DUNE NuTau Meeting

DIS & Structure Functions

CC-ν_τ in DUNE

Barbara Yaeggy

(05/13/2021)

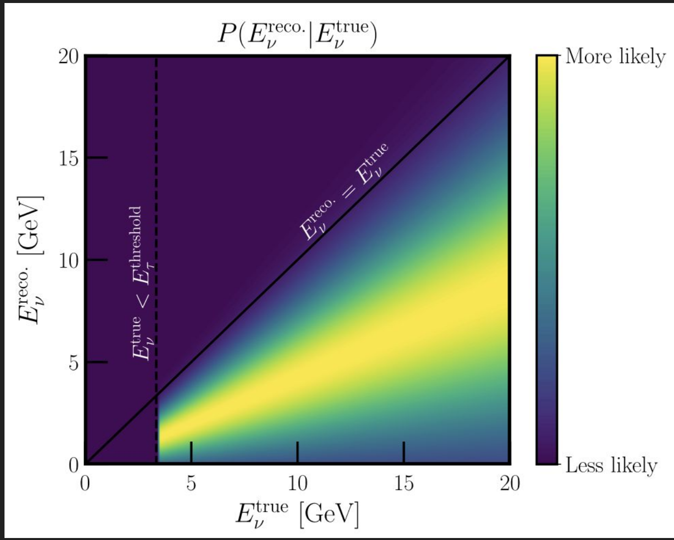
University of Cincinnati

DUNE Deep Underground Neutrino Experiment

Fermilab

CC-ν_τ scattering in DUNE

- Up to today, 14 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



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.

INTERESTING BECAUSE...

- **To test the Standard Model predictions and check the validity of the lepton universality hypothesis.**
- **Interaction studies** are also required to better **understanding of the neutrino oscillation parameters (SHiP, DsTau experiments).**
- The interaction cross sections for all three flavors of neutrinos should be known to high accuracy requiring better measurements of the ν_τ / $\overline{\nu}_\tau$ cross section.
- IceCube plan to explain the mechanism for production of high-energy neutrinos from astrophysical sources and for the MC simulation of the events, a **good control on the cross-section estimated is required.**

Why check over structure functions?

Nucleon Form Factors: basic observables of the nucleon

Nucleon form factors describe the spatial distributions of electric charge and current inside the nucleon

QCD: quarks are bind through gluons to form hadrons (baryons and mesons)

The fundamental understanding of the nucleon form factors in terms of QCD is one of the outstanding problems in nuclear physics

DIS: Deep (Q^2 >>M^2) Inelastic (W^2 >> M^2) Scattering
It plays a key role in determining the partonic structure

- Structure functions are a measure of the partonic structure of hadrons, which is important for any process which involves colliding hadrons.
- They are a key ingredient for deriving partons distributions in nucleons.

Bodek-Yang model aims for describing DIS cross section in all Q^2 regions

Structure Functions:

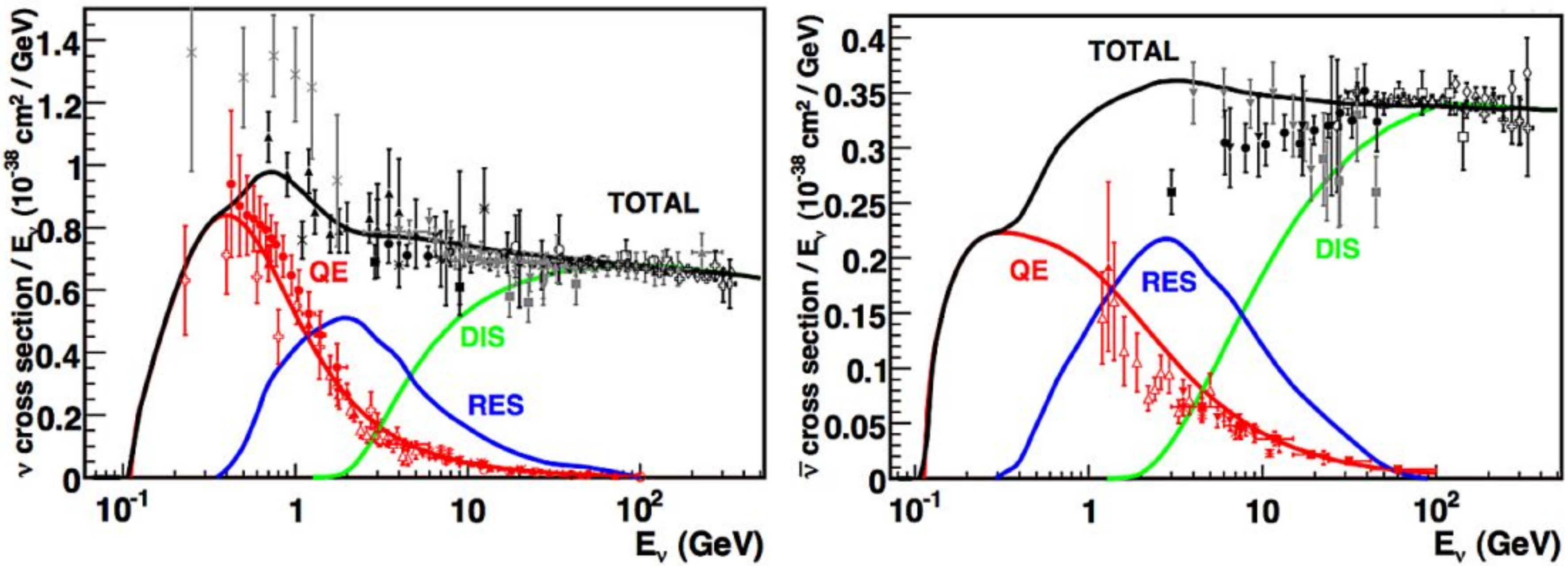
$2xF_1 = F_2$

$-xF_3 = F_2$

$xF_5 = F_2$

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

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



- The name DIS here is used loosely for inelastic processes with W > 1.8 GeV (in the continuum at all Q^2, including Q^2 =0.
- We need to predict vector parts of both the longitudinal and transverse structure functions (form factors)
- Neutrino scattering data can then be used to constrain the axial structure functions (form factors).
- We also need the nuclear corrections to the vector and axial structure functions.

Differential Cross-Section

arXiv:2008.03527

The structure functions **F4 and F5**, are pointed out by Albright and Jarlskog **are neglected in muon neutrino interactions** because of a suppression factor depending on the square of the charged lepton mass divided by the nucleon mass times neutrino energy.

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

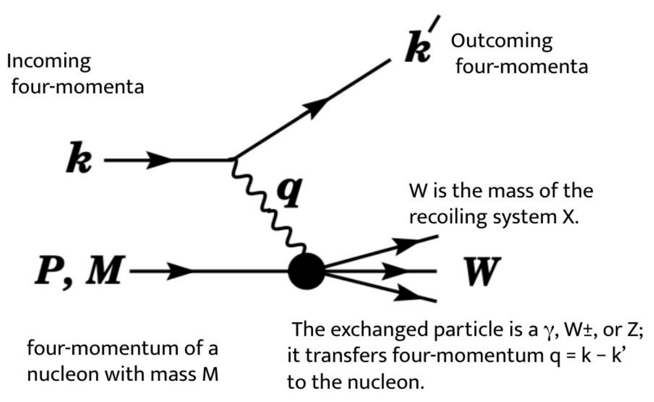
Where:

$$\begin{aligned} Q^2 &= -q^2 = -(k-k')^2 \,, \\ x &= Q^2/2p\cdot q = Q^2/2M_N\nu \,, \\ y &= p\cdot q/p\cdot k = \nu/E \,, \\ W^2 &= (p+q)^2 = M_N^2 + 2M_N\nu - Q^2 \,, \\ \nu &= q\cdot P/M_N = E - E' \,, \\ k'^2 &= m_l^2 \,, \quad \text{and} \quad p^2 = M_N^2 \,. \end{aligned}$$

Fraction of lepton's energy lost in the nucleon rest frame. (← y)

Energy loss of the lepton. (← ν)

Mass squared of the outgoing lepton & target nucleon respectively. (← k'^2, p^2)



Given the higher mass value of the τ lepton, **F_4 and F_5 contribute**, instead, to the **tau neutrino cross-section.**

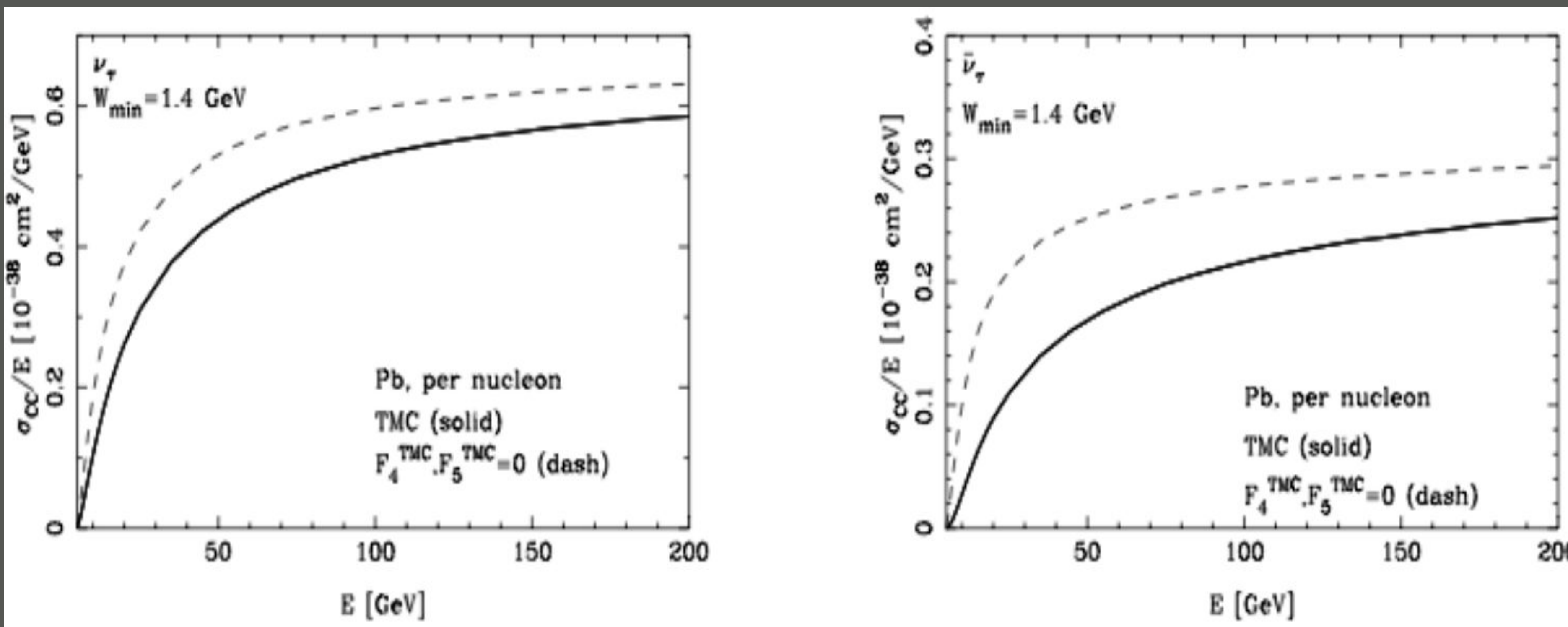
At leading order, in the limit of massless quarks and target hadrons, ***F4 = 0 and 2xF5 = F2***, where *x* is the Bjorken-x variable. **NLO show that *F_4 ~ 1% of F_5*** arXiv:hep-ph/0605295

The SHip Proposal showed the hypothesis of $F_4 = F_5 = 0$ would result in an increase of the ν_τ and $\nu_{\bar{\tau}}$ charged-current DIS cross-sections and consequently, of the number of expected ν_τ and $\nu_{\bar{\tau}}$ interactions.

ν_τ

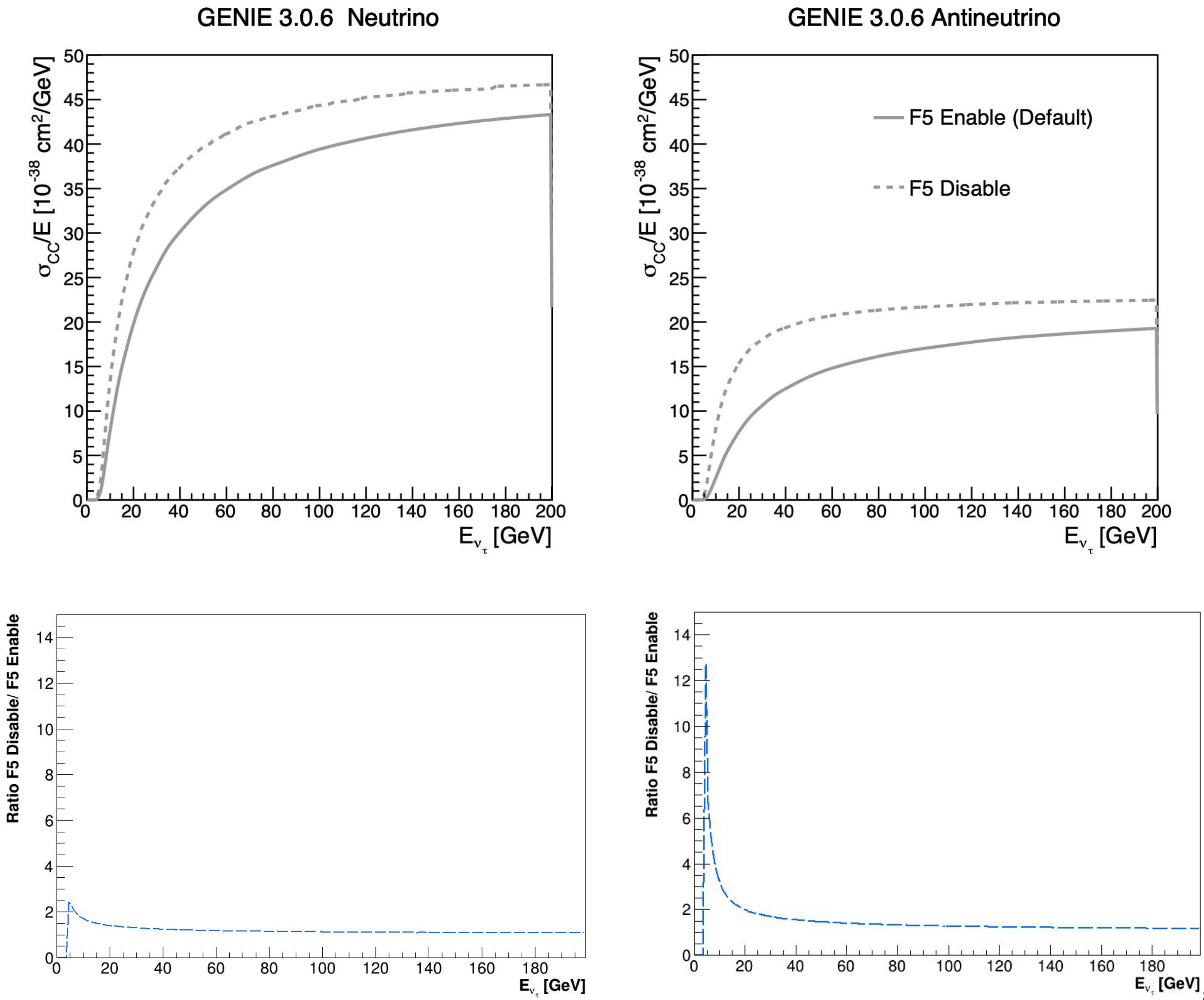
SM prediction (solid)
F4=F5=0 hypothesis (dashed)

$\bar{\nu}_\tau$

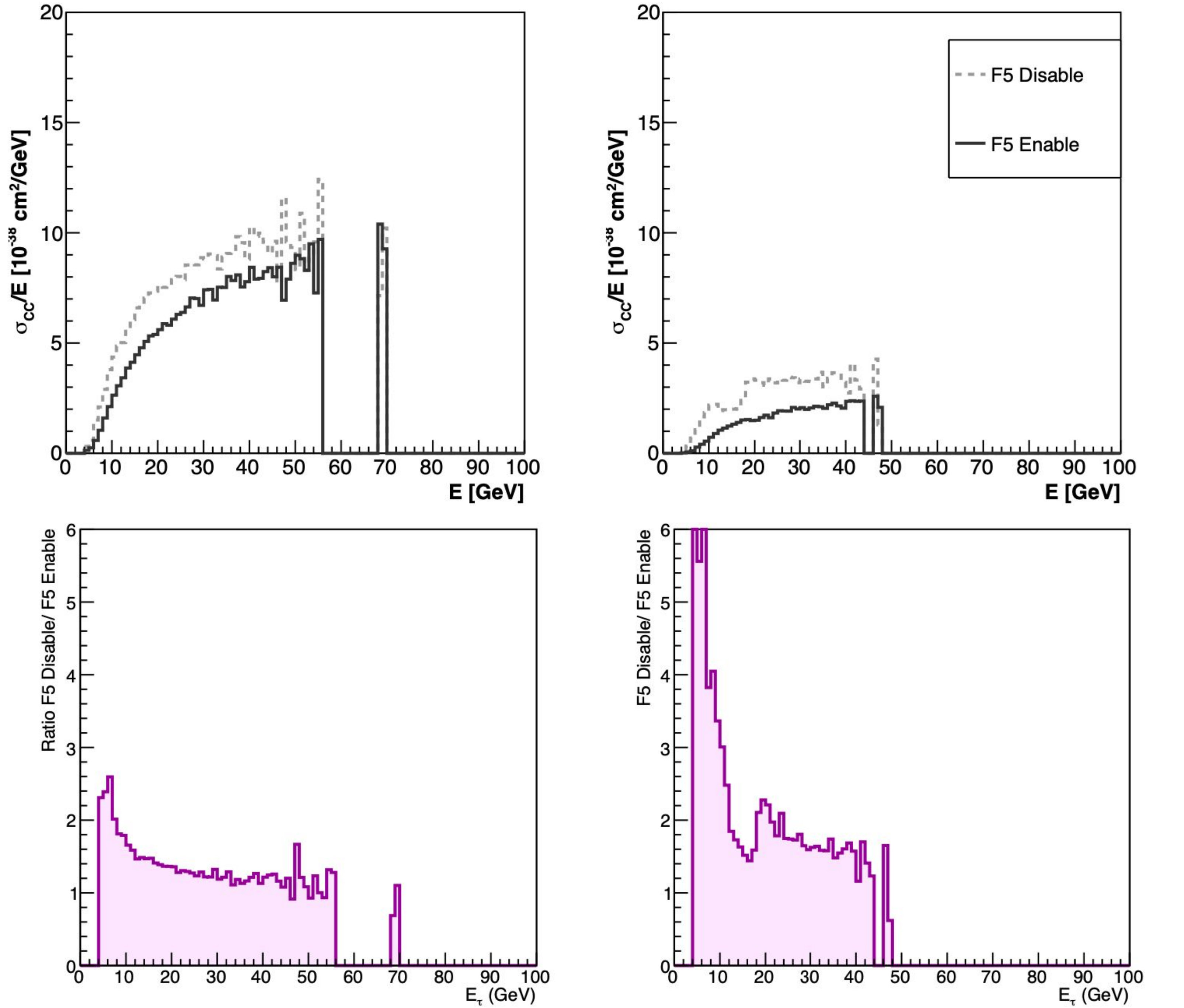


Notice the difference between the cross-sections in the $F_4 = F_5 = 0$ hypothesis and the SM prediction is larger for lower neutrino energies.

Cross Section from the Splines I.e without FSI



Cross Section after generate events (gevgen) i.e with FSI



Starting Point: LBNF/DUNE TDR Publication arXiv:2103.04797

- Genie 2.12.10 (with F5 enable, $2xF_5 = F_2$)
- Flux isn't Tau Optimized
- Pandora toolkit
- CVN for event classification (look just for electrons) arXiv:2006.15052

FIRST STEP: check kinematic variables & see if the F_5 hypothesis is fulfilled.

- Genie 3.0.6 (with F5 enable and disable, $F_5 = 0$)
- Flux is Tau Optimized
- I'm getting my own splines (DIS)

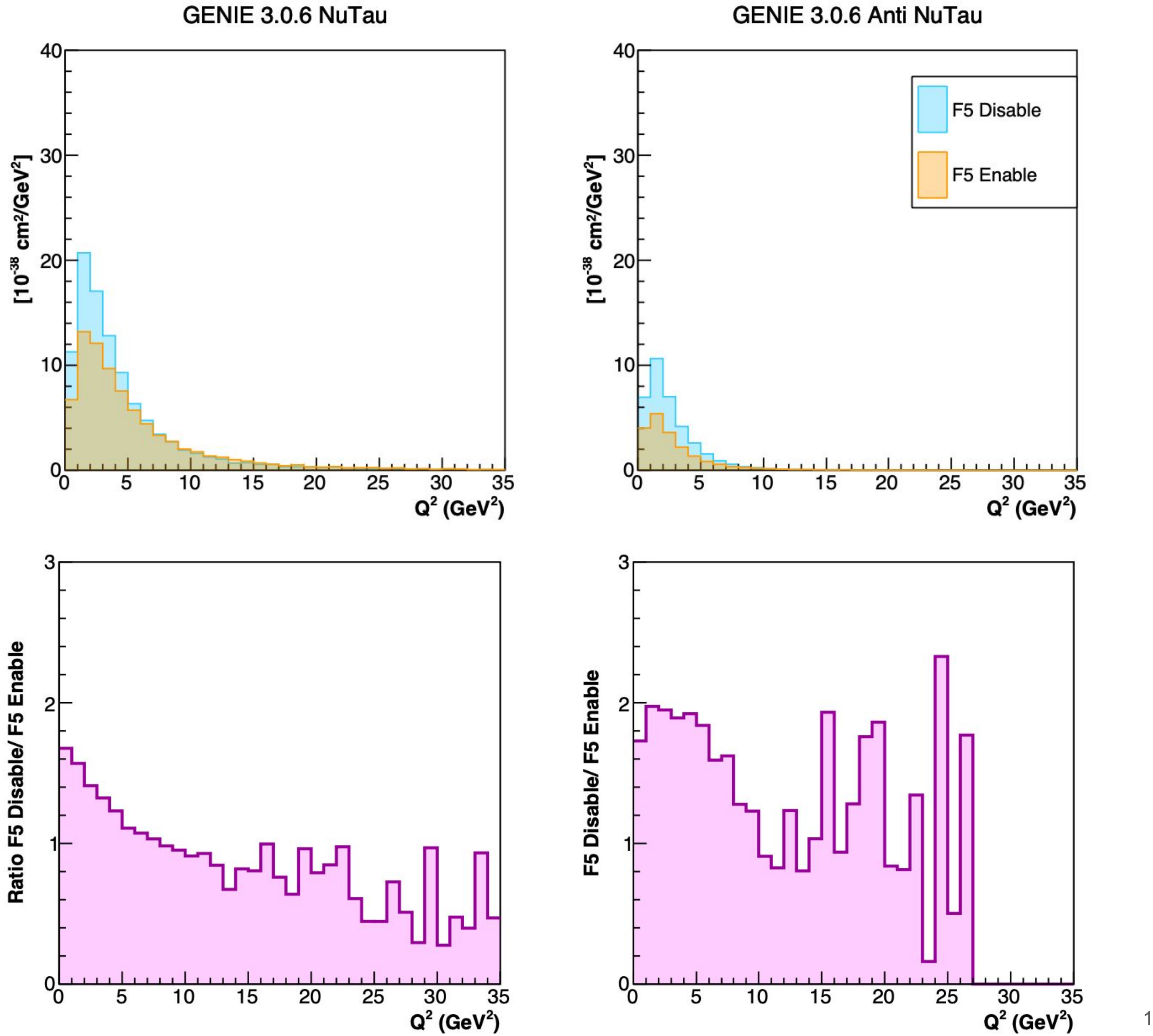
$$q_0 = E_\nu - E_\mu$$

$$q_3 = p_\nu - p_\mu$$

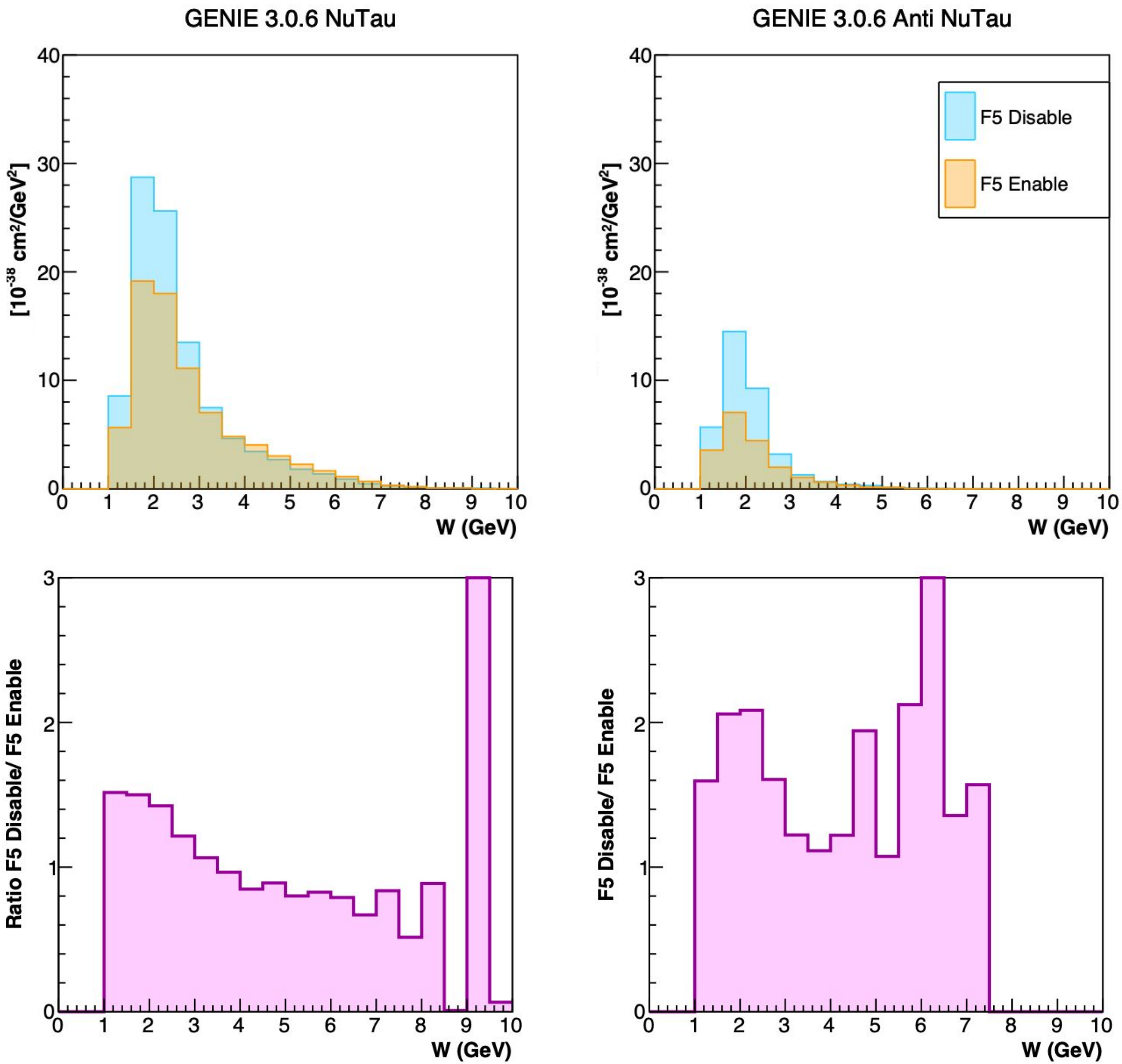
$$Q^2 = q_3^2 - q_0^2$$

$$W^2 = M^2 + 2Mq_0 - Q^2$$

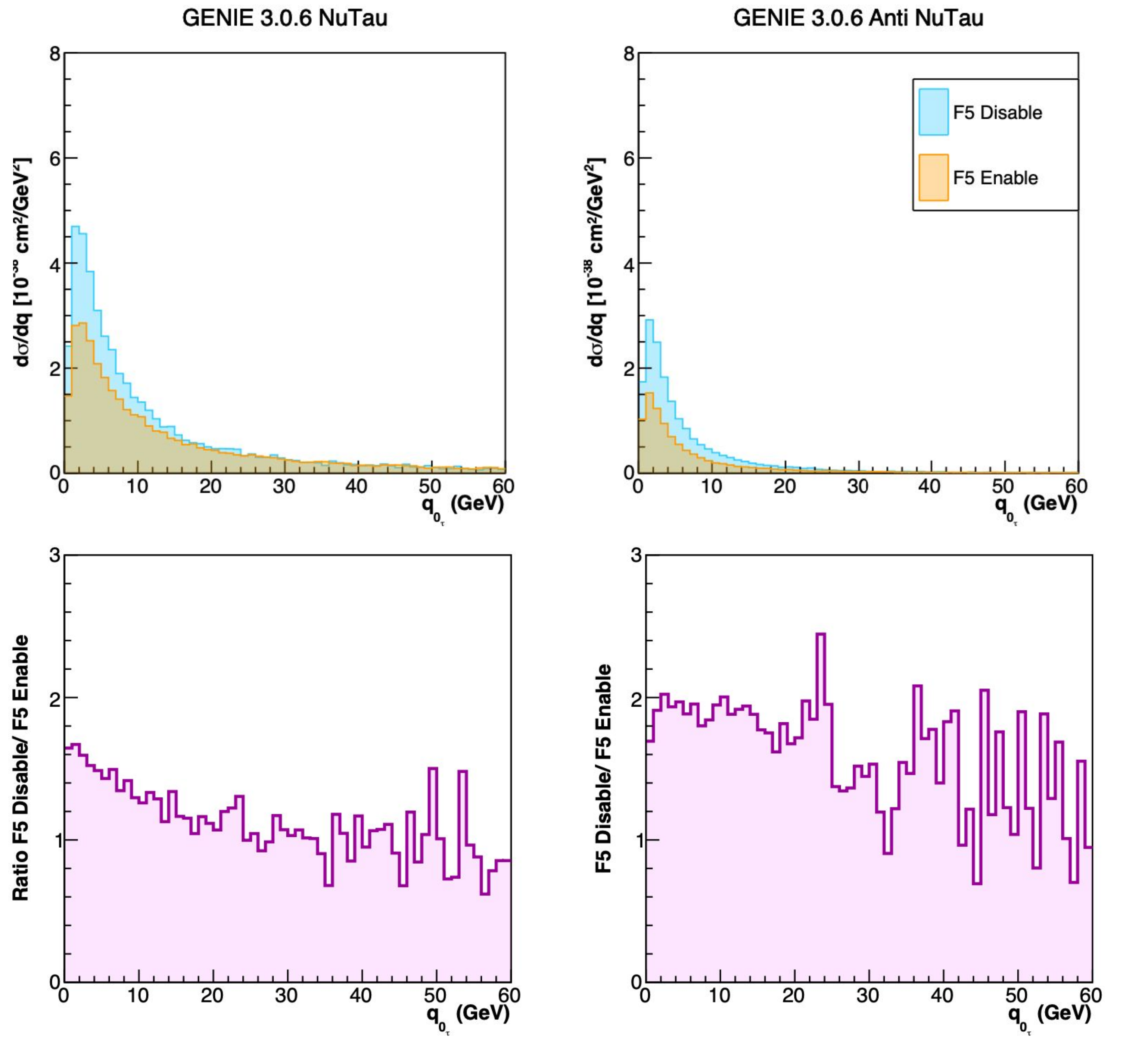
Q^2 Cross Section: Genie 3.06



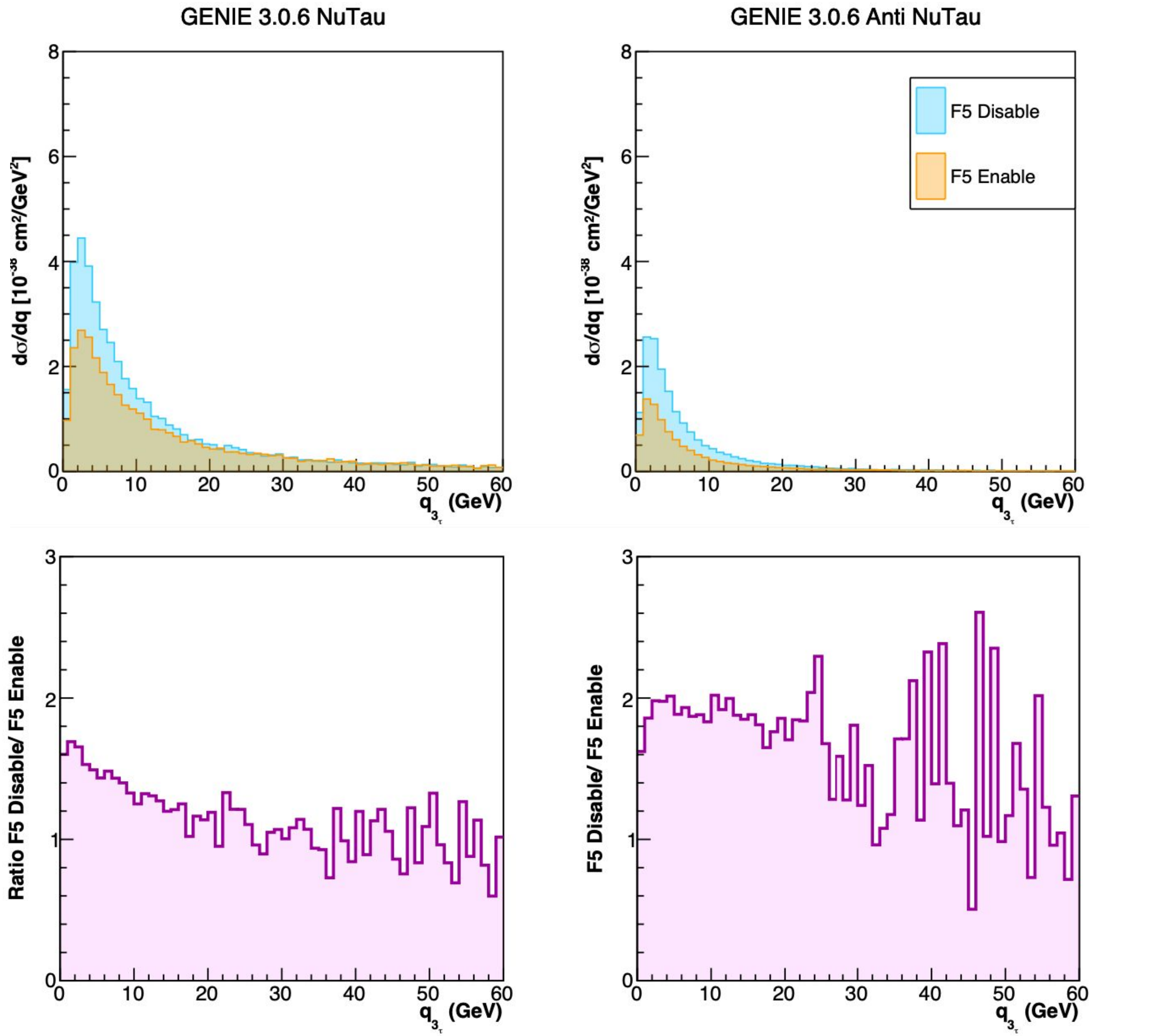
W Cross Section: Genie 3.06



q_0 Cross Section: Genie 3.06

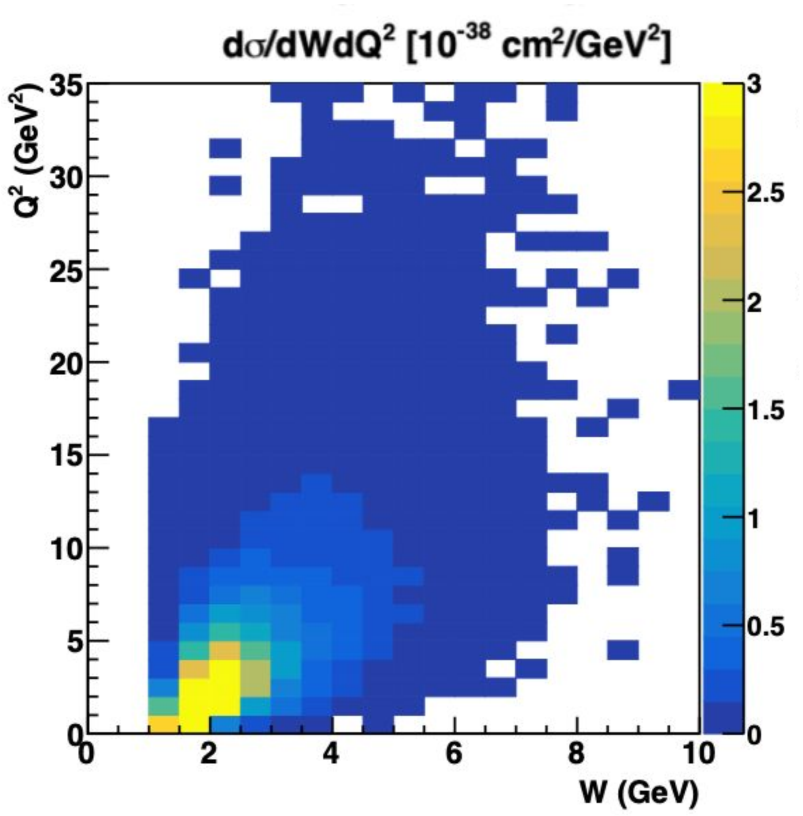


q_3 Cross Section: Genie 3.06

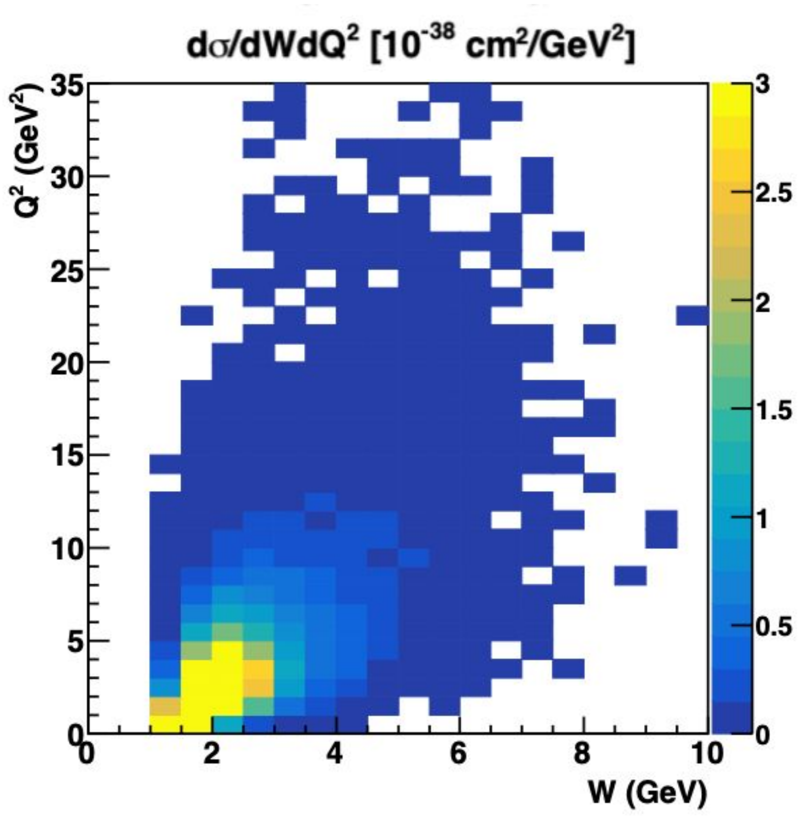


W vs Q^2 NuTau Cross Sections: F5 Enable vs F5 Disable

F5 Enable

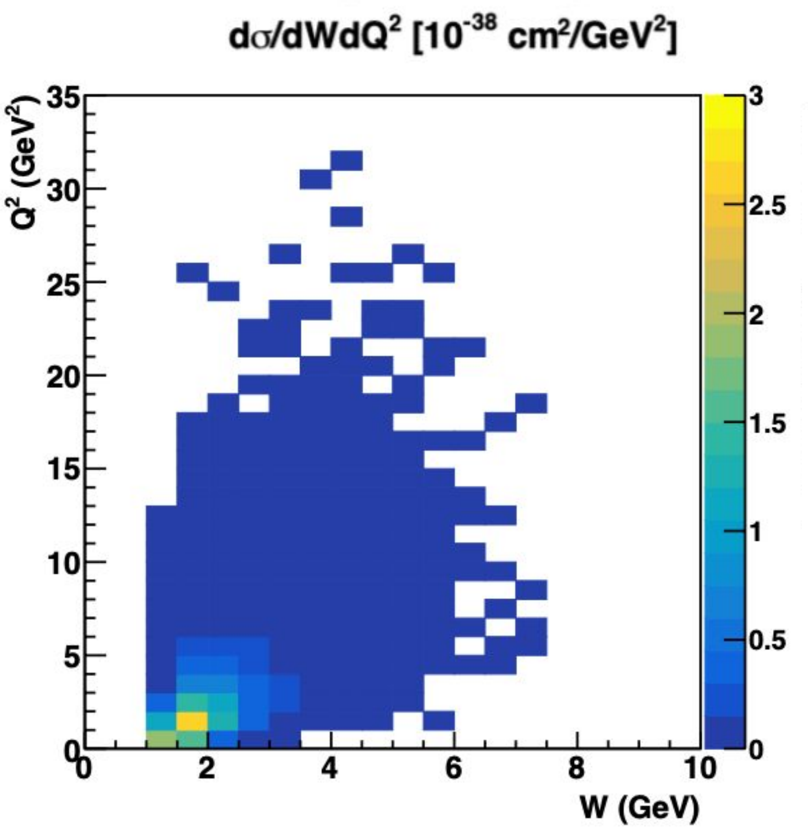


F5 Disable

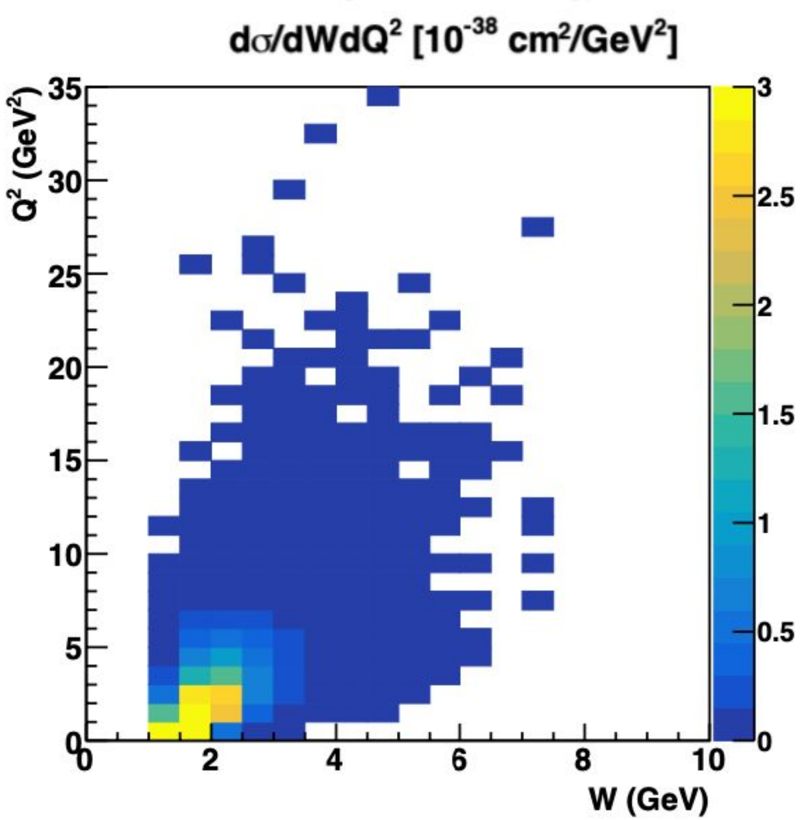


W vs Q^2 Anti NuTau Cross Sections: F5 Enable vs F5 Disable

F5 Enable

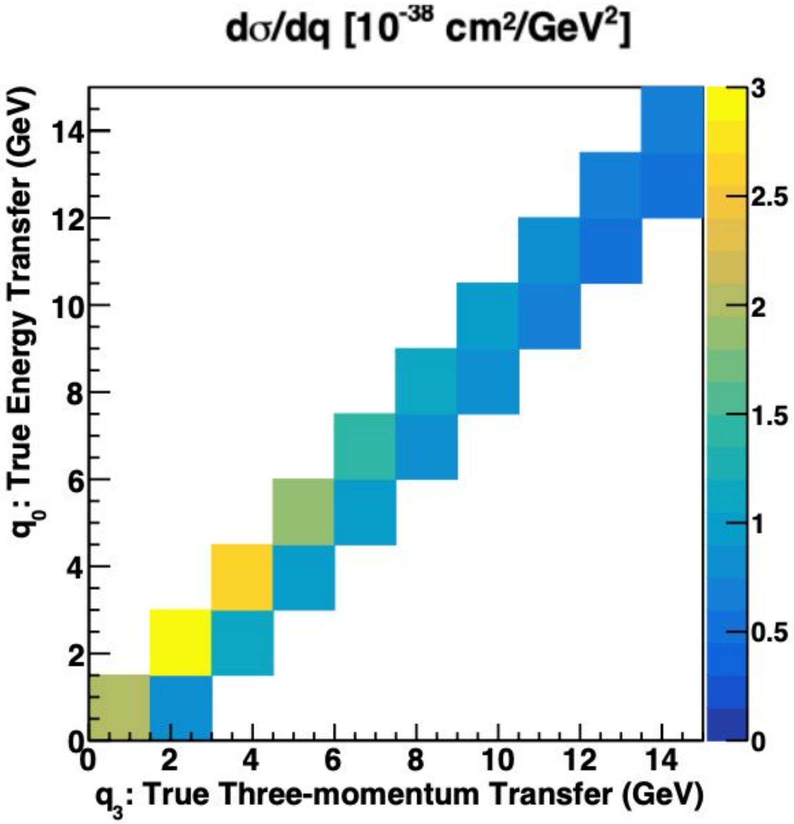


F5 Disable

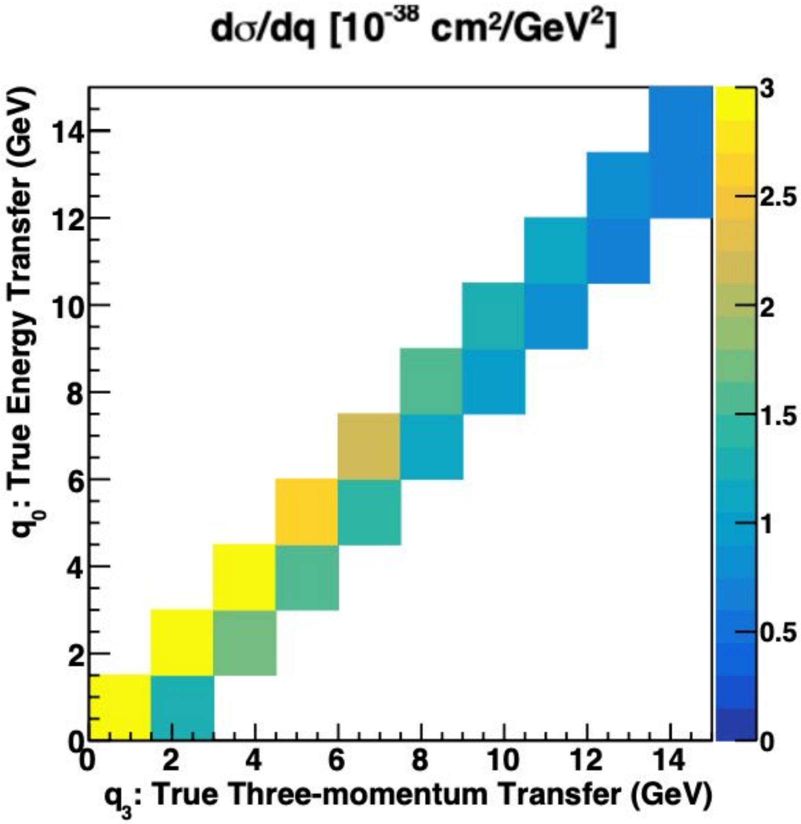


q_3 vs q_0 NuTau Cross Sections: F5 Enable vs F5 Disable

F5 Enable

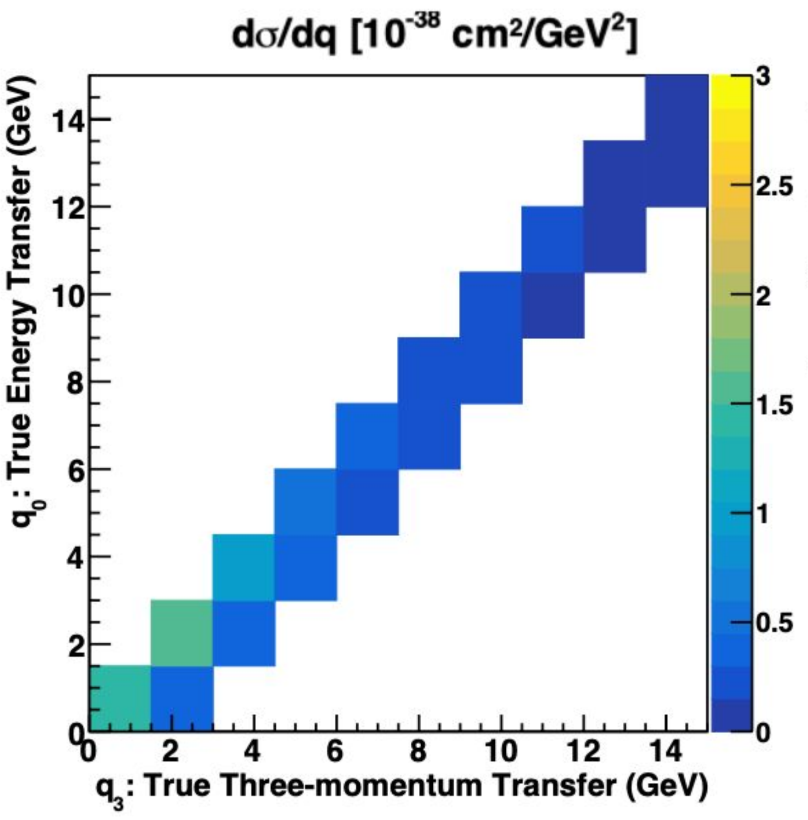


F5 Disable

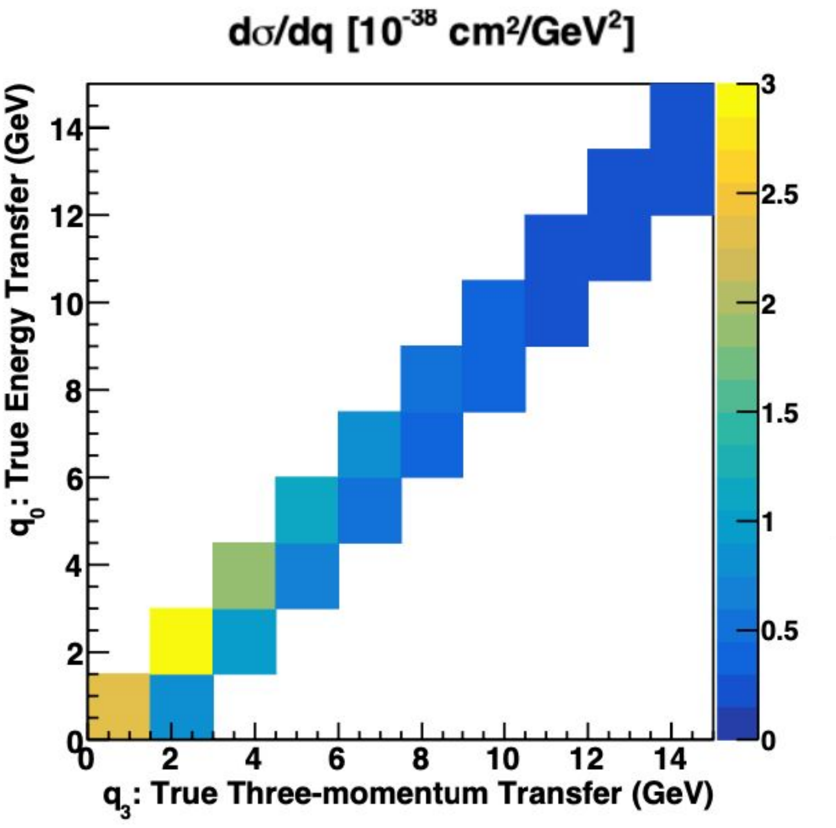


q_3 vs q_0 Anti NuTau Cross Sections: F5 Enable vs F5 Disable

F5 Enable



F5 Disable



Starting Point: LBNF/DUNE TDR Publication https://arxiv.org/abs/2103.04797

- Genie 2.12.10 (with F5 enable, $2xF_5 = F_2$)
- Flux isn't Tau Optimized
- Pandora toolkit
- CVN for event classification (look just for electrons)

FIRST STEP: check kinematic variables & see if the F_5 hypothesis is fulfilled.

It does

- Genie 3.0.6 (with F5 enable and disable, $F_5 = 0$)
- Flux is Tau Optimized
- Im getting my own splines (DIS)

$$q_0 = E_\nu - E_\mu$$

$$q_3 = p_\nu - p_\mu$$

$$Q^2 = q_3^2 - q_0^2$$

$$W^2 = M^2 + 2Mq_0 - Q^2$$

SECOND STEP: Get Pandora locally and able to work with my local Genie 3.0.6, F_5 Enable/Disable, get benchmarks.

- Get all the machinery working was whiny.
- At the end you have to "fool" LAr, manually tracked down all the dependencies GENIE requires.

PANDORA: hopefully we will found out results close to the ones shown before

```
lar -c prodgenie_nutau_dune10kt.fcl -n 1000
lar -c standard_g4_dune10kt.fcl -n 1000 prodgenie_nutau_dune10kt_gen.root
lar -c standard_detsim_dune10kt.fcl -n 1000
prodgenie_nutau_dune10kt_gen_g4.root
```

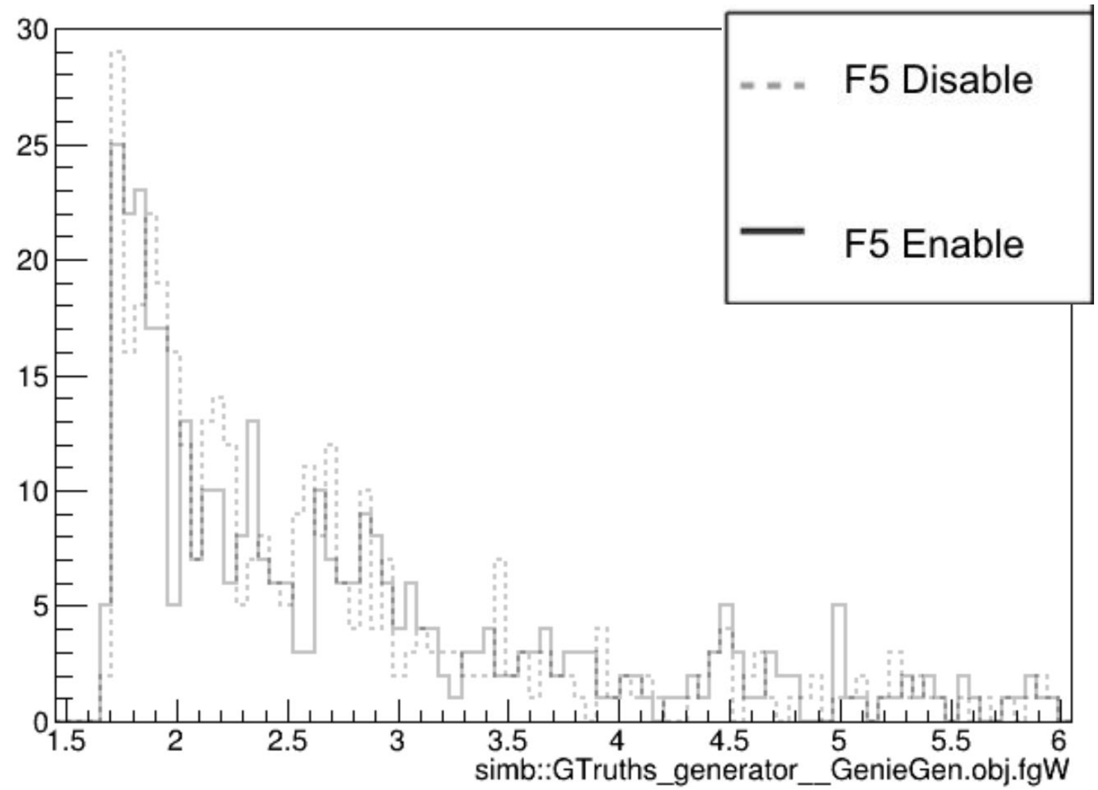
COMMENTS

- Similar to slide 10 result :)

- Official splines are been used (DIS, RES, etc).

- Need to increase the number of events.

- Test the limits of the baseline reconstruction



Thank you!

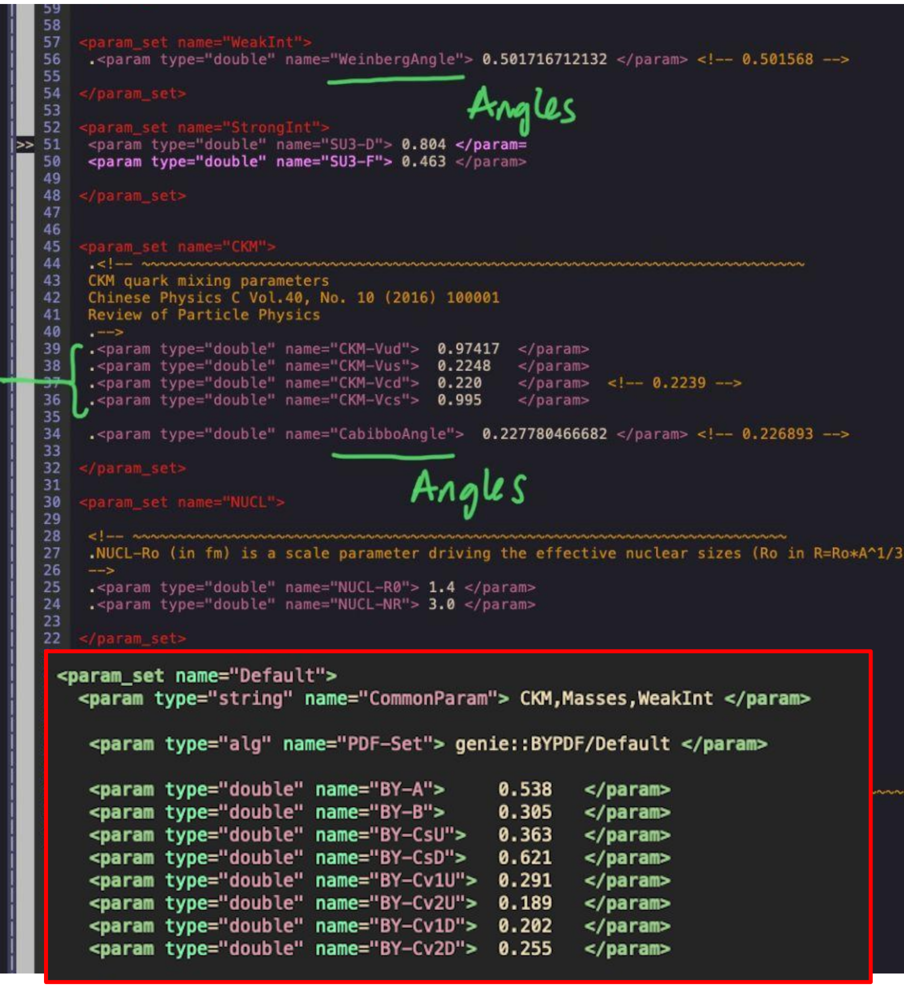
Milky Way and Volcan de Fuego , Guatemala

Backup

Genie 2.12.10 Use values listed at the July 2006 particle physics booklet

Genie 3.0.6 Use values listed by Chinese Physics C Vol.40, No. 10 (2016) 100001 Review of Particle Physics


```
*******************************************************************************
-->

 <param_set name="Default">

 <!--
  ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
  CKM quark mixing parameters
  Use values listed at the July 2006 particle physics booklet
  -->
  <param type="double" name="CKM-Vud">  0.97377  </param>
  <param type="double" name="CKM-Vus">  0.2257   </param>
  <param type="double" name="CKM-Vcd">  0.230    </param>  <!-- 0.2239 -->
  <param type="double" name="CKM-Vcs">  0.957    </param>

 <!--
  ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
  Cabibbo and Weinberg angles
  -->
  <param type="double" name="CabibboAngle">  0.22853207 </param> <!-- 0.226893 -->
  <param type="double" name="WeinbergAngle"> 0.49744211 </param> <!-- 0.501568 -->

 <!--
  ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
  Constants in Feynman-Kislinger-Ravndal model for baryon excitation used in the Rein-Sehgal
  resonance model
  -->
  <param type="double" name="RS-Omega"> 1.05  </param>
  <param type="double" name="RS-Zeta">  0.762 </param> <!-- 0.75 -->

 <!--
  ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
  Parameters for the Berger-Sehgal / Kuzmin-Lyubushkin-Naumov Delta models.
  Set to true to use tuning to axial, vector form factors by MiniBoone (J. Nowak)
  -->
  <param type="bool" name="miniboonеGA">  true </param>
  <param type="bool" name="miniboonеGV">  true </param>

 <!--
  ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
  Constants in the Bodek-Yang DIS structure function model and in the Bodek-Yang GRV-LO-9* PDF
  corrections
  -->
  <param type="double" name="BY-A">     0.538    </param>
  <param type="double" name="BY-B">     0.305    </param>
  <param type="double" name="BY-CsU">   0.363    </param>
  <param type="double" name="BY-CsD">   0.621    </param>
  <param type="double" name="BY-Cv1U">  0.291    </param>
  <param type="double" name="BY-Cv2U">  0.189    </param>
  <param type="double" name="BY-Cv1D">  0.202    </param>
  <param type="double" name="BY-Cv2D">  0.255    </param>
  <param type="double" name="BY-X0">   -0.00817  </param>
  <param type="double" name="BY-X1">    0.0506   </param>
  <param type="double" name="BY-X2">    0.0798   </param>

 <!--
  ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
```



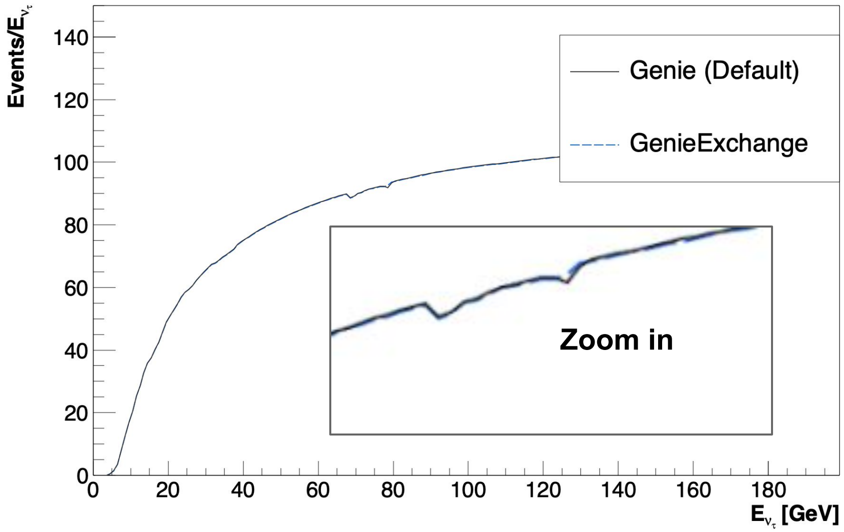

```
 <param_set name="WeakInt">
  .<param type="double" name="WeinbergAngle"> 0.501716712132 </param> <!-- 0.501568 -->

 </param_set>

 <param_set name="StrongInt">
  <param type="double" name="SU3-D"> 0.804 </param=
  <param type="double" name="SU3-F"> 0.463 </param>

 </param_set>


 <param_set name="CKM">
  .<!-- ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
  CKM quark mixing parameters
  Chinese Physics C Vol.40, No. 10 (2016) 100001
  Review of Particle Physics
  .-->
  .<param type="double" name="CKM-Vud">  0.97417  </param>
  .<param type="double" name="CKM-Vus">  0.2248   </param>
  .<param type="double" name="CKM-Vcd">  0.220    </param>  <!-- 0.2239 -->
  .<param type="double" name="CKM-Vcs">  0.995    </param>

  .<param type="double" name="CabibboAngle">  0.227780466682 </param> <!-- 0.226893 -->

 </param_set>

 <param_set name="NUCL">

  <!-- ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
  .NUCL-Ro (in fm) is a scale parameter driving the effective nuclear sizes (Ro in R=Ro*A^1/3)
  -->
  .<param type="double" name="NUCL-R0"> 1.4 </param>
  .<param type="double" name="NUCL-NR"> 3.0 </param>

 </param_set>
```

```
<param_set name="Default">
  <param type="string" name="CommonParam"> CKM,Masses,WeakInt </param>

   <param type="alg" name="PDF-Set"> genie::BYPDF/Default </param>

   <param type="double" name="BY-A">     0.538    </param>
   <param type="double" name="BY-B">     0.305    </param>
   <param type="double" name="BY-CsU">   0.363    </param>
   <param type="double" name="BY-CsD">   0.621    </param>
   <param type="double" name="BY-Cv1U">  0.291    </param>
   <param type="double" name="BY-Cv2U">  0.189    </param>
   <param type="double" name="BY-Cv1D">  0.202    </param>
   <param type="double" name="BY-Cv2D">  0.255    </param>
```

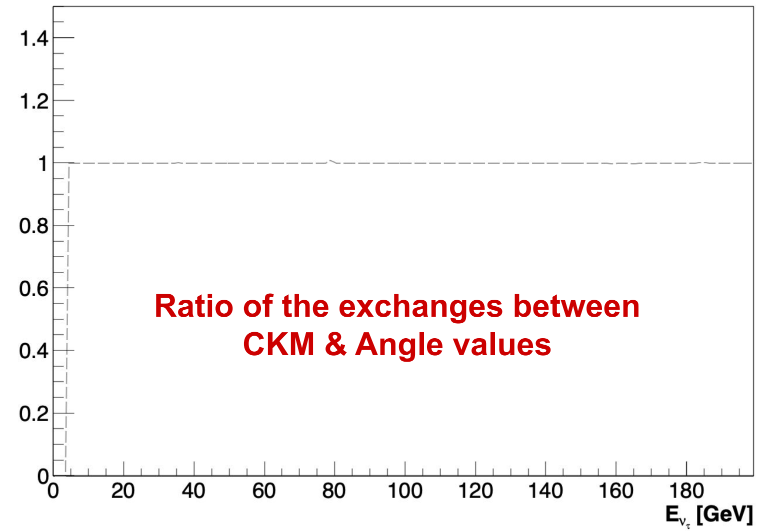
Does changes come from just CKM & Angles values differences or from the DIS Model as well?

Splines for Genie 3.0.6 after exchange CKM & Angle values

NuTau Genie 3.0.6

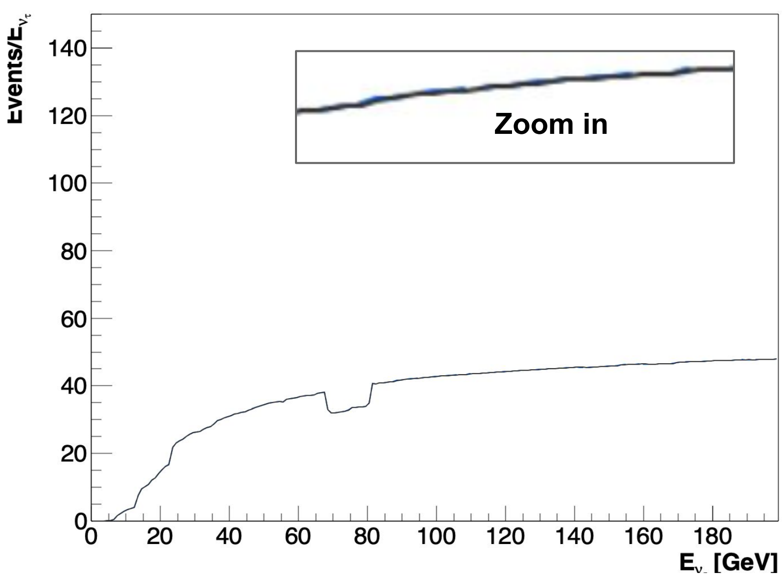


NuTau Genie 3.0.6



Splines for Genie 2.12.10 after exchange CKM & Angle values

AntiNuTau Genie 2.12.10



AntiNuTau Genie 2.12.10