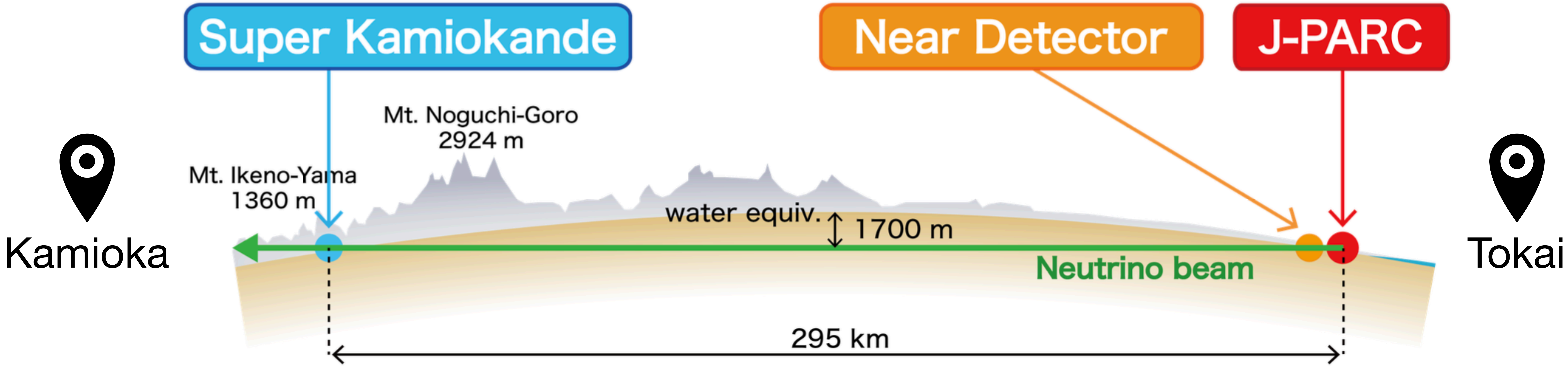
Comité de Suivi Individuel
deuxième année

Lavinia Russo
LPNHE - Neutrino group

Introduction and little recap

The T2K Experiment

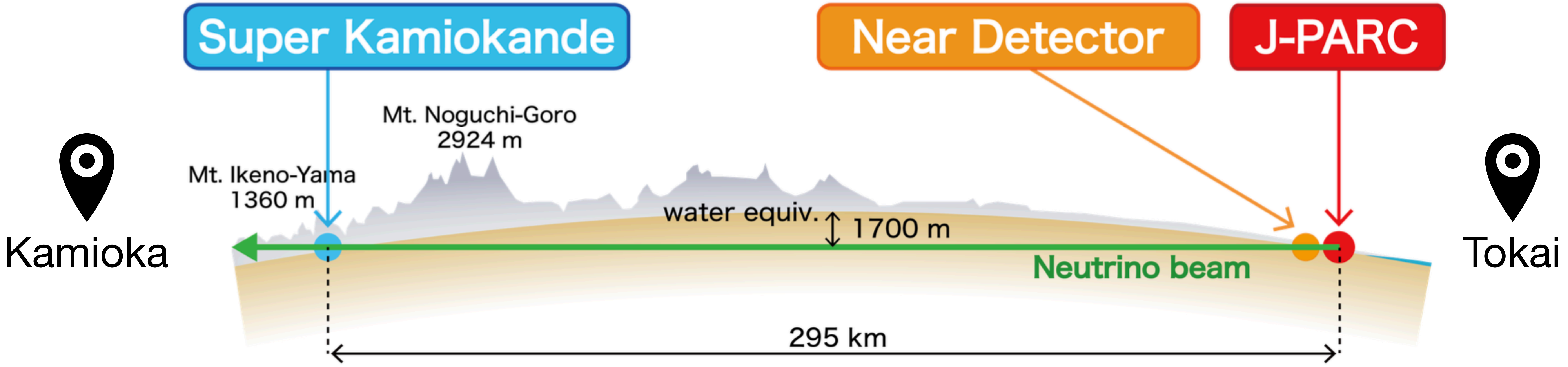
a long-baseline oscillation neutrino experiment



Tokai To Kamioka

The T2K Experiment

a long-baseline oscillation neutrino experiment



Tokai To Kamioka

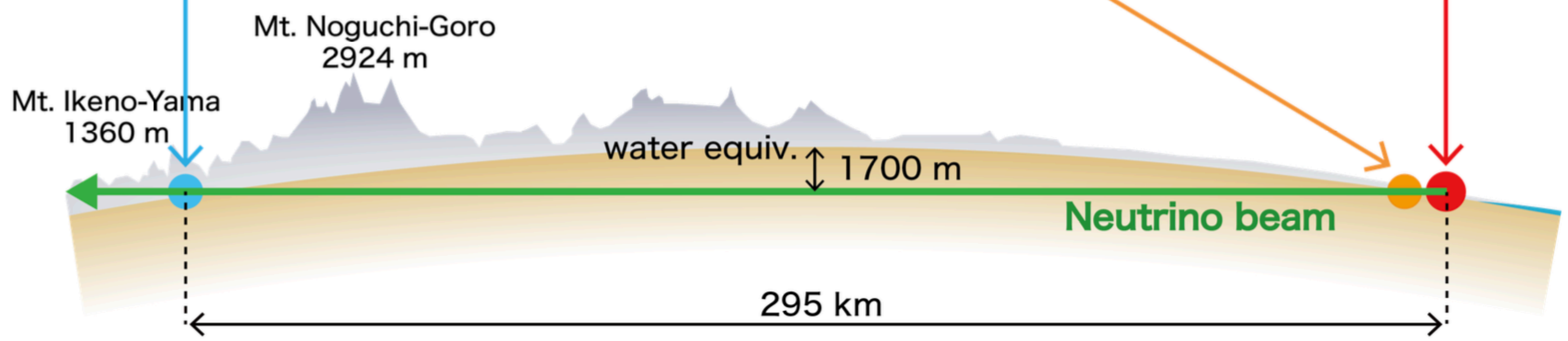
The T2K Experiment

*with the help of NA61/SHINE experiment @ CERN

a long-baseline oscillation neutrino experiment

Super Kamiokande | Near Detector | J-PARC

Kamioka



Tokai

measure the ϕ_ν after the oscillation

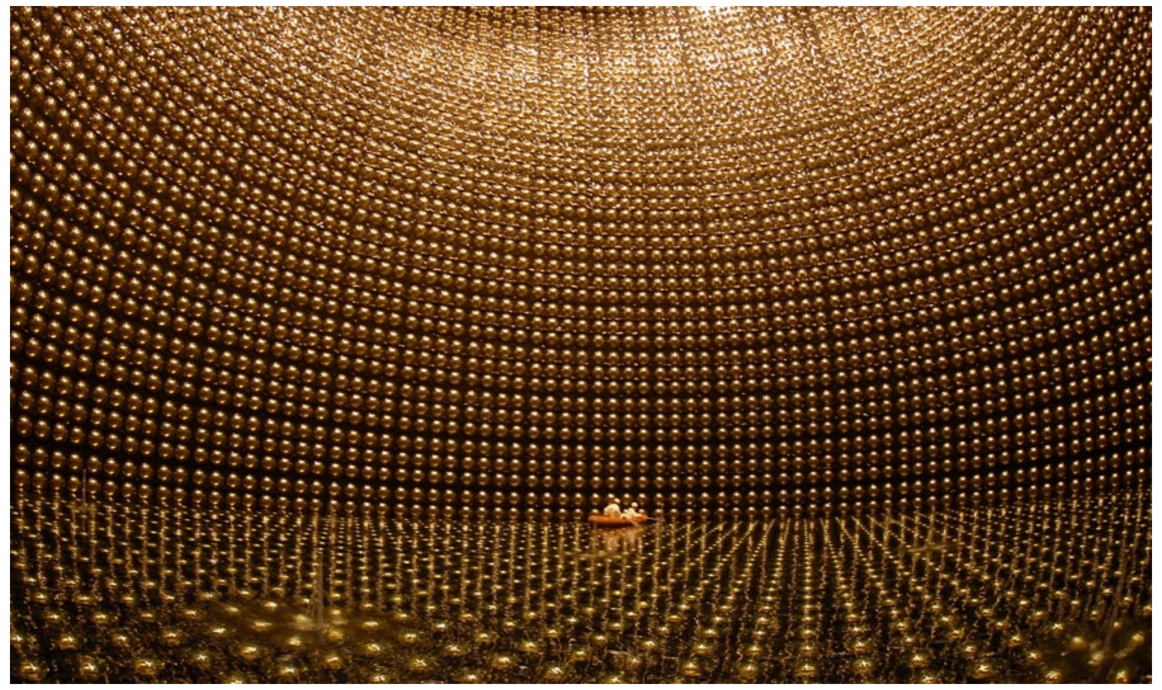
target = ^{16}O

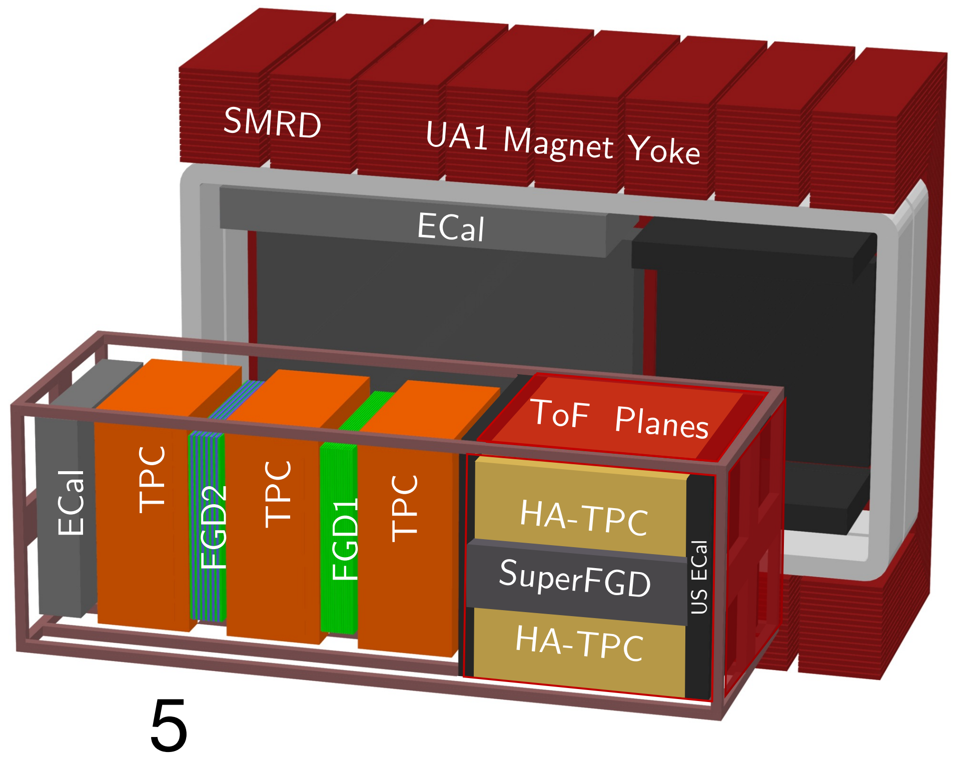
295 km

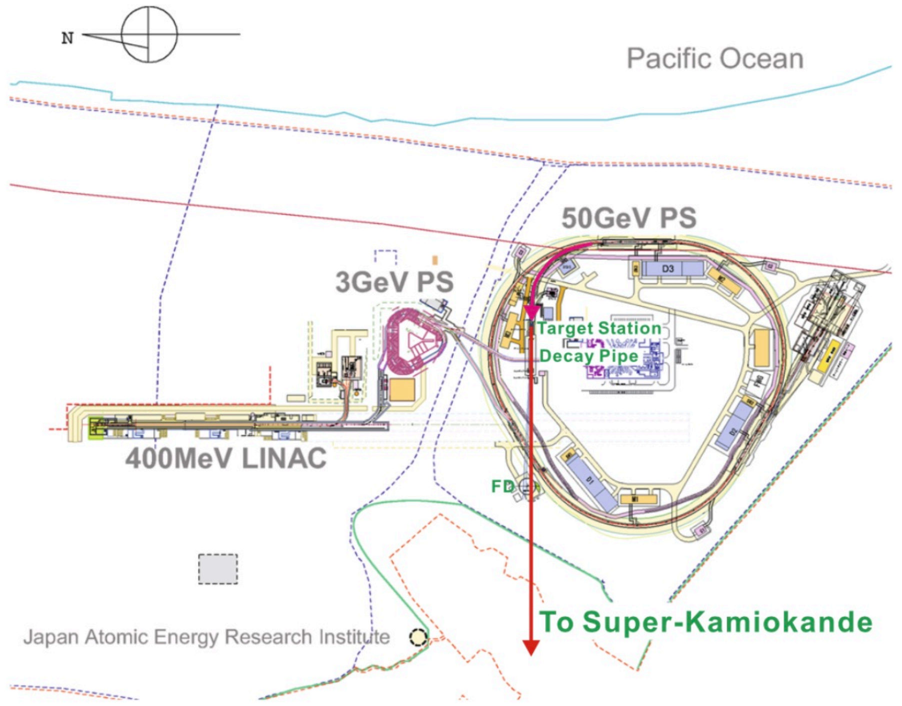
characterise the ϕ_ν before the oscillation *

target = ^{12}C

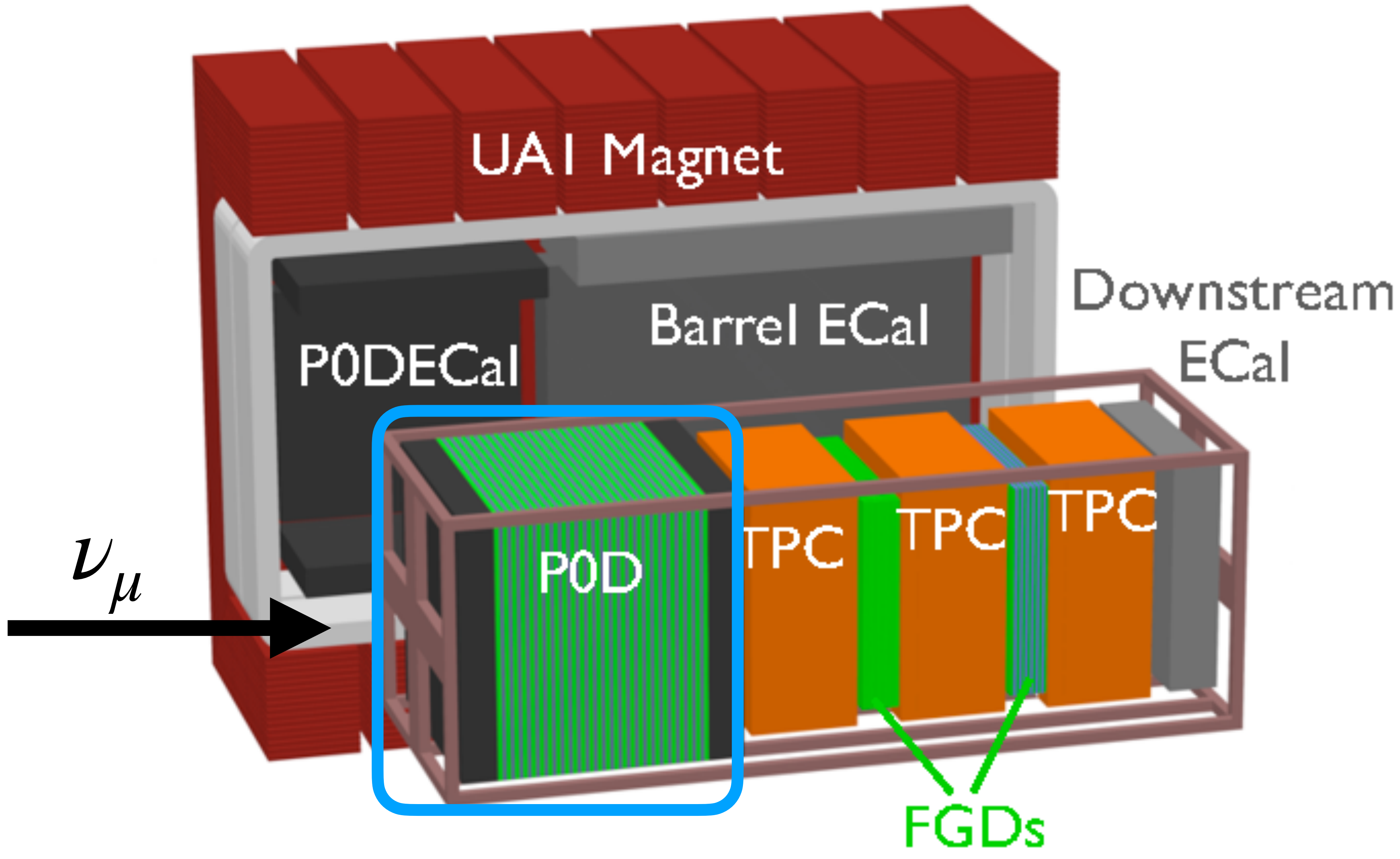
ν_μ beam production



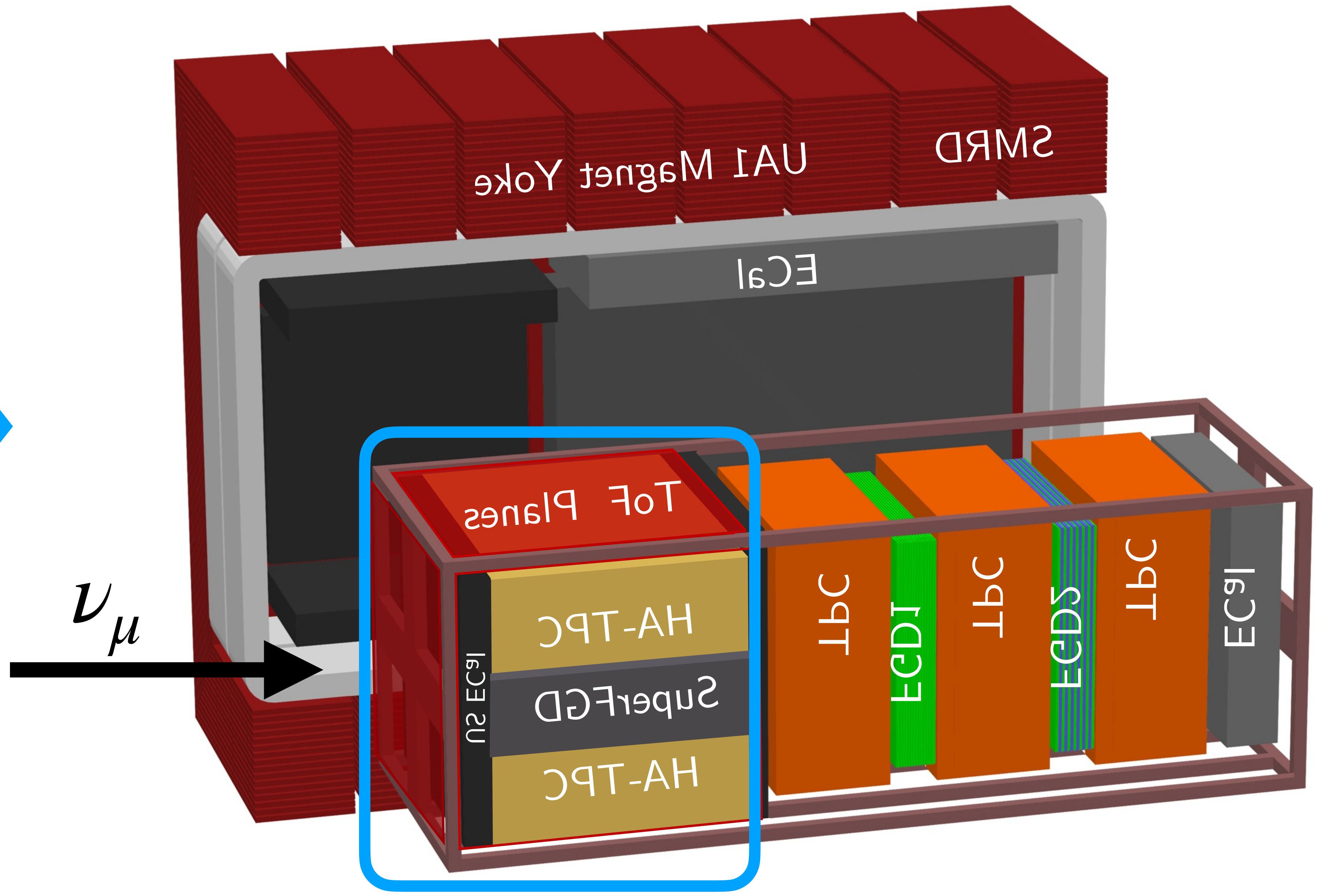




The ND280 upgrade



ND280 upgrade



The ND280 upgrade

- reduce the ~400 MeV/c reconstruction momentum threshold and increase the interaction probability (SFGD)
- reproduce the 4π angular acceptance of the far detector (HA-TPC)

The ND280 upgrade

- reduce the ~400 MeV/c reconstruction momentum threshold and increase the interaction probability (SFGD)
- reproduce the 4π angular acceptance of the far detector (HA-TPC)

NEUTRINO group @ LPNHE is involved in:

- commissioning, operation, data taking of HA-TPC
- software development for ND280

topic of my PhD 2

Neutrino oscillation experiments

the importance of the cross section

$$\underbrace{N_{\nu_\beta}(E_\nu^{rec})}_{\text{number of } \nu_\beta \text{ detected events}} \sim \int \underbrace{\Phi_{\nu_\alpha}(E_\nu^{true})}_{\nu_\alpha \text{ flux}} \; \underbrace{P_{\nu_\alpha \to \nu_\beta}(E_\nu^{true}, L, \Theta)}_{\nu_\alpha \to \nu_\beta \text{ oscillation probability}} \; \underbrace{\sigma_{\nu_\beta}(E_\nu^{true})}_{\nu_\beta \text{ cross section}} \; \underbrace{\epsilon_{\det}}_{\text{detector efficiency}} \; \underbrace{d(E_\nu^{true}, E_\nu^{rec})}_{\text{migration matrix}} \, dE_\nu$$

reconstructed energy (E_ν^{rec}); true energy (E_ν^{true}); baseline length (L); oscillation parameters (Θ)

The ν_β **cross section** appears:

- explicitly
- implicitly in the detector efficiency
- implicitly in the migration matrix

⟶ **modelling** the **neutrino - nucleus cross section** is **crucial !**

Neutrino oscillation experiments

the importance of the cross section

reconstructed energy — true energy — baseline length — oscillation parameters

$$\underbrace{N_{\nu_\beta}(E_\nu^{rec})}_{\text{number of } \nu_\beta \text{ detected events}} \sim \int \underbrace{\Phi_{\nu_\alpha}(E_\nu^{true})}_{\nu_\alpha \text{ flux}} \underbrace{P_{\nu_\alpha \to \nu_\beta}(E_\nu^{true}, L, \Theta)}_{\nu_\alpha \to \nu_\beta \text{ oscillation probability}} \underbrace{\sigma_{\nu_\beta}(E_\nu^{true})}_{\nu_\beta \text{ cross section}} \underbrace{\epsilon_{\text{det}}}_{\text{detector efficiency}} \underbrace{d(E_\nu^{true}, E_\nu^{rec})}_{\text{migration matrix}} dE_\nu$$

The ν_β **cross section** appears:

- explicitly
- implicitly in the detector efficiency
- implicitly in the migration matrix

→ **modelling** the **neutrino - nucleus cross section** is **crucial !**

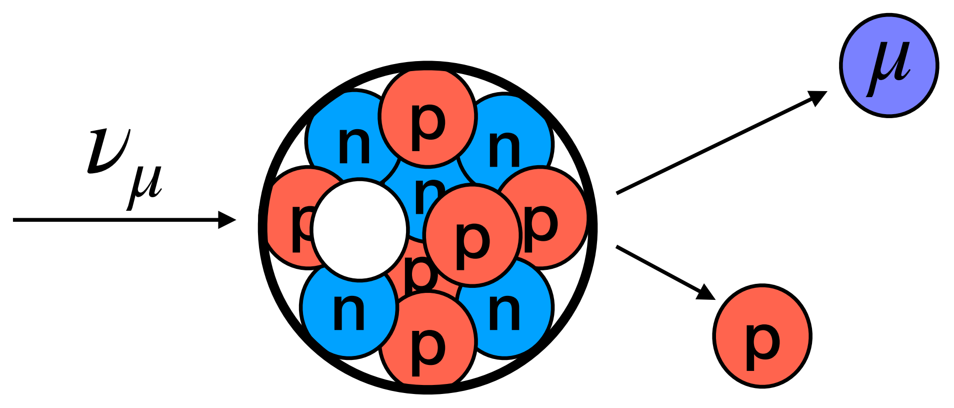
topic of my PhD (1)

Martini et al model implementation in GENIE MC Generator

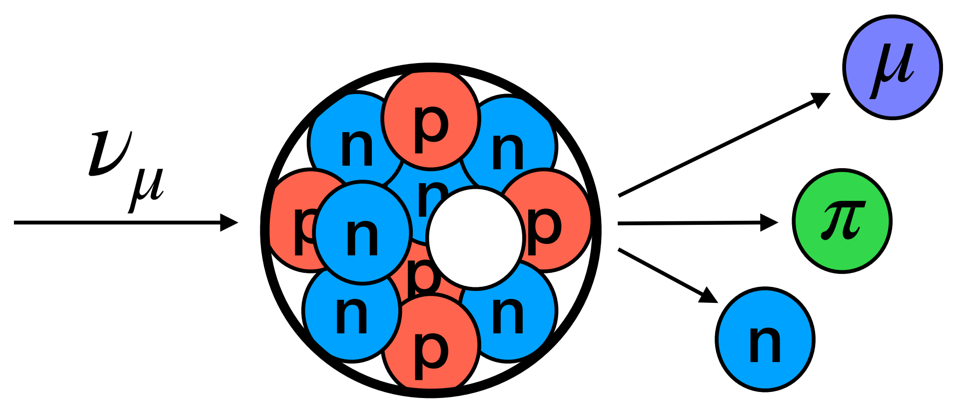
Introduction

Neutrino - nucleus interactions at $E_\nu \sim \mathcal{O}(1\mathrm{GeV})$

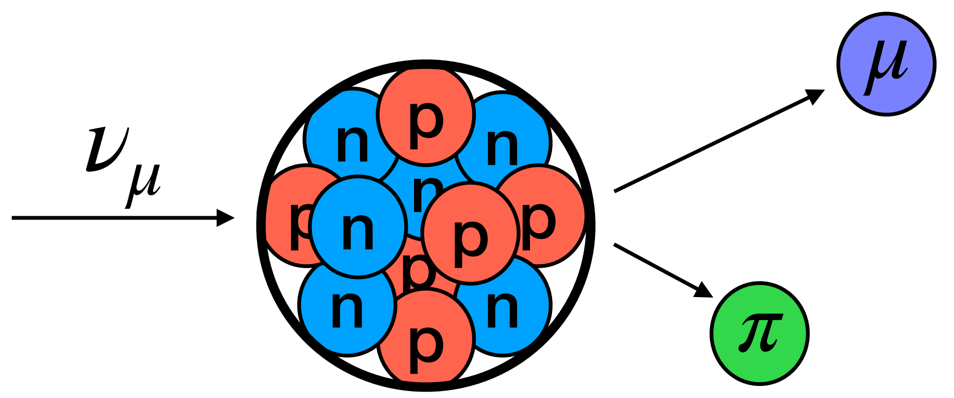
- quasielastic (CCQE)



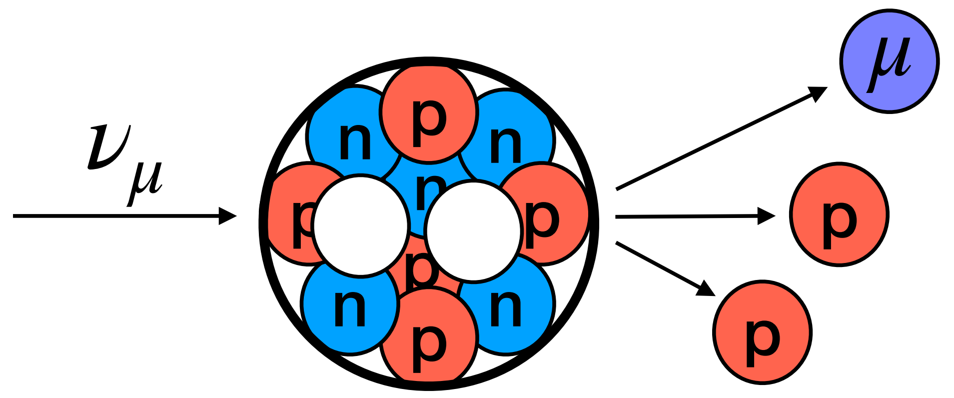
- incoherent π production

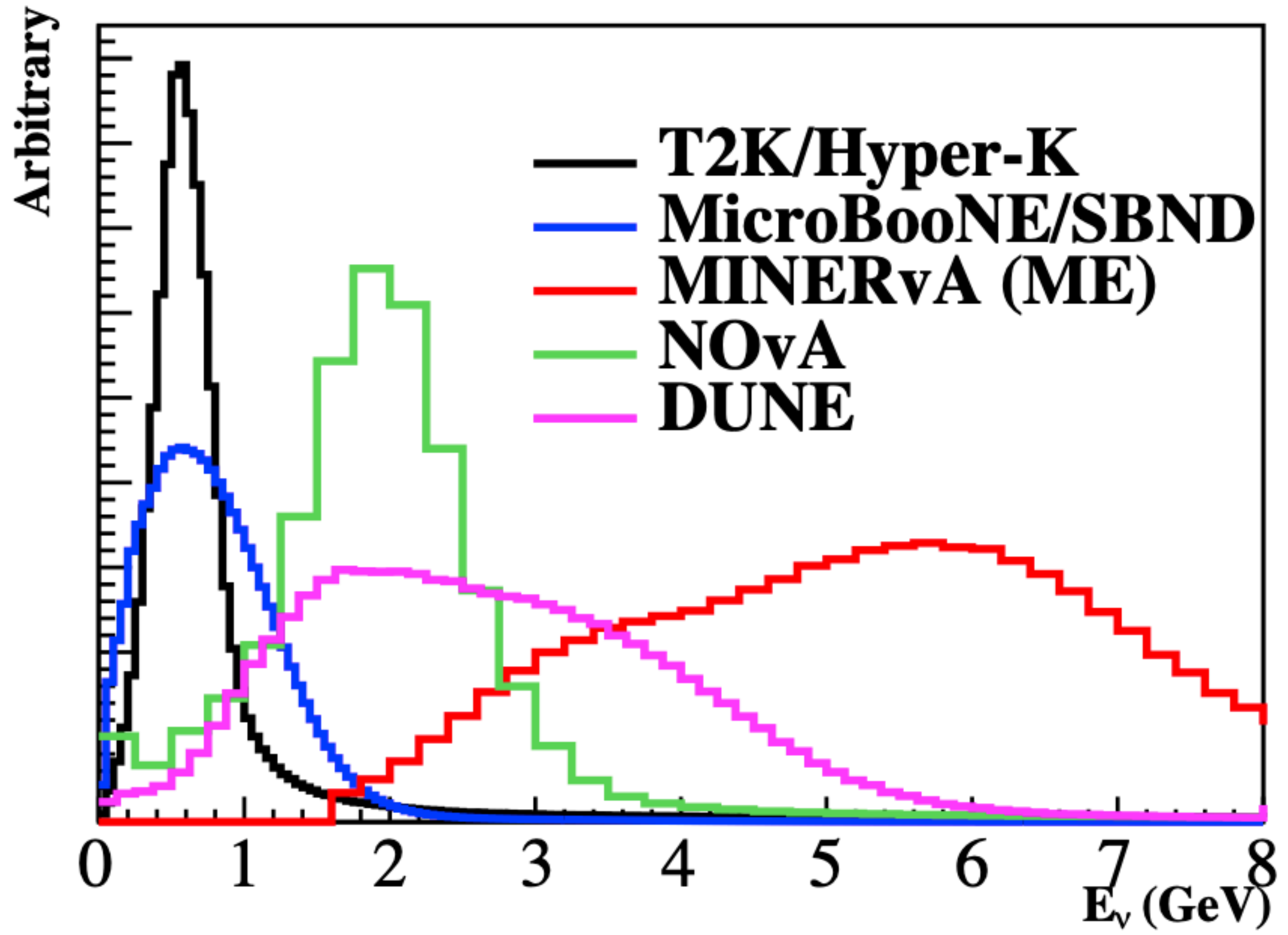


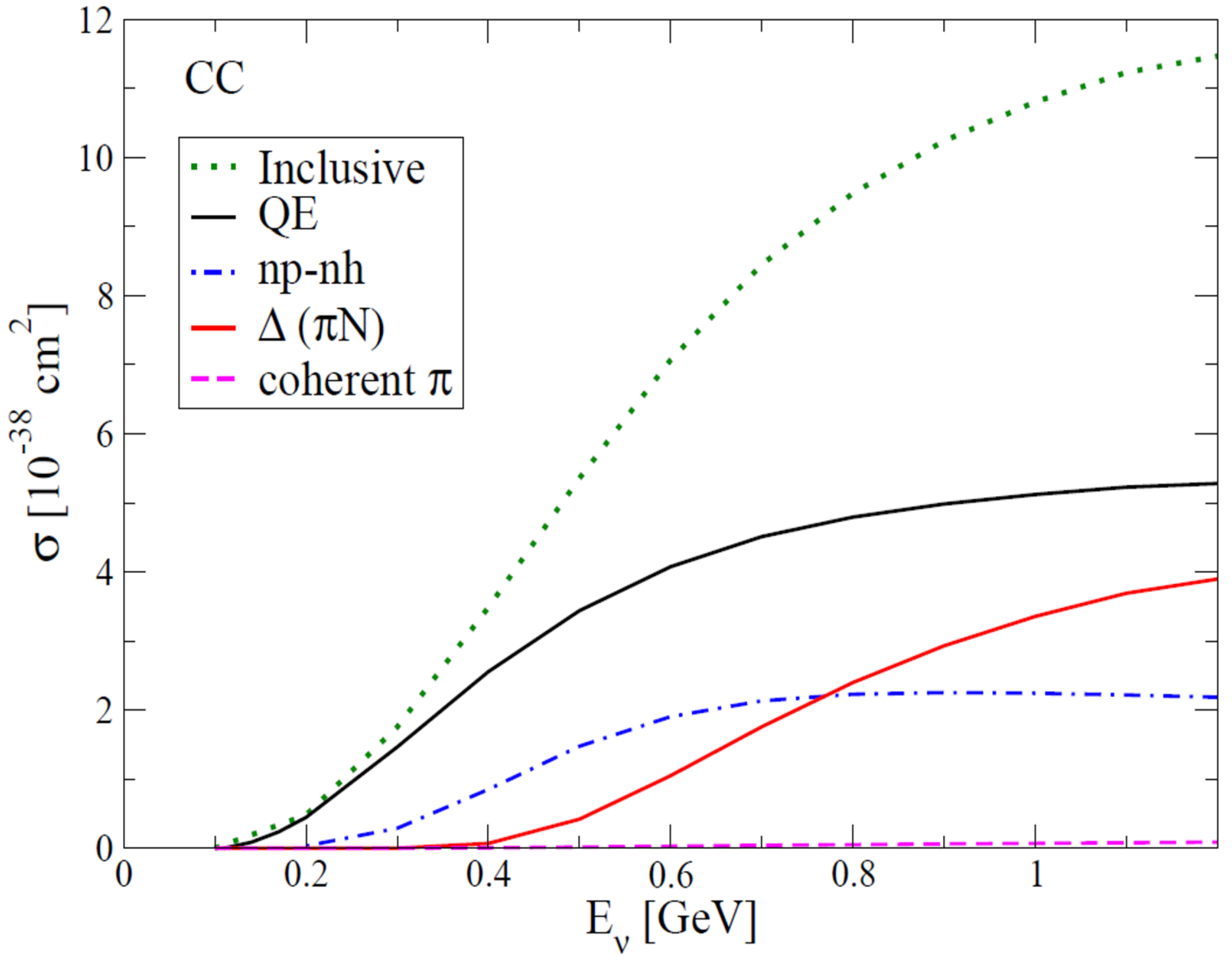
- coherent π production



- n nucleons knocked out (npnh)



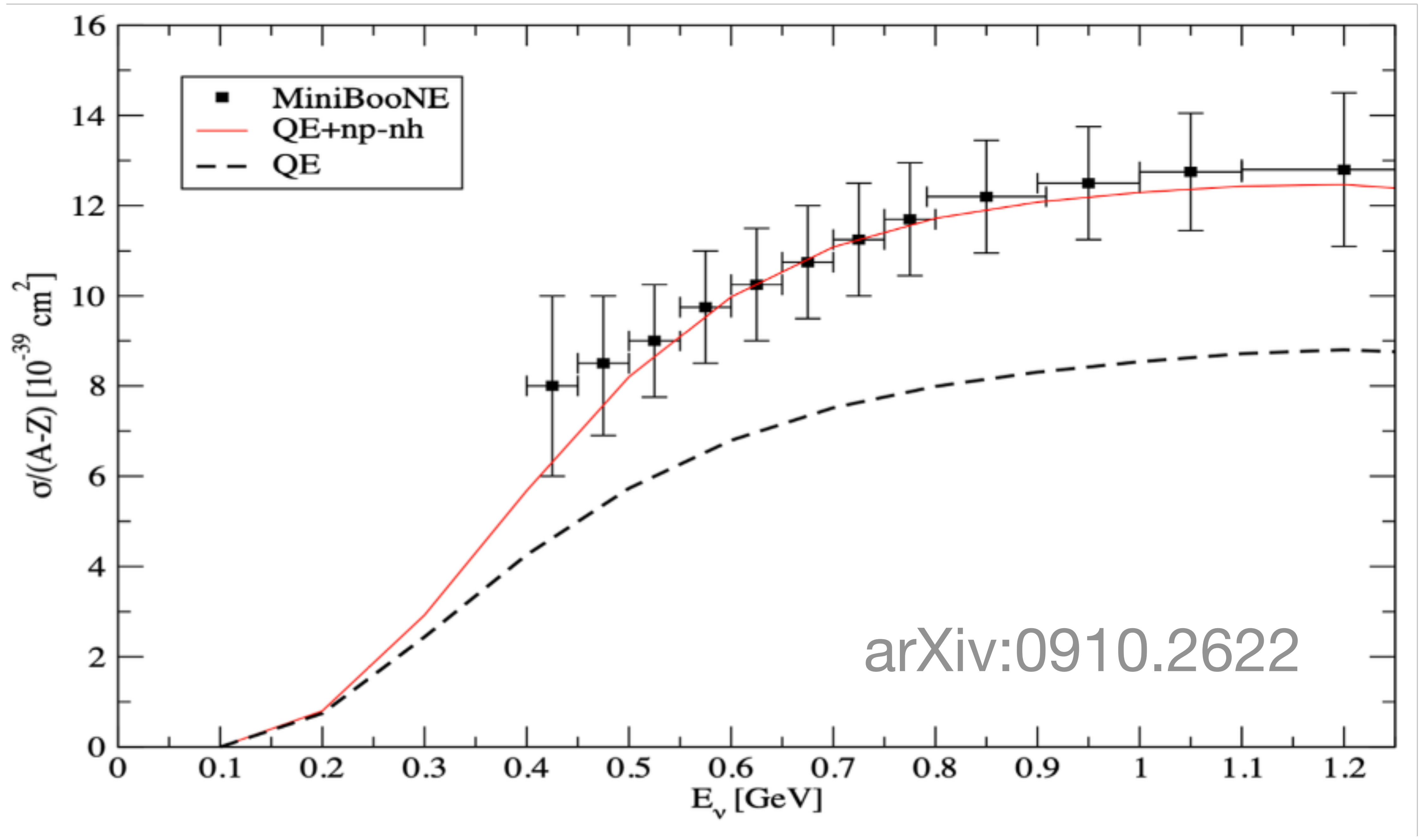




Martini et al model offers a **unified description** of these channels **without** risk of **double counting**

First explanation of the MiniBooNE CCQE-like σ

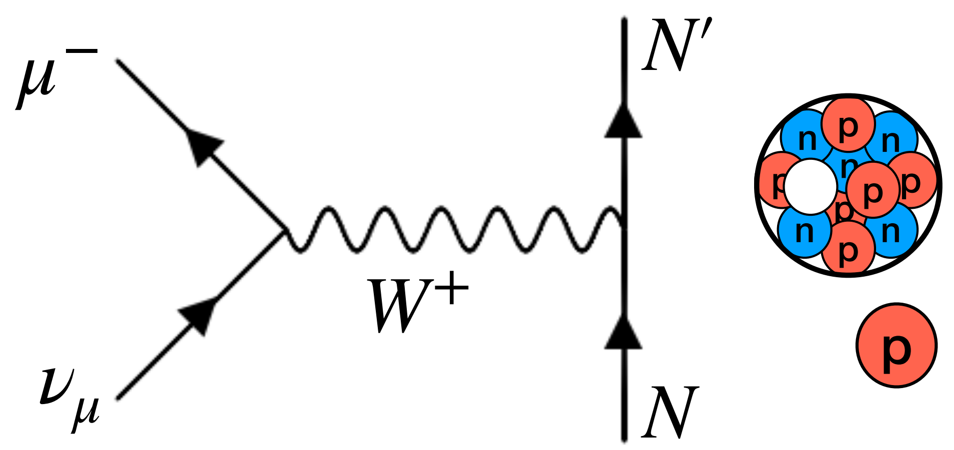
M. Martini, M. Ericson, G. Chanfray, J. Marteau
Phys. Rev. C 80 065501 (2009)



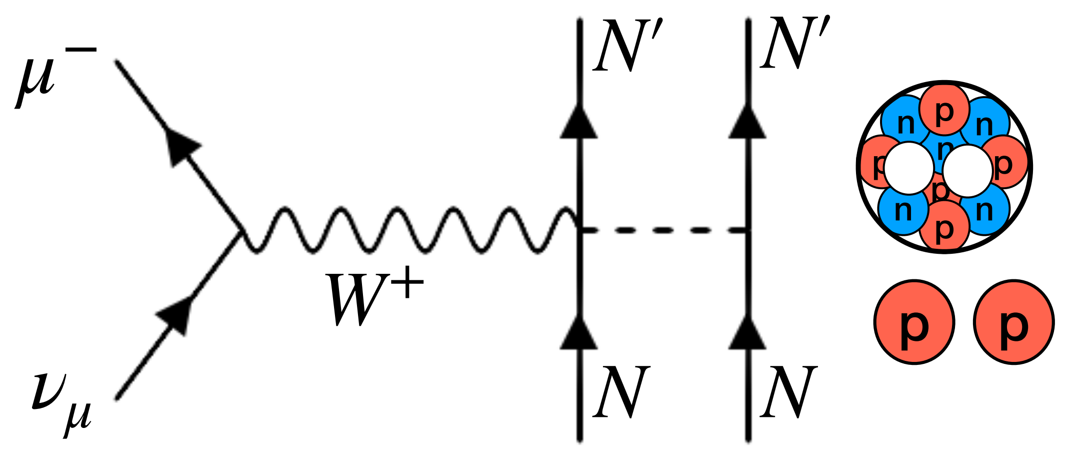
- MiniBooNE studied CCQE-like events **reconstructing** just the **leptonic part**
- Genuine CCQE and npnh have the **same final states** if one looks at the leptonic part only

CCQE-like = genuine CCQE + npnh

- **genuine CCQE**



- **npnh**



inclusion of the multinucleon emission channel - **npnh** ⟶ **agreement with MiniBooNE**

Many models and many MC event generators

- Main models to calculate the nuclear responses and the ν cross sections:
  - Local Fermi Gas + RPA (Nieves et al, Martini et al)
  - Hartree-Fock + (Continuum) RPA
  - SuperScaling (SuSAv2)

- Main MC event generators for neutrino interactions:

Motivation and strategy

Up to now there is no implementation of Martini et al model in any of the MC generators

Present project : full Martini et al model implementation into GENIE MC generator

Same **strategy**, approach and tools as:

✳ SuSAv2: npnh [2]

PHYSICAL REVIEW D **101,** 033003 (2020)

Implementation of the SuSAv2-meson exchange current 1p1h and 2p2h models in GENIE and analysis of nuclear effects in T2K measurements

S. Dolan,[1,2,3] G. D. Megias,[1,2,4] and S. Bolognesi[2]

✳ CRPA: QE [3]

PHYSICAL REVIEW D **106,** 073001 (2022)

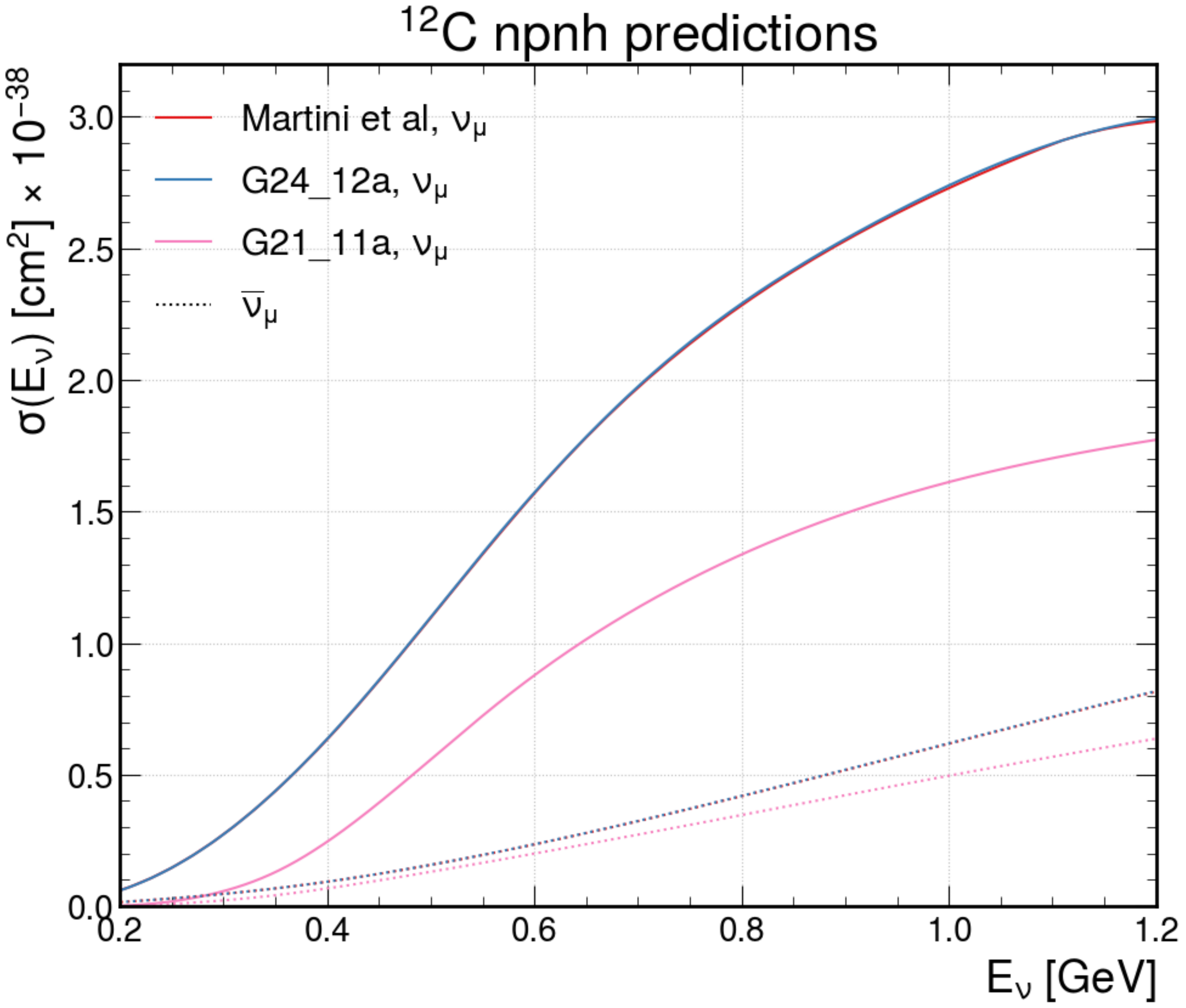
Implementation of the continuum random phase approximation model in the GENIE generator and an analysis of nuclear effects in low-energy transfer neutrino interactions

S. Dolan,[1,*] A. Nikolakopoulos,[2,†] O. Page,[3] S. Gardiner,[2] N. Jachowicz,[4] and V. Pandey[2,5]

Collaborators: Stephen Dolan and Laura Munteanu @ CERN

npnh implementation

total σ on ^{12}C



perfect match with data produced out GENIE:

- neutrinos ✓
- antineutrinos ✓

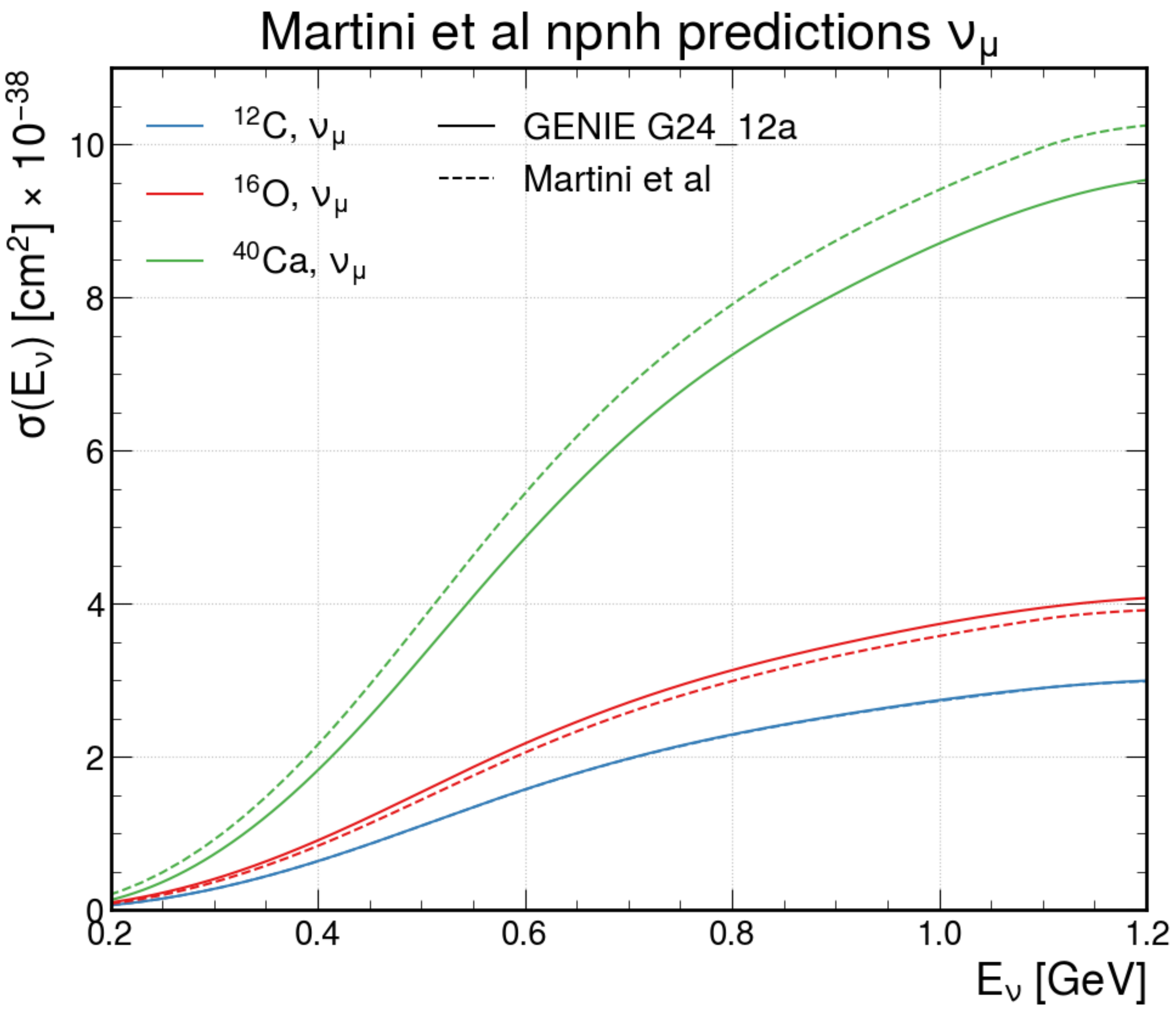
Martini et al model implementation in GENIE MC Generator

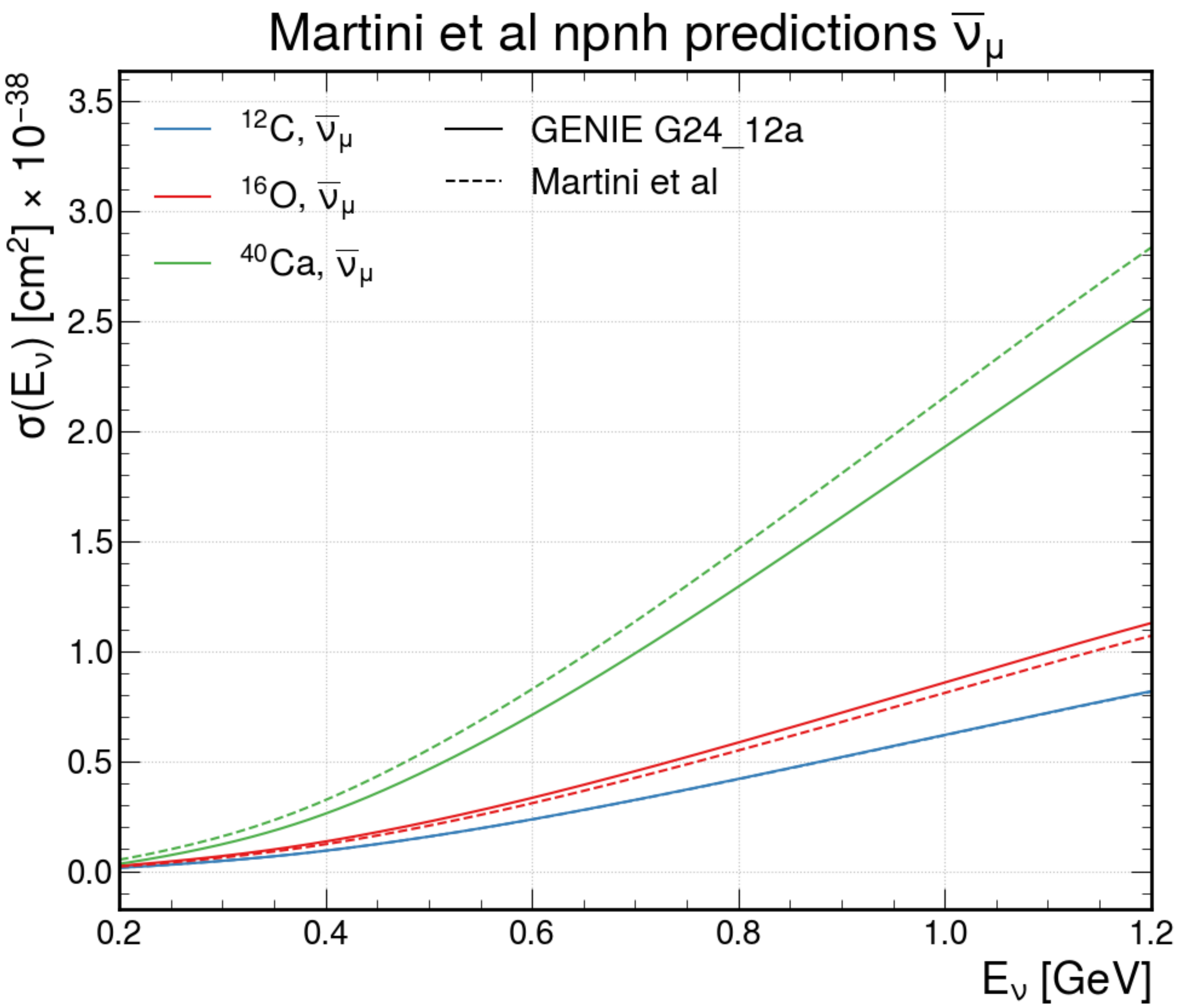
New results

npnh implementation

MISMATCH for ^{16}O and ^{40}Ca

total σ on ^{12}C, ^{16}O and ^{40}Ca



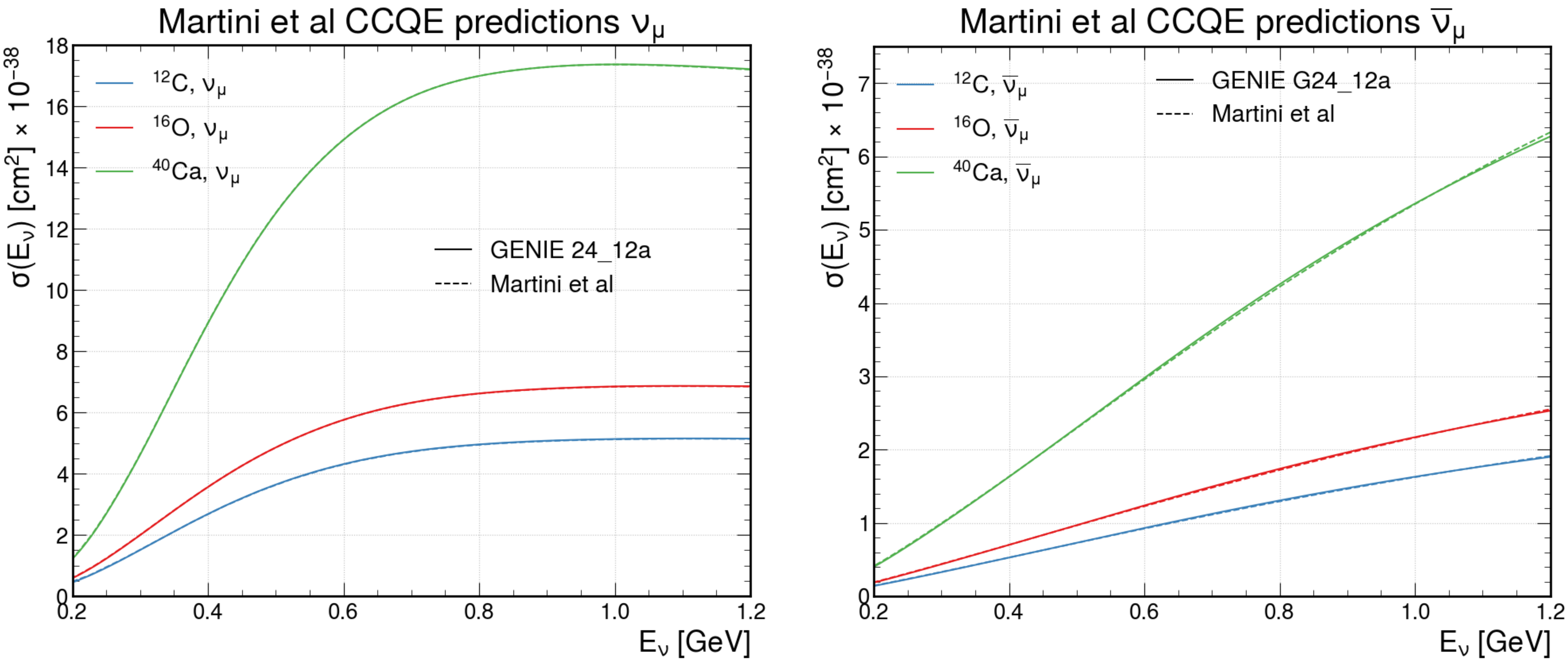


CCQE implementation

little discrepancies for ^{16}O and ^{40}Ca - $\bar{\nu}_\mu$ because Marco's data are non relativistic

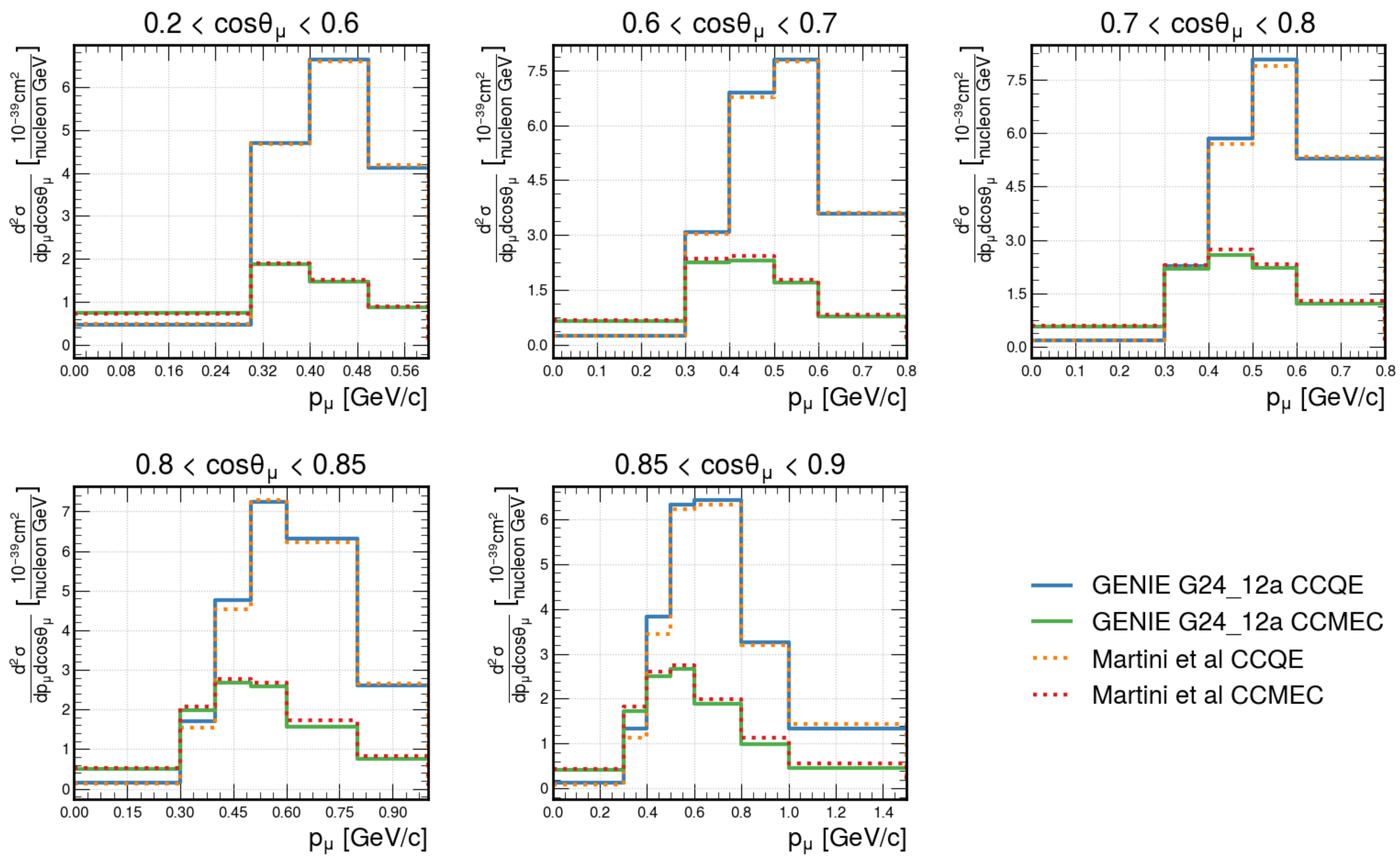
total σ on ^{12}C, ^{16}O and ^{40}Ca

MATCHING for the 3 targets



double differential σ

ϕ_ν^{T2K} on ^{12}C CCQE and CCMEC channel



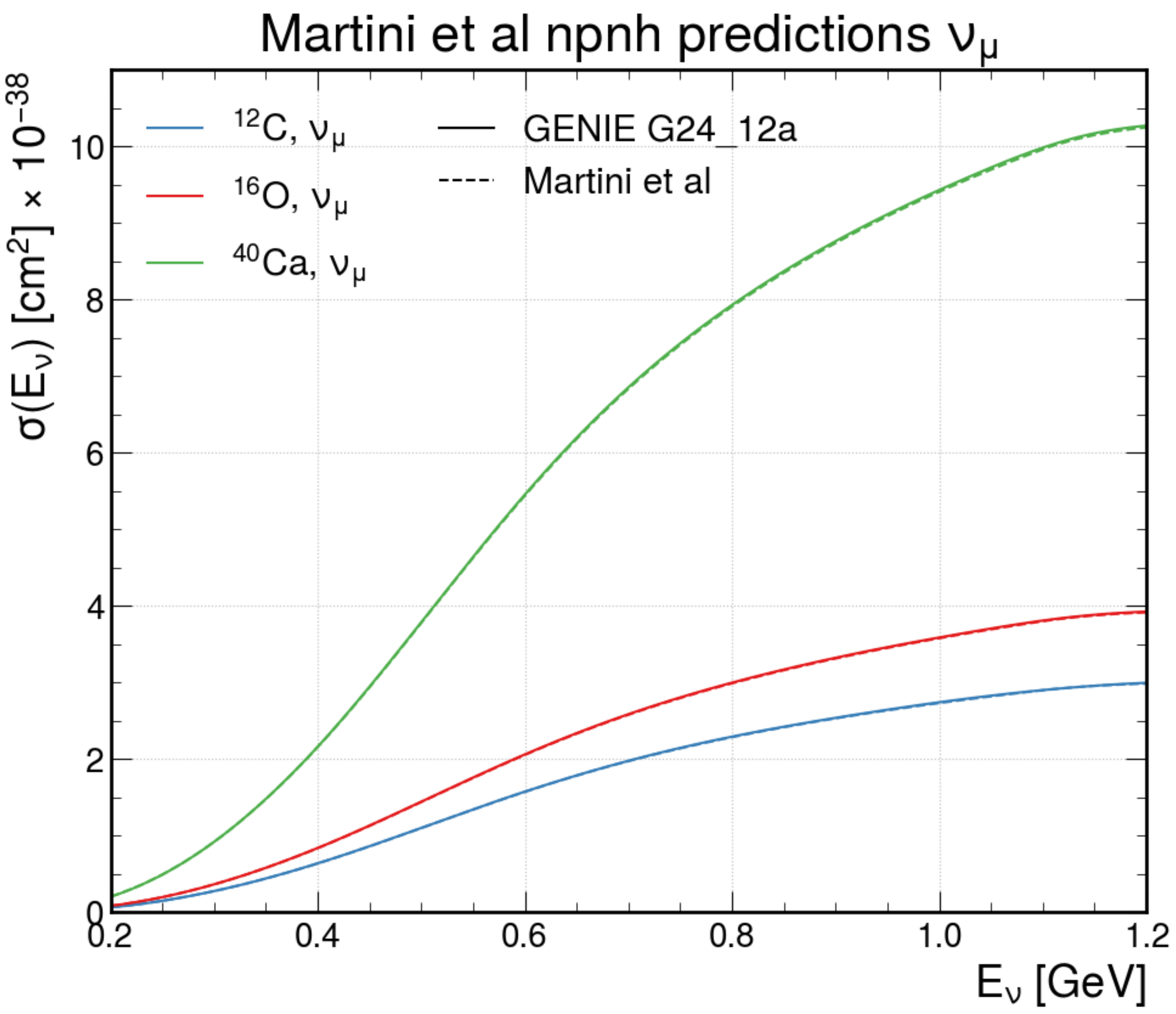
double differential σ

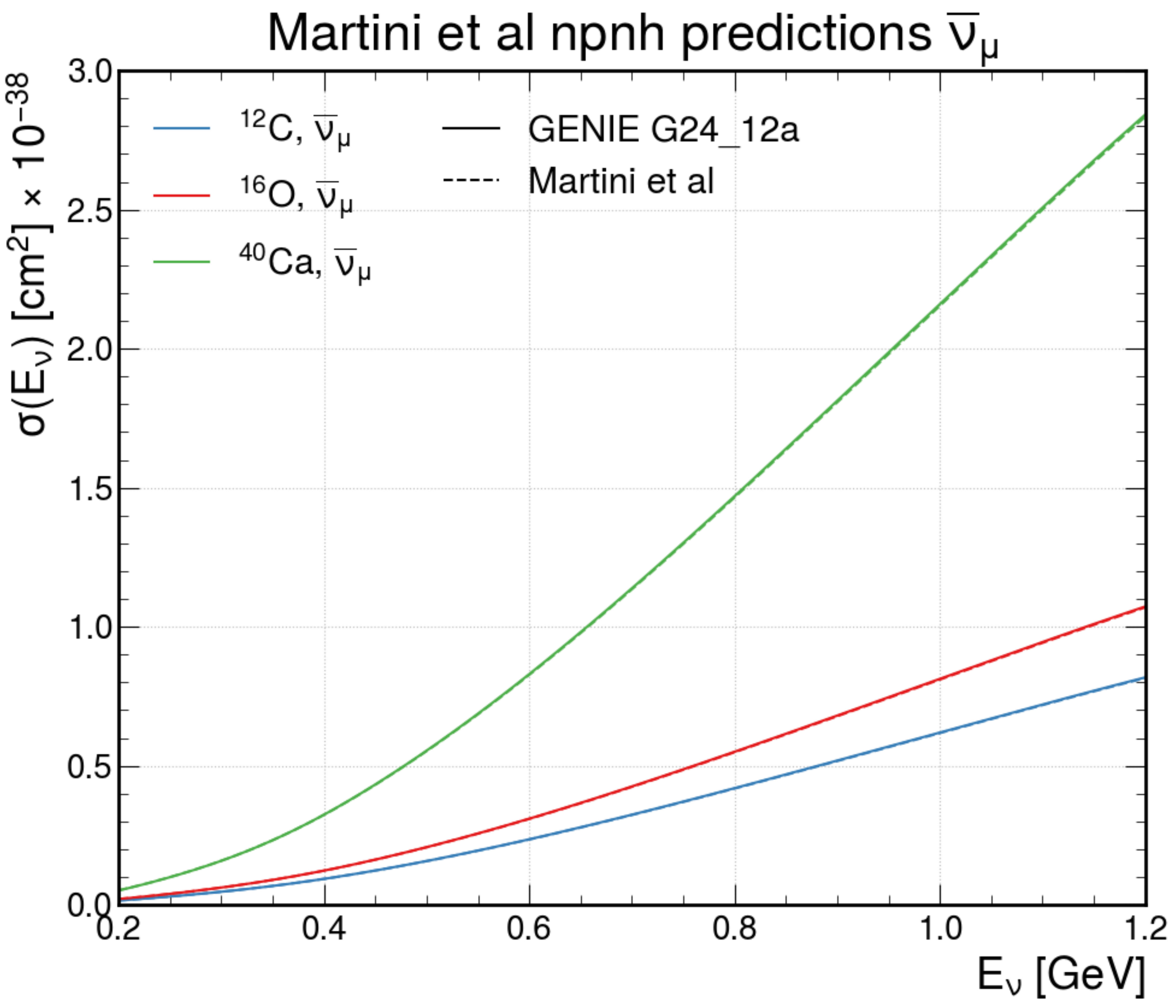
$E_\nu = 0.575\ GeV$ on ^{12}C CCQE and CCMEC channel

npnh implementation

total σ on ^{12}C, ^{16}O and ^{40}Ca

GREAT MATCH !
problem solved for ^{16}O and ^{40}Ca





double differential σ

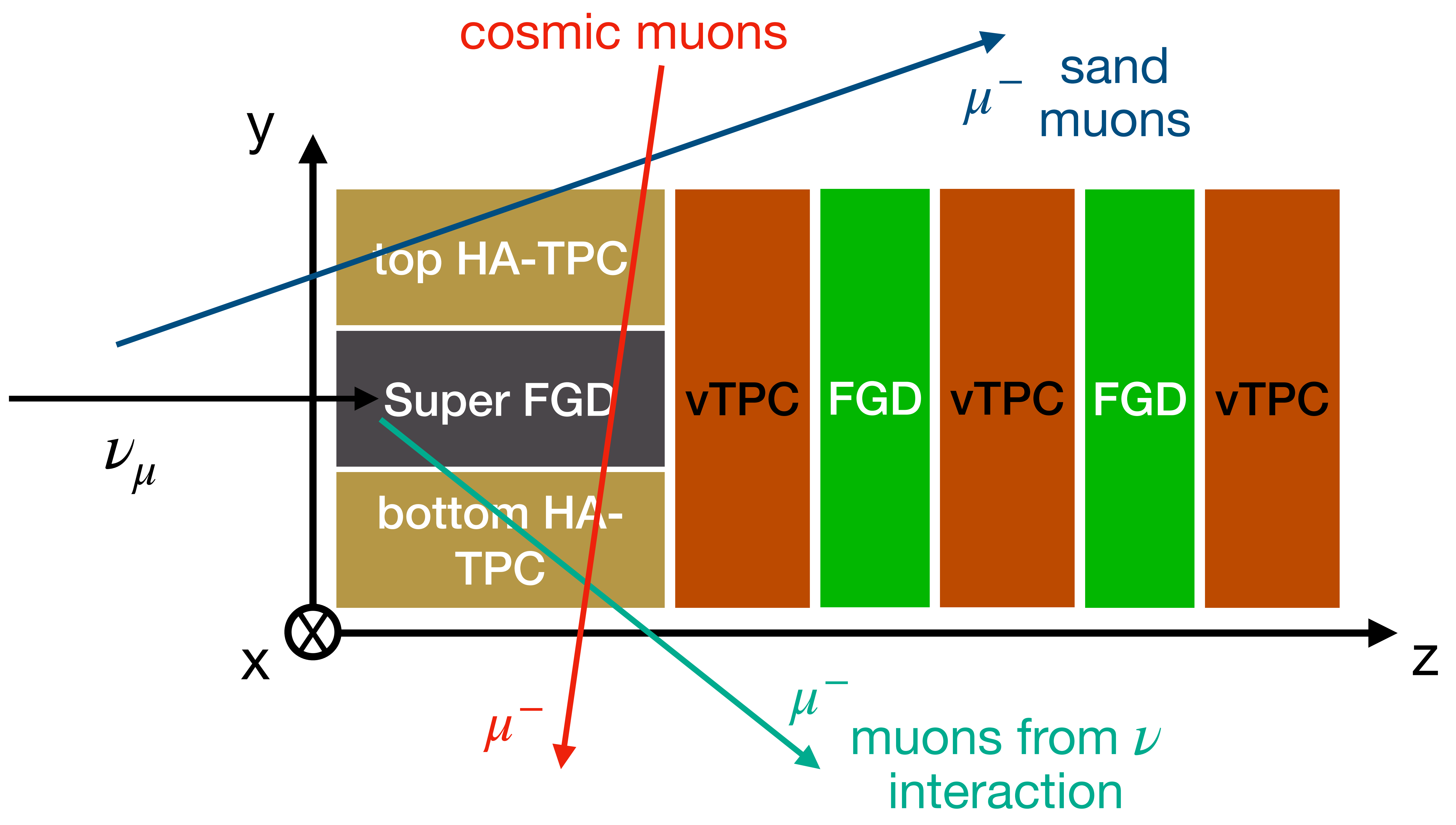
$E_\nu = 0.575\ GeV$ on ^{16}O CCQE and CCMEC channel

The characterisation of the HA-TPCs of upgraded near detector of T2K

Introduction

HA-TPCs perfomances

collected data tracks types

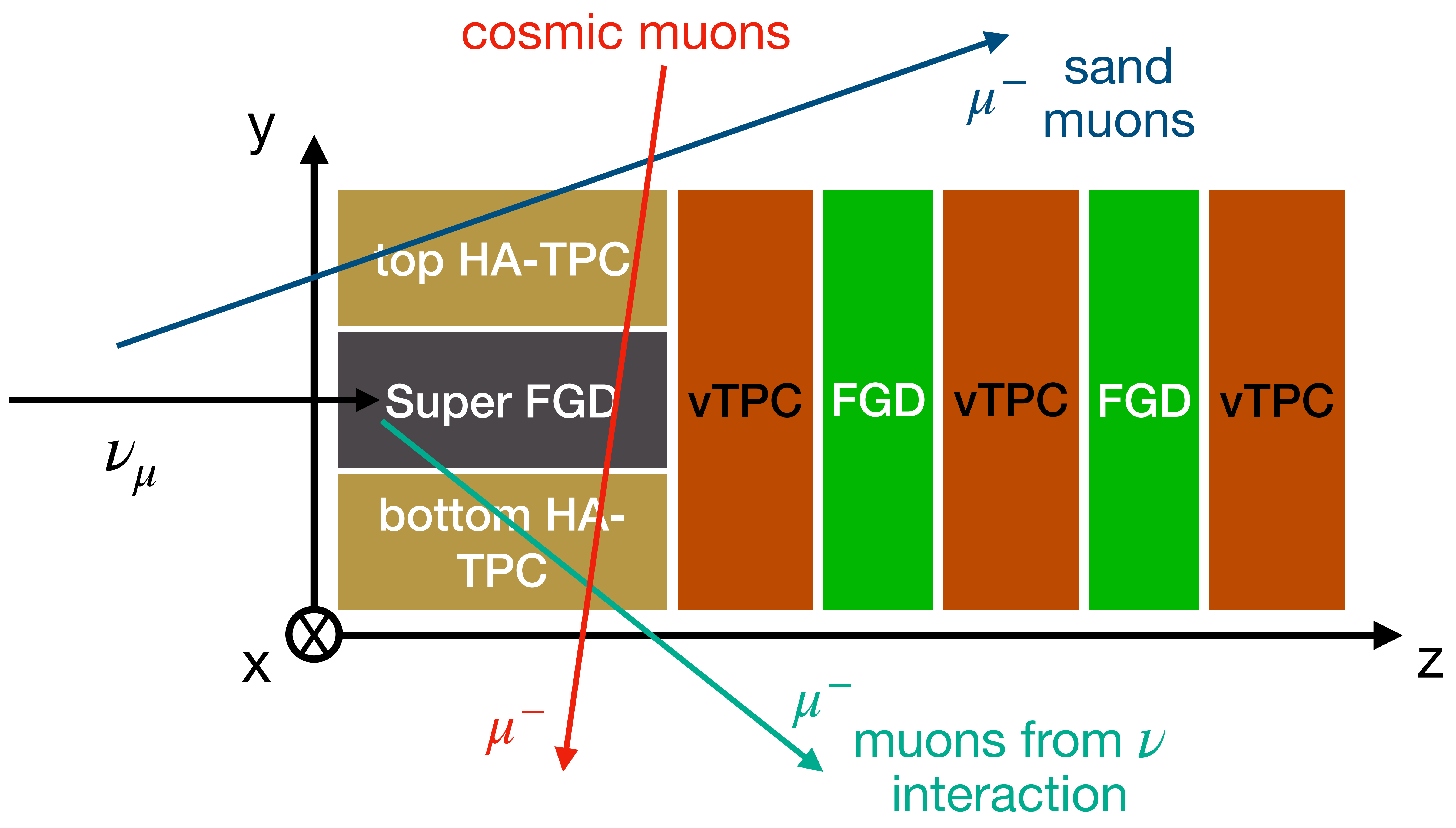


We collect data of 2 types:

- **cosmic data:**
  - cosmic muons
- **beam data:**
  - cosmic muons
  - sand muons
  - muons from neutrino interactions in ND280

HA-TPCs perfomances

collected data tracks types



We collect data of 2 types:

- **cosmic data:**
  - cosmic muons — vertical tracks
- **beam data:**
  - cosmic muons
  - sand muons
  - muons from neutrino interactions in ND280

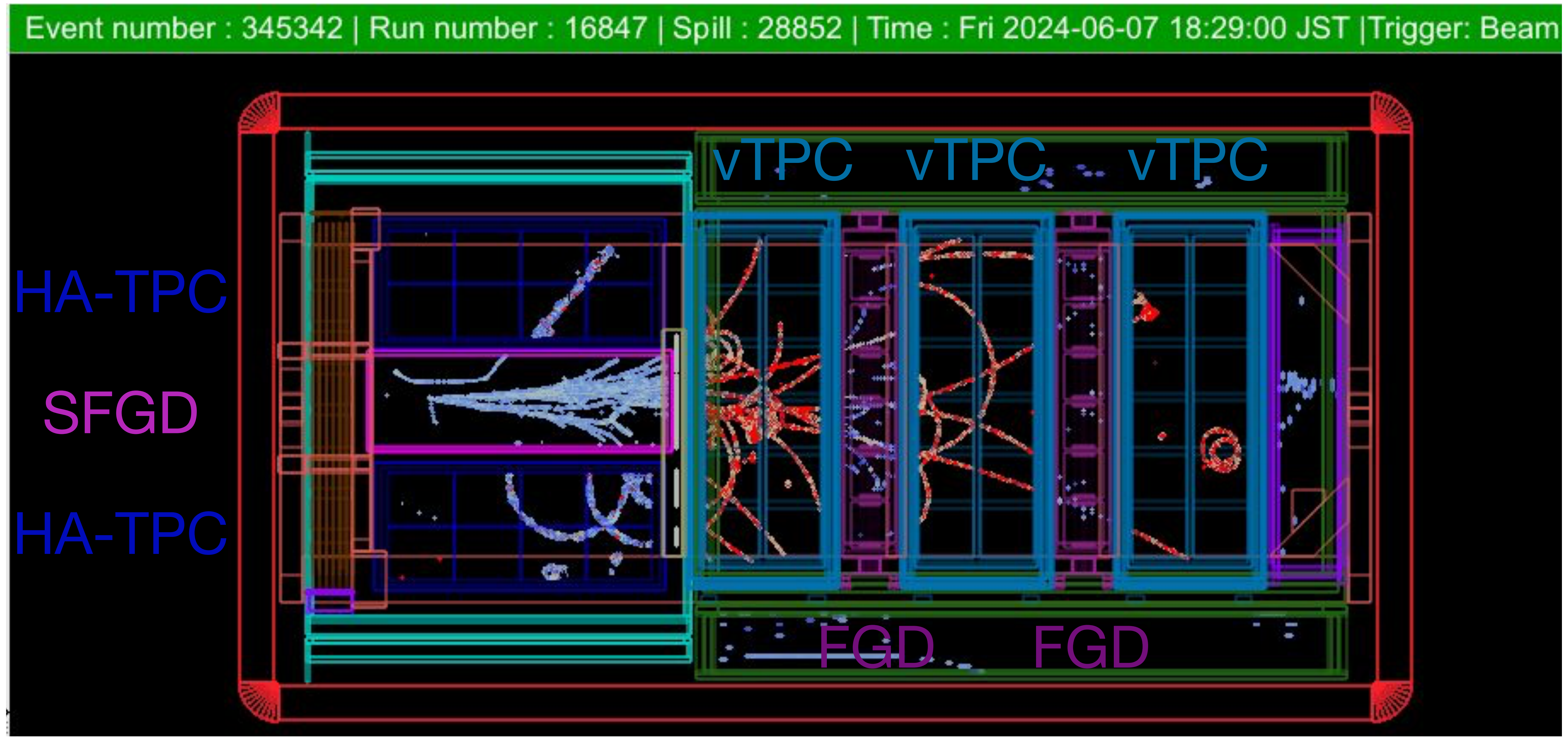
horizontal tracks

The ND280 upgrade

me in November 2024 data taking

becoming a TPC expert shifter @ JPARC

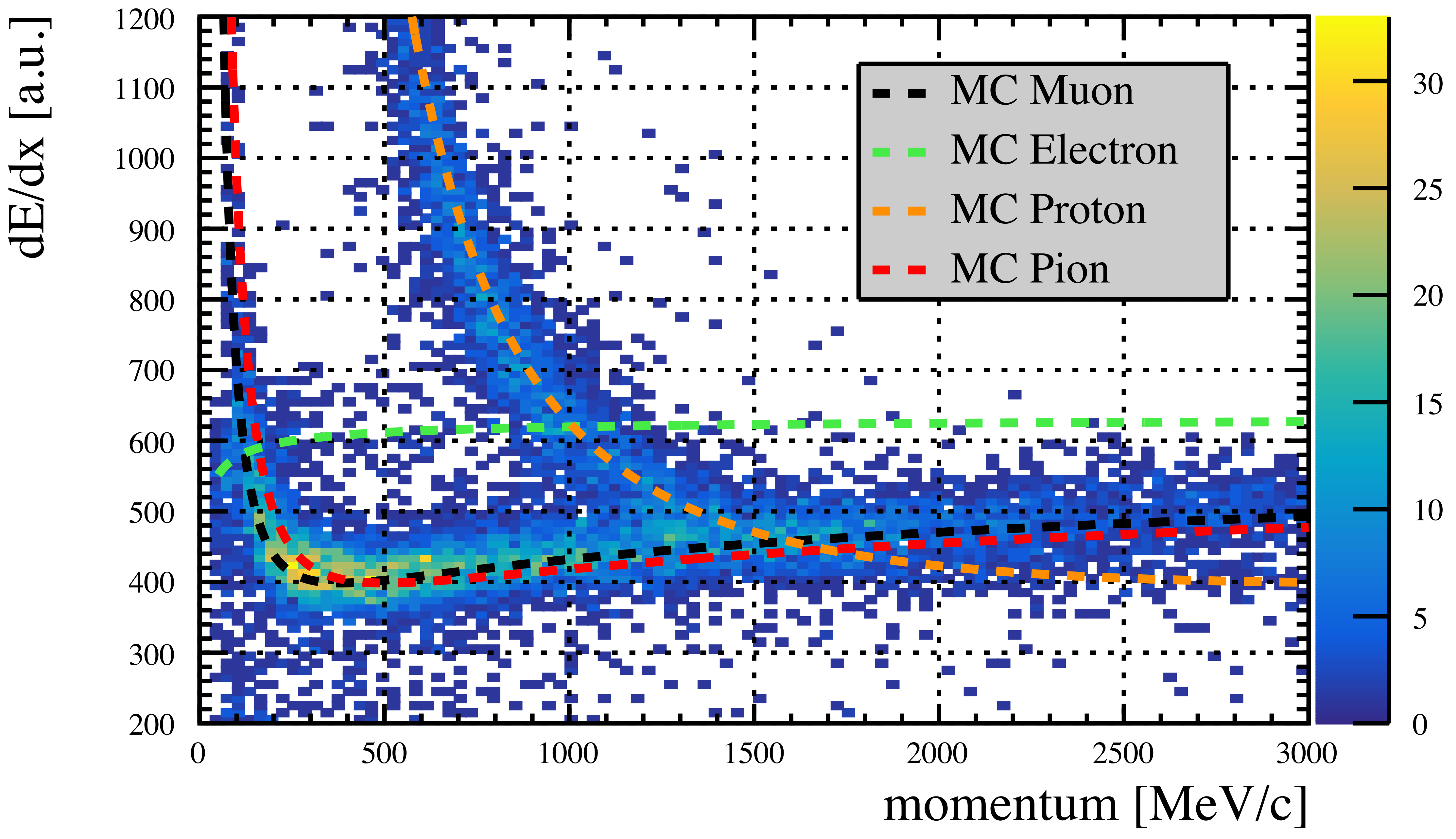
event display with the fully upgraded detector



HA-TPCs perfomances

- **spatial resolution (SR)**
  - related to the momentum resolution
  - better SR ⇒ more precise momentum estimation
  - requirement: momentum resolution < 10% ⇒ SR ~ 0.6 mm
- **dE/dx resolution**
  - is used in combination to the momentum to evaluate the likelihood of the particle being an e^-, μ^- or a p
  - better dE/dx res ⇒ more reliable PID
  - requirement: dE/dx resolution < 10%

I look at the performances comparing data and MC



paper submitted soon !

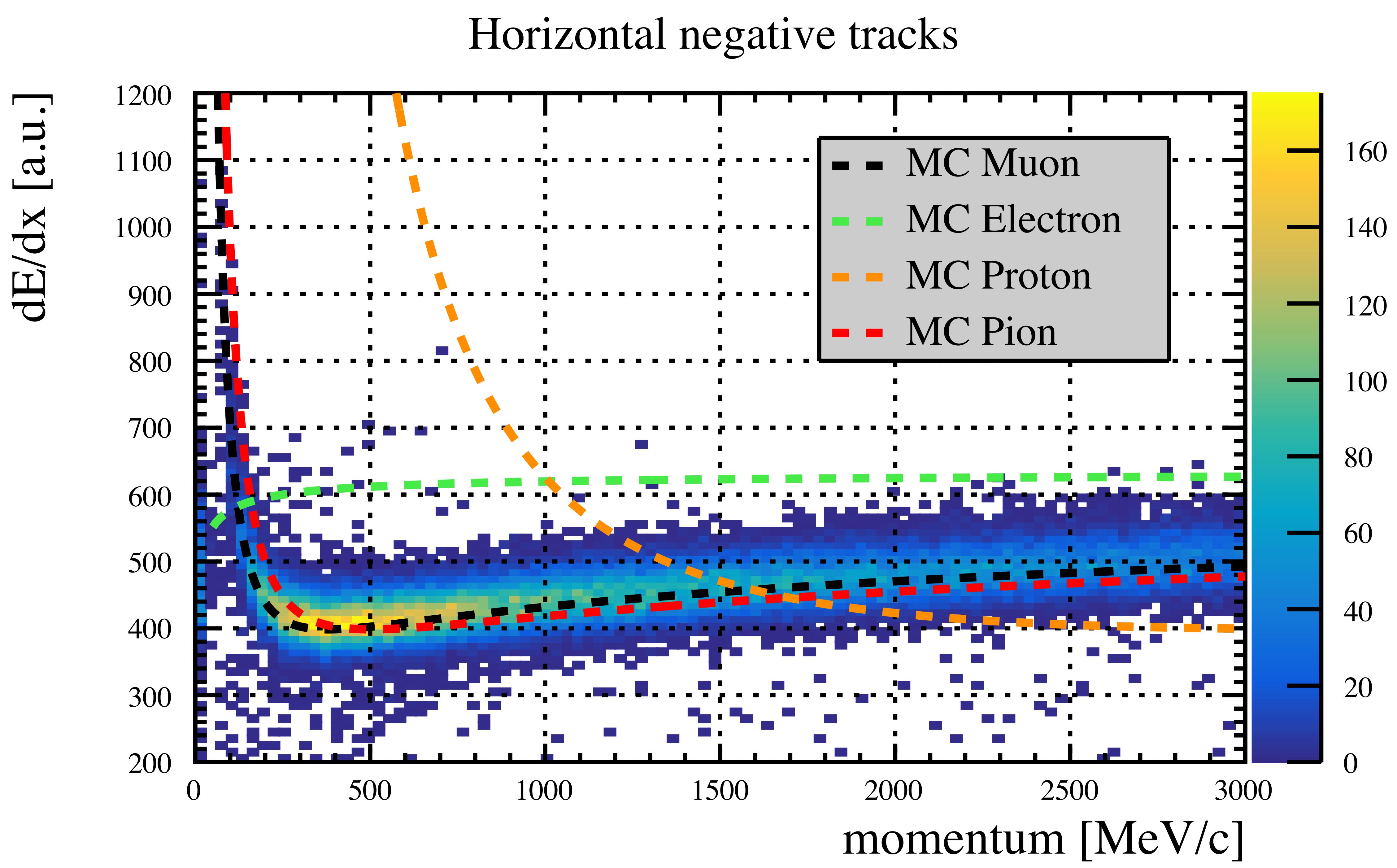
The characterisation of the HA-TPCs of upgraded near detector of T2K

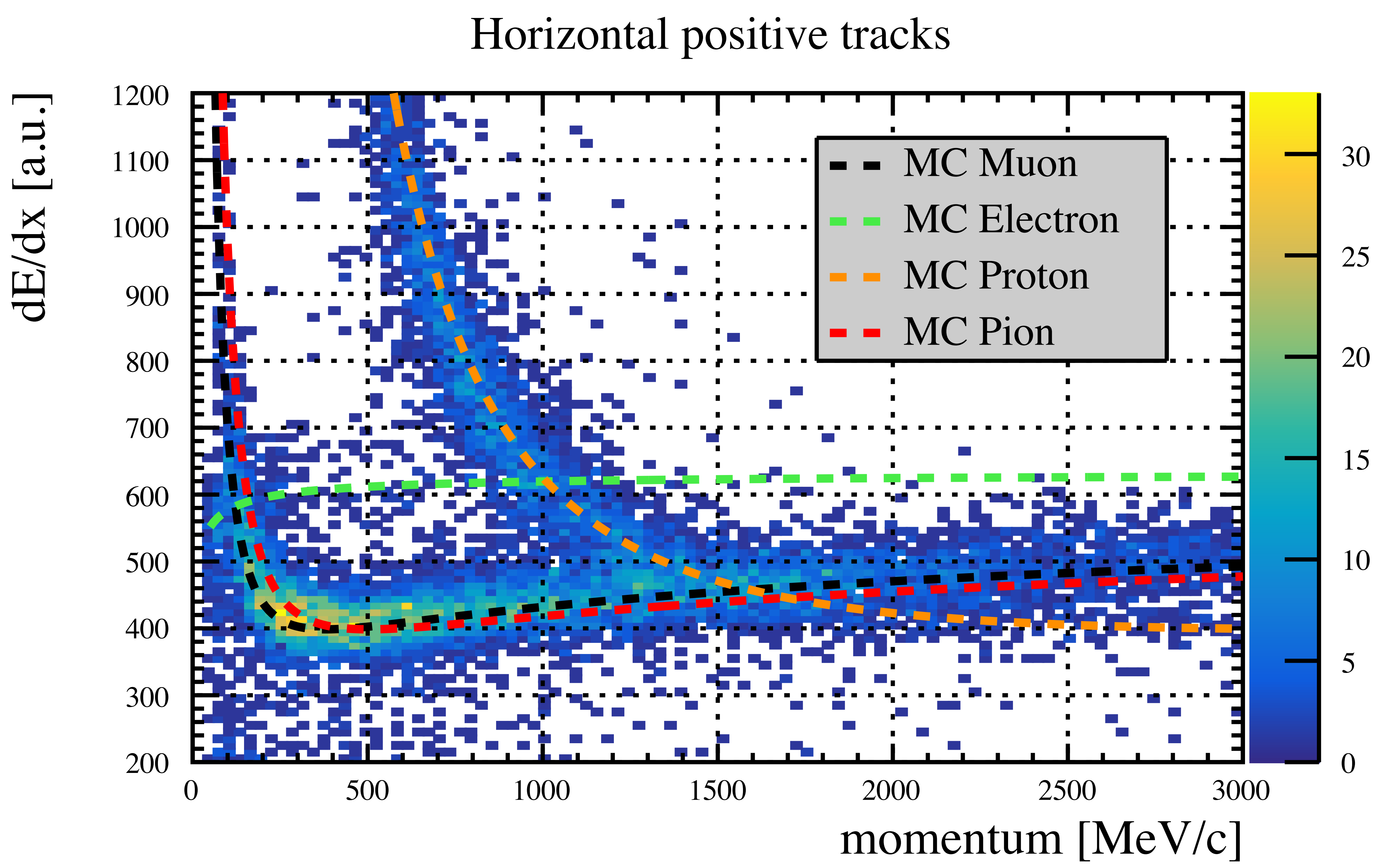
New results

dE/dx

horizontal tracks

- compatibility with what we expect to have in both negative and positive tracks

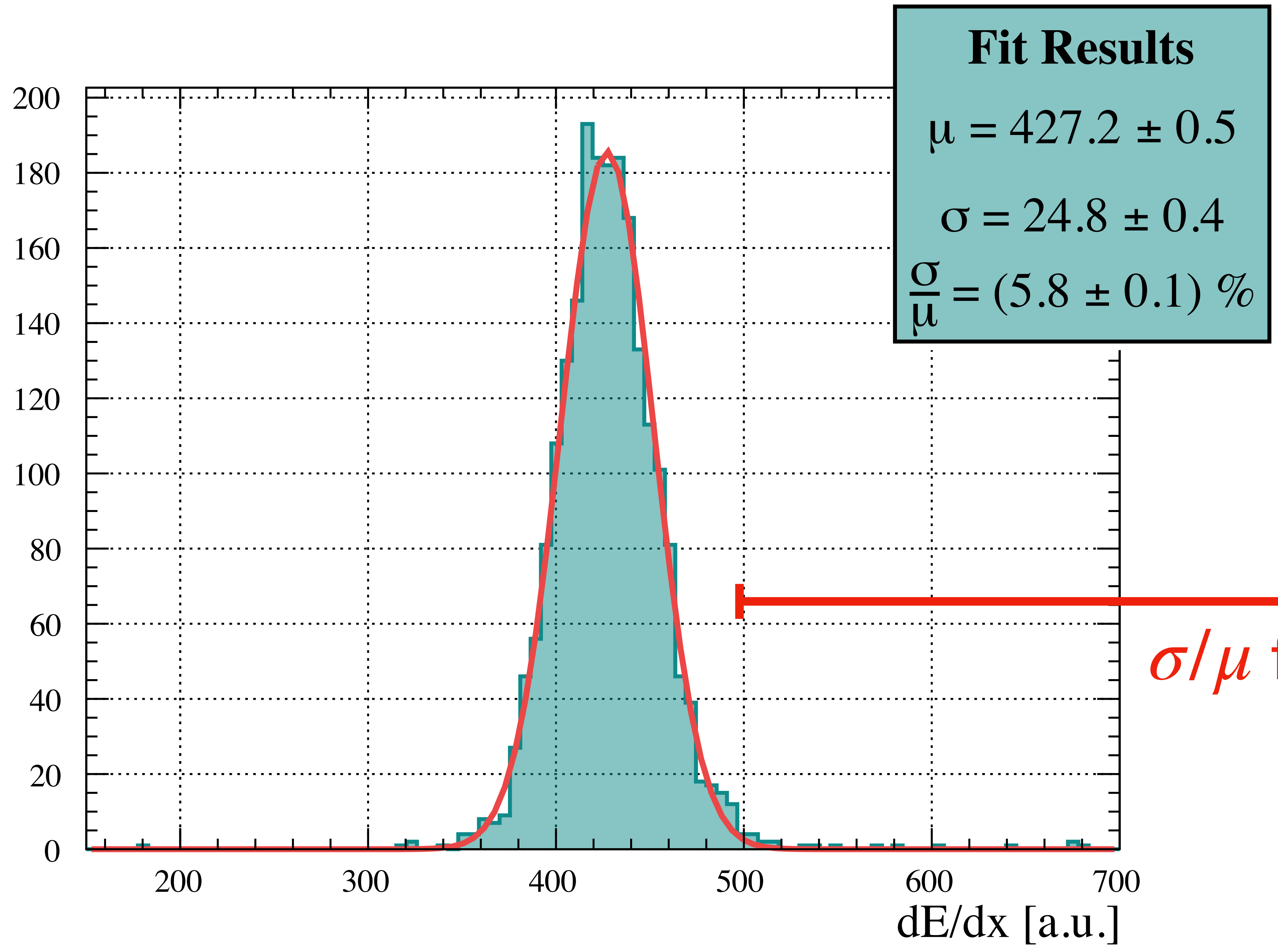




dE/dx resolution

horizontal tracks

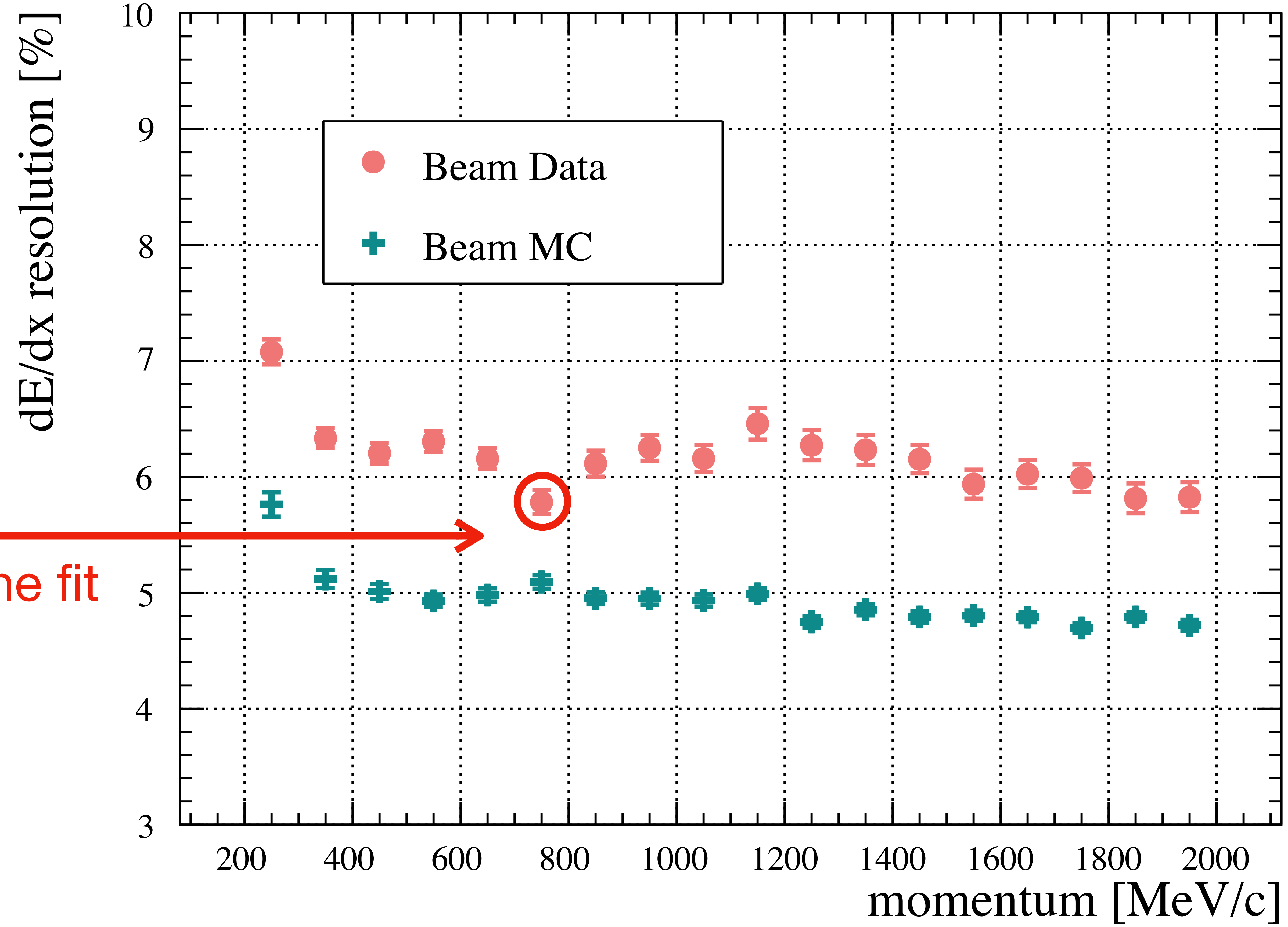
from dE/dx binned in |p|



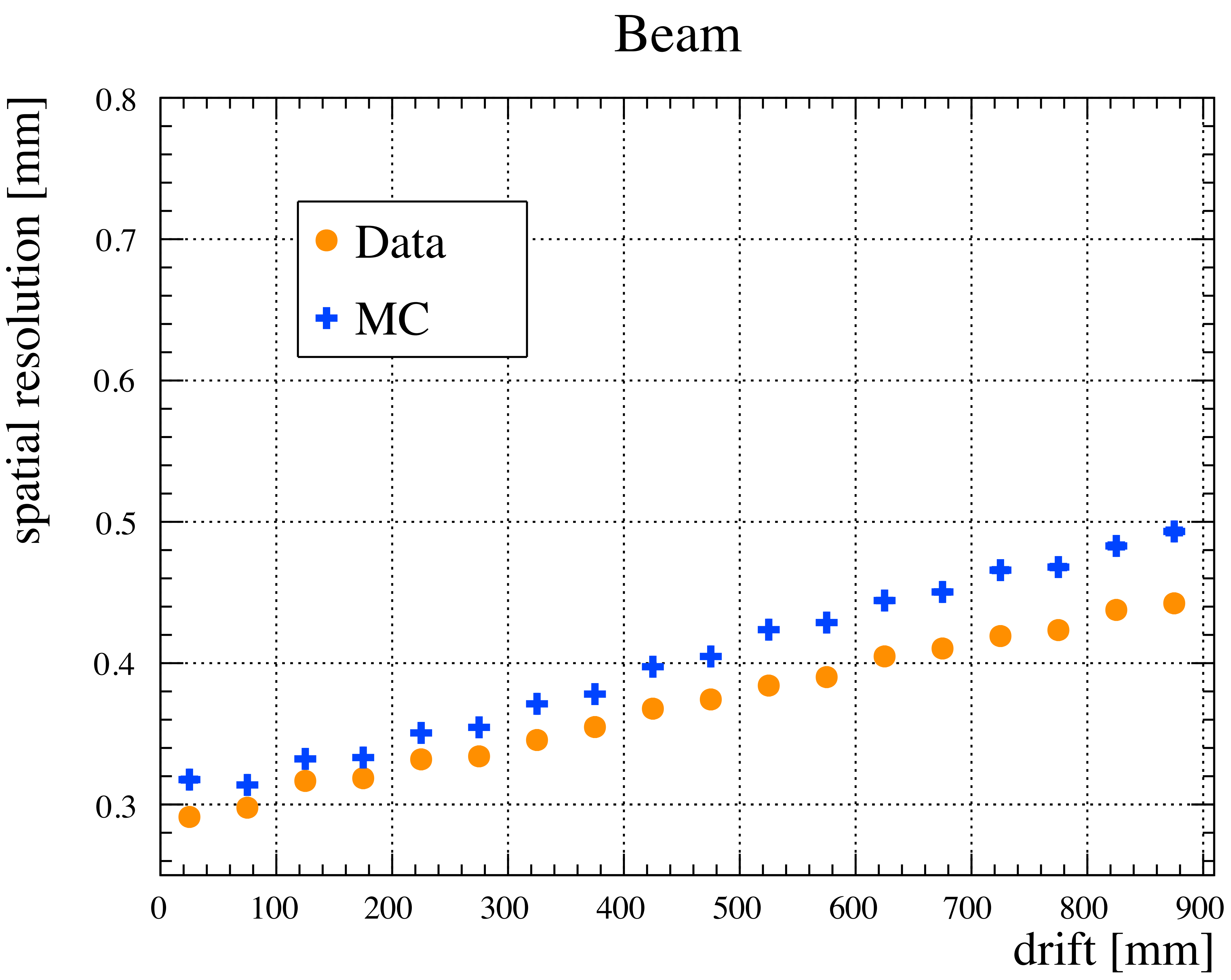
σ/μ from the fit

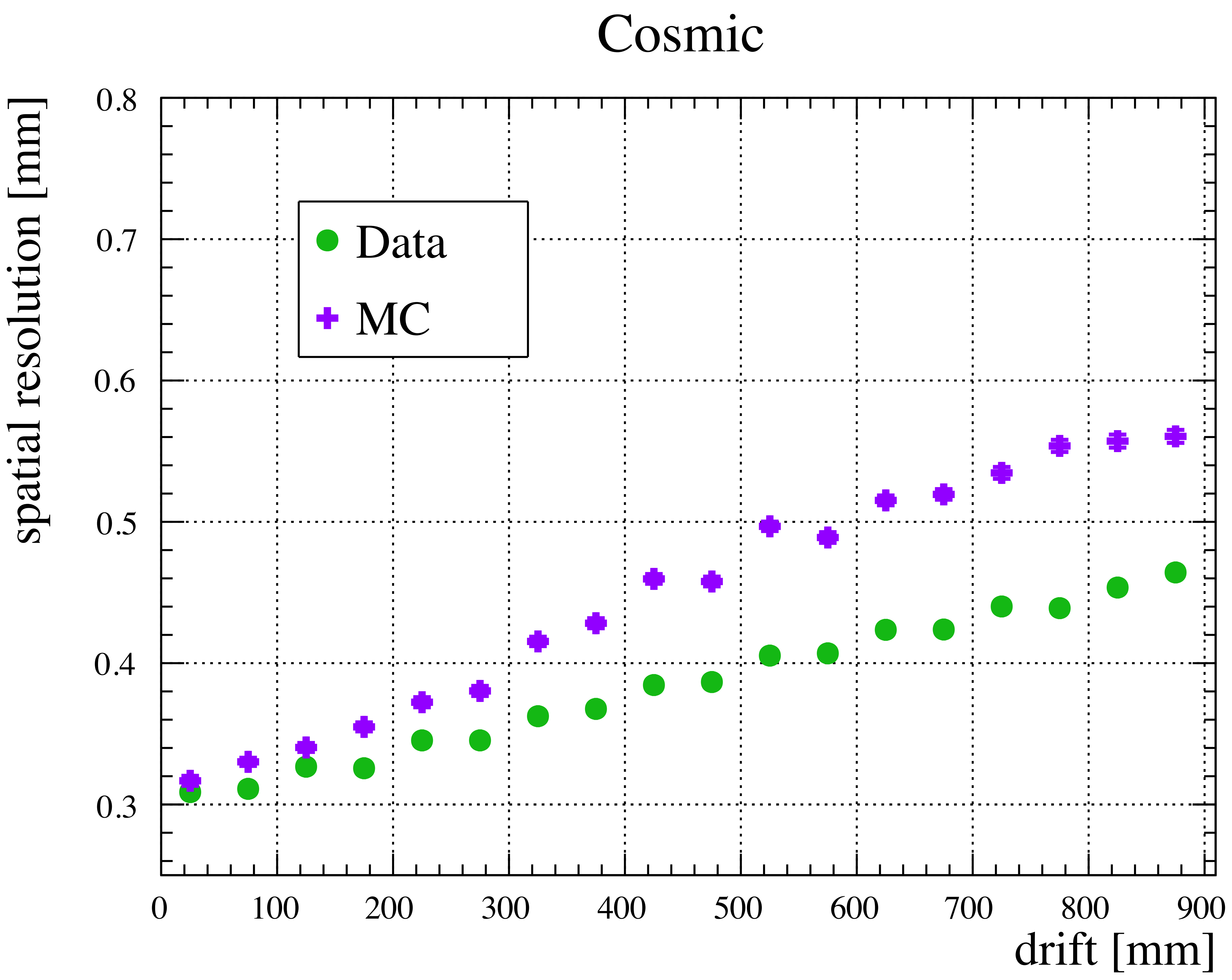
dE/dx resolution vs |p|

- expected dependence on |p|
- 16% discrepancy between data and MC



spatial resolution





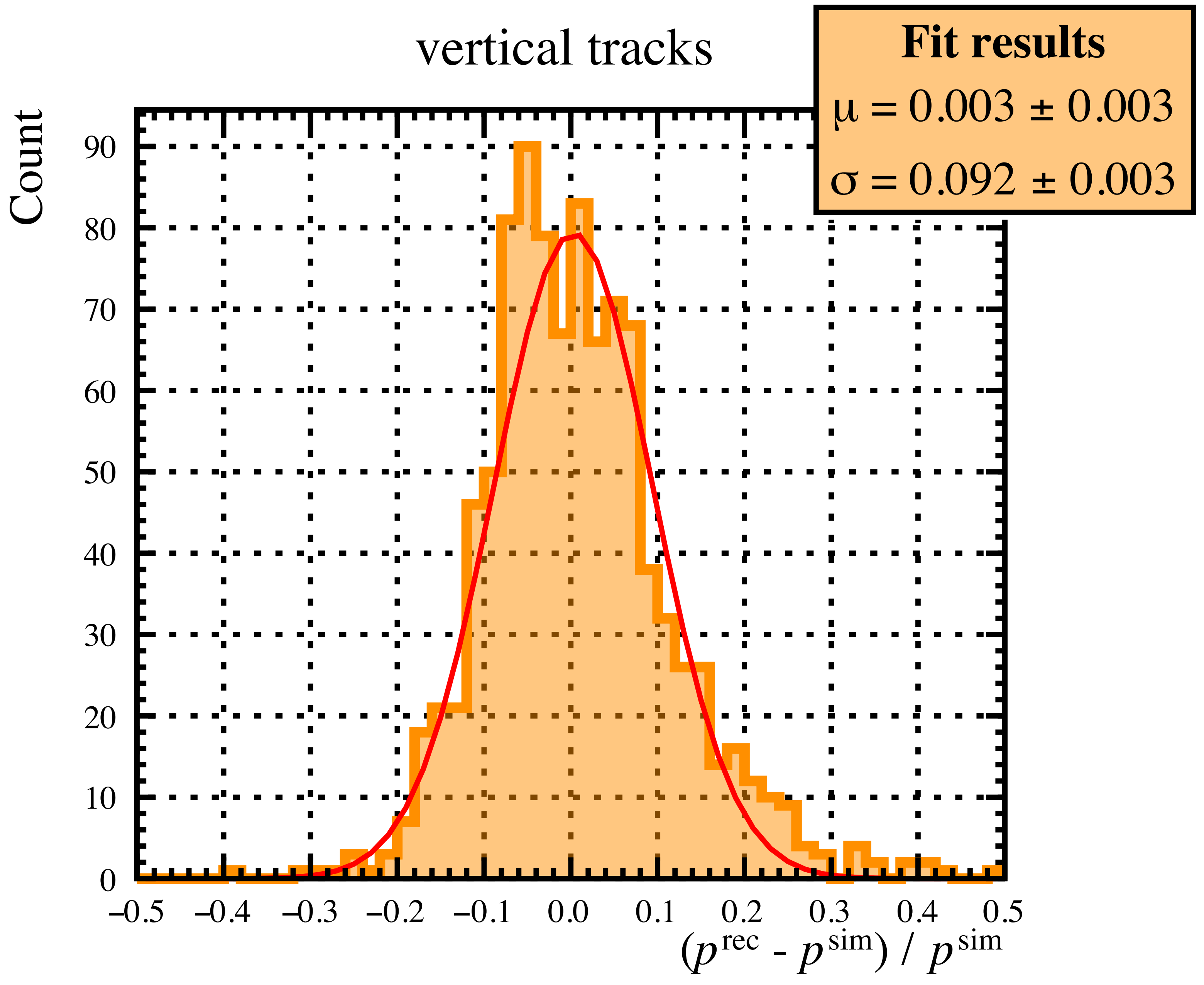
momentum resolution

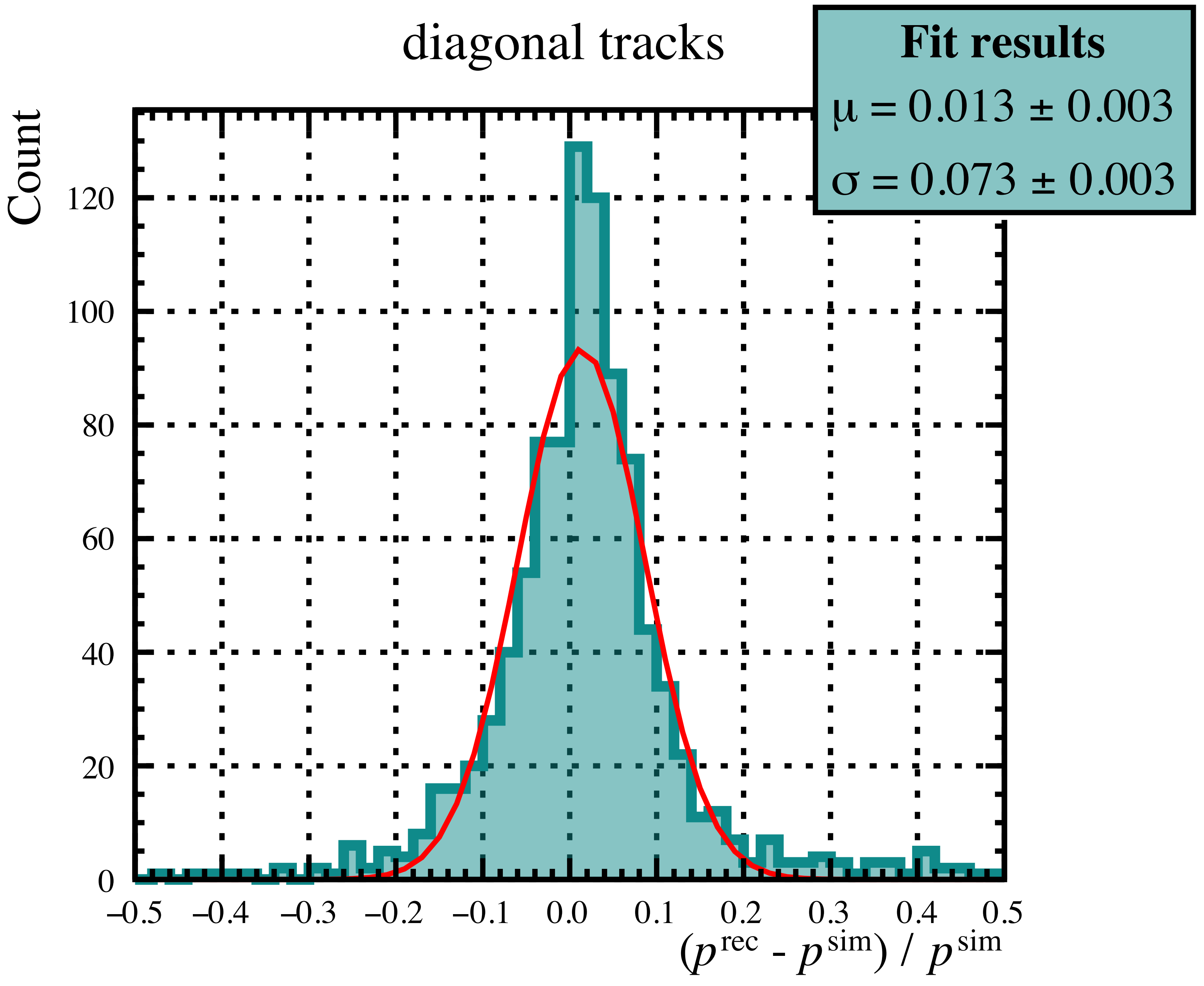
Gluckstern formula

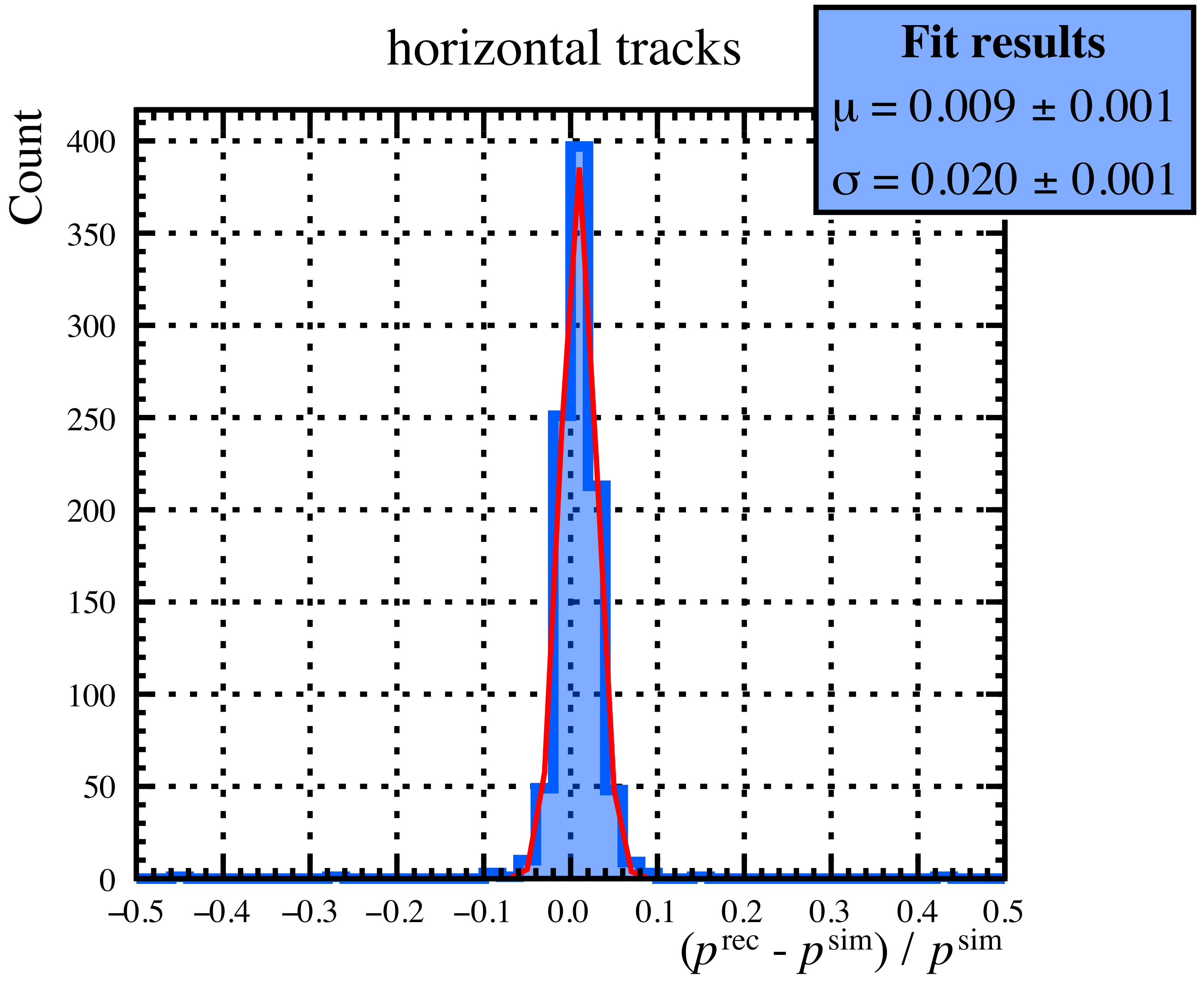
$$\frac{\sigma_{p_t}}{p_t\ [GeV/c]} = \sigma_{xy} \frac{p_t\ [GeV/c]}{e\ B\ [T]\ l^2\ [m^2]} \sqrt{\frac{720}{N_p + 4}}$$

I produced 3 type of MC (at p = 1 GeV/c)

- vertical tracks (the shortest)
- diagonal tracks
- horizontal tracks (the longest) → better momentum resolution







Conferences, experiences and formations de l’ED

Conferences and experiences

done planned

1st year

	aim	when	contribution
CERN	start Martini's model implementation	February 2024	:)
JPARC, Tokai - Japan	shifts + CM	March 2024	2 preliminary talks
NuSTEC summer school - CERN	XSec summer school	June 2024	:)
Neutrino 2024 - Milano	conference	June 2024	poster about Martini model implementation into GENIE
T2K workshop - CERN	CM	July 2024	plenary talk on HA-TPCs

NuSTEC 2024 summer school

june 2024

train the next generation of scientists working on neutrino-nucleus interactions

Lectures topics:

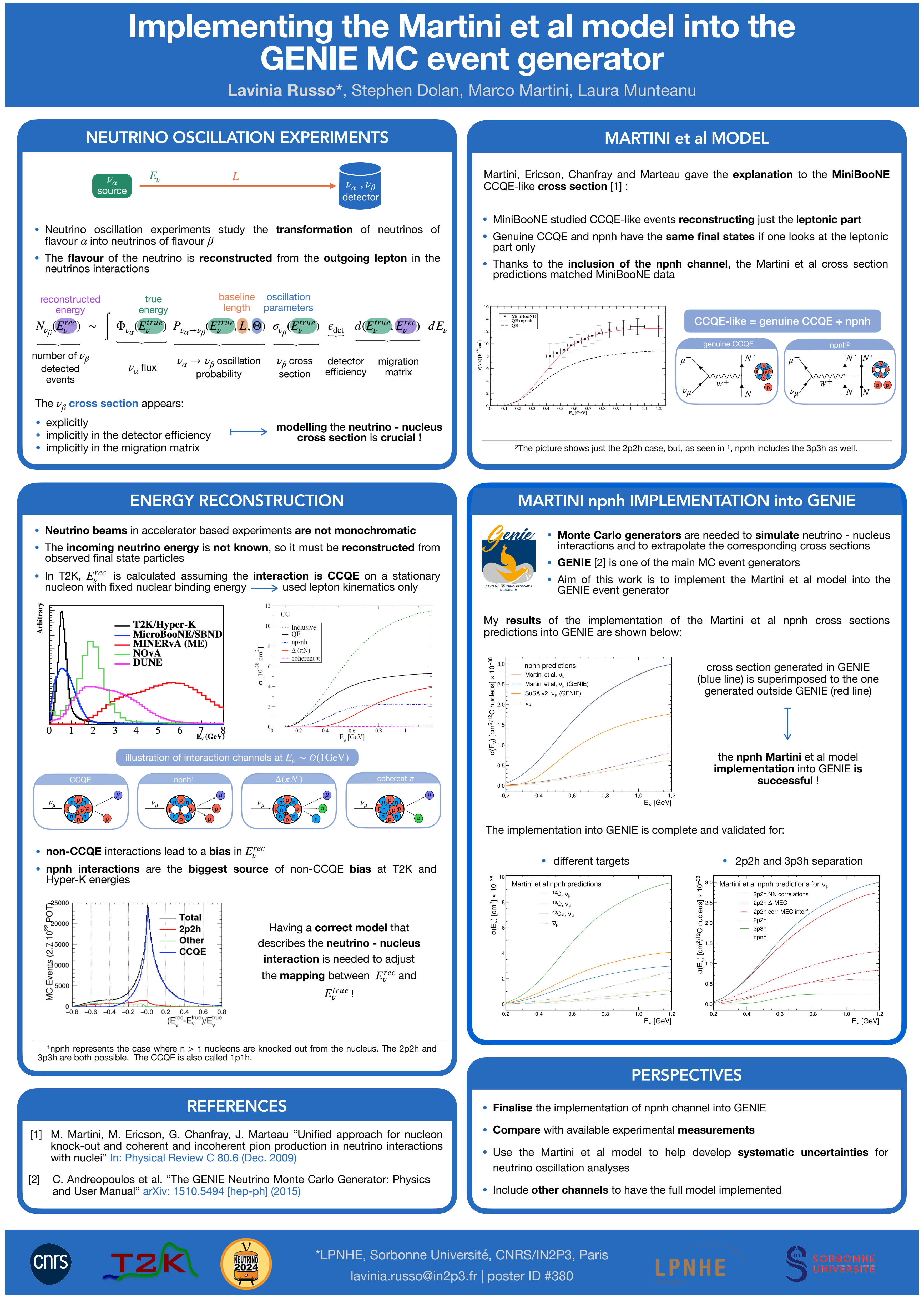
- theoretical modeling of neutrino-nucleus interactions
- neutrino cross section measurements
- MC simulations
- physics at long baseline neutrino experiments

Learning methods:

- lectures
- discussion sessions
- tutorials

Neutrino 2024

my poster on the Martini et al implementation



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Neutrino 2024 - Milano	conference	June 2024	poster about Martini model implementation into GENIE
T2K workshop - CERN	CM	July 2024	plenary talk on HA-TPCs

Conferences and experiences

done planned

2nd year

	aim	when	contribution
JPARC - Tokai, Japan	TPC expert shifts + CM	November 2024	2 preliminary talks
JPARC - Tokai, Japan	TPC expert shifts + CM	March 2025	1 preliminary talk
CERN	finalising Martini's model implementation	May 2025	-
IRN meeting - Lyon	conference	June 2025	talk on the HA-TPC
T2K workshop - CERN	CM	July 2025	talk ?
NuFact 2025 - Liverpool	conference	September 2025	parallel talk on GENIE paper
NuInt 2025 - Mainz	conference	Octorber 2025	poster on GENIE paper

Points de l'école doctorale

organisation de PIF

- **Formations scientifiques**
  - initiale: cours M2, initiation à un logiciel ou une technique expérimentale
  - d'approfondissement: cours de l'ED, écoles d'été, cours du collège de France
- **Formations d'ouverture**
  - découvrir d'autres domaines de la physique ou d'autres sciences
- **Formations transverses**
  - renforcer des compétences nouvelles à donner des clés pour définir son projet professionnel

Points de l’école doctorale

obligatoire

Organisation de PIF

+ formation sur **l'éthique** et **intégrité scientifique**

+ formation **science ouverte**

- **Formations scientifiques**
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Chacun doit suivre **un minimum de 90 h** de formation sur l’ensemble de sa thèse, mais il n’est **pas possible** de **valider plus de 40h dans un des trois types de formation**

Points de l'école doctorale

fait | en cours | planifié

obligatoire

ma situation

Formation	Duration	PIF cathegory
Cours de **français**	30 h	transverses
MOOC* **intégrité scientifique**	15 h	transverses
MOOC **science ouverte**	15 h	transverses
NuSTEC **summer school**	40 h	scientifiques
Vacations à l'UPC	24 h	-
-	10 h	d'ouverture

transverses
60 h → 40 h

scientifiques
40 h

d'ouverture
au moins 10 h

*MOOC = Massive Open Online Courses

Points de l'école doctorale

fait | en cours | planifié

obligatoire

ma situation

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transverses
60 h → 40 h

scientifiques
40 h

d'ouverture
au moins 10 h

À faire :

- formation d'ouverture (10 h)
- MOOC sur intégrité scientifique (~fait)
- MOOC science ouverte (à commencer)

*MOOC = Massive Open Online Courses

Conclusions (1)

So far in my PhD:

- Implementation of Martini's et al model in GENIE MC Generator
  - almost finalised project, we are writing a **paper**
- Data analysis and data taking of the HA-TPC of the ND280 in T2K
  - spatial resolution and dE/dx resolution, we are writing a **paper**
  - TPC expert shift at J-PARC
- Experiences and ED points
  - 24 h de vacations à UPC
  - 60 h de formations transverses, 40h de formations scientifiques

Conclusions (2)

Plans for the future:

- CC0π cross section analysis:
  - looking at the interactions in the gas of the HA-TPC and vertical TPCs
  - project already started by Lukas Koch (still in T2K in Mainz)
- Experiences and ED points:
  - 10 h formations d'ouverture
  - attend the 2 mandatory MOOCs
- Starting writing the thesis (from the 2 on going papers)

Grazie per l’attenzione !

Backup slides

The T2K timeline

my PhD: dec 2023 – dec 2026

2010

started data taking

goal: observing $\nu_\mu \rightarrow \nu_e$

2013

definitely established ν_e appearance

2014

started taking data in ν mode and $\bar{\nu}$ mode

goal: observing CP violation* comparing $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

2019

started T2K-II

goal: confirming CP violation with 3σ significance

2024 – 2026

data taking with T2K-II

ND280 upgrade for reducing the systematics

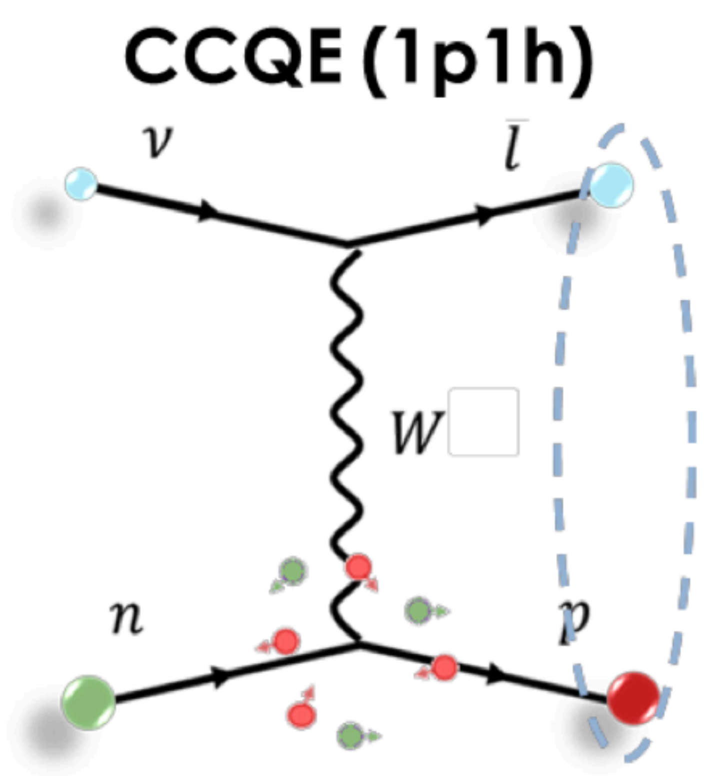
2027 ...

HK data taking (ND280 as near detector)

goal: confirming CP violation with 5σ significance

*CP (charge, parity) violation = matter-antimatter violation

E_ν reconstruction in T2K



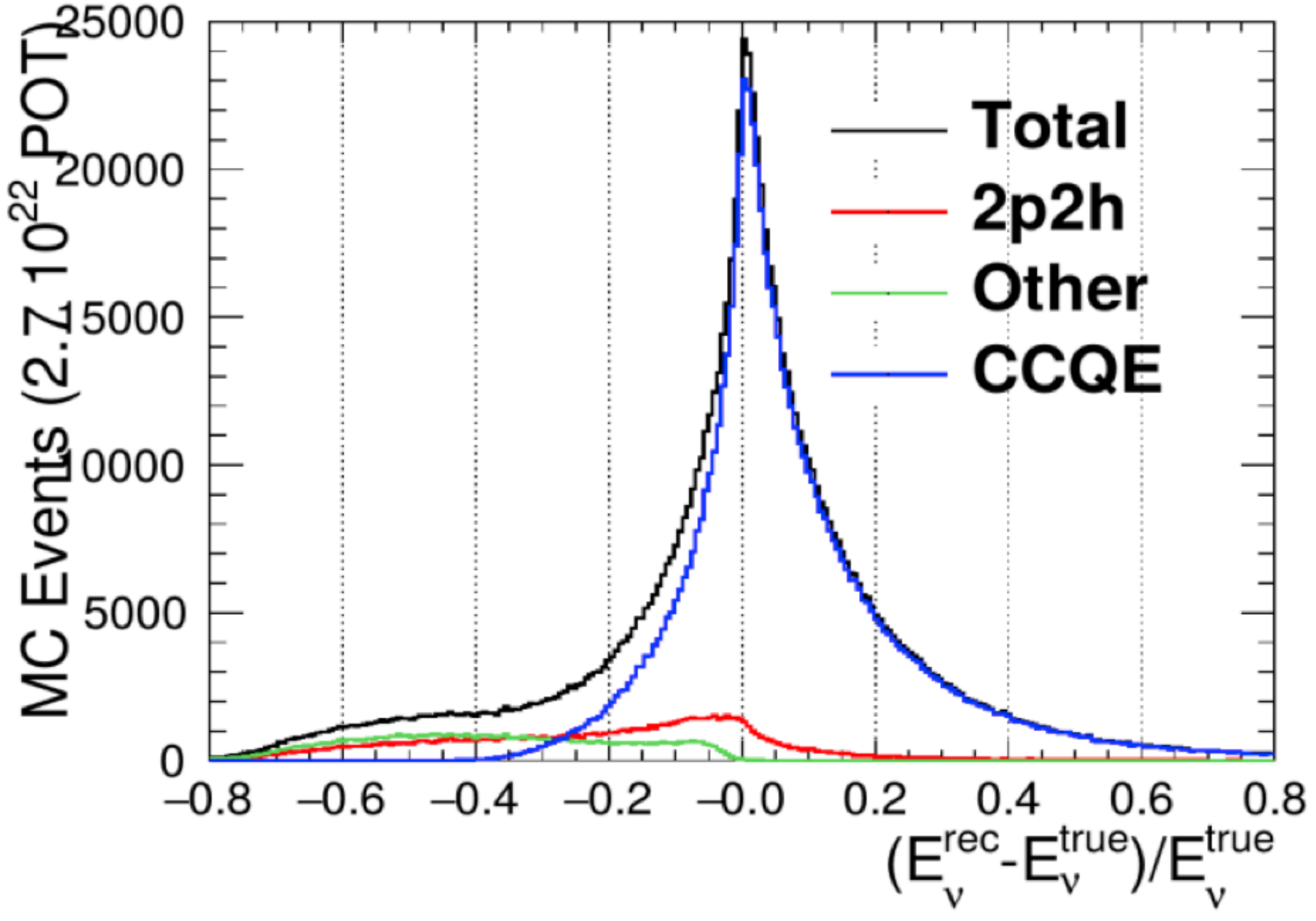
- identify the neutrino interactions without any mesons in the final state
- E_ν is reconstructed **assuming** the interaction is **CCQE** on a stationary nucleon with fixed nuclear binding energy

only use lepton kinematics to get E_ν^{rec} !

$$E_\nu^{rec} \equiv E_\nu^{CCQE} = \frac{2\,(m_n - E_B)\,E_l - (E_B^2 - 2m_nE_B^2 + m_l^2 + \Delta M)}{2\left[(m_n - E_B) - E_l + p_l \cos\theta_l\right]}$$

↓

smearing from nuclear effects (e.g. Fermi motion) and **bias** from non CCQE backgrounds



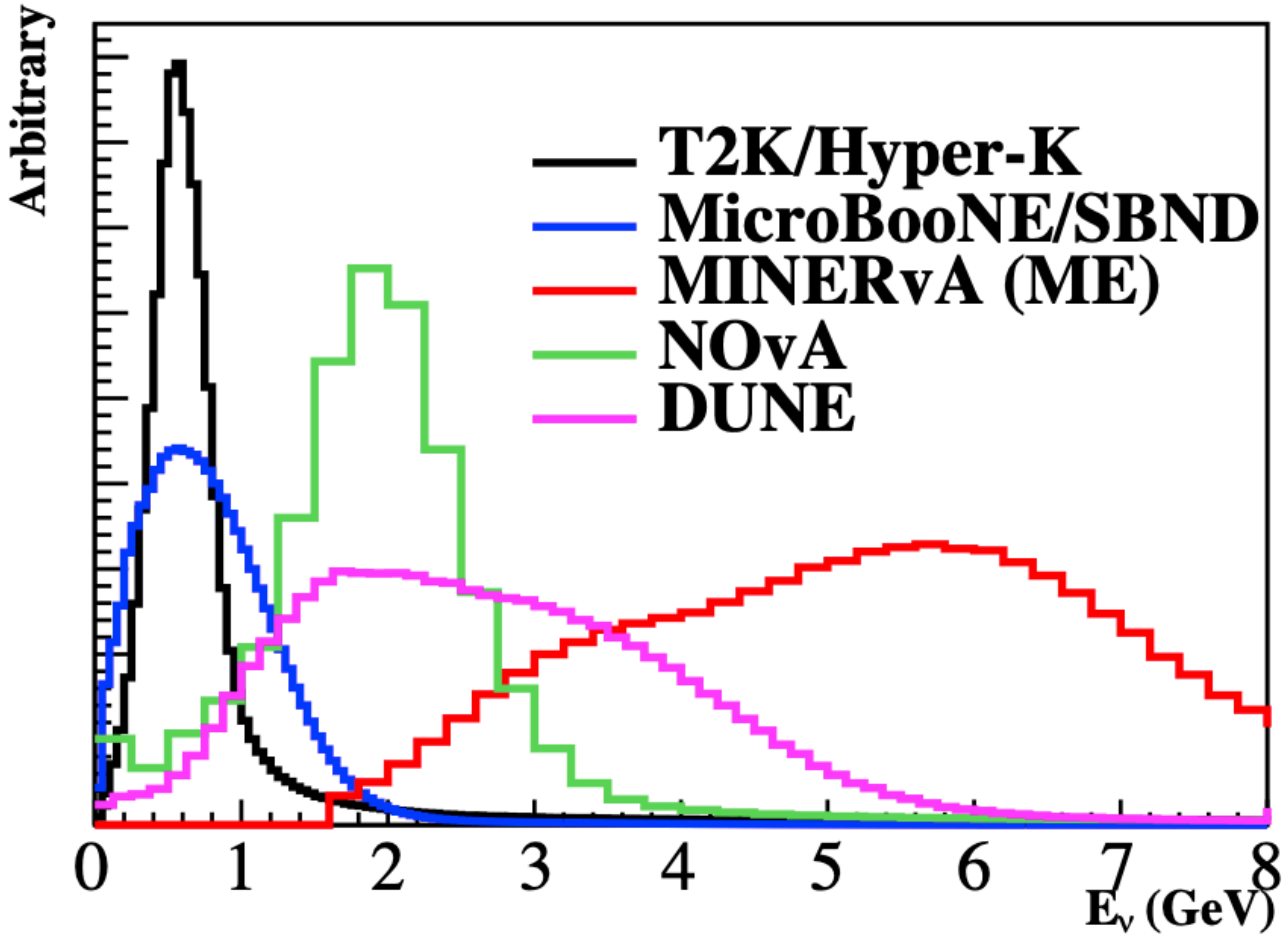
Having a (correct) model that describes the ν - nucleus interaction is crucial !

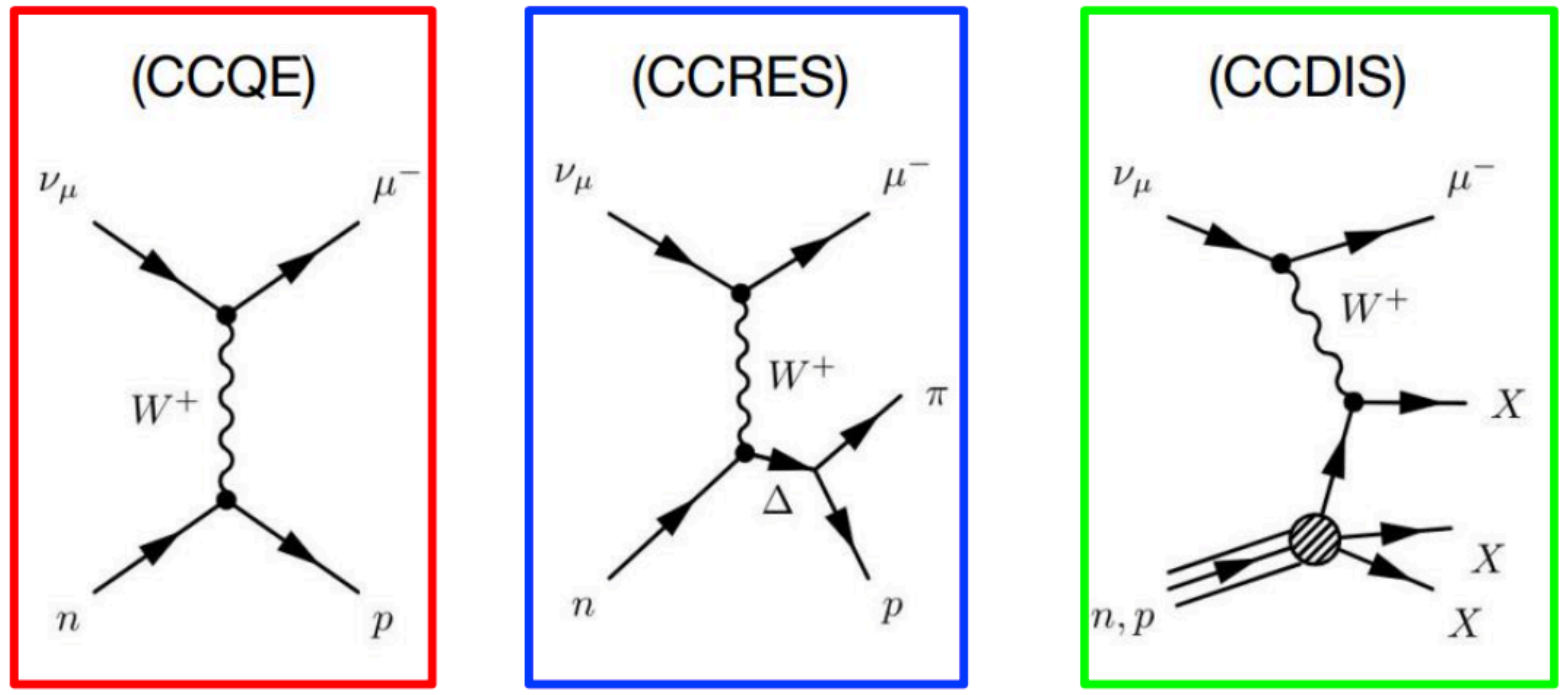
Neutrino oscillation experiment

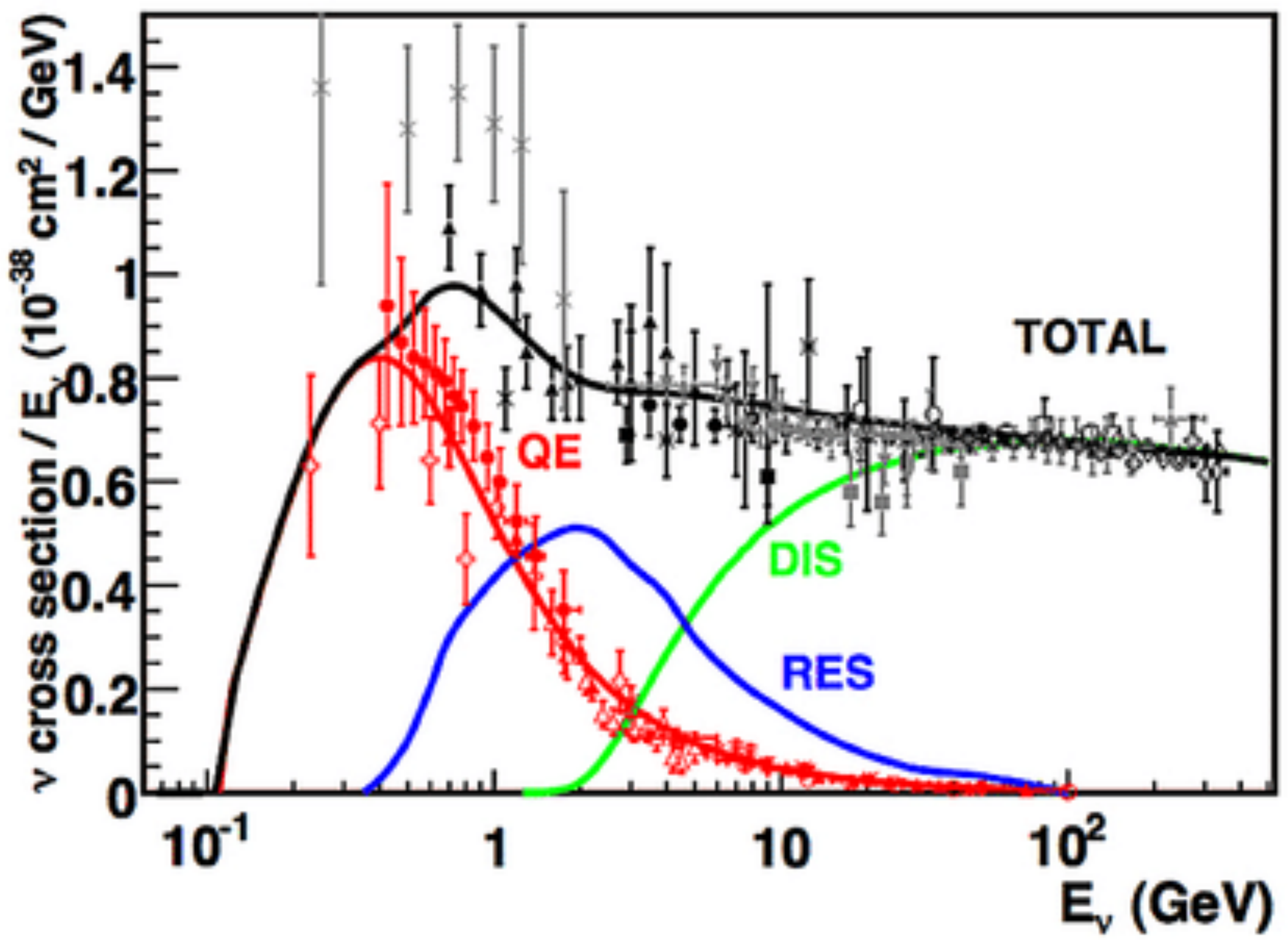
accelerator based case

2. Different reaction mechanism contribute

1. Neutrino beams are not monochromatic



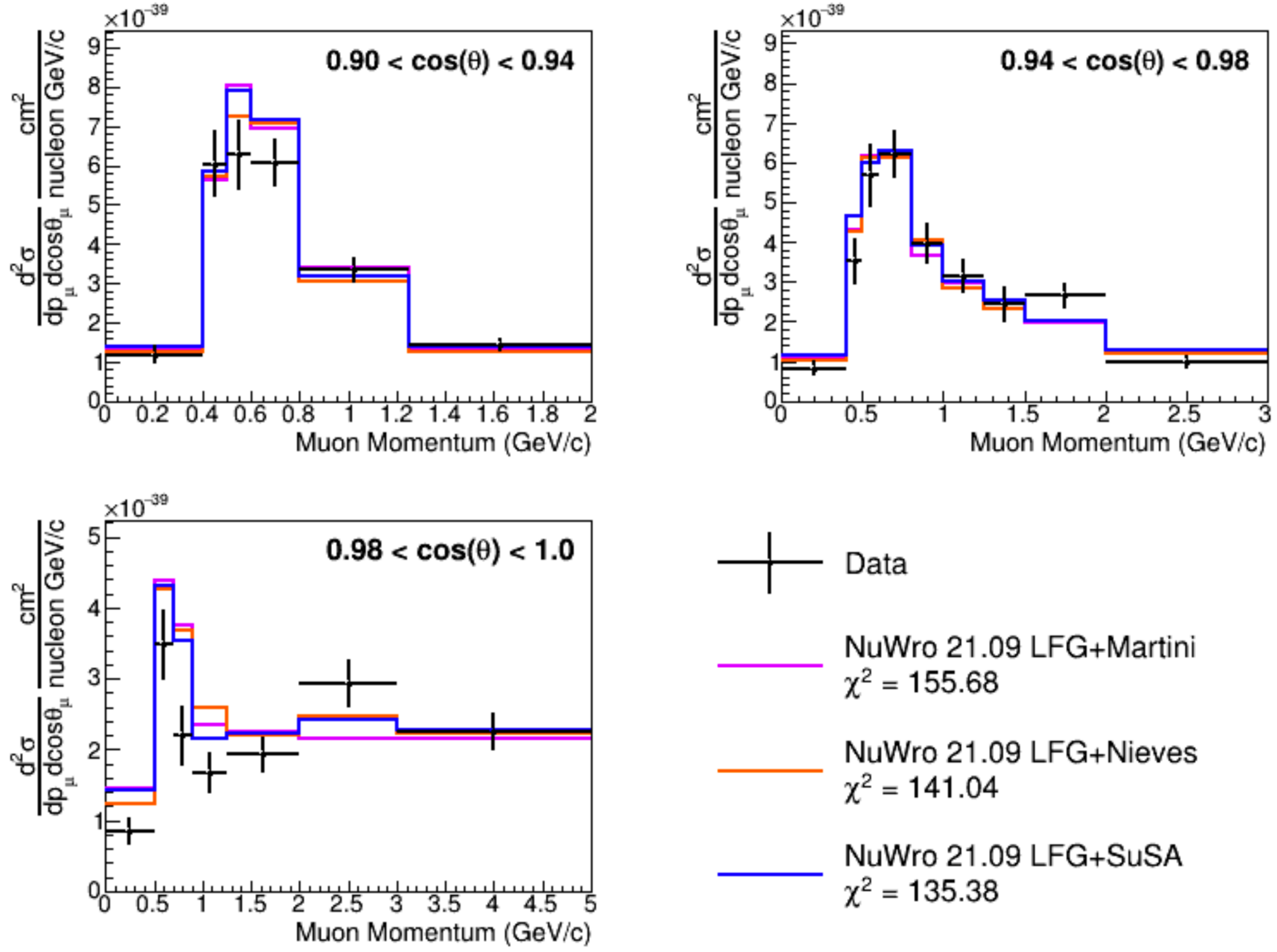




Comparison between models

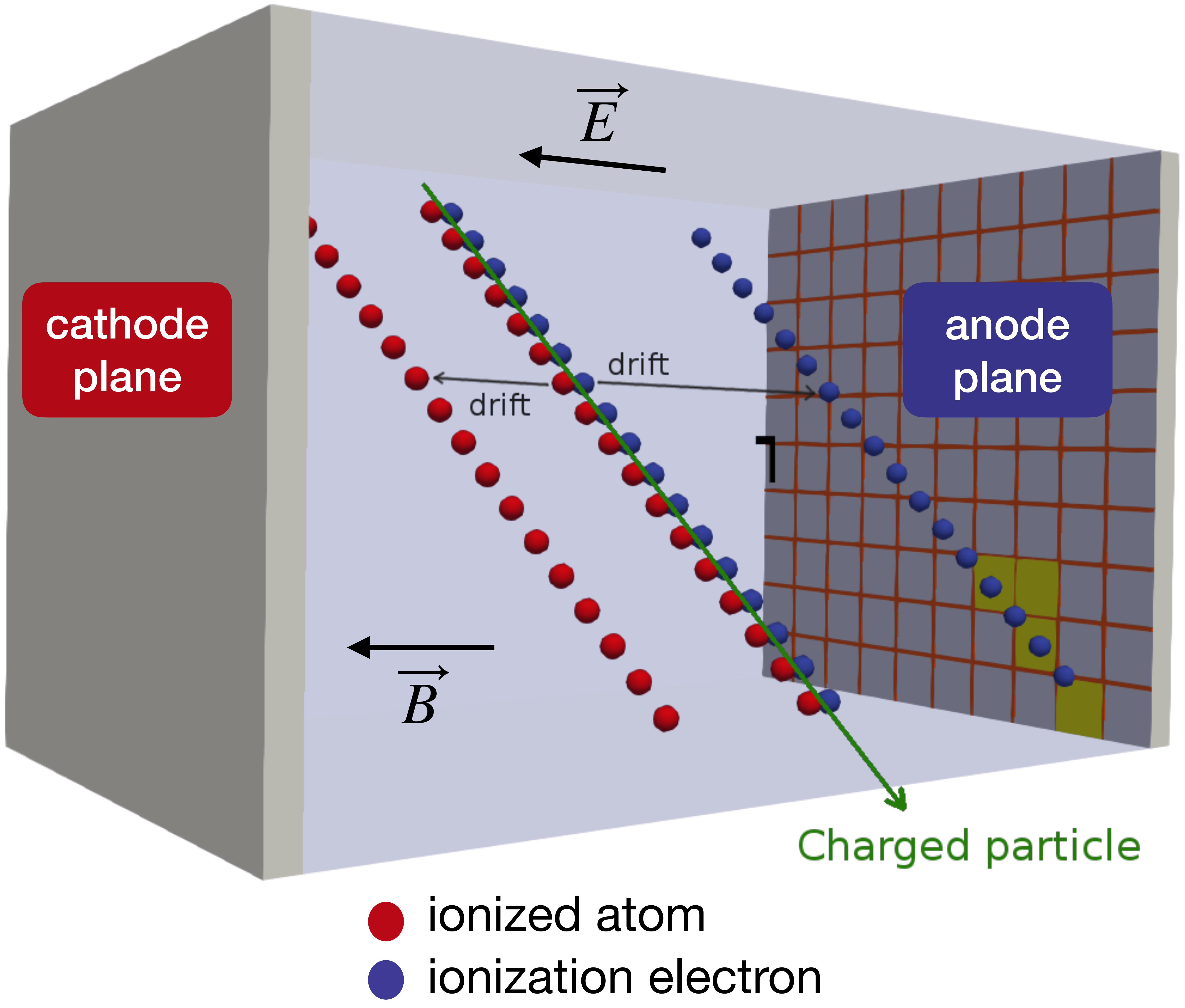
$d^2\sigma$ in NuWro MC generator

DOI: 10.1103/PhysRevD.108.112009



- Different approximations by different groups lead to different results by each group
- Models are often mixed (LFG + Martini/ Nieves/SuSA) and this can raise problems

TPC working principle



- a charged particle crosses the TPC
- it ionizes the gas the ionization electrons that drift towards the anode plane
- a 2D projection of the track on the readout plane is produced
- the drift time can be used to reconstruct the 3rd dimension
- the particles' momentum and charge can be determined based on the track curvature produced by $\vec{B}$

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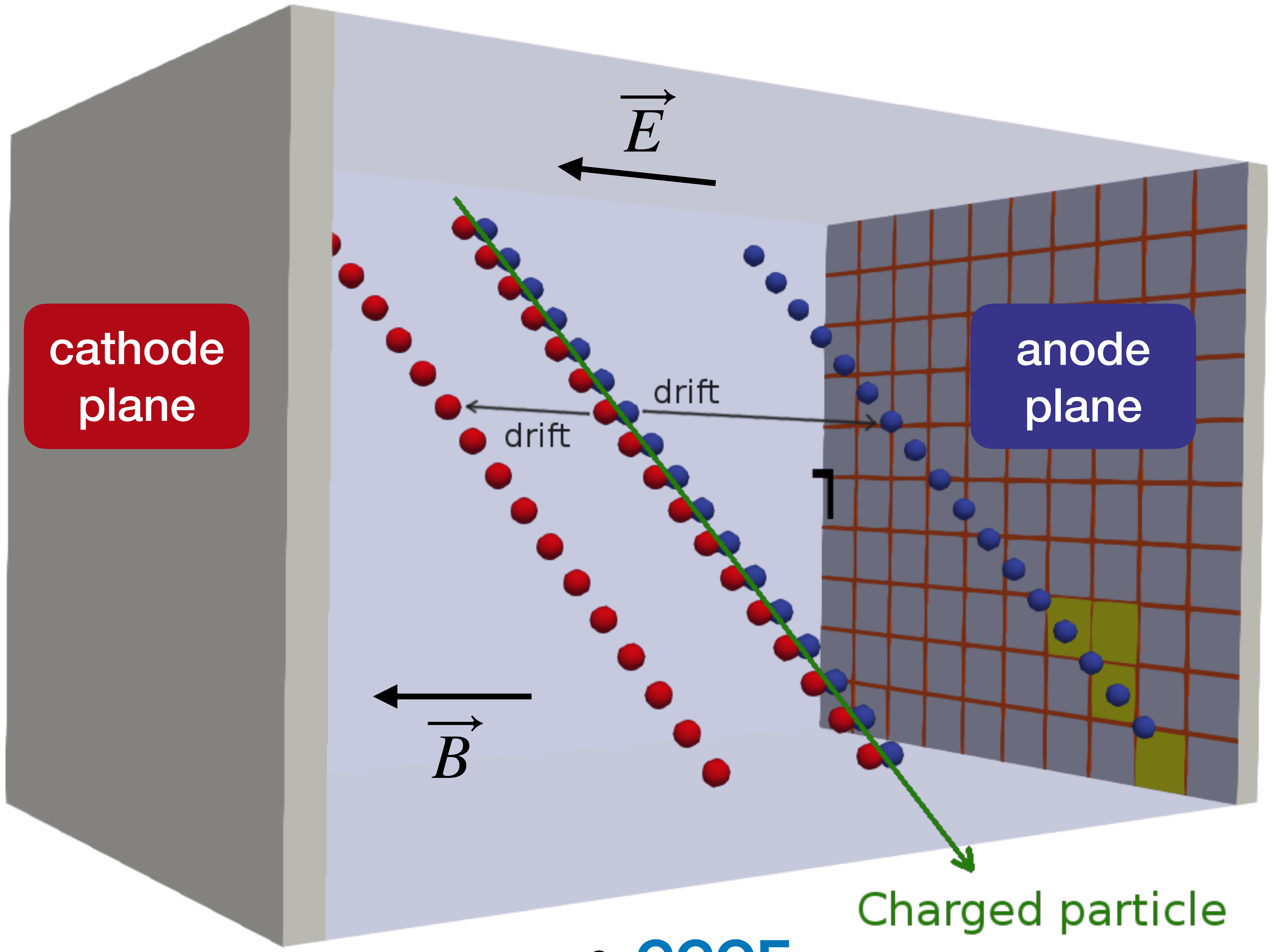

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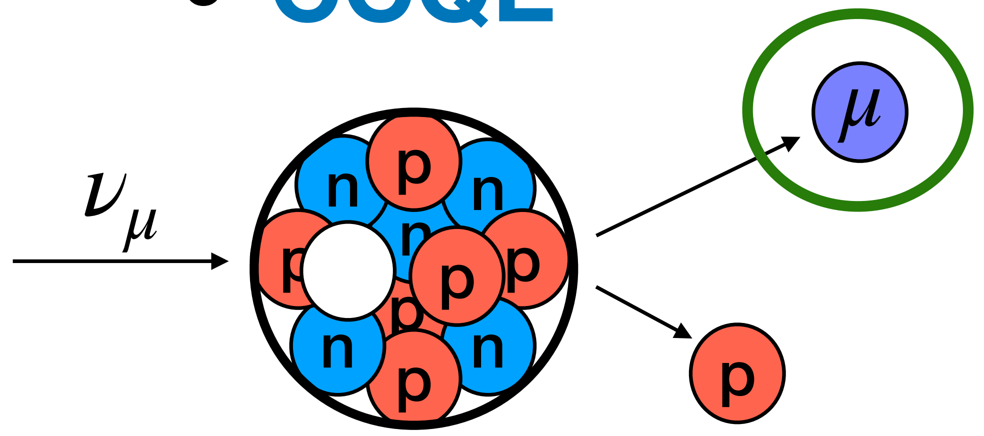
- **CCQE**



- we have a neutrino interaction in ND280
- the μ crosses the detectors of ND280 (TPCs) $\rightarrow$ we perform PID
- we characterise the Φ_ν and the σ $\rightarrow$ reduce the systematics

How to get the spatial resolution ?

- each track is fitted with a circle/parabola
- for each cluster in the track compute the residuals:

$$res = \sqrt{(\ z_{rec}^{cluster} - z^{track\ fit}\ )^2 + (\ y_{rec}^{cluster} - y^{track\ fit}\ )^2} - R$$

- fill a histogram with res from all the tracks
- fit the histogram with a gaussian
- SR = σ from the fit
- perform the process separating the 4 EPs of the HA-TPCs and for different drift distance ranges