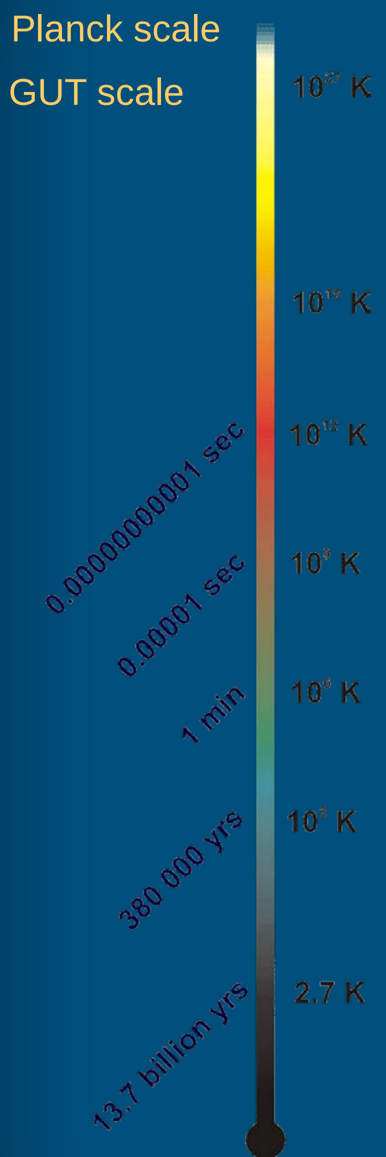
SHiP
Search for Hidden Particles

An Experiment to Search for Hidden Particles at the SPS

- Introduction, physics scope and requirements -

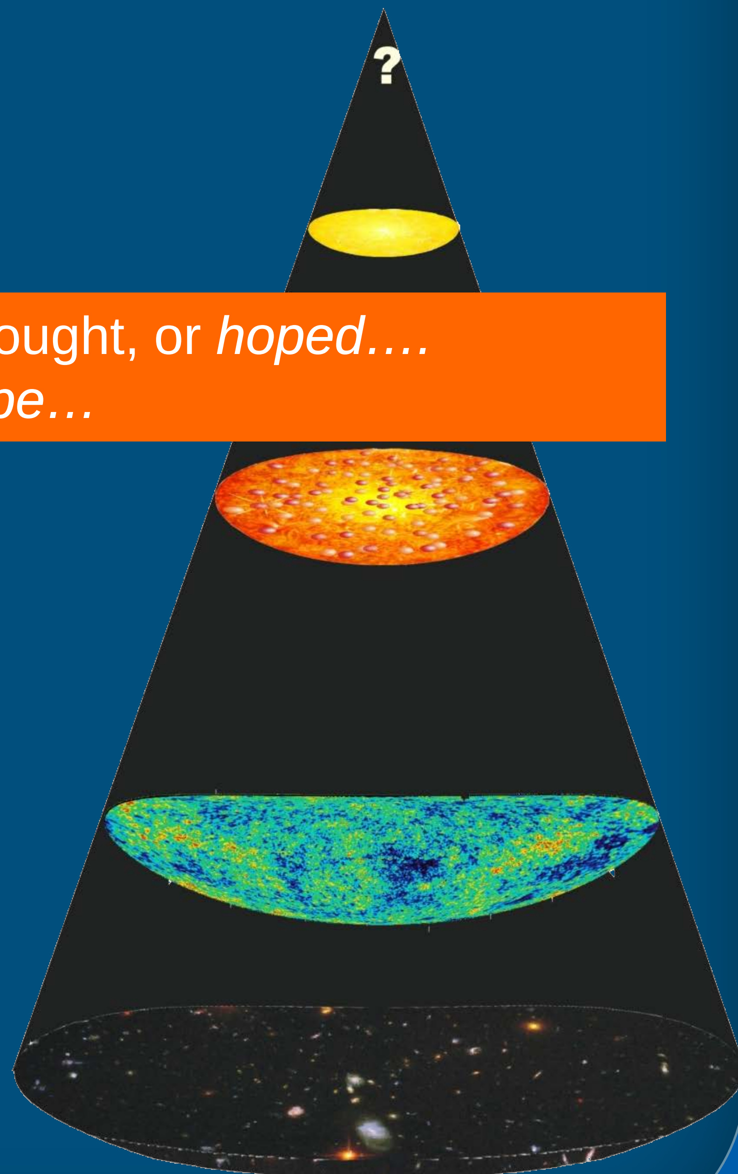
Richard Jacobsson

Validity of SM after LHC Run 1



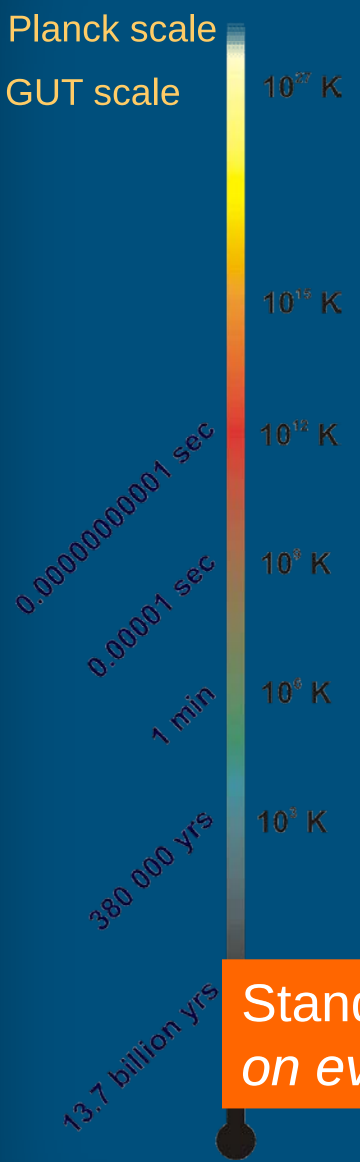
New Physics
(SUSY, extra dimensions, GUT, …)

Standard Model



What we thought, or *hoped….*
And still hope…

Validity of SM after LHC Run 1

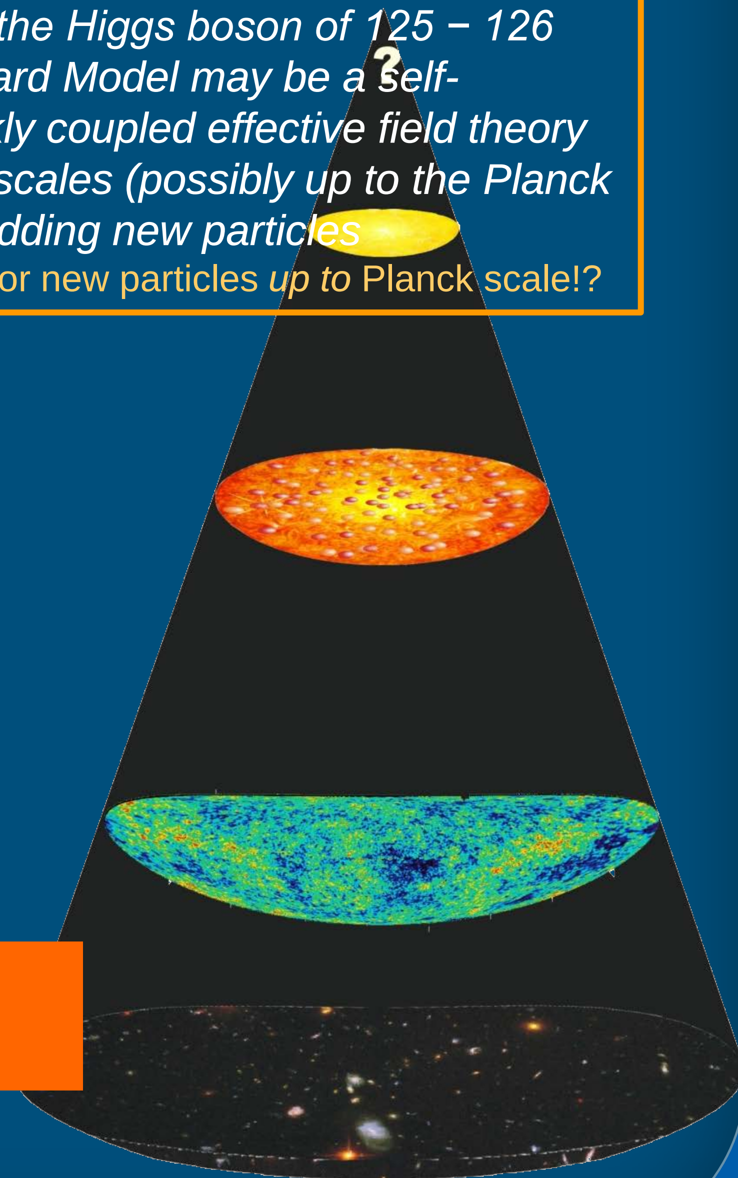


New Physics

Standard Model

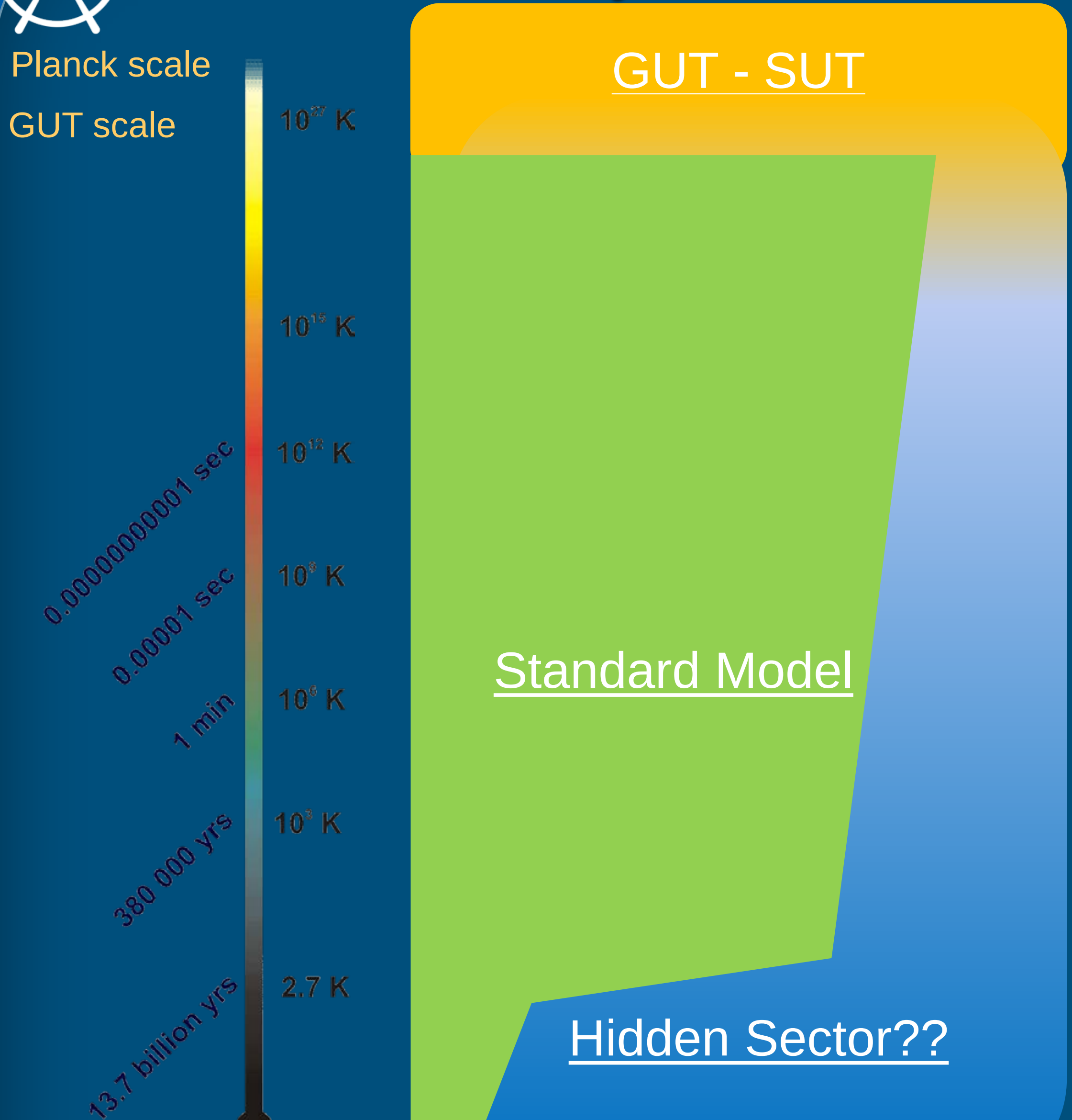
With a mass of the Higgs boson of 125 − 126 GeV, the Standard Model may be a self-consistent weakly coupled effective field theory up to very high scales (possibly up to the Planck scale) without adding new particles

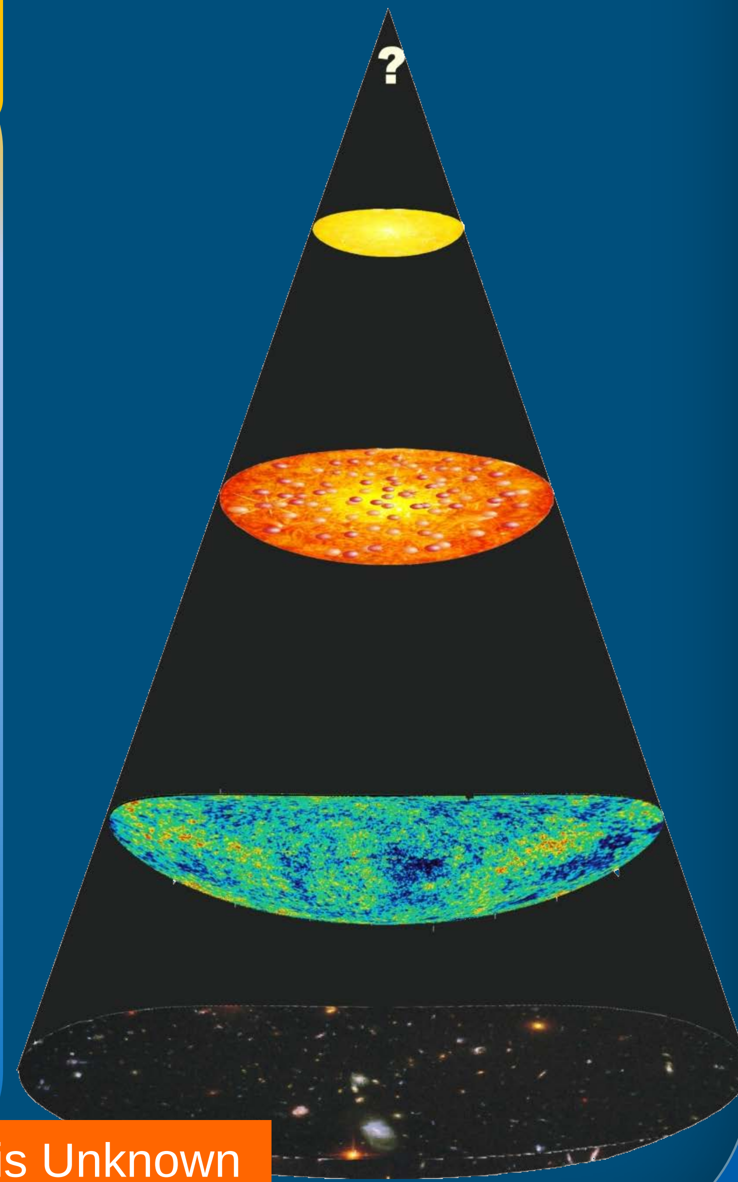
➔No *need* for new particles *up to* Planck scale!?



Standard Model works perfectly well *on everything it attempts to explain*

Validity of SM after LHC Run 1





95% of energy content in Universe today is Unknown

Evidence for New Physics

Experimental evidence for New Physics

1. Neutrino oscillations: *tiny* masses and flavour mixing
   → Requires new degrees of freedom in comparison to SM
2. Matter/antimatter asymmetry of the Universe
   → Measurements from BBN and CMB $\eta = \left\langle \frac{n_B}{n_\gamma} \right\rangle_{T=3K} \sim \left\langle \frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \right\rangle_{T \gtrsim 1\,GeV} \sim 6 \times 10^{-10}$
   → Current measured CP violation in quark sector ➔ $\eta \sim 10^{-20}$!!
3. Dark Matter from indirect gravitational observations
   → Non-baryonic, neutral and stable or long-lived
4. Dark Energy

➔ No prejudice on energy scale!

Theoretical "evidence" for New Physics

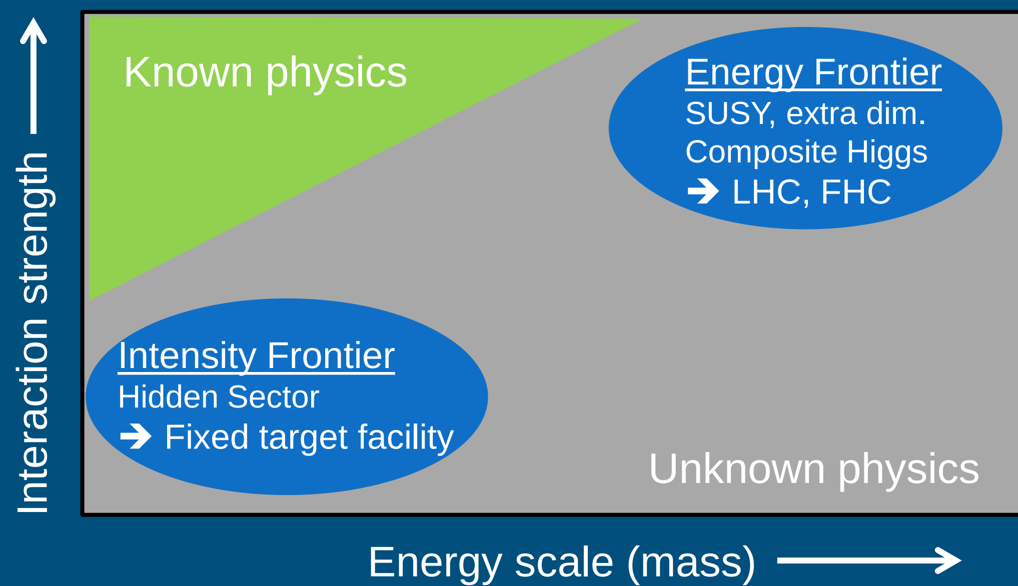
1. Hierarchy problem and stability of Higgs mass
2. SM flavour structure
3. Strong CP problem
4. Unification of coupling constants
5. Gravity
6. ….

➔ Preference for high energy scales….

➔ *While we had unitarity bounds for the Higgs, no such indication on the next scale….*
And, $M_{NP} > 10^4$ TeV from observables in neutral meson mixing (for generic Yukawa coupling)

But where!? What if...?

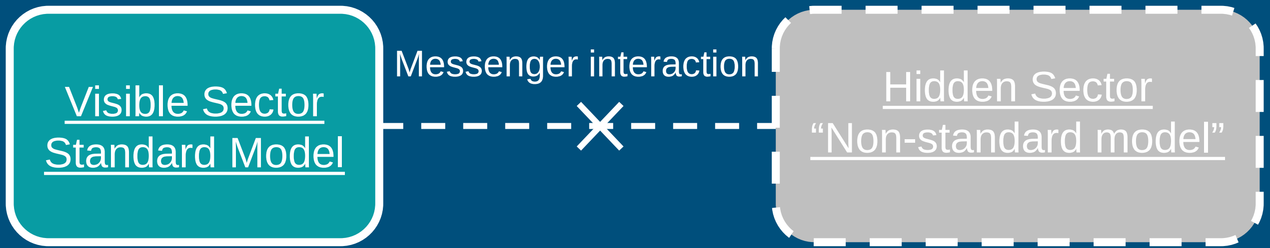
What about solutions to (some) these questions *below* Fermi scale?



➔Must have very weak couplings ➔ Hidden Sector

Hidden Sector?

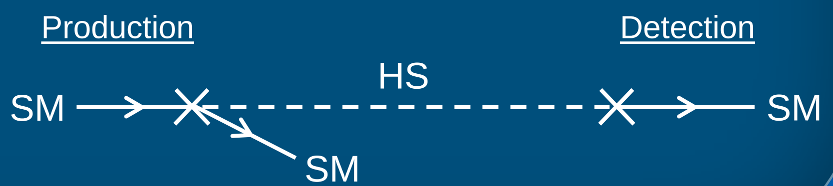
$$\mathcal{L}_{World} = \mathcal{L}_{SM} + \mathcal{L}_{mediation} + \mathcal{L}_{HS}$$



- Most Hidden Sector particles have none of the charges of SM, only make up mass!
  - Hidden Sector may have their own charges and dynamics! ➔ Mirror World

- Some may have both SM and HS charges!
  - ➔ "Portals" to the Hidden Sector !
  - ➔ Dynamics of Hidden Sector may drive dynamics of Visible Sector!
    - Dark Matter
    - Higgs mass
    - Neutrino oscillations
    - Baryon asymmetry
    - Dark Energy
    - Inflaton
    - ……

1. "Indirect detection" through portals in (missing mass)
2. "Direct detection" through both portals in and out



Many different possibilities for Hidden Sector

- 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
    - Mixing with dark scalar χ : $(\mu\chi + \lambda\chi^2)H^\dagger H$

    ➔ Mass to Higgs boson and right-handed neutrino, and function as inflaton in accordance with Planck and BICEP measurements
  - D = 5/2: Neutrino portal, e.g. νMSM
    - 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, 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

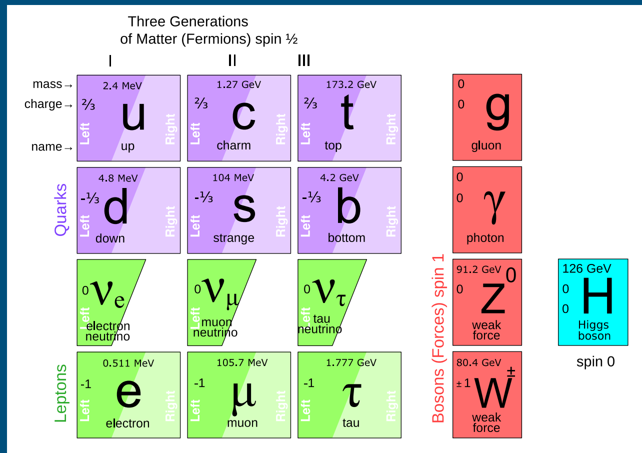
    ➔ Solve strong CP problem
  - And possiby higher dimensional operator portals and super-symmetric portals (light neutralino, light sgoldstino,…)

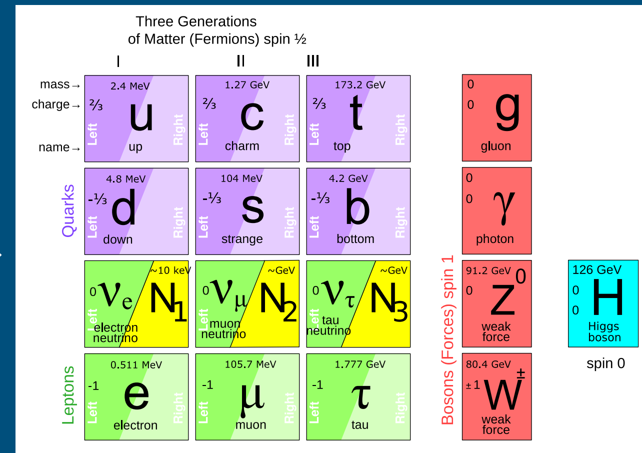
    ➔ SUSY parameter space explored by LHC

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

FYI

Just one example: HNLs in νMSM (Asaka, Shaposhnikov)

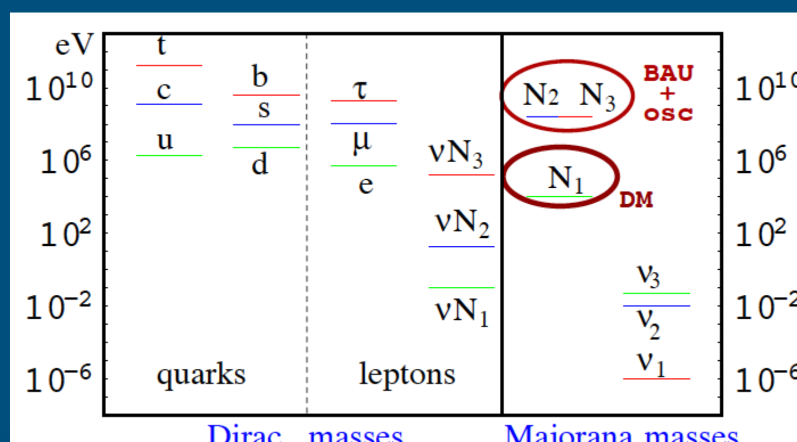




Role of N_1 ➔ Dark Matter

Role of N_2 and N_3 : Neutrino oscillations and mass, and matter/antimatter asymmetry

➔ No new energy scale!



HS Common experimental features

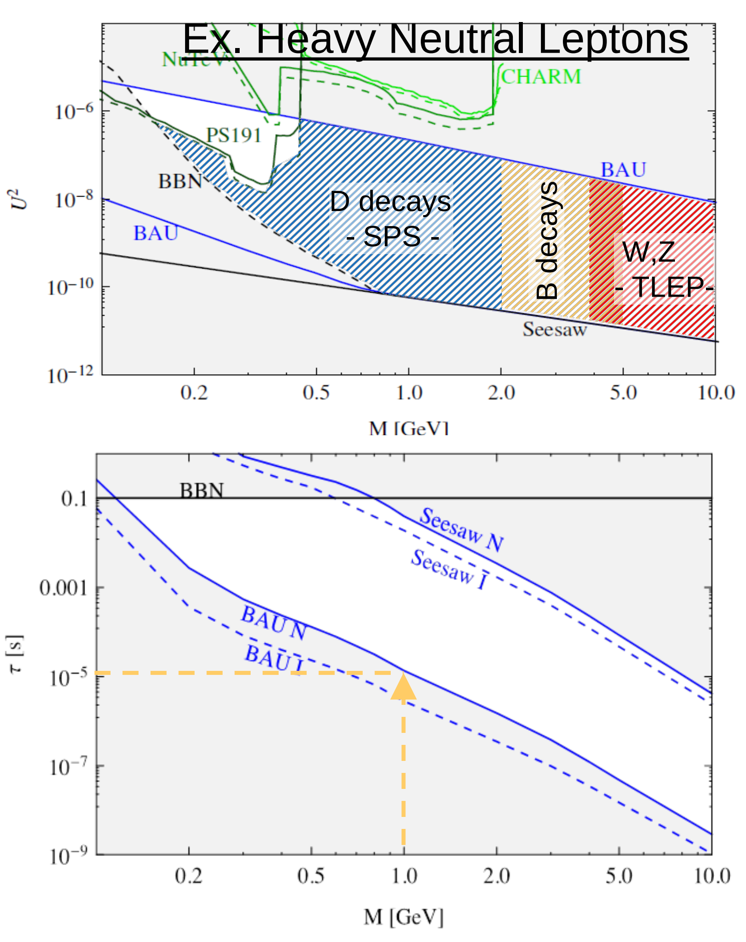
- Cosmologically interesting and experimentally accessible $m_{HS} \sim \mathcal{O}(MeV - GeV)$
  - ➔ Production through meson decays (π, K, D, B), proton bremsstrahlung,…
  - ➔ Decay to l^+l^-, $\pi^+\pi^-$, $l\pi$, $l\rho$, $\gamma\gamma$, etc (and modes including neutrino)
  - ➔ Full reconstruction and particle ID aim at maximizing the model independence

- Production and decay rates are very suppressed relative to SM
  - Production branching ratios $\mathcal{O}(10^{-10})$
  - Very long-lived objects
    - ➔ light objects out of reach at LHC
  - Travel unperturbed through *ordinary* matter
  - ➔ Challenge is background suppression

➔ Fixed-target ("beam-dump") experiment

- ➔ Large number of protons on target and large decay volume!

➔ Complementary physics program to searches for new physics by LHC!



Experimental Requirements/Challenges

Proposal: ***fixed-target (beam dump like) experiment at the SPS***

1. E.g. sensitivity to HNL $\propto \mathcal{U}^4$ → Number of protons on target (p.o.t.)
   - ➔ SPS: 4×10^{13} / 7s @ 400 GeV = 500 kW → 2×10^{20} in 5 years (similar to CNGS)
2. Preference for relatively slow beam extraction $\mathcal{O}(ms - 1s)$ to reduce detector occupancy
   - ➔ Reduce combinatorial background
3. As uniform extraction as possible for target and combinatorial background/occupancy
4. Heavy material target to stop π, K before decay to reduce flux of active neutrinos
   - ➔ Blow up beam to dilute beam energy on target
5. Long muon shield to range out flux of muons
6. Away from tunnel walls to reduce neutrino/muon interactions in proximity of detector
7. Vacuum in detector volume to reduce neutrino interactions in detector
8. Detector acceptance compromise between lifetime and production angles
   - …and length of shield to filter out muon flux

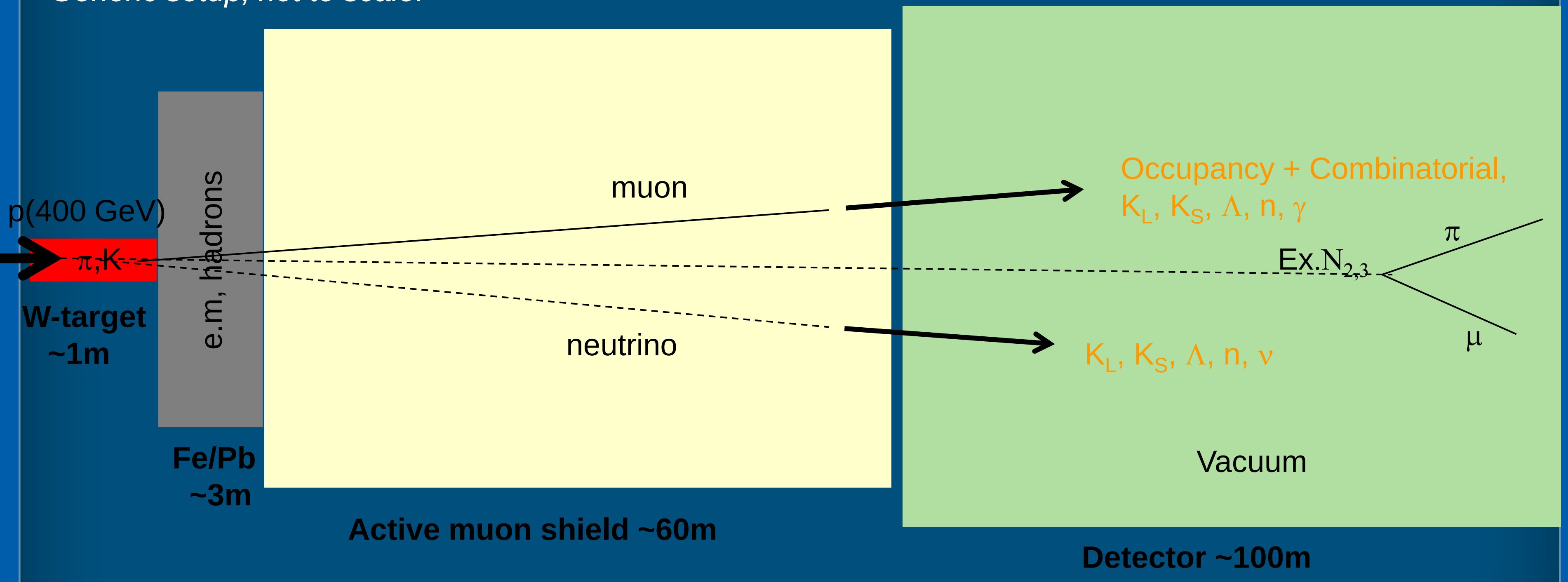
➔ Defines the list of critical parameters and layout for the sensitivity of the experiment

- ➔ Incompatible with conventional neutrino facility
- ➔ But a very powerful general-purpose facility for now and later!

Schematic Principle of Experimental Setup

- Residual backgrounds:
  1. Neutrinos scattering
  2. Muon inelastic scattering
  3. Muon combinatorial (μμ with μ mis-ID)

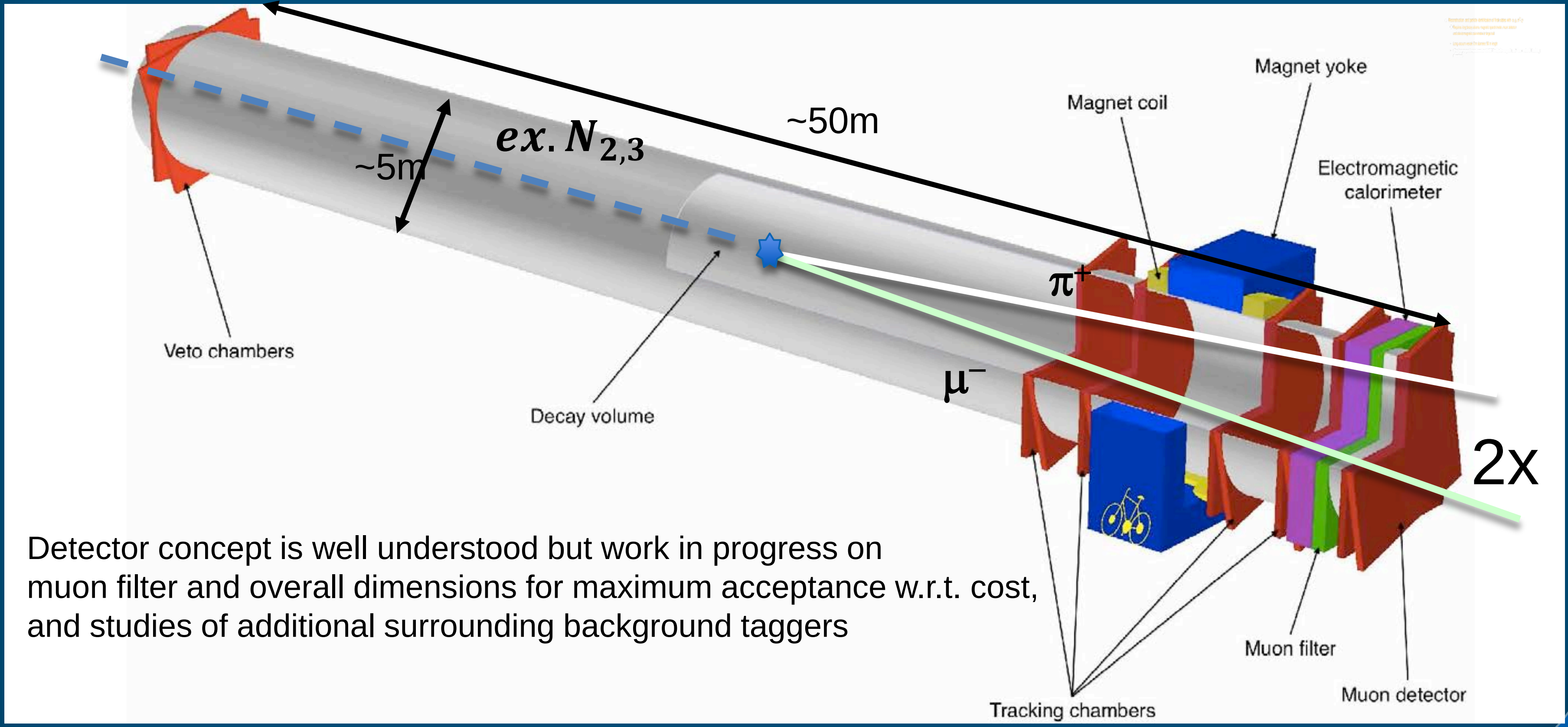
Generic setup, not to scale!



Initial Detector Concept for EOI

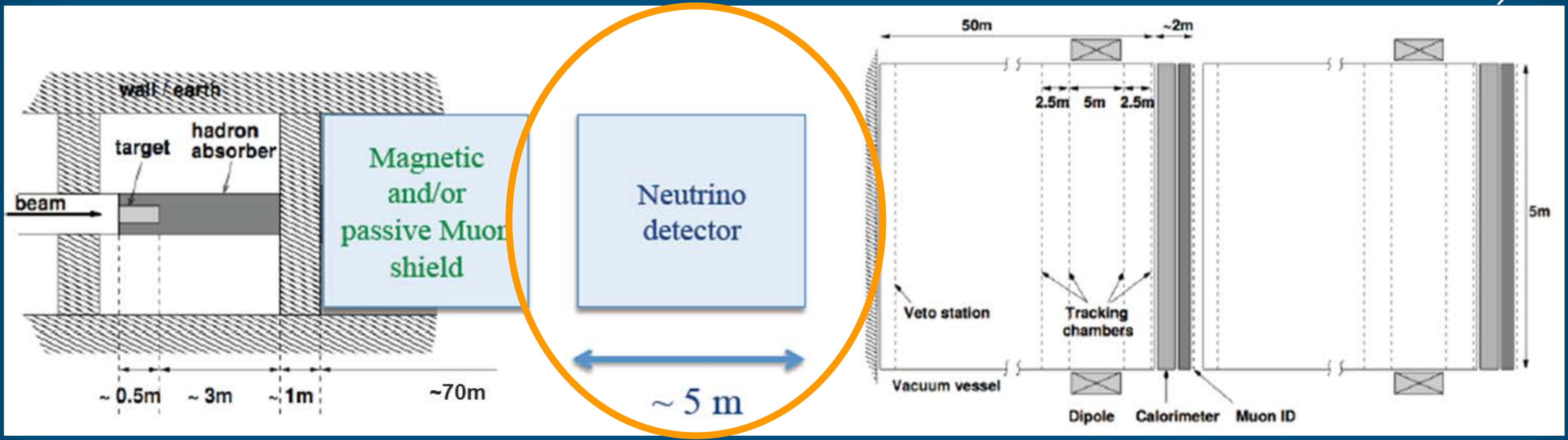
- Full reconstruction and particle identification of final states with e, $\mu, \pi^{\pm}, \gamma$
  - ➔ Requires long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter in large hall

- Long vacuum vessel, 5 m diameter, 50 m length
- 10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers



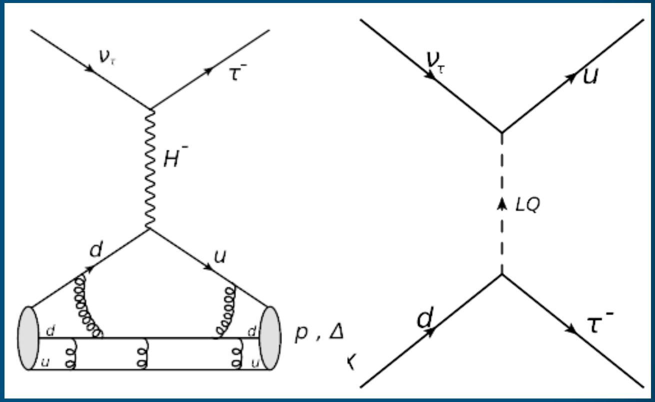
Detector concept is well understood but work in progress on muon filter and overall dimensions for maximum acceptance w.r.t. cost, and studies of additional surrounding background taggers

++ SM physics: Prospects for ν_τ Physics



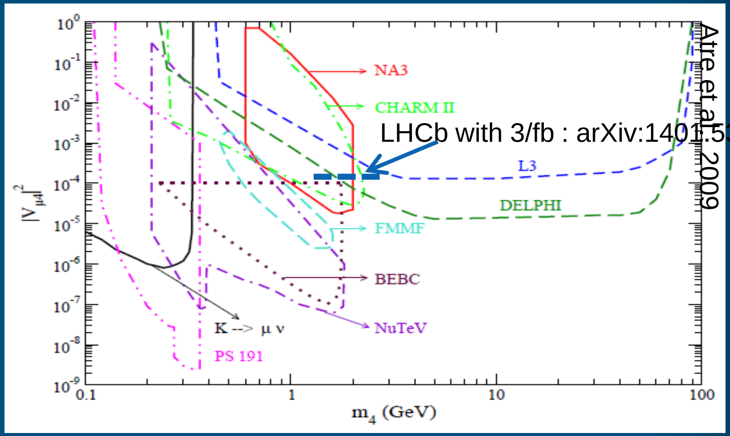
- Expecting $\mathcal{O}(3500)$ ν_τ interactions in 6 tons of emulsion target
  - Tau neutrino and anti-neutrino physics

- Charm physics with neutrinos and anti-neutrinos
  - ➔ ν_μ- induced charm production: 11 000 events (2000 in CHORUS)
  - ➔ $\overline{\nu_\mu}$ - induced charm production: 3500 events (32 in CHORUS)
  - Electron neutrino studies (high energy cross-section and ν_e induced charm production ~ 2 x ν_μ induced)
  - ➔ **Normalization for hidden particle search!**

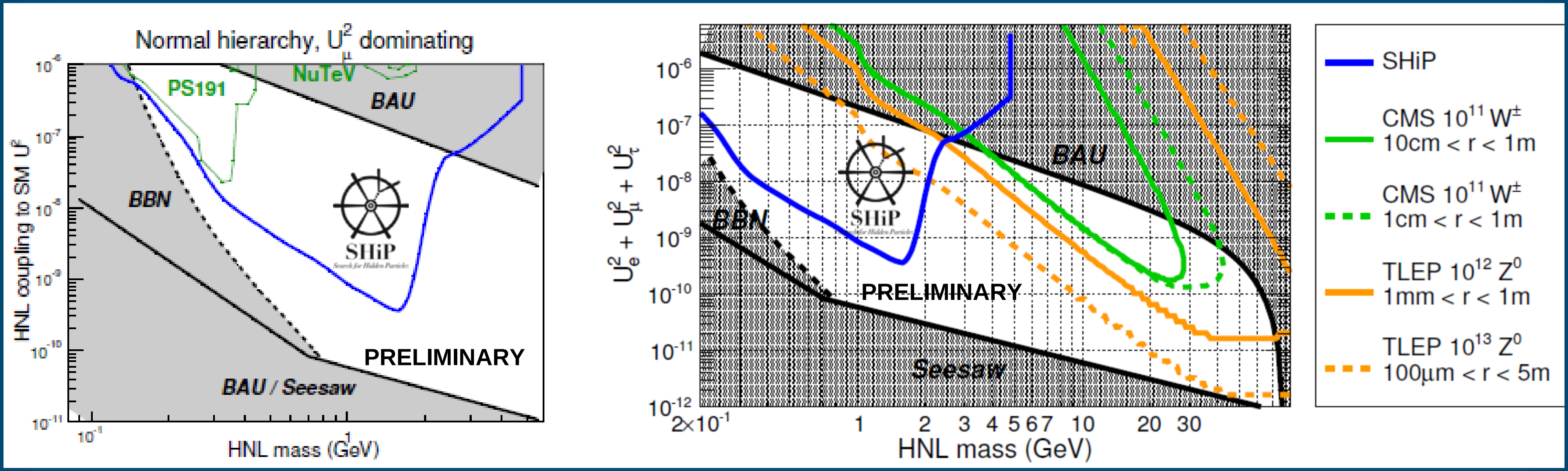


Example of estimates of HNL sensitivity

Summary of past Searches for N_I



- Colliders out of luck with low mass / long lifetimes
  - LHC ($\sqrt{s}$ = 14 TeV): with 1 ab^{-1}, i.e. 3-4 years: ~ 2x10^{16} D's in 4π
  - SPS@400 ($\sqrt{s}$ = 27 GeV) with 2x10^{20} pot, i.e. ~5 years: ~ 2x10^{17} D's
  - BELLE-2 using $B \rightarrow XlN$, where $N \rightarrow l\pi$ and X reconstructed using missing mass may go well below 10^{-4} in 0.5<M_N<5 GeV
- SHiP sensitivity based on current SPS with 2x10^{20} p.o.t at 400 GeV in ~5 years of nominal CNGS-like operation

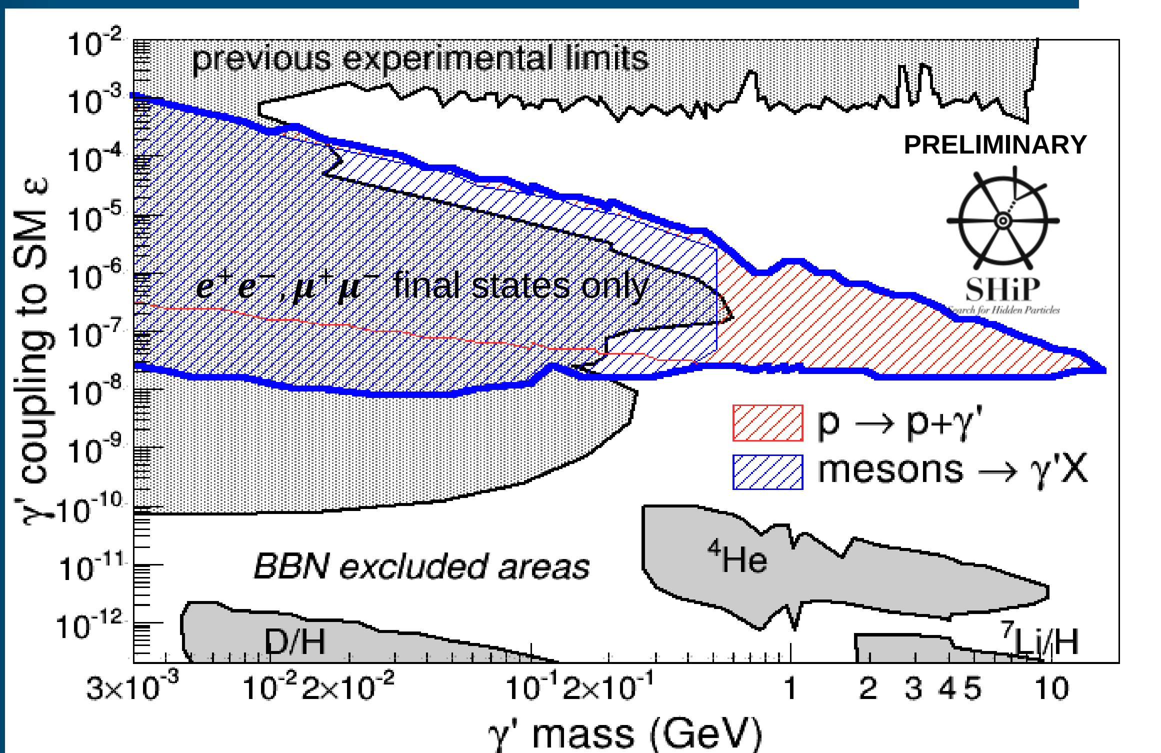


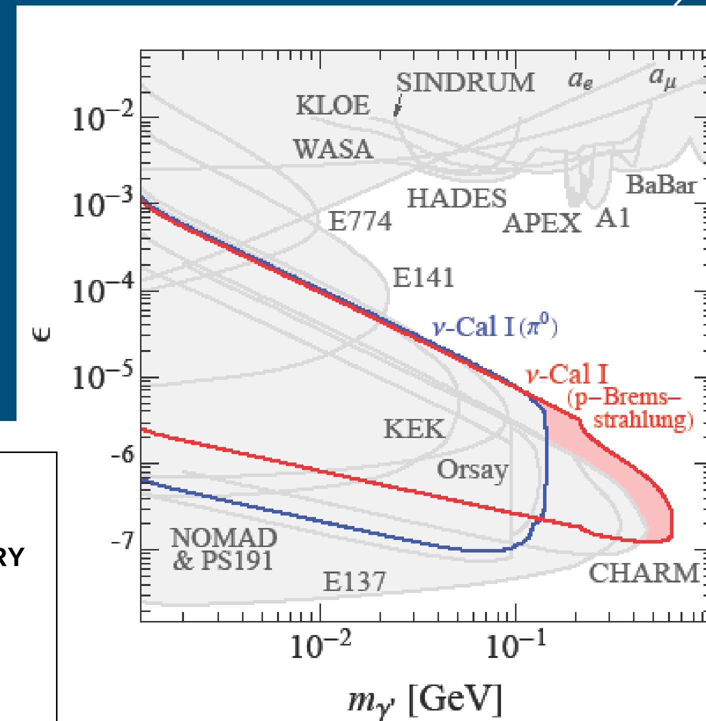
- W ➔ ℓN at LHC: extremely large BG, difficult triggering/analysis.
- Z ➔ Nν at e$^+$e$^-$ collider [M. Bicer et al. 2013]: clean

Ex. Expected sensitivity to Dark Photons

- Predominant dark photon production at SPS
  - Proton bremsstrahlung
  - Meson decays ($\pi^0, \eta, \ \omega, \ \eta', \ldots$)
  - Lifetime limit from BBN: $\tau_\gamma < 0.1s$

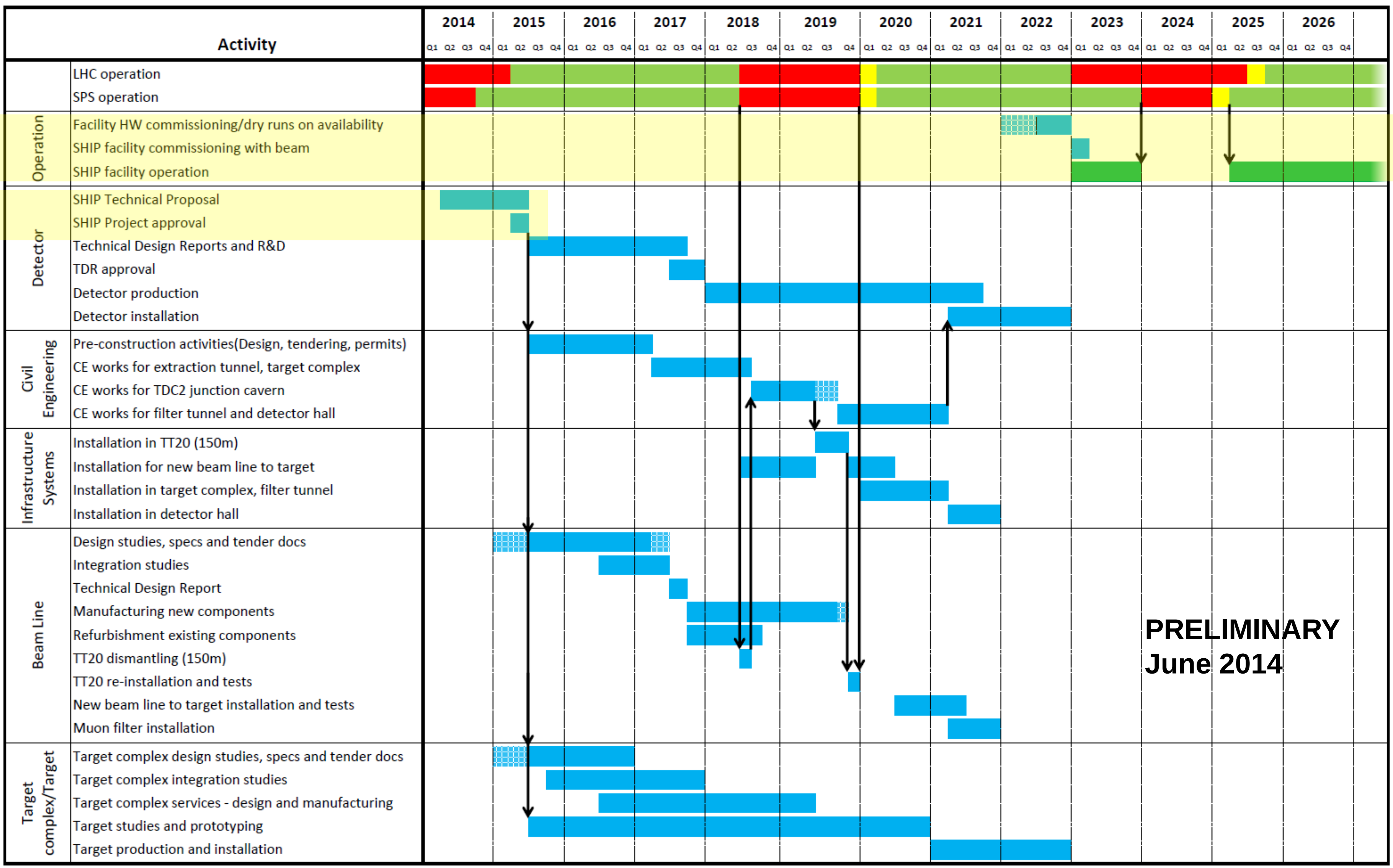
- Dark photon decays
  - $e^+e^-, \mu^+\mu^-, q\bar{q}\ (\pi^+\pi^-, \ldots), \ldots$





arXiv:1311.3870

Preliminary Schedule (as from task force)



Current Status and Conclusion

- Work towards Technical Proposal in full swing
  - Signal background studies and optimization, detector specification, simulation and some detector R&D
    ➔ Full detector including muon filter and surrounding structures implemented in GEANT: FairSHIP!
  - Optimization of Experimental Facility - beam line, target, and muon filter, RP, overall layout

  ➔ This needs iterations between experiment - machine

- At SHiP Collaboration Meeting in September, ~30 institutes agreed to provide a “letter of intent” as basis for the formalization of the Collaboration in at meeting in December 2014.
  - Others in the pipeline to join later for TDR

- 4^{th} SHiP Collaboration meeting in Napoli 9-11 February 2015 to finalize contents of TP

- Aim to produce Technical Proposal for April 2015

- TP will be complemented by a separate “Physics Proposal” being prepared mainly by a large group of invited theorists
  - Contains a description of the complete physics program, and extensions beyond SHiP
  - Further extension of complete physics program still ongoing

- Facility and physics case based on the current injector complex and SPS
  - 2×10^{20} at 400 GeV in 5 nominal years by “inheriting” CNGS share of the SPS beam time <u>from 2023</u>

- Proposed experiment perfectly complements the searches for New Physics at the LHC

SHiP Technical Proposal

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHiP
Search for Hidden Particles

CERN-SPSC-2014-XXX
8 September 2014

Technical Proposal

An Experiment to Search for Hidden Particles (SHiP) at the SPS

The SHiP Collaboration[1]

Abstract

The SHiP experiment is a new general-purpose fixed target facility at the SPS to search for hidden particles. These are predicted by a very large number of recently elaborated models of Hidden Sectors which are capable of accommodating dark matter, neutrino oscillations, and the origin of the full baryon asymmetry in the Universe. The high intensity of the SPS and in particular the large production of charm mesons with the 400 GeV beam allow accessing a wide variety of light long-lived exotic particles of such models and of SUSY. Moreover, the facility is ideally suited to study the interactions of tau neutrinos.

The SHIP detector consists of two 40 m long evacuated decay volumes, each of which is followed by a 10 m magnetic spectrometer, a calorimeter and muon detectors in order to allow full reconstruction and particle identification, together with an upstream emulsion target. As an example, with an integrated total of 2x1020 protons on target, the experiment achieves sensitivity for heavy neutral leptons that is four orders of magnitude better than previous searches, accessing a significant fraction of the unexplored parameter space consistent with cosmological constraints.

[1] Authors are listed on the following pages.

Technical Proposal - Outline

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SHiP location

- Proposed location by CERN beams and support departments