# Tau neutrino reconstruction (in LArTPC)

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# Why tau neutrinos ?

- Tau neutrino remains the least particle studied in the Standard Model :
  - DoNuT 9 candidates **0711.0728**
  - OPERA 10 candidates **1804.04912**
  - Atmospheric nutau appearance by IceCUBE **1901.05366** and SuperK **1206.0328**

- Physics with tau neutrino in DUNE (nutau working group) :
  - cross-section measurement,
  - 3 flavour phenomenology consistency,
  - PMNS unitarity,
  - non-standard interactions,
  - tau neutrino appearance at the ND.

**Physics with Beam Tau-Neutrino Appearance at DUNE**

André de Gouvêa,[1] Kevin J. Kelly,[1,2] G. V. Stenico,[1,3] and Pedro Pasquini[2,3]

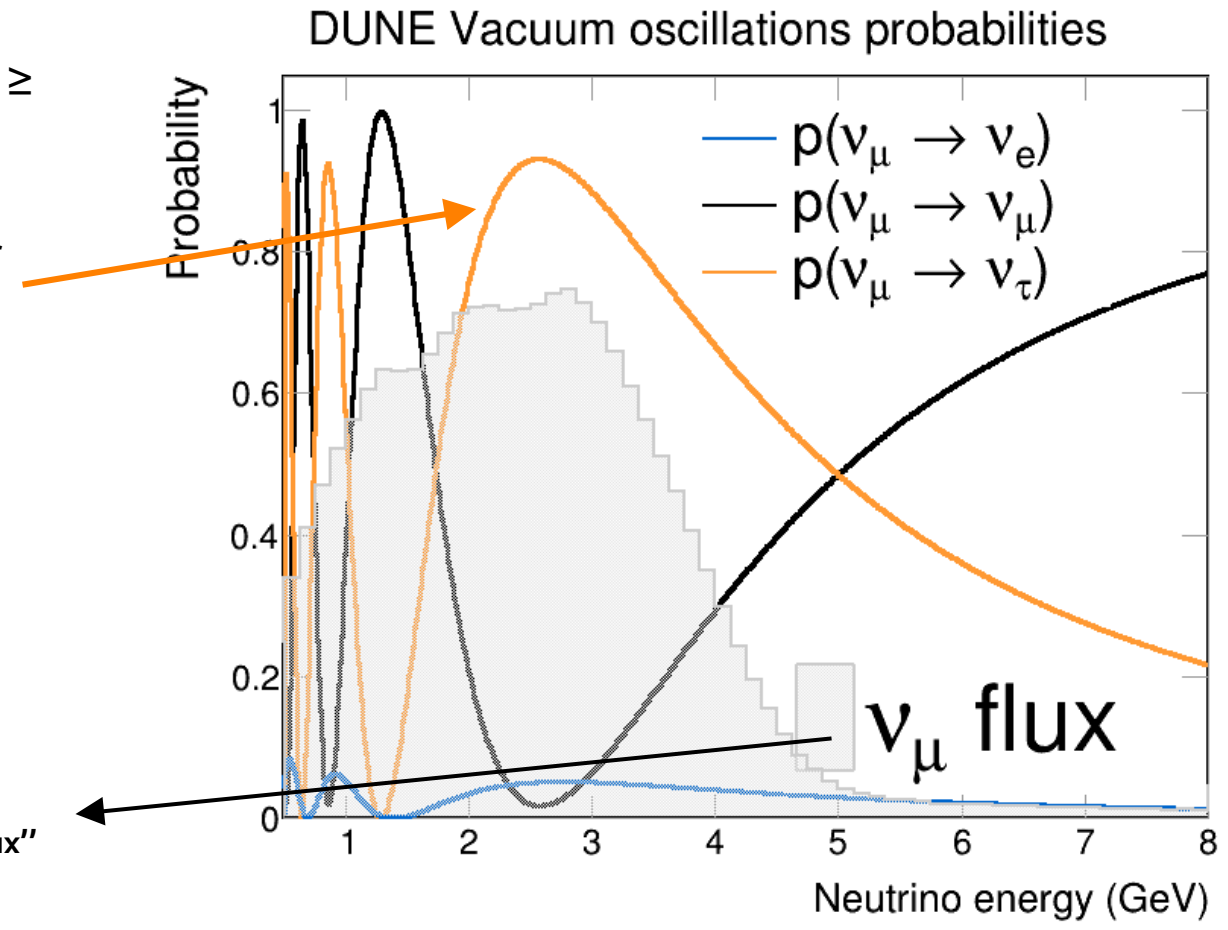
1904.07265

- Broader interest including not only DUNE (nutau workshop september 2021)

**Tau Neutrinos in the Next Decade: from GeV to EeV** 2203.05591

# DUNE as a tau neutrino observatory

- numu→nutau is the main oscillation channel at energies ≥ 1 GeV.
- Most muon neutrinos cross far detectors as tau neutrinos !




**Actually this is "unoscillated flux"**

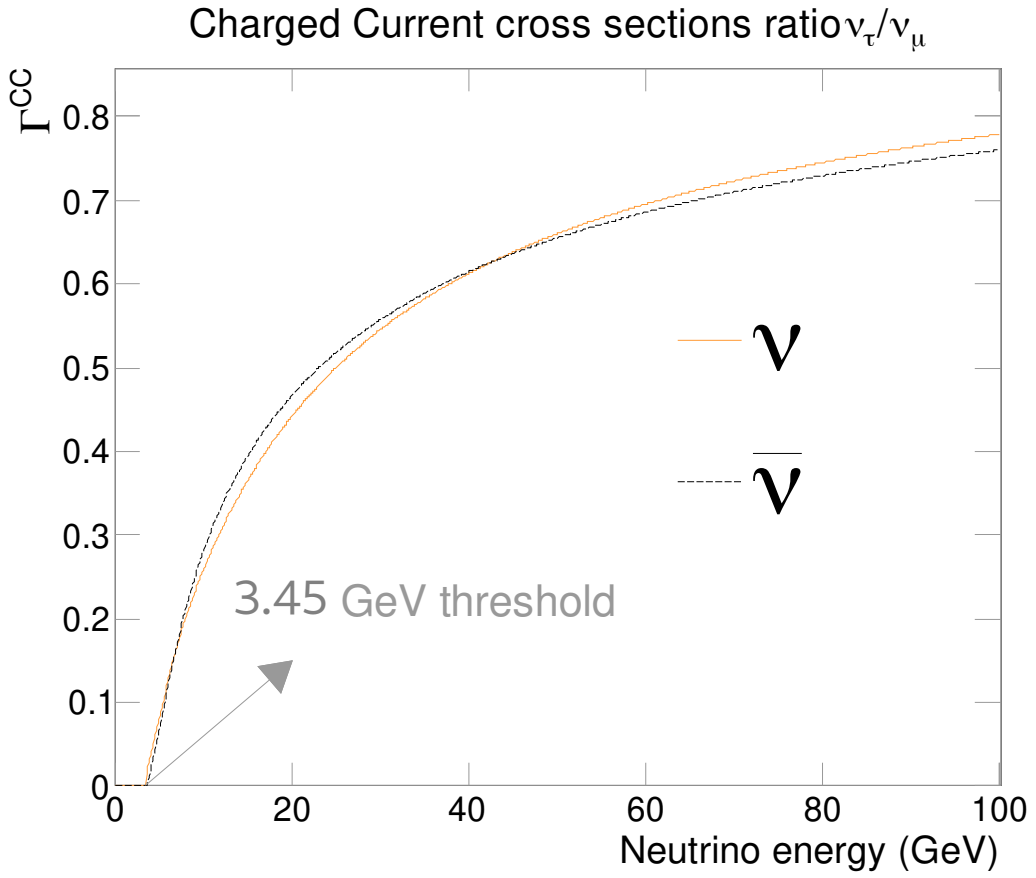
# Challenges for tau neutrinos : energy threshold

- nutau quasi elastic charged current interaction : $\nu_\alpha(E_\nu) + n(m_n; \vec{p}_n) \rightarrow \alpha(M_\alpha; \vec{p}_\alpha) + p(m_p; \vec{p}_p)$
- Most general case where target neutron has Fermi momentum.

$$E_\nu \geqslant \frac{(m_p^2 - m_n^2) + 2m_p M_\alpha + M_\alpha^2 + p_n^2}{2(m_n + p_n)}.$$

- Numerical values with $p_n = 0$ :
  - Electron neutrino : no threshold
  - Muon neutrino : 0.11 GeV
  - Tau neutrino : **3.45 GeV**
- Most of tau neutrinos crossing DUNE far detectors will not trigger any charged current interaction.

# Challenges for tau neutrinos : unfavourable cross-section




- The large mass of the tau lepton makes nutau interactions less favourable.
- At DUNE energies, nutau CC cross-section is about 10-15 % of numu CC cross-section.

# Event rates

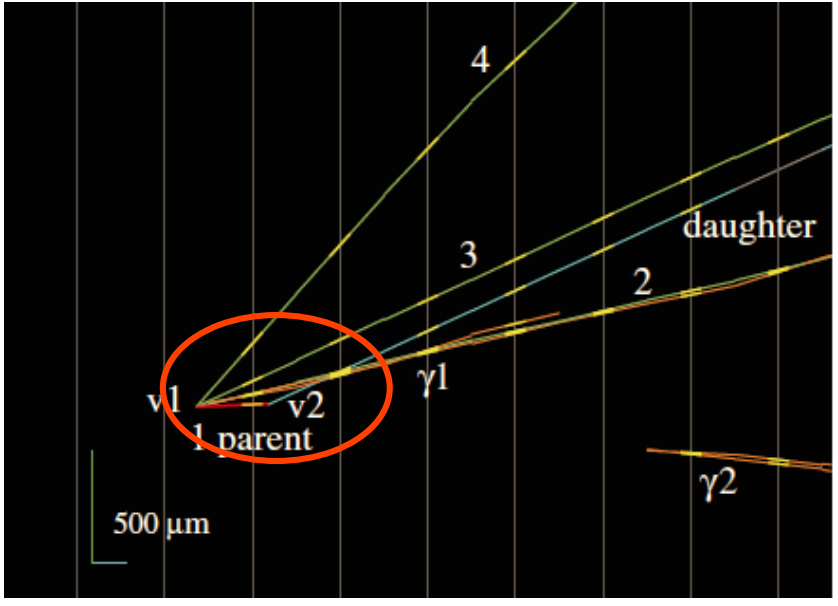
- 20 kTon x 5 years far detector neutrino event rates (normal hierarchy assumed, inverted hierarchy shown between brackets).
  Baseline 1285 km, constant density 2.8 g/cm3.

| $\nu$ mode | |
|---|---|
| $\nu_e$ from osc. | 1197 (564) |
| $\bar{\nu}_e$ from osc. | 18 (29) |
| $\nu_e$ from beam cont. | 365 (371) |
| $\bar{\nu}_e$ from beam cont. | 57 (56) |
| $\nu_\mu$ | 9660 (9674) |
| $\bar{\nu}_\mu$ | 741 (732) |
| $\nu_\tau$ from oscillation | 270 (290) |
| $\bar{\nu}_\tau$ from oscillation | 25 (26) |
| NC | 8832 (8832) |

- nueCC, numuCC and NC are background to tau neutrino search

# Ideal reconstruction technique

- Ideally one would reconstruct :
  - the track of the tau lepton with great spatial resolution (see a kink !),
  - the energy flow of the final state.
- → Works pretty well at identifying tau neutrinos (OPERA on the left and DONuT on the rigth).

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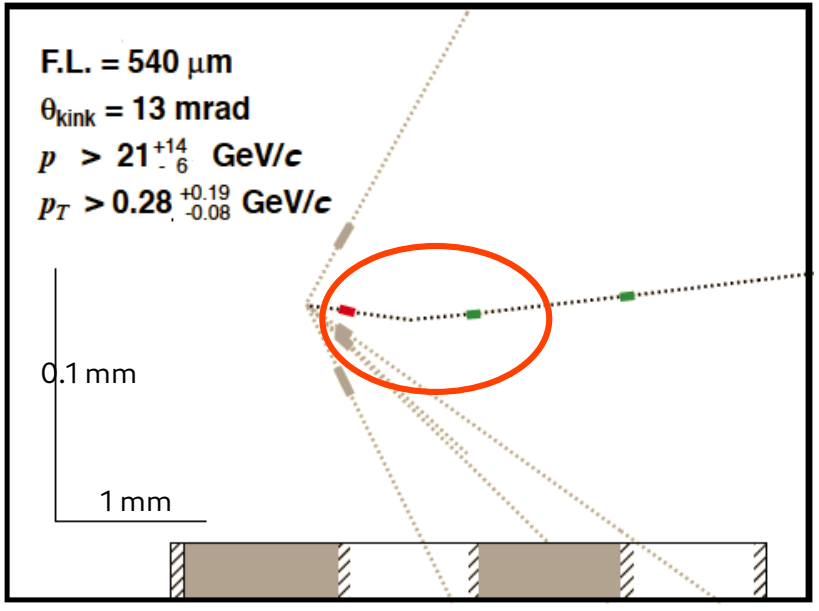


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# Typical track length before decay in DUNE

- LArTPC typically have a **few millimeters** spatial resolution.
- Tau lepton decay lifetime is 3x10^-13 s in its restframe.

$$t_\tau = 3 \times 10^{-13} s$$

$$L_{lab} = t_\tau \times c \times \left(\frac{E_\tau}{m_\tau}\right) \simeq 150\,\mu m \left(E_\tau = 3\,GeV\right)$$

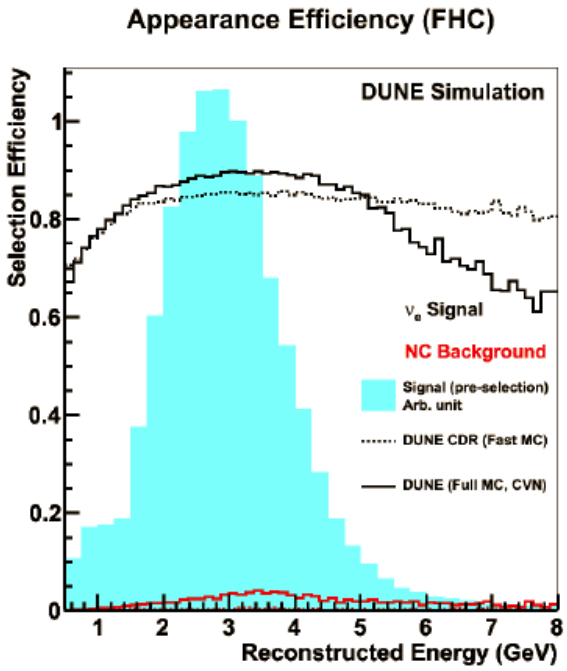
- DUNE far detectors **will not have sufficient spatial resolution** to resolve the kink associated to the tau lepton decay !
- Tau leptons decay both leptonically and hadronically → tricky reconstruction.

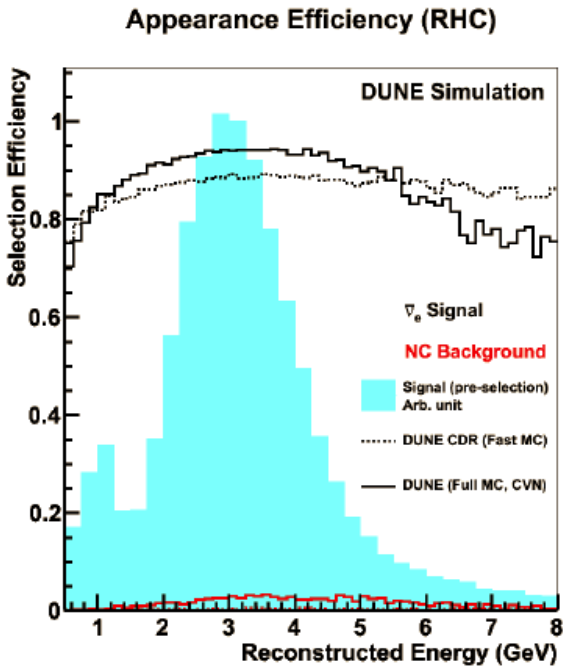
| $\tau \to e$ | $\tau \to \mu$ | $\tau \to \rho \to \pi^{\pm}\pi_0$ | $\tau \to \pi$ | $\tau \to 3\pi$ |
|---|---|---|---|---|
| $17.83 \pm 0.04$ | $17.41 \pm 0.04$ | $25.52 \pm 0.09$ | $10.83 \pm 0.06$ | $9.31 \pm 0.06$ |

**81% branching ratio percentages of tau decay**

# CVN to identify tau neutrinos ?

- Convolutionnal Neural Networks (CVN) are used by the collaboration as a neutrino flavour identifier. Working pretty well on electron and muon neutrinos.




- In the TDR we published ~90 % of selection efficiency at max event rate.

# CVN to identify tau neutrinos ?

- CVN results not yet available for new FD production. In my thesis I studies results from the TDR production (mc11).

| CVN classification | p($\nu_e$CC)>0.85 | p($\nu_\mu$CC)>0.5 | p($\nu_\tau$CC)>0.5 | p(NC)>0.5 | else |
|---|---|---|---|---|---|
| Fraction (%) | 9.9 | 16.0 | 15.4 | 41.0 | 17.7 |

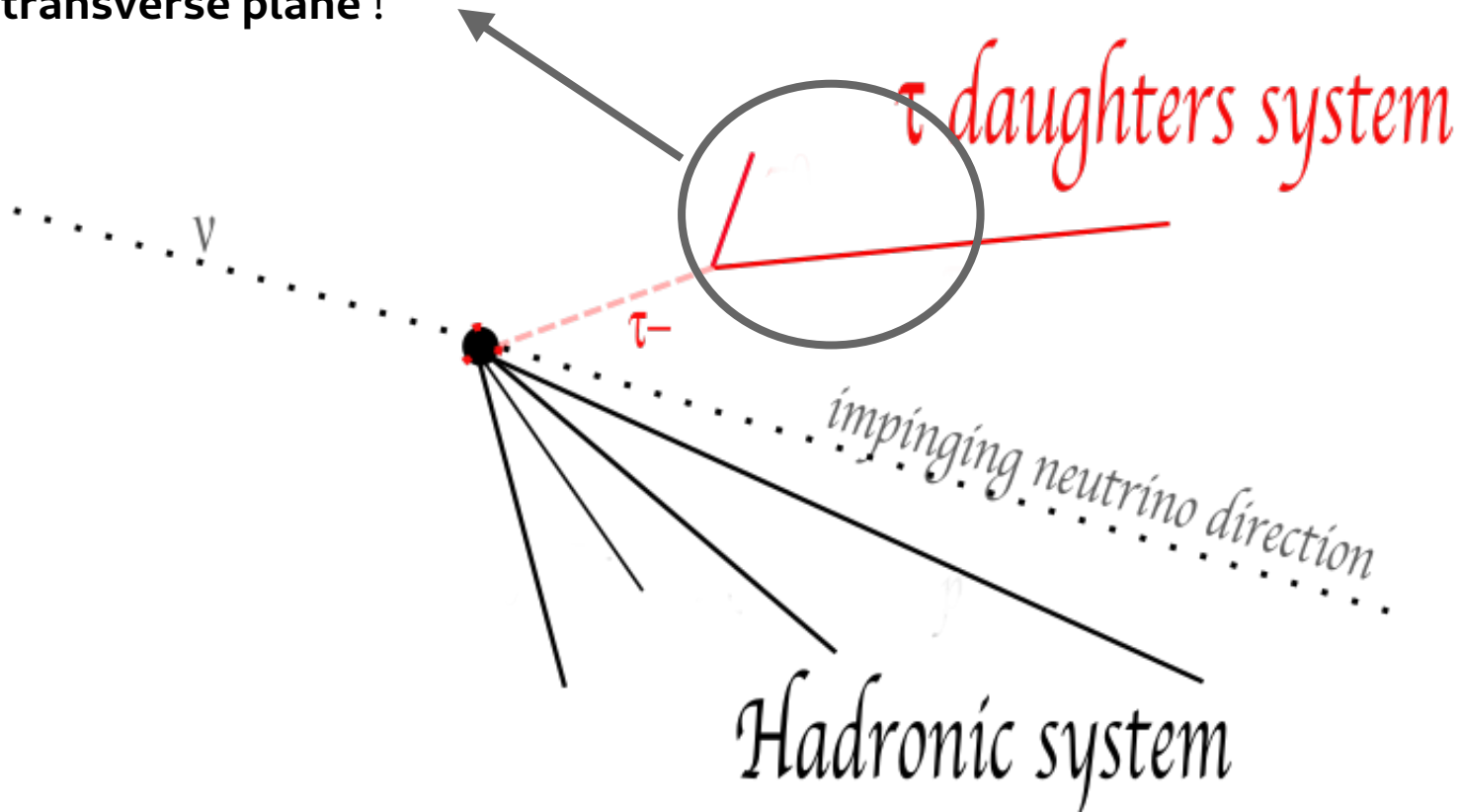
**CVN classification of simulated beam nutauCC interactions at DUNE far detectors**

- Most of nutau are misclassified as NC (hadronic decays). Sometimes as nue or numu (leptonic decays)

- Only 15.4 % of nutau are correctly classified.

# Key elements of kinematic analysis

- The impinging (beam) tau neutrino direction is known
- At least one undetected neutrino (missing momentum) in the leptonic system → move to **transverse plane** !

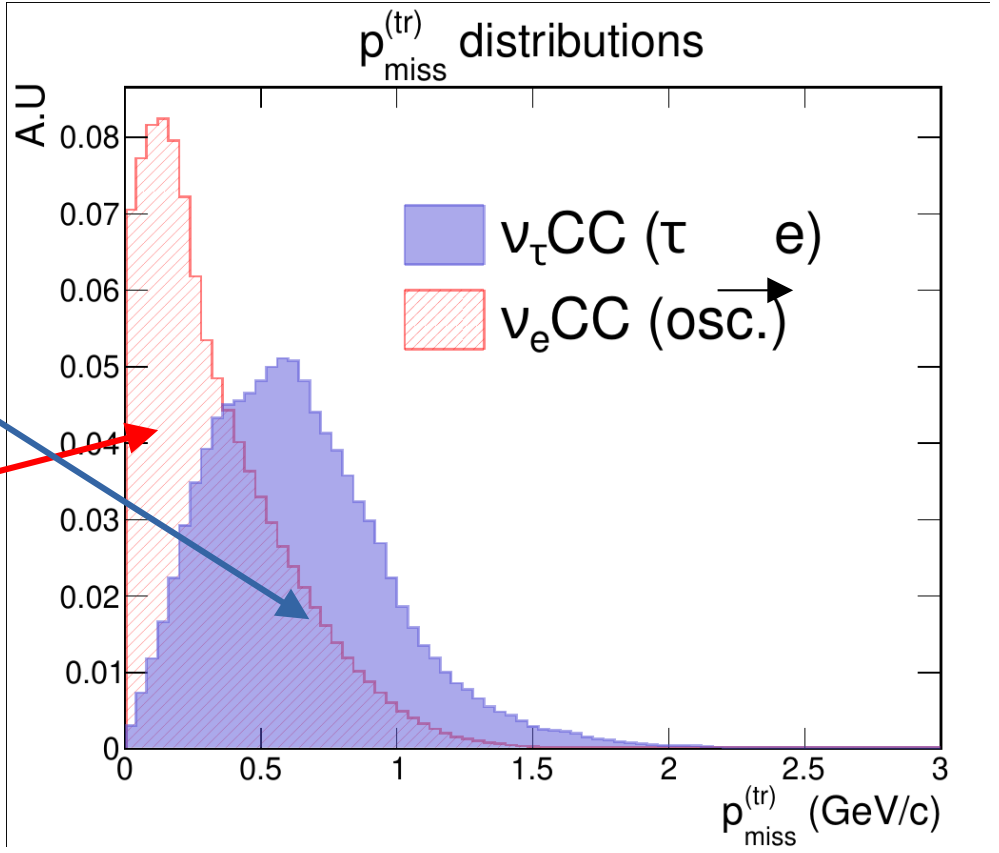


# Transverse missing momentum

- Compare :
  - **nutau CC interactions (tau lepton decays electronically)**
  - **nue CC interactions (numu→nue)**

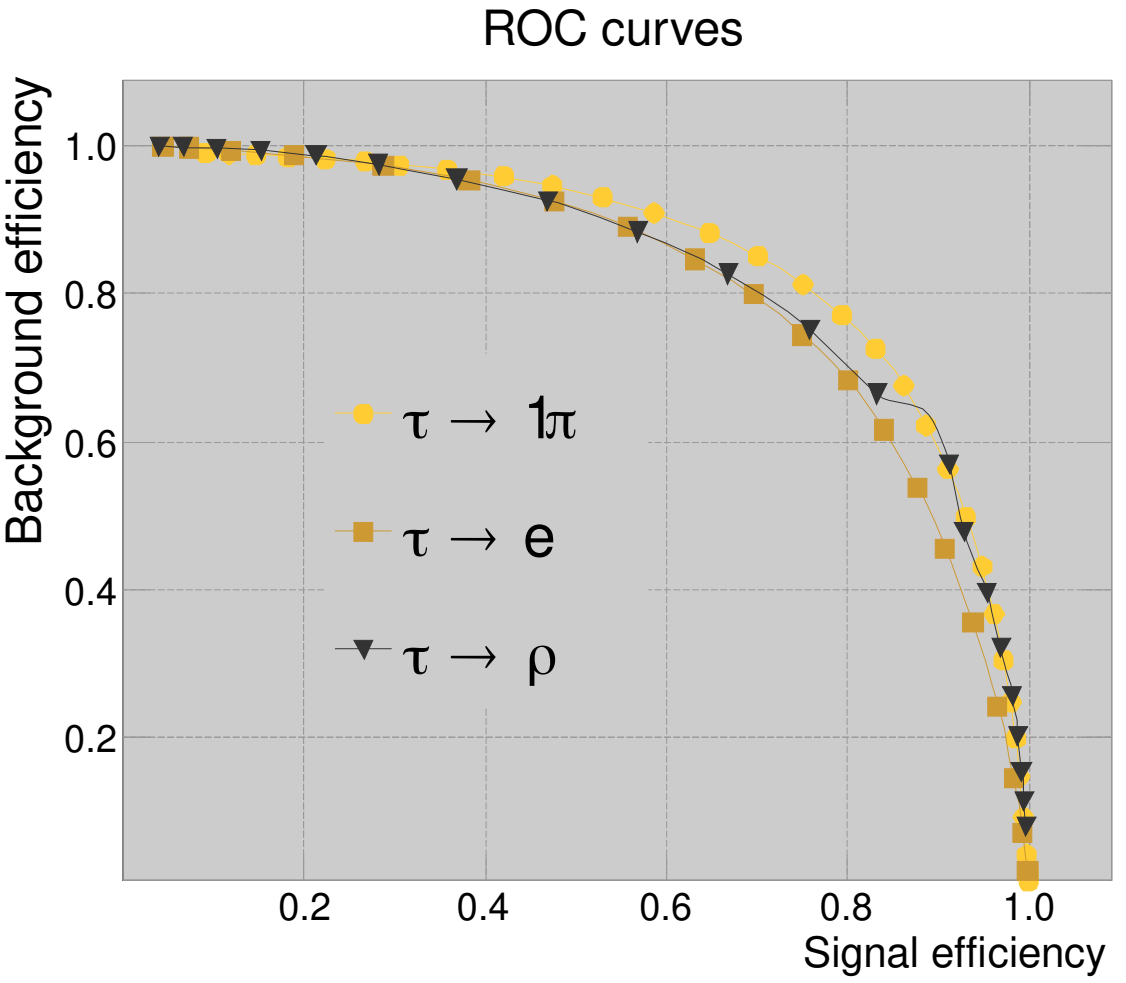
- Higher transverse missing momentum for nutauCC (undetected neutrinos).

- Non-zero transverse missing momentum for nueCC (neutrons + Fermi momentum + nuclear effects + FSI…).



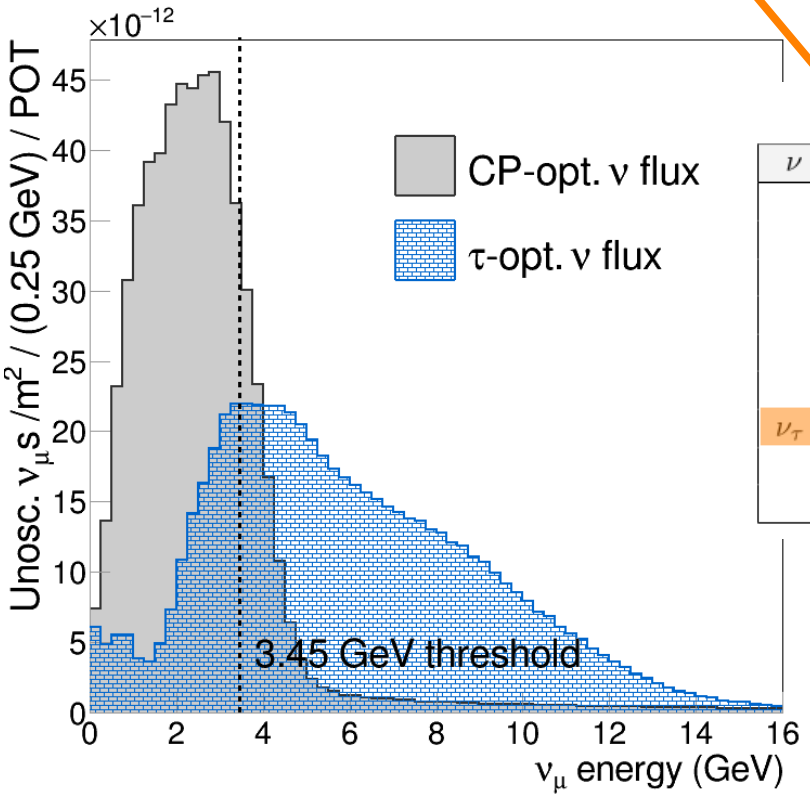
# DUNE expected efficiency for nutau appearance

- In my thesis I developped kinematic studies for 3 tau decay modes, each with its own background), no full chain simulation.
- Background rejection > 95 % means signal selection < 40 %
- Remind unfavourable initial signal to background ratio !



# Tau optimized neutrino beam

- Possibility to change horns configuration in order to select higher energy muon neutrinos
- Boost tau neutrino charged current event rate




| $\nu$ mode | CP optimized flux | $\tau$ optimized flux |
|---|---|---|
| $\nu_e$ from osc. | 1197 | 1199 |
| $\bar{\nu}_e$ from osc. | 18 | 11 |
| $\nu_e$ from beam cont. | 365 | 543 |
| $\bar{\nu}_e$ from beam cont. | 57 | 56 |
| $\nu_\mu$ | 9660 | 37673 |
| $\bar{\nu}_\mu$ | 741 | 683 |
| $\nu_\tau$ from oscillation (QEL/RES/DIS) | 270 (124/62/70) | 1658 (531/597/448) |
| $\bar{\nu}_\tau$ from oscillation | 25 | 22 |
| NC | 8832 | 18126 |

# Discussion

- Tau neutrino as a promising secondary scientific program of DUNE.
- Challenges are in the reconstruction of tau neutrino interactions. LArTPC offer good opportunity to tackle the challenge.
- Kinematic analysis, resolving the tau lepton track is out of scope for far detectors.

# Thank you !

# CVN to identify tau neutrinos ?

- CVN results displayed with respect to tau decay modes. **Each row must be read separately** !

| $\tau$ decay mode (BR %) | p($\nu_e$CC)>0.85 | p($\nu_\mu$CC)>0.5 | p($\nu_\tau$CC)>0.5 | p(NC)>0.5 | else |
|---|---|---|---|---|---|
| $\tau^- \to e^-$ (17.8) | 45.7 | 0.7 | 10.4 | 16.7 | 26.5 |
| $\tau^- \to \mu^-$ (17.5) | 0.1 | 66.2 | 5.5 | 17.5 | 10.7 |
| $\tau^- \to \rho^-$ (22.4) [1] | 3.6 | 4.7 | 21.2 | 53.5 | 17.0 |
| $\tau^- \to 2\pi^- 1\pi^+$ (9.3) | 0.6 | 12.4 | 19.8 | 53.5 | 13.7 |
| Others (33.0) | 2.6 | 6.3 | 18.3 | 54.6 | 18.2 |

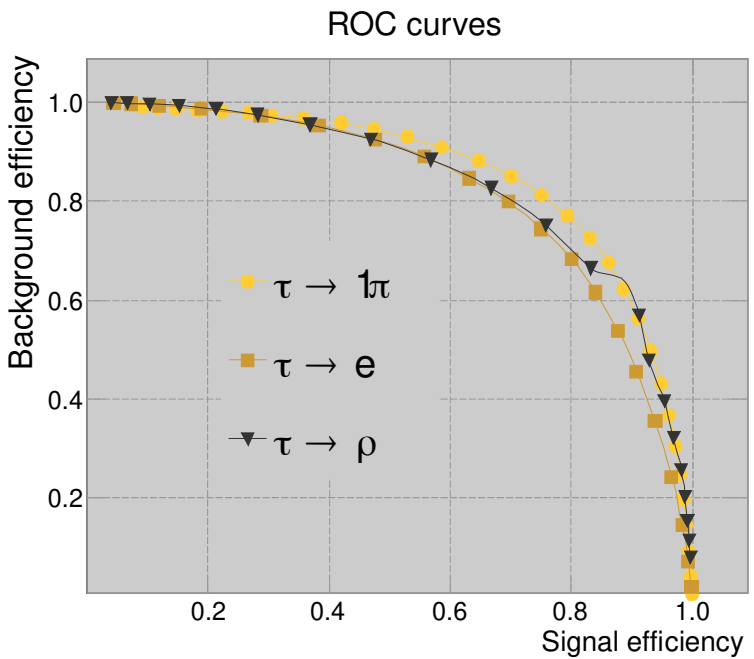
**CVN classification of simulated beam nutauCC interactions at DUNE far detectors with respect to tau decay modes**

- Reading example : 45.7 % of nutauCC interactions for which the tau decays electronically are classified as nueCC interactions.

- We can infer that the CVN tags neutrino interactions when it spots ''unusual large hadronic activities'' (but that must be confirmed with some event displays).

# DUNE expected sensitivity for nutau appearance

- In my thesis I developped kinematic studies for 3 tau decay modes (each with its own background) and combined the expected S/N ratios and sensitivities (no full chain simulations).
- Background rejection > 95 % often means signal selection < 40 %
- 20 kton x 5 years → expect 3sigma of nutau appearance with standard LBNF beam.




| | Standard LBNF $\nu$ beam | $\tau$ optimized beam |
|---|---|---|
| **$\tau \to e$** | | |
| $\nu_\tau(\tau \to e)$ | $22.4 \pm 0.2$ | $151.6 \pm 1.2$ |
| $\nu_e$ osc. | $87.0 \pm 0.5$ | $143.6 \pm 0.5$ |
| $\nu_e$ beam | $63.6 \pm 1.5$ | $82.3 \pm 2.0$ |
| $\nu_e$ total | $150.6 \pm 1.5$ | $225.9 \pm 2.1$ |
| Significance | $1.8 \pm 0.0$ | $9.2 \pm 0.1$ |
| **$\tau \to \rho$** | | |
| $\nu_\tau(\tau \to \rho)$ | $18.8 \pm 0.2$ | $116.2 \pm 0.9$ |
| NC($\geq 1\pi^{\pm}1\pi_0$) | $40.0 \pm 1.2$ | $122.5 \pm 3.3$ |
| Significance | $2.8 \pm 0.0$ | $9.3 \pm 0.1$ |
| **$\tau \to 1\pi$ (QEL-like)** | | |
| $\nu_\tau(\tau \to 1\pi)$ | $2.8 \pm 0.1$ | $16.4 \pm 0.6$ |
| NC($\geq 1\pi^{\pm}$) | $12.3 \pm 0.7$ | $26.9 \pm 1.3$ |
| Significance | $0.8 \pm 0.0$ | $2.9 \pm 0.1$ |
| **3 channels combined** | | |
| $\nu_\tau$ | $44.0 \pm 0.3$ | $284.2 \pm 1.6$ |
| Backgrounds | $202.9 \pm 2.1$ | $375.4 \pm 4.1$ |
| Significance | $3.0 \pm 0.0$ | $13.2 \pm 0.1$ |