# Future experiments at intensity frontier

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- How to reconsile this with evidence for new physics?

## Experimental evidence for new physics beyond the Standard Model:

- Observations of neutrino oscillations (in the SM neutrinos are massless and do not oscillate)
- Evidence for Dark Matter (SM does not have particle physics candidate for DM).
- No antimatter in the Universe in amounts comparable with matter (baryon asymmetry of the Universe is too small in the SM)
- Cosmological inflation is absent in canonical variant of the SM
- Accelerated expansion of the Universe (?) - though can be “explained” by a cosmological constant.

Theoretical evidence for new physics beyond the Standard Model:

- Cosmological constant problem: Why $\epsilon_{vac}/M_{Pl}^4 \lll 1$?
- Hierarchy problem: Why $M_W/M_{Pl} \ll 1$?
- Stability of the Higgs mass against radiative corrections.
- Strong CP-problem: Why $\theta_{QCD} \ll 1$?
- Fermion mass matrix: Why $m_e \ll m_t$?
- ...

# Where is new physics?

# Only at the Planck scale?

Does not work: neutrino masses from five-dimensional operator

$$\frac{1}{M_P} A_{\alpha\beta} \left(\bar{L}_\alpha \tilde{\phi}\right) \left(\phi^\dagger L^c_\beta\right)$$

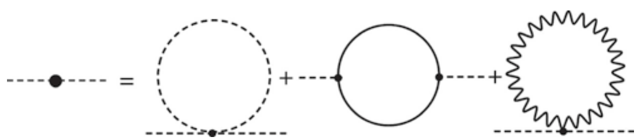
suppressed by the Planck scale are too small, $m_\nu < 10^{-5}$ eV.

# Below the Planck scale, but where?

- Neutrino masses and oscillations: the masses of right-handed see-saw neutrinos can vary from $\mathcal{O}(1)$ eV to $\mathcal{O}(10^{15})$ GeV
- Dark matter, absent in the SM: the masses of DM particles can be as small as $\mathcal{O}(10^{-22})$ eV (super-light scalar fields) or as large as $\mathcal{O}(10^{20})$ GeV (wimpzillas, Q-balls).
- Baryogenesis, absent in the SM: the masses of new particles, responsible for baryogenesis (e.g. right-handed neutrinos), can be as small as $\mathcal{O}(10)$ MeV or as large as $\mathcal{O}(10^{15})$ GeV
- Higgs mass hierarchy : models related to SUSY, composite Higgs, large extra dimensions require the presence of new physics right above the Fermi scale, whereas the models based on scale invariance (quantum or classical) may require the absence of new physics between the Fermi and Planck scales

# Arguments for absence of new heavy particles above the Fermi scale

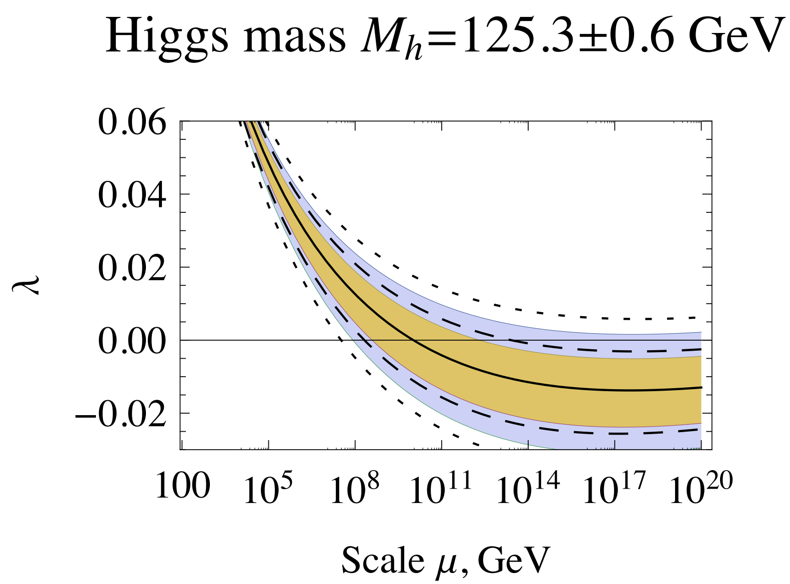
- Stability of the Higgs mass against radiative corrections



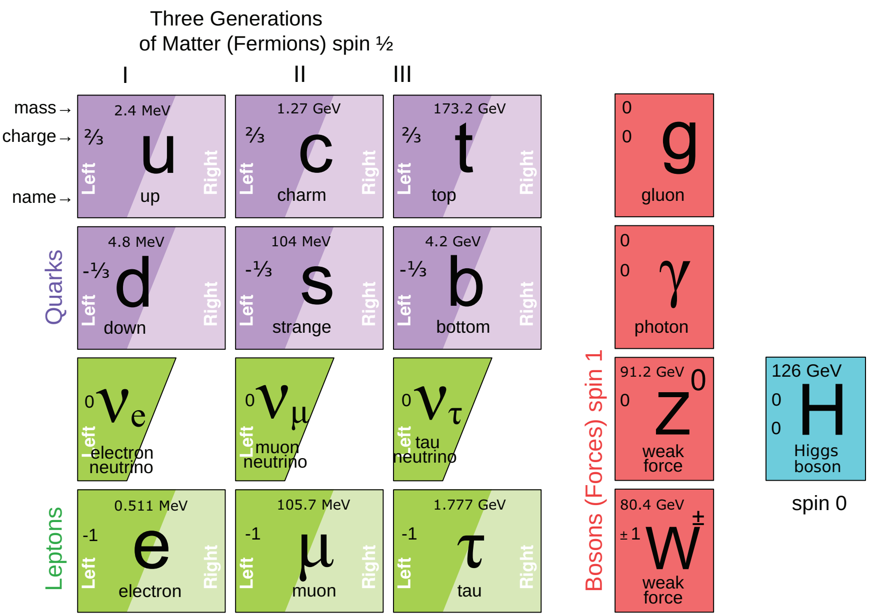
$$\delta m_H^2 \simeq \alpha_{GUT}^n M_{heavy}^2$$

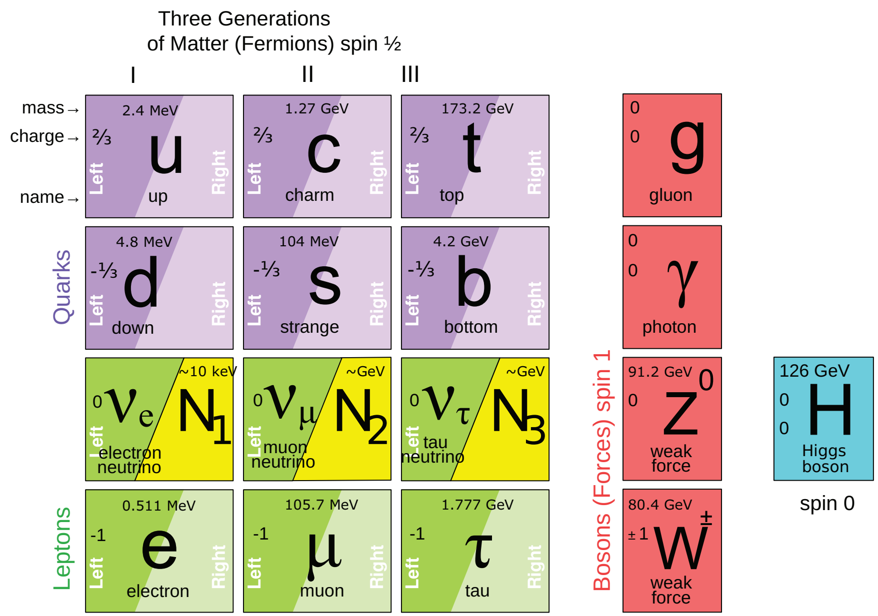
No heavy particles - no large contributions - no fine tuning

- Higgs self coupling $\lambda \approx 0$ at the Planck scale (criticality of the SM - asymptotic safety?). This is violated if new particles contribute to the evolution of the SM couplings.



# Example of “complete” theory: the $\nu$MSM



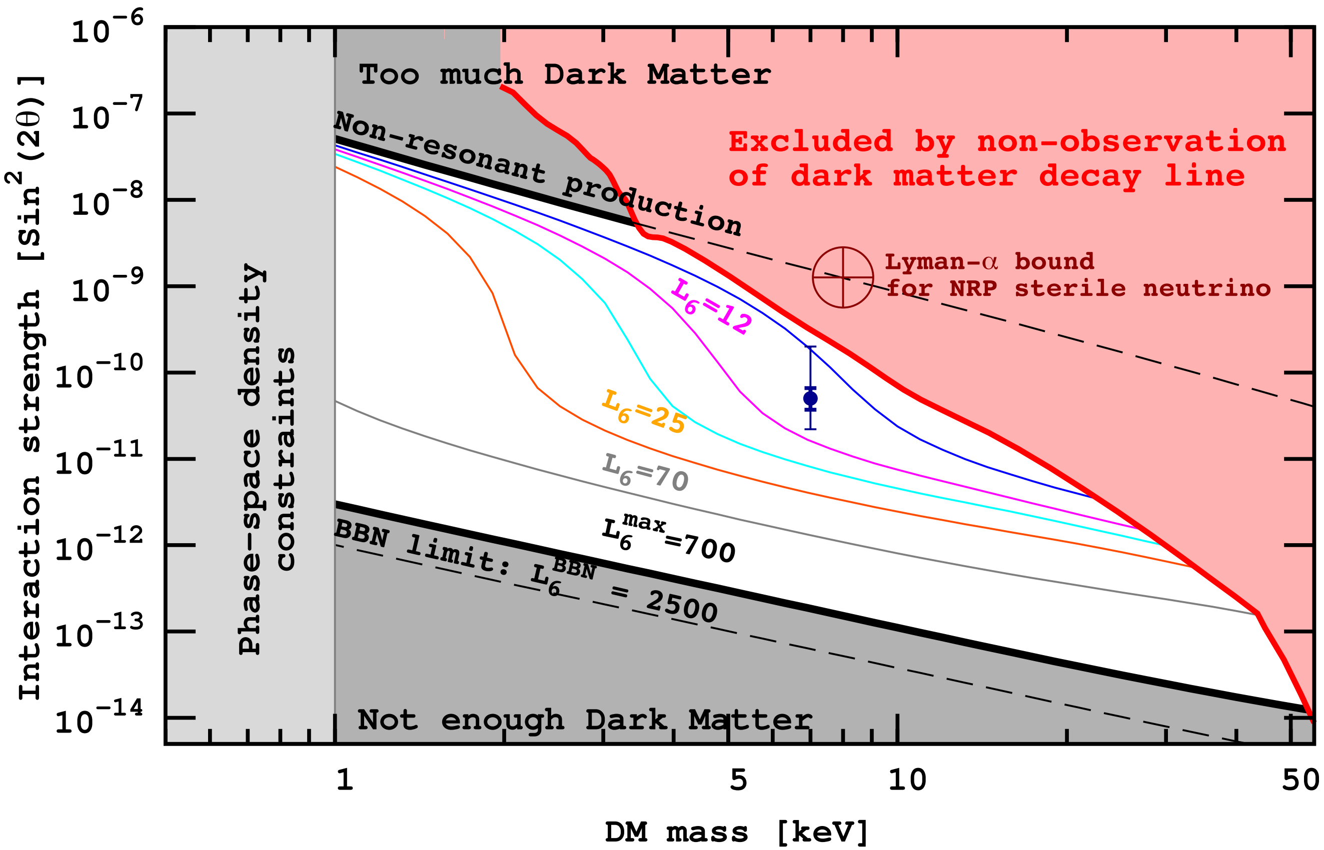




Role of the Higgs boson: break the symmetry and inflate the Universe

Role of $N_1$ with mass in keV region: dark matter.

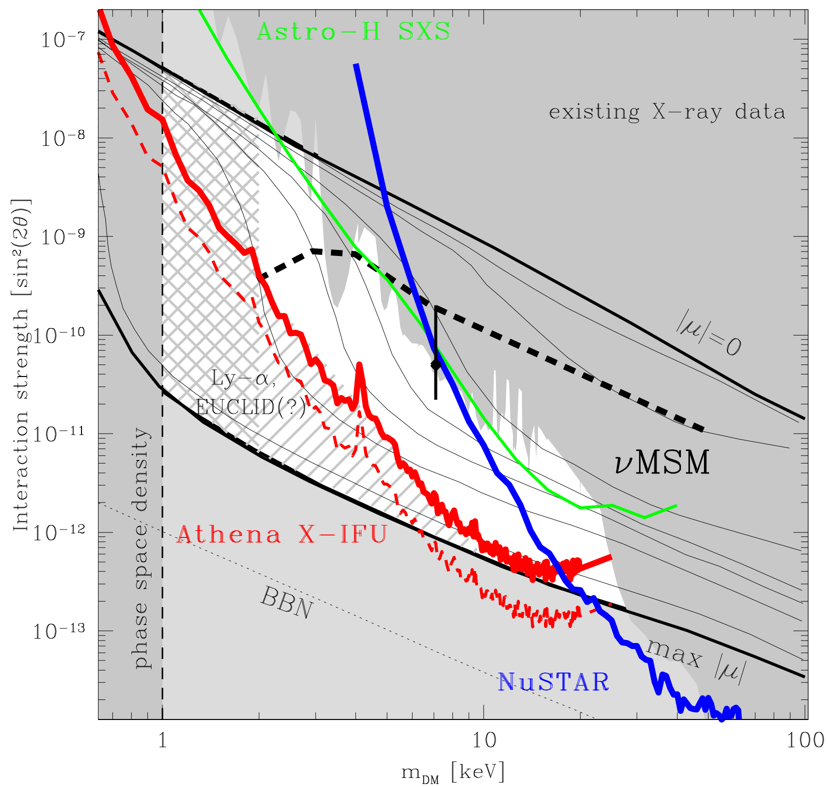
Role of $N_2,\ N_3$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe.

# DM: sterile neutrino $N_1$

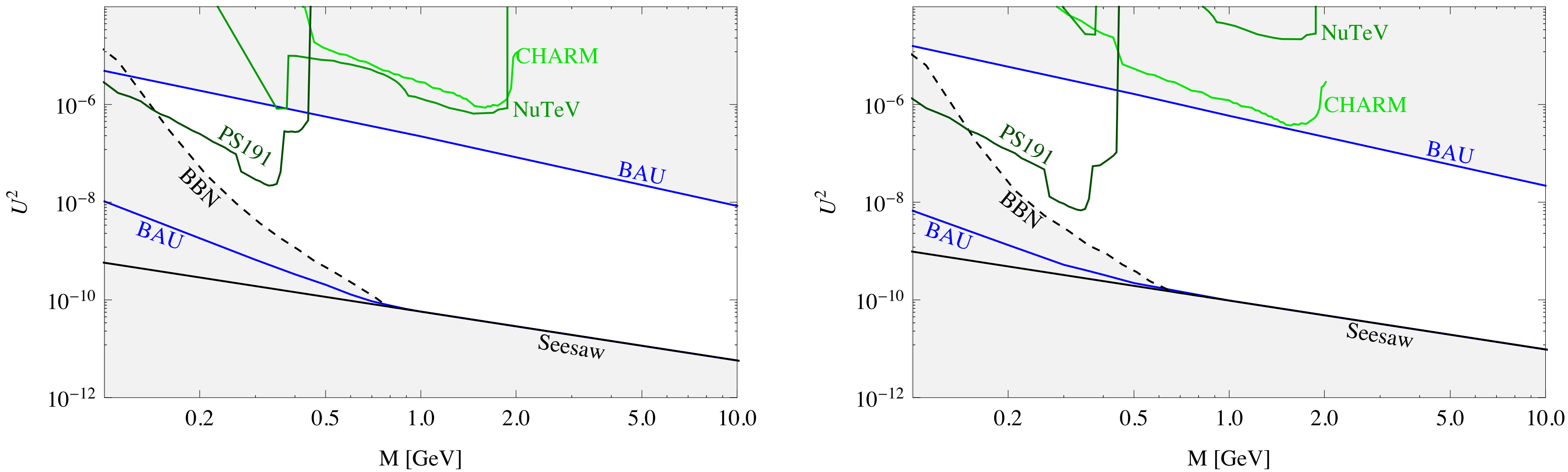



3.5 keV line: E. Bulbul et al, Boyarsky et al

- HNL ($N_1$) dark matter searches in X-rays, future after Astro-H failure
  - Micro-calorimeter on sounding rocket (2017): instrument with large field-of-view and very high spectral resolution
  - Large ESA X-ray mission (2028) – Athena + , X-ray spectrometer (X-IFU) with unprecedented spectral resolution



# Baryon asymmetry: HNLs $N_{2,3}$



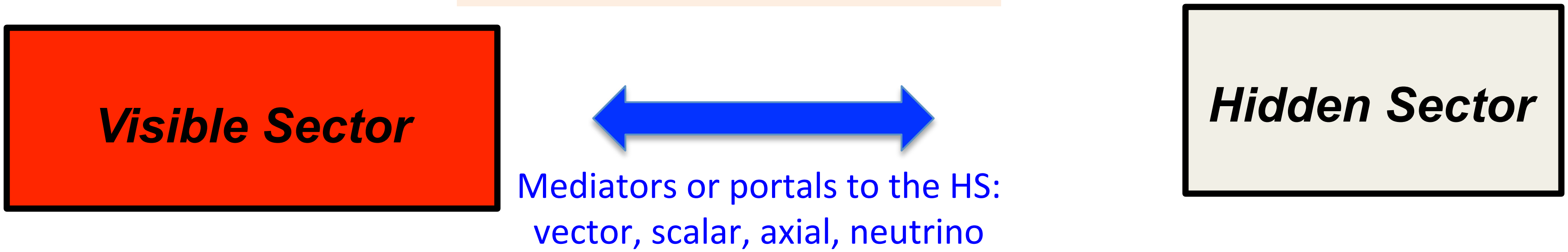

Constraints on $U^2$ coming from the baryon asymmetry of the Universe, from the see-saw formula, from the big bang nucleosynthesis and experimental searches. Left panel - normal hierarchy, right panel - inverted hierarchy (Canetti, Drewes, Frossard, MS). Other studies: Drewes et al., Hernandez et al

# New physics at high scale - we may still have new light particles

- axion and ALPS
- mirror or dark photon
- light Higgs-like particles, dilaton
- light sgoldsinos, R-parity violating neutralinos

# *Search for Hidden Sector (HS)*
*or very weakly interacting NP*

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

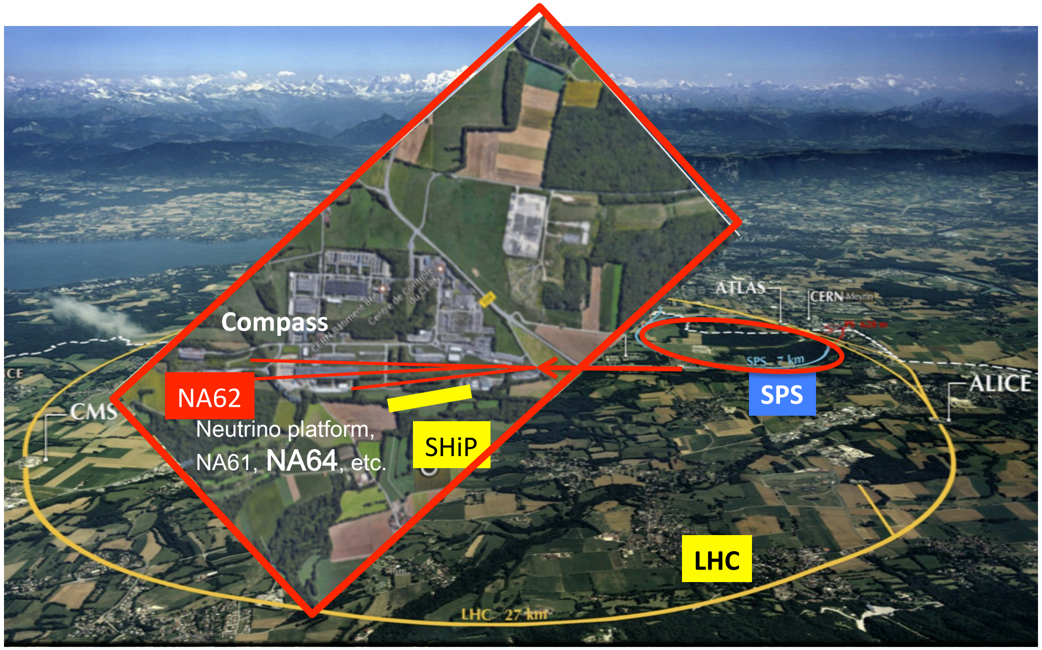



✓ *HS production and decay rates are strongly suppressed relative to SM*
  - *Production branching ratios $O(10^{-10})$*
  - *Long-lived objects*
  - *Interact very weakly with matter*

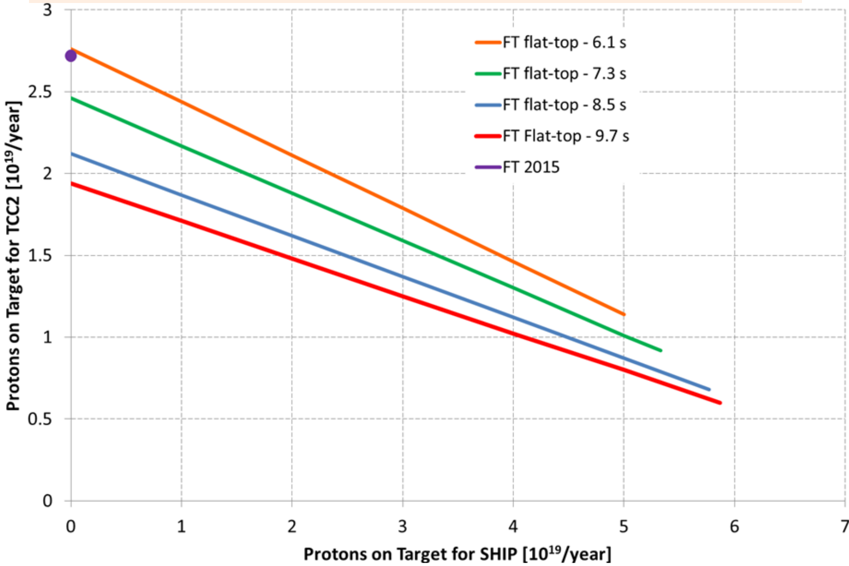
| *Models* | *Final states* |
| --- | --- |
| ***HNL, SUSY neutralino*** | $\ell^+\pi^-$, $\ell^+K^-$, $\ell^+\rho^-$ $\rho^+\to\pi^+\pi^0$ |
| ***Vector, scalar, axion portals, SUSY sgoldstino*** | $\ell^+\ell^-$ |
| ***HNL, SUSY neutralino, axino*** | $\ell^+\ell^-\nu$ |
| ***Axion portal, SUSY sgoldstino***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

# The Fixed-target facility at the SPS: Prevessin North Area site

*Very intense proton beam with highest in the world energy delivered to fixed target exp. at CERN SPS.* ***The aim is to deliver with 4×10¹³ protons / spill (at slow extraction)***




***Sharing of pot between current fixed target exp. and planned Beam Dump Facility (BDF)***

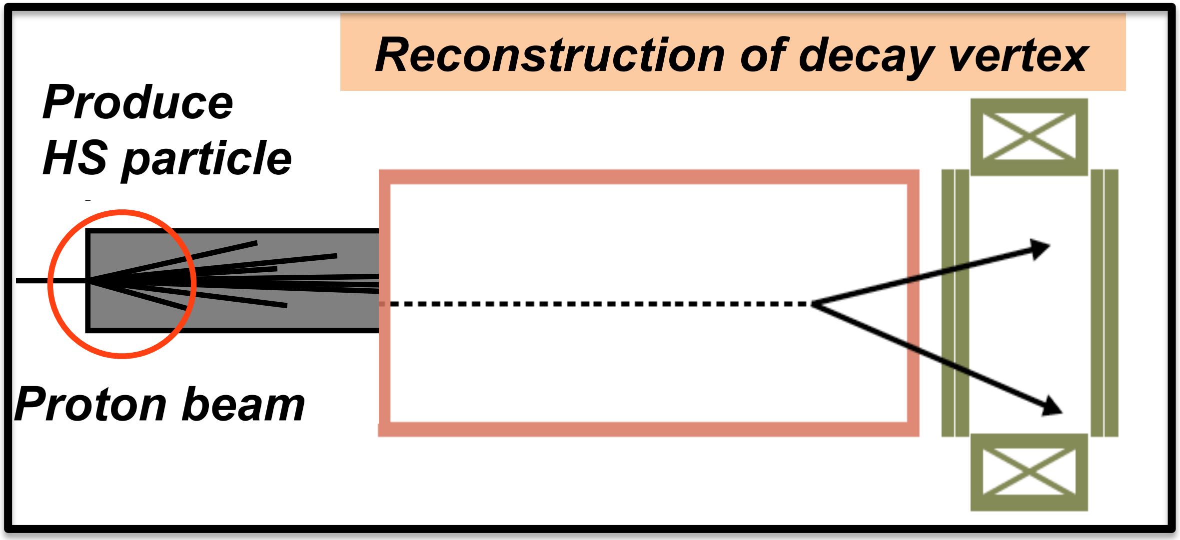


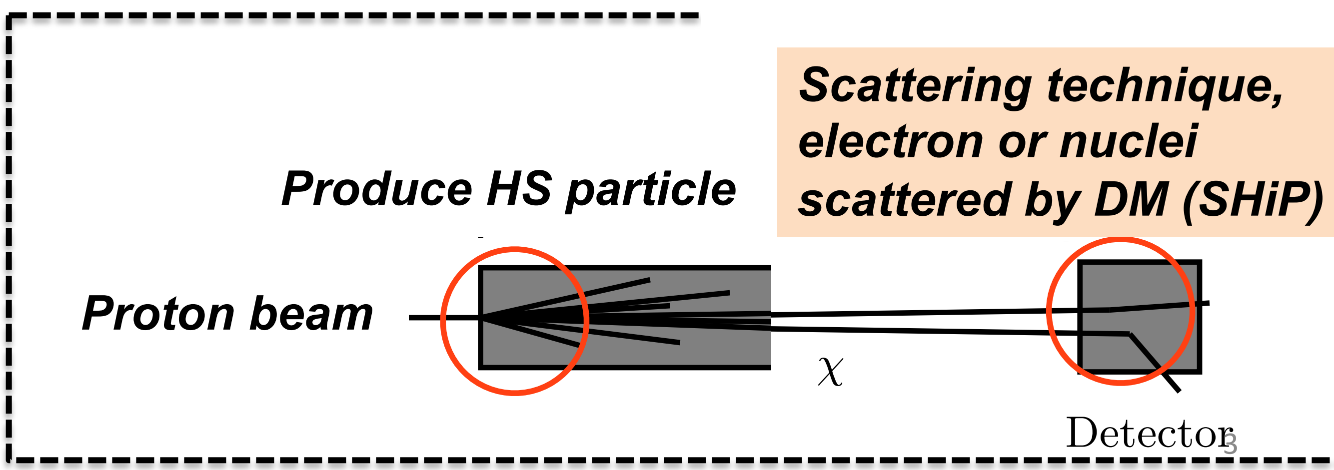

***Proposed implementation is based on minimal modification to the current SPS complex***

# Two strategies at CERN SPS

## Direct observation (SHiP & NA62)

## Indirect detection



## ***The SHiP experiment at SPS***

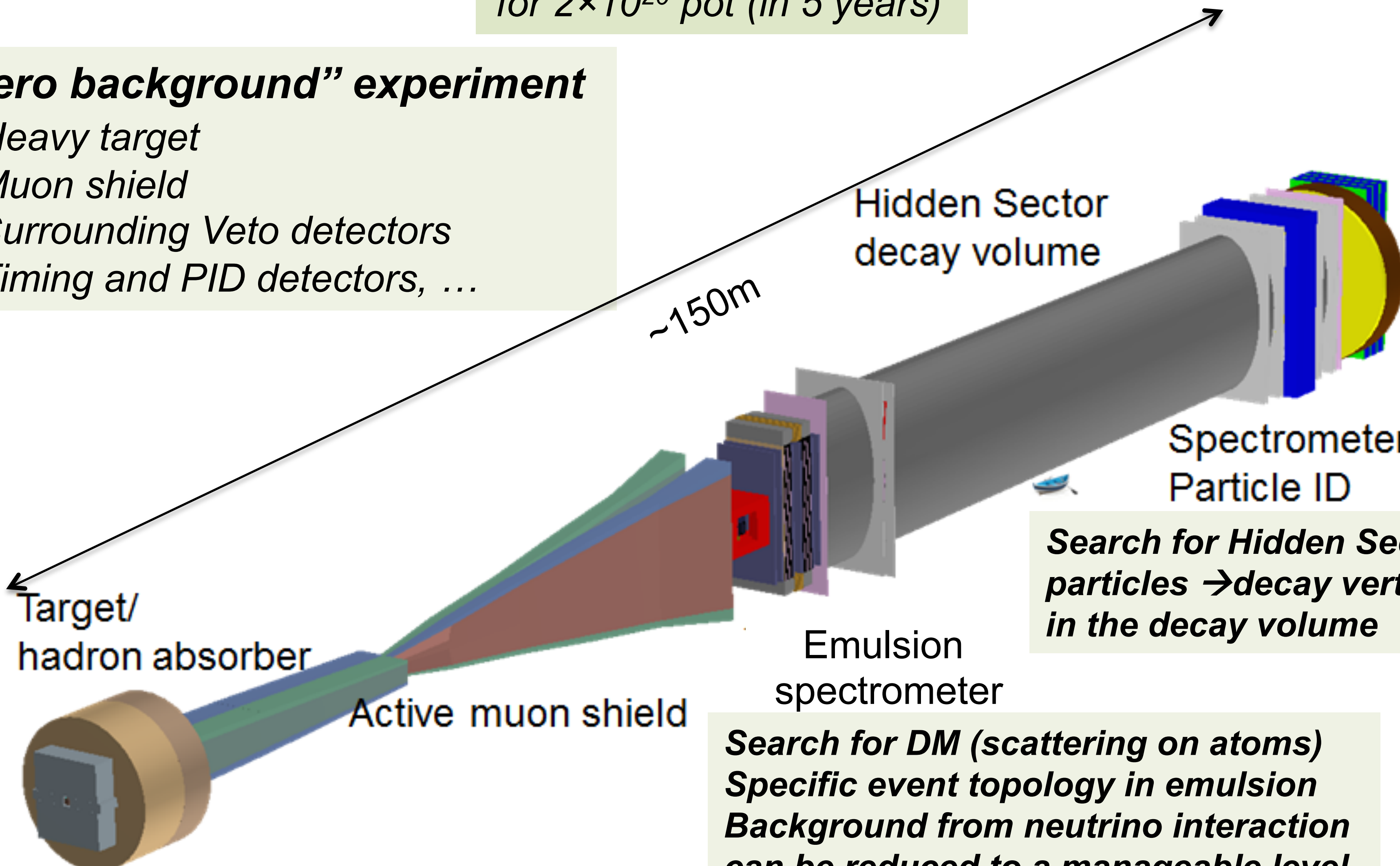
*( to search for HS particles with O(10 GeV) masses)*

SHiP Technical Proposal: 1504.04956

*>$10^{18}$ D, >$10^{16}$ $\tau$, >$10^{20}$ $\gamma$*
*for $2\times10^{20}$ pot (in 5 years)*

### ***"Zero background" experiment***

- *Heavy target*
- *Muon shield*
- *Surrounding Veto detectors*
- *Timing and PID detectors, …*

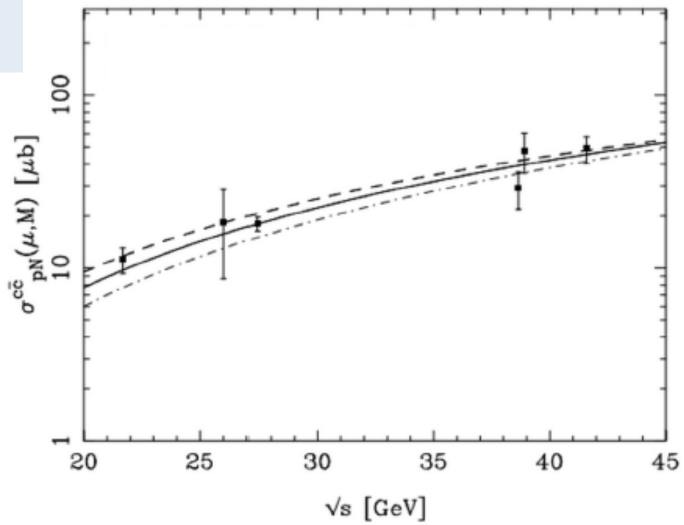



***Search for Hidden Sector particles →decay vertex in the decay volume***

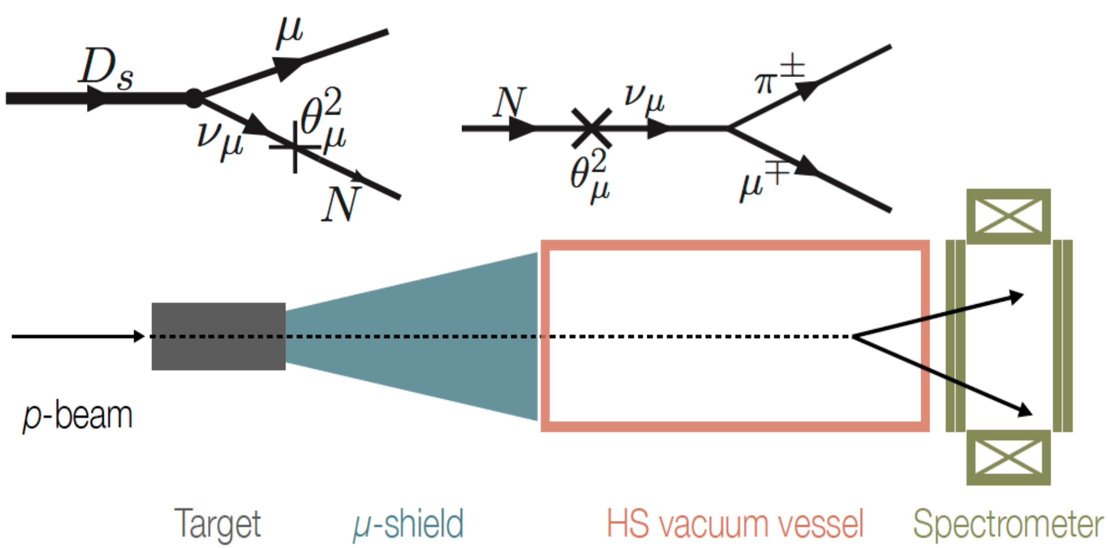
***Search for DM (scattering on atoms)***
***Specific event topology in emulsion***
***Background from neutrino interaction can be reduced to a manageable level***

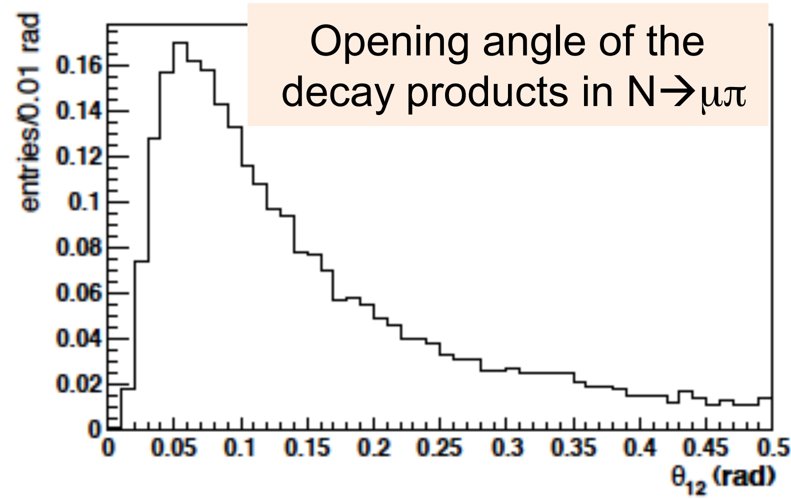
## ***General experimental requirements***
## *to search for HS at beam dump experiment*

- ✓ *Search for HS particles in Heavy Flavour decays*
  *Charm (and beauty) cross-sections strongly depend on the beam energy*




- ✓ *HS produced in charm and beauty decays have significant $P_T$*




***Detector must be placed close to the target to maximize geometrical acceptance. Effective (and "short") muon shield is the key element to reduce muon-induced backgrounds***

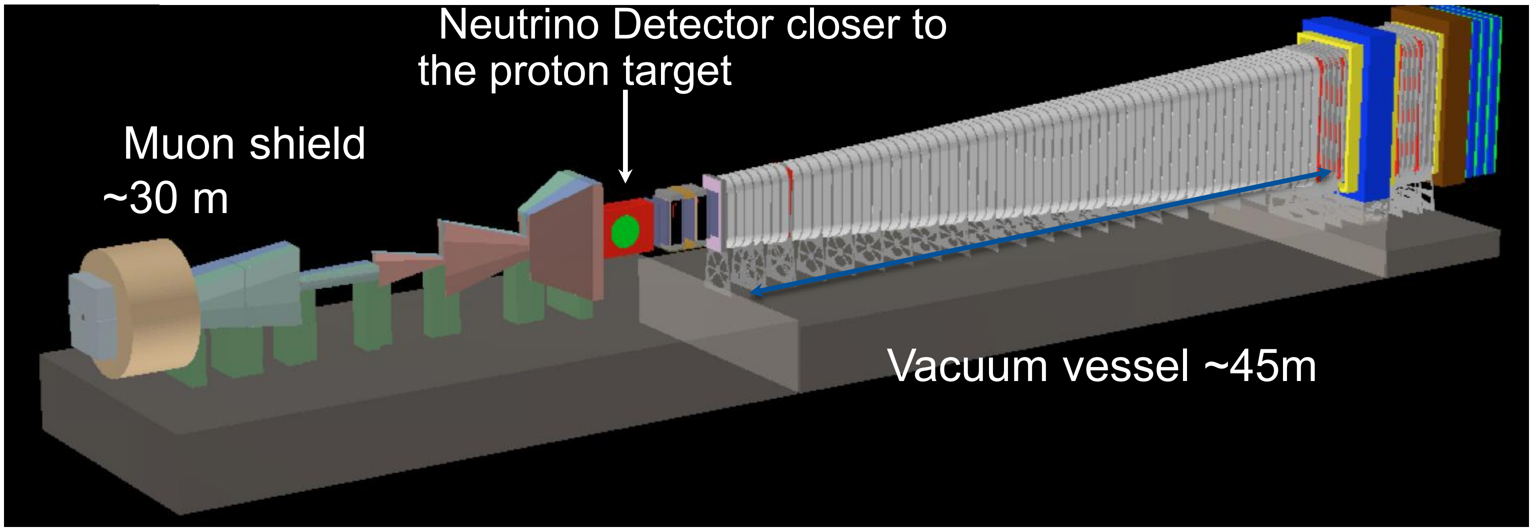
## *Brief history and current status of SHiP*

- ✓ *Letter Of Intent - October 2013*
- ✓ *Technical Proposal & Physics Paper - April 2015*
- ✓ *Reviewed by the SPSC and CERN RB by March 2016, and recommended to prepare a Comprehensive Design Study (CDS) by 2018*
  → *Input to the European strategy consultation to take a decision about approval of SHiP in 2019/2020*

***CDS will improve SHiP TP version*** *respecting cost constraints*

# *Main goals of the SHiP optimization for the CDS*

- ✓ *Further optimization of the target*
- ✓ *Configuration of the muon shield, including magnetization of the hadron stopper (**MC to be validated with data**)*
- ✓ *Shape, dimension and evacuation of the decay volume*

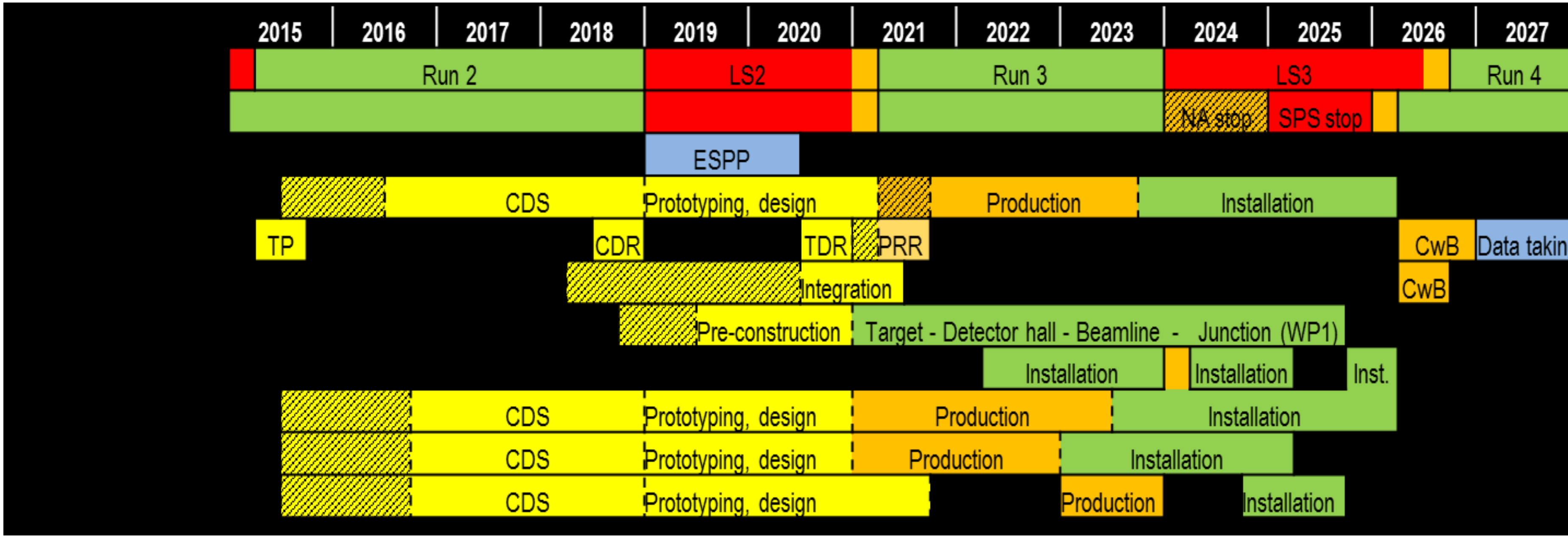



- ✓ *Optimization of the emulsion detector to search for LDM*
- ✓ *Optimization of physics performance for various sub-detectors*
- ✓ *Revisit detector technologies, including new sub-detectors, to further consolidate background rejection and extend PID*

***Updated background estimates and signal sensitivities, and cost***

- ✓ *Contribution from the secondary interactions in the target improves signal yield by ~50% (**to be validated with data)***

# Global SHiP schedule




- ✓ ***Planning very well aligned with***
  - *Update of European strategy 2019/2020*
  - *Accelerator schedule (to be followed closely)*
  - *Production Readiness Reviews (PRR) 2020Q1 →*
  - *Construction / production 2020 →*
  - *Data taking (pilot run) 2026 (start of LHC Run 4)*

- ✓ ***Main current priority: Comprehensive Design Study by 2018***

# *NA62 plans to search for HS (2021-2023)*

T. Spadaro
PBC, March 2017

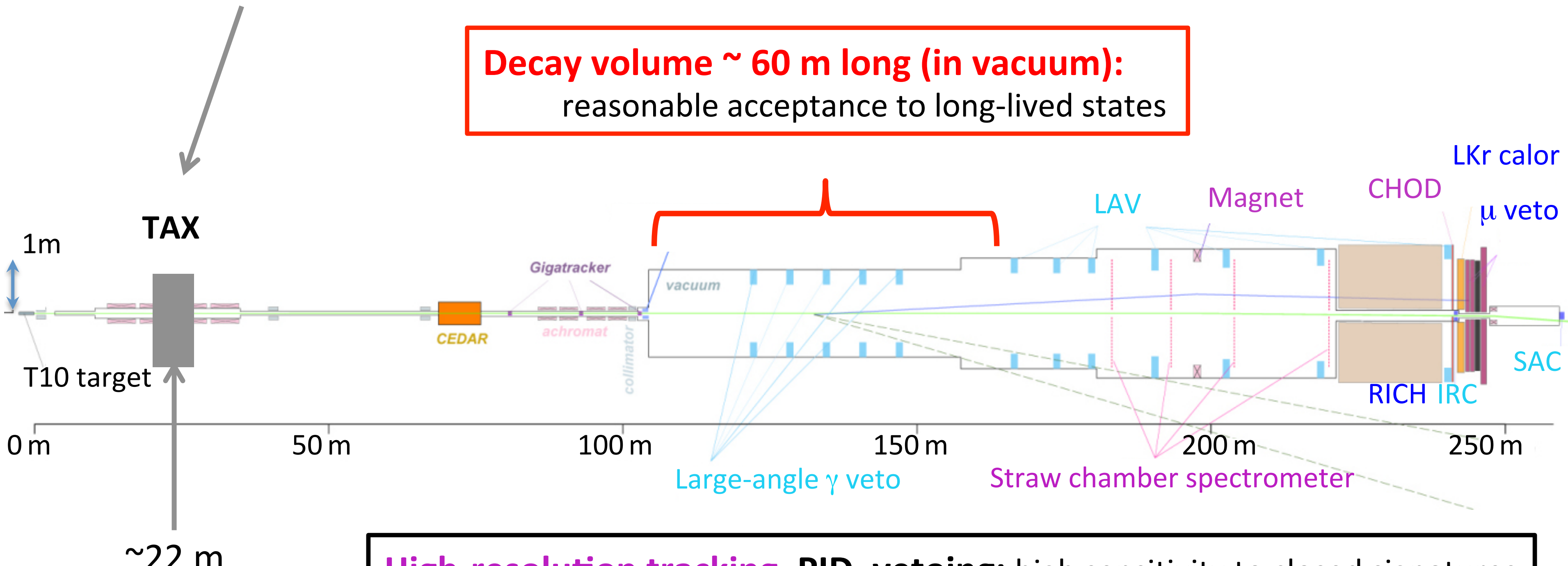
**High-intensity 400-GeV proton beam →** boost charm/beauty, other meson production

**$10^{18}$ POT / nominal year:** $10^{12}$ POT/sec on spill, 3.5-s/16.8 s, 100 days/year, 60% run efficiency

**$10^{15}$ $D_{(S)}$, $10^{14}$ K, $10^{18}$ $\pi^0/\eta/\eta'/\Phi/\rho/\omega$ with ratios 6.4/0.68/0.07/0.03/0.94/0.95**

**Compact beam dump**: ~11 $\lambda_I$ Cu-based beam-defining collimator (TAX)
radioprotection-compliant even if target removed

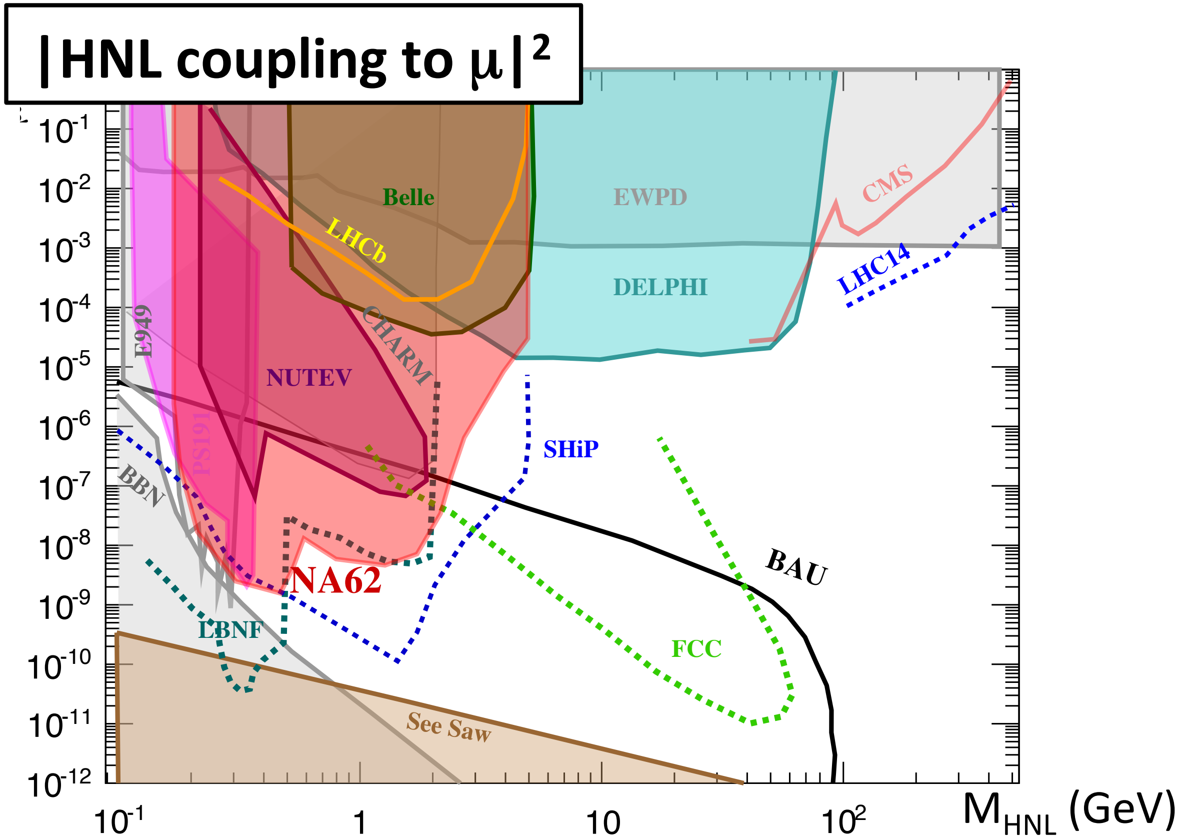
**Decay volume ~ 60 m long (in vacuum):**
reasonable acceptance to long-lived states




**High-resolution tracking, PID, vetoing:** high sensitivity to closed signatures

# *Future prospects and comparison with other facilities*

***HNLs:***




Z → N ν, N → lqq̄

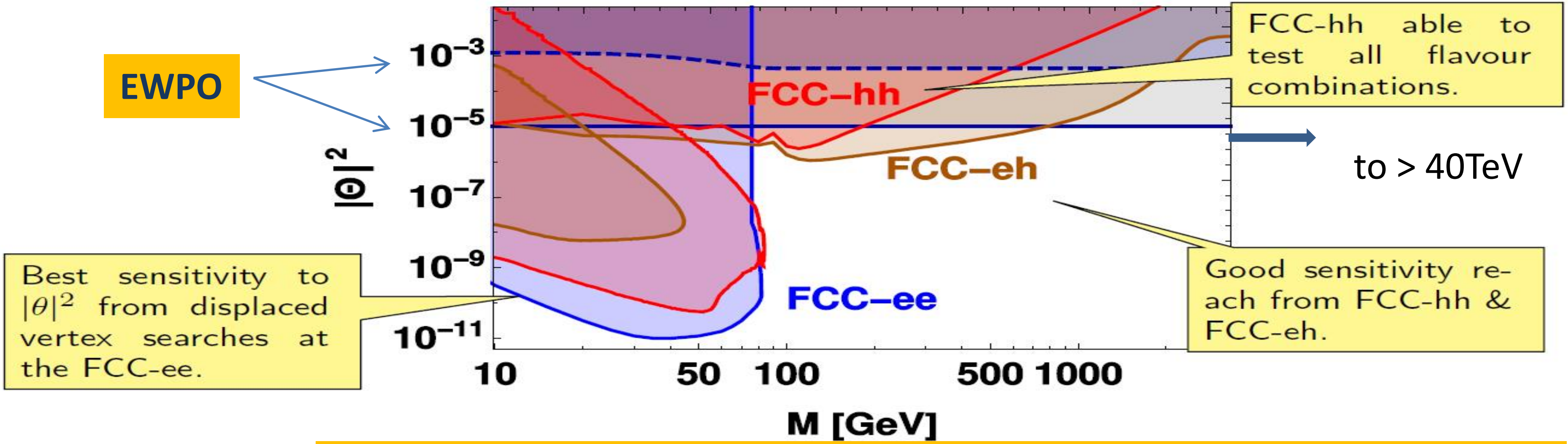
- ✓ *$M_{HNL} < M_b$ LHCb, Belle2*
  ***SHiP will have much better sensitivity***
- ✓ *$M_b < M_{HNL} < M_Z$* ***FCC in $e^+e^-$ mode*** *(improvements are also expected from ATLAS / CMS)*
- ✓ *$M_{HNL} > M_Z$* ***Prerogative of ATLAS/CMS @ HL LHC***

***SHiP will also have the best prospects for HS particles produced in heavy flavour decays, e.g. hidden scalars***

# Summary

## Another example of Synergy and complementarity

- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - **FCC-hh:** LFV signatures and displaced vertex search
  - **FCC-eh:** LFV signatures and displaced vertex search
  - **FCC-ee:** Indirect search via EWPO and displaced vertex search





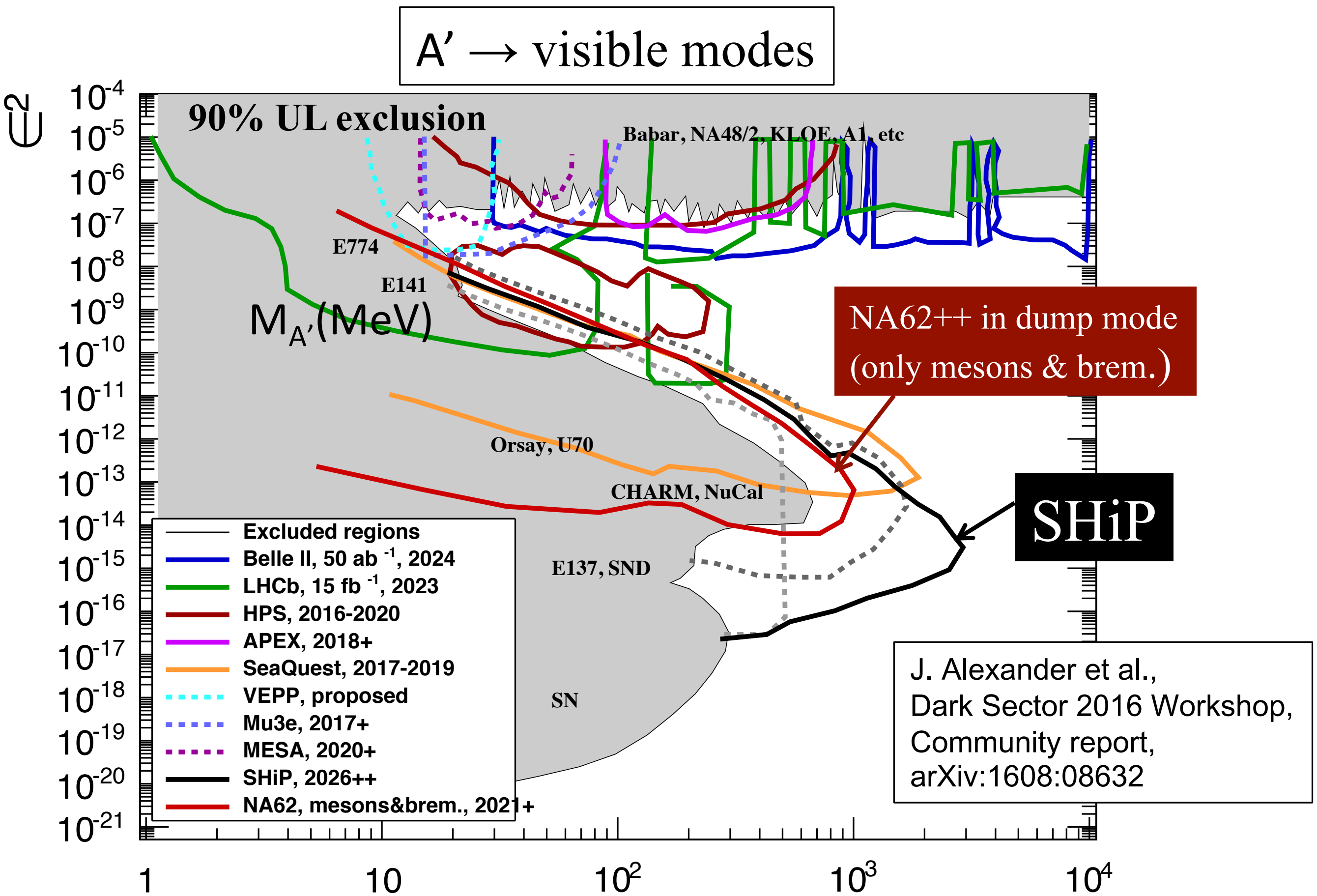

detailed study required for all FCCs – especially FCC-hh to understand feasibility at all

# *Future prospects and comparison with other facilities*

## *Dark photons:*

***SHiP is unique up to O (10GeV) and $\varepsilon^2 < 10^{-11}$***

$M_{A'}/M_\chi$=3



# Conclusions

- High energy and high intensity frontier are complimentary:
  - High energy: search for new heavy particles with $\mathcal{O}(1)$ couplings. Low energy SUSY, composite Higgs, large extra dimensions, ... LHC, FCC in hh mode
  - High intensity: indirect search for new heavy particles with couplings $\ll 1$ leading to deviations from the SM through the loops. LHCb, NA62, BELLE, flavour physics experiments,...
  - High intensity: search new light particles with couplings $\ll 1$. Heavy neutral leptons, dark photon, ALPs, ... SHiP, NA62, NA64, FCC in ee mode, ...
- CERN is an ideal place to search for Hidden Sector at SPS North Area with SHiP and NA62 in < $\mathcal{O}(10)$ GeV range
- FCC ee in Z-peak : up to $\mathcal{O}(100)$ GeV

# Backup slides

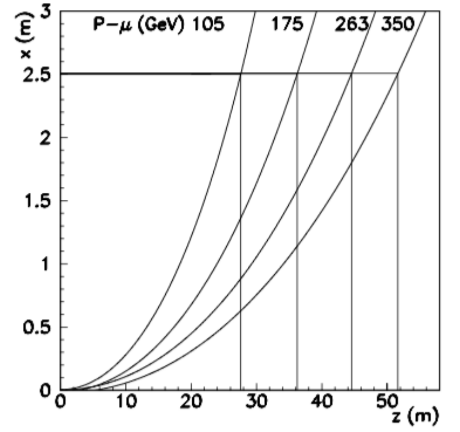
# SHiP at CERN @ 400 GeV vs US-SHiP at Fermilab @ 120 GeV

***Assume:***

*- Hypothetical detector US-SHiP has similar size to the SHiP detector*
*- Slow beam extraction (*)*
*- The target with the same material (*)*
*- Full background suppression*
***- Dedicated to US-SHiP operation (in conflict with neutrino programme)***
*(*) – technical feasibility to be demonstrated for US-SHiP*

| | SHiP | US-SHiP 40 m long and at 37 m from the target |
|---|---|---|
| $N_{pot}$ / year delivered at ~1s extraction | $4\times10^{19}$ | $\sim5.3\times10^{20}$ |
| $\sigma_{cc}$ ($E_{beam}$), au | 1 | 1/7 |
| Detector acceptance (E), au | 1 | 0.6 |

Trajectory of mu in Fe(1.8T)




- ✓ ***Similar performance for HS produced in charm decays***
  *Sensitivity for HS produced in B decay is severely compromised, $\sigma_{bb}$ (120/400) = 625*
- ✓ ***Really poor prospects for tau neutrino physics at 120 GeV beam energy***
- ✓ ***SPS @ 400 GeV is ideal to perform the physics programme of SHiP***