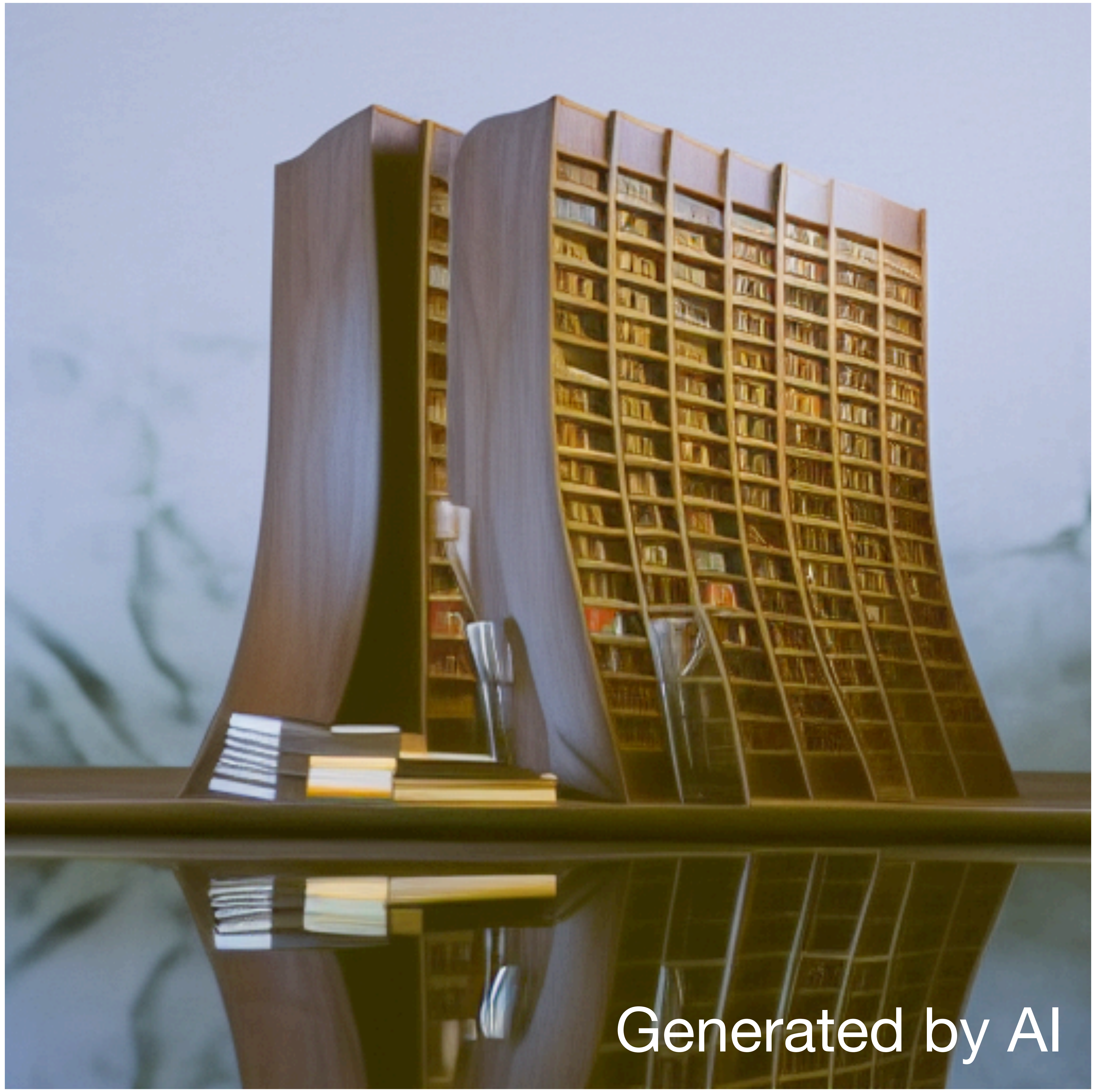
Measurement of neutrino scattering on hydrocarbon at 6 GeV with low momentum transfer using MINERvA

MINERνA Experiment

Marvin V. Ascencio Sosa*

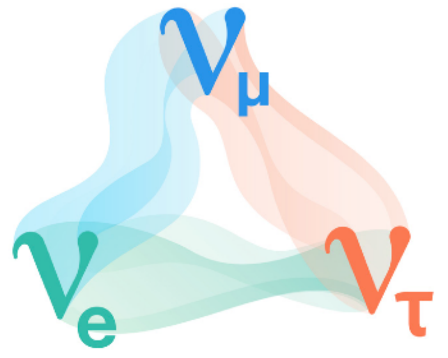
*now at Iowa State University

Outline



Why a cross-section measurement?
The neutrino source
MINERvA Detector
Neutrino cross-section
Analysis Definition
Event Selection
New model prediction
Cross-section extraction
Uncertainties
Conclusions

Why a cross-section measurement?

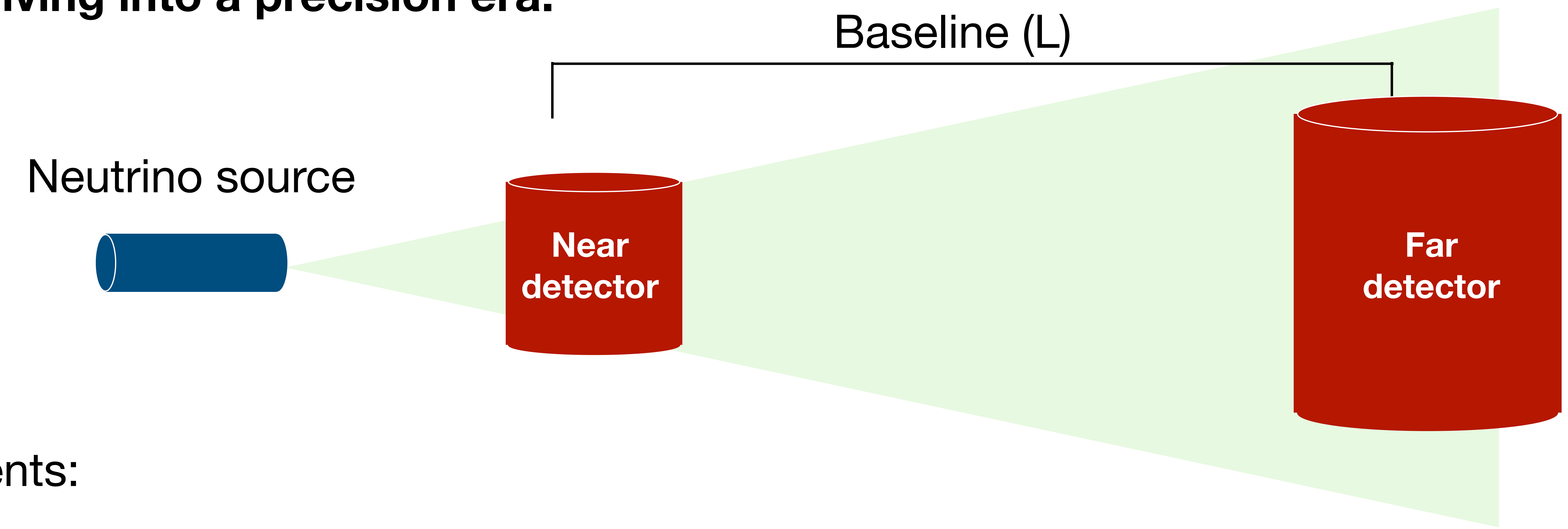


https://neutrino.physics.iastate.edu/project/dune

Neutrino oscillation → $M_\nu \neq 0$ → Beyond the Standard Model.

↓

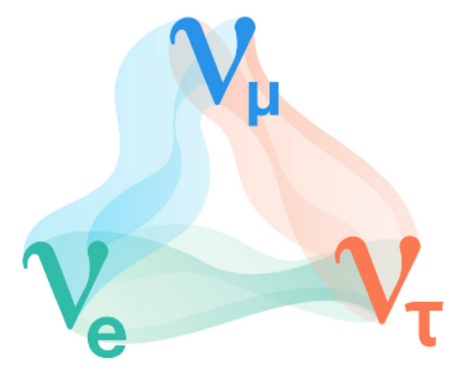
Evolving into a precision era.



Oscillation experiments:

$$N_\beta(E_{\text{reco}}, L) \propto \int_i \Phi_\alpha(E) \times P_{(\alpha\to\beta)}(E, L) \times \sigma_i(E) \times \text{nuclear effects} \times f_{\sigma_i}(E, E_{\text{reco}})dE$$

Why a cross-section measurement?



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Neutrino oscillation $\rightarrow M_\nu \neq 0 \rightarrow$ Beyond the Standard Model.

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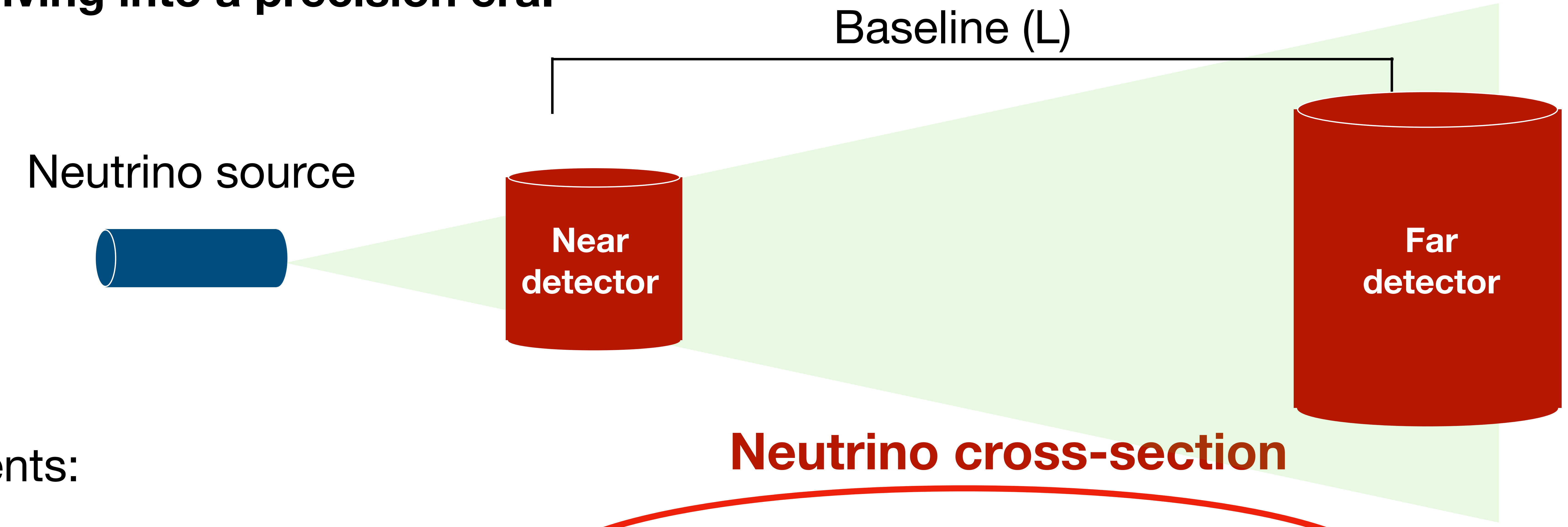
Evolving into a precision era.



Oscillation experiments:

Neutrino cross-section

$$N_\beta(E_{\text{reco}}, L) \propto \int_i \Phi_\alpha(E) \times P_{(\alpha\rightarrow\beta)}(E, L) \times \sigma_i(E) \times \text{nuclear effects} \times f_{\sigma_i}(E, E_{\text{reco}})dE$$

- The FD neutrino spectra depends on energy reconstruction.
- Model limitations can be a major source of systematic uncertainty for oscillation experiments.

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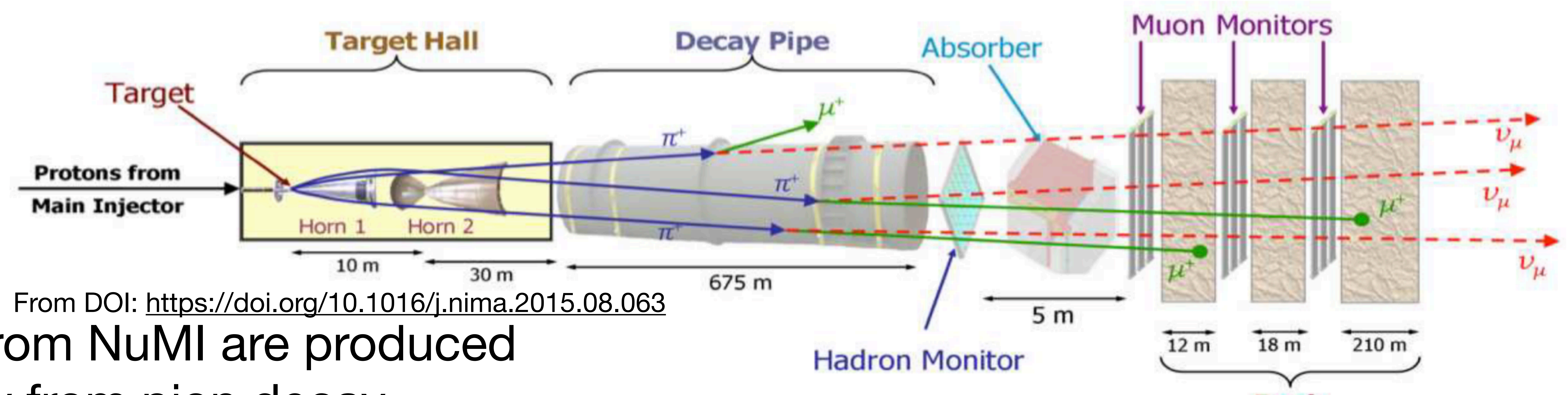
Neutrino source



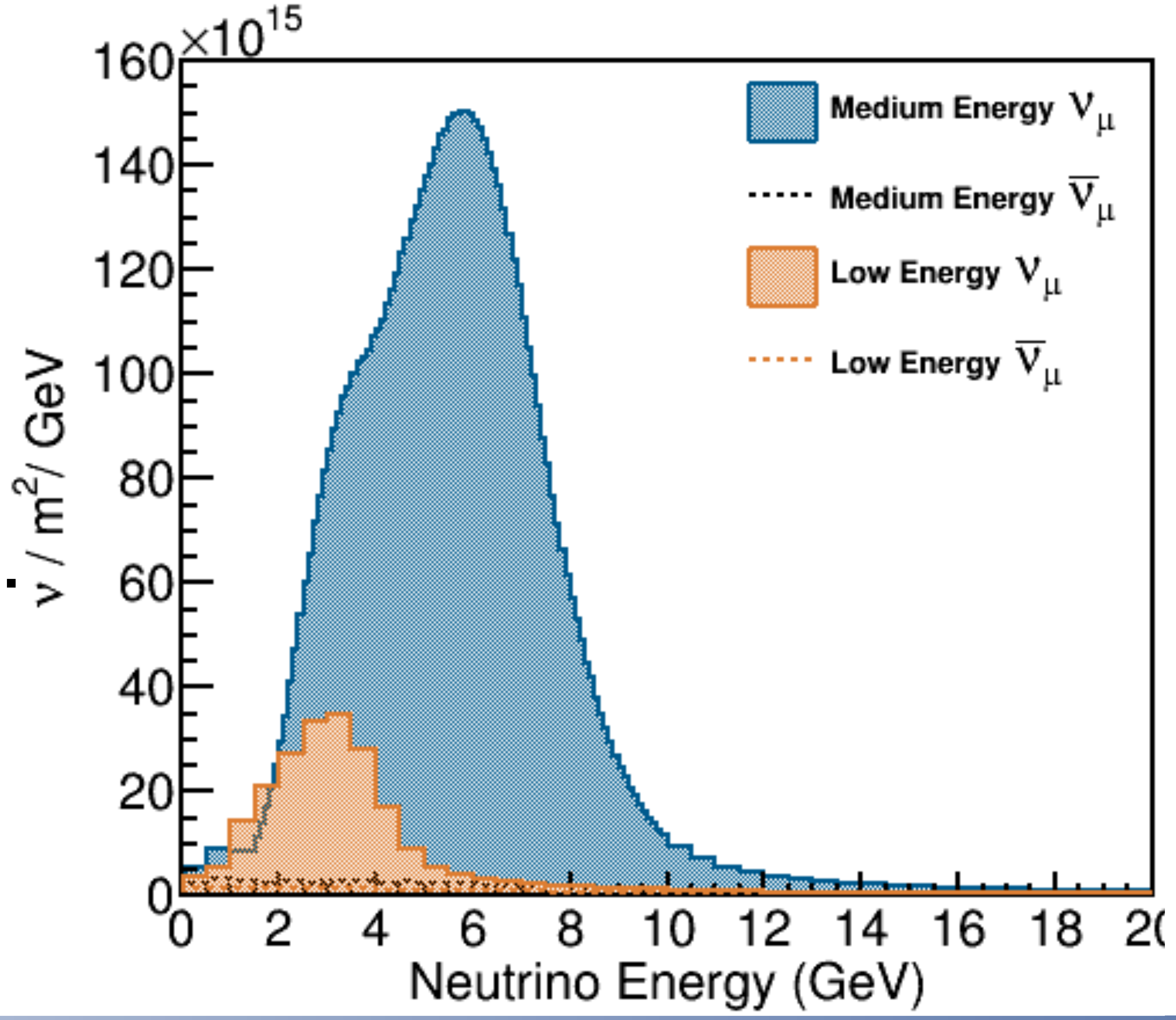
From DOI: https://doi.org/10.1016/j.nima.2015.08.063

Neutrinos from NuMI are produced mostly from pion decay.

Important uncertainties come from focusing and hadronic production.

Constrained with thin-target hadron production **measurements** (PPFX).

Nu+e constraint with **MINERvA data**, which reduces the flux uncertainty from 7.8% to 3.9%.



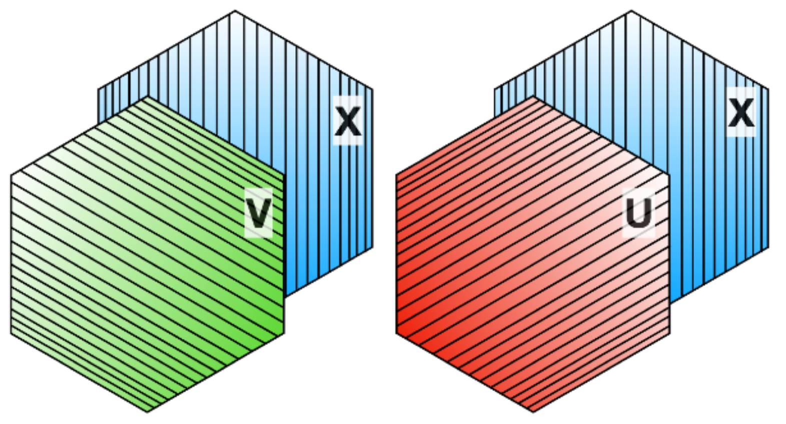
Thanks to the Fermilab Accelerator Division!

Medium energy (ME): 2013-2019

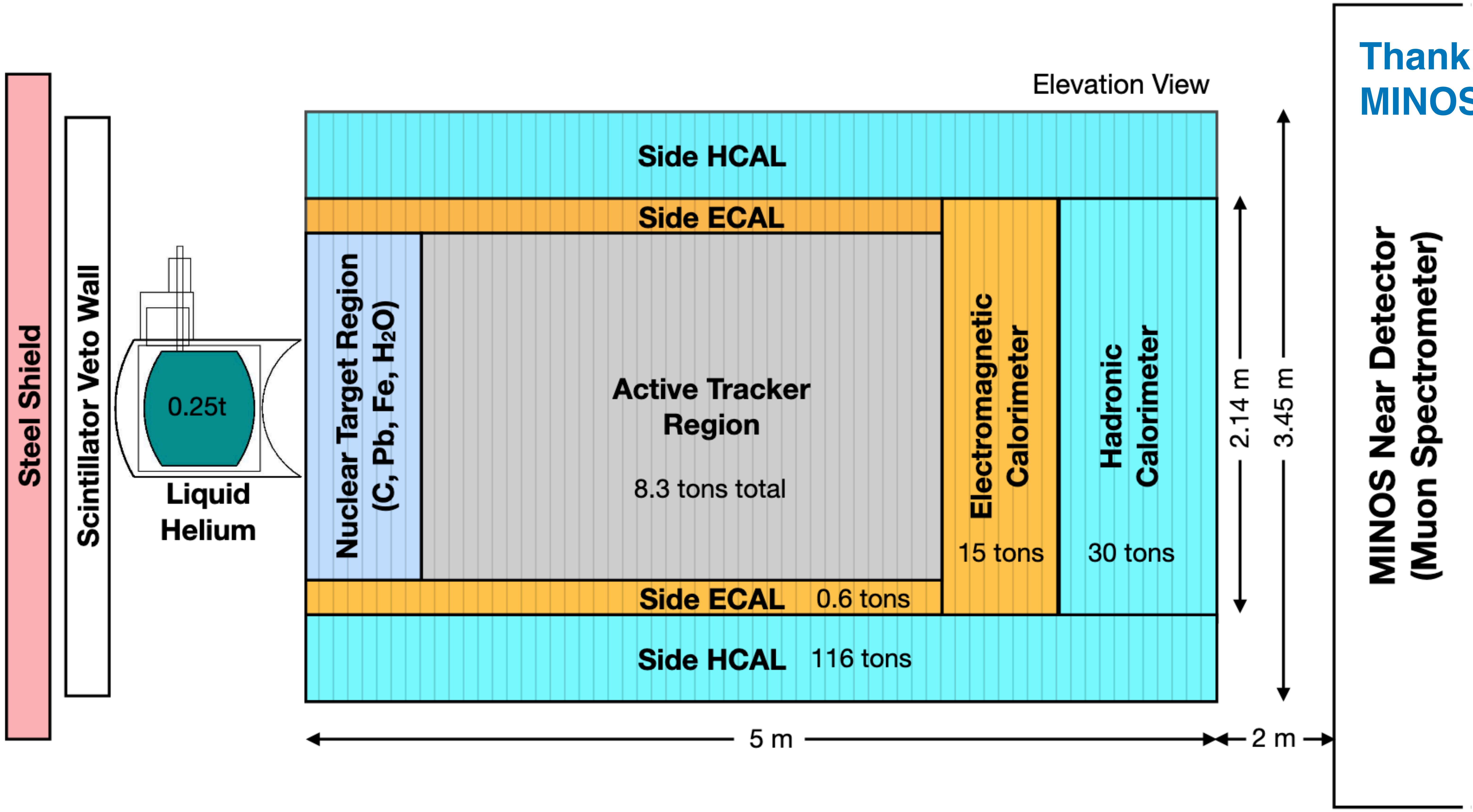
12.1×10^{20} POT

MINERvA (Main Injector Neutrino ExpeRiment to study ν-A) - Detector

MINERvA was a dedicated cross-section experiment built by a fine-grained scintillator tracker surrounded by an electromagnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL).



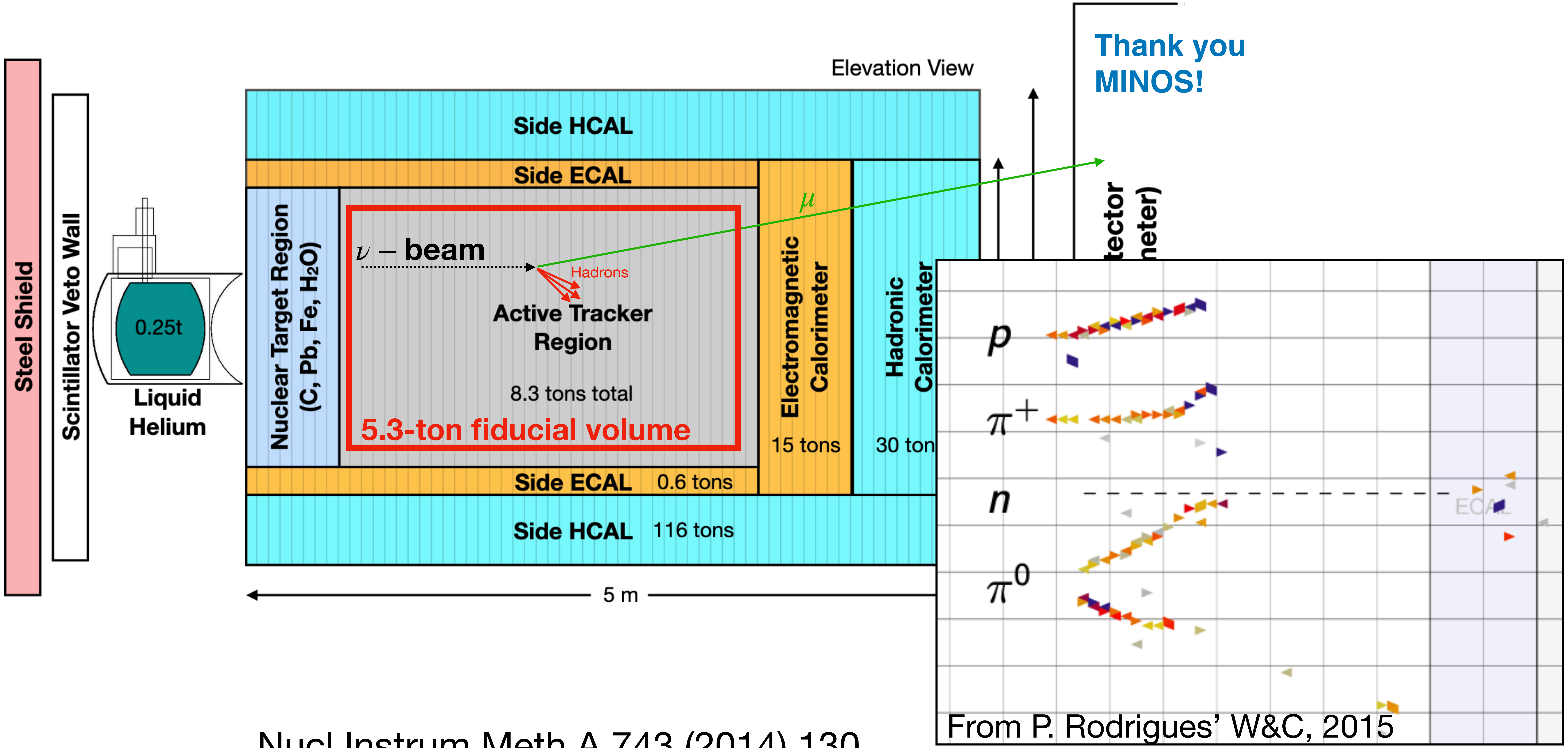
3 orientations
0°, +60°, –60°



Scintillator - Tracking
Lead - ECAL
Steel - HCAL

Nucl.Instrum.Meth.A 743 (2014) 130
and test beam Nucl.Instrum.Meth.A 789 (2015) 28

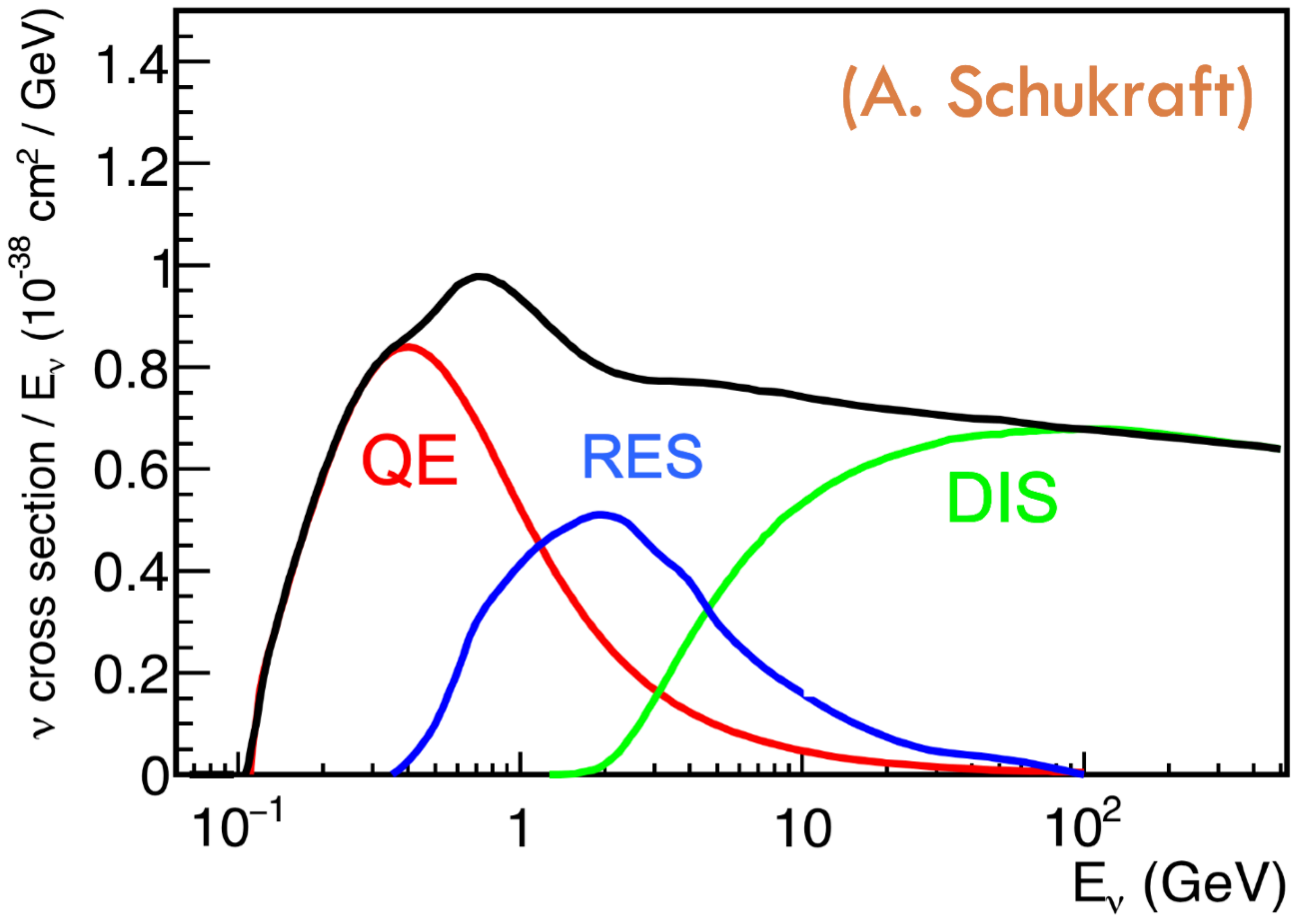
MINERvA Detector



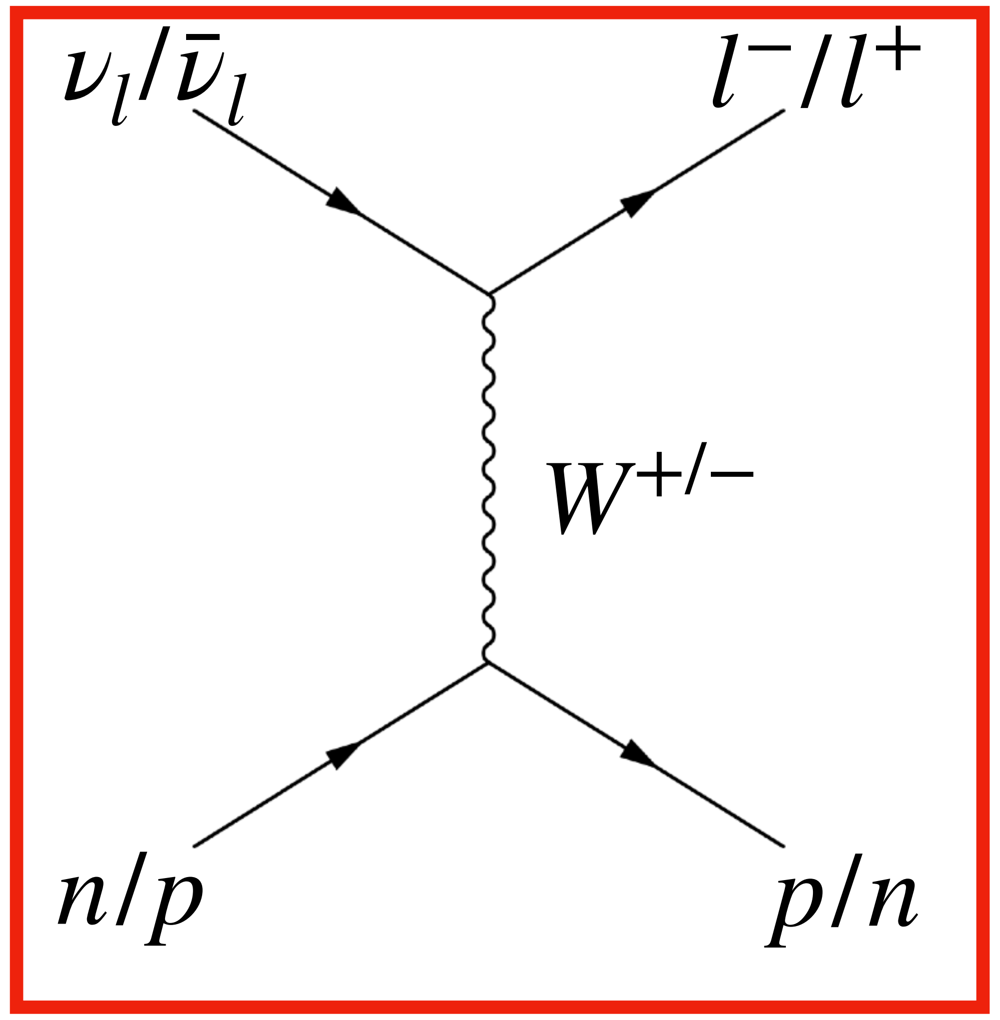
Carbon (88.51%),
Hydrogen (8.18%),
Oxygen (2.5%),
Titanium (0.47%),
Chlorine (0.2%),
Aluminum (0.07%),
Silicon (0.07%).

Nucl.Instrum.Meth.A 743 (2014) 130
and test beam Nucl.Instrum.Meth.A 789 (2015) 28

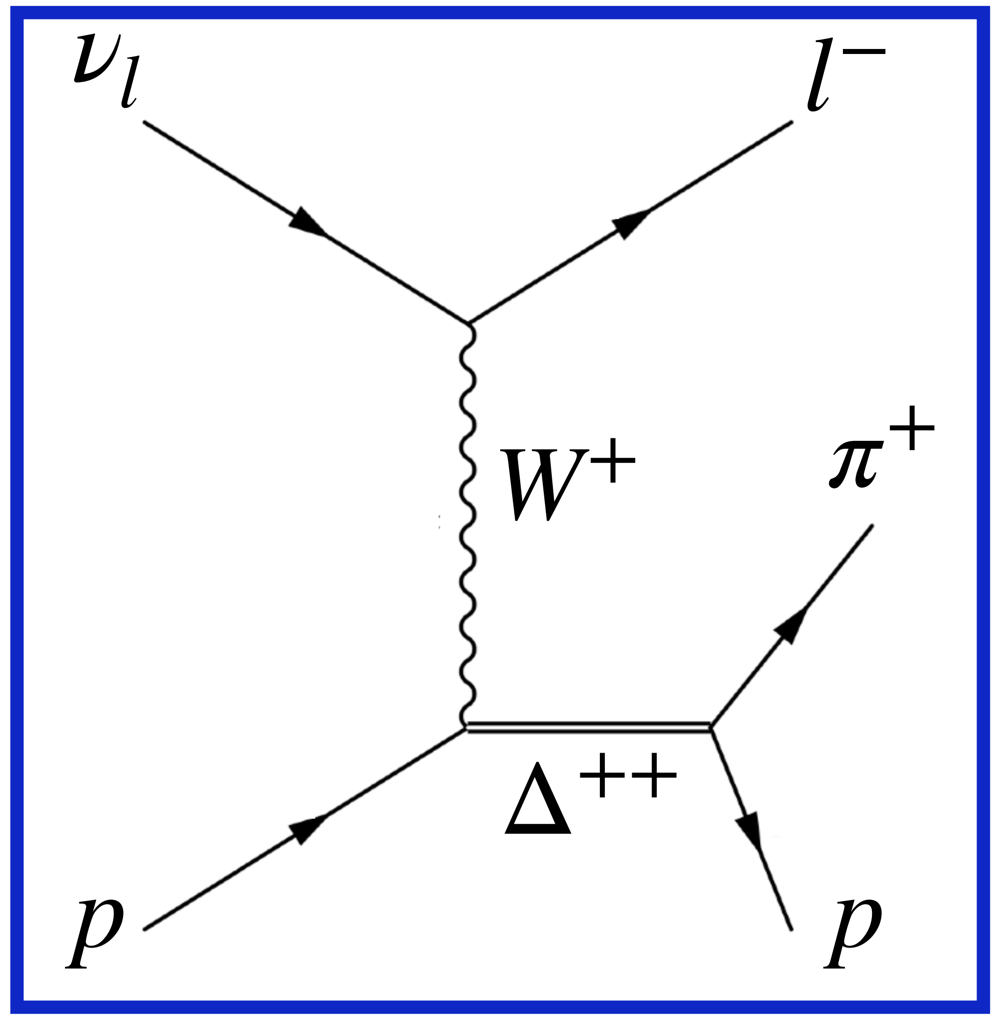
Neutrino cross-section



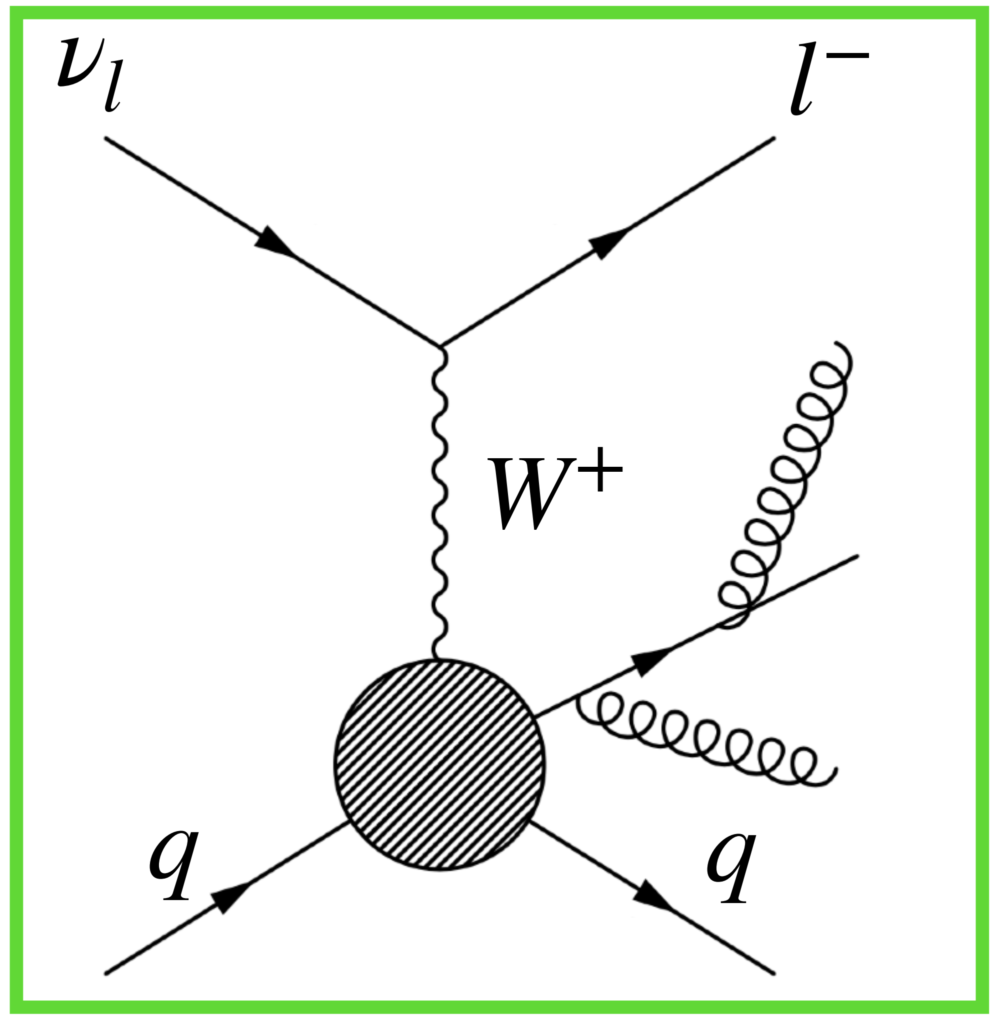
Free nucleon (FN) interaction:



Quasi-elastic



Resonant



Deep Inelastic Scattering

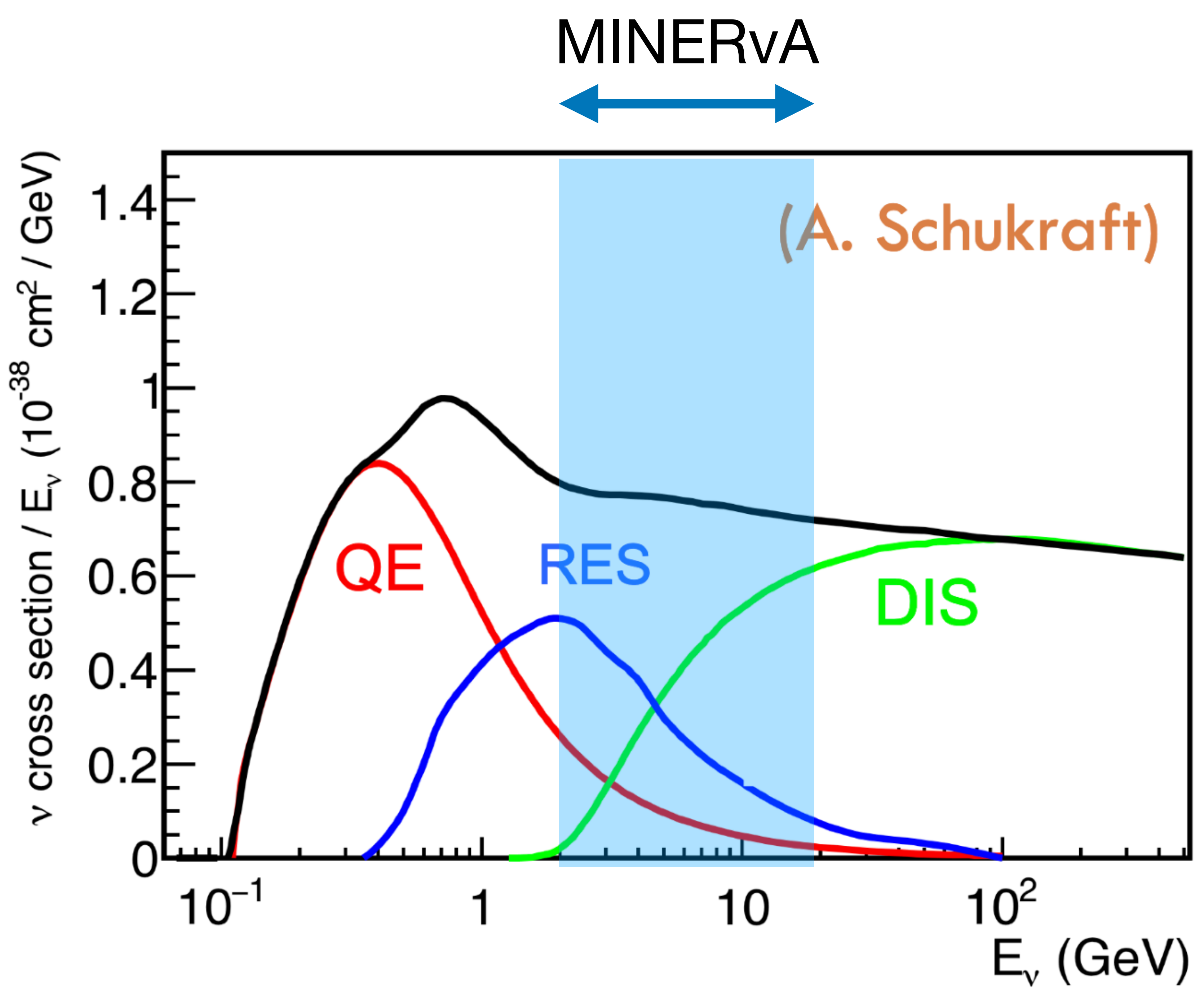
A lot of oscillation experiments are running at several GeV of energy.

T2K and MicroBooNE are below 1 GeV (mostly QE)

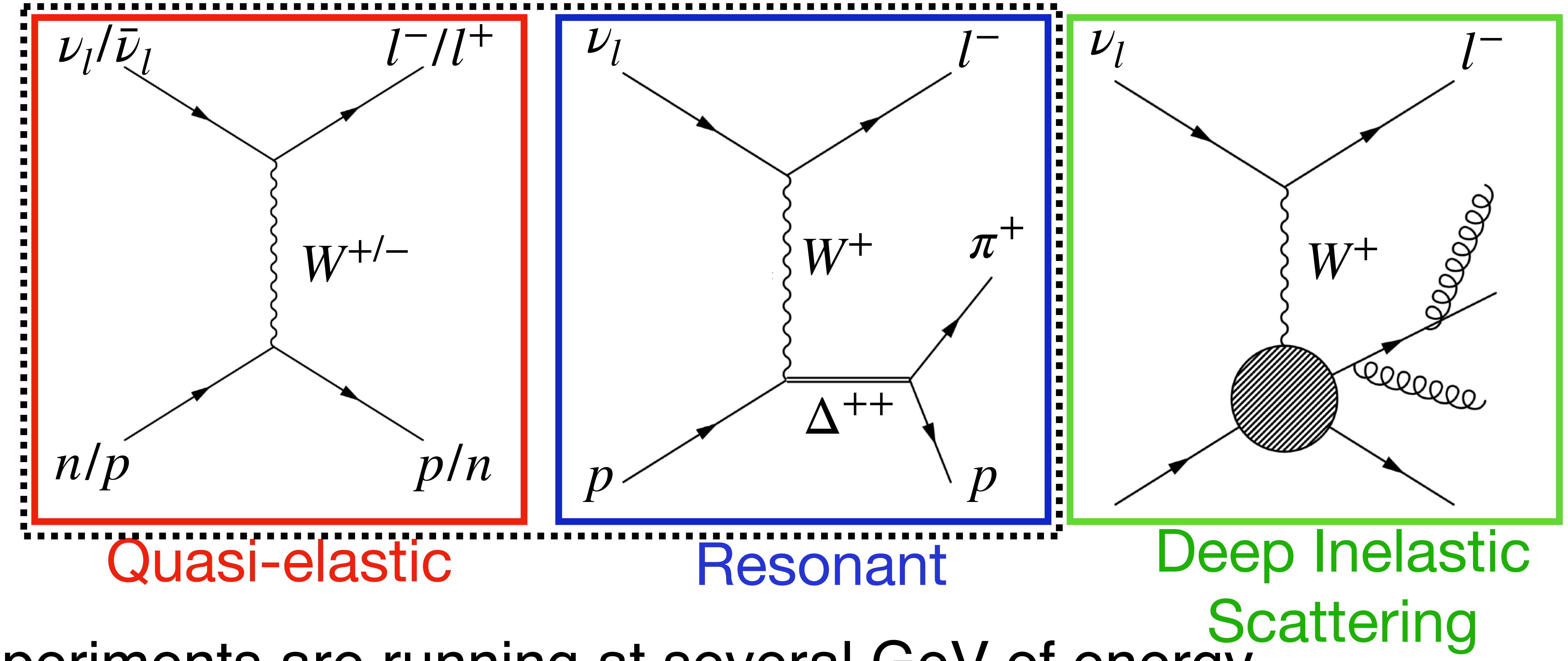
NOvA is at 2 GeV, as is DUNE's oscillation max, mostly QE and RES.

DUNE flux at 5 GeV will have significant amounts of DIS

Neutrino cross-section



Free nucleon interaction:



A lot of oscillation experiments are running at several GeV of energy.

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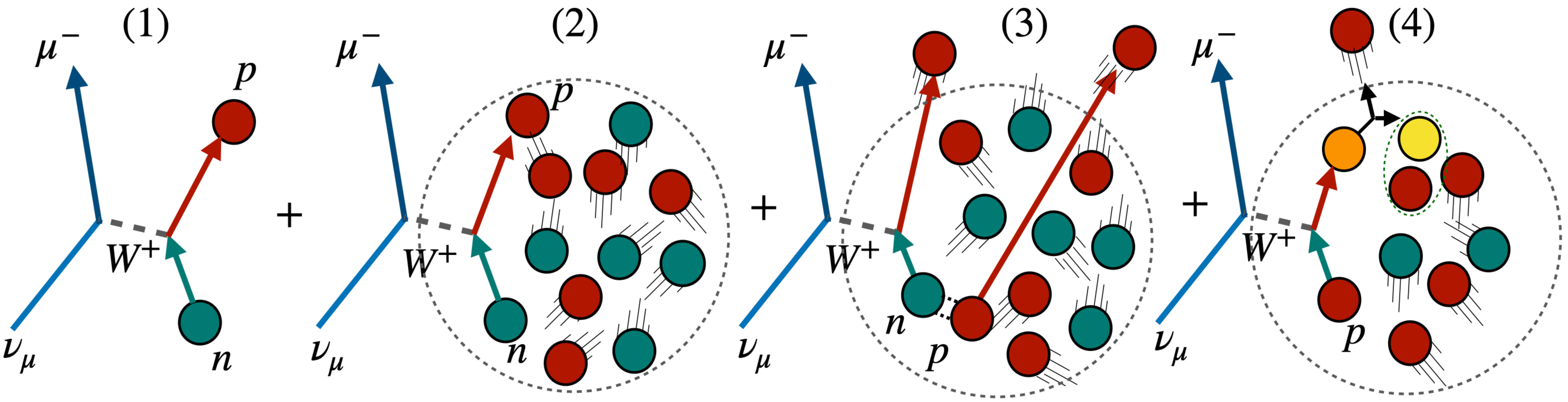
MINERvA range of energy (Medium Energy), there are several processes for the free nucleon. Today's results are mostly QE and Resonant interactions (**inclusive analysis**).

Neutrino cross-section

Nucleons in the nucleus:



(1) Free nucleon interaction.
(2) Interaction inside of the nucleus.
(3) Nuclear effects in the neutrino-nucleus interaction.
(4) Final State Interactions (FSI).

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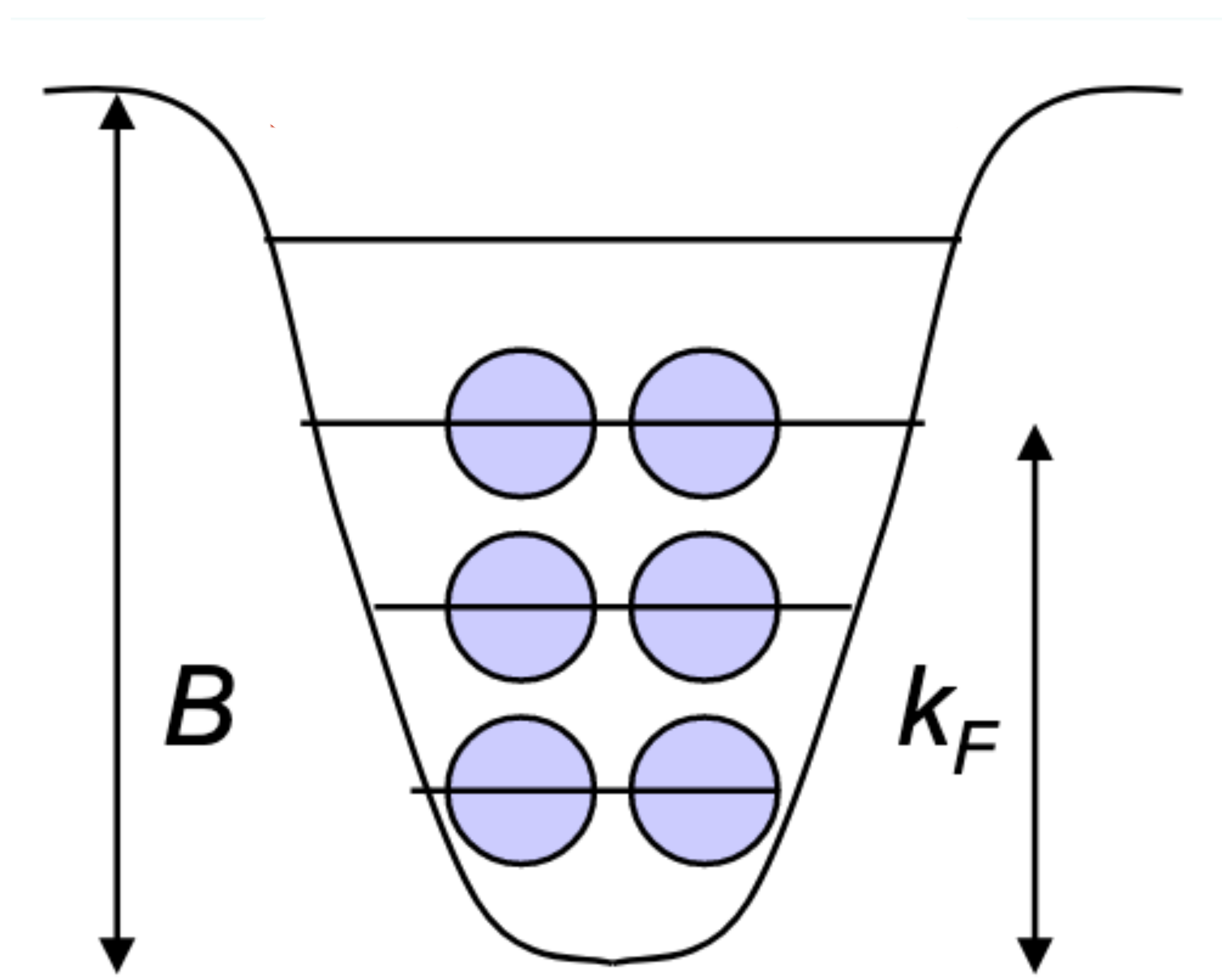
Neutrino cross-section

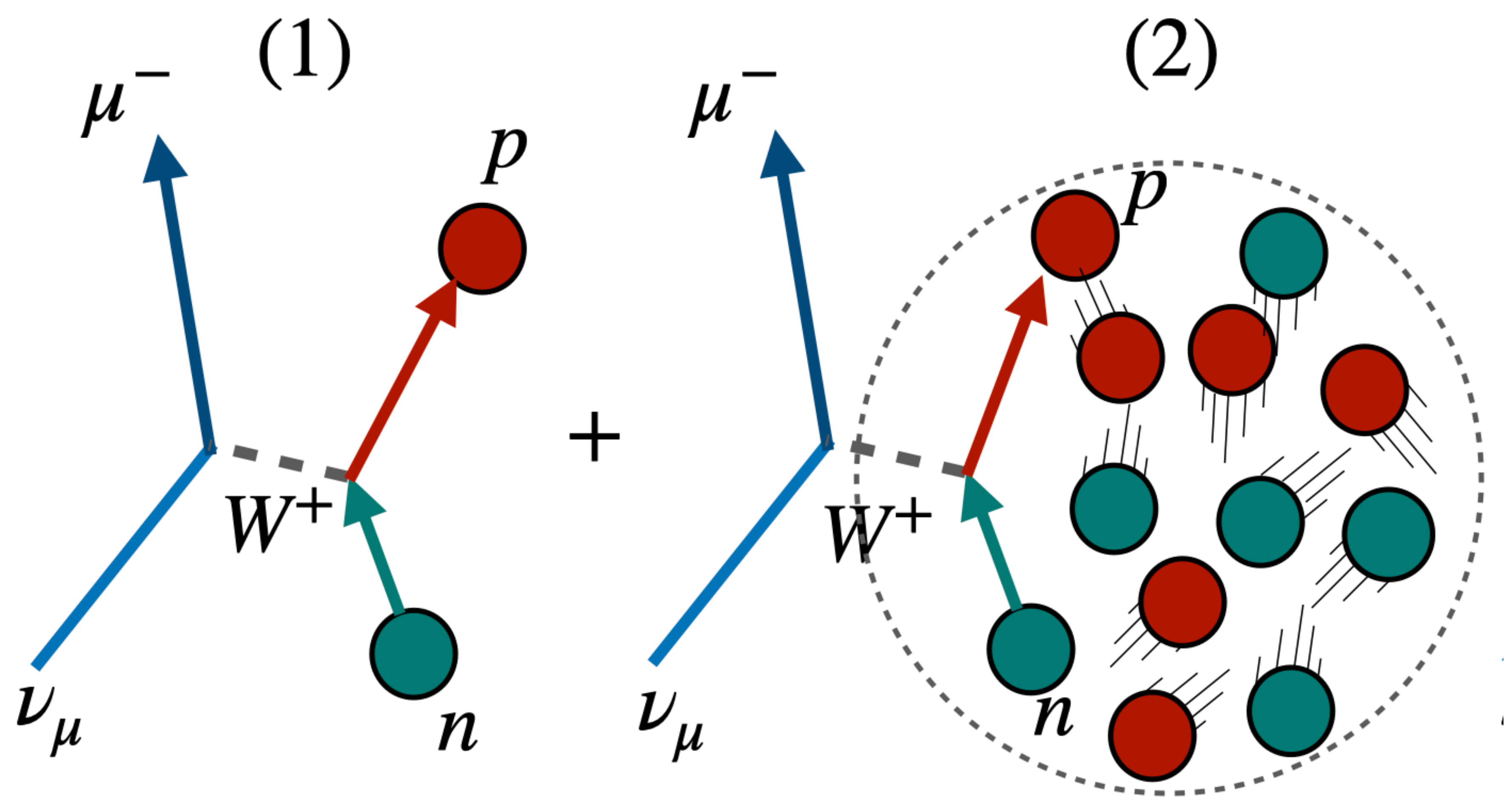
Modeling the nucleus



For instance Fermi Gas:

* Fermi motion.
* Binding energy.
* Pauli Blocking.

Nucleons in the nucleus:



(1) Free nucleon interaction.

(2) Interaction inside of the nucleus.

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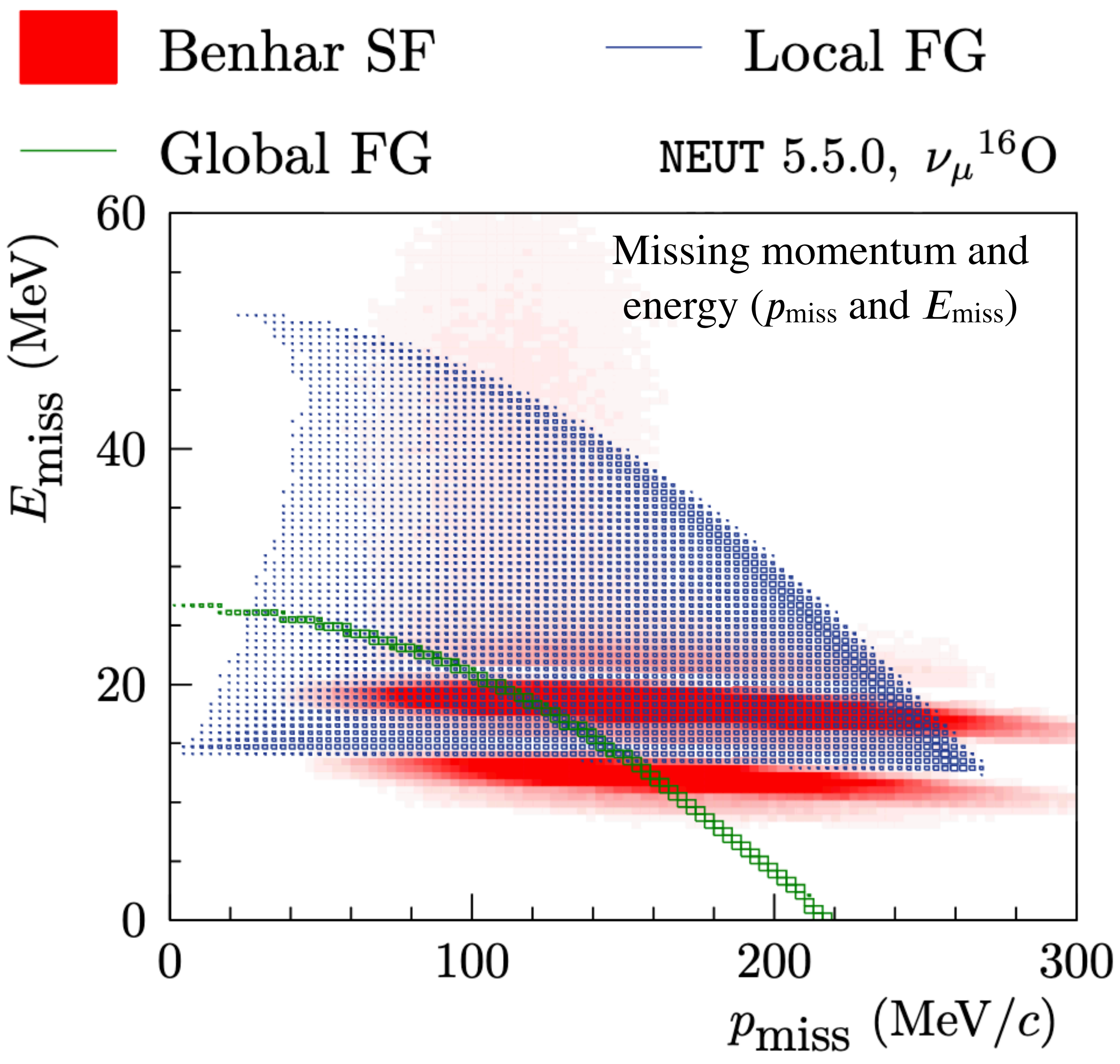
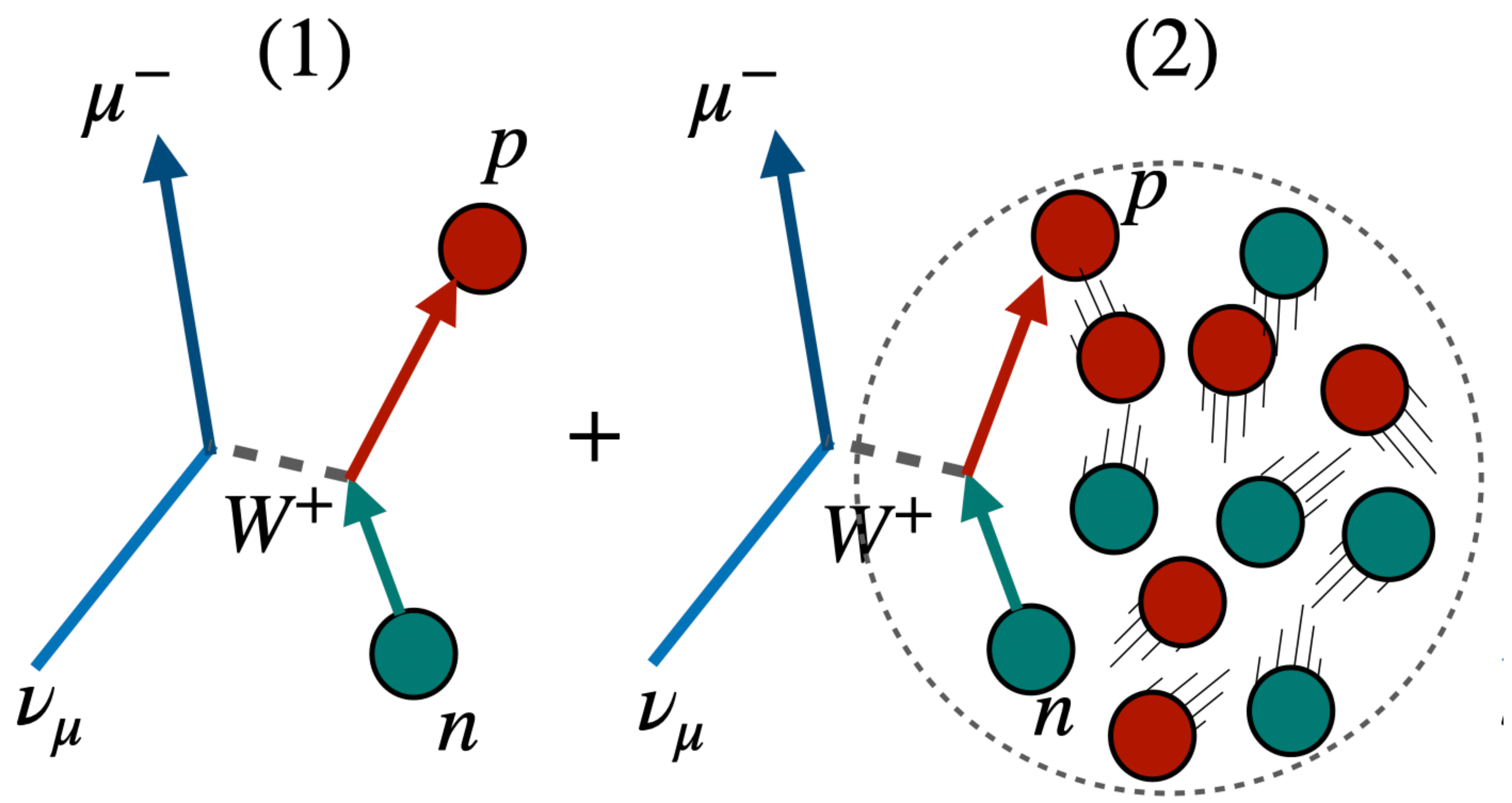
Neutrino cross-section

Modeling the nucleus
(nuclear ground state)



The NEUT neutrino interaction simulation program library.
Hayato, Y., Pickering, L.
Eur. Phys. J. Spec. Top. **230**, 4469–4481 (2021)

Nucleons in the nucleus:



(1) Free nucleon interaction.

(2) Interaction inside of the nucleus.

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Neutrino cross-section

Random Phase Approximation (**RPA**)

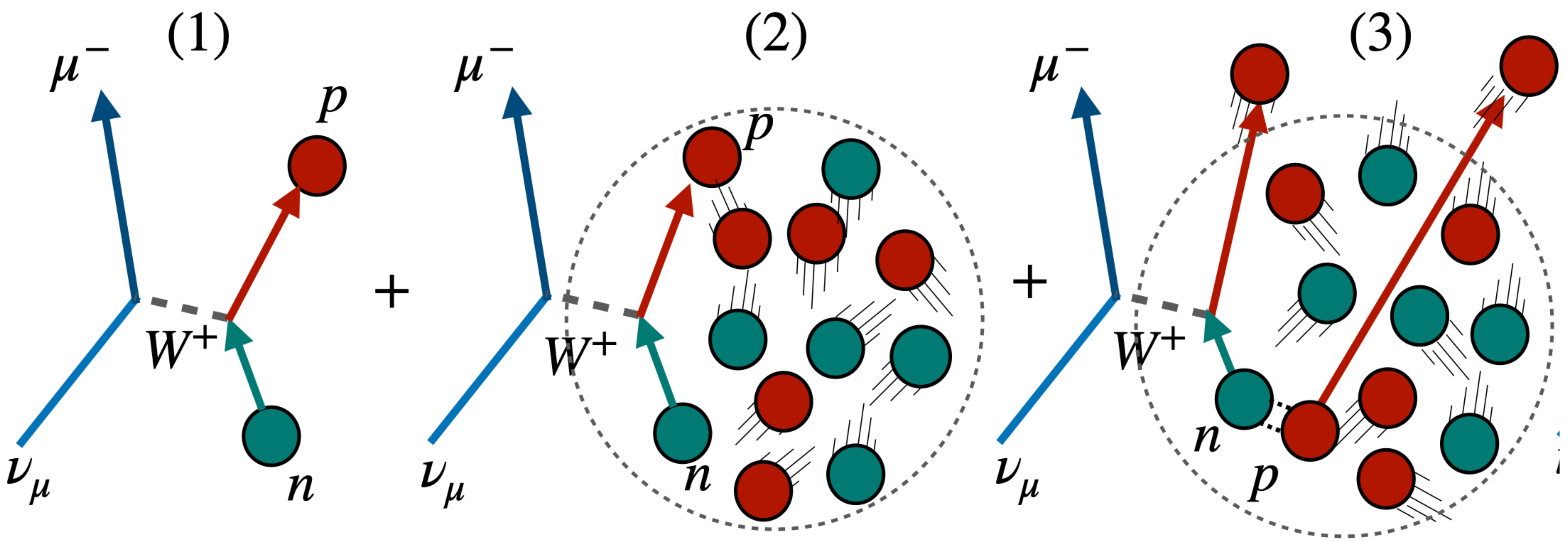
- In the nucleus, the nucleons are highly correlated with the <u>long-range</u> correlations.

- In the nuclear medium, the weak interaction changes due to the presence of strongly interacting **nucleons**

Electroweak couplings

free nucleons $\neq$ bound nucleons.

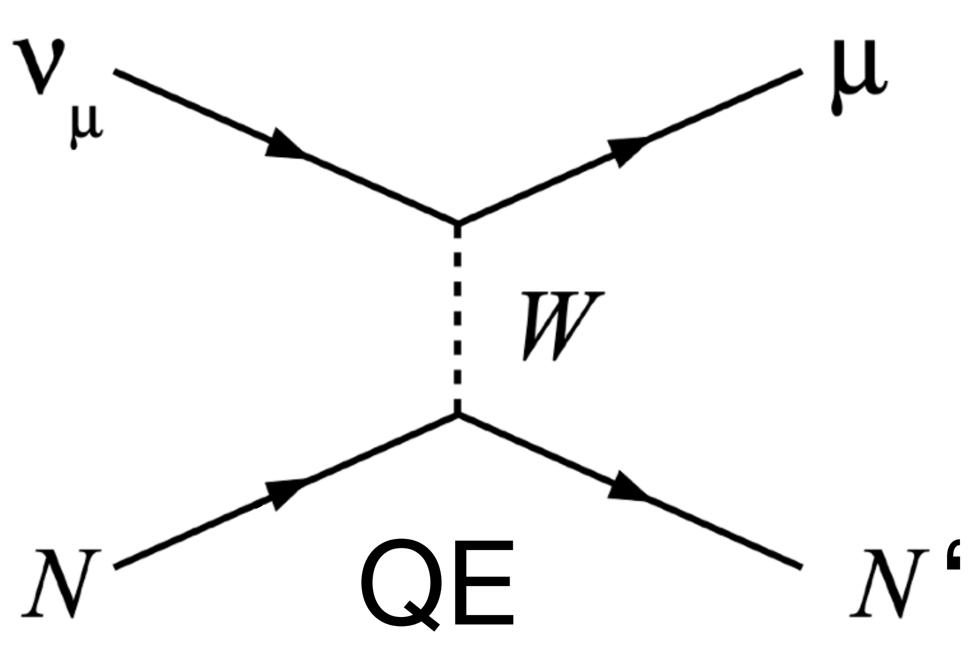
Nucleons in the nucleus:

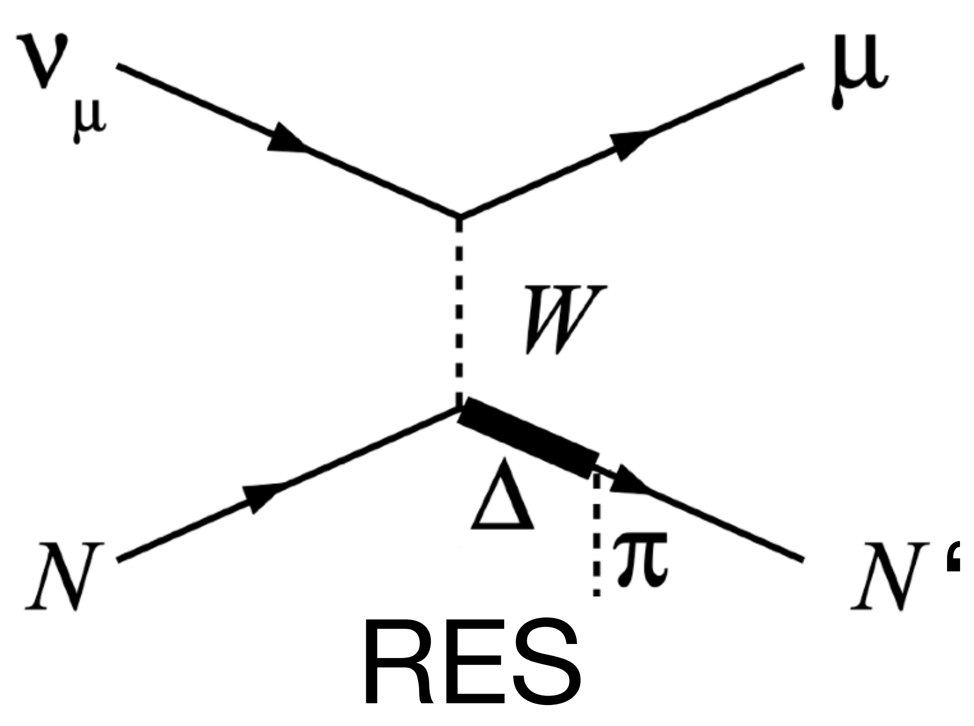


(1) Free nucleon interaction.
(2) Interaction inside of nuclei.
(3) Nuclear effects in the neutrino-nuclei interaction.

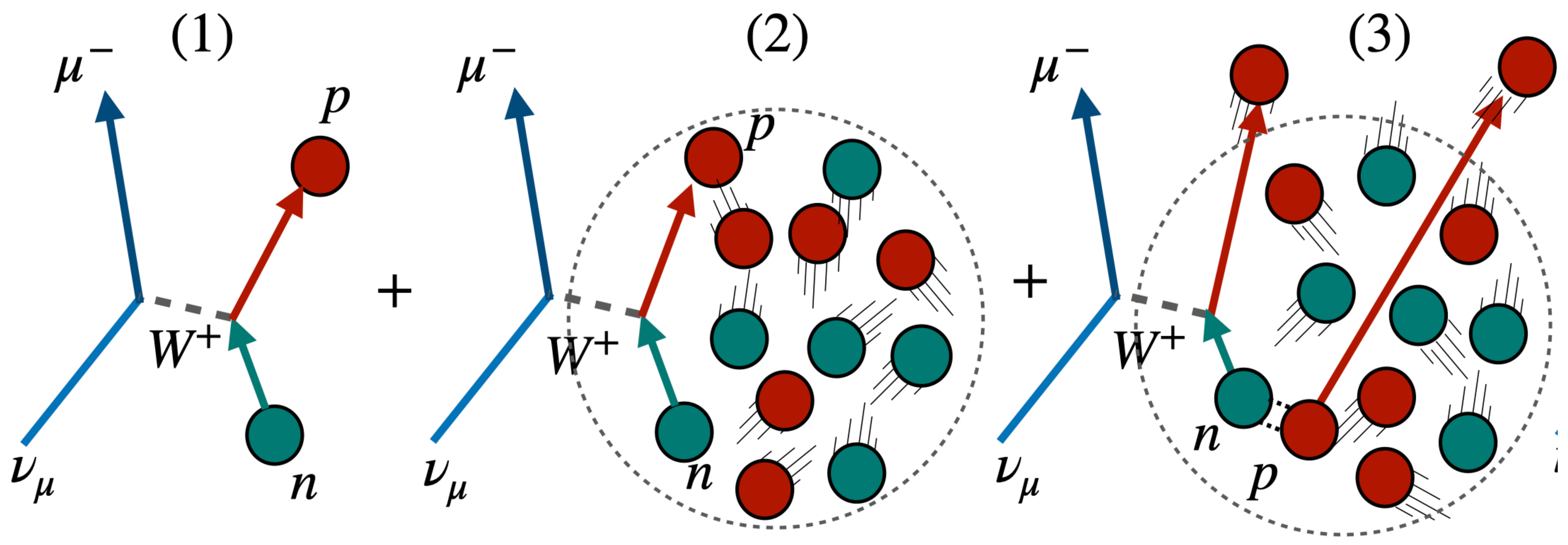
Neutrino cross-section

Multi Nucleon Effects





Nucleons in the nucleus:



(1) Free nucleon interaction.
(2) Interaction inside of nuclei.
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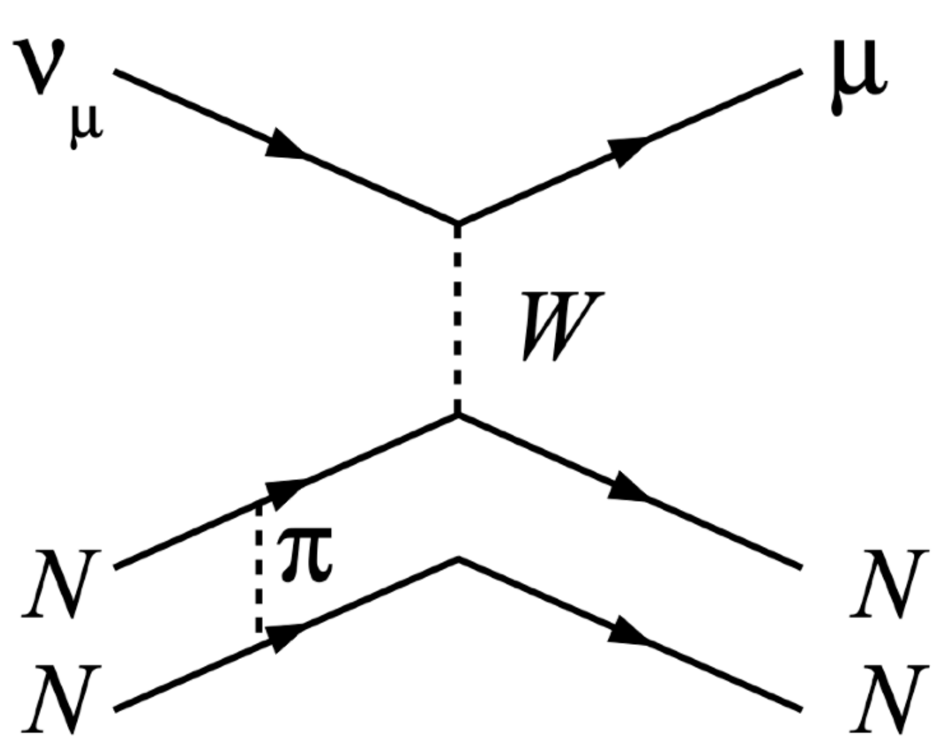
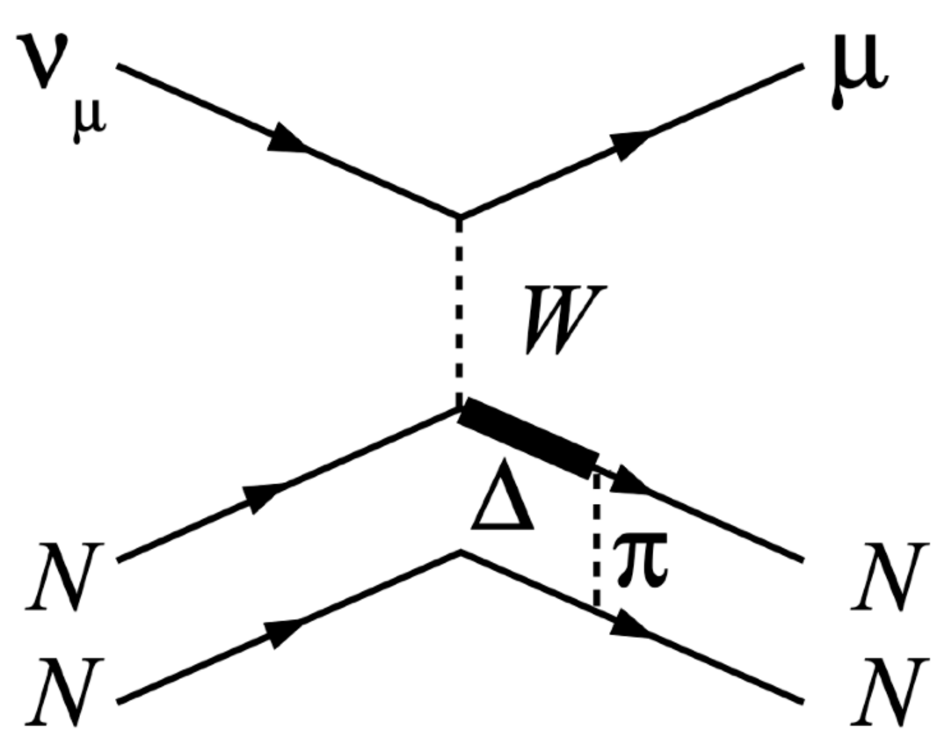
Neutrino cross-section

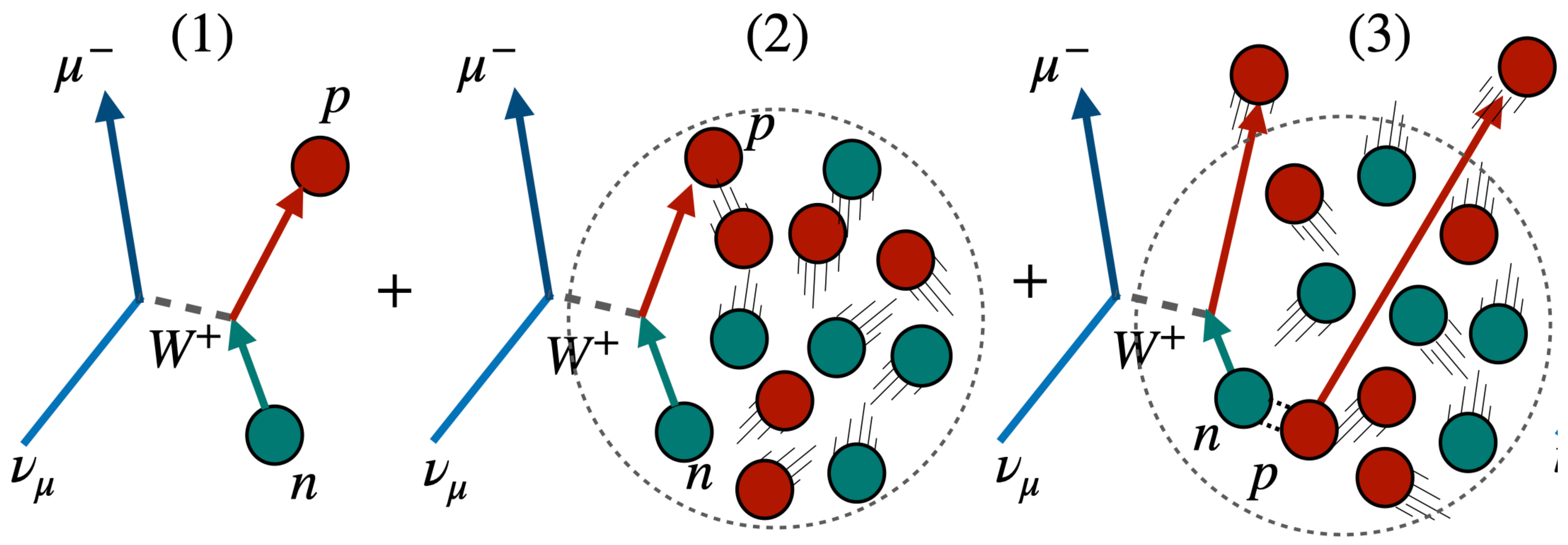
Multi Nucleon Effects
"2p2h"





"Dip region" between
QE and RES

Nucleons in the nucleus:



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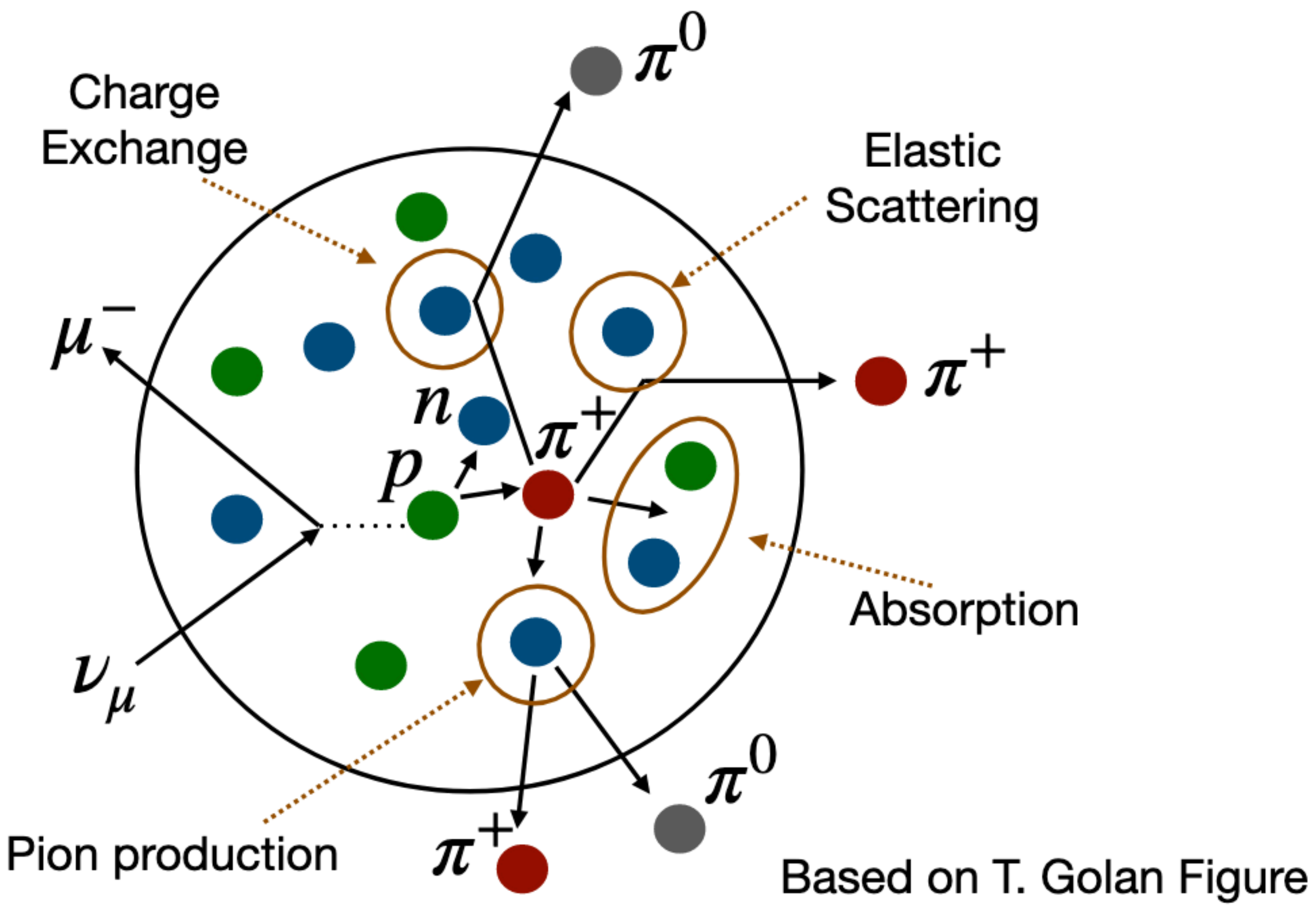
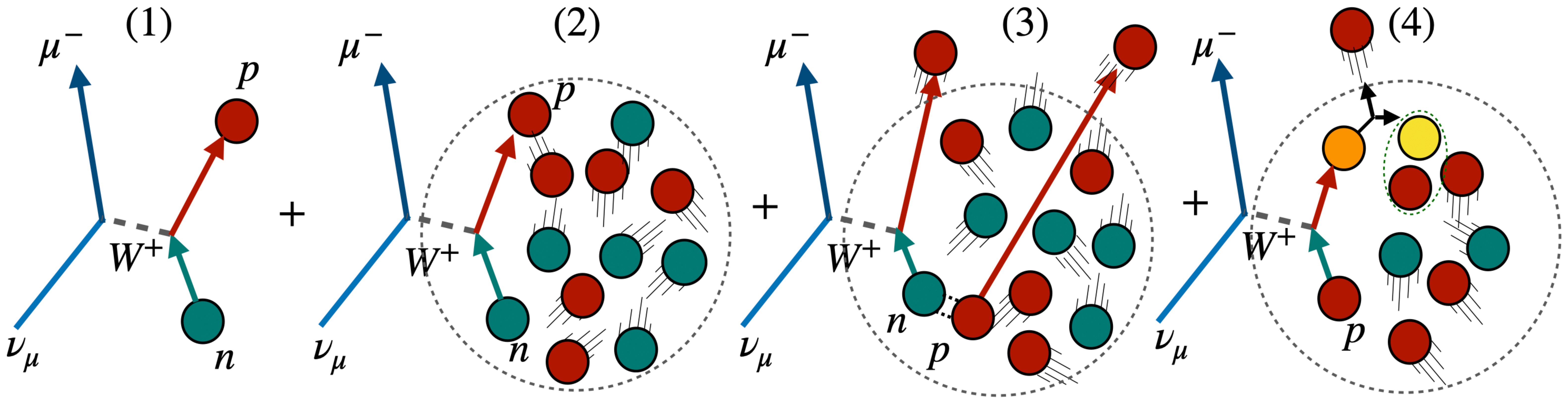
Neutrino cross-section

Final state interaction



Nucleons in the nucleus:



(1) Free nucleon interaction.
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Previous papers and W&C talks

Rodrigues, Demgen, Miltenberger, [MINERvA] PRL 116 071802 (2016).

Neutrino Low Energy

Gran, Betancourt, Elkins, Rodrigues, [MINERvA] PRL 120 221805 (2018).

Antineutrino Low Energy

This talk:

Ascencio, Andrade, Mahbub, [MINERvA] PRD 106, 032001 (2022)

Neutrino Medium Energy

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Antineutrino Low Energy

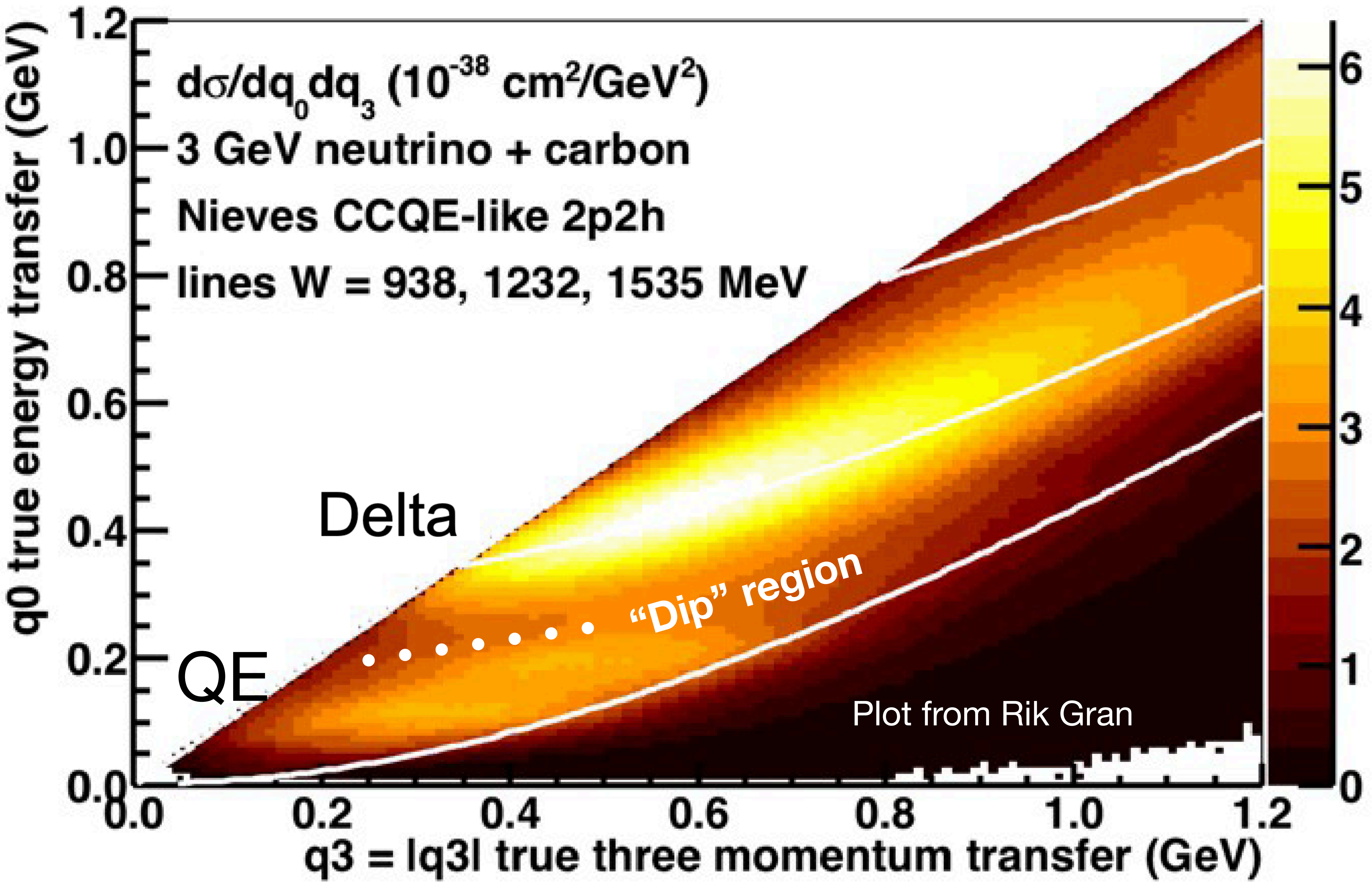
This talk:

Ascencio, Andrade, Mahbub, [MINERvA] PRD 106, 032001 (2022)

Neutrino Medium Energy

- **Higher statistics ~45 times.**
- **More regions of momentum transfer.**
- **New flux constrains.**
- **More models studied**

Kinematic Definition



Given the E_μ , θ_μ and E_{had}:

$$E_\nu = E_\mu + q_0$$

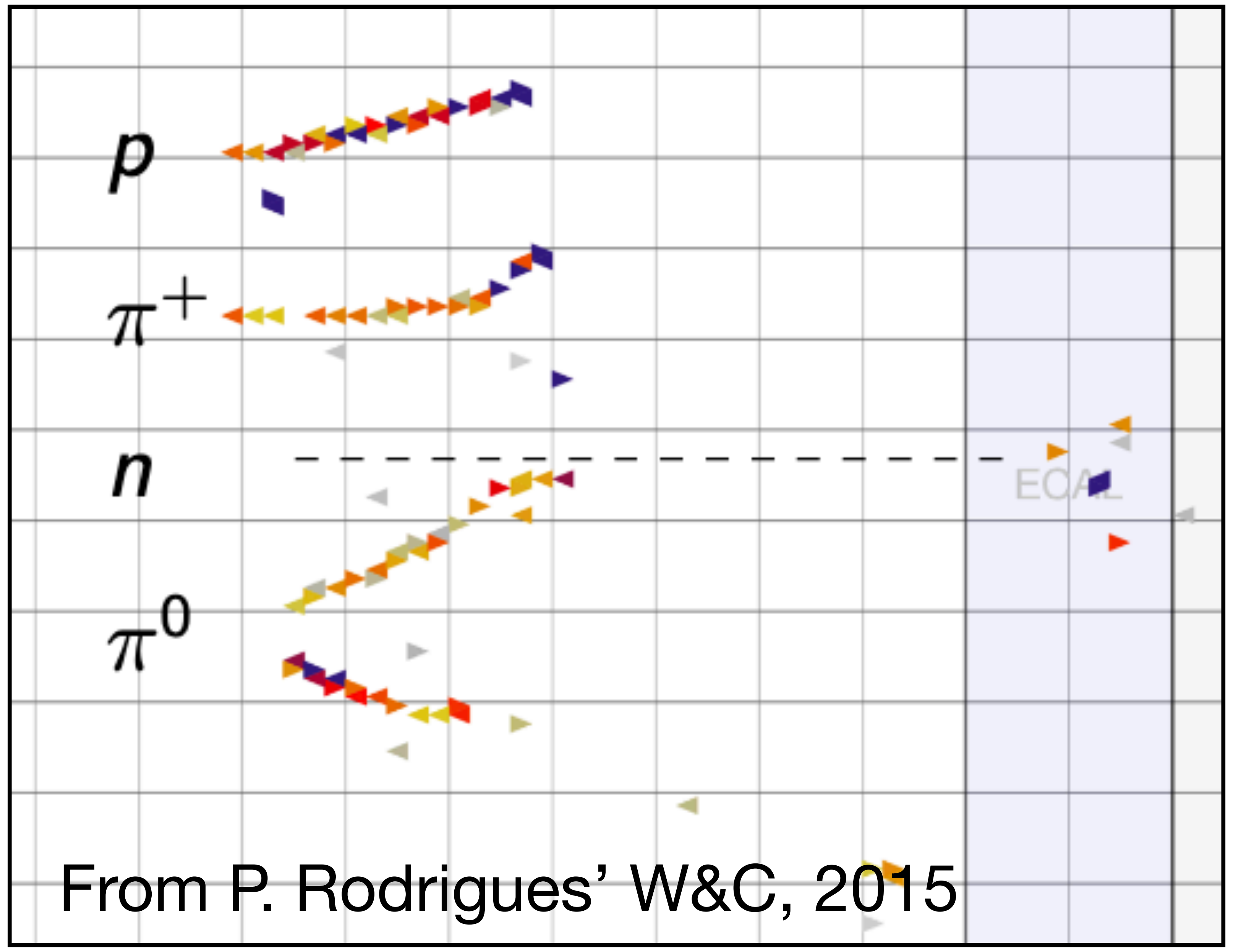
$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - M_\mu^2$$

$$q_3 = \sqrt{Q^2 + q_0^2}$$

q_3 : Three momentum transfer

q_0 : Energy transfer

Kinematic Definition



From P. Rodrigues' W&C, 2015

$$q_3 = \sqrt{Q^2 + q_0^2}$$

$$E_{\text{avail}} = \sum T_p + \sum T_{\pi^\pm} + \sum E_{\text{particles}}$$ (Except neutrons) ~ q_0

From the calorimetric reconstruction, we start with the detected energy (hadronic visible energy), discounting the neutrons, we define the E_{avail}.

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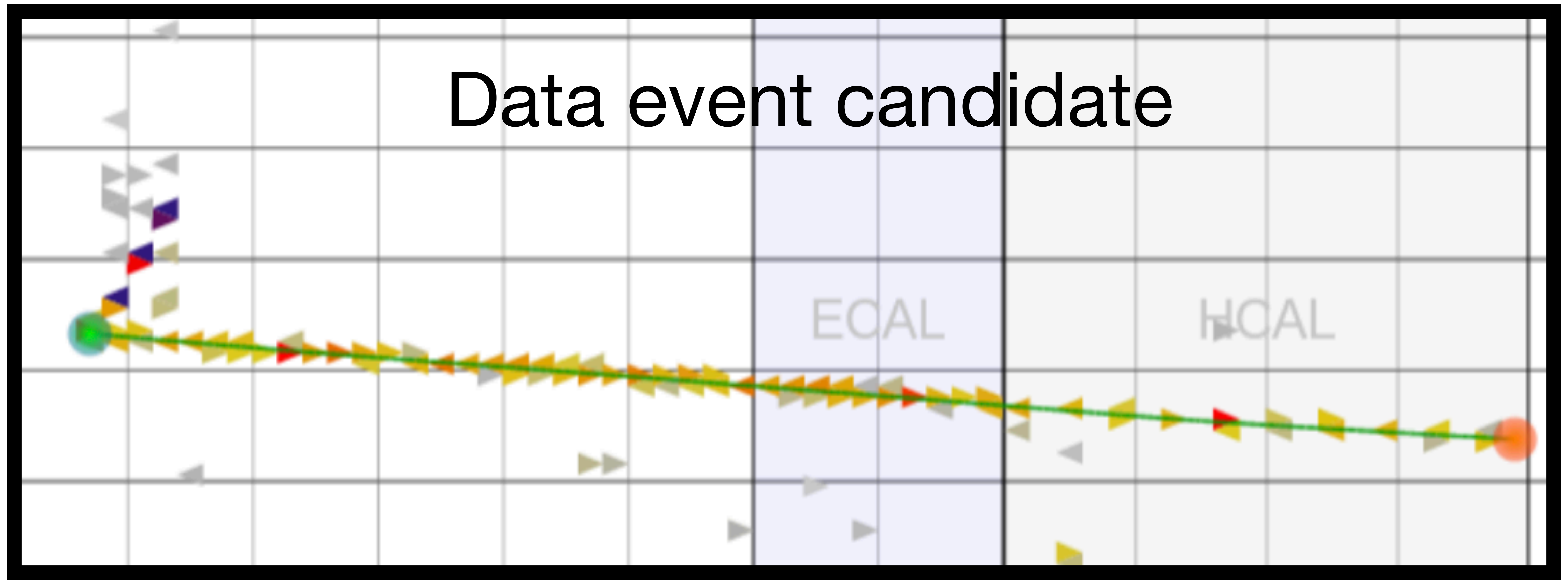
Inclusive charge current at low three-momentum transfer

1. The events should be charged current (CC)
2. The muon scattering angle $\theta_\mu < 20^\circ$
3. The muon momentum should be

$$1.5 < p_\mu < 20.0 \text{ GeV}$$



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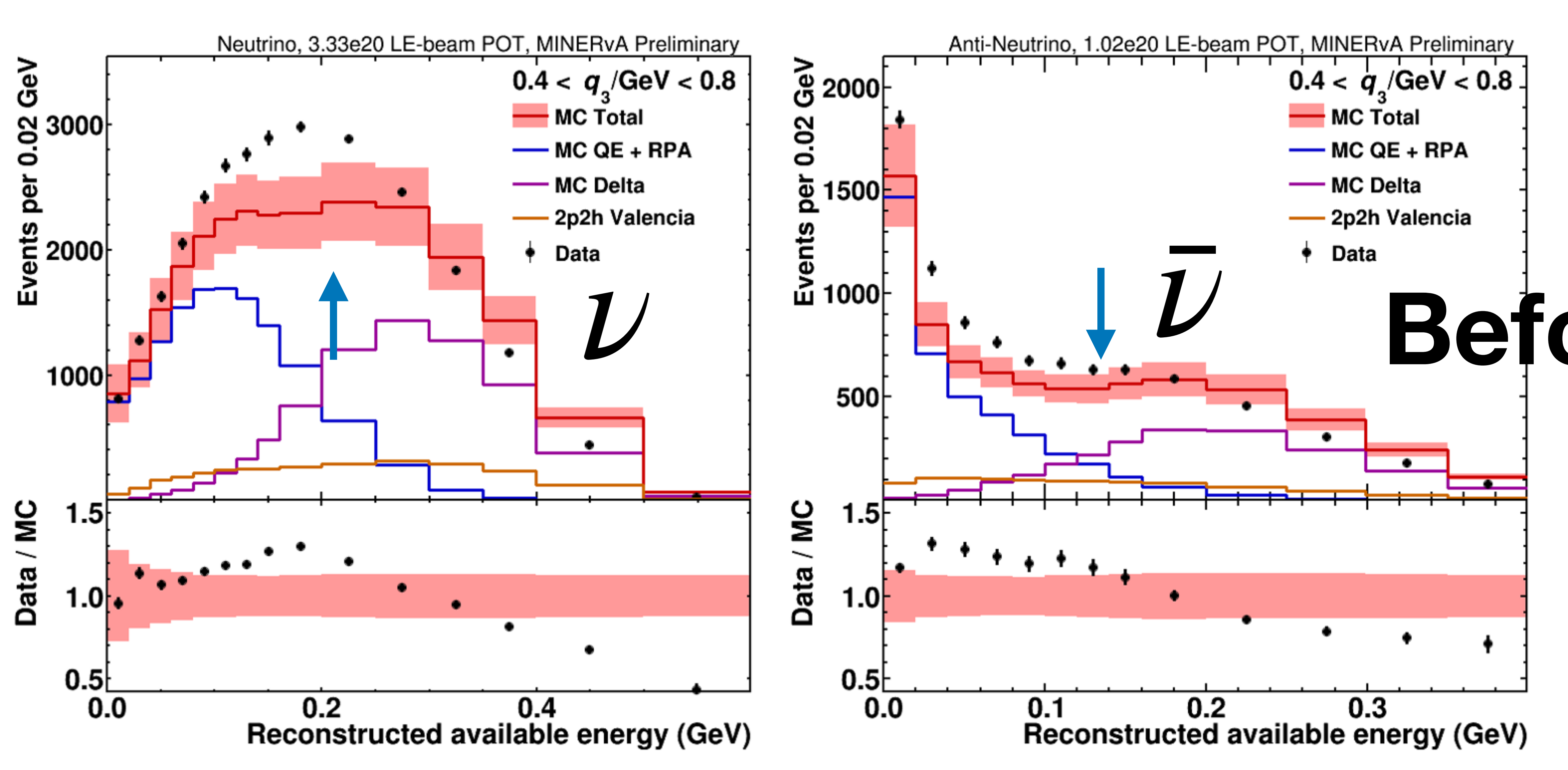
Previous Results (comparison)

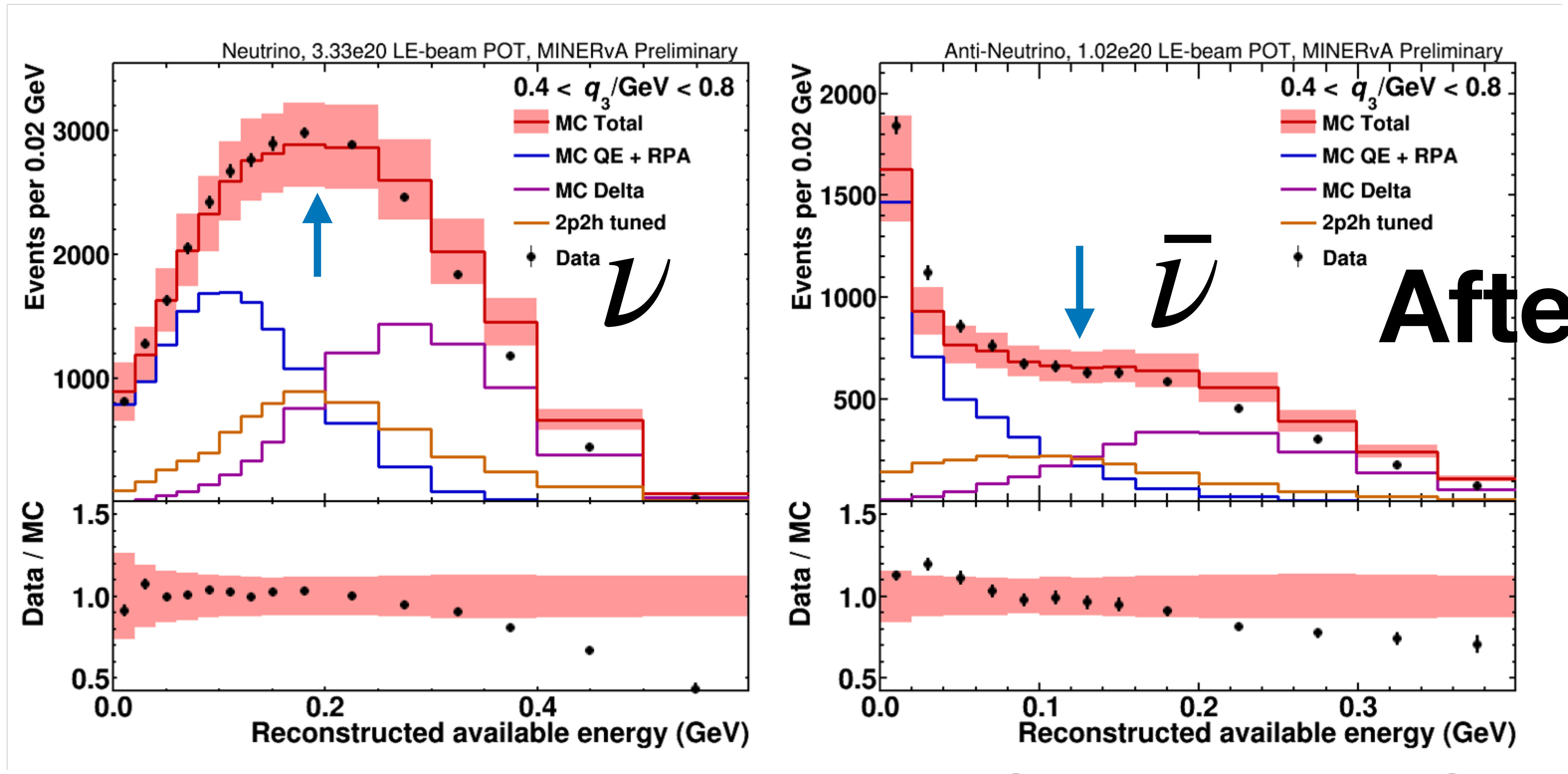
Neutrino/Antineutrino Low Energy



Before tune

- MC Total
- MC QE + RPA
- MC Delta
- 2p2h Valencia
- Data

MINERvA Simulation:
GENIE 2.12.6
QE RPA
Valencia 2p2h
non-resonant pion suppression
Flux correction (ppfx + NuE constraint)



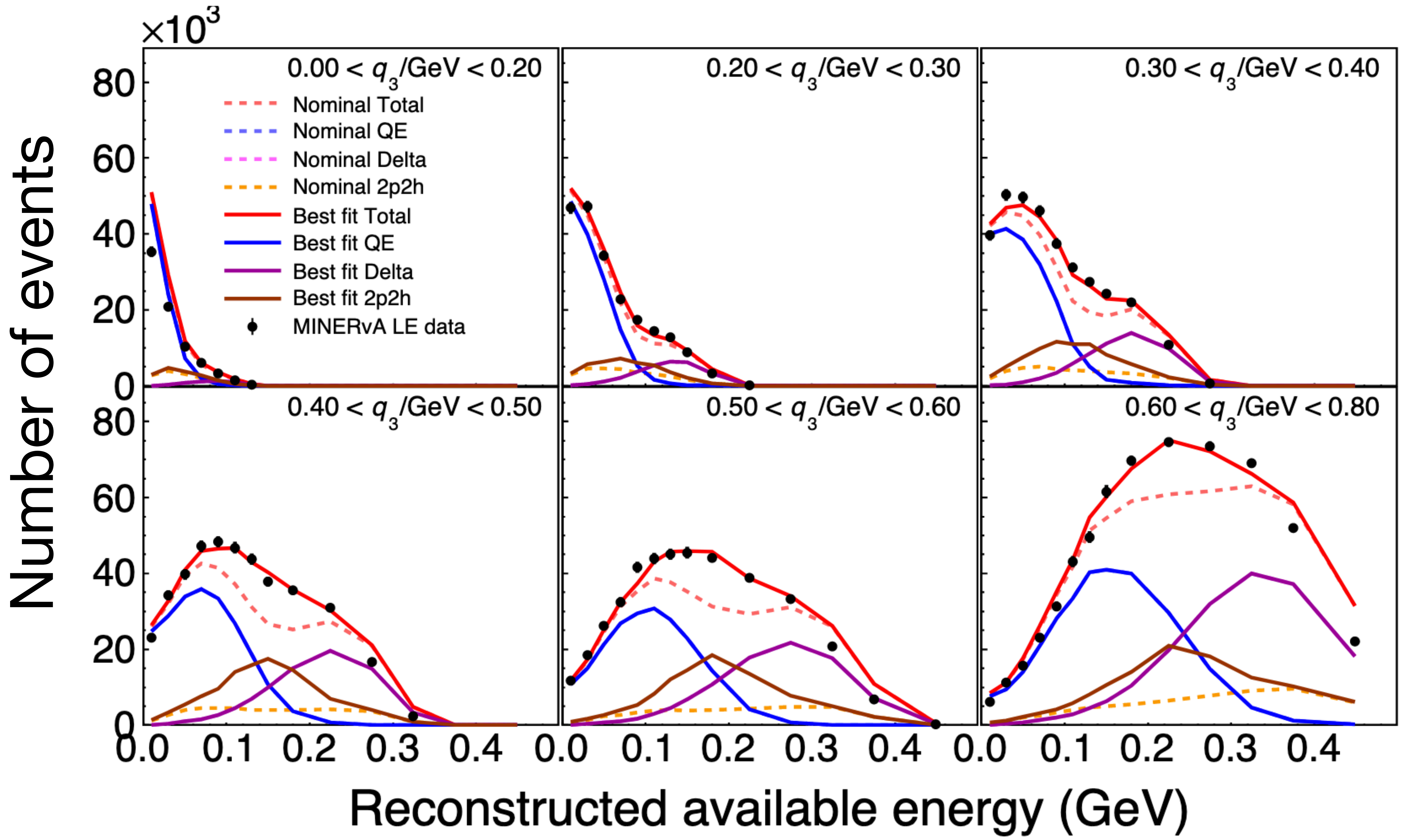
After tune

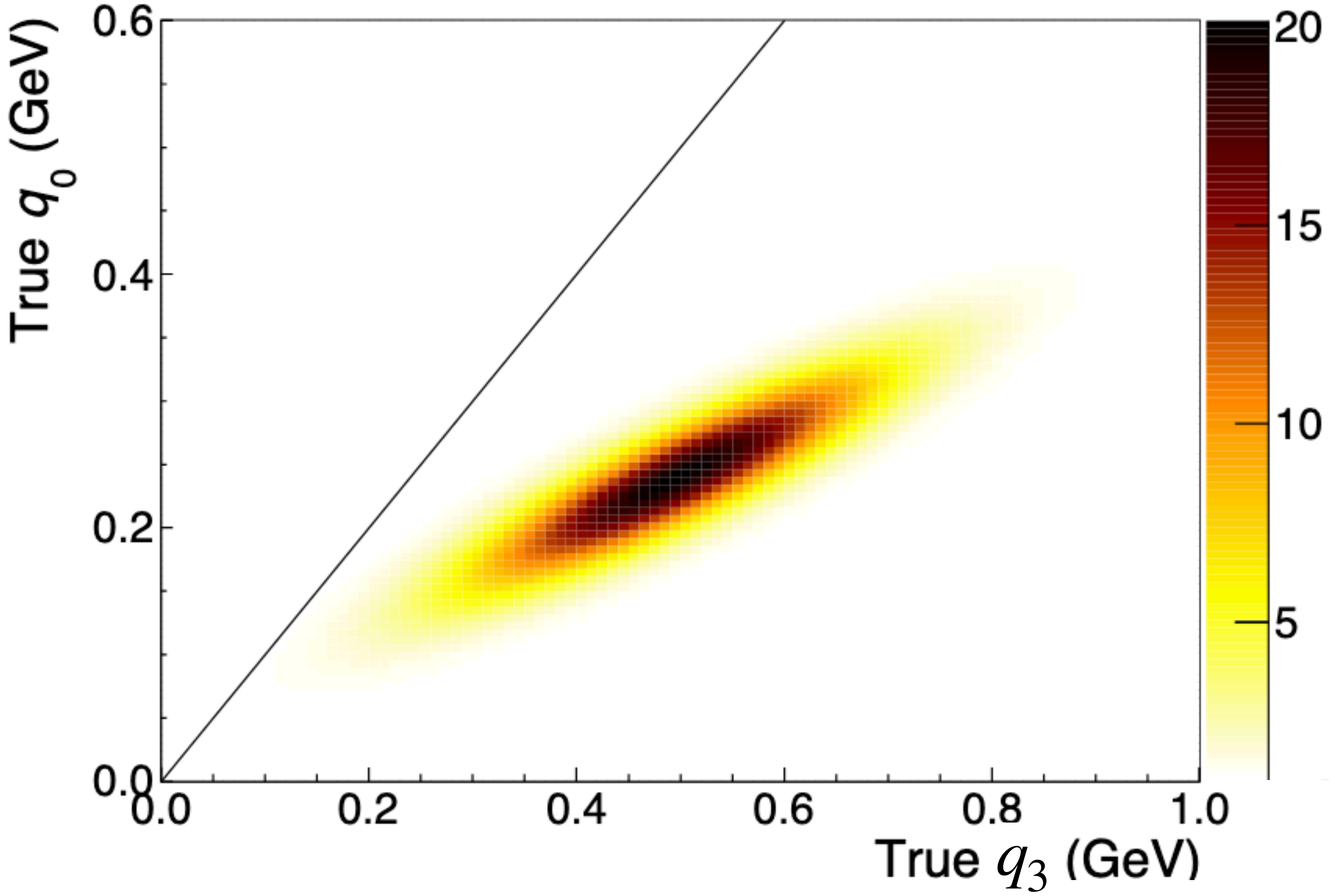
- MC Total
- MC QE + RPA
- MC Delta
- 2p2h tuned
- Data

MINERvA Simulation (**MnvTune v1**):
GENIE 2.12.6
QE RPA
2p2h **tune fit** (on top of Valencia 2p2h)
non-resonant pion suppression
Flux correction (ppfx + NuE constraint)

R. Gran, W&C *** Fit was done in neutrinos and applied to antineutrinos.**

2p2h fit in Low Energy Neutrino Result





The fit is a 2D Gaussian in the true variable (q_3, q_0) applied to 2p2h events only.

The 2p2h events involve initial-states nn or np pairs.

The systematic uncertainty takes the extreme cases reweighing nn pair, np and QE

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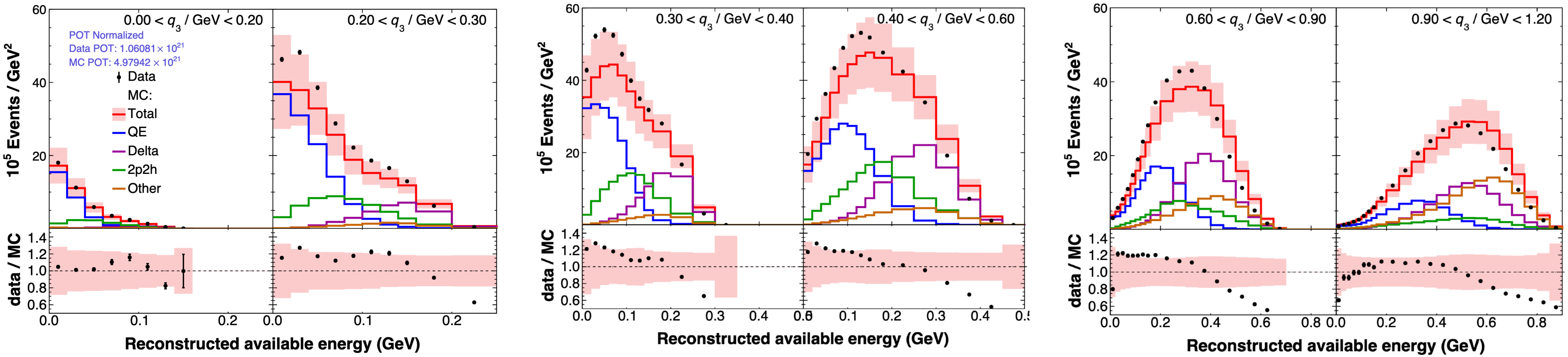
Event Selection - **Medium Energy**

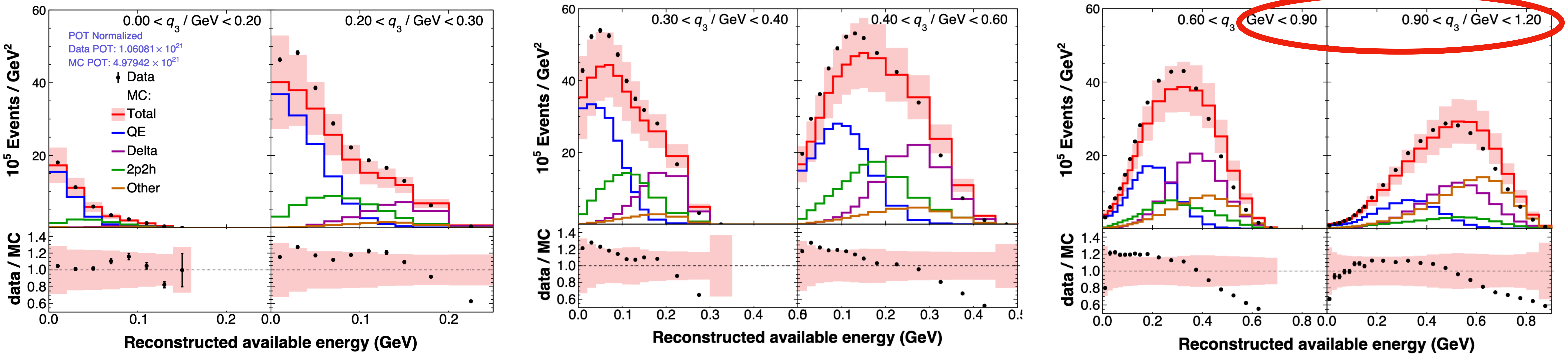


Data
MC:
Total
QE
Delta
2p2h
Other

MnvTune.v1.2 (Monte Carlo)
GENIE 2.12.6
2p2h tune fit (LE) (on top of Valencia 2p2h)
non-resonant pion suppression
QE RPA
Coherent suppression (LE)
Best flux with ppfx + Nu+e constraint

Data sample:
3,390,718 selected events.
74,749 events (Low energy)

Event Selection - Medium Energy



MnvTune.v1.2 (Monte Carlo)

GENIE 2.12.6

2p2h tune fit (LE) (on top of Valencia 2p2h)

non-resonant pion suppression

QE RPA

Coherent suppression (LE)

Best flux with ppfx + Nu+e constraint

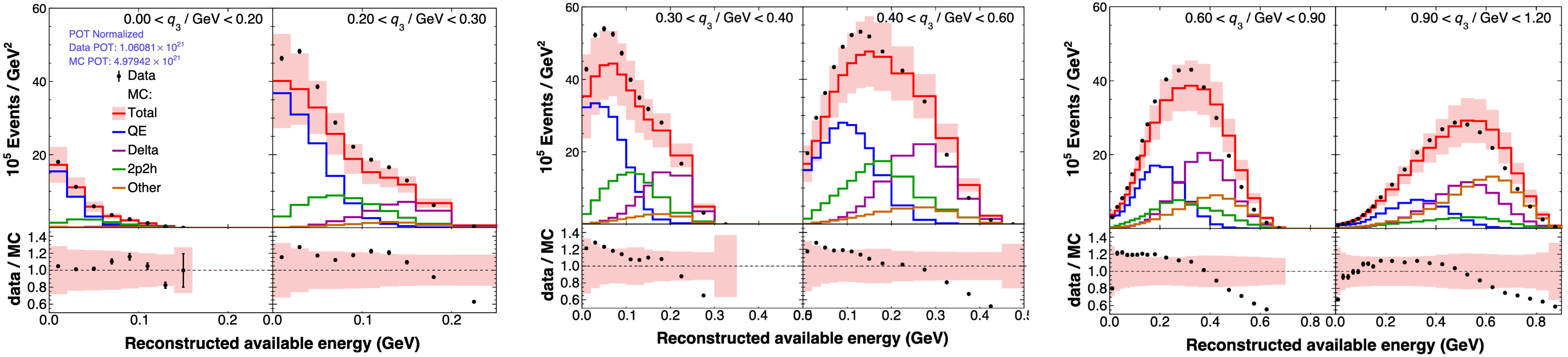
Differences from the LE base model:

We have more bins of q_3.

Estimating the flux, the ME result uses the 12% $\nu + e$ scattering adjustment, compared to 8% in LE.

The 3.6% muon energy scale correction is applied to the ME data.

Event Selection - Medium Energy

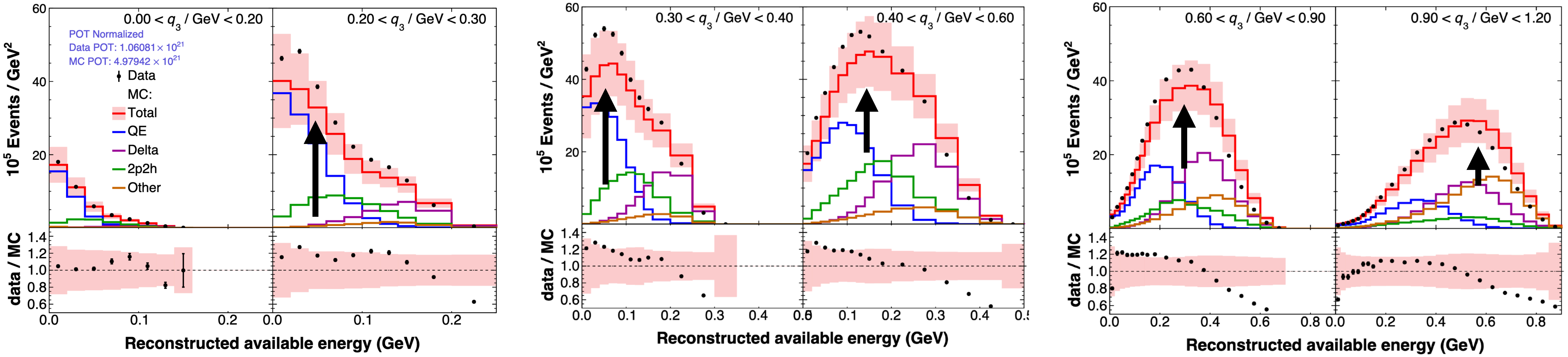


MnvTune.v1.2 (Monte Carlo)
GENIE 2.12.6
2p2h tune fit (LE) (on top of Valencia 2p2h)
non-resonant pion suppression
QE RPA
Coherent suppression (LE)
Best flux with ppfx + Nu+e constraint

Differences from the LE base model:

Overall changes are 10% to 20%in some regions of the sample.

Event Selection - Medium Energy



MnvTune.v1.2 (Monte Carlo)

GENIE 2.12.6

2p2h tune fit (LE) (on top of Valencia 2p2h)

non-resonant pion suppression

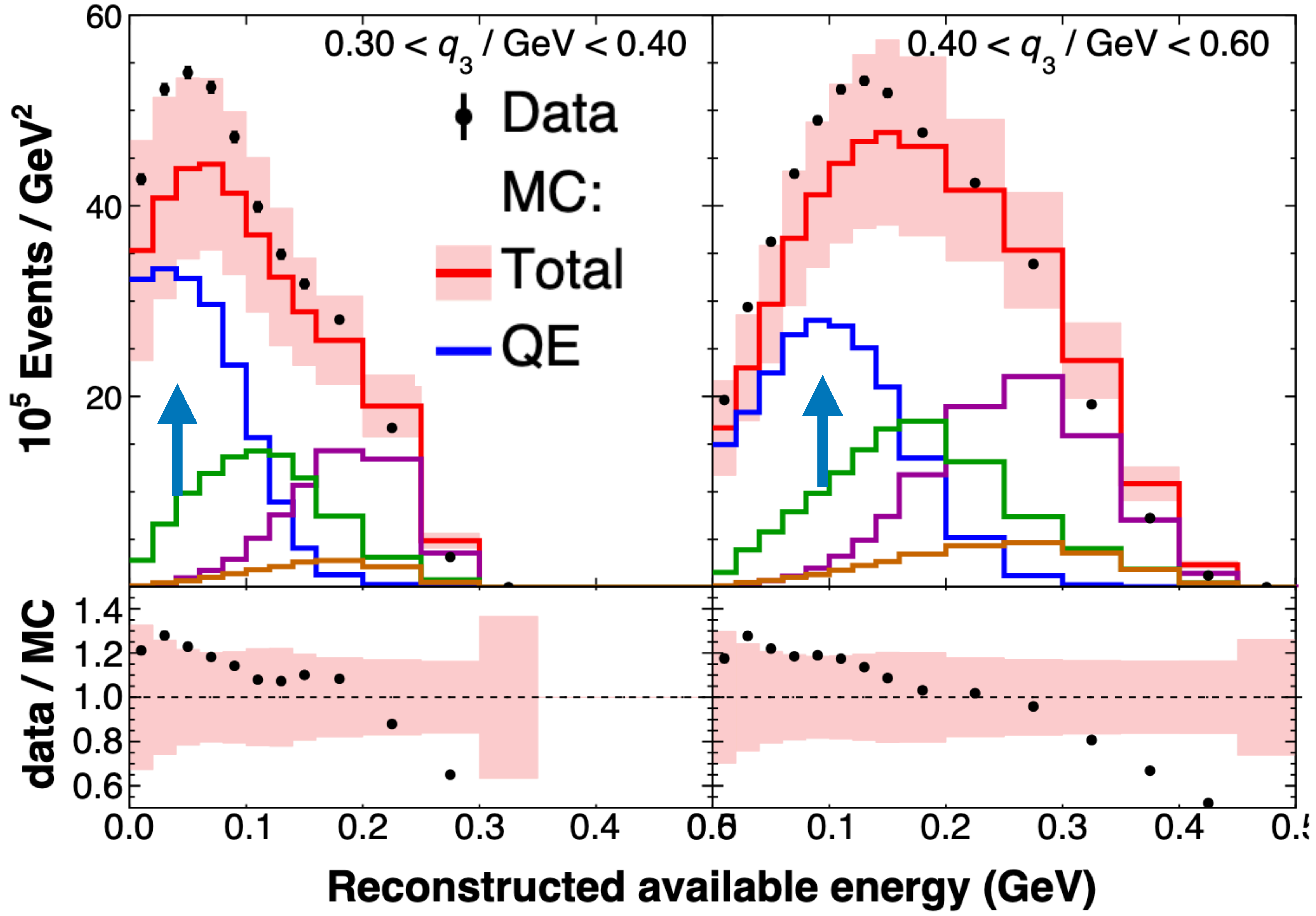
QE RPA

Coherent suppression (LE)

Best flux with ppfx + Nu+e constraint

Even with with the tune
we still have discrepancies
between data and Monte Carlo

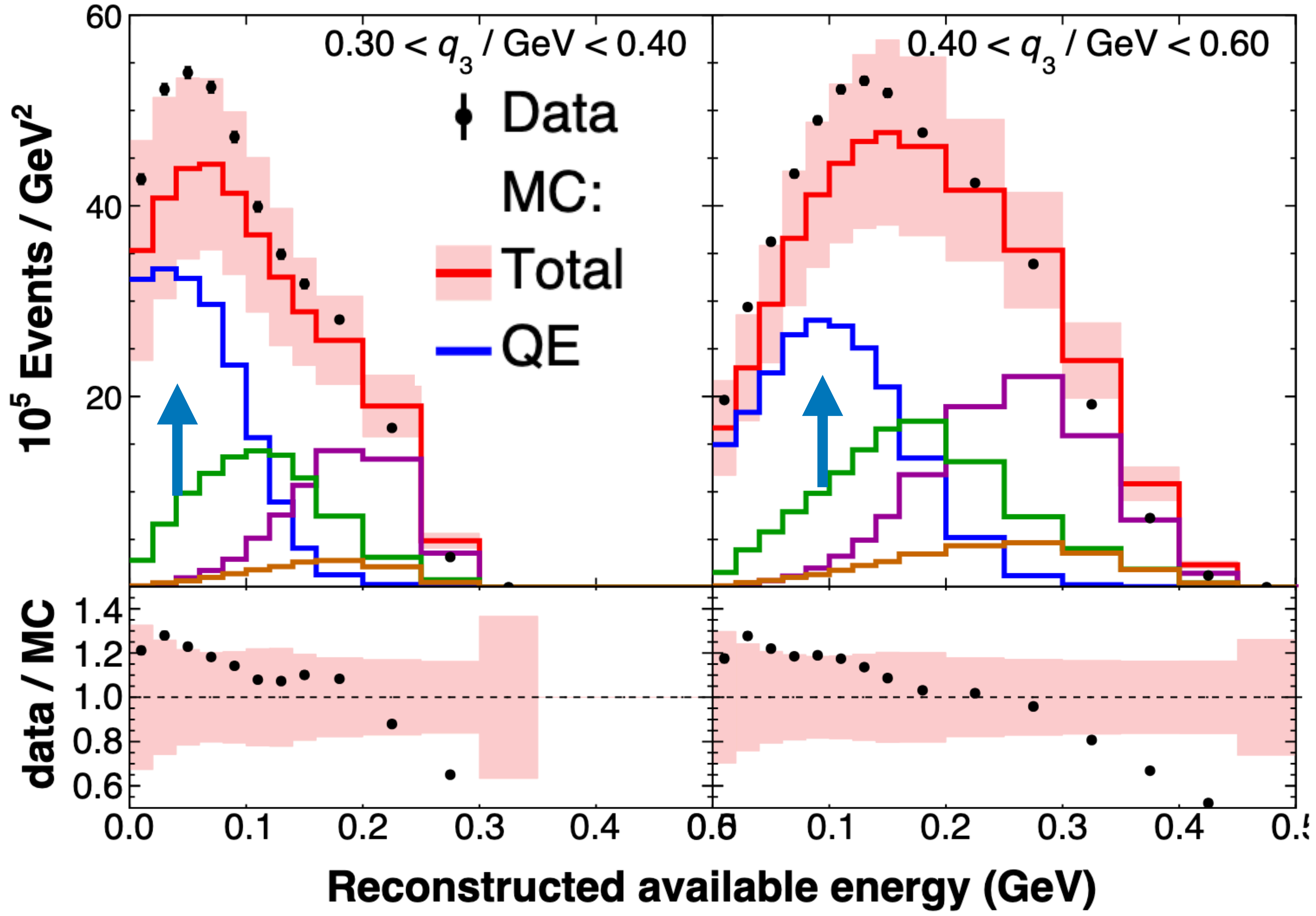
Event Selection - Medium Energy - $0.3 < q_3$ GeV < 0.6



Which component needs to be improved to have a better data-MC agreement?

Quasi-elastic region

Event Selection - **Quasi-elastic Region**



QE process is ~symmetric.

The spread comes
from the initial momentum of the struck nucleon.

Which component needs to be improved to have a better data-MC agreement?

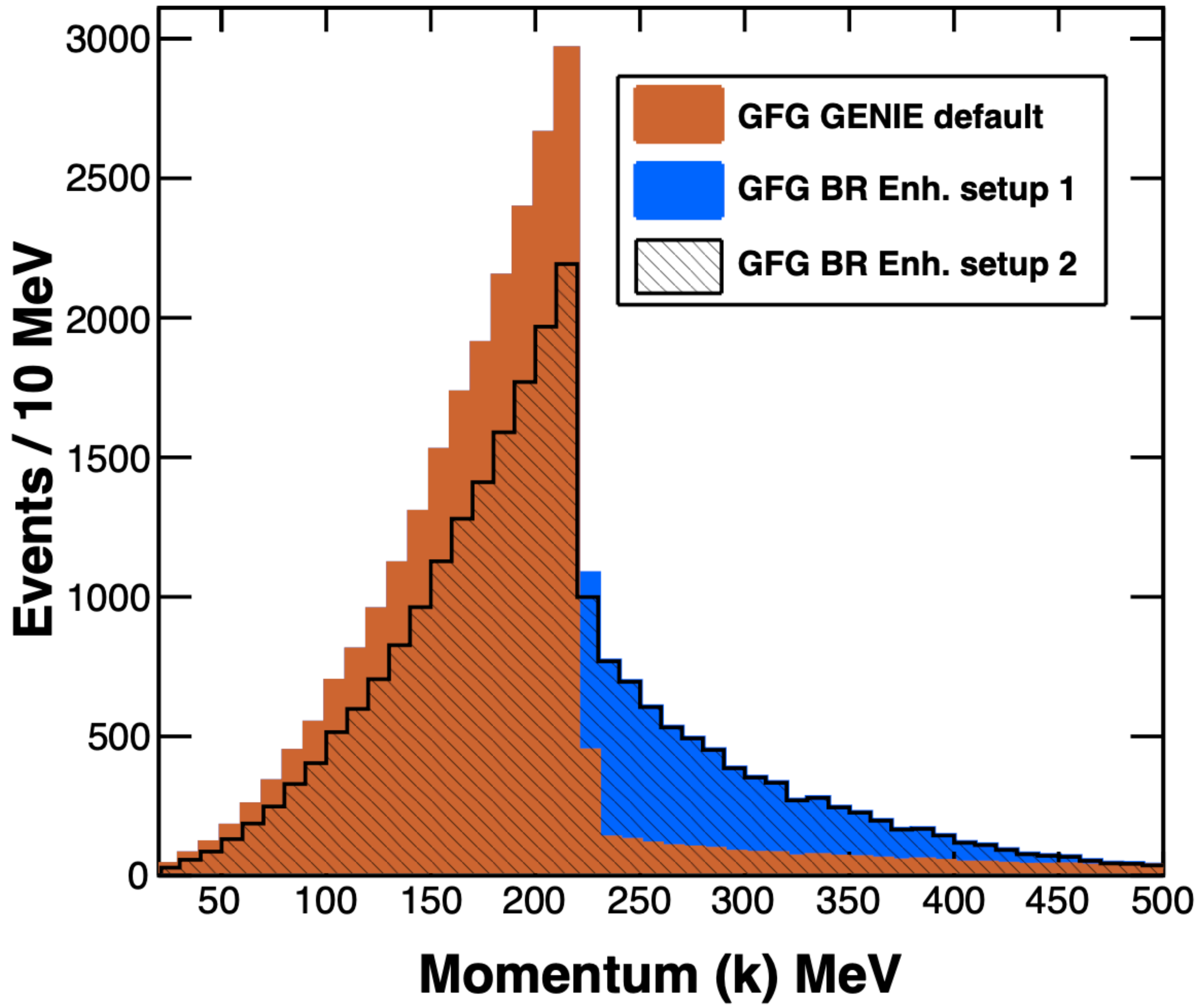
Quasi-elastic region

Several theoretical approaches describe a tail to this distribution at higher energy transfer that will populate the dip region.

One way to enhance the QE events in the dip regionis to explicitly enhance events where the struck nucleon had unusually high momentum.

Study on **Quasi-elastic Region**

Bodek-Ritchie Tail Enhancement



Enhancement (24%) to the
initial nucleon momentum from 221 to 500 MeV

Which component needs to be improved to have a better data-MC agreement?

Quasi-elastic region

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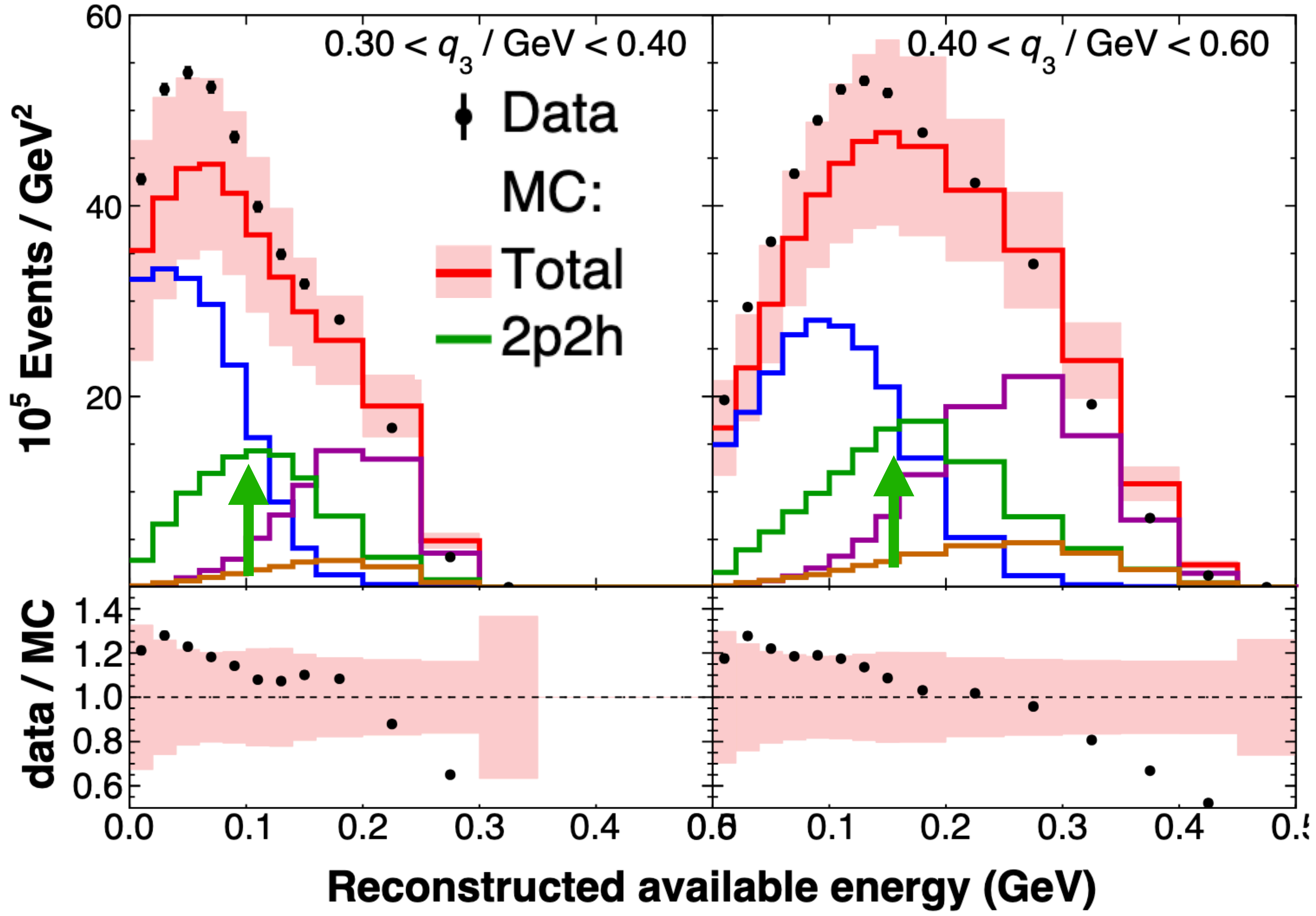
Event Selection - **2p2h Region**



The MC is MnvTune-v1.2
2p2h: Valencia 2p2h + 2p2h tune

We used an empirical tune.
Is there another 2p2h model on the market?

2p2h region

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Study on **2p2h Region**

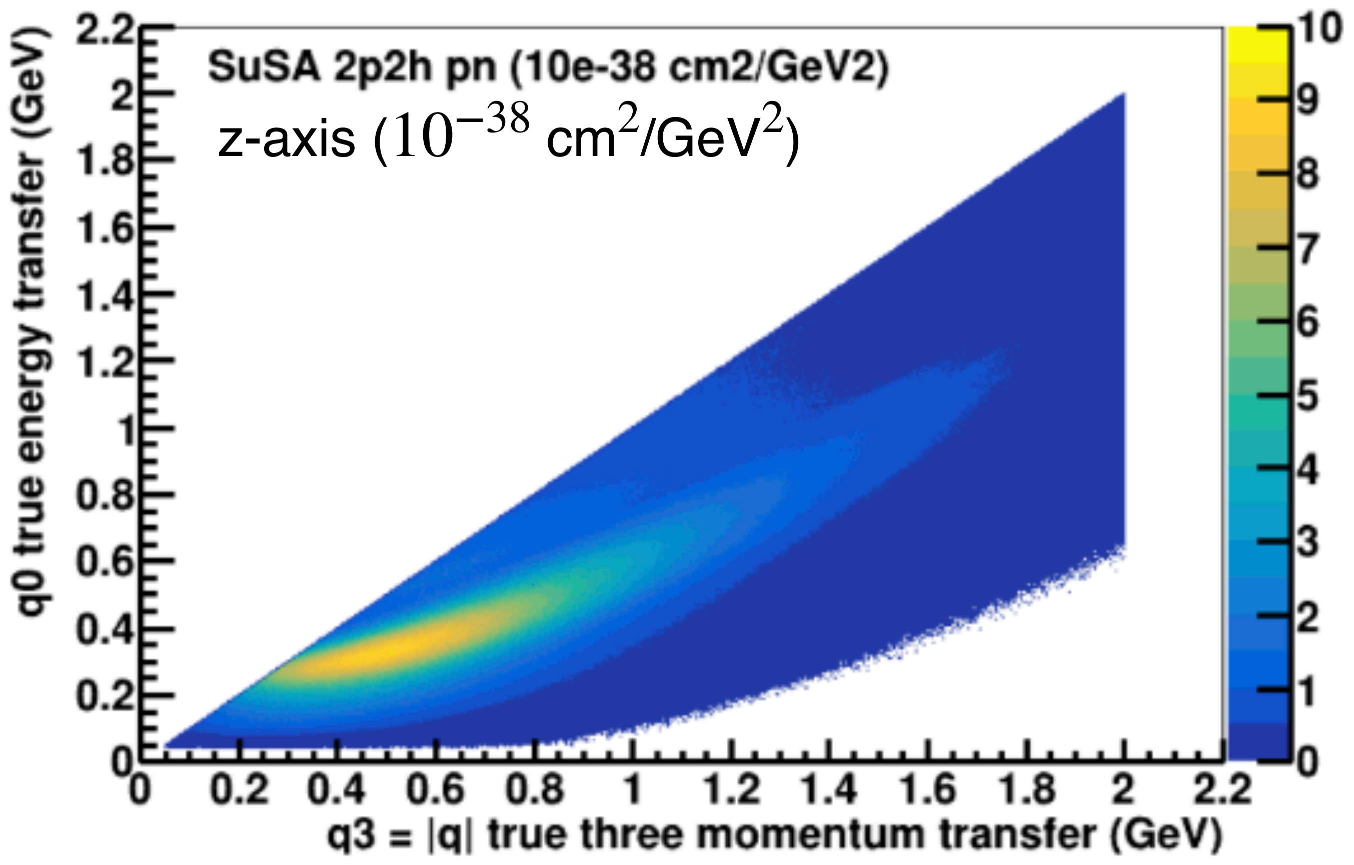
SuSAv2 2p2h uses the RFG as a nuclear model, and it is fully relativistic.

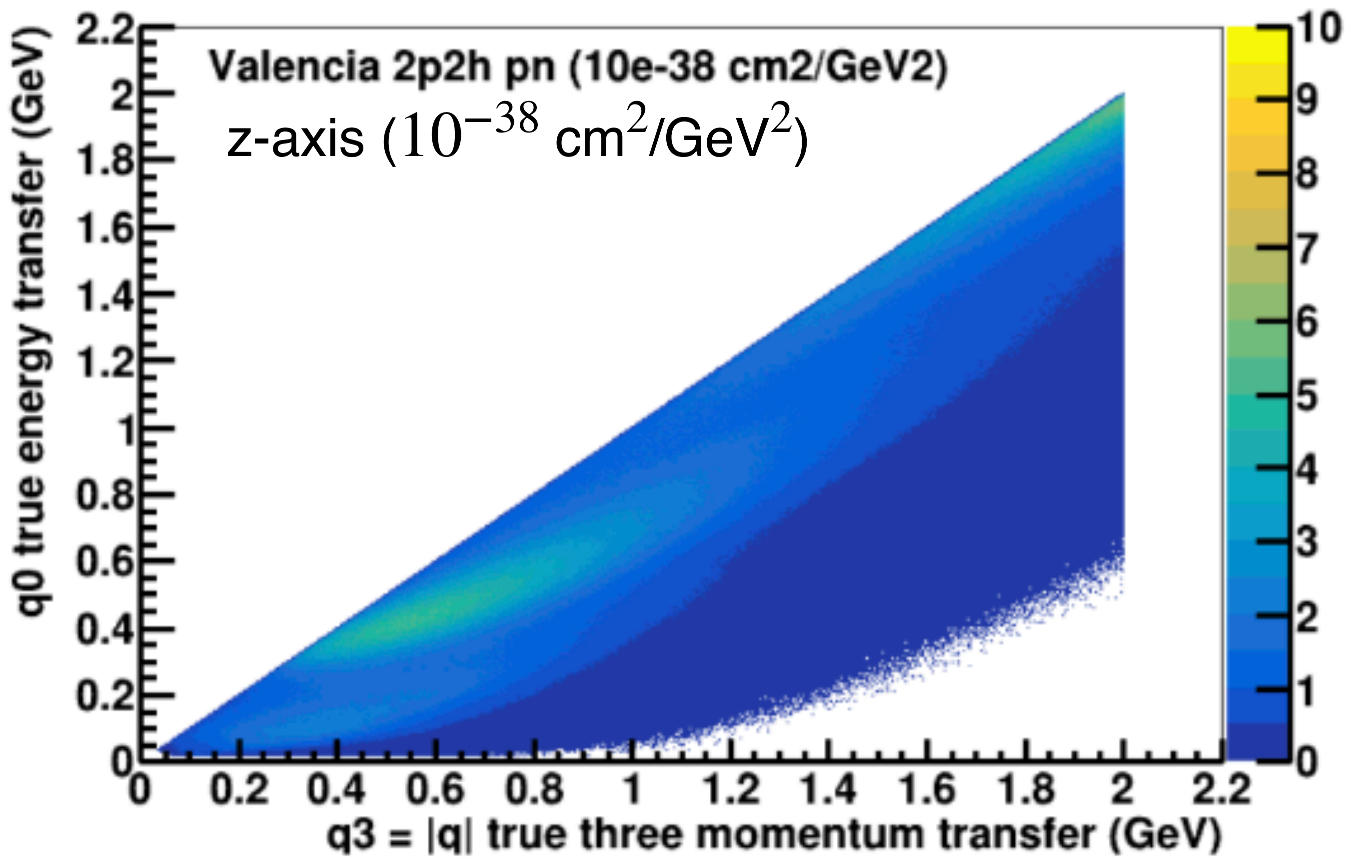
Has new terms like the axial MEC operator and five nuclear response functions.

<u>Valencia and SuSAv2 2p2h:</u>

SuSAv2 2p2h: Real part of the Delta propagator in the 2p2h pion-exchange diagrams (avoid double counting).

Valencia: Partial real and Imaginary and rho resonances.

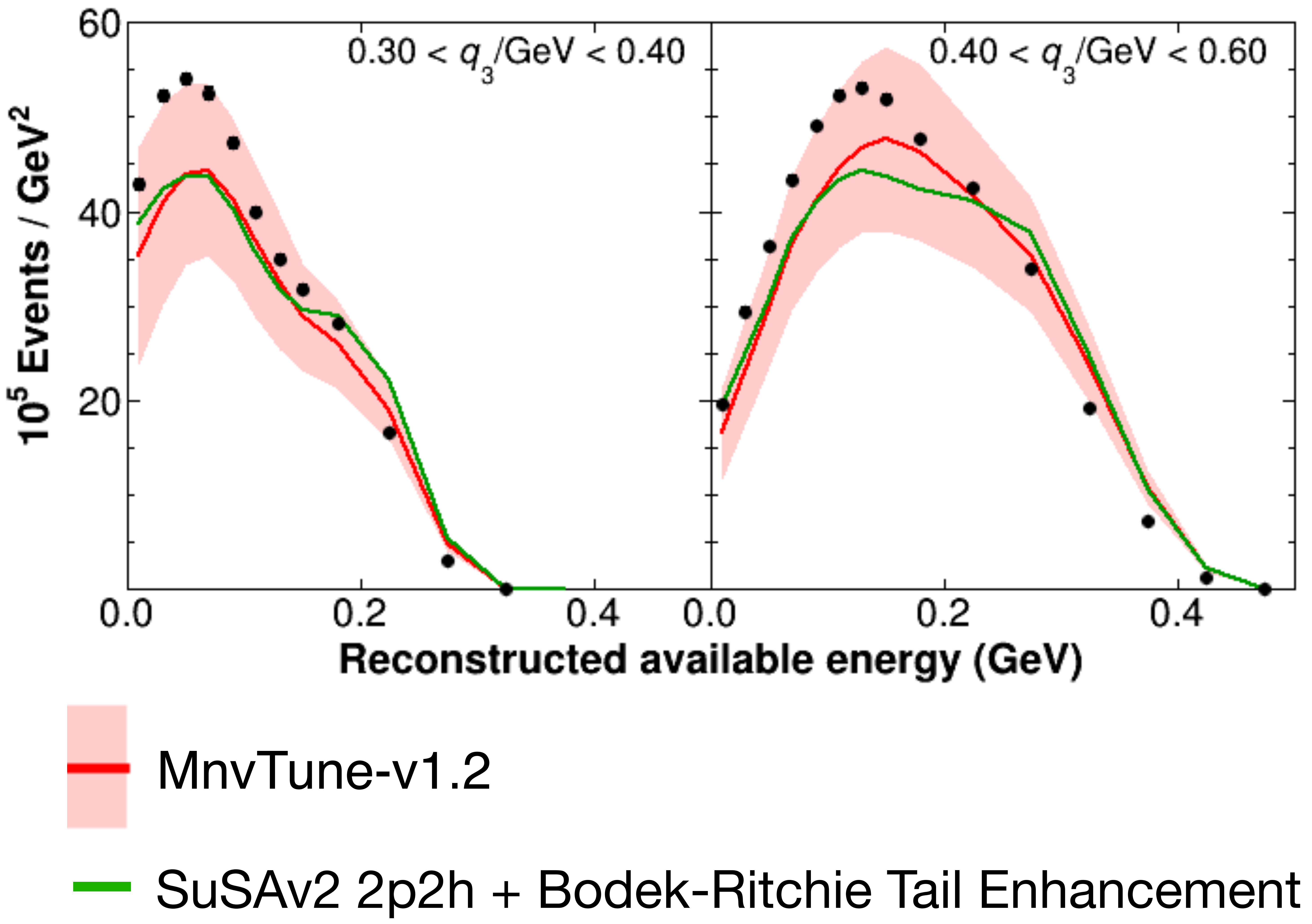




SuSAv2 enhances the dip region
Valencia 2p2h tend to enhance the Delta Region

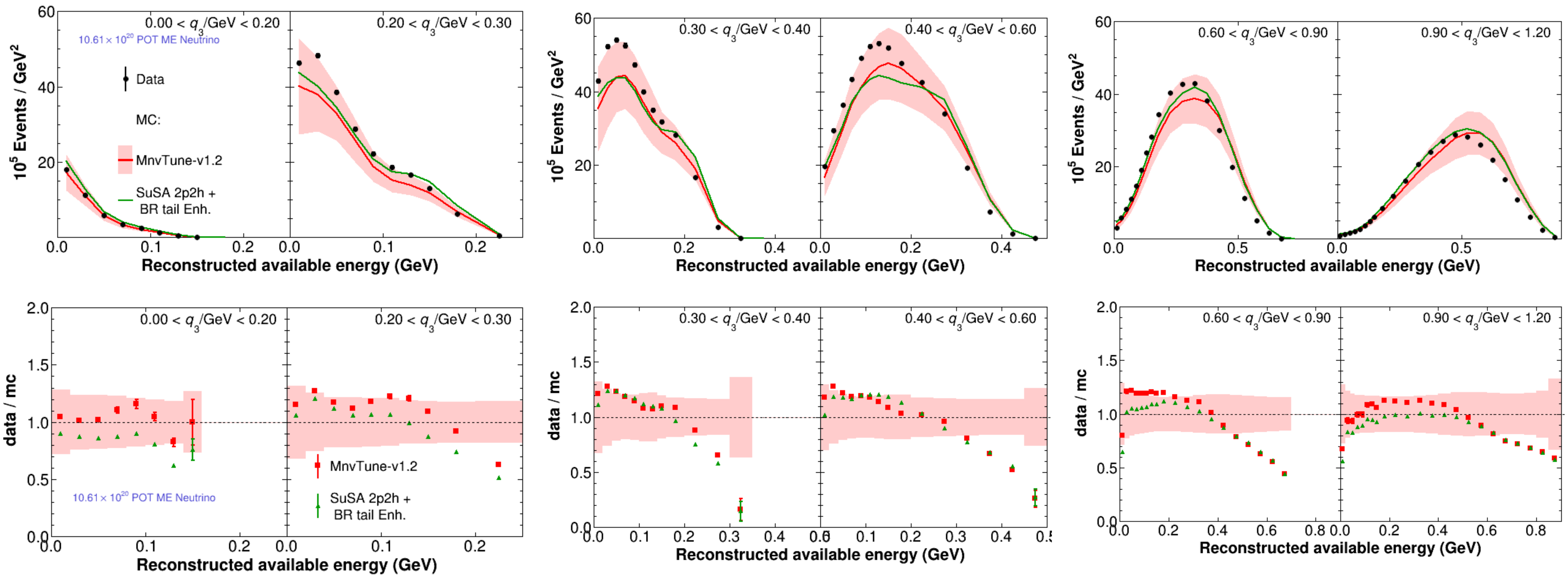
For the reweighing, the Valencia 2p2h was extended up to 2 GeV

Bodek-Ritchie Tail Enhancement with SuSAv2 2p2h



Both combinations to the dip region almost reach the MINERvA 2p2h tune making a good candidate to use as new central value.

Bodek-Ritchie Tail Enhancement with SuSAv2 2p2h



The improvement is better in high q3 regions (0.6 to 1.2 GeV)

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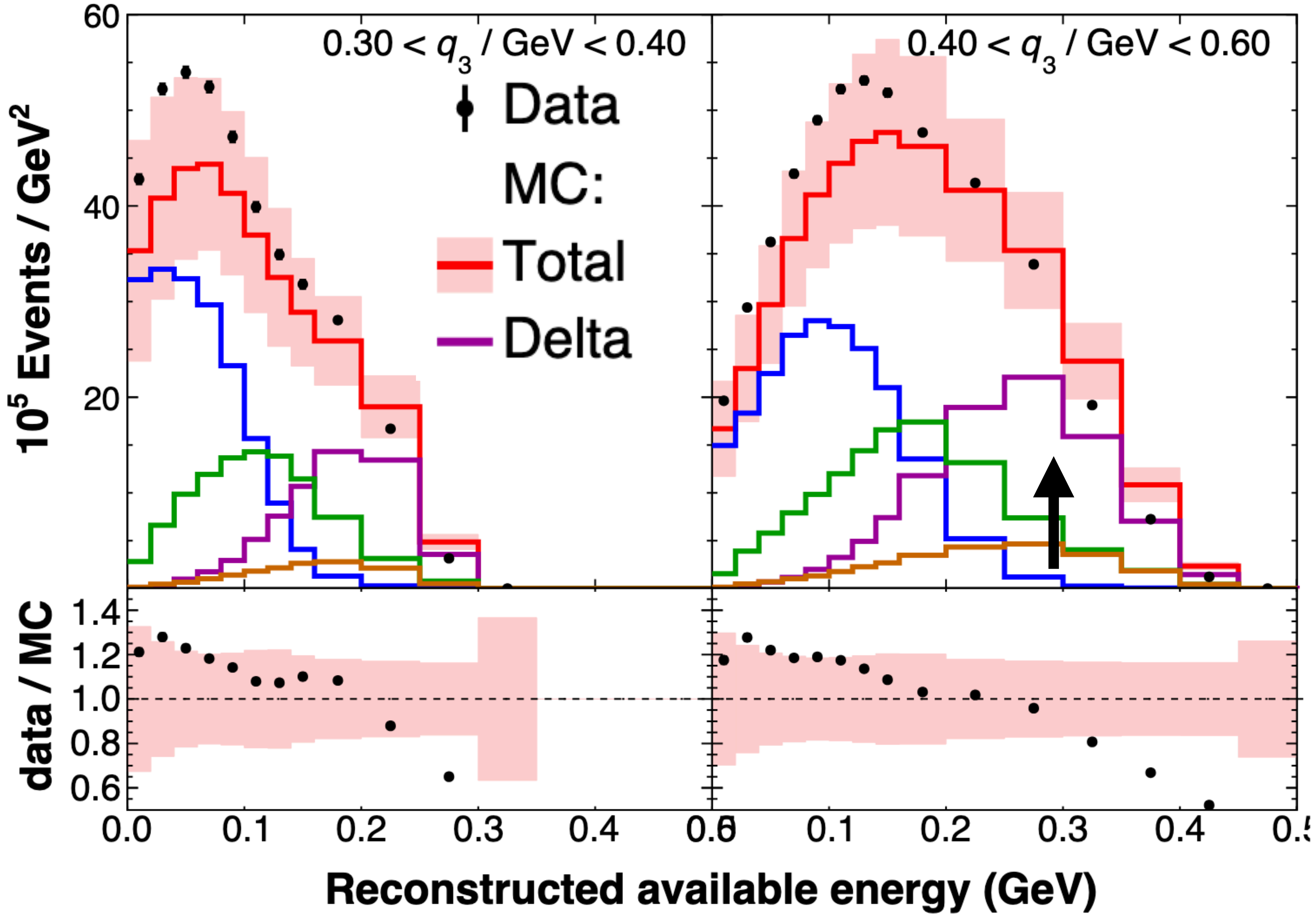
Event Selection - **Resonant region**



Removing 25 MeV
to the Eavail

Which component needs to be improved to have a better data-MC agreement?

Resonant region

3rd way to add event on the dip region

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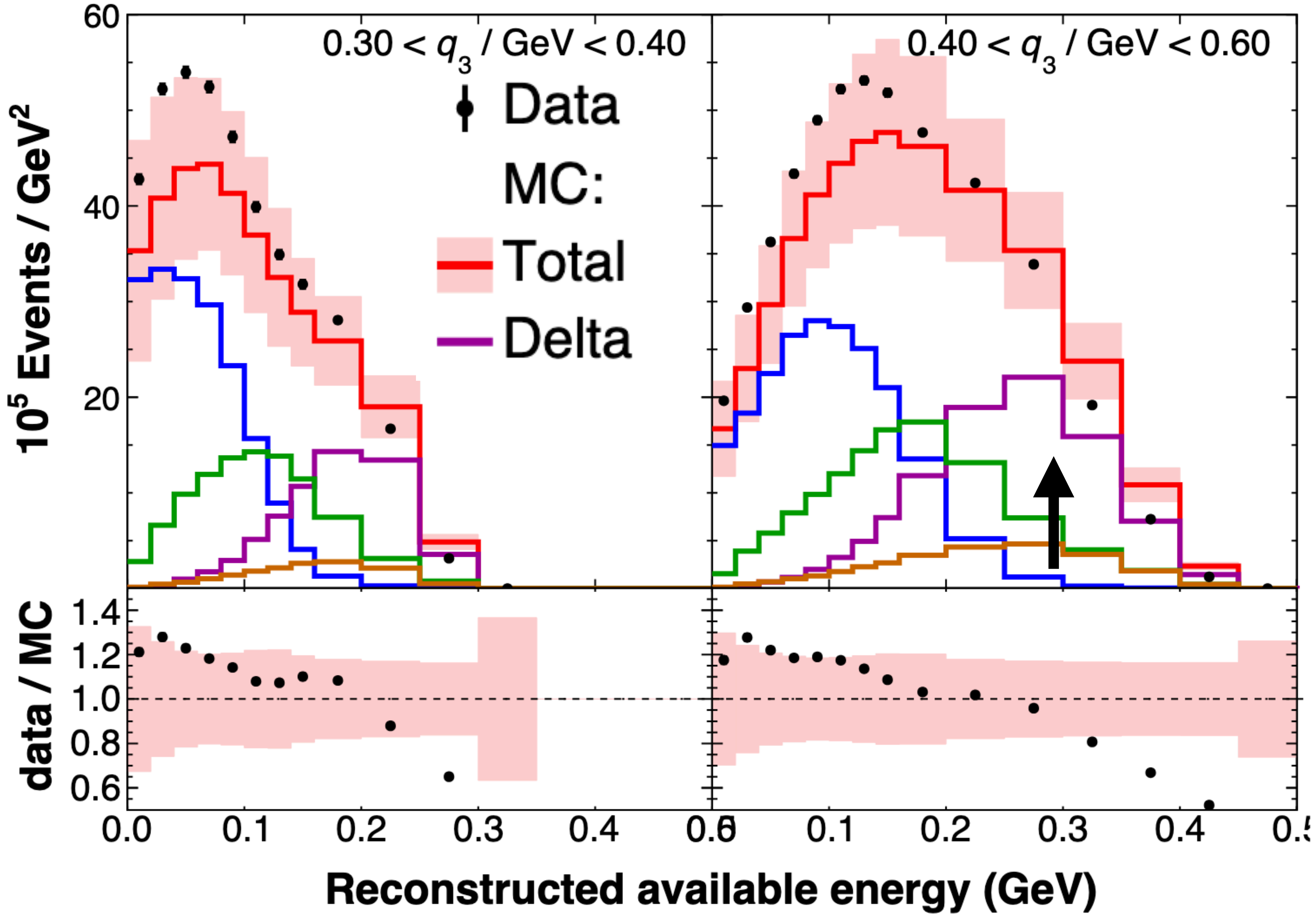
Event Selection - Resonant region



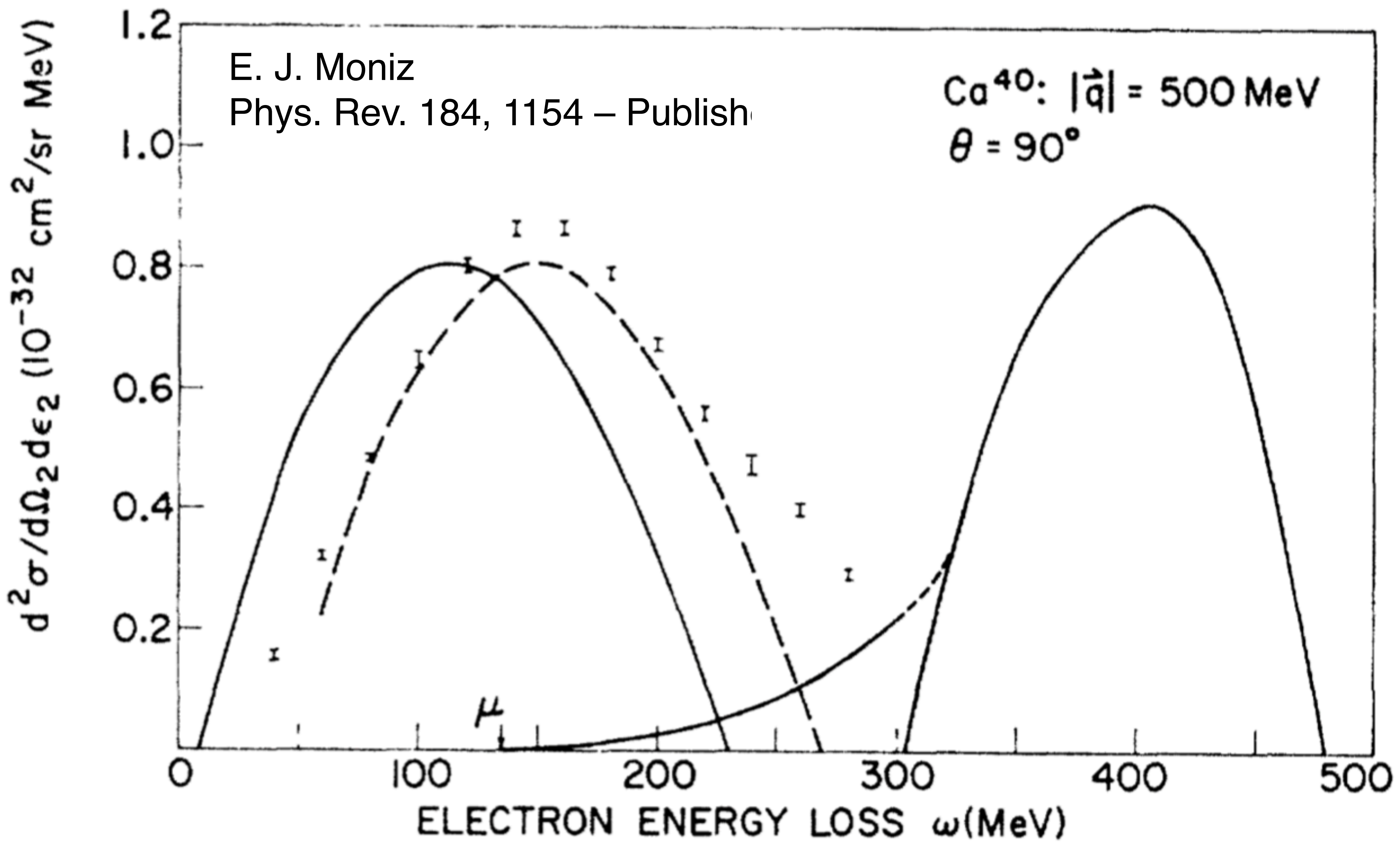
Removing 25 MeV
to the Eavail

Which component needs to be improved to have a better data-MC agreement?

Resonant region

3rd way to add event on the dip region

Resonant removal Energy
(inspired by QE removal energy)



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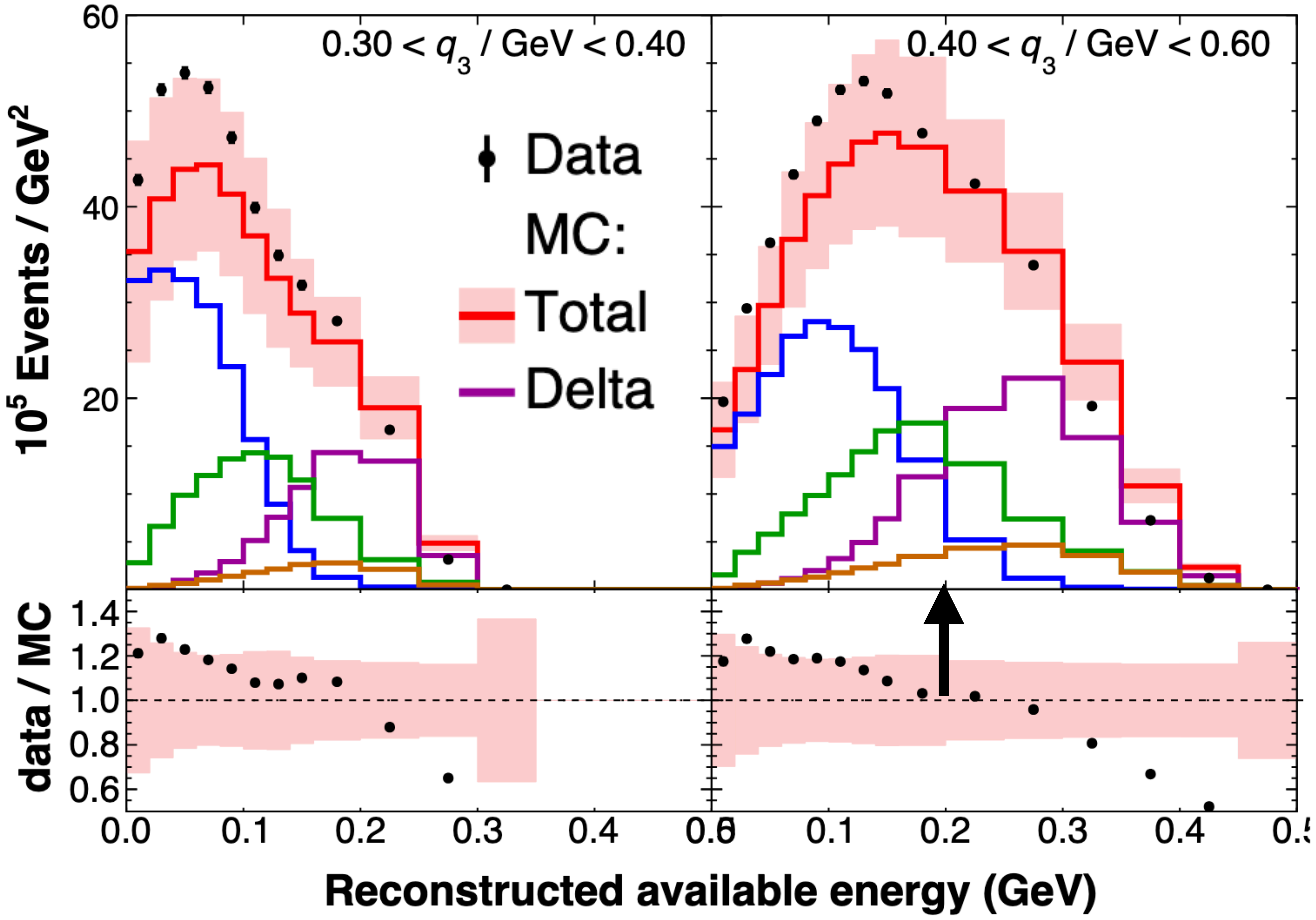
Event Selection - Resonant region



Other models and tunes tested in the resonant region:

- Low Q^2 Pion Suppression (#).
- Minoo Kabirnezhad Model (*).
- Berger-Sehgal with Pauli Blocking.

Low Q2 Pion Supp
(From LE analysis)

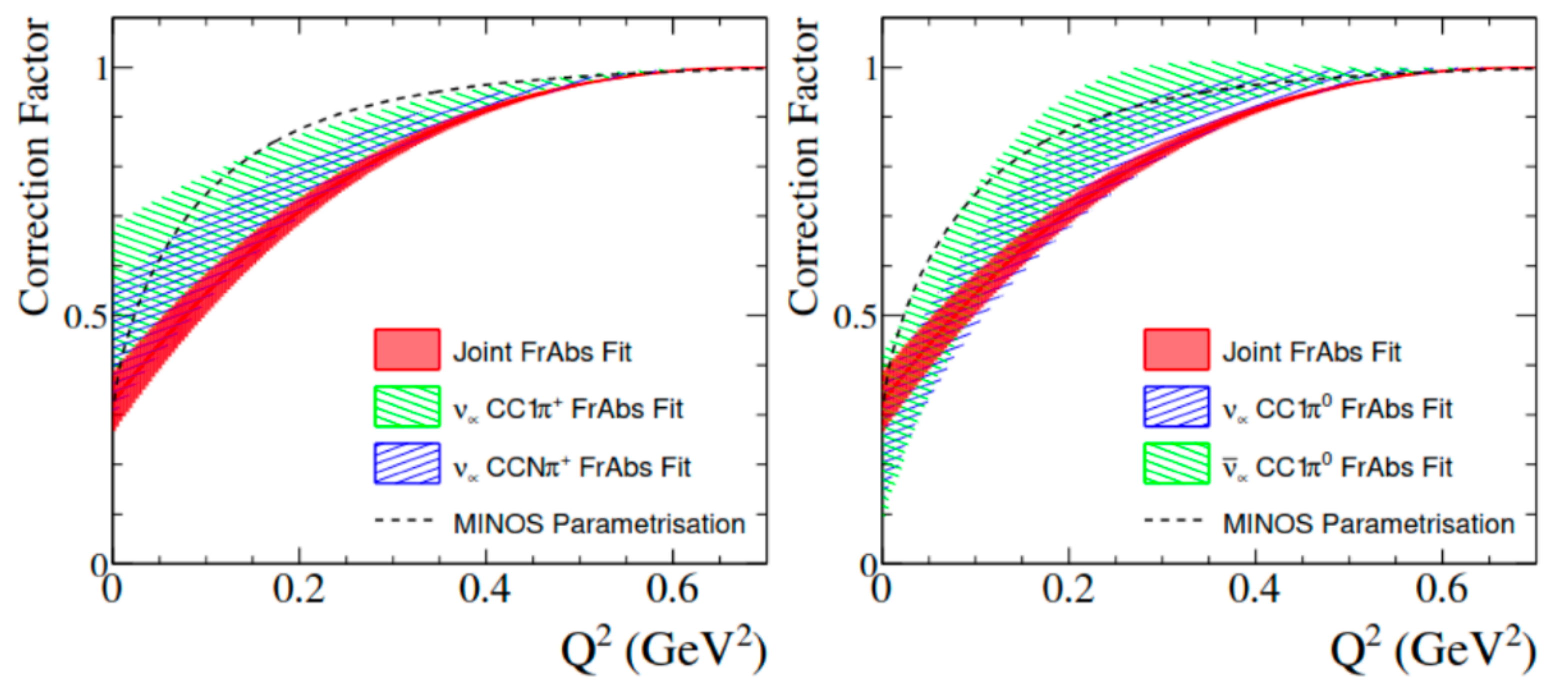
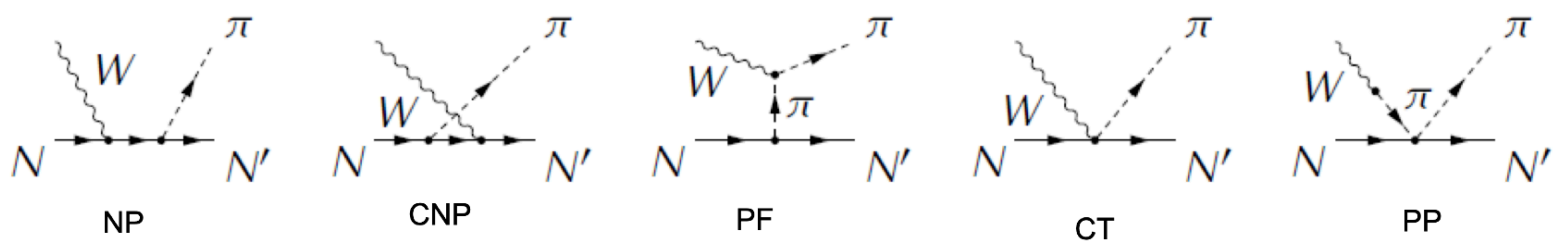


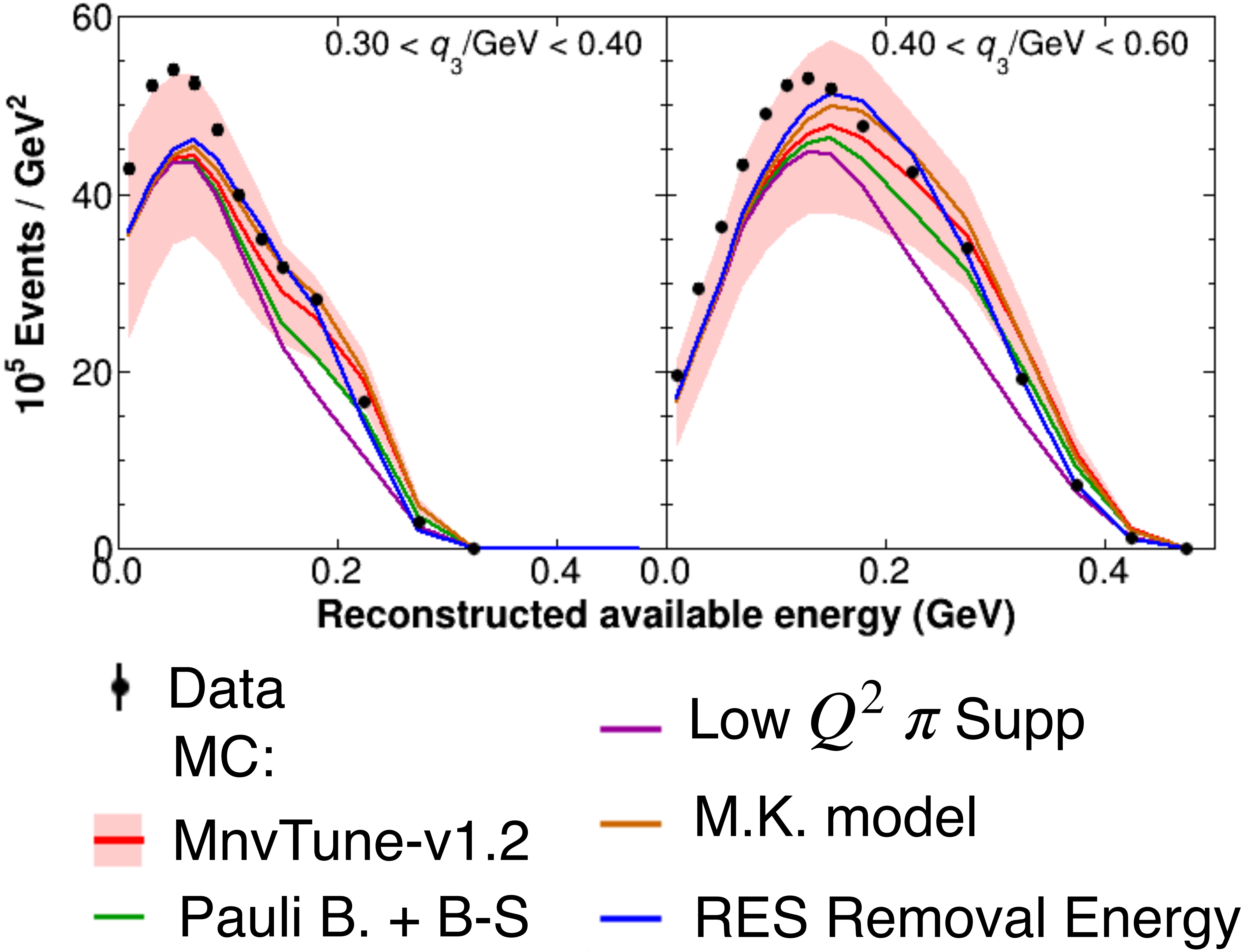
Fig. from (#)

MK (non-res π production):



* M. Kabirnezhad, Phys. Rev. D 97, 013002 (2018)
# P. Stowell et al. (MINERvA Collaboration) Phys. Rev. D 100, 072005

Models/tunes to the resonant region at reconstructed level



The model/tunes are compared with MnvTune-v1.2

The q3 region showed has the best improvement coming from RES Removal Energy.

Other models like MK, also agrees with the MC at high Eavail

Models/tunes to the resonant region at reconstructed level

Comparison along all the q3 regions shows a better agreement with RE.
At high Eavail, the low statics makes large data points.

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Defining new central value: **MnvTune-v3**

MnvTune-V3

GENIE 2.12.6

QE RPA

Bodek-Ritchie Tail Enhancement

SuSAv2 2p2h

non-resonate pion suppression

Coherent suppression (LE)

RES Removal energy

Flux correction (ppfx + NuE constrain)

Data
MC:
Total (MnvTune-v1.2)
Total (MnvTune-v3)
QE
Delta
2p2h
Other
Data/MnvTune-v1.2
Data/MnvTune-v3

Theory-motivated changes.
Replacing 2p2h tune with SuSAv2 2p2h.

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Cross-section extraction

Unfolding matrix

Reconstructed distribution

Background distribution

$$\frac{d^2\sigma}{dE_{\text{avail}}dq_3} = \frac{\sum U_{ij\alpha\beta}\left(N_{\text{data, }ij} - N^{\text{bkgd}}_{\text{data, }ij}\right)}{A_{\alpha\beta}(\Phi T)(\Delta E_{\text{avail}}\Delta q_3)}$$

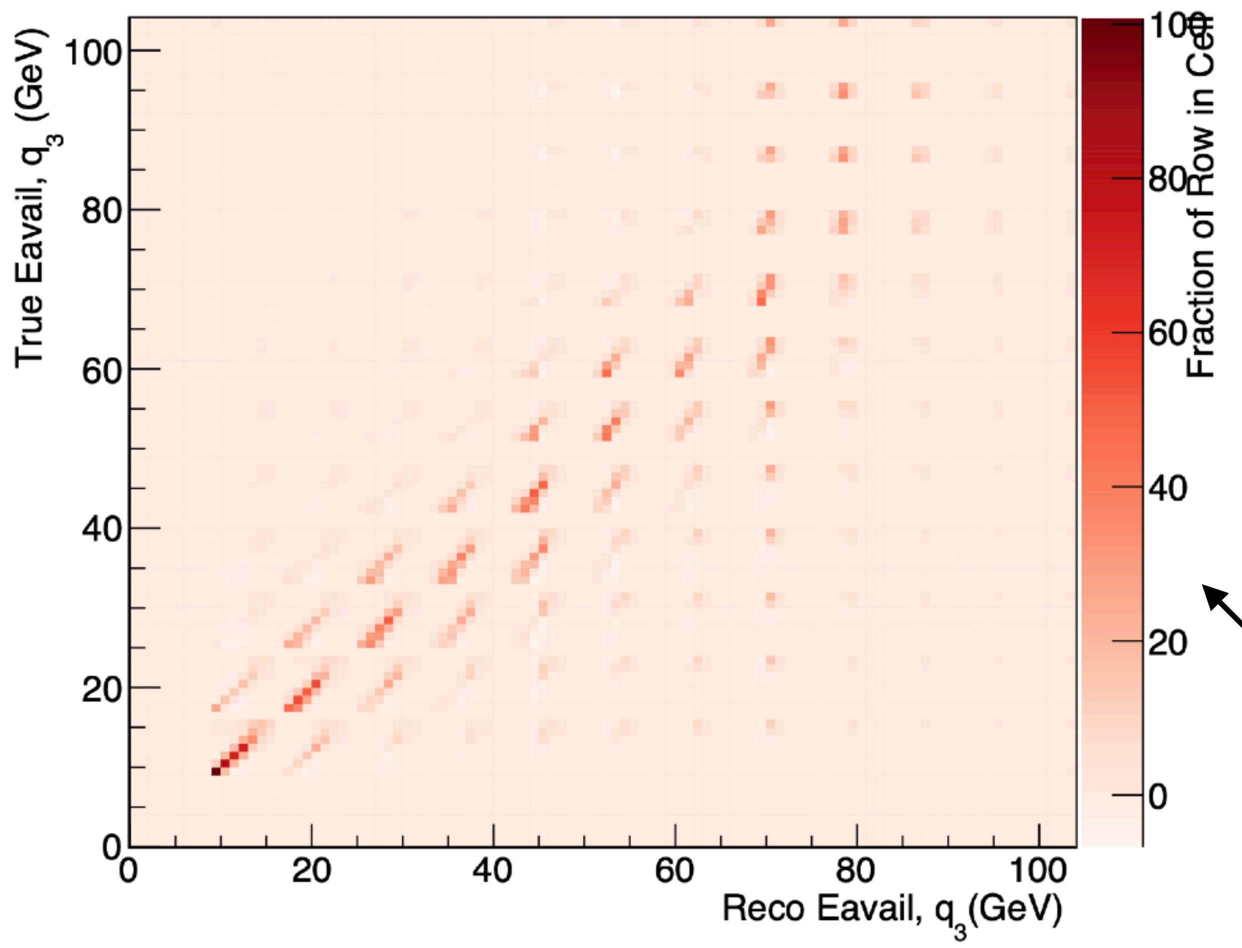
Double differential cross-section

Efficiency correction

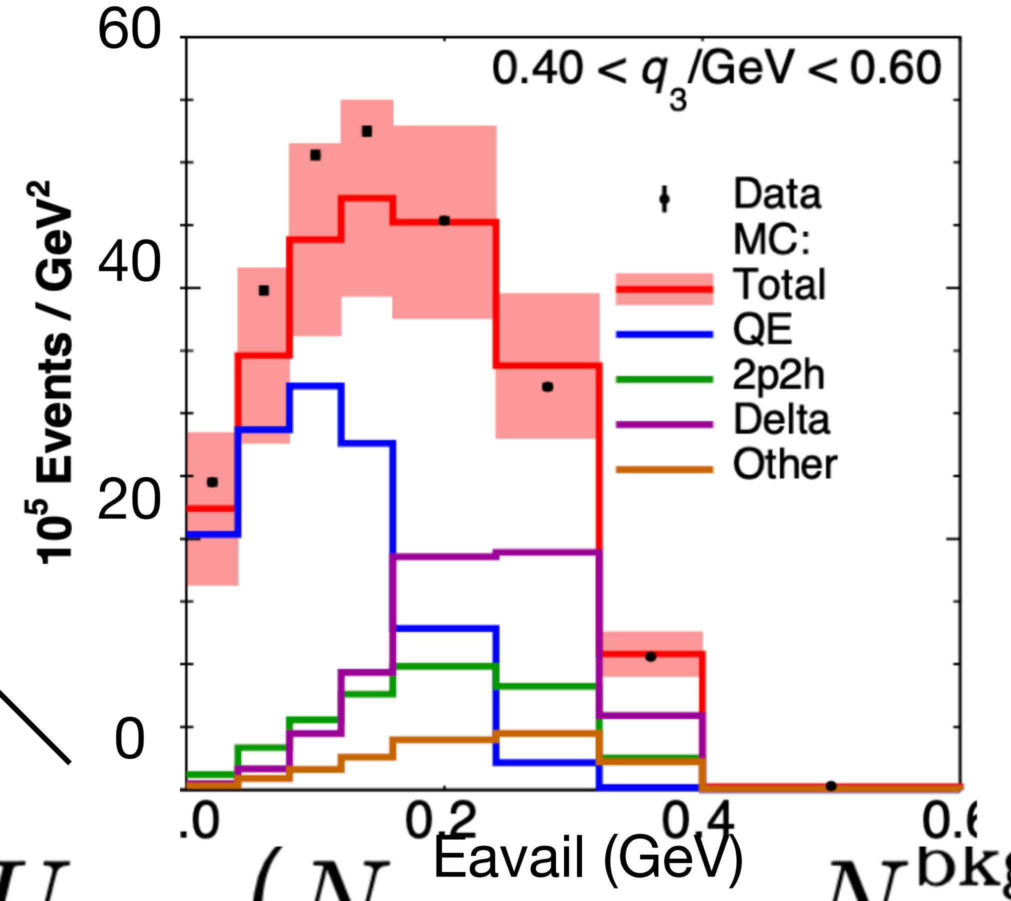
Normalization factor (POT, Flux integral, bin width)

Cross-section extraction

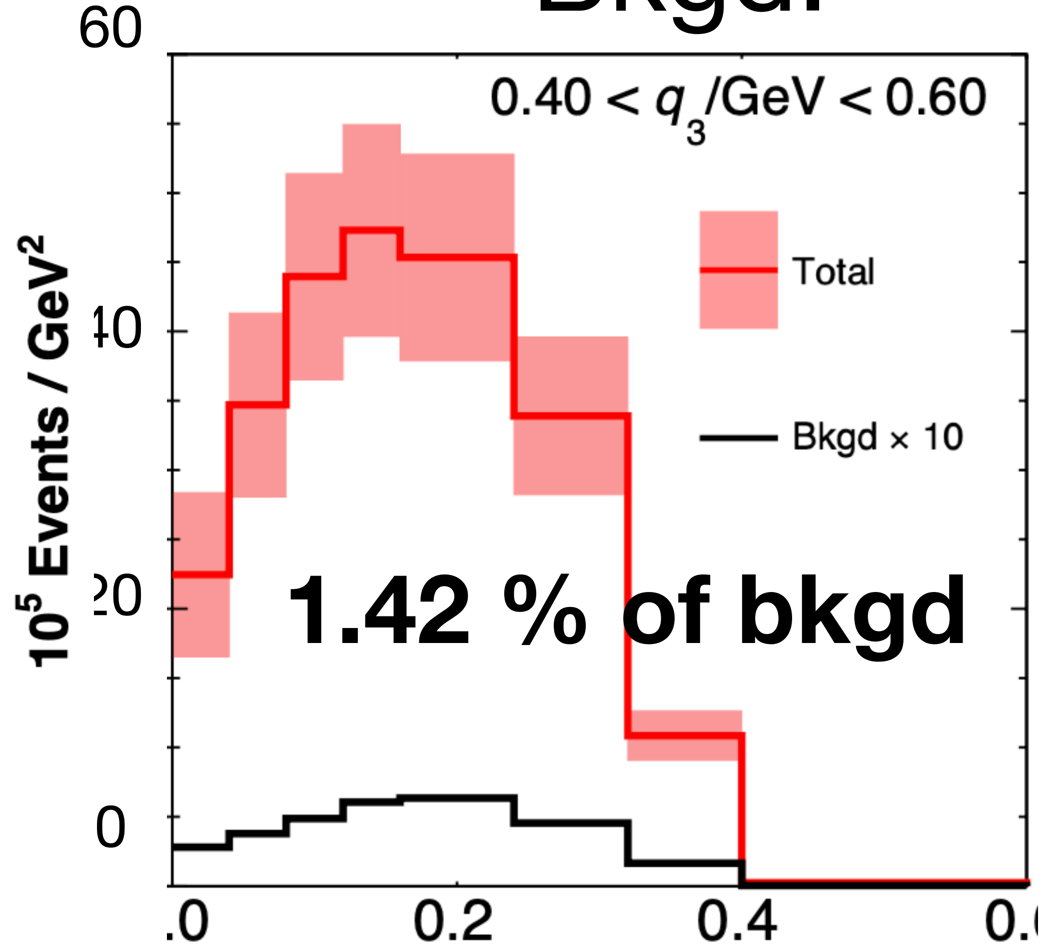
Unfolding matrix



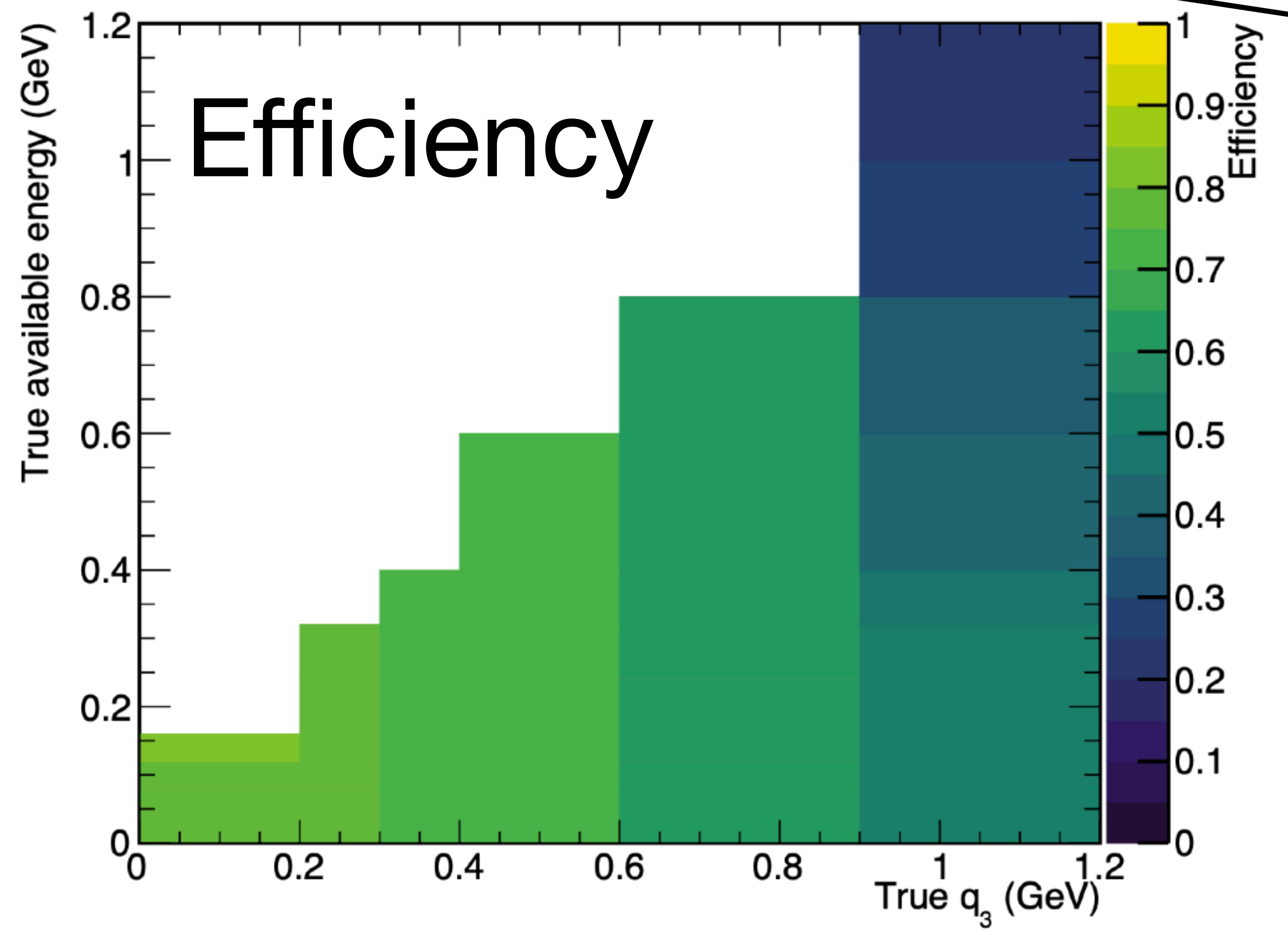
Reconstructed distribution

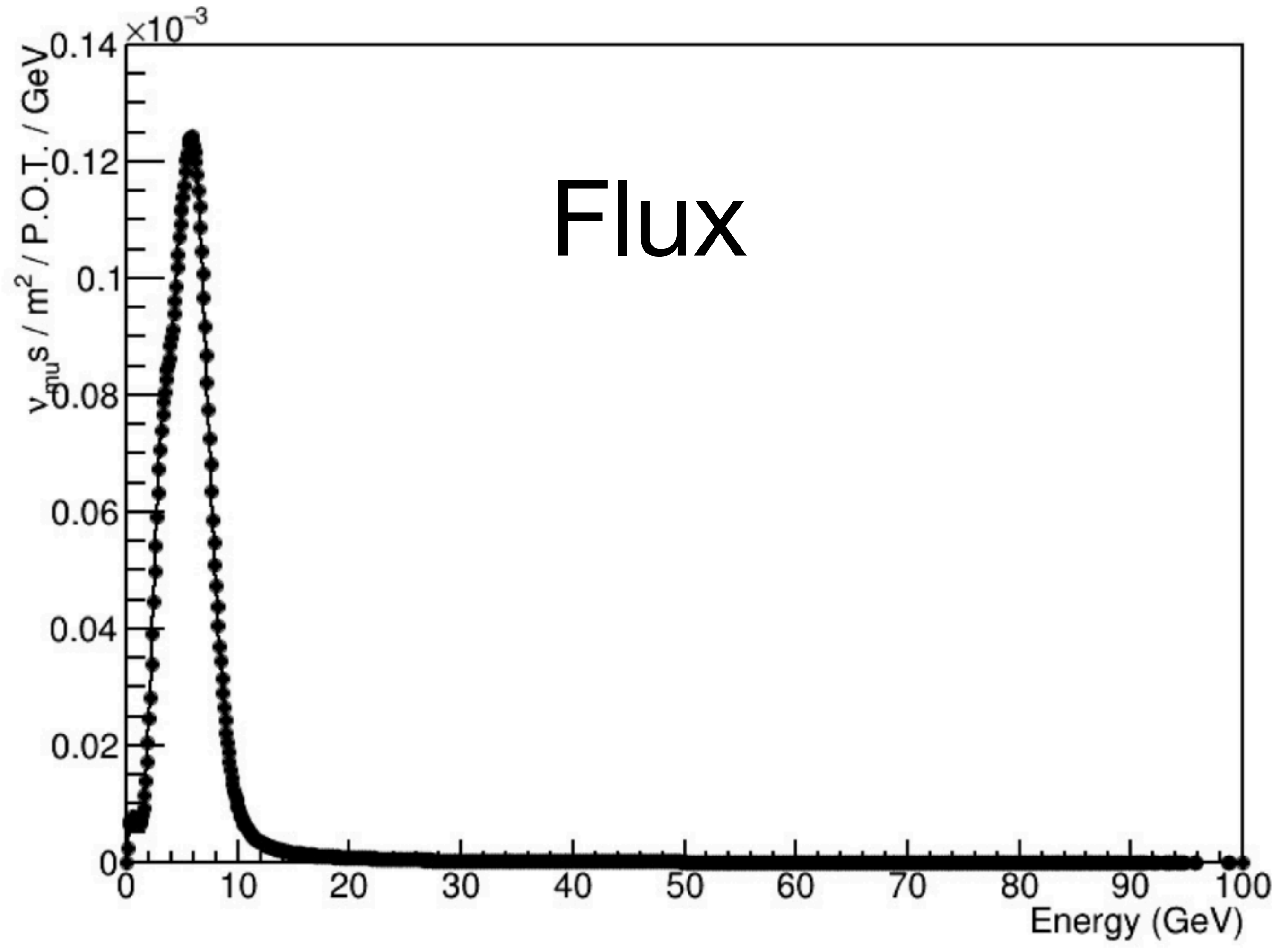


Bkgd.



$$\frac{d^2\sigma}{dE_{\text{avail}}dq_3} = \frac{\sum U_{ij\alpha\beta}\left(N_{\text{data, }ij} - N^{\text{bkgd}}_{\text{data, }ij}\right)}{A_{\alpha\beta}(\Phi T)(\Delta E_{\text{avail}}\Delta q_3)}$$





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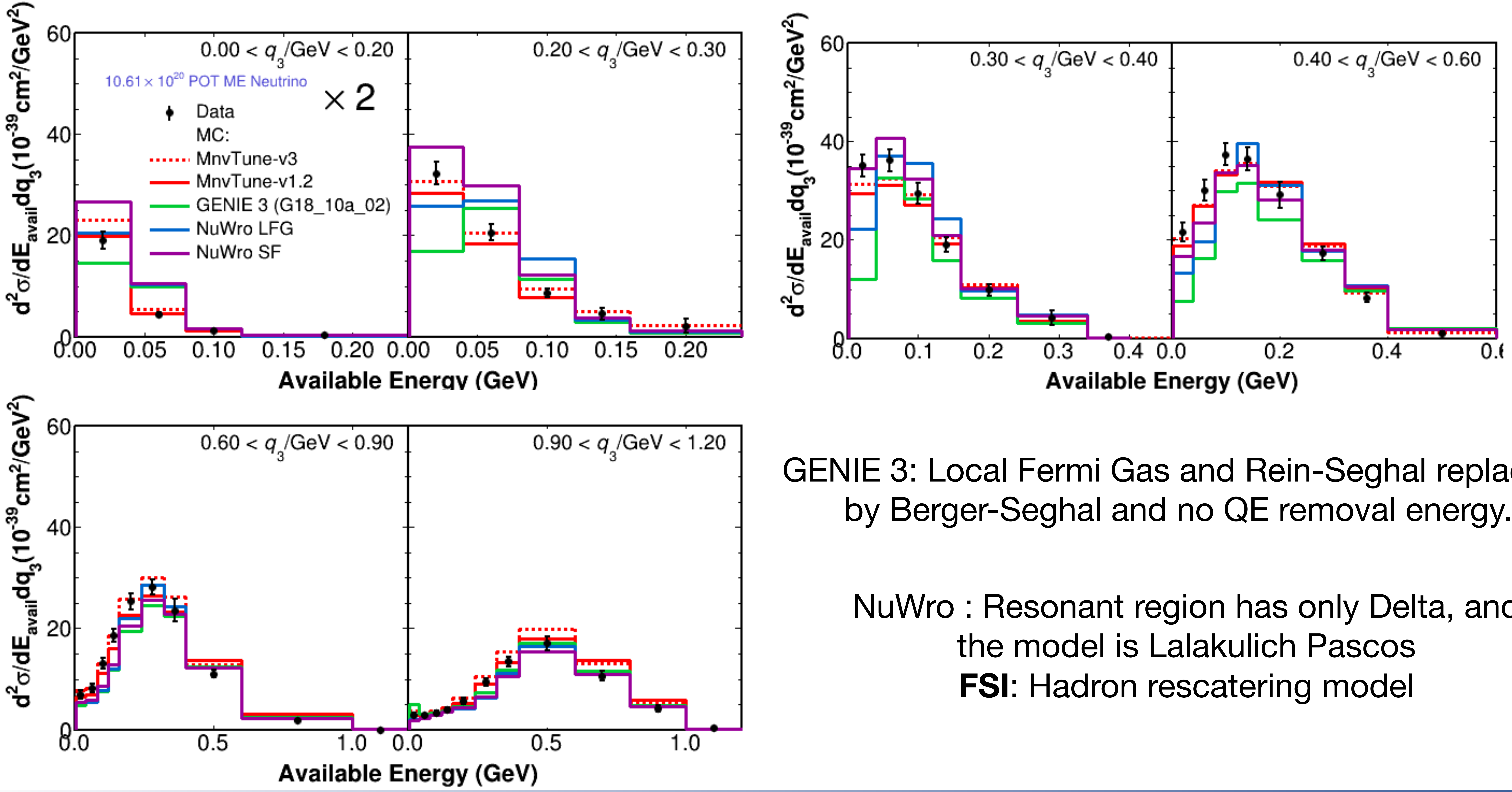
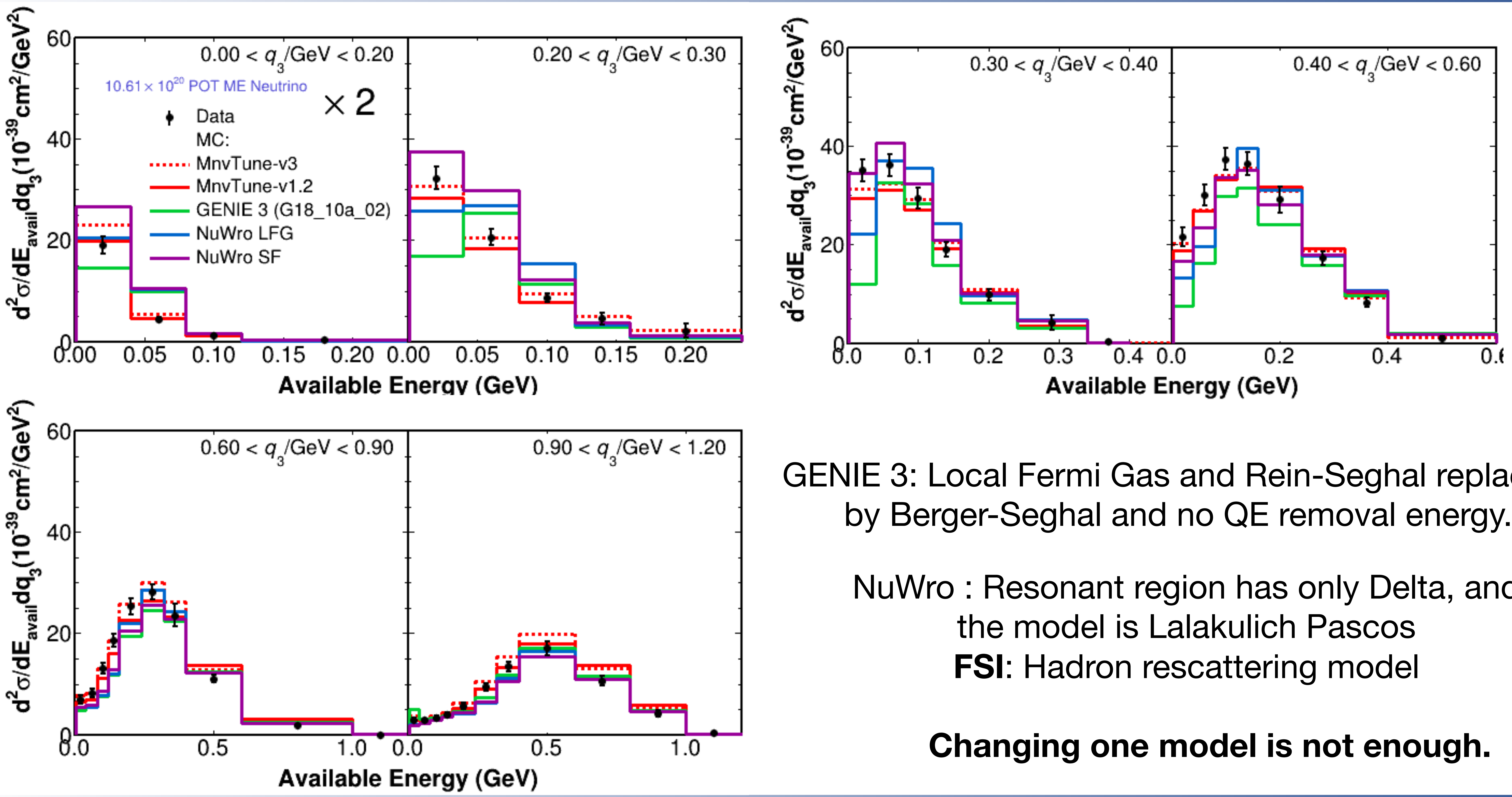
Results!



GENIE 3: Local Fermi Gas and Rein-Seghal replaced by Berger-Seghal and no QE removal energy.

NuWro : Resonant region has only Delta, and the model is Lalakulich Pascos

FSI: Hadron rescatering model

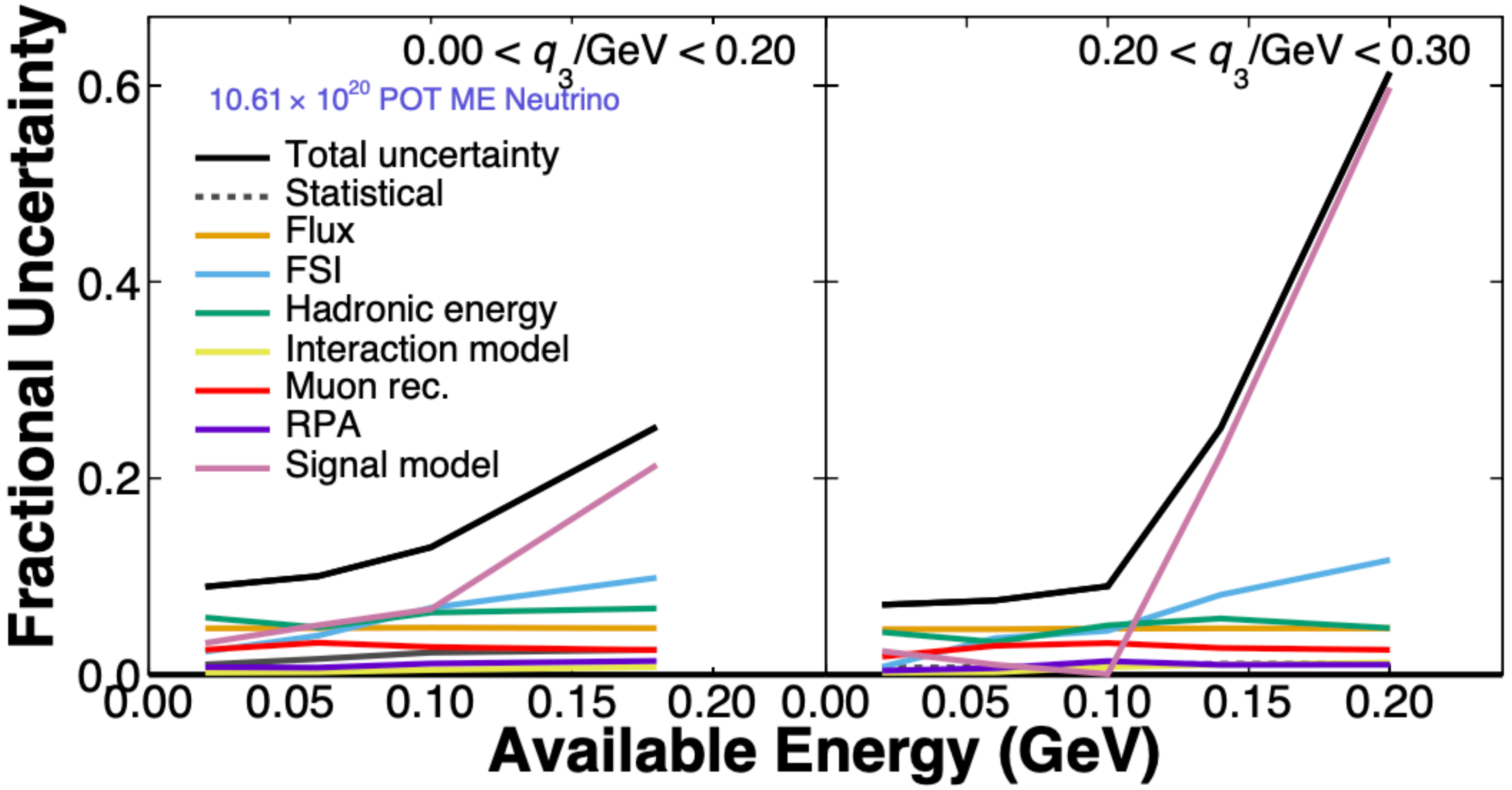


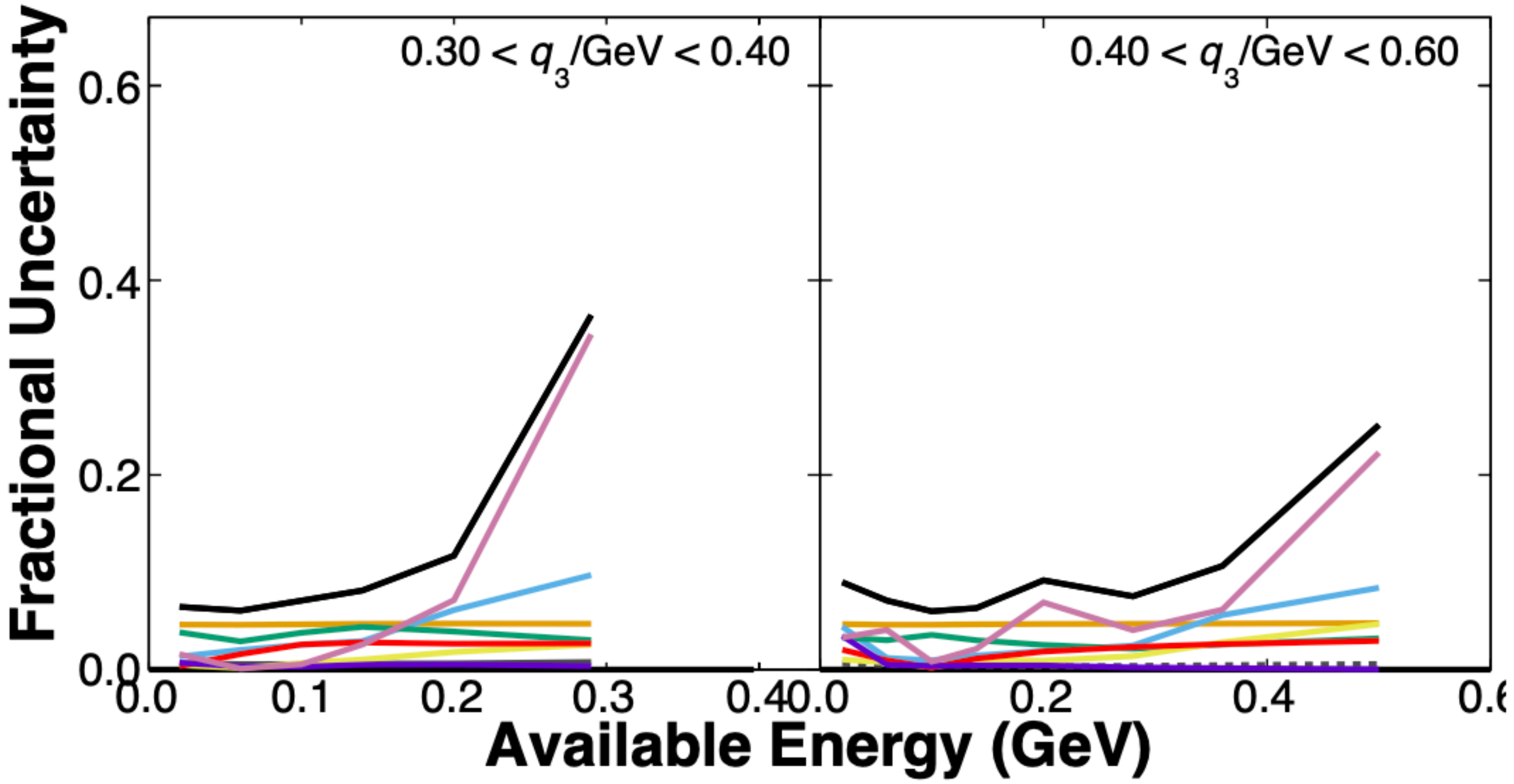
GENIE 3: Local Fermi Gas and Rein-Seghal replaced by Berger-Seghal and no QE removal energy.

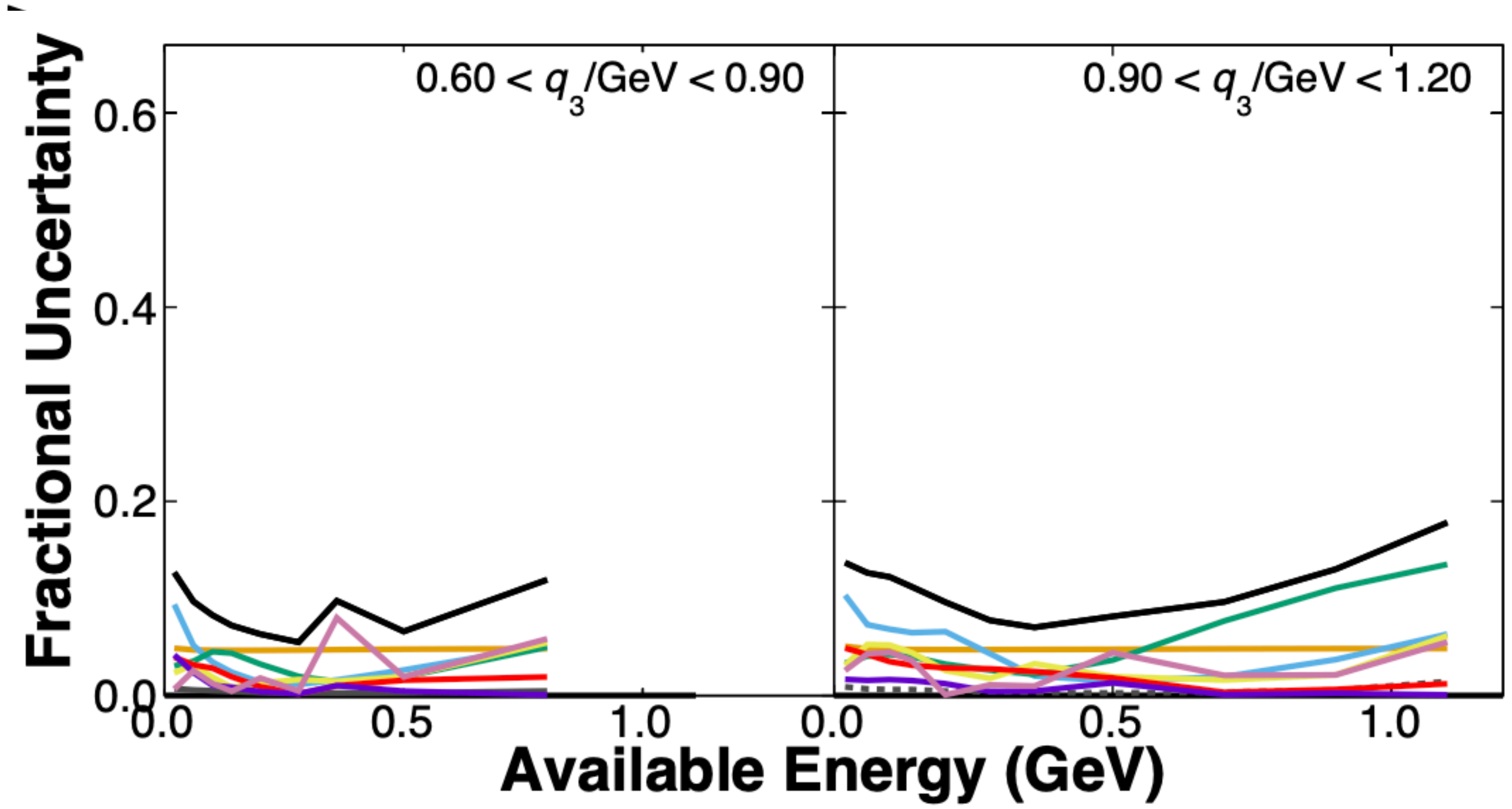
NuWro : Resonant region has only Delta, and the model is Lalakulich Pascos
FSI: Hadron rescattering model

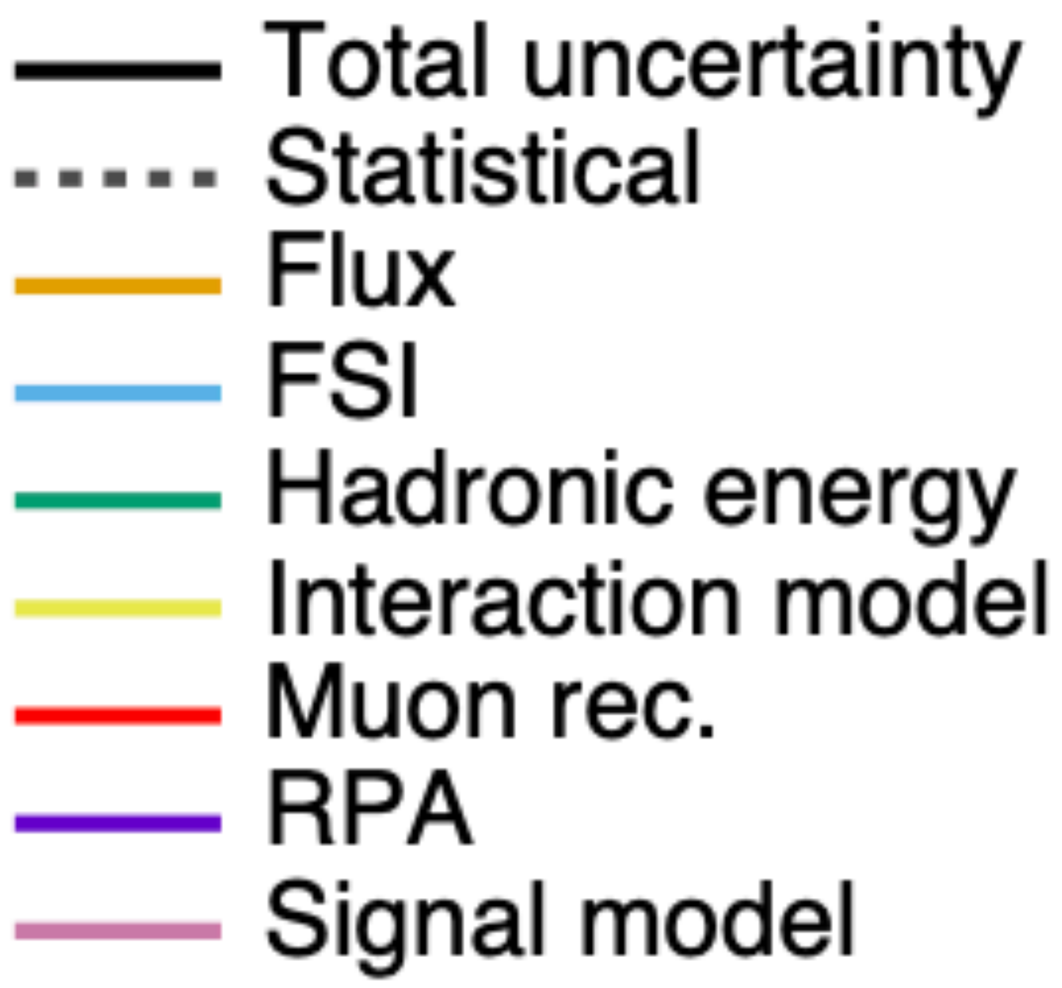
Changing one model is not enough.

Cross-section measurement (Uncertainties)









The signal model comes from the difference between data unfolded with MvnTune.v1.2 and MnvTune.v3

Conclusions

We report a new high statistical 2D measurement of inclusive charge current muon neutrino cross-section with carbon in ME and low momentum transfer.

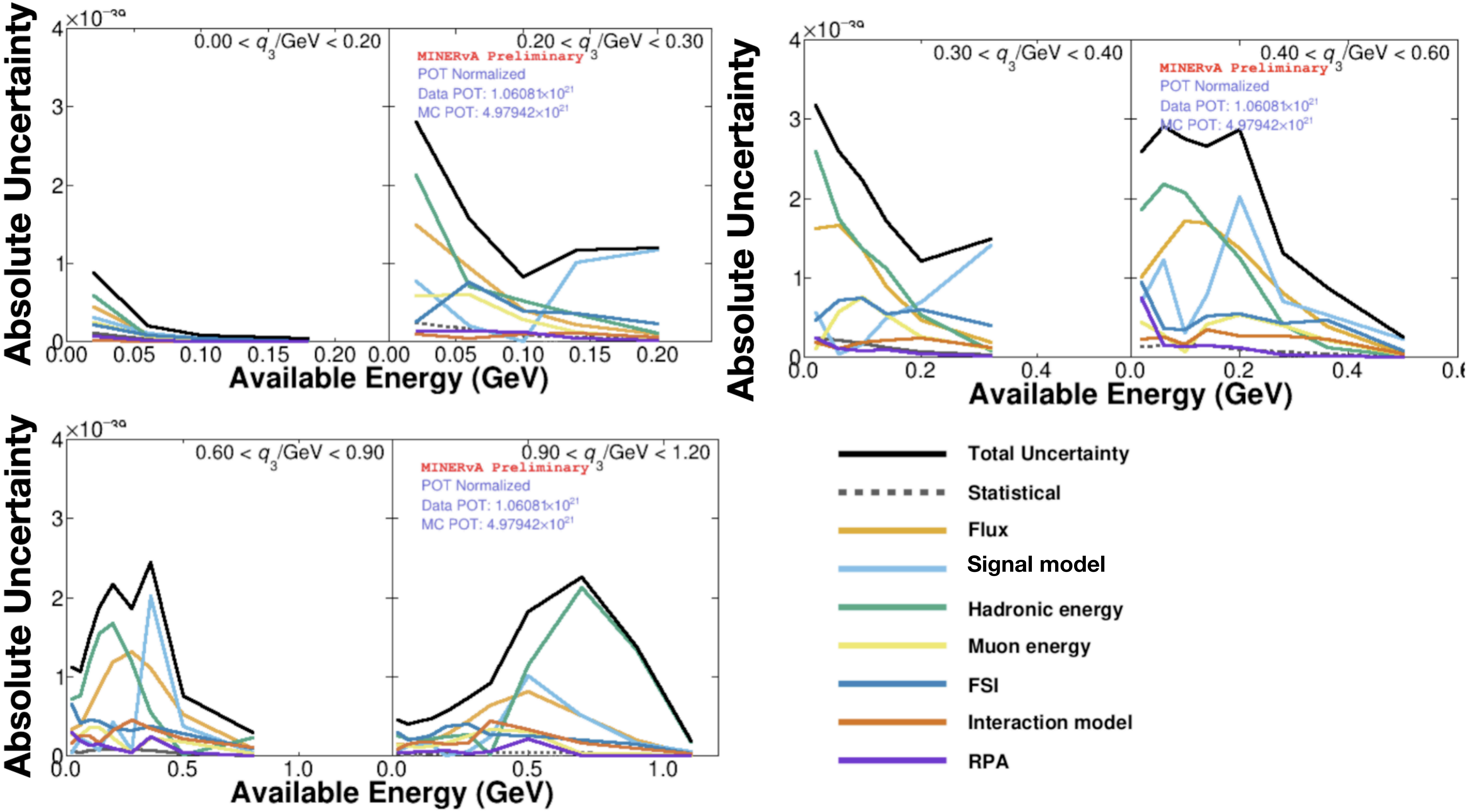
We explore outside of the tune with the new central values (the combination of removal energy, SuSAv2, and Bodek-Ritchie tail enhancement) with more theoretically motivated modifications.

Resolving differences between data and models remains a significant challenge.


Thank you!

Backup

Cross-section extraction



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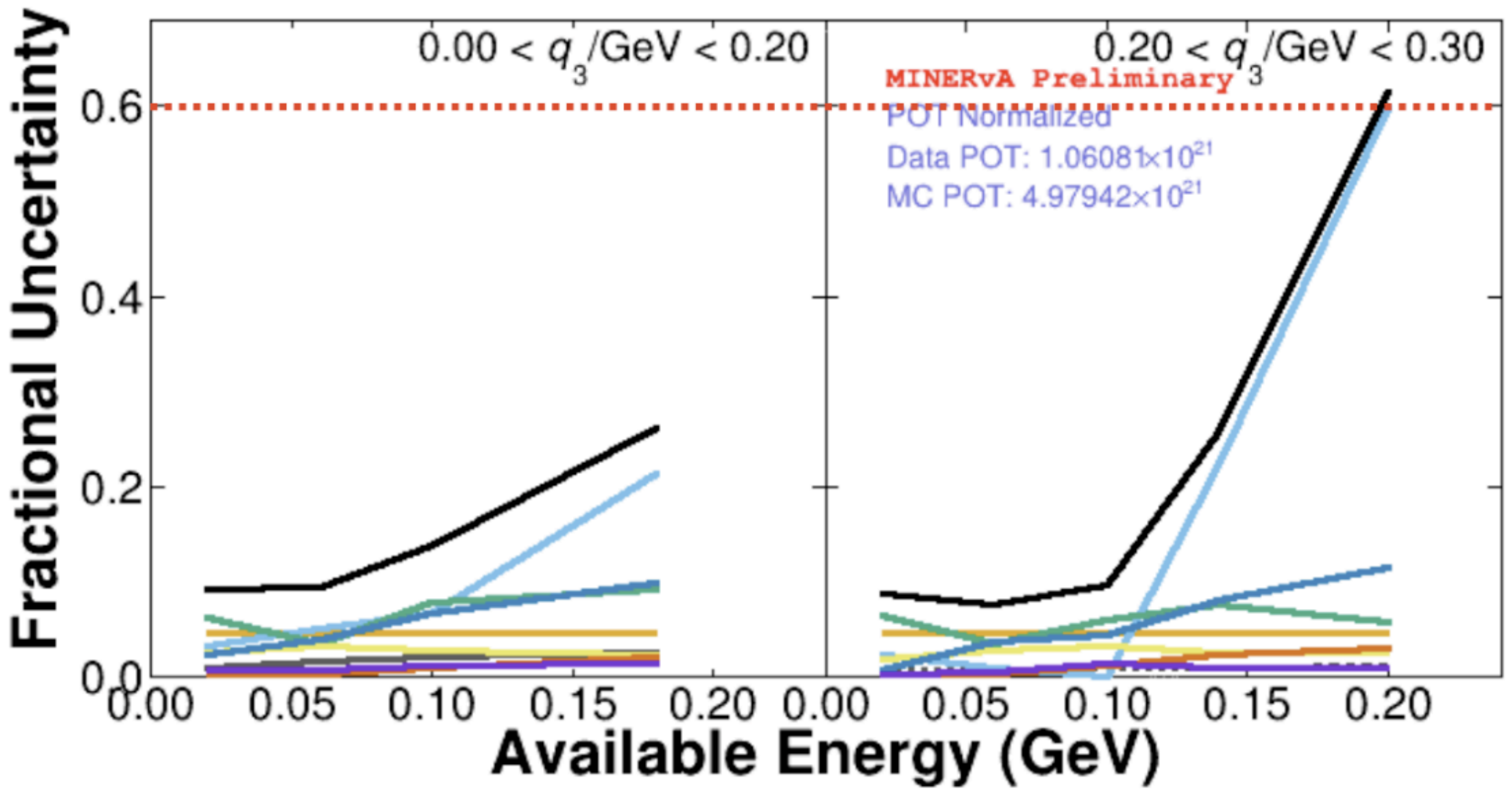
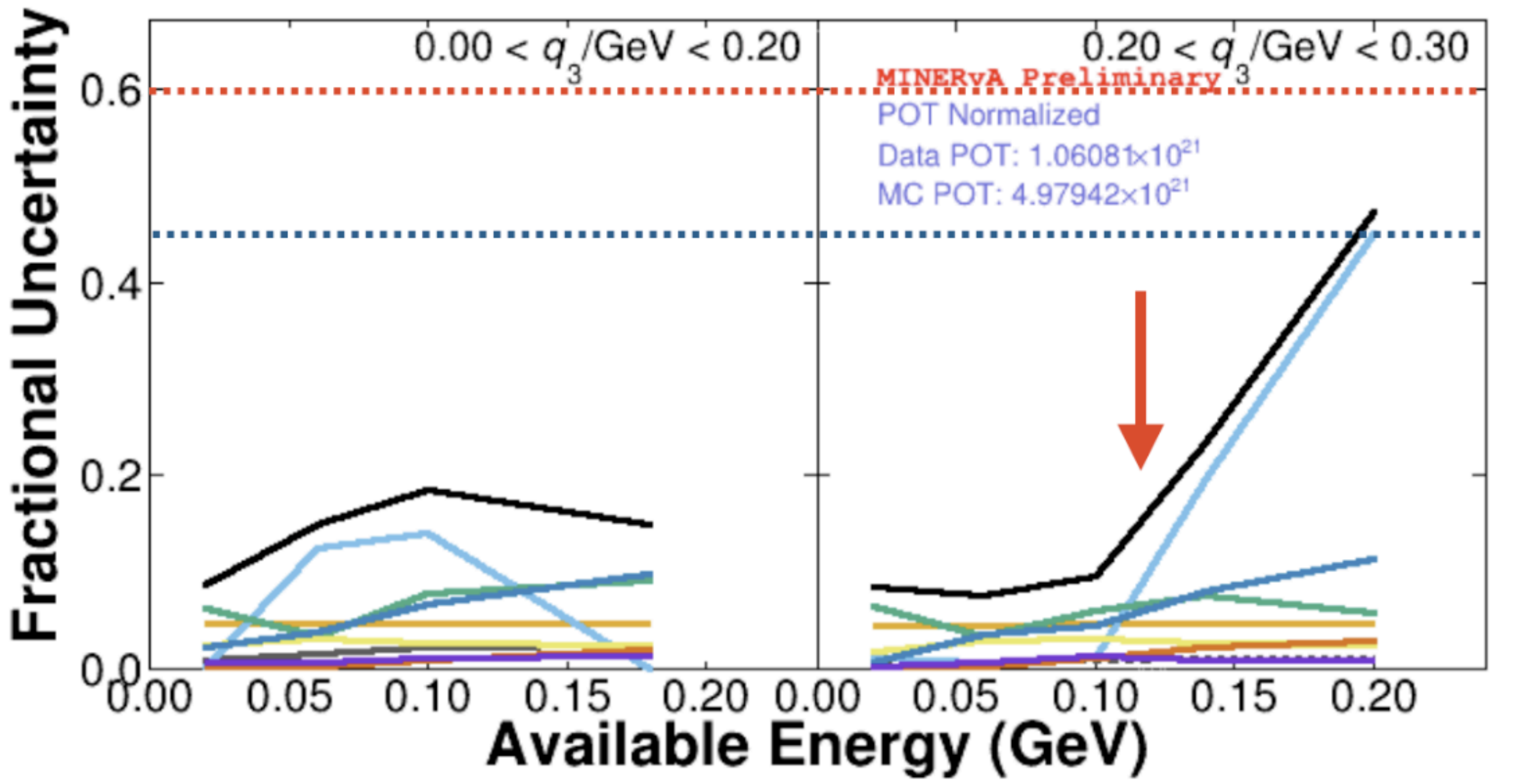
Cross-section extraction

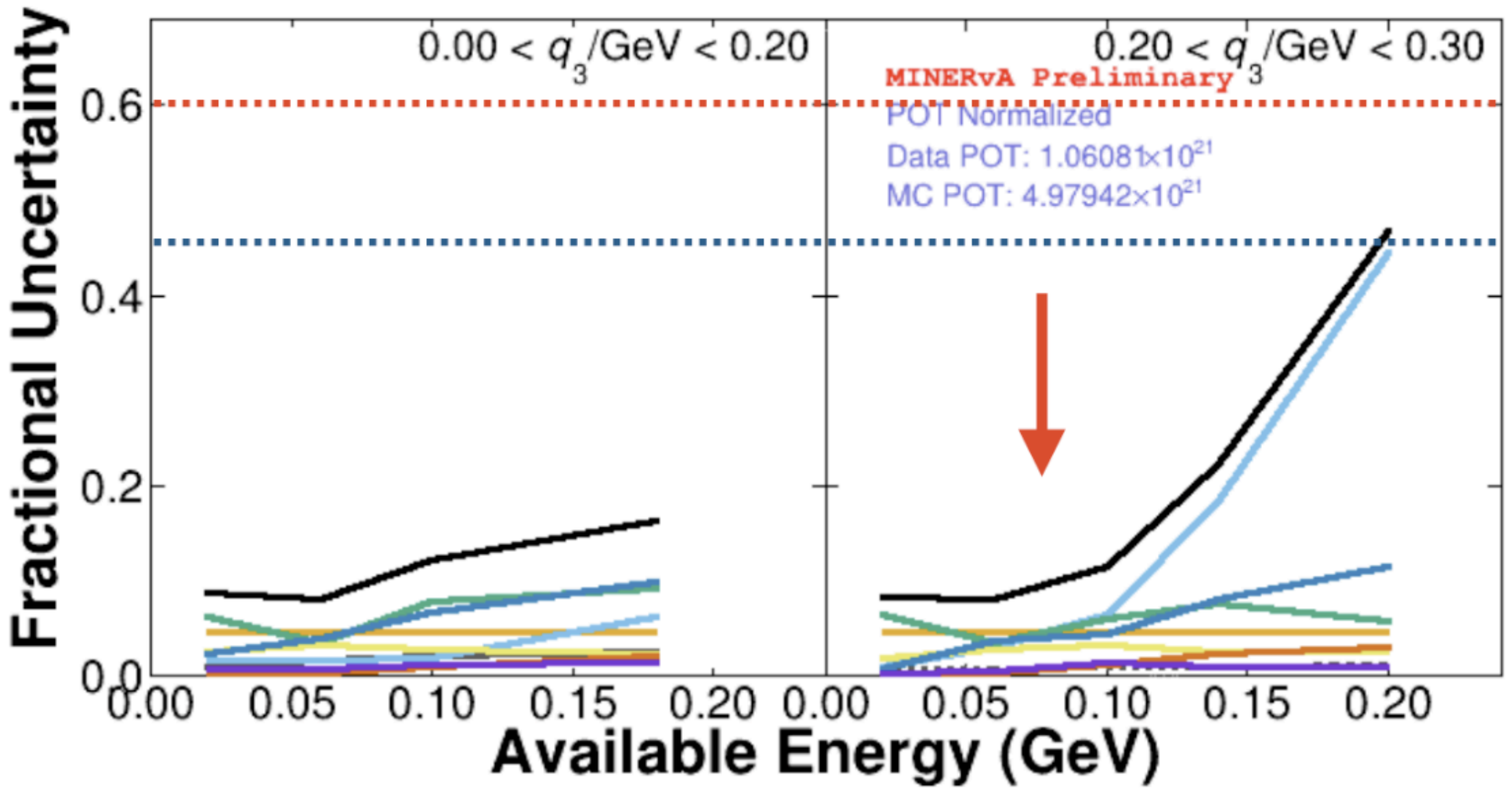
(newCV : MnvTune.v1)



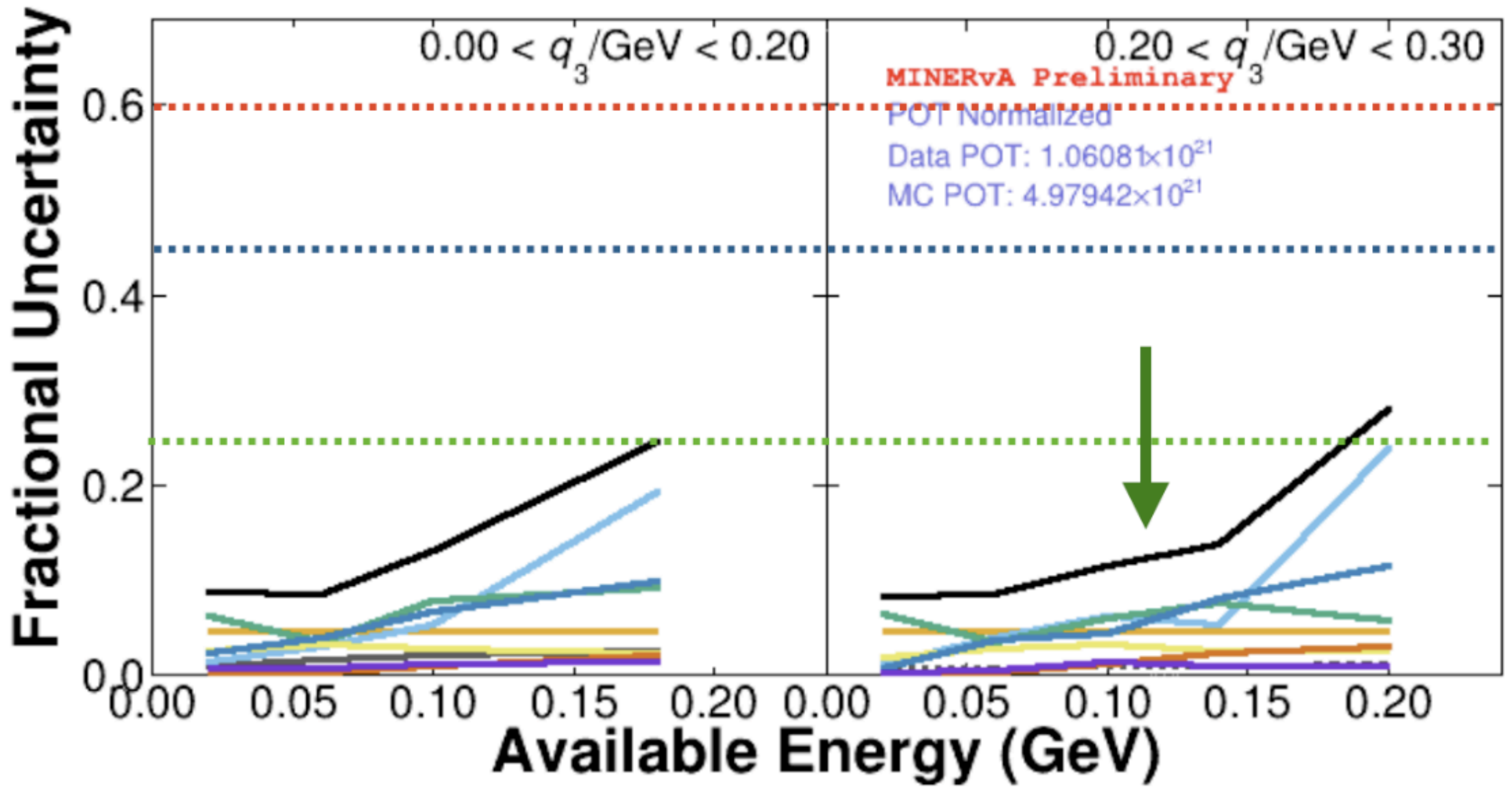
(newCV : newCV + noSuSA2p2h)



(newCV : MnvTune.v1+RE)



(newCV : newCV + noRE)



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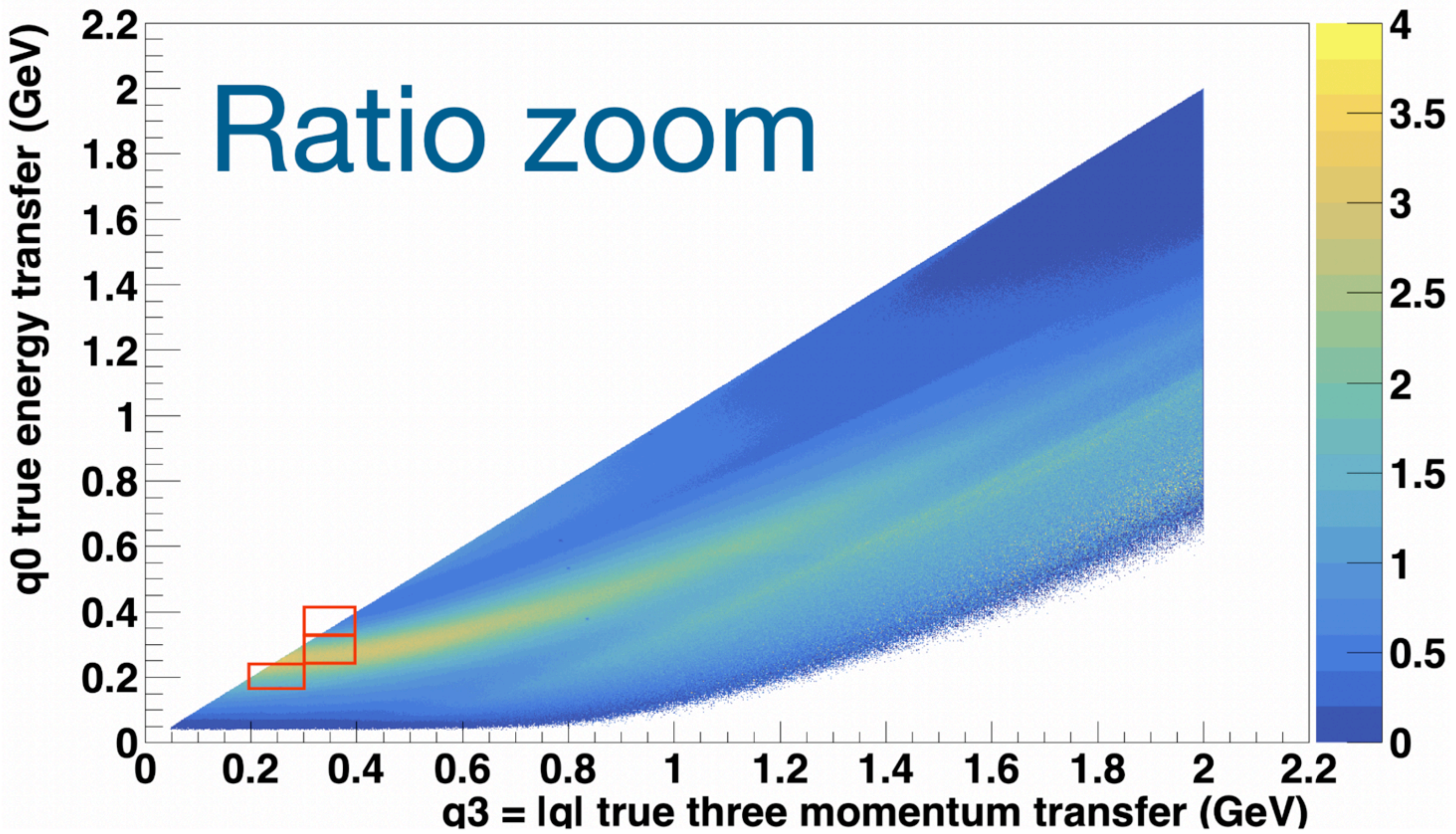
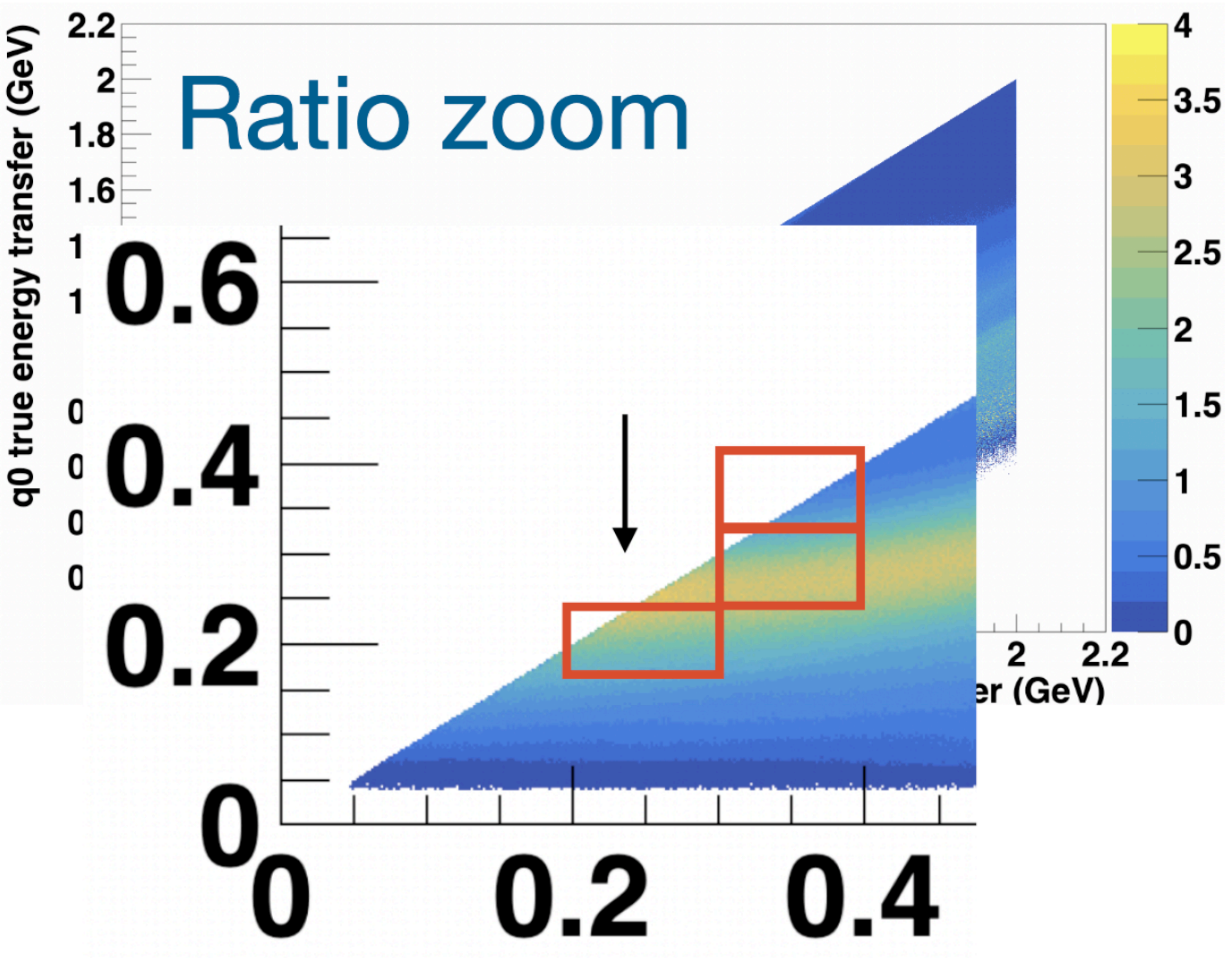
Cross-section extraction





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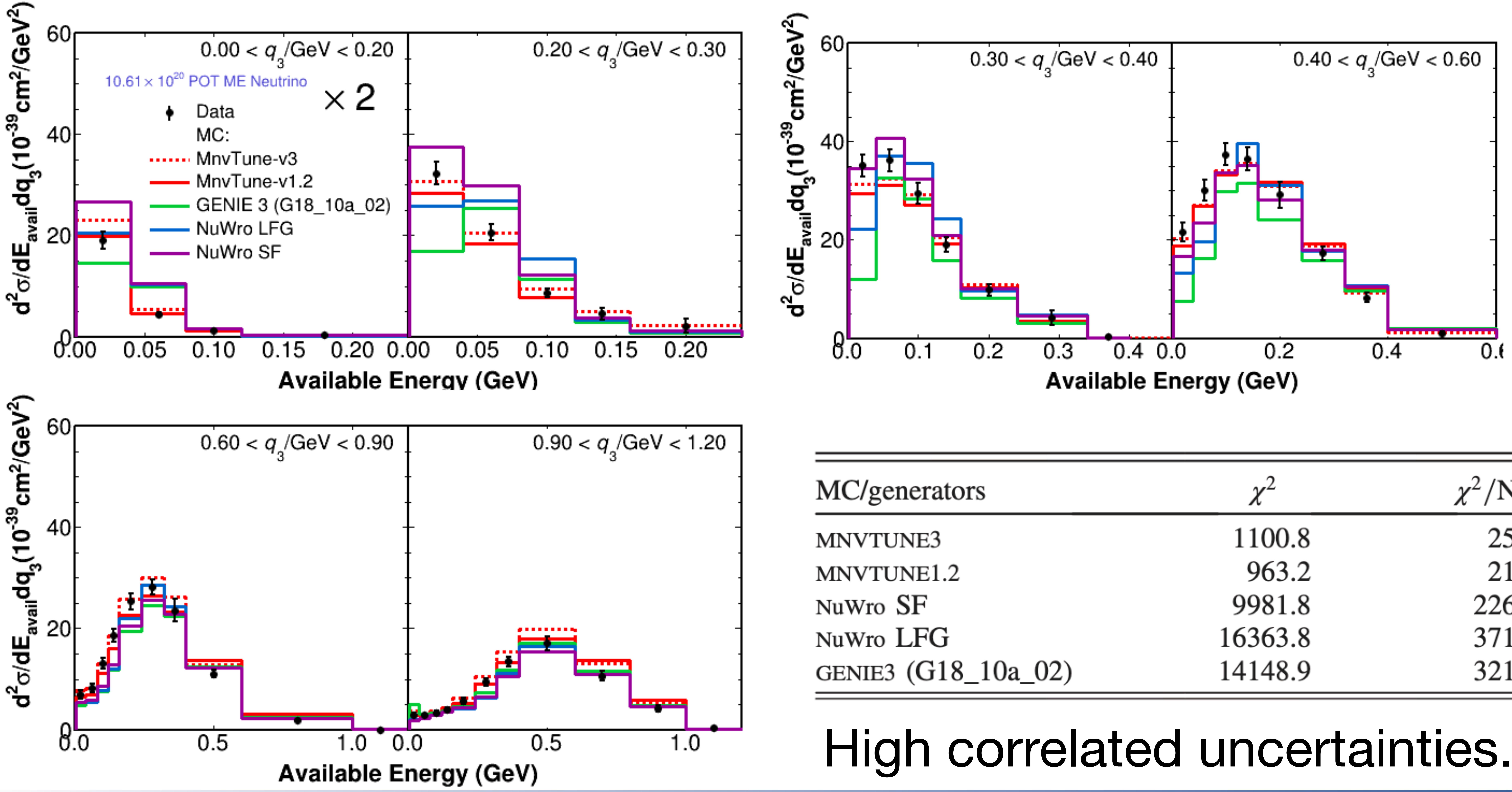
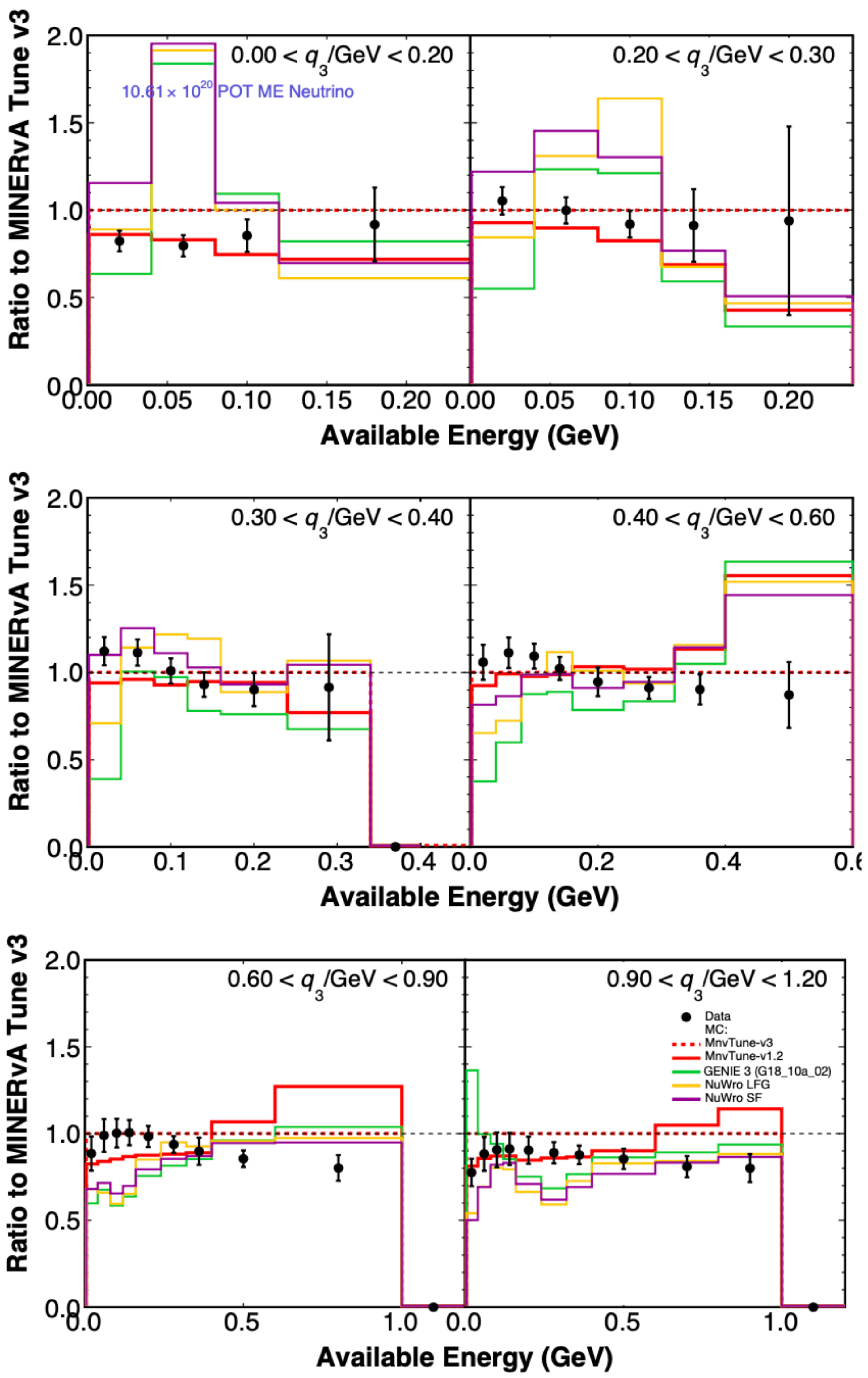
Cross-section extraction Results!



MC/generators	χ^2	χ^2/NDF
MNVTUNE3	1100.8	25
MNVTUNE1.2	963.2	21.9
NuWro SF	9981.8	226.9
NuWro LFG	16363.8	371.9
GENIE3 (G18_10a_02)	14148.9	321.6

High correlated uncertainties.

Cross-section measurement



The double differential cross-section are compared with other generator:

- MnvTune-v3
- MnvTune-v1.2
- GENIE 3 (G18_10a_02)
- NuWro LFG
- NuWro SF

MC/Generators	χ^2	χ^2/NDF
MnvTune-V3	1100.8	25.
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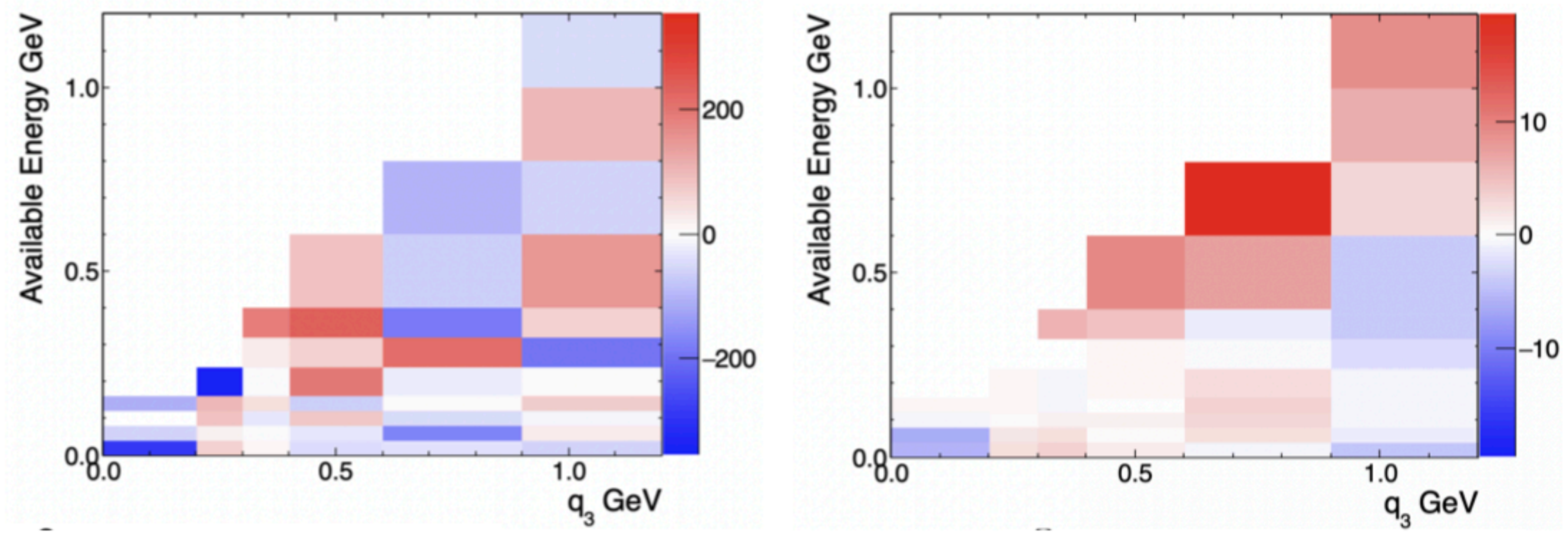

$$\Delta\chi_i^2 = \sum_j \left(\chi^2_{i,j_{\text{model}}} - \chi^2_{i,j_{\text{MINERvA Tune v3}}} \right)$$

Model: Mnvtune.v.1.2

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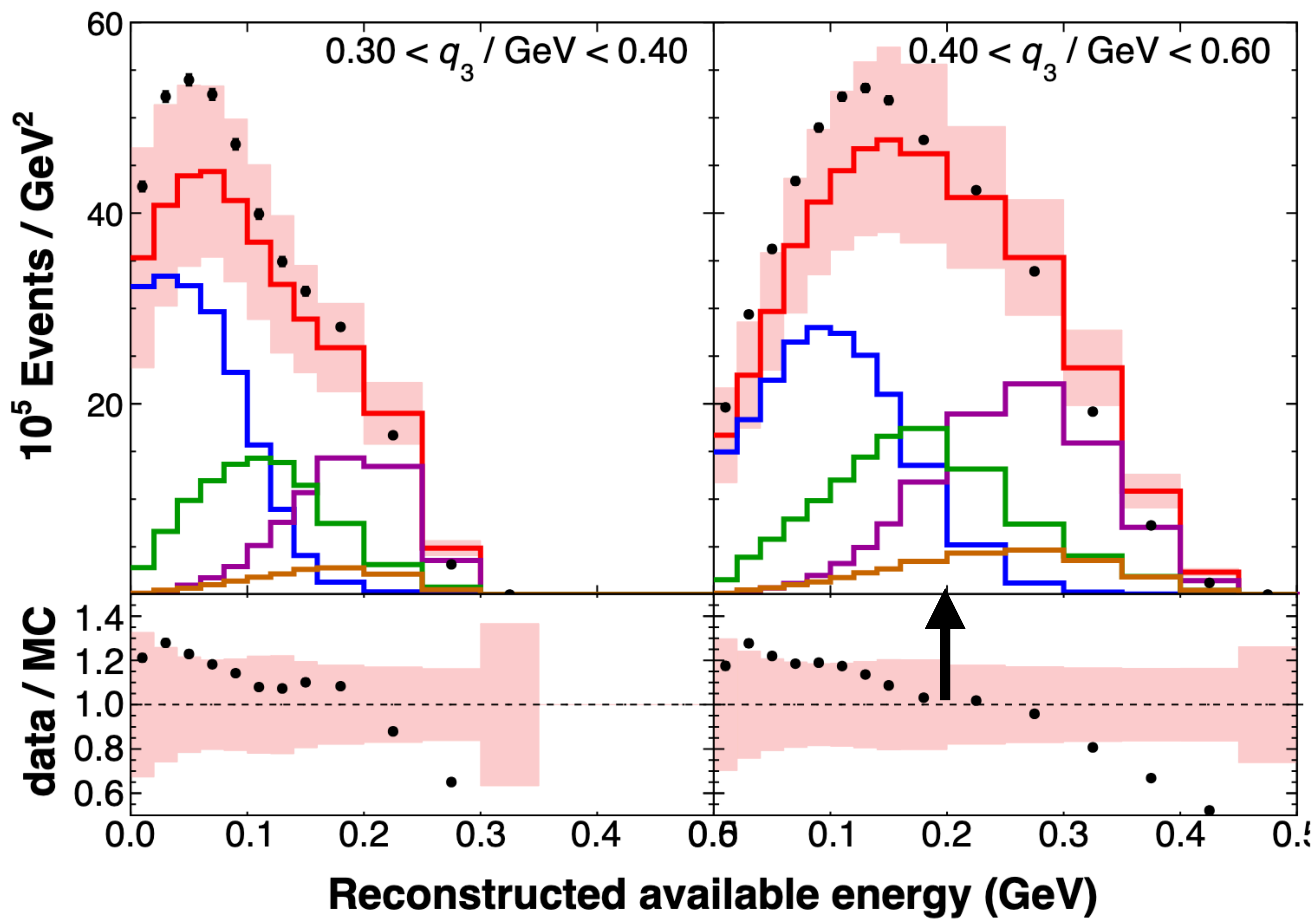
Event Selection - **Resonant region**



Other models and tunes tested in the resonant region:

- Minoo Kabirnezhad Model (*).
- Berger-Sehgal with Pauli Blocking.
- Low Q2 Pion Suppression (#).

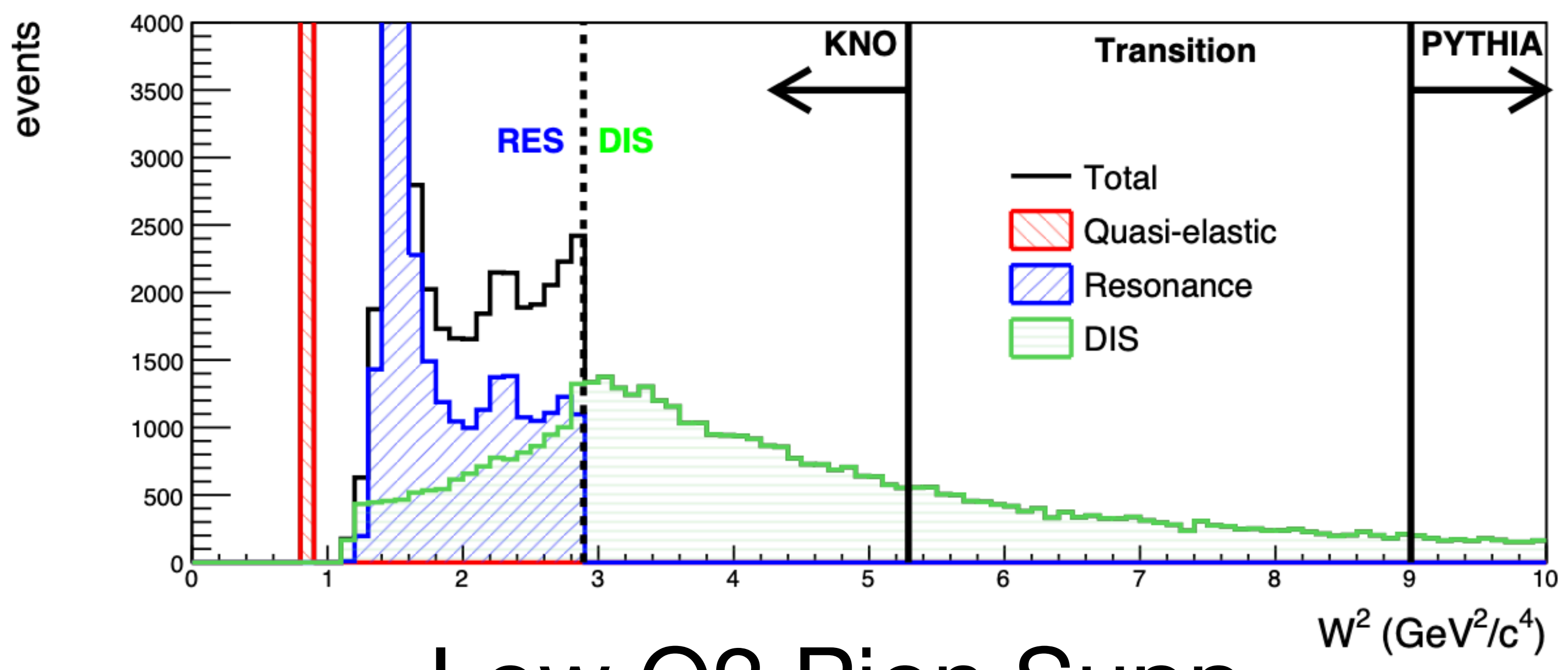


Fig. from (&)

Low Q2 Pion Supp
(From LE analysis)

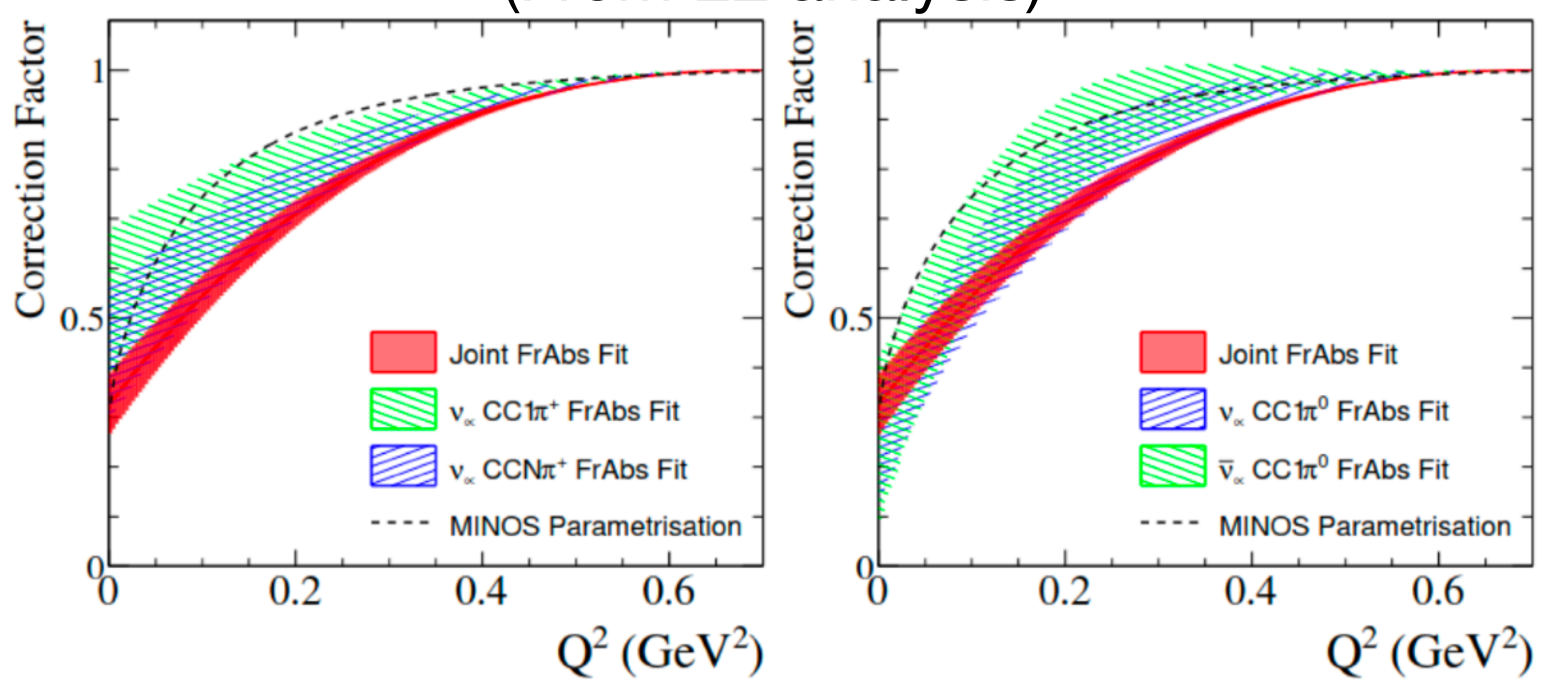
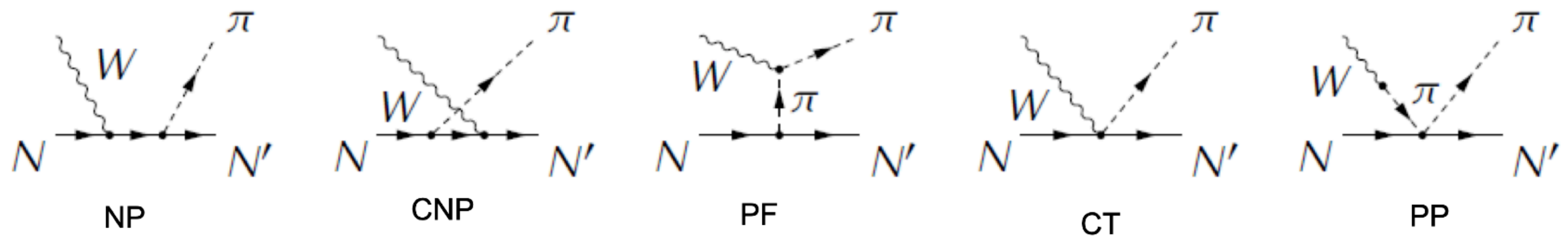


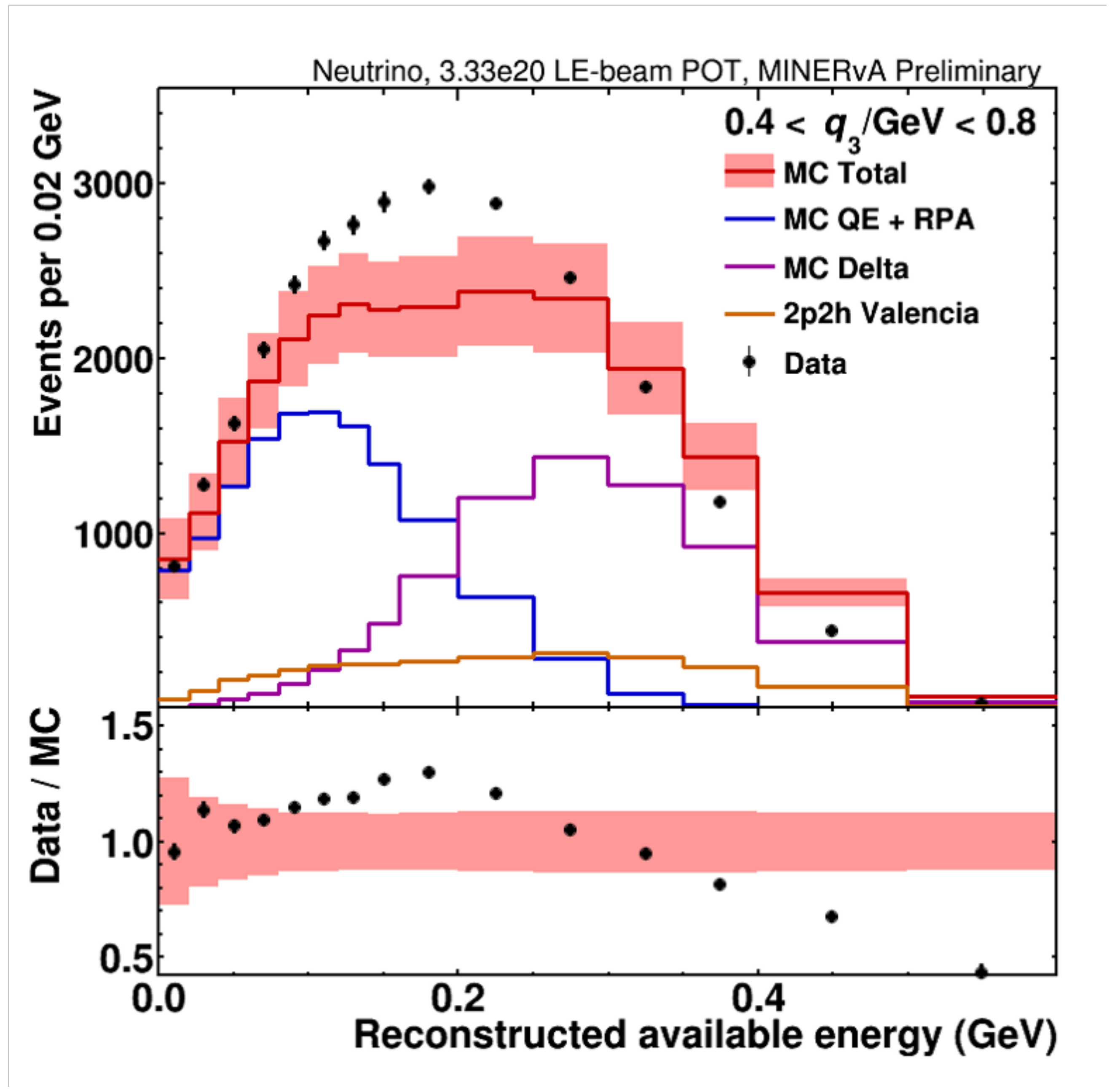
Fig. from (#)

MK (non-res π production):

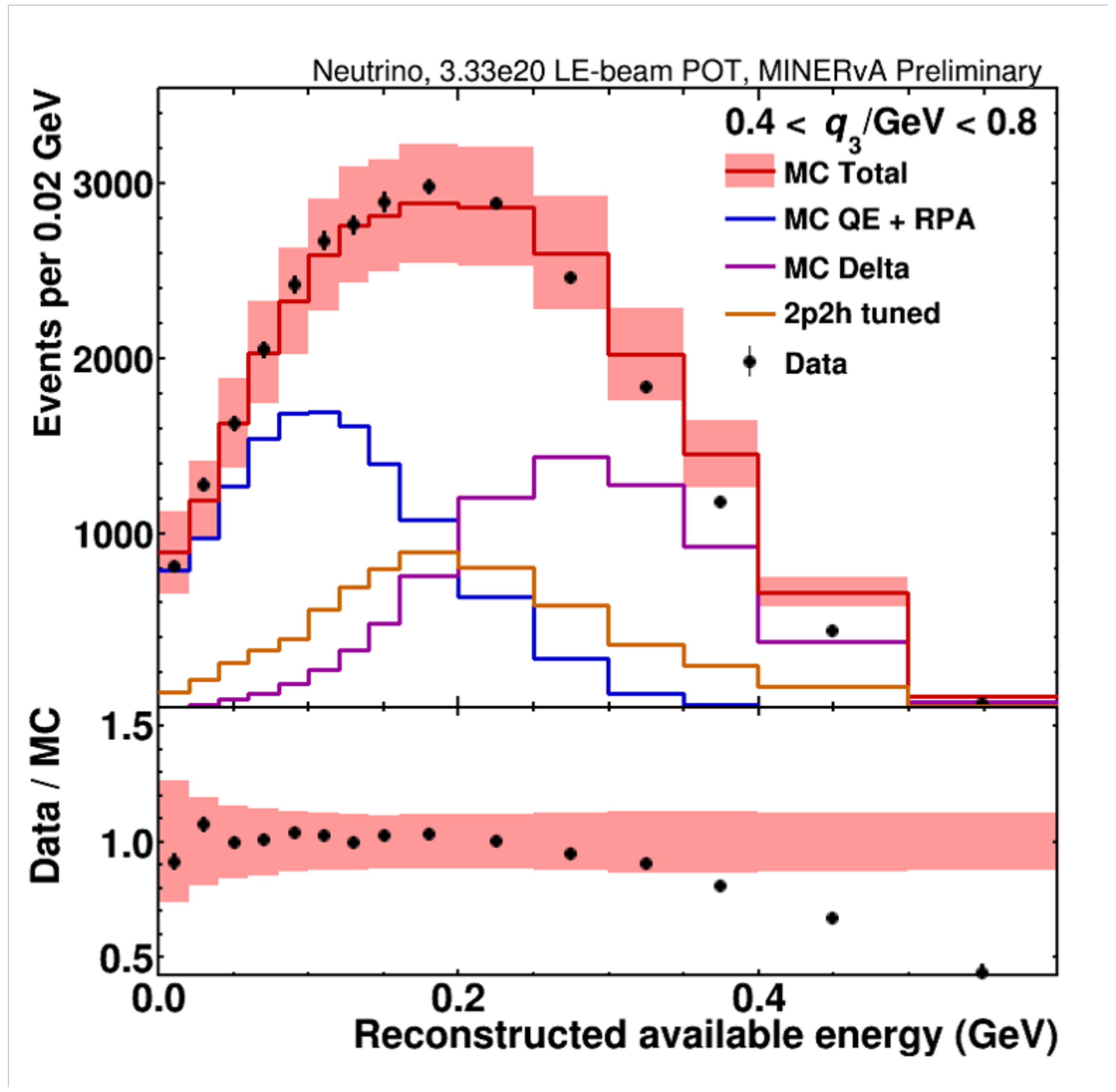


* M. Kabirnezhad, Phys. Rev. D 97, 013002 (2018)
\# P. Stowell et al. (MINERvA Collaboration) Phys. Rev. D 100, 072005
& *JPS Conf.Proc.* 12 (2016) 010033

Neutrino Low Energy

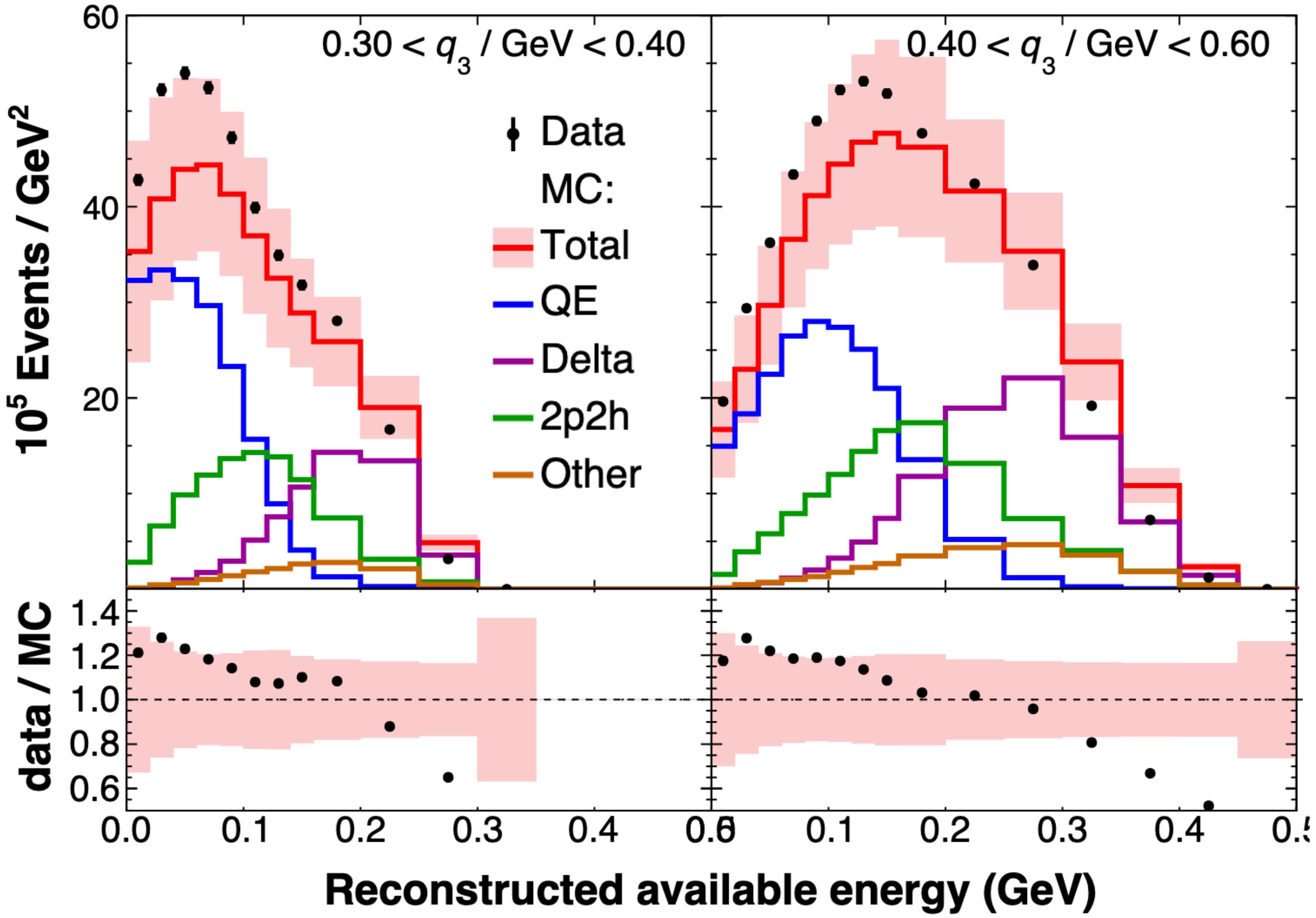


Before 2p2h tune



After 2p2h tune

Neutrino Medium Energy



With LE 2p2h tune 2p2h tune

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SuSA

SuSA (Super Scaling Approximation)

Formalism describesthe charged lepton scattering.

Scaling variable:

-Does not depend on momentum transfer (scaling of the first kind).

-Independent of Fermi Momentum (k_F) (scaling of the second kind).

$$\psi = \frac{1}{\sqrt{\xi_F}} \frac{\lambda - \tau}{\sqrt{(1+\lambda)\tau + \kappa\sqrt{\tau(1+\tau)}}}$$

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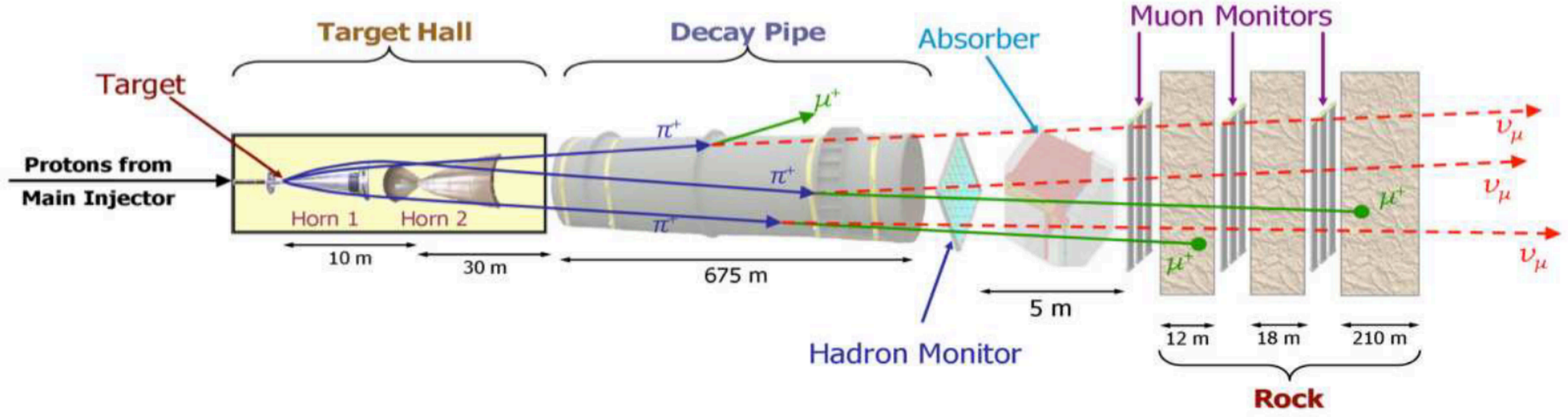
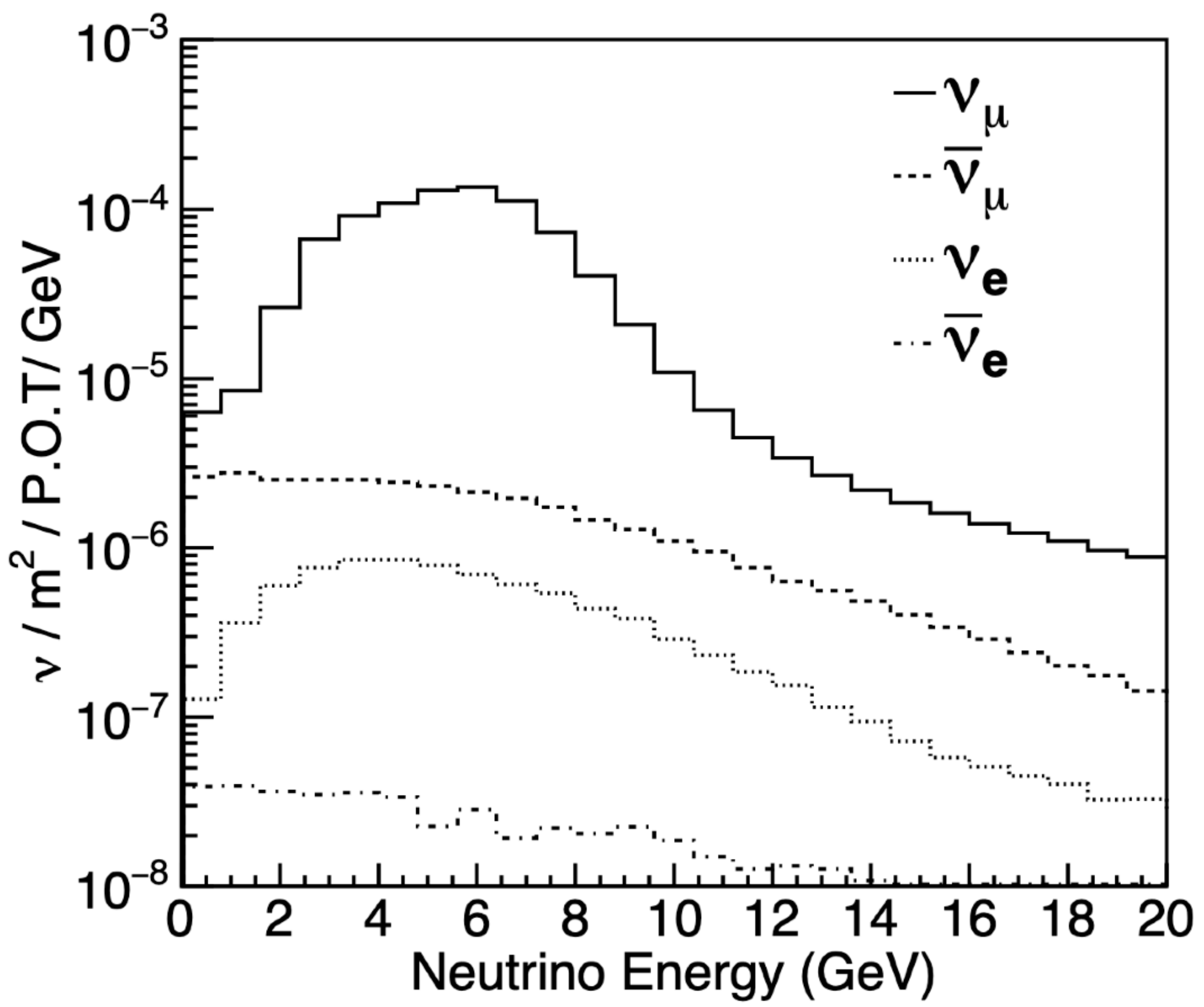
MINERvA Experiments

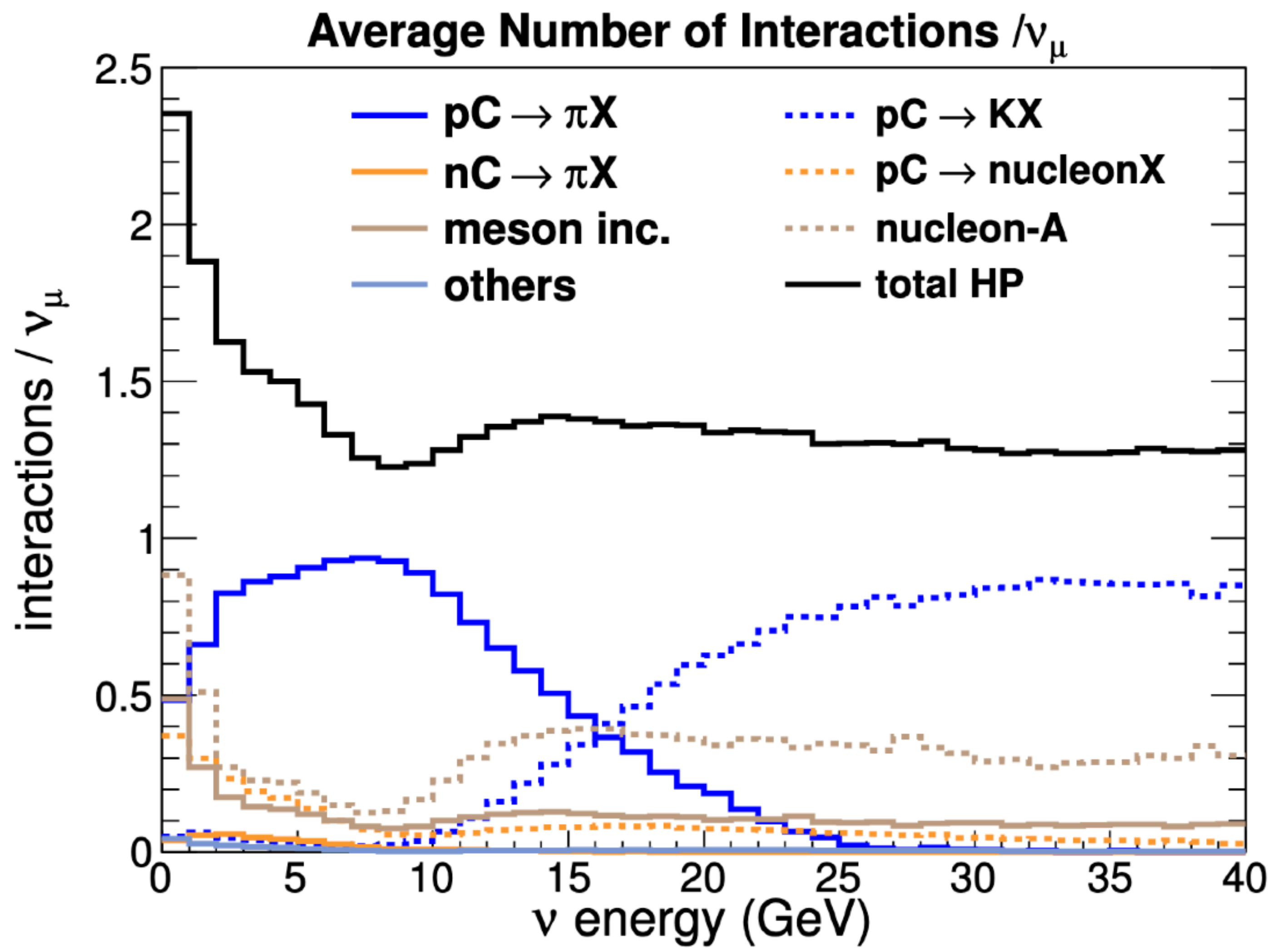
Creating neutrinos:



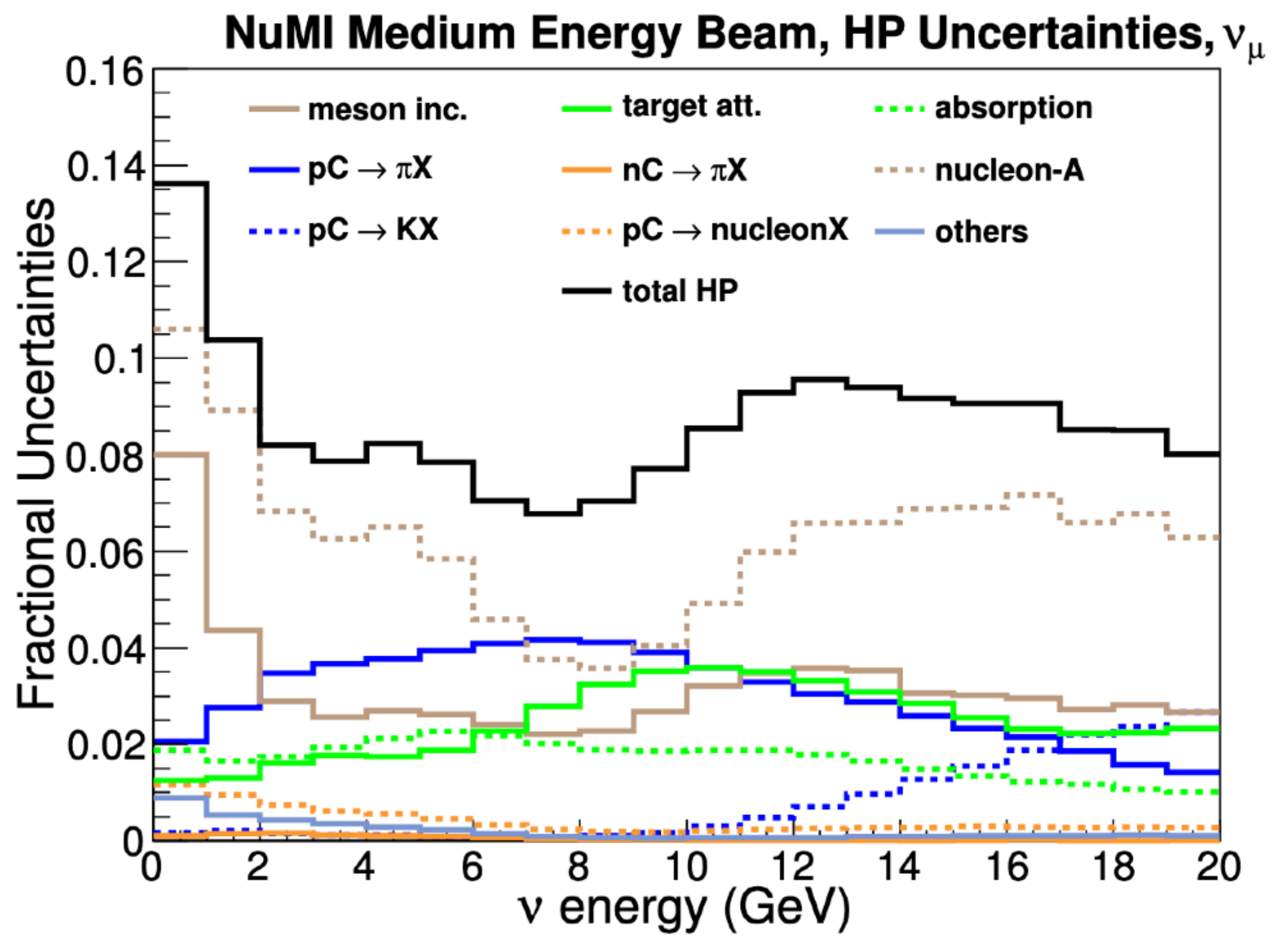
Neutrino flux:

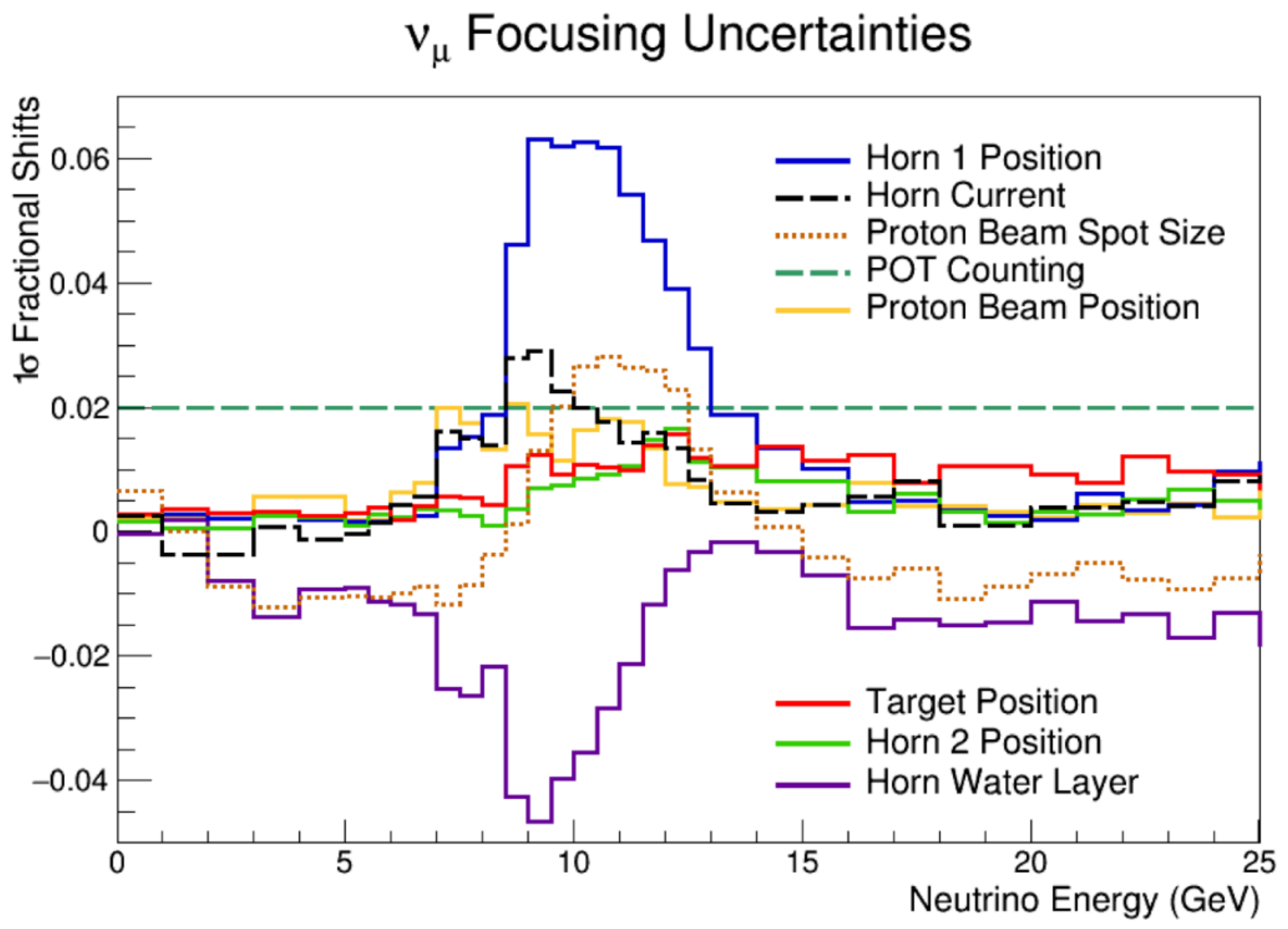


MINERvA Experiments



We have to take into an account the uncertainties





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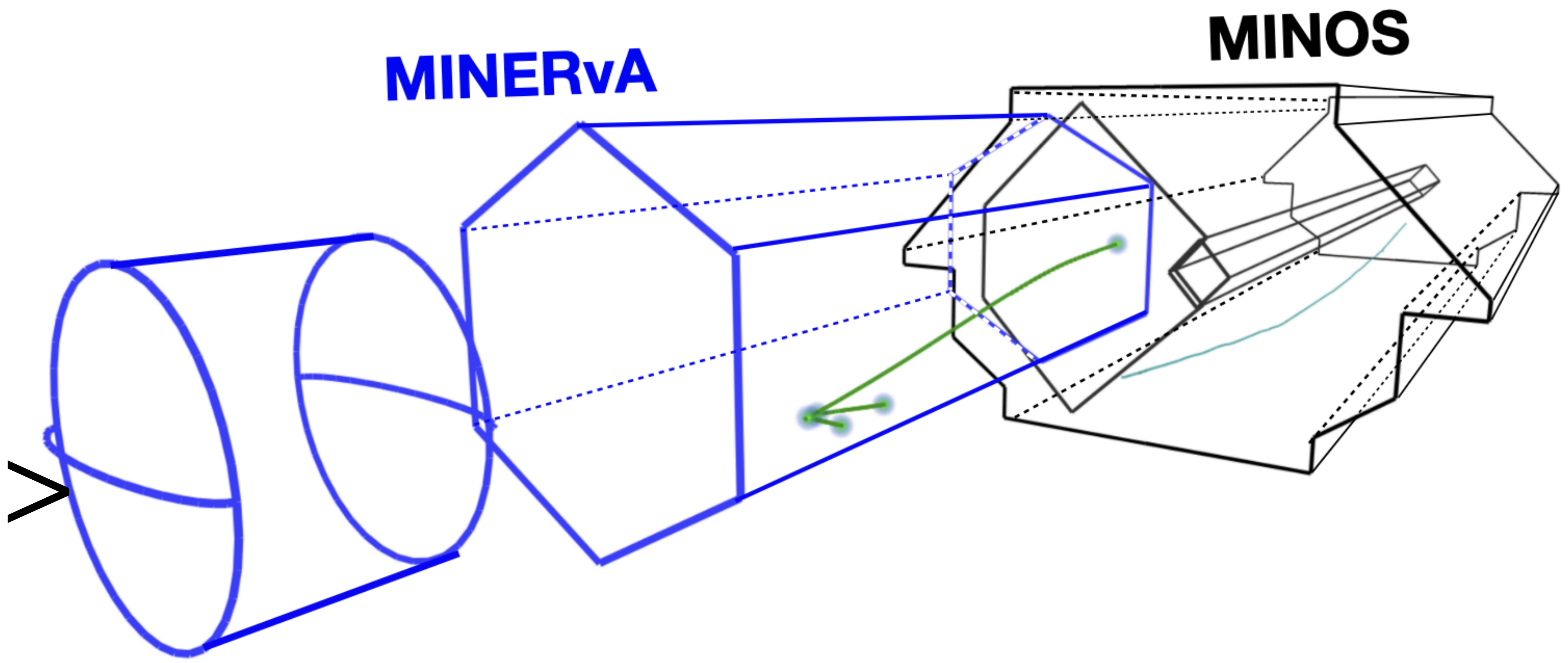
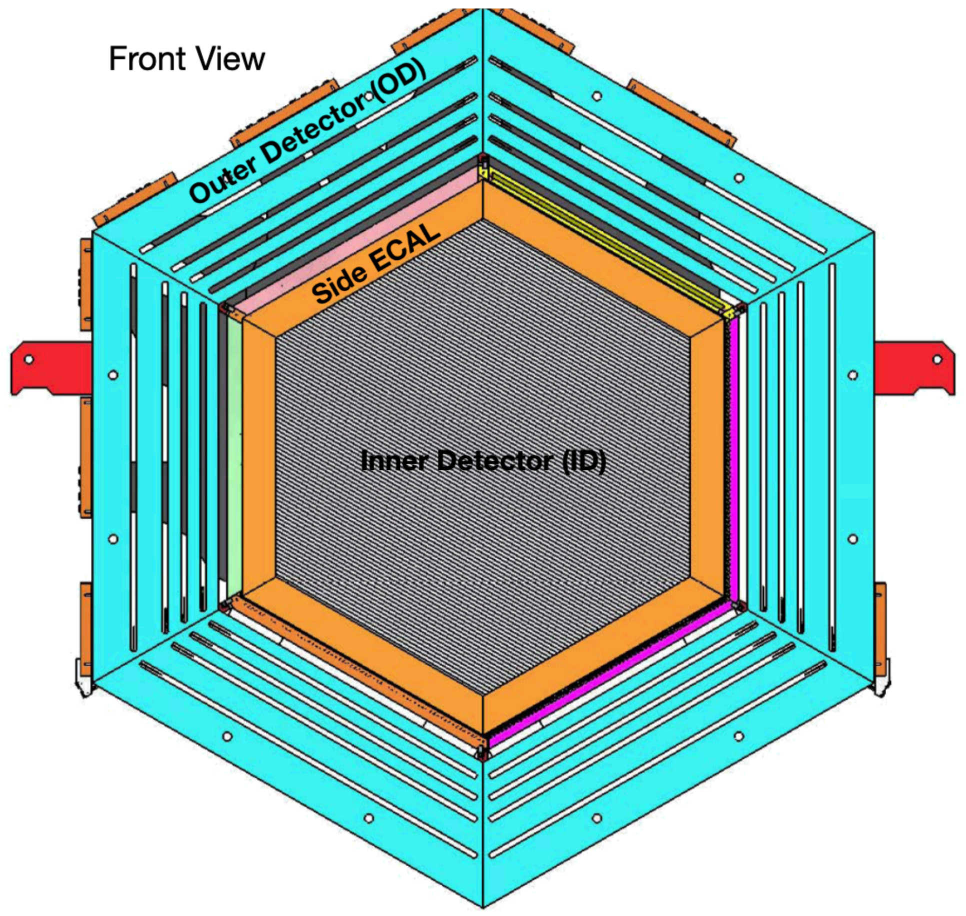
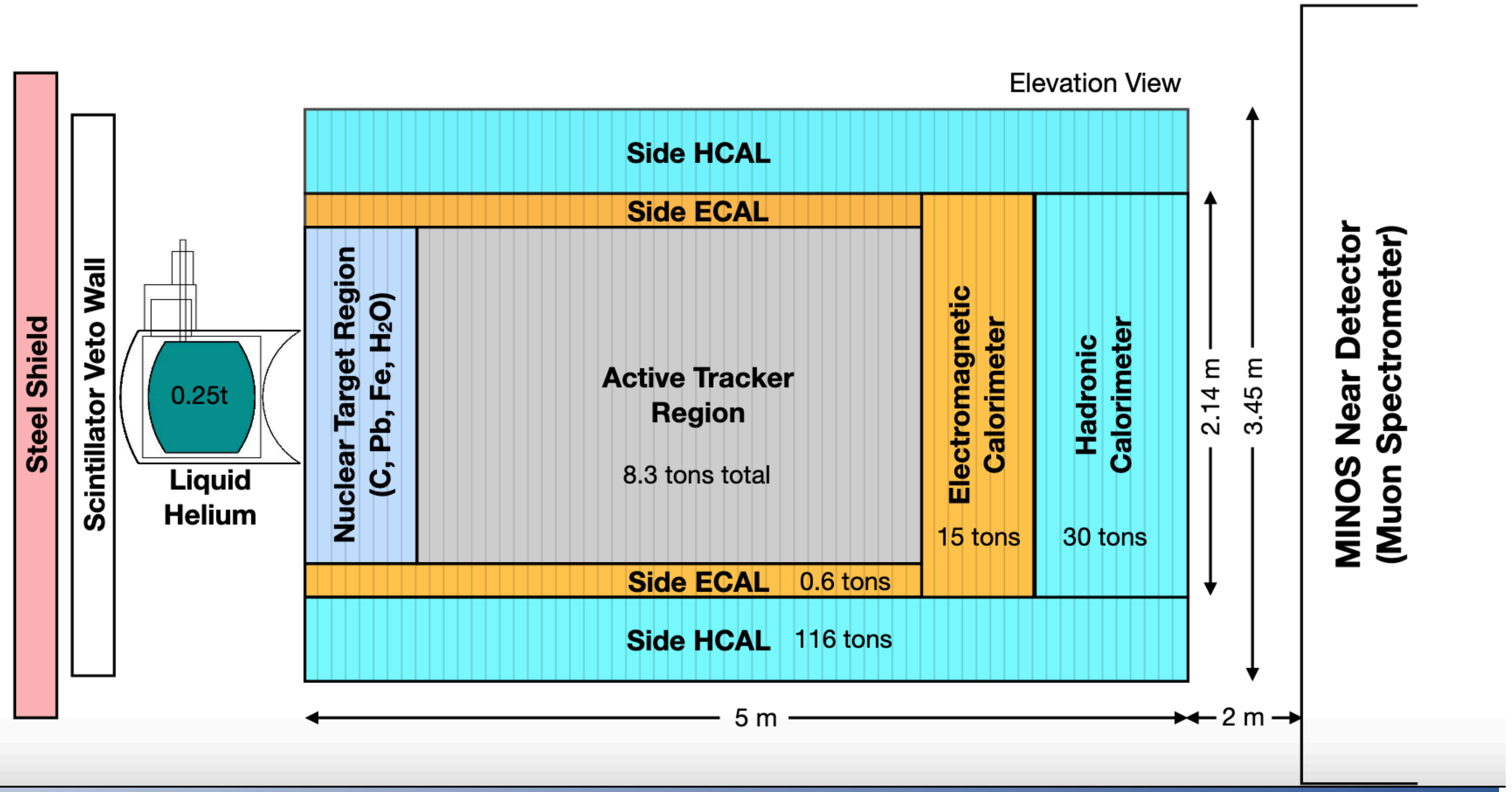
MINERvA Experiments

Neutrinos ->







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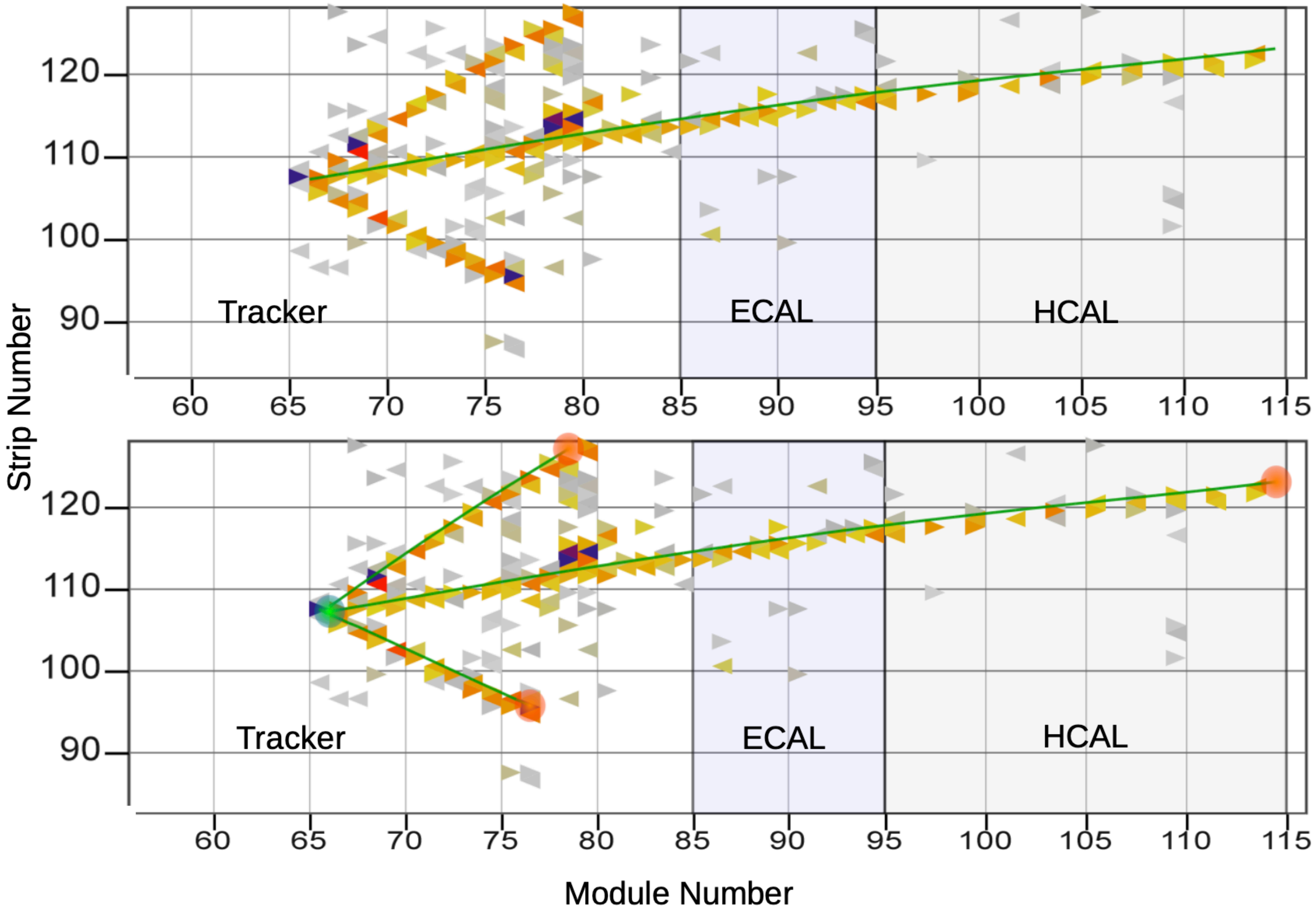
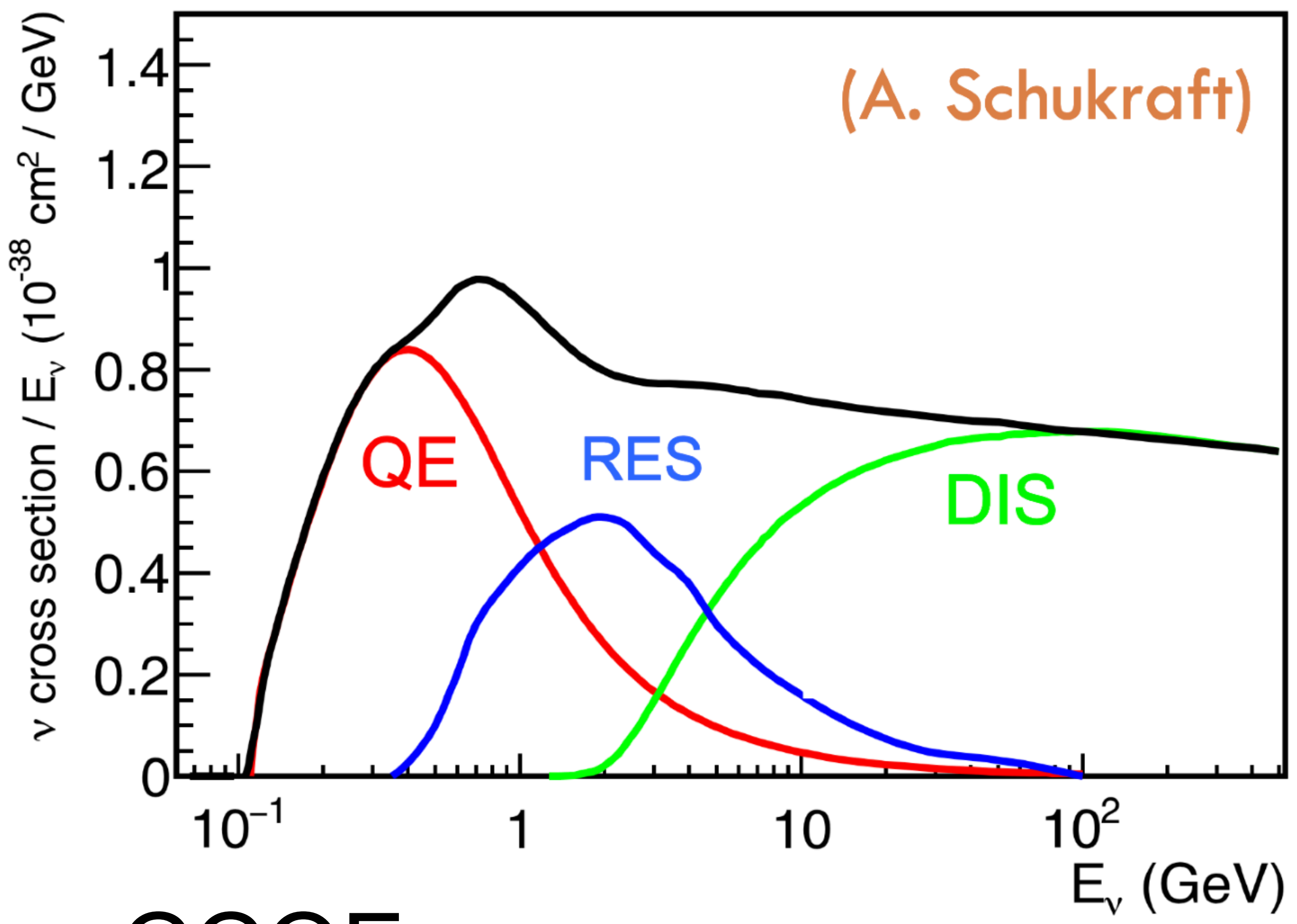
Analysis definition

Event reconstruction:



Introduction

Neutrino Cross-Section

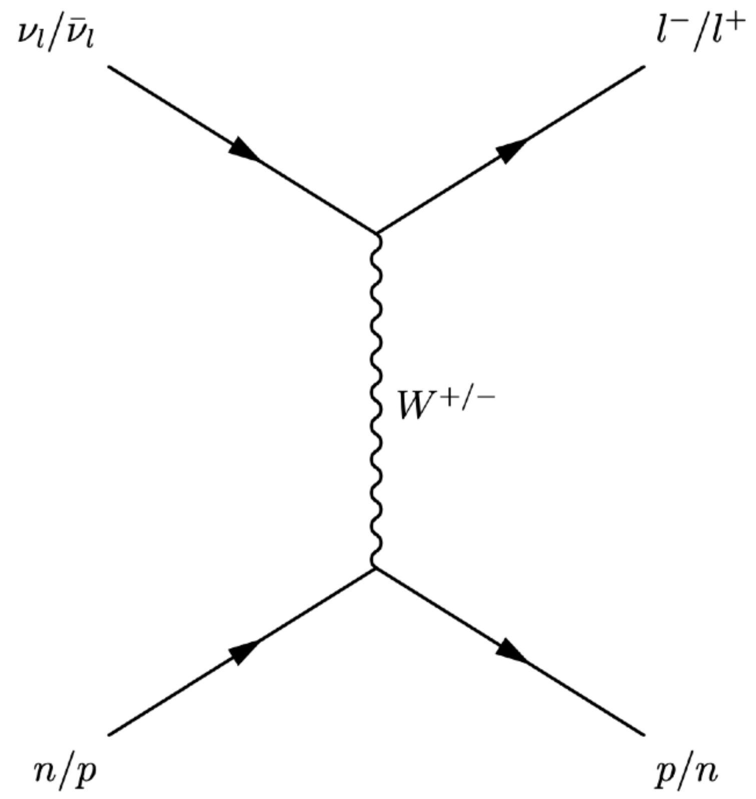


Leptonic Tensor

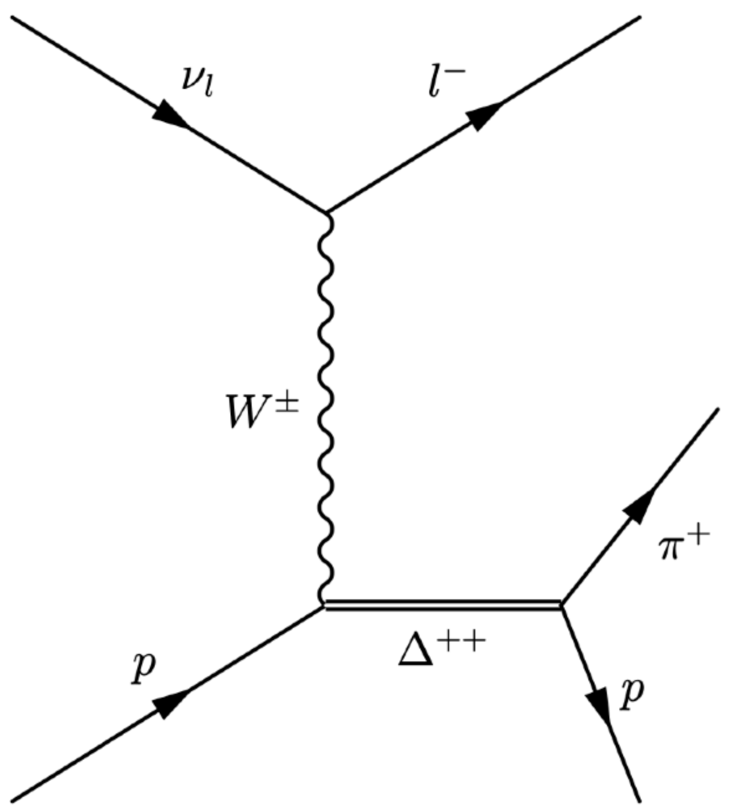
$$\frac{d^2\sigma}{d\Omega(\hat{k}')dE_l'} = \frac{|\vec{k}'|}{|\vec{k}|}\frac{G^2}{4\pi^2}L_{\mu\sigma}W^{\mu\sigma}$$

Hadronic Tensor

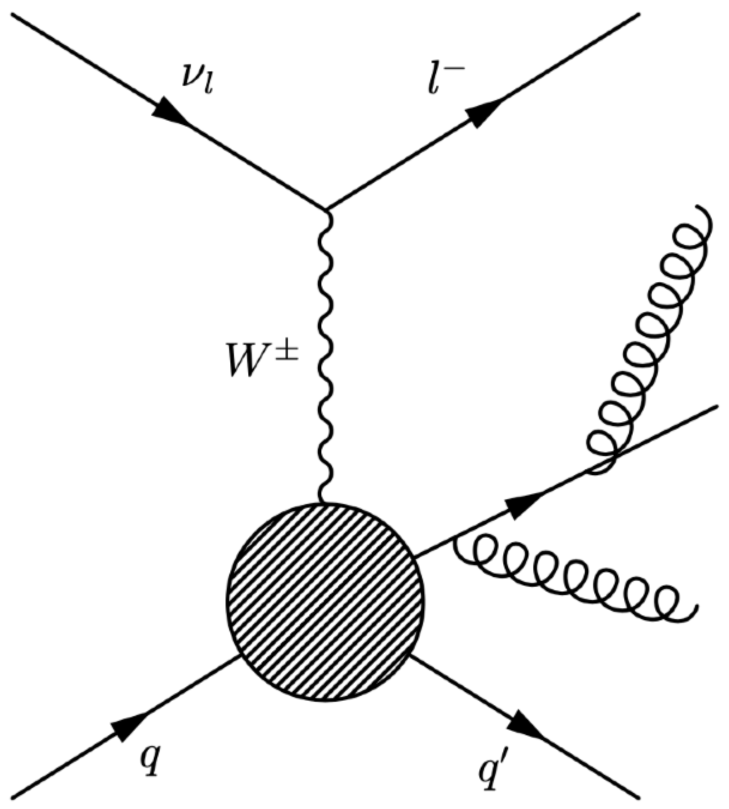
CCQE



CCRES



CCDIS



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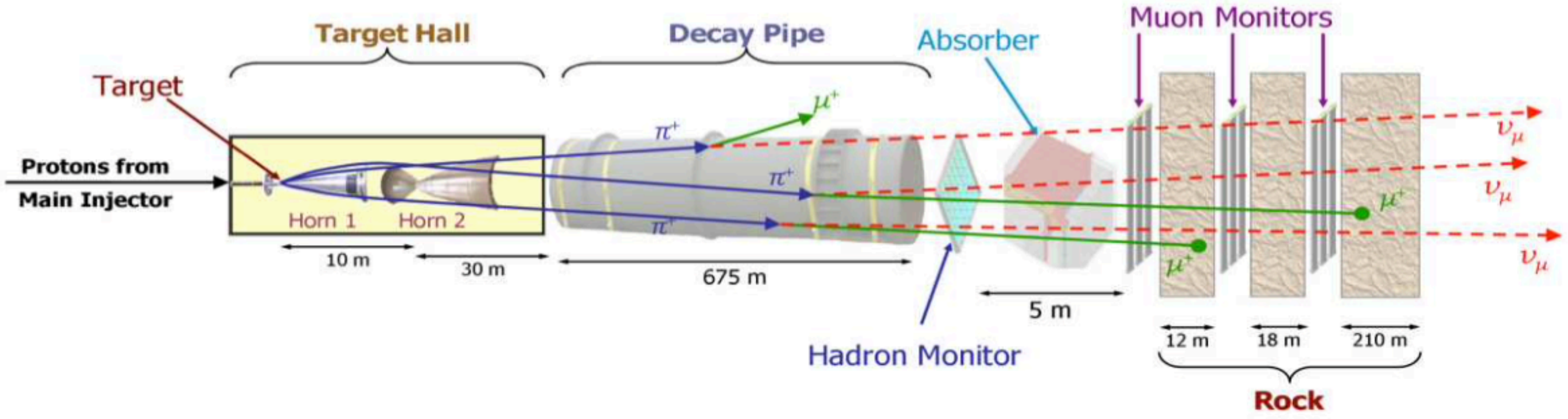
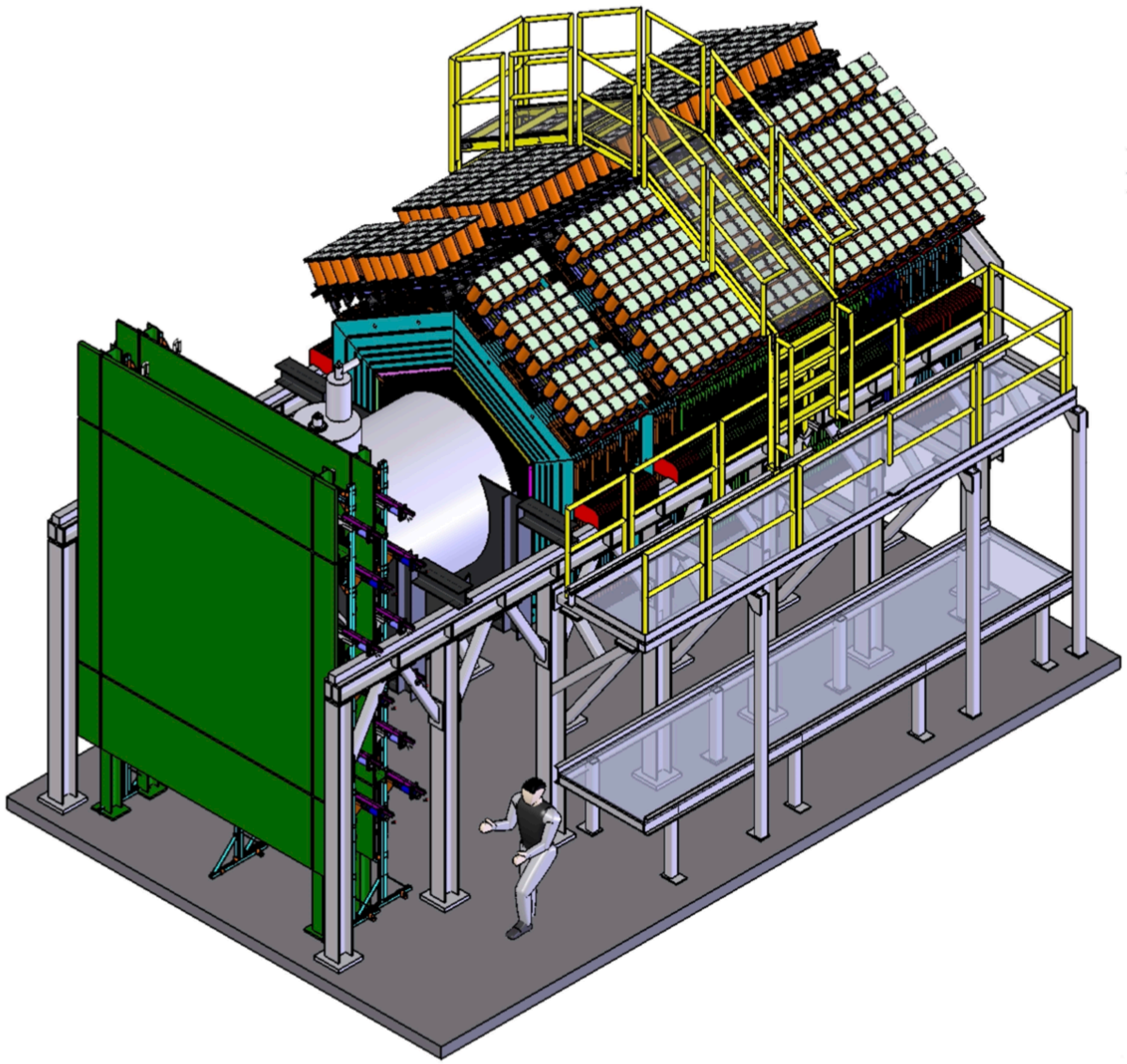


Figure 3.3: Big picture of neutrino production. Figure taken from [167].



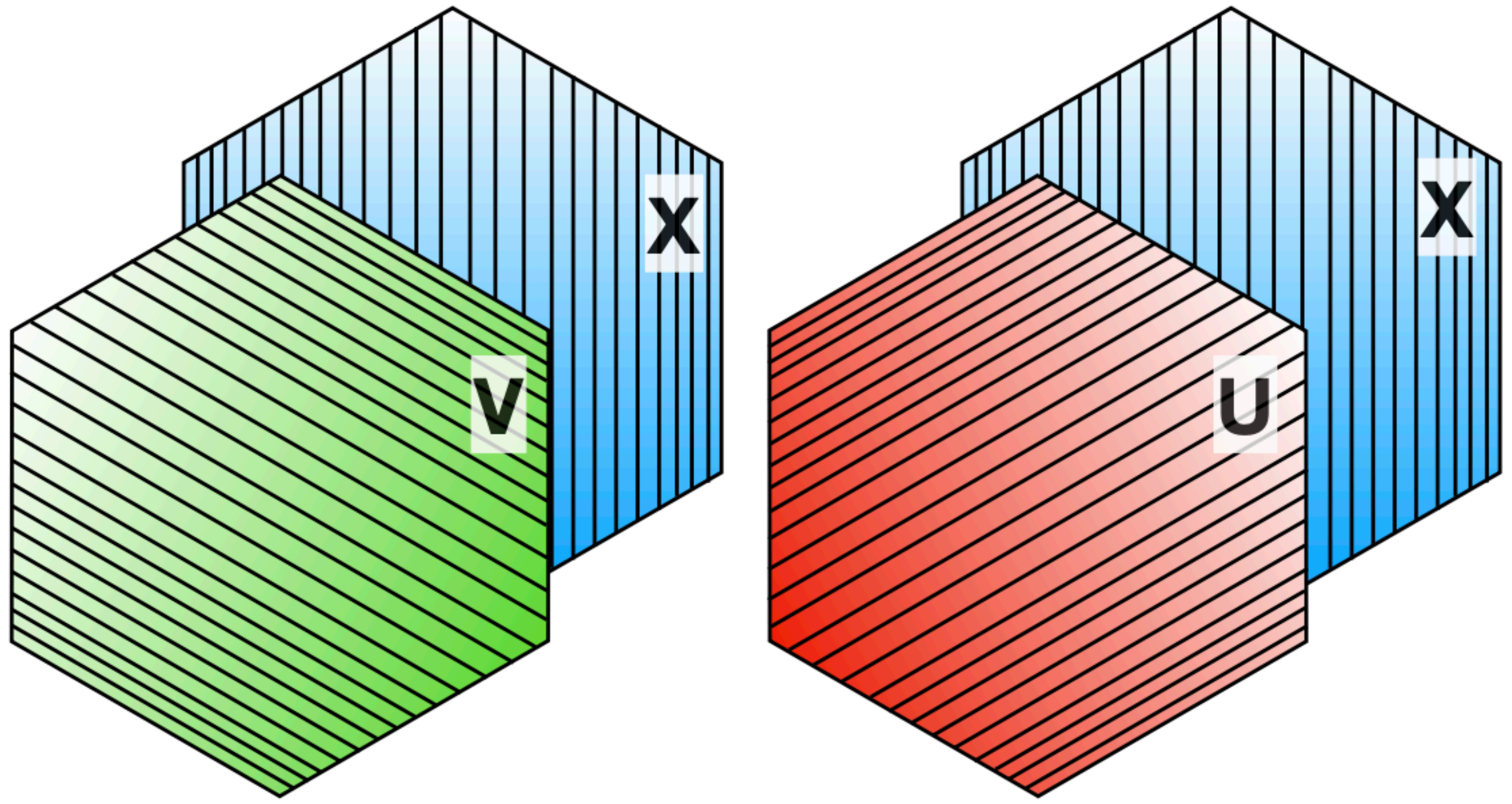


Figure 4.7: Plane orientation, “VX” view on left and “UX” on the right side.

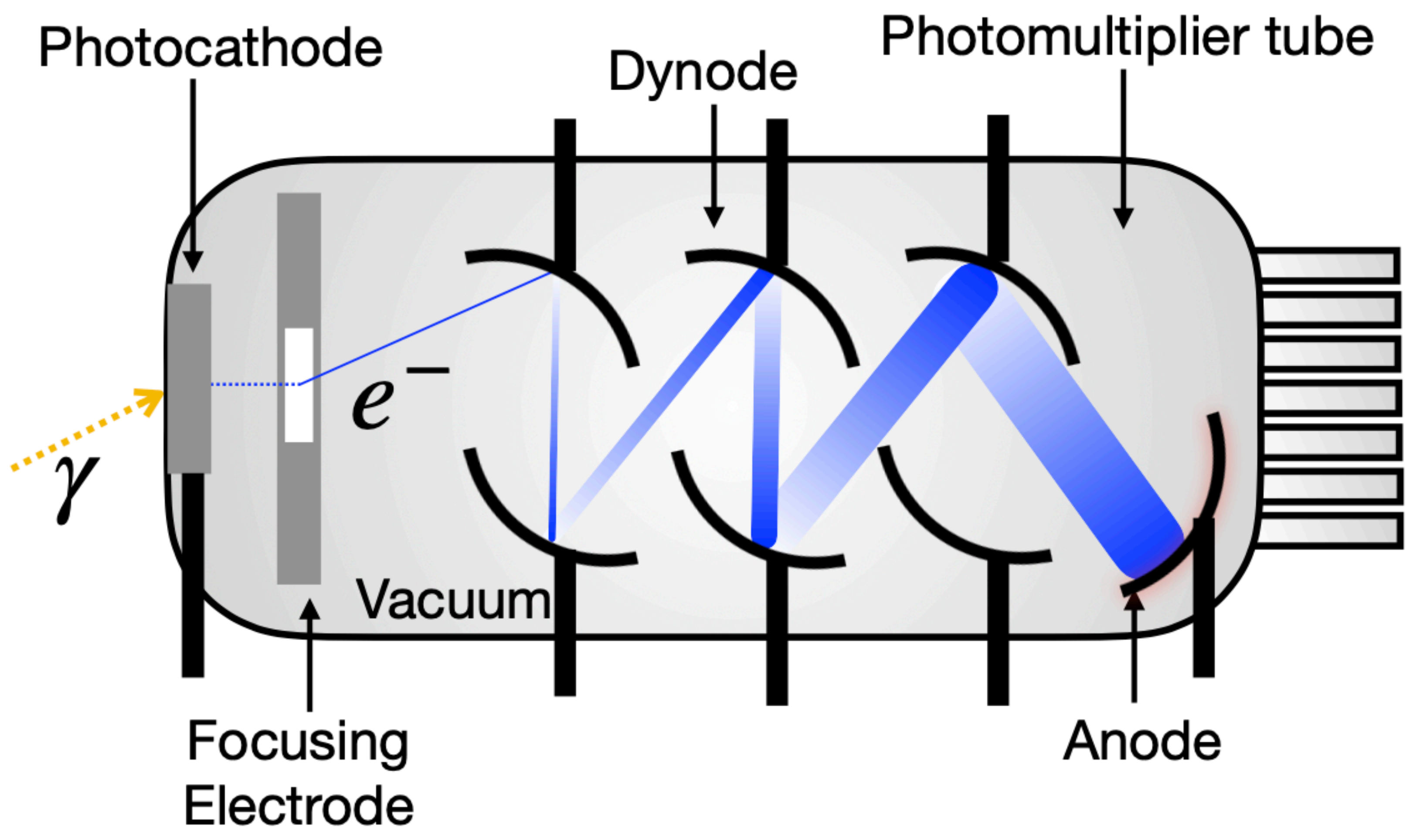
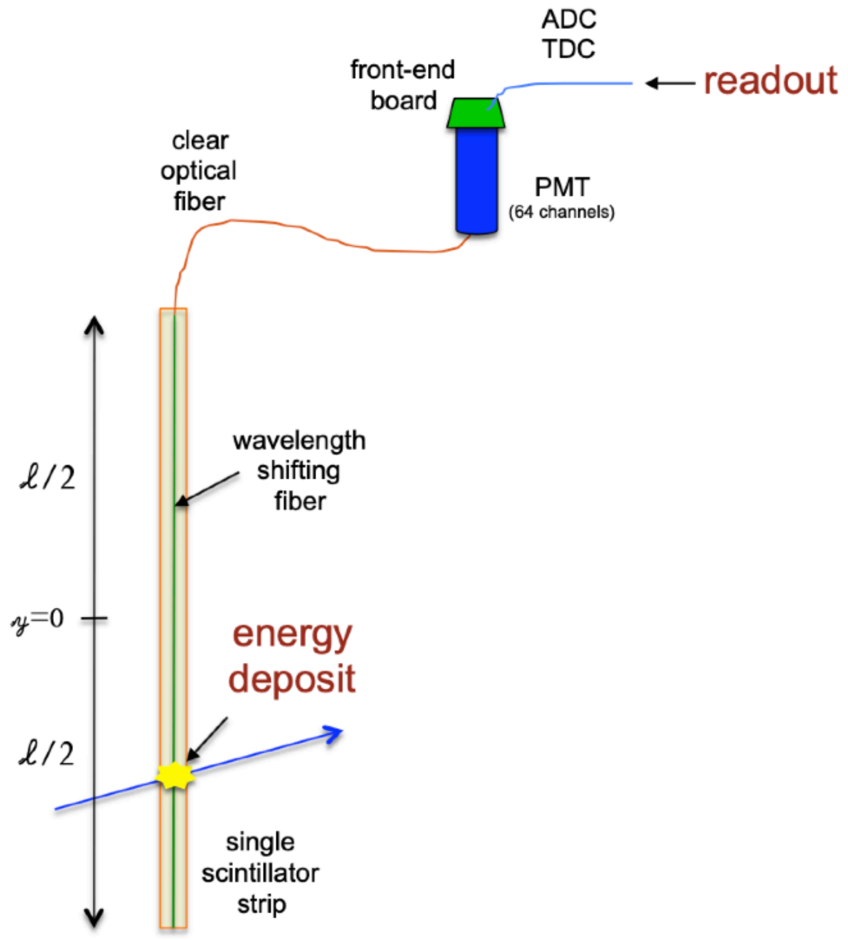
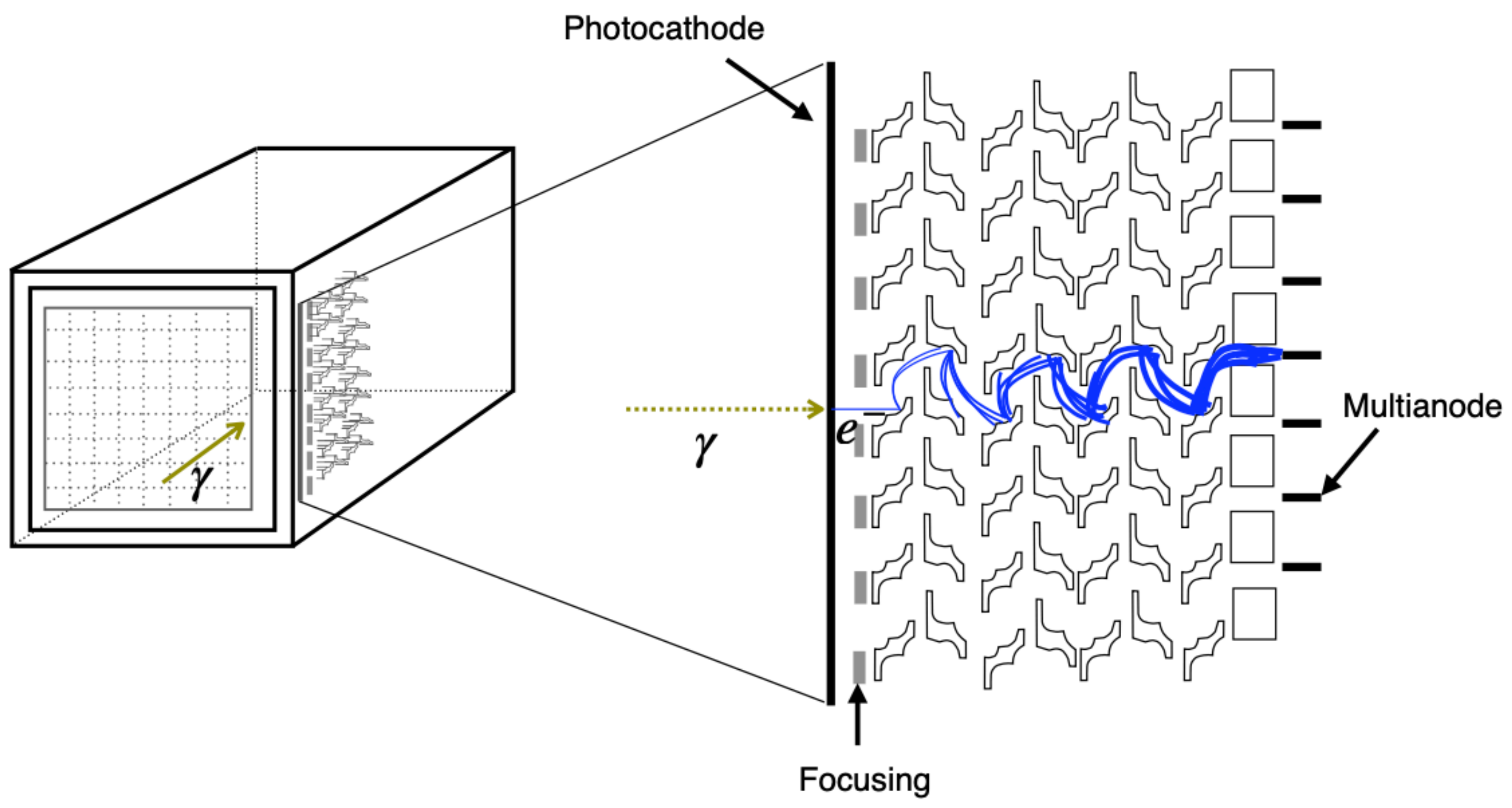
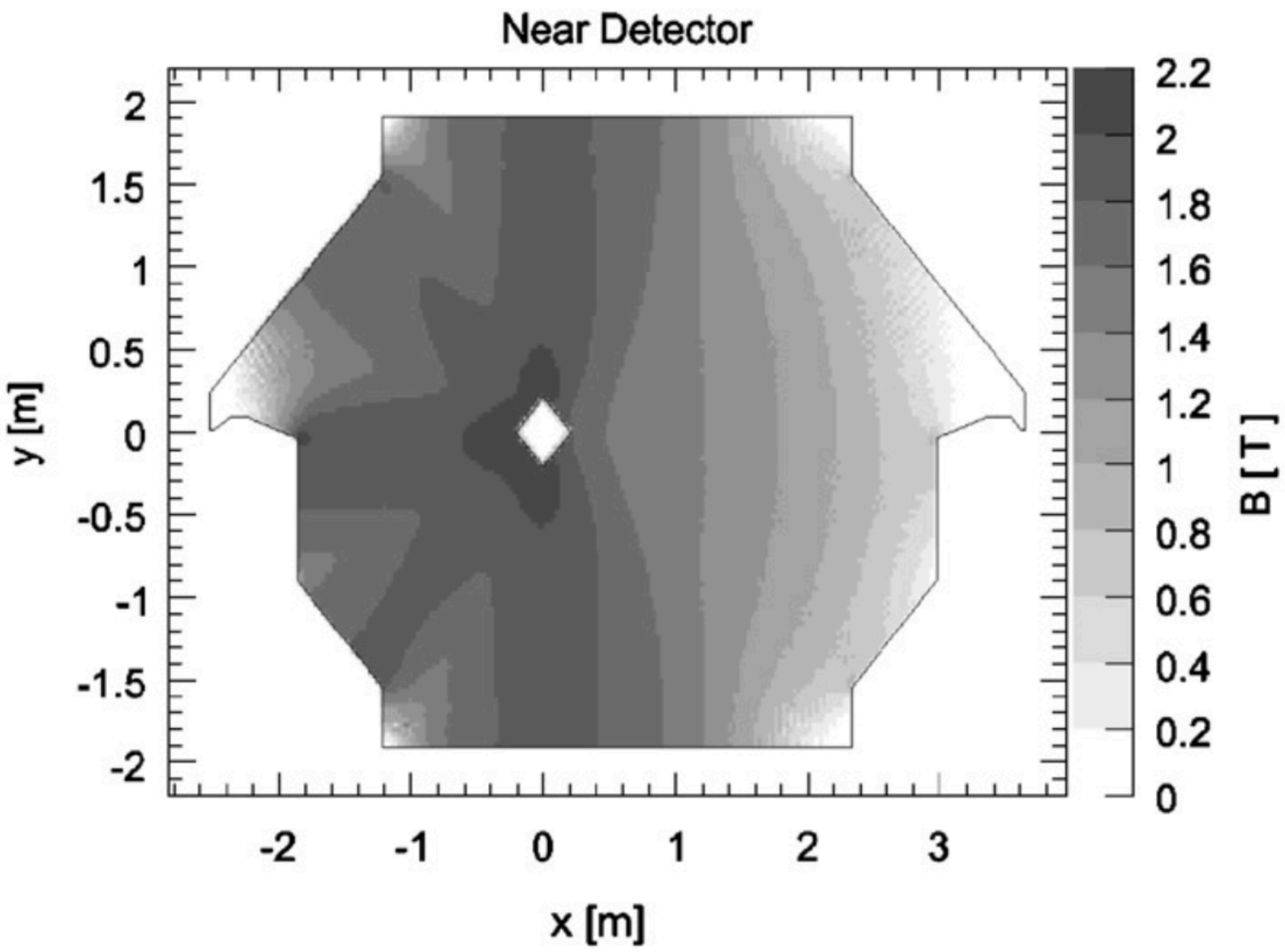


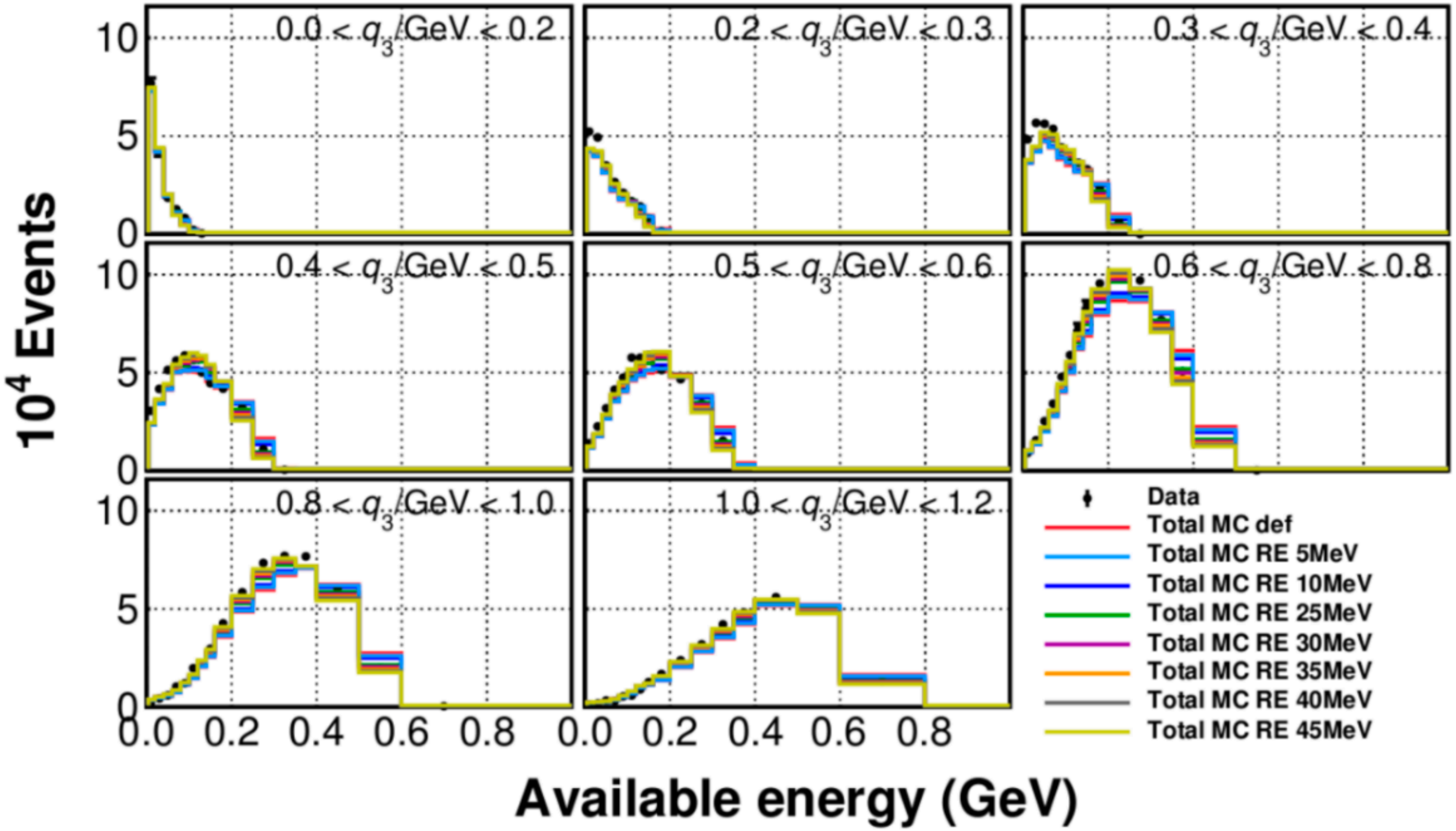
Figure 4.9: Basic working principle of photo-multiplier tube (PMT).







Near Detector
y [m]
x [m]
B [T]
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2
-1
0
1
2
3
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0



10⁴ Events
0.0 < q3/GeV < 0.2
0.2 < q3/GeV < 0.3
0.3 < q3/GeV < 0.4
0.4 < q3/GeV < 0.5
0.5 < q3/GeV < 0.6
0.6 < q3/GeV < 0.8
0.8 < q3/GeV < 1.0
1.0 < q3/GeV < 1.2
Data
Total MC def
Total MC RE 5MeV
Total MC RE 10MeV
Total MC RE 25MeV
Total MC RE 30MeV
Total MC RE 35MeV
Total MC RE 40MeV
Total MC RE 45MeV
Available energy (GeV)

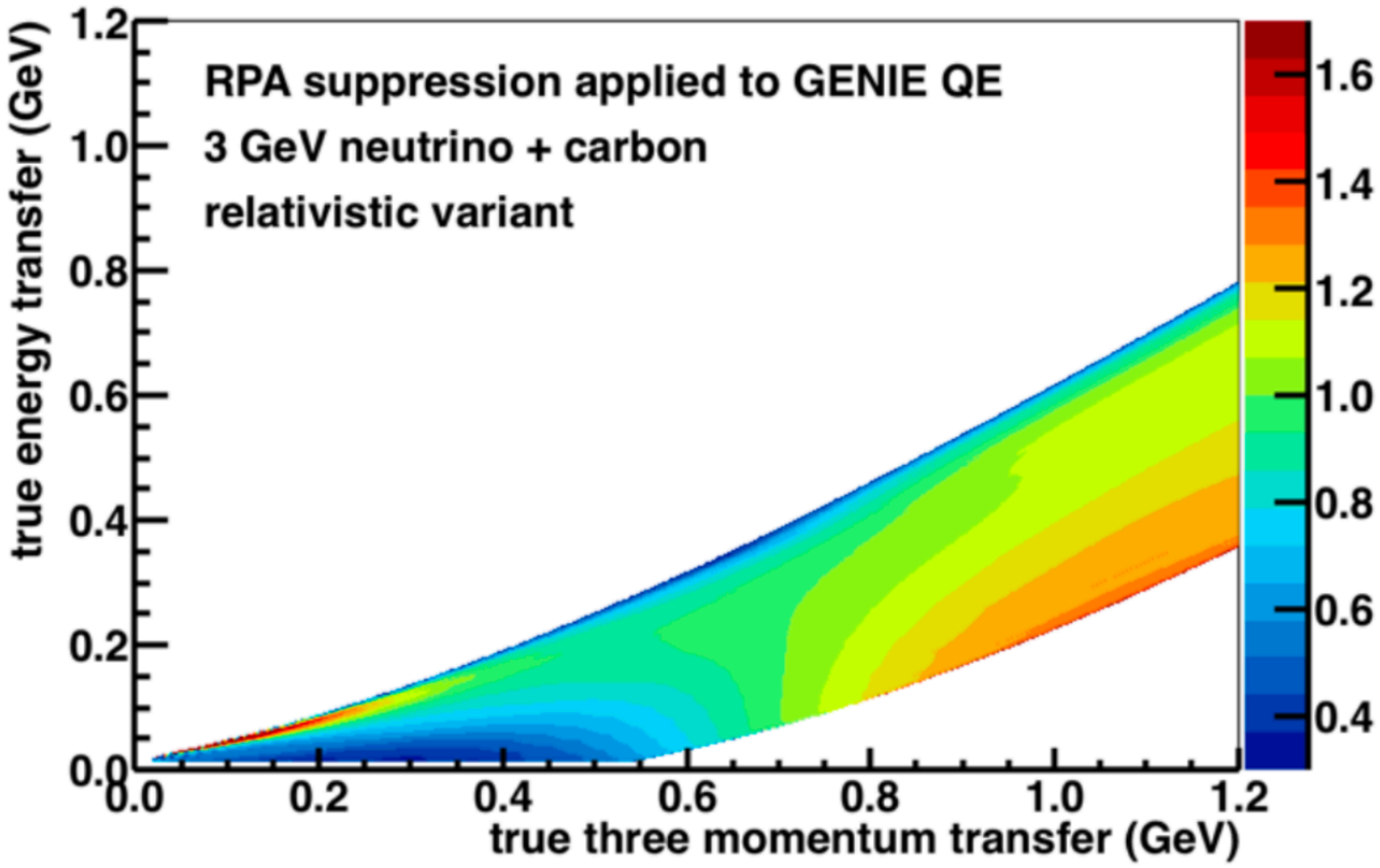
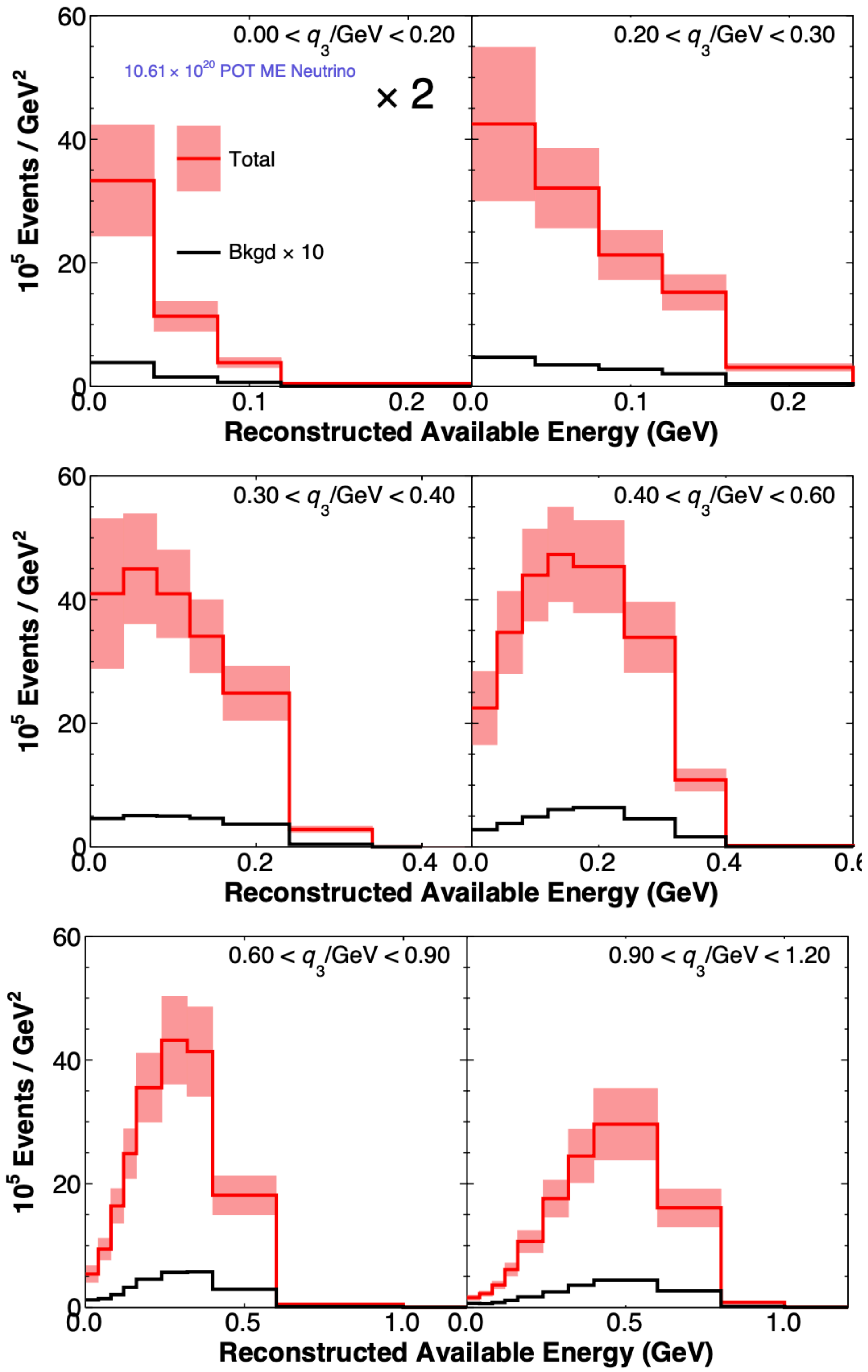
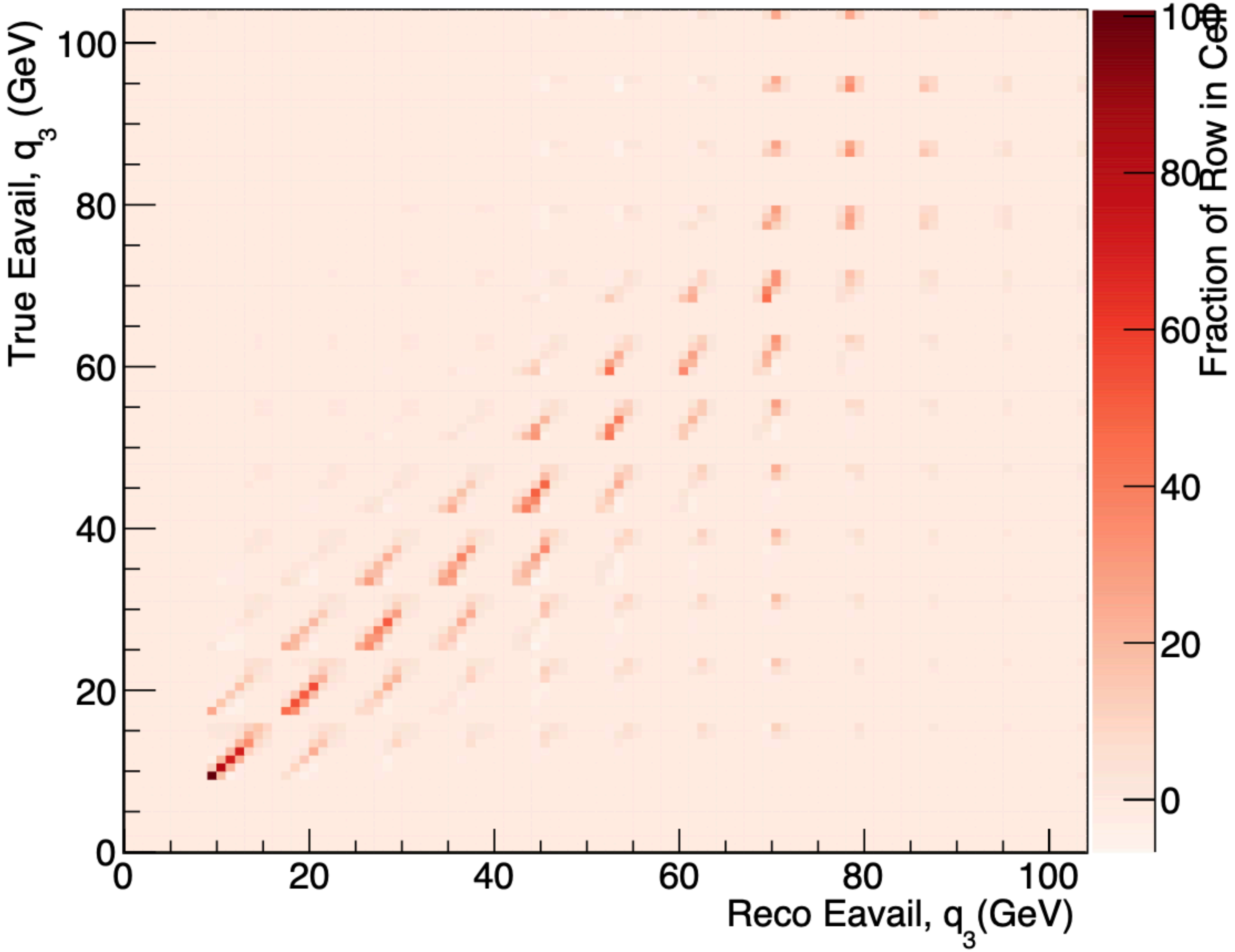


Figure 6.47: Quasi-elastic RPA weight, figure taken from [227].

Model	$0.0 < q_3 < 0.2$	$0.2 < q_3 < 0.3$	$0.3 < q_3 < 0.4$	$0.4 < q_3 < 0.6$	$0.6 < q_3 < 0.9$	$0.9 < q_3 < 1.2$	total q_3
MnvTune-v3	392.055	348.078	1143.55	2150.36	2139.16	4831.46	11004.7
MnvTune-v1.2	55.197	1276.2	2398.66	7111.61	16091.7	12580.2	39513.6
RES Removal En.	138.873	1244.33	1588.71	2213.51	4047.33	4534.58	13767.3
SuSA 2p2h	344.72	2914.46	6405.35	14673.6	16161.3	10755.1	51254.6
SuSA 2p2h + B-R t.	392.573	1011.05	3340.57	8301.42	11645.4	10988.3	35679.3
Pauli B. + B-S.	166.02	2099.61	2943.02	5545.34	14061.8	12635	37450.8
MK model	46.8538	1014.62	2226.67	5977.98	9325.34	7041.15	25632.6
Low $Q^2\pi$ Supp	248.074	3129.47	5531.65	11324.6	15413	4548.34	40195.1
RPA to RES	122.432	1727.42	2724.15	7083.15	17545.2	12373.6	41575.9
Bodek-Ritchie T.	888.343	248.365	1036.13	4867.08	12489.2	12093.5	31622.7



0.00 < q_3/GeV < 0.20
10.61 × 10^{20} POT ME Neutrino
× 2
Total
Bkgd × 10
0.20 < q_3/GeV < 0.30
0.30 < q_3/GeV < 0.40
0.40 < q_3/GeV < 0.60
0.60 < q_3/GeV < 0.90
0.90 < q_3/GeV < 1.20
10^5 Events / GeV^2
Reconstructed Available Energy (GeV)


True Eavail, q3 (GeV)
100
80
60
40
20
0
0
20
40
60
80
100
Reco Eavail, q3(GeV)
100
80
60
40
20
0
Fraction of Row in Cell

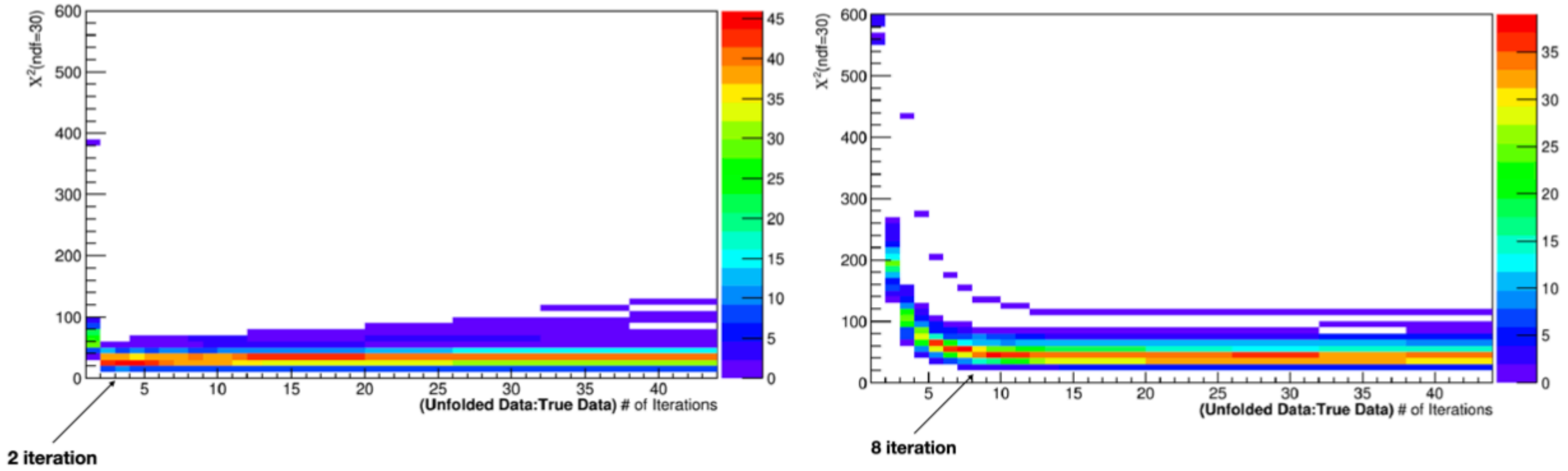
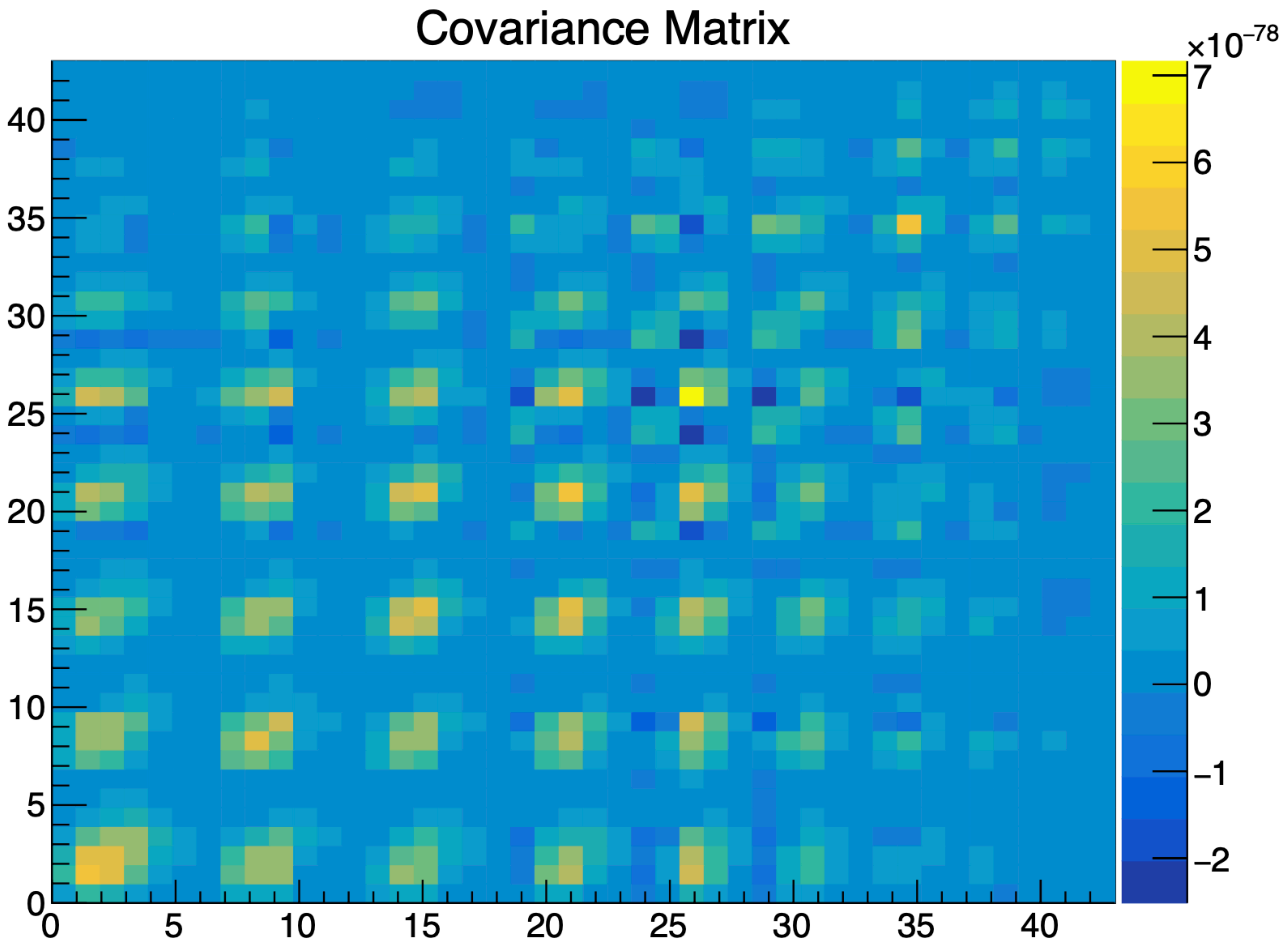
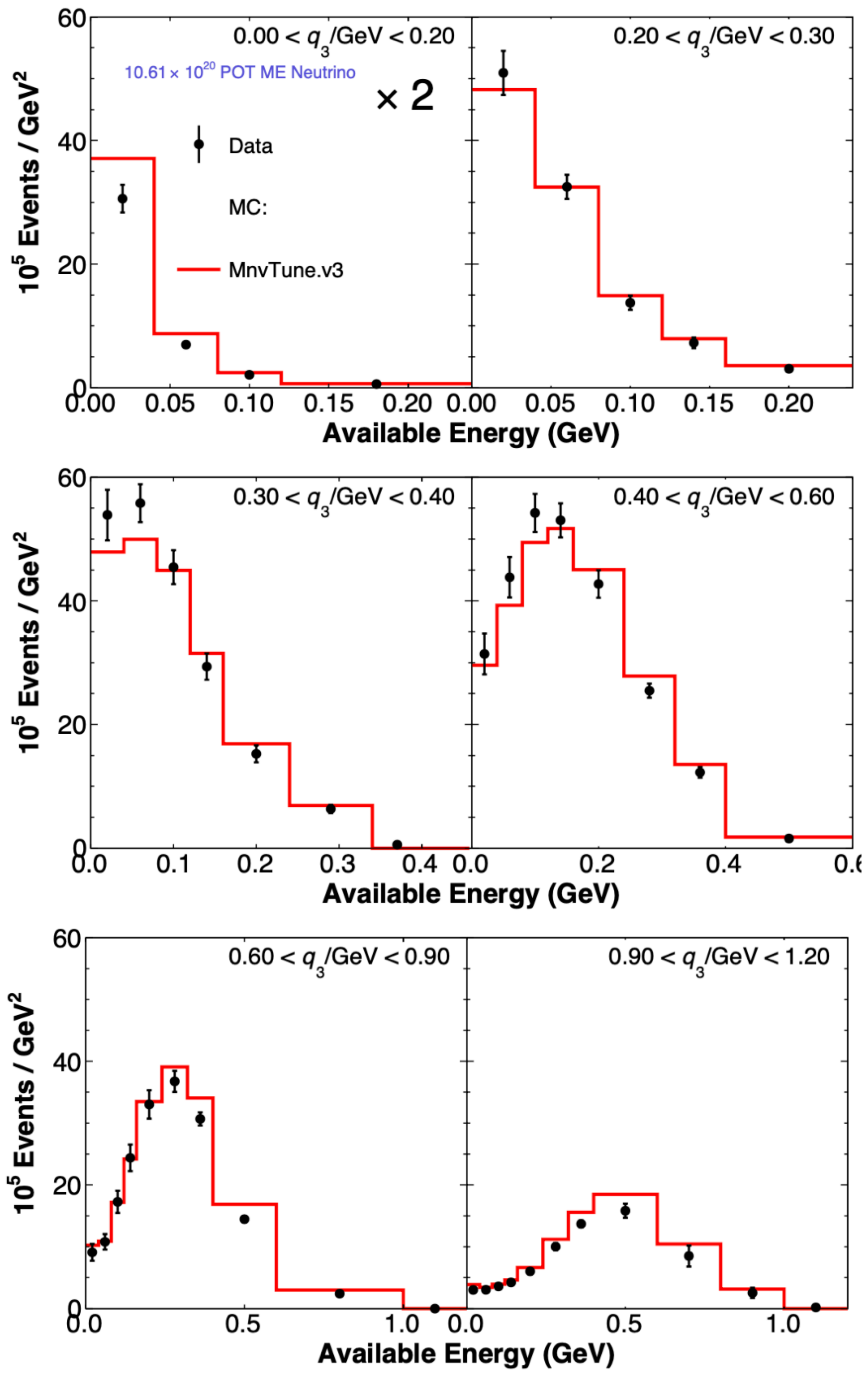


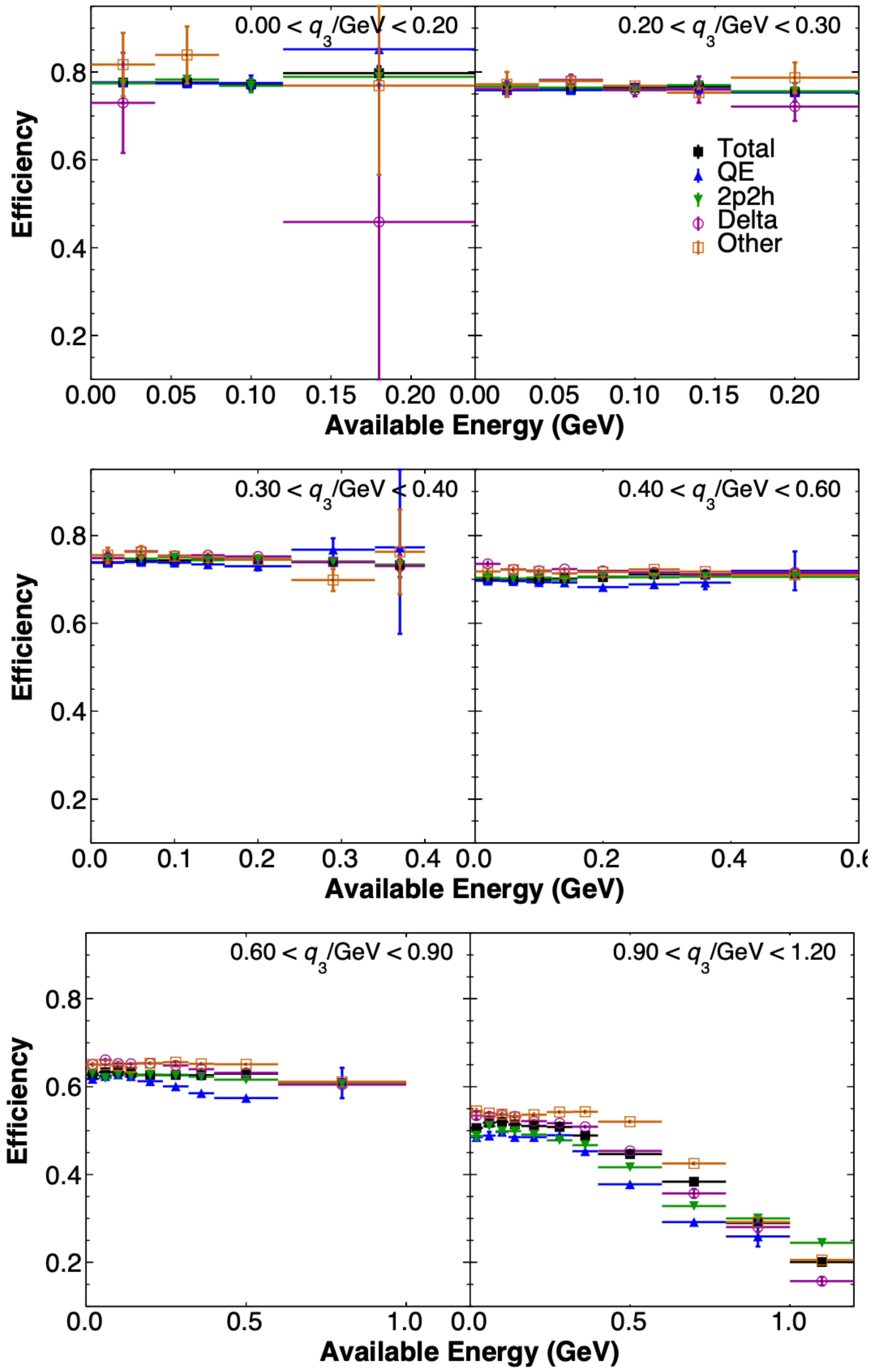
Figure 7.16: Number of iterations vs χ^2 of "truth fake data" and unfolded distribution. Left, reconstructed MC unfolded with 1 σ RPA variantion. Right, reconstructed mc unfolded with one of the low recoil fit uncertainties. Thrown with 100 Poisson random variations.

PUCP





Marvin V. Ascencio Sosa


0.00 < q3/GeV < 0.20
0.20 < q3/GeV < 0.30
Total
QE
2p2h
Delta
Other
Efficiency
Available Energy (GeV)
0.30 < q3/GeV < 0.40
0.40 < q3/GeV < 0.60
0.60 < q3/GeV < 0.90
0.90 < q3/GeV < 1.20

PUCP

$$\chi^2_{ij_{\text{model}}} = (x_{i,\text{measured}} - x_{i,\text{expected}_{\text{model}}}) \times V_{ij}^{-1} \times (x_{j,\text{measured}} - x_{j,\text{expected}_{\text{model}}})$$

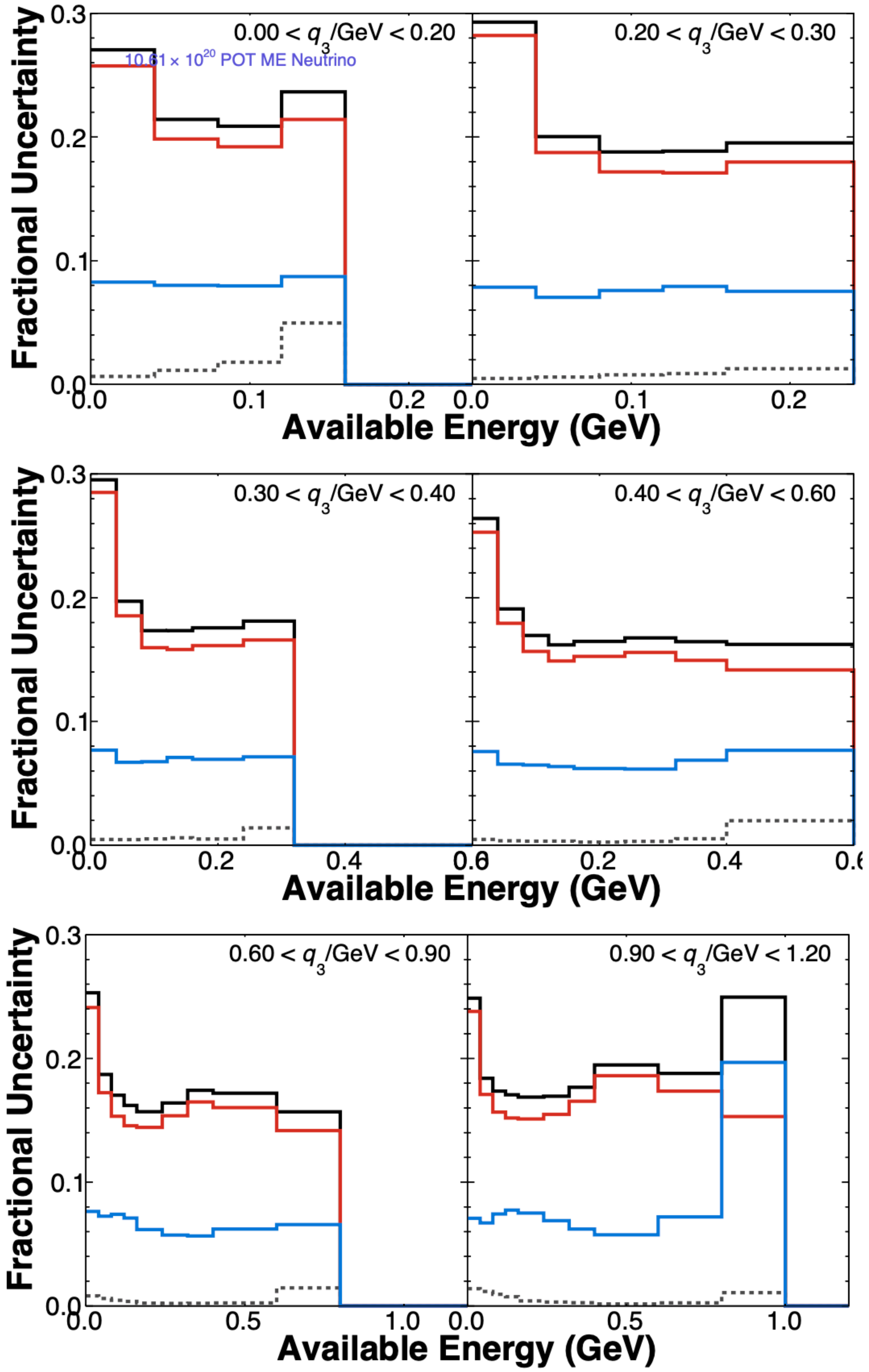
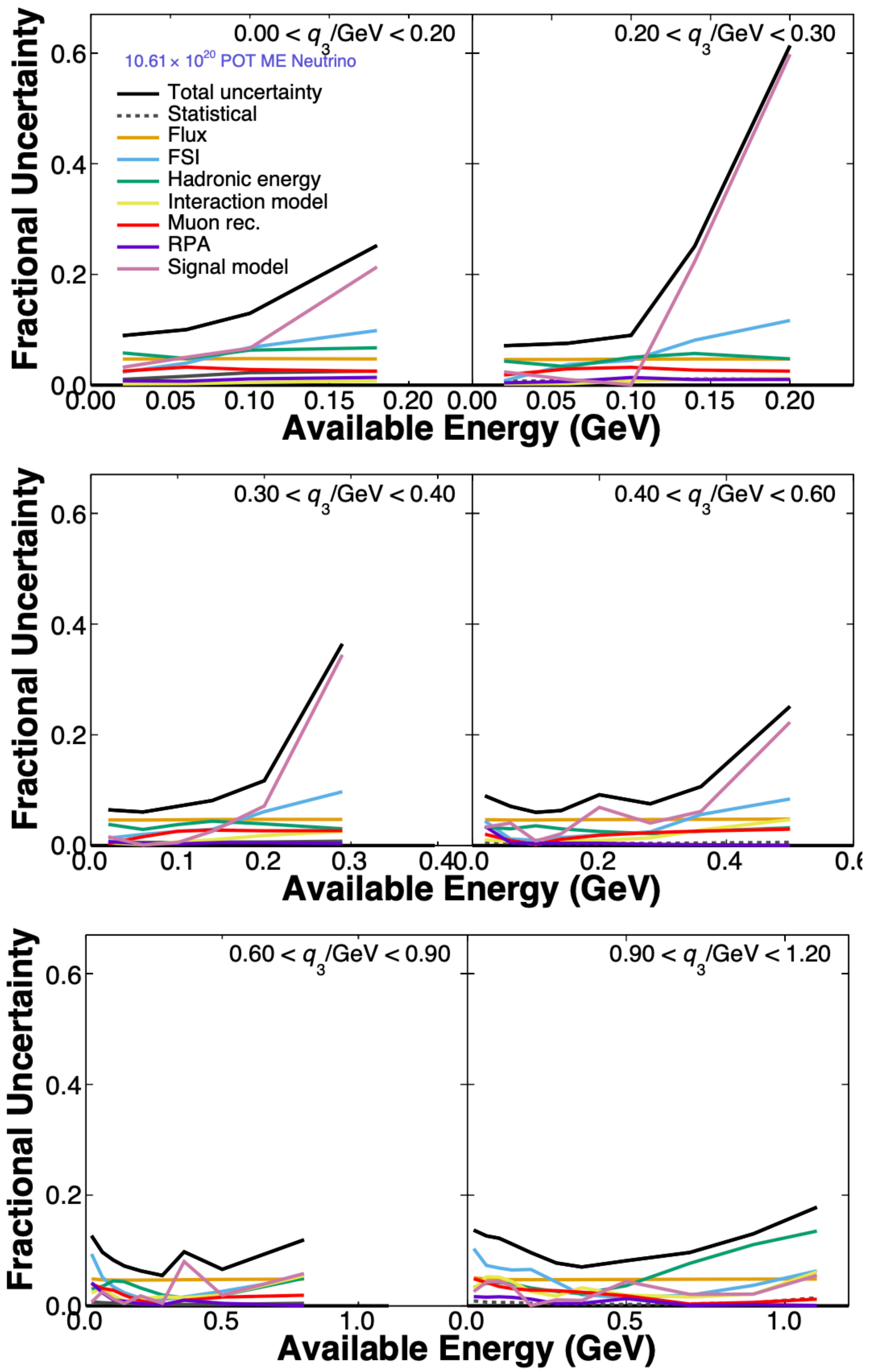
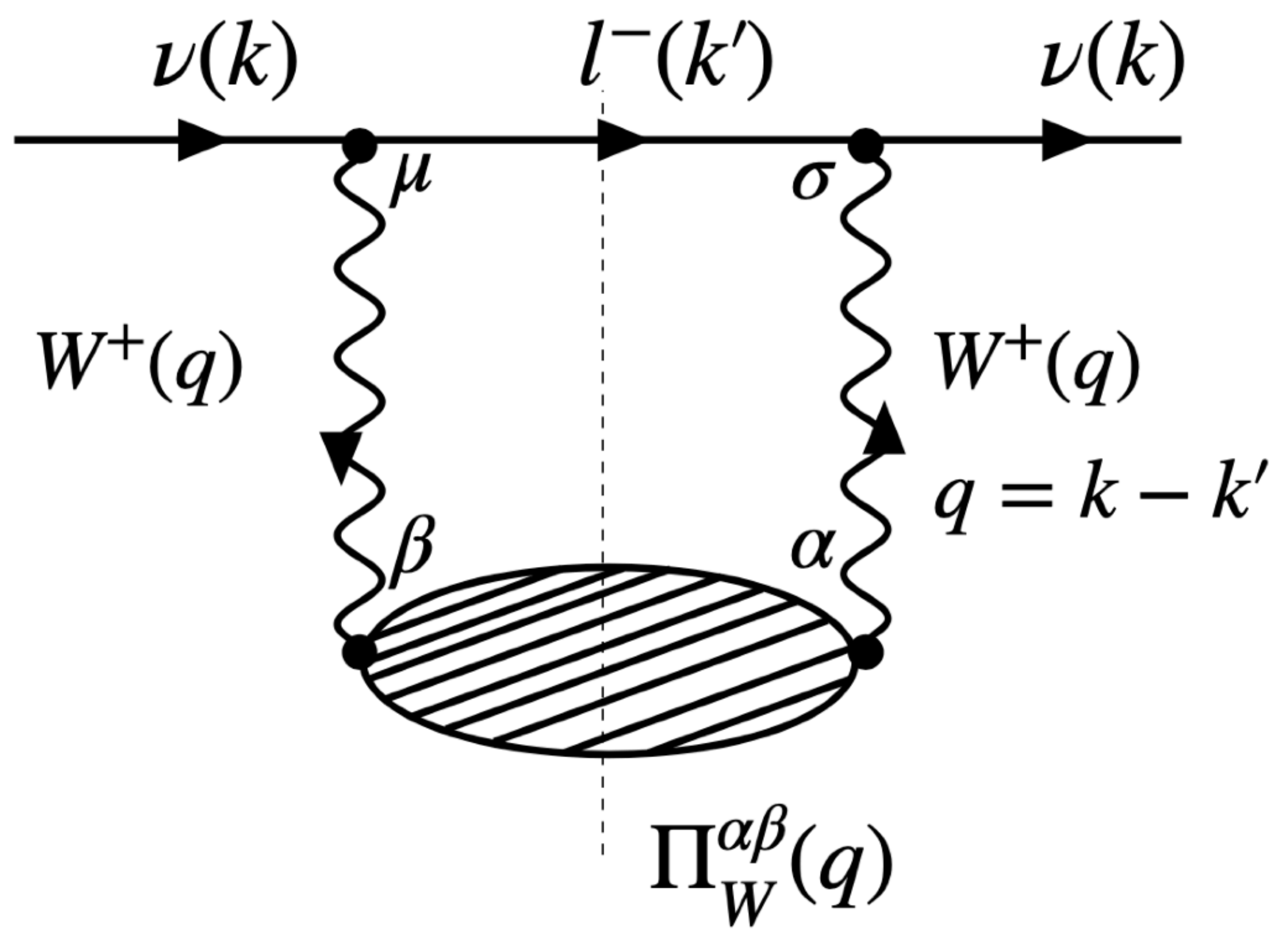
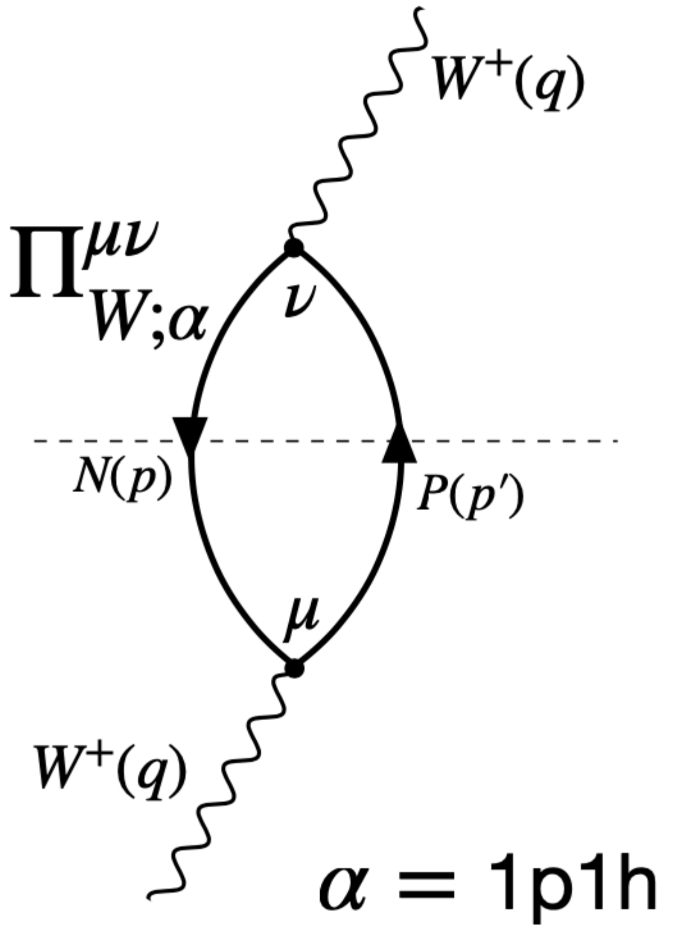


Figure 7.29: Fractional detector uncertainty.

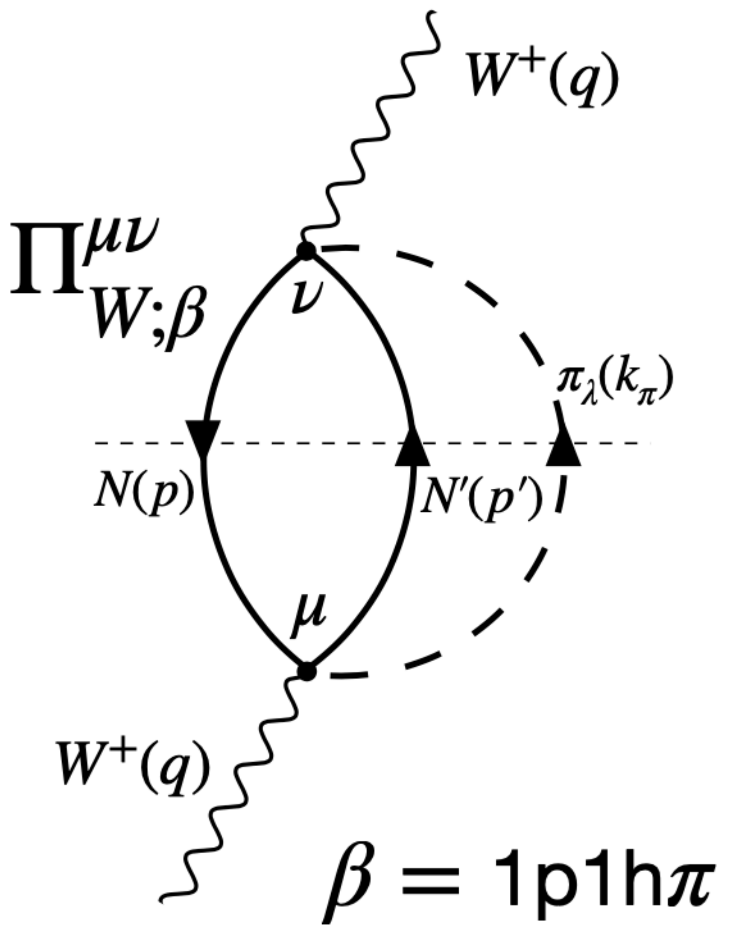

0.00 < q_3/GeV < 0.20
0.20 < q_3/GeV < 0.30
0.30 < q_3/GeV < 0.40
0.40 < q_3/GeV < 0.60
0.60 < q_3/GeV < 0.90
0.90 < q_3/GeV < 1.20
10.61×10^{20} POT ME Neutrino
Total uncertainty
Statistical
Flux
FSI
Hadronic energy
Interaction model
Muon rec.
RPA
Signal model
Fractional Uncertainty
Available Energy (GeV)



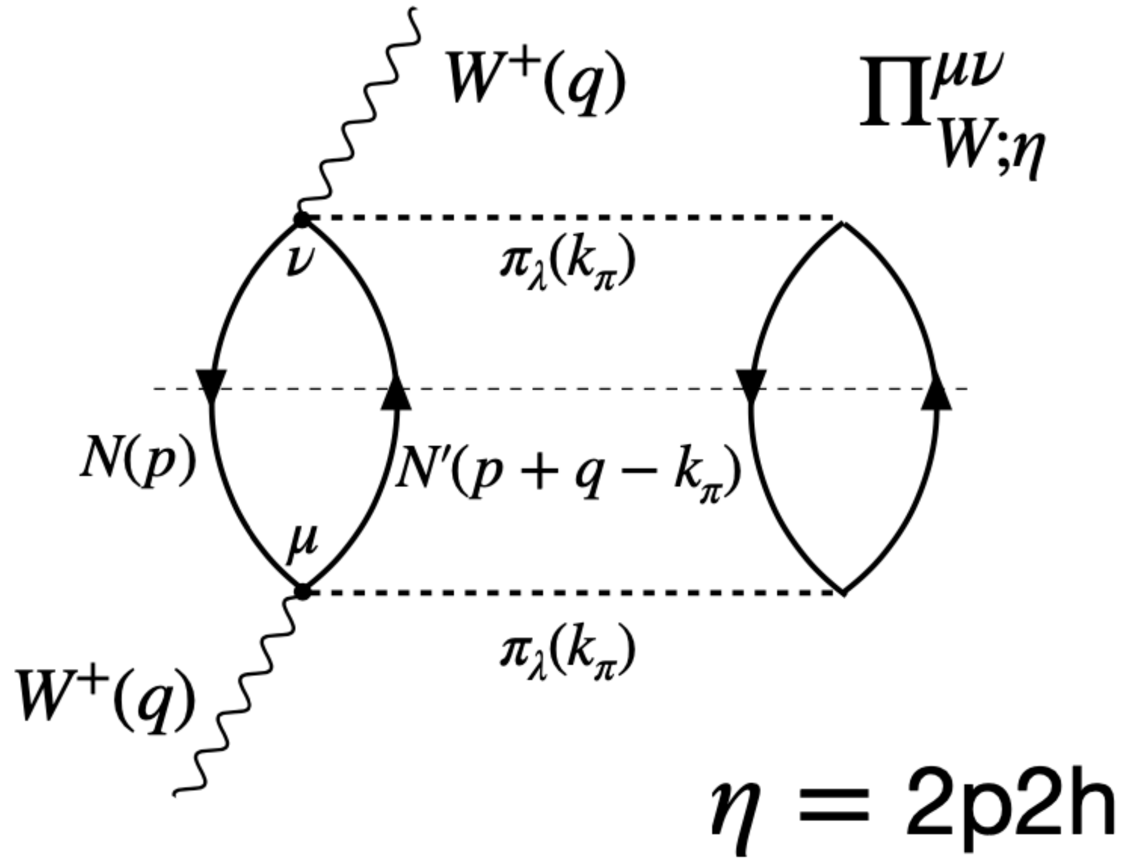
$\nu(k)$
$l^-(k')$
$\nu(k)$
μ
σ
$W^+(q)$
$W^+(q)$
$q = k - k'$
β
α
$\Pi_W^{\alpha\beta}(q)$



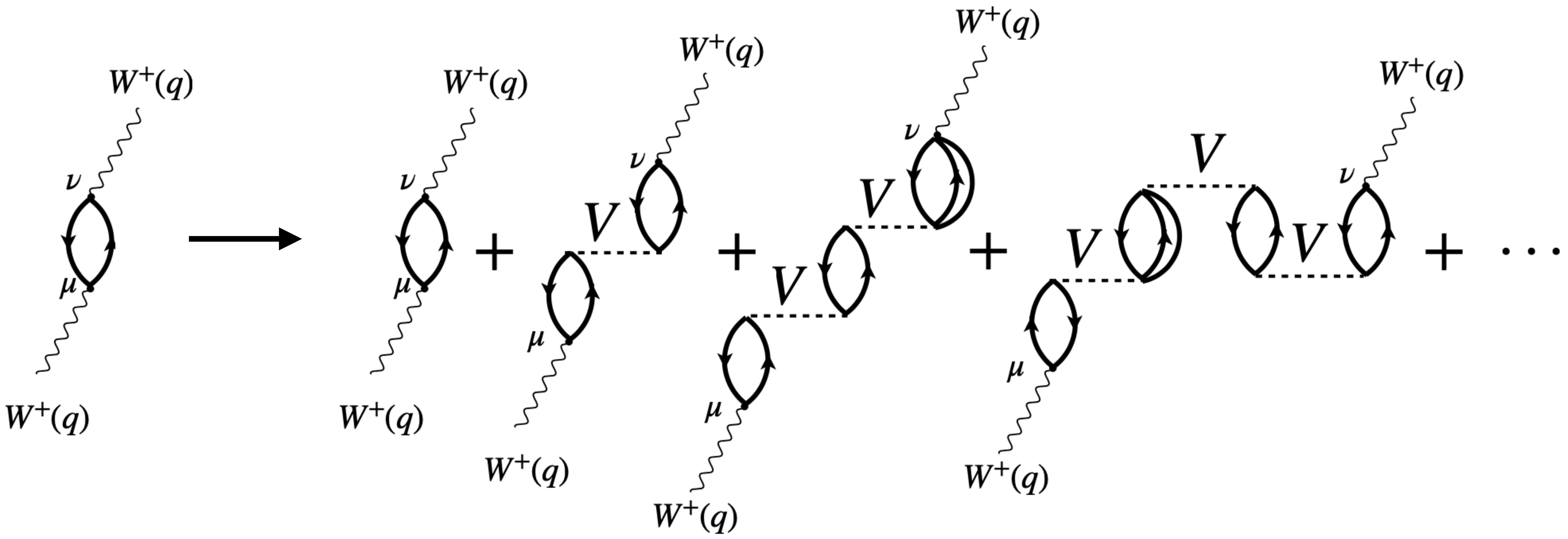
$W^+(q)$
$\Pi^{\mu\nu}_{W;\alpha}$
ν
$N(p)$
$P(p')$
μ
$W^+(q)$
α = 1p1h



$W^+(q)$
$\Pi^{\mu\nu}_{W;\beta}$
ν
$\pi_\lambda(k_\pi)$
$N(p)$
$N'(p')$
μ
$W^+(q)$
β = 1p1hπ



$W^+(q)$
$\Pi^{\mu\nu}_{W;\eta}$
ν
$\pi_\lambda(k_\pi)$
$N(p)$
$N'(p+q-k_\pi)$
μ
$\pi_\lambda(k_\pi)$
$W^+(q)$
η = 2p2h



π and ρ exchanges. The effective interaction V for the particle-hole, can be [233],

$$V = c_0\{f_0(\rho) + f_0'(\rho)\vec{\tau}_1\vec{\tau}_2 + g_0(\rho)\vec{\sigma}_1\vec{\sigma}_2\} + \vec{\tau}_1\vec{\tau}_2 \sum_{i,j=1}^{3} \sigma_1^i \sigma_2^j V_{ij}^{\sigma\tau}(q) \qquad \text{(D.11)}$$