**Cosmic background neutrinos**

You want to detect the cosmic neutrino background by aiming a proton beam at empty space. The number density of Standard Model neutrinos is $56/\mathrm{cm}^3$/species $\times$ 6 species (3 flavors and neutrino - antineutrino) Space is full of cosmic photons as well, with similar density. so you want to use the inverse beta decay process $p + \overline{\nu}_e \to n + e^+$

1. Assuming that neutrinos have mass and are nonrelativistic ($m_\nu >> p_\nu$) you can neglect the motion of the anti-neutrinos, what is the minimum proton momentum $P$ you need to create this reaction. Assume $m_P =$ 938.2 MeV, $m_N = 938.6$ MeV, $m_e = 0.511$ MeV, $m_\nu < 1$ eV. [Hint, you can neglect nonleading terms in $m_\nu$ and $m_P$ as $P >> m_P$ and $m_\nu << m_P, m_N, m_e$.]

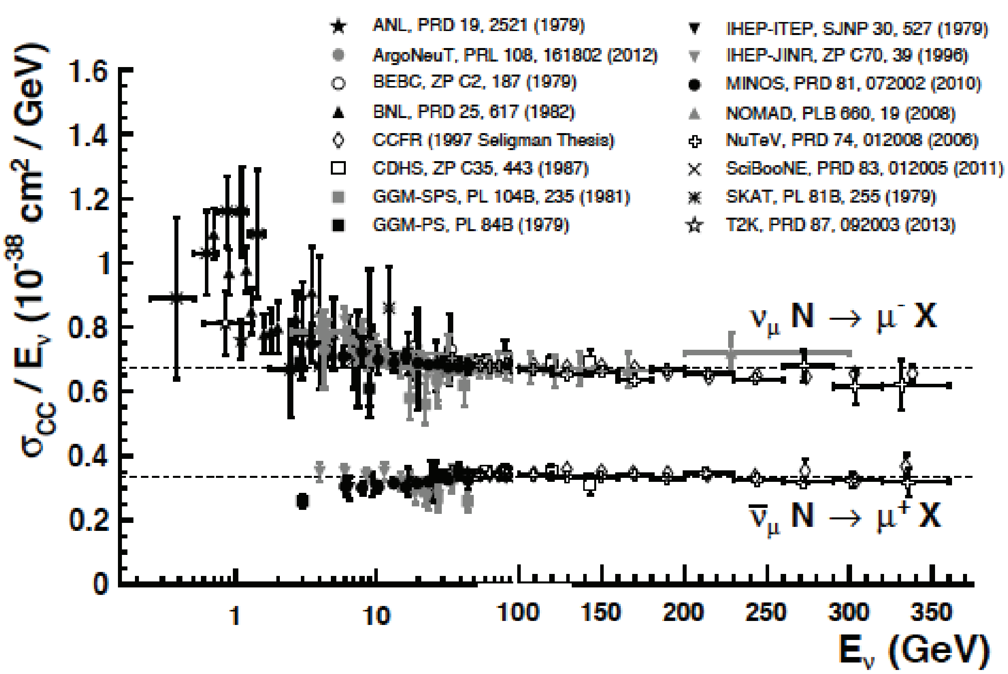
   How does this change if one scatters off of a $\overline{\nu}_\tau$ ($m_\tau$ $1.777MeV$)?

2. Now to estimate cross sections for this process - can be done without #1

   (a) Use the plot of the neutrino and anti-neutrino cross section in the lecture notes (PDG Chapter 49, page 2) as a function of neutrino energy $E_\nu \simeq s/(2m_p)$ when the **proton** is at rest to figure out the dependence of cross section on cm energy when $E_{cm} >> m_p, m_n$.

   (b) A cosmic ray proton that starts 10 billion light years away might scatter before reaching the earth, assuming that the neutrino density is uniform. Estimate the center of mass energy necessary to make that likely.

   (c) Why is that answer at higher energy likely to be wrong? Aside from the impracticality of the whole thing.



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$\sigma_{CC} / E_\nu$ ($10^{-38}$ cm$^2$ / GeV)
$\nu_\mu$ N $\rightarrow$ $\mu^-$ X
$\bar{\nu}_\mu$ N $\rightarrow$ $\mu^+$ X
$E_\nu$ (GeV)