DUNE Collaboration
Nu Interactions SM Group

Introduction to the theory of NuTaus in DUNE
DIS & Structure Functions

Barbara Yaeggy
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UNIVERSITY OF Cincinnati

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

About NuTau production & detection

- Direct production of NuTau in the atmosphere is small L. Pasquali and M. H. Reno - PhysRevD.59.093003

- Oscillations of atmospheric NuMuon to NuTau can result in a large upward $\nu_\tau + \bar{\nu}_\tau$ fluxes at certain energies Fei-Fan Lee, Guey-Lin Lin arXiv:hep-ph/0412383

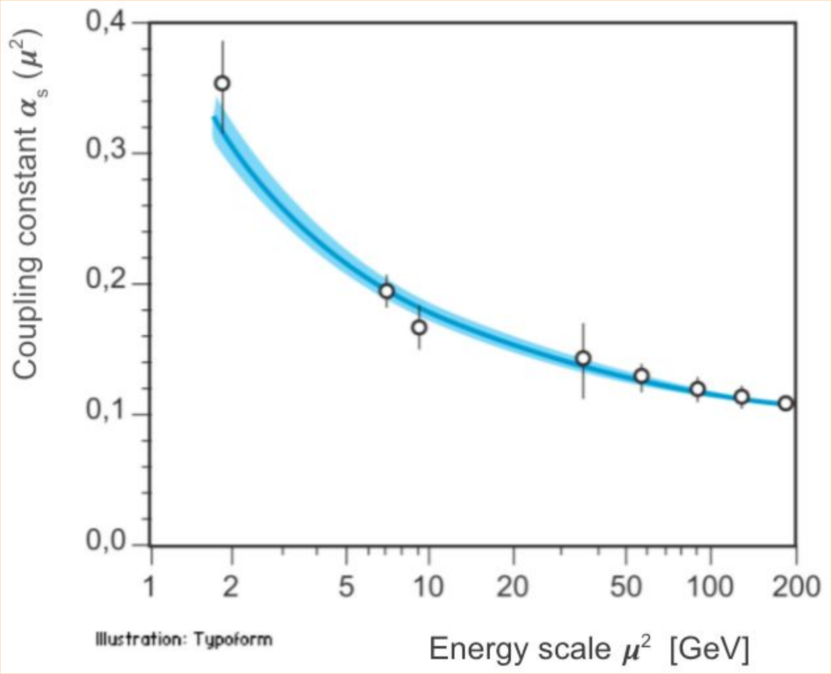
- With the low atmospheric backgrounds at high energies, NuTau signals from conventional and astrophysical sources may be important.

Albright and Jarlskog, in Nucl. Phys. B 84, 467 (1975)., pointed out that there are two additional structure functions, F_4 and F_5 that contribute to the ν_τ XSec.

- We examine the deep inelastic scattering contribution to the NuTau and Anti NuTau charged current cross sections.

- We discuss the cross sections associated with the structure functions at low momentum transfers.

Asymptotic freedom makes it possible to calculate the small distance interaction for quarks and gluons, assuming that they are free particles.



$\alpha_s(\mu^2)$ runs with μ^2	Factorization Theorem:	
As $\alpha_s(\mu^2)$ decreases, μ^2 increases	**Nonperturbative** $\mu^2 \sim 1$ GeV i.e. $\alpha_s(\mu^2)$ very large	**Perturbative** $\alpha_s(\mu^2) << 1$ if $\mu^2 >> 1$ GeV^2

The production of any particle can be determined by the cross section.

We can use Deep ($Q^2 >> M^2$) Inelastic ($W^2 >> M^2$) Scattering to probe the structure of hadrons.

DIS experiments extract information from the lepton scattering cross sections to measure Structure Functions of the target, which are directly related to the nonperturbative Parton Distribution Functions, PDFs.

A. De Roeck, R.S. Thorne / Progress in Particle and Nuclear Physics 66 (2011) 727–781

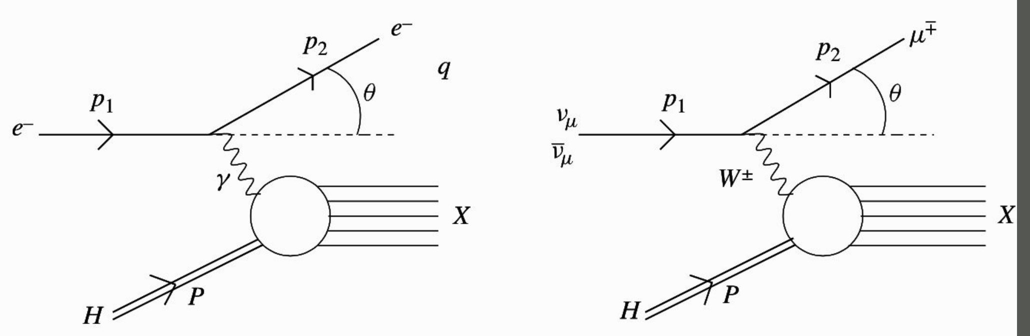


Fig. 1. The kinematics for deep inelastic scattering.

ν_l / $\bar{\nu}_l$ - N scattering

The basic reaction for the (anti)neutrino induced charged current deep inelastic scattering process on a free nucleon target is given by

$$\nu_l(k)/\bar{\nu}_l(k) + N(p) \quad \rightarrow \quad l^-(k')/l^+(k') + X(p'), \qquad (l = e, \nu, \tau)$$

The general expression for the double differential scattering cross section (DCX):

$$\frac{d^2\sigma}{dxdy} = \frac{yM_N}{\pi} \frac{E}{E'} \frac{|\mathbf{k}'|}{|\mathbf{k}|} \frac{G_F^2}{2} \left(\frac{M_W^2}{Q^2 + M_W^2} \right)^2 L_{\mu\nu} W_N^{\mu\nu},$$

Leptonic tensor: $L_{\mu\nu} = 8(k_\mu k'_\nu + k_\nu k'_\mu - k.k' g_{\mu\nu} \pm i\varepsilon_{\mu\nu\rho\sigma} k^\rho k'^\sigma)$

Hadronic tensor:

$$W_N^{\mu\nu} = -g^{\mu\nu} W_{1N}(\nu, Q^2) + W_{2N}(\nu, Q^2) \frac{p^\mu p^\nu}{M_N^2} - \frac{i}{M_N^2} \varepsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma W_{3N}(\nu, Q^2) + \frac{W_{4N}(\nu, Q^2)}{M_N^2} q^\mu q^\nu + \frac{W_{5N}(\nu, Q^2)}{M_N^2}(p^\mu q^\nu + q^\mu p^\nu) + \frac{i}{M_N^2}(p^\mu q^\nu - q^\mu p^\nu) W_{6N}(\nu, Q^2).$$

$W_{iN}(\nu, Q^2)$ $(i = 1-6)$ are the weak nucleon structure functions

In the limit of $Q^2 \rightarrow \infty$, $\nu \rightarrow \infty$, $x \rightarrow$ finite and $W_{iN}(\nu, Q^2)$ $(i = 1-5)$ are written in terms of the dimensionless nucleon structure functions as:

$$F_{1N}(x) = W_{1N}(\nu, Q^2) \quad F_{2N}(x) = \frac{Q^2}{2xM_N^2} W_{2N}(\nu, Q^2) \quad F_{3N}(x) = \frac{Q^2}{xM_N^2} W_{3N}(\nu, Q^2)$$

$$F_{4N}(x) = \frac{Q^2}{2M_N^2} W_{4N}(\nu, Q^2) \quad F_{5N}(x) = \frac{Q^2}{2xM_N^2} W_{5N}(\nu, Q^2)$$

ν_l / $\bar{\nu}_l$ - N scattering

The differential scattering cross section is given by

$$\frac{d^2\sigma}{dxdy} = \frac{G_F^2 M_N E_\nu}{\pi(1+\frac{Q^2}{M_W^2})^2}\Big\{\Big[y^2x+\frac{m_l^2 y}{2E_\nu M_N}\Big]F_{1N}(x,Q^2)+\Big[\Big(1-\frac{m_l^2}{4E_\nu^2}\Big)-\Big(1+\frac{M_N x}{2E_\nu}\Big)y\Big]F_{2N}(x,Q^2)$$

$$\pm\Big[xy\Big(1-\frac{y}{2}\Big)-\frac{m_l^2 y}{4E_\nu M_N}\Big]F_{3N}(x,Q^2)+\frac{m_l^2(m_l^2+Q^2)}{4E_\nu^2 M_N^2 x}F_{4N}(x,Q^2)-\frac{m_l^2}{E_\nu M_N}F_{5N}(x,Q^2)\Big\}.$$

For $\nu(\bar{\nu})$-proton scattering

$$F_{2p}^{\nu}(x) = 2x[d(x)+s(x)+\bar{u}(x)+\bar{c}(x)]$$
$$F_{2p}^{\bar{\nu}}(x) = 2x[u(x)+c(x)+\bar{d}(x)+\bar{s}(x)]$$
$$xF_{3p}^{\nu}(x) = 2x[d(x)+s(x)-\bar{u}(x)-\bar{c}(x)]$$
$$xF_{3p}^{\bar{\nu}}(x) = 2x[u(x)+c(x)-\bar{d}(x)-\bar{s}(x)]$$

For $\nu(\bar{\nu})$-neutron scattering

$$F_{2n}^{\nu}(x) = 2x[u(x)+s(x)+\bar{d}(x)+\bar{c}(x)]$$
$$F_{2n}^{\bar{\nu}}(x) = 2x[d(x)+c(x)+\bar{u}(x)+\bar{s}(x)]$$
$$xF_{3n}^{\nu}(x) = 2x[u(x)+s(x)-\bar{d}(x)-\bar{c}(x)]$$
$$xF_{3n}^{\bar{\nu}}(x) = 2x[d(x)+c(x)-\bar{u}(x)-\bar{s}(x)].$$

At the leading order

Callan-Gross relation:

$$F_2(x)=2xF_1(x)$$

Albright-Jarlskog relations:

$$F_4(x)=0 \qquad F_2(x)=2xF_5(x)$$

In this work MMHT PDFs parameterization (Harland-Lang *et al.*, Eur. Phys. J. C **75**, no. 5, 204 (2015)) has been used.

Charm quark is considered to be a massive object and in four flavor scheme we consider:

$$F_{iN}(x,Q^2)=F_{iN}^{n_f=4}(x,Q^2)=\underbrace{F_{iN}^{n_f=3}(x,Q^2)}_{\text{for massless}(u,d,s)\text{ quarks}}+\underbrace{F_{iN}^{n_f=1}(x,Q^2)}_{\text{for massive charm quark}}$$

Details in ref. Ansari *et al.*, Phys. Rev. D **102**, 113007 (2020)

NuTau 2021 Workshop

For E=100 GeV, F_5 contributes ~10% for $\nu_\tau N$ and ~30% for $\bar{\nu}_\tau N$ CC cross section.

Cross Section for NuTau: ν/ν_τ (k) + N(p) $\rightarrow \tau/\tau$ (k')

The DIS the expression for the CC differential cross section shows a mass dependence: Tomalak, PRD 103 (2021) 013006, Fatima, Athar, Singh, PRD 102 (2020) 113009

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

Suppressed for $\nu_{\mu,e}$

Where:

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

$$W^2 = (p+q)^2 = M_N^2 + 2M_N\nu - Q^2 ,$$

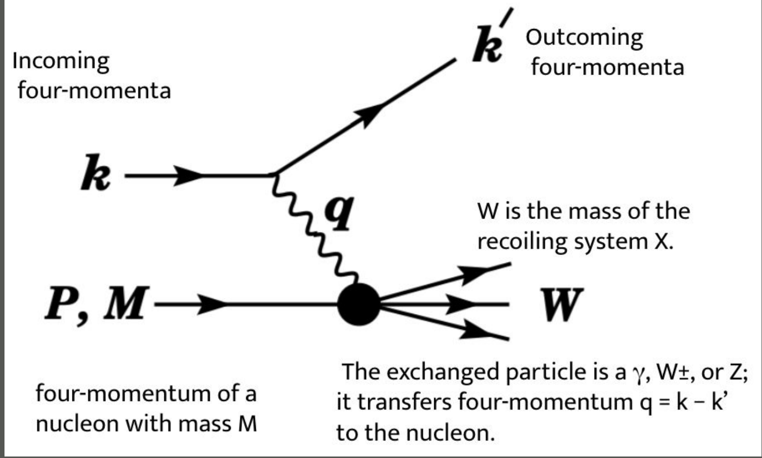
And:

$$\frac{m_\tau^2}{2M_N(E_\nu - m_\tau)} \leq x \leq 1$$

$$a - b \leq y \leq a + b$$

$$a = \frac{1 - m_\tau^2\left(\frac{1}{2M_N E_\nu x} + \frac{1}{2E_\nu^2}\right)}{2\left(1+\frac{M_N x}{2E_\nu}\right)}$$

$$b = \frac{\sqrt{\left(1-\frac{m_\tau^2}{2M_N E_\nu x}\right)^2 - \frac{m_\tau^2}{E_\nu^2}}}{2\left(1+\frac{M_N x}{2E_\nu}\right)} .$$



Structure Functions:

$2xF_1 = F_2$

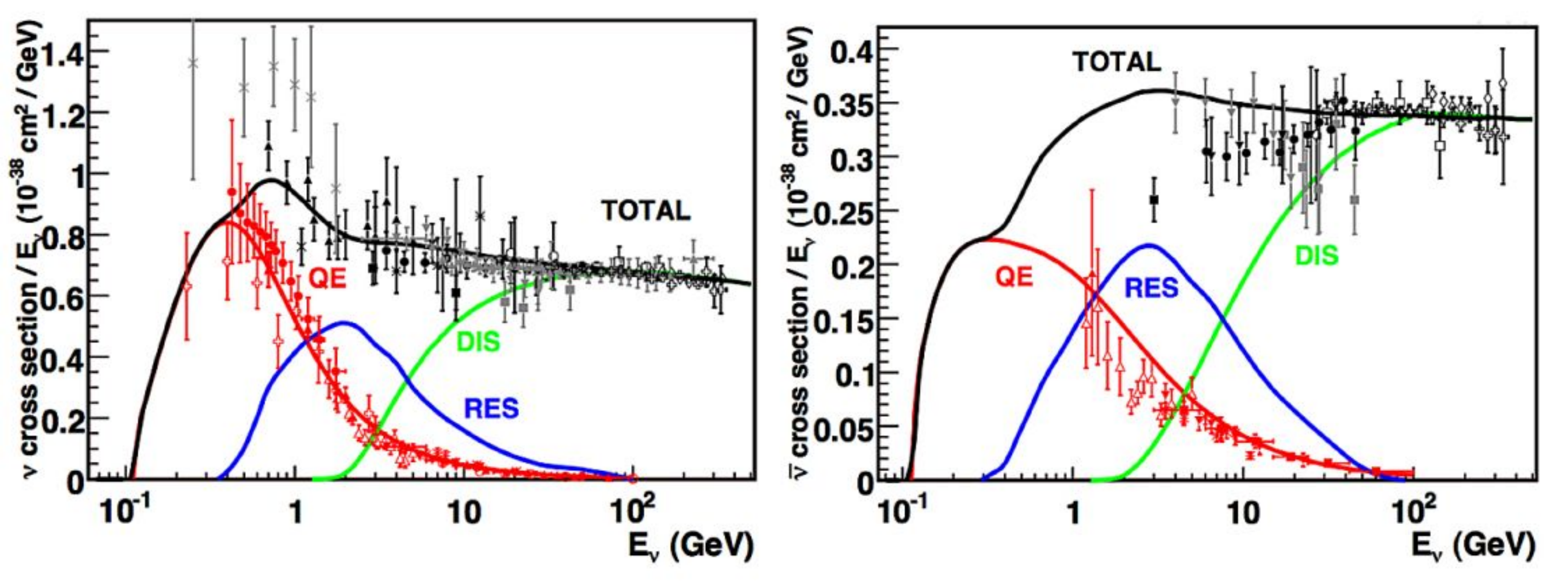
$-xF_3 = F_2$

$xF_5 = F_2$

$F_4 = 0$ also holds when the nucleon target is replaced by a lepton target.

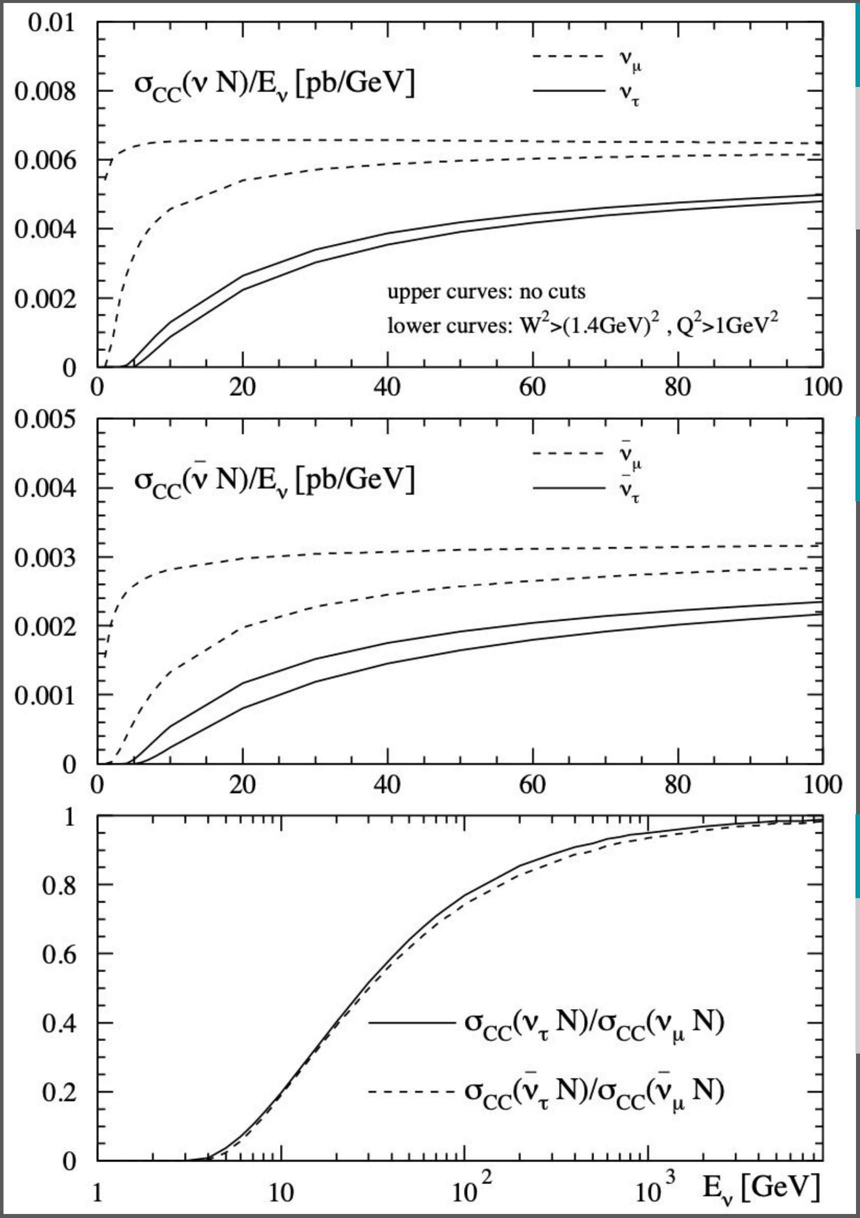
Bodek-Yang model aims for describing DIS cross section in all Q^2 regions arXiv:hep-ex/0308007

In the 1-10 GeV region all three processes (QE, Resonance & DIS) contribute to neutrino charged current total cross section



- To avoid double counting, the evaluation of the inelastic piece is done over a restricted phase space.
- Generally, a limit on the hadronic final state invariant mass W is applied, such as $W > W_{min}$.
- This W_{min} is used to separate the exclusive and inclusive calculations.

A look to the CC ν_τ and ν_μ Cross Section [M. H. Reno - PhysRevD.74.033001]



Nu

- With cuts, W_{min} and Q^2 cuts agree to within 3% for E_ν > 20 GeV

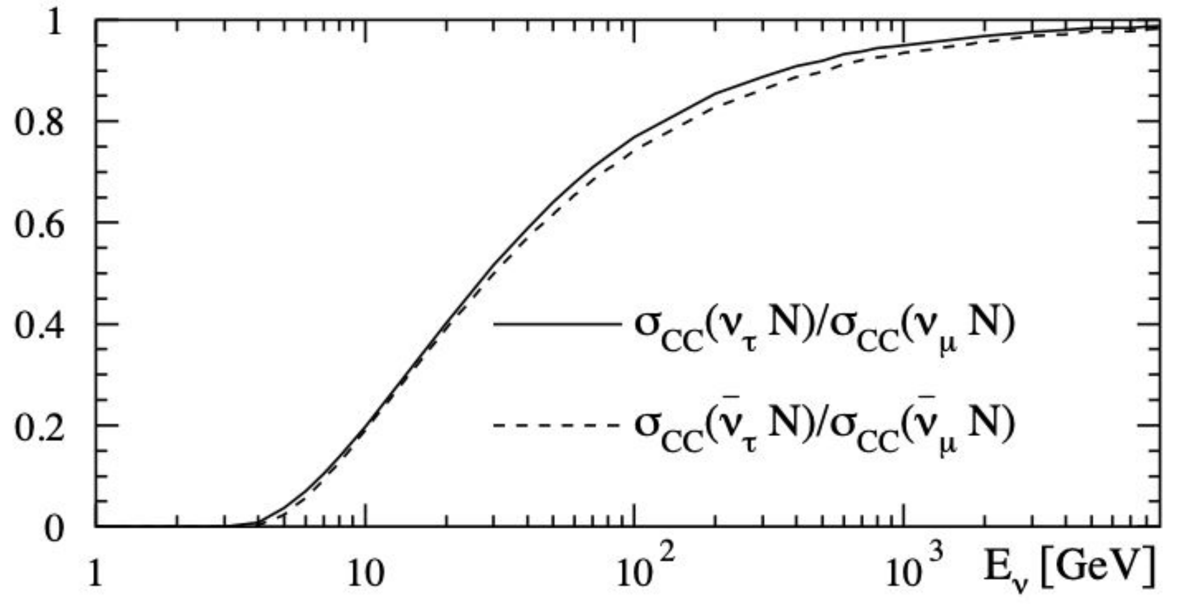
Anti Nu

The additional structure functions F_4 and F_5 leads to a significant reduction in the cross section as compared to muon and electron neutrino cross sections.

Ratios

The ratios ν_τ / ν_μ & $\overline{\nu}_\tau / \overline{\nu}_\mu$ are insensitive to DIS cuts

The ratios ν_τ / ν_μ & $\bar{\nu}_\tau / \bar{\nu}_\mu$ are insensitive to DIS cuts



- Shows the ratio of the $\nu_\tau N$ to $\nu_\mu N$ CC cross sections (solid lines) and the same ratio for antineutrinos.
- Shown are the uncut results, but the results with the W_{min} and Q^2 cuts agree to within 3% for $E_\nu > 20$ GeV.

At $E_\nu = 10^3$ GeV, the ratio ν_τ / ν_μ cross section ratio is 5% below unity, at 100 GeV, the ratio is 0.76

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

Reasons for the deficit in the ν_τ CC cross section

The reduced phase space is reflected in the integration limits for x and y.

F_5 term appear without a factor of x. Since:

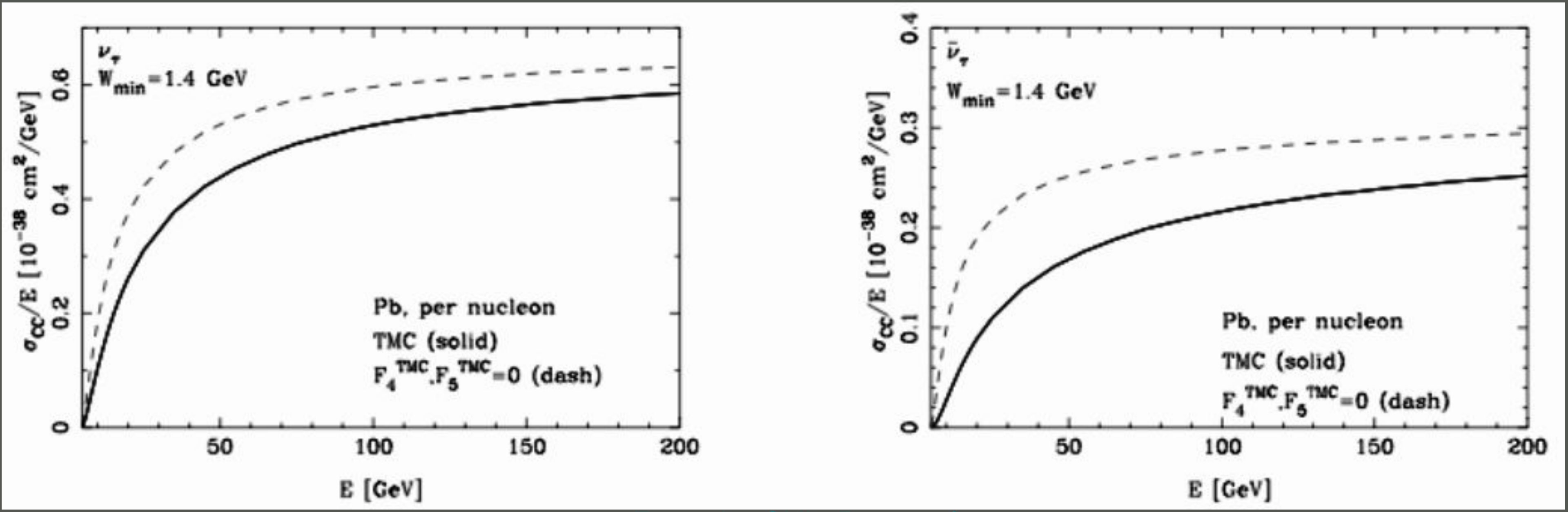
$$F_5 \sim F_1 \sim q(x, Q^2)$$

There is a small-x enhancement of its contribution to the cross section at high energies.

The F_5 term accounts for the rest of the suppression of the ν_τ cross section at high energies.

The tau mass corrections to the prefactors of F_1, F_2 and F_3 become negligible at high energies because the low-x rise of q(x) is tempered by factors of x or y for these structure function.

ν_τ **SM prediction (solid)**
F4=F5=0 hypothesis (dashed) $\bar{\nu}_\tau$

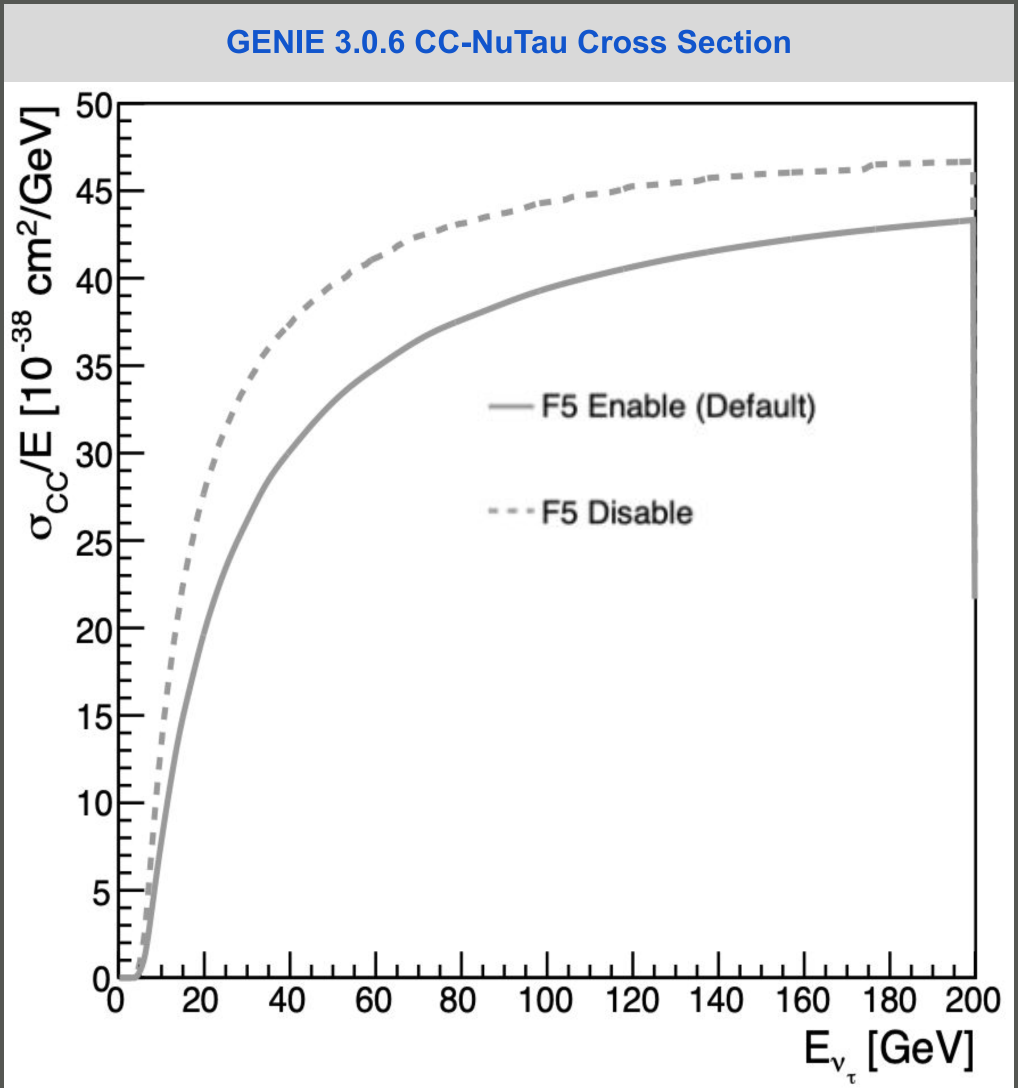


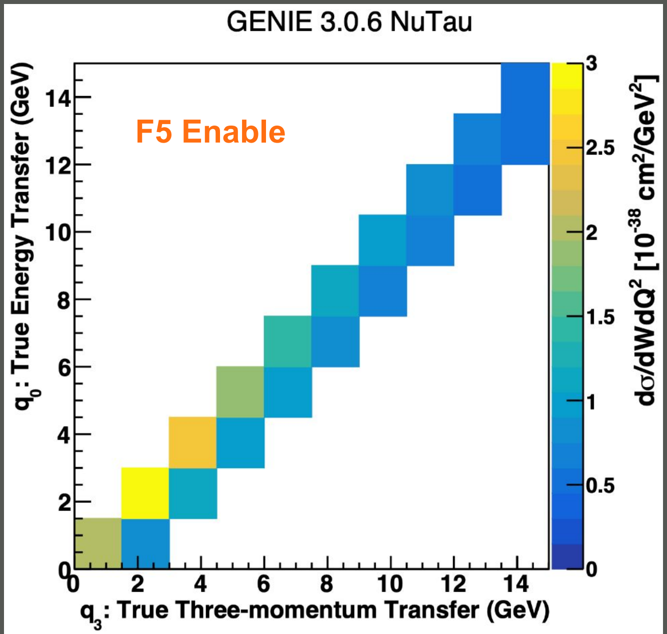
[From the SHip Proposal]

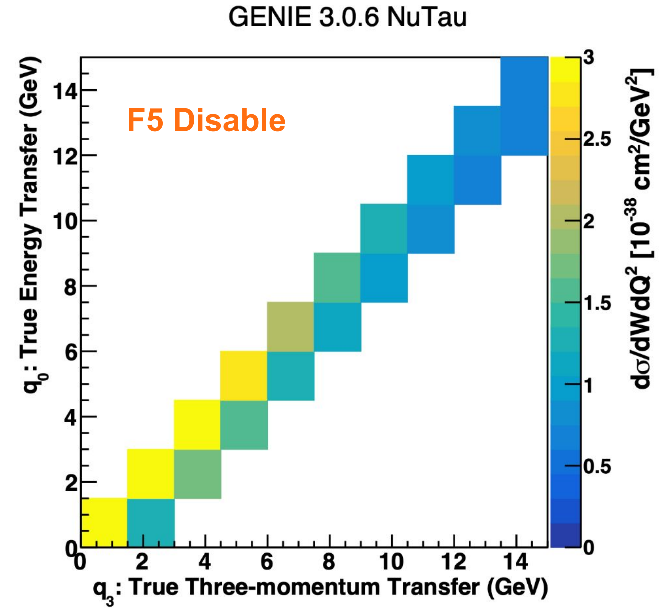
Notice the difference between the cross-sections in the $F_4 = F_5 = 0$ hypothesis and the SM prediction is larger for lower neutrino energies.

CC - ν_τ TRUTH Level studies show that indeed, when DIS cuts are applied and $F_5 = 0$ we can extract new information from the lepton cross section.

ν_τ

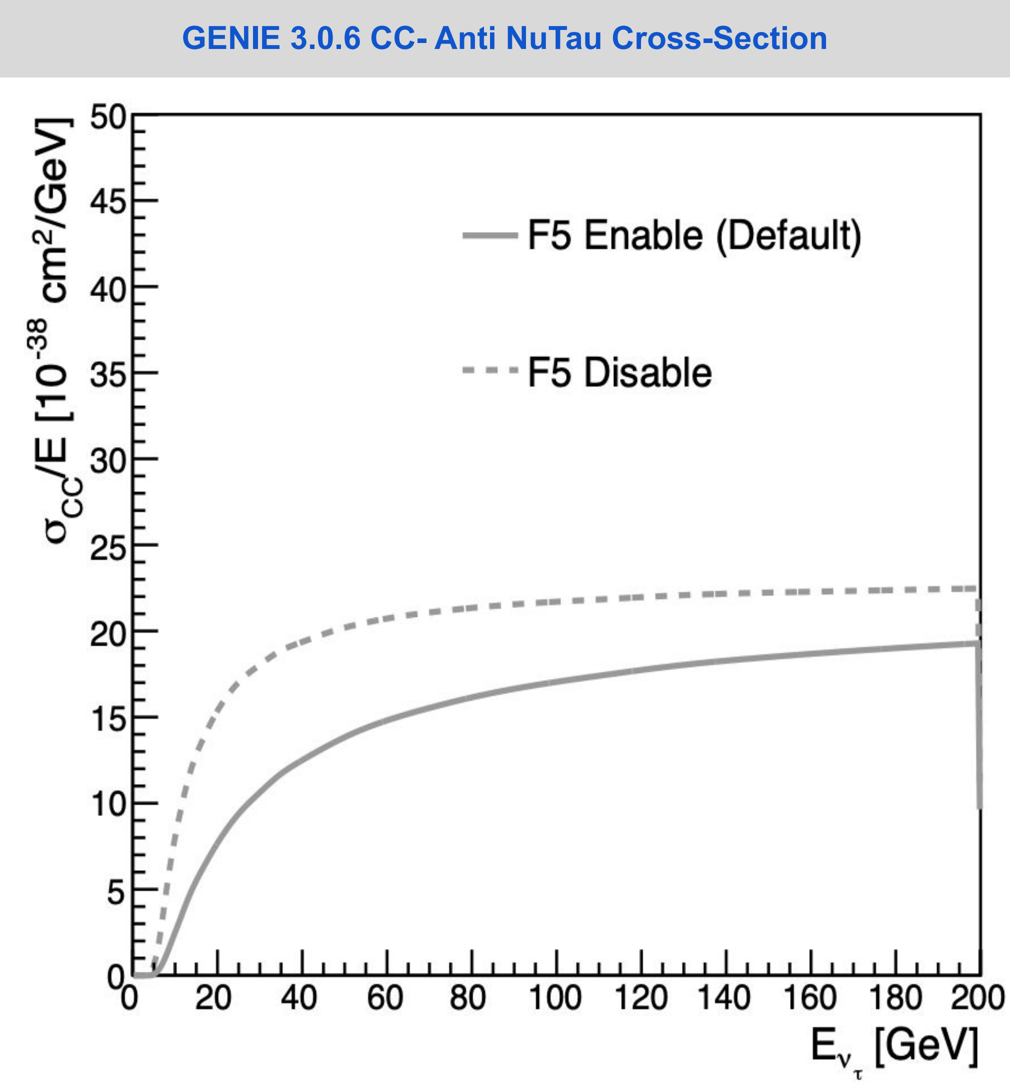


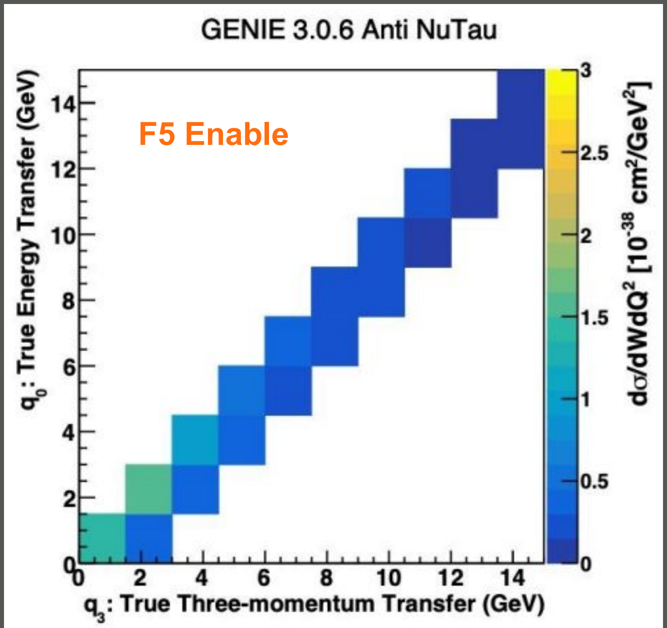


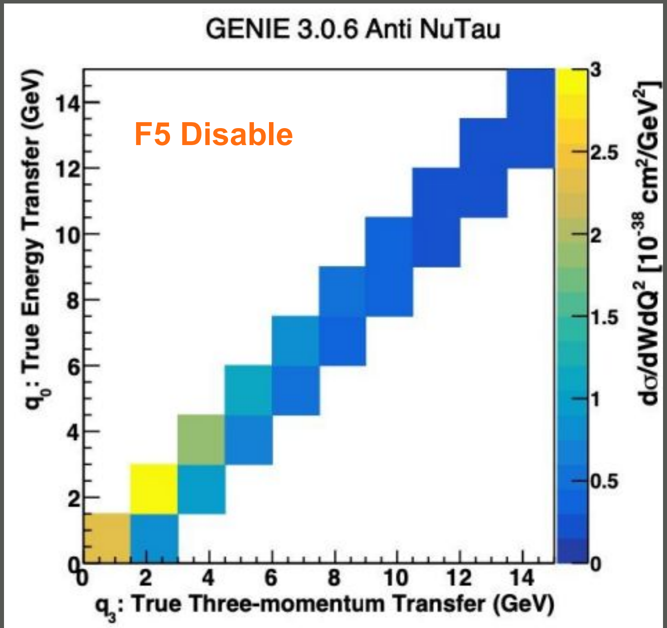


CC - ν_τ TRUTH Level studies show that indeed, when DIS cuts are applied and $F_5 = 0$ we can extract new information from the lepton cross section.

$\overline{\nu}_\tau$





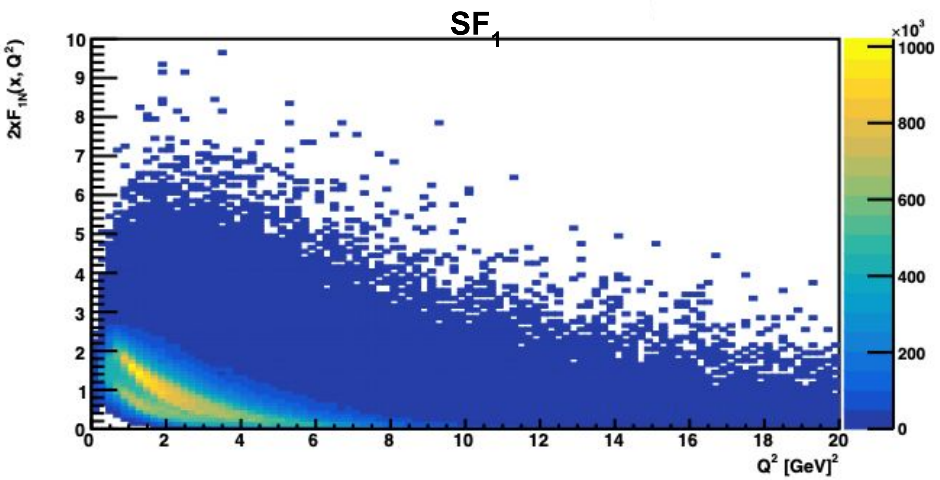


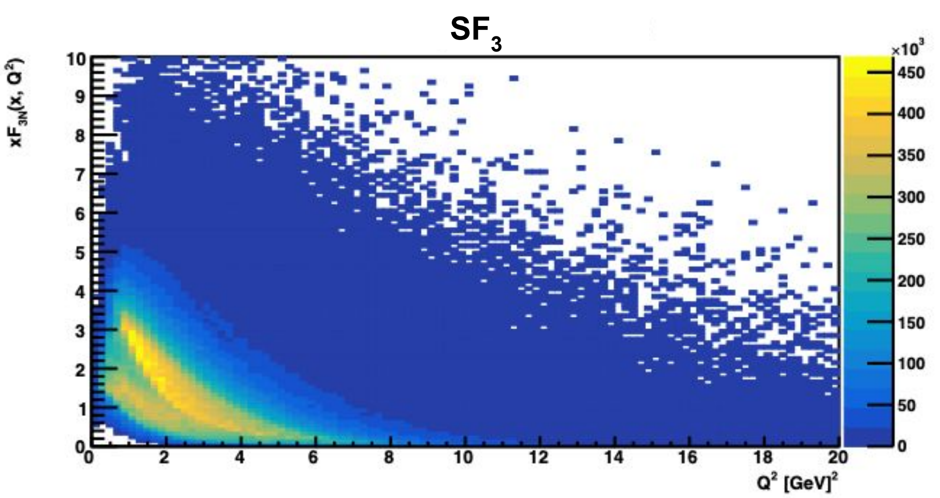
Exploring The Structure Functions with Genie 3.0.6

Q^2 vs Structure Functions

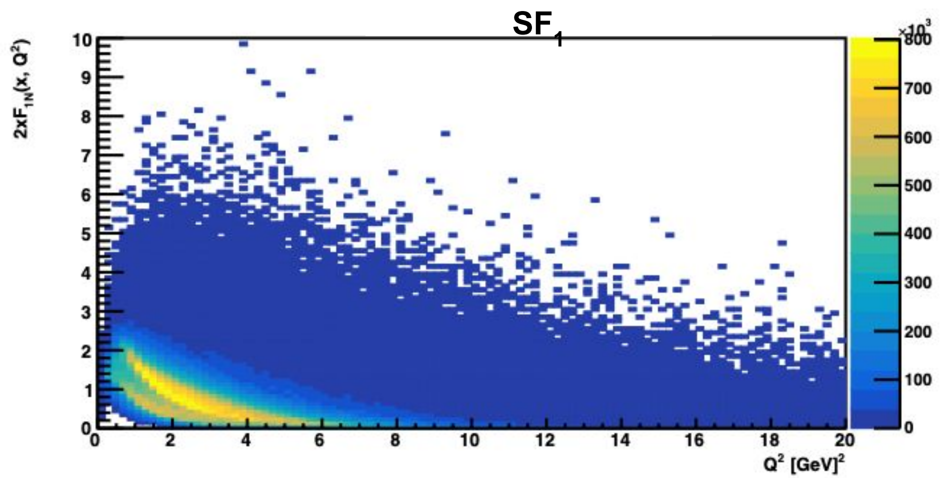
ν_τ

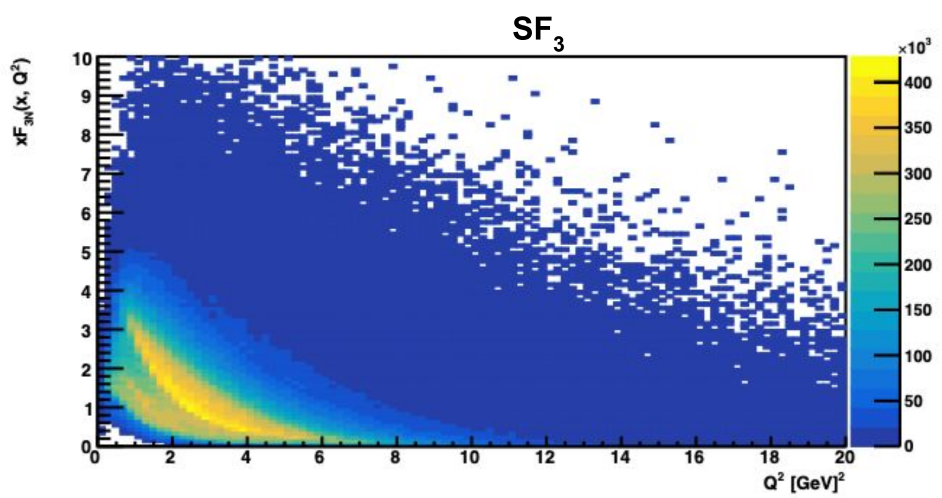
SF_5 Disable





SF_5 Enable

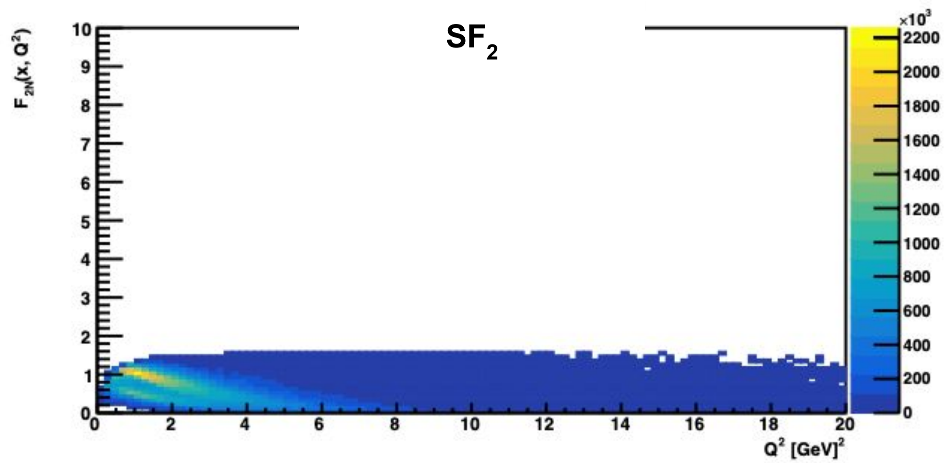


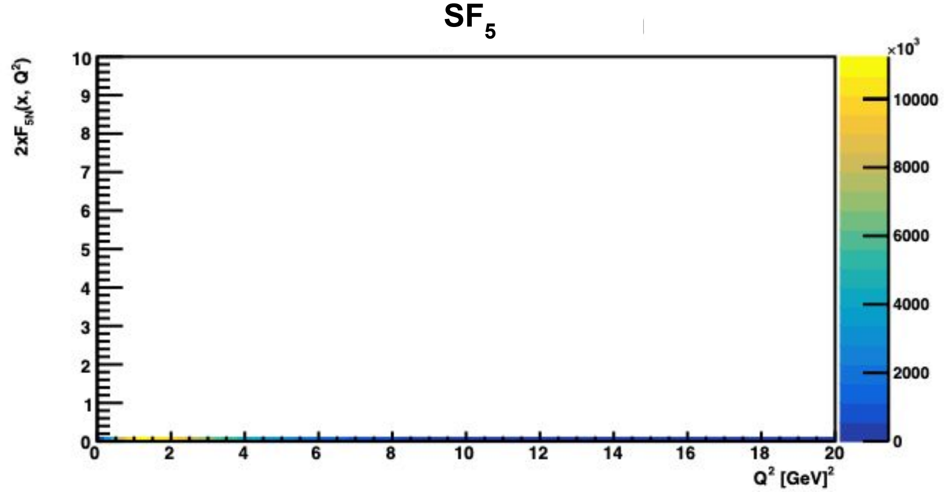


Q^2 vs Structure Functions

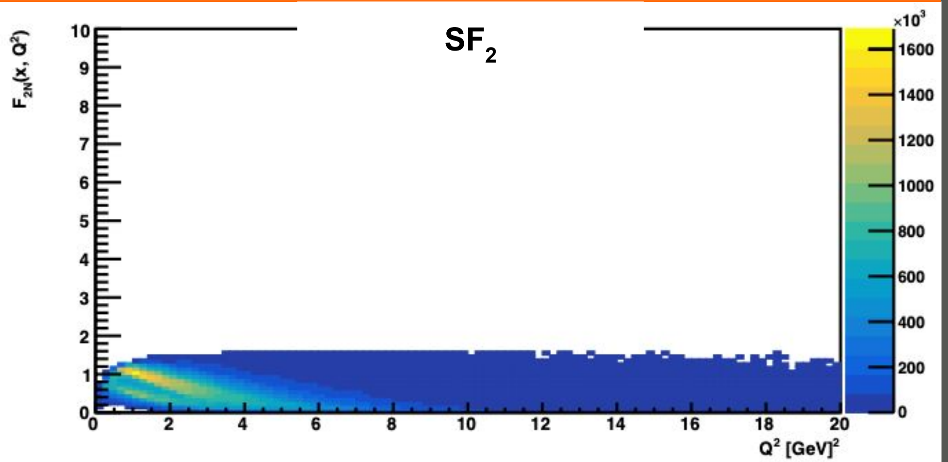
ν_τ

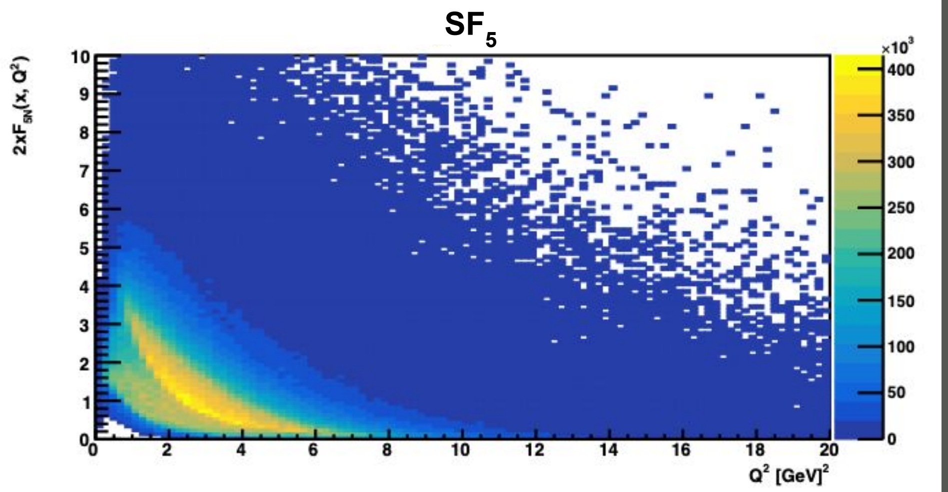
SF_5 Disable





SF_5 Enable





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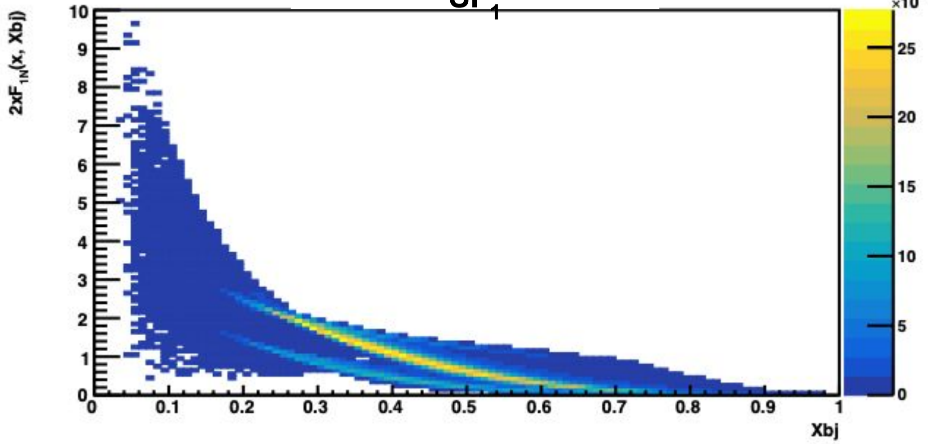
X_{Bj} vs Structure Functions

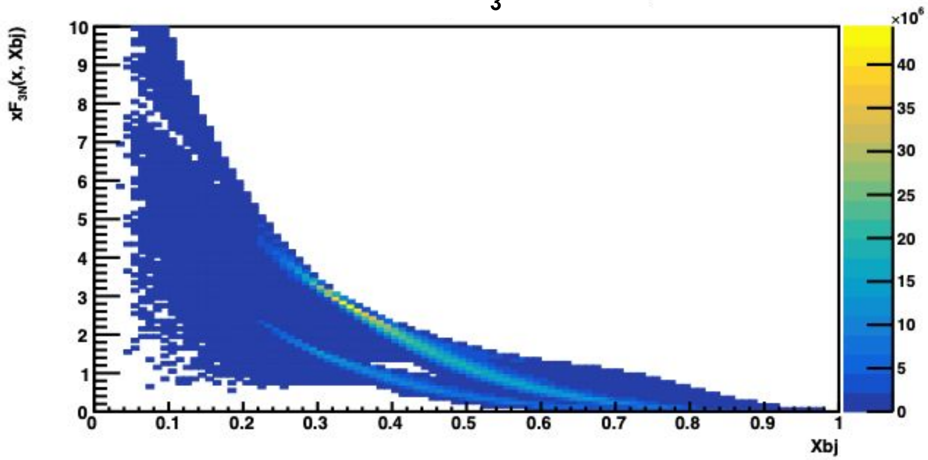
ν_τ

SF_5 Disable

SF_1

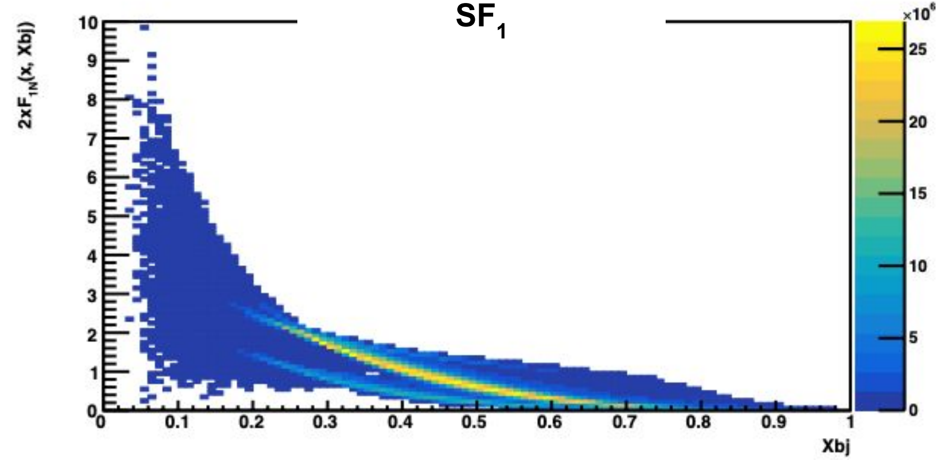


SF_3

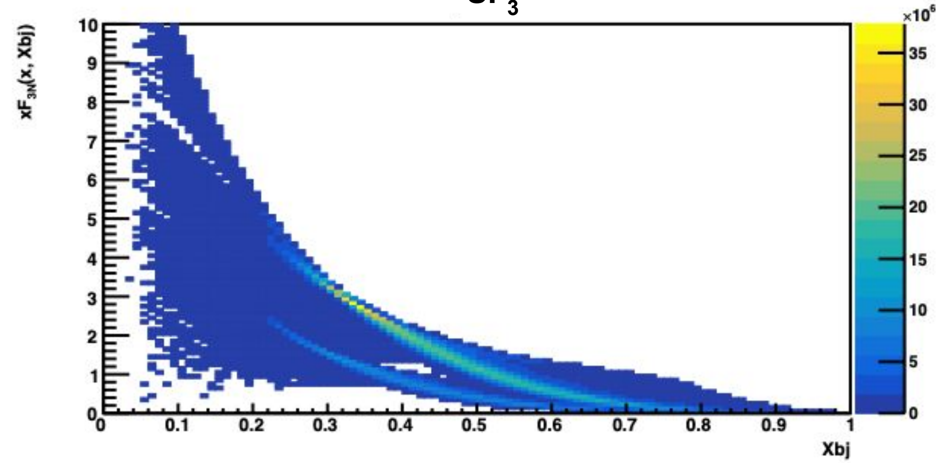


SF_5 Enable

SF_1



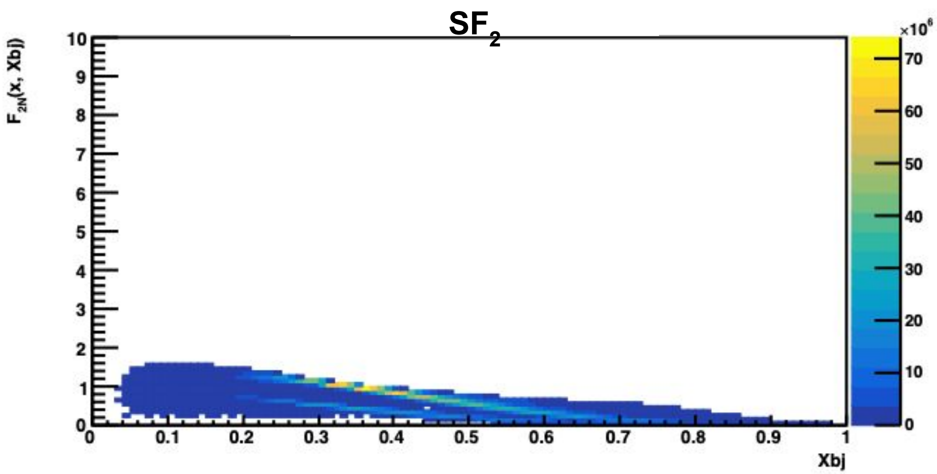
SF_3

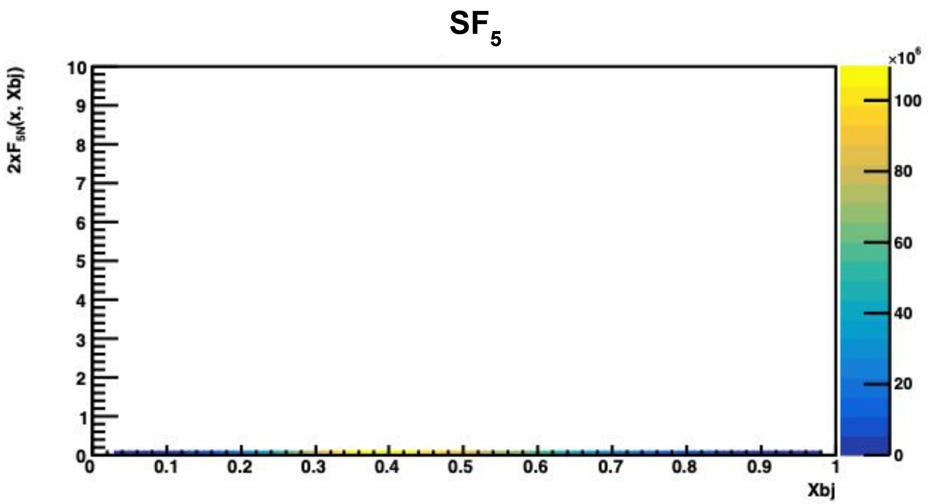


X_{Bj} vs Structure Functions

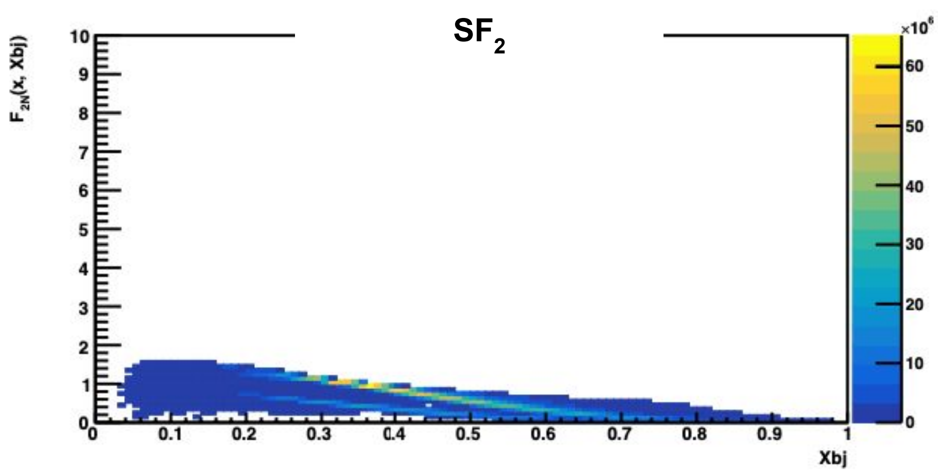
ν_τ

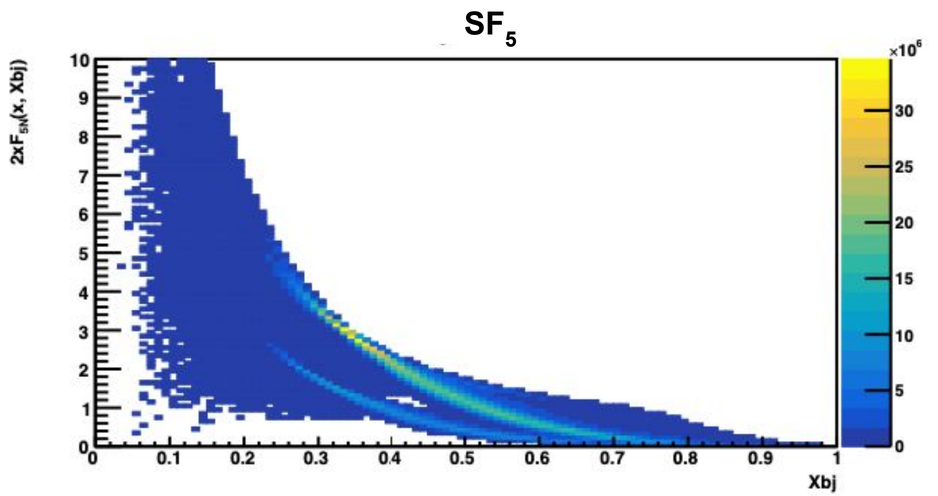
SF_5 Disable





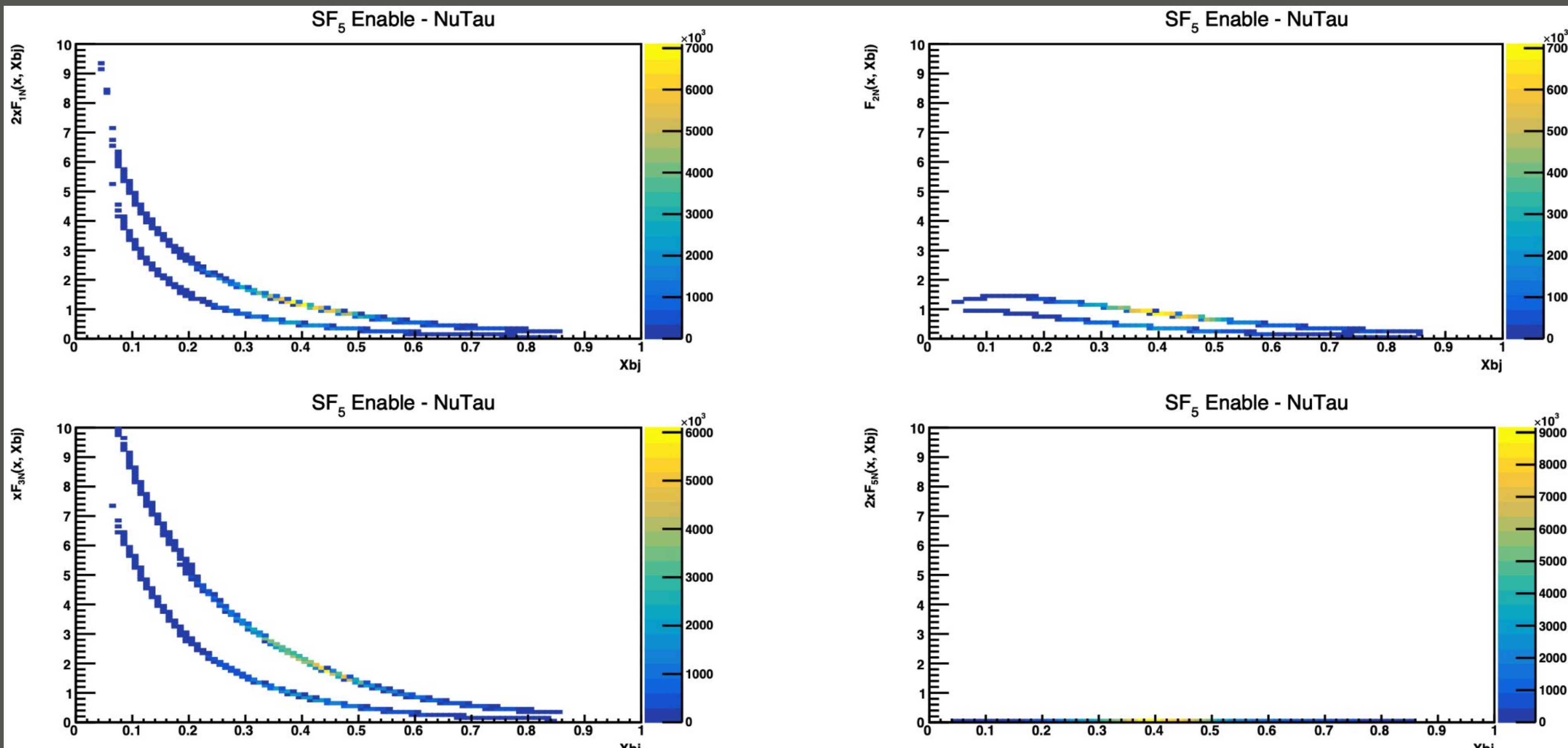
SF_5 Enable





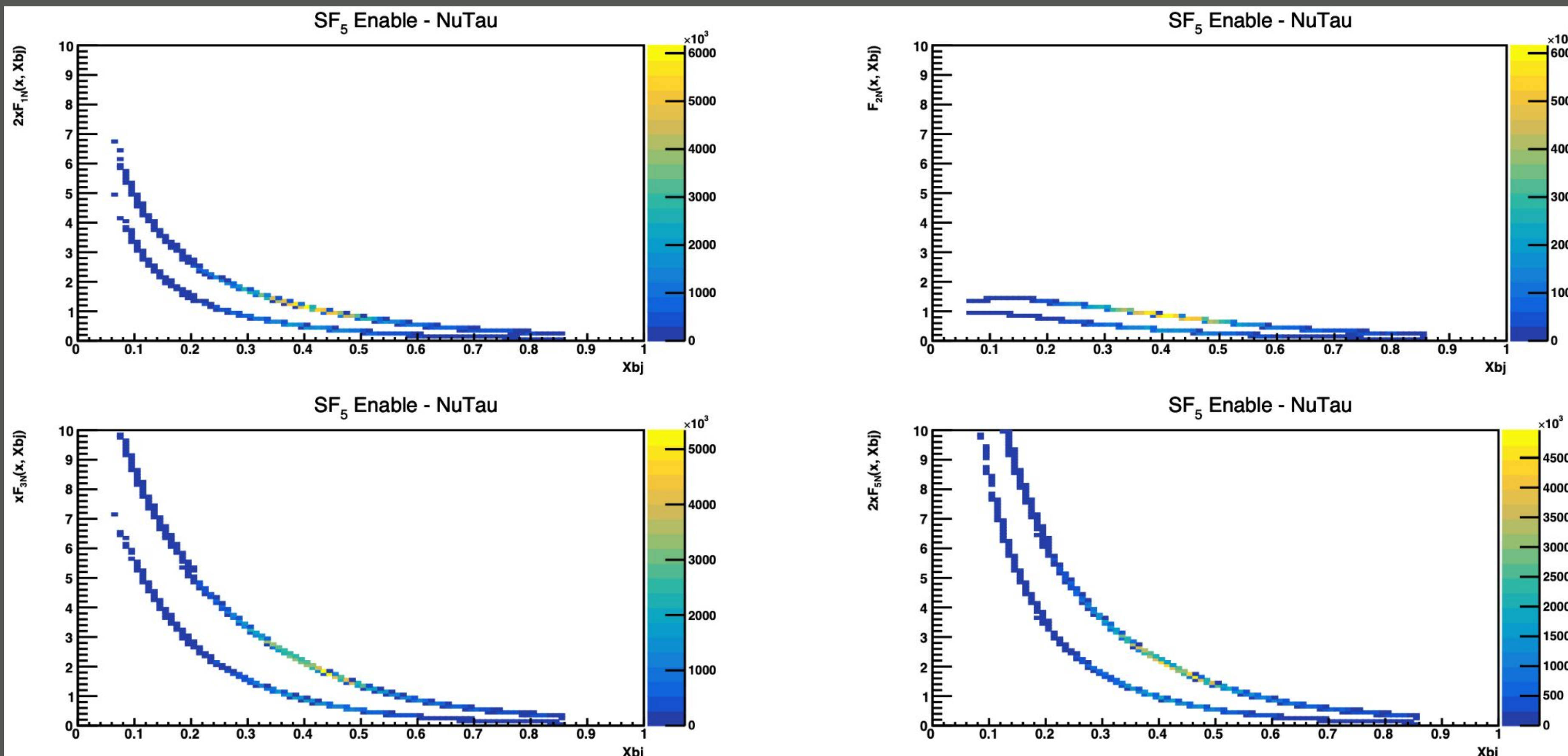
When $Q^2 > 1.8$ & $Q^2 <= 2.0$ GeV SF_5 DISABLE

ν_τ



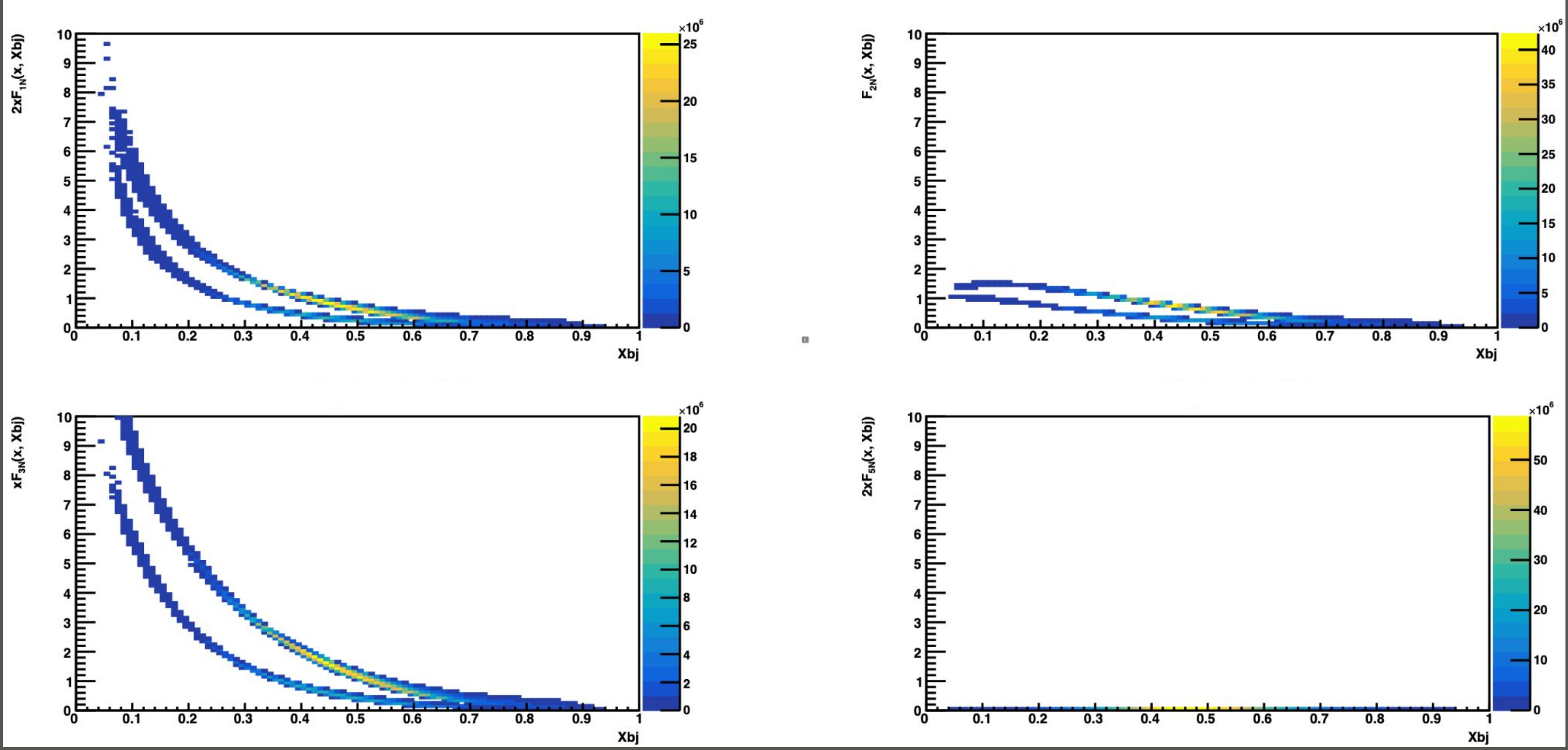
When Q^2 > 1.8 & Q^2 <= 2.0 GeV SF_5 ENABLE

ν_τ



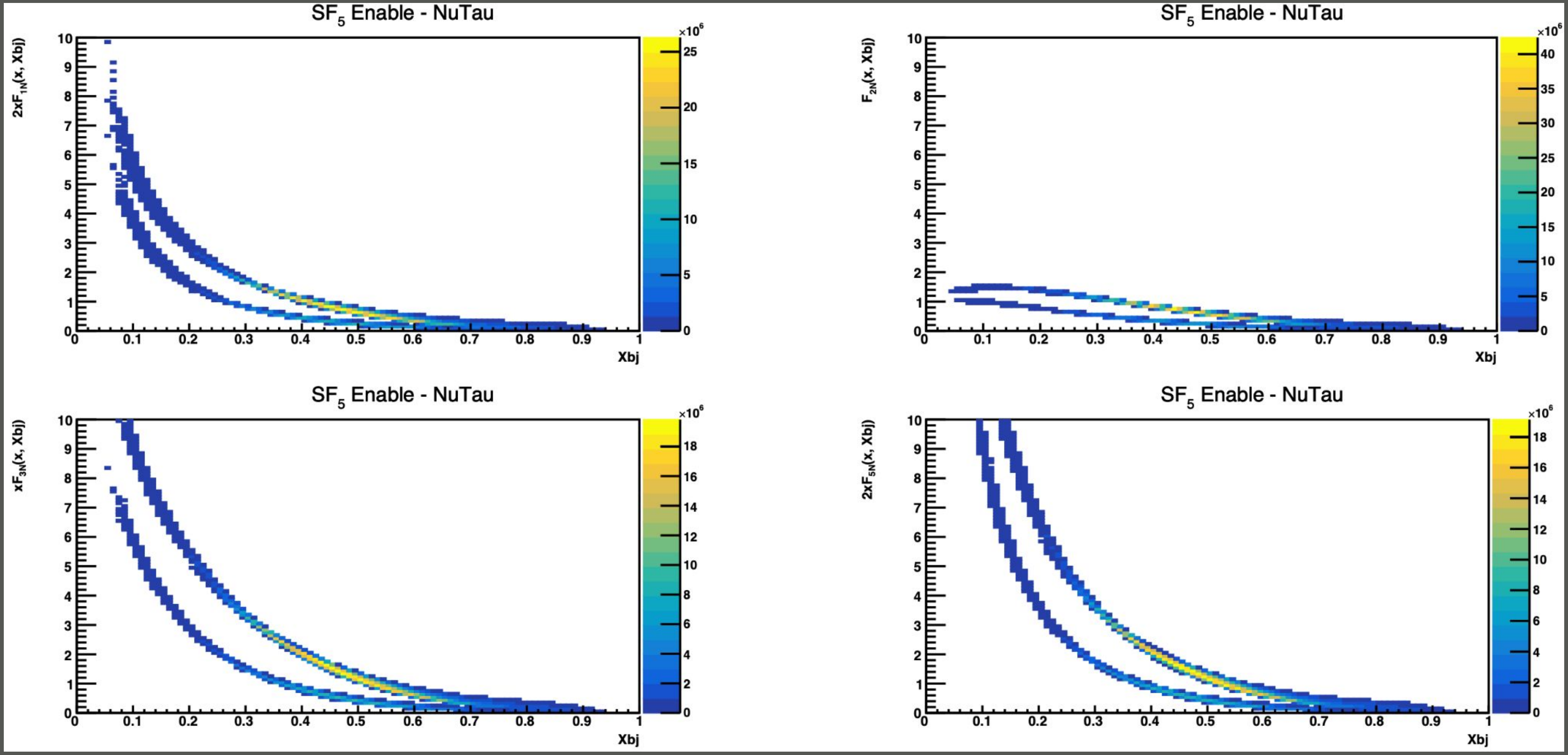
When $Q^2 > 2.0$ & $Q^2 < 5.0$ GeV SF_5 DISABLE

ν_τ



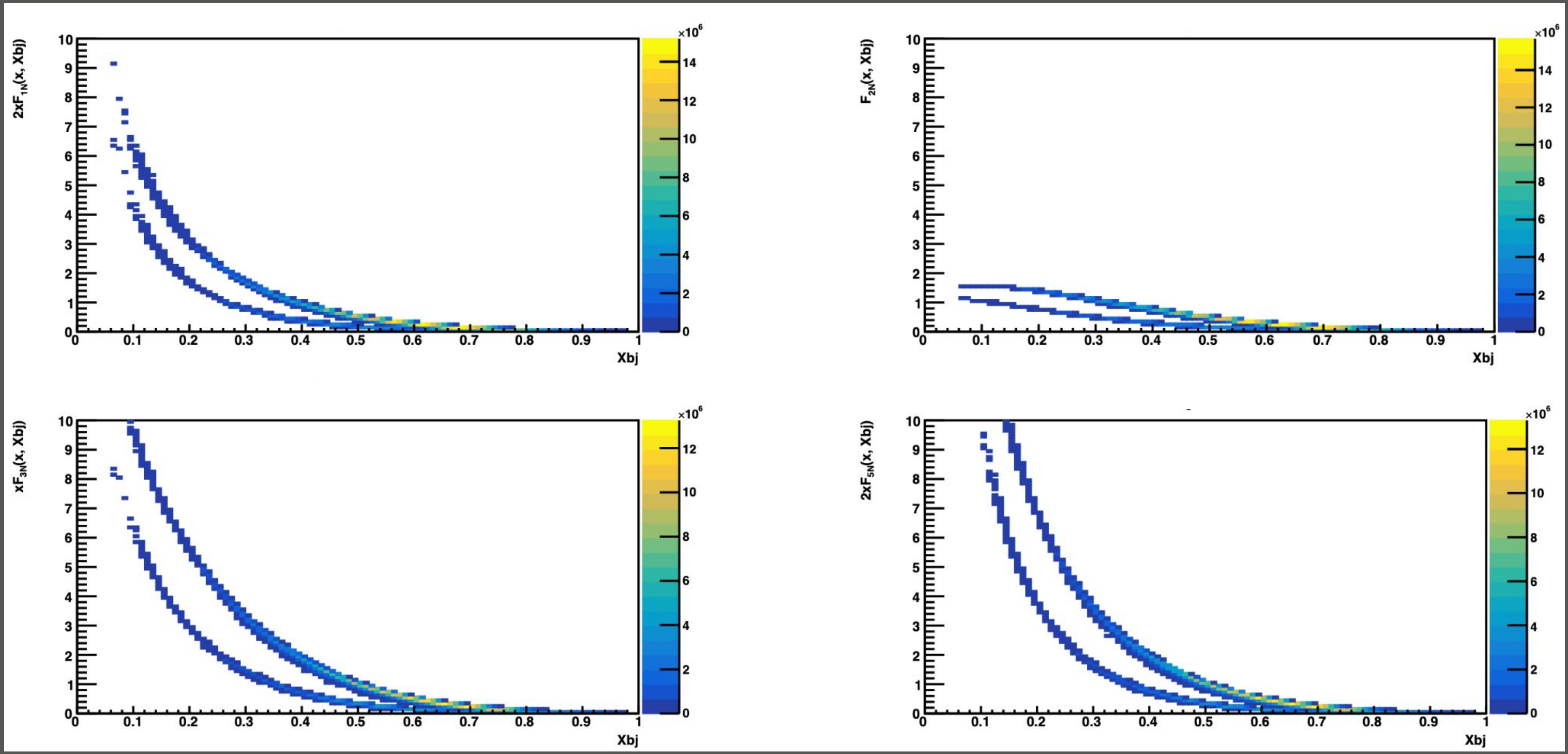
When $Q^2 > 2.0$ & $Q^2 < 5.0$ GeV SF_5 ENABLE

ν_τ



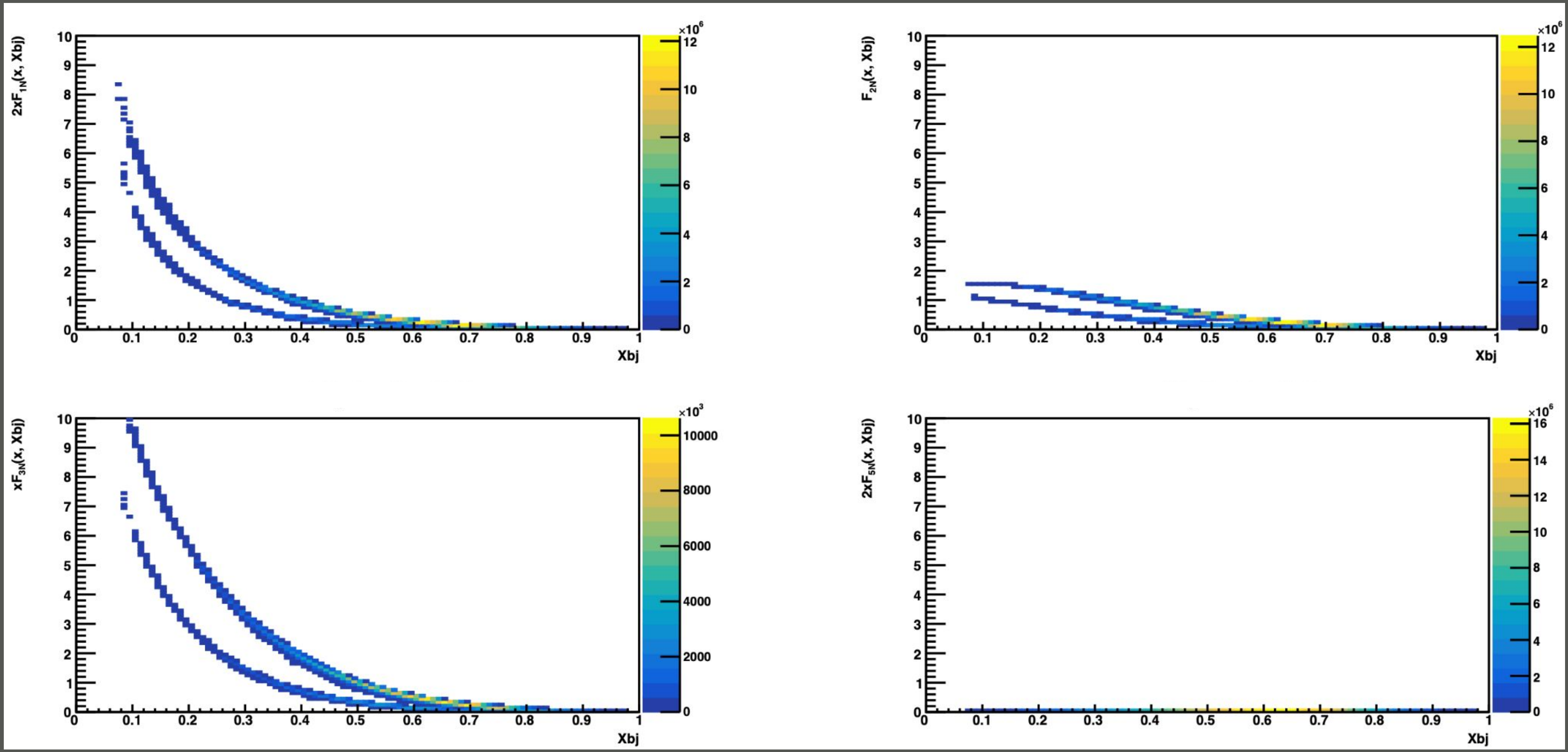
When Q^2 >= 5.0 GeV SF_5 ENABLE

ν_τ



When Q^2 >= 5.0 GeV SF_5 DISABLE

ν_τ



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The new features which appear in the case of the ντ−nucleon interaction as compared to the νe−nucleon and νμ−nucleon interactions and contribute to modify the cross sections are:

- the kinematical change in Q^2 and E_l due to the presence of m_τ, the finite mass of the τ lepton.
- the contributions due to the additional nucleon structure functions $F_{4N}(x,Q^2)$ and $F_{5N}(x,Q^2)$ in the presence of $m_\tau \neq 0$.
- the modifications in cross sections due to the effect of polarization state of the τ leptons produced in the final state.
- the additional effects in the Q^2 evolution of the nucleon structure functions $F_{iN}(x,Q^2)$; $(i = 1-5)$ due to $m_\tau \neq 0$ in the presence of massive heavy flavored quarks like the charm quark.
- the additional effects of the higher twist (HT) [43, 44] and the target mass corrections (TMC) [45] on the structure functions $F_{iN}(x,Q^2)$; $(i = 1-5)$ in the presence of $m_\tau \neq 0$ and $m_q \neq 0$.

Some of the above effects are modified in the nuclear medium and need to be calculated using a reliable nuclear model to describe the deep inelastic scattering of leptons from the nuclear targets. For example,

- the structure functions are modified due to the nuclear medium effects(NMEs). This was for the first time observed in the case of $F_{2A}(x,Q^2)$ and $F_{1A}(x,Q^2)$ by the EMC collaboration and later on confirmed by many other experiments done with electrons and neutrinos.
- in the presence of nuclear medium effects, the nuclear structure functions $F_{1A}(x,Q^2)$ and $F_{2A}(x,Q^2)$ may deviate from the Callan-Gross relation [46], and the nuclear structure functions $F_{4A}(x,Q^2)$ and $F_{5A}(x,Q^2)$ may not satisfy the Albright-Jarlskog relation [42]. It is required that independently these nuclear structure functions are studied.
- the produced τ leptons in the final state may get depolarized in the nuclear medium affecting the production cross section from nuclear targets. The depolarization of τ will also affect the topologies and characteristics of its decay products.
- there would be additional contributions to the structure functions due to non-nucleonic degrees of freedom in nuclei like pion and rho meson, except for $F_{3A}(x,Q^2)$ where only valence quarks contribute.
- the shadowing and the antishadowing effects in the respective kinematic regions of the Bjorken variable x which are known to be present in the ν_μ-nucleus deep inelastic scattering will also be present in the case of ν_τ-nucleus scattering and need to be taken into account.

Zaidi, Ansari, arXiv:2111.07609v1

COMMENTS

- **Work on the reconstruction of these variables is coming. How well we can do this?.**

- **Perturbative and Non-perturbative effects are very important in the evaluation of nucleon structure functions as well as for the differential cross-section in the different regions of X_{Bj} and Q^2 .**

Thank you!

Milky Way and Volcan de Fuego , Guatemala

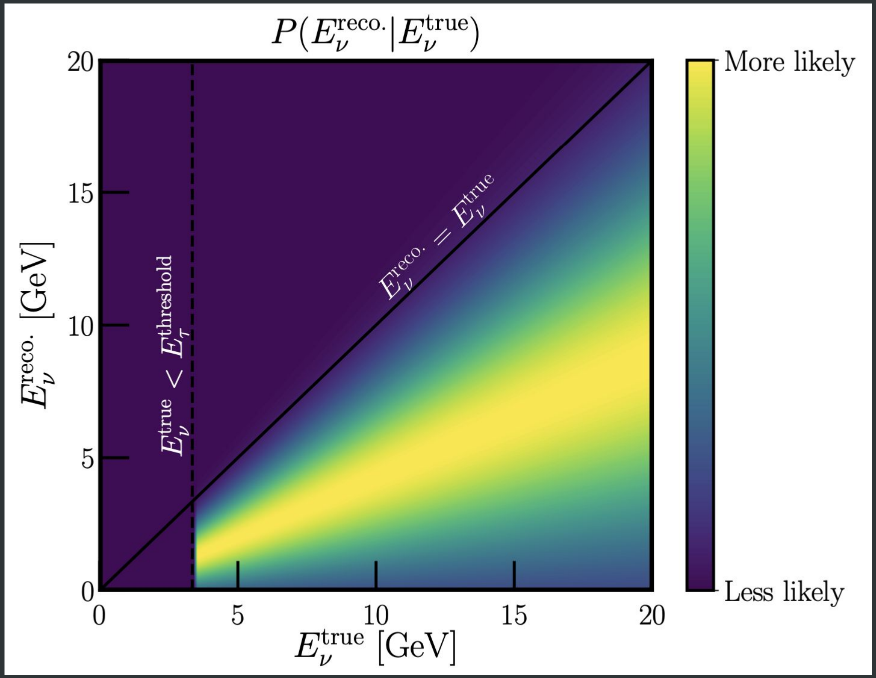
Backup

CC-ν_τ scattering in DUNE

- Up to today, 18 ν_τ have been identified by DONuT (decay of Ds mesons) and OPERA ($\nu_\mu \rightarrow \nu_\tau$ oscillations)
- DUNE will combine bubble chamber quality data with calorimetry and large statistics.
- It will therefore provide an unprecedented opportunity to study the ν_τ sector

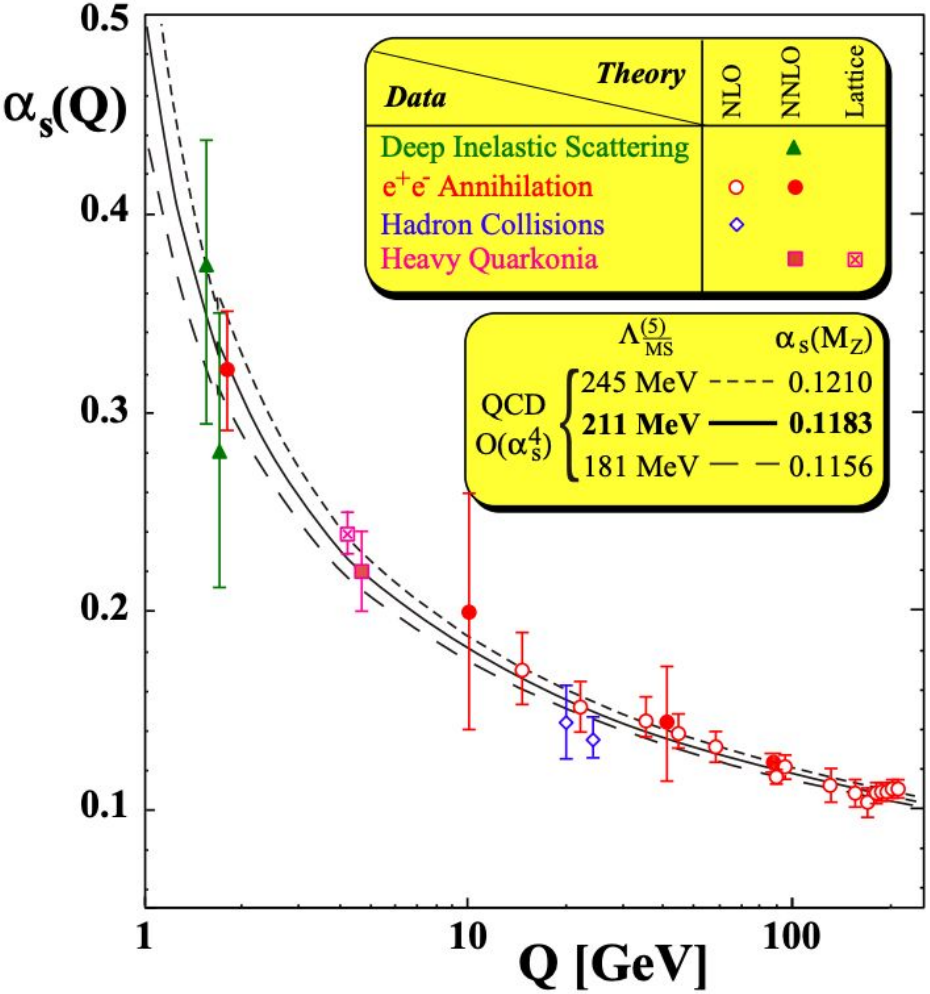
INTERESTING BECAUSE...

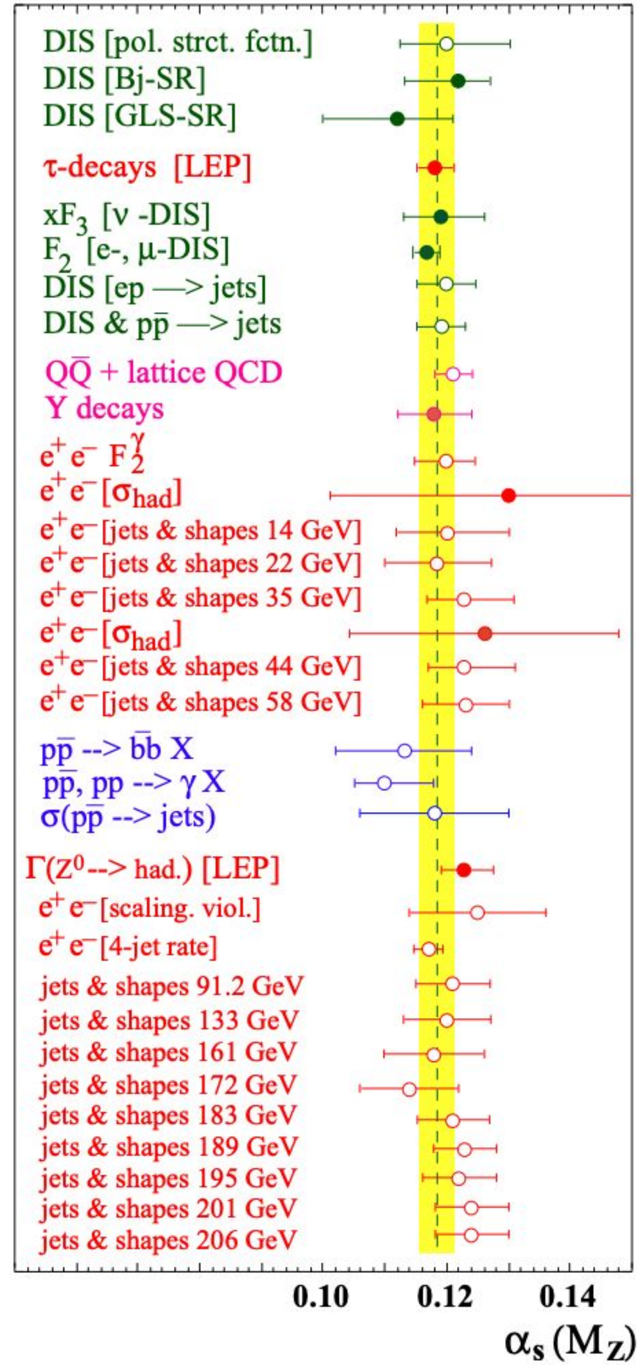
- A test of the **oscillation hypothesis** is ν_τ production of τ through charged current interactions.
- The solar & atmospheric neutrino anomalies evolved into the very robust **three-massive-neutrinos paradigm**
- For **precision measurements of oscillation mixing angles and eventually CP violation**, **neutrino cross sections** will ideally be know to the level of a few percent.



Migration matrix for hadronically decaying τ leptons produced via ν_τ charged-current interactions. PhysRevD.100.016004
Due to the large mass of the τ ± relative to the e ± and μ ±, the threshold for this process to occur is 3.5 GeV.

α_s 2002 by Siegfried Bethke (MPI of Physics, Munich, Germany) arXiv:hep-ex/0211012





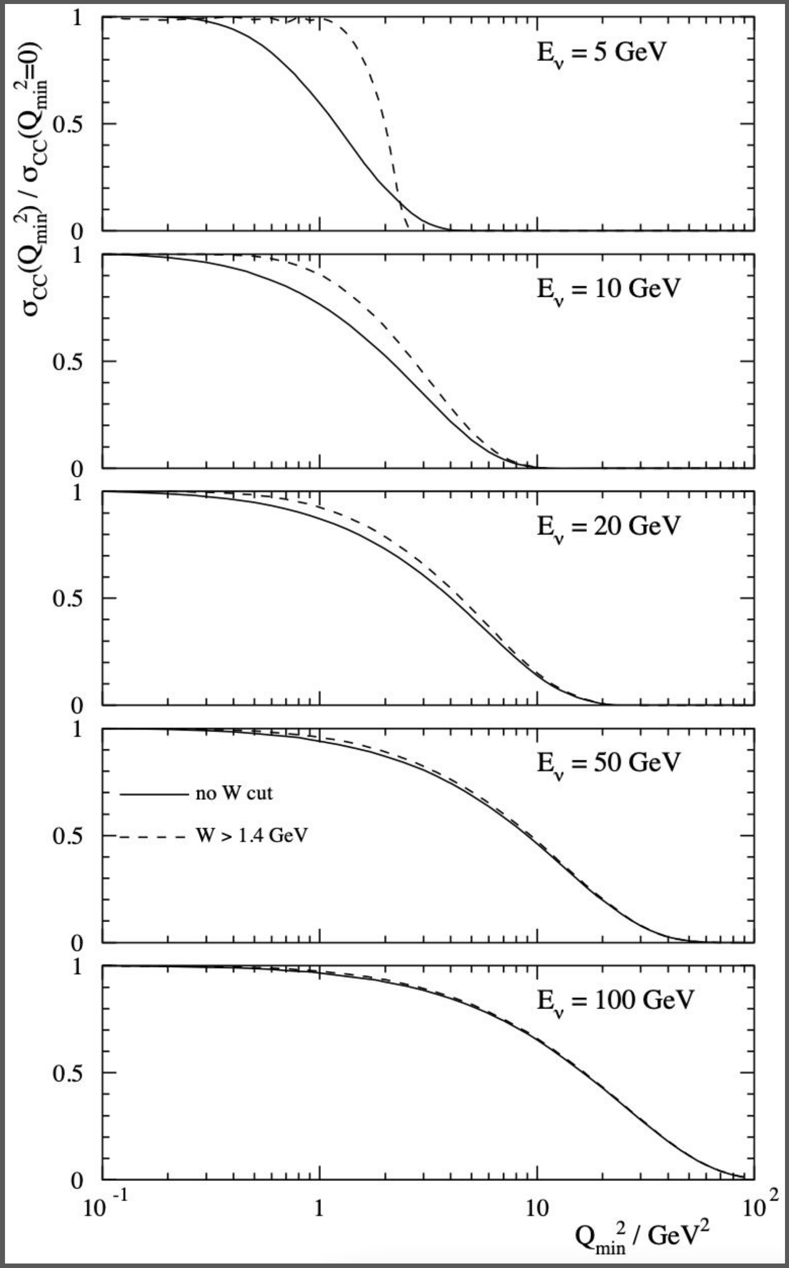
A look to the CC Interactions Cross Section M. H. Reno - PhysRevD.74.033001

With a W_{min} = 1.4 GeV the tau neutrino CC cross section is fairly insensitive to the Q^2 cut of 1 GeV^2.

The Q^2 cut has a larger impact on σ_{CC} (ν_μ N)

At E_ν = 20 GeV : ν_τ N-CC Ratio = 0.93
ν_μ N-CC Ratio = 0.85

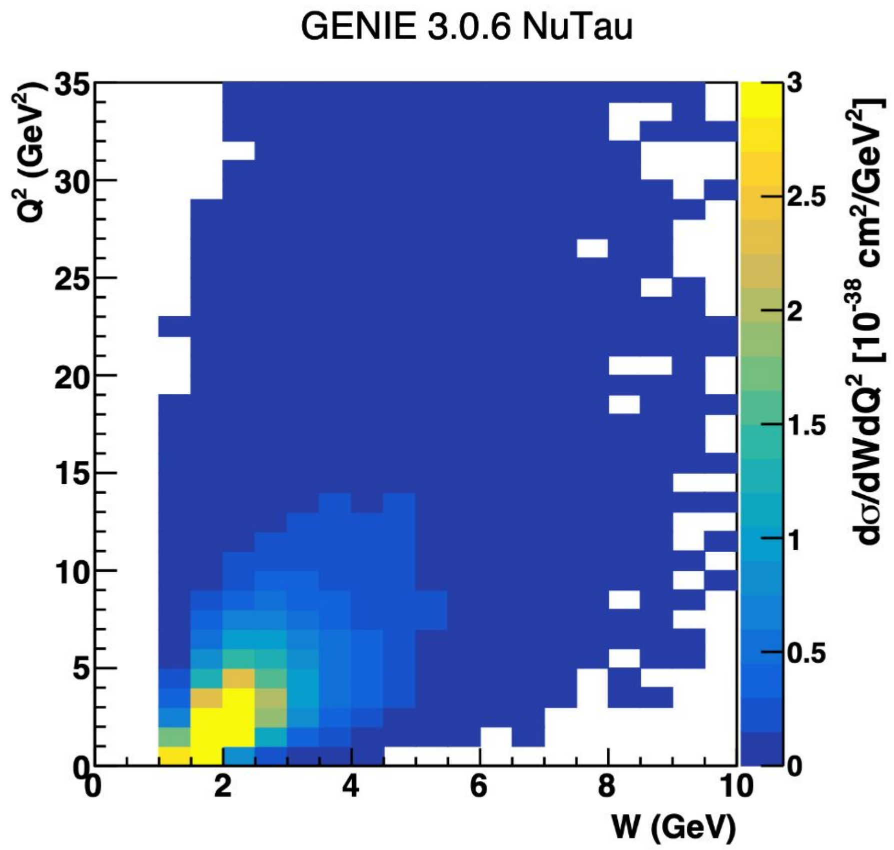
- The small changes in the CC-cross sections with Q^2_{min} = 1 GeV^2 **lead to expect that non-perturbative effects at low Q^2 are unlikely to be large when the W_{min} = 1.4 GeV**
- At low energies, without the W_{min} cut a substantial contribution to the cross sections comes from Q^2 < 1 GeV^2.
- This is precisely where the DIS cross section is only a rough approximation to the true cross sections with QE and RES as well as non-resonant contributions.

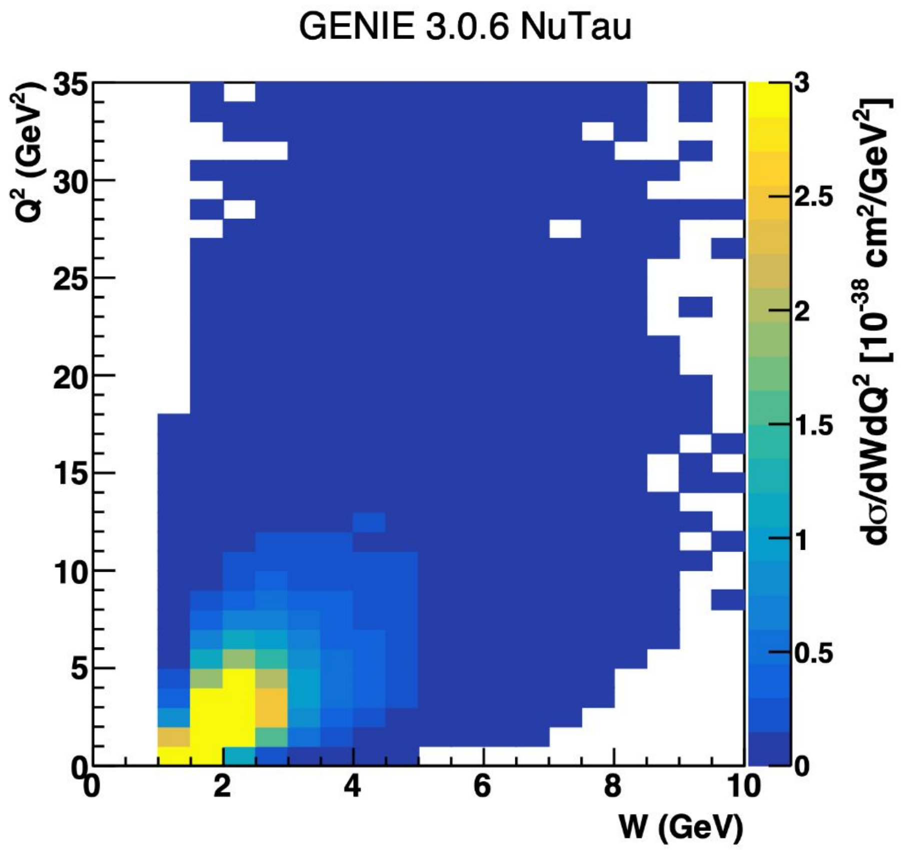


Q^2 vs W

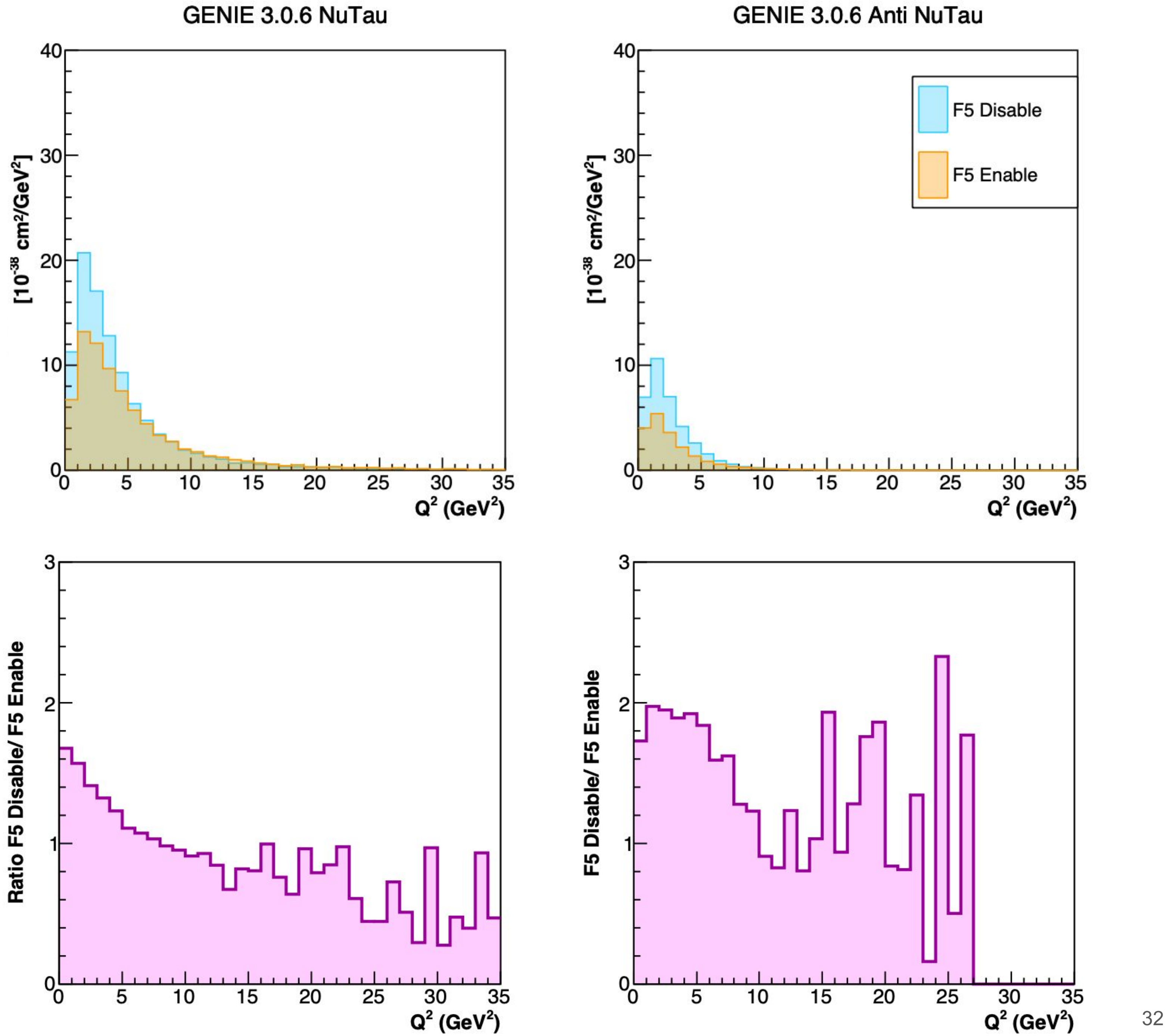
ν_τ

SF$_5$ Disable	SF$_5$ Enable

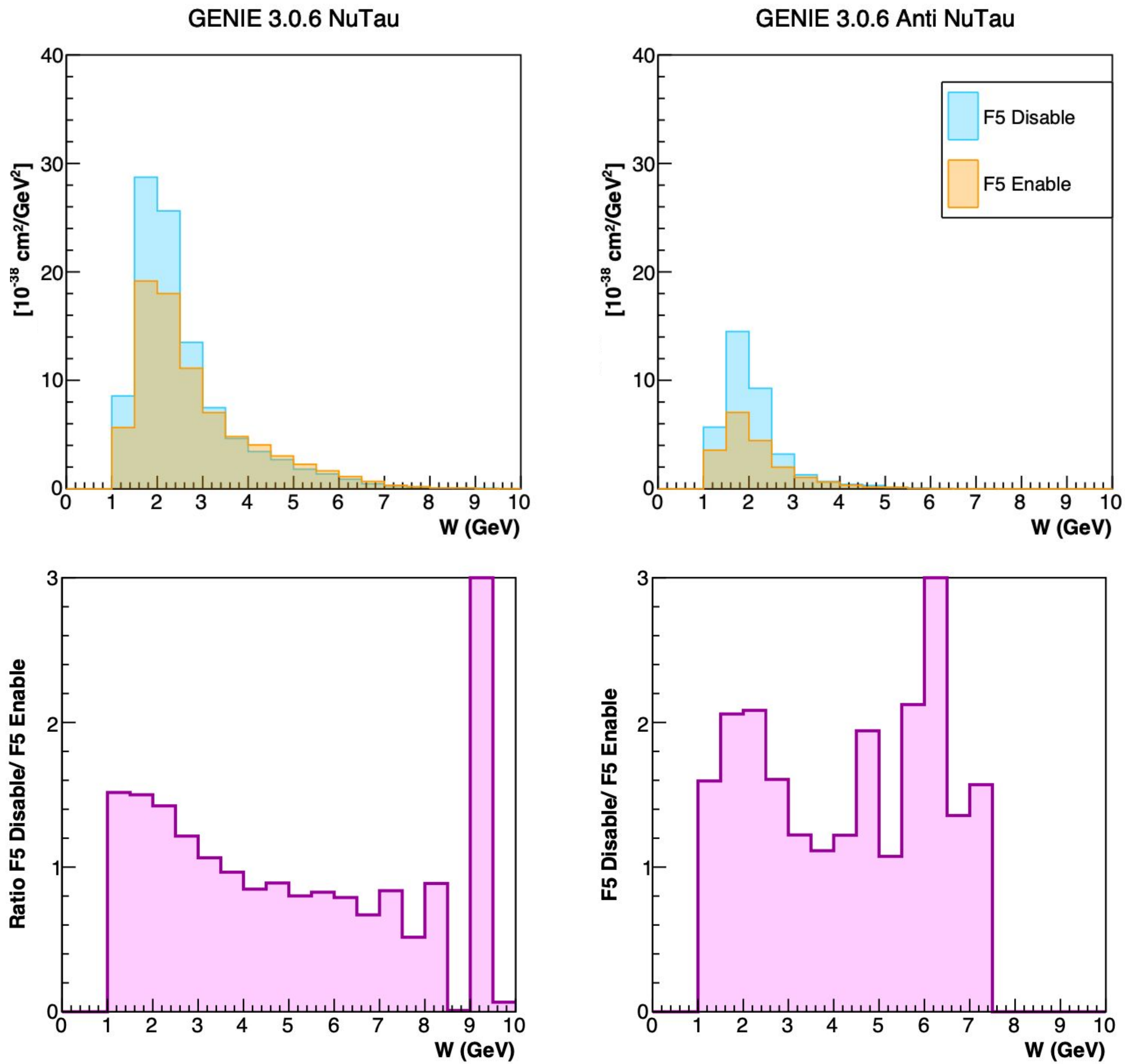




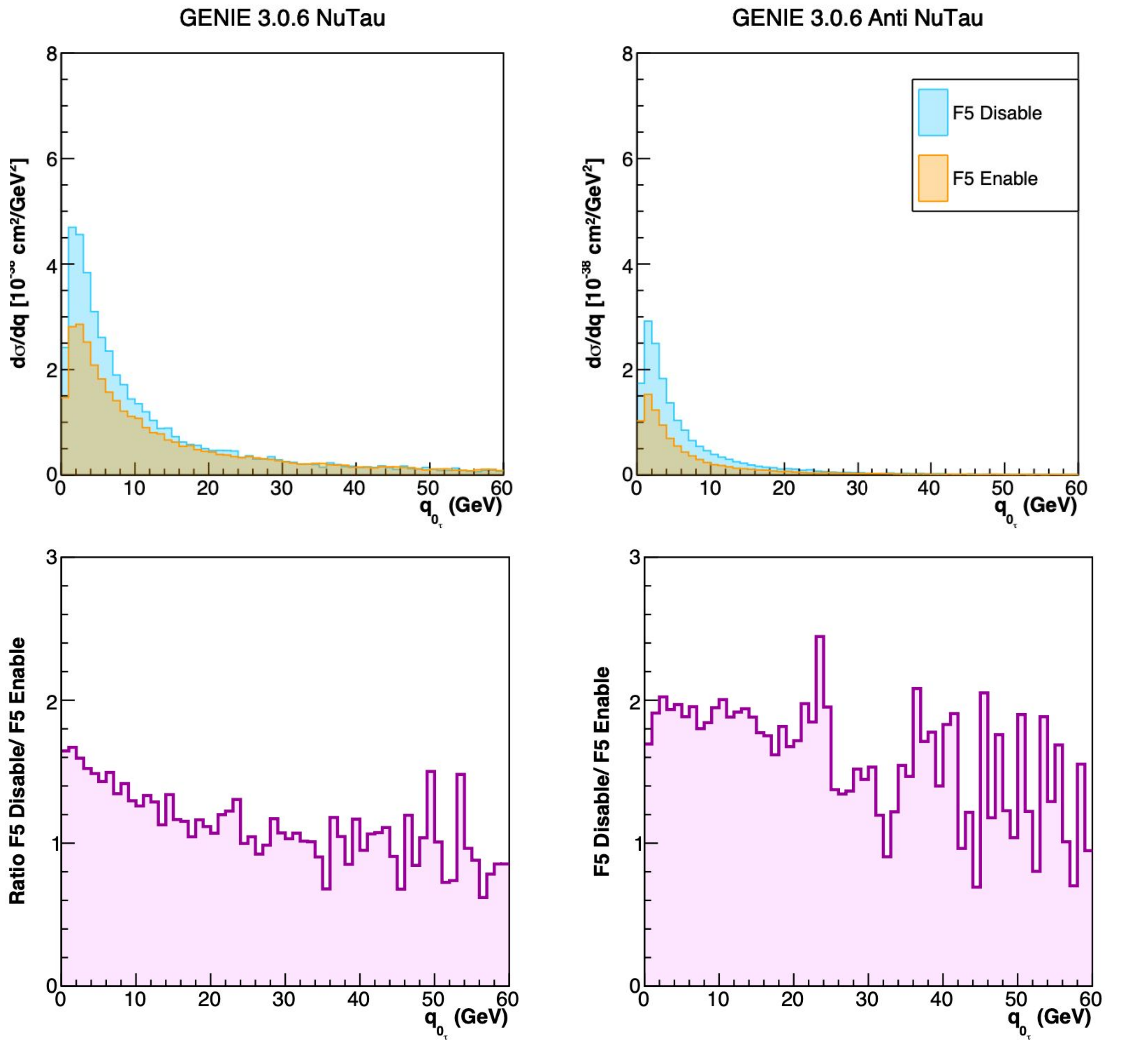
Q^2 Cross Section: Genie 3.06



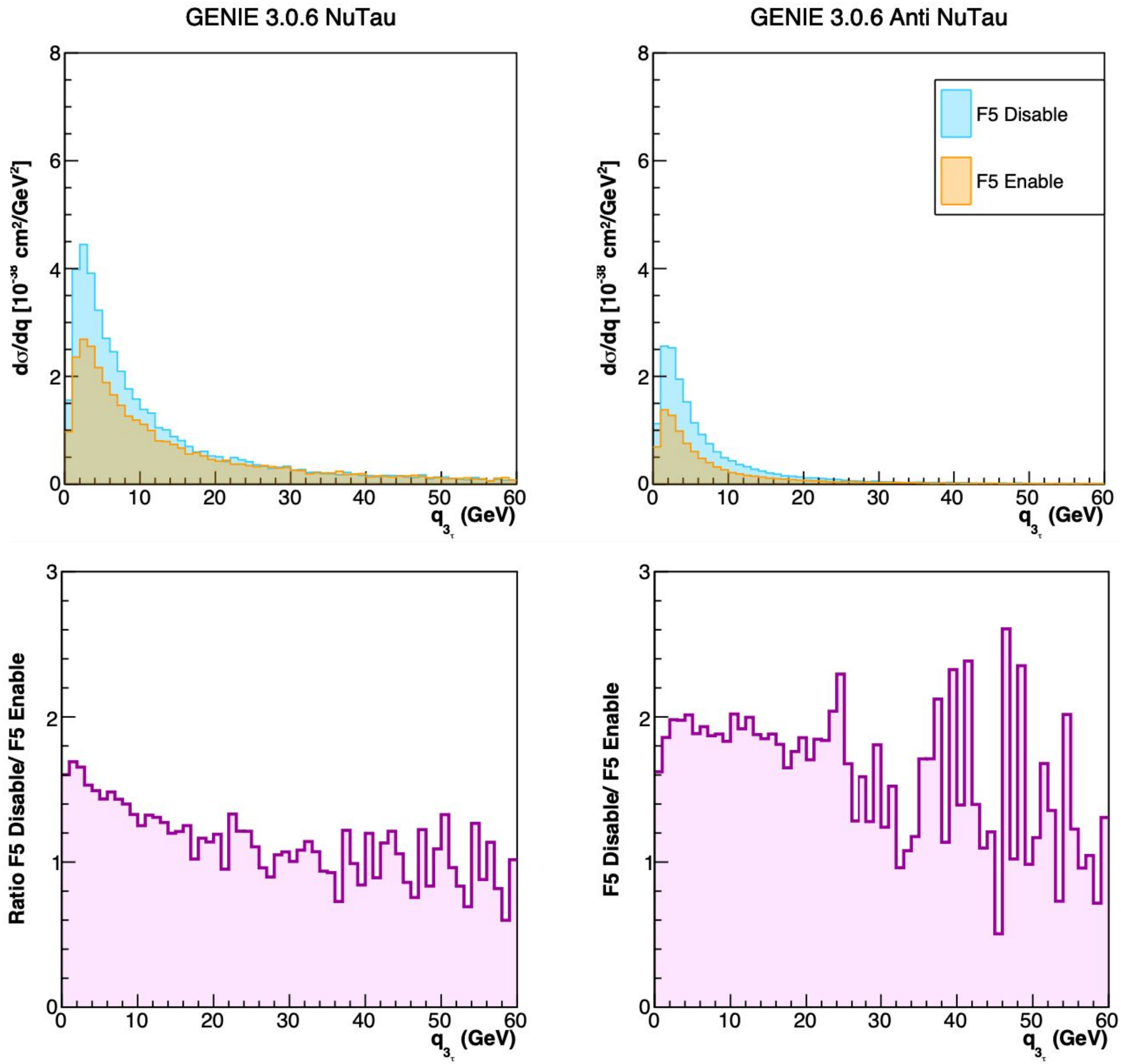
W Cross Section: Genie 3.06



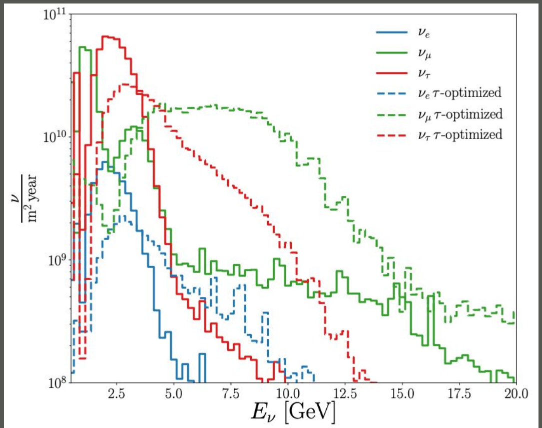
q_0 Cross Section: Genie 3.06



q_3 Cross Section: Genie 3.06



A key element in the study of tau neutrino physics is the decay modes of the tau lepton



Neutrino fluxes at the DUNE far detector. arXiv:2007.00015

Tau decay length ~ 87 μm
Ar nuclear radius, ~ 3.4 fm

Tau decay products aren't subject to the Ar nuclear potential

Tau lifetime (2.903 ±0.005)×10^{-13} s

Tau doesn't lead to observables displaced vertices

DUNE granularity is limited by wire spacing of a few millimeters

Observation of Tau tracks is unlikely

Background for τ_μ signal mainly comes from CC-ν_μ being ν_μ flux very large.

Background for τ_e signal are CC-ν_e events, being ν_e flux a small fraction of the total neutrino flux.

Decay mode	Branching ratio
Leptonic	35.2%
$e^-\bar{\nu}_e\nu_\tau$	17.8%
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.4%
Hadronic	64.8%
$\pi^-\pi^0\nu_\tau$	25.5%
$\pi^-\nu_\tau$	10.8%
$\pi^-\pi^0\pi^0\nu_\tau$	9.3%
$\pi^-\pi^-\pi^+\nu_\tau$	9.0%
$\pi^-\pi^-\pi^+\pi^0\nu_\tau$	4.5%
other	5.7%

Dominant decay modes of τ− Kaonic decays and others go into the "other" category. arXiv:2007.00015