Simulating neutrino interaction events using SBN@PBC neutrino fluxes

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CERN EP-NU group meeting

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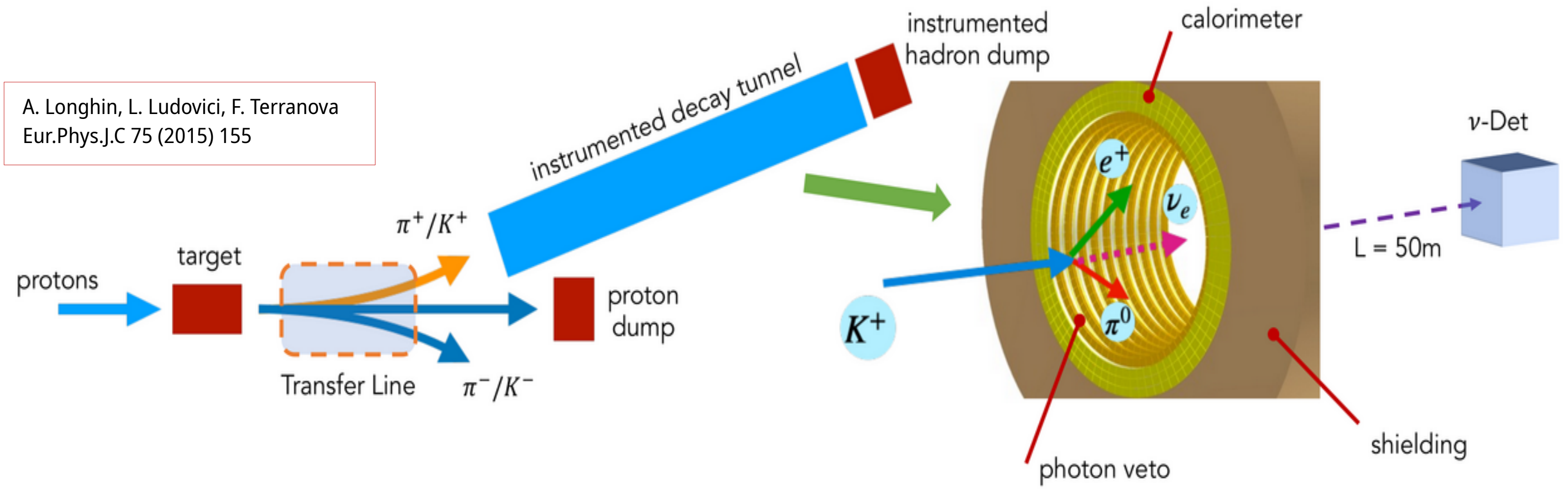
ENUBET : the first monitored neutrino beam

- **Monitored neutrino beams** are a novel technology aimed at measure the flux and flavour of neutrinos produced at the source at percent level.

Conventional beamline with **instrumented decay tunnel** for the identification of charged leptons

measuring **charged lepton rate** ⇔ monitoring **ν flux**

A. Longhin, L. Ludovici, F. Terranova
Eur.Phys.J.C 75 (2015) 155



- **ERC project** focused on :
  measure **positrons** from K_{e3} ($K^+ \rightarrow e^+ \pi^0 \nu_e$) decay by means of the instrumented decay tunnel ⇒ **ν_e flux** measurement
- As **CERN NP06/ENUBET experiment** extends at :
  measure **muons** from $K_{\mu\nu}$ ($K^+ \rightarrow \mu^+ \nu_\mu$) with the instrumented decay tunnel and from $\pi_{\mu\nu}$ ($\pi^+ \rightarrow \mu^+ \nu_\mu$) instrumenting the hadron dump as a range meter ⇒ **ν_μ flux** measurement
- **Lepton monitoring** bypasses the main systematics : hadron production, beamline geometry and focusing, protons on target (POT).

The narrow-band off-axis technique

Narrow-band off-axis technique

Narrow momentum beam O(10%)

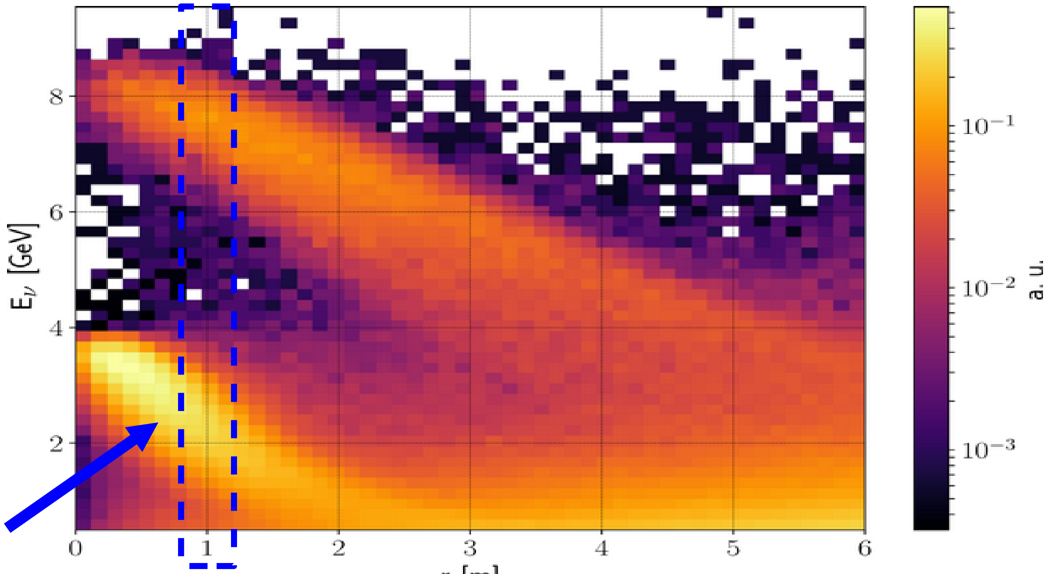
↓

(E_ν,R) are strongly correlated

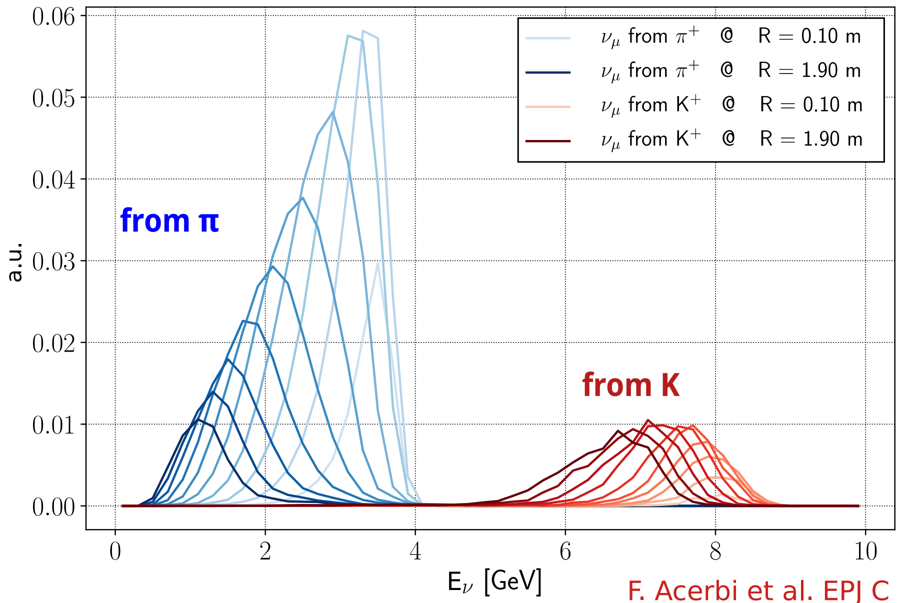
- **E_ν** = neutrino energy
- **R** = radial distance of interaction vertex from beam axis

precise determination of E_ν :
w/o relying on reconstruction of final state particles from ν_μ^{CC} interactions

- **10 - 25% E_ν resolution from π in DUNE energy range**
- ongoing R&D: Multi-Momentum Beamline (**4.5**, **6** and **8.5 GeV**)
  ⇒ optimized for HyperK and DUNE



Select ν_μ with given energy by performing cut on R



π / K populations well separated

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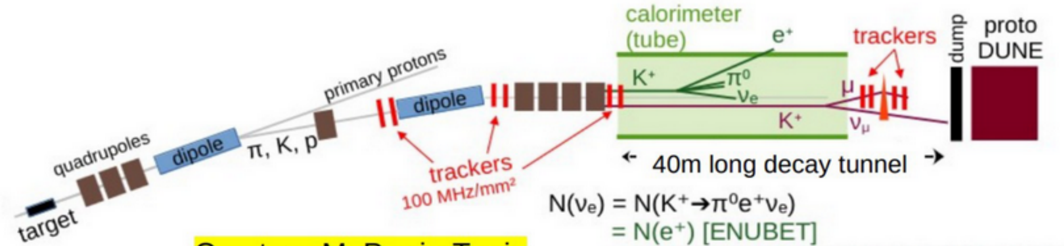
Energy measurement by neutrino tagging: the NuTag concept

- Unlike monitored neutrino beams, a **tagged neutrino beam** uniquely associate the neutrino with its accompanying particles in the beamline.
- The use of state-of-the-art silicon trackers is the core of the **NuTAG** concept:
  - **Associate individually each neutrino interaction with its production mechanism**
  - A **tagger** (pixel detectors) is installed in the beam line to track **π**, **K** and **μ**
  - **Neutrino** are **reconstructed** based on **decay kinematics**

$$p_\nu = p_{\pi,K} - p_\mu$$

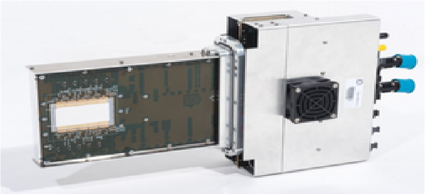
Courtesy
M. Perrin-Terrin



$N(\nu_e) = N(K^+ \rightarrow \pi^0 e^+ \nu_e)$
$= N(e^+)$ [ENUBET]
$= N(K^+ \rightarrow \mu^+ \nu_\mu)\, B(K^+ \rightarrow \pi^0 e^+ \nu_e)/B(K^+ \rightarrow \mu^+ \nu_\mu)$ [NuTAG]

Courtesy M. Perrin-Terrin

NA62-GTK



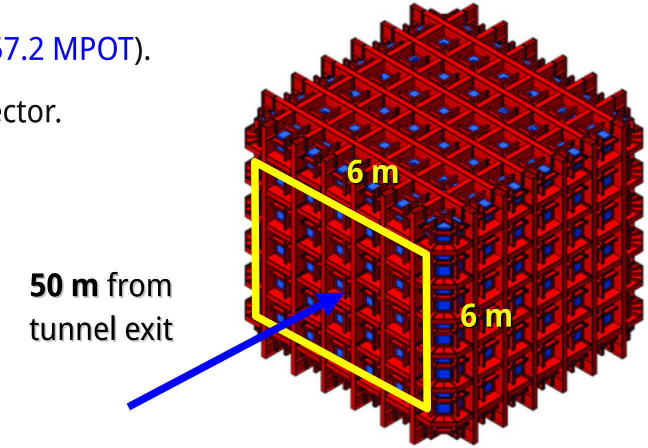
	Available	Max. Radiation	Max. Flux
NA62-GTK	since 2015	10^{14} n_{eq}/cm^2	2 MHz/mm²
HL-LHC	before 2028	$10^{16\text{-}17}$ n_{eq}/cm^2	10-100 MHz/mm²

- This technique is ideally suited for 2-body decays ($\pi_{\mu\nu}$, $K_{\mu\nu}$) to reconstruct the neutrino energy E_ν :
  - **parent momentum $p_{\pi/K}$** : tracking before and after a dipole
  - **neutrino production angle θ_ν** (i.e. the interaction vertex in ProtoDUNE or WCTE)

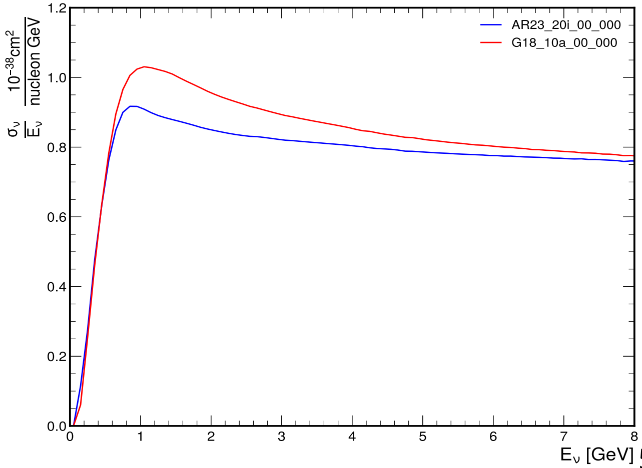
$$E_\nu = \frac{(1 - m_\mu^2/m_\pi^2)\,p_\pi}{1 + \gamma^2 \theta_{\pi\nu}^2}$$

NP06/ENUBET neutrino fluxes for the CERN site dependent implementation

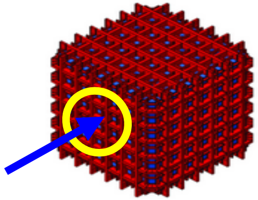
- The neutrino fluxes are computed using the simulation of the instrumented decay tunnel (**G4TAG**) for the latest **SBN@PBC** transferline (**SBNv12.1**).
- The neutrino fluxes are obtained using **G4TAG simulation** for **SBNv12.1 transferline** (1057.2 MPOT).
- The neutrino flux is computed as the neutrinos crossing the front area of the neutrino detector.
- The neutrino detector is **ProtoDUNE**:
  - front-face area of **6 x 6 m^2**
  - fiducial mass of **500 ton**
  - located at a **distance of 50 m from the tunnel exit**
- The **total pot statistic** expected to be collected is **4.5 · 10^{19} pot**.



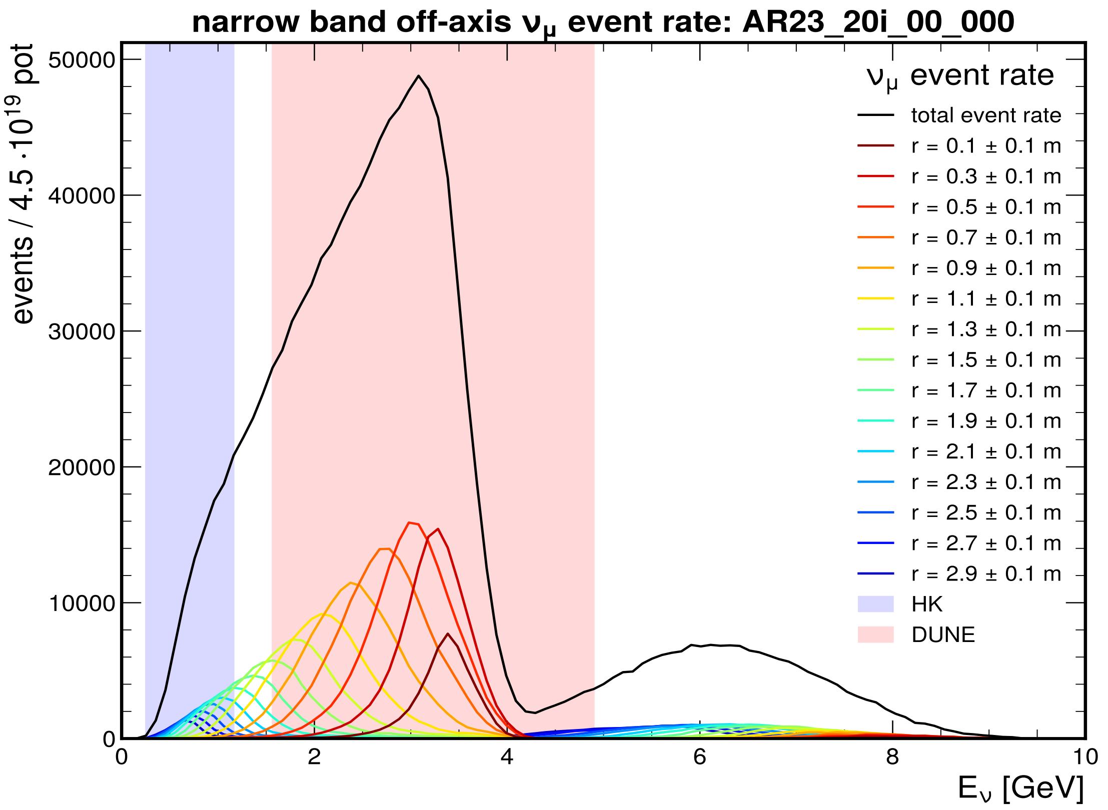
- Neutrino interactions are simulated with **GENIE** and output is flattened by **NUISANCE** :
  → **flat trees** are easy to work with and with the same format for other generators.
- The **GENIE tunes** used are AR23_20i_00_000 and G18_10a_00_000:
  - the main difference is the size of the RES and the 2p2h model.
- **AR23** model is the **DUNE baseline model**, used for sensitivity studies and simulation.



The narrow band off-axis

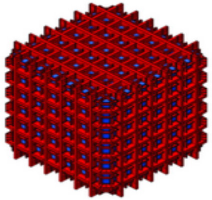


- The narrow band off-axis technique can provide an **"a priori" measurement of neutrino energy** for ν_μ w/o relying on final-state particles, i.e. by exploiting two-body kinematics.
- The neutrino flux is computed for 15 different circular rings with increasing radii, w/ a 20 cm radial window.

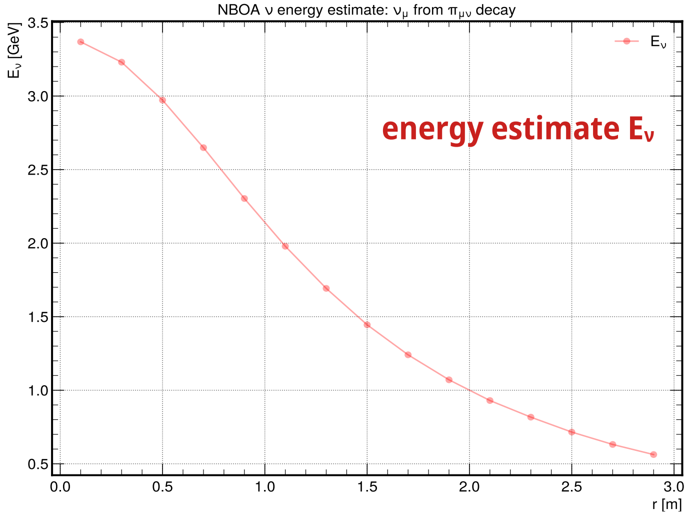


- The $\boldsymbol{\pi_{\mu\nu}}$ and $\mathbf{K_{\mu\nu}}$ peaks in the NBOA fluxes can be easily separated using an energy cut.
- The fluxes for $\pi_{\mu\nu}$ and $K_{\mu\nu}$ peaks - for each off-axis position – are fitted using a gaussian on a restricted range.
- The fluxes are not actually very gaussian: the most probable value (mpv) and the standard deviation at both sides w.r.t. the mpv can be used to provide a more conservative estimate → asymmetric flux width

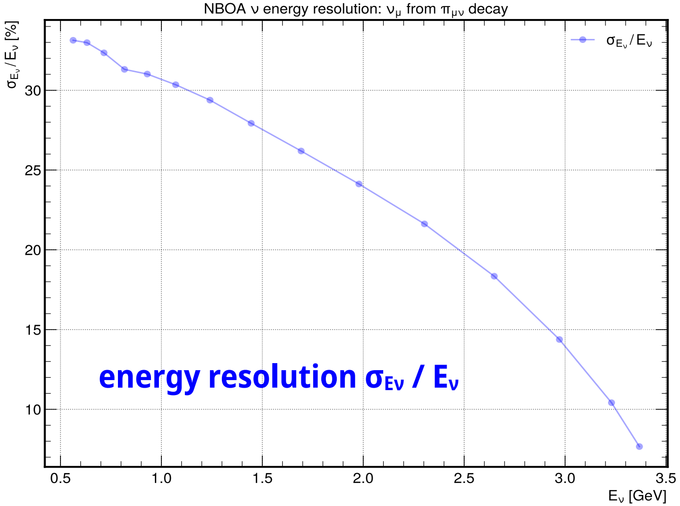
ν_μ energy estimate with NBOA: **ν_μ from $\pi_{\mu\nu}$**

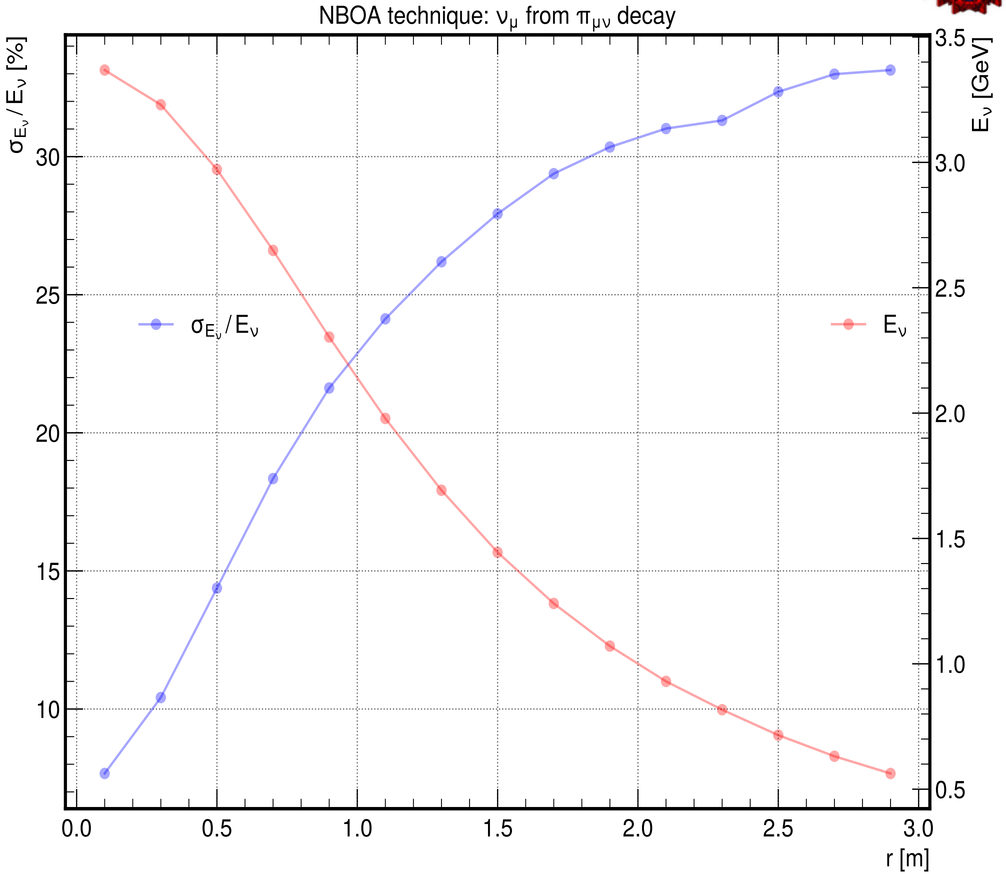


E_ν



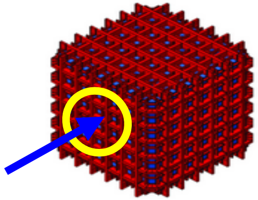
$\sigma_{E\nu} / E_\nu$





- **ν_μ** energy resolution spanning **~ 10 - 30 %** for **$\pi_{\mu\nu}$** for energies in range **E_ν = [1 , 3.3] GeV**.

Flux averaged neutrino cross section measurments using NBOA



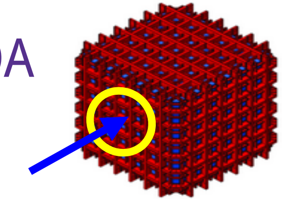
- Since the incident neutrino energy is not known on an event-by-event basis, most modern neutrino cross-section measurements are reported as **flux-averaged cross sections**.
- The average cross section σ is reported as the number of expected events N per total incident neutrino flux ϕ, number of target nucleons N_{tgts} and total protons on target (pot) exposure.

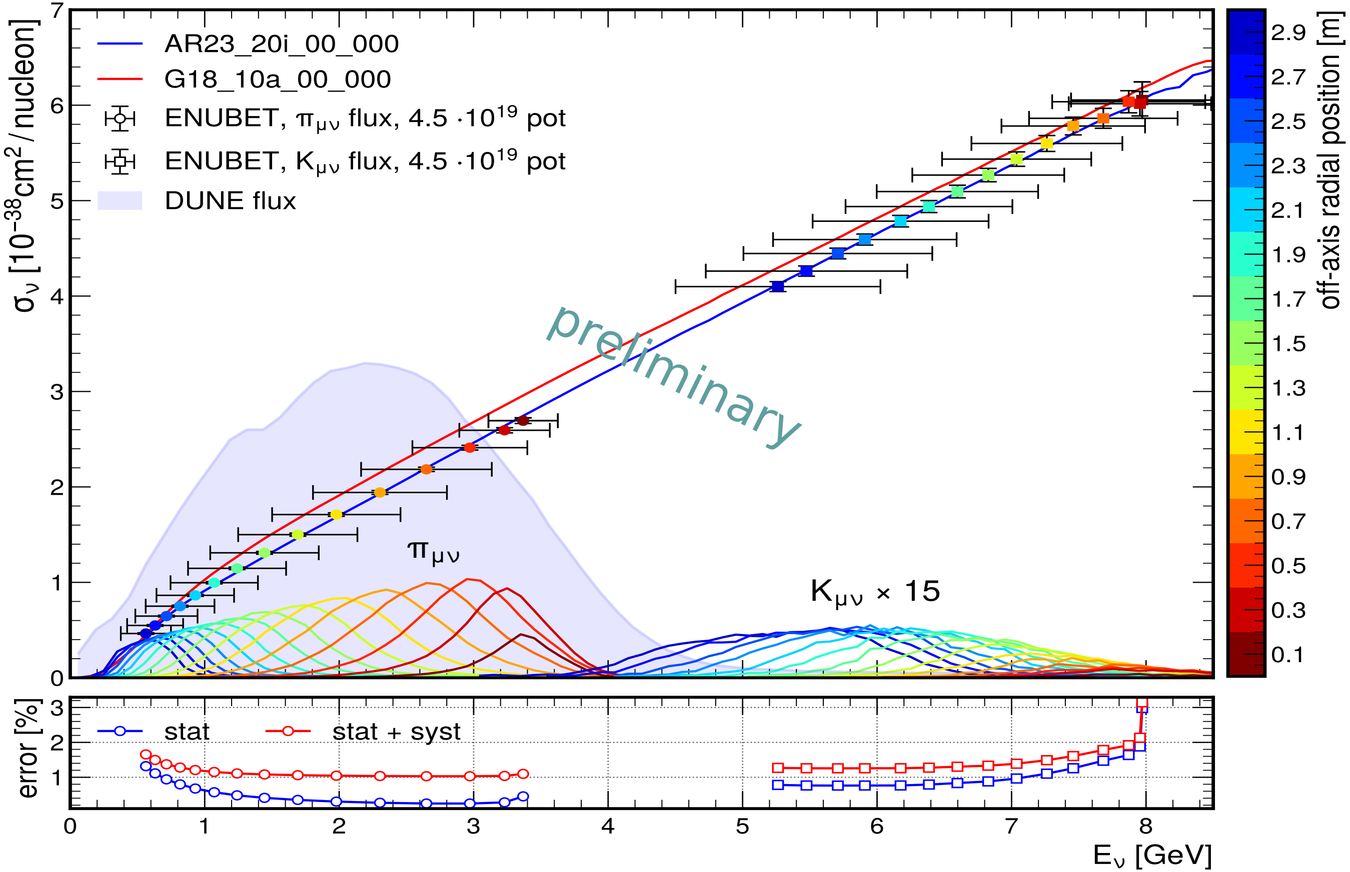
$$\langle \sigma \rangle_{\Phi} = \frac{N}{\Phi N_{tgts} N_{pot}}$$

$$N_{tgts} = \frac{M_{det}[\mathrm{g}]}{A_{iso}[\mathrm{g/mol}]} \cdot A \cdot N_A$$

- Using the **narrow band off-axis** thin neutrino fluxes, flux averaged neutrino cross section can be extracted for each radial position with an "a priori" measurement of neutrino energy with precision spanning from 10-30% in DUNE roi.
- Since $\boldsymbol{\pi_{\mu\nu}}$ and $\boldsymbol{K_{\mu\nu}}$ peaks are well separated, flux averaged neutrino cross section can be performed using both peaks.
- Thanks to the **NuTag** concept the neutrino energy resolution can be pushed to **1%** using a tagged sample with reduced statistic.

Flux averaged neutrino cross section measurements using NBOA

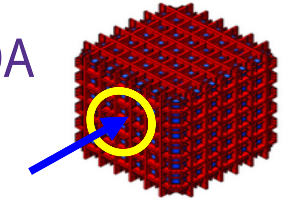


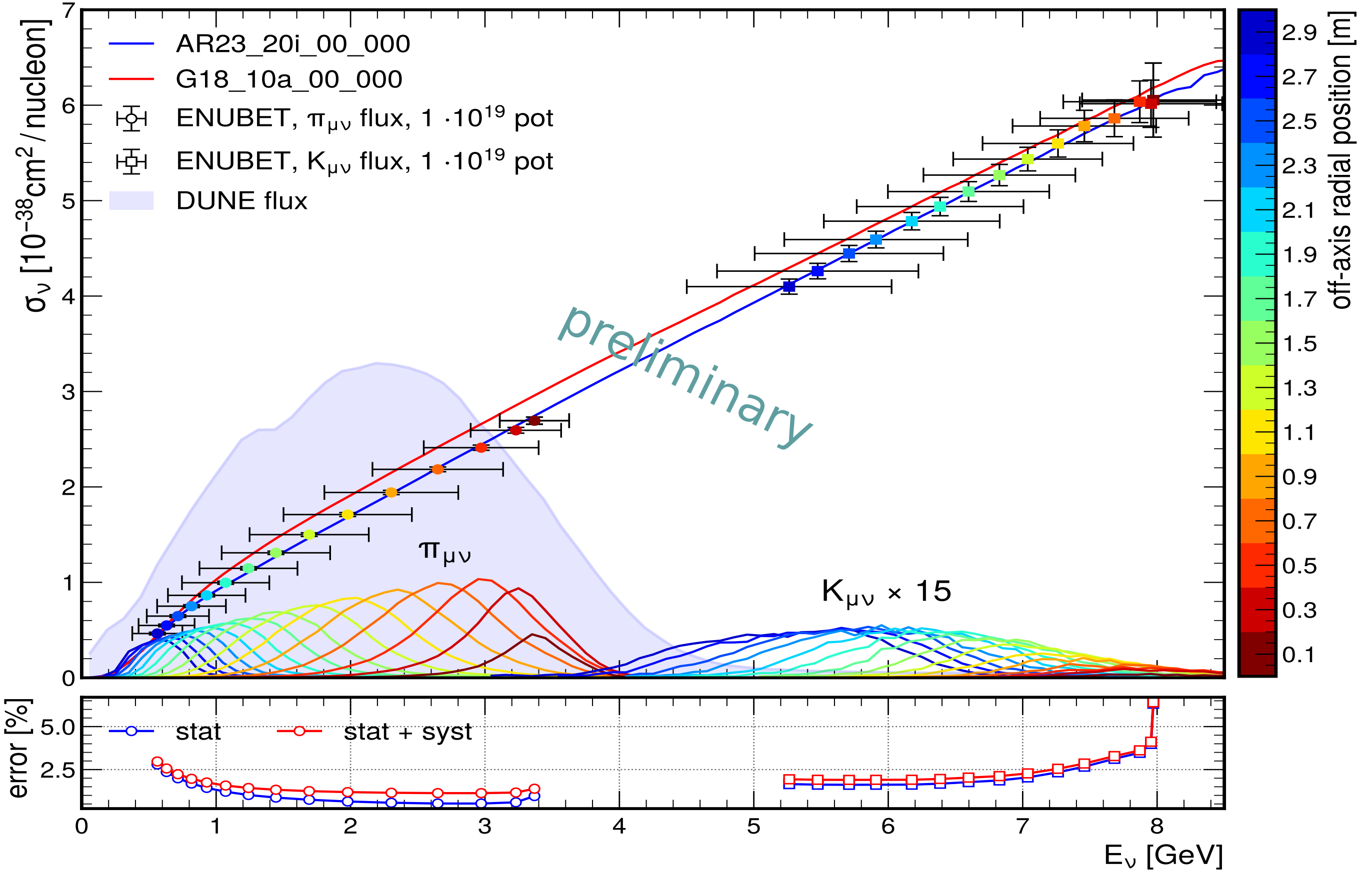


The **total pot statistic** is **4.5 · 10^{19} pot**.

- First demonstration that NP06/ENUBET would accurately map the evolution of the neutrino energy with pretty fine granularity over the whole range of energies relevant for DUNE.

Flux averaged neutrino cross section measurements using NBOA

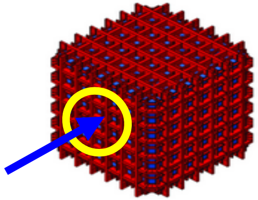


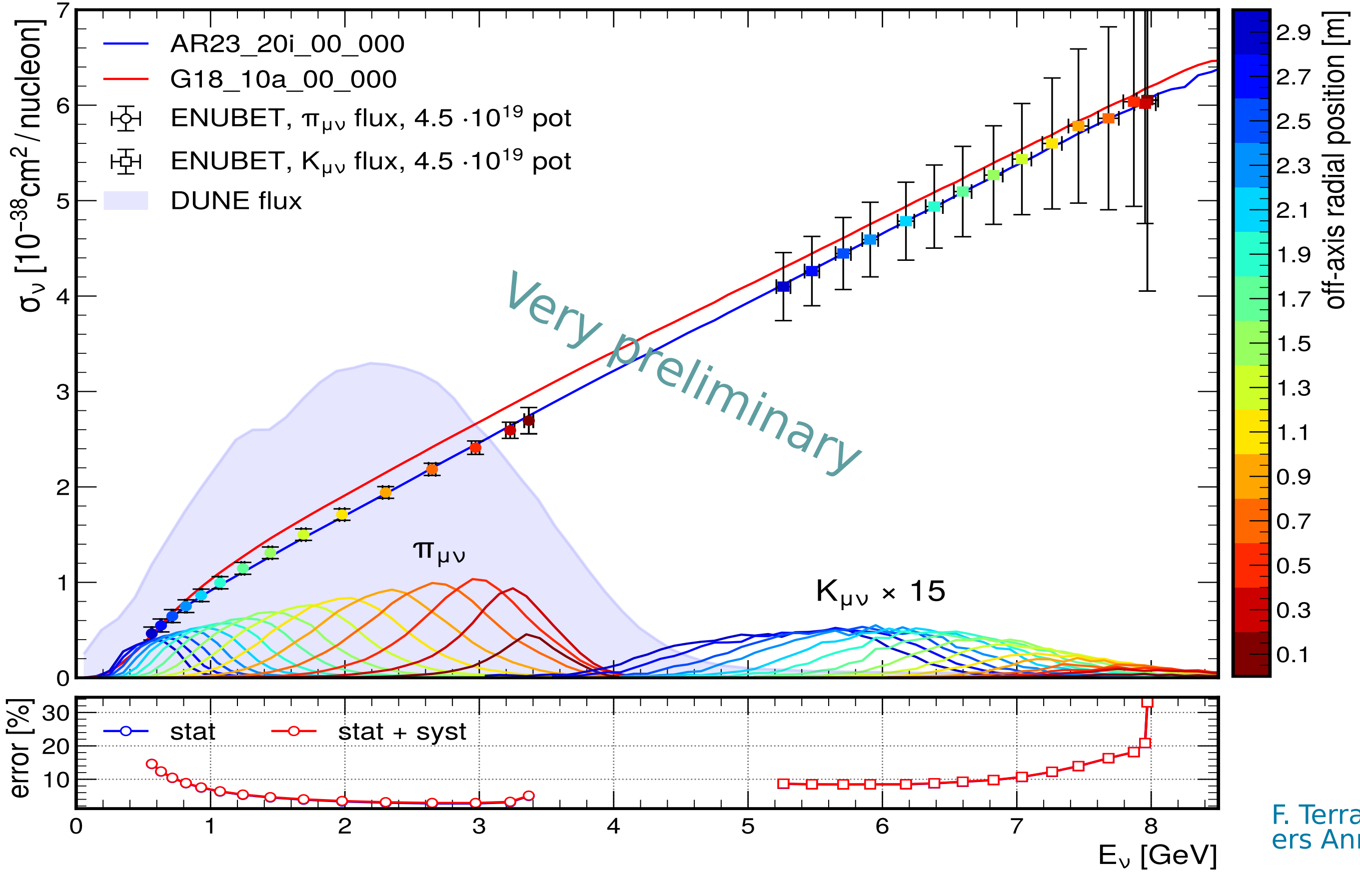


The **total pot statistic** is **$1 \cdot 10^{19}$ pot**.

- First demonstration that NP06/ENUBET would accurately map the evolution of the neutrino energy with pretty fine granularity over the whole range of energies relevant for DUNE.

Flux averaged cross section using NBOA + NuTag





The **total pot statistic** is **$4.5 \cdot 10^{19}$ pot**.

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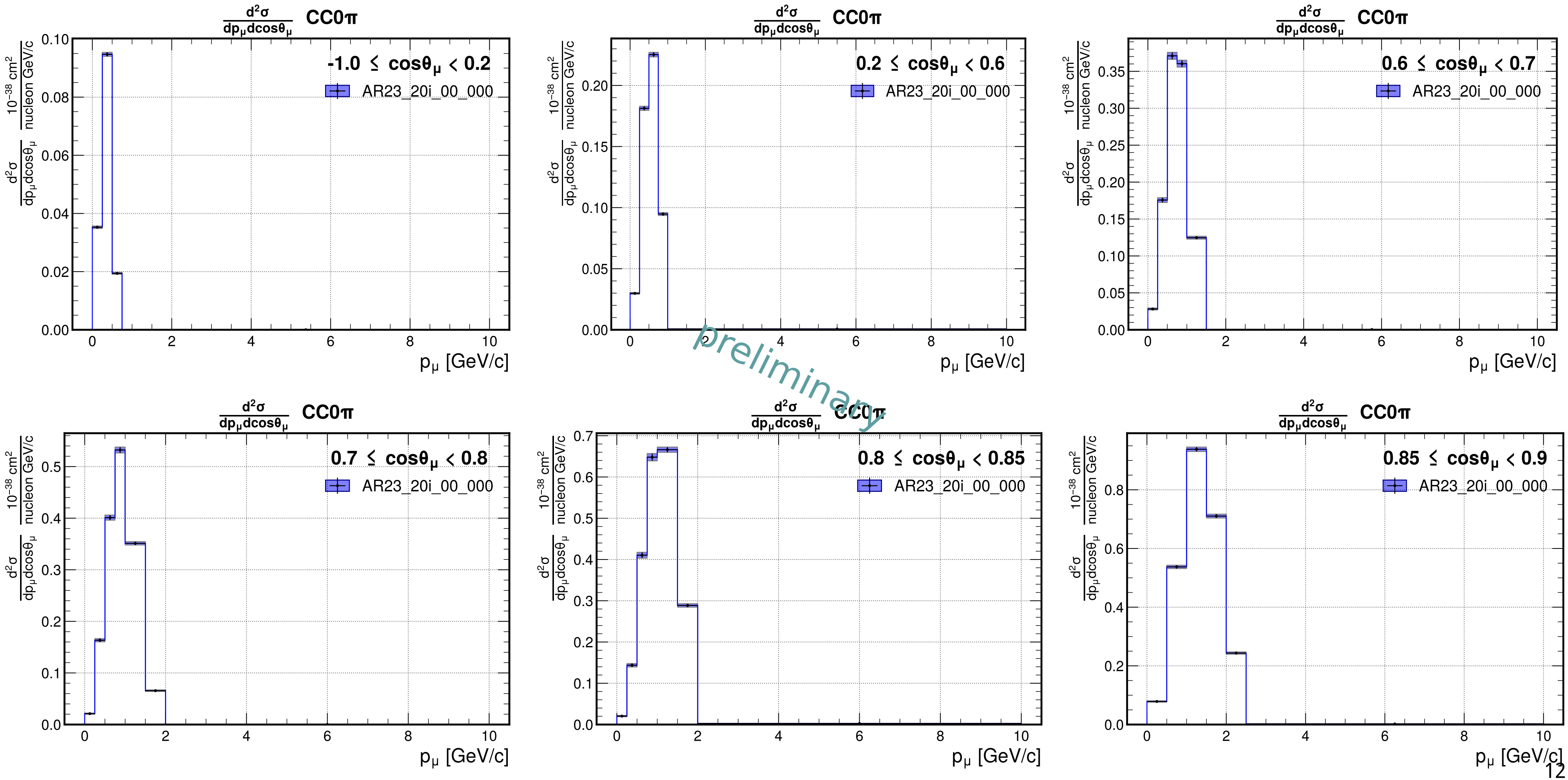
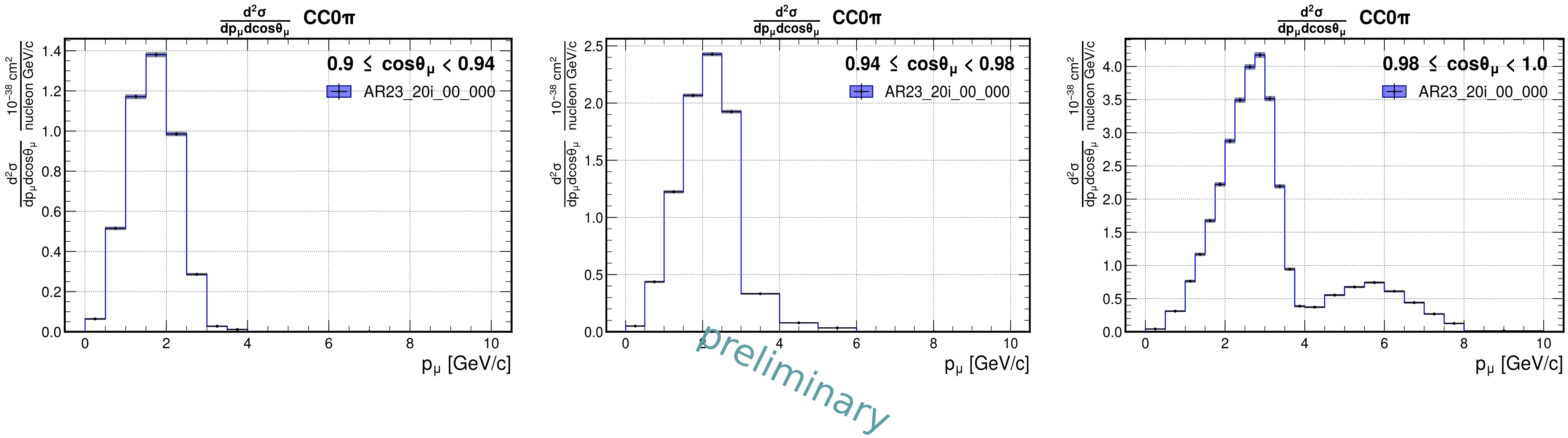
- Consider a **tagged ν_μ sample** with **statistic of 10^4 ν_μ CC events** (rescaling bin contents and fluxes) and **energy resolution** expected to be **1%**.
- Note that 10^4 ν_μ CC events is 0.8% ot the total ν_μ CC statistic (~ $12 \cdot 10^5$ ν_μ CC events with $4.5 \cdot 10^{19}$ pot).

double differential cross section for CC0π events (lepton kinematics)



double differential cross section for CC0π events (lepton kinematics) [cont'd]



Conclusion and next step

- The neutrino fluxes and expected rate were using the G4TAG for the latest **SBN@PBC** transferline (**SBNv12.1**).
- Neutrino interactions simulated by GENIE and NUISANCE using the NP06/ENUBET fluxes.
- **Narrow band off axis**:
  - **ν_μ** energy resolution spanning **~ 10 - 30 %** for **$\pi_{\mu\nu}$** for energies in range **E_ν = [1 , 3.3] GeV**.
  - **ν_μ** energy resolution spanning **~ 7 – 14 %** for **$K_{\mu\nu}$** for energies in range **E_ν = [5.2, 8] GeV**.
- First demonstration of NBOA ability to map the evolution of neutrino energy with pretty fine granularity over the DUNE r.o.i.

- Next step : double differential cross section for **ν_e** and **ν_μ**
- Next step : use DUNE-PRISM concept to build virtual fluxes from linear combination of thin off-axis fluxes to fill the gap in the **$\pi_{\mu\nu}$** and **$K_{\mu\nu}$** separation region and even lower energies.

Backup

The ENUBET transfer line : the final design

- The beamline is based on **static focusing** elements ("direct current"), i.e. **without** employing a **pulsed magnetic horn** :
  - **slow extraction of primary protons** ⇒ full intensity continuously extracted in few seconds (**~ 2 sec**)
    - particle rate in the tunnel reduced at a sustainable level for detectors (< 100 kHz/cm^2)
    - static focusing elements : **dipoles** and **quadrupoles** ⇒ cost-effective and operationally more stable
  - **short length** to minimize kaon decays ⇒ w/ L = 20 m about 30% of K are lost, and K/π abundance ratio drops by ~ 25%
  - optimized **graphite target** (L = 70 cm, R = 3 cm)
  - **tungsten foil** (5 cm) after target to screen e^+ background
- **Narrow-band beamline**: secondary mesons K^+ / π^+ selected w/ **p = 8.5 GeV/c ± 10%**.

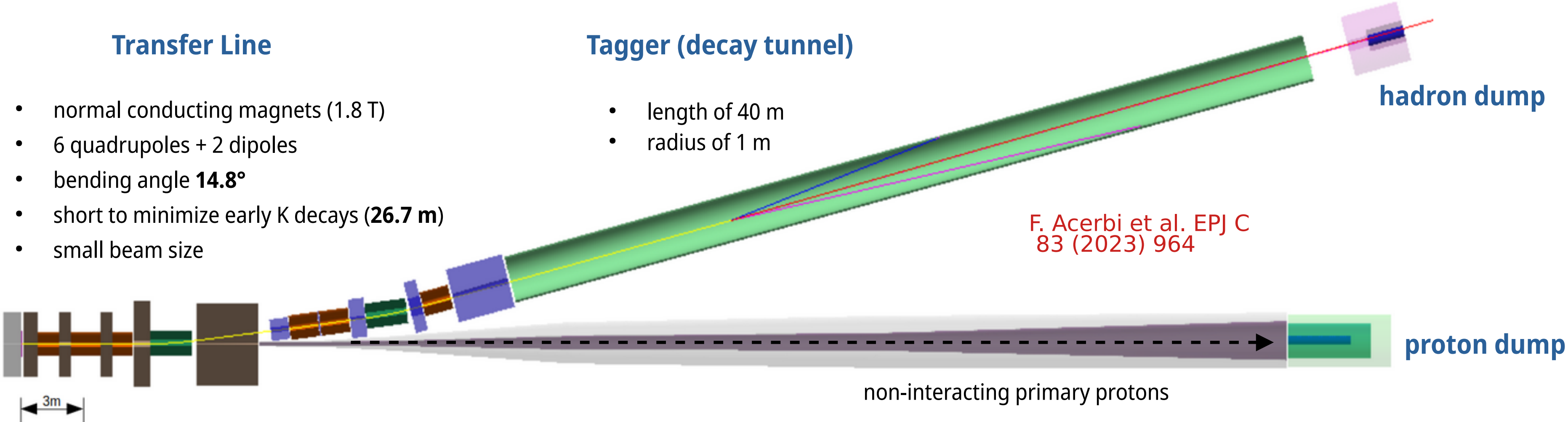
Optimized for the DUNE r.o.i. (E_ν ~ 3 GeV)

Transfer Line

- normal conducting magnets (1.8 T)
- 6 quadrupoles + 2 dipoles
- bending angle **14.8°**
- short to minimize early K decays (**26.7 m**)
- small beam size

Tagger (decay tunnel)

- length of 40 m
- radius of 1 m



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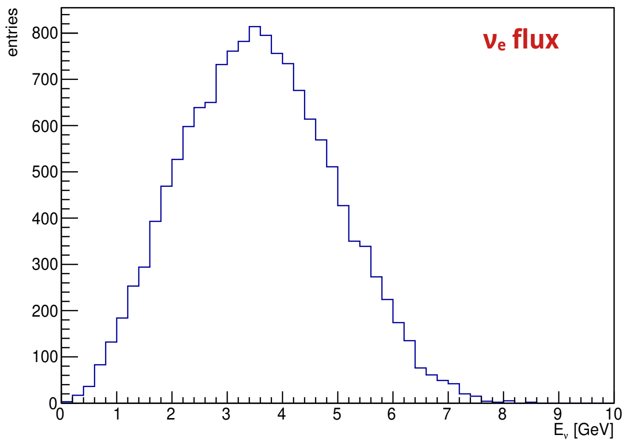
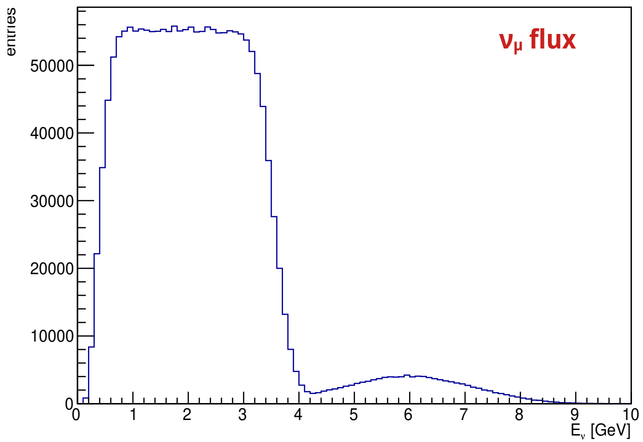
ν_e and ν_μ flux and CC interaction rate @ 50 m from tunnel exit using ProtoDUNE

- The neutrino detector is ProtoDUNE with a fiducial mass of **500 ton** and with front-face area of **6 x 6 m²**.

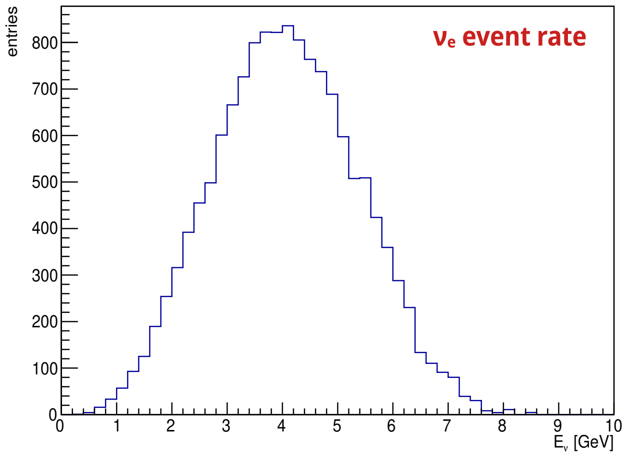
ν_e spectrum in ProtoDUNE



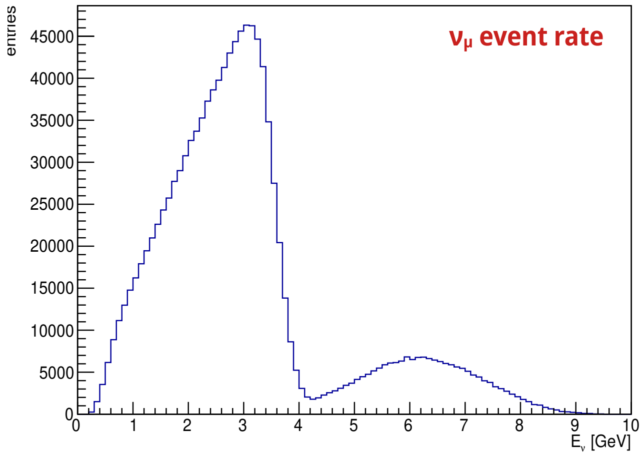
ν_μ spectrum in ProtoDUNE



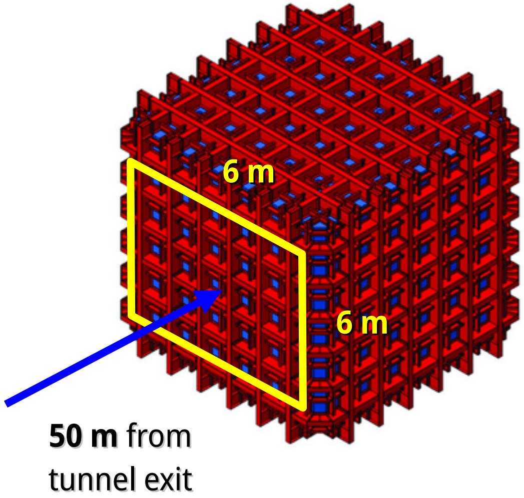
ν_e CC interaction rate in ProtoDUNE with 4.5$10^{19}$ pot



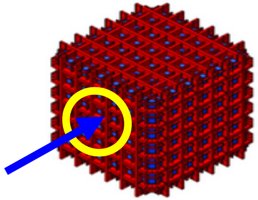
ν_μ CC interaction rate in ProtoDUNE with 4.5 · 10^{19} pot



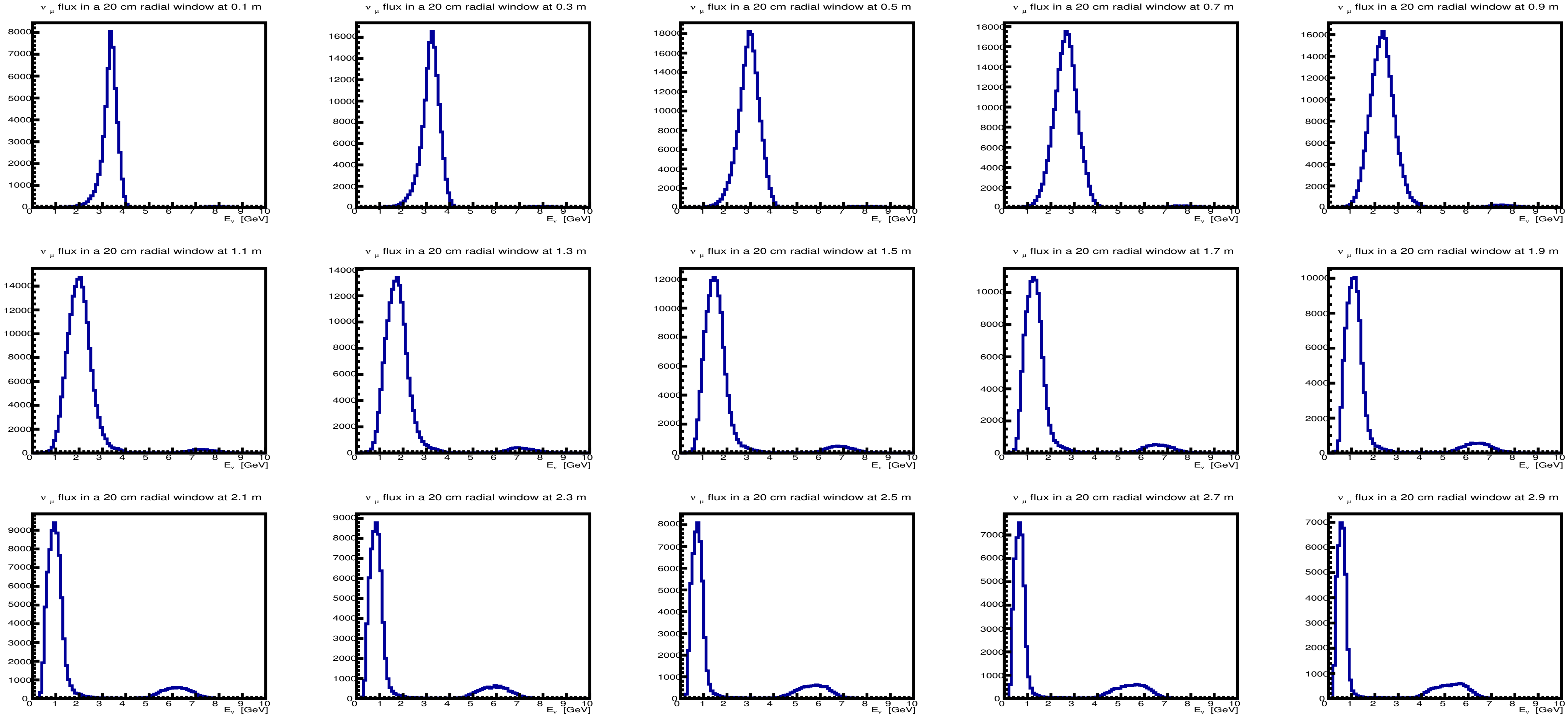
ν_e CC rate : 14128.4
ν_μ CC rate : 1.16289e+06



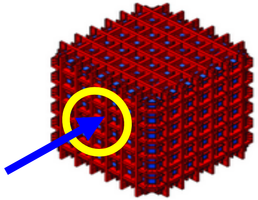
The narrow band off-axis



- The neutrino detector is ProtoDUNE with a fiducial mass of **500 ton** and with front-face area of **6 x 6 m²**.



The narrow band off-axis : gaussian fit



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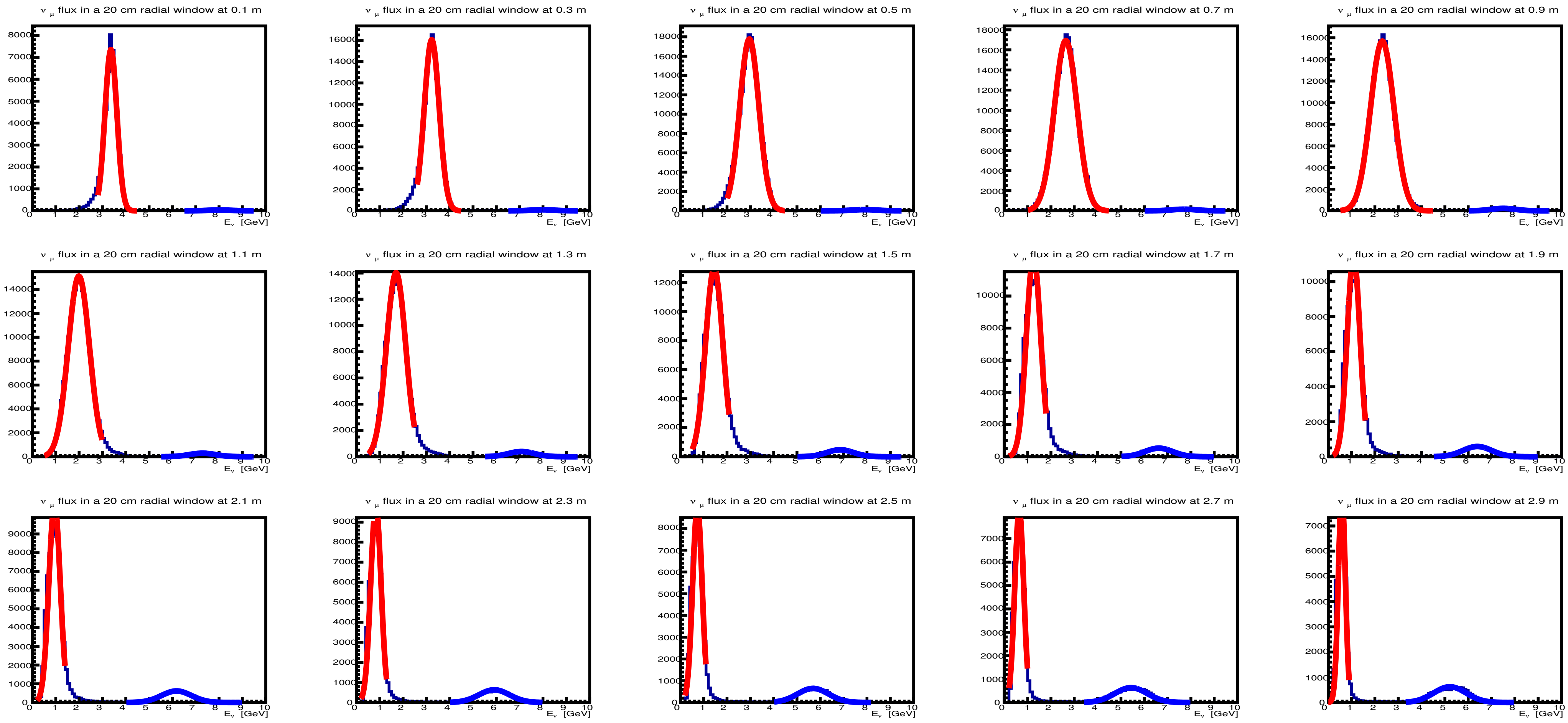
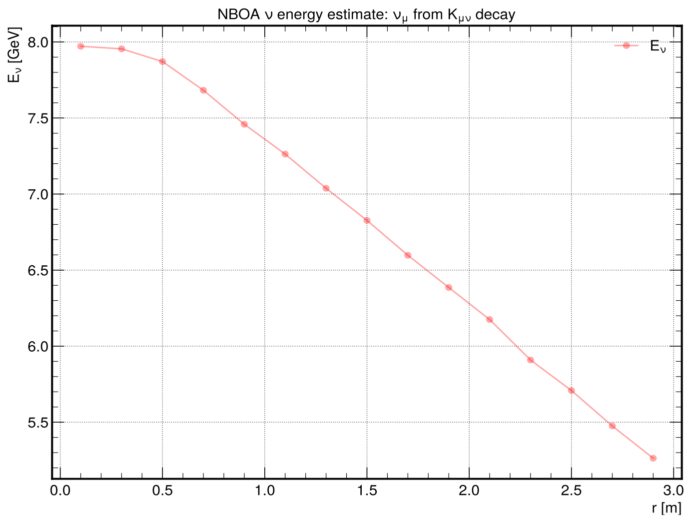
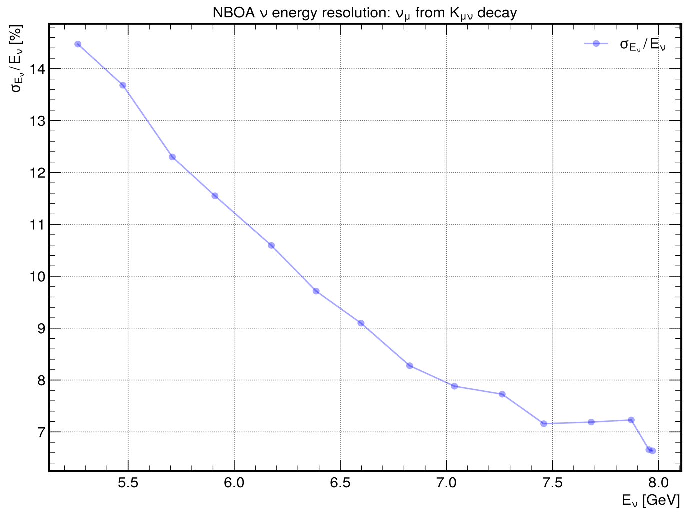


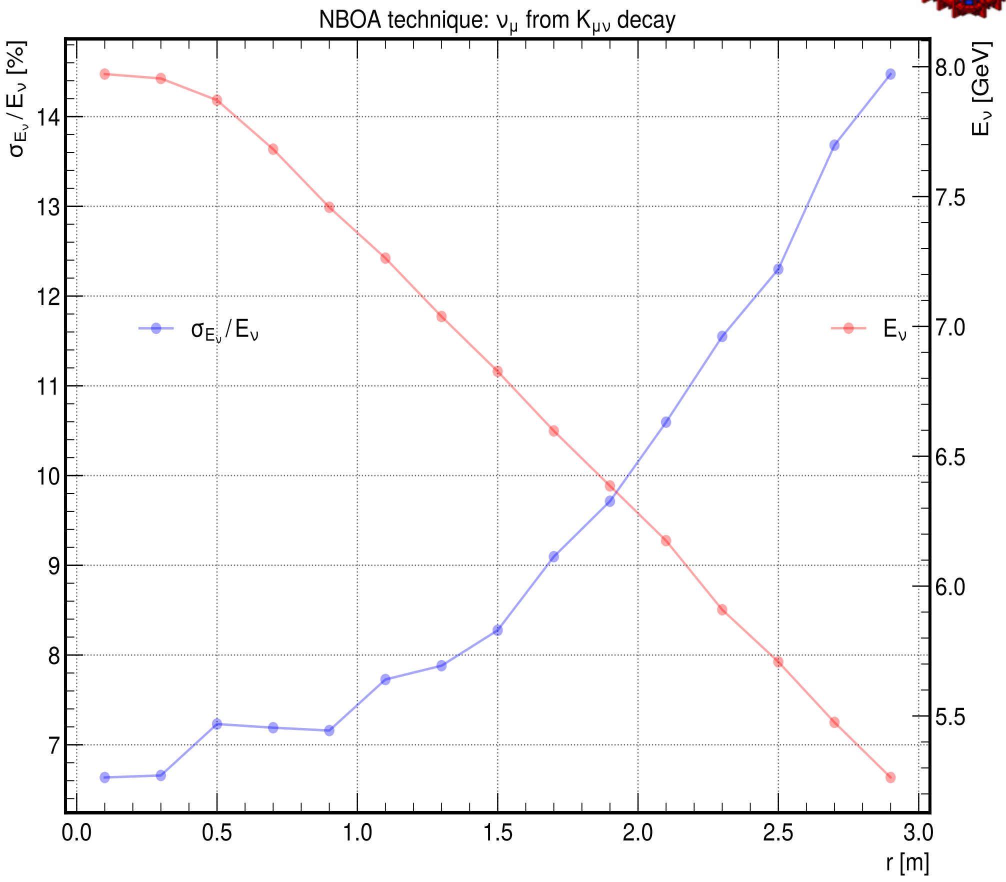
ν_μ energy estimate with NBOA: **ν_μ from $K_{\mu\nu}$**

E_ν



$\sigma_{E\nu} / E_\nu$

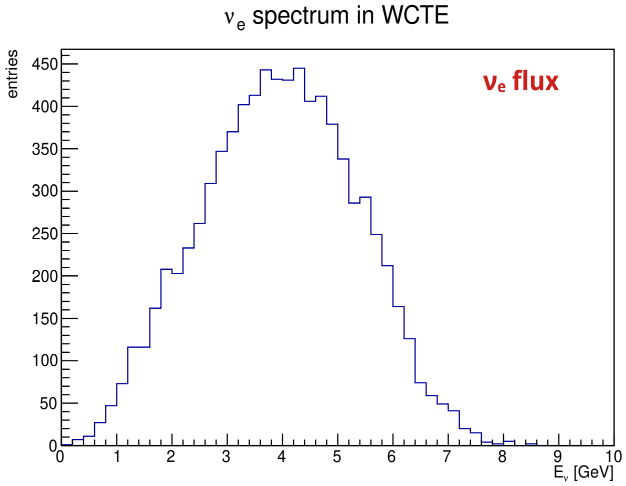


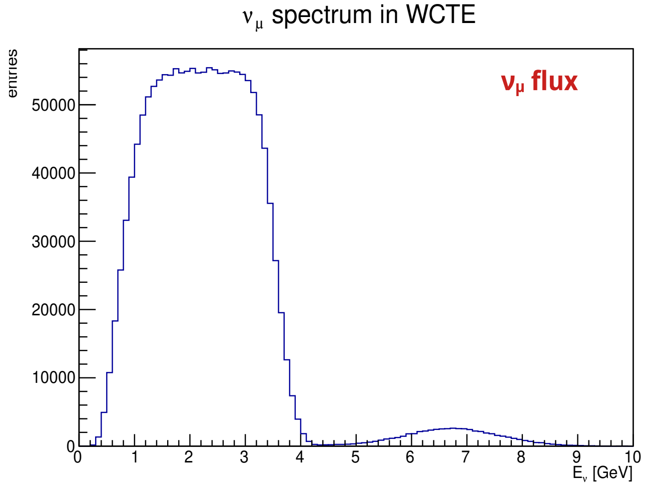


- **ν_μ** energy resolution spanning ~ **7 – 14 %** for **$K_{\mu\nu}$** for energies in range **E_ν = [5.2, 8] GeV**.

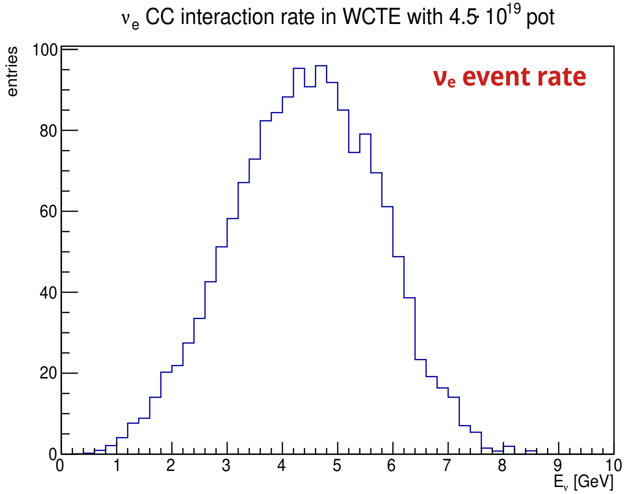
ν_e and ν_μ flux and CC interaction rate @ 50 m from tunnel exit using WCTE

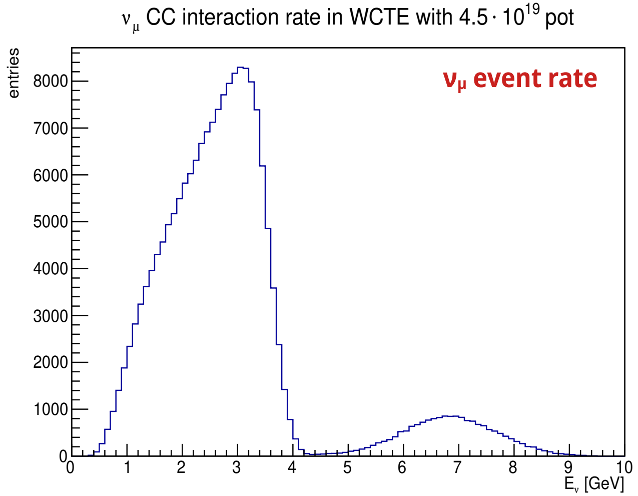
- The neutrino detector is **WCTE** with a mass of **40 ton** and with central-area of **4 x 4 m²**.

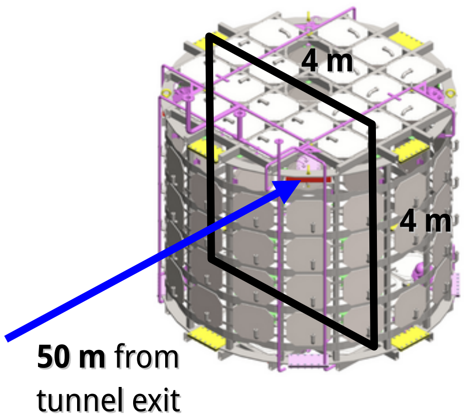




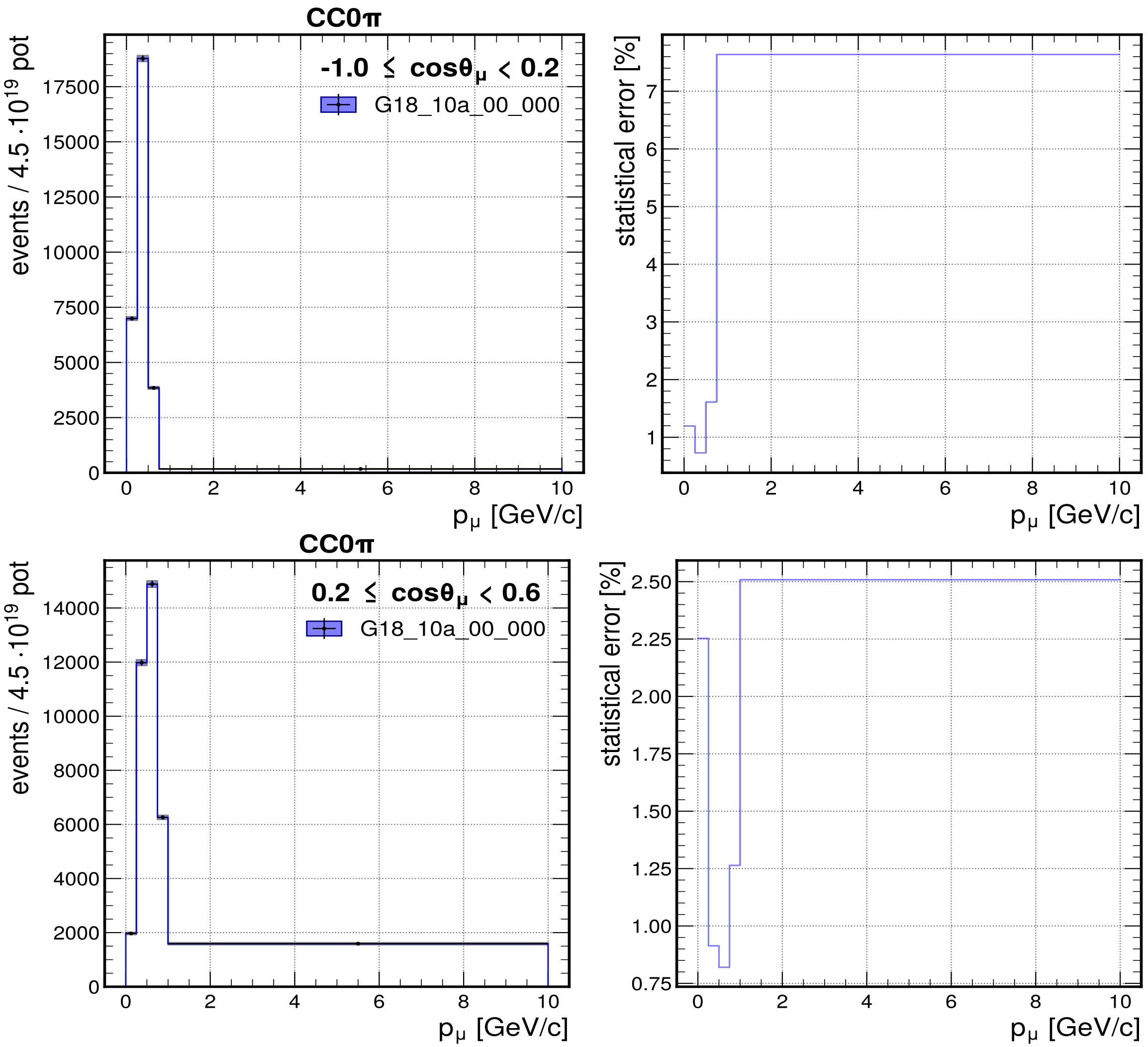
ν_e CC rate : 1609.11
ν_μ CC rate : 185570







event rate and stat. error for double differential cross section for CC0π events



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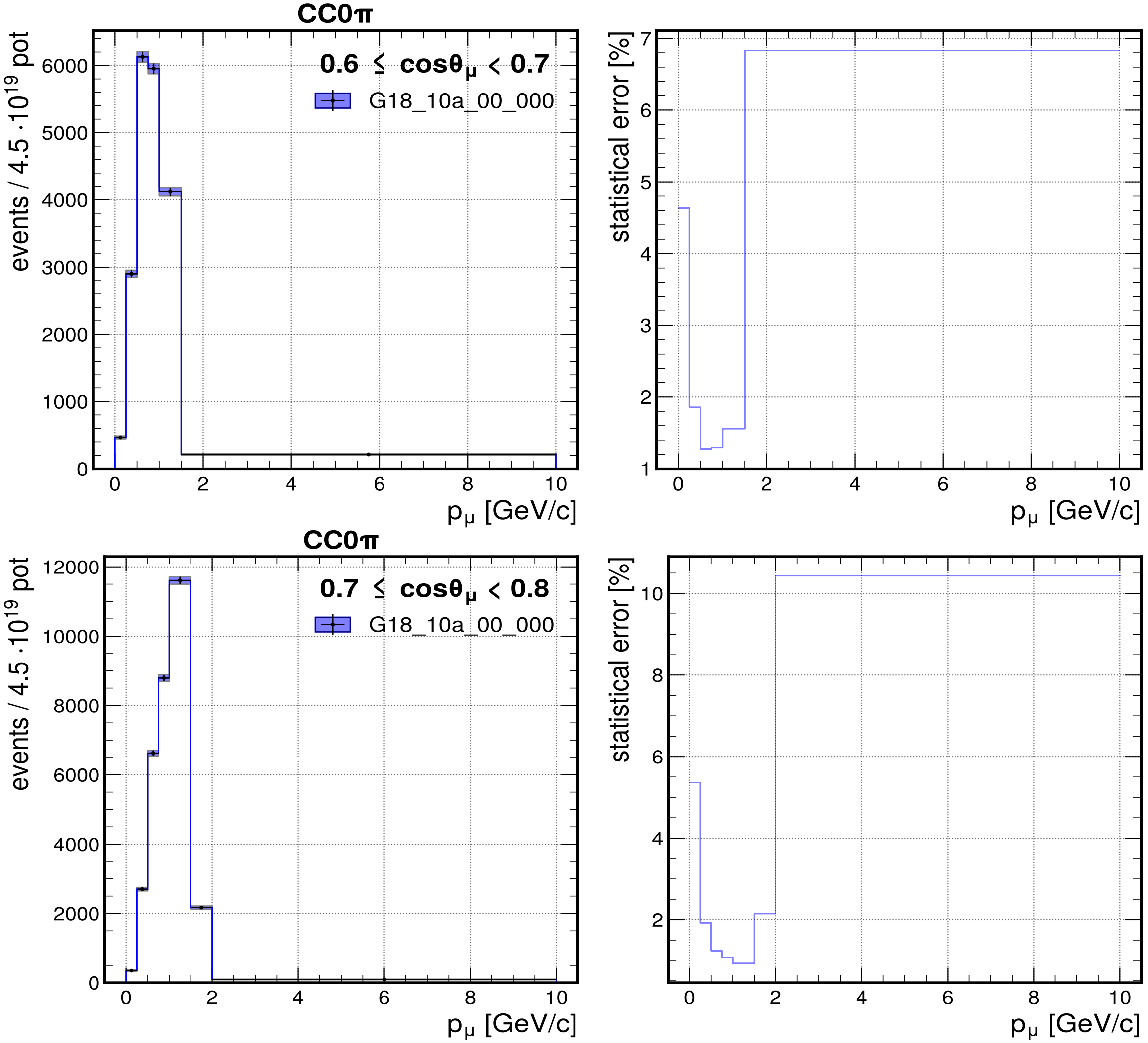

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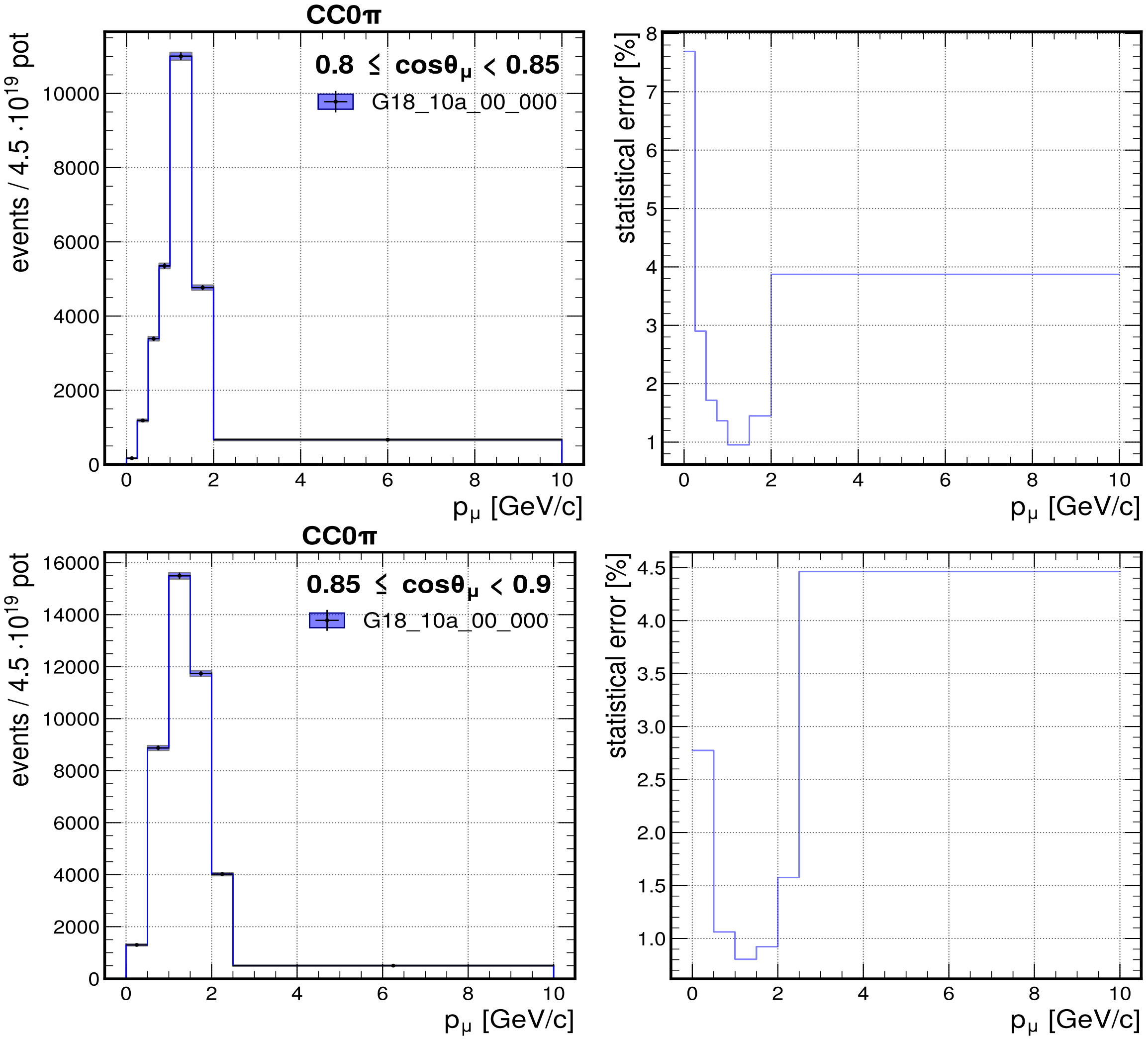

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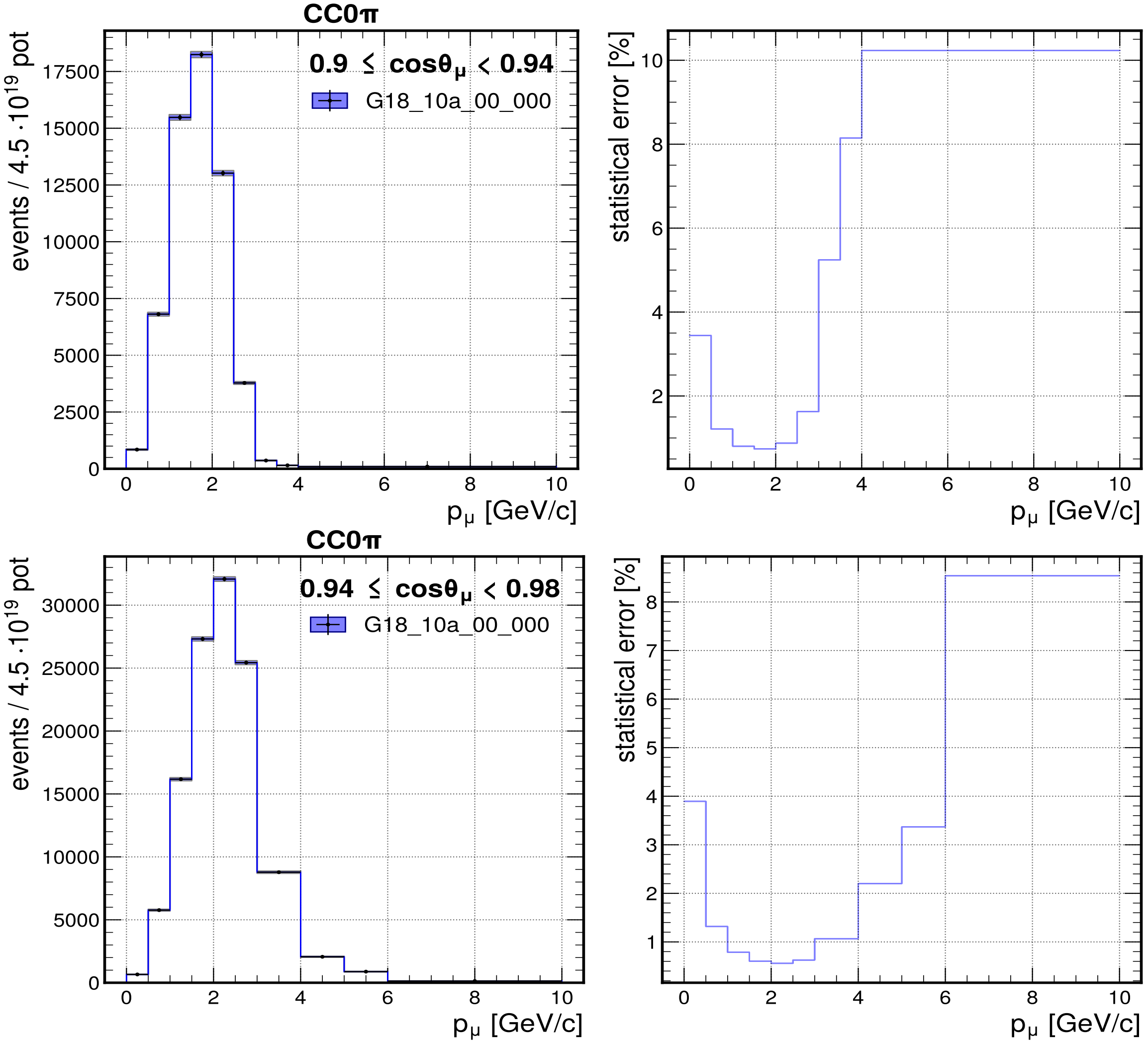

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