Tau Neutrino Physics in SHiP

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SHiP (Search for Hidden Particles)

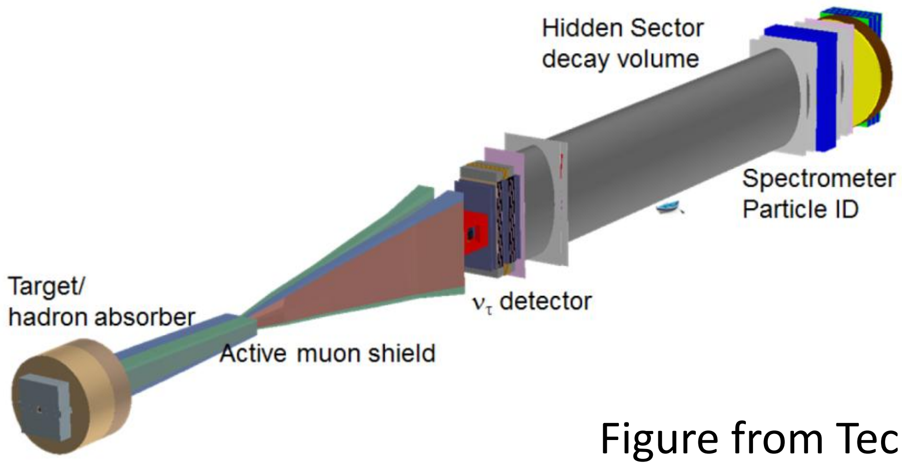


Figure from Technical Proposal (2015) by the SHiP Collaboration

- Proton beam dump experiment at the CERN SPS

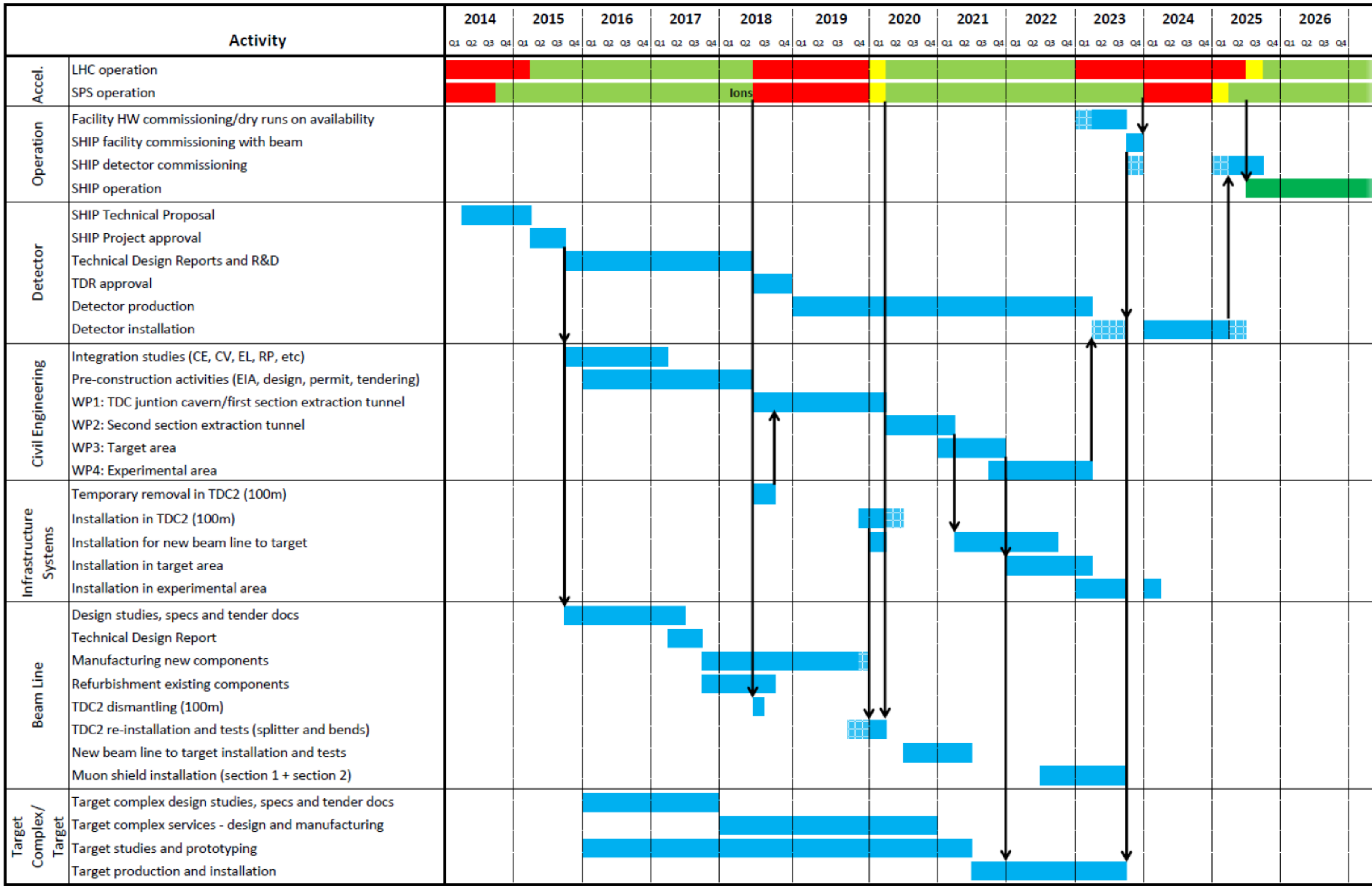
  Beam energy Ep = 400 GeV

  Total number of proton Np= 2 x 10^{20} p.o.t.

  (total Np for DONUT = 3.6 x 10^{17} p.o.t.)

SHIP location : Prevessin Campus North Area

Project Schedule



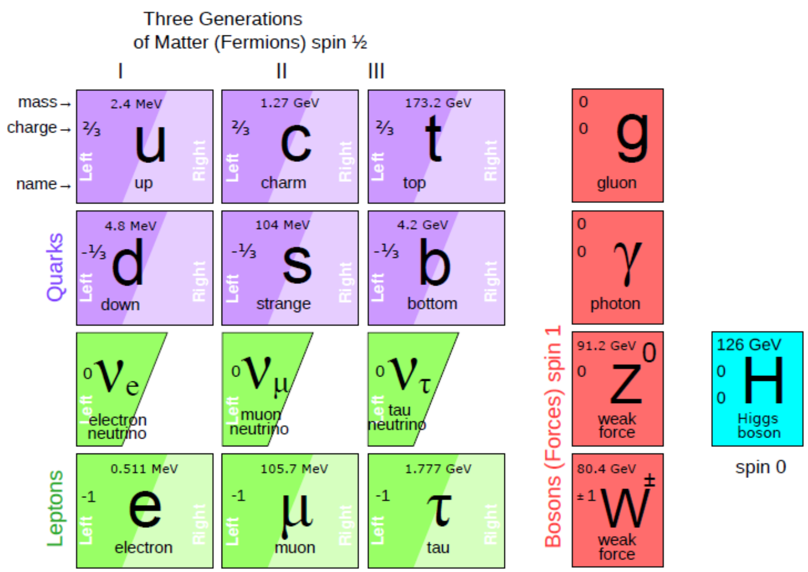
Physics goal of SHiP – New Particles

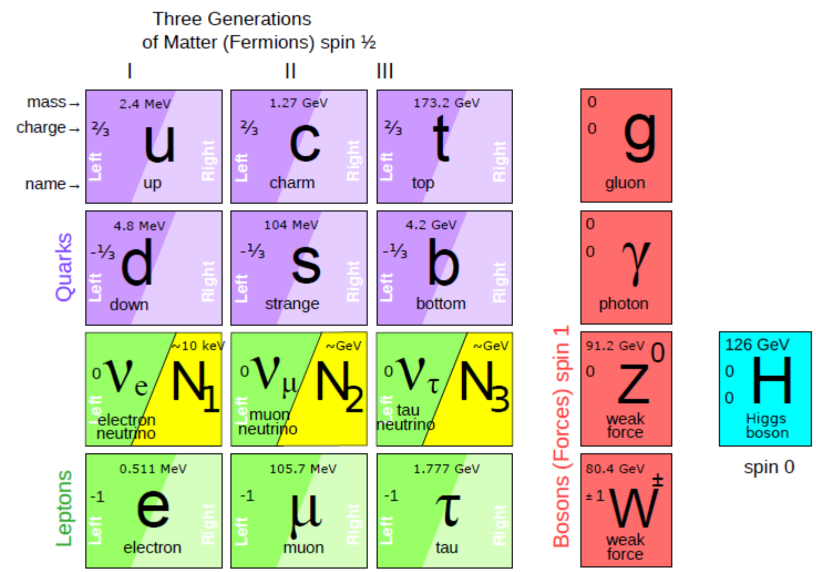
- To search the new physics with the hidden particles

  e.g.) nuMSM – attempts to explain the problems such as neutrino mass, dark matter and BAU by 3 additional HNLs.

  N1 – the lightest, DM candidate.

  N2, N3 – for the neutrino mass and the baryon asymmetry.





W. Bonivento et. al. – 2013 proposal (arXiv:1310.1762)

Physics goal of SHiP – Tau Neutrinos

- Tau neutrinos so far
  - DONuT : 9 tau neutrino events

$$\sigma_{\nu_\tau}^{avg} / E = 0.39 \pm 0.13 \pm 013 \times 10^{-38}\ \mathrm{cm}^2\ \mathrm{GeV}^{-1}$$

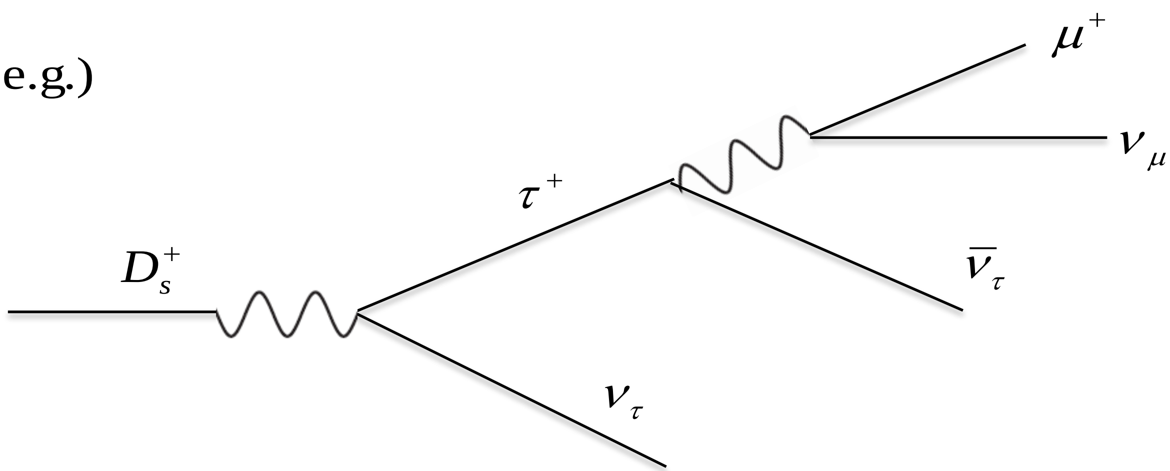
  - OPERA : 4 tau neutrinos from ν_μ -> ν_τ oscillations
  - Anti-tau neutrino has NOT been detected directly.

- Goals of SHiP for tau neutrinos
  - observation of anti-ν_τ
  - separate measurement of ν_τ and anti-ν_τ cross sections
  - extraction of the structure functions F_4 and F_5

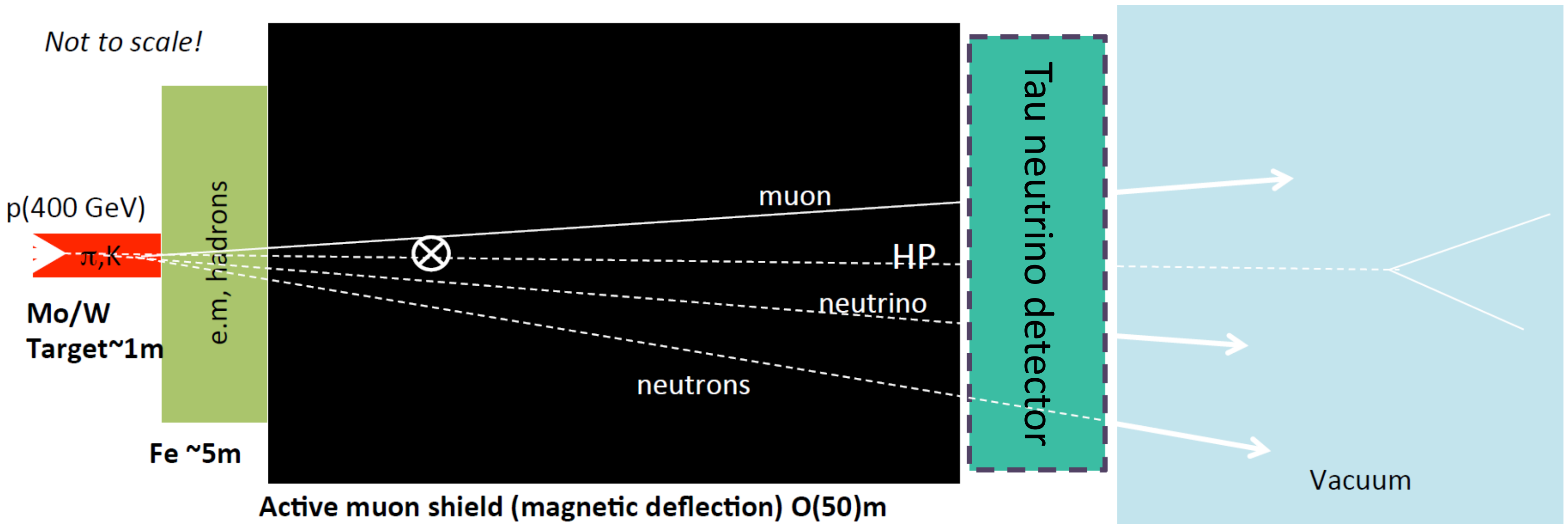
Production of tau neutrinos

- Proton beam collides on a nuclear target (molybdenum/ tungsten) and produce the charmed particles (e.g. D and Ds). Among them Ds is a primary source of tau neutrinos.
- The Ds decay produces two tau neutrinos: One is from the direct decay of Ds (Ds -> ν_τ) and the other is from the chain decay (Ds -> τ -> ν_τ).

e.g.)



➢ Schematic Diagram

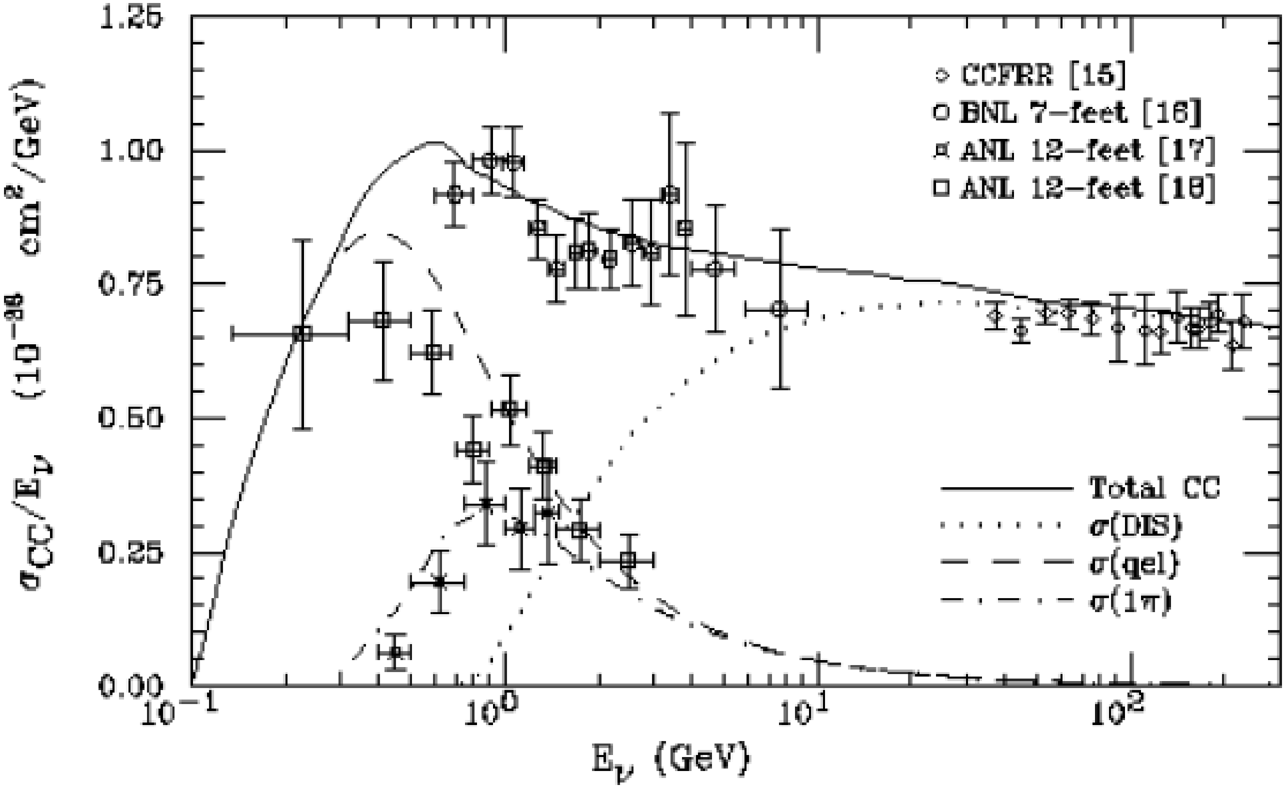


➢ Hypothesis in evaluation

- Tau neutrino detector
  - is made of lead.
  - has the cross sectional area 2m × 0.75m.
  - placed at 51.5m from the target.

Cross Sections

Neutrino Cross section

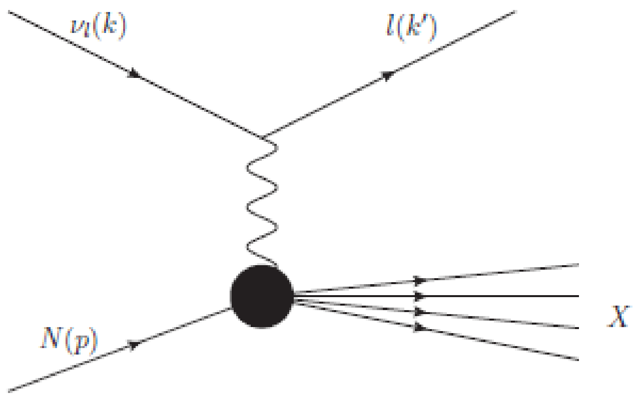


Lipari, Lusignoli and Sartogo, PRL 74 (1994)

Quasi-elastic Scattering (QE) / 1-pion production

Deep Inelastic Scattering (DIS) – dominates above 10 GeV.

DIS charge current cross section



$$\nu_\tau(k) + N(p) \to \tau(k') + X$$

$$N = (n + p)/2$$

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

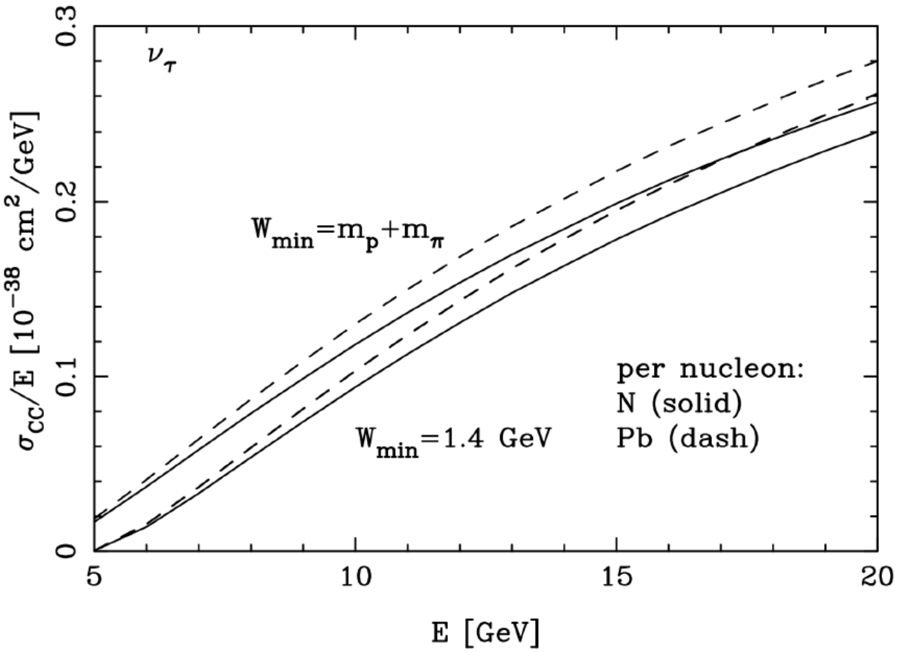
$$\left. \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4 - \frac{m_\tau^2}{E_\nu M}F_5 \right)$$

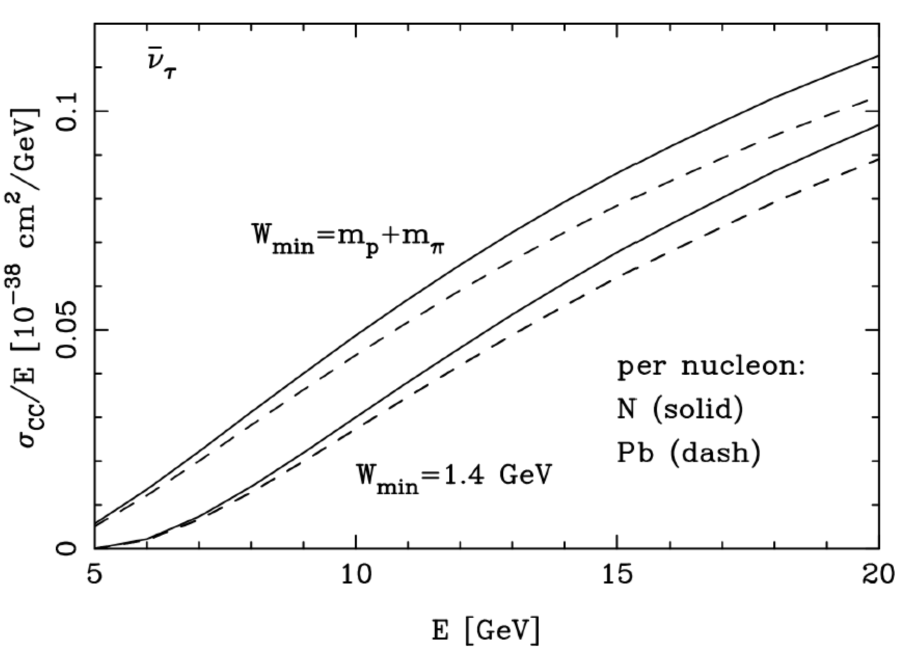
$$Q^2 = -(k-k')^2 = -q^2 \qquad x = Q^2/2p\cdot q, \qquad y = p\cdot q/p\cdot k$$

$$F_4 = 0, \qquad 2xF_5 = F_2$$

S. Kretzer and M. H. Reno Phys. Rev. D 66, 113007 (2002)

DIS charged current cross section (ν-N/Pb)

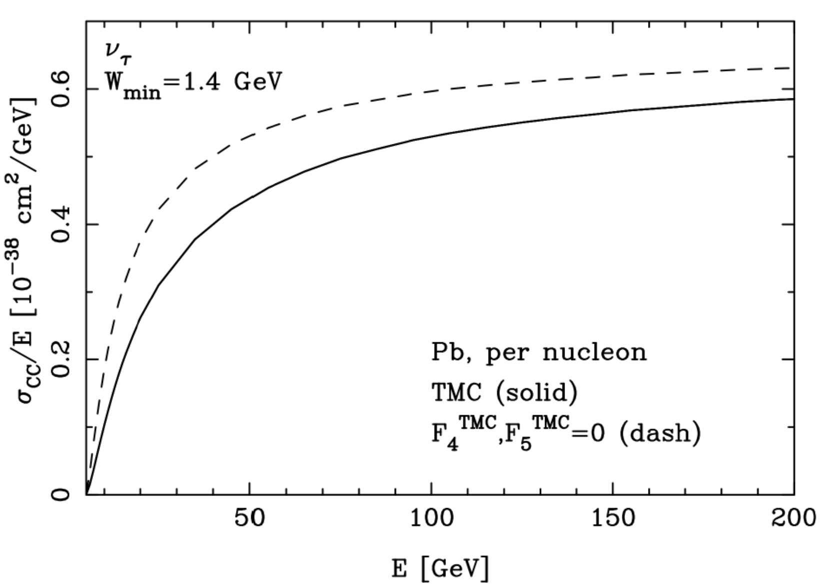


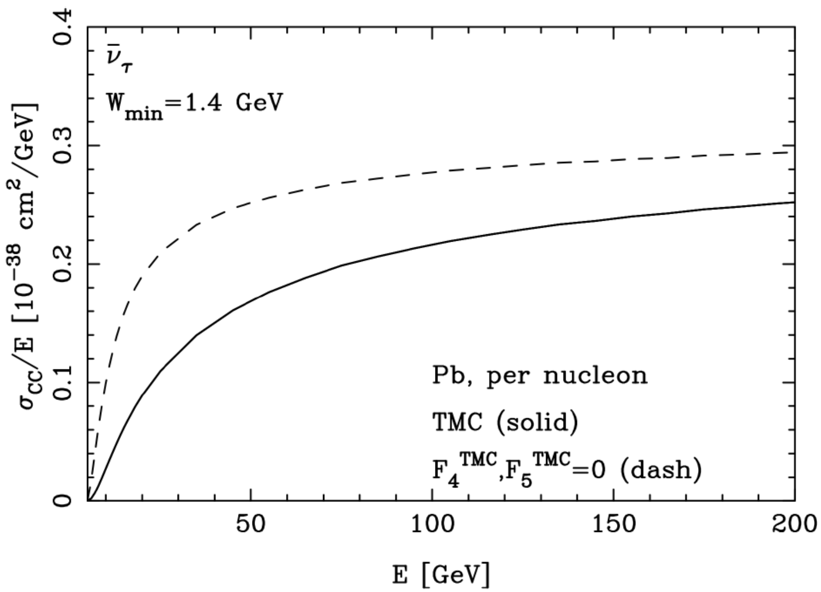


$$\sigma_{\nu A}^{cc} = \frac{Z\sigma_{\nu p} + (A-Z)\sigma_{\nu n}}{A}$$

$$W^2 = Q^2\left(\frac{1}{x} - 1\right) + M^2 \geq W_{\min}^2$$

Impact on F4 and F5 on DIS cross section (ν-Pb)





- The difference is mainly from the F5 contribution.
- The effect of F4 and F5 decreases with energy.

e.g.) 30% at 20 GeV -> 7% at 200 GeV for tau neutrino

53% -> 14% at the corresponding energy for anti-neutrino

Tau Neutrino Flux

Neutrino Flux – cascade equations

The neutrino flux is obtained by solving the coupled cascade equations for nucleon, meson and neutrino fluxes.

$$\frac{d\phi_p}{dX} = -\frac{\phi_p}{\lambda_p} + S(pA \to pY)$$

$$\frac{d\phi_{D_s}}{dX} = S(pA \to D_s Y) - \frac{\phi_{D_s}}{\lambda_{D_s}} - \frac{\phi_{D_s}}{\lambda_{D_s}^{dec}} + S(D_s A \to D_s Y)$$

$$\frac{d\phi_\nu}{dX} = S(D_s \to \nu Y)$$

Initial proton flux of SHiP

$$\phi_p(E) = p_0 \, \delta(E - E_b) \qquad p_0 = 2 \times 10^{20}$$

Flux – (re)generation function

$$S(k \to j) = \int_E^\infty dE_k \frac{\phi_k(E_k)}{\lambda_k(E_k)} \frac{dn(k \to j; E_k, E_j)}{dE_j}$$

- The energy distribution of the final particles

$$\frac{dn(k \to j; E_k, E_j)}{dE_j} = \frac{1}{\sigma_{kA}(E_k)} \frac{d\sigma(kA \to jY, E_k, E_j)}{dE_j} \quad \text{for production}$$

$$= \frac{1}{\Gamma_k} \frac{d\Gamma(k \to jY, E_j)}{dE_j} \quad \text{for decay}$$

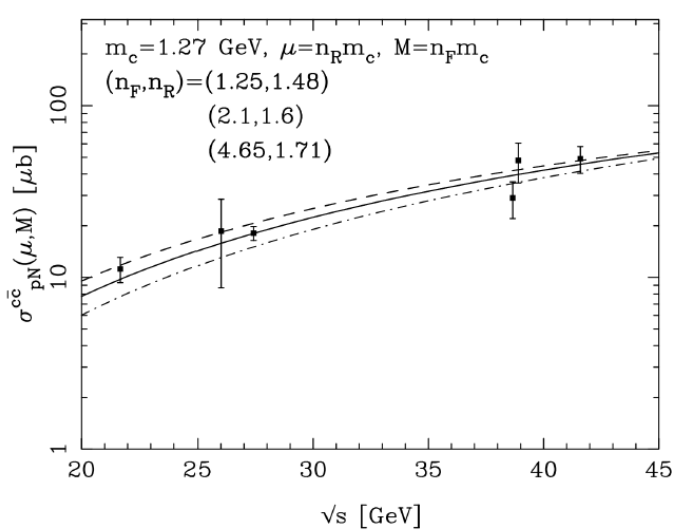
Tau Neutrino Flux

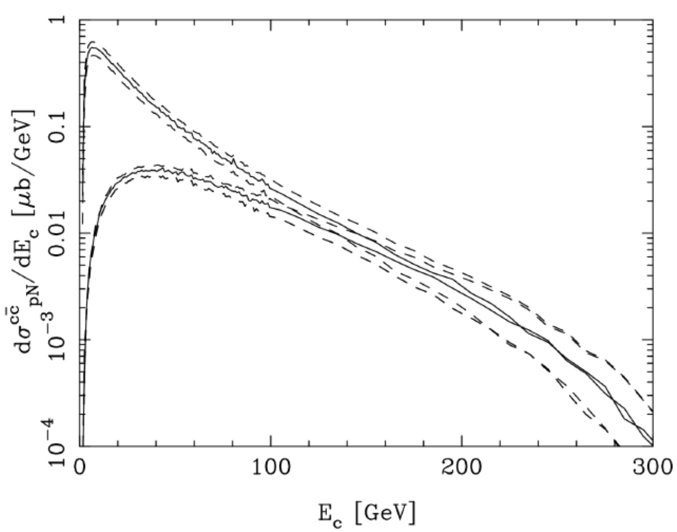
$$\varphi_{\nu_\tau+\bar{\nu}_\tau} \cong 2p_0\int_{E_\upsilon}^{E_b} dE_{D_s}\ \frac{1}{\sigma_{pA}}\frac{d\sigma_{pA\to D_s X}}{dE_{D_s}}(E_b,E_{D_s})\sum_i \frac{dn_i}{dE_\upsilon}(E_{D_s},E_\upsilon)$$

$i=$ direct or chain decay

- Production cross section of Ds meson

$$\frac{d\sigma_{pA\to D_s X}}{dE_{D_s}} = \int_{E_{D_s}}^{E_b} \frac{dE_c}{E_c}\frac{d\sigma(pA\to cX)}{dE_c}\ f_c^{D_s}$$





Decay distributions

- Direct decay (Ds → ν_τ)

$$\frac{dn}{dE_\upsilon} = \frac{1}{E_{D_s}} \frac{B(D_s \to \nu_\tau \tau)}{1 - R_\tau}$$

$$R_\tau = m_\tau^2 / m_{D_s}^2$$

$$B(D_s \to \nu_\tau \tau) = (5.54 \pm 0.24)\%$$

- Chain decay (Ds → τ → ν_τ)

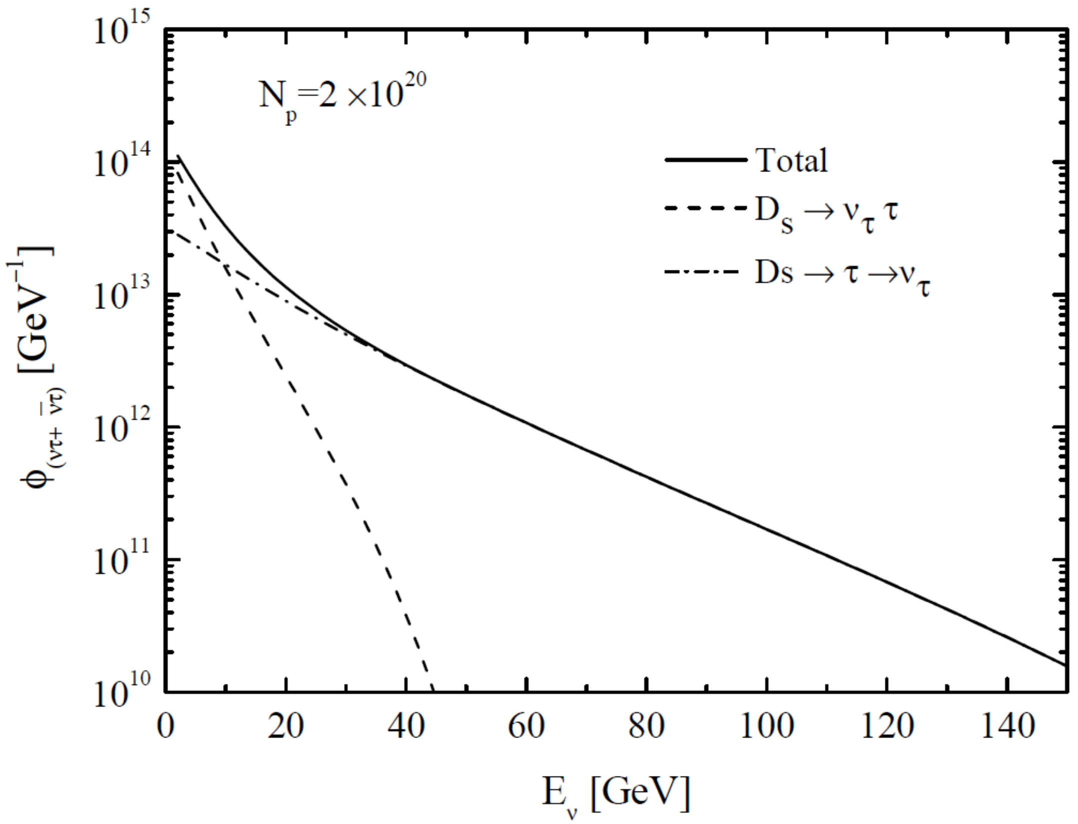
$$\frac{dn}{dE_\upsilon} = \int_0^1 \frac{dy}{y} \frac{1}{E_{D_s}} \frac{B(D_s \to \nu_\tau \tau)}{1 - R_\tau} \frac{dn_{\tau \to \nu_\tau}}{dy}$$

$$\frac{dn_{\tau \to \nu_\tau}}{dy} = B_\tau [g_0(y) - P_\tau \, g_1(y)]$$

$$P_\tau = \frac{2R_{D_s}}{1 - R_{D_s}} \frac{E_{D_s}}{E_\tau} - \frac{1 + R_{D_s}}{1 - R_{D_s}}$$

Process	B_τ	g_0	g_1
$\tau \to \nu_\tau \mu \nu_\mu$	0.18	$\frac{5}{3} - 3y^2 + \frac{4}{3}y^3$	$\frac{1}{3} - 3y^2 + \frac{8}{3}y^3$
$\tau \to \nu_\tau \pi$	0.12	$\frac{1}{1 - r_\pi}$	$-\frac{2y - 1 + r_\pi}{(1 - r_\pi)^2}$
$\tau \to \nu_\tau \rho$	0.26	$\frac{1}{1 - r_\rho}$	$-\left(\frac{2y - 1 + r_\rho}{(1 - r_\rho)^2}\right)\left(\frac{1 - 2r_\rho}{1 + 2r_\rho}\right)$
$\tau \to \nu_\tau a_1$	0.13	$\frac{1}{1 - r_{a_1}}$	$-\left(\frac{2y - 1 + r_{a_1}}{(1 - r_{a_1})^2}\right)\left(\frac{1 - 2r_{a_1}}{1 + 2r_{a_1}}\right)$

Fluxes of (ν_τ +anti-ν_τ)



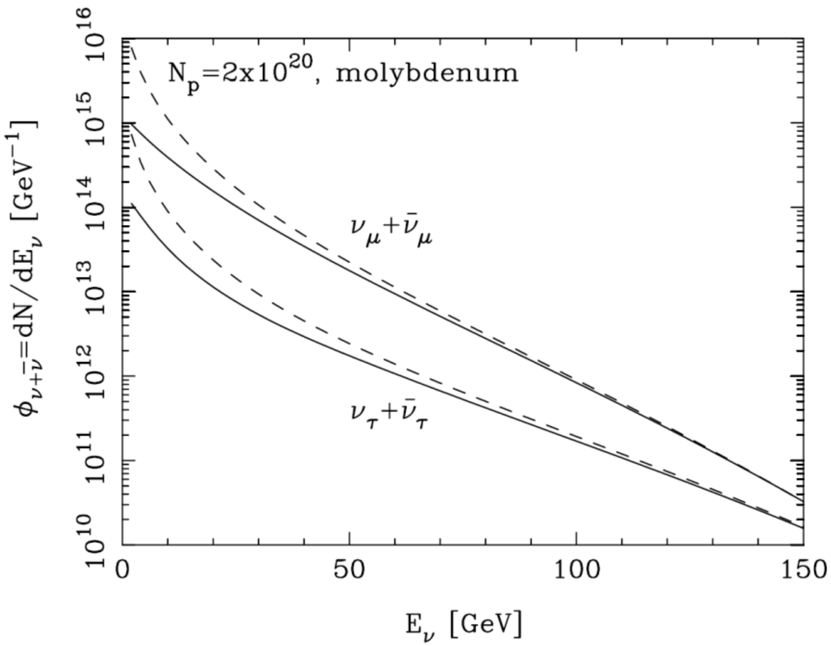
$$0 \le E_\upsilon \le (1 - R_\tau) E_D$$

$$R_\tau E_D \le E_\tau \le E_D$$

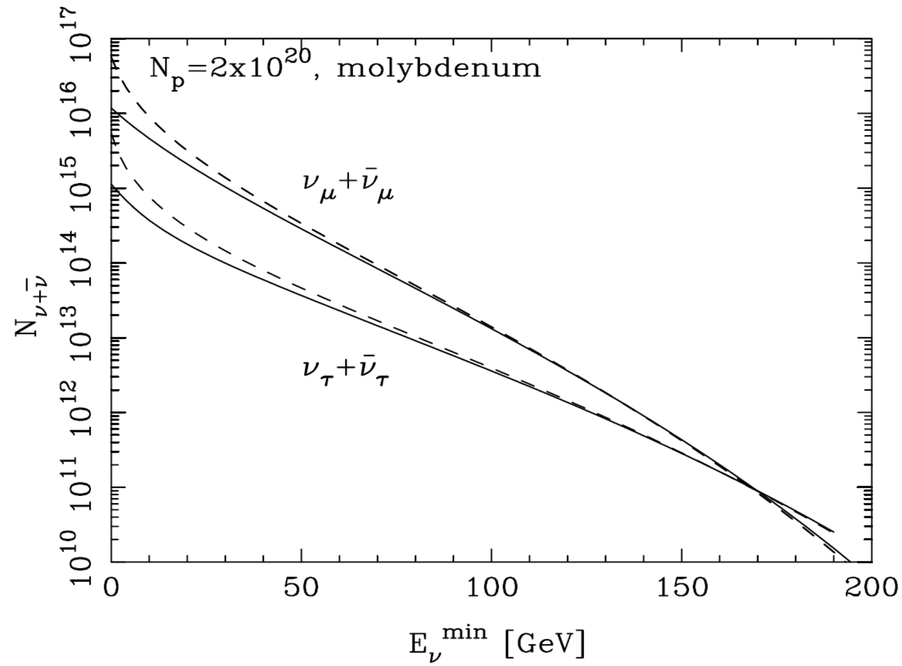
$$R_\tau = m_\tau^2 / m_D^2$$

- Above ~10 GeV, neutrinos produced from τ decay are dominant.

Fluxes



Number of the produced neutrinos



$$N_{\nu_\tau+\bar{\nu}_\tau} = \int_{E_\nu^{\min}}^{E_b} dE_\nu \phi_{\nu_\tau+\bar{\nu}_\tau}$$

Event numbers

Event Numbers

$$N = N_T \int_{E_{\min}}^{E_{\max}} dE_\nu \varphi_\nu(E) \sigma_{\nu Pb}(E)$$

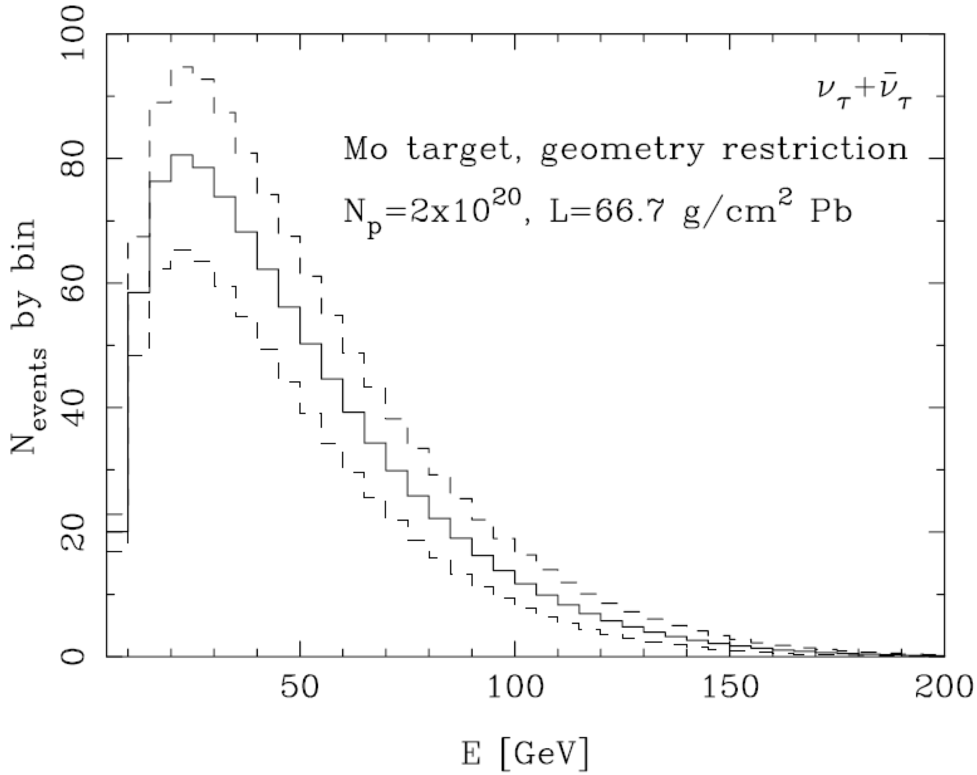
$$= \int_{E_{\min}}^{E_{\max}} dE_\nu \left(\varphi_\nu(E) \frac{L_{Pb}}{\lambda_{\nu,Pb}} + \varphi_{\bar{\nu}}(E) \frac{L_{Pb}}{\lambda_{\bar{\nu},Pb}} \right)$$

$$\lambda_{\nu,Pb} = \frac{A}{N_{avo} \sigma_{\nu Pb}}$$

- For $M_{detector}$ = 1 ton, (2m x 0.75m) cross sectional detector and ρ_{pb} gives L_{pb} = 66.7 g/cm2.

- The total event number is 937;
  - 685 for tau neutrinos
  - 252 for anti neutrinos

Event Numbers by bin



Summary

- The expected tau neutrino interactions can be highly improved.
- Large number of tau neutrinos and anti-tau neutrinos can be observed .
- With the high statistics, SHiP could measure the effect F_4 and F_5 on DIS interaction for the first time.
- SHiP will be good chance to study the anti tau neutrino interactions and the properties of the cross sections.