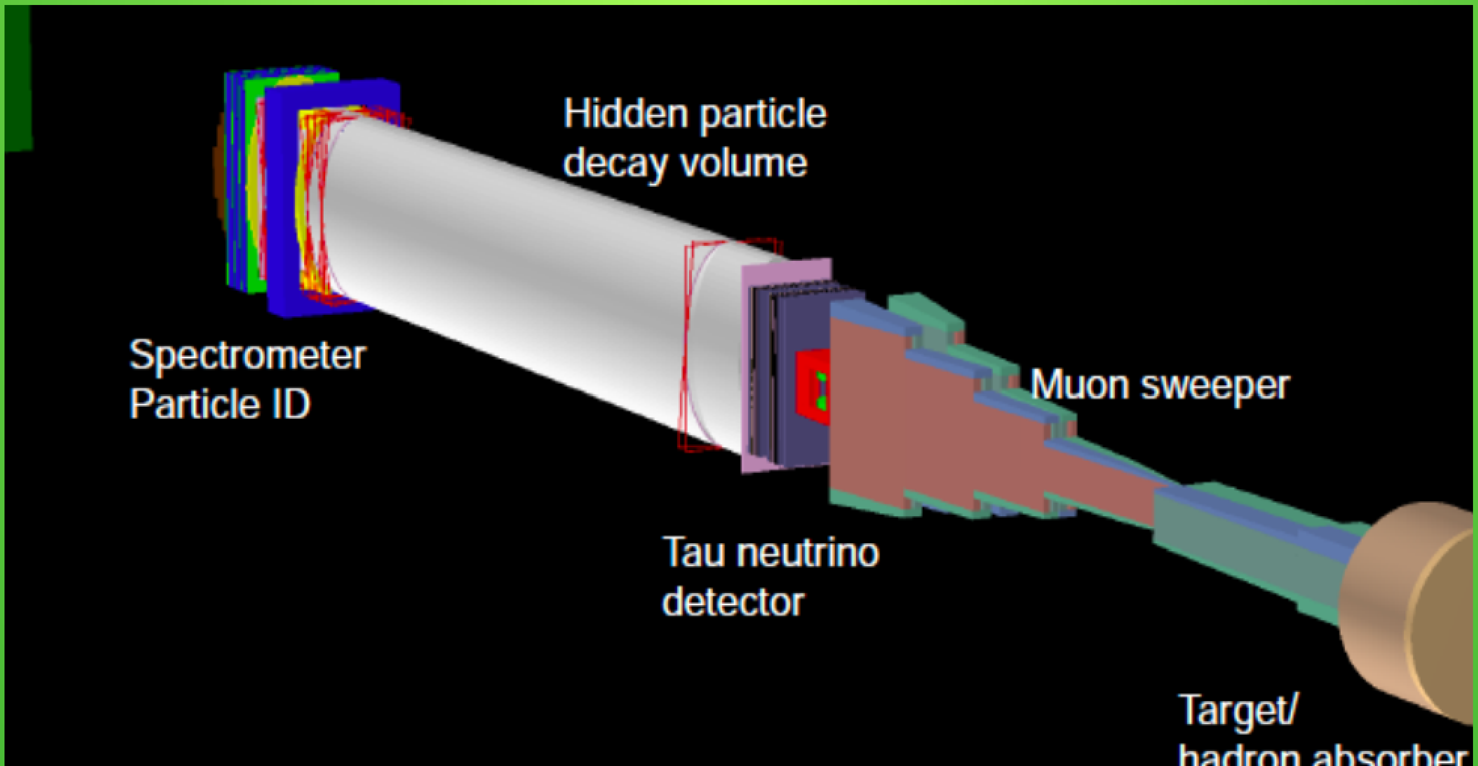
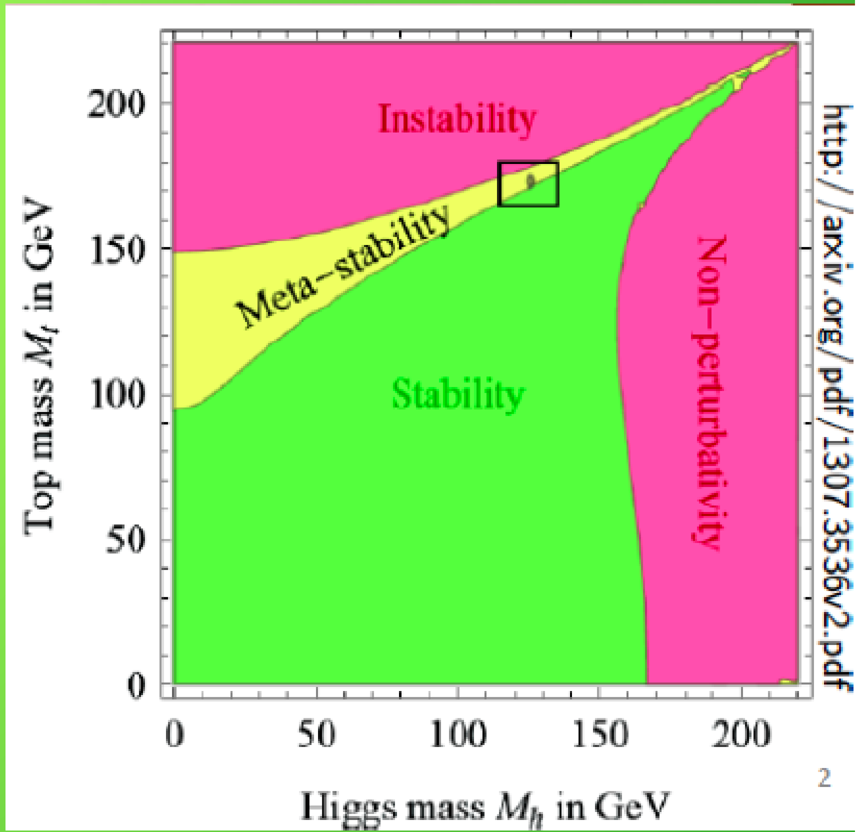


The Standard Model and beyond

- All SM particles have been discovered so far (apart from anti-ν_τ)
- Despite some anomalies, no compelling evidence of new physics found so far
- The Higgs mass points to a (meta-) stable universe
- The SM could be valid to the Plank scale
- Naturalness only a problem if we assume new particles between theEW and Plank scales



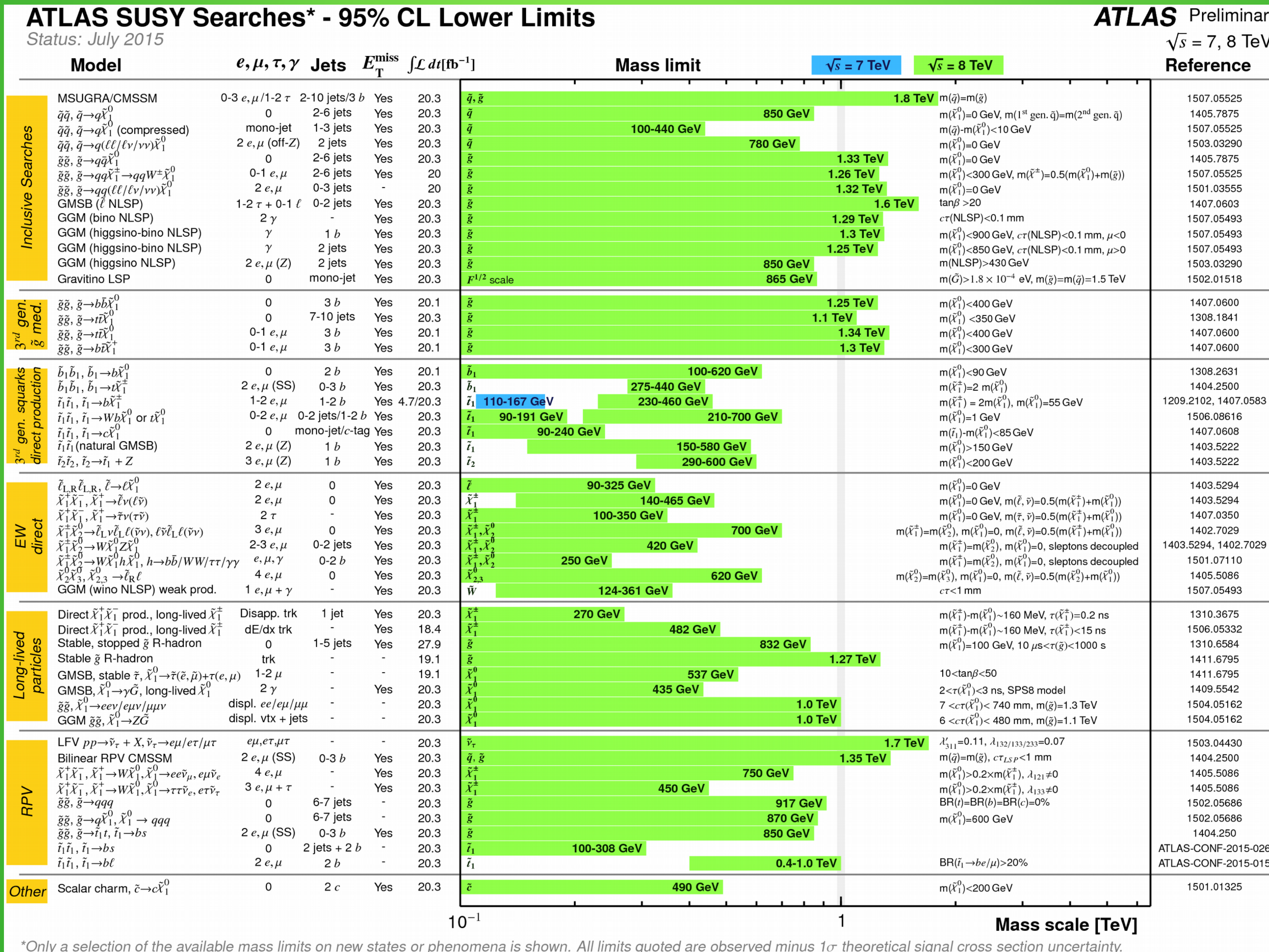
What we know we do not know

- Apart from naturalness, we do not understand:
  - Barion Asymmetry of the Universe
  - Dark Matter (indications are for cold, non-barionic)
  - The pattern of masses and mixings
  - Inflation

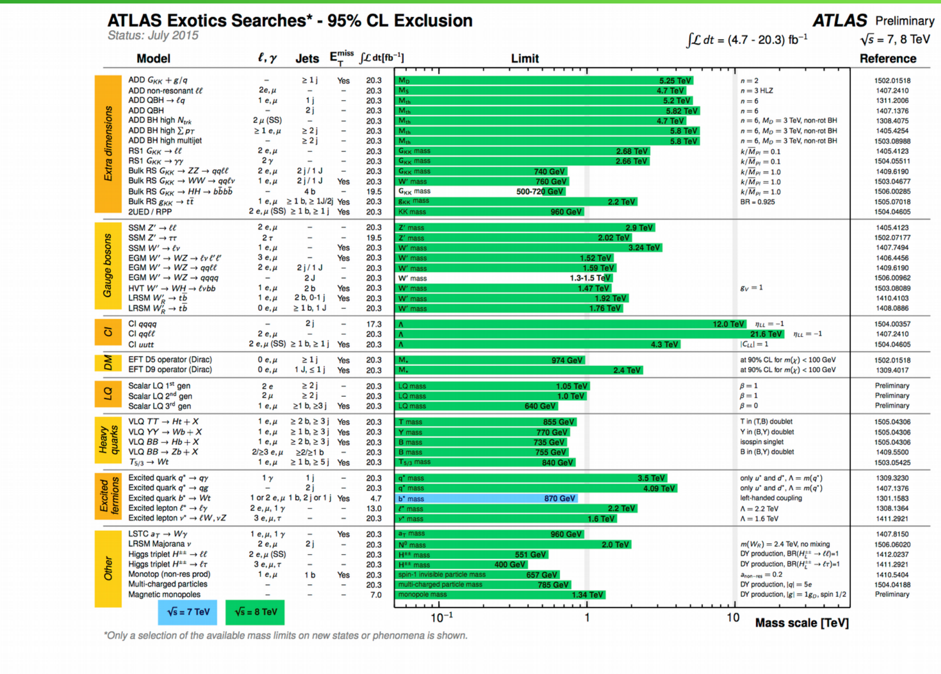
- Limits to masses of new particles being pushed in the TeV scale by the LHC.

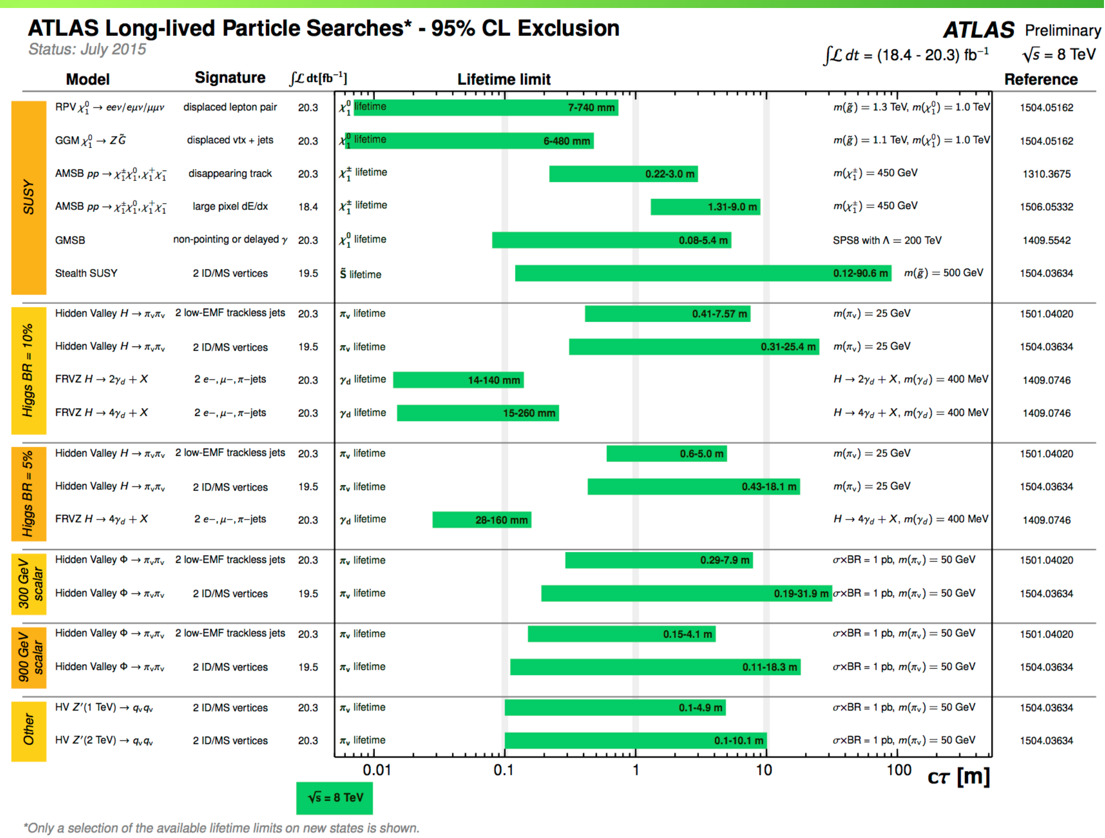
  → “protection” against a small Higgs mass getting weaker

ATLAS limits for SUSY



“Exotics” limits

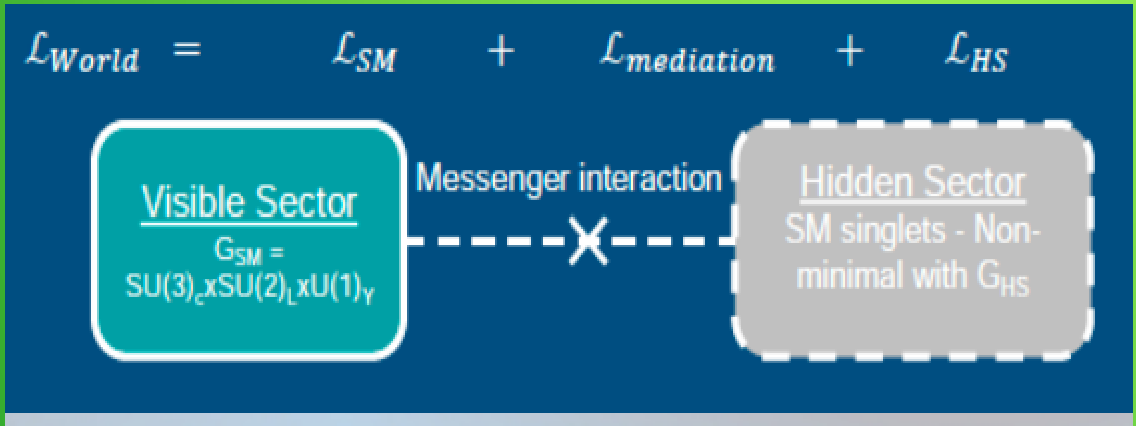




- Keep in mind: limits on particle lifetimes limited by size of LHC detectors

The “hidden sector” approach to new physics

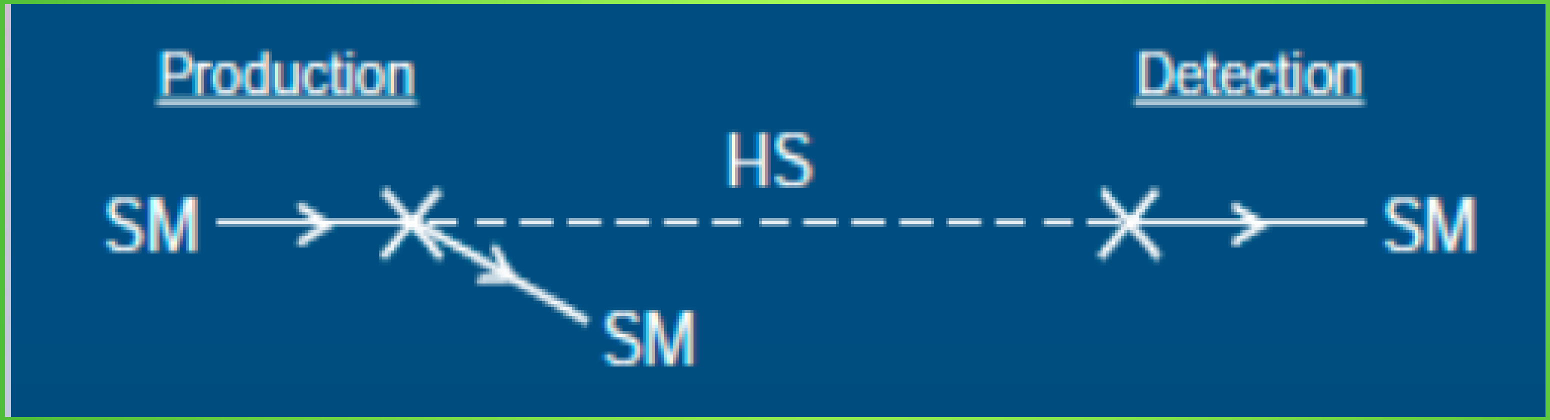
- Maybe new particles have not been yet found not because they are heavy, but because their coupling is very small, or null
- If an additional term to the Lagrangian is not interacting with SM, there could be invisible particles contributing to dark matter, and no naturalness issues
- However, an interference term between the Lagrangians would allow a very small coupling:



$$\mathcal{L}_{mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{HS}^{(k)} \mathcal{O}_{SM}^{(l)}}{\Lambda^n}$$

"Portals"

- Indications for a Hidden Sector may come from "ordinary" particles (SM, SUSY, axions etc.) acting as mediators with the HS Lagrangian
- The experimental signature is either missing energy or the appearance of SM particles very far away from its production, indicating an "oscillation" into the HS (and back)



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	$\pi^{0}\pi^{0}$

- Standard Model portals:
  - **D = 2: Vector portal**
    - Kinetic mixing with massive dark/secluded/paraphoton V : $\frac{1}{2}\varepsilon F^{SM}_{\mu\nu} F^{\mu\nu}_{HS}$

    ➔ Interaction with 'mirror world' constituting dark matter
  - **D = 2: Higgs portal**
    - Mass mixing with dark singlet scalar χ : $(\mu\chi + \lambda\chi^2)H^\dagger H$ $\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\rho & -\sin\rho \\ \sin\rho & \cos\rho \end{pmatrix} \begin{pmatrix} \phi_0' \\ S' \end{pmatrix}$

    ➔ Mass to Higgs boson and right-handed neutrino, and function as inflaton in accordance with Planck and BICEP measurements
  - **D = 5/2: Neutrino portal**
    - Mixing with right-handed neutrino N (Heavy Neutral Lepton): $YH^\dagger \bar{N}L$

    ➔ Neutrino oscillation, baryon asymmetry, dark matter
  - **D = 4: Axion portal**
    - Mixing with Axion Like Particles, pseudo-scalars pNGB, axial vectors : $\frac{a}{F} G_{\mu\nu}\tilde{G}^{\mu\nu}$, $\frac{\partial_\mu a}{F}\bar{\psi}\gamma_\mu\gamma_5\psi$, etc

    ➔ Solve strong CP problem, Inflaton
  - And possiby higher dimensional operator portals and **SUper-SYmmetric portals** (light neutralino, light sgoldstino,…)

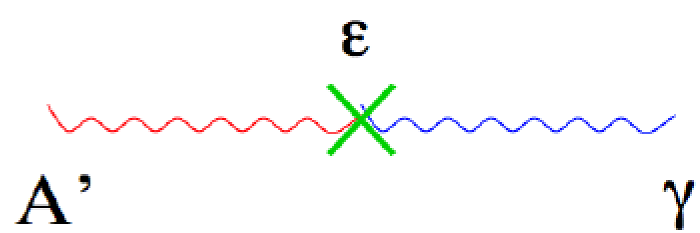
    ➔ SUSY parameter space explored by LHC

    ➔ Some of SUSY low-energy parameter space open to complementary searches

Vector and scalar portals

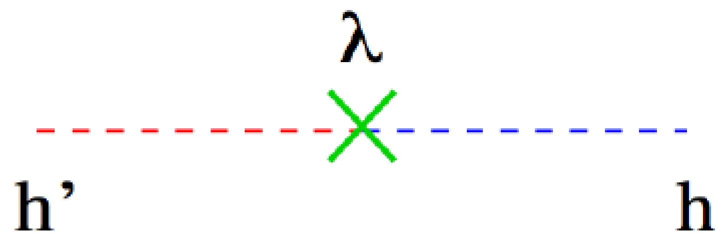
- Vector Portal:
  (A' = "hidden photon")

$$\epsilon F'_{\mu\nu} F^{\mu\nu}$$



- Higgs Portal:
  (H' = "hidden Higgs")

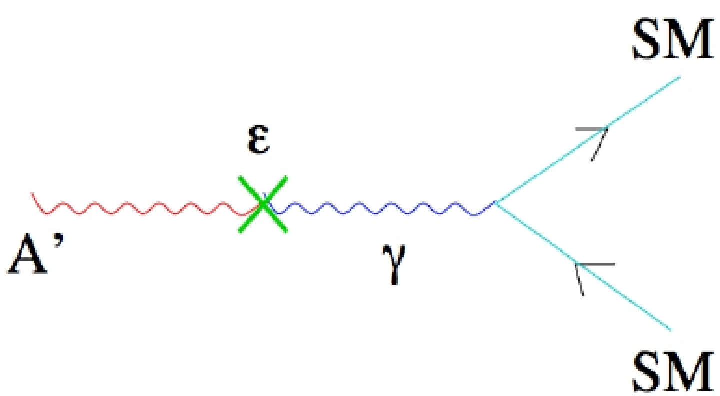
$$\lambda |H'|^2 |H|^2$$

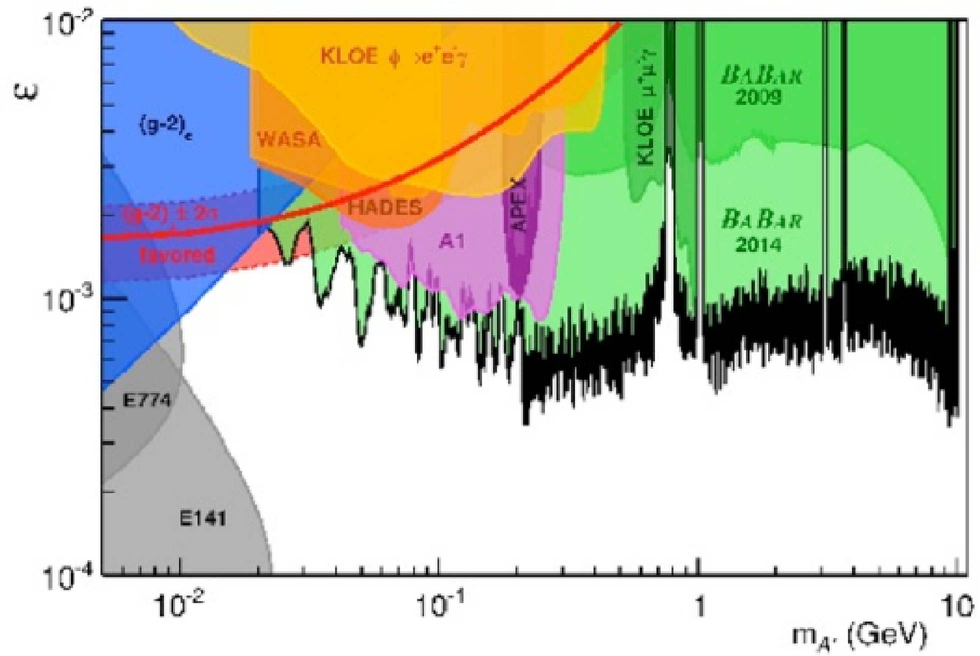


Vector portal search at colliders: the BaBar example

Minimal Vector Portal

- Hidden photon A' with mass $m_{A'}$, A' → SM+SM:





[Bjorken, Essig, Schuster, Toro 2009; ...; BaBar 2014]

Sterile neutrinos

Fermions get mass via the Yukawa couplings:

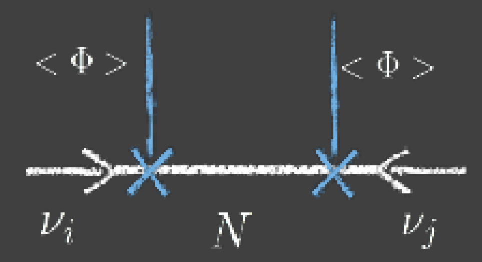
$$-\mathcal{L}_{\text{Yukawa}} = Y^d_{ij}\overline{Q_{Li}}\phi D_{Rj} + Y^u_{ij}\overline{Q_{Li}}\tilde{\phi} U_{Rj} + Y^\ell_{ij}\overline{L_{Li}}\phi E_{Rj} + \text{h.c.}$$

If we want the same coupling for neutrinos, we need right-handed (sterile) neutrinos… the most generic Lagrangian is

$$\mathcal{L}_N = i\overline{N}_i\partial_\mu\gamma^\mu N_i - \frac{1}{2}M_{ij}\overline{N^c}_i N_j - Y^\nu_{ij}\overline{L_{Li}}\tilde{\phi} N_j$$

Kinetic term | Majorana mass term | Yukawa coupling

$$U_{I\ell} \sim \frac{M_D^\ell}{M_N^I} = \frac{Y_{I\ell}v}{M_N^I}$$



Seesaw mechanism:

$$\mathcal{V} = (\nu_{Li}, N_j)$$

$$-\mathcal{L}_{M_\mathcal{V}} = \frac{1}{2}\overline{\mathcal{V}} M_\mathcal{V} \mathcal{V} + h.c.$$

if $M_N \gg M_D$:

$$M_\nu = \begin{pmatrix} 0 & M_D \\ {M_D}^T & M_N \end{pmatrix}$$

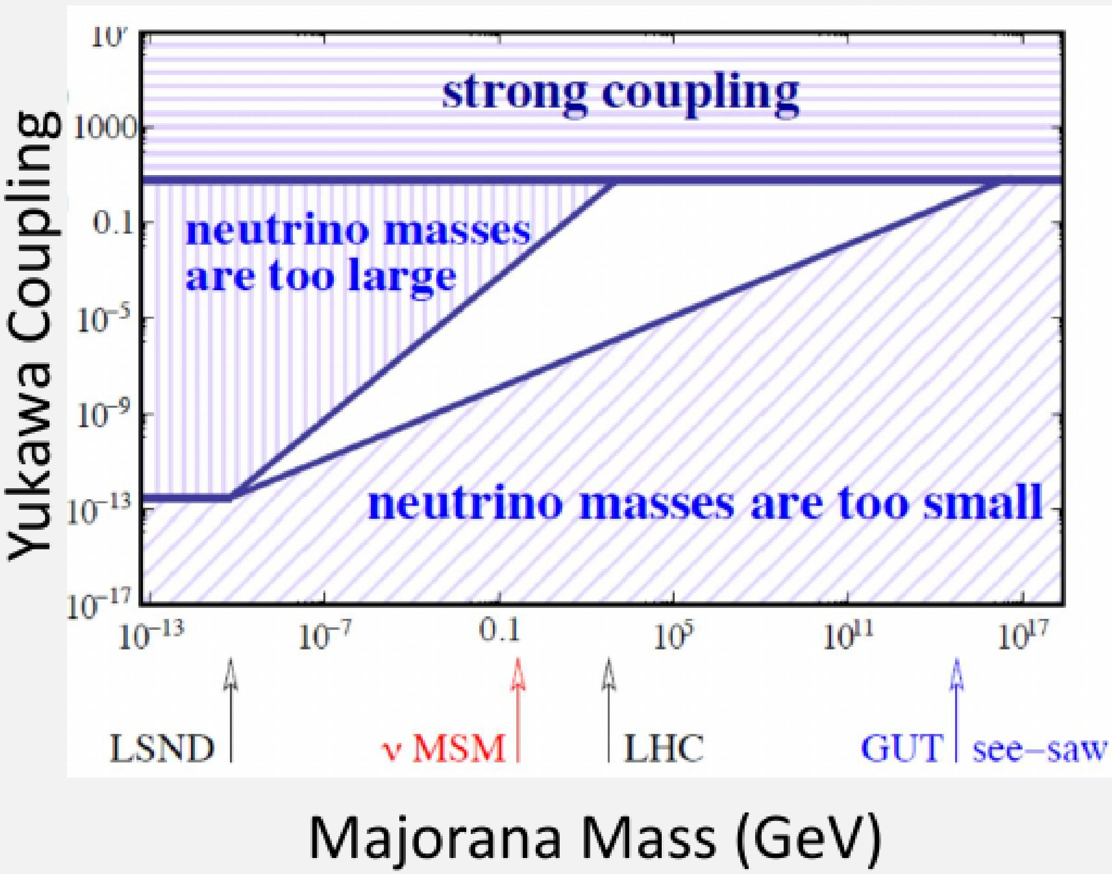
$$\lambda_\pm = \frac{M_N \pm \sqrt{M_N^2 + 4M_D^2}}{2}$$

$$\lambda_- \sim \frac{M_D^2}{M_N}$$

$$\lambda_+ \sim M_N$$

The see-saw mechanism

Seesaw formula $m_D \sim Y_{I\alpha} < \phi >$ and $m_\nu = \frac{m_D^2}{M}$

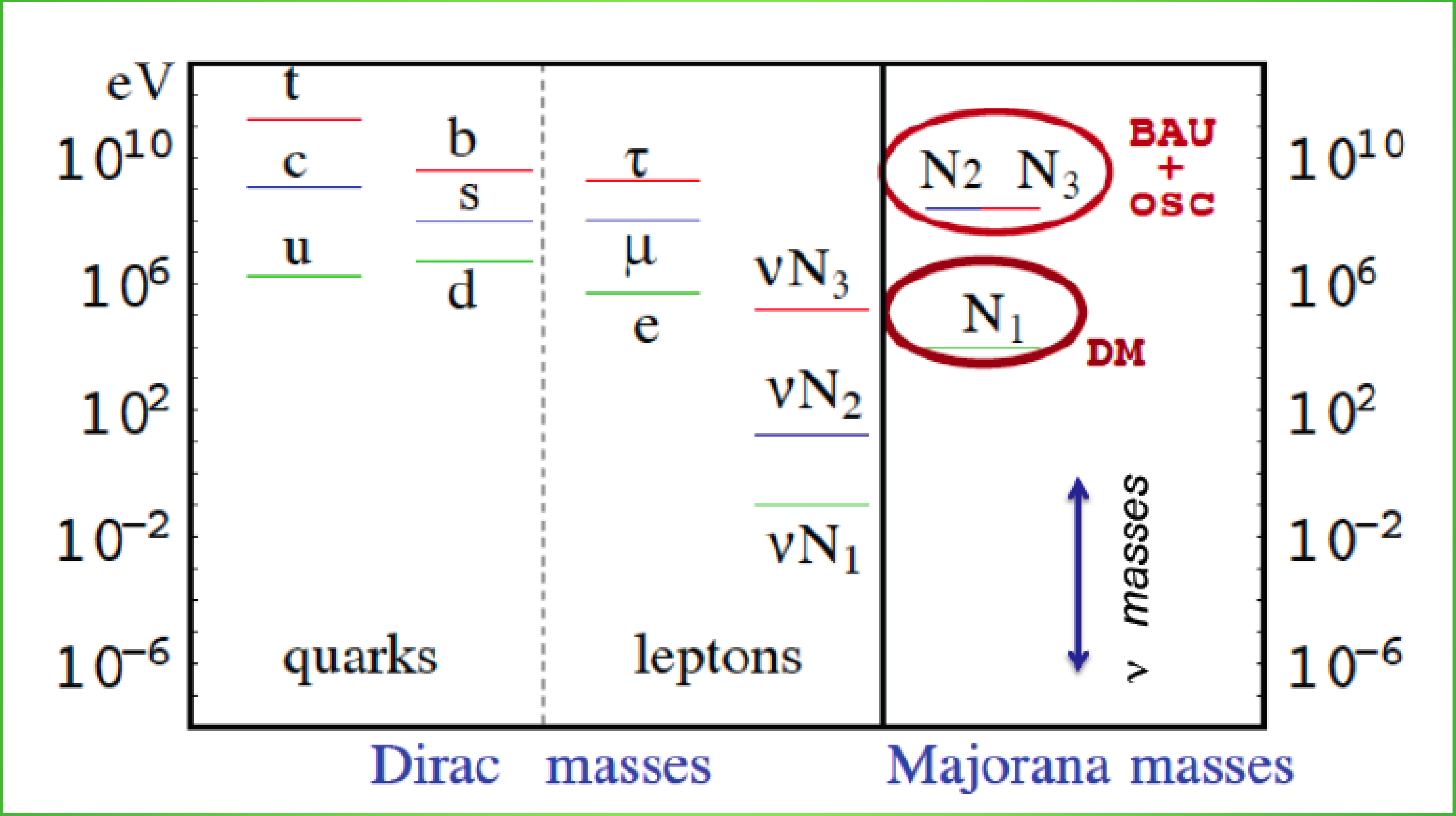


- Assuming $m_\nu = 0.1\text{eV}$
- if $Y \sim 1$ implies $M \sim 10^{14}\text{GeV}$
- if $M_N \sim 1\text{GeV}$ implies $Y_\nu \sim 10^{-7}$

remember $Y_{top} \sim 1.$ and $Y_e \sim 10^{-6}$

If we want to explain the smallness of neutrino masses (in a natural way) the mass of sterile neutrinos should be at least at the GeV scale

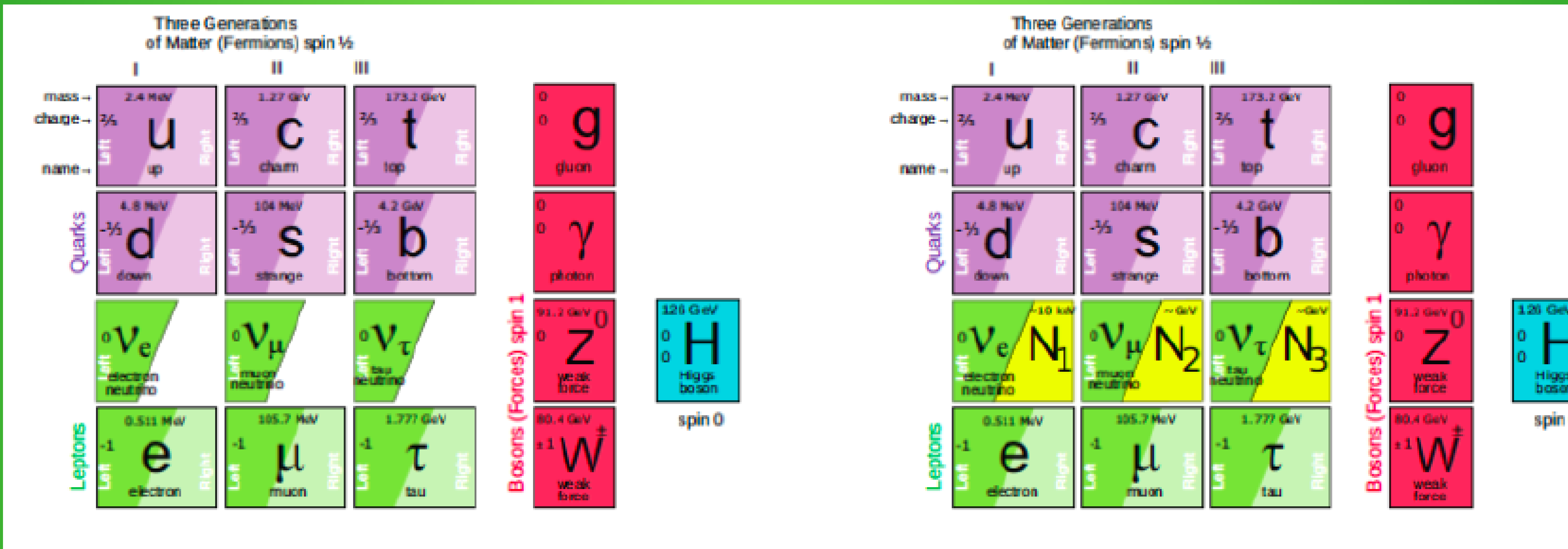
Resulting mass ranges



- Sterile neutrinos could have masses and couplings similar to those of the ordinary charged leptons

The νMSSM

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

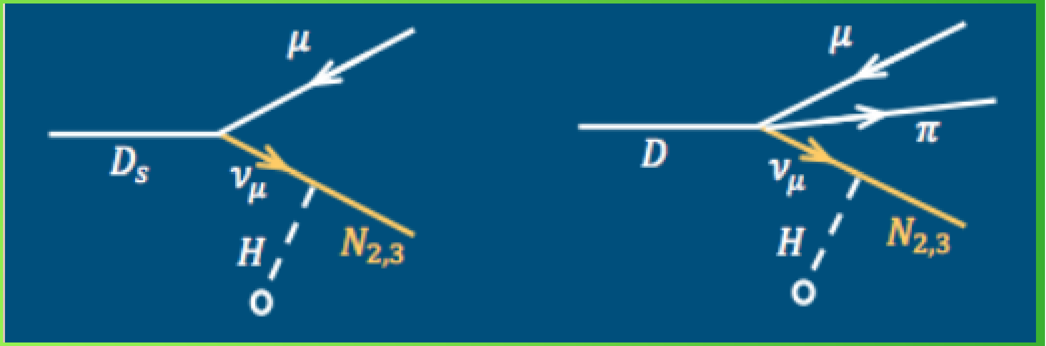


Particle content of SM made symmetric by adding 3 HNL: N_1, N_2, N_3

With M(N) ~ few KeV, it is a good DM candidate (or DM can be generated outside of this model through decay of inflaton)

With M(N , N) ~ GeV, could explain Barion Asymmetry of Universe (via leptogenesis), and generate neutrino masses through see-saw.

HNL production mechanism

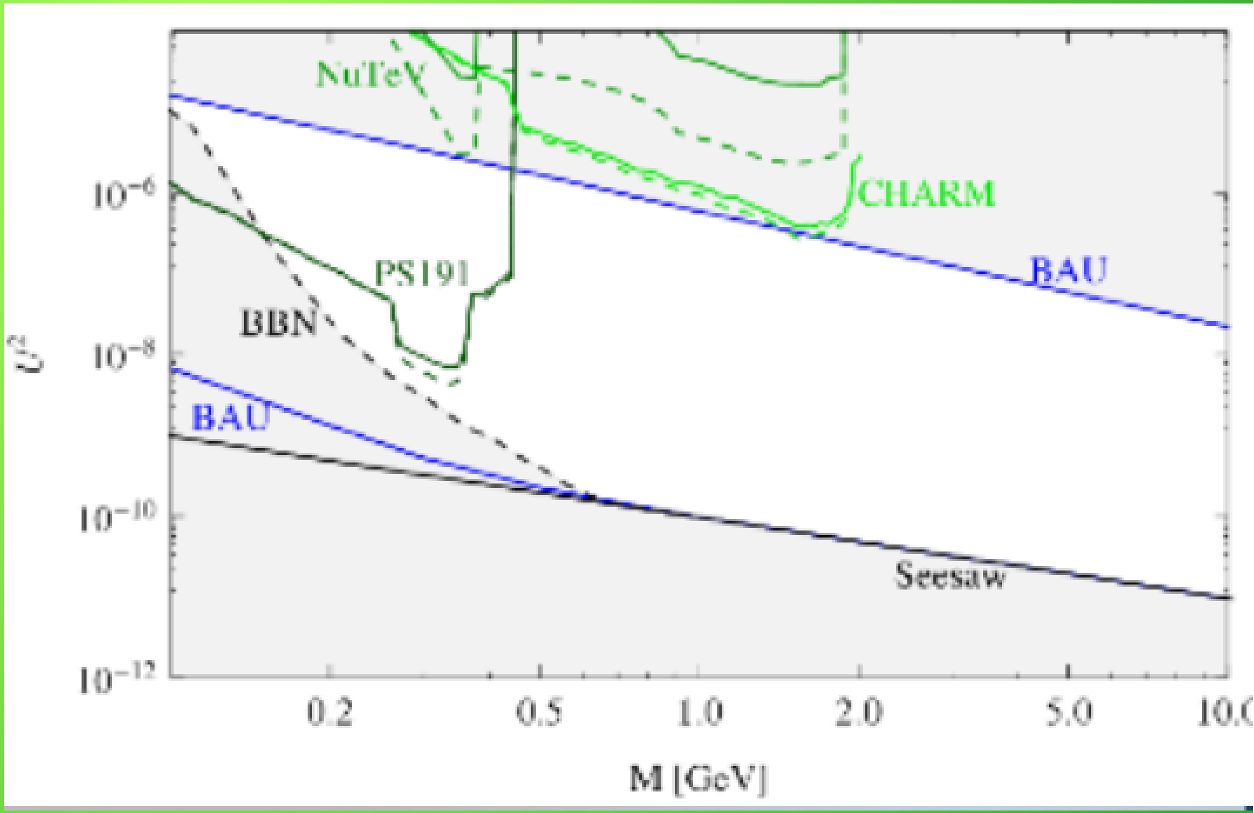


Interaction with Higgs vev leads to a mixing with active neutrinos

Several past searches; PS191 used neutrinos from K decays, while other experiments not sensitive to mixings of cosmological interest.

Latest result: LHCb with B decays obtained U2≈10-4, arXiv:1401.5361

Further exploration needed of the region with higher masses and smaller mixings

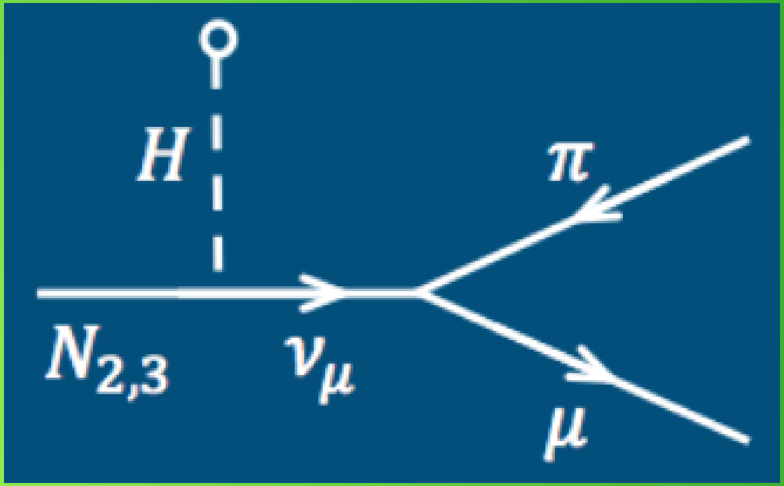


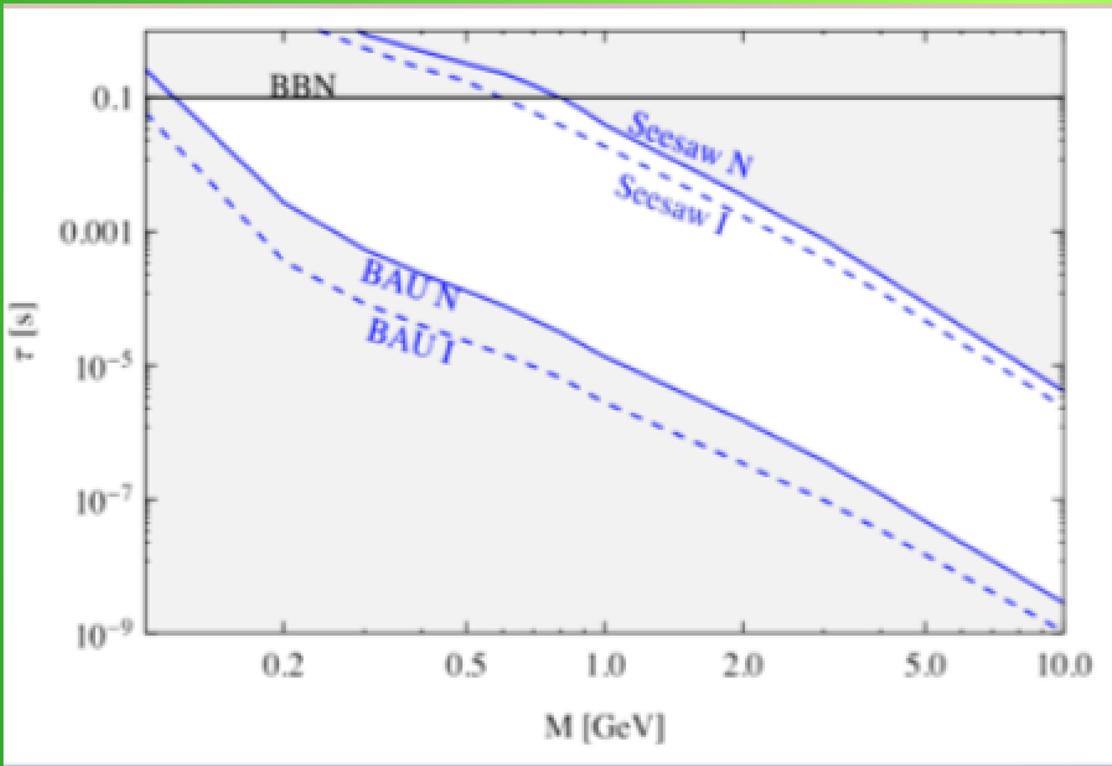
HNL decay modes

Interaction with Higgs vev would make it oscillate back into a virtual neutrino, that produces a muon and a W (→ hadrons, eg pions)

Exact branching fractions depend n flavor mixing

Due to small couplings, ms lifetimes, decay paths O(km)

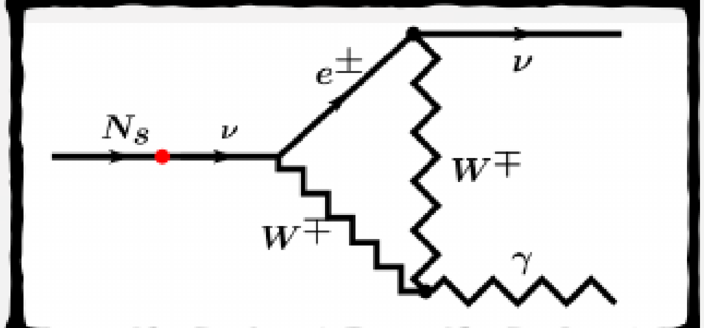


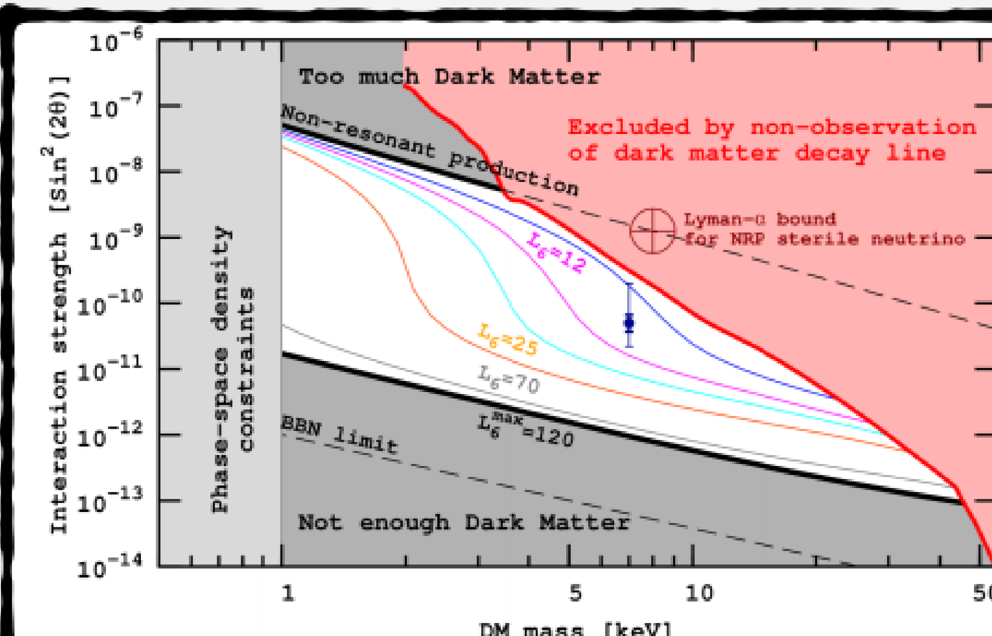


Decay mode	Branching ratio
$N_{2,3} \to \mu/e + \pi$	0.1 - 50 %
$N_{2,3} \to \mu^-/e^- + \rho^+$	0.5 - 20 %
$N_{2,3} \to \nu + \mu + e$	1 - 10 %

Constraints on N_1 mass

DM sterile neutrinos decay subdominantly as $N_1 \to \nu\gamma$ with a branching ration $\mathcal{B}(N_1 \to \gamma\nu) \sim \frac{1}{123}$





Discussion in the community, not yet clear if this is a "good" signal, needs confirmation

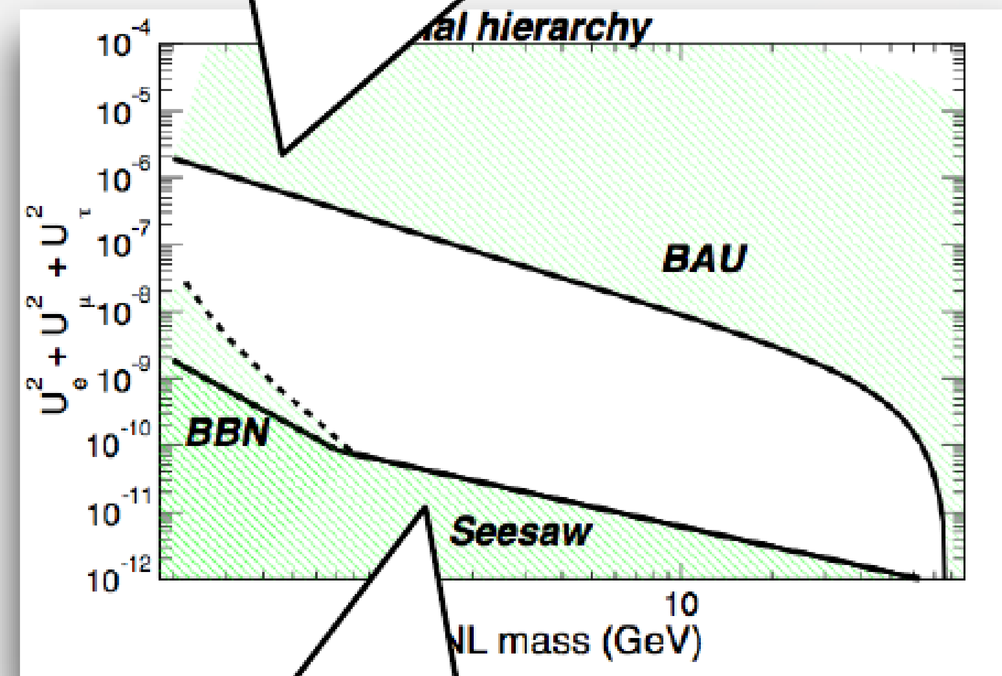
Bulbul et al. 2014 (arXiv:1402.2301)

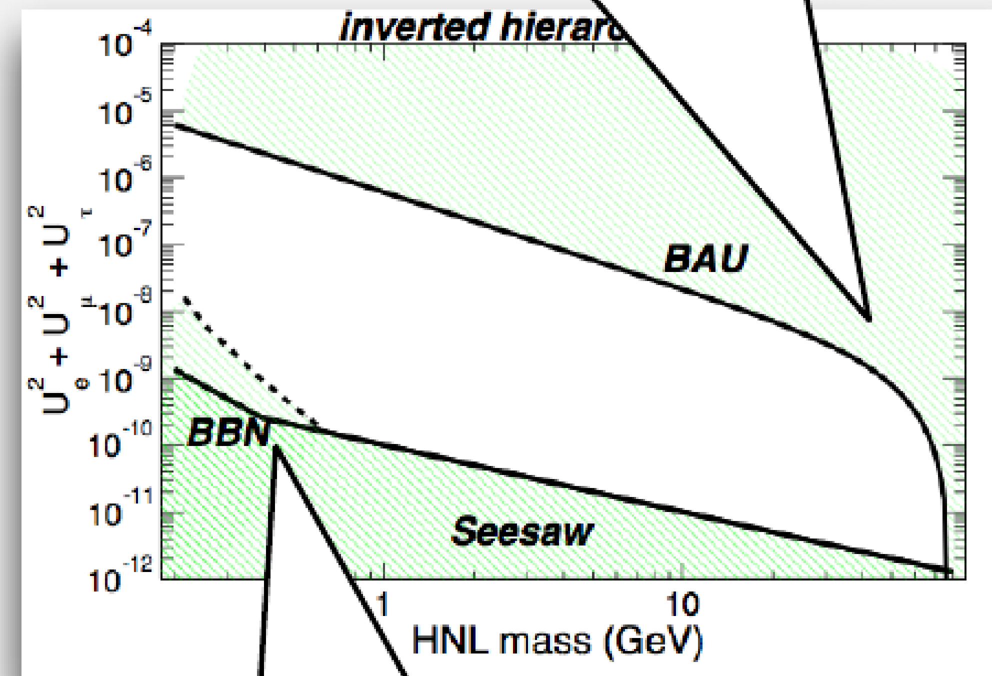
Boyarsky et al. 2014 (arXiv:1402.4119)

Constraints on N_2, N_3 masses

If U^2 is too large, $N_{2,3}$ are in **thermal equilibrium** during the expansion of the Universe

At $M_N \geq M_W$ the rate is **enhanced** by $N \rightarrow Wl$ leading to stronger constraints on U^2





The **seesaw** limit defines the region where $N_{2,3}$ can explain the observed active neutrino Δm^2

If $\tau(N_2, N_3) < 0.1\ s$, they cannot affect the **Big Bang nucleosynthesis**

High-mass searches at the LHC

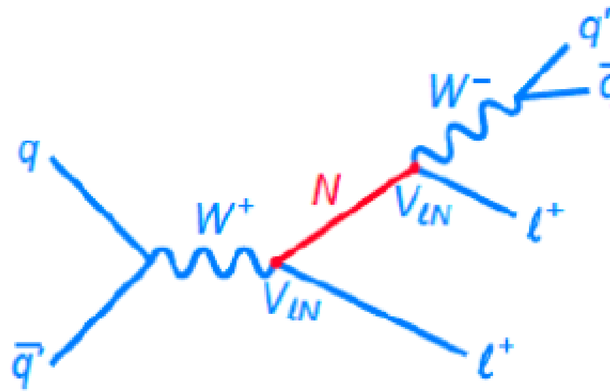
Unique possibility to explore HNL mass range above 100 GeV

✓ ***Experimental signature: two same-sign leptons and no missing energy***

Majorana-type N would contribute to the signal with both opposite-sign and same-sign leptons. Same-sign lepton events have much lower SM background

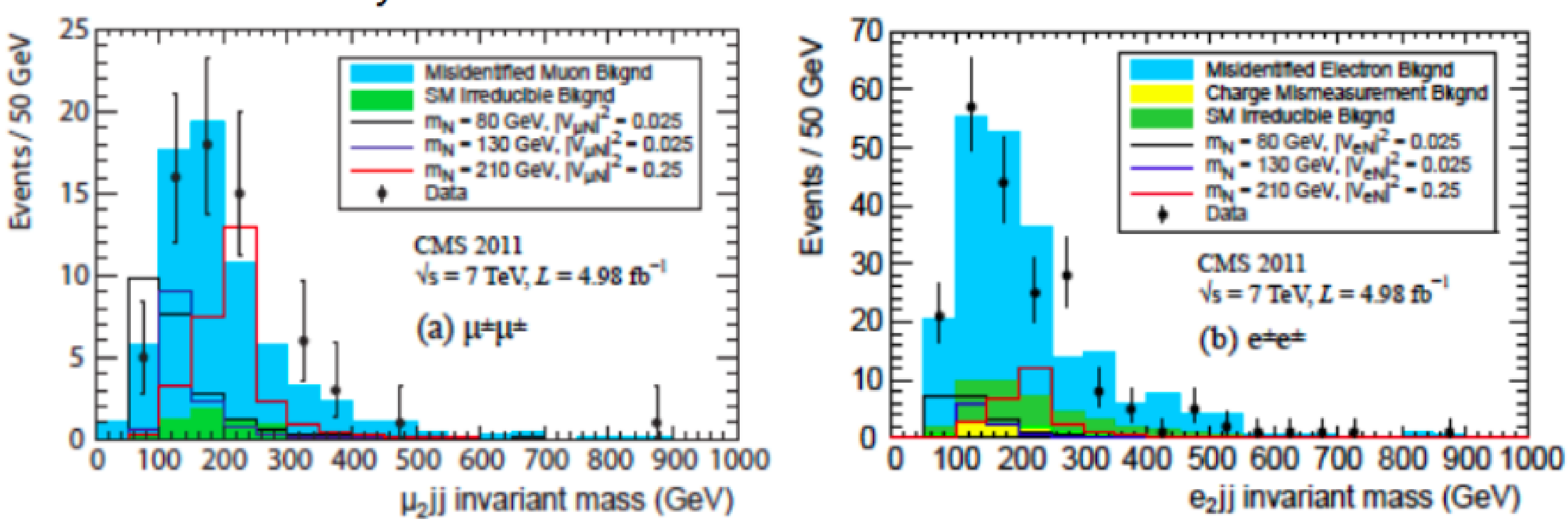
✓ *With currently available data samples experiments are only sensitive to large U^2 (or short lifetimes) of N*

For $U^2 > 10^{-4}$ (and $M_N \geq 50$ GeV) a typical N flight distance is ≤ 100 microns

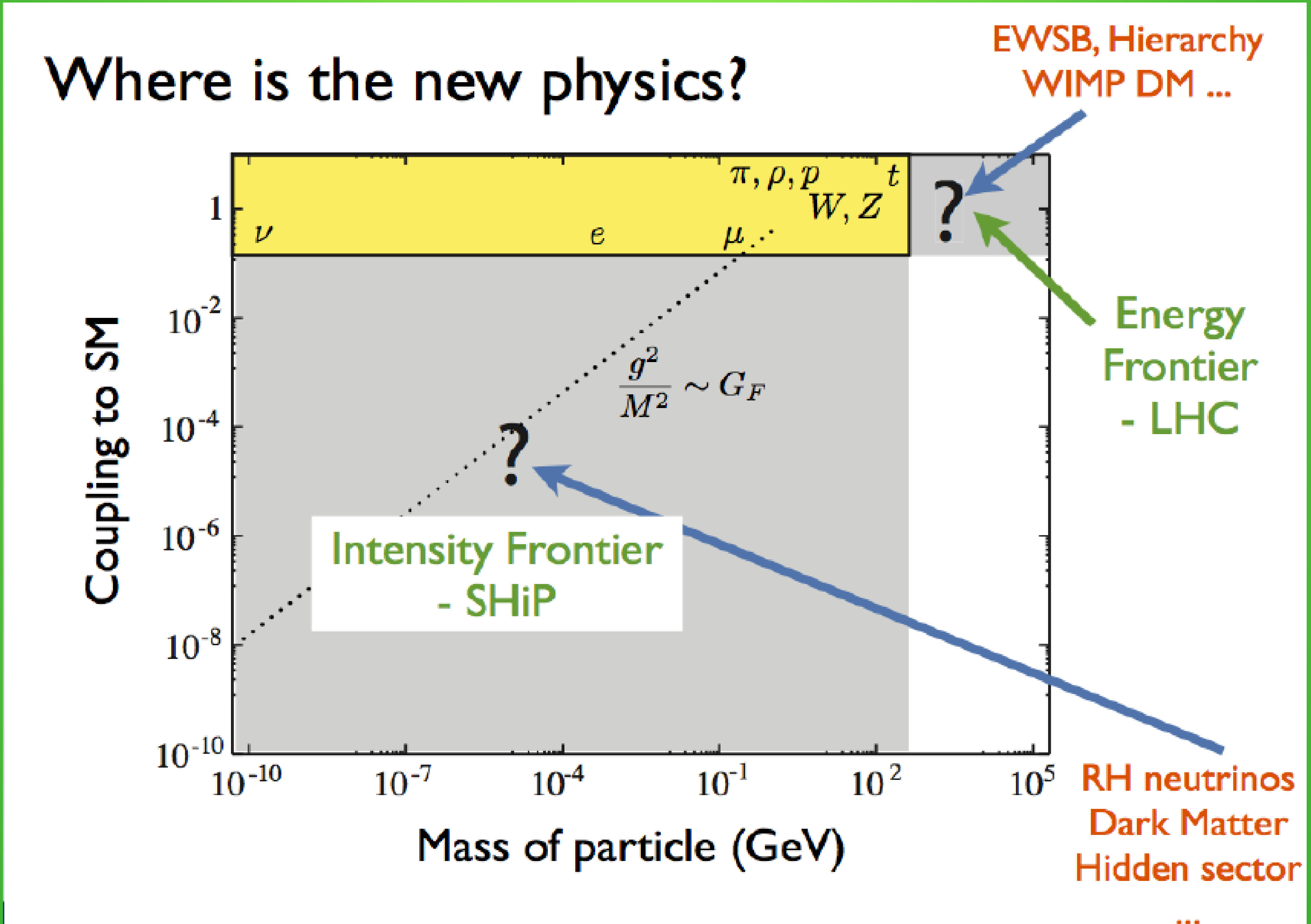


✓ *No use of detached vertex possible*

→ *large backgrounds from multi-jet events with faked leptons or leptons from b-decays*



Searches in the cosmologically-interesting region



Model-independent experimental considerations

We have to look for very weakly interacting particles:

- Production BR O(1E-10)
- Lifetimes O(km)
- Can travel through ordinary matter

Cosmologically interesting masses O(GeV)

- Produced through decays of mesons
- Can decay to mesons or charged leptons
- Full final-state reconstruction and particle ID

To have high intensities:

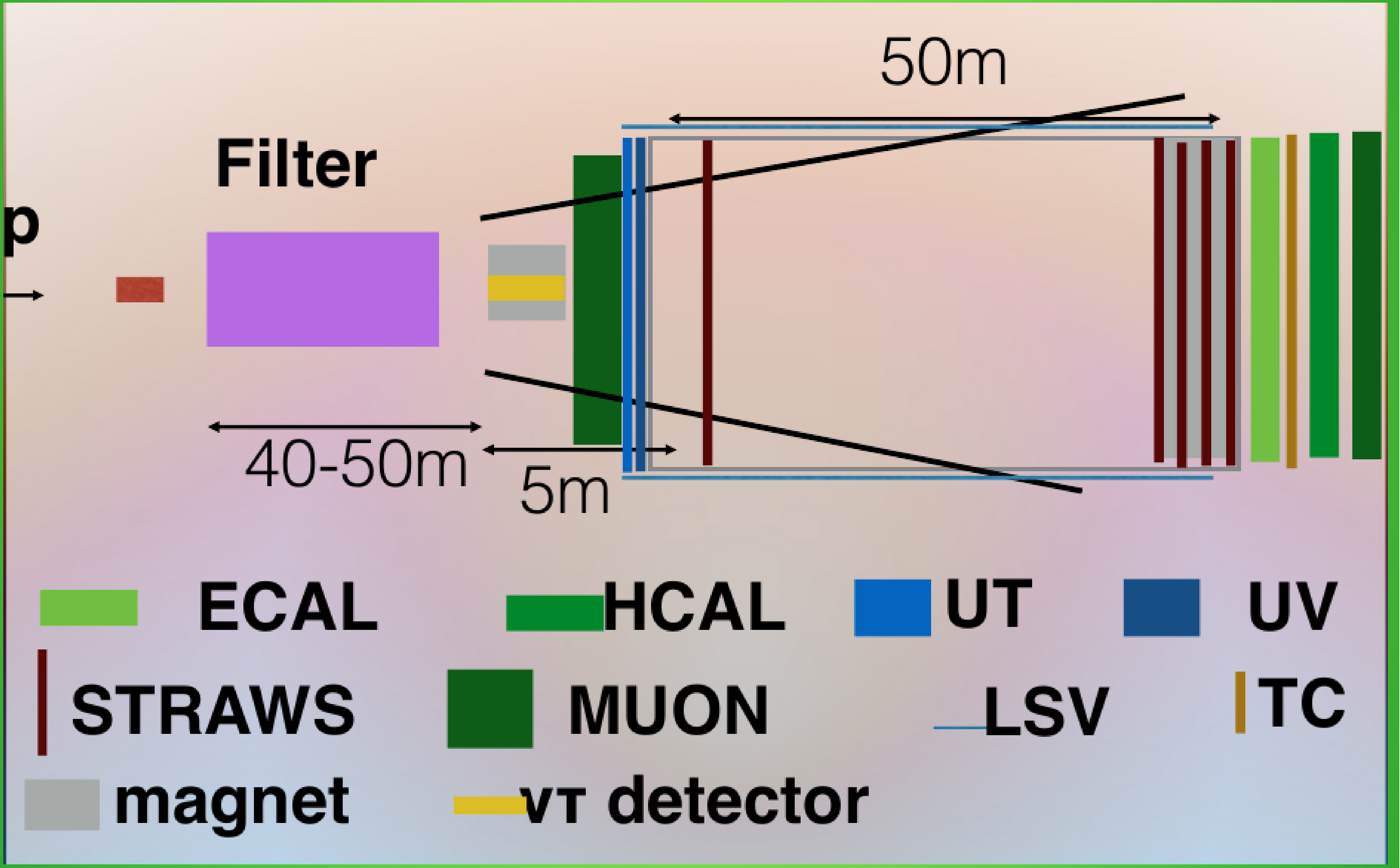
- fixed-target against a beam dump
- followed by a long decay tunnel and a spectrometer at the end

An experiment in practice

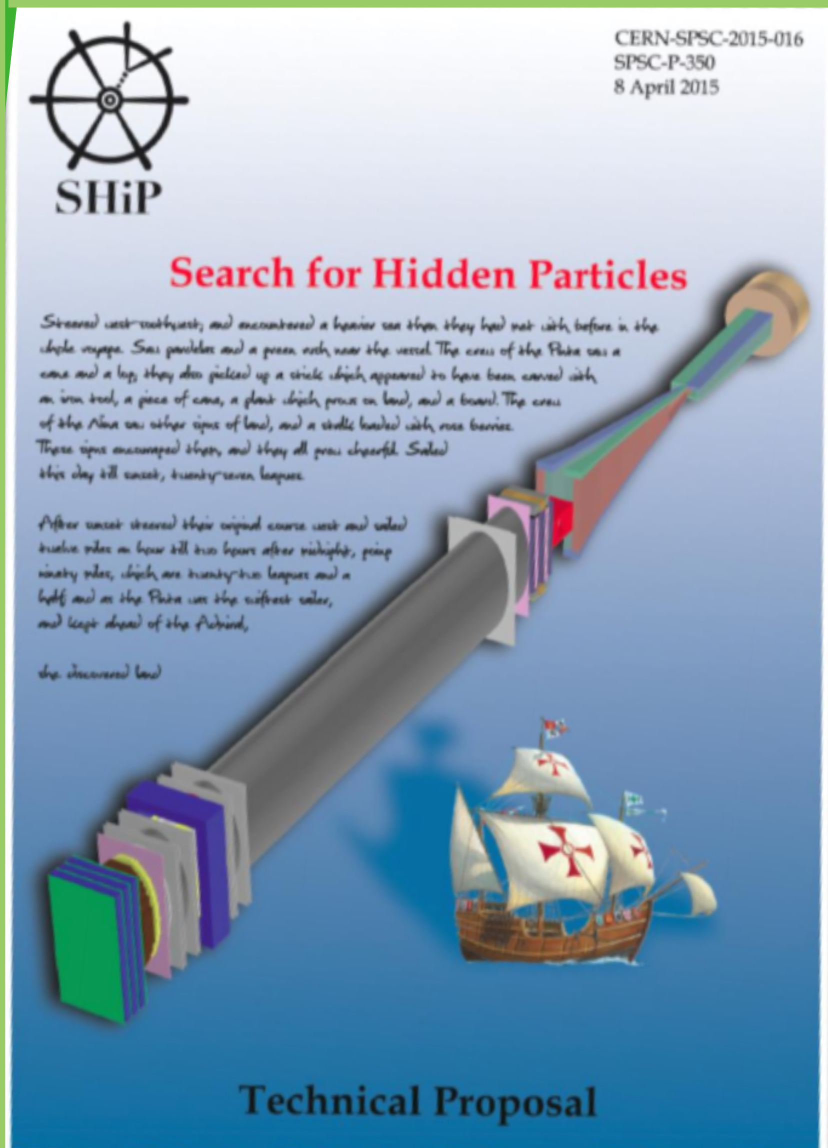
Use protons from CERN's SPS: 500 kW is 4x1E13 protons/7 s ->2E20 in 5y

- Slow (ms → 1s) and uniform extraction to reduce detector occupancy and combinatorics
- HS particles produced by mesons (mainly charm) decays; need to absorb all SM decay products to minimise BG → heavy material thick target, with wide beam to dilute energy deposition (different from neutrino facility)
- Muons cannot be absorbed by target: muon shield, possibly magnetised
- Long decay tunnel away from external walls to minimise rescattering of muons and neutrons close to detector
- Vacuum in decay tunnel to reduce neutrino interactions
- Far-away detector with good PID and resolutions

Schematically...



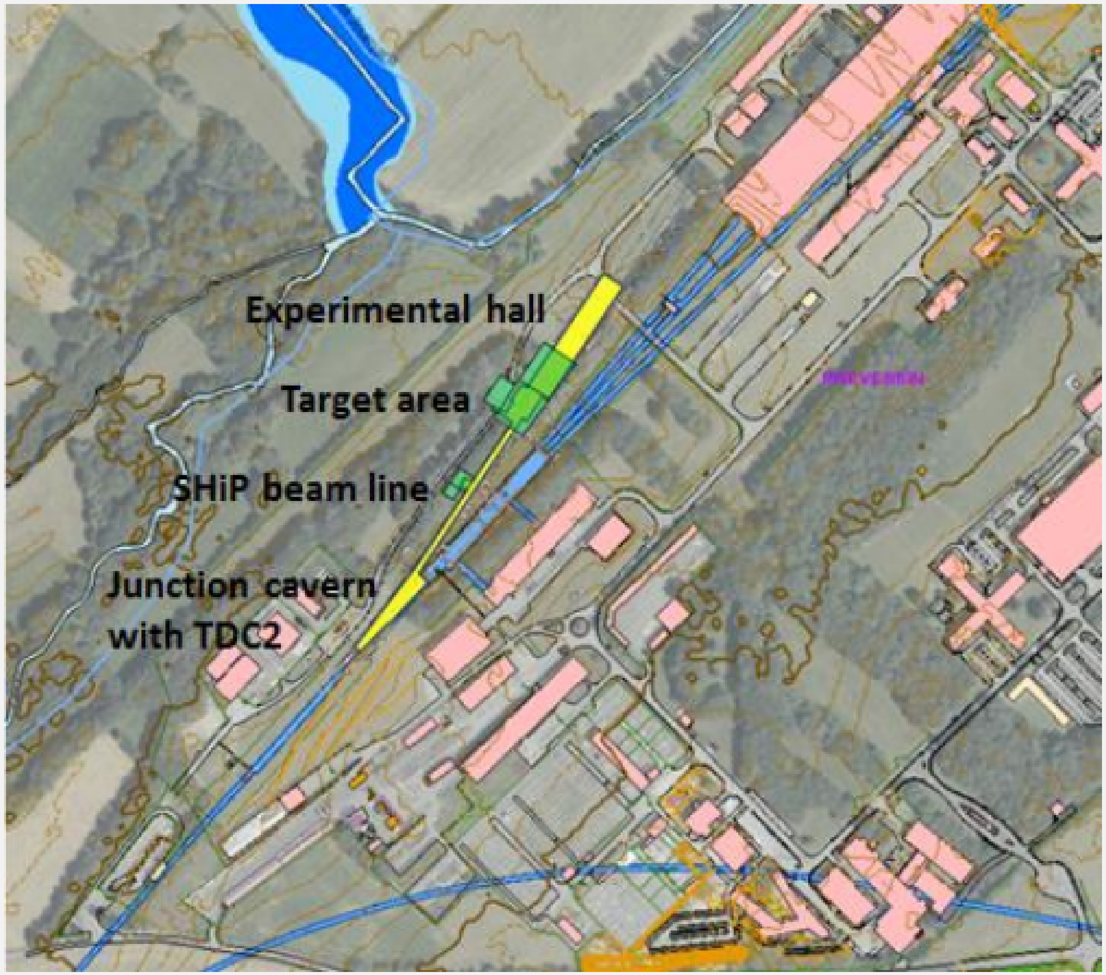
The ShiP proposal



- Proposal for a new facility at the CERN SPS accelerator:
  - hidden sector detector
  - ντ facility

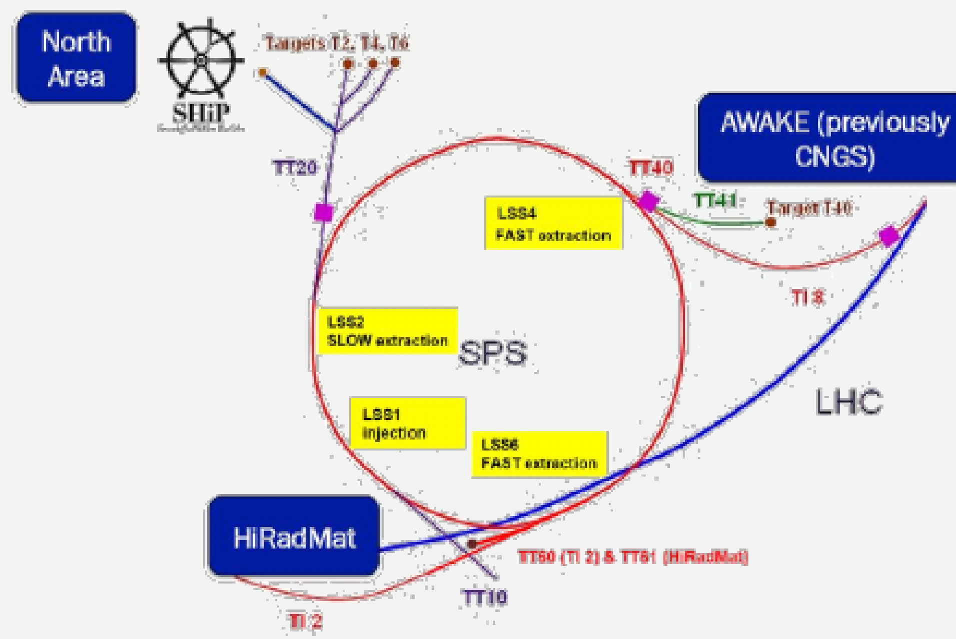
  235 experimentalists from 45 institutes and 15 countries + CERN
- Technical Proposal submitted in April (arXiv:1504.04956)
- Physics Proposal signed by 80 theorists (arXiv:1504.04855)
- Presently under scrutiny by the SPSC

The ShiP facility



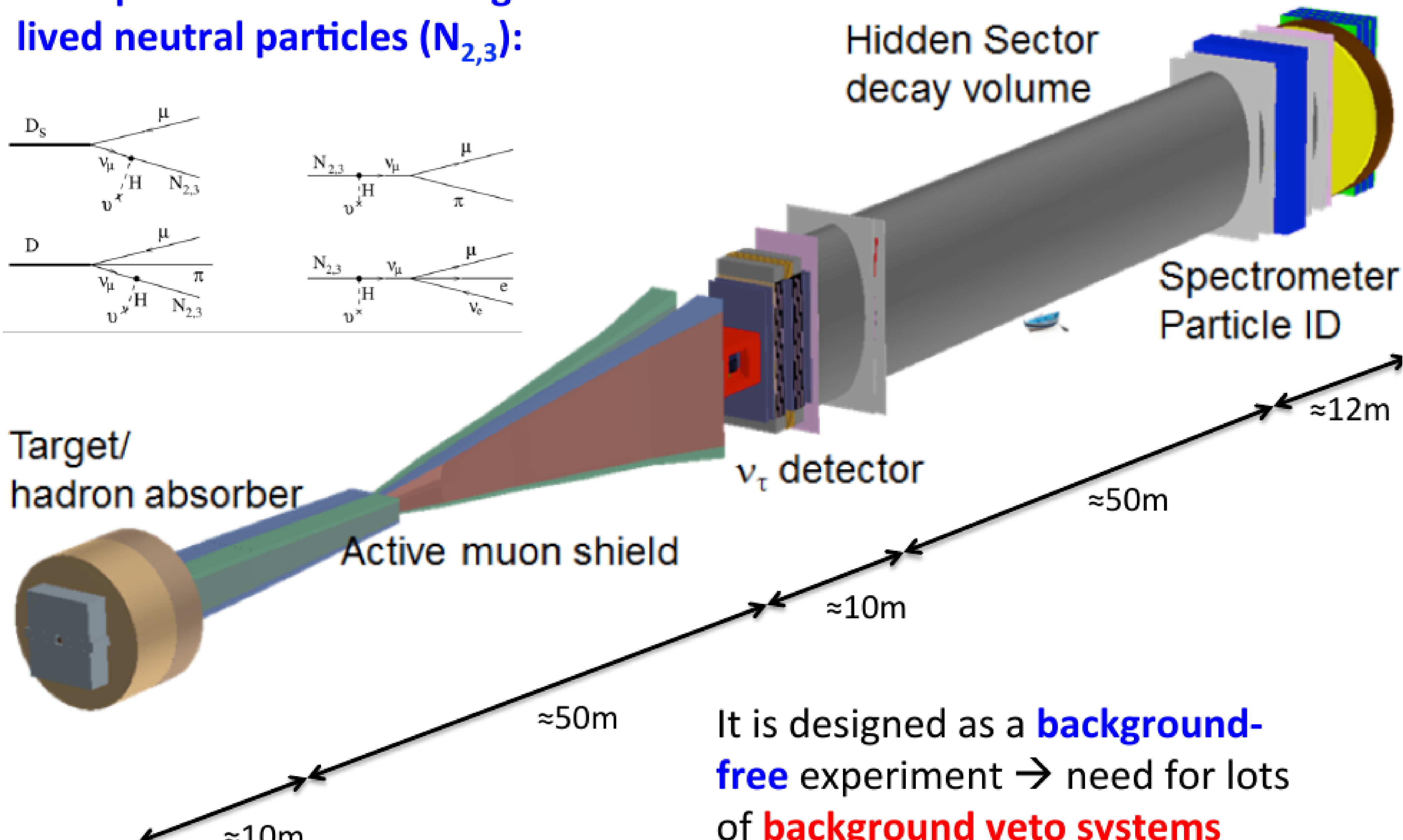
Proposed implementation is based on minimal modification to the SPS complex.

Share transfer line and slow extraction mode with existing facilities.



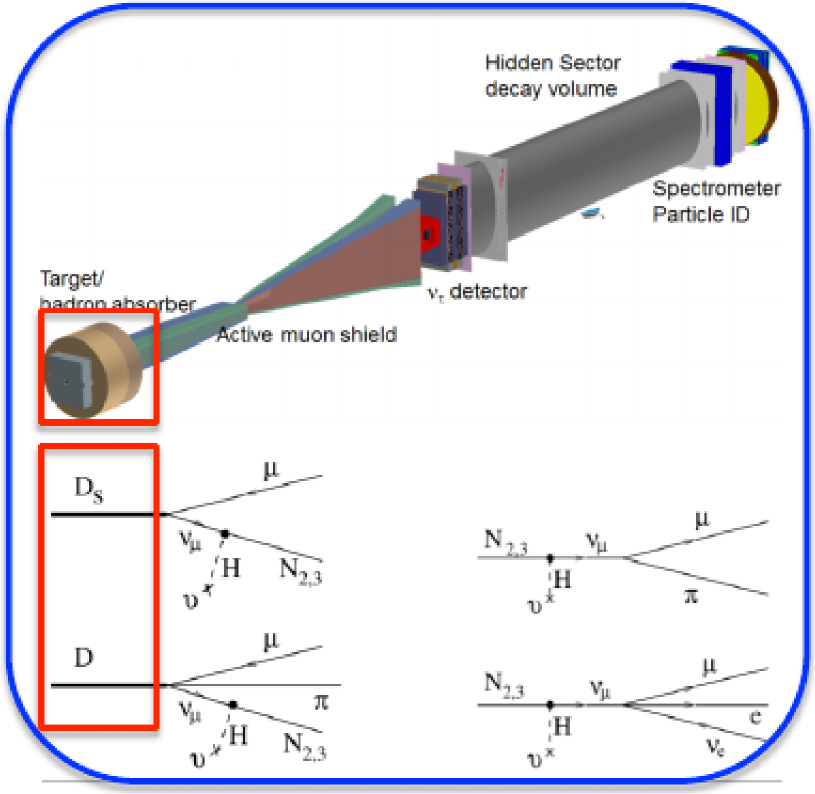
The ShiP experiment

Example of creation of long-lived neutral particles ($N_{2,3}$):

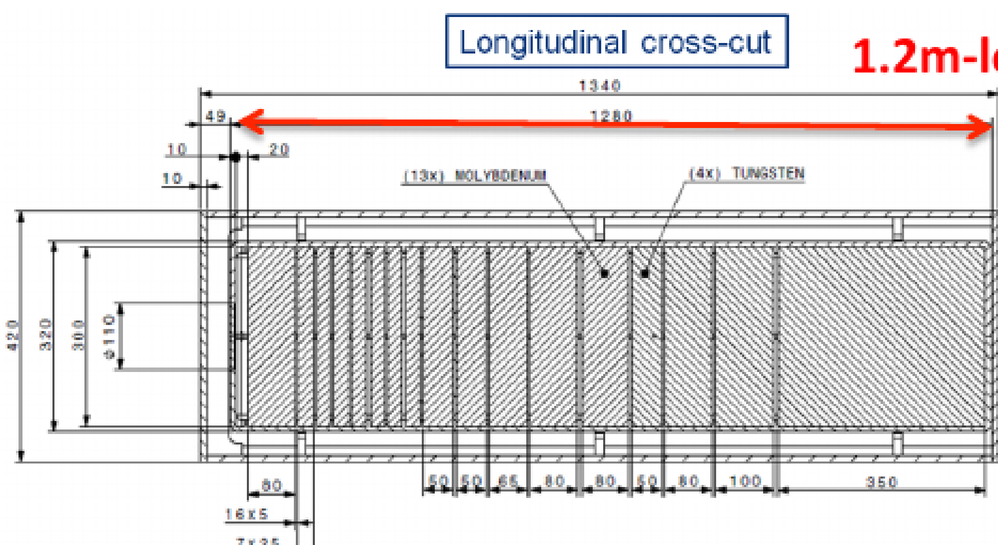


It is designed as a **background-free** experiment → need for lots of **background veto systems**

The target

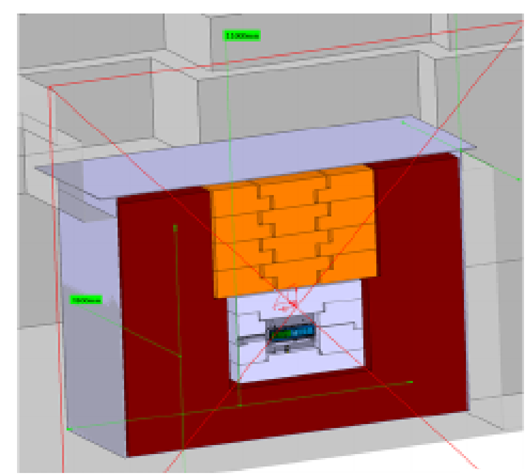


- **Challenging** due to high average beam power deposited on the target (2.56MW during spill of 1s (peak), ~350 kW averaged over 7s cycle)
- **Hybrid** target, with 58cm of titanium-zirconium doped molybdenum followed by 58cm of pure tungsten, water cooled
  - **Heavy** target to **suppress π/K decays**
  - Tungsten cannot be used at start because of too much thermo-mechanical stress
- Embedded in **cast iron bunker** ($440m^3$)



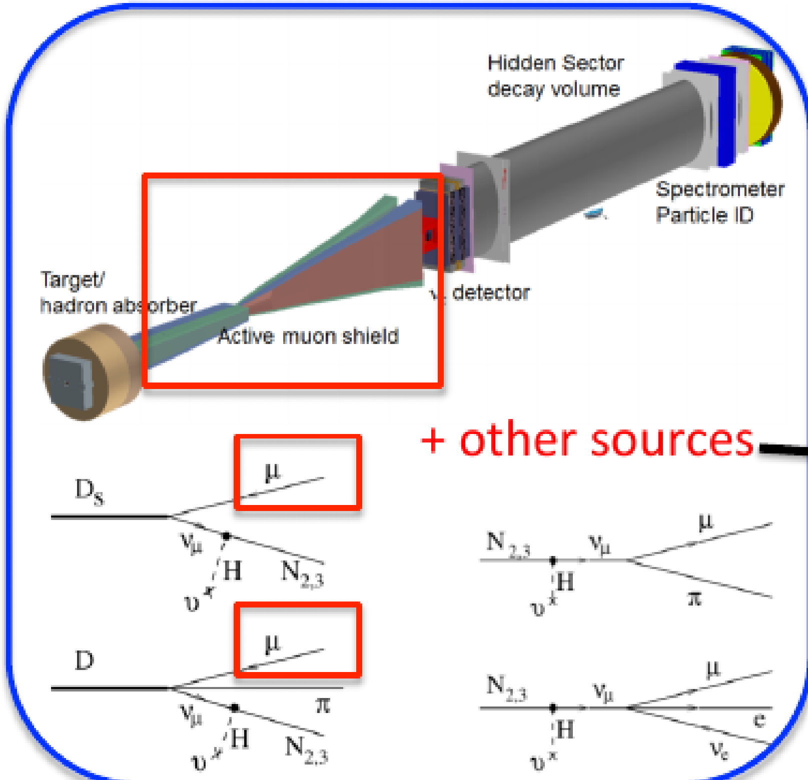
1.2m-long

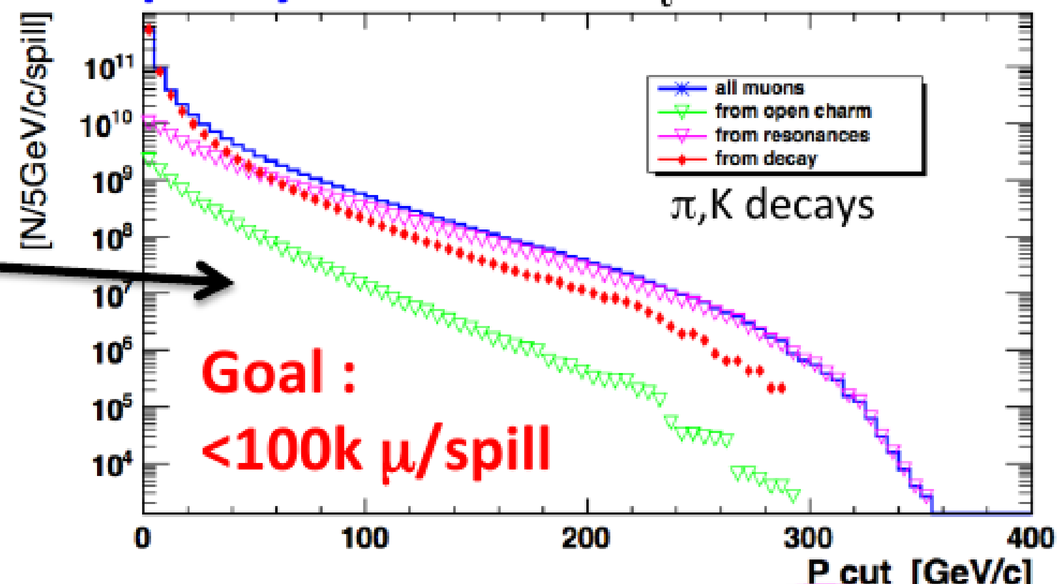
$30x30cm^2$ to maximize shower containment



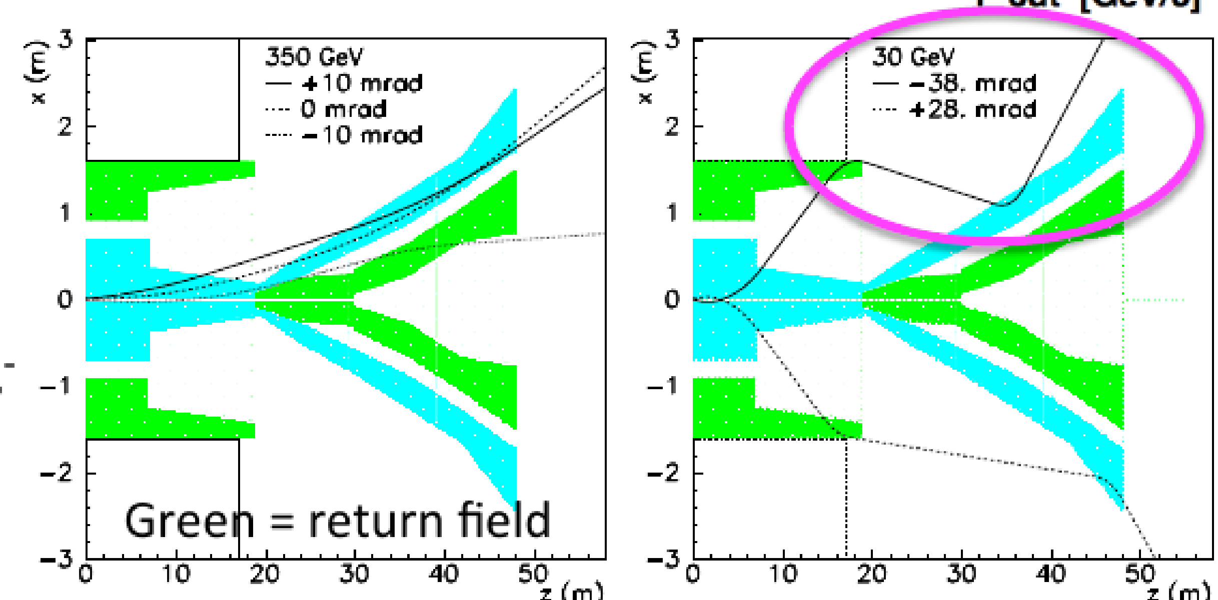
The muon filter

- **Clear the μ flux** to a level inferior to the ν-induced background and not to compromise the **occupancy limit** in the ν_τ detector

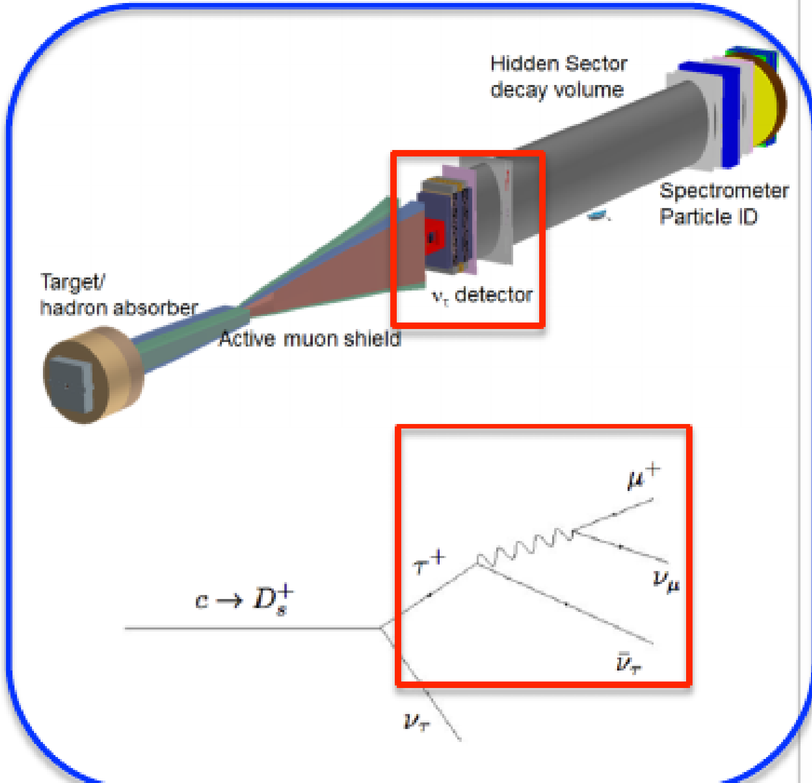


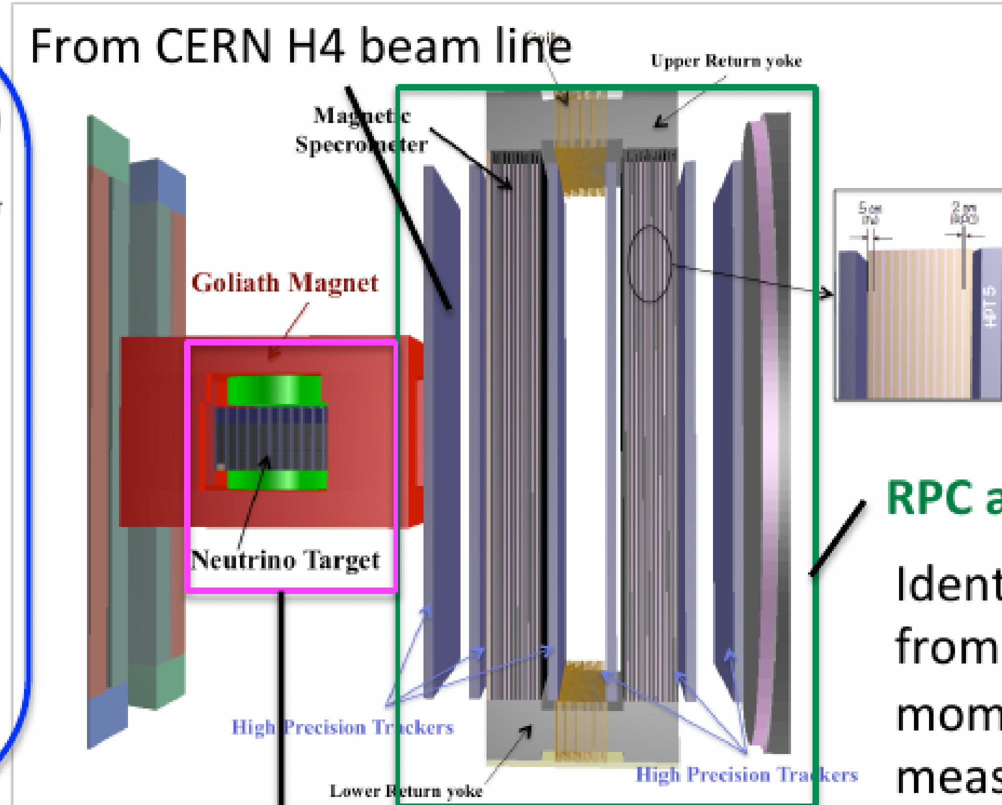


- **Active** muon filter made of two magnets (B_y = 40 Tm to bend out 350 GeV μ beyond the 5 m vacuum vessel aperture)
  - **1^{st} part** to separate μ^+/μ^-
  - **2^{nd} part** to bend the muons **further outward**



Bonus intermezzo: the ν_τ detector

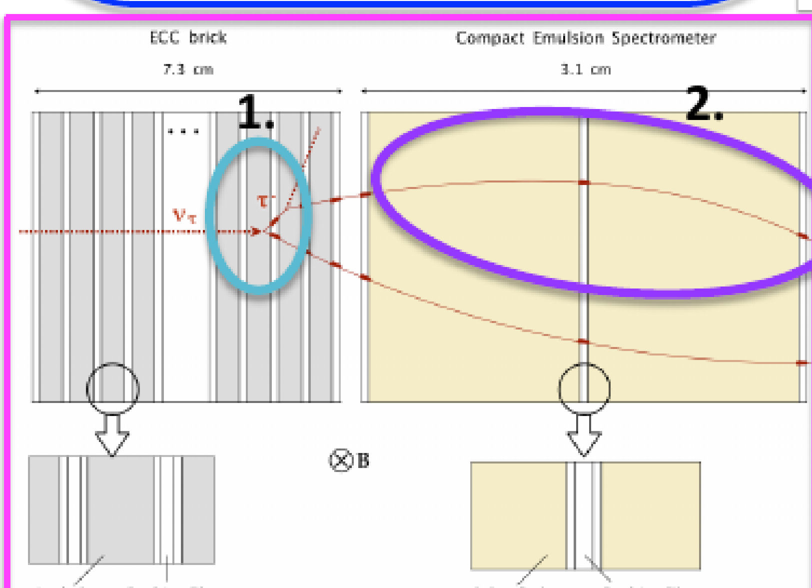




μ flux :
10^3 μ/mm^2
in 6 months

RPC and drift tubes

Identify μ coming from τ decays; μ momentum measurement

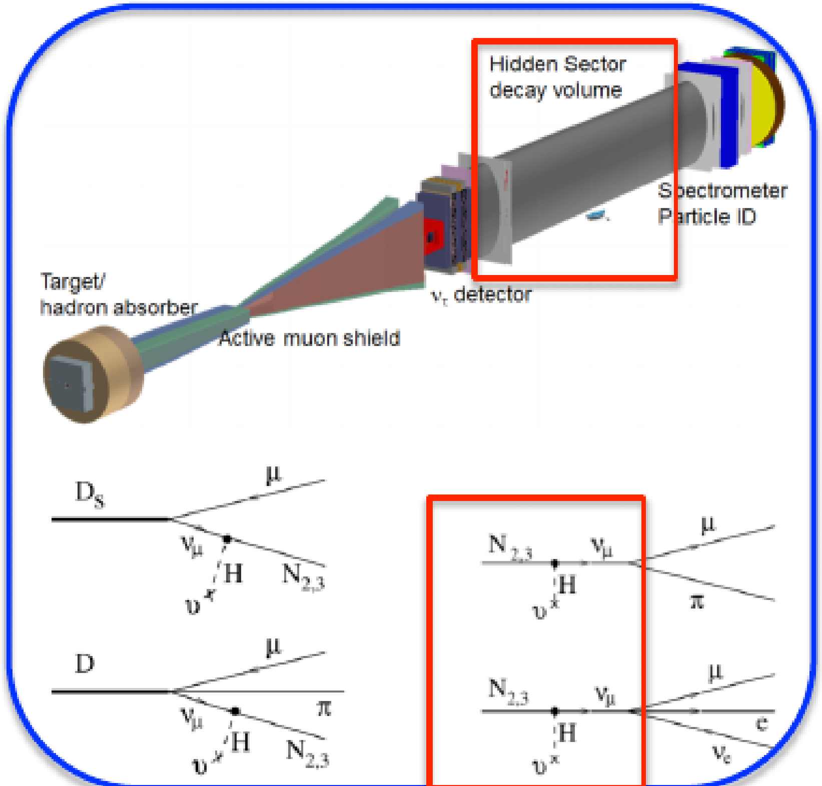


OPERA-type modules (emulsion cloud chambers (ECC))

- 1x1m, close to the beam line
- 2 parts : ECC brick and compact spectrometer

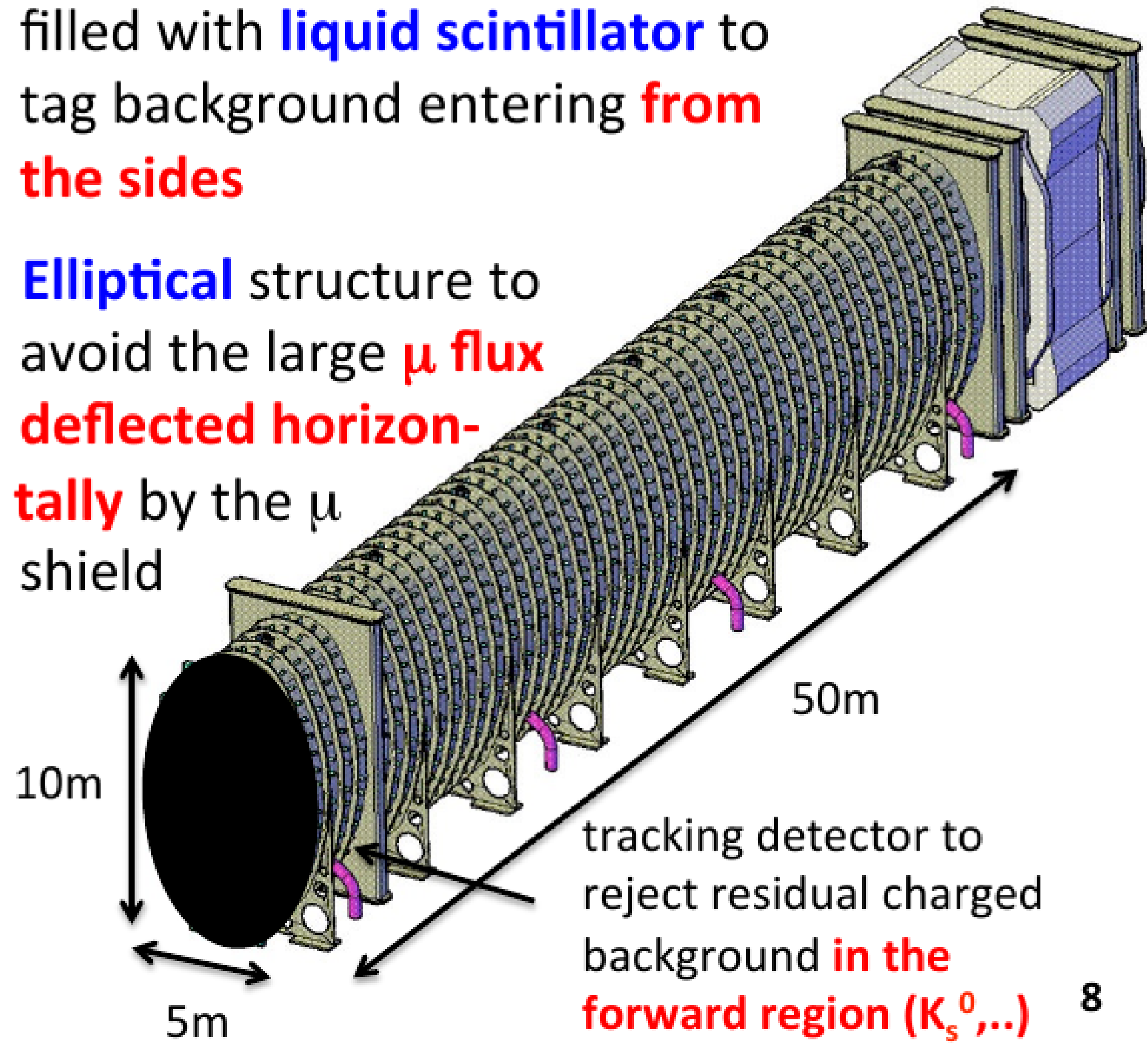
1. **ν interaction :** identified through **detection of τ production and decay** (contained within a brick due to short τ lifetime)
2. **distinguish ν_τ anti-ν_τ :** Look at the **charge of the τ decay** products

The vacuum vessel

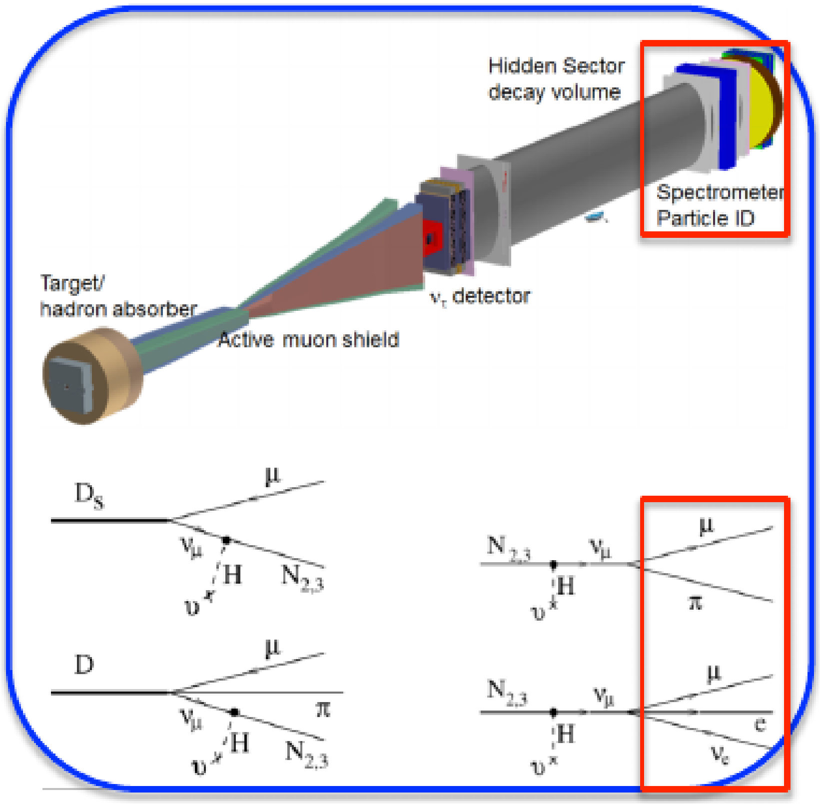


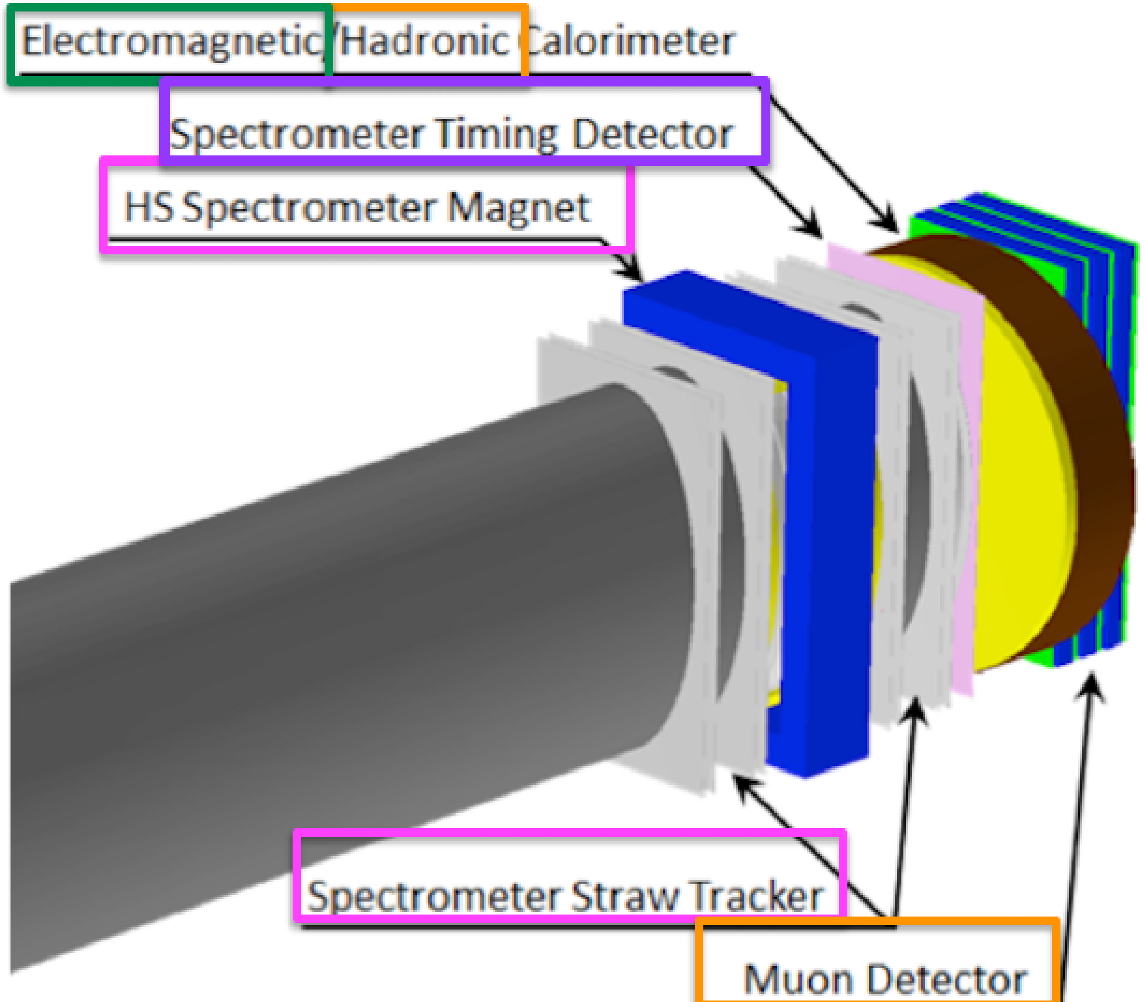
- **10^{-6} mbar vacuum** needed suppress the **neutrino interactions**
- Double-wall structure, space filled with **liquid scintillator** to tag background entering **from the sides**
- **Elliptical** structure to avoid the large **μ flux deflected horizontally** by the μ shield

- **Veto tagger** located just after ν_τ detector to tag indirectly **neutral K** produced by ν and μ interactions in the passive material of the ν_τ detector and **μ entering the vessel from the front**



The spectrometer





Signal reconstruction and background rejection: warm magnet (LHCb) with 0.65Tm bending power; tracker (NA62) with horizontal straws and stereo angle

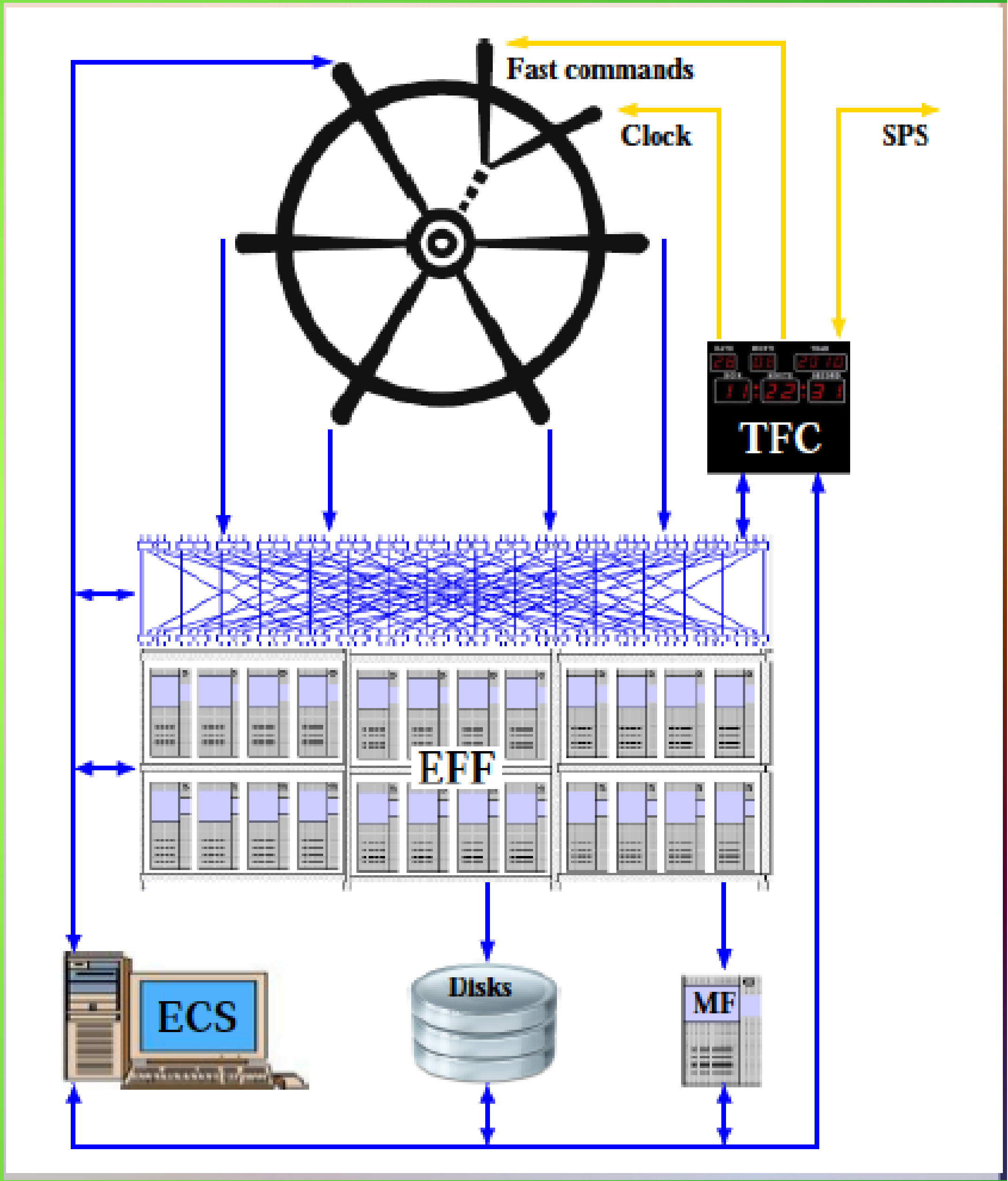
e/γ identification, π^0 and η reconstruction: ECAL (Shashlik technique, LHCb)

Veto anti-coincidence from combinatorial : timing detector (50ps resolution)

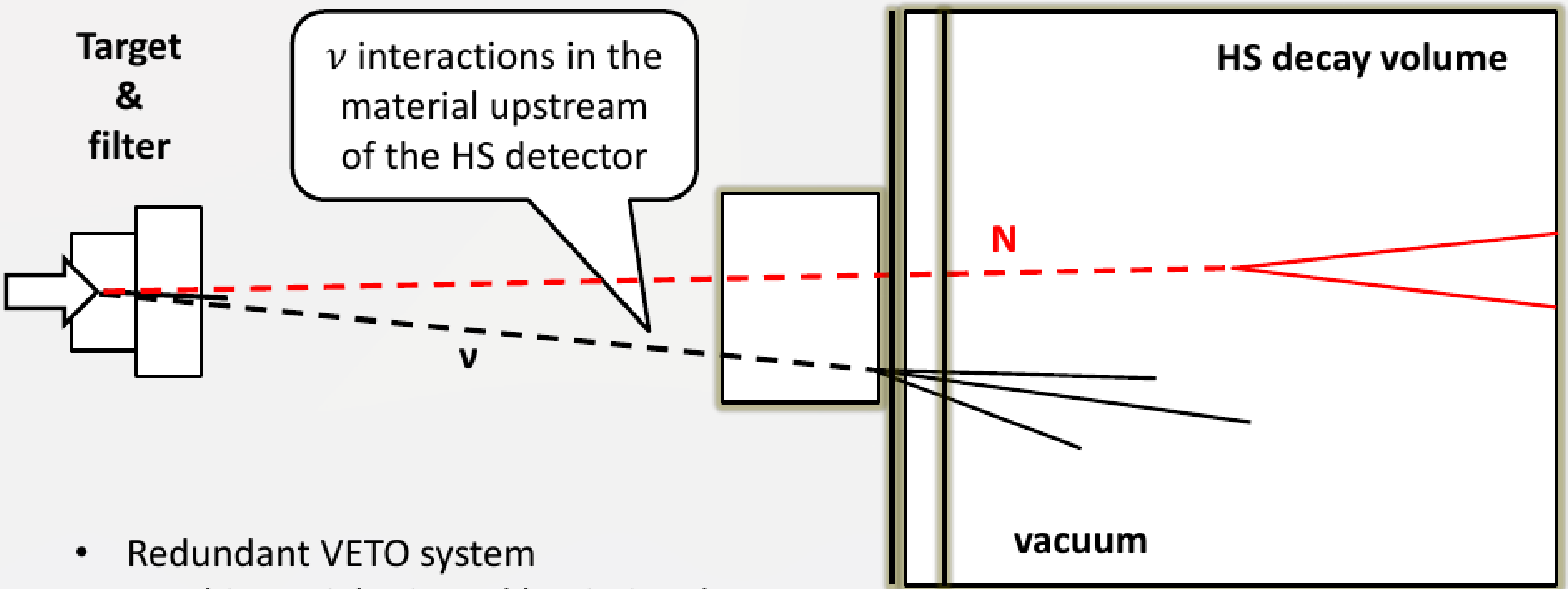
π/μ separation : hadronic calorimeter (similar technology as ECAL), muon detector (WLS fiber bars, MINOS)

Trigger and DAQ

- Trigger andEvent building on all data and trigger decision at EF
- TFC system generates the clock
- All sub-systems send data through ethernet links (no need for radiation hardness) to Event Filter Farm via a switch
- Fraction of data sent to Monitoring
- Farm to evaluate performance
- Smallest time slice that could potentially contain all data from one pot (100 ns)
- Since some events spread over more than one frame, 100 frames are combined into a “package”, with 1 overlap



Background rejection: upstream neutrino interactions

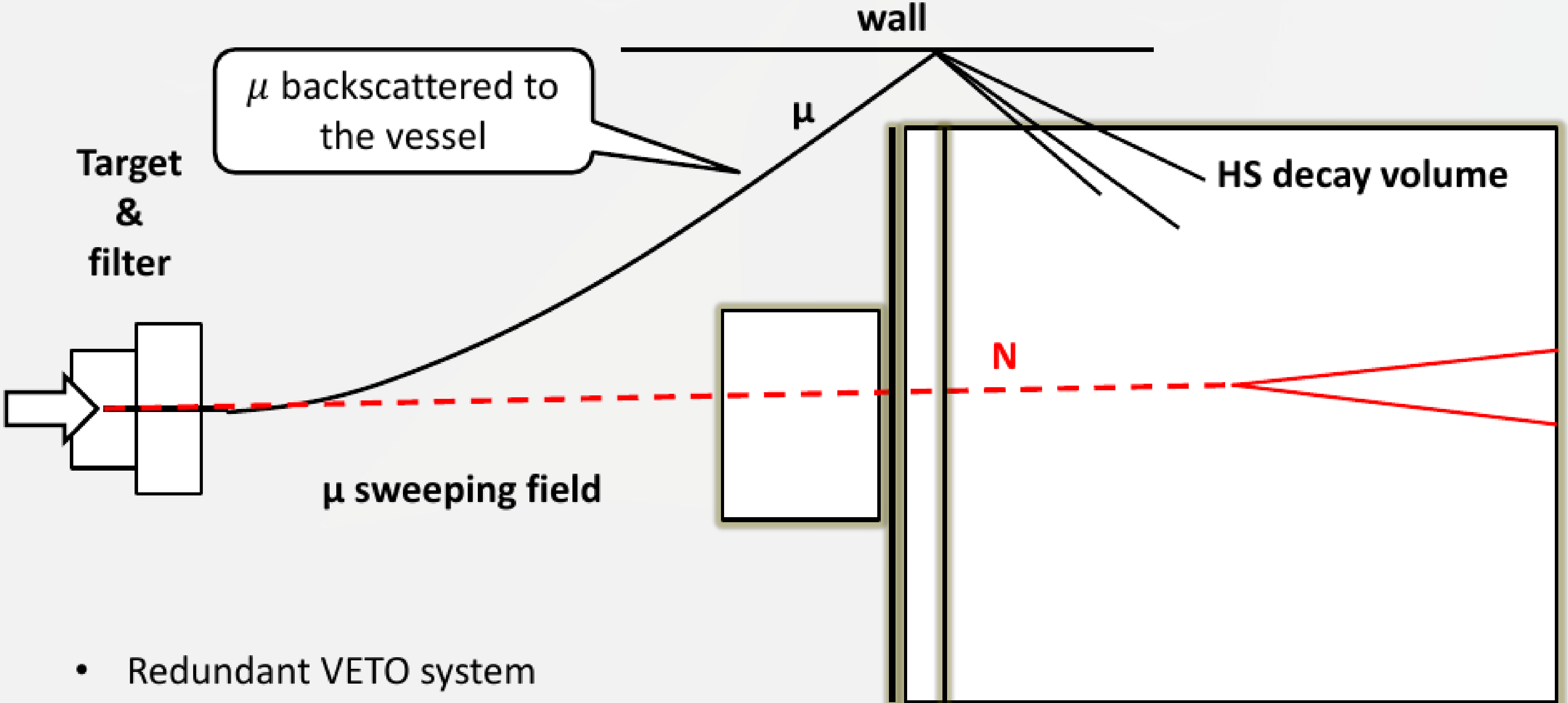


- Redundant VETO system
- Combinatorial rejected by timing detector
- Impact parameter to the target
- 75% selection efficiency for signal

After selections:

≤ 0.1 bkg / 5 y

Background rejection: interactions with experimental hall

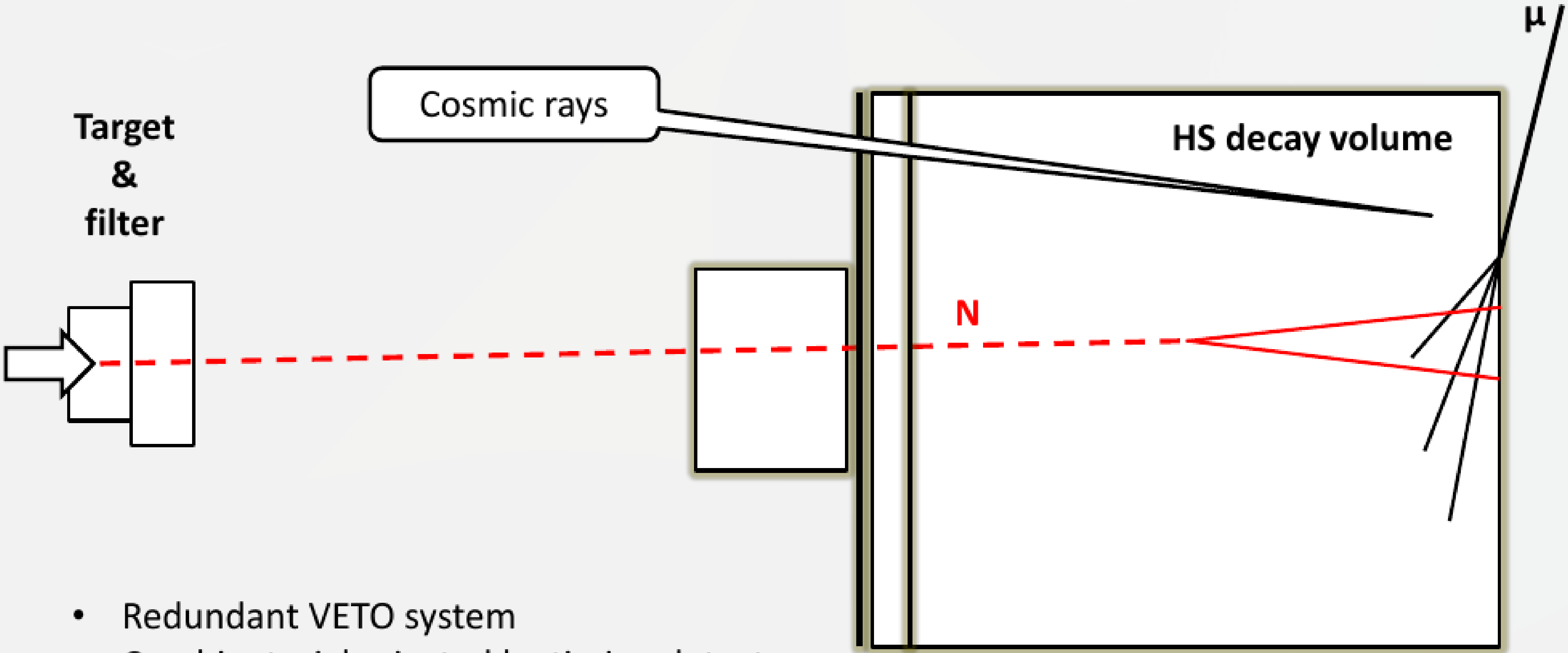


- Redundant VETO system
- Combinatorial rejected by timing detector
- Impact parameter to the target
- 75% selection efficiency for signal

After selections:

≤ 0.1 bkg / 5 y

Background rejection: cosmics



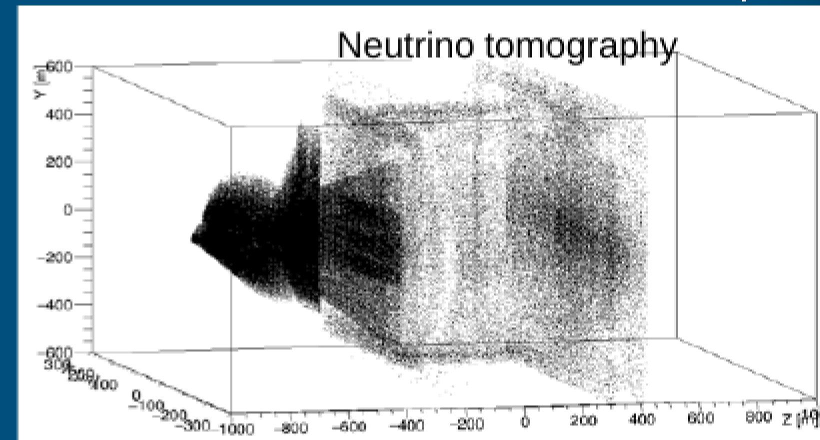
- Redundant VETO system
- Combinatorial rejected by timing detector
- Impact parameter to the target
- 75% selection efficiency for signal

After selections:

≤ 0.1 bkg / 5 y

Backgrounds: summary

Background source	Decay modes
ν or μ + nucleon $\rightarrow X + K_L$	$K_L \rightarrow \pi e \nu, \pi \mu \nu, \pi^+\pi^-, \pi^+\pi^-\pi^0$
ν or μ + nucleon $\rightarrow X + K_S$	$K_S \rightarrow \pi^0\pi^0, \pi^+\pi^-$
ν or μ + nucleon $\rightarrow X + \Lambda$	$\Lambda \rightarrow p\pi^-$
n or p + nucleon $\rightarrow X + K_L$, etc	as above



Background summary: no evidence for any irreducible background

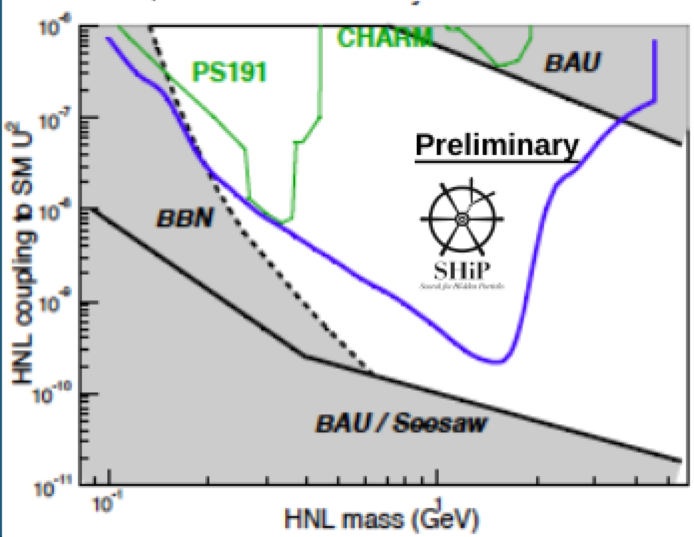
- No events selected in MC ➔ Expected background UL @ 90% CL

Background source	Stat. weight	Expected background (UL 90% CL)
ν-induced		
$2.0 < p < 4.0$ GeV/c	1.4	1.6
$4.0 < p < 10.0$ GeV/c	2.5	0.9
$p > 10$ GeV/c	3.0	0.8
$\overline{\nu}$-induced		
$2.0 < p < 4.0$ GeV/c	2.4	1.0
$4.0 < p < 10.0$ GeV/c	2.8	0.8
$p > 10$ GeV/c	6.8	0.3
Muon inelastic	0.5	4.6
Muon combinatorial	–	<0.1
Cosmics		
$p < 100$ GeV/c	2.0	1.2
$p > 100$ GeV/c	1600	0.002

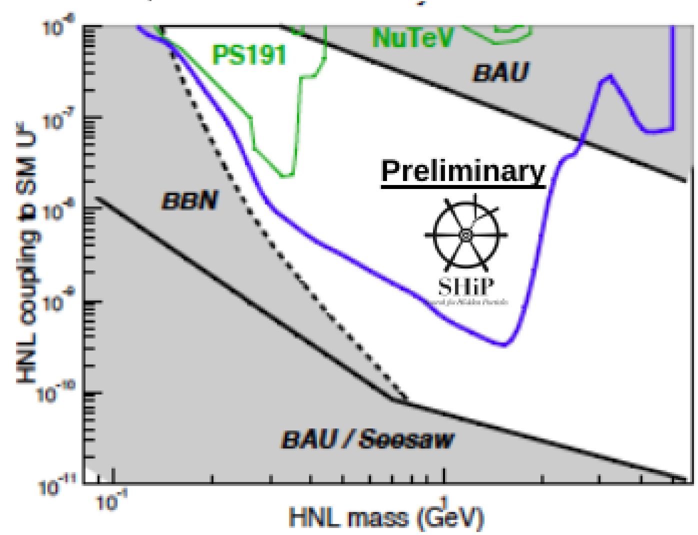
Sensitivity to HNL

- Visible decays = At least two tracks crossing the spectrometer
  - Ex. For m_N = 1 GeV with $\mathcal{U}^2$= 10^{-8} and $\mathcal{BR}(N \to \mu\pi)$ = 20%, expect ~330 signal events

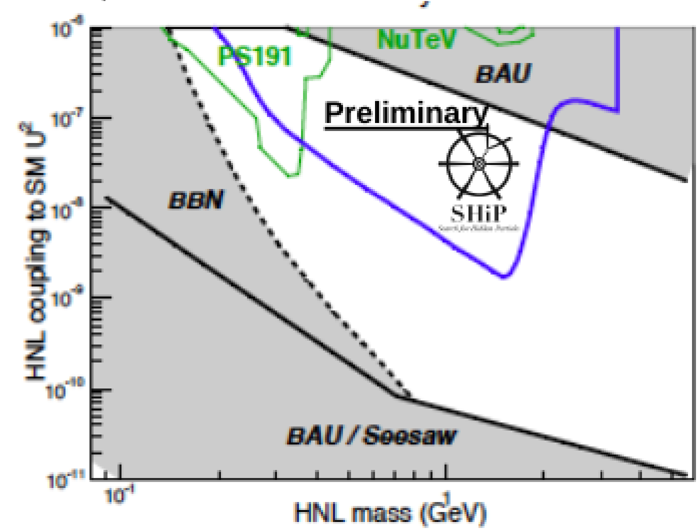
$U_e^2 : U_\mu^2 : U_\tau^2 \sim 52:1:1$, inverted hierarchy



$U_e^2 : U_\mu^2 : U_\tau^2 \sim 1:16:3.8$, normal hierarchy

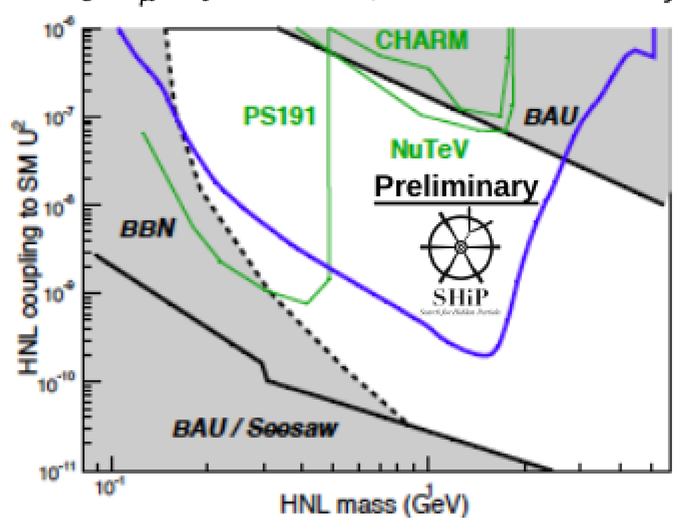


$U_e^2 : U_\mu^2 : U_\tau^2 \sim 0.061:1:4.3$, normal hierarchy

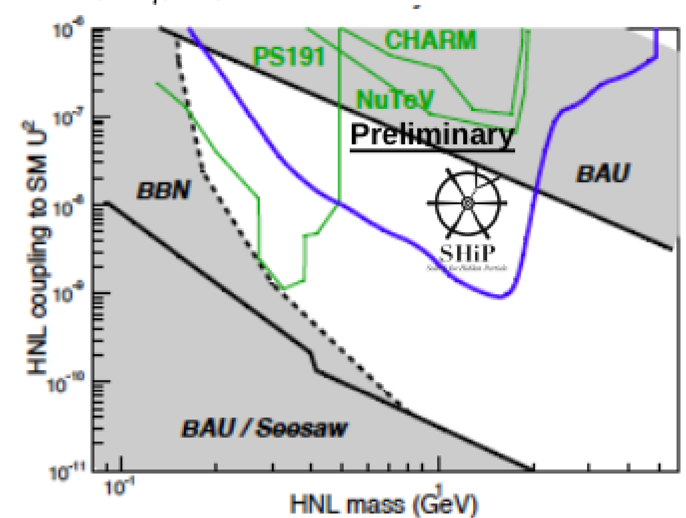


Scenarios for which baryogenesis was numerically proven

$U_e^2 : U_\mu^2 : U_\tau^2 \sim 48:1:1$, inverted hierarchy



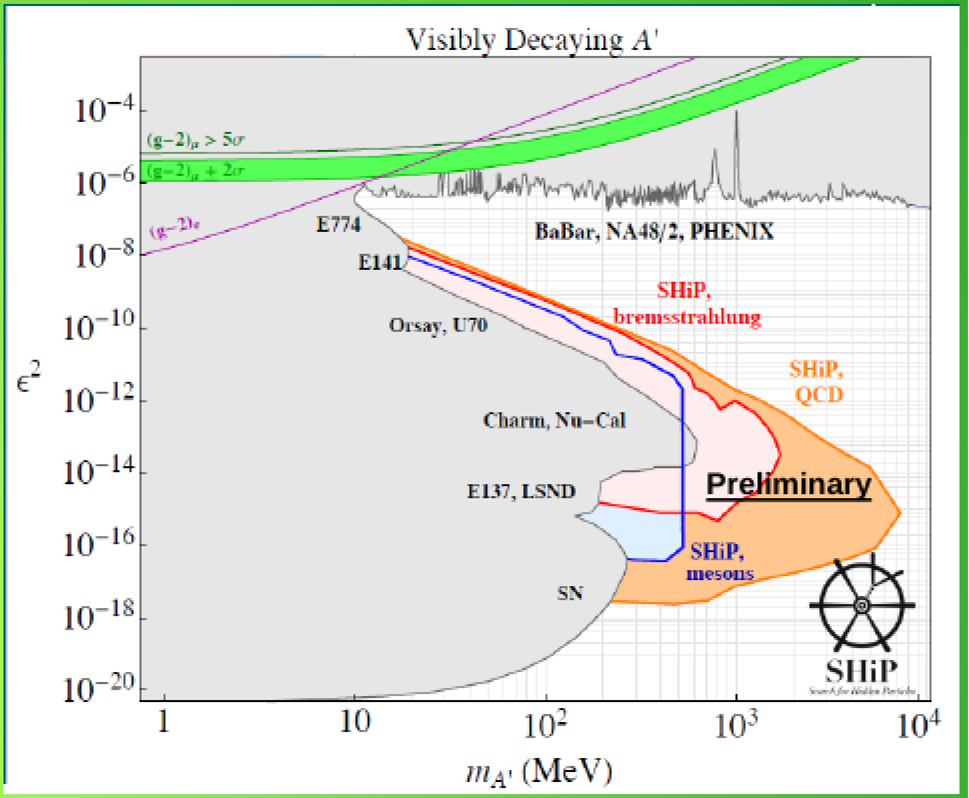
$U_e^2 : U_\mu^2 : U_\tau^2 \sim 1:11:11$, normal hierarchy

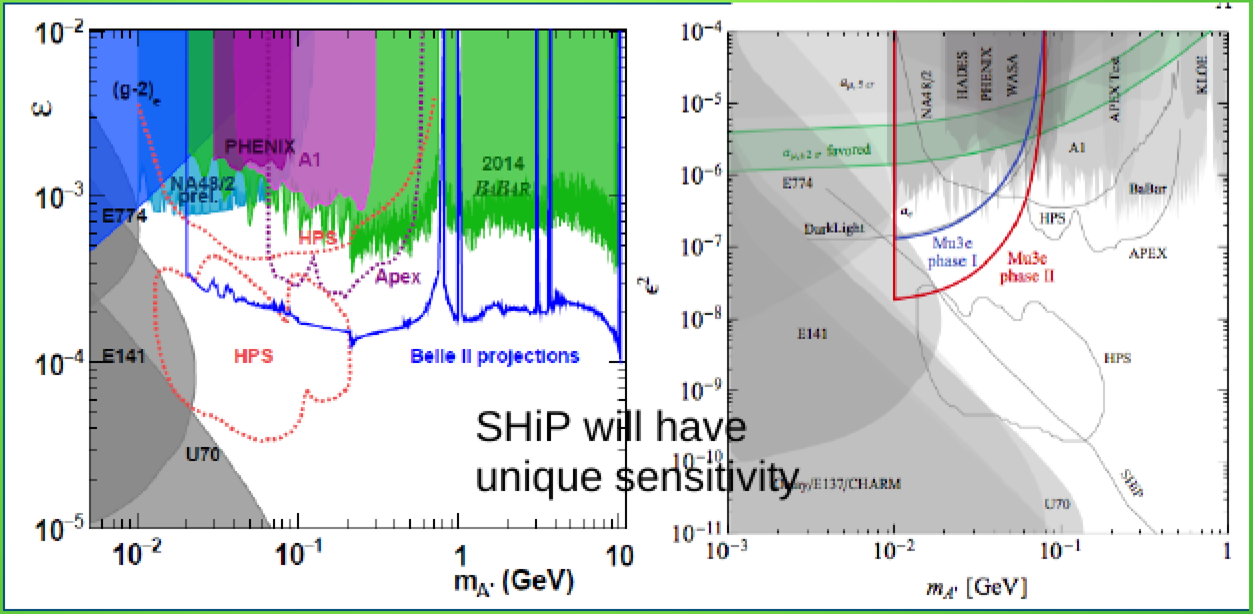


Sensitivity to dark photons

Production

- Decays of $\pi^0 \rightarrow V\gamma$, $\eta \rightarrow V\gamma$, $\omega \rightarrow V\pi^0$
- Proton bremsstrahlung and parton bremsstrahlung above Λ QCD
- Decay into pair of SM particles



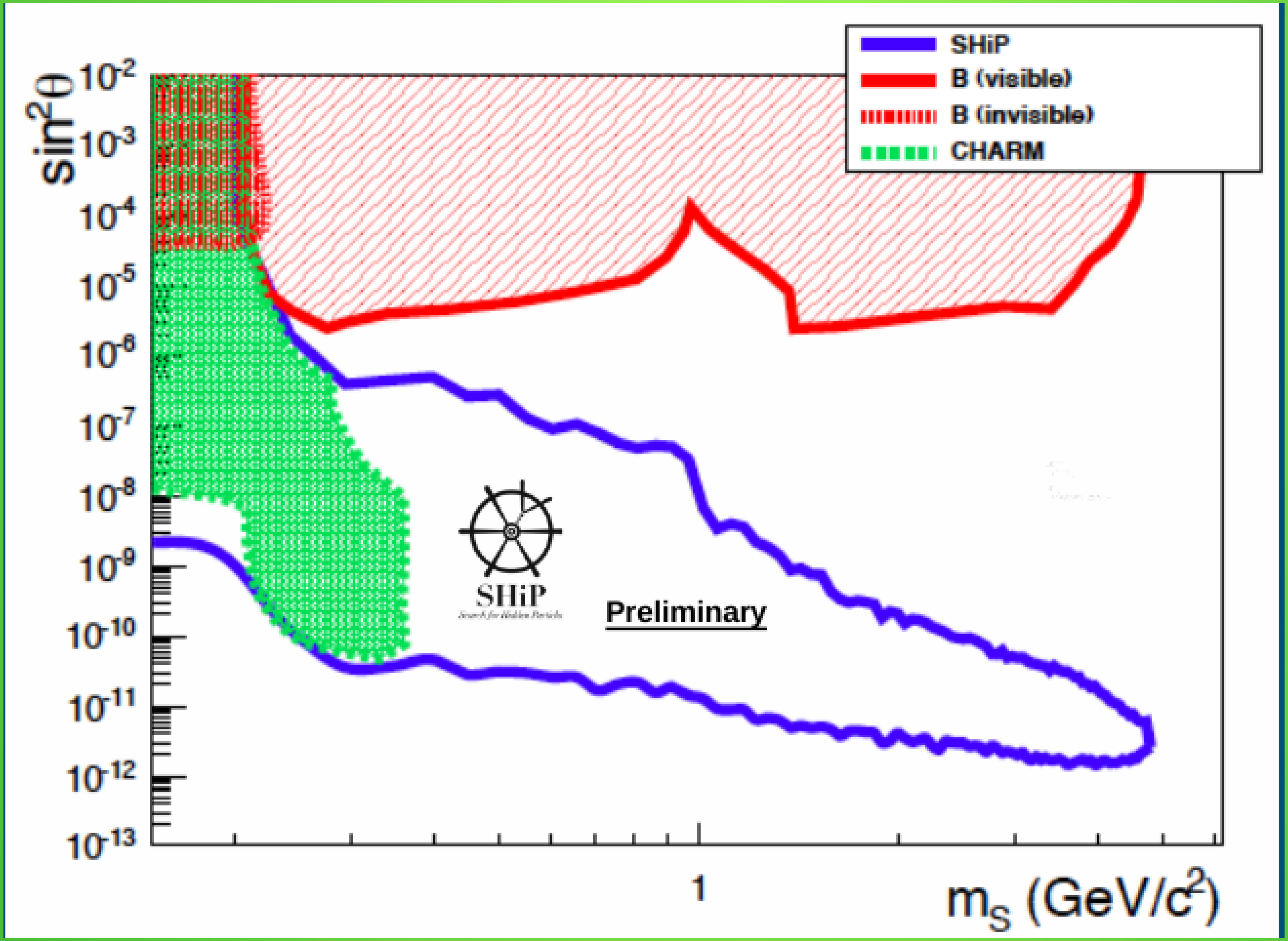


SHiP will have unique sensitivity

Hidden scalars

Production from B and K decays

Decay into fermion or meson pairs



Axion portal

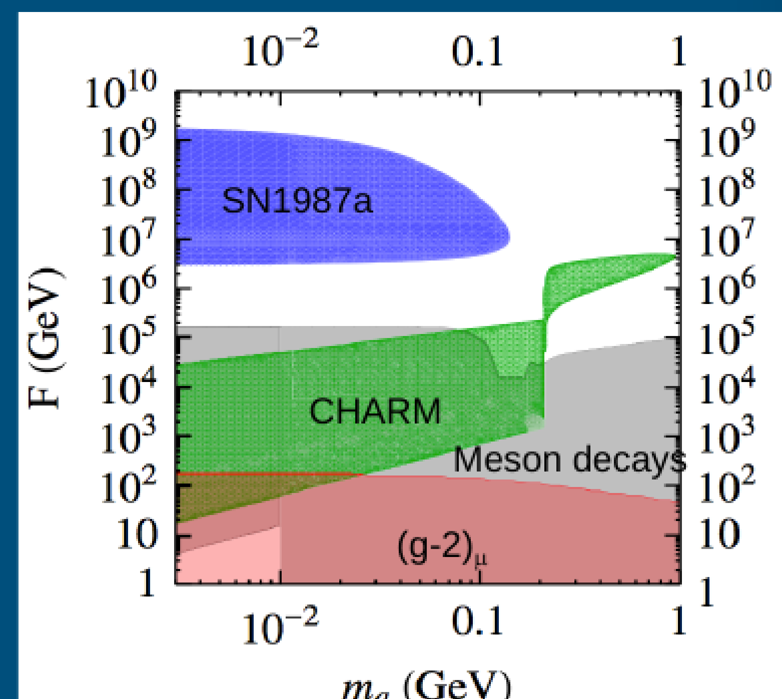
- Axion Like Particles, pseudo-scalars pNGB, axial vectors a
  - Appear in extended Higgs, SUSY breaking, motivated by coupling with dark sector, possibility of inflaton, etc
  - Generically light pseudo-scalars arise in spontaneous breaking of approximate symmetries at a high mass scale F

    ➔ Couplings suppressed by the breaking scale F and masses are light $\sim\Lambda/F^2$

  - SM portal through mixing with gauge bosons and fermions

$$\mathcal{L} = \frac{a}{F} G_{\mu\nu}\tilde{G}^{\mu\nu}, \frac{\partial_\mu a}{F}\bar{\psi}\gamma_\mu\gamma_5\psi \text{ , etc}$$

- Production
  - Resonant production from Drell-Yan photons
  - Production from mixing with pions and heavy meson decays
- Decays
  - Decays to $e^+e^-, \mu^+\mu^-$, hadrons above 1 GeV
  - Decays to photon pair



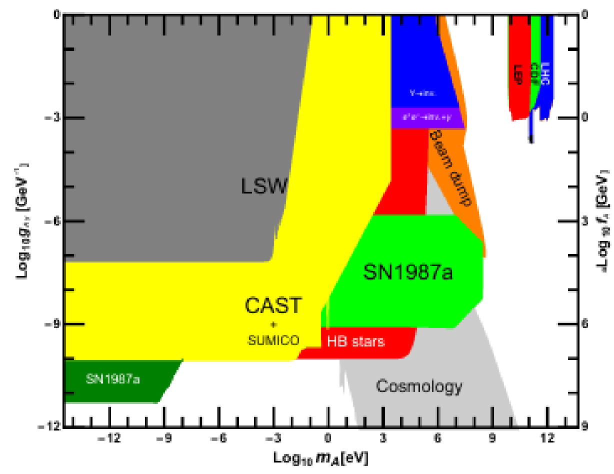
PRD 82,113008 (2010)

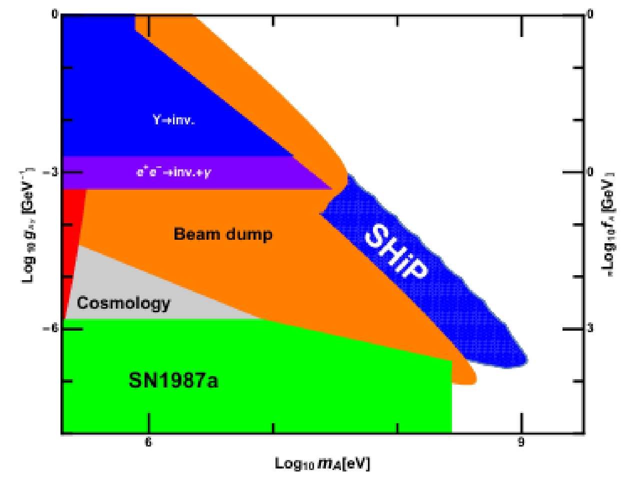
Perspectives for ShiP (from physics paper)

$$pp \to A + X,\ A \xrightarrow{\text{long lived}} \gamma\gamma$$

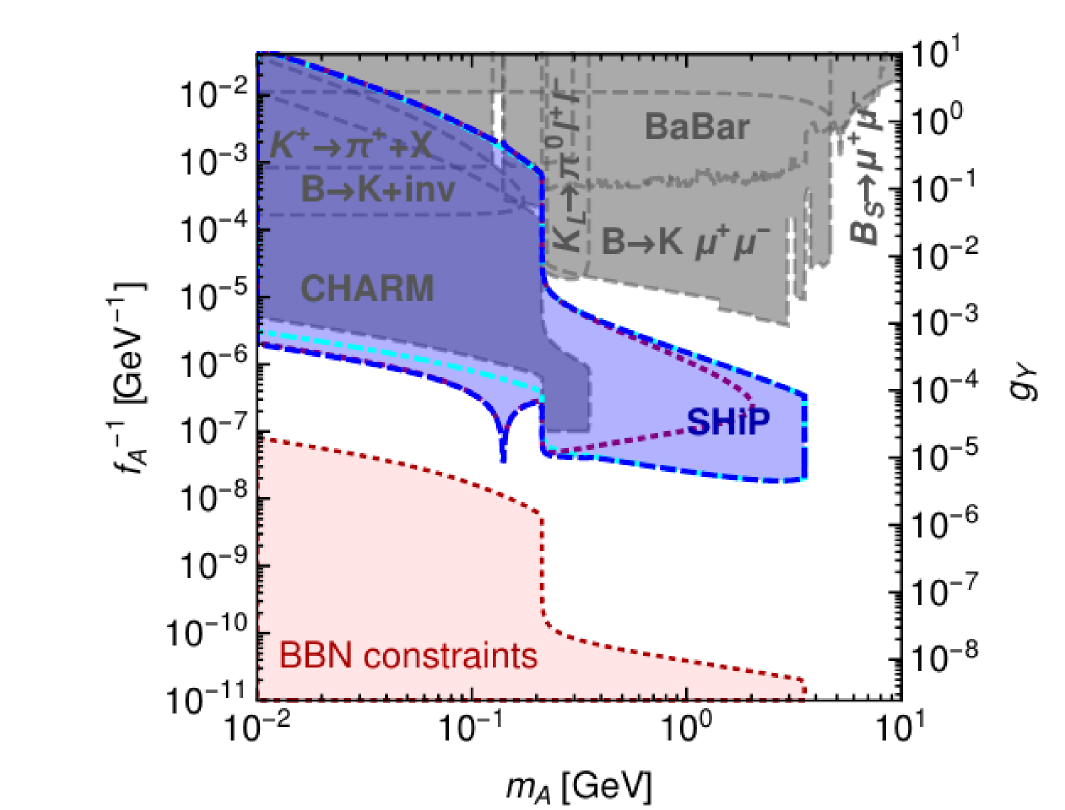
An extension of the ECAL needed to increase acceptance to photon pairs.

Some coverage in the region of interest in models where ALP serve as mediators to a DM sector





$$pp \to B + X \to A + K + X,\ A \xrightarrow{\text{long lived}} \mu^+\mu^-$$



Associate production of axions and strange mesons from B-meson decays can be observed in dimuon final state.
It covers similar mass range but smaller couplings than the b-factories

Tau neutrino physics

- Charged current neutrino nucleon scattering

neutrino scattering → $+$

anti-neutrino scattering → $-$

$$\frac{d^2\sigma}{dx\,dy} = \frac{G_F^2 M_N E_\nu}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2\Bigg[\left(xy^2+\frac{m_l^2 y}{2E_\nu M_N}\right)F_1+\left(1-y-\frac{M_N x y}{2E_\nu}-\frac{m_l^2}{4E_\nu^2}\right)F_2 \pm \left(xy\left(1-\frac{y}{2}\right)-\frac{m_l^2 y}{4E_\nu M_N}\right)F_3+\frac{m_l^2(m_l^2+Q^2)}{4E_\nu^2 M_N^2 x}F_4-\frac{m_l^2}{E_\nu M_N}F_5\Bigg]$$

<u>Structure functions</u>

- F_1
- F_2

F_1, F_2 → More precise estimation from other experiments

- F_3 → Opposite sign for **ν** and **anti-ν**
- F_4
- F_5

F_4, F_5 → Dependent on the lepton mass. Suppressed in case of ν_μ interactions, becomes relevant for ν_τ interactions

- Evaluation of F_3
- First evaluation of F_4 and F_5, not accessible with lighter neutrinos

Some tau neutrino numbers

Current status of tau neutrino observations:

- DONUT observed 9 events (from charm) with a background of 1.5
- OPERA observed 4 events (from oscillations)
- No tau antineutrino has been even observed
- Ship can increase by 200 the current tau neutrino sample, and discover tau antineutrinos

- Measurement of tau neutrino differential cross-section in CC interactions

- Measurement of charm production for muon neutrinos and antineutrino (factor of
- 100 increase wrt CHORUS)
- A good fraction of the old OPERA collaborators are joining SHiP to build the neutrino sub-detector and analyse its data.

Ship people: experiment and theory

arXiv:1504.04956v1 [physics.ins-det]

The SHiP Collaboration

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arXiv:1504.04855v1 [hep-ph]

A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case

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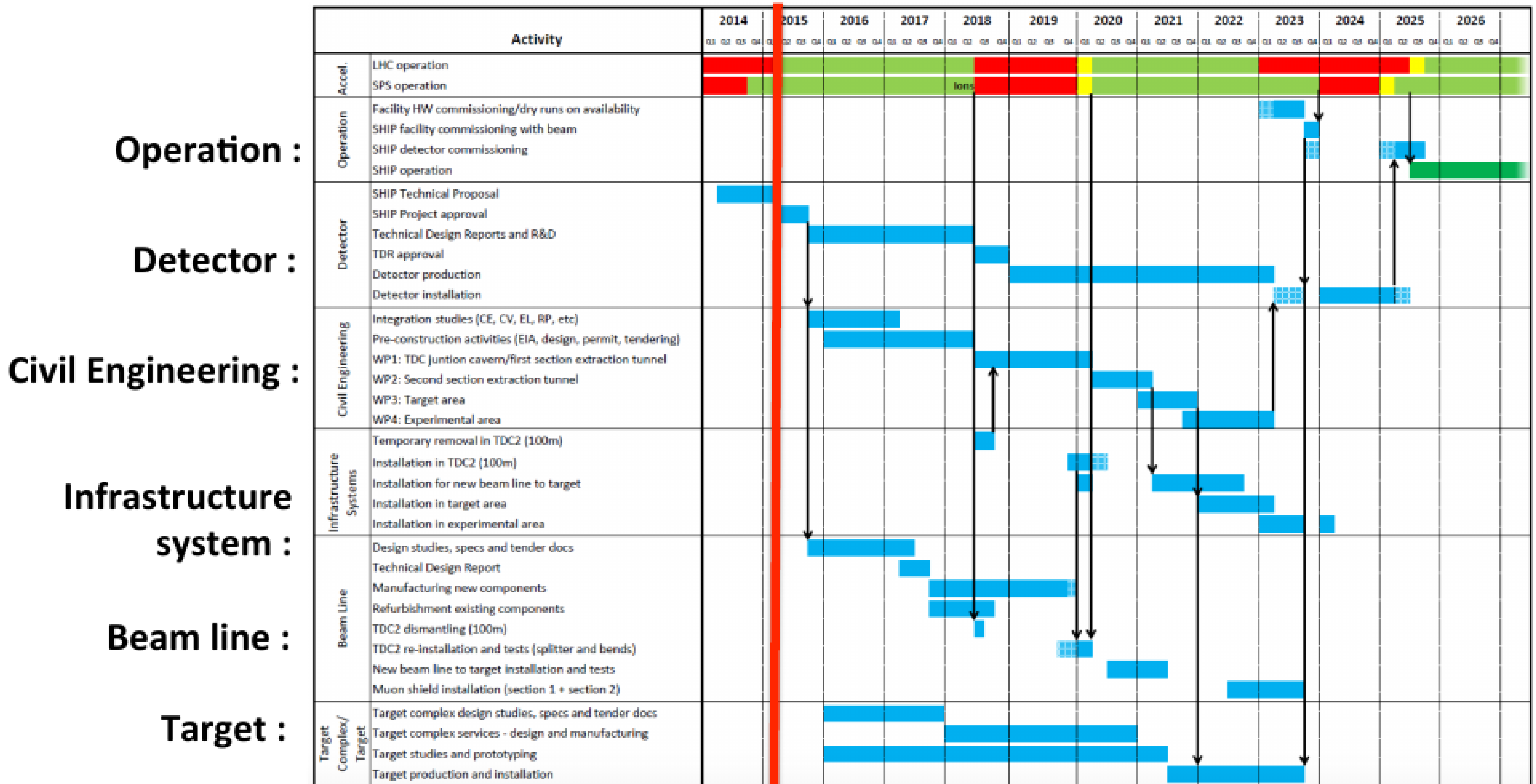
SHiP
Search for Hidden Particles

Come aboard !

Timescale



- CERN decision on the strategy with SHiP **within a year**
- Detector construction, 5 years of data taking (from 2022) and data analysis of 2×10^{20} protons on target can be all achieved **within 10 years**

SHiP in the UK

- Imperial College London has been involved since the very beginning, and expresses the spokesperson

  (Andrei Golutvin); main activity active muon filter

- UCL (N.Brook, M.C) to work on trigger/DAQ

- RAL PPD (engineering support, but also physicists like S.Ricciardi)

- Bristol (K. Petridis)

- Warwick (G.Barker)

- Manchester, Liverpool may join in a second stage

Conclusions, and considerations on the future of particle physics

- LHC Run 1 results geve no positive evidence for new physics; Run 2 results out soon, let's hope for the best

- But in current (and foreseeable) resource climate, a next big brute-force, general-purpose high-energy collider is difficult

- Particle physics could reinvent itself in becoming smaller and smarter, designing experiments that target specific problems (dark matter, neutrinos, etc.)

- A detector like ShiP perfectly fits this philosophy

- Very positive feedback so far from CERN, we have just been invited to submit a CDR (2-3 years of work) by the new management, that will also organise workshops to investigate further uses of the facility.