

Tau Neutrino Physics in SHiP

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SHiP (Search for Hidden Particles)

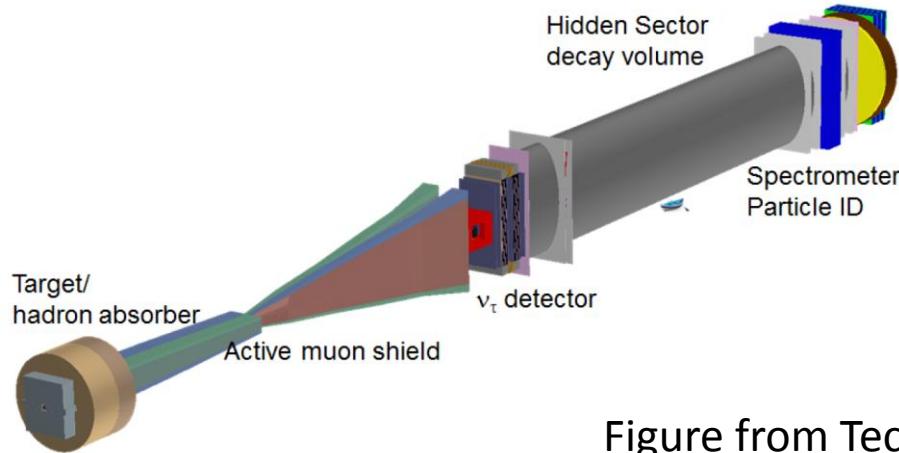


Figure from Technical Proposal
(2015) by the SHiP Collaboration

- Proton beam dump experiment at the CERN SPS
 - Beam energy $E_p = 400 \text{ GeV}$
 - Total number of proton $N_p = 2 \times 10^{20} \text{ p.o.t.}$
(total N_p for DONUT = $3.6 \times 10^{17} \text{ p.o.t.}$)

SHiP location : Prevessin Campus North Area

Slide from J. Osborne's for the 1st SHiP Workshop



Project Schedule

The Gantt chart illustrates the project timeline across different phases and activities. The horizontal axis represents time from 2014 to 2026, divided into quarters (Q1, Q2, Q3, Q4). The vertical axis lists the activities and their corresponding phases.

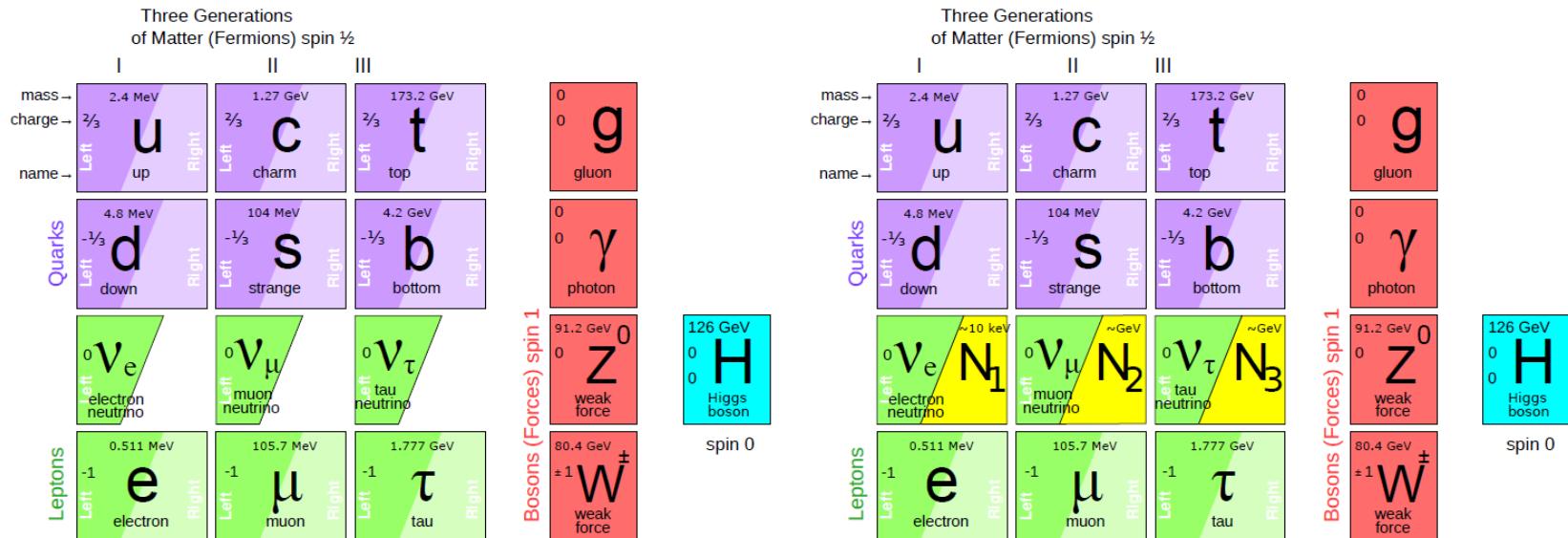
Activity	2014				2015				2016				2017				2018				2019				2020				2021				2022				2023				2024				2025				2026											
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4												
LHC operation																																																												
SPS operation	Red				Green				Green				Green				Red				Green				Green				Red				Green				Red				Green				Red				Green											
Accel.																																																												
Operation																																																												
Detector																																																												
Civil Engineering																																																												
Infrastructure Systems																																																												
Beam Line																																																												
Target Complex/ Target																																																												

Legend:

- Red: LHC operation, SPS operation, Ion beam tests, Beam line installation, Target complex installation.
- Green: Facility commissioning, Detector production, Infrastructure work, Target studies.
- Blue: Technical proposal, Project approval, Design reports, TDR approval, Integration studies, Pre-construction, WP1-4, Installation in TDC2, Installation in target area, Experimental area.
- Yellow: Target complex services, Target production.

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.



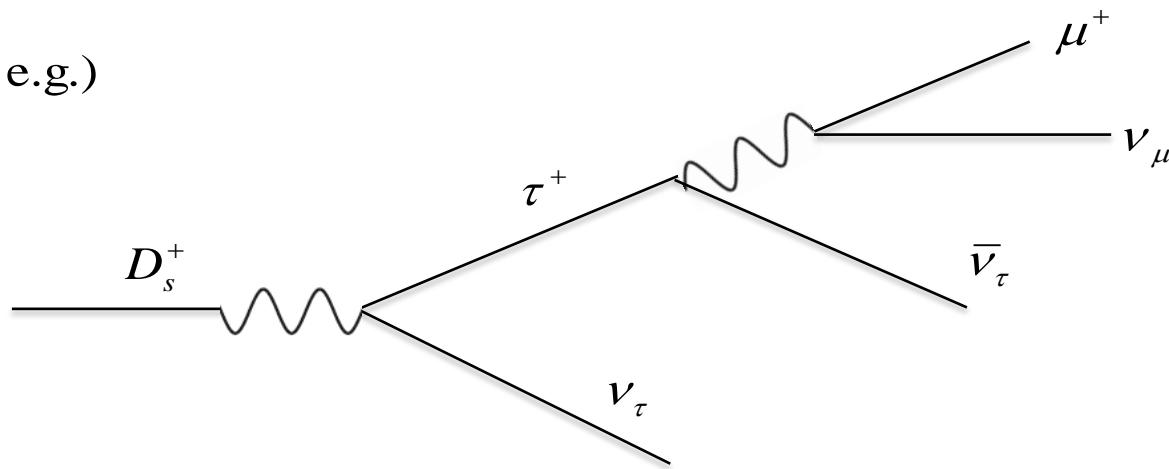
Physics goal of SHiP – Tau Neutrinos

- Tau neutrinos so far
 - DONuT : 9 tau neutrino events
$$\sigma_{\nu_\tau}^{avg} / E = 0.39 \pm 0.13 \pm 0.13 \times 10^{-38} \text{ cm}^2 \text{ GeV}^{-1}$$
 - OPERA : 4 tau neutrinos from $\nu_\mu \rightarrow \nu_\tau$ 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

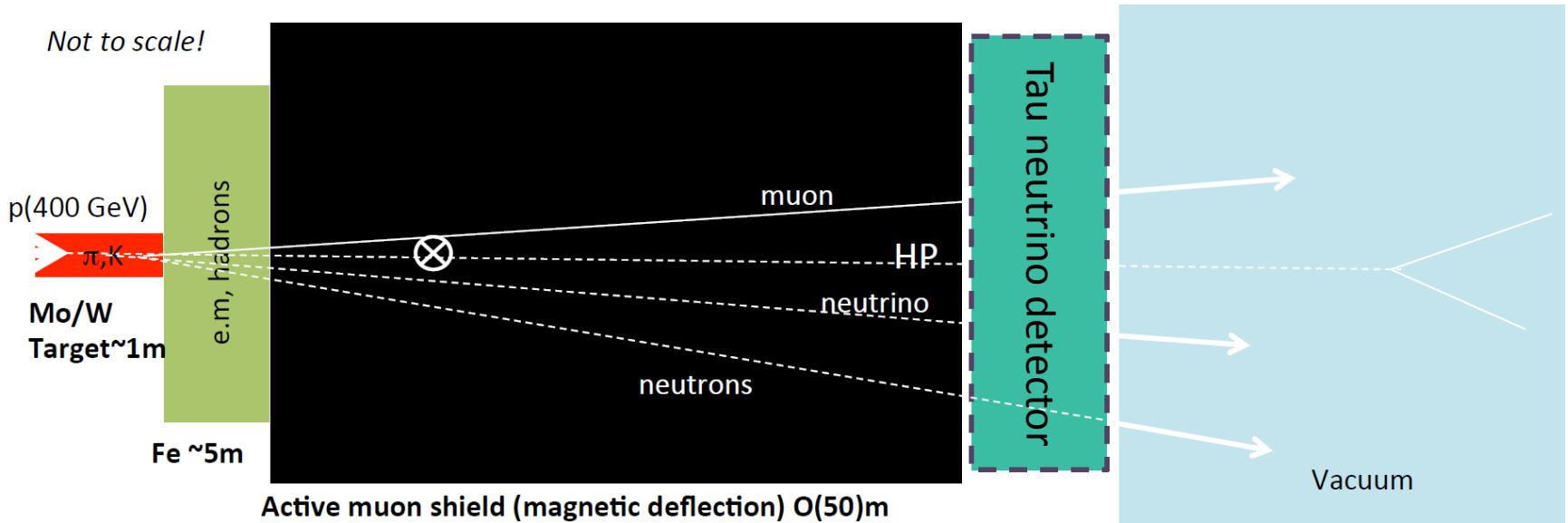
Production of tau neutrinos

- 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 ($D_s \rightarrow \nu_\tau$) and the other is from the chain decay ($D_s \rightarrow \tau \rightarrow \nu_\tau$).

e.g.)



➤ Schematic Diagram

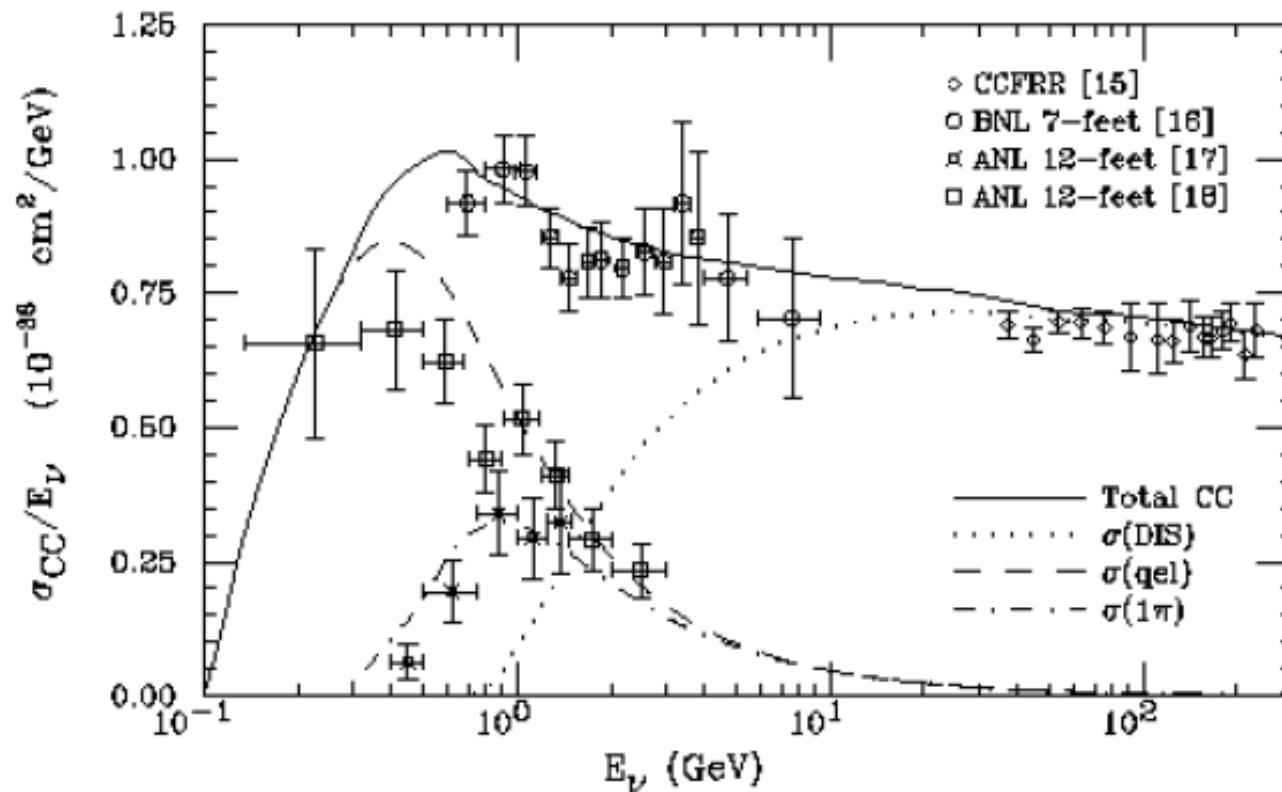


➤ Hypothesis in evaluation

- Tau neutrino detector
 - is made of lead.
 - has the cross sectional area $2\text{m} \times 0.75\text{m}$.
 - placed at 51.5m from the target.

Cross Sections

Neutrino Cross section

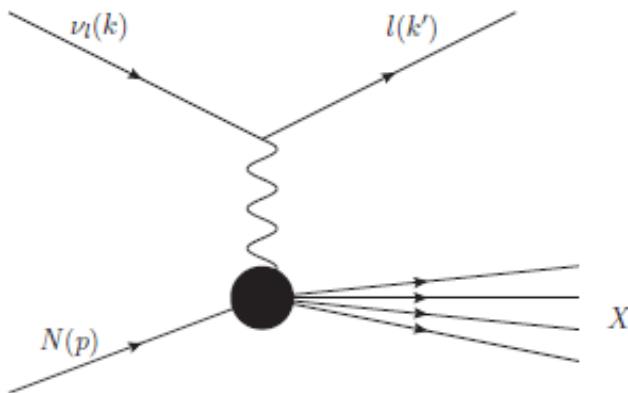


Lipari, Lusignoli and Sartogo, PRL 74 (1994)

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

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

DIS charge current cross section



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

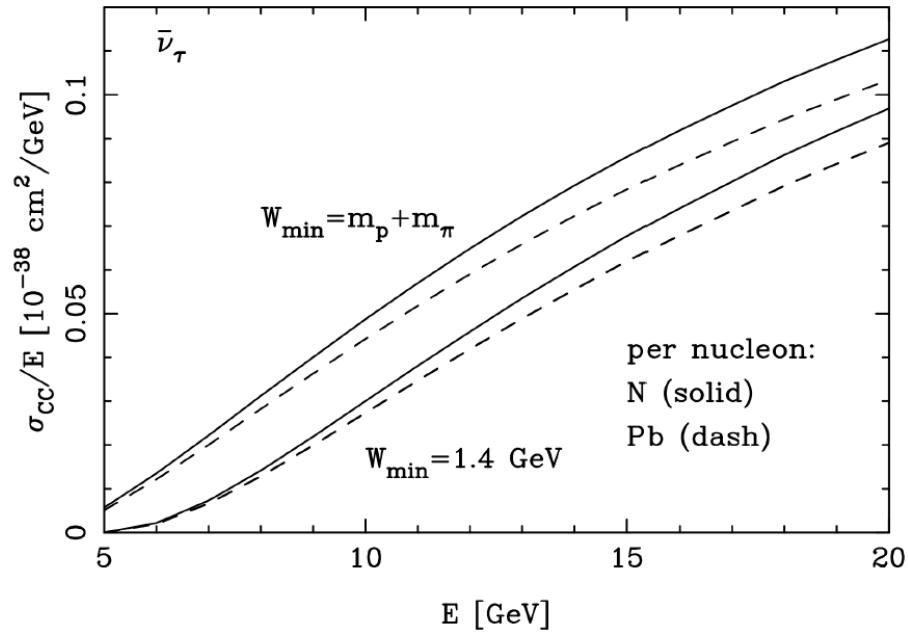
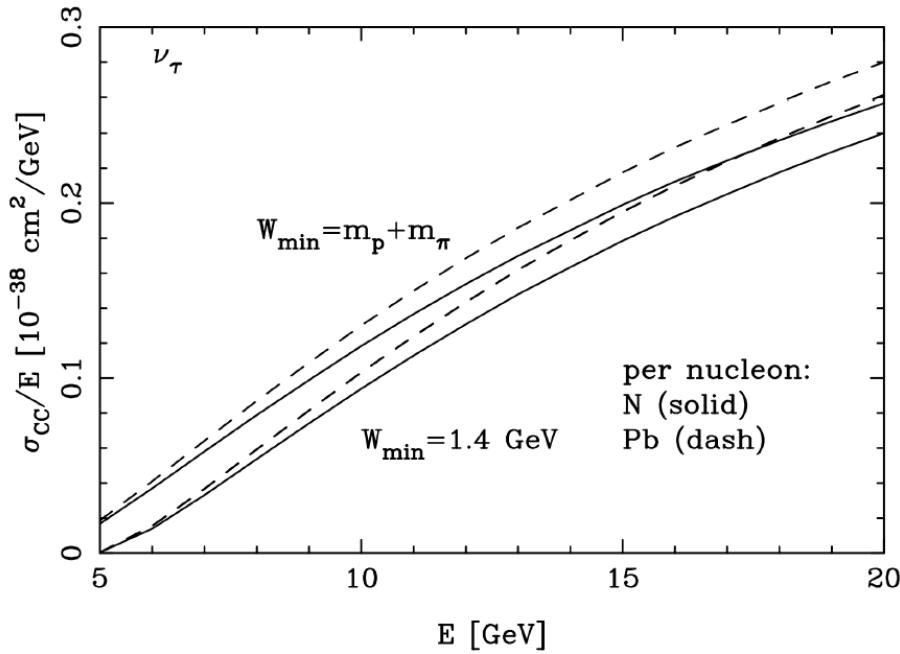
$$N = (n + p)/2$$

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

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

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

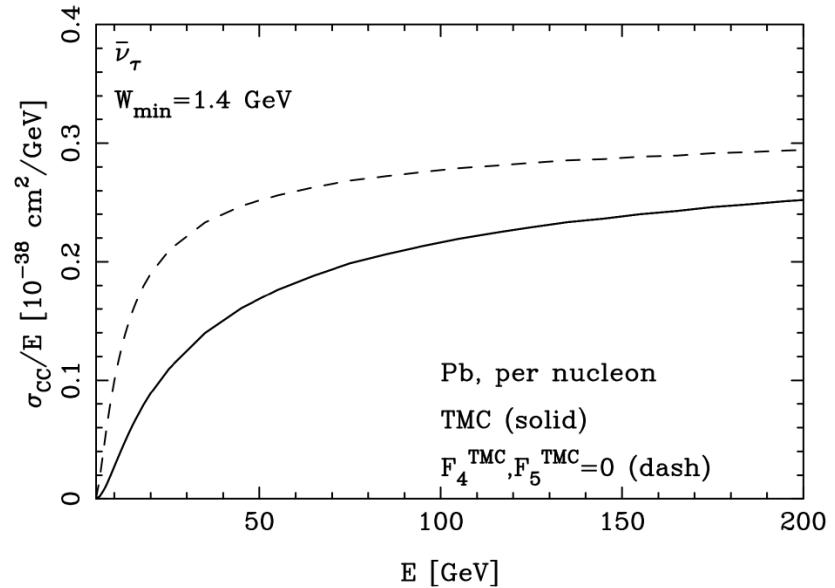
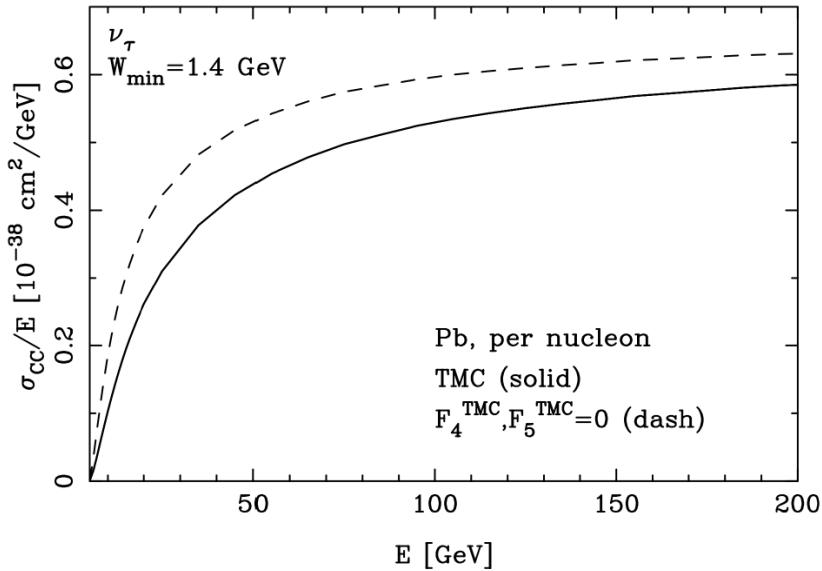
DIS charged current cross section (ν -N/Pb)



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

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

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 \rightarrow 7% at 200 GeV for tau neutrino
53% \rightarrow 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.

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

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

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

Initial proton flux of SHiP

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

Flux – (re)generation function

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

- The energy distribution of the final particles

$$\begin{aligned} \frac{dn(k \rightarrow j; E_k, E_j)}{dE_j} &= \frac{1}{\sigma_{kA}(E_k)} \frac{d\sigma(kA \rightarrow jY, E_k, E_j)}{dE_j} \quad \text{for production} \\ &= \frac{1}{\Gamma_k} \frac{d\Gamma(k \rightarrow jY, E_j)}{dE_j} \quad \text{for decay} \end{aligned}$$

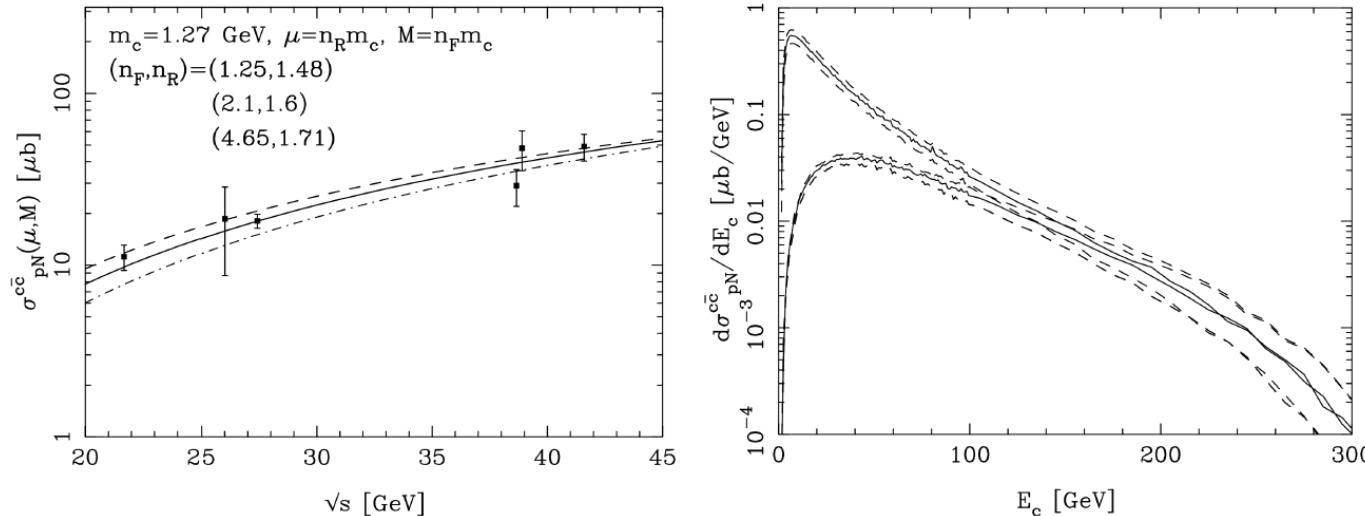
Tau Neutrino Flux

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

$i = \text{direct or chain decay}$

- Production cross section of D_s meson

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



Decay distributions

- Direct decay ($D_s \rightarrow \nu_\tau \tau$)

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

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

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

- Chain decay ($D_s \rightarrow \tau \rightarrow \nu_\tau \tau$)

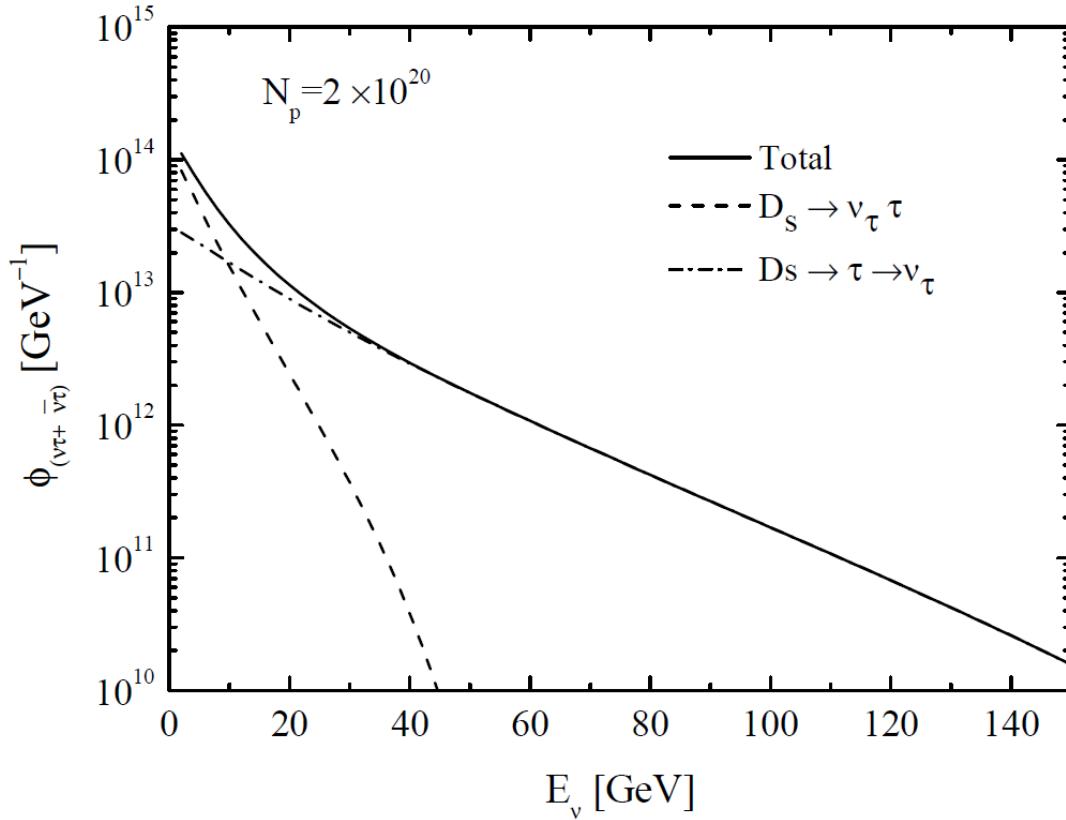
$$\frac{dn}{dE_\nu} = \int_0^1 \frac{dy}{y} \frac{1}{E_{D_s}} \frac{B(D_s \rightarrow \nu_\tau \tau)}{1 - R_\tau} \frac{dn_{\tau \rightarrow \nu_\tau}}{dy}$$

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

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

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



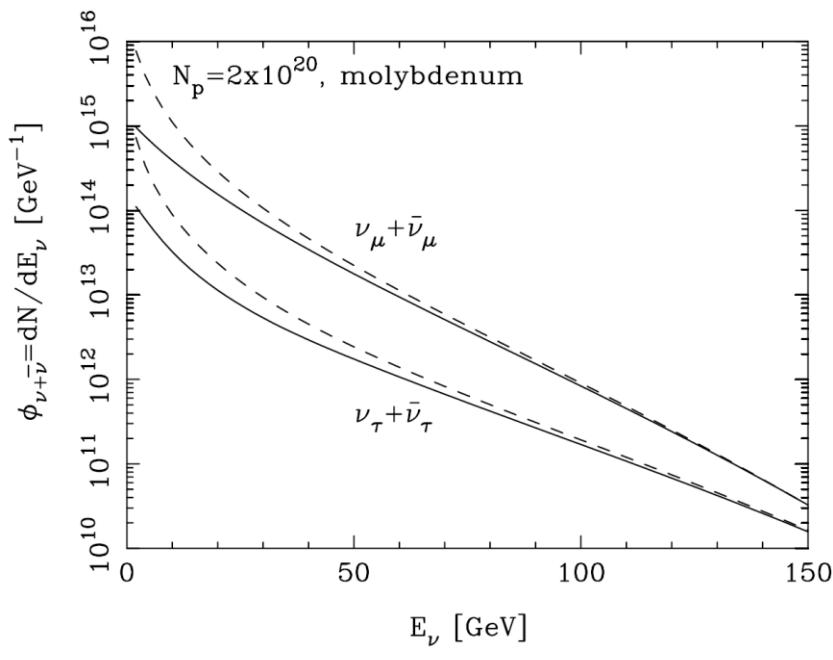
$$0 \leq E_\nu \leq (1 - R_\tau) E_D$$

$$R_\tau E_D \leq E_\tau \leq E_D$$

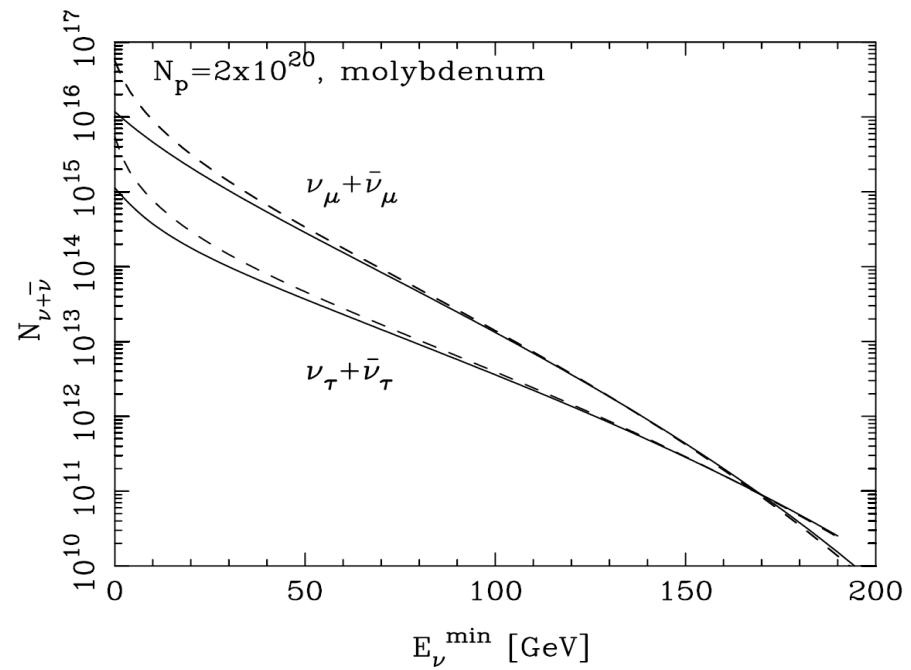
$$R_\tau = m_\tau^2 / m_D^2$$

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

Fluxes



Number of the produced neutrinos



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

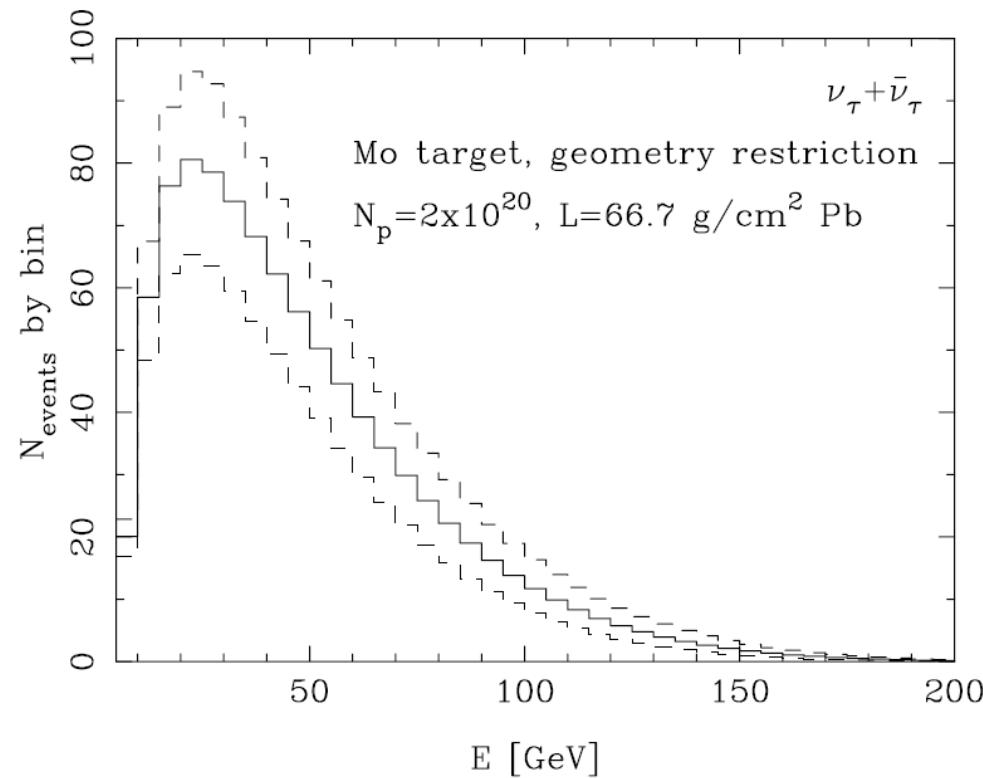
Event numbers

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 $M_{\text{detector}} = 1 \text{ ton}$, $(2\text{m} \times 0.75\text{m})$ cross sectional detector and ρ_{pb} gives $L_{\text{pb}} = 66.7 \text{ g/cm}^2$.
- 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.