

SHIP – Search for Hidden Particles

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The 15th International Workshop on Tau Lepton Physics,
Amsterdam, 2018

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 (TeV 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

Heavy particles: active LHC searches

ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.2 - 20.3) \text{ fb}^{-1}$$

$$\sqrt{s} = 8, 13 \text{ TeV}$$

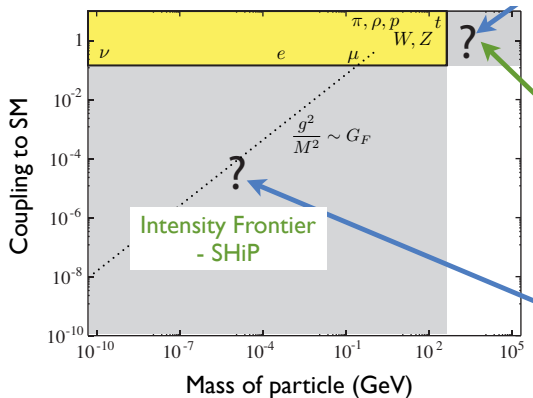
Model	ℓ, γ	Jets†	$E_{\text{miss}}^{\text{min}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{\mu\nu} \rightarrow g/g$	-	≥ 2 J	Yes	3.2	1604.07773
	ADD non-resonant $t\bar{t}$	$2 e, \mu$	-	-	20.3	1407.2410
	ADD $G_{\mu\nu} \rightarrow f\bar{f}$	$1 e, \mu$	1 J	-	20.3	1311.2096
	ADD $G_{\mu\nu} \rightarrow W^+W^-$	2 J	-	-	15.7	ATLAS CONF-2016-069
	ADD BH high Σp_T	$\geq 1 e, \mu$	≥ 2 J	-	3.2	1606.03265
	ADD BH multiple	-	≥ 2 J	-	3.6	1512.02586
	RSt $G_{\mu\nu} \rightarrow \ell\bar{\ell}$	$2 e, \mu$	-	-	20.3	1405.4123
	RSt $G_{\mu\nu} \rightarrow \gamma\gamma$	2 γ	-	-	3.2	1606.03623
	Bulk RS $G_{\mu\nu} \rightarrow WW \rightarrow q\bar{q}l\nu$	$1 e, \mu$	1 J	Yes	13.2	ATLAS CONF-2016-062
	Bulk RS $G_{\mu\nu} \rightarrow HH \rightarrow b\bar{b}b\bar{b}$	-	4 b	-	13.3	ATLAS CONF-2016-049
Bulk RS $g_{\mu\nu} \rightarrow t\bar{t}$	$1 e, \mu$	$\geq 1 b, \geq 12b$	Yes	20.3	1505.07018	
ZUED RPP	$1 e, \mu$	$\geq 2 b, \geq 4$	Yes	3.2	ATLAS CONF-2016-013	
Gauge bosons	SStM $Z' \rightarrow \ell\bar{\ell}$	$2 e, \mu$	-	-	13.3	ATLAS CONF-2016-045
	SStM $Z' \rightarrow \tau\bar{\tau}$	2 τ	-	-	19.5	1502.07177
	Leptophobic $Z' \rightarrow b\bar{b}$	$1 e, \mu$	2 b	-	3.2	1603.06791
	SStM $W' \rightarrow f\bar{f}$	$1 e, \mu$	-	Yes	13.3	ATLAS CONF-2016-061
	HVT $W' \rightarrow WZ \rightarrow q\bar{q}l\nu$ model A	$0 e, \mu$	1 J	Yes	13.2	ATLAS CONF-2016-062
	HVT $W' \rightarrow WZ \rightarrow q\bar{q}l\nu$ model B	-	2 J	-	15.5	ATLAS CONF-2016-055
	HVT $W' \rightarrow WZ$ model B	multi-channel	-	-	3.2	1607.05621
	LRSM $W'_2 \rightarrow b\bar{b}$	$1 e, \mu$	2 b, 0-1 J	Yes	20.3	1410.4103
	LRSM $W'_3 \rightarrow b\bar{b}$	$0 e, \mu$	$\geq 1 b, 1 J$	-	20.3	1408.0885
	CI	CI open	-	2 J	-	15.7
CI $t\bar{t}q\bar{q}$		$2 e, \mu$	-	-	3.2	1607.05669
DM	CI $t\bar{t}W$	$2(1S)/3 e, \mu$	$\geq 1 b, \geq 1 J$	Yes	20.3	1504.04625
	Axial-vector mediator (Dirac DM)	$0 e, \mu$	$\geq 1 J$	Yes	3.2	1604.07773
	Scalar-vector mediator (Dirac DM)	$0 e, \mu, 1 \gamma$	1 J	Yes	3.2	1604.01266
ZZ _{1,2} EFT (Dirac DM)	$0 e, \mu$	1 $\Delta, 1 \Delta, 1 J$	Yes	3.2	ATLAS CONF-2015-080	
LO	Scalar LQ 1 st gen	$2 e, 2 \mu$	≥ 2 J	-	3.2	1605.06035
	Scalar LQ 2 nd gen	$2 e, \mu$	≥ 2 J	-	3.2	1605.06035
	Scalar LQ 3 rd gen	$1 e, \mu$	$\geq 1 b, \geq 1 J$	Yes	20.3	1508.04720
Heavy quarks	VLO $T \rightarrow H + X$	$1 e, \mu$	$\geq 2 b, \geq 3 J$	Yes	20.3	T in (T) doublet
	VLO $V \rightarrow W + X$	$1 e, \mu$	$\geq 1 b, \geq 3 J$	Yes	20.3	V in (V) doublet
	VLO $BB \rightarrow Hb + X$	$1 e, \mu$	$\geq 2 b, \geq 3 J$	Yes	20.3	isospin singlet
	VLO $BB \rightarrow Zb + X$	$2b, 3e, 3\mu$	$\geq 2b, 1 b$	-	20.3	B in (B _V) doublet
	VLO $QQ \rightarrow WqWq$	$1 e, \mu$	$\geq 4 J$	Yes	20.3	
VLO $T_{1,2,3} \rightarrow WWq\bar{q}$	$2(1S)/3 e, \mu$	$\geq 1 b, \geq 1 J$	Yes	3.2	This mass	
Exotic fermions	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 J	-	3.2	$q^* \rightarrow q^* \text{ and } q^*, A = m(q^*)$
	Excited quark $q^* \rightarrow qg$	-	2 J	-	15.7	$q^* \rightarrow q^* \text{ and } q^*, A = m(q^*)$
	Excited quark $q^* \rightarrow q\bar{q}$	-	1 b, 1 J	-	8.6	
	Excited quark $q^* \rightarrow W\bar{q}$	1 or 2 e, μ	1 b, 0-2 J	Yes	20.3	
	Excited lepton ℓ^*	3 e, μ	-	-	20.3	
	Excited lepton ν^*	3 $e, \mu, 1 \gamma$	-	-	20.3	
Other	LSTC $\nu\bar{\nu} \rightarrow W\gamma$	$1 e, \mu, 1 \gamma$	-	Yes	20.3	
	LRSM Majorana ν	$2 e, \mu$	2 J	-	20.3	$m(W_2) = 2.4 \text{ TeV}$, no mixing
	Higgs triplet $H^{\pm 1,2} \rightarrow e\bar{e}$	2 e (SS)	-	-	13.9	DF production, BR(H ^{±1,2}) → e [±] e [±]
	Higgs triplet $H^{\pm 1,2} \rightarrow f\bar{f}$	3 e, 3 μ	-	-	20.3	DF production, BR(H ^{±1,2}) → f [±] f [±]
	Monopole (non-res prod)	$1 e, \mu$	1 b	Yes	20.3	$A_{\text{mon}} = 0.2$
	Multi-charged particles	-	-	-	7.0	DF production, $ \lambda = 1e$
Magnetic monopoles	-	-	-	20.3	DF production, $ \lambda = \text{Mpl. spin } 1/2$	

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

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter J (Δ).

Intensity frontier searches for feebly interacting particles

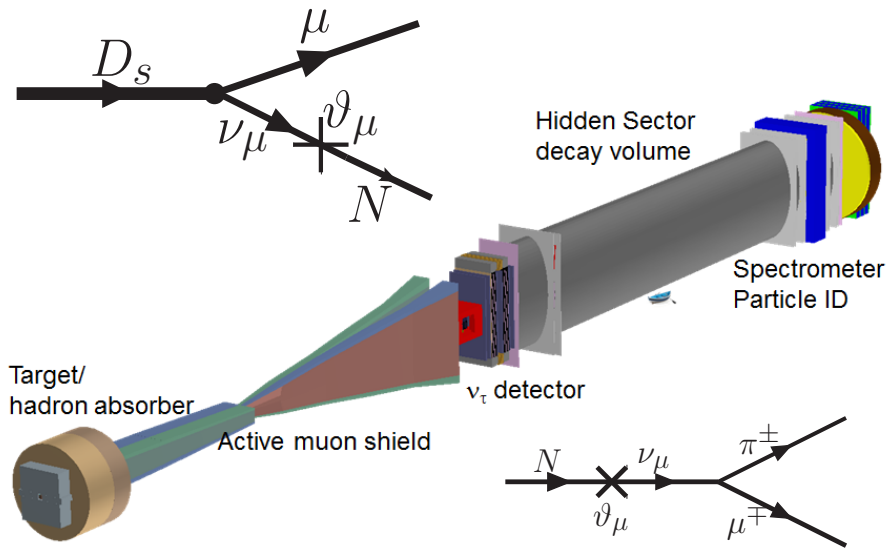


Intensity frontier has been paid much less attention in the recent years:

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

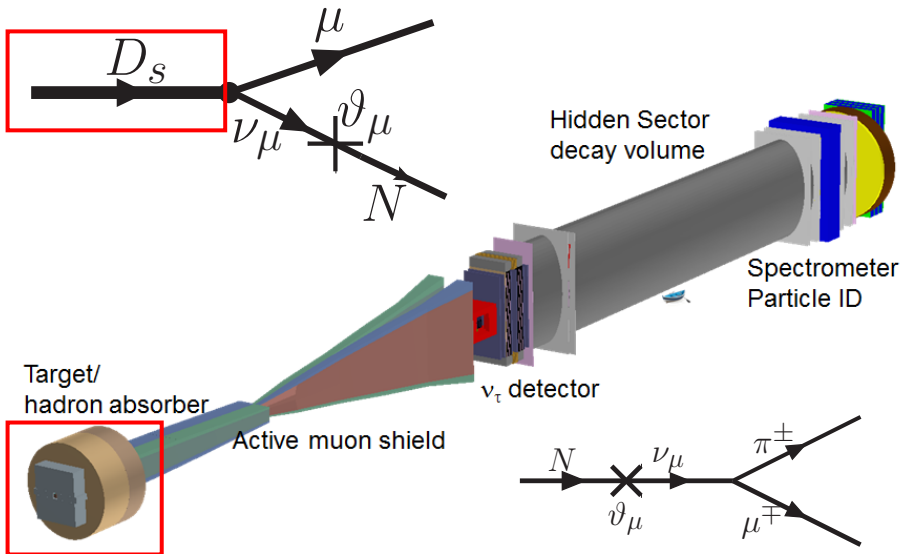
SHiP (*Search for Hidden Particles*) experiment

Step by step overview



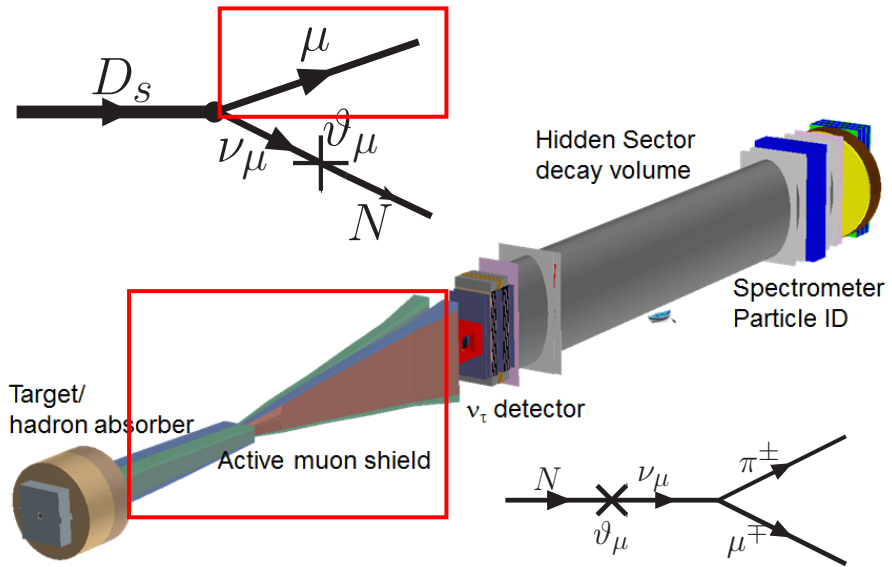
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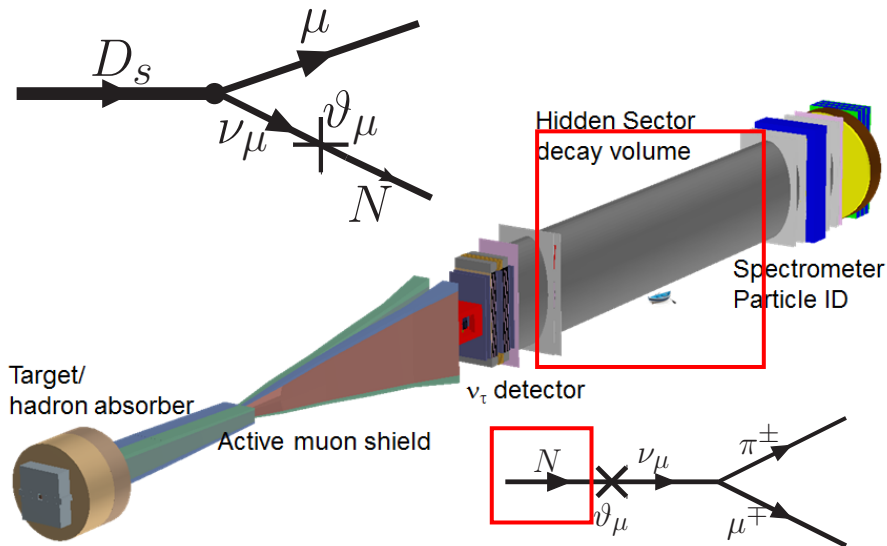
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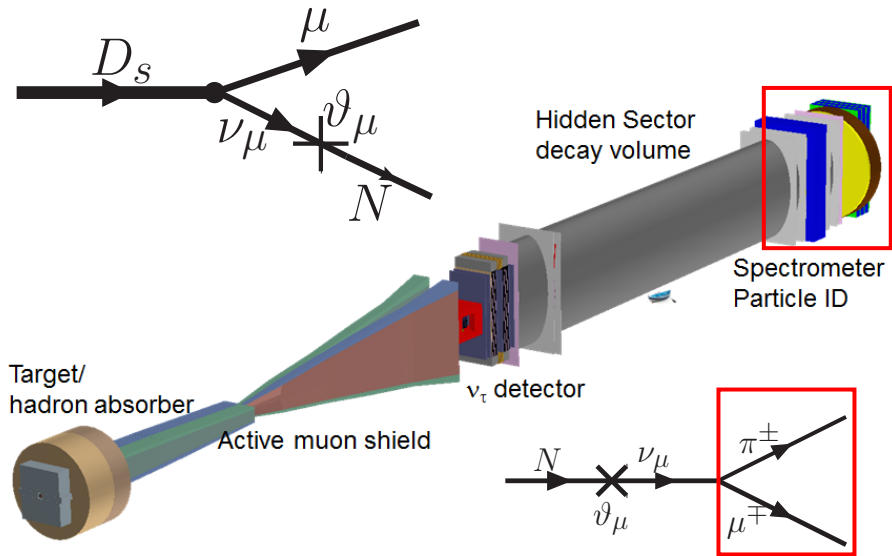
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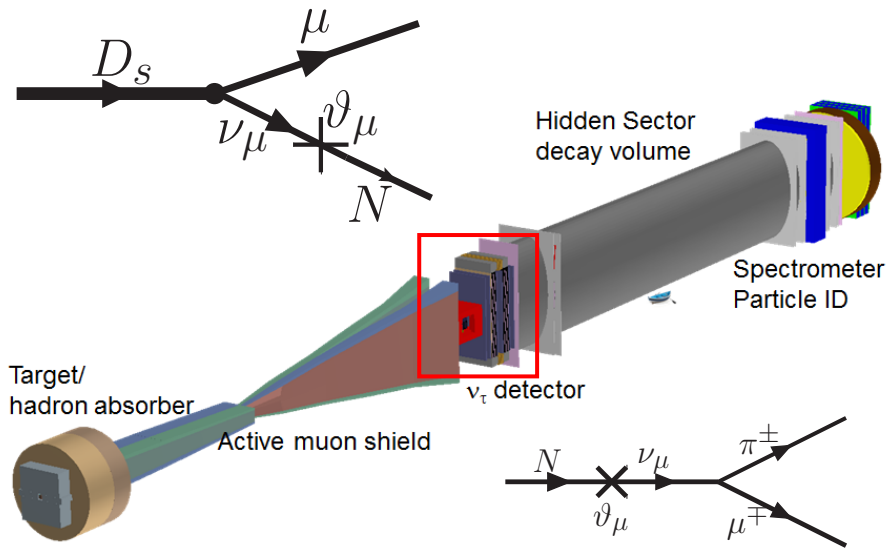
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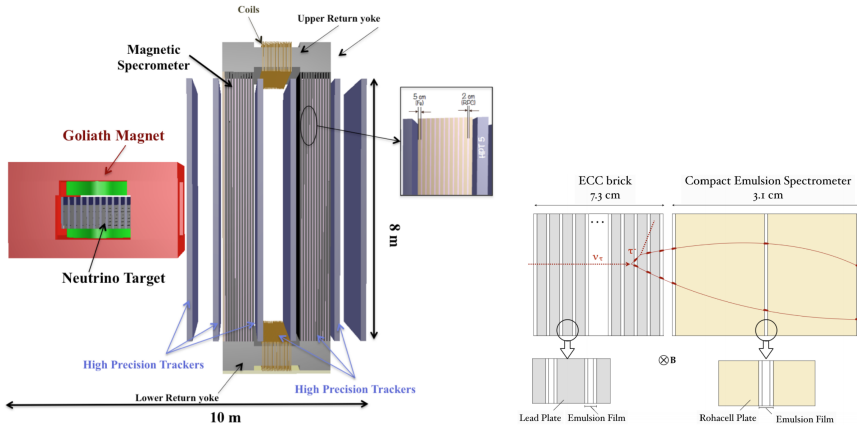


SHiP (*Search for Hidden Particles*) experiment

Step by step overview



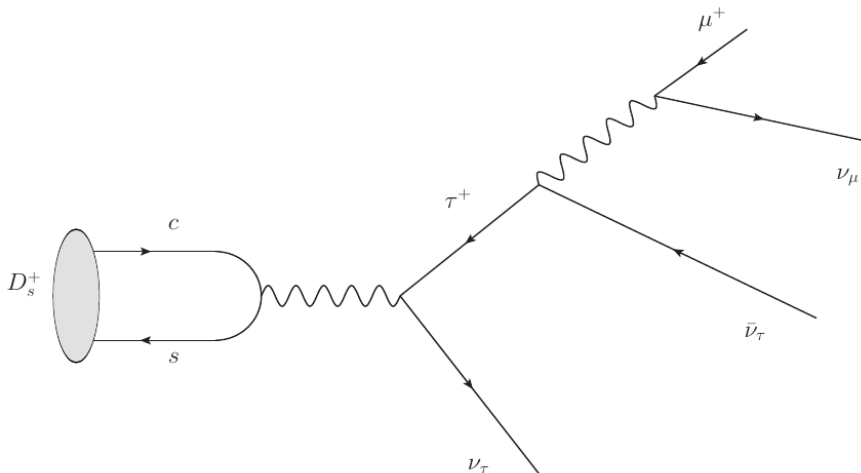
iSHIP detector



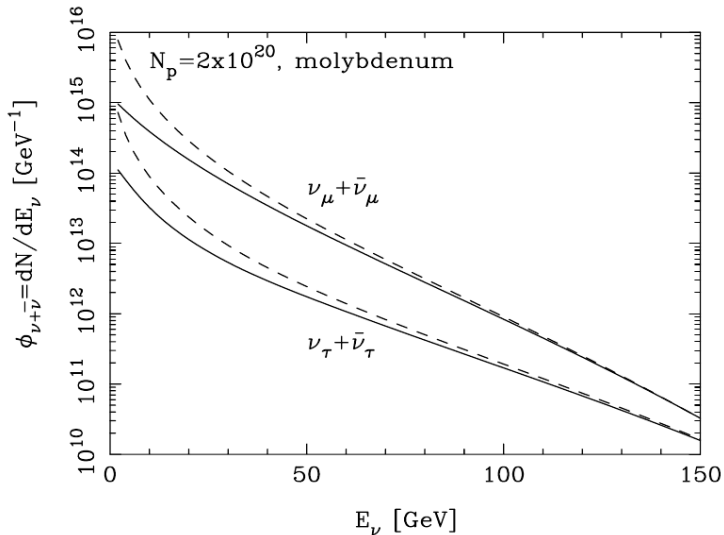
Tau neutrino measurements

- 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 [\[1407.3513\]](#)
- These neutrinos were produced in $\nu_\mu \rightarrow \nu_\tau$ oscillations, so no tau antineutrino was detected

Tau neutrinos at SHiP



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

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

- 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

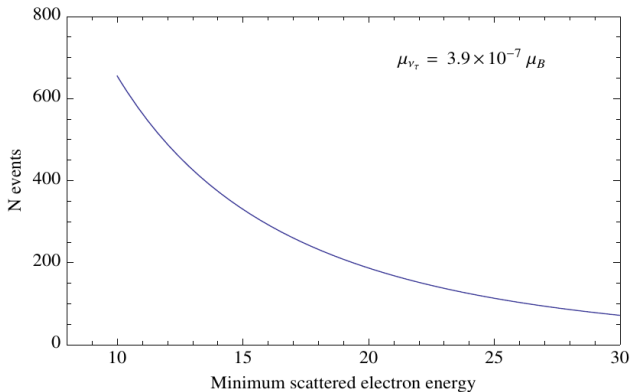
$$\frac{d\sigma_{\nu e}}{dT_e} = \frac{\pi\alpha_{\text{EM}}^2}{m_e^2} \left(\frac{1}{T_e} - \frac{1}{E_\nu} \right) \frac{\mu_\nu^2}{\mu_B^2}$$

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

Tau neutrino magnetic momentum at SHiP

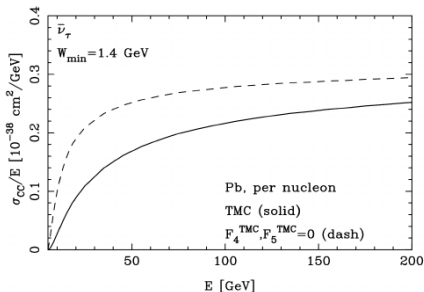
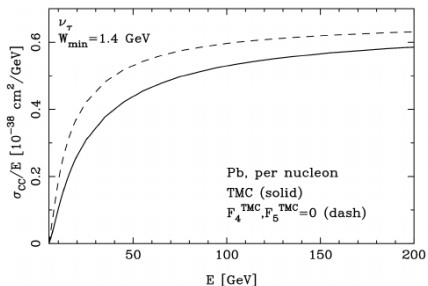
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- SHiP can significantly increase this limit



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 $W_{\min} = 1.4$ 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.