SHiP – Search for Hidden Particles

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Structure of the Standard Model

In the past the structure of the Standard Model was predicting where to expect new physics

We searched for new particles required for the consistency of our explanation of all the previous experiments

- We knew that something should— be found at energies below $E < G_{\text{Fermi}}^{-1/2}$
- Without the top quark the Standard Model would be **non-unitary**
- Without the Higgs boson the Standard Model would be **non-unitary**

Higgs boson was the last predicted but unseen particle

- **Did century long quest come to its end?**
- **Where do we need to look for something else?**

Should we believe that new particles exist?

Physics **Beyond** the Standard Model

Neutrino masses and oscillations

What makes neutrinos disappear and then re-appear in a different form? Why do they have mass?

- Neutrino oscillations do not tell us what is the scale of new physics
- It can be **anywhere** between sub-eV and 10^{15} GeV

Dark matter

What is the most prevalent kind of matter in our Universe?

- Physics at high scales (10^{12} GeV for axions), at intermediate scales (TeVs for WIMPs) or at low scales (keV-ish sterile neutrino, physics below electroweak scale) can be responsible for this

Baryon asymmetry of the Universe

what had created tiny matter-antimatter disbalance in the early Universe?

- Physics on the very different scales can be responsible for it

Question about the evolution of the Universe as a whole

Cosmological inflation:

What sets the initial conditions for all the structure that we see in the Universe? (possibly Higgs field)

Dark Energy:

What drives the accelerated expansion of the universe now (possibly this is just Λ-term)

Deep theoretical questions

- Strong CP problem
- Why Planck scale 10^{19} GeV is much higher than the electroweak scale (100 GeV)?
- How to describe gravity quantum mechanically?

(Fundamental questions, but it is possible to be agnostic about them for quantitative description of what was observed so far)

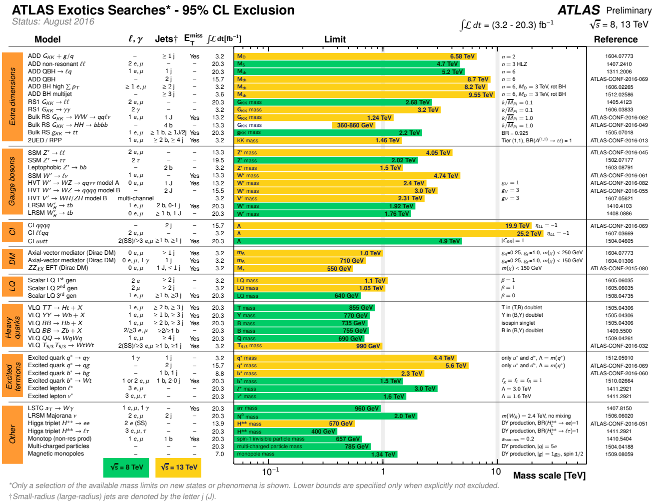
Unsolved problems mean that new particles probably exist

We did not detect them because

they are **heavy**

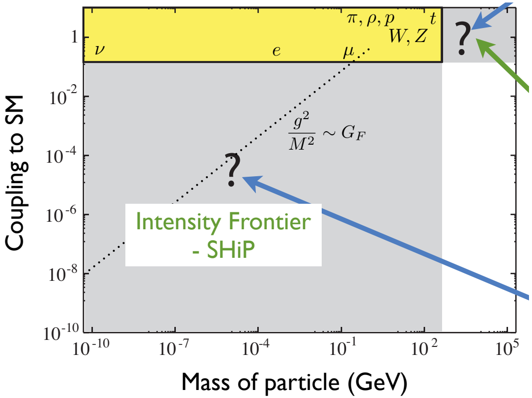
OR

they are light but
very weakly interacting



Probed scale $\ll 10^{19}$ GeV

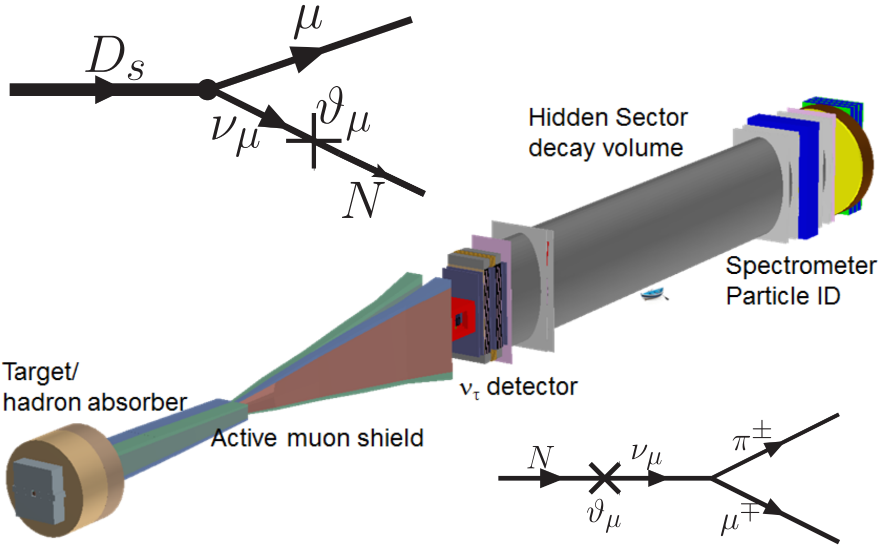
Intensity frontier searches for feebly interacting particles



Intensity frontier has been paid much less attention in the recent years:

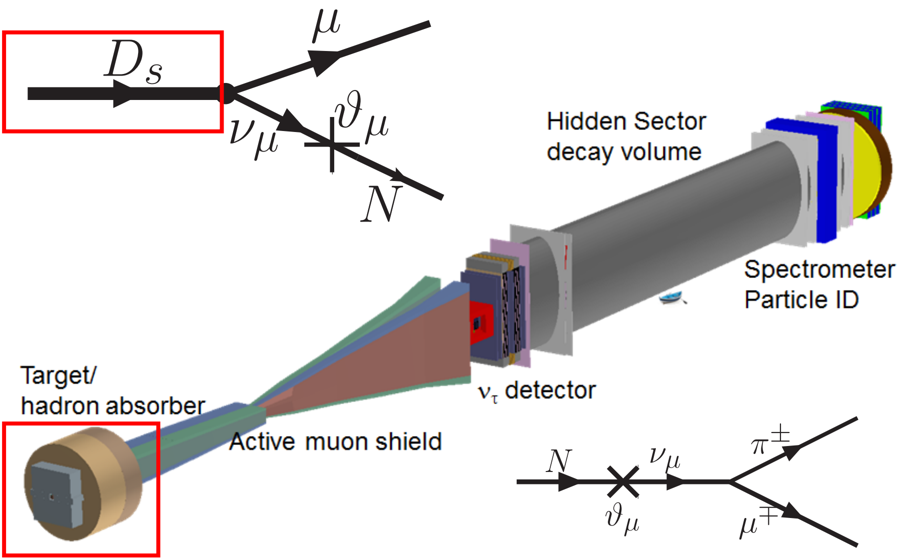
- PS 191 (early 1980s)
- CHARM: 1980s
- NuTeV: 1990s
- DONUT: late 1990s – early 2000

SHiP (*Search for Hidden Particles*) experiment



SHiP (*Search for Hidden Particles*) experiment

Step by step overview



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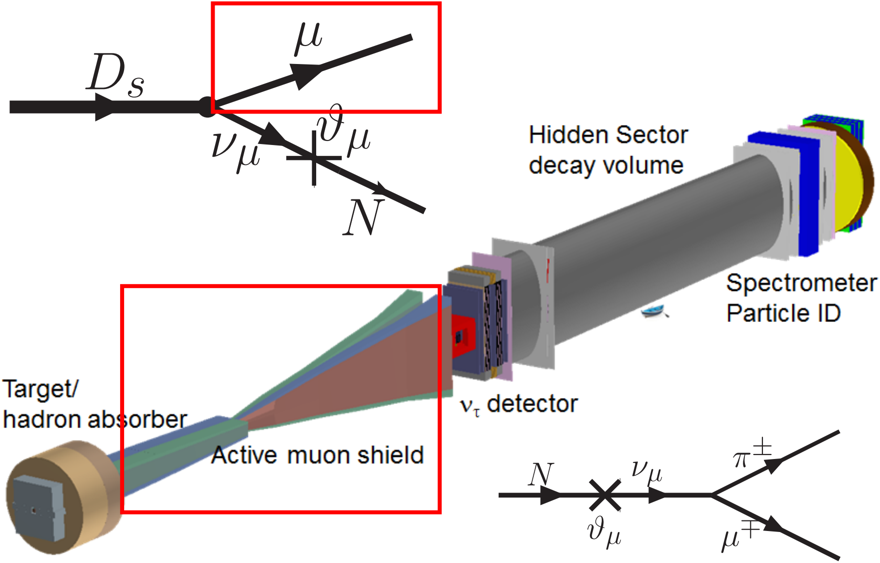

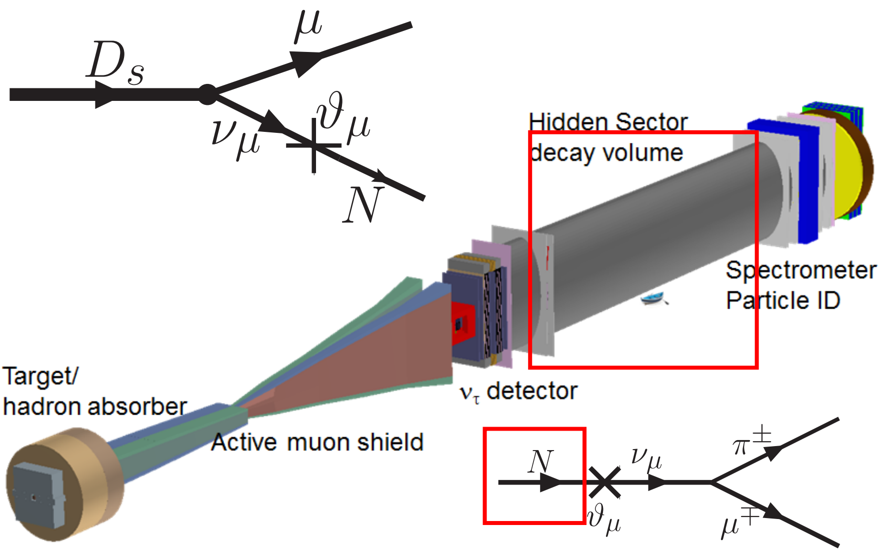

D_s
μ
ν_μ
ϑ_μ
N
Hidden Sector
decay volume
Spectrometer
Particle ID
Target/
hadron absorber
Active muon shield
ν_τ detector
N
ν_μ
ϑ_μ
$\pi^\pm$
$\mu^\mp$

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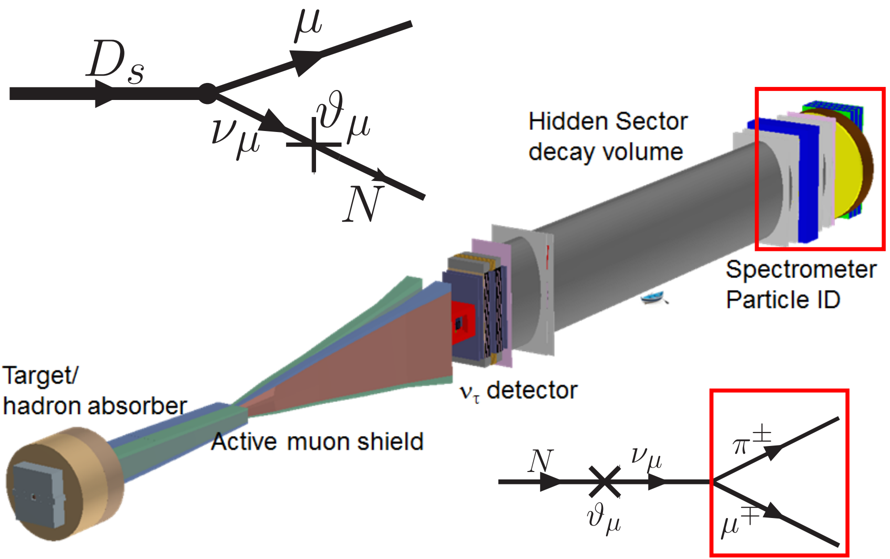

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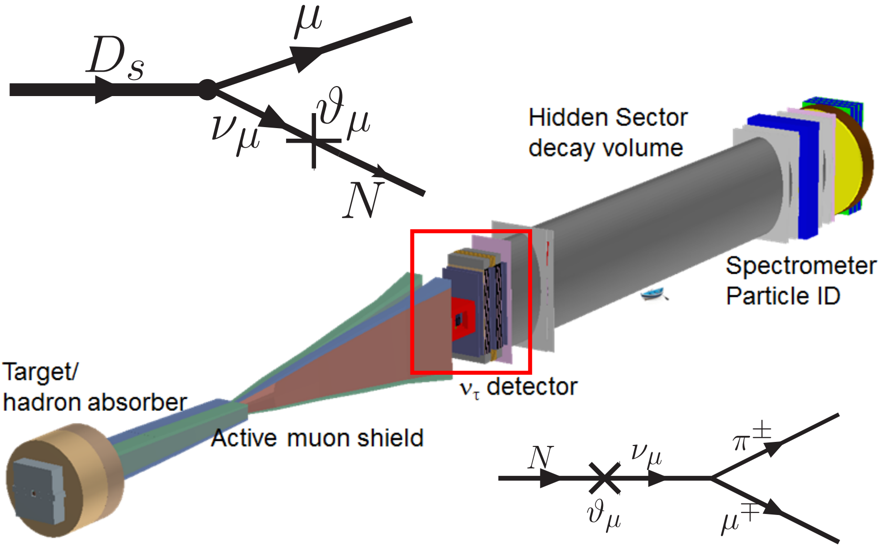
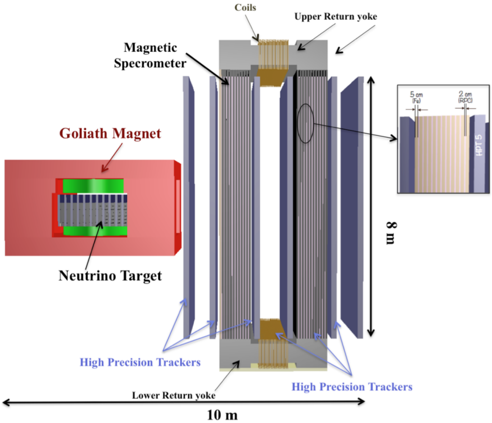
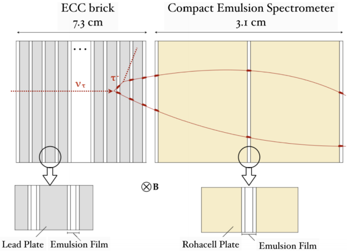


iSHiP detector

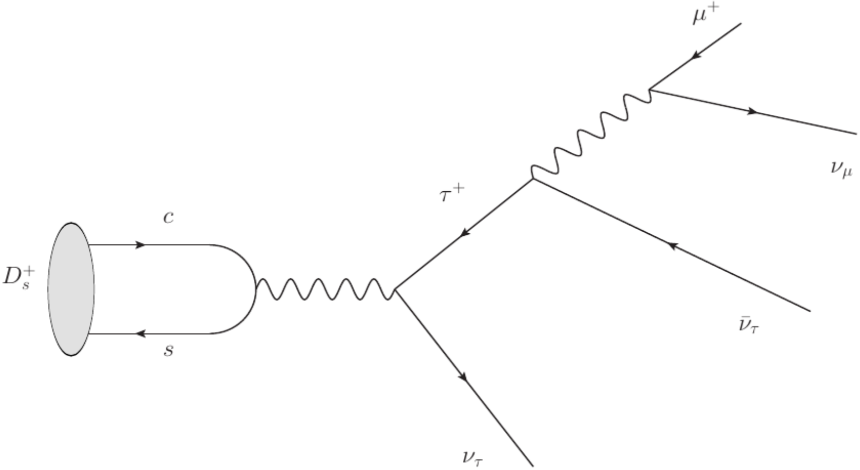




Tau neutrino measurements

- Direct measurements of tau neutrino charged-current (CC) interactions are a fairly recent phenomenon
- The DONUT experiment reported 9 tau neutrino events with a background of 1.5 events from their neutrino beam produced with the 800 GeV Tevatron beam at Fermilab **[0711.0728]**.
- The DONUT does not detect the charge of tau lepton and average over neutrino and antineutrino
- The OPERA experiment reported 4 tau neutrino events with practically no background **[1407.3513]**
- There neutrinos were produced in $\nu_\mu \to \nu_\tau$ oscillations, so no tau antineutrino was detected

Tau neutrinos at SHiP



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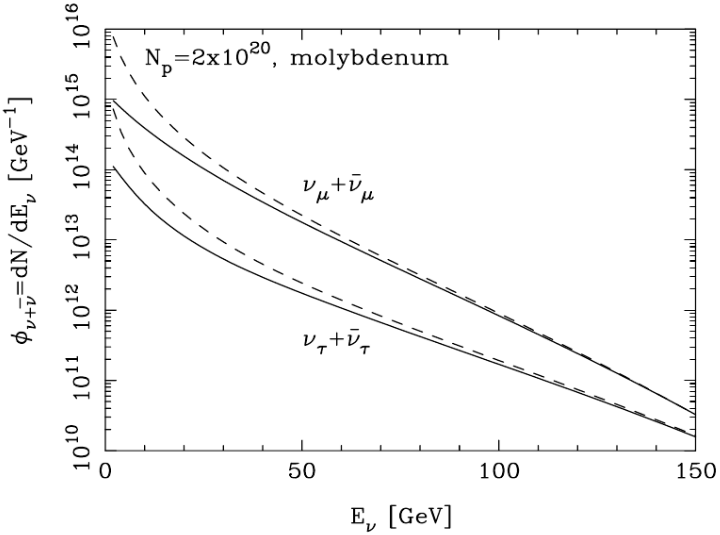

Tau neutrinos at SHiP

- The SHiP experiment allows to measure separately ν_τ and $\bar{\nu}_\tau$ cross sections
- We expect several thousands ν_τ and $\bar{\nu}_\tau$ events at SHiP
- Neutrino charged current scattering cross-section

$$\frac{d^2\sigma^{\nu/\bar{\nu}}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left(\left[y^2x + \frac{m_\tau^2 y}{2E_\nu M}\right]F_1 + \left[1 - y - \frac{m_\tau^2}{4E_\nu^2} - \frac{Mxy}{2E_\nu}\right]F_2 \pm \right.$$
$$\left. \pm \left[xy(1-y/2) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4 - \frac{m_\tau^2}{E_\nu M}F_5\right)$$

- The SHiP experiment offers the first opportunity to measure the structure functions F_4, F_5

Tau neutrino magnetic momentum

- Neutrinos are electrically neutral fundamental particles that couple to the other particles only through weak interaction in the Standard Model (SM)
- In the minimal extension of the SM where neutrinos are proposed to be Dirac particles, they can acquire a magnetic moment (μ_ν) and give rise to electromagnetic interactions **[Fujikawa and Shrock, 1980]** and

$$\mu_\nu \simeq 3.2 \times 10^{-19} \left(\frac{m_\nu}{1 \text{ eV}} \right) \mu_B$$

but it can be significantly enhanced in other new physics models

- Contribution from the neutrino magnetic momentum to electron-neutrino scattering

$$\frac{d\sigma_{\nu e}}{dT_e} = \frac{\pi \alpha_{\text{EM}}^2}{m_e^2} \left(\frac{1}{T_e} - \frac{1}{E_\nu} \right) \frac{\mu_\nu^2}{\mu_B^2}$$

Tau neutrino magnetic momentum at SHiP

- The current limit on tau neutrino magnetic momentum of $3.9 \times 10^7\ \mu_B$ has been set by the DONUT experiment **[0711.0728]**
- SHiP can significantly increase this limit

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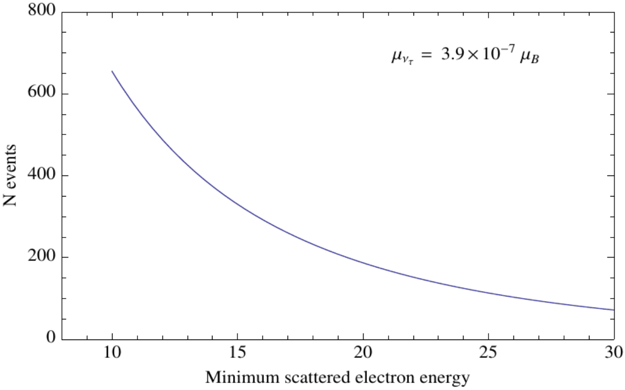
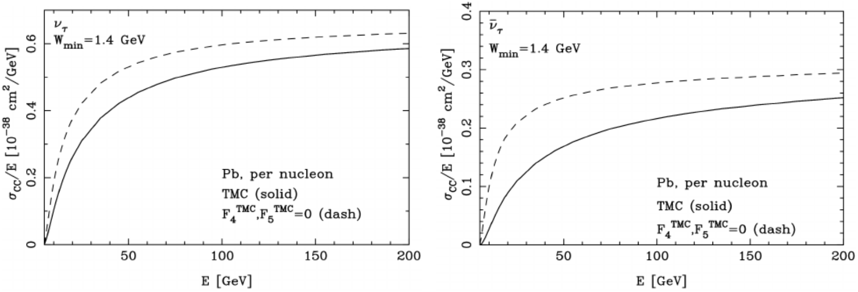


Conclusions

- The SHiP experiment is high-intensity fixed-target experiment with 400 GeV proton beam
- The main physics goal is the search for light feebly interacting particles. But because of its design, SHiP is a perfect place to study tau neutrino (and antineutrino) physics
- Few thousands of tau neutrino charge current scattering is expected. It is enough to study the differential cross-section and measure F_5 structure function for the first time
- SHiP can put a stronger limit on tau neutrino magnetic momentum (study is in progress)

Tau neutrino production cross-section



- The charged current cross section per nucleon, scaled by incident energy for (a) ν_τ and (b) $\bar{\nu}_\tau$ scattering with a lead target with $W_{\text{min}} = 1.4$ GeV. The dashed curve has F_4 and F_5 set to zero, while the solid curve has the full expression for the target mass corrected (TMC) cross-section.