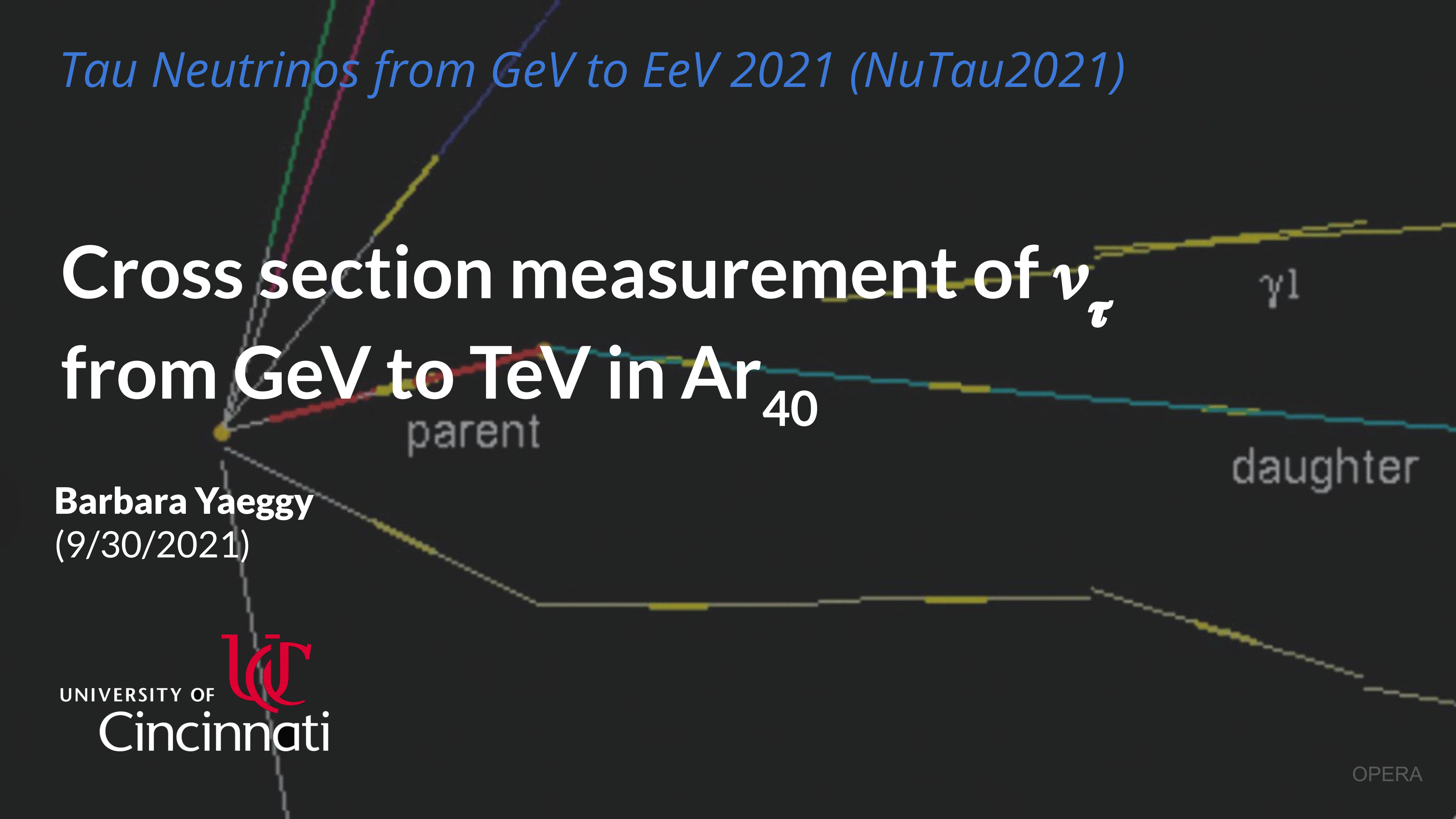
Tau Neutrinos from GeV to EeV 2021 (NuTau2021)

Cross section measurement of ν_τ from GeV to TeV in Ar_{40}

Barbara Yaeggy
(9/30/2021)

UNIVERSITY OF Cincinnati



OPERA

Why cross sections are important?

Check talkfs from Laura Fields, Stephen Parke, Tyce deYoung, Julia Gehrlein

- **Neutrino interactions** (cross section) are the major contributor of systematic uncertainties in oscillation measurements (T2k, NOvA).

- E_ν & **ν**-nucleus interactions relies on **reconstruction techniques** either based on kinematics (T2K/HK) or calorimetric methods (DUNE/NOvA/SBN) and both requires reliable predictions from **interaction models.**

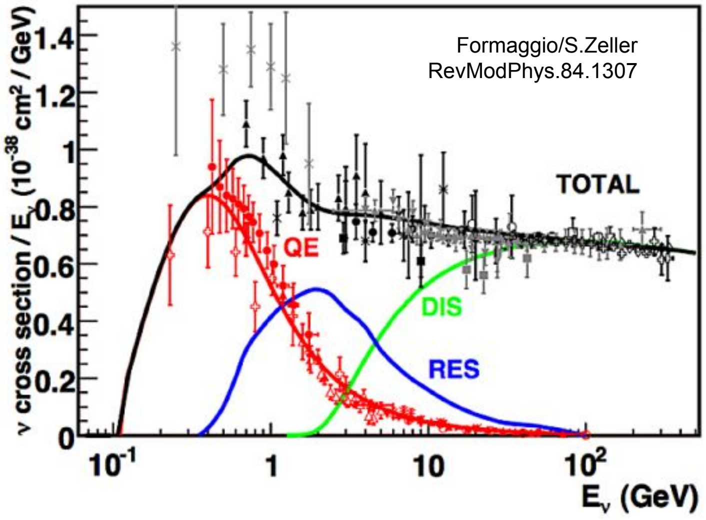
- Extraction of **oscillation parameter** is biased by the interaction model.

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{ij}\ \sin^2\left(\frac{\Delta m^2_{ij}}{4}\frac{L}{E_\nu}\right)$$

$$N^{\alpha\to\beta}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_\nu)\times\sigma^i_\beta(E_\nu)\times P(\nu_\alpha \to \nu_\beta)\times\epsilon_\beta(E_\nu, E_{\nu,rec})$$

Nuclear and hadronic effects are energy dependent too!.

Neutrino Cross Sections at a Few GeV



Formaggio/S.Zeller
RevModPhys.84.1307

Nowadays, we are getting new accelerators and detectors!
→ precise interaction models and study phenomena.

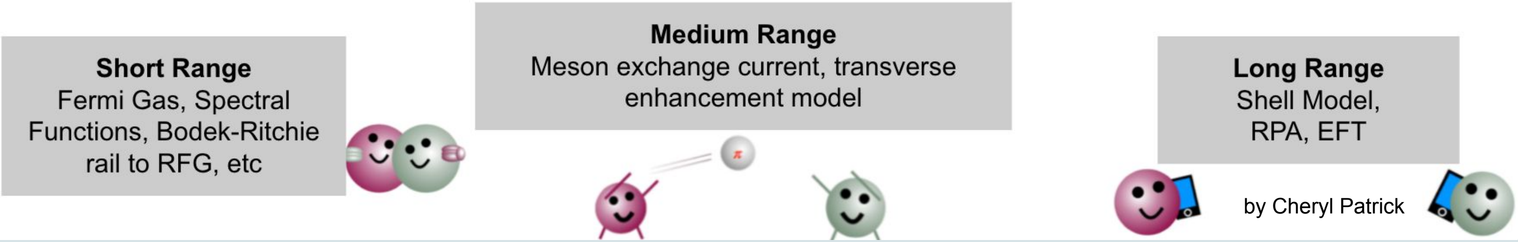
Example: the oscillation of the ν_τ in long-baseline experiments with detectors with Ar40.

Given their resolution could provide higher statistics than previous experiments (OPERA/DONUT) but also:

More statistics → accurate insights for $\nu_\mu \rightarrow \nu_\tau$ oscillation and these results could be used as proof of the properties of neutrinos and their interactions.

Nuclear models rely on different approximations, which are valid in specific kinematics and for specific process.

Can ν_τ give us access to a better understanding of some processes?



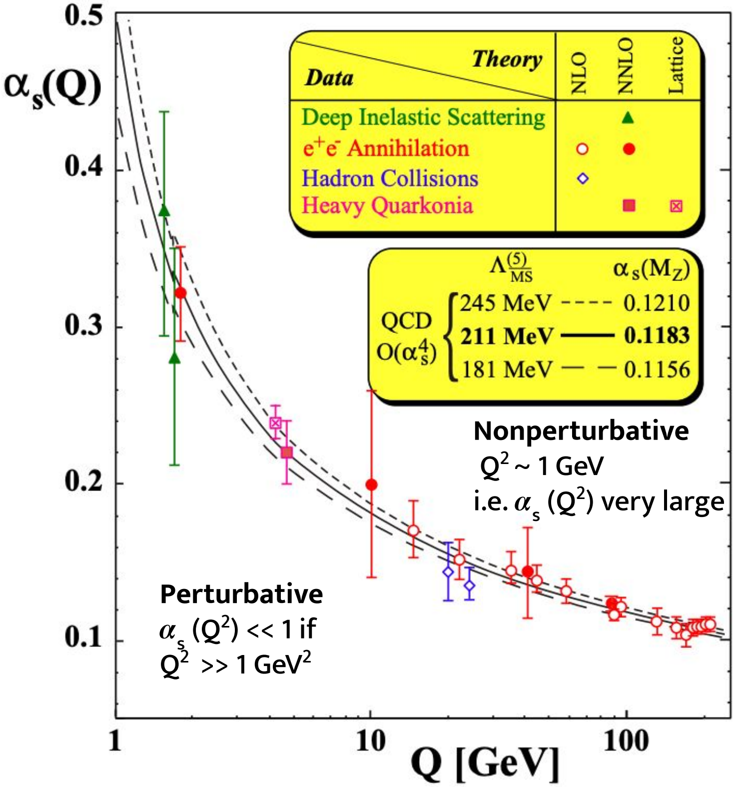
Short Range
Fermi Gas, Spectral Functions, Bodek-Ritchie rail to RFG, etc

Medium Range
Meson exchange current, transverse enhancement model

Long Range
Shell Model, RPA, EFT

by Cheryl Patrick

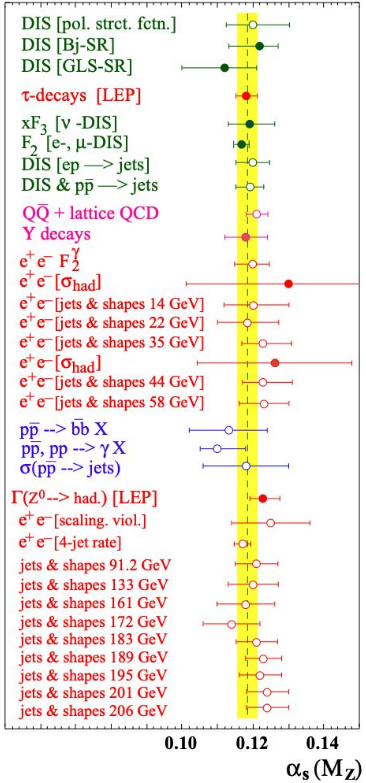
Asymptotic freedom makes it possible to calculate the small distance interaction for quarks and gluons, assuming that they are free particles.



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

Perturbative
$\alpha_s(Q^2) << 1$ if
$Q^2 >> 1\ \text{GeV}^2$

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



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

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

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.

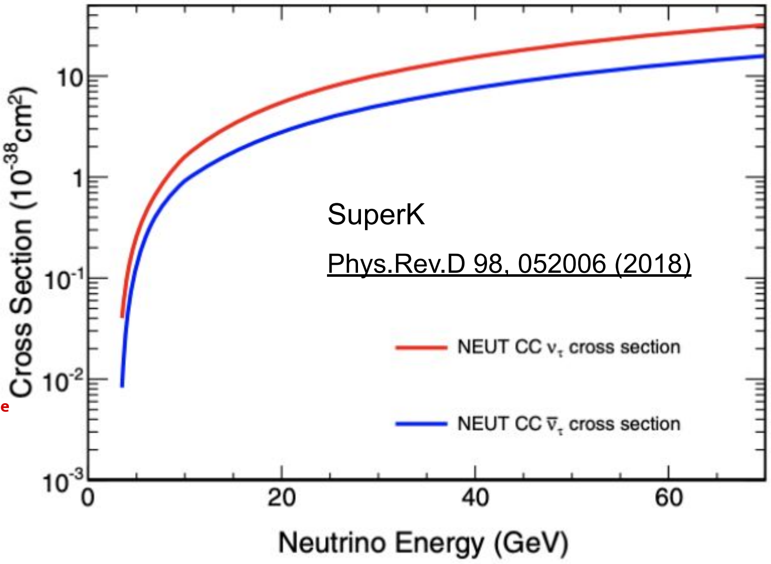
Bodek-Yang model aims for describing DIS cross section in all Q^2 regions
arXiv:hep-ex/0308007

Cross Section for NuTau: ν/ν_{τ} (k) + N(p) → τ/τ (k')

For the DIS the expression for the CC differential cross section is:

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

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



SuperK

Phys.Rev.D 98, 052006 (2018)

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.

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.

The tau mass corrections to 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.

$$\begin{aligned} W^2 &= (p+q)^2 = M_N^2 + 2M_N\nu - Q^2 \ , \\ Q^2 &= -q^2 = -(k-k')^2 \ , \\ x &= Q^2/2p\cdot q = Q^2/2M_N\nu \ , \end{aligned}$$

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

$$a - b \le y \le a + b$$

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

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

A look to the CC - ν_τ and CC-ν_μ Cross Section with and without DIS Cuts

M. H. Reno - PhysRevD.74.033001

Next speaker

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

Reasons of the deficit in CC ν_τ:

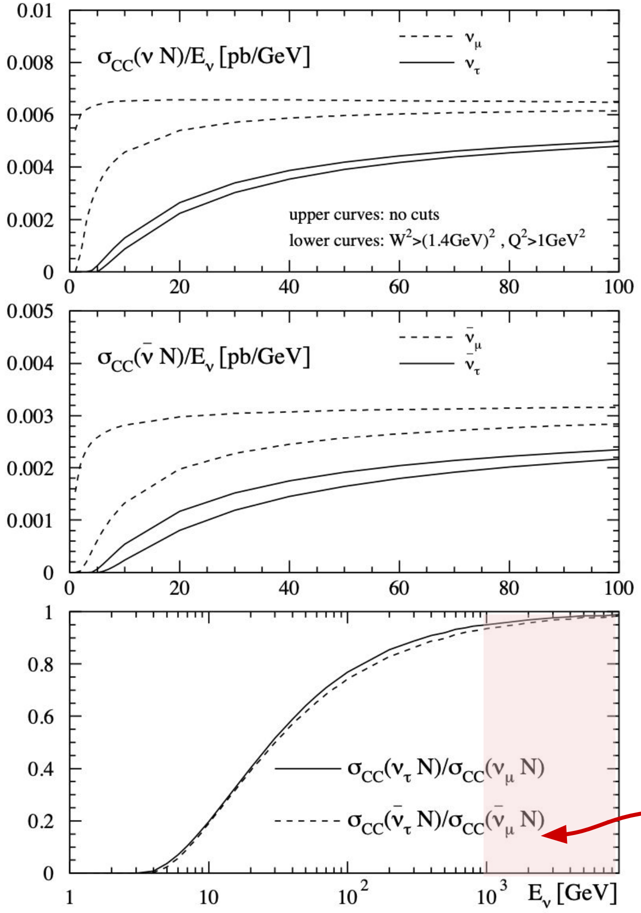
- **Reduce phase space:** integration limits (x,y).

- **F_5 contribution:** independent of x and minus sign.

Also:

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

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



Cuts

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

Ratios

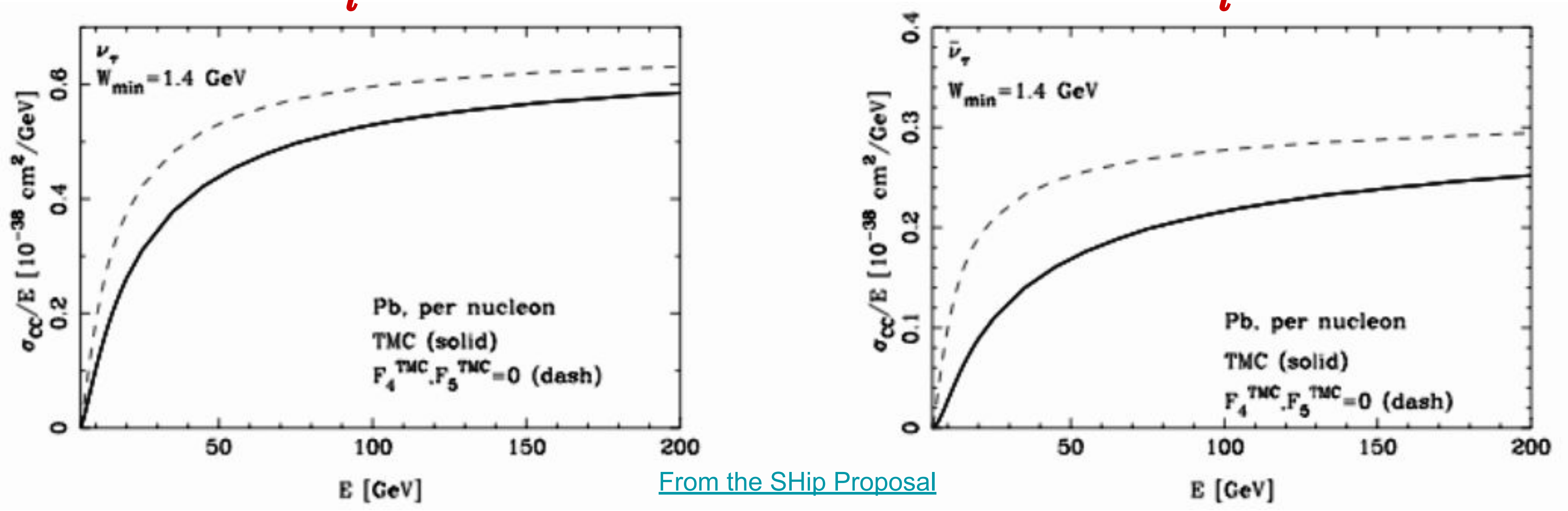
The ratios ν_τ / ν_μ & $\bar\nu_\tau / \bar\nu_\mu$ are insensitive to DIS cuts

There is a deficit for CC-ν_τ
Even at 10^3 GeV the ratio is below 1.

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.

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

ν_τ on PB **$\bar{\nu}_\tau$ on PB**

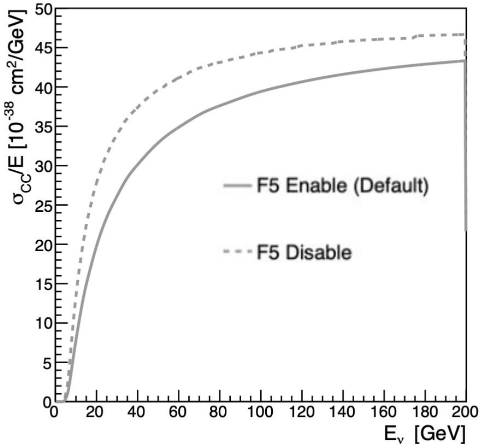


From the SHip Proposal

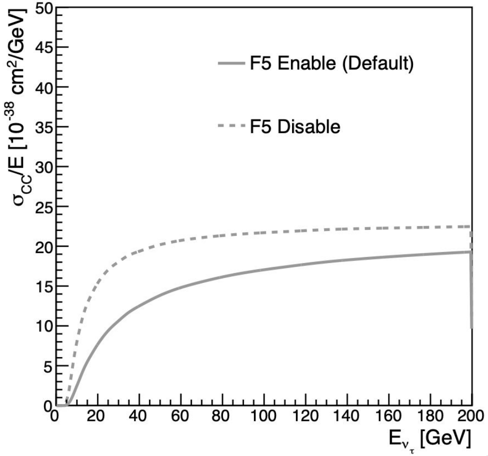
In short, we want to check ν_τ cross-sections in the DIS regime and due its relevance, we choose to conduct those studies in Ar_{40}.

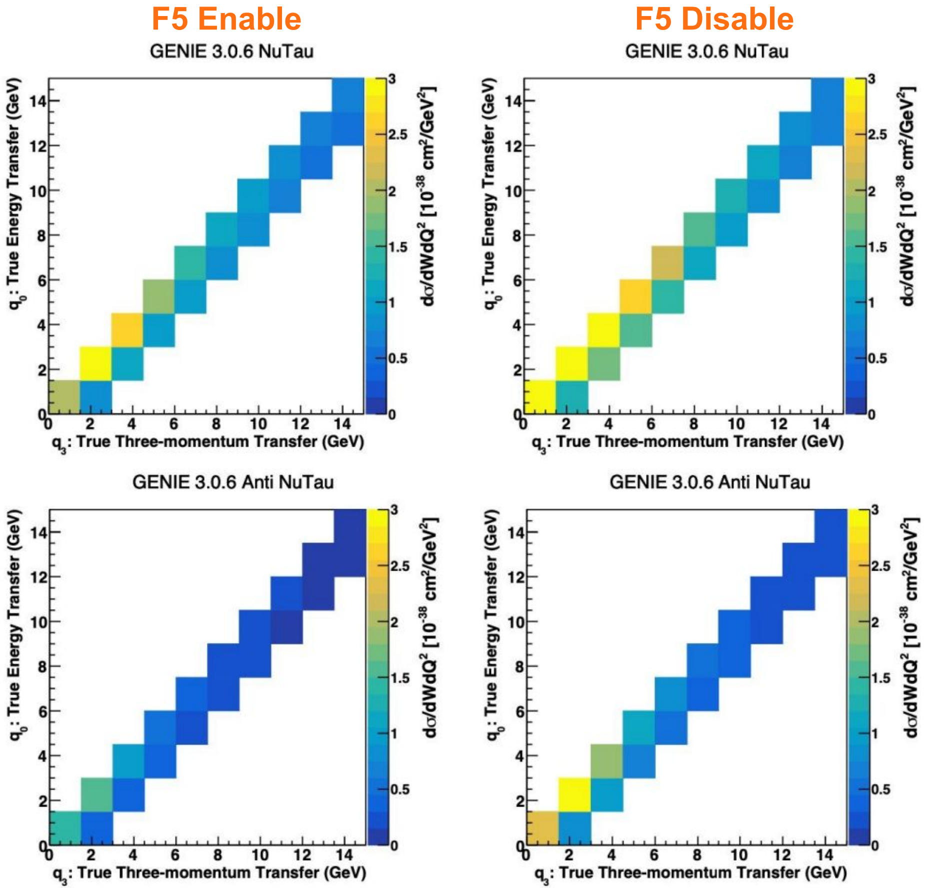
CC - ν_τ TRUTH Level studies show that indeed, when DIS cuts are applied and F_5 = 0 we can extract new information from the lepton cross section.

GENIE 3.0.6
CC-NuTau Cross Section



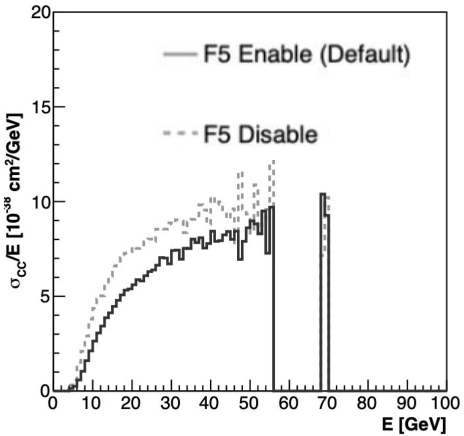
GENIE 3.0.6
CC- Anti NuTau Cross-Section



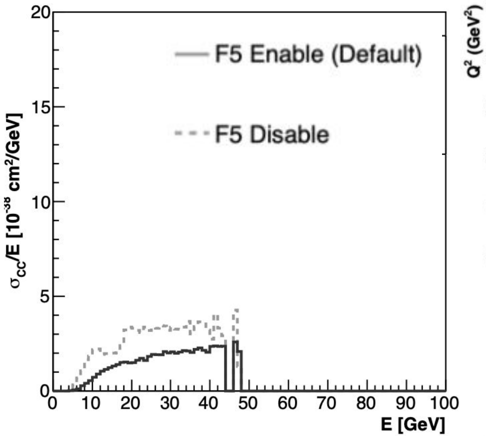


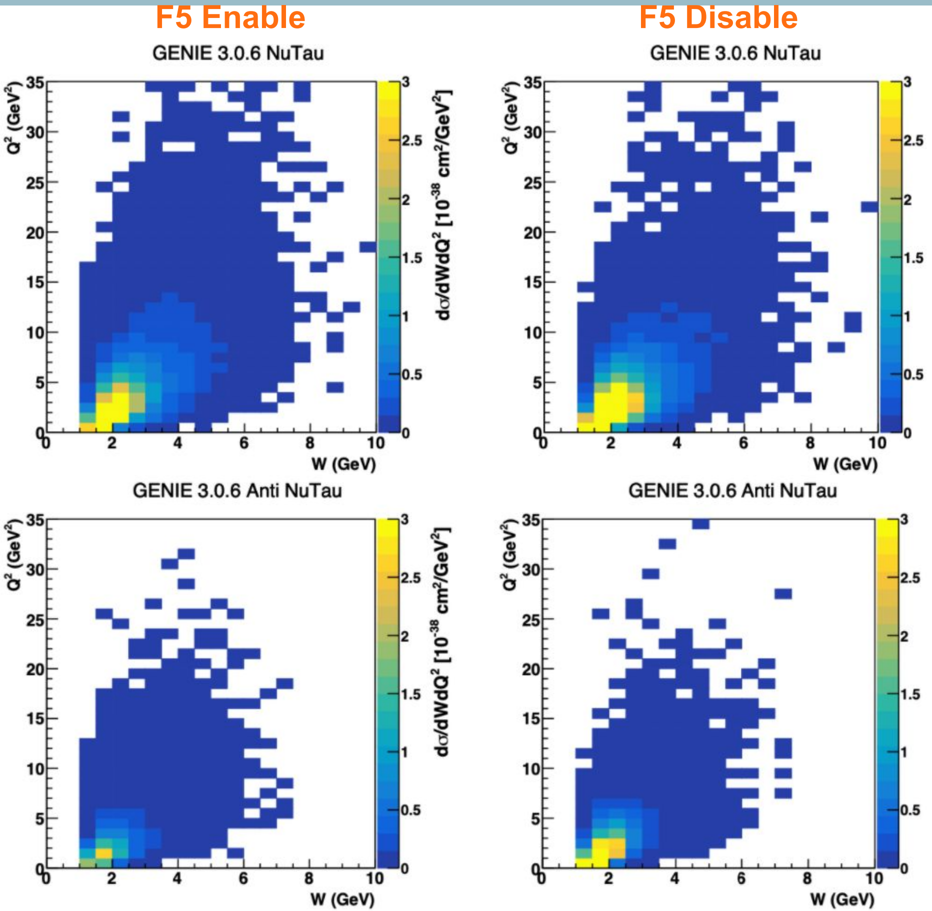
CC - ν_τ TRUTH Level studies show that indeed, when DIS cuts are applied and $F_5 = 0$ we can extract new information from the lepton cross section.

GENIE 3.0.6 NuTau



GENIE 3.0.6 Anti NuTau

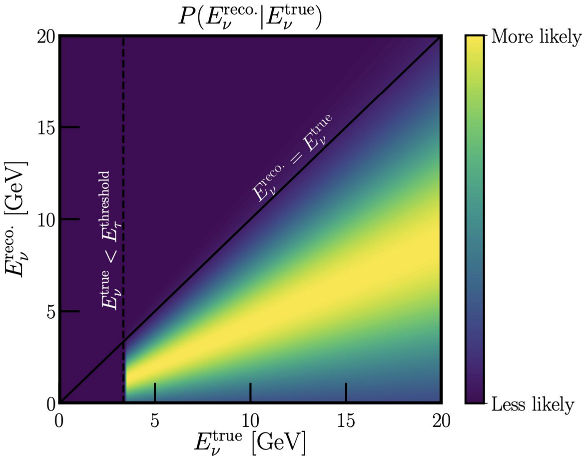




Can we reconstruct kinematic variables?.

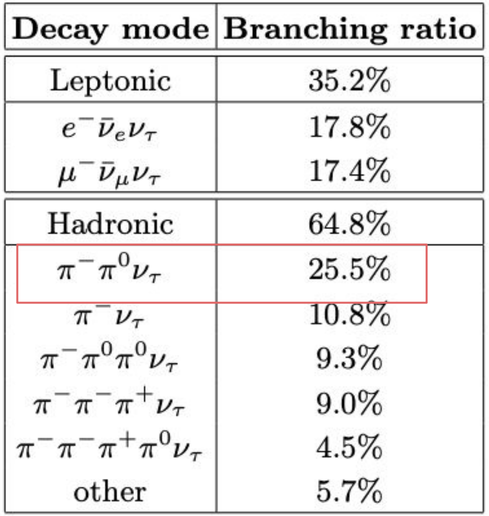
Can we have a minimum resolution to get a cross section?

Tau Neutrino Interactions



A.Gouvea, K. Kelly, G.Stenico, P.Pasquini
PhysRevD.100.016004

P.Machado, J.Turner. H. r Schulz
arXiv:2007.00015



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%

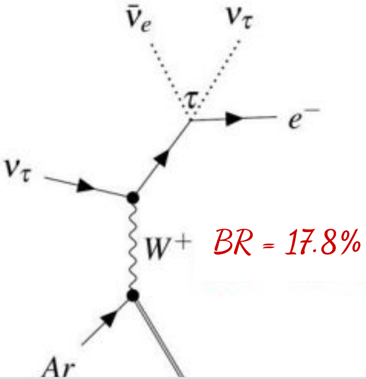
τ is heavy, ~ 1.777GeV

$\tau_{\text{energy threshold}}$ ~ 3.5 GeV

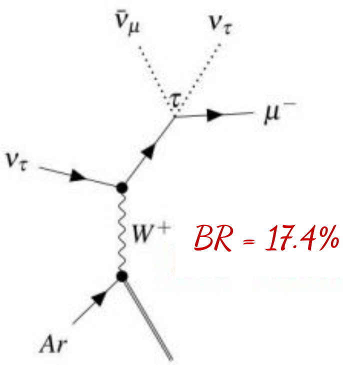
Low statistics

$\tau_{\text{life}} \sim 2.9 \times 10^{-13}$ sec

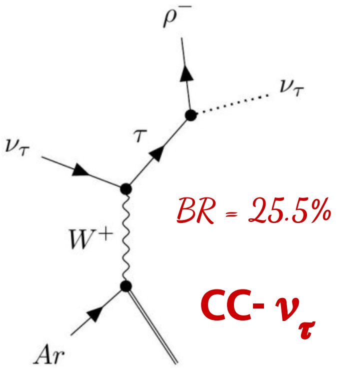
Challenge: ν_τ reconstruction and the background rejection from NC.



BR = 17.8%

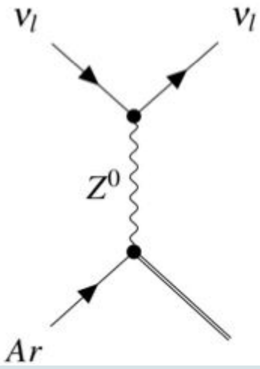


BR = 17.4%



BR = 25.5%

CC- ν_τ



NC- ν_τ

Rho Channel: $\tau \rightarrow \nu_\tau \rho^-$ $\rightarrow \pi^-\pi^0$ Background & Signal Separation

Based on the BDT work by **Miriama Rajaoalisoa,** see also **Thomas Kosc** talk

- Select Rho candidates
- Use a **BDT (Boosted Decision Tree)** classifier to separate the NC-ν_τ from CC- ν_τ

- BDT trained on transverse kinematic variables.

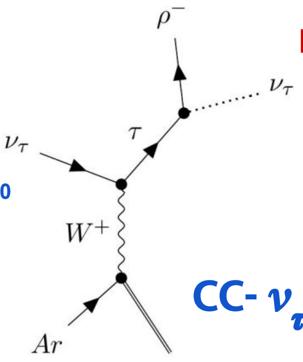
- BDT (Pre-selection): Check for rho decay products identification.

True Rho:

Signal CC: $\tau \rightarrow \nu_\tau \rho^-$

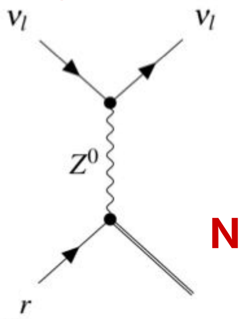
Signal NC: $\rho^- \rightarrow \pi^-\pi^0$

BR = 25.5%



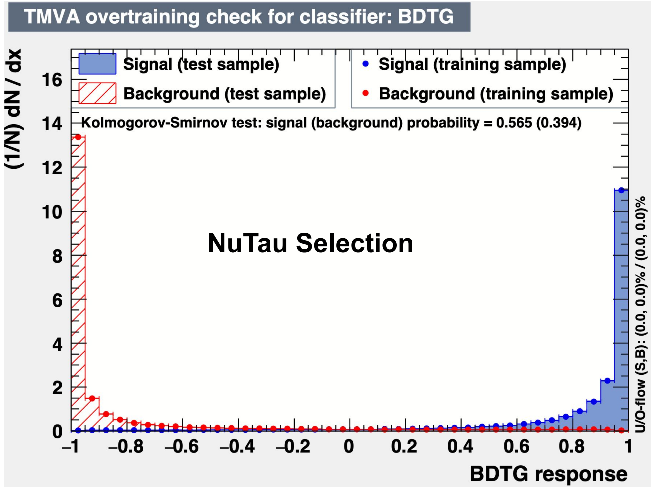
CC- ν_τ

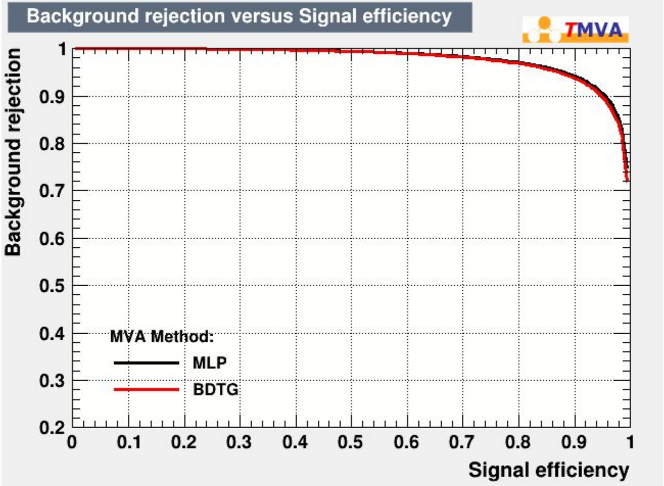
Background - False Rho:



Any $\pi^{-/+}\pi^0$ couple created out of the hadronic τ- decay, i.e not a True Rho.

NC- ν_τ

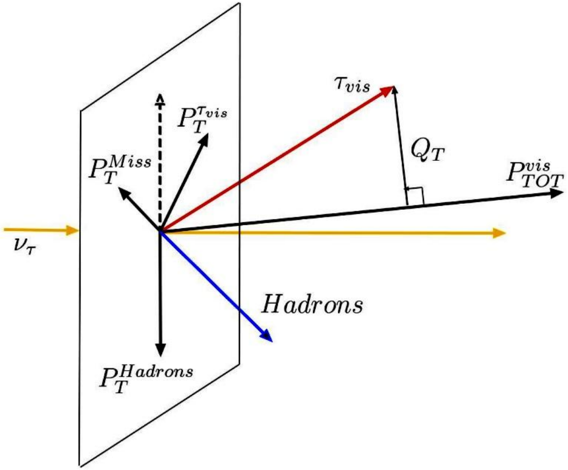


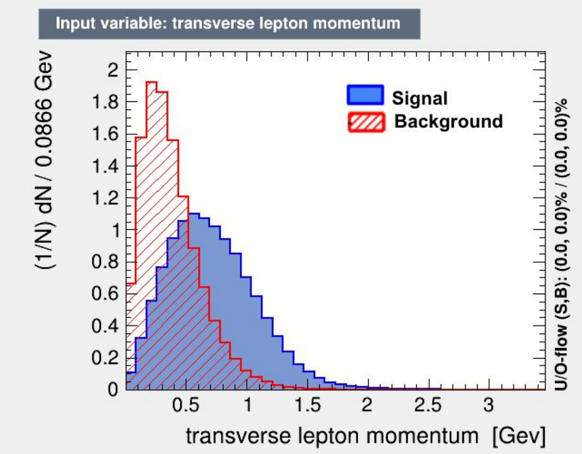


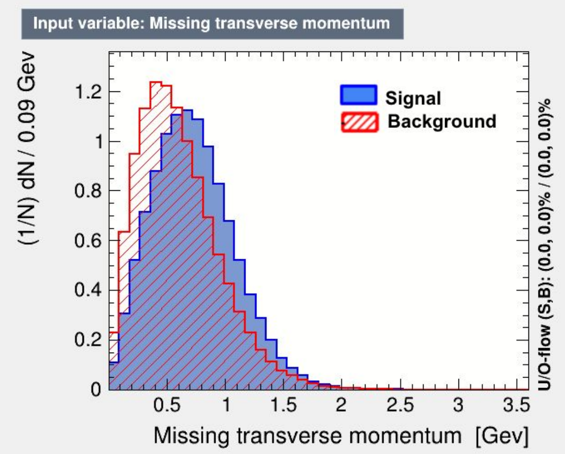
MVA:
Multivariate analysis

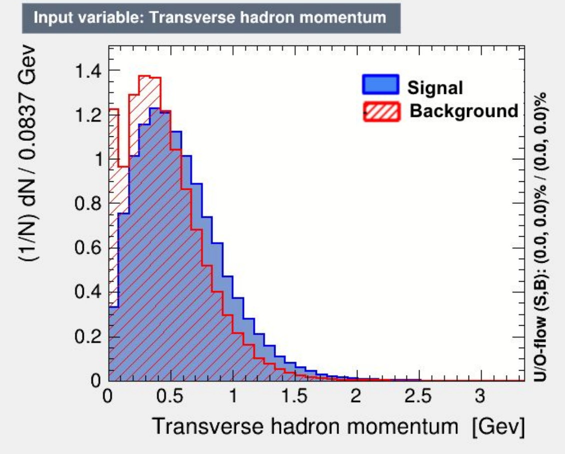
MLP:
Multi Layered Perceptrons

Transverse Kinematic Variables - BDT trained with non-smeared

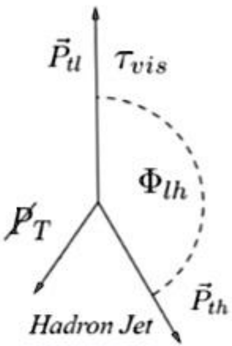



Input variable: transverse lepton momentum

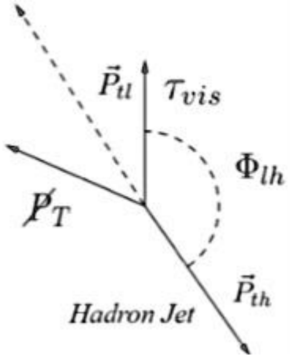

Input variable: Missing transverse momentum


Input variable: Transverse hadron momentum

Background Interaction Products



NuTau Interaction Products

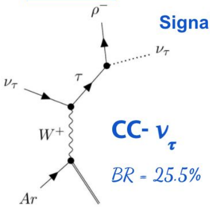


Rho Selection - BDT trained with non-smeared

True Rho:

Signal CC: $\tau \to \nu_\tau \rho^-$

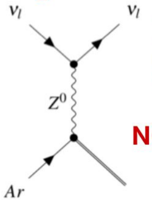
Signal NC: $\rho^- \to \pi^- \pi^0$



CC- ν_τ

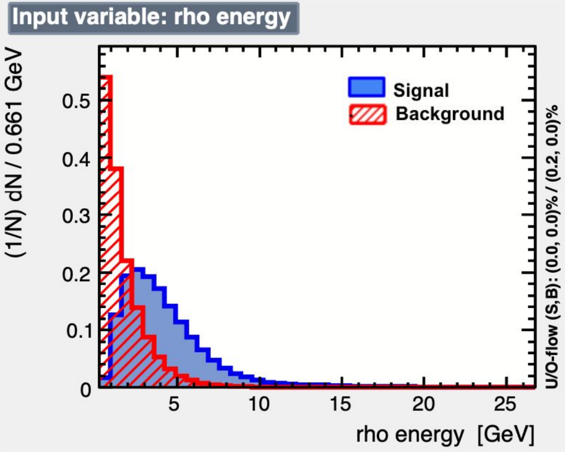
BR = 25.5%

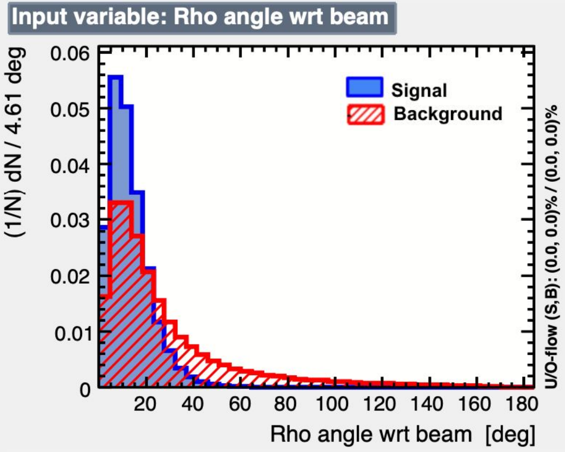
Background - False Rho:

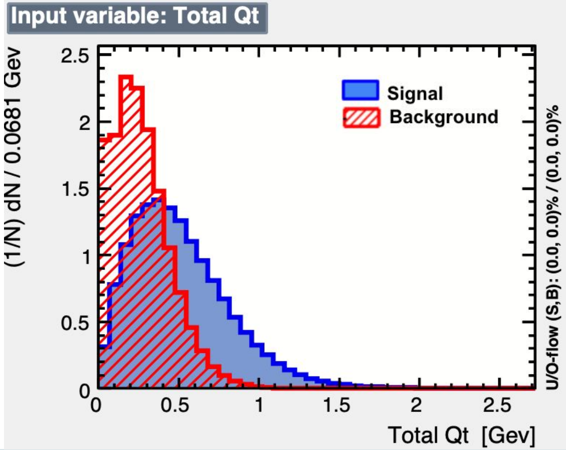


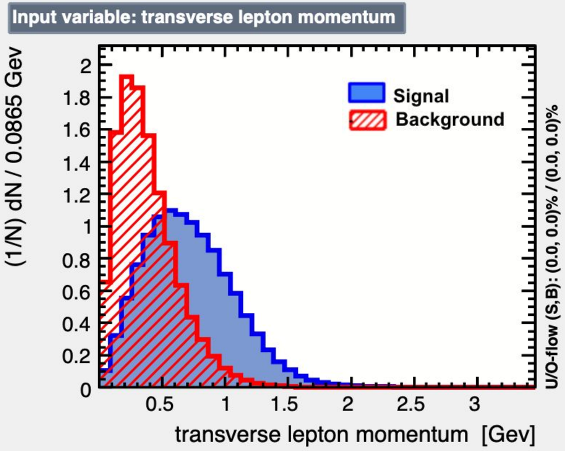
Any $\pi^{-/+}\pi^0$ couple created out of the hadronic τ- decay, i.e not a True Rho.

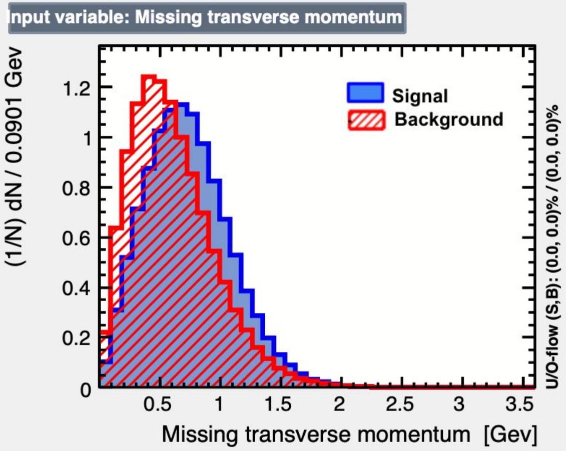
NC- ν_τ


Input variable: rho energy


Input variable: Rho angle wrt beam


Input variable: Total Qt


Input variable: transverse lepton momentum


Input variable: Missing transverse momentum

COMMENTS

In general:

- NuTau physics is challenging but everything that we could learn from it would be productive & worthwhile.

In specific:

- Signal and background separation over the transverse kinematic variables is acceptable.
- There is room to test other reconstruction tools different than the BDT score.
- **Coming soon: kinematic variables reconstruction.**

Thank you!

Milky Way and Volcan de Fuego , Guatemala

Backup

Leptonic channels

- Missing transverse momentum P_T^{miss}.
- Angle between the transverse hadronic system momentum and transverse lepton (tau visible product) momentum φ_{lh}.
- Angle between the missing transverse momentum and transverse lepton (tau visible product) momentum φ_{ml}.
- Lepton transverse momentum P_T^l.
- Hadronic system transverse mometum P_T^h.
- Lepton (tau visible product) energy E_l.
- Total visible energy E_{Total}^{vis}.
- Transverse mass M_T.
- Angle between the neutrino direction and missing transverse momentum $\theta_{\nu m}$.
- Angle between the neutrino direction and the hadronic system $\theta_{\nu h}$.
- Angle between the neutrino direction and the lepton (tau visible product) $\theta_{\nu l}$.
- Ratio between the hadronic system and the total visible energy.
- Component of the lepton (tau visible product) momentum perpendicular tot the total visible momentum.
- Ratio of the transverse lepton (tau visible product) momentum and the missing transverse momentum.

Rho classification

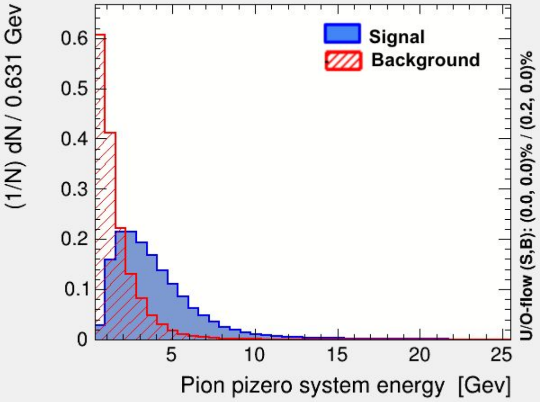
- Energy of the $\pi^0/\pi^\pm$ couple.
- Energy of the $\pi^\pm$.
- Invariant mass of the pion.
- Invariant mass of the π^0.
- Pion energy sharing $r_\pi^K = \frac{E_\pi^K}{E_\pi^K + E_{\pi^0}^K}$.
- Distance invariant mass and mass d $= \sqrt{(M_{\pi^0}^{(inv)} - m_{\pi^0})^2 + (M_\rho^{(inv)} - m_\rho)^2}$.
- Angle between the $\pi^\pm$ and π^0.
- $\pi^\pm$ momentum.
- π^0 momentum.

Rho channel vs NC classification

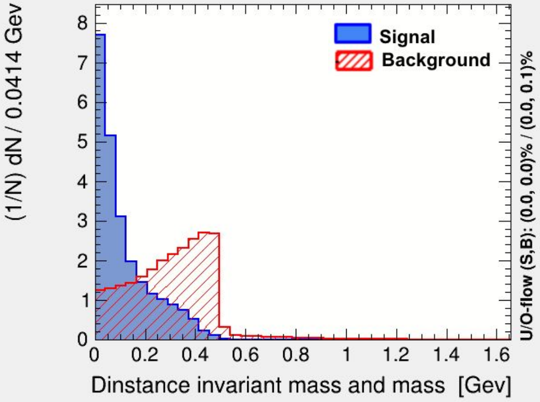
- All previous variables including those used for the leptonic channels.
- Minimum angle between the tau visible daughter and the hadronic system.
- Ratio between the transverse size of the hadronic system and the full event.

Rho Selection - BDT trained with non-smeared

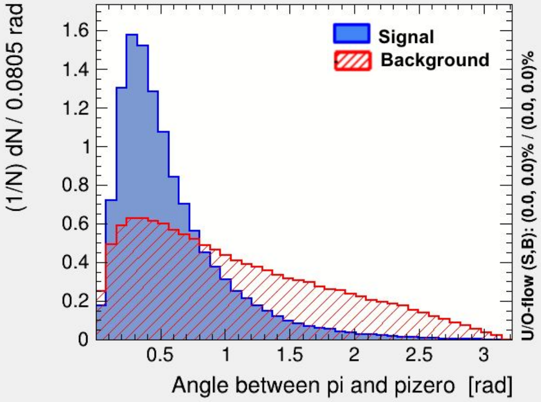
Input variable: Pion pizero system energy



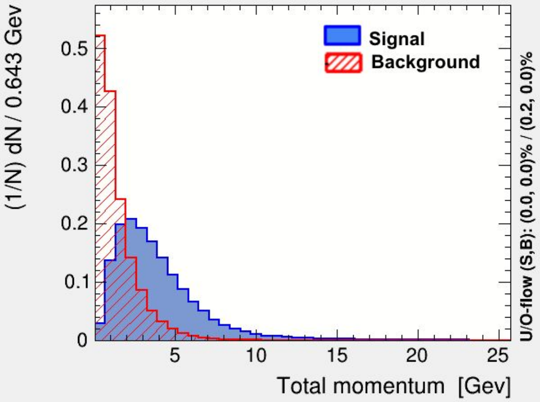
Input variable: Dinstance invariant mass and mass



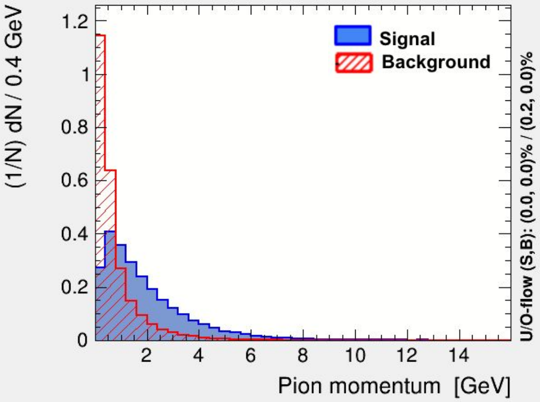
Input variable: Angle between pi and pizero



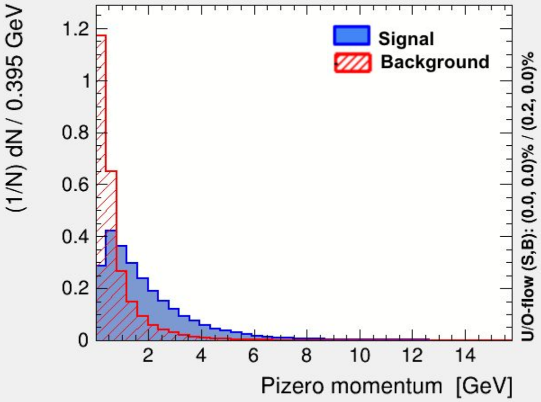
Input variable: Total momentum



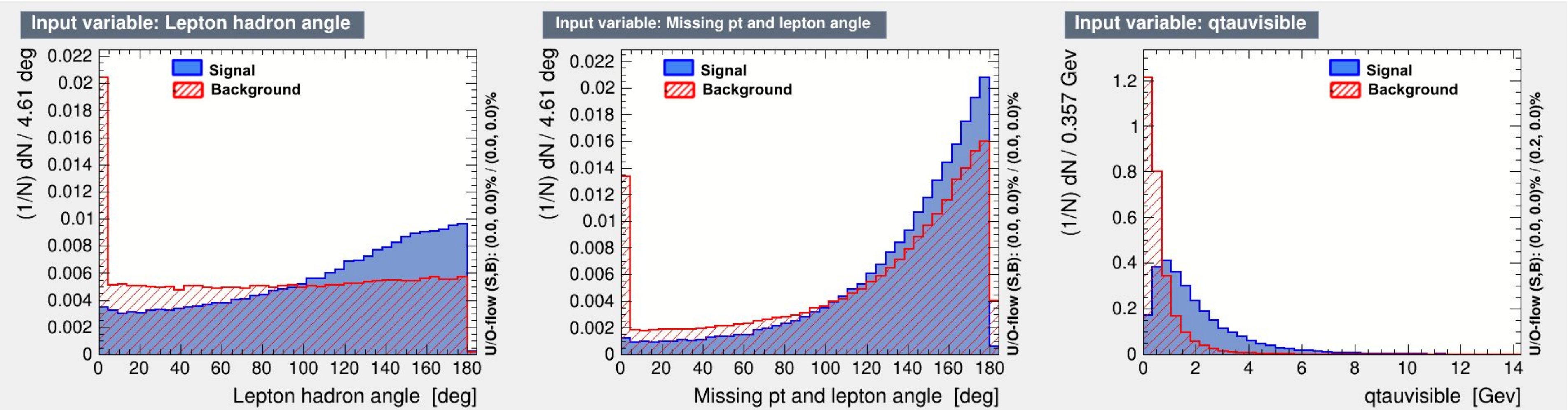
Input variable: Pion momentum

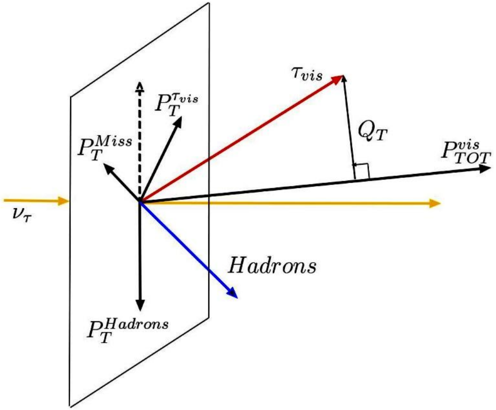


Input variable: Pizero momentum

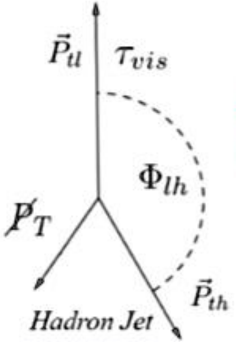


Transverse Kinematic Variables - BDT trained with non-smeared

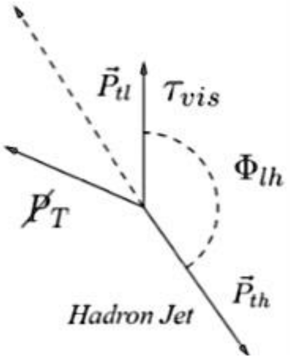




Signal interaction products



Background interaction products



Transverse Kinematic Variables - BDT trained with non-smeared