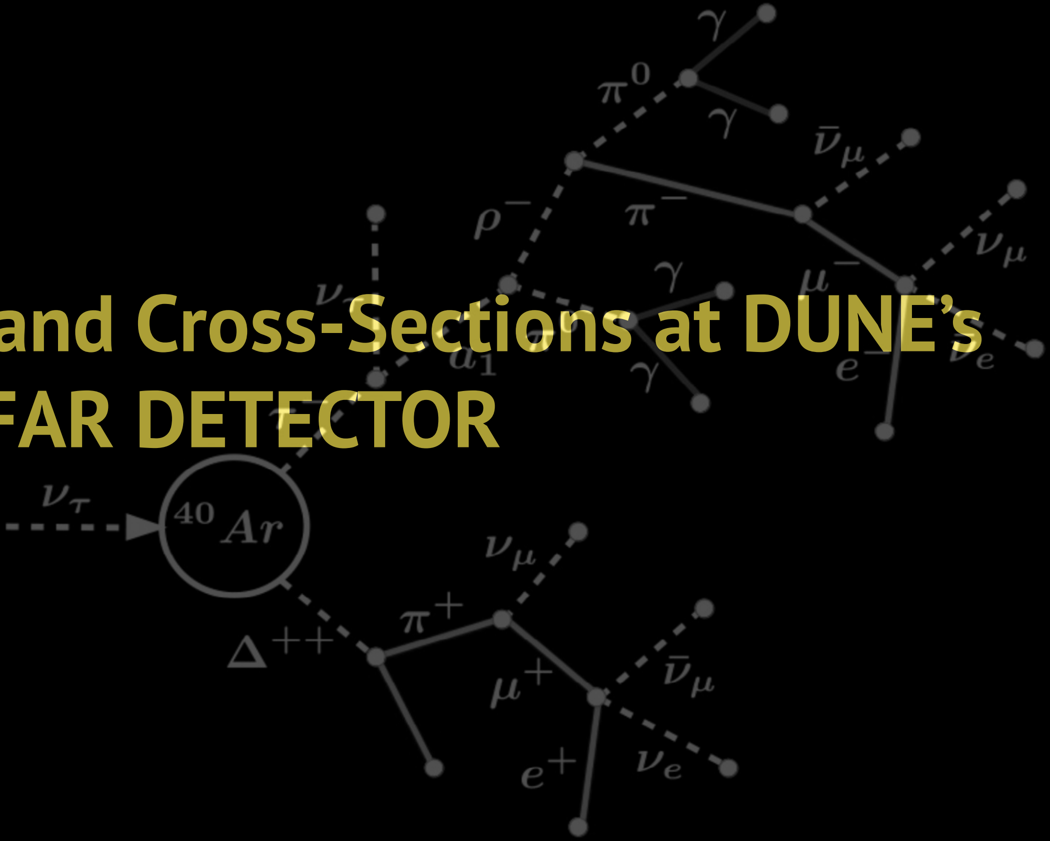
APS April Meeting 2022
Neutrino Cross Sections

Tau Neutrinos and Cross-Sections at DUNE’s FAR DETECTOR



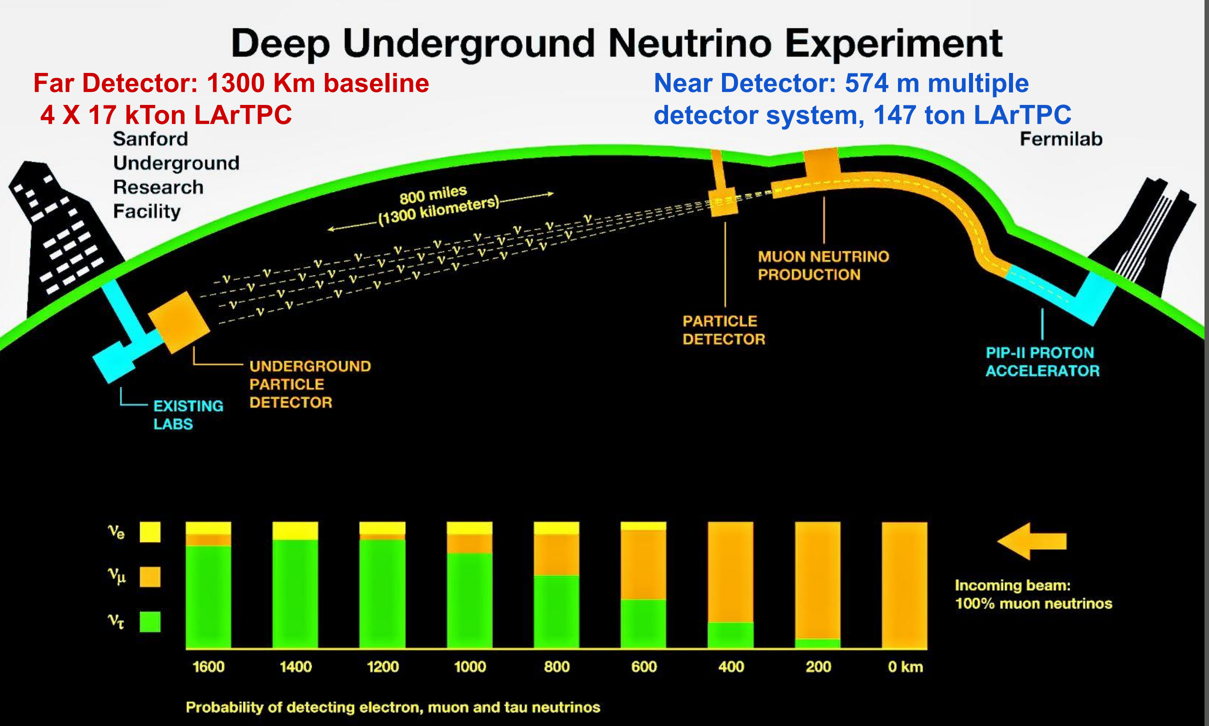
Barbara Yaeggy
(04/09/2022)

UNIVERSITY OF Cincinnati

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

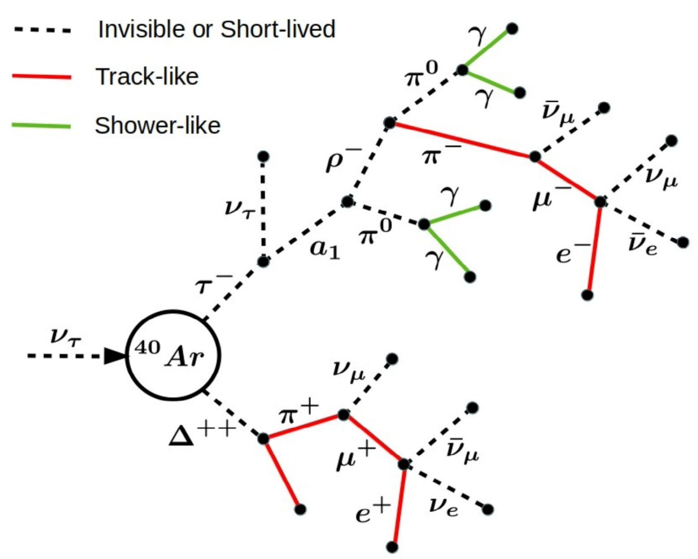
NuTau at DUNE

- While DUNE is optimized to measure ν_e appearance in a ν_μ beam the broadband beam and long baseline lead to significant ν_τ appearance above the kinematic threshold to produce a τ -lepton.
- Due to this, DUNE is the only upcoming neutrino experiment expected to be able to collect a sample of oscillated ν_τ - CC beam events.
- DUNE will be capable to distinguish between electrons, photons, muons, and pions with high efficiency at the typical energies of beam produced ν_τ - CC beam interactions.



Far Detector: 1300 Km baseline
4 X 17 kTon LArTPC

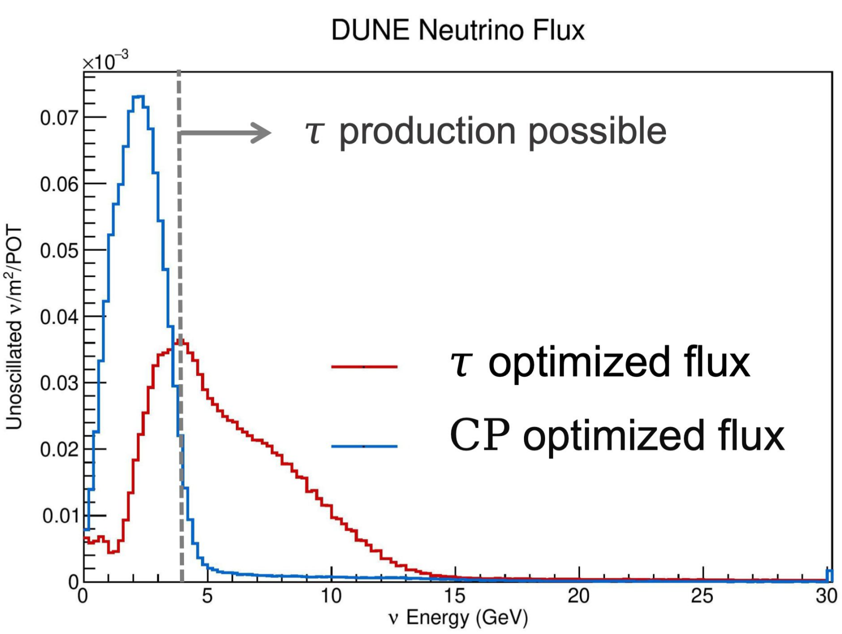
Near Detector: 574 m multiple detector system, 147 ton LArTPC



DUNE will be able to constraint the three flavor paradigm!

Barbara Yaeggy - University of Cincinnati

Beam Flux
NuTau at DUNE



- **Optimized for the CP sensitivity phase measurement**
  - Low energy
  - Default starting configuration

- **Tau-optimized beam: modified to produce a higher energy spectrum by modifying the relative position of the target and horns, and using NuMI style parabolic horns**

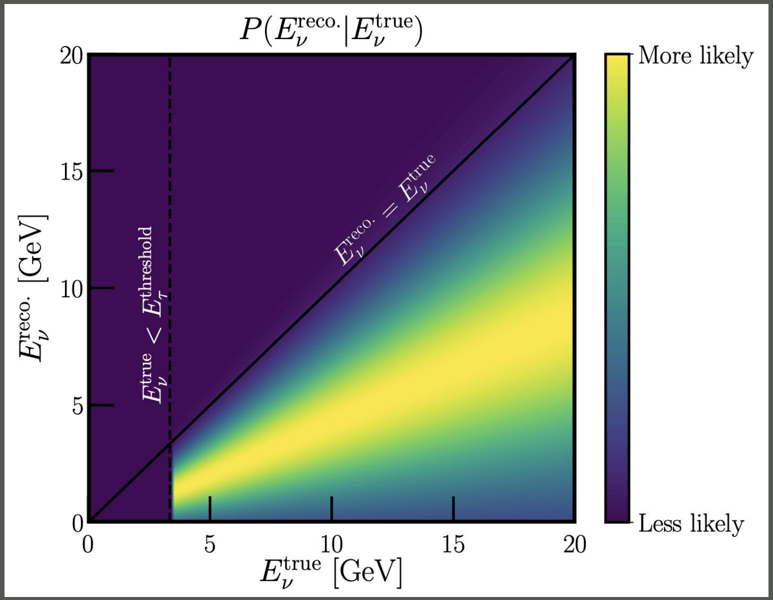
Expected counts/year:

~ 30 ν_τ in CP-optimized neutrino mode
~ 130 ν_τ in CP-optimized neutrino mode
~ 800 ν_τ in Tau-optimized neutrino mode

SELECTION
NuTau at DUNE

DUNE has studied using kinematic cuts (first proposed in J. Conrad, et al, PRD 82, 093012 (2010))

- Select ν_τ with hadronically decaying tau lepton
- Assume near perfect e/γ and μ/π discrimination
- Simple kinematic cuts on $\pi^{+/-}$ yield good ν_τ-CC/NC discrimination

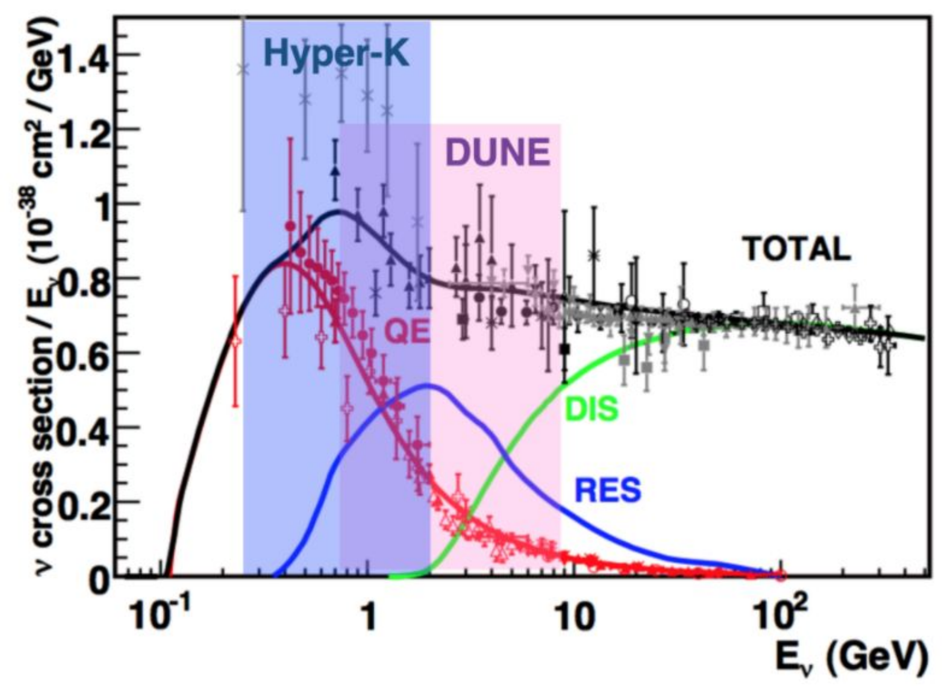


Migration matrix for hadronically decaying τ leptons produced via ν_τ charged-current interactions. PhysRevD.100.016004
Due to the large mass of the τ ± relative to the e ± and μ ±, the threshold for this process to occur is 3.5 GeV.

In the few GeV region [1-10] GeV there are contributions from several kinds of lepton-nucleon interaction processes as defined by W and Q^2.

Quasi-elastic (QE): $W < 1.07$ GeV
Resonance Δ(1232): $1.1 < W < 1.4$ GeV
Higher mass resonances: $1.4 < W < 1.8$ GeV
Inelastic continuum: $W > 1.8$ GeV, at low Q^2 (Shallow Inelastic) and at high Q^2 (DIS)

At low Q^2 (< 1 GeV) there are large non-perturbative contributions to the inelastic cross section: target mass corrections, dynamic higher twist effects, higher order QCD terms, and nuclear effects in nuclear targets.



- 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.

DIS CC-ν_τ Cross-section

$$\frac{d^2\sigma_A}{dxdy} = \frac{G_F^2 M_N E_\nu}{\pi(1+\frac{Q^2}{M_W^2})^2}\Bigg\{\left[y^2x+\frac{m_l^2 y}{2E_\nu M_N}\right]F_{1A}(x,Q^2)+\left[\left(1-\frac{m_l^2}{4E_\nu^2}\right)-\left(1+\frac{M_N x}{2E_\nu}\right)y\right]F_{2A}(x,Q^2)$$

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

The scaling variables $x(=\frac{Q^2}{2p\cdot q})$ and $y(=\frac{\nu}{E_\nu}=\frac{q_0}{E_\nu})$ lie in the range:

$$\frac{m_l^2}{2M_N(E_\nu-m_l)}\leq x\leq 1 \qquad \text{and} \qquad a-b\leq y\leq a+b,$$

where

$$a=\frac{1-m_l^2\left(\frac{1}{2M_N E_\nu x}+\frac{1}{2E_\nu^2}\right)}{2\left(1+\frac{M_N x}{2E_\nu}\right)} \qquad \text{and} \qquad b=\frac{\sqrt{\left(1-\frac{m_l^2}{2M_N E_\nu x}\right)^2-\frac{m_l^2}{E_\nu^2}}}{2\left(1+\frac{M_N x}{2E_\nu}\right)}.$$

Albright, Jarlskog '75 Paschos, Yu '98 Kretzer, Reno '02

F_4 and F_5 are ignored in the muon neutrino interactions because of a suppression factor depending on the square of the m_ℓ divided by the nucleon mass times neutrino energy, $m^2_\ell/(M_N E_\nu)$.

At leading order, in the limit of massless quarks and target hadrons:

- **Albright-Jarlskog relations:**

$$F_4 = 0 \quad \text{and } F_2 = 2xF_5$$

Which are a generalization Callan-Gross relation:

$$F_2(x,Q^2) = 2xF_1(x,Q^2)$$

$\nu\tau$ (CC) interactions give access to cross section physics not accessible otherwise!

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

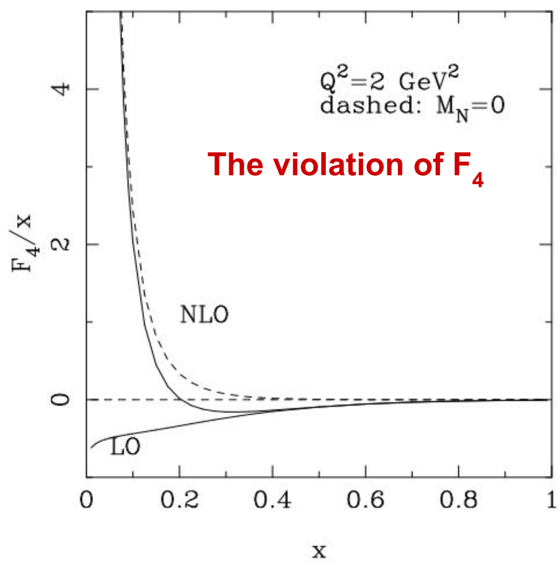
The effect of these imposed cuts is much less pronounced for ν_τ DIS where m_τ acts as a physical cut-off of non-DIS interaction.

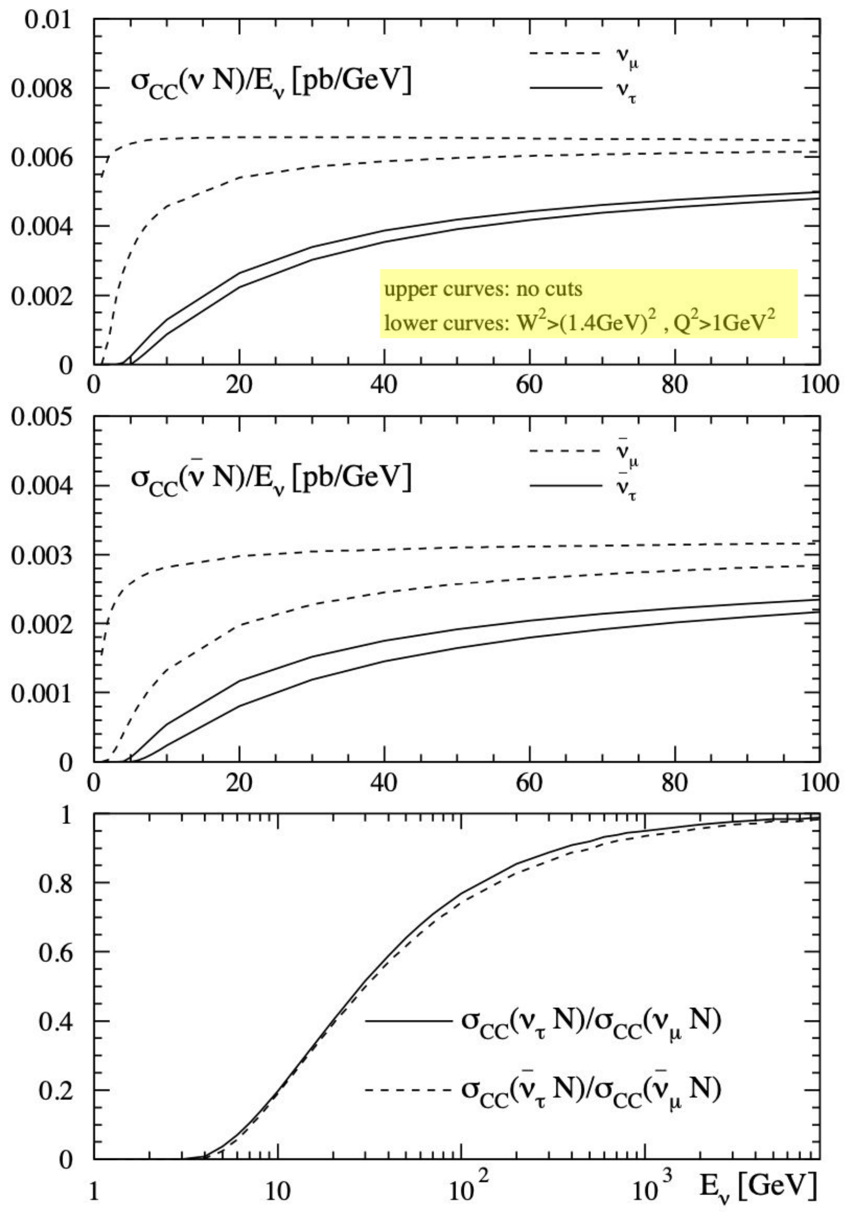
See how slowly $\sigma_{CC}(\nu_\tau)$ approaches to $\sigma_{CC}(\nu_\mu)$ from below at very HE indicating a persistent τ threshold effect.

About half of the reduction at high energies is actually of dynamic origin, to be attributed to a negative contribution of F5

$$-\frac{m_\tau^2}{E_\nu M_N} F_5^{W^\pm}$$

Suppressed around 1 TeV and is compensated to some extent by the low-x rise of $F_5 \sim q(x)$

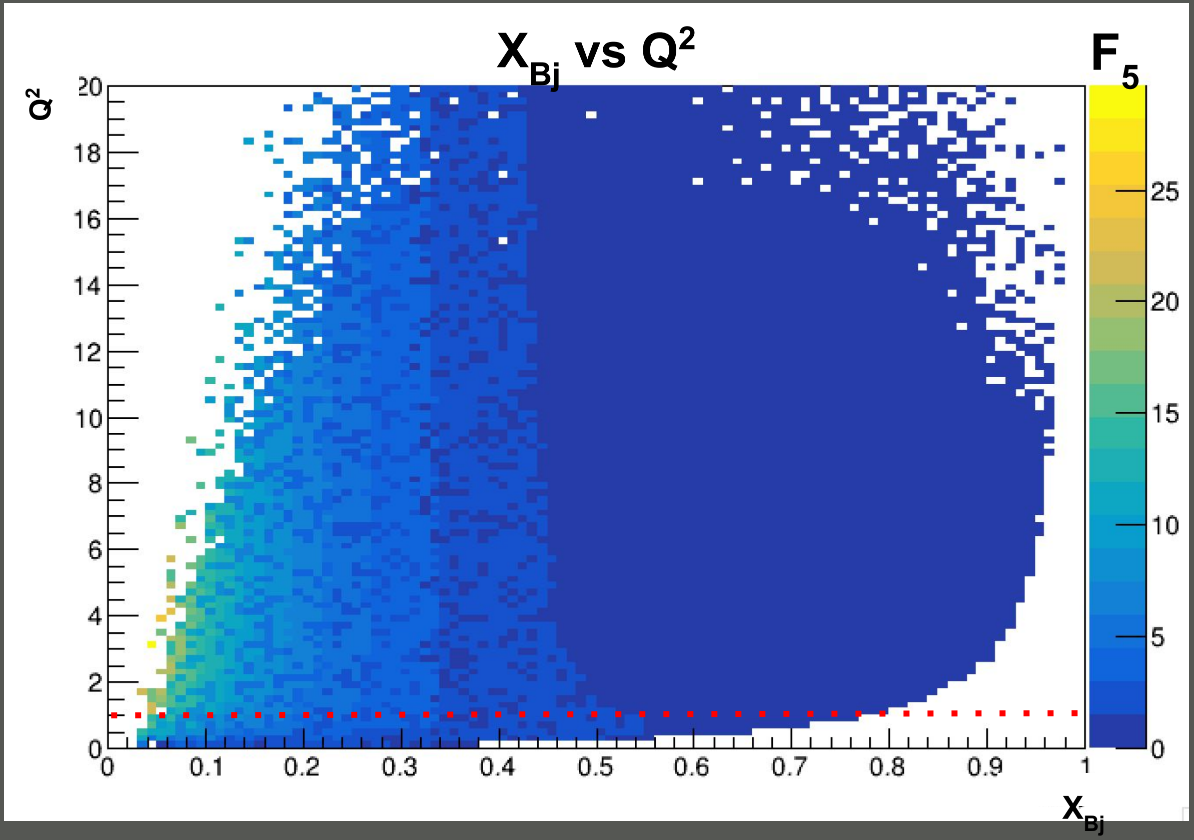




Exploring The Nature of F_5

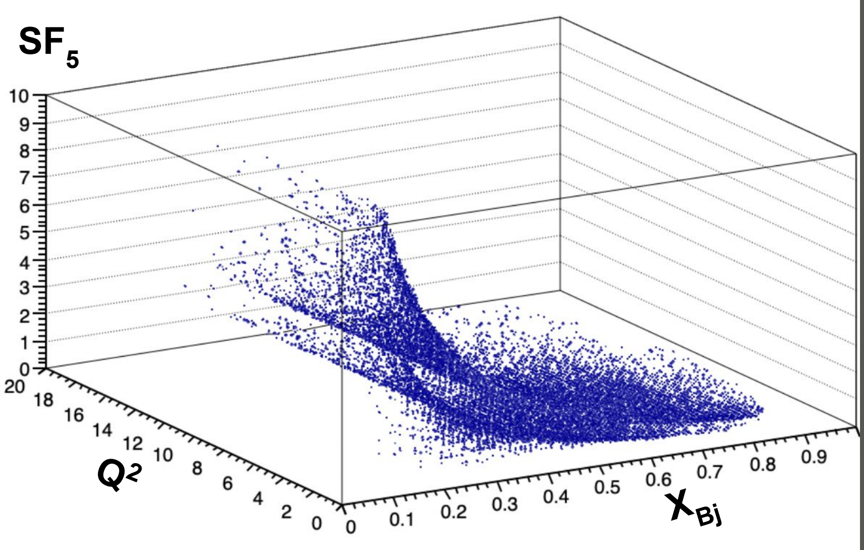
Nature of $F_5\ (x, Q^2)$

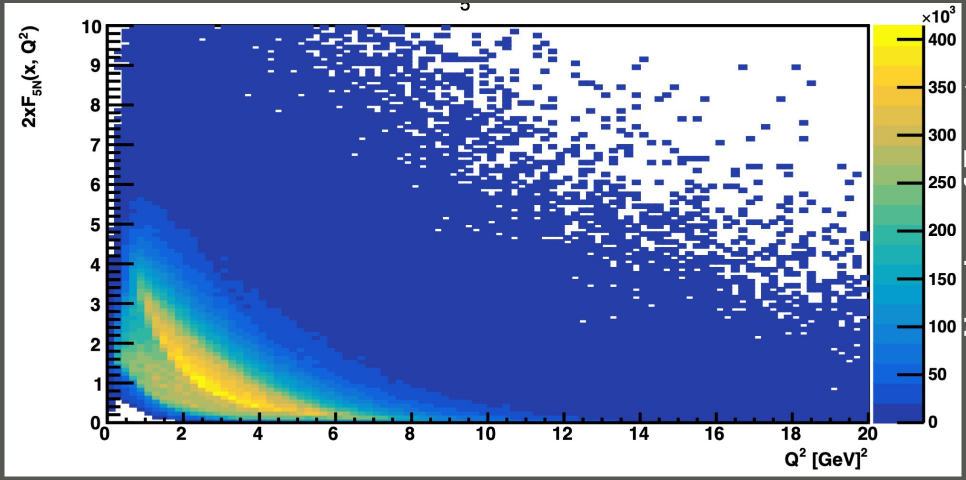
- This is F_5 in terms of x and Q^2, its effect is in all [x,Q^2] phase space.
- At lower X_{Bj} , F_5 values are high.
- Below Q^2 =1 , non-perturbative
- Above Q^2 =1 , perturbative

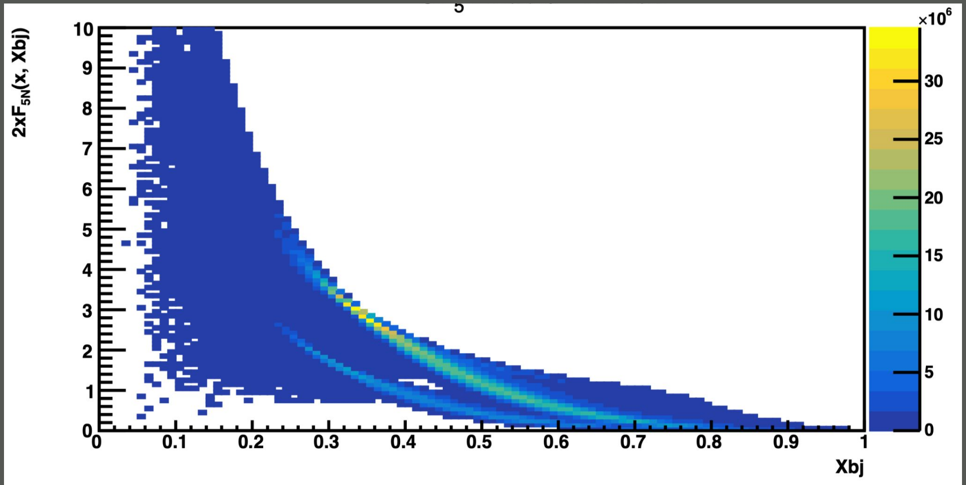


$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dx\,dy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left((y^2x+\frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2})-(1+\frac{Mx}{2E_\nu})\right]F_2 \pm \left[xy(1-\frac{y}{2})-\frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2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

F_5 Enable

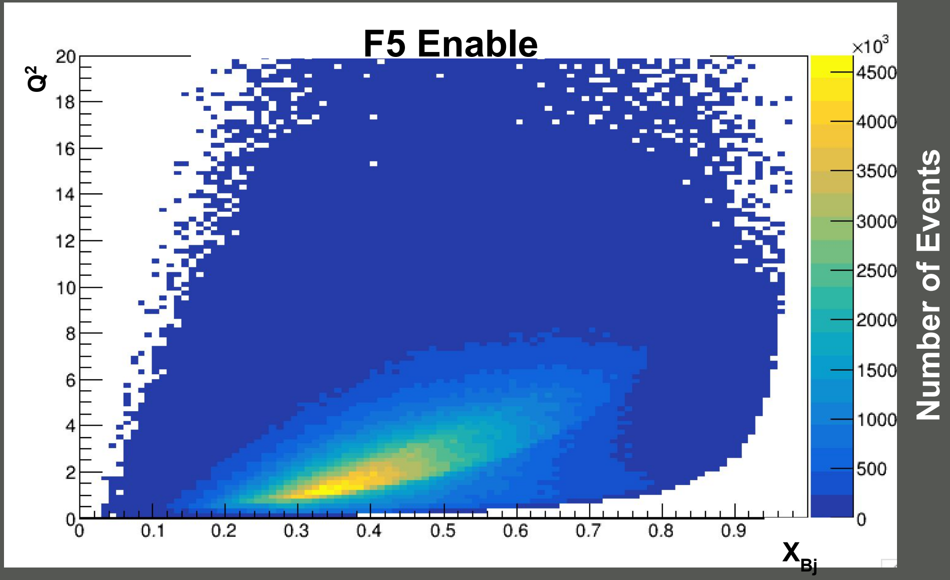




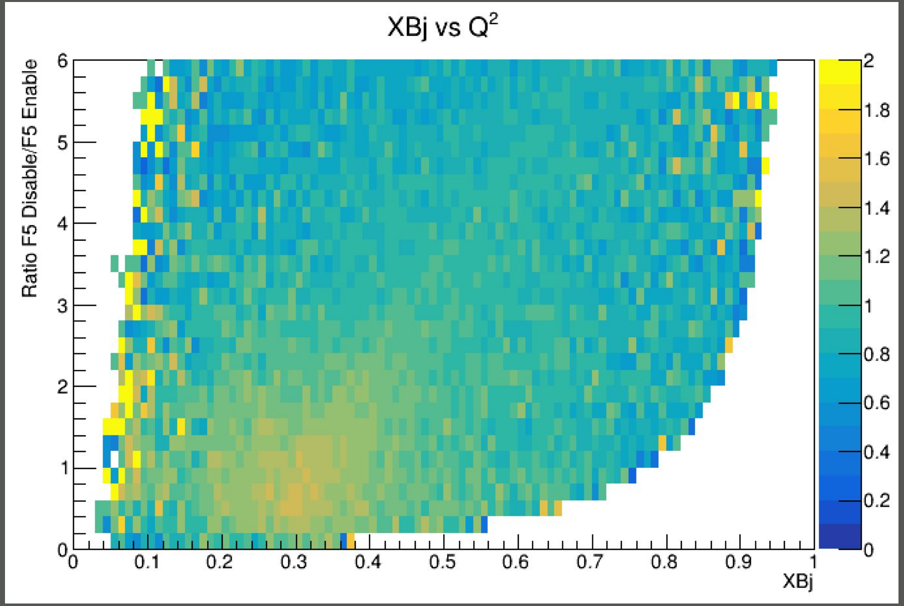


- This is F_5 in terms of x and Q^2, its effect is in all [x,Q^2] phase space.

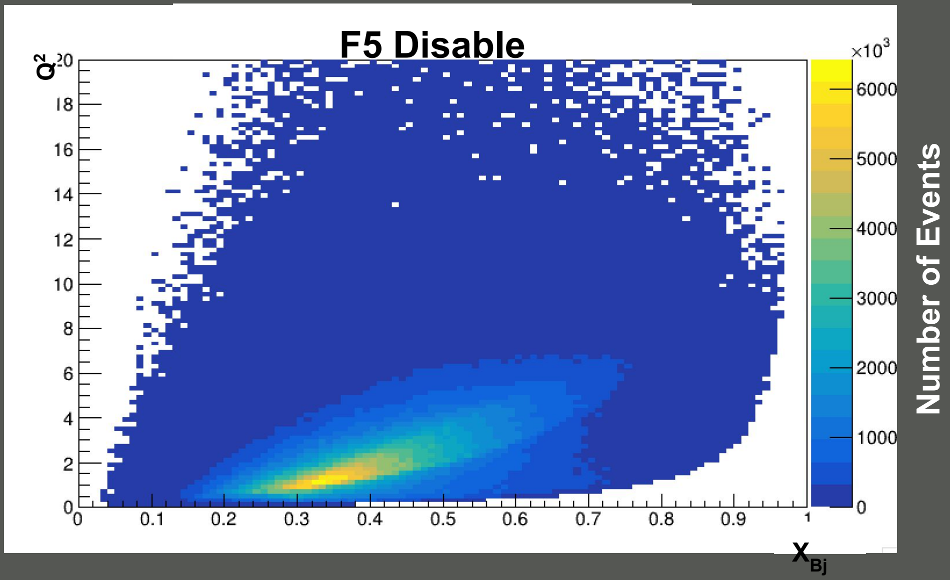
Effect of F_5 in the total number of events.



In Xsec and Events the F_5 value covers all the phase space



Ratio of F5 Disable / F5 Enable

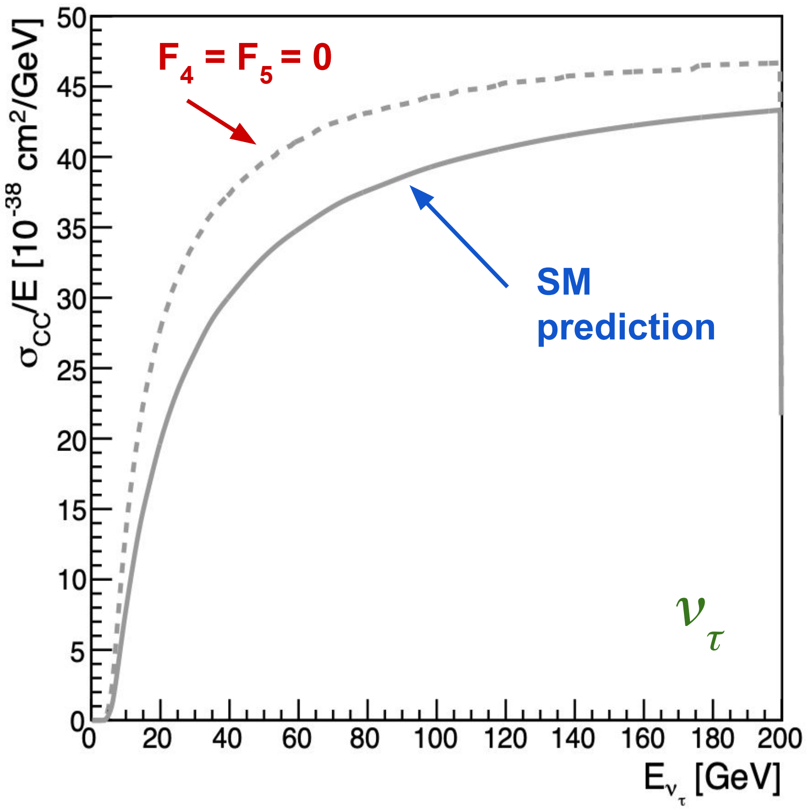


The ratio is greater than 1:

- Which is expected since F_5 is a subtracted component of the total XSec.
- Also, it means that there is a chance to disentangle an overall normalization change from a scaling of F5

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.

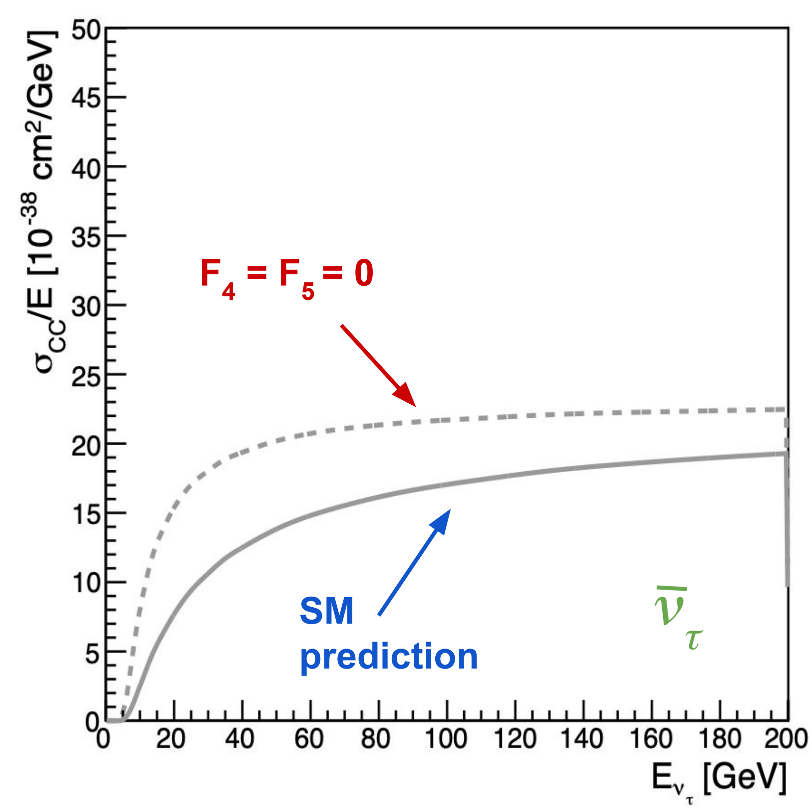
GENIE 3.0.6 CC-NuTau Cross Section



$F_4 = F_5 = 0$

SM prediction

GENIE 3.0.6 CC- Anti NuTau Cross-Section



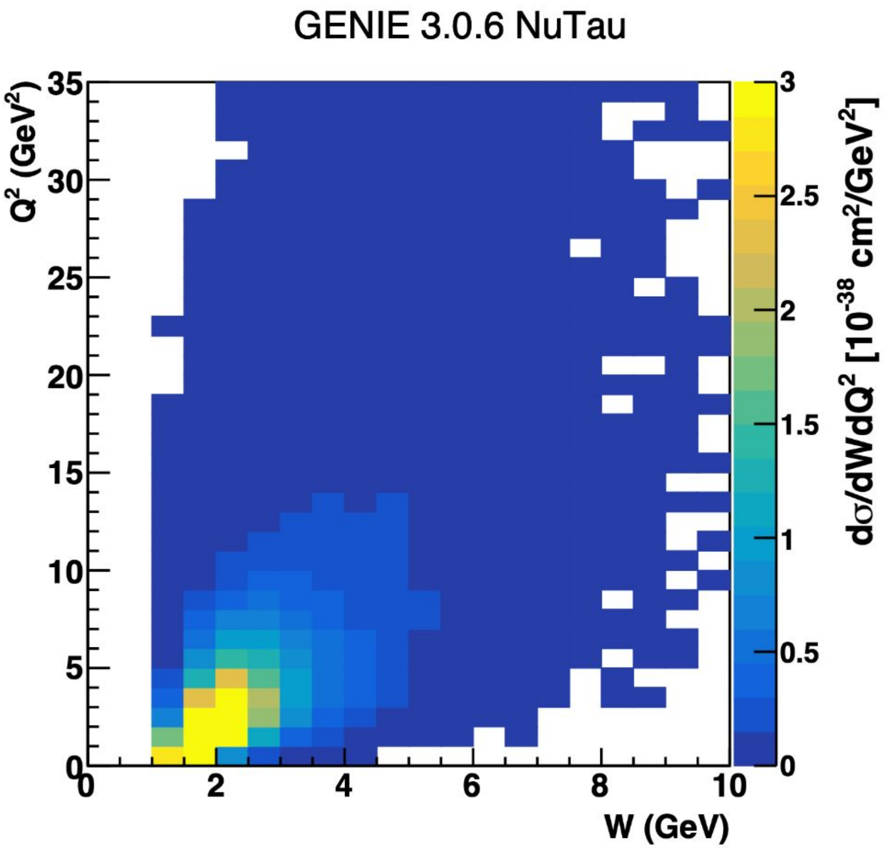
$F_4 = F_5 = 0$

SM prediction

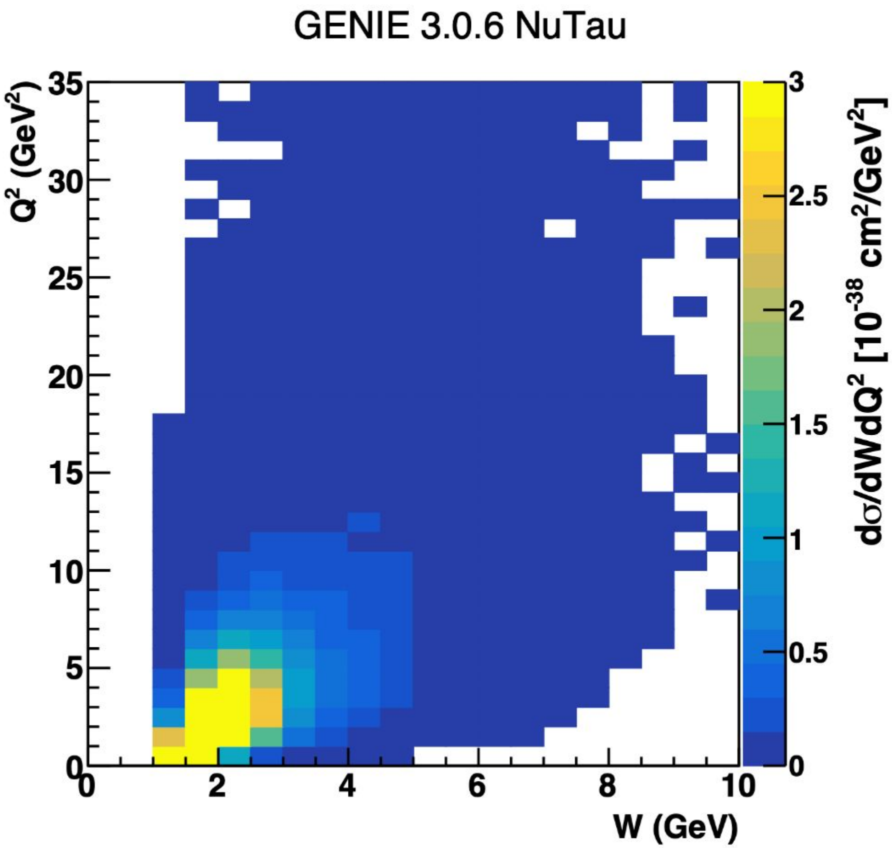
Q^2 vs W

ν_τ

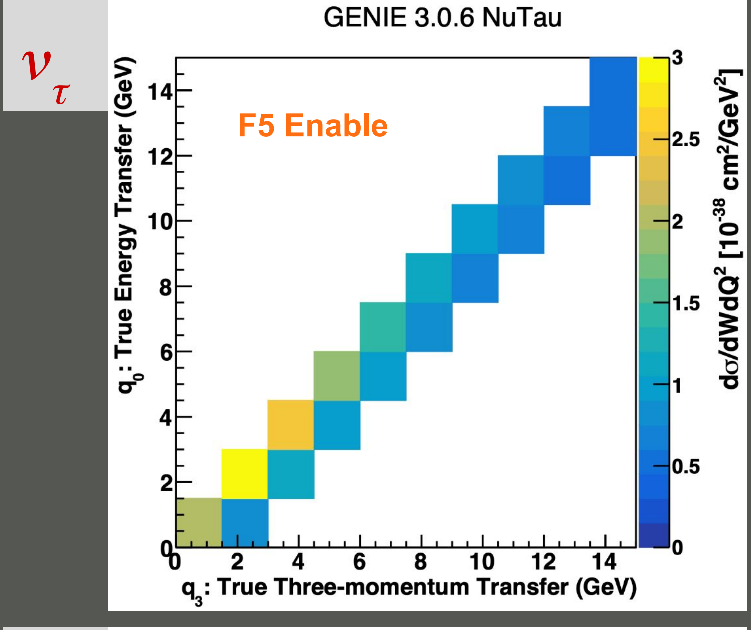
SF_5 Disable

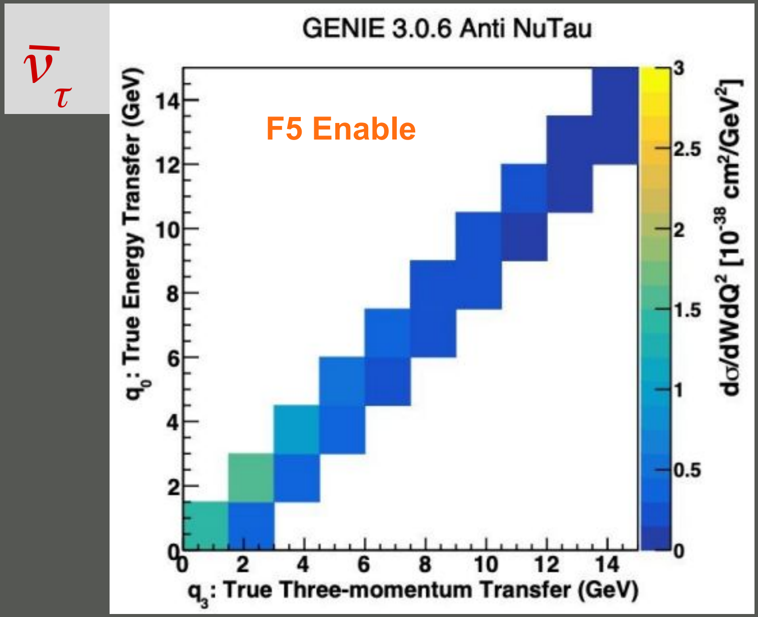


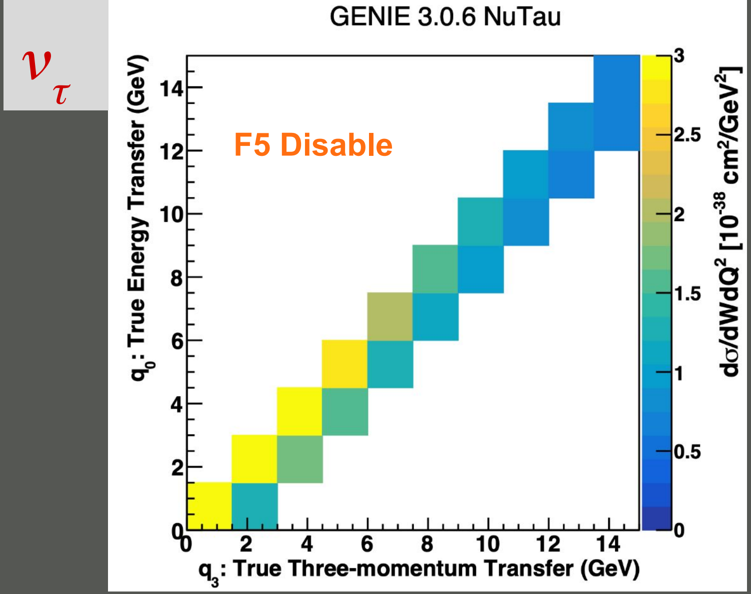
SF_5 Enable

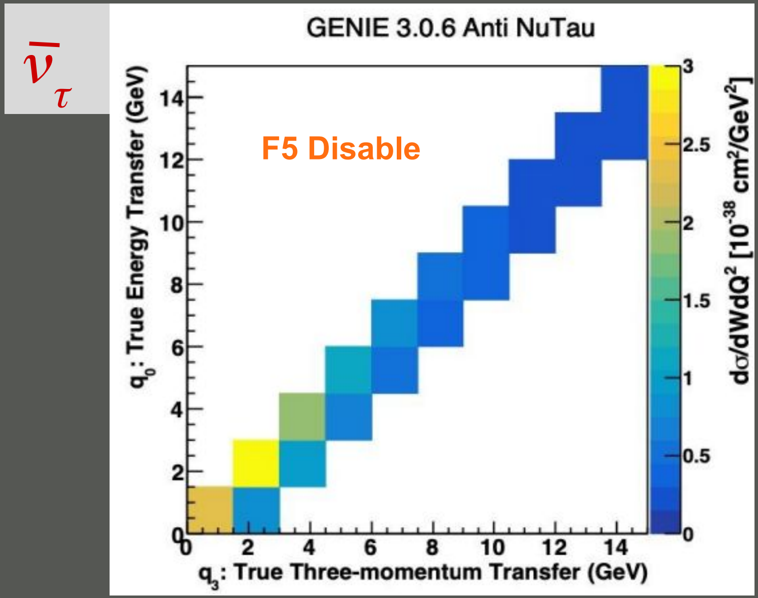


CC - ν_τ TRUTH Level studies show that indeed, when DIS cuts are applied and $F_5 = 0$ we can extract new information from the lepton cross section.









Comments

The new features which appear in the case of the ν_τ–A interaction as compared to the ν_e–A and ν_μ–nucleon interactions and contribute to modify the cross sections are:

- Kinematical changes in Q^2 and E_ℓ due to the presence of m_τ
- The contributions due to the additional nucleon structure functions F_{4N} (X,Q^2) and F_{5N} (X,Q^2) in the presence of $m_\tau \neq 0$.
- Modifications in cross-sections due to the effect of polarization state of the **τ** leptons produced in the final state.

Some of the above effects are modified in the nuclear medium ⟶ we need reliable nuclear model to describe DIS of leptons from nuclear targets.

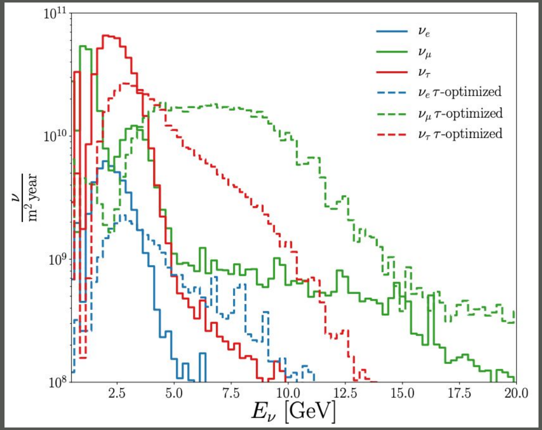
- The produced **τ**-leptons in the final state may get polarized in the nuclear medium affecting the cross-section from nuclear targets. The polarization will also affect the topologies and characteristics of its decay products.
- The shadowing and anti-shadowing effects in the respective kinematics regions of the Bjorken variable x.

Thank you!

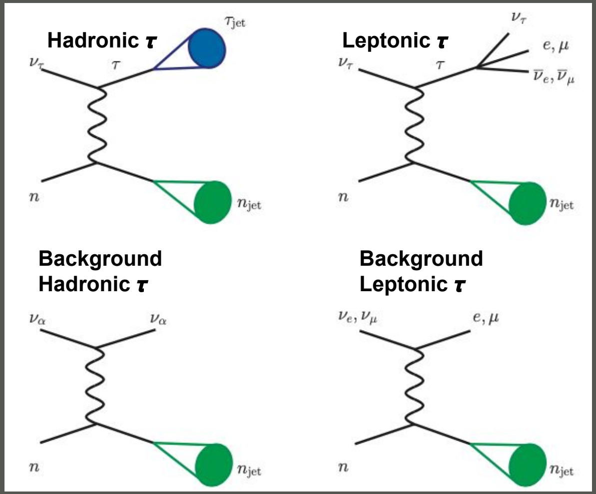
Milky Way and Volcan de Fuego , Guatemala

Backup

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

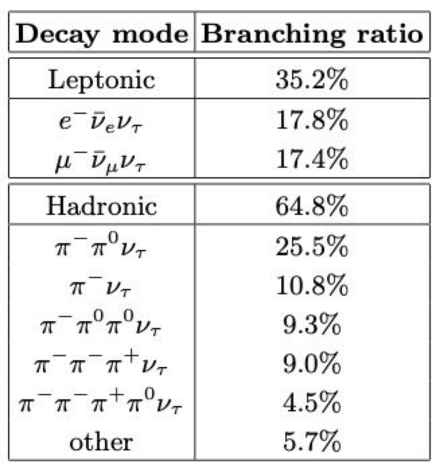
→ **Tau doesn't lead to observables displaced vertices**

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.

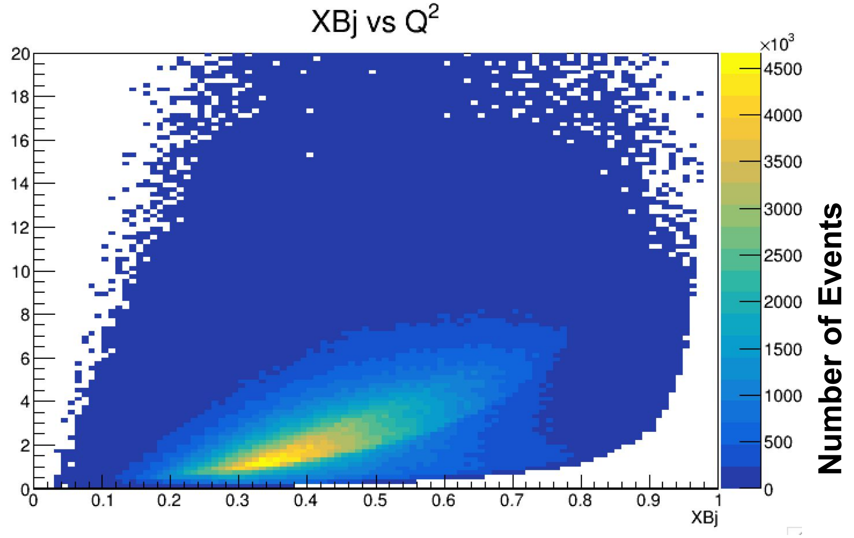
Background for τ_e signal are CC-ν_e events, being ν_e flux a small fraction of the total neutrino flux.



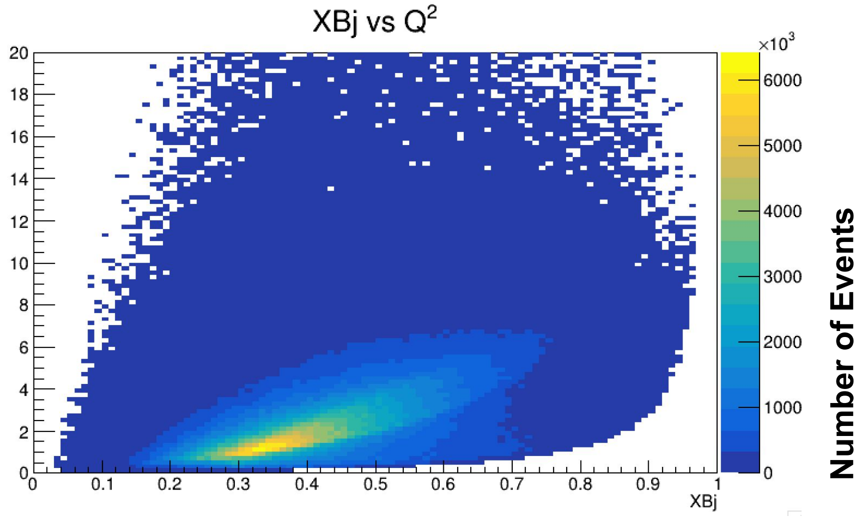
Decay mode	Branching ratio
Leptonic	35.2%
$e^-\bar{\nu}_e\nu_\tau$	17.8%
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.4%
Hadronic	64.8%
$\pi^-\pi^0\nu_\tau$	25.5%
$\pi^-\nu_\tau$	10.8%
$\pi^-\pi^0\pi^0\nu_\tau$	9.3%
$\pi^-\pi^-\pi^+\nu_\tau$	9.0%
$\pi^-\pi^-\pi^+\pi^0\nu_\tau$	4.5%
other	5.7%

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

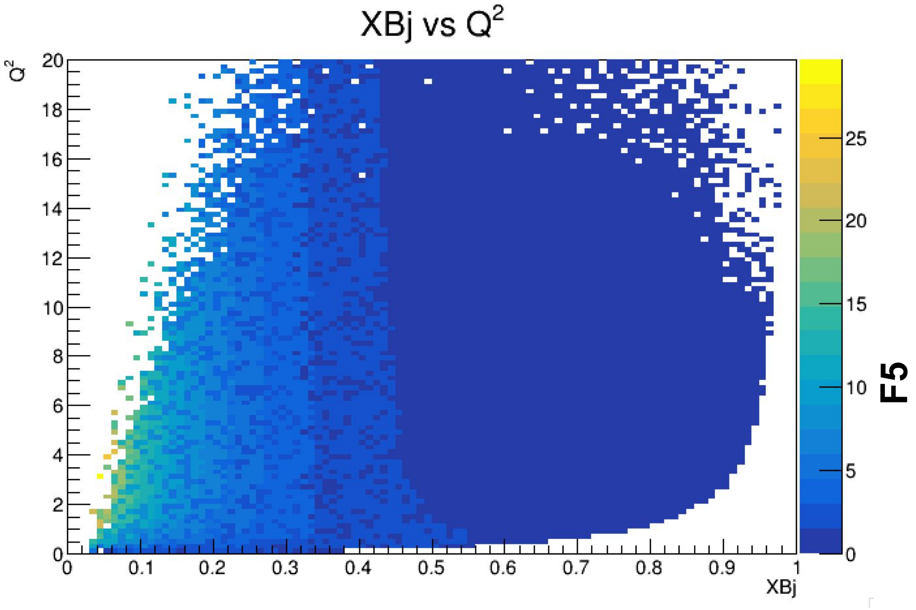
F5 Enable



F5 Disable

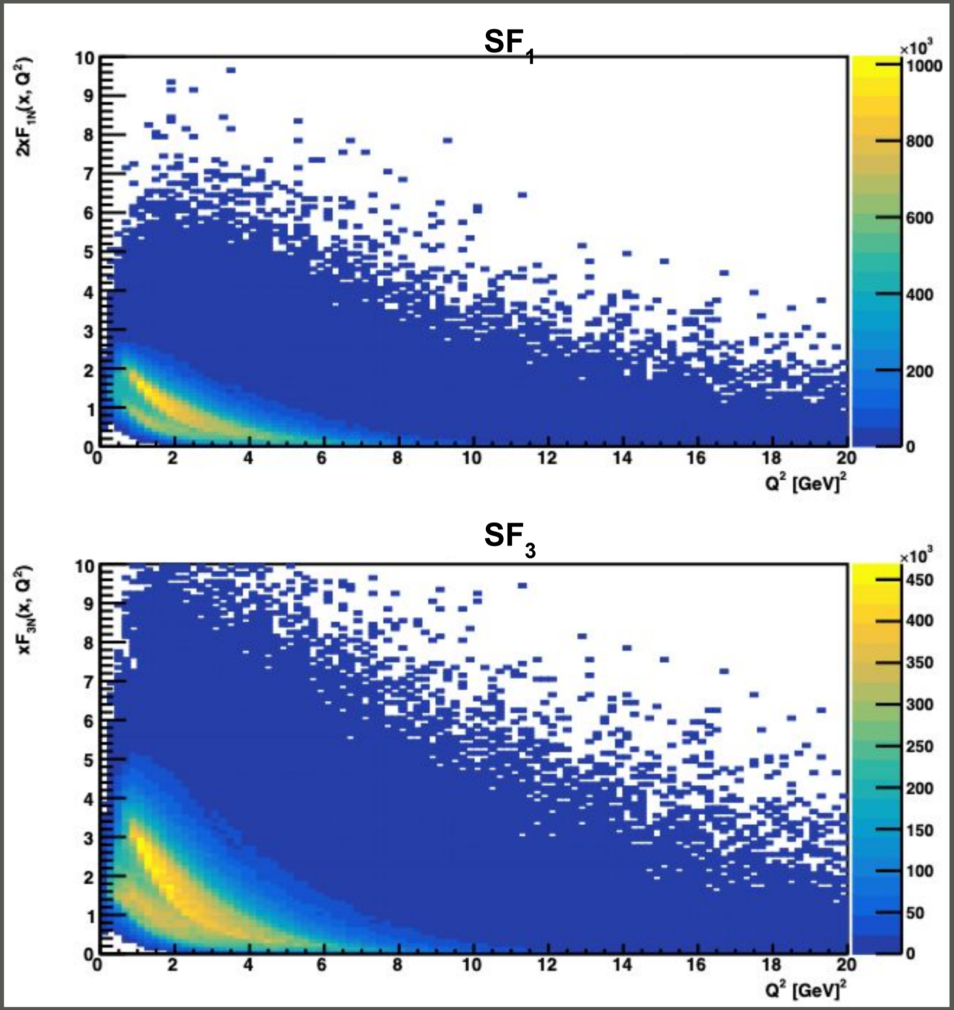


- In Xsec and Events the F5 value covers all the phase space



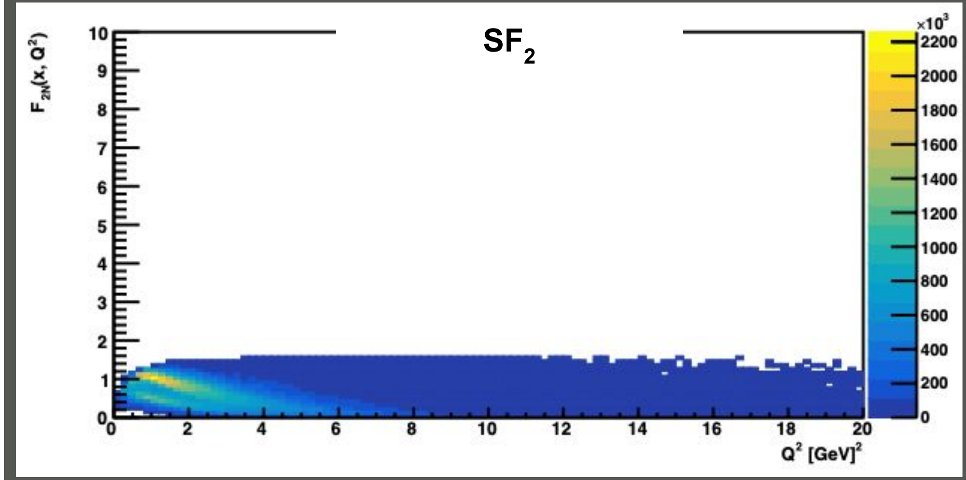
Q^2 vs Structure Functions

ν_τ



SF$_1$

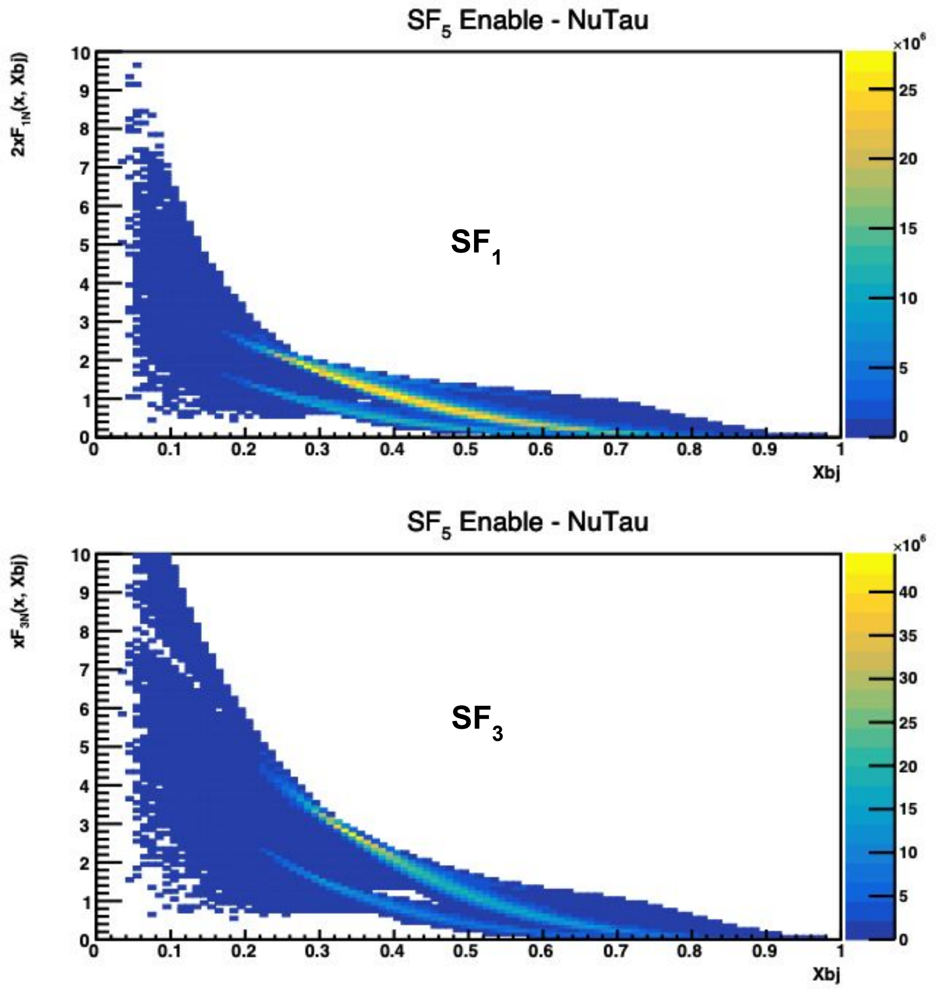
SF$_3$



SF$_2$

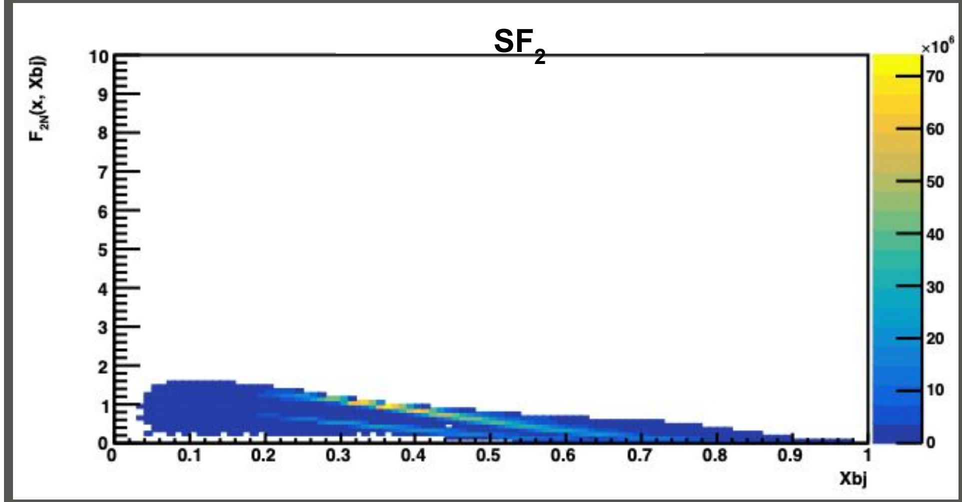
X_{Bj} vs Structure Functions

ν_τ

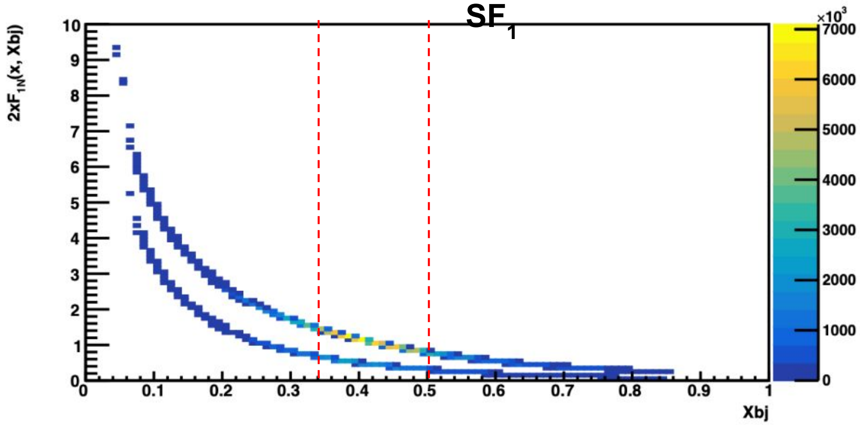


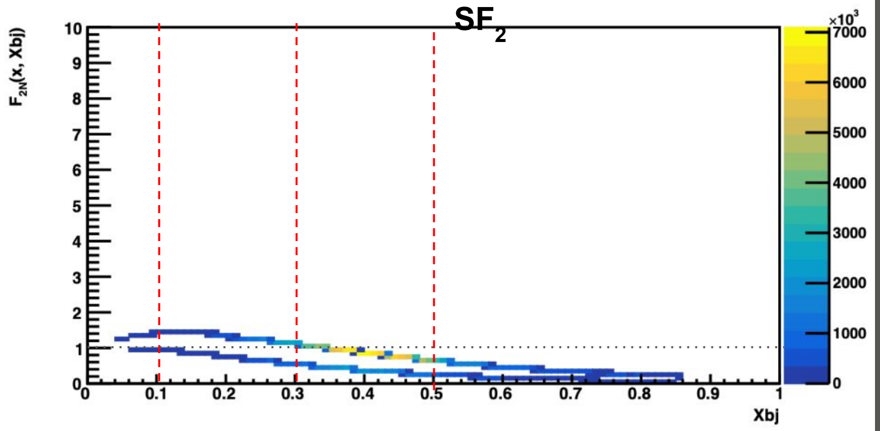
SF$_5$ Enable - NuTau

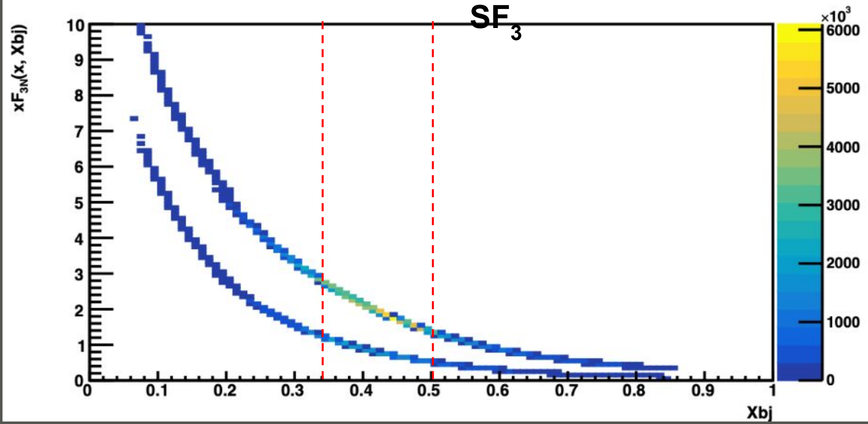
SF$_5$ Enable - NuTau

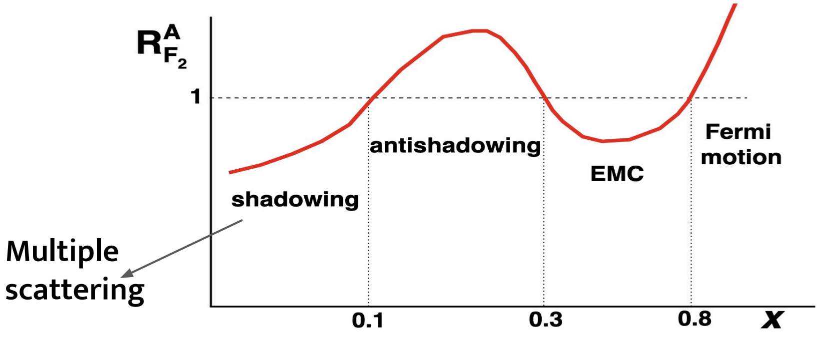


When Q^2 > 1.8 & Q^2 <= 2.0 GeV F_5 DISABLE







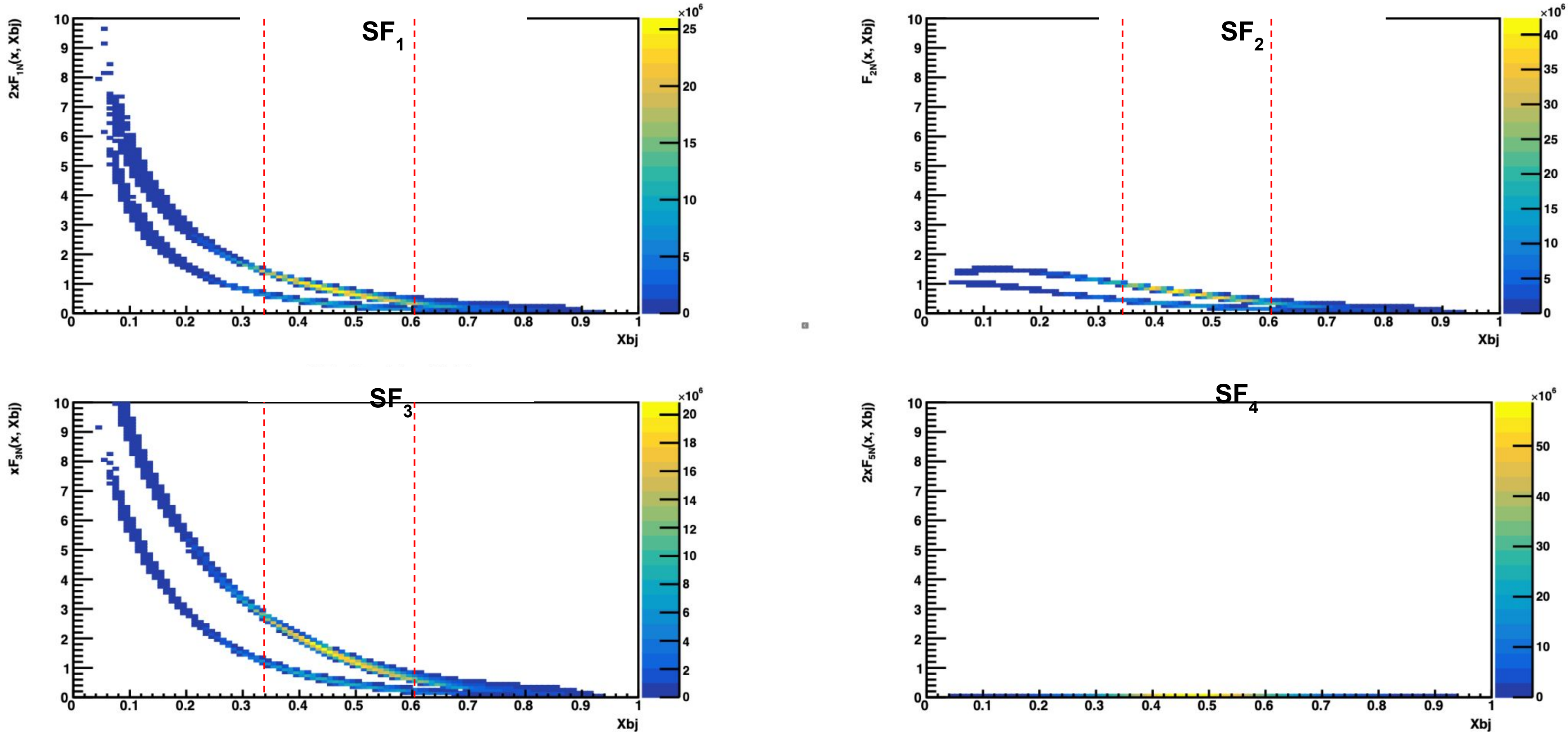


Multiple scattering

Figure 2. Schematic behaviour of $R^A_{F_2}(x, Q^2)$ as a function of x for a given fixed Q^2.

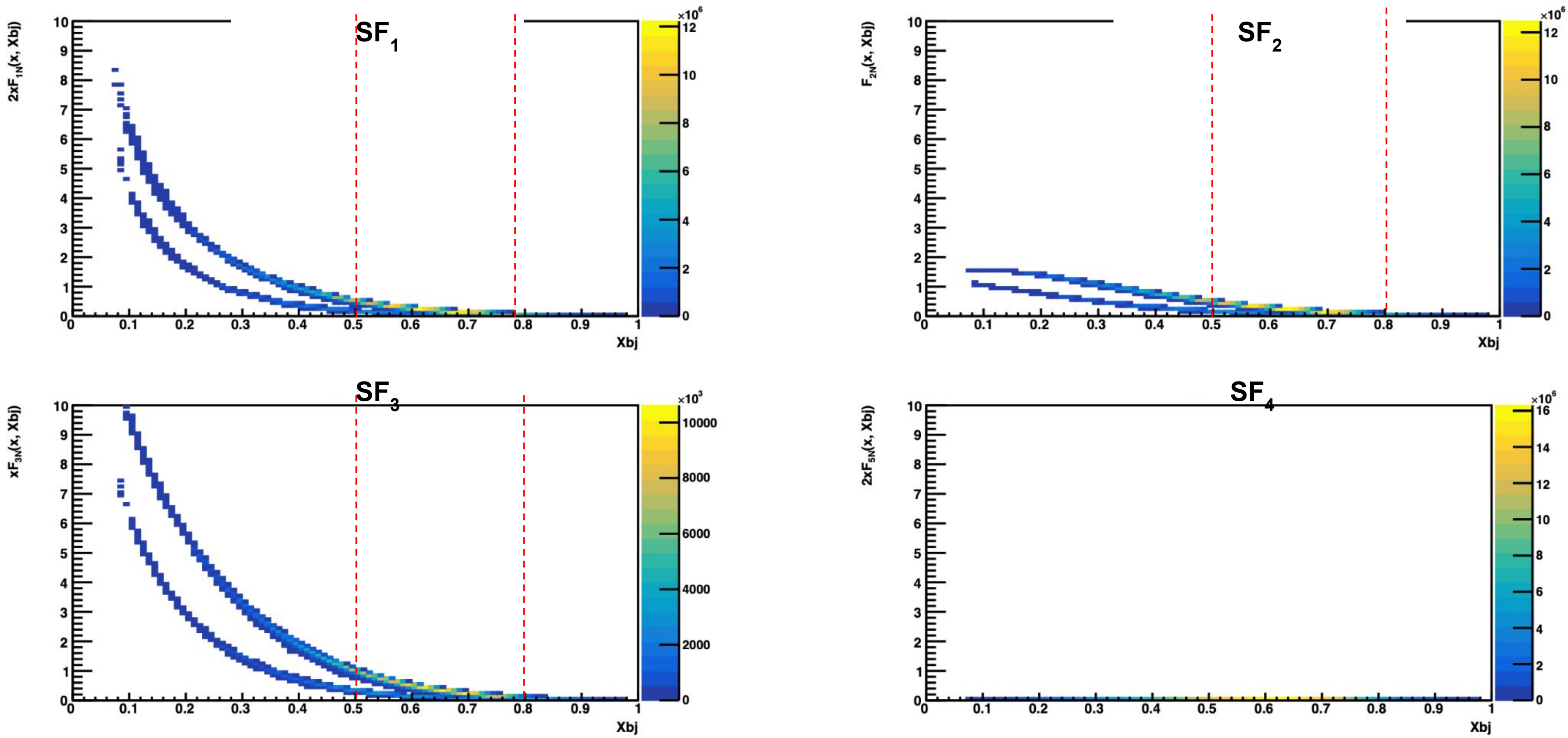
When $Q^2 > 2.0$ & $Q^2 < 5.0$ GeV SF_5 DISABLE

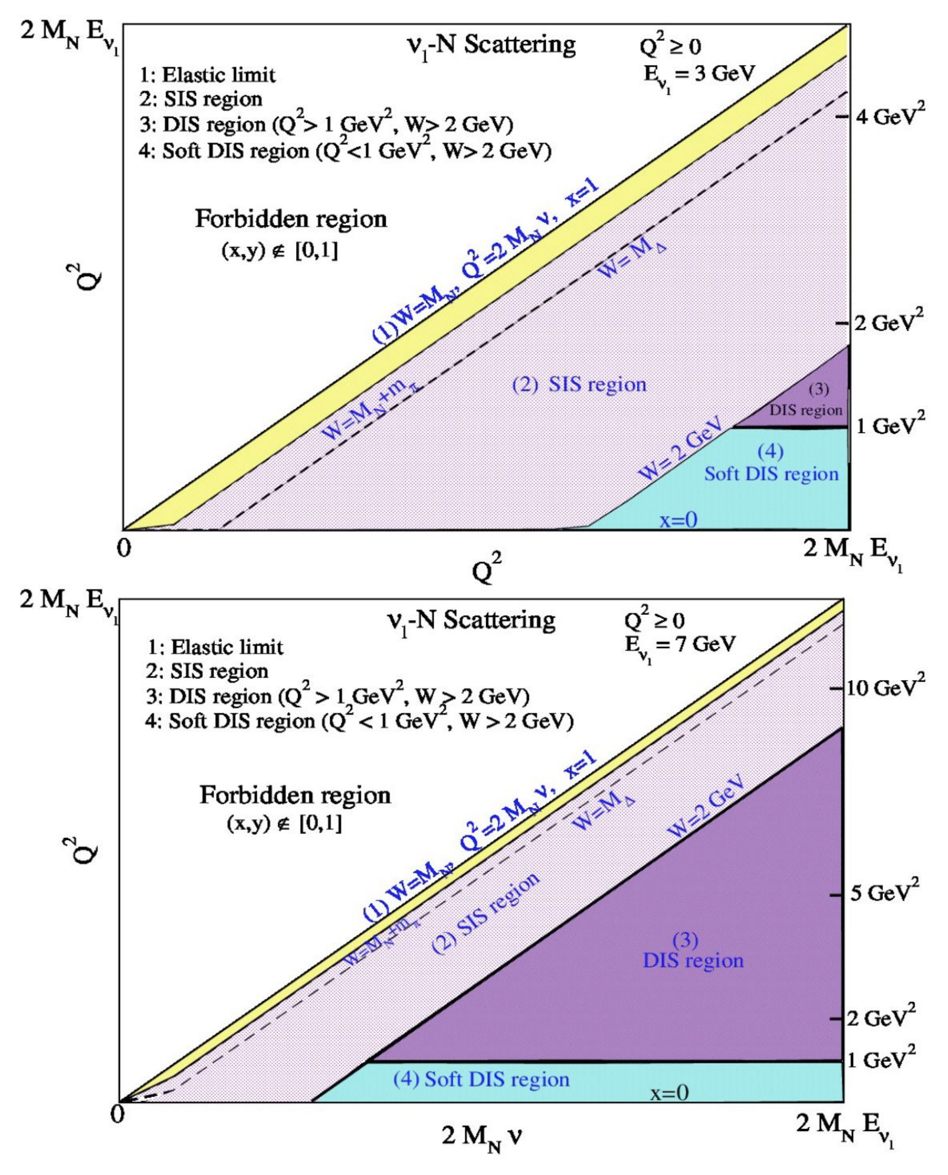
ν_τ



When Q^2 >= 5.0 GeV SF_5 DISABLE

ν_τ

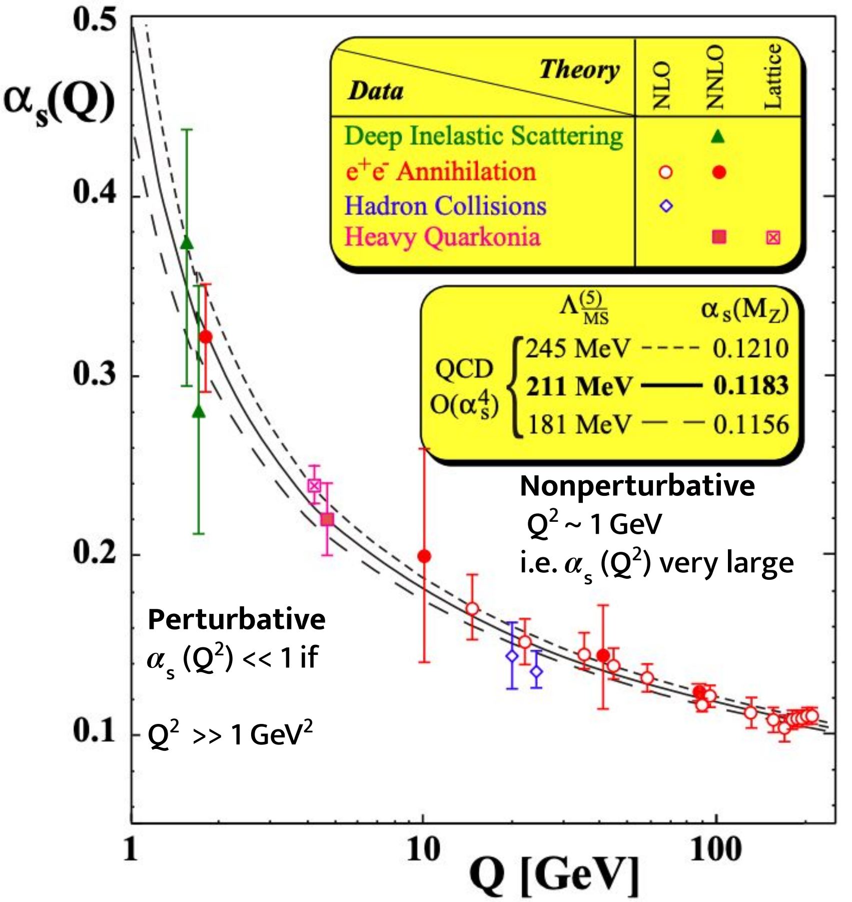




ν_l-N Scattering
$Q^2 \geq 0$
$E_{\nu_l} = 3$ GeV
1: Elastic limit
2: SIS region
3: DIS region ($Q^2 > 1$ GeV^2, W> 2 GeV)
4: Soft DIS region ($Q^2 < 1$ GeV^2, W> 2 GeV)
Forbidden region
$(x,y) \notin [0,1]$
(1) $W=M_N$, $Q^2=2M_N\nu$, x=1
$W=M_\Delta$
$W=M_N+m_\pi$
(2) SIS region
(3) DIS region
(4) Soft DIS region
W= 2 GeV
x=0
4 GeV^2
2 GeV^2
1 GeV^2
$2 M_N E_{\nu_l}$
Q^2
0
Q^2
$2 M_N E_{\nu_l}$
ν_l-N Scattering
$Q^2 \geq 0$
$E_{\nu_l} = 7$ GeV
1: Elastic limit
2: SIS region
3: DIS region ($Q^2 > 1$ GeV^2, W > 2 GeV)
4: Soft DIS region ($Q^2 < 1$ GeV^2, W > 2 GeV)
Forbidden region
$(x,y) \notin [0,1]$
(1) $W=M_N$, $Q^2=2M_N\nu$, x=1
$W=M_\Delta$
$W=M_N+m_\pi$
(2) SIS region
W=2 GeV
(3) DIS region
(4) Soft DIS region
x=0
10 GeV^2
5 GeV^2
2 GeV^2
1 GeV^2
$2 M_N E_{\nu_l}$
Q^2
0
$2 M_N \nu$
$2 M_N E_{\nu_l}$

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

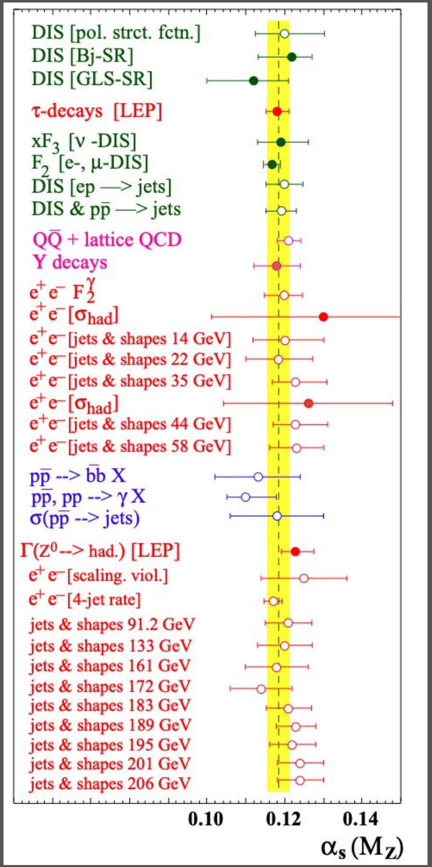
The production of any particle can be determined by the cross section!



Nonperturbative
$Q^2 \sim 1$ GeV
i.e. α_s (Q^2) very large

Perturbative
α_s (Q^2) << 1 if

Q^2 >> 1 GeV^2



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

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

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.

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.