UNDERSTANDING THE QUASI-ELASTIC NEUTRINO ENERGY RECONSTRUCTION

भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

BASED ON : Nuclear Physics B, Volume 1008, November 2024, 116703

R LALNUNTLUANGA

DEPARTMENT OF PHYSICS
IIT HYDERABAD

OCTOBER 16, 2024

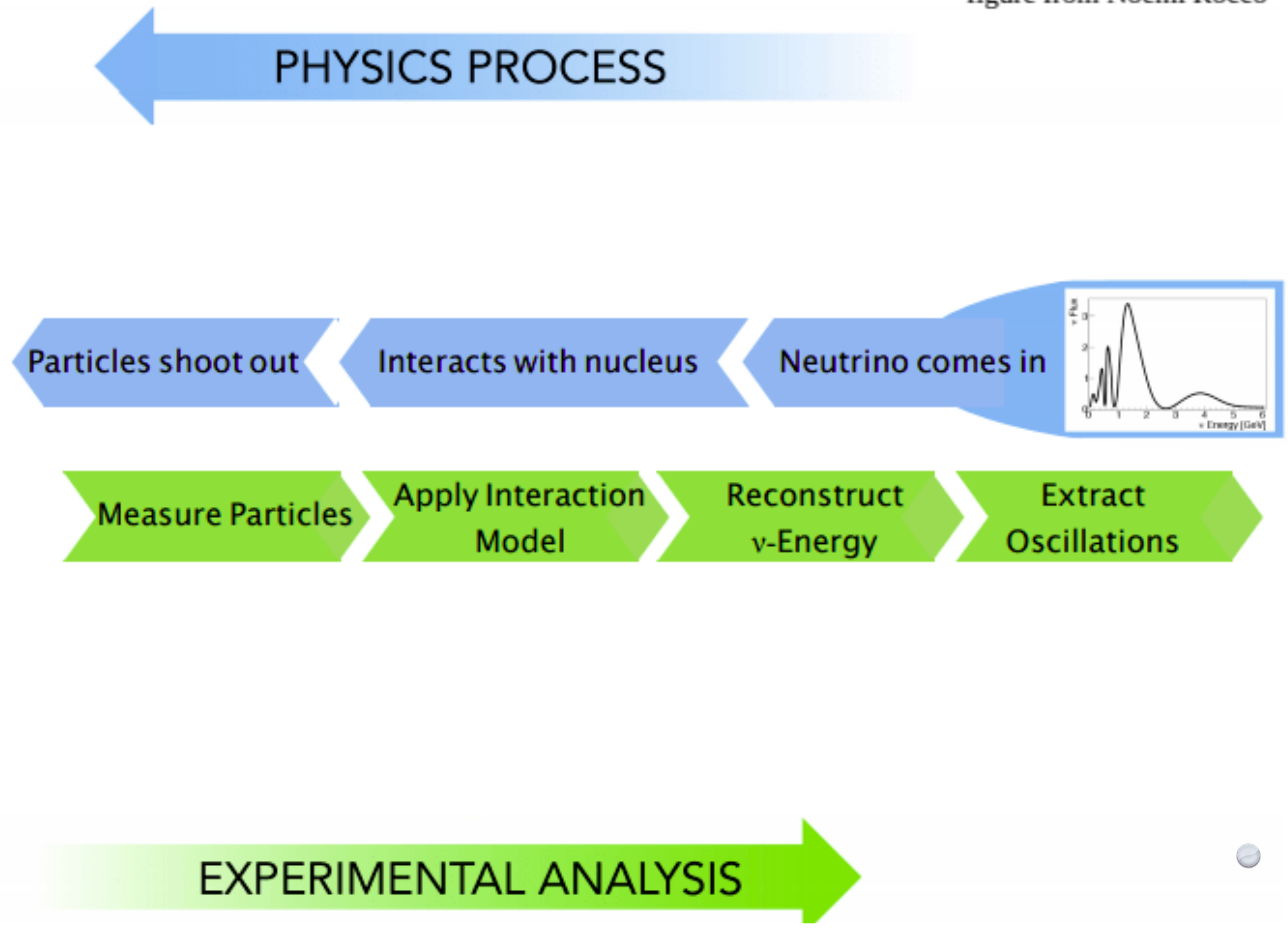
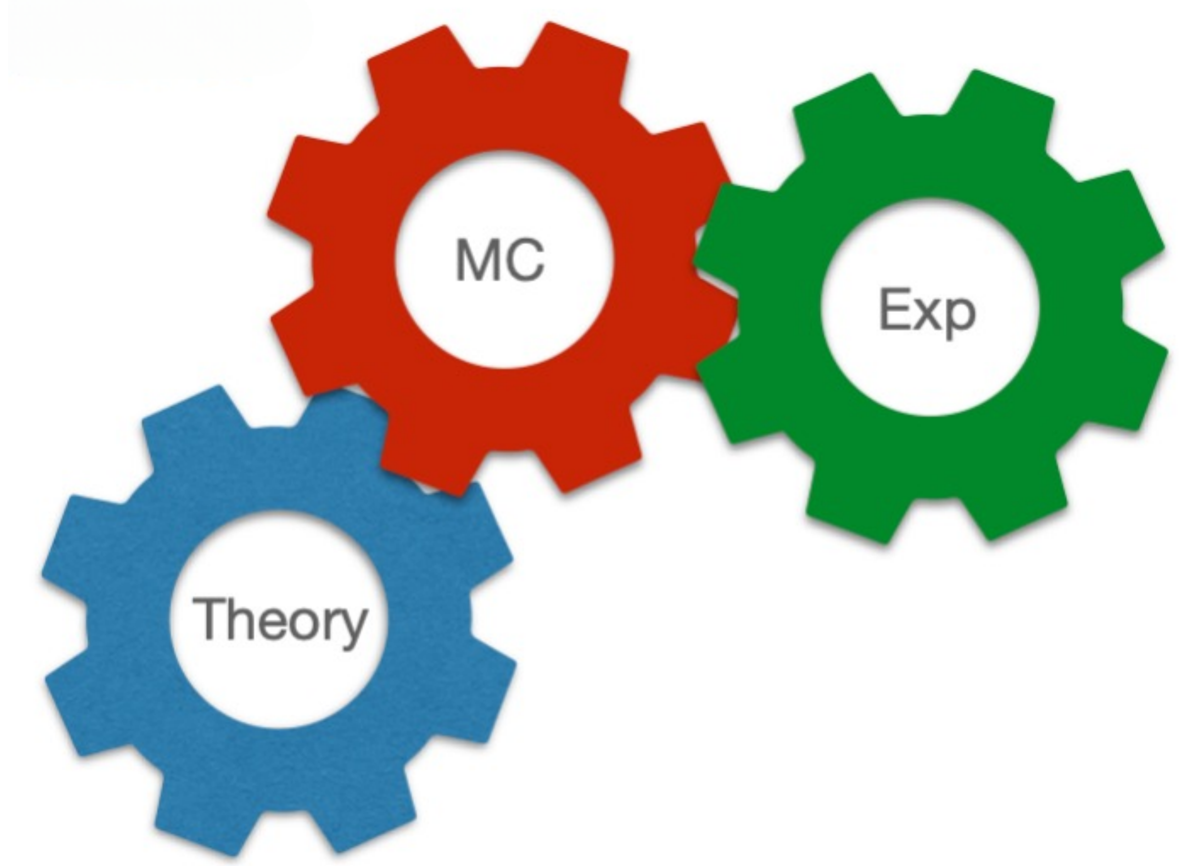


figure from Noemi Rocco

- Monte Carlo event generators connects theoretical predictions to experimental measurement

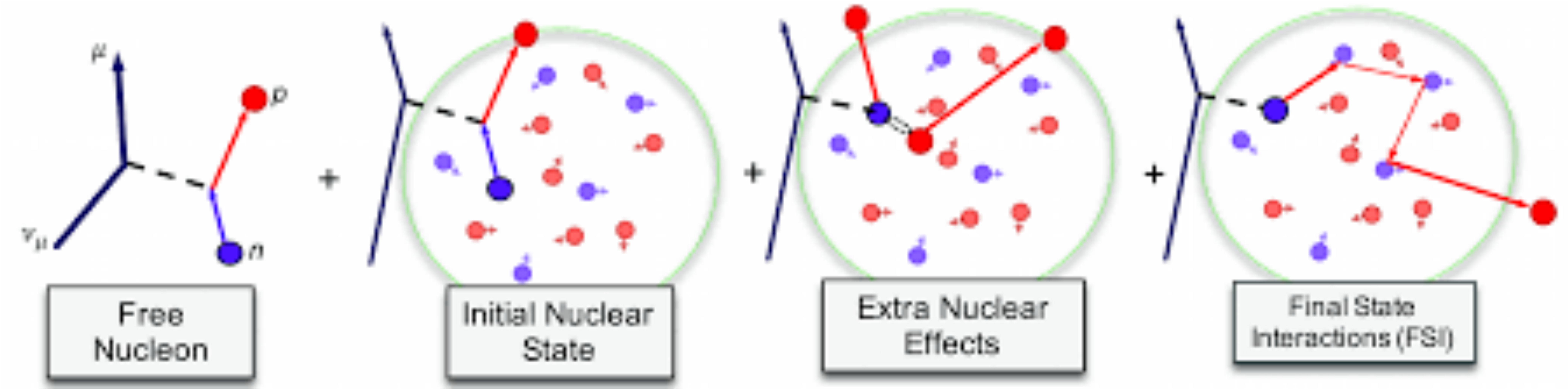


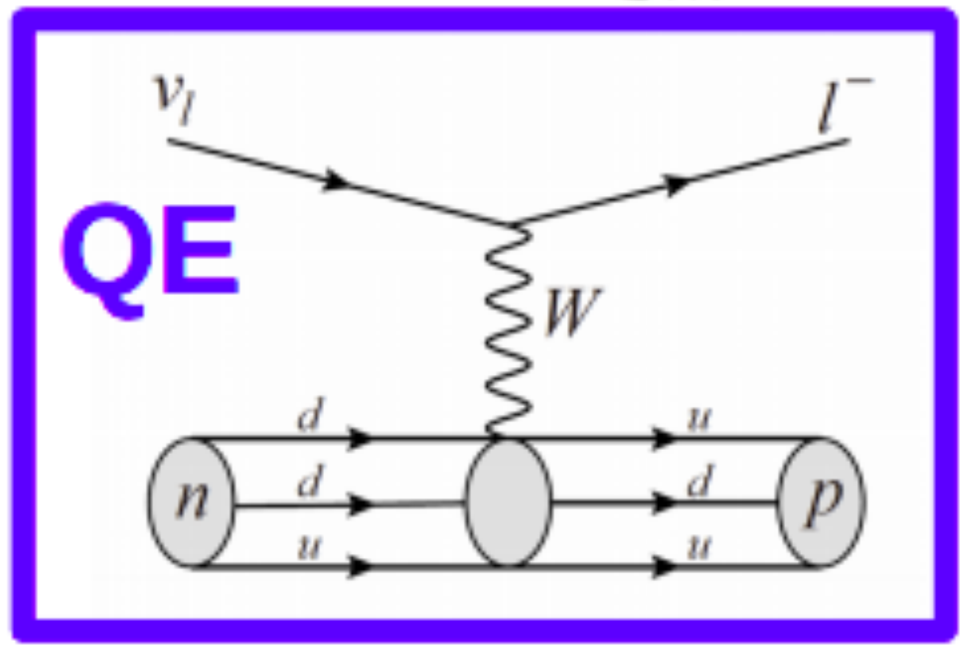
- E_ν reconstruction is required
- E_ν from the final states particles kinematic

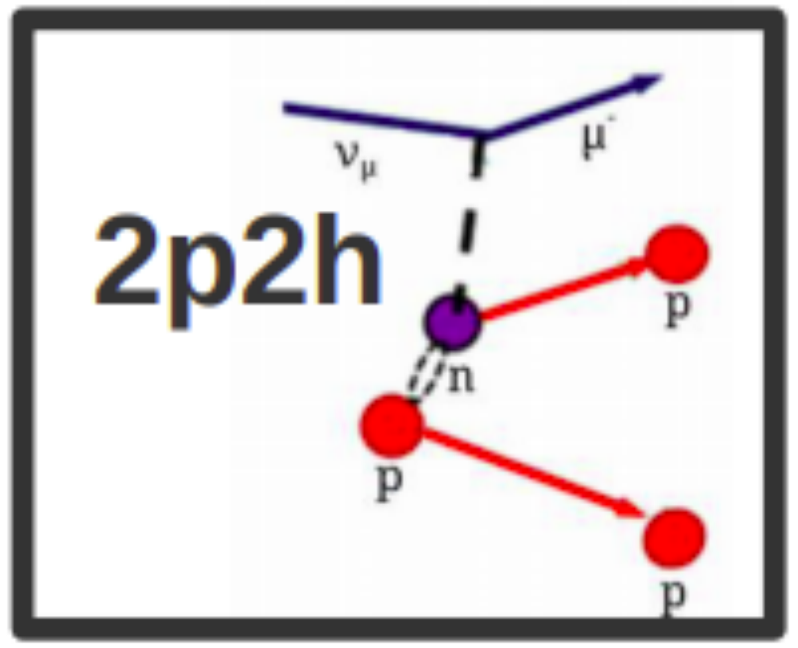
- Neutrino interactions: GENIE, NuWro, GiBUU, NEUT
- Particle transport: Geant4, Fluka

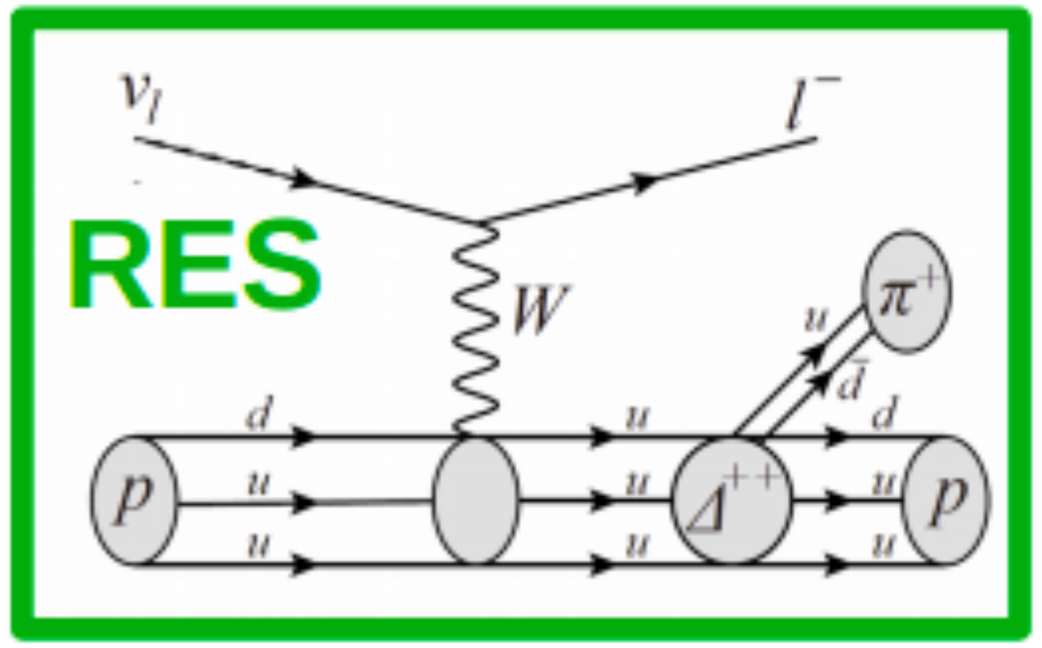
Cross-section:

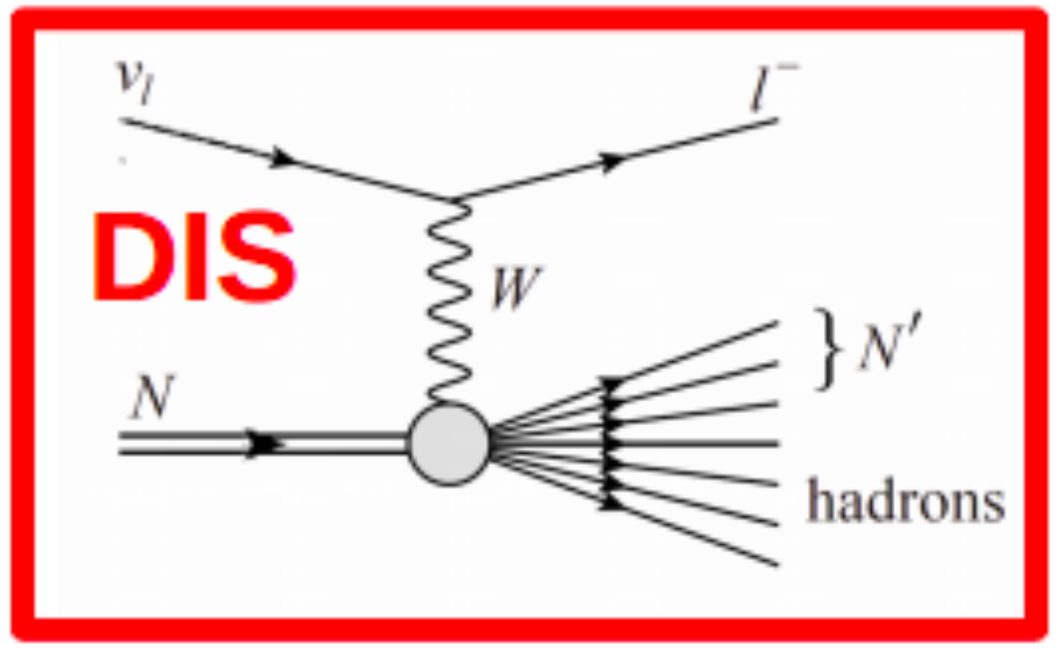
- Uncertainty in cross-section models











- Neutrino experiments measure ν interaction event rates:

$$\underbrace{N(E_{rec},L)}_{\text{Measurement}} \propto \int \underbrace{\Phi(E_\nu,L)}_{\text{incoming } \nu \text{ flux}} \; x \; \underbrace{\sigma(E_\nu)}_{\text{cross-section}} \; x \, \underbrace{\epsilon(E_\nu,T,\Theta..)}_{\text{efficiency}} \, dE_\nu (\text{ND un-oscillated})$$

- After oscillation:

$$\frac{N^{FD}_{\nu_\beta}}{N^{ND}_{\nu_\alpha}} \approx \frac{\phi^{FD}_{\nu_\beta}(E_\nu)}{\phi^{ND}_{\nu_\alpha}(E_\nu)} x \frac{\sigma^{FD}_{\nu_\beta}(E_\nu)}{\sigma^{ND}_{\nu_\alpha}(E_\nu)} x \frac{\epsilon^{FD}_{\nu_\beta}}{\epsilon^{ND}_{\nu_\alpha}} x P_{\nu_\alpha \to \nu_\beta}(E_\nu)$$

- Particle selection is different for ND and FD:

- ϵ depends on the kinematics of the final states which relies on cross-section model

- Different model predicts different particle multiplicity in the final state. Which results in uncertainty (systematic)

Neutrino energy reconstruction:

- Systematic Uncertainties in neutrino-nucleus interaction for precision physics

$$E_\nu^{cal} = E_l + \epsilon_n + \sum_i (E_{n_i} - M) + \sum_j E_{m_j}$$

(Calorimetric method)

Subshell	E_α (MeV)	σ_α (MeV)	No. neutron n_α
$1s_{1/2}$	40.8	9.1	2
$1p_{3/2}$	20.3	5	4

Neutron Shell structure for C12

- Gaussian distribution for nucleon separation energy

$$P(E) = \frac{1}{N} \sum_\alpha n_\alpha G(E - E_\alpha, \sigma_\alpha)$$

$$N = \sum_\alpha n_\alpha$$

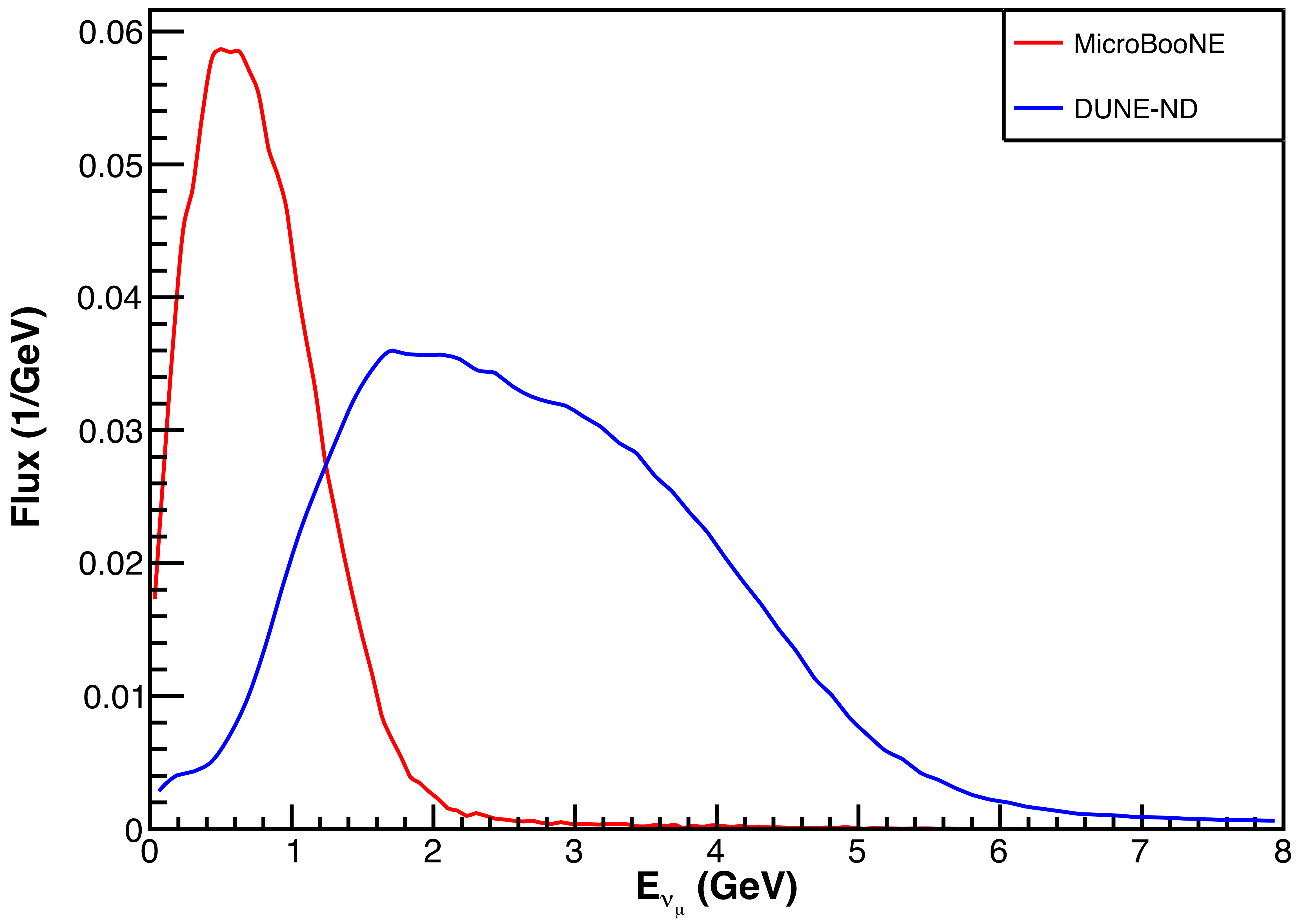
(Sum of neutrons)

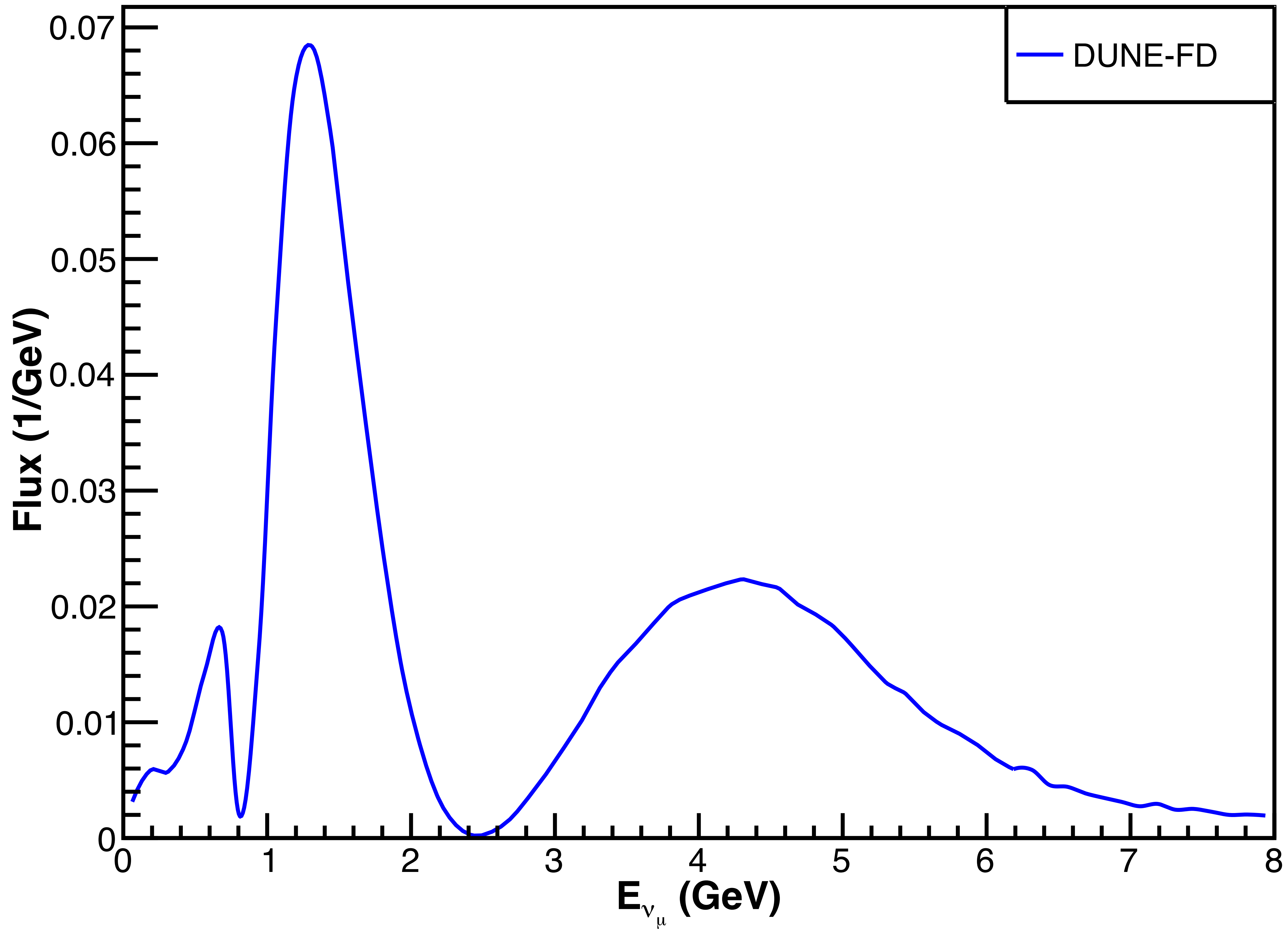
Subshell	E_α (MeV)	σ_α (MeV)	No. neutron n_α
$1s_{1/2}$	62	6.25	2
$1p_{3/2}$	40	3.75	4
$1p_{1/2}$	35	3.75	2
$1d_{5/2}$	18	1.25	6
$2s_{1/2}$	13.15	1	2
$1d_{3/2}$	11.45	0.75	4
$1f_{7/2}$	5.56	0.75	2

Neutron Shell structure for Ar40

Neutrino Flux:

$$P_{\nu_\mu \rightarrow \nu_\mu}(E_\nu, L) \approx 1 - sin^2 2\theta_{\mu\mu} \, sin^2 \frac{\Delta m^2_{\mu\mu} L}{4E_\nu}$$





NuFit v5.3

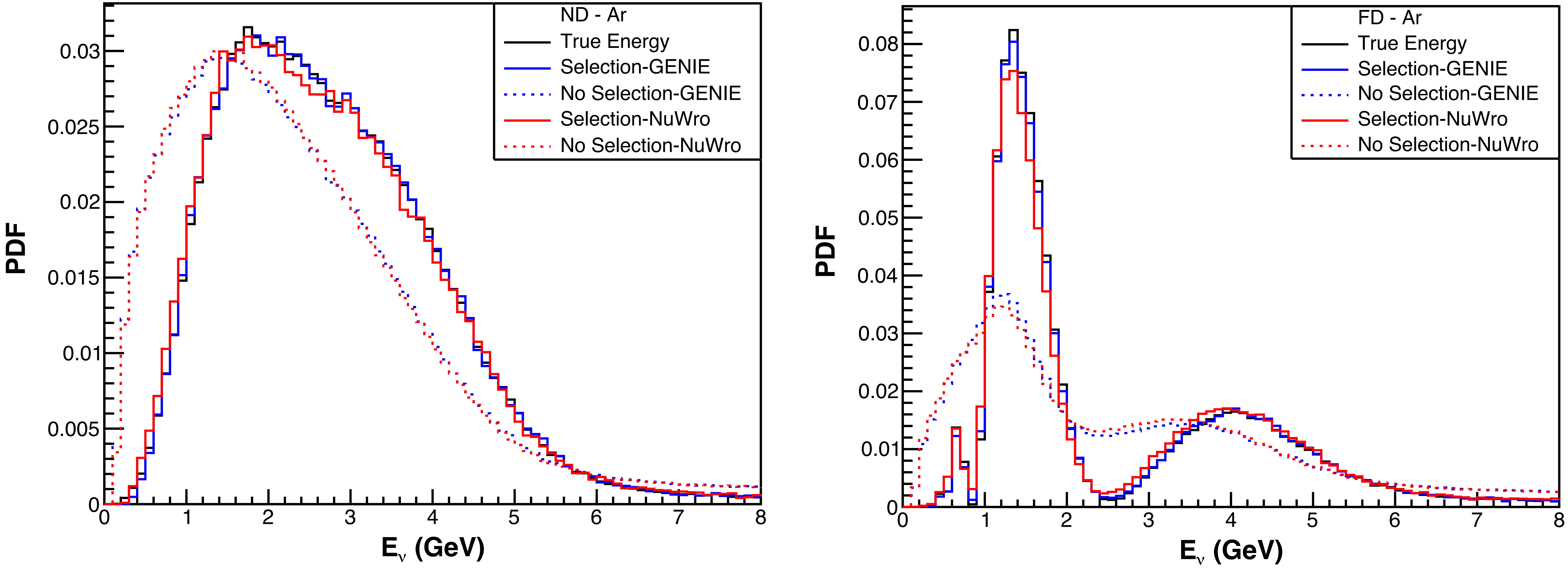
Normal Ordering

CCQE: Purity Selection -> 1 mu + 1 proton + X neutron

DUNE:

Particle	Detector cut
Muon	$p > 200$ MeV
Proton	$p > 3$ MeV
Neutron	$50 < p < 700$ MeV

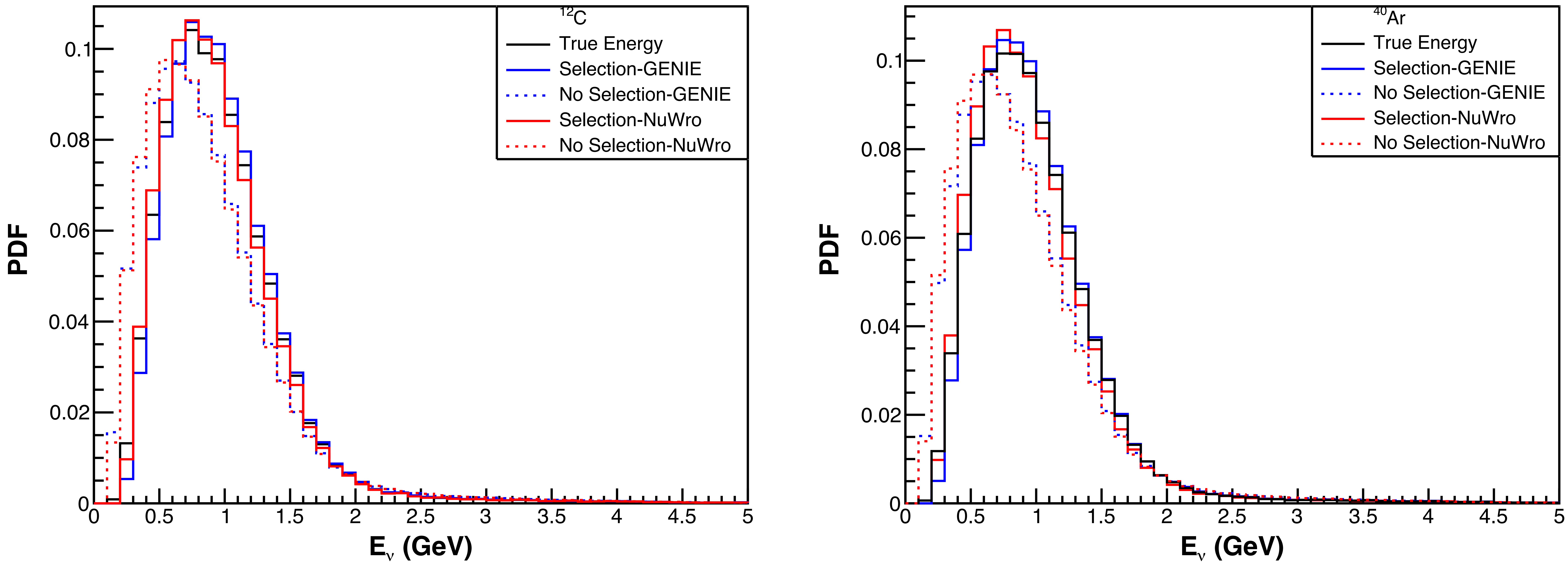
Particle	Detector cut
Muon	$p > 30$ MeV
Proton	$p > 50$ MeV
Neutron	$p < 50$ MeV



Improvement in E_{rec} (< 100 MeV)

MicroBooNE:

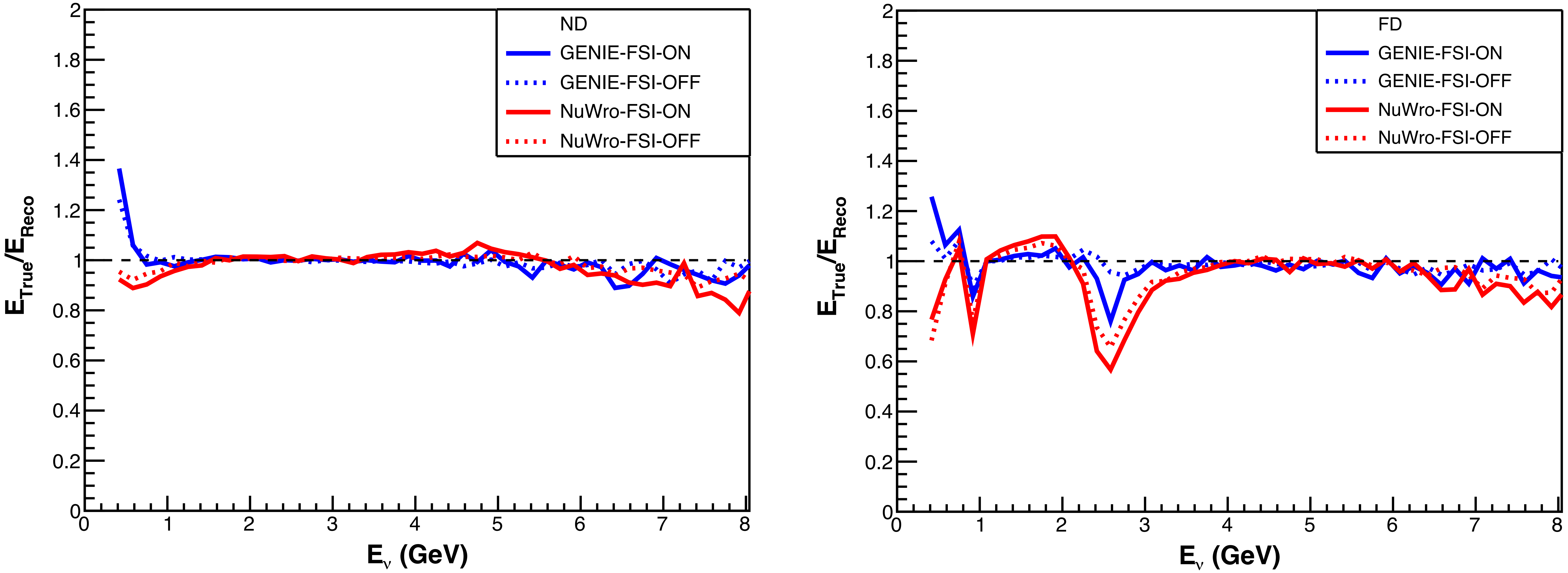
Particle	Detector cut
Muon	p > 100 MeV
Proton	p > 300 MeV



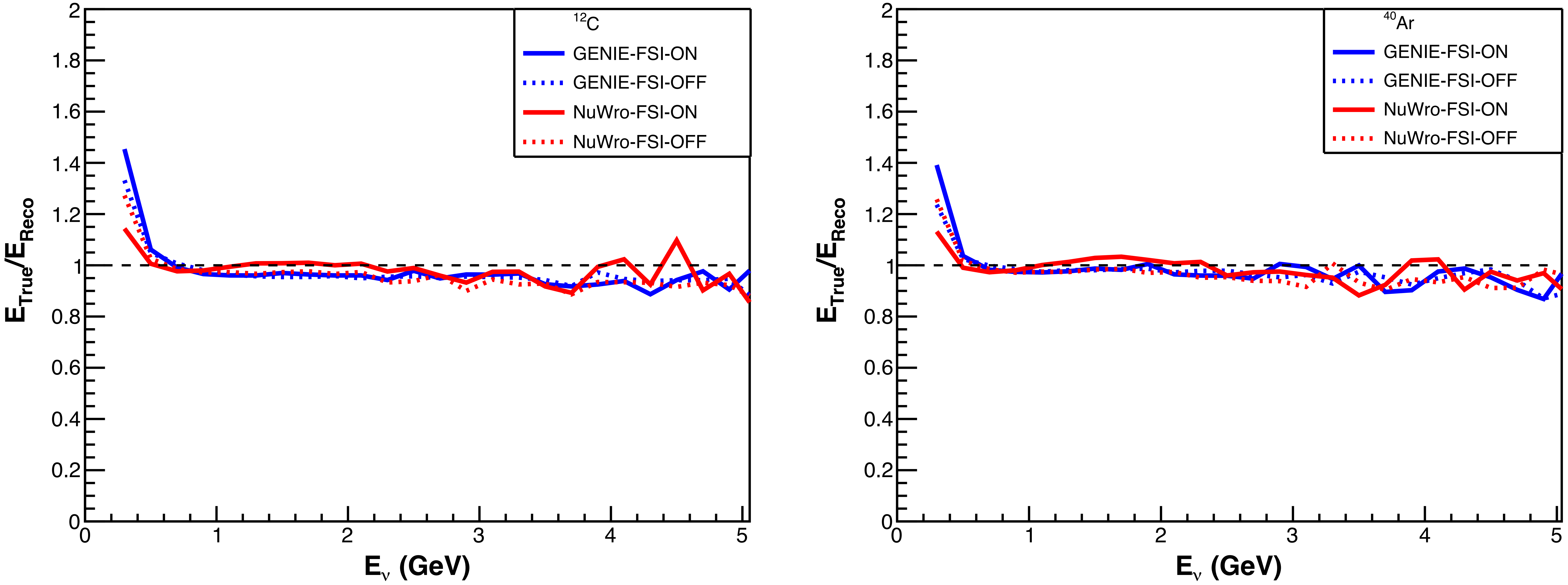
Improvement in E_{rec} (< 100 MeV)

Purity Selection:

DUNE



MicroBooNE



“No FSI” slightly better!!!

Conclusion:

- Purity of QE selection for DUNE and MicroBooNE using calorimetric method

- Selection of 1 proton, 0 pions, and X neutrons shows significantly well-reconstructed neutrino energy (< 100 MeV)

- Deviation from unity without FSI also highlighted the importance of other nuclear effects in energy reconstruction for precision physics

References:

- **Probing neutrino-nucleus interaction in DUNE and MicroBooNE**
  Nuclear Physics B, Volume 1008, November 2024, 116703. (https://doi.org/10.1016/j.nuclphysb.2024.116703)

- **The MicroBooNE Technical Design Report**
  https://doi.org/10.2172/1333130)

- **High-Pressure Gaseous Argon TPC for the DUNE Near Detector**

  https://arxiv.org/abs/1910.06422

- **Experiment Simulation Configurations Approximating DUNE TDR**

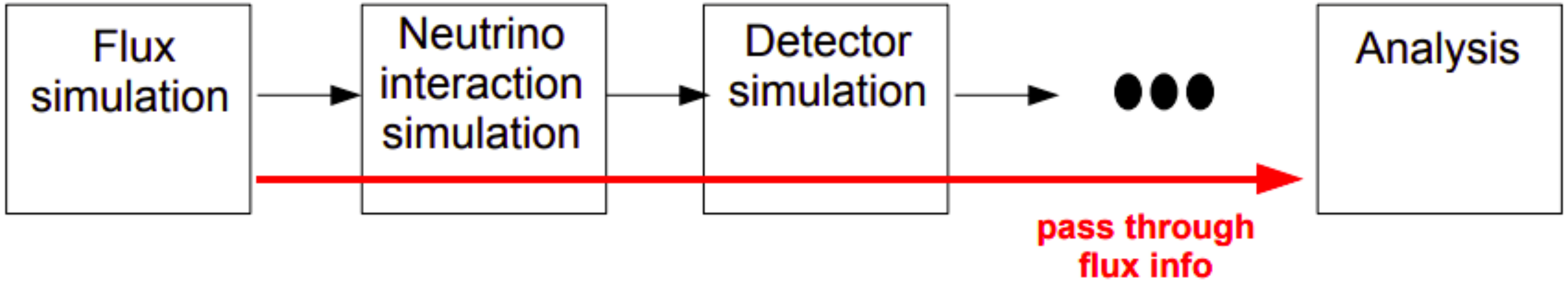
  (arXiv:2103.04797)

- **Energy reconstruction in the long-baseline neutrino experiment**
  Phys. Rev. Lett., 112 (2014), Article 151802,

THANK YOU !!!

BACK UP SLIDE

Neutrino interaction simulation :


Flux simulation

Neutrino interaction simulation

Detector simulation

●●●

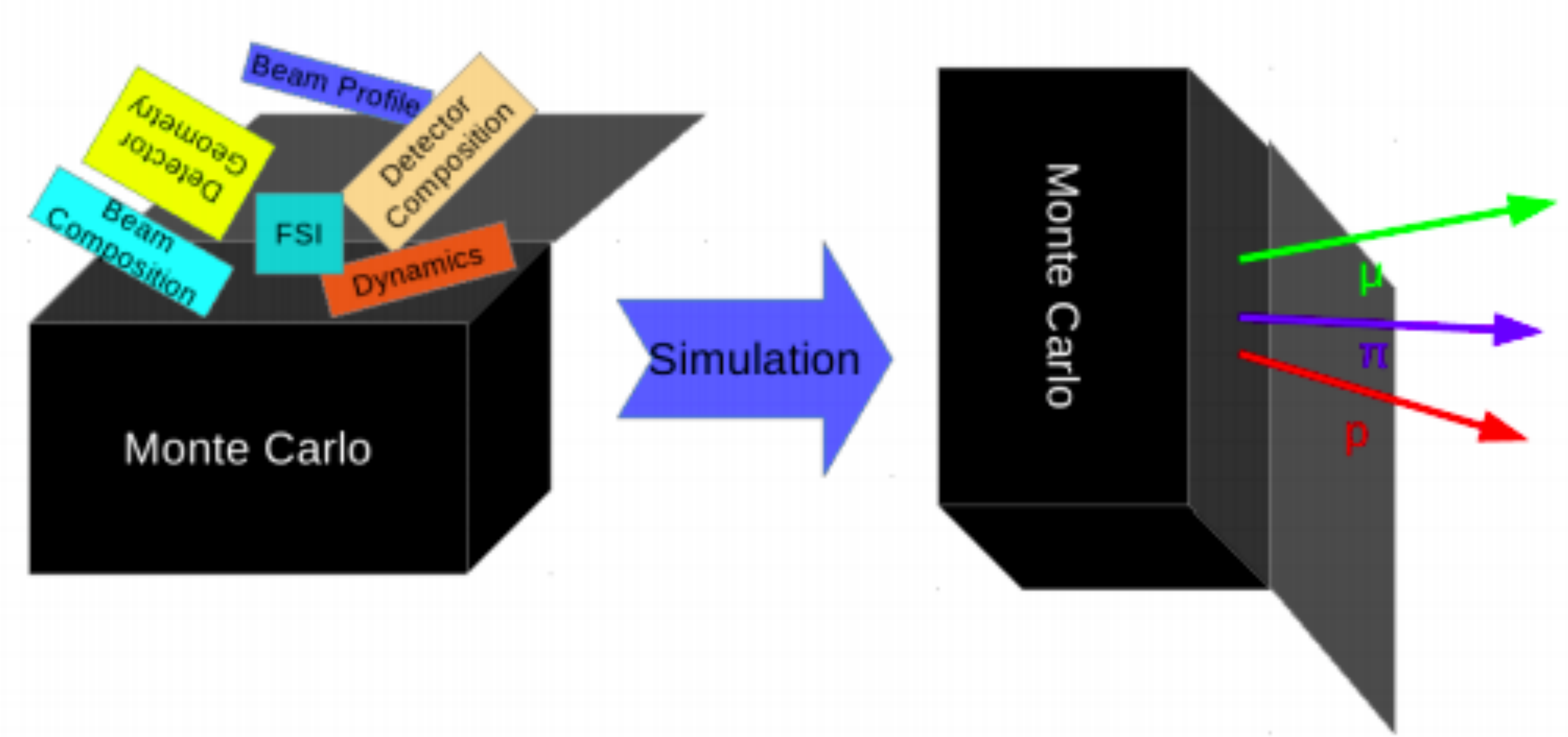
Analysis

pass through flux info

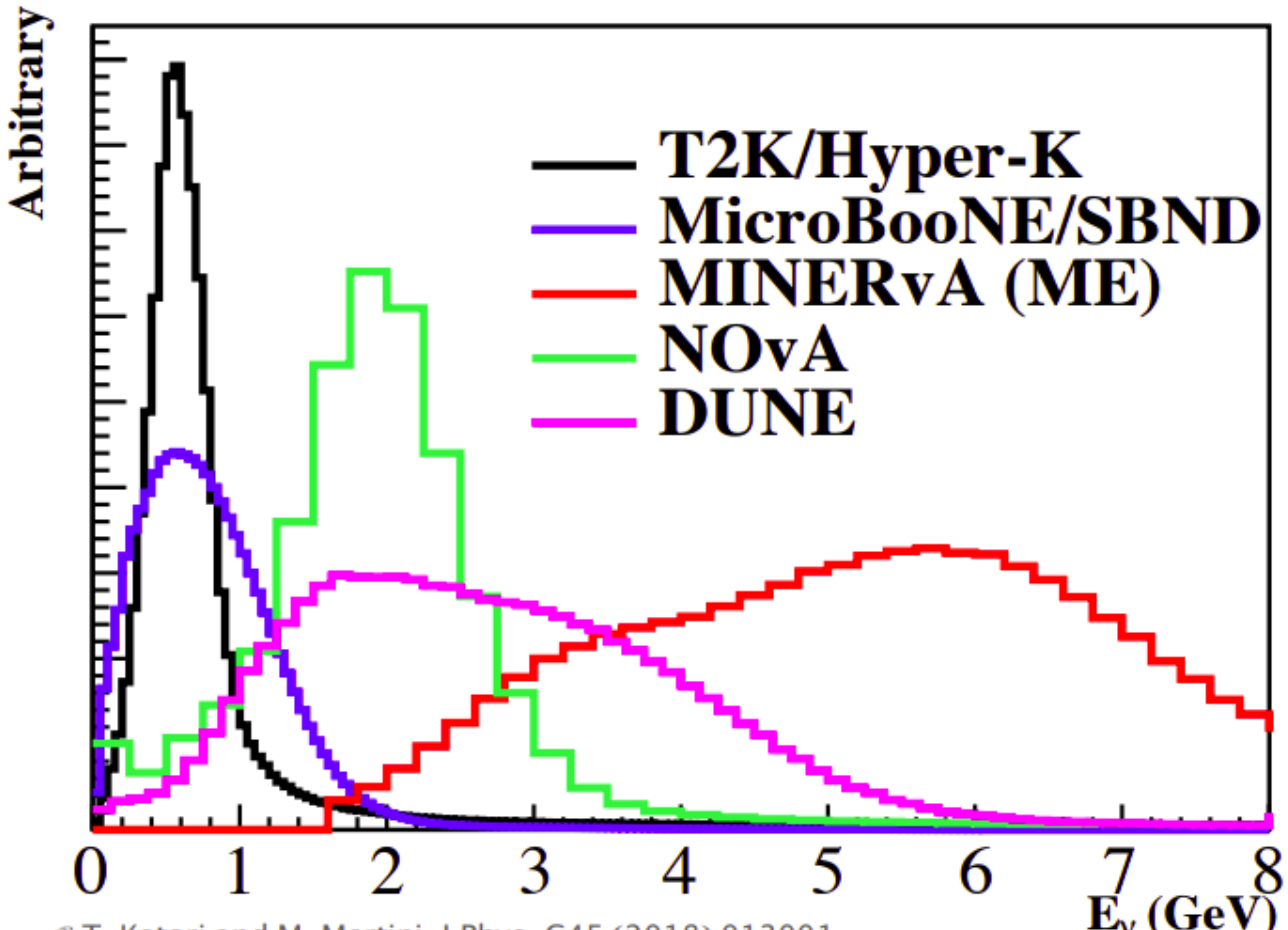
from Costas Andreopoulos, Rutherford Appleton Lab

- Monte Carlo generators are used to predict neutrino flux, detector responses and generate interaction

- MC predictions are compared with data

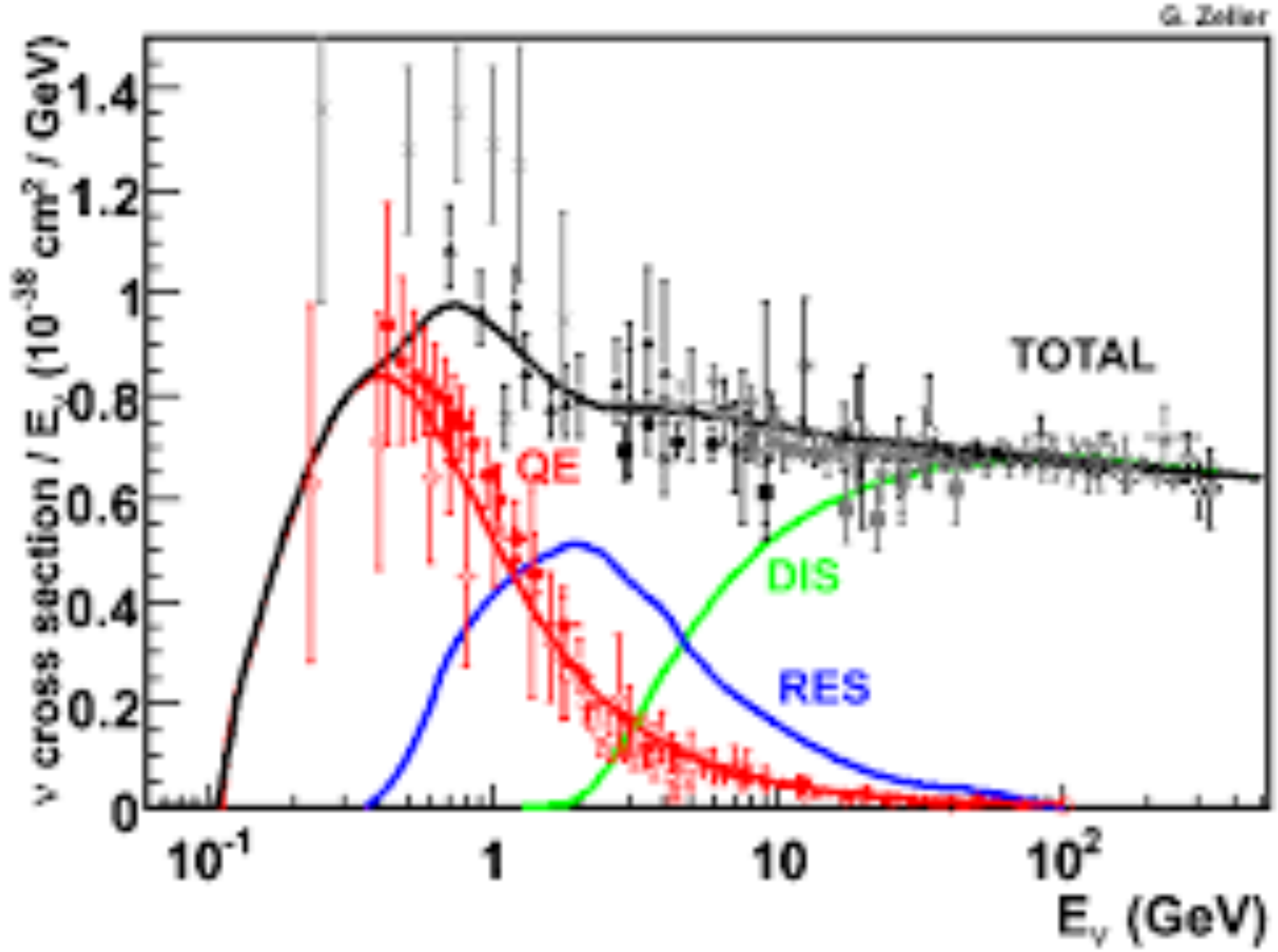


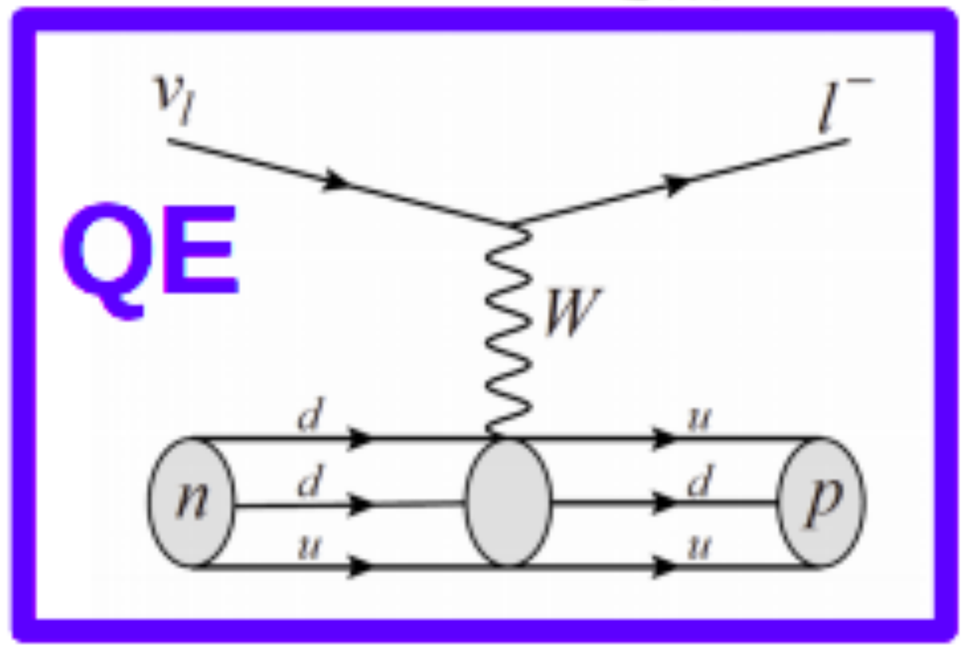
Neutrino Flux:

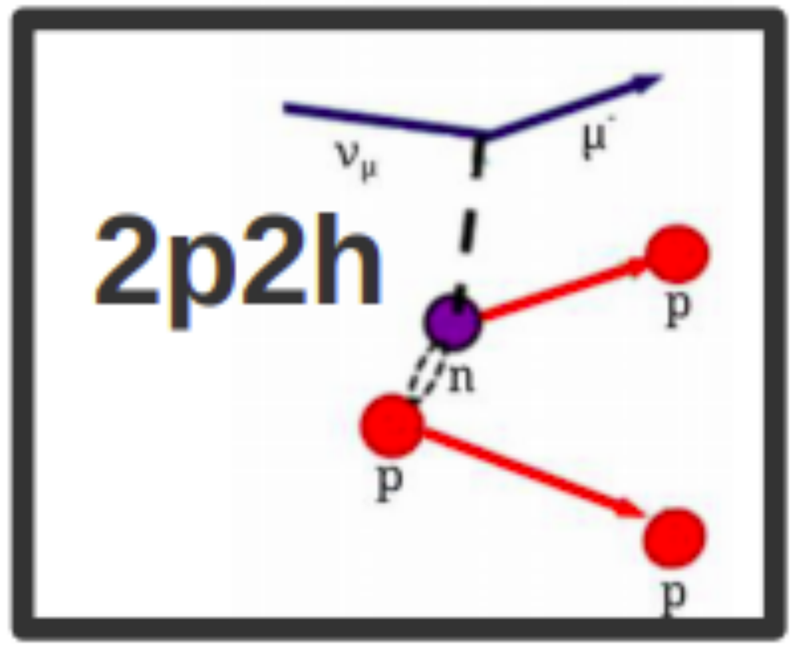


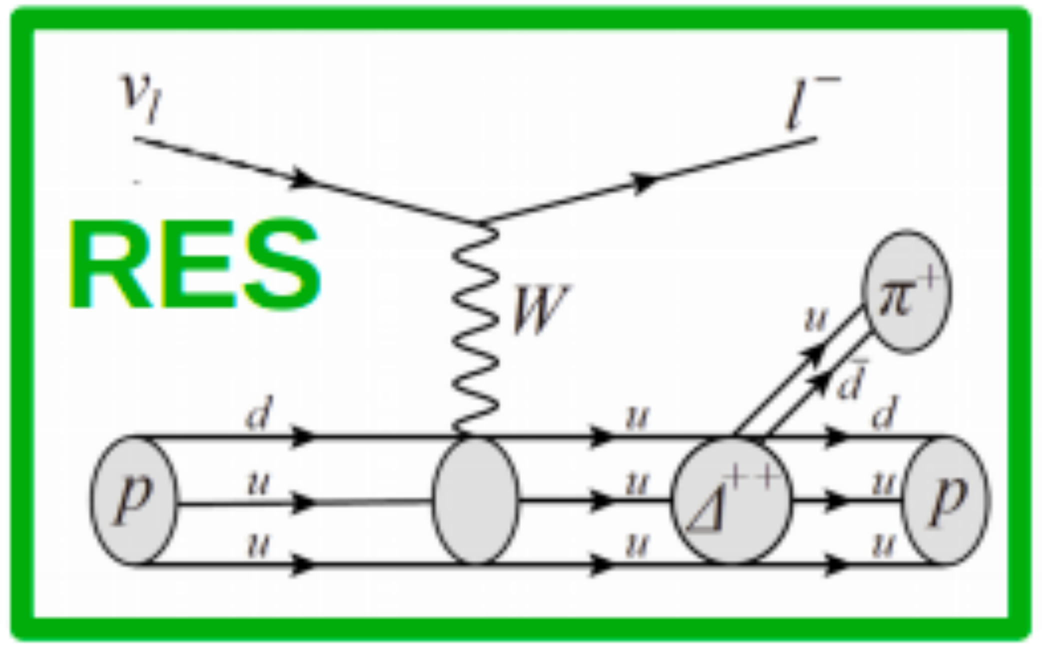
T. Katori and M. Martini, J.Phys. G45 (2018) 013001

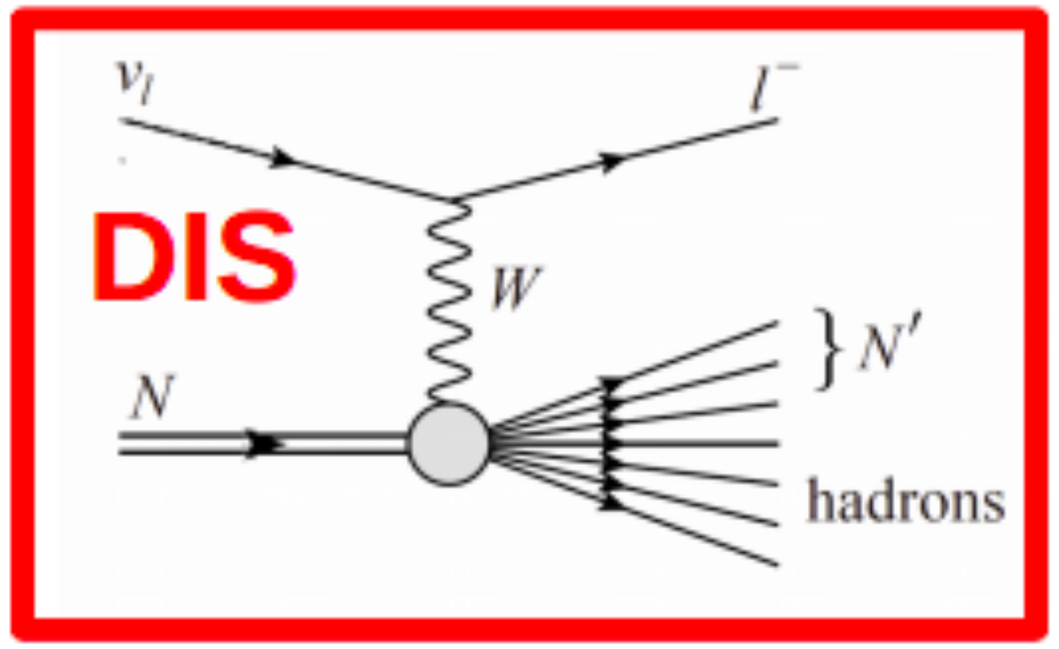
- Current and Future neutrino experiments range 1-10 GeV
- Systematic uncertainty by 10% flux uncertainty contribution (plans to reduce by EMPHATIC)


G. Zeller
ν cross section / E_ν (10^{-38} cm^2 / GeV)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^{-1}
1
10
10^2
E_ν (GeV)
TOTAL
QE
DIS
RES


QE
ν_l
l^-
W
d
d
u
u
d
u
n
p


2p2h
ν_μ
μ^-
n
p
p
p
p


RES
ν_l
l^-
W
π^+
u
$\bar{d}$
d
u
u
u
u
d
u
Δ^{++}
p
p


DIS
ν_l
l^-
W
N
$\} N'$
hadrons