Probing ν interactions for ν physics

Adi Ashkenazi

Probing ν interactions for ν physics

ν

Intro

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Probing ν interactions for ν physics

ν → μBooNE

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Probing ν interactions for ν physics

ν → μBooNE ← e4V

Intro

Jefferson Lab
Exploring the Nature of Matter

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Probing ν interactions for ν physics

ν → µBooNE ← e4ν → DUNE

Intro

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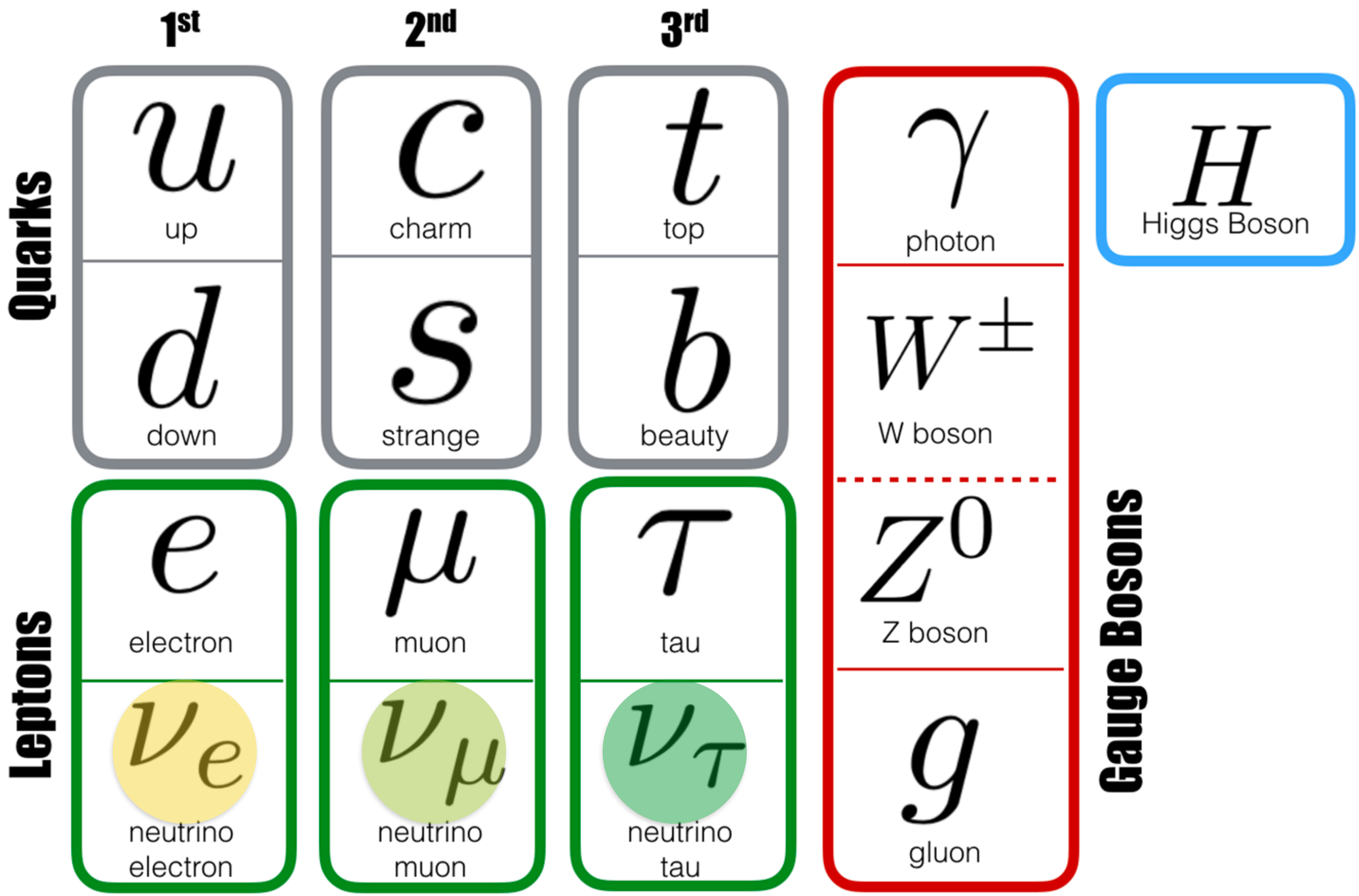
Introduction to Neutrino Oscillations



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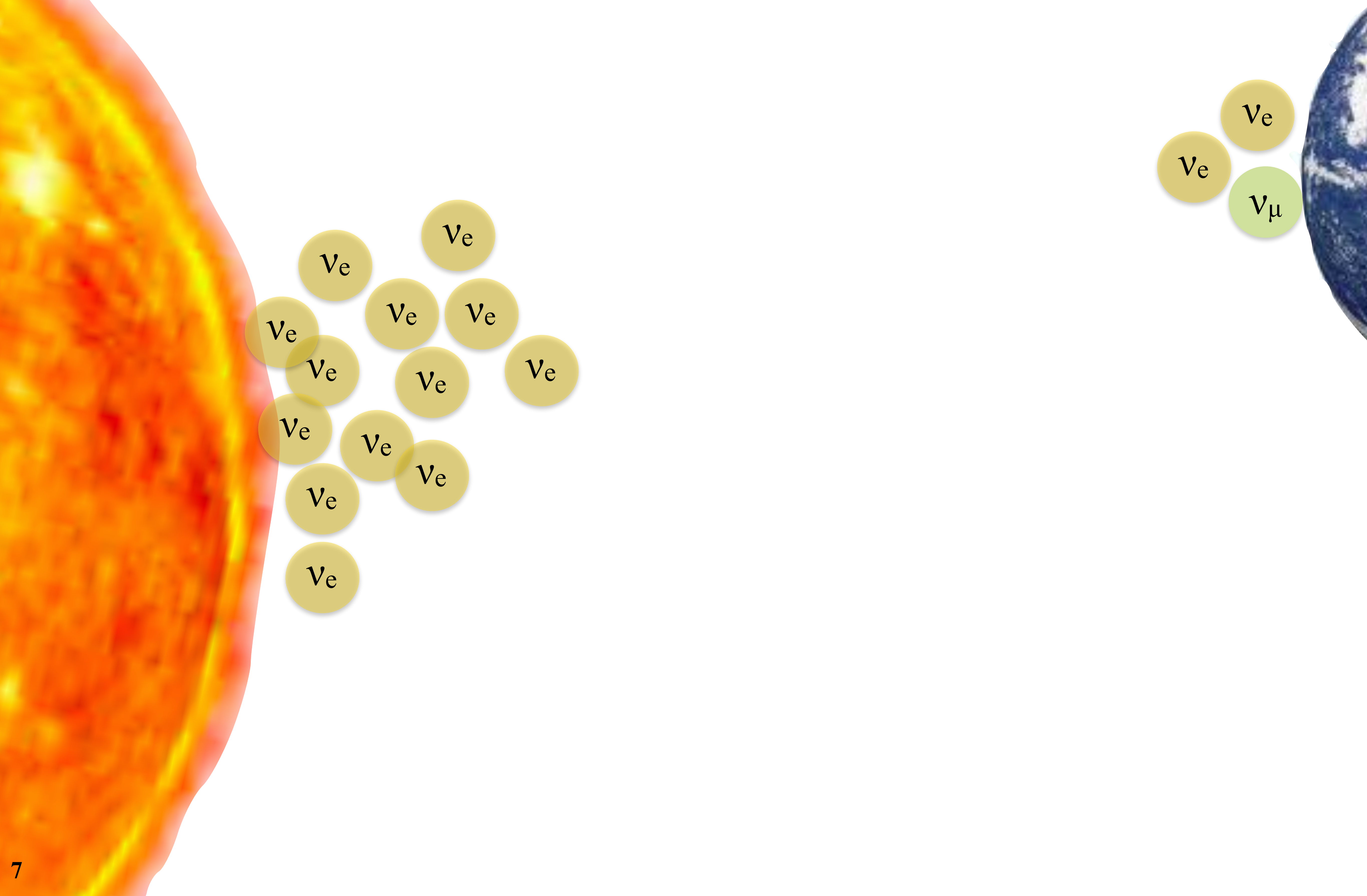

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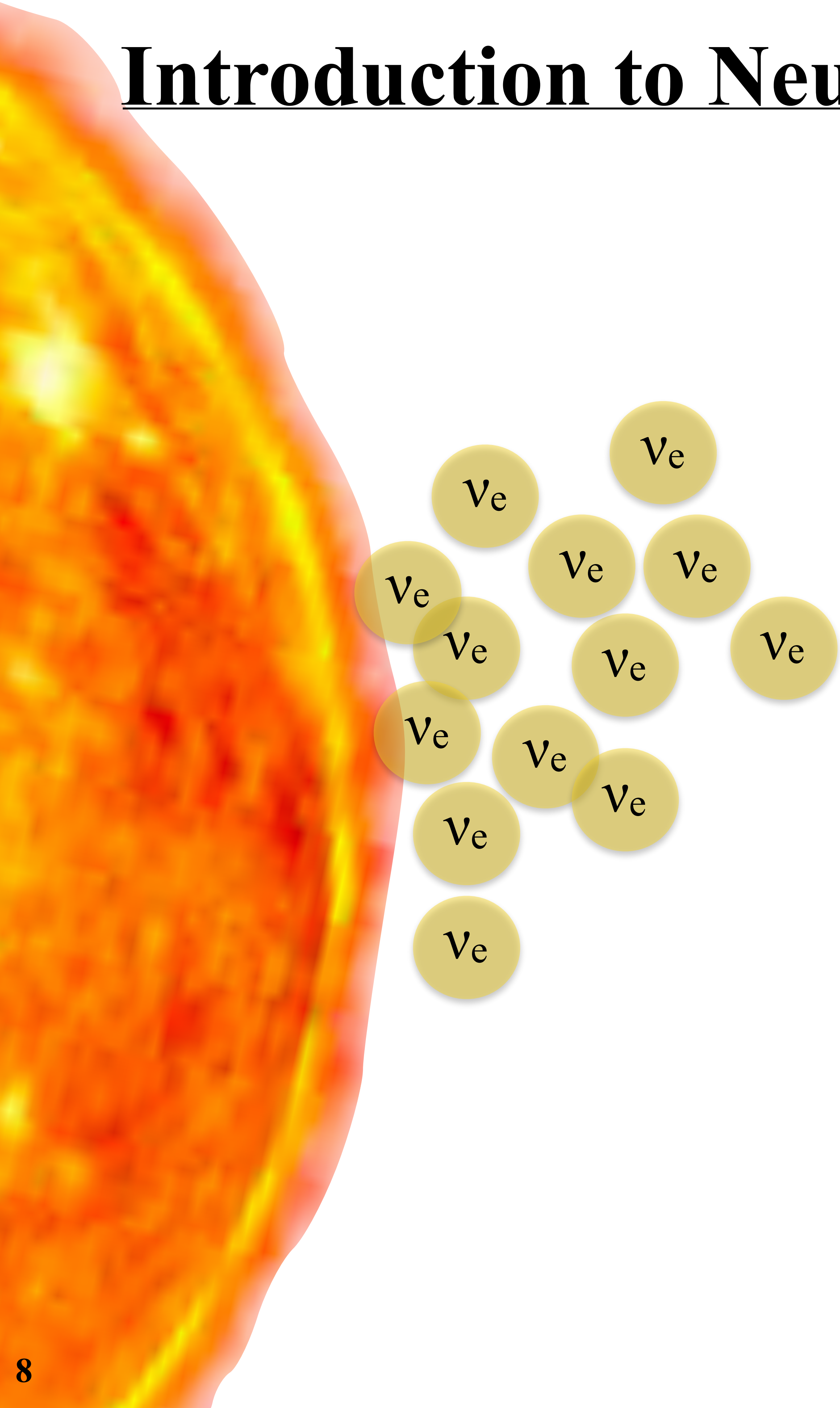
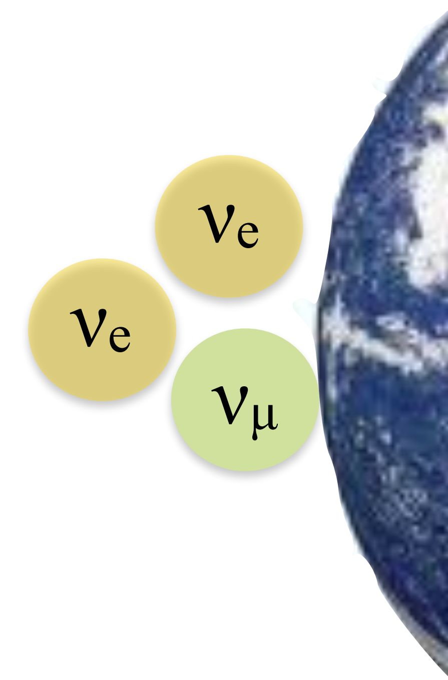


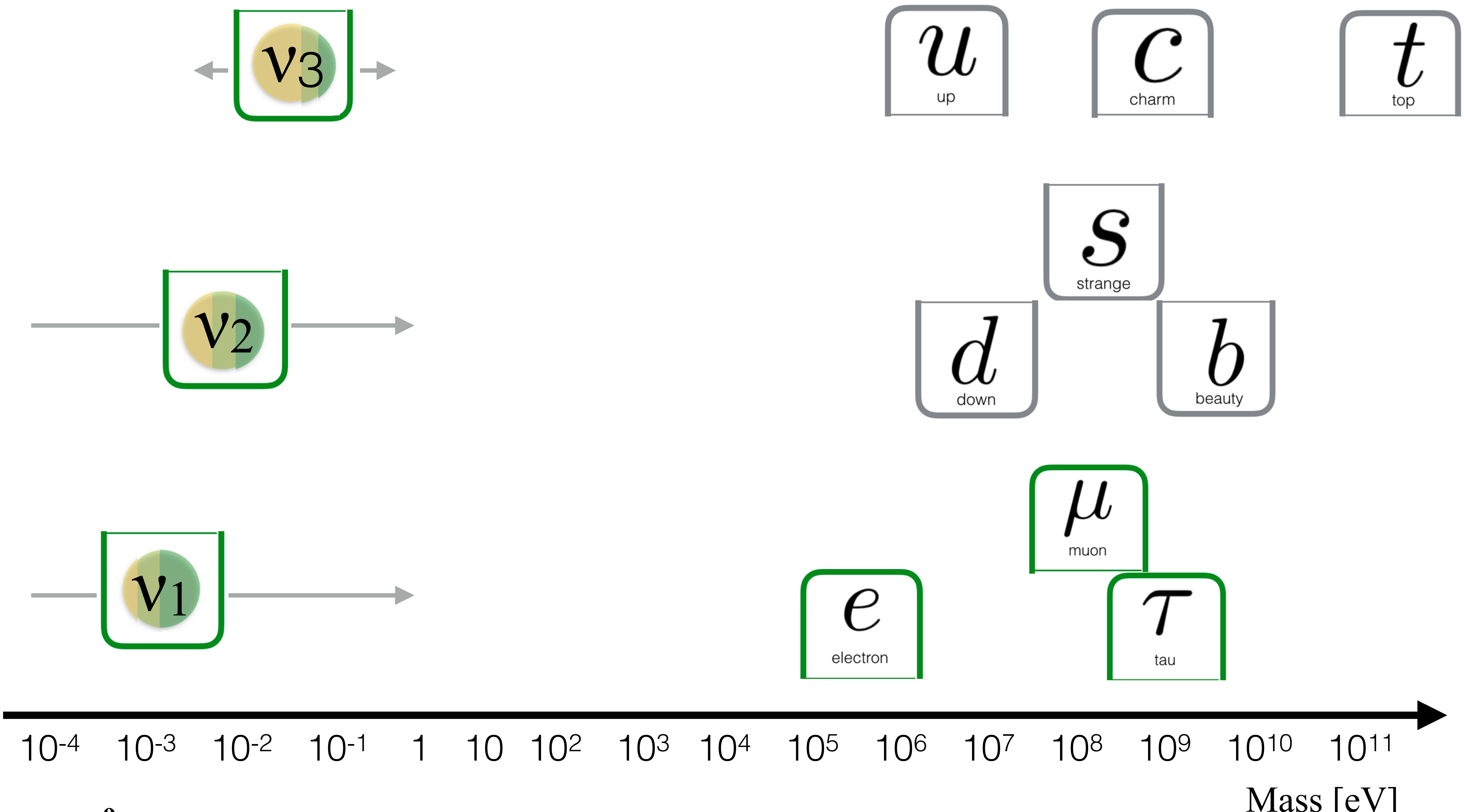


$$\begin{vmatrix} \nu_e \\ \nu_\mu \end{vmatrix} = \begin{vmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{vmatrix} \cdot \begin{vmatrix} \nu_1 \\ \nu_2 \end{vmatrix}$$

$$P_{osc} = |< \nu_e \mid \nu_\mu(t) >|^2$$

$$= \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

Introduction to Neutrino Oscillations



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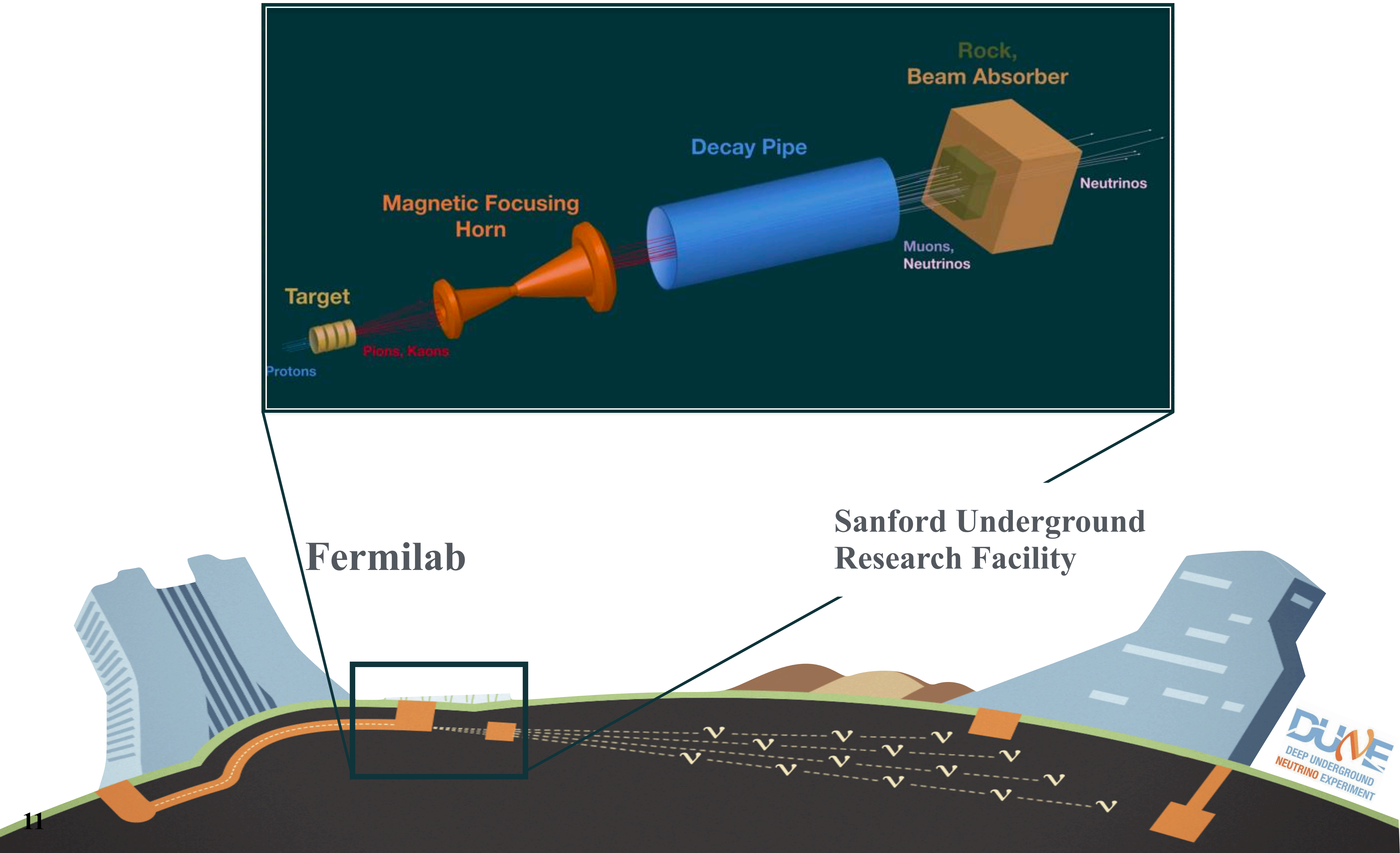
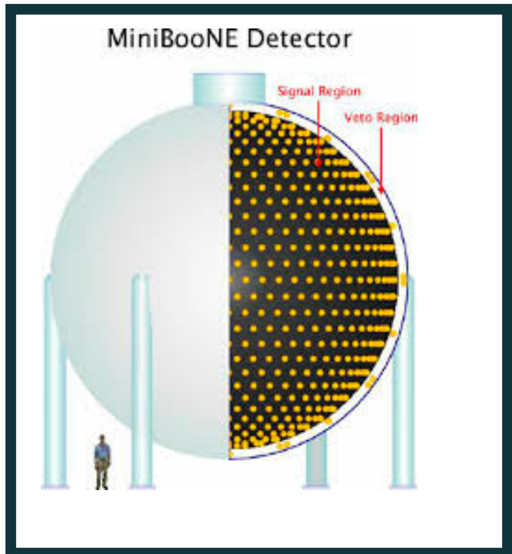
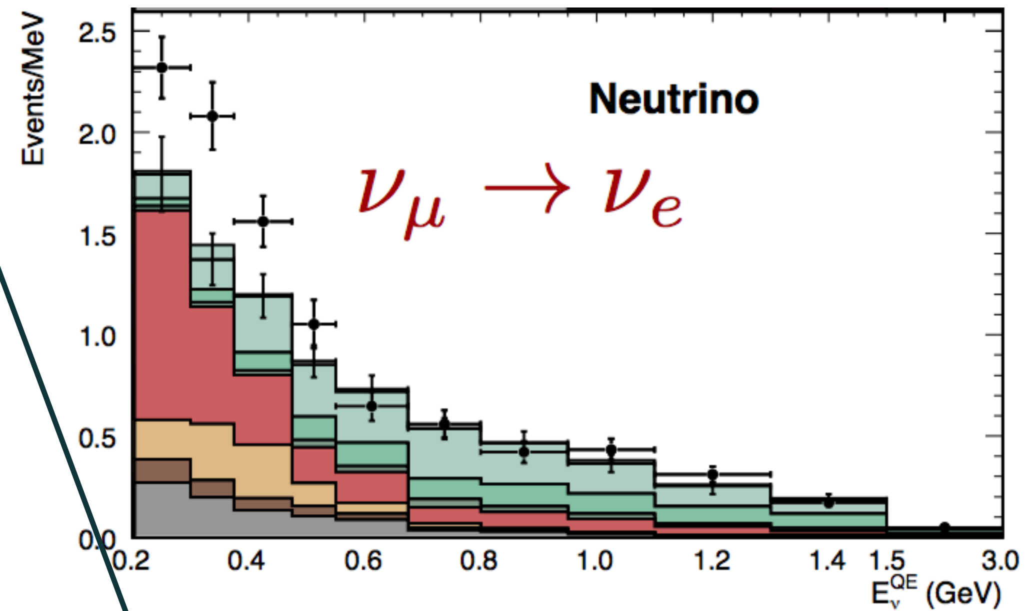
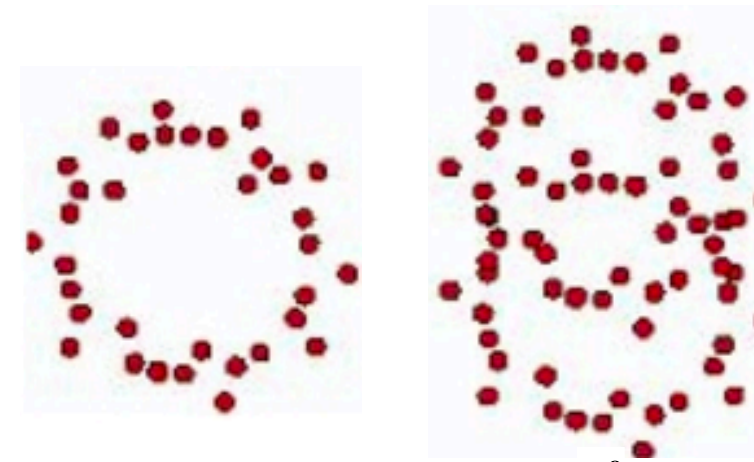


Introduction to Neutrino Oscillations

Low Energy Excess ν_e appearance Anomaly

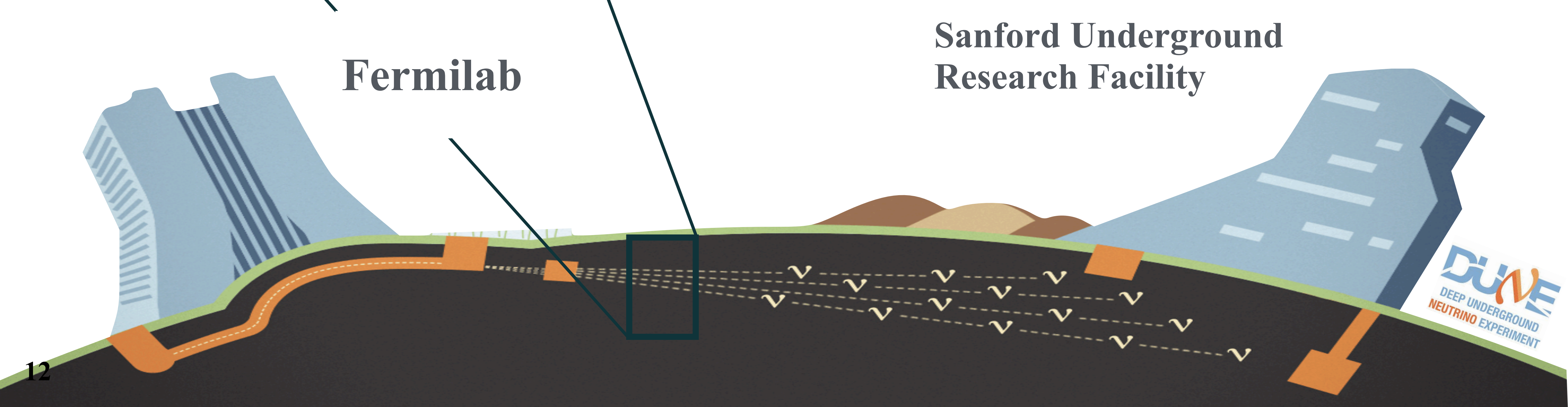




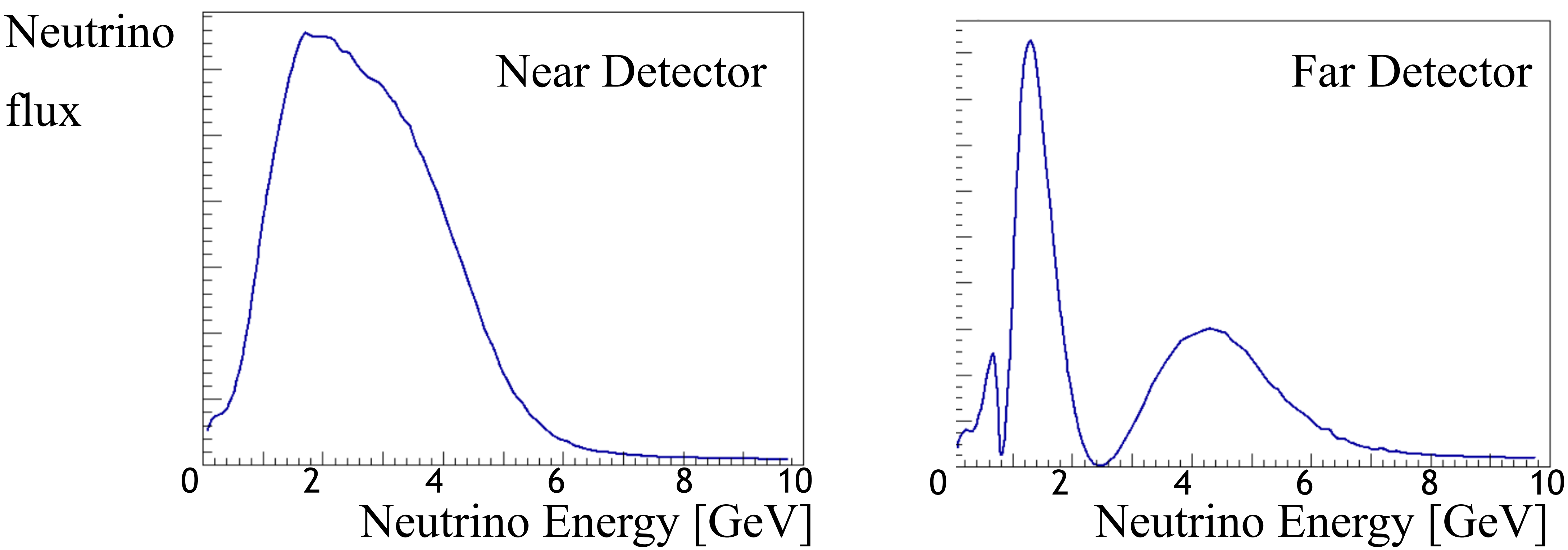


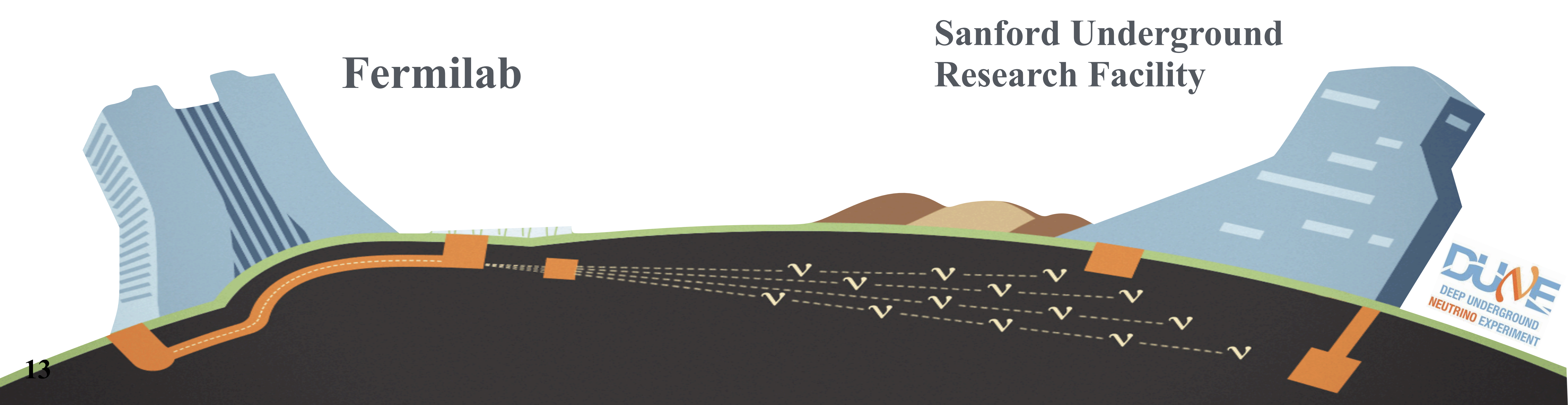
e

π^0

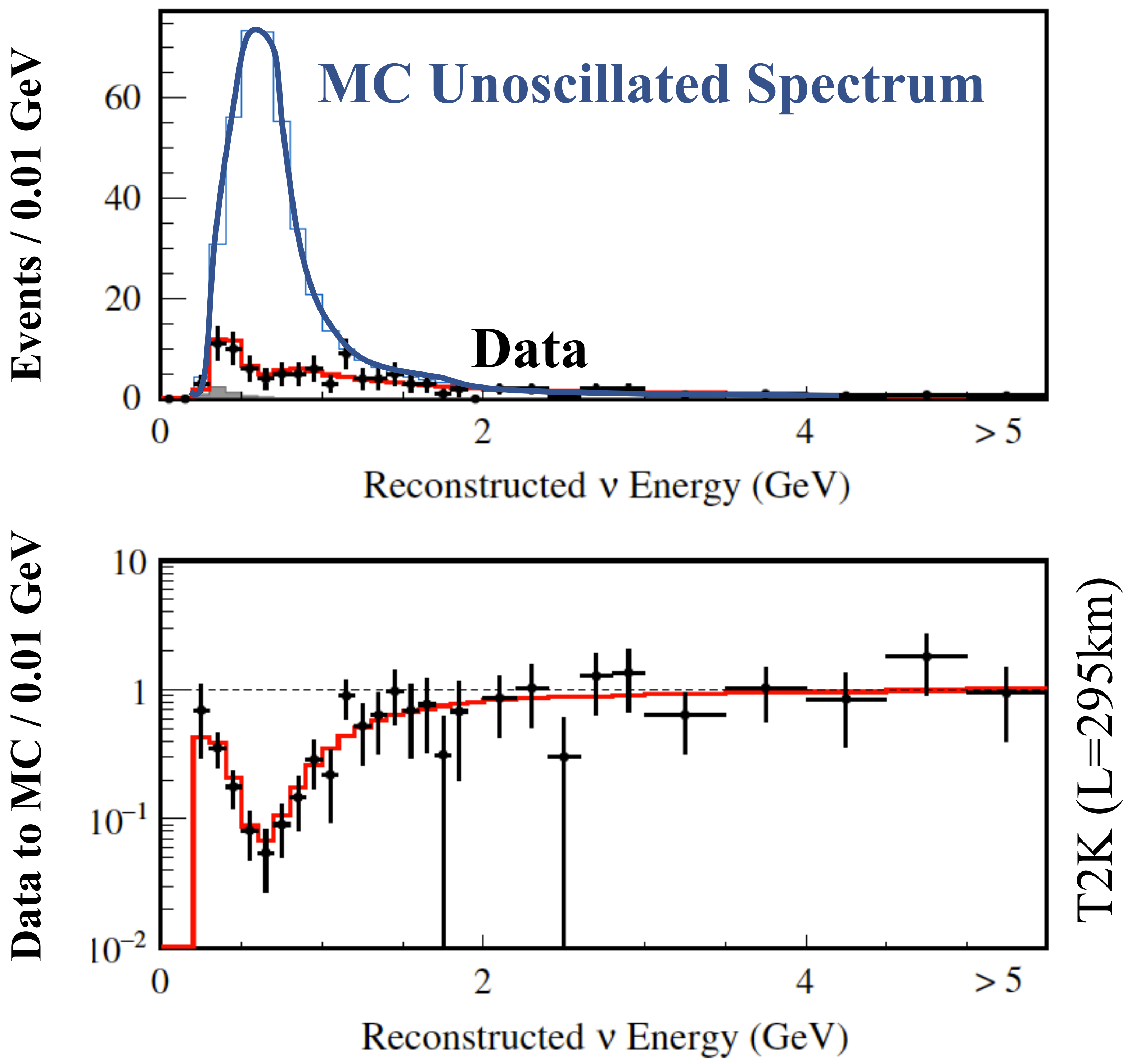


Introduction to Neutrino Oscillations





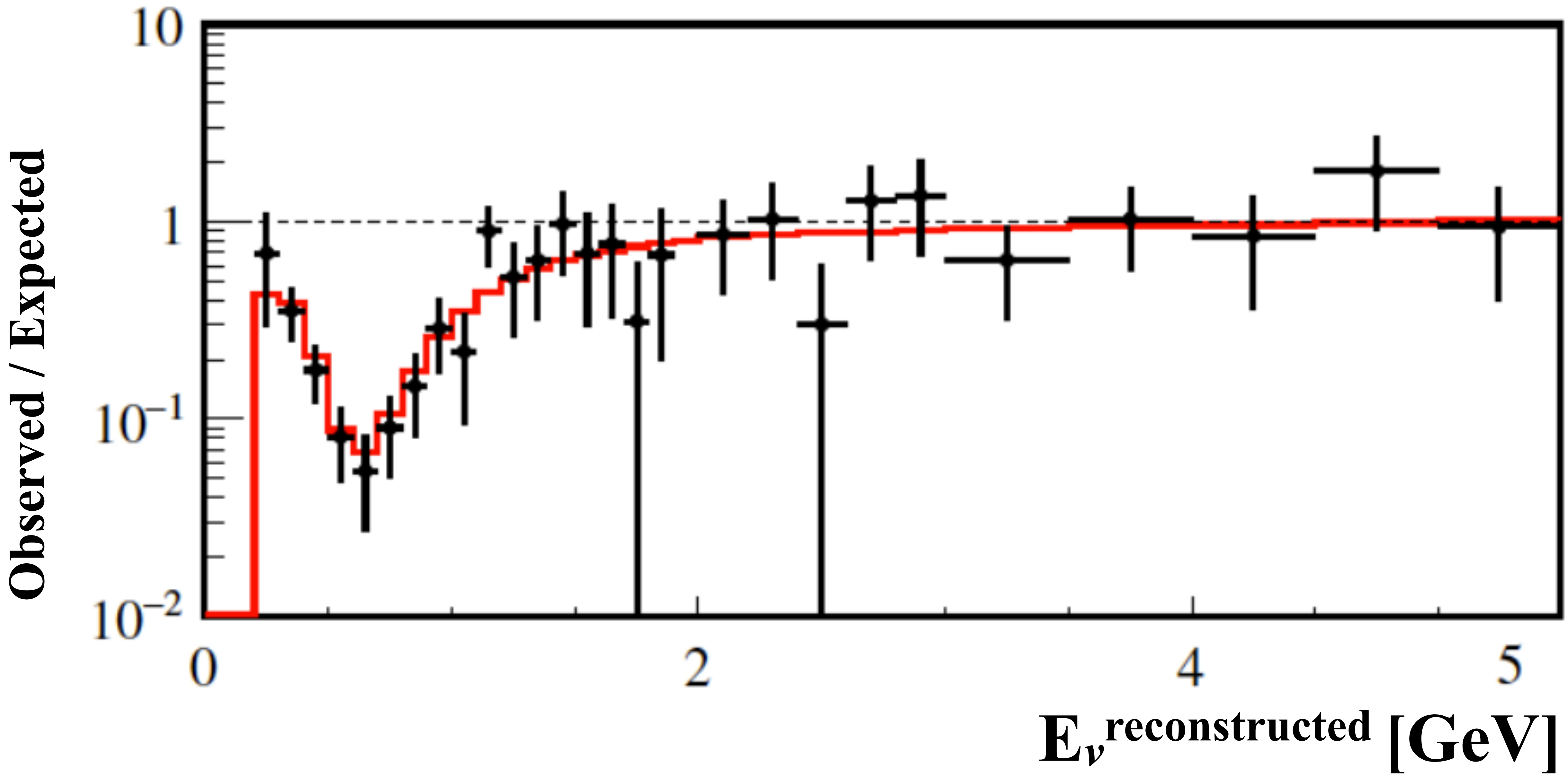
Oscillations Require incoming E_ν Reconstruction



 T2K, Phys. Rev. D 91, 072010 (2015)

Oscillations Require incoming E_ν Reconstruction

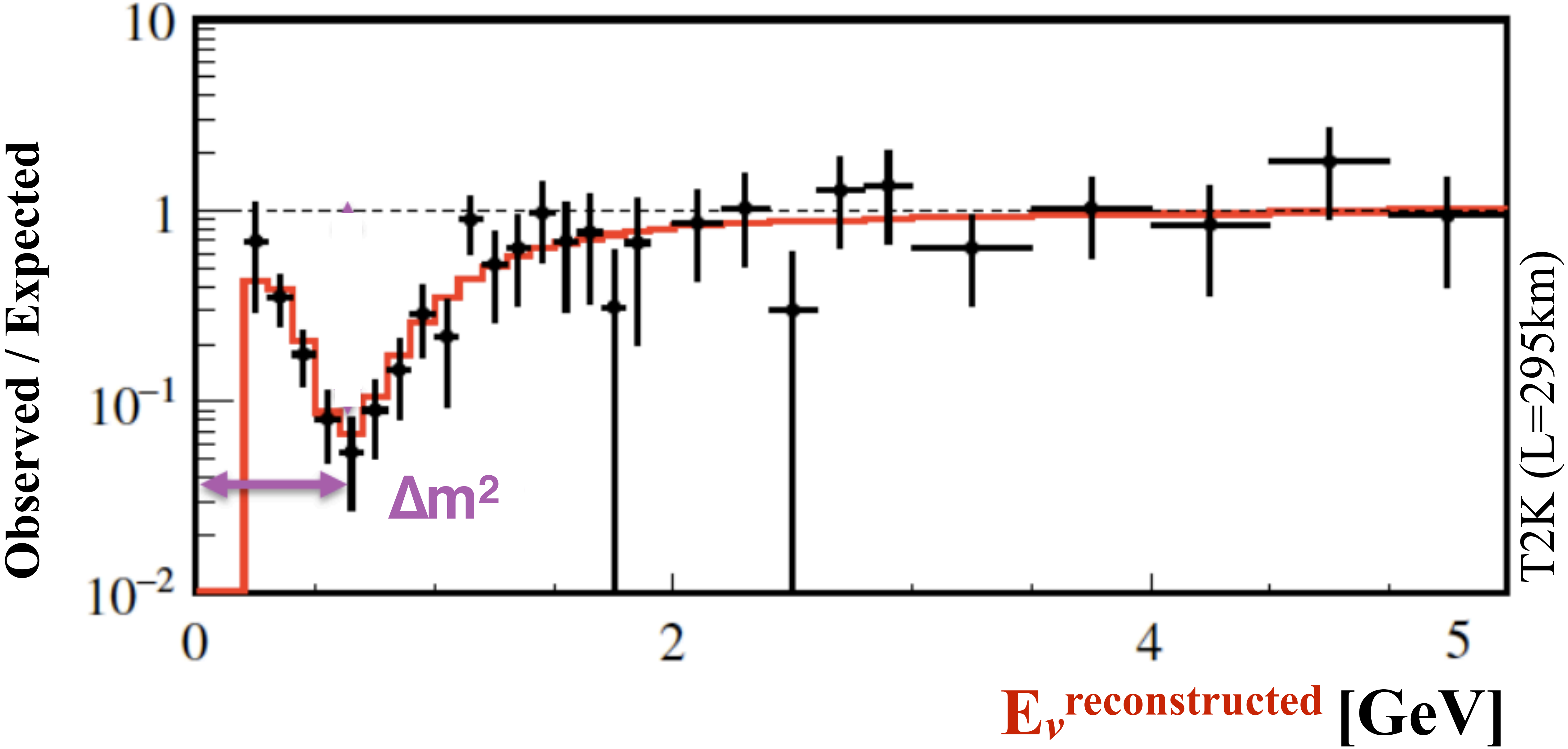
$$P(\nu_\mu \to \nu_x) = \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$



15 T2K, Phys. Rev. D 91, 072010 (2015)

Oscillations Require incoming E_ν Reconstruction

$$P(\nu_\mu \rightarrow \nu_x) = \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu^{real}}\right)$$



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Oscillations Require incoming E_ν Reconstruction

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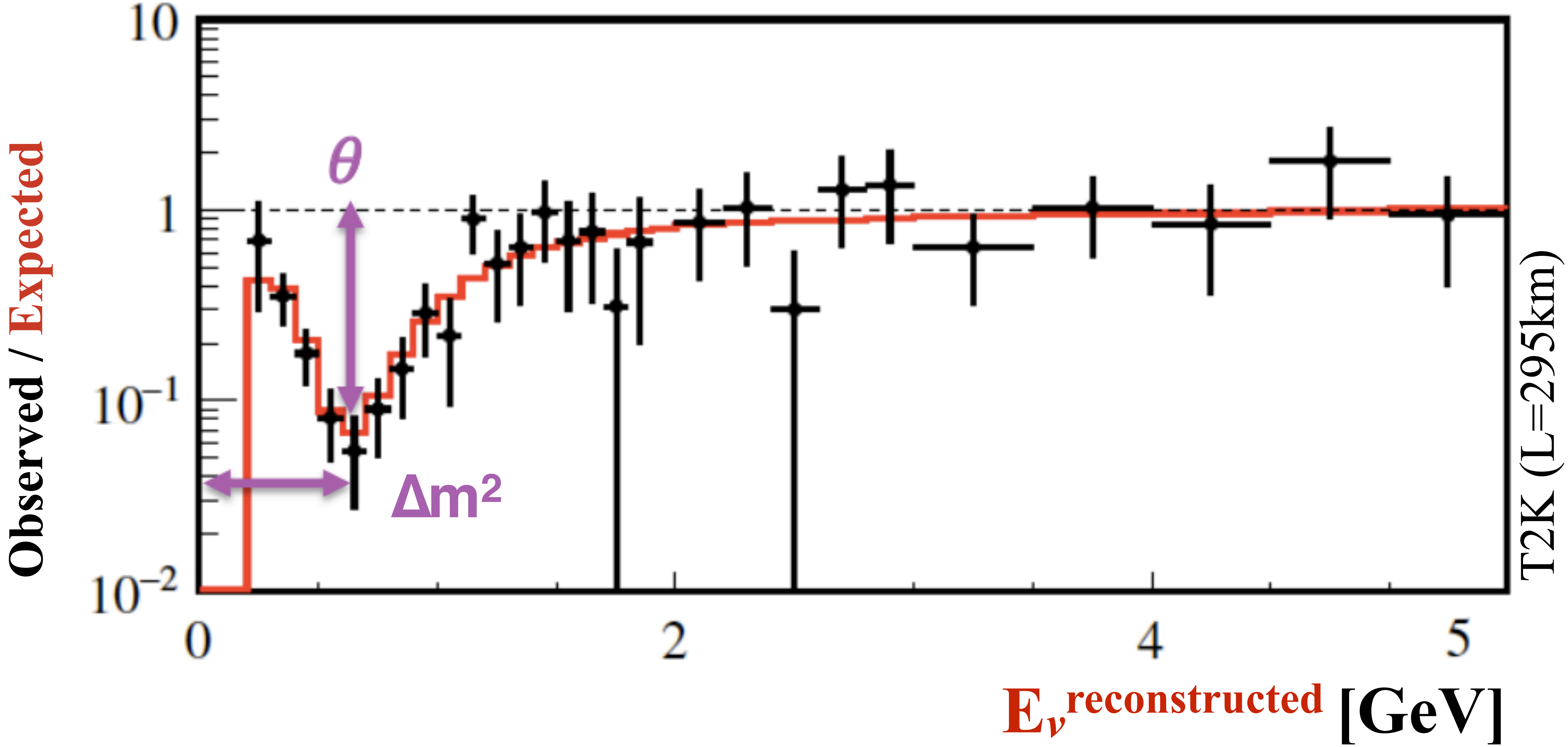
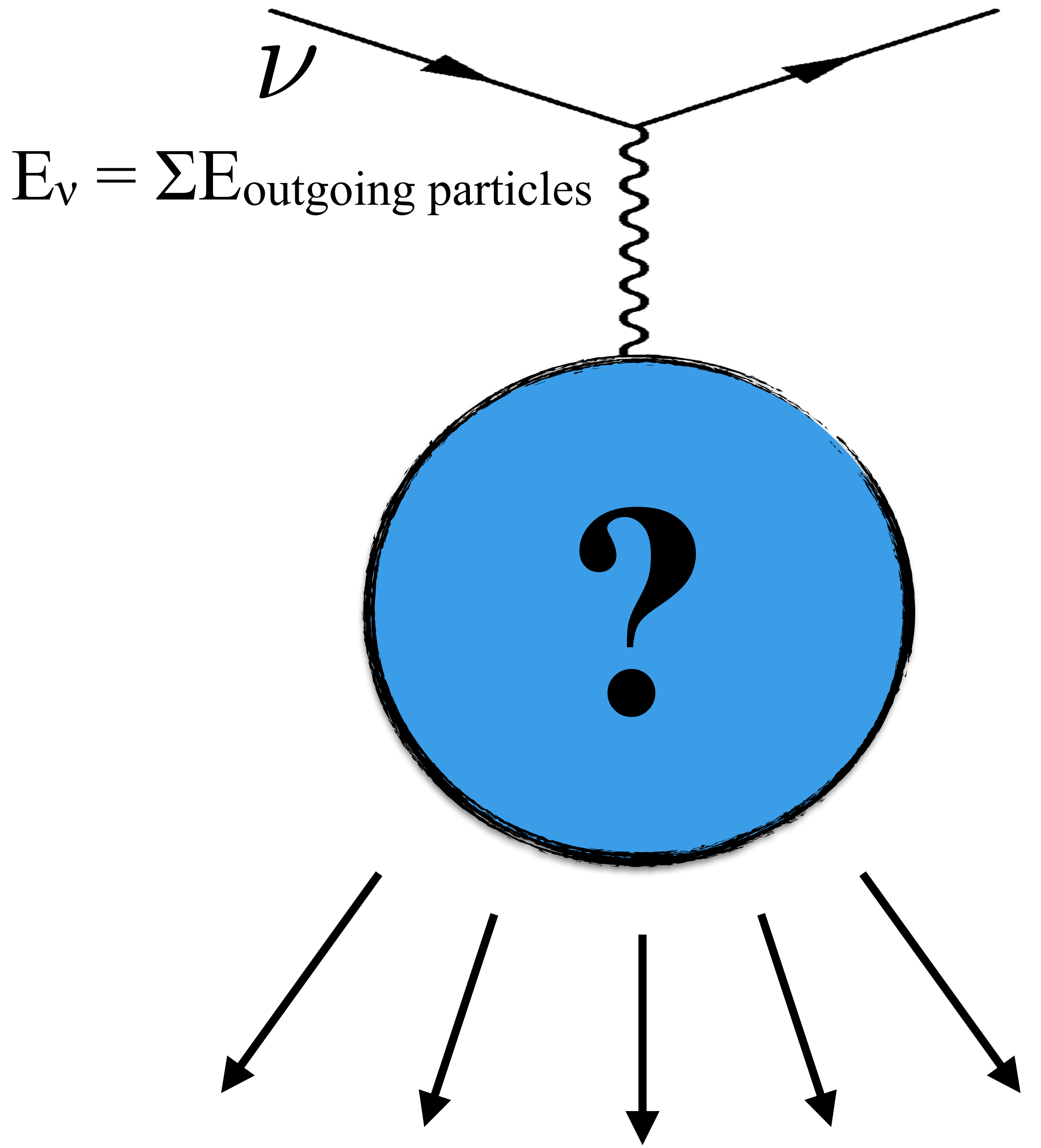
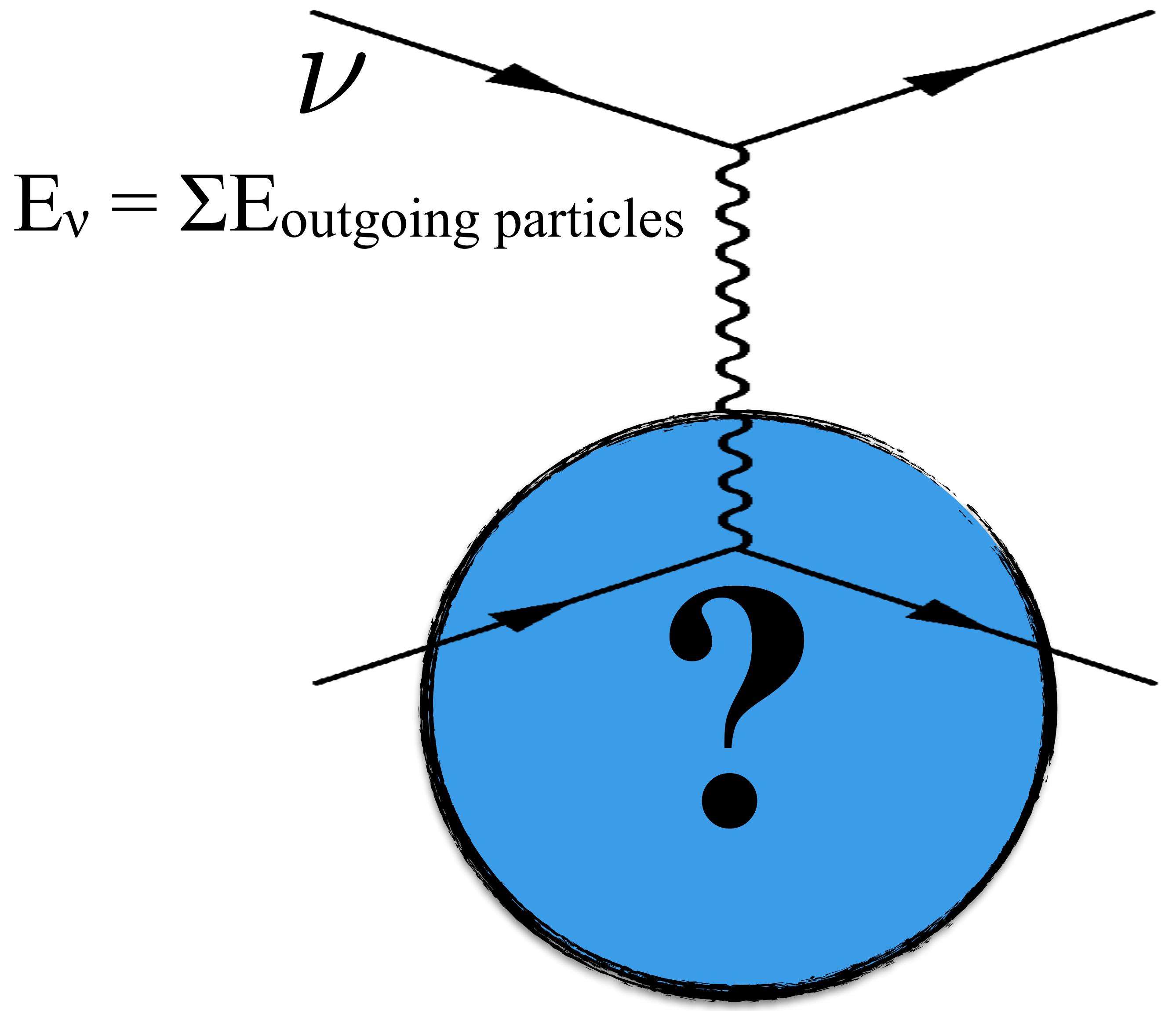


 T2K, Phys. Rev. D 91, 072010 (2015)

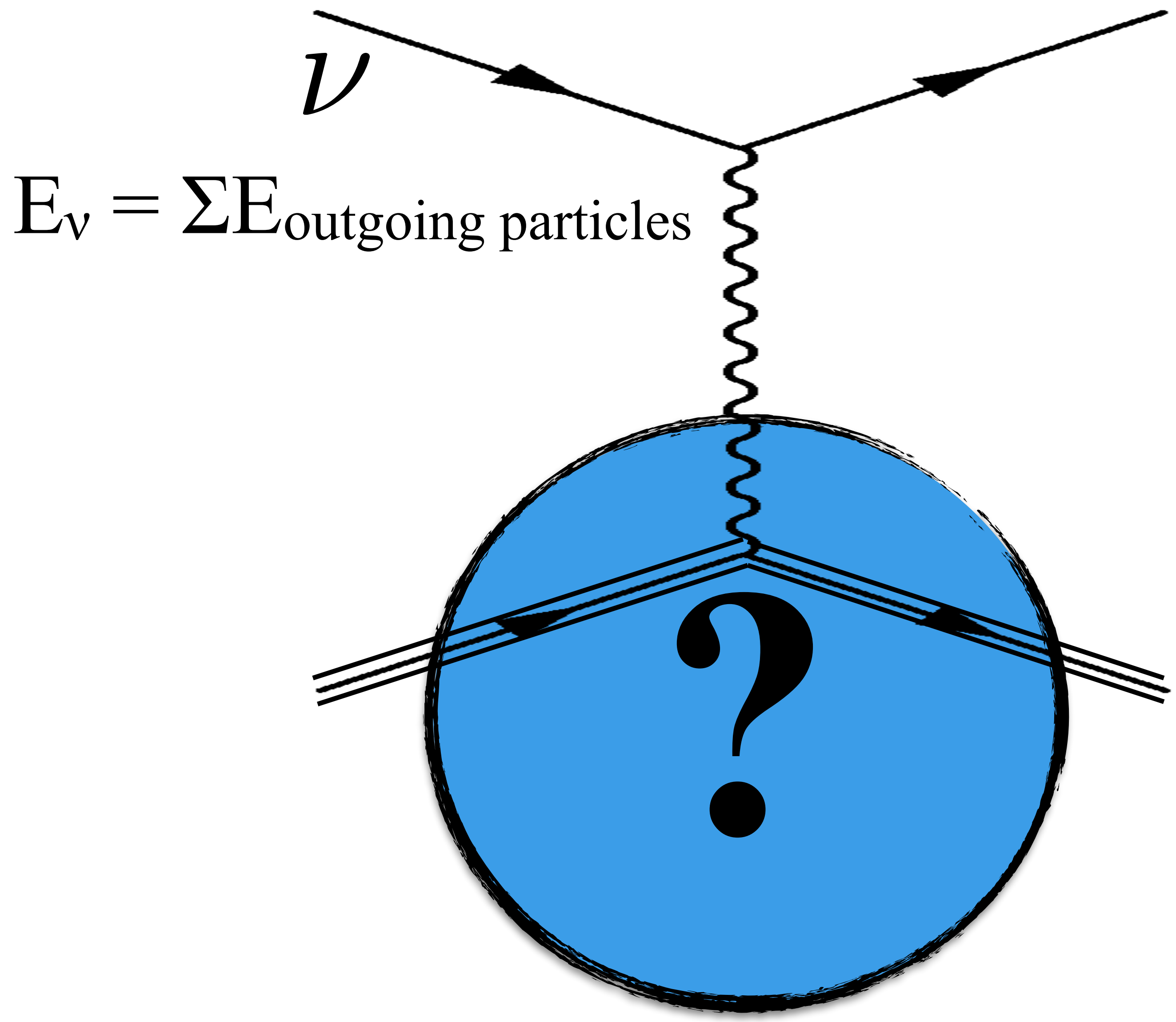
E_ν Reconstruction: Interaction Modeling



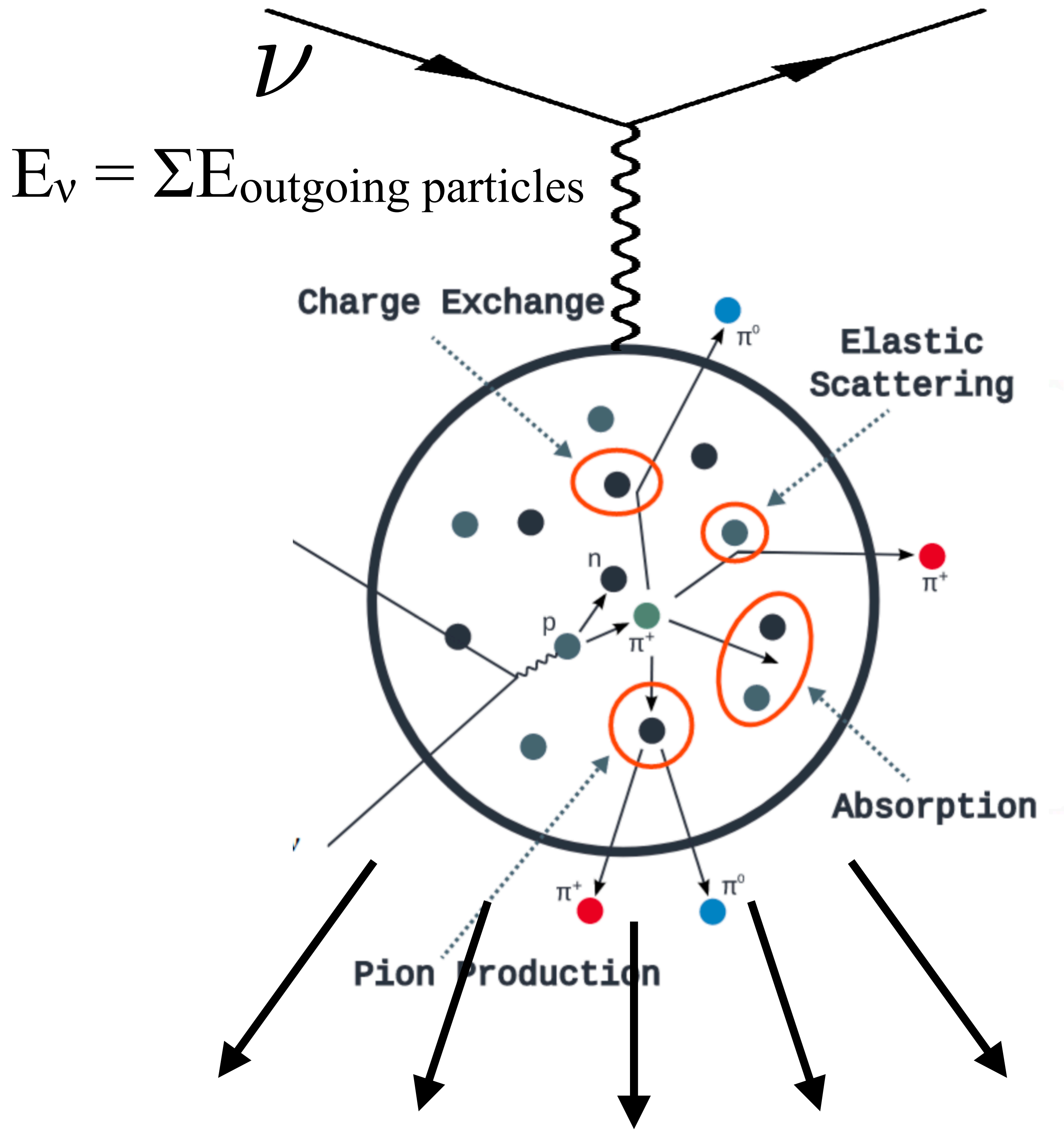
E_ν Reconstruction: Interaction Modeling



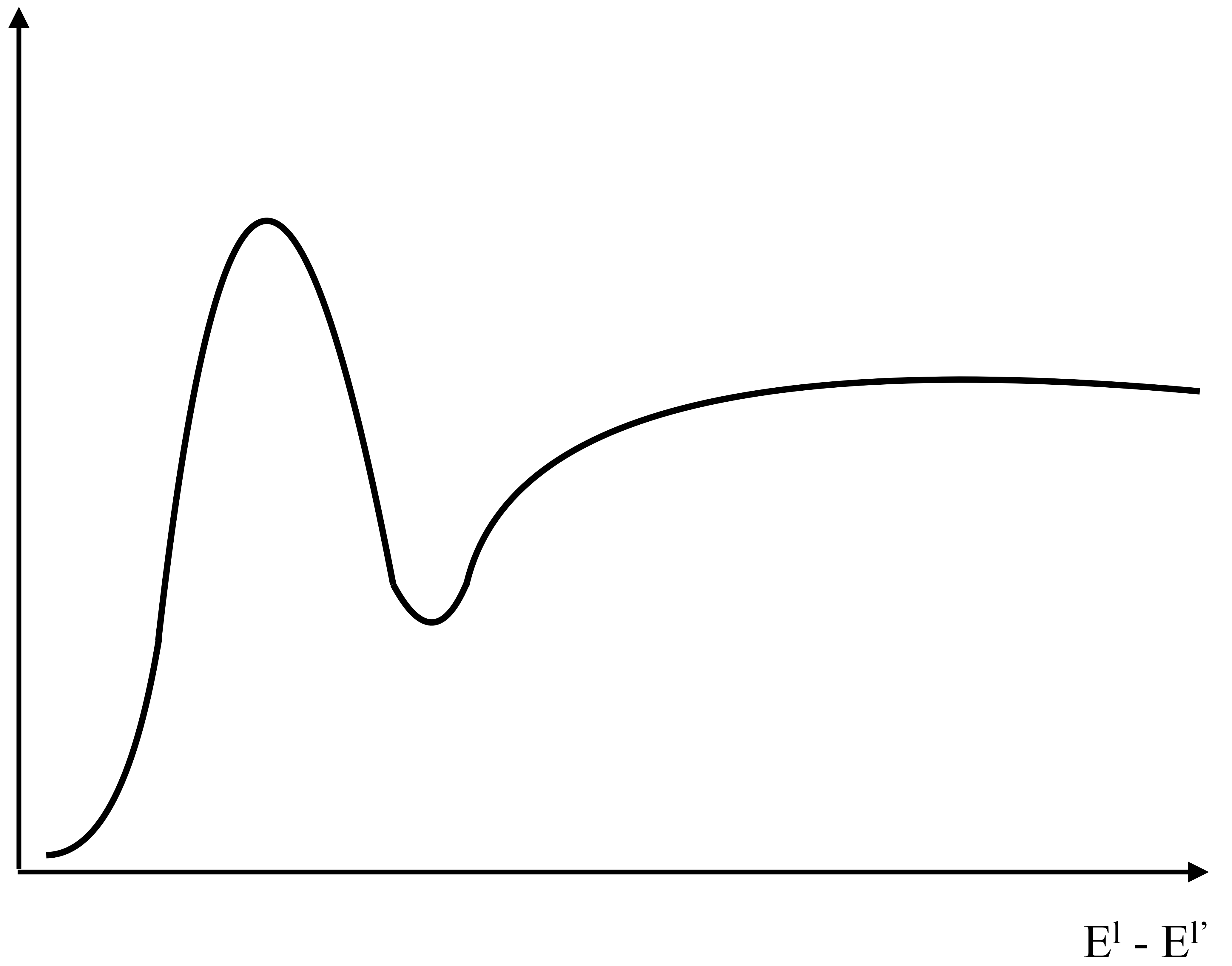
E_ν Reconstruction: Interaction Modeling



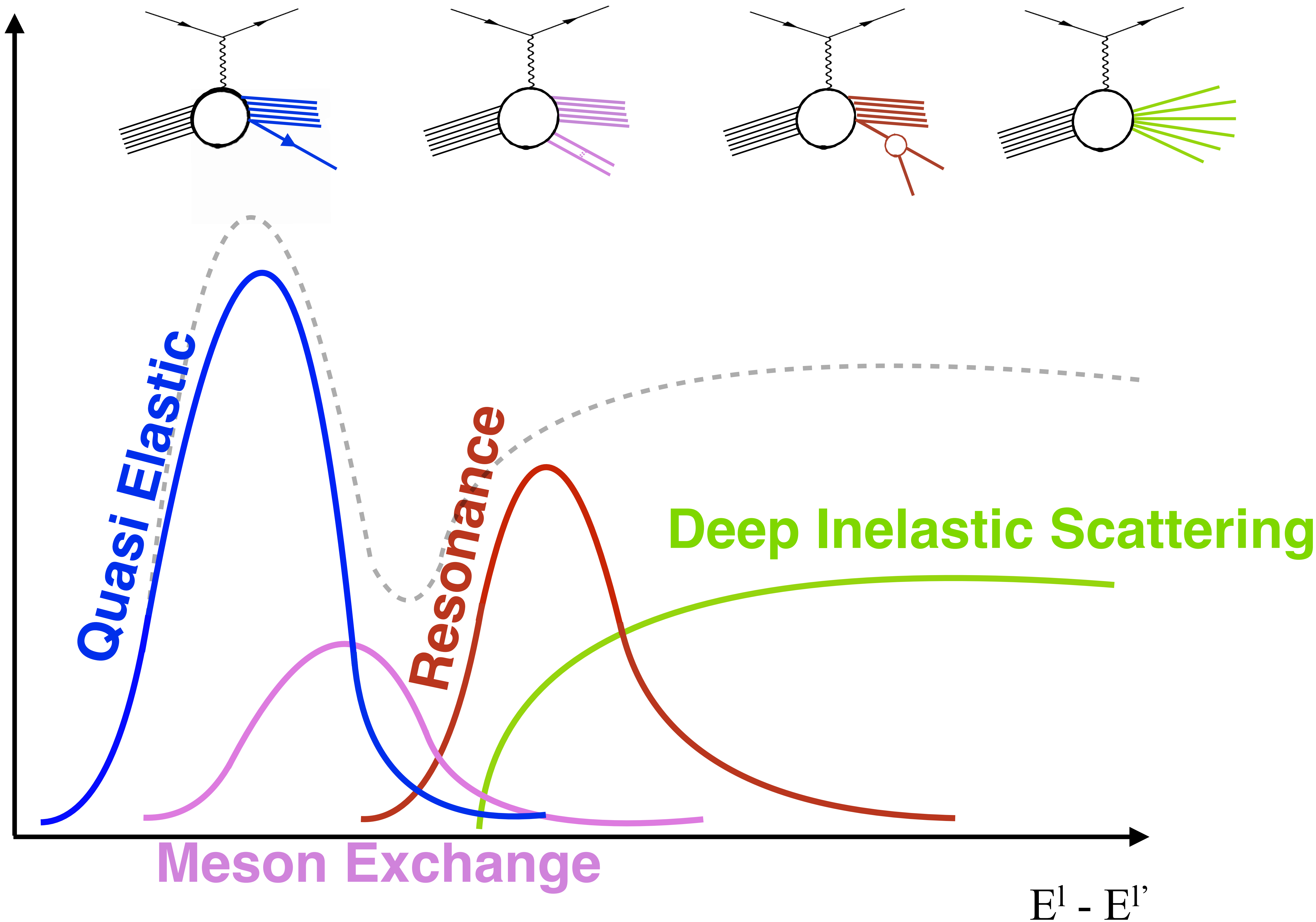
E_ν Reconstruction: Interaction Modeling



E_ν Reco Requires Interaction Modeling



E_ν Reco Requires Interaction Modeling



νA Interaction Modelling

Neutrino event generators are used to simulate a νA interaction

Among those:

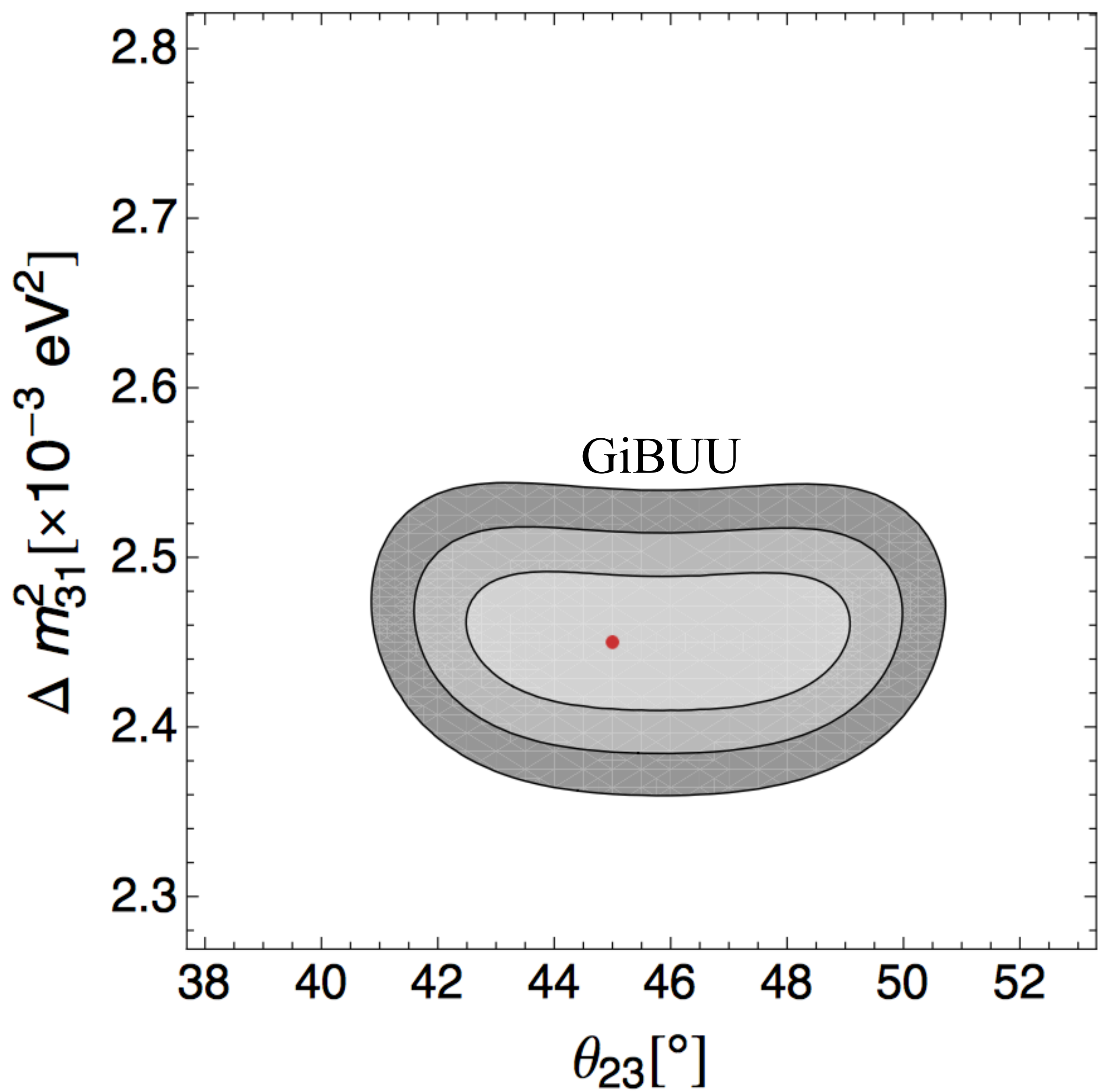
Genie

GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

and more

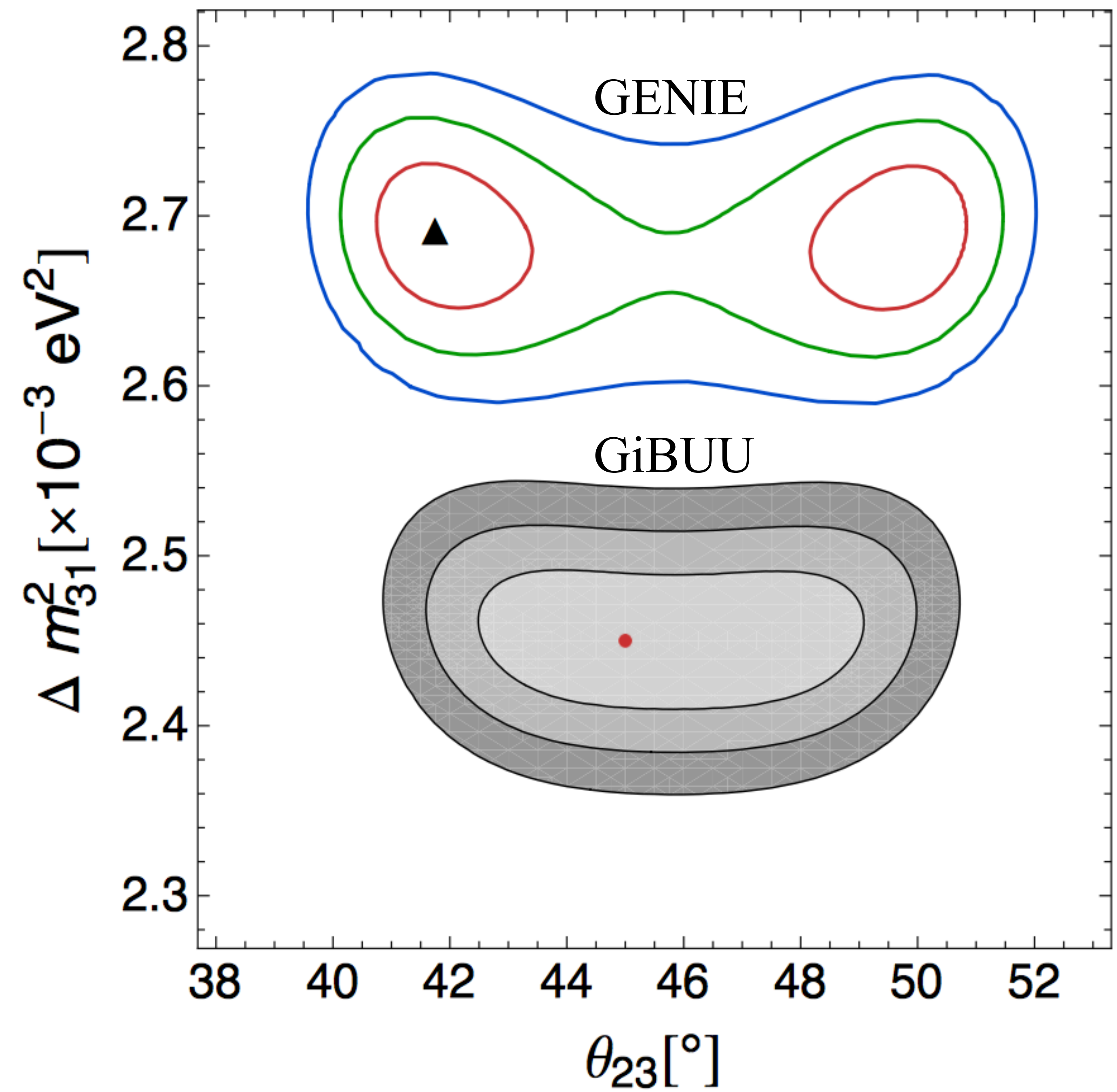
Nuclear Uncertainties are significant



Phys. Rev. D 89, 073015 (2014)

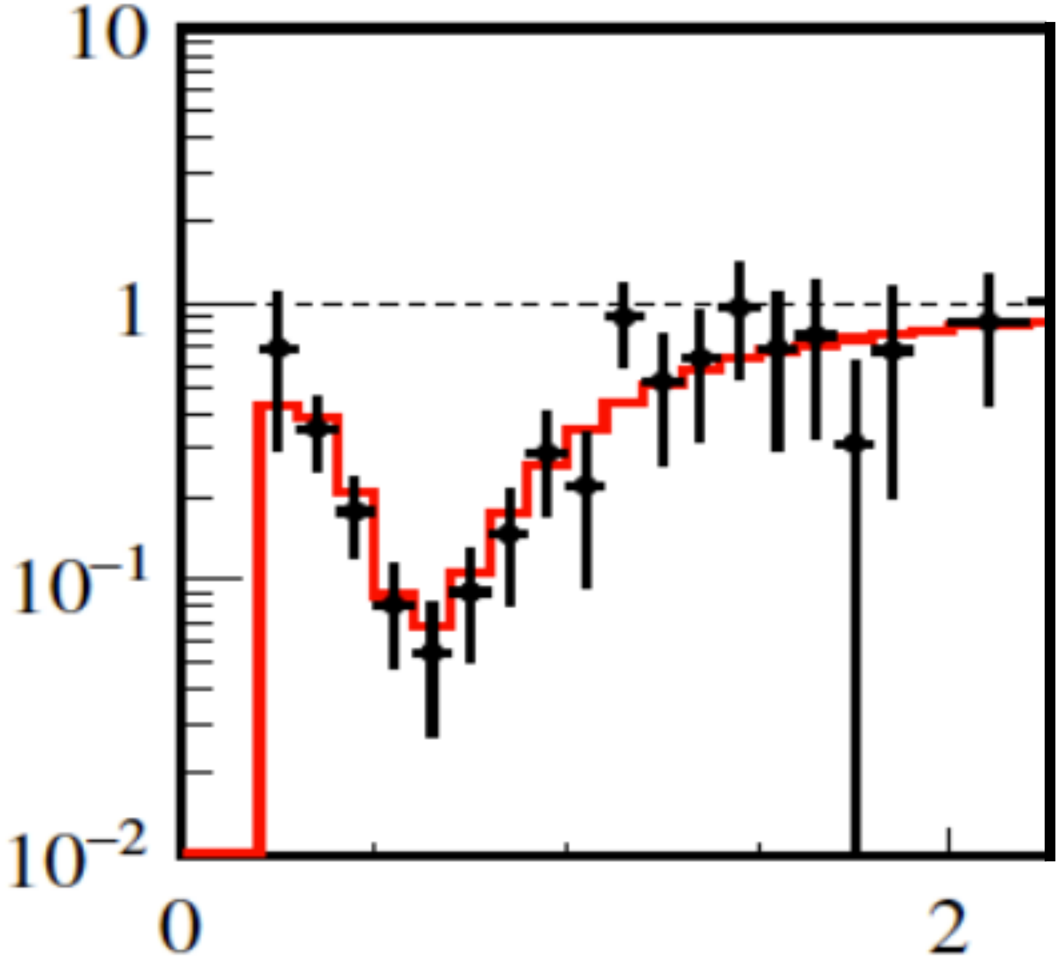
Nuclear Uncertainties are significant

Could lead to wrong extraction of the mixing parameters due to incomplete modelling of the nuclear physics involved.



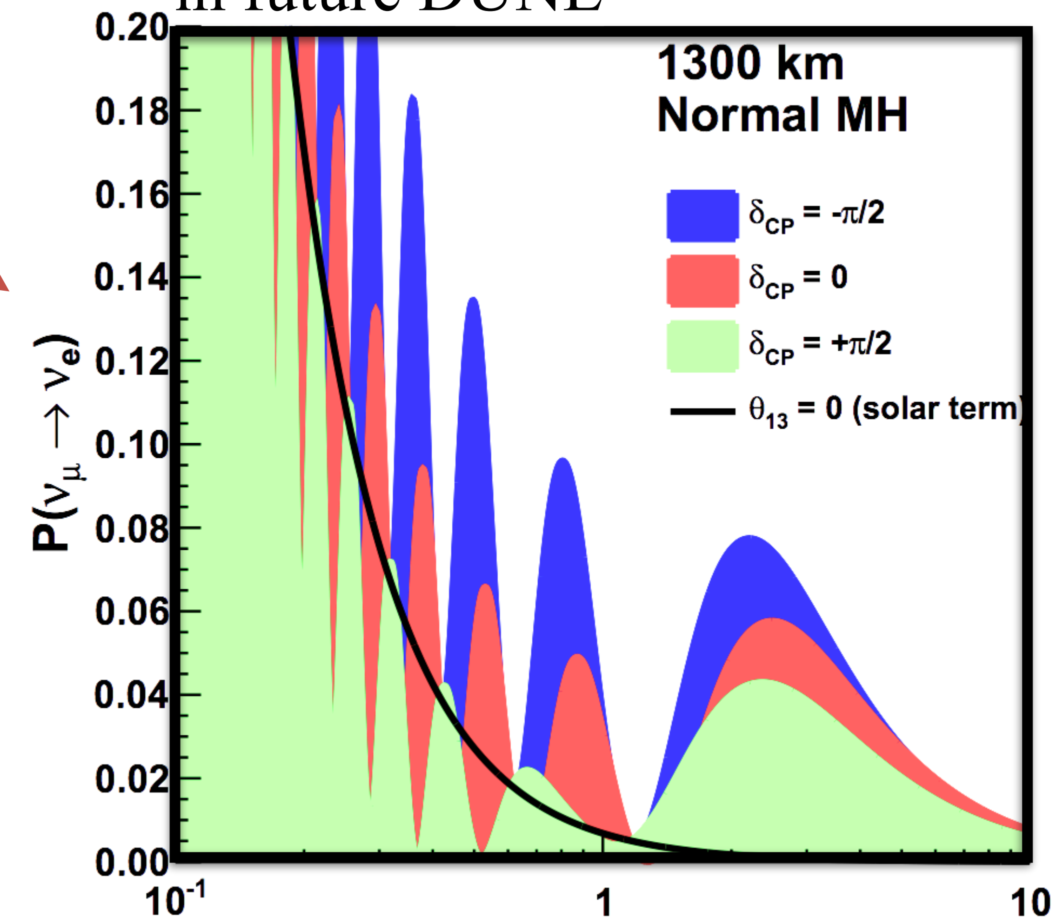
Phys. Rev. D 89, 073015 (2014)

Next generation - High Precision Challenge



Neutrino Energy [GeV]

Simulation of oscillation effects in future DUNE



Neutrino Energy [GeV]

μBooNE Cross section measurement

SBN - Short Base Line Program

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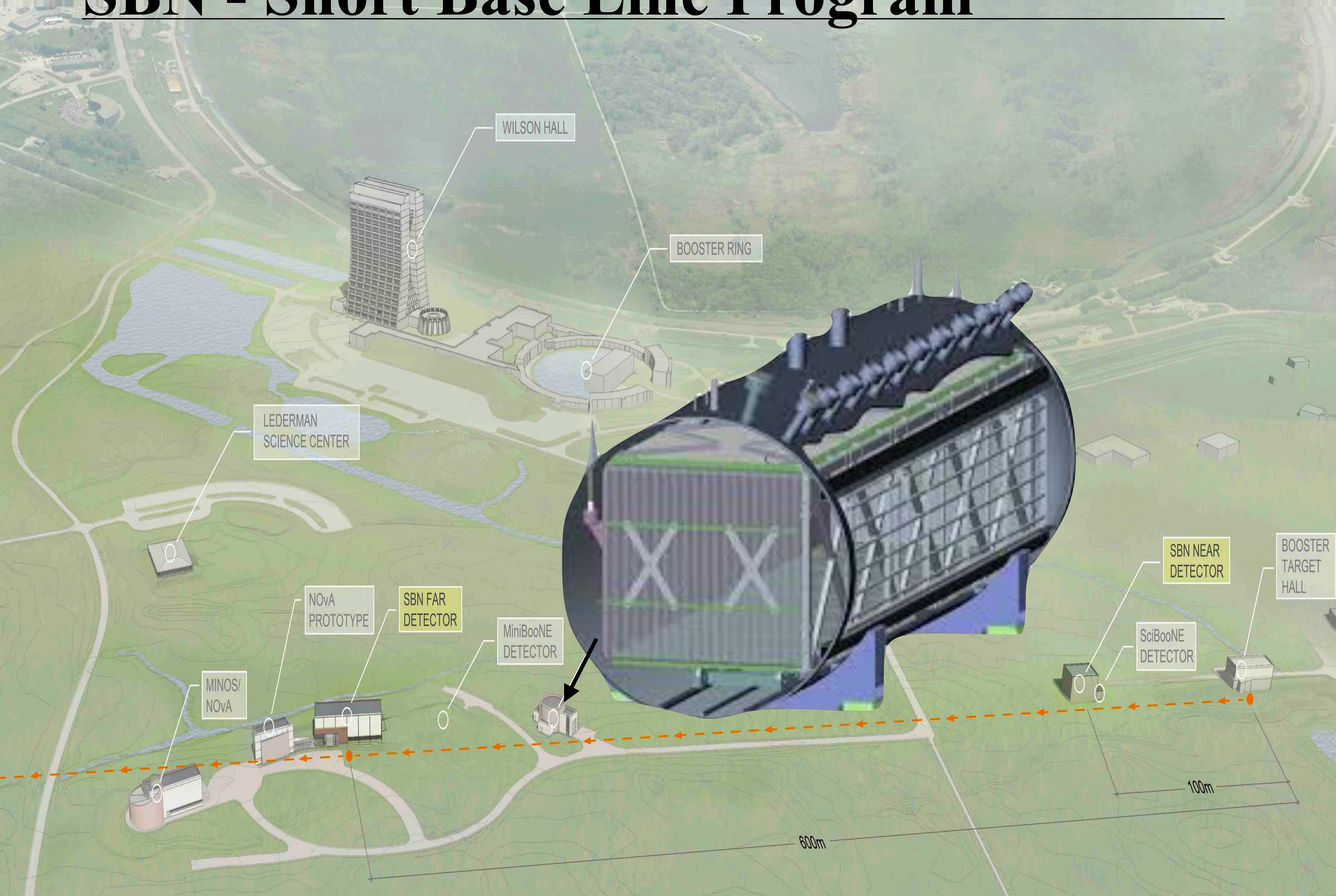


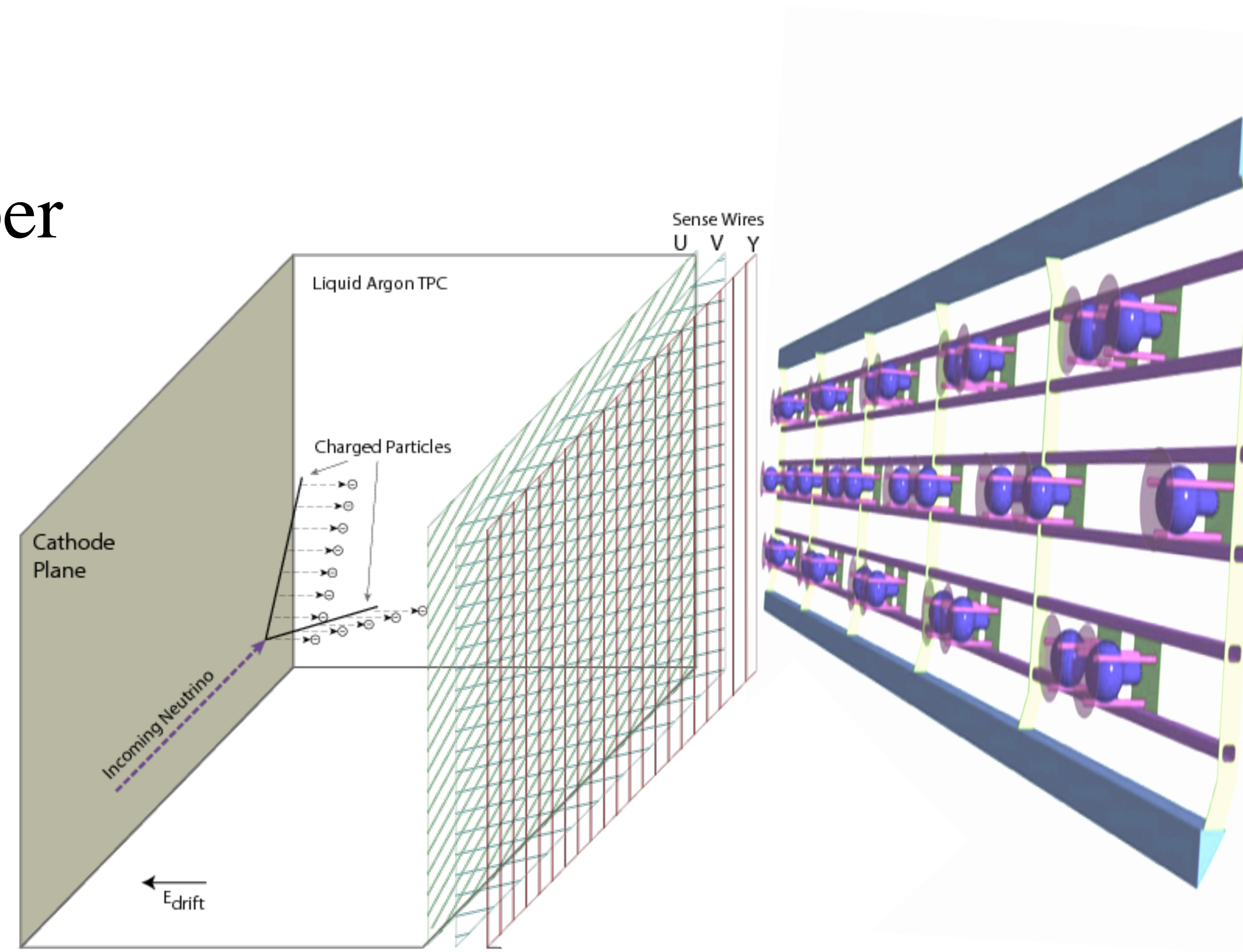
LAr TPC - MicroBooNE

LAr Time Projection Chamber

Near surface detector

Active mass : 85 tons

Triggered by PMTs



LAr TPC - MicroBooNE

Has 3 wire planes

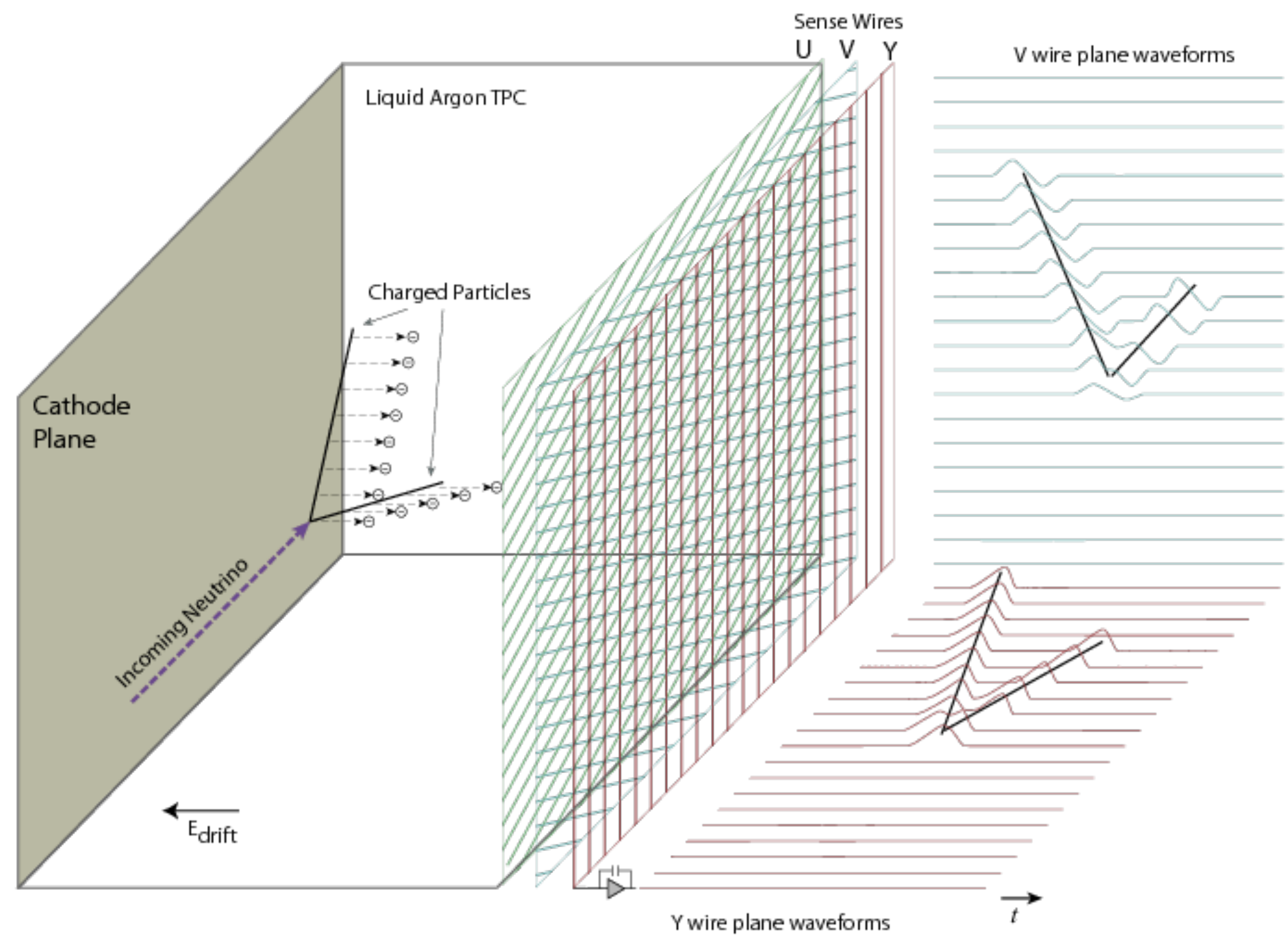
- 3 mm wire spacing

  giving impeccable spatial resolution

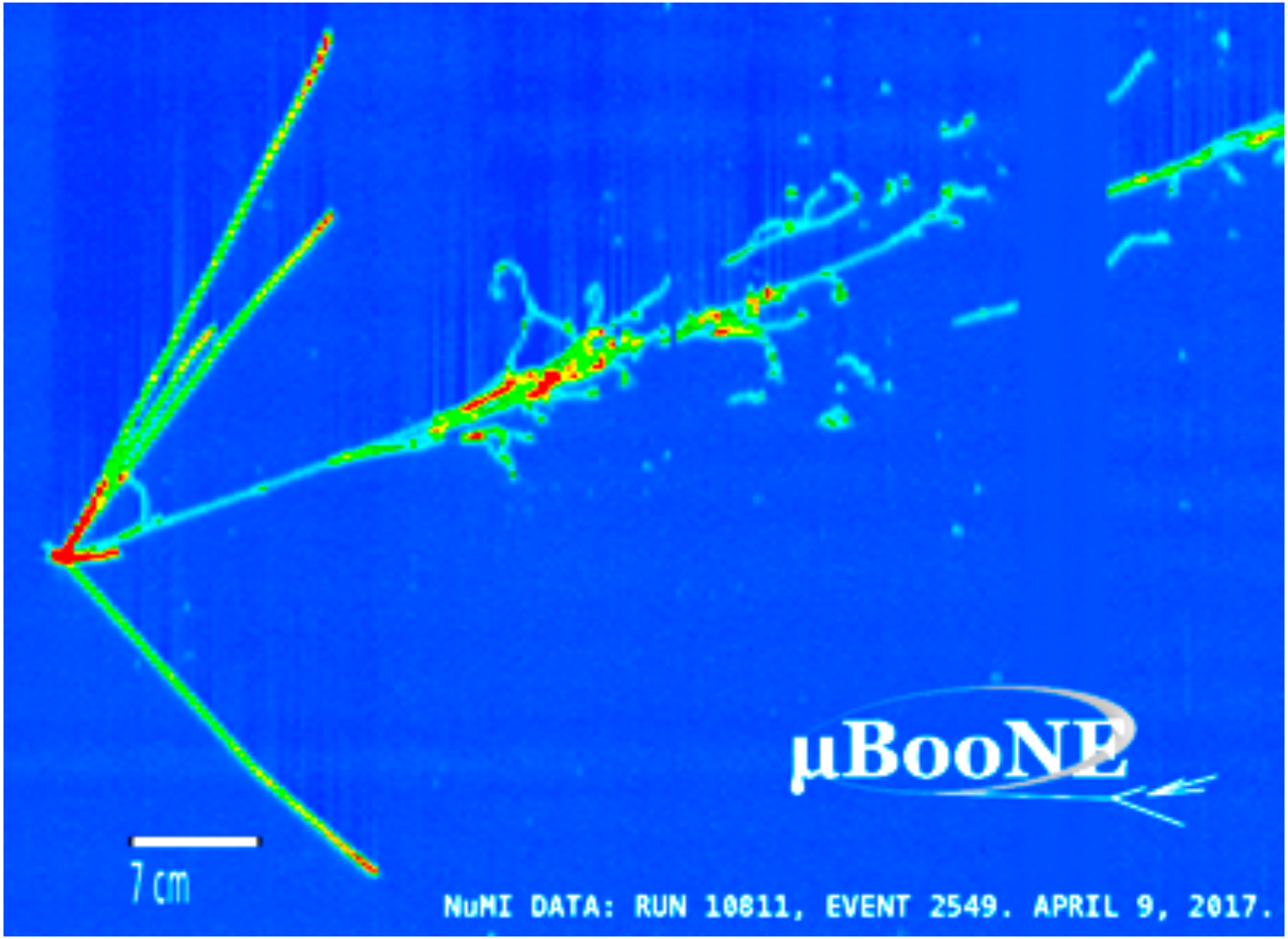
- Final plane collects charge

  giving calorimetric measurement

  Low tracking threshold

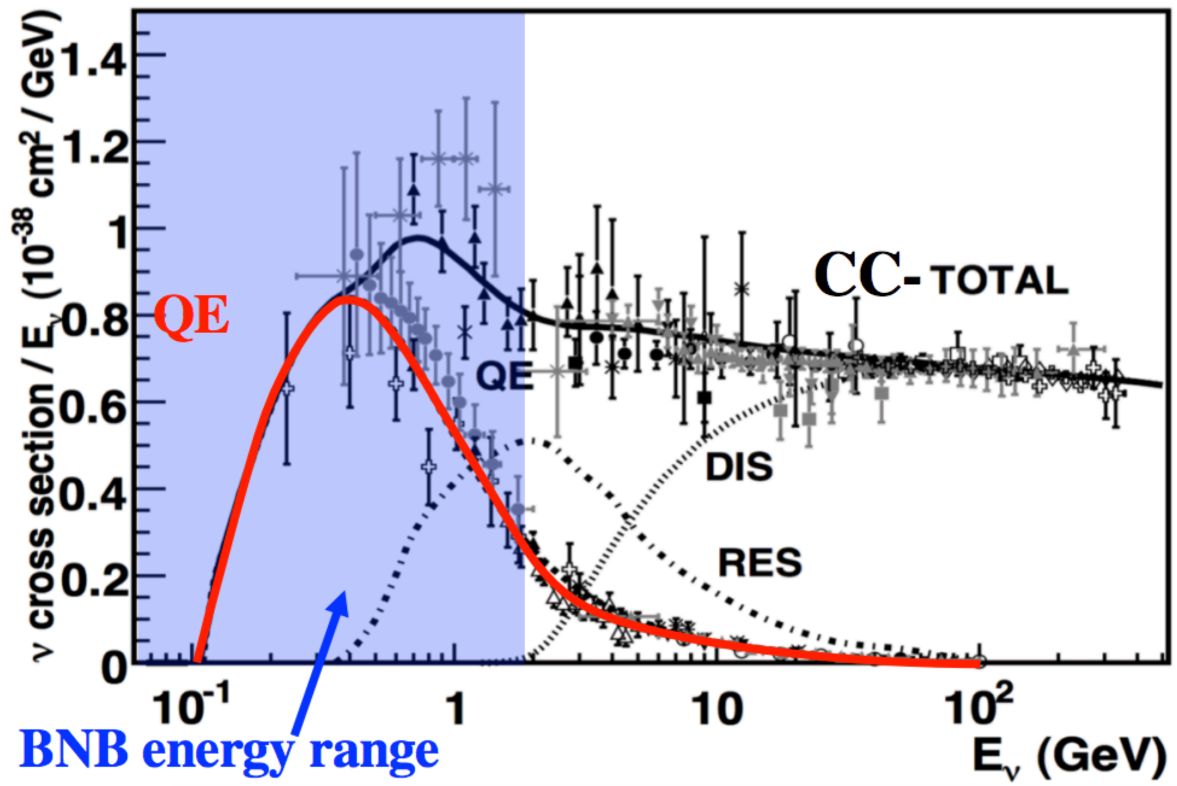


LAr TPC

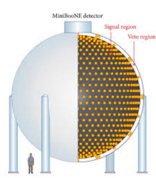


Charge Current Quasi Elastic (CCQE)

- Most relevant for the BNB energies
- The simplest interaction
- Was studies for years with electrons scattering
- Enables energy reconstruction



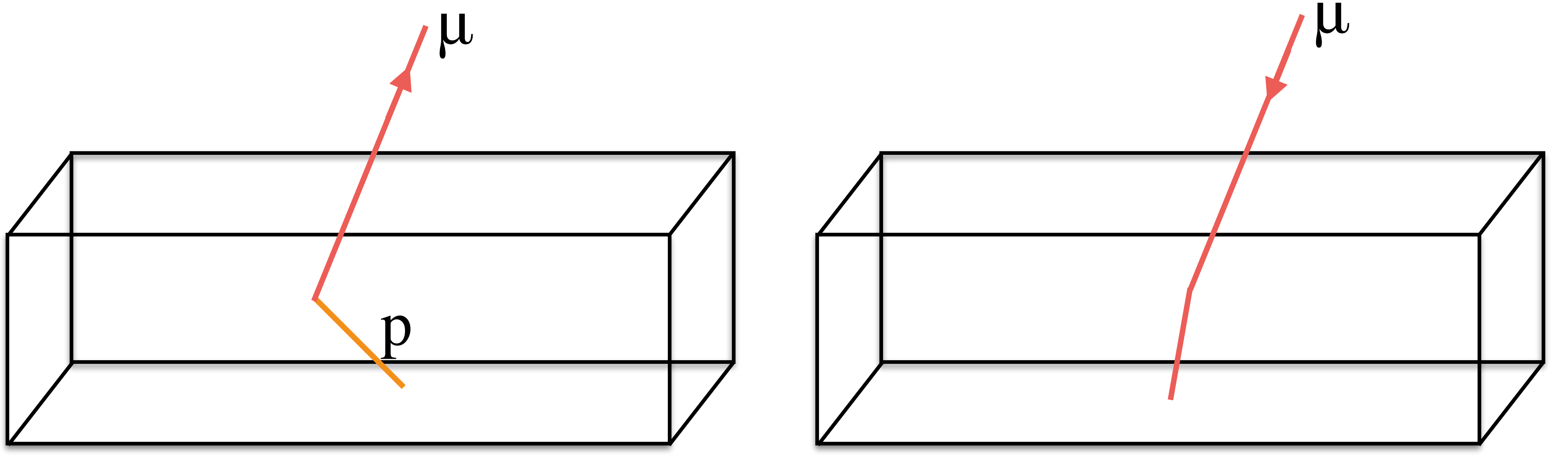
Charge Current Quasi Elastic (CCQE)

Experiment	Target	μ-dependence	p-dependence
SciBooNE	^{12}C	$d\sigma/dE_\nu$ doi: 10.1063/1.3661556	
MiniBooNE Detector 	^{12}C	$d^2\sigma/dP_\mu d\cos\theta_\mu$ Phys Rev D88 (2013)	
T2K	^{12}C, ^{16}O	$d\sigma/d\theta_\mu$ Phys Rev D92 (2015) $d^2\sigma/dP_\mu d\cos\theta_\mu$ PhysRevD.98.0124004	$d^2\sigma/dP_p d\cos\theta_p$ arXiv:1802.05078 [hep-ex]
MINERvA	^{12}C, ^{56}Fe, ^{208}Pb	$d^2\sigma/dP_{\parallel}dP_T$ Phys Rev D97.052002	$d^2\sigma/dQ^2{}_p$ Phys Rev Lett 119 (2017)
μBooNE	^{40}Ar	$d\sigma/dP_\mu$, $d\sigma/d\cos\theta_\mu$, $d\sigma/d\varphi_\mu$	$d\sigma/dP_p$, $d\sigma/d\cos\theta_p$, $d\sigma/d\varphi_p$

CCQE - Background rejection

The signal is a vertex with associated 1μ1p solely

Since MicroBooNE is a surface detector the main background is cosmic related, and needs to be properly estimated

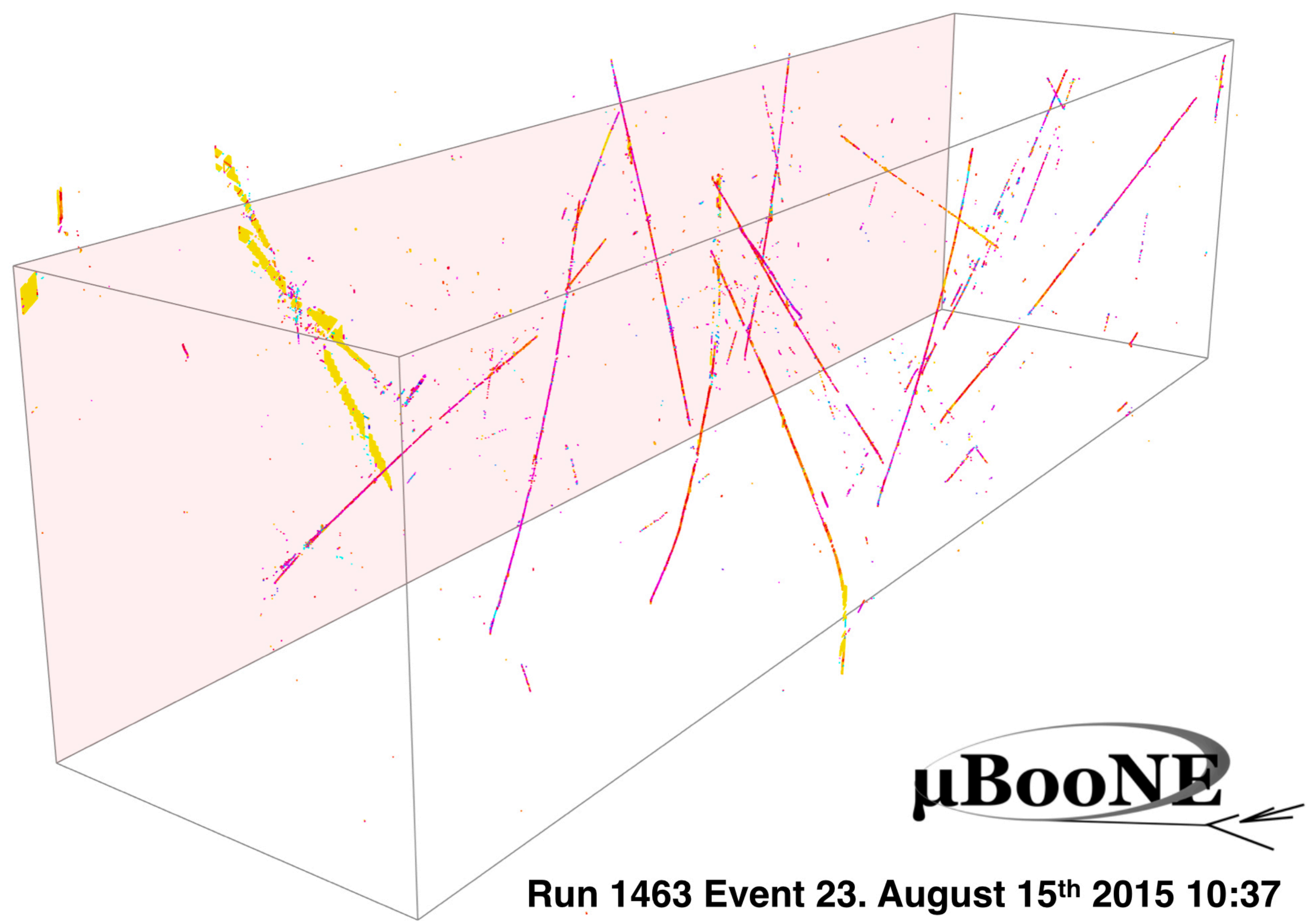


Overlay

Improving simulation by using cosmic data from MicroBooNE

- Simulated BNB using GENIE event generator.

- Cosmic events from external unbiased data.



CCQE - Event Selection

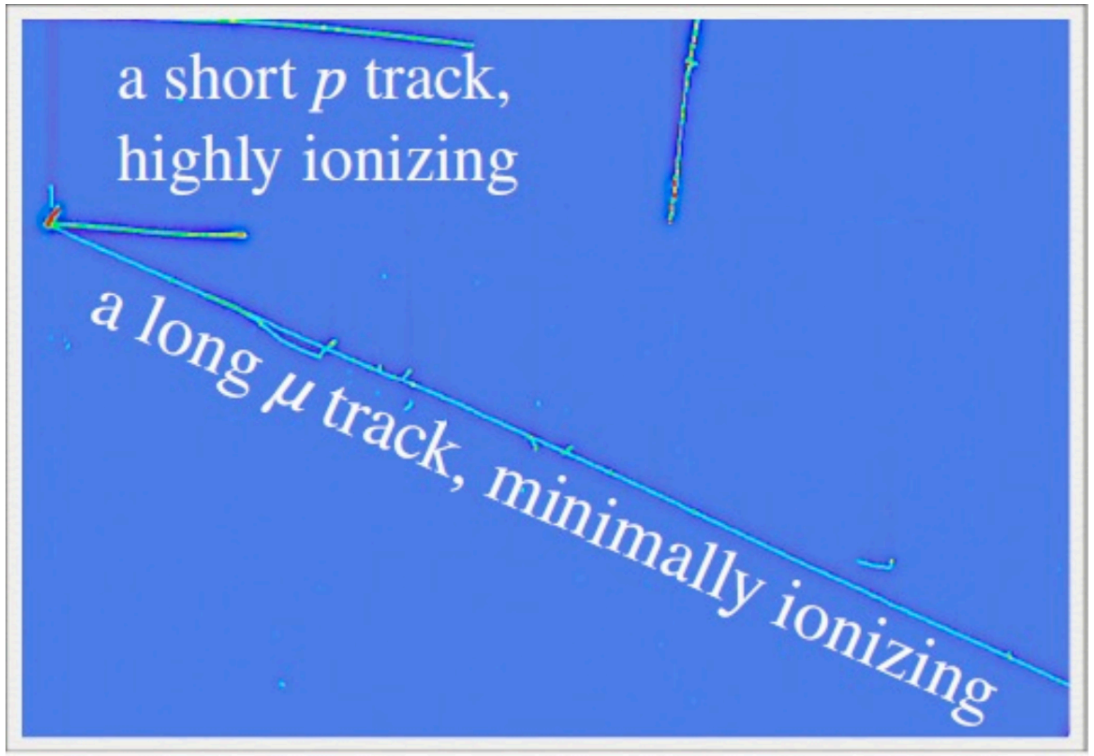
Vertex of 2 semi-contained tracks

(start within the fiducial volume)

one muon (≥ 100 MeV/c)

one proton (≥ 200 MeV/c)

no π0 , no charged π (≥ 70 MeV/c)



We allow any number of e, γ, n and charged hadrons below these thresholds.

CCQE - Event selection

After a year with 5E19 Protons On Target (POT):

	Number of events	**Beam-on equivalent**
Beam on	462±21.5	
Beam off	15±3.9	10.6±2.7
Overlay CC1p0π	9538±97.7	486.6±5.0

CCQE - Cross section extraction

$$\left(\frac{d^3\sigma}{dp_\mu d\cos\theta_\mu d\phi_\mu}\right)_n = \frac{N_n^{\text{on}} - N_n^{\text{off}} - B_n}{\eta_n^\mu \cdot \Phi_n \cdot N_{\text{targets}} \cdot \Delta_n}$$

and similarly for protons

N^{on} - # of events in beam-on data
N^{off} - # of events in beam-off data

DATA

B_n - Background
η_n^μ - Effective detection efficiency

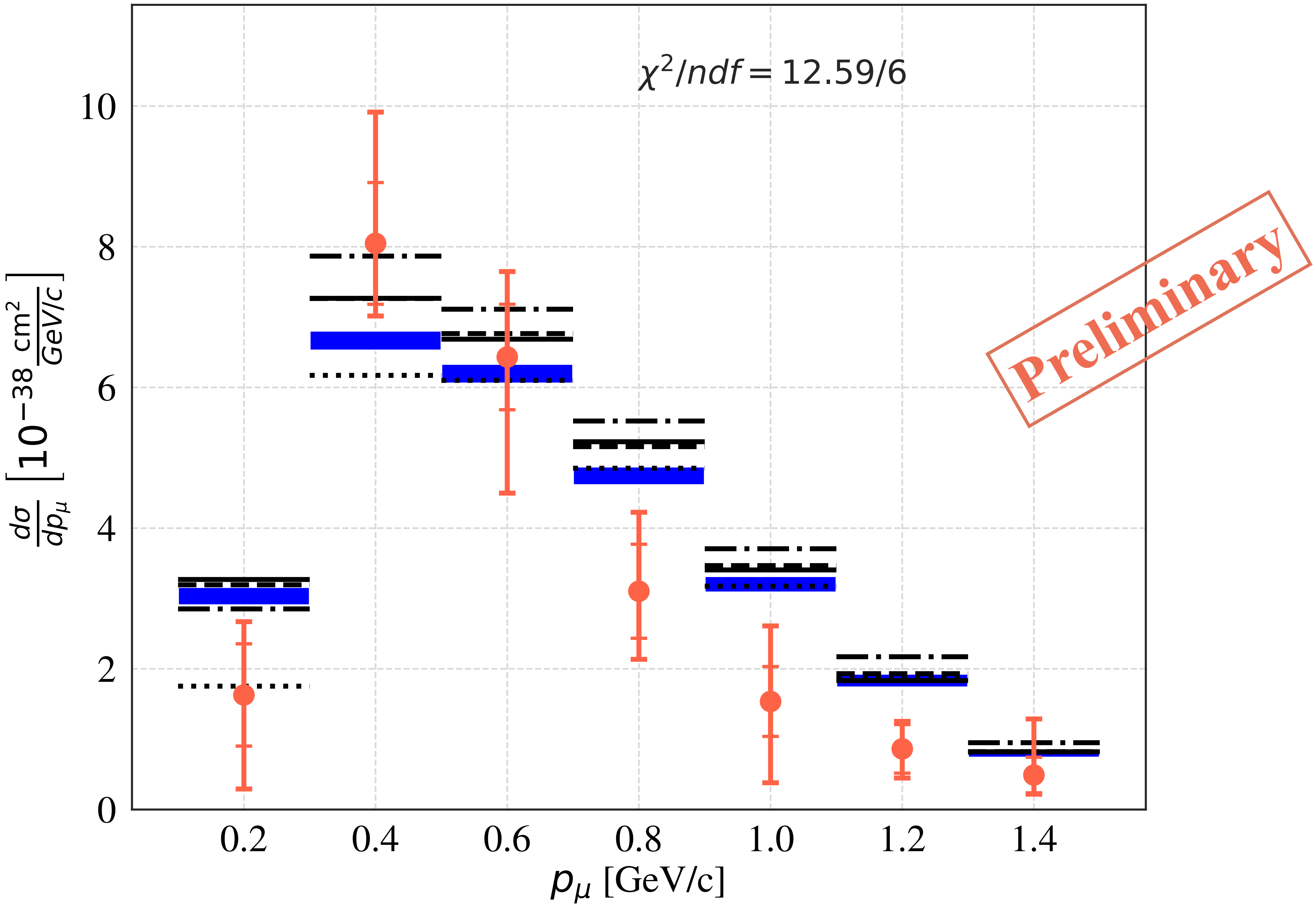
MC

$N_{targets}$ - number of scattering nuclei
ϕ_ν - neutrino flux
Δ - bin width (product of bin widths)

constants

CCQE - Results

$\nu + {}^{40}Ar \rightarrow \mu + p + {}^{39}Ar$



CCQE - Results

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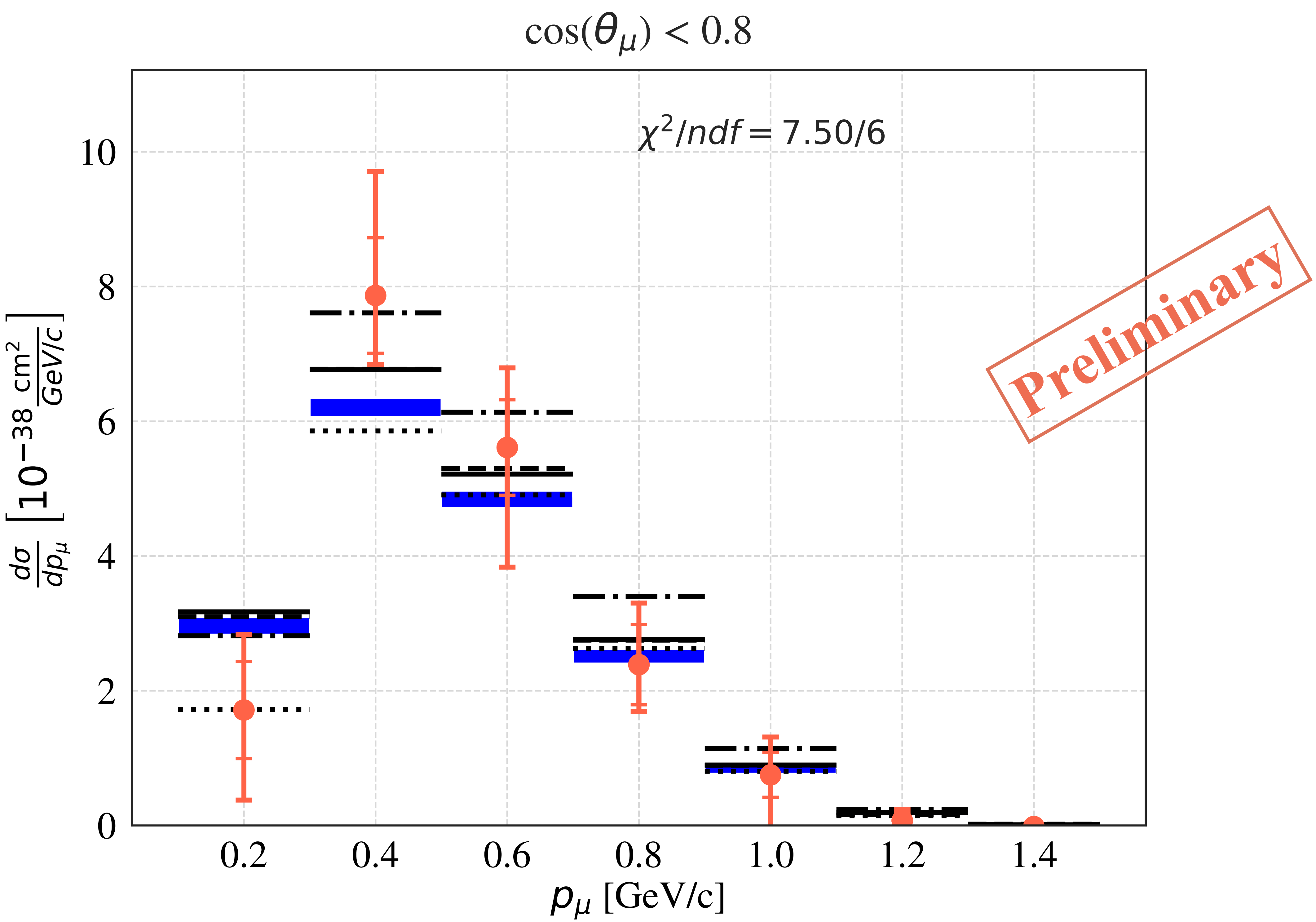
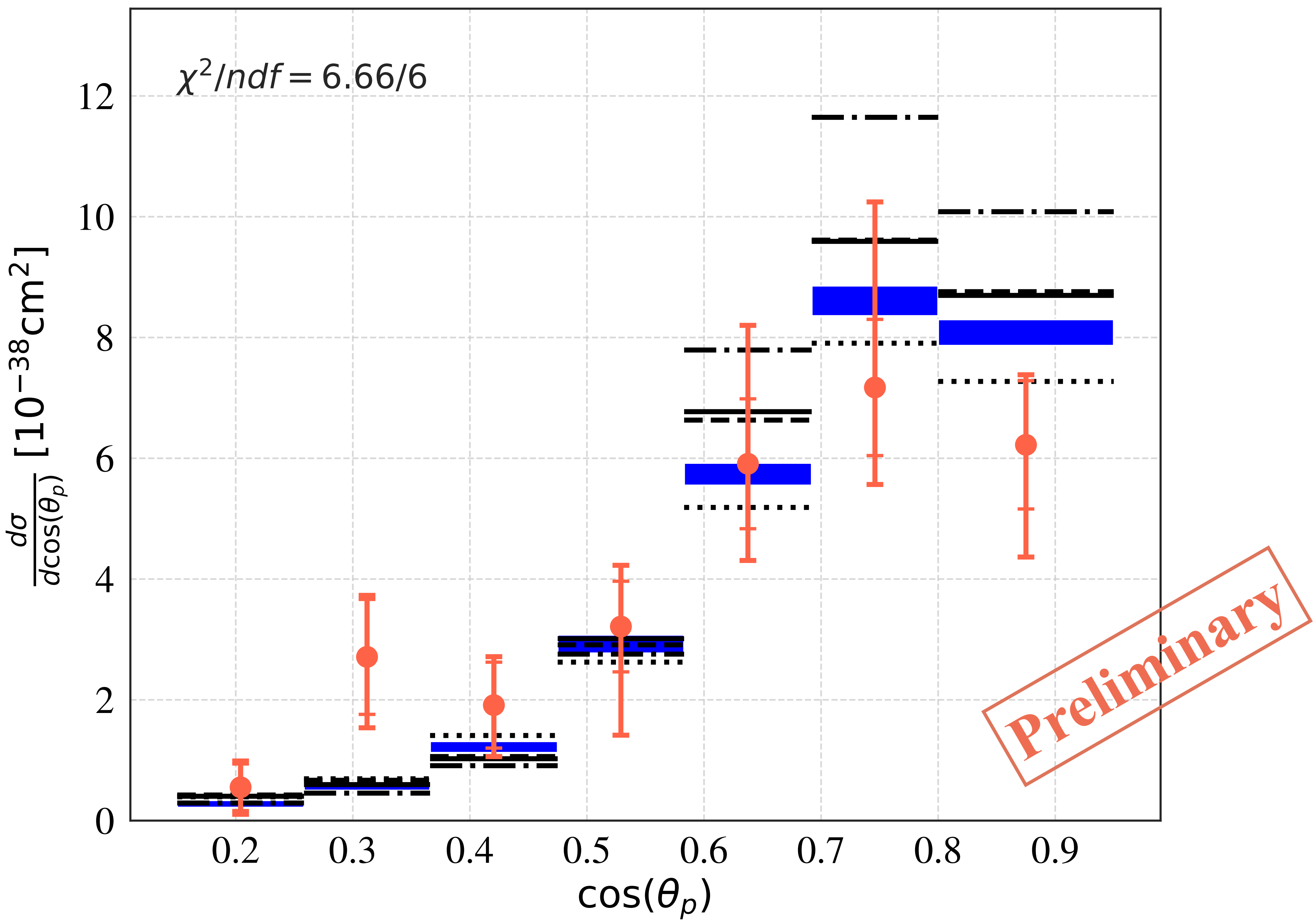
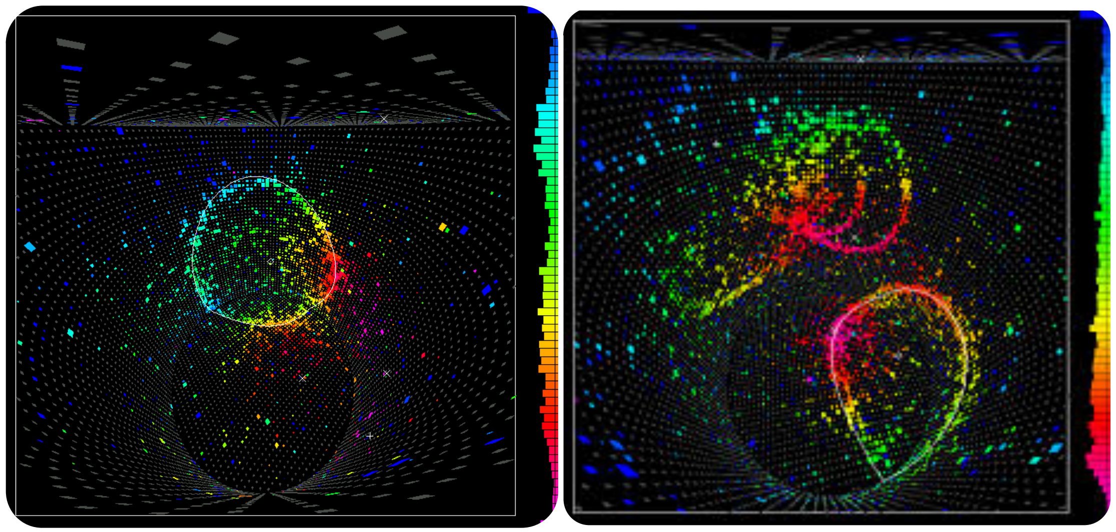


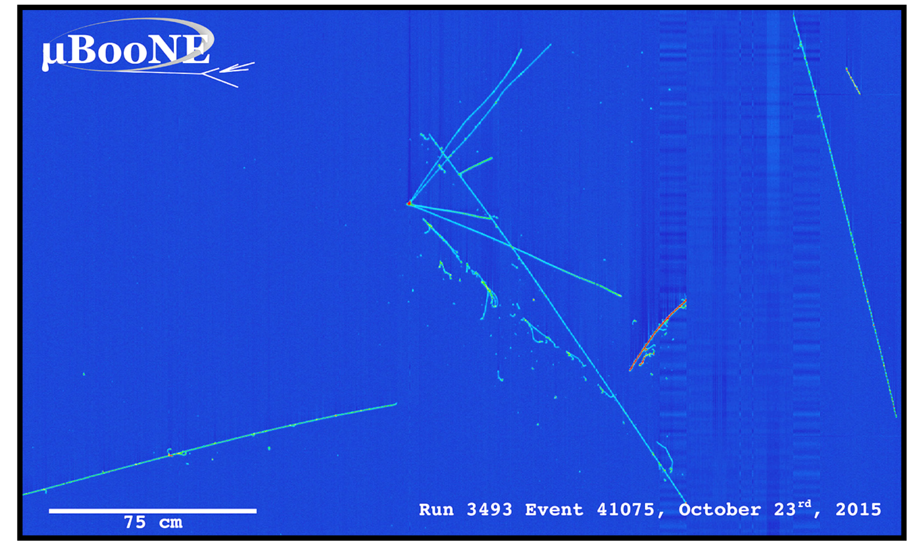
CCQE - Results

$\nu + {}^{40}Ar \rightarrow \mu + p + {}^{39}Ar$



Incoming neutrino Energy Reconstruction





Cherenkov detectors:

Assuming QE interaction

Using solely the final state lepton

$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l| cos\theta)}$$

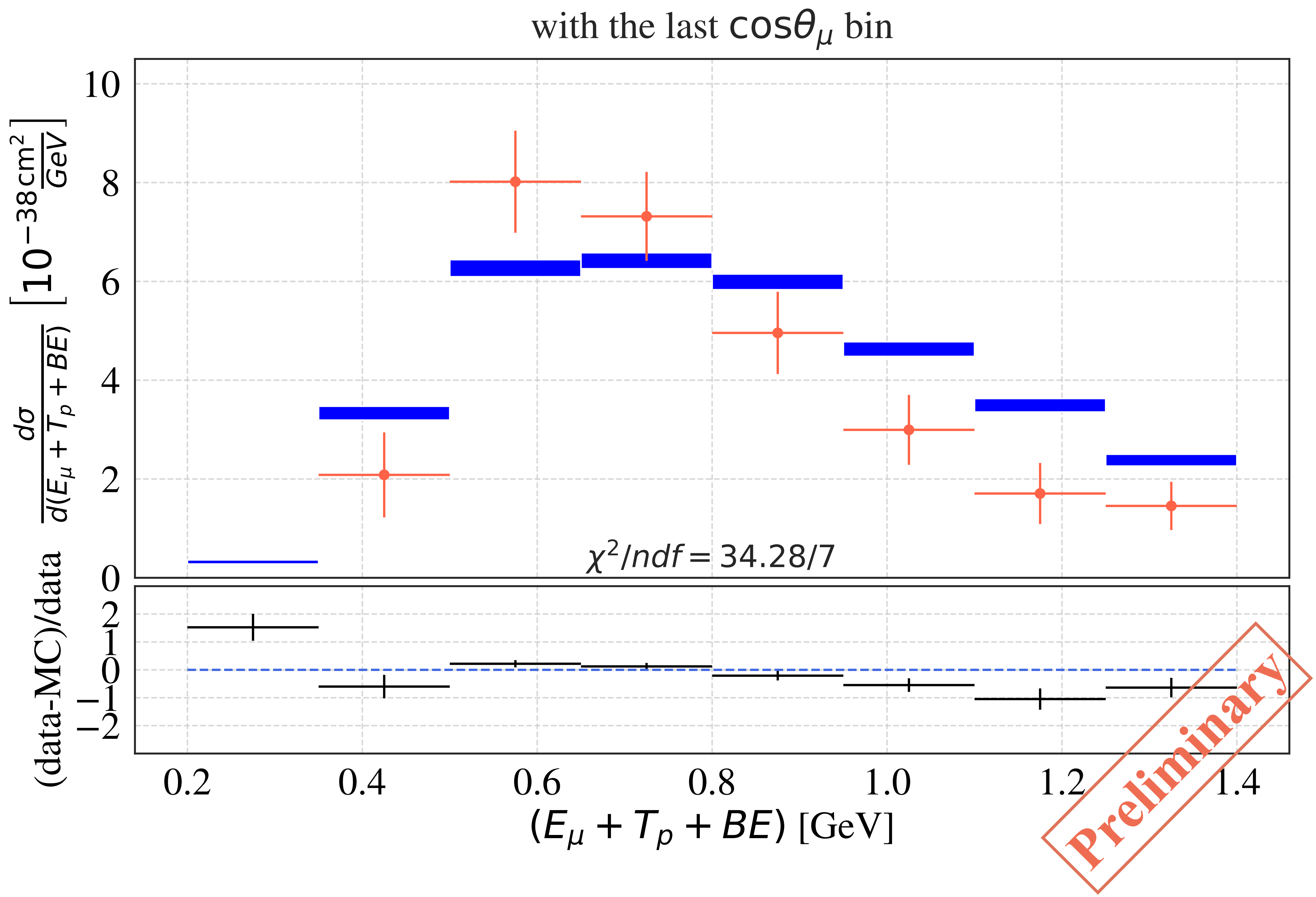
Tracking detectors:

Need good hadronic reconstruction

$$E_{\text{cal}} = E_l + E_p^{\text{kin}} + \epsilon$$

ϵ is the nucleon separation energy ~ 20 MeV

CCQE - Results



Energy Reconstruction Approaches

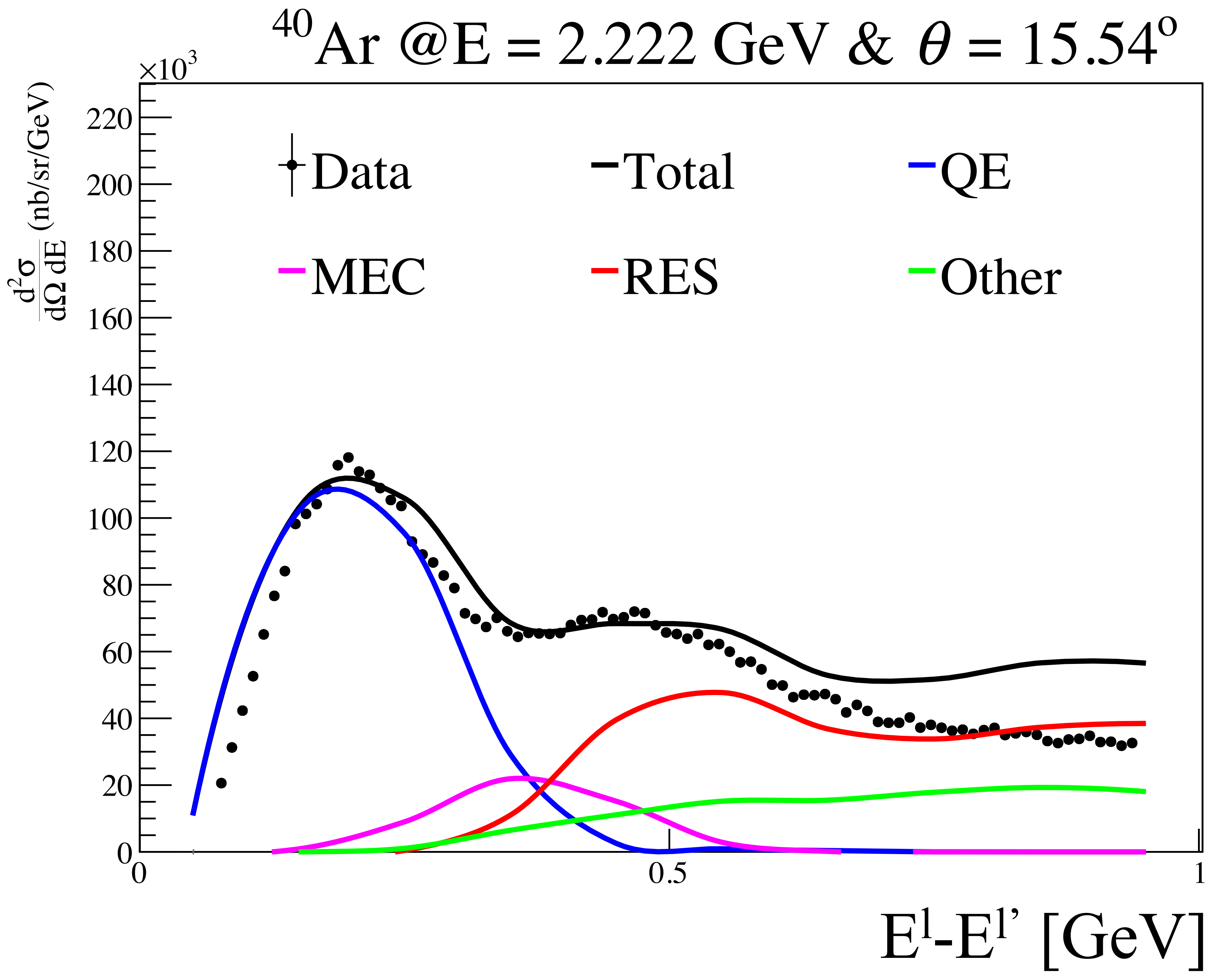
- Improved theory
- **External constraints on nuclear model**
- Use near detector
  - Where we wish to probe nuclear physics and no oscillation effects
  - But flux and nuclear models are convoluted

e4ν Electron for neutrinos

- Electrons and Neutrinos have:
  - Similar interactions
  - Same nuclear effects

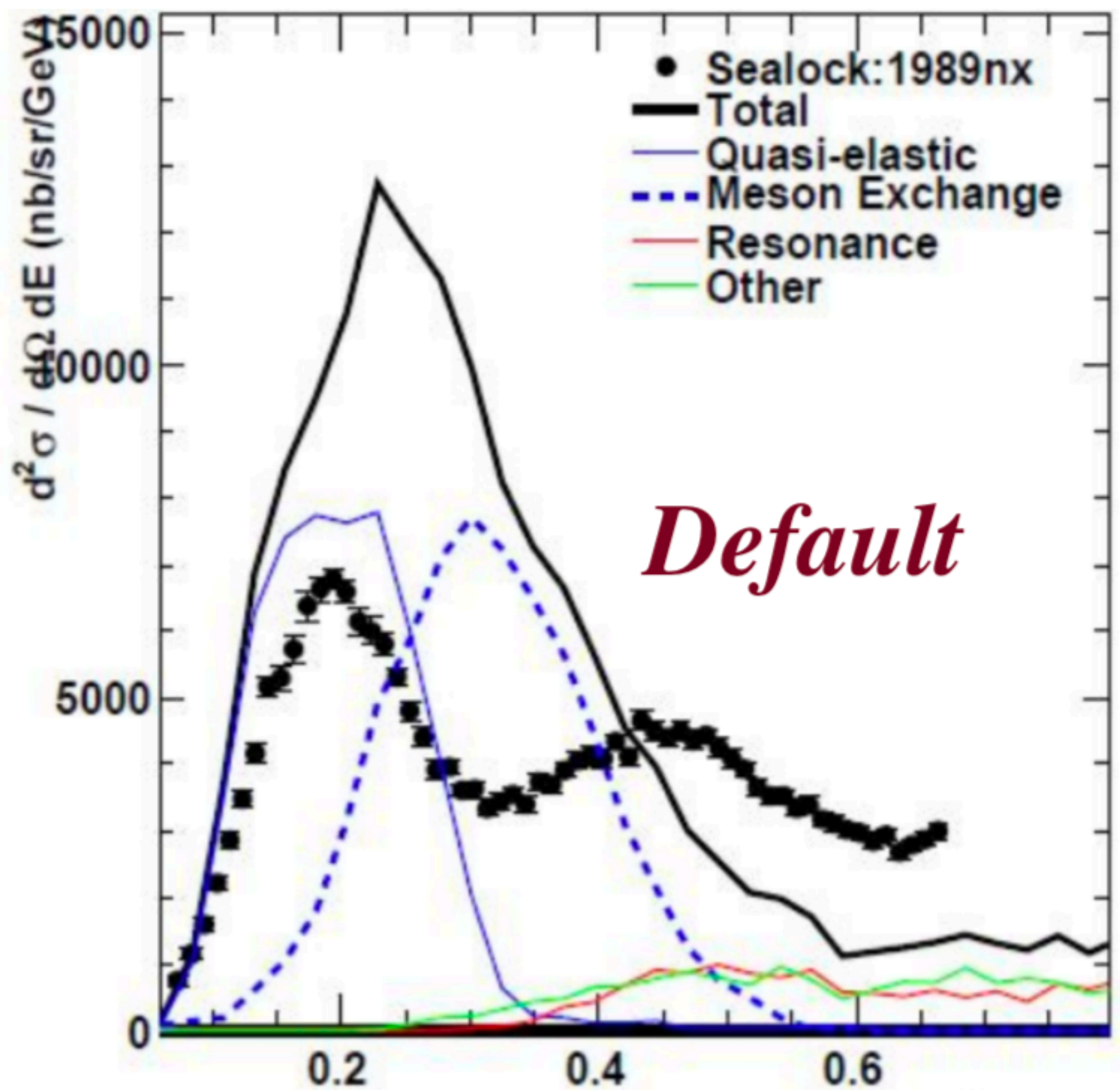
Electron beam have known energy

Testing neutrino generators with inclusive electron scattering data

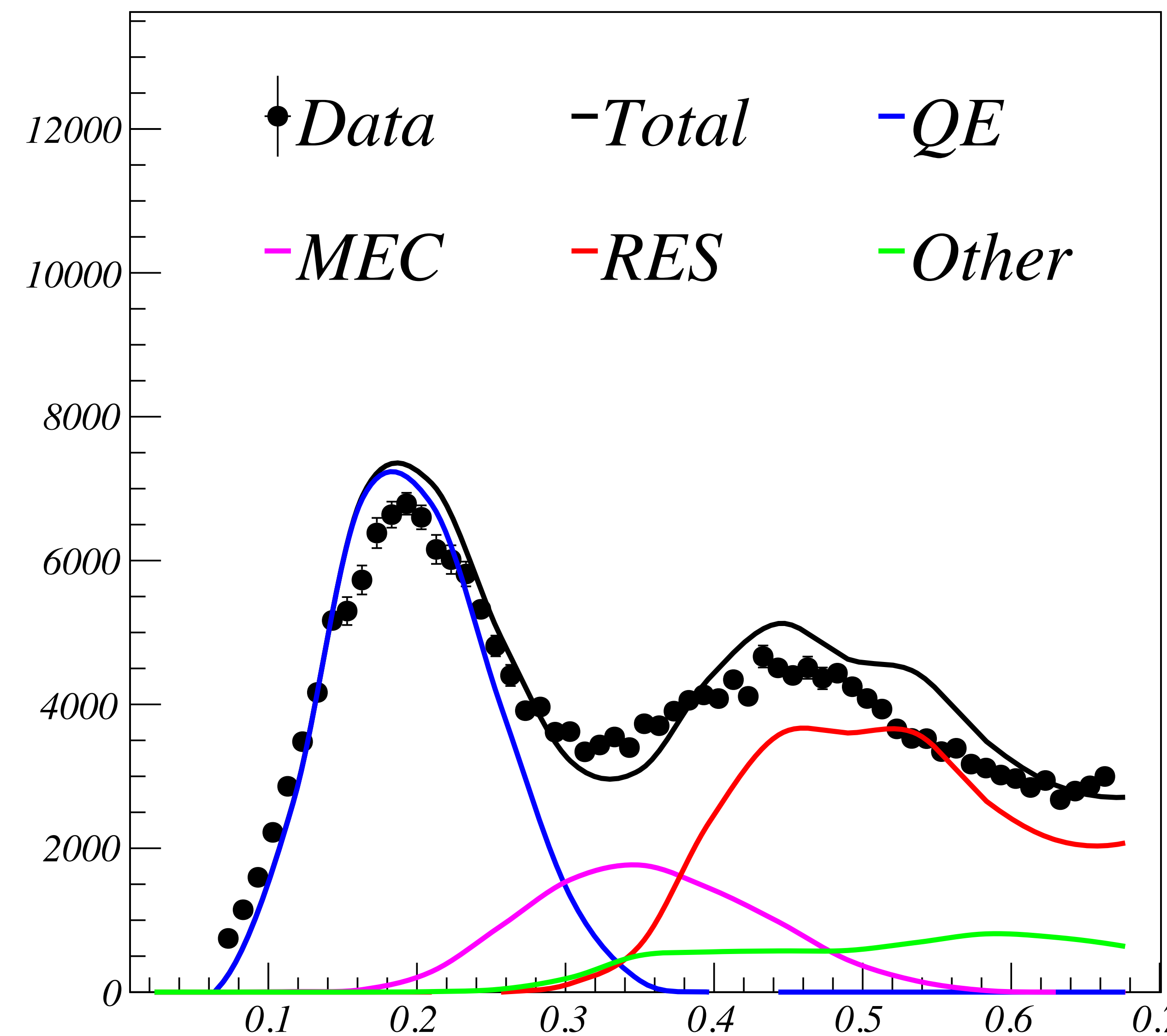


Testing neutrino generators with inclusive electron scattering data

$^{12}C(e,e')$ $E = 0.961$ GeV $\theta = 37.5^\circ$



$E^l - E^{l'}$ [GeV]



$E^l - E^{l'}$ [GeV]

e4ν: Playing the Neutrino game

Let's analyse electron data as if it was 'Neutrino data'

- Select a specific interaction
- Scale the electron data
- Compare to event generators

CLAS Detector

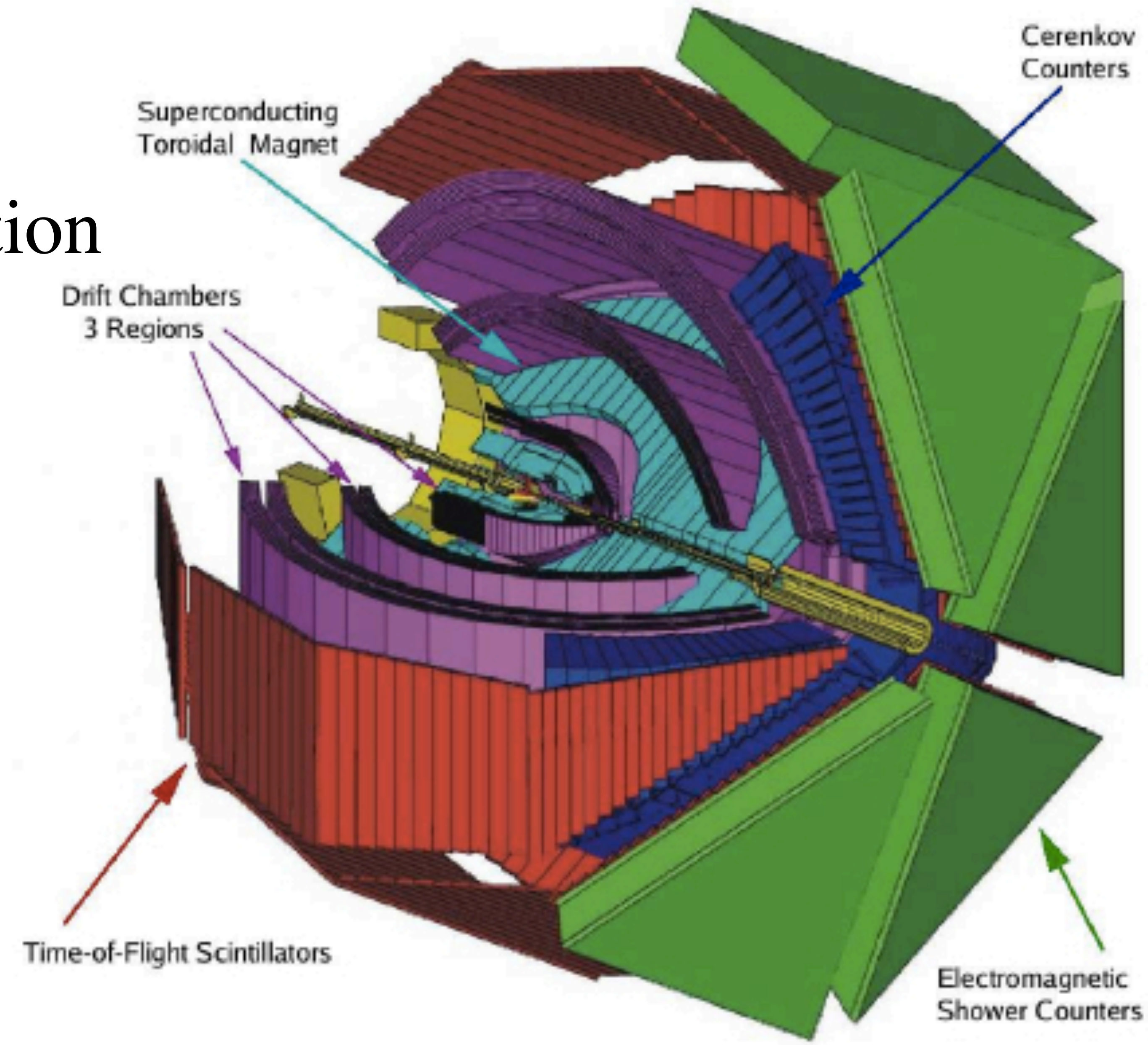
Electron beam with energies up to 6 GeV

Large (~4π) acceptance

Charged particles above detection threshold:

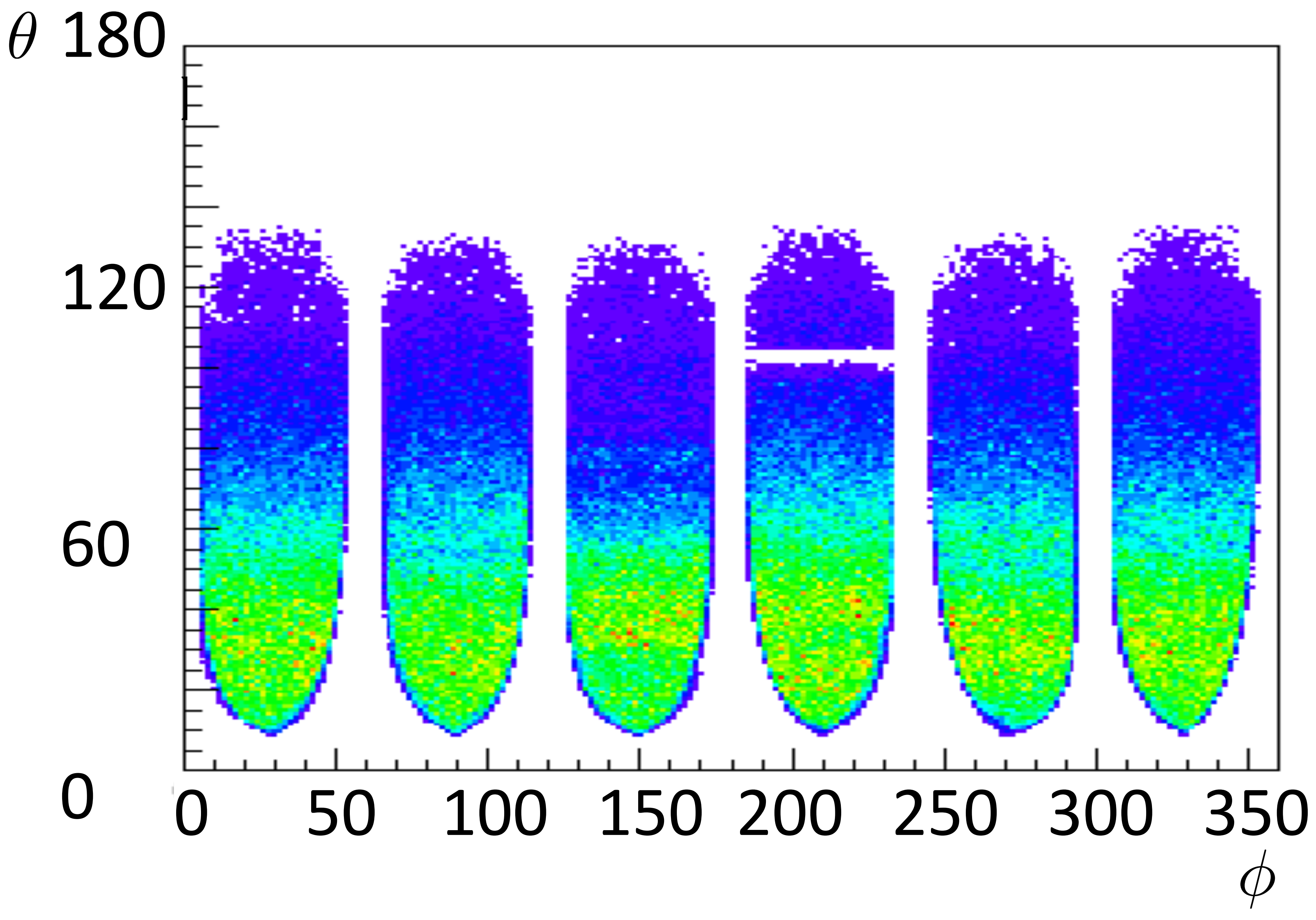
$P_p > 300$ MeV/c

$P_{\pi+/-} > 150$ MeV/c



Open Trigger

Wide Phase Space



CLAS A(e,e'p) Data

Targets:

^{4}He, ^{12}C, ^{56}Fe

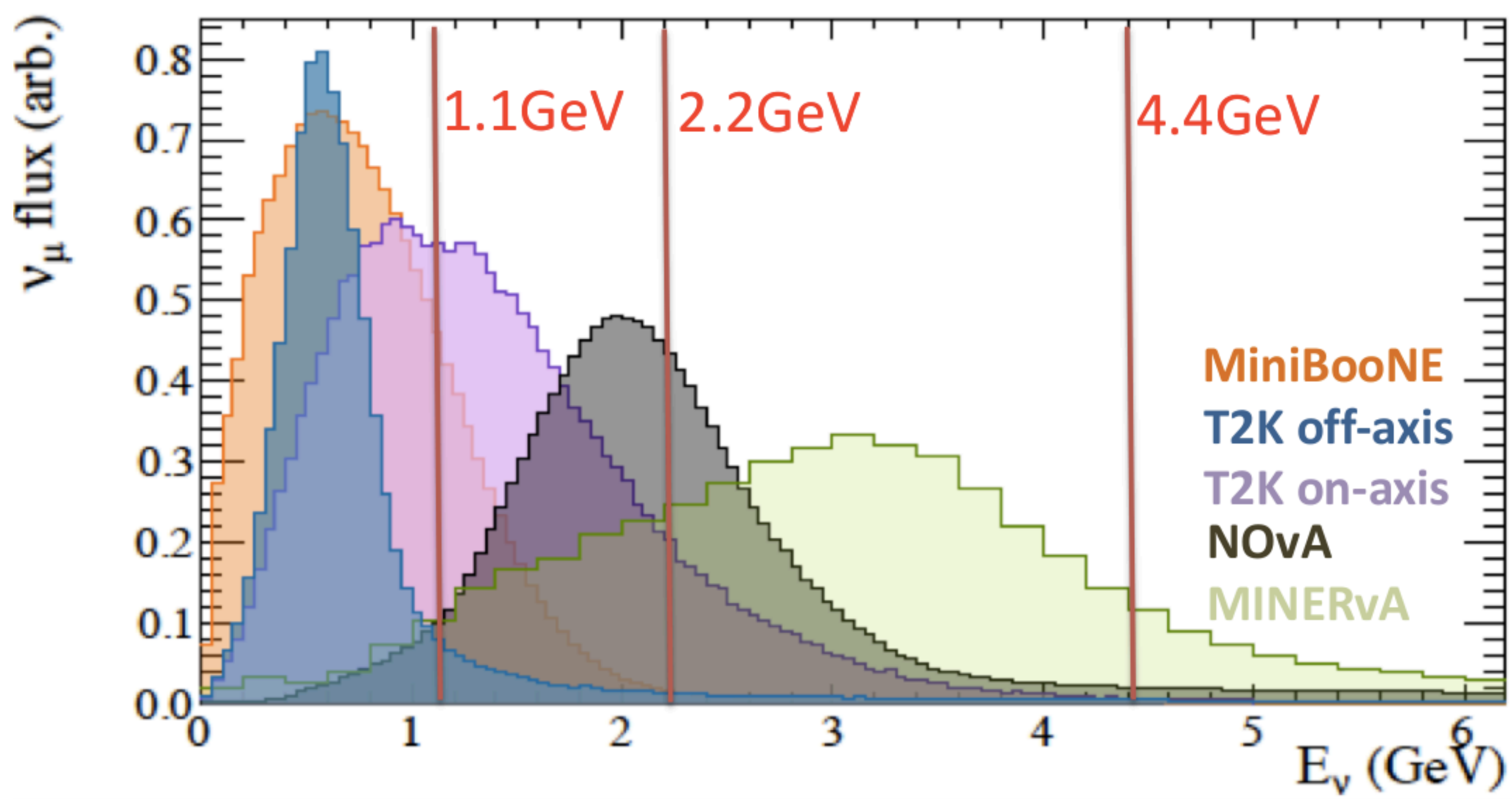
H_2O

CH

Ar

Energies:

1.1, 2.2, 4,4 GeV



e4ν A(e,e'p) Event Selection

Focus on QE events:

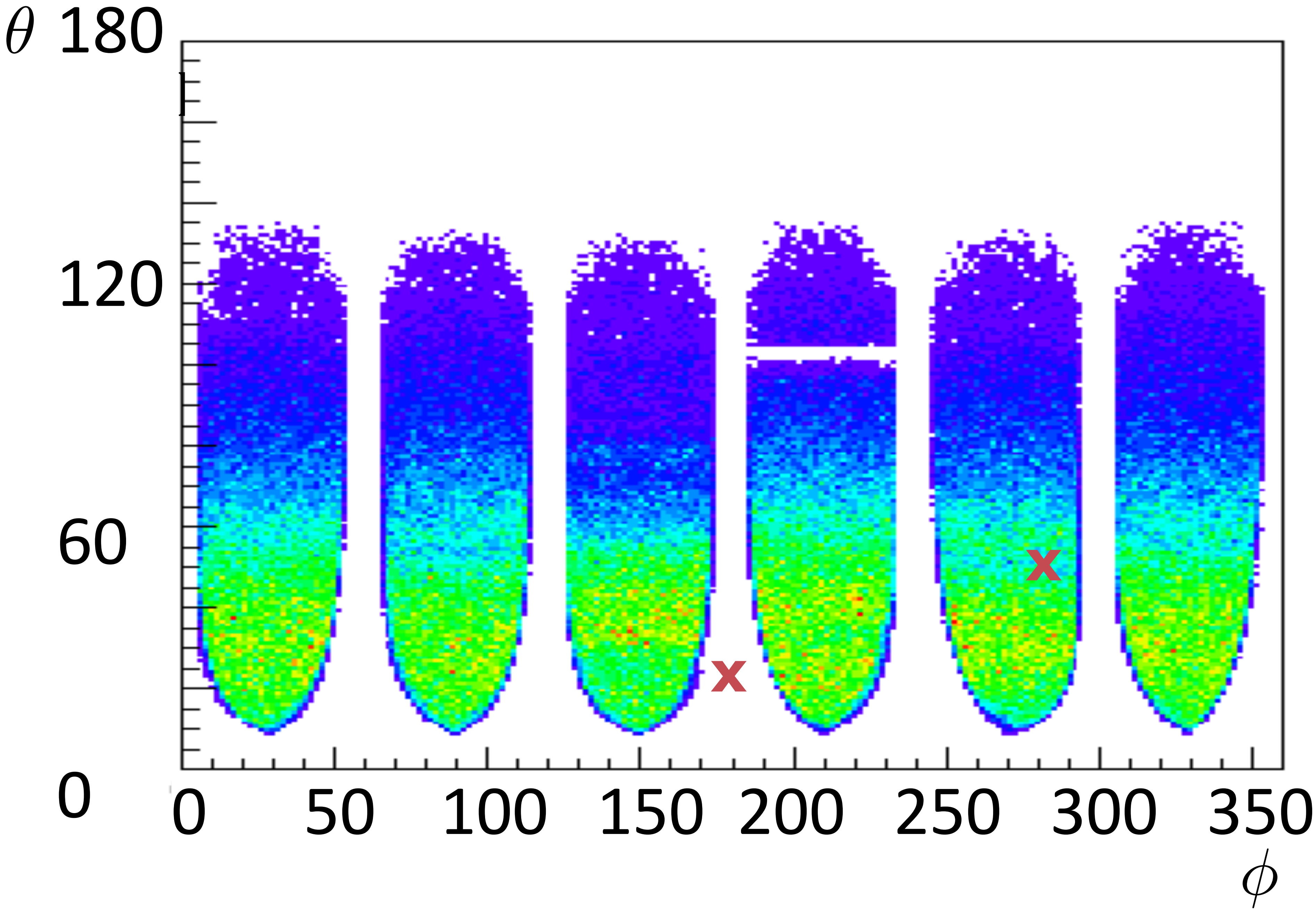
1 proton above 300 MeV/c

no additional charged hadrons above threshold

Background Subtraction

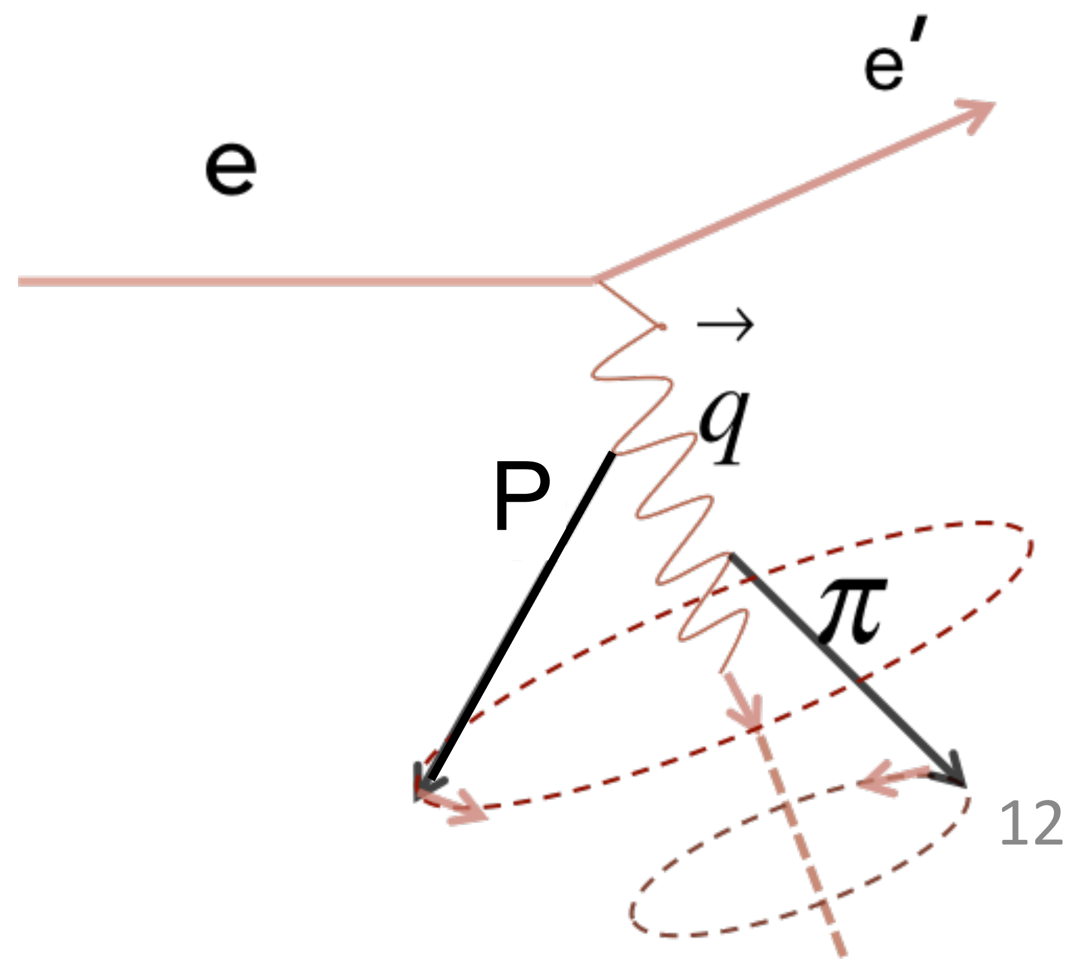
Different interaction lead to multi-hadron final states

Gaps can make them loop like QE-like events with outgoing 1μ1p



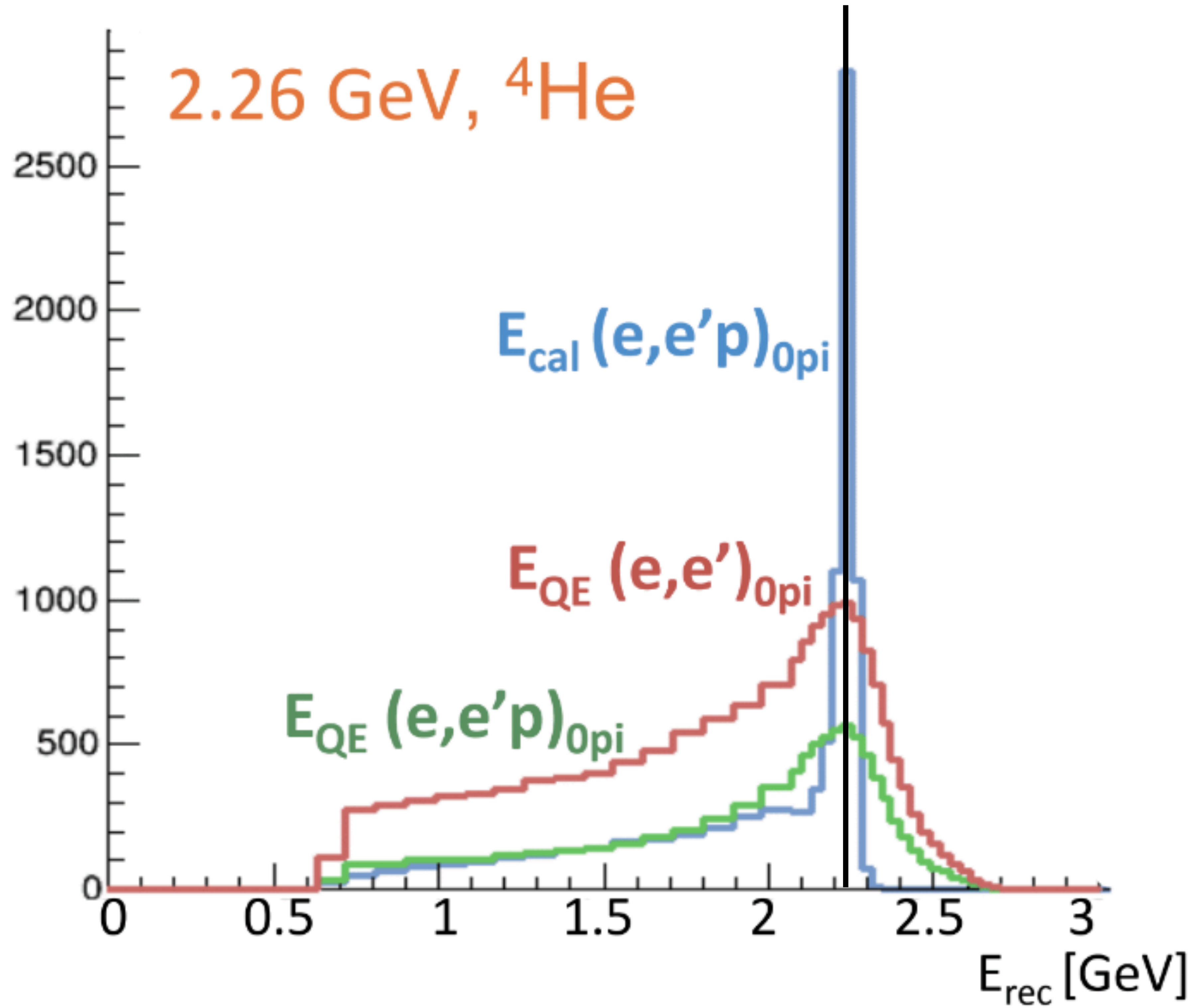
Data driven Background Subtraction

- Using events with two hadrons,
- Rotating p,π around q and determine π detection efficiency
- Subtract contribution to QE-like

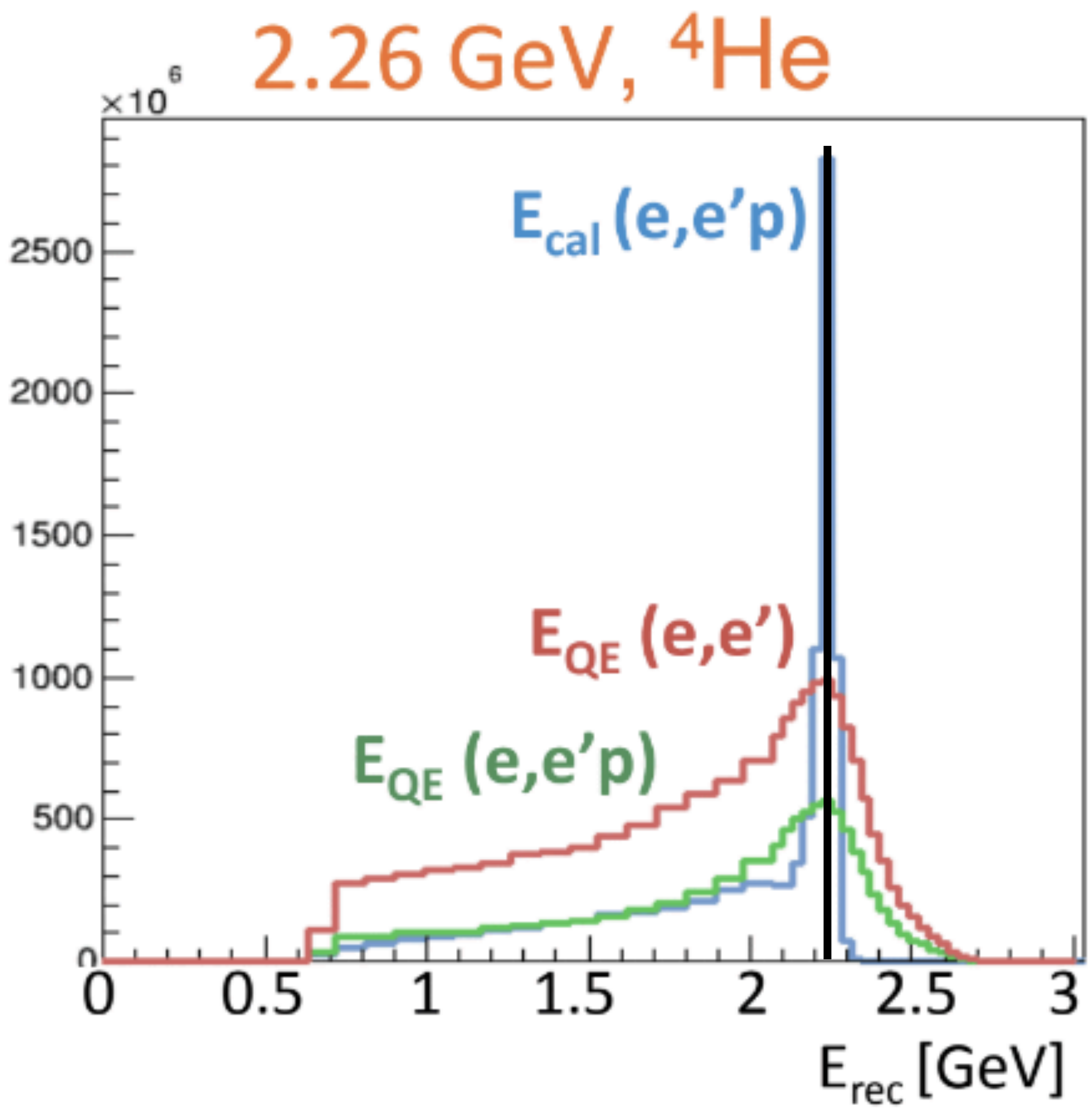


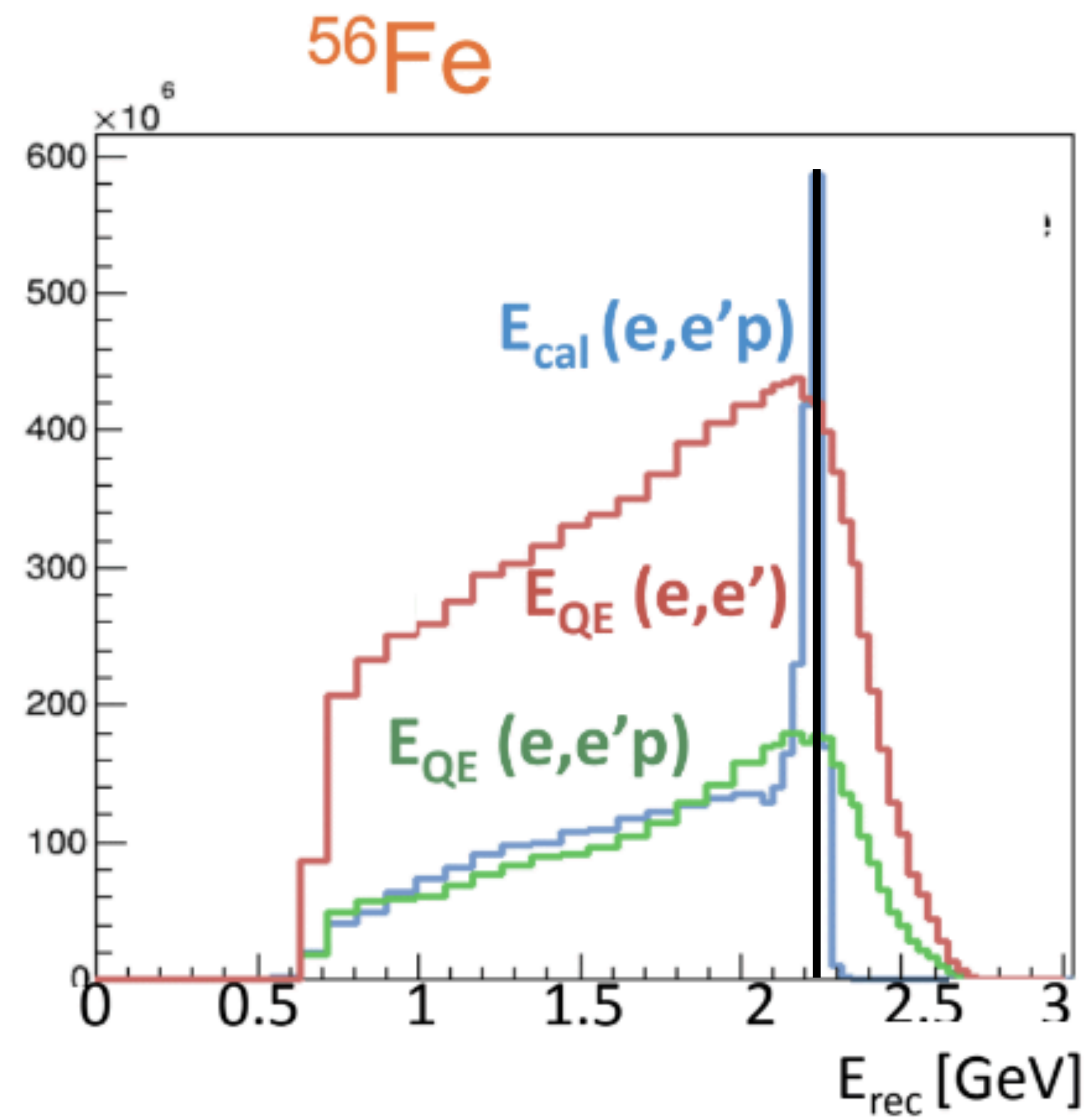
Same for final states with more than 2 hadrons

Testing the incoming energy reconstruction

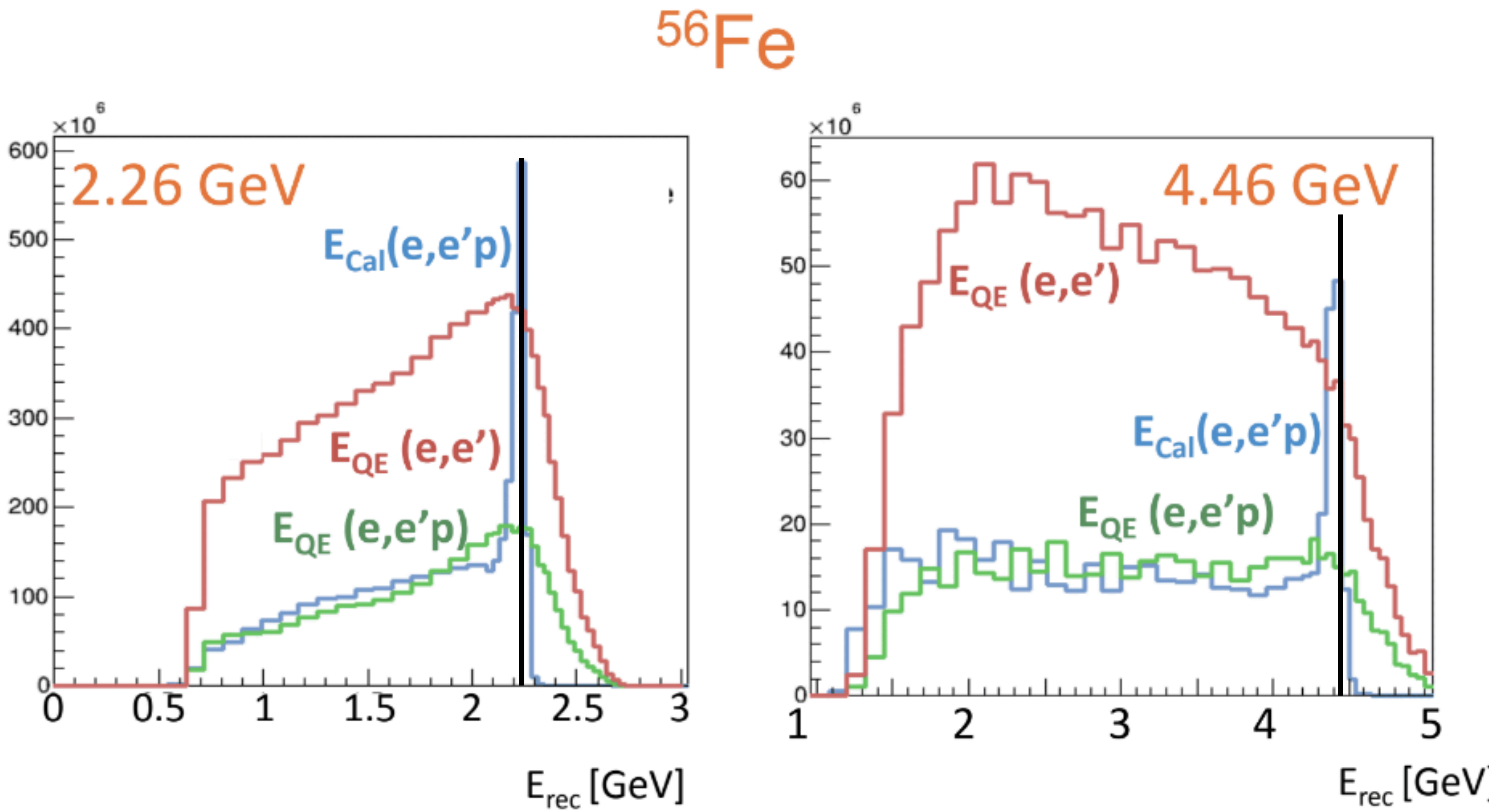


E_{rec} Worse with Higher Mass Number





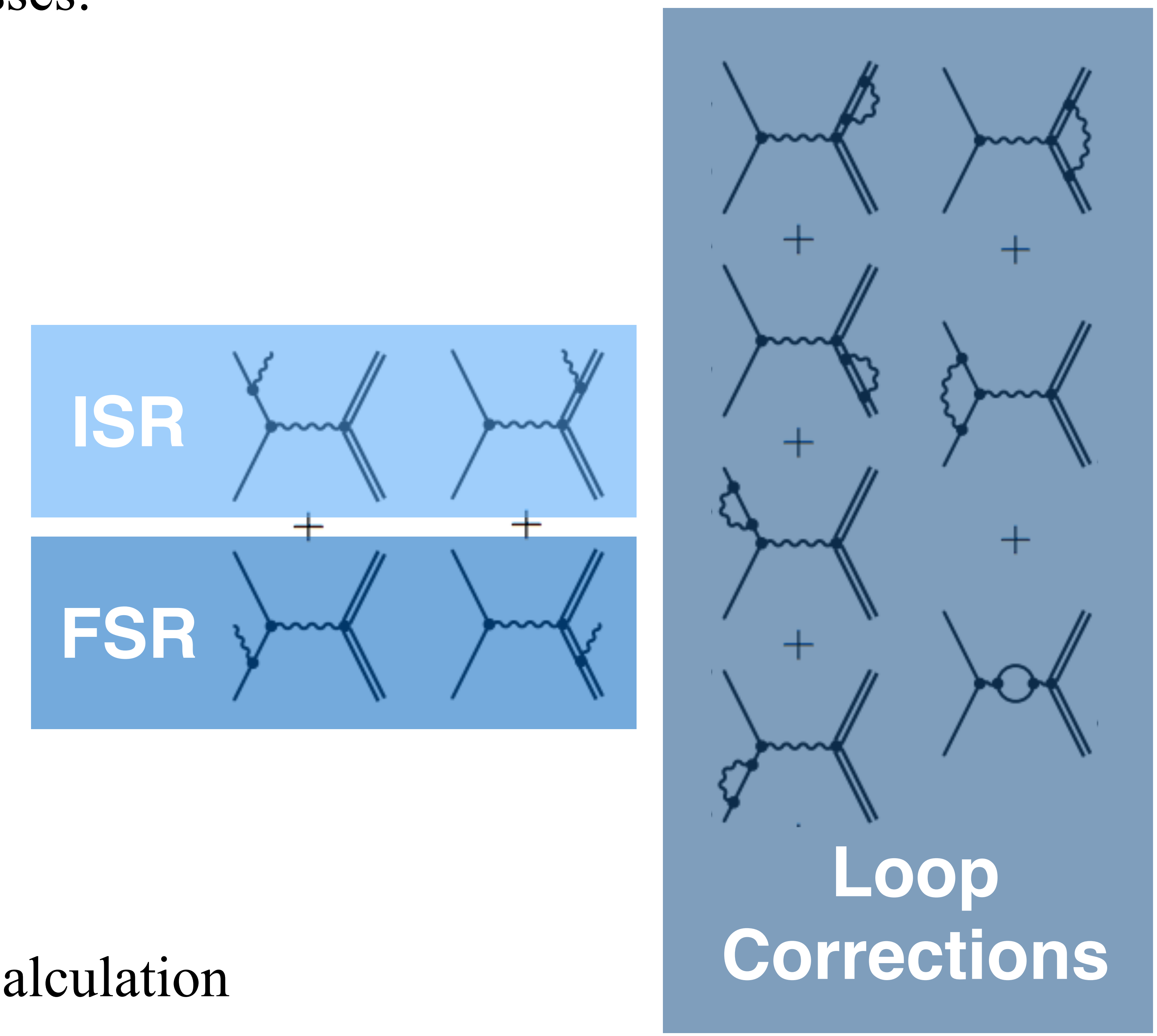
E_{rec} Worse with Higher Energy



Data Simulation Comparison

Radiative Correction

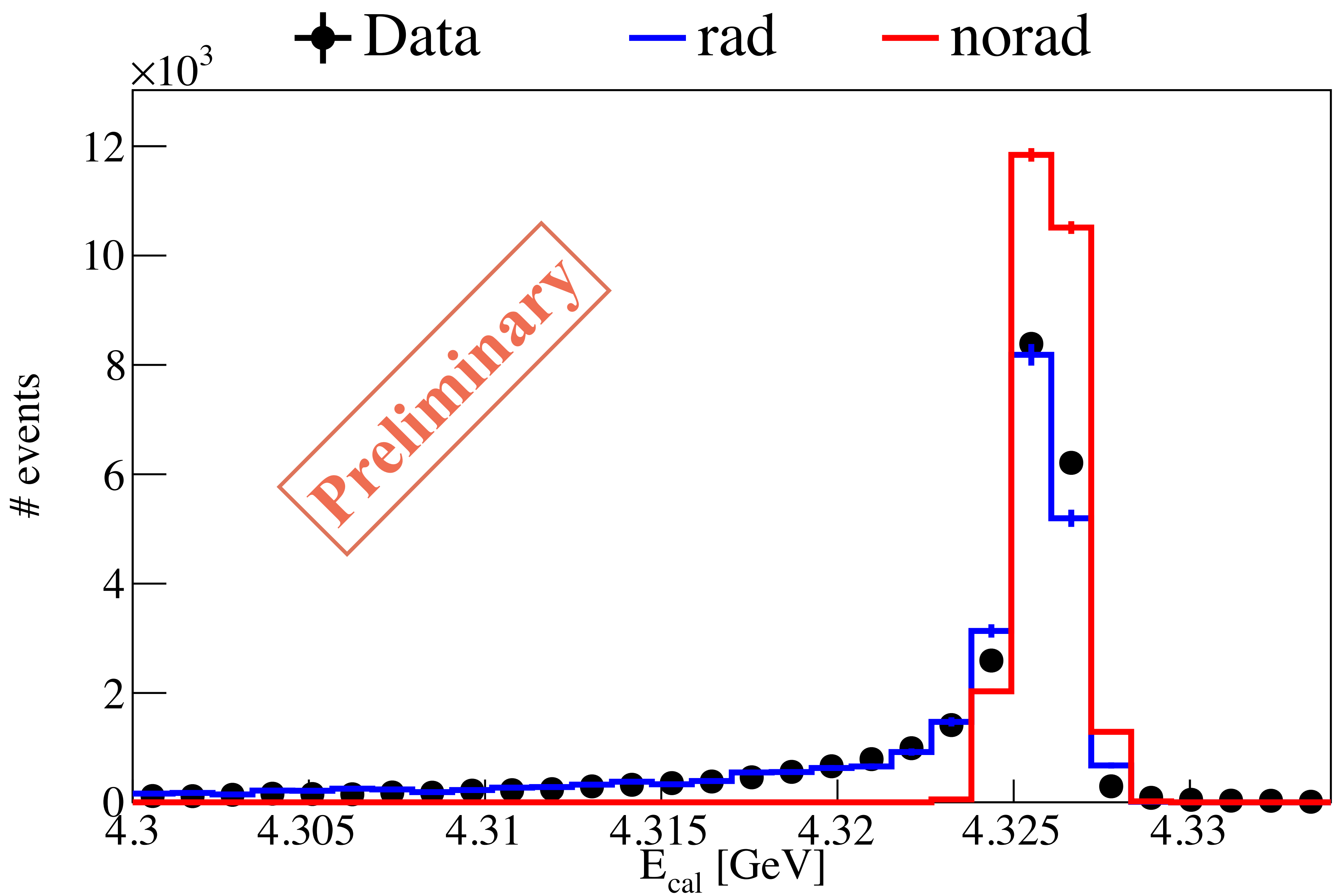
A first implementation of the radiative corrections to GENIE to account for the following processes:



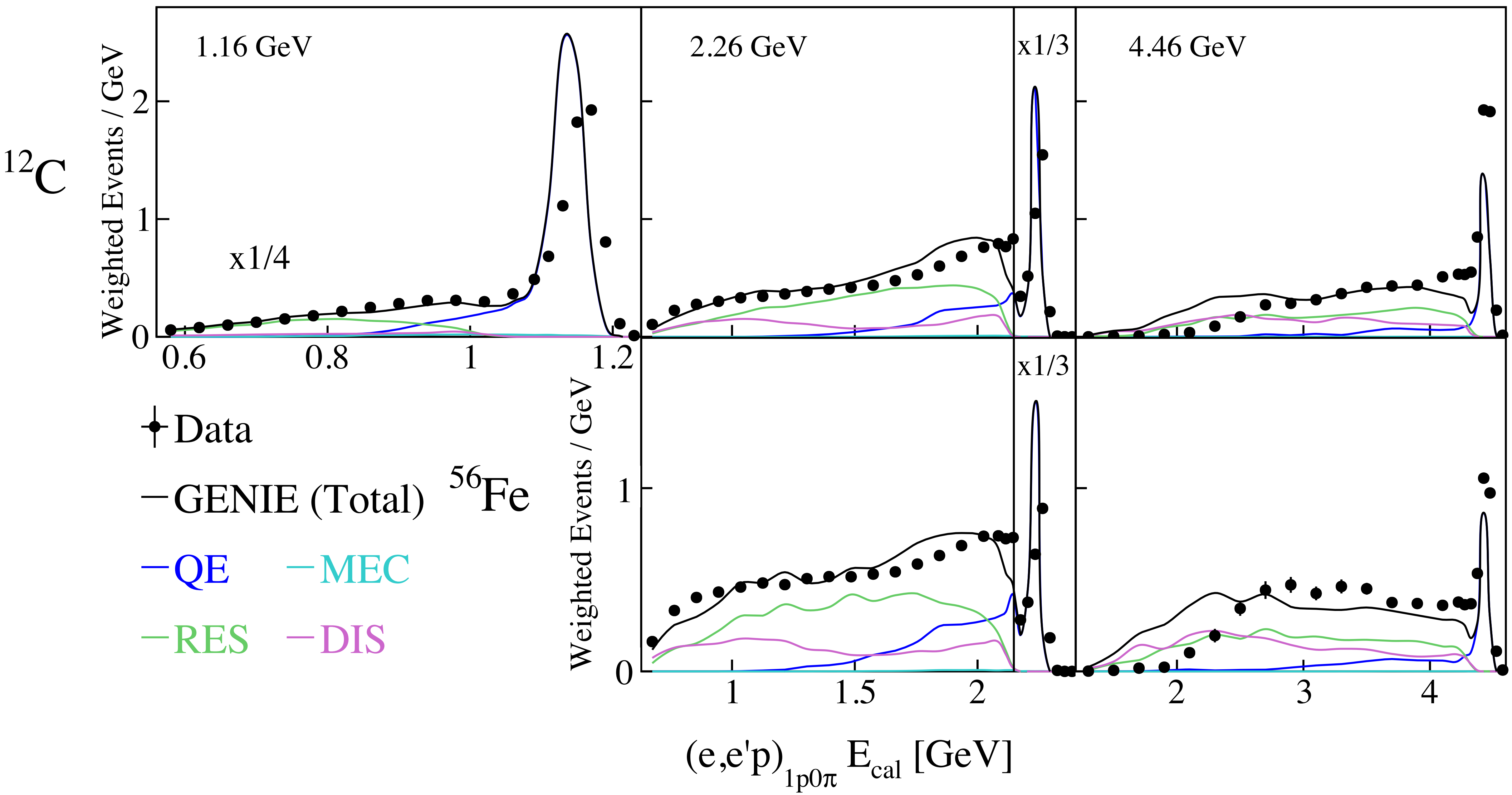
Based on Mo and Tsai calculation

Radiative Correction - Validation

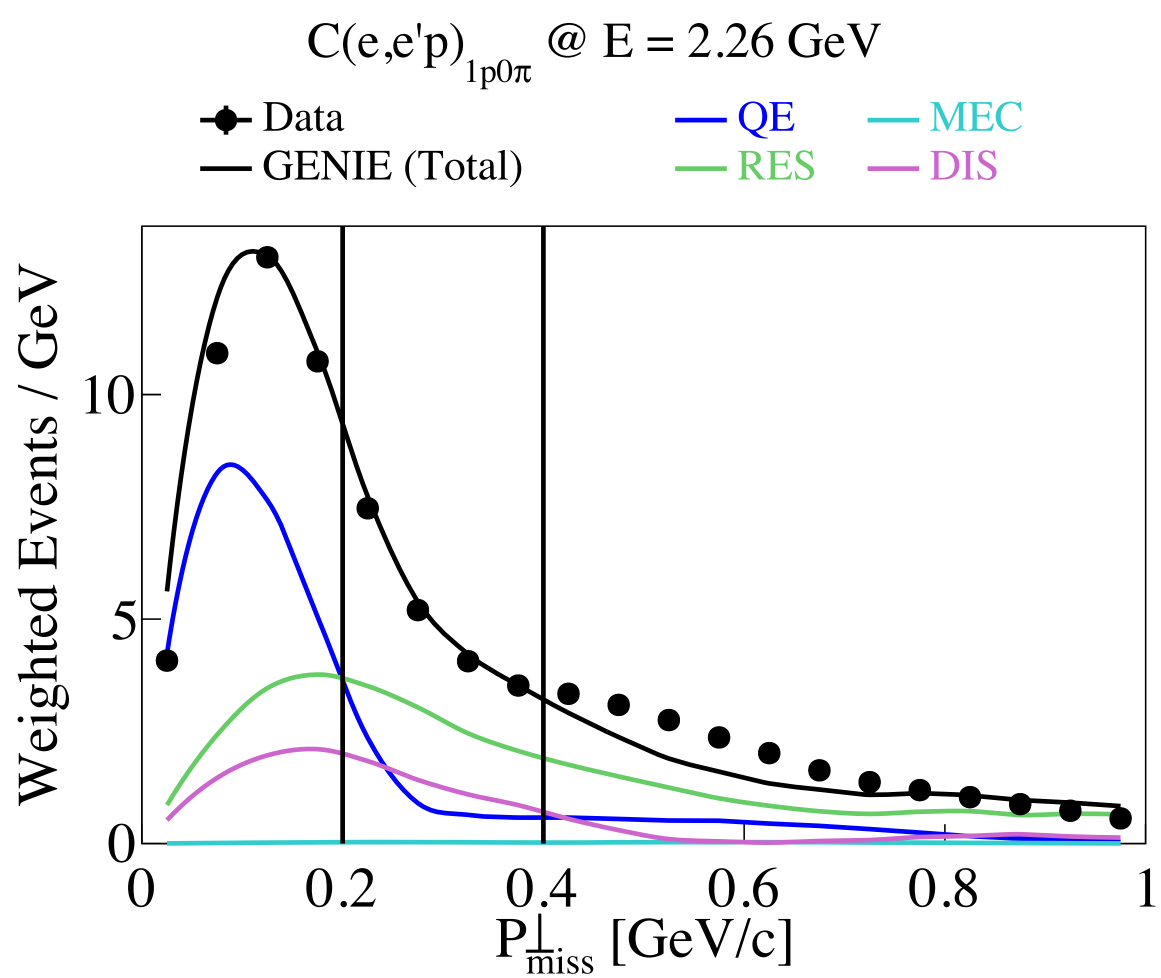
(e,e'p) @ E = 4.325 GeV on ^{1}H

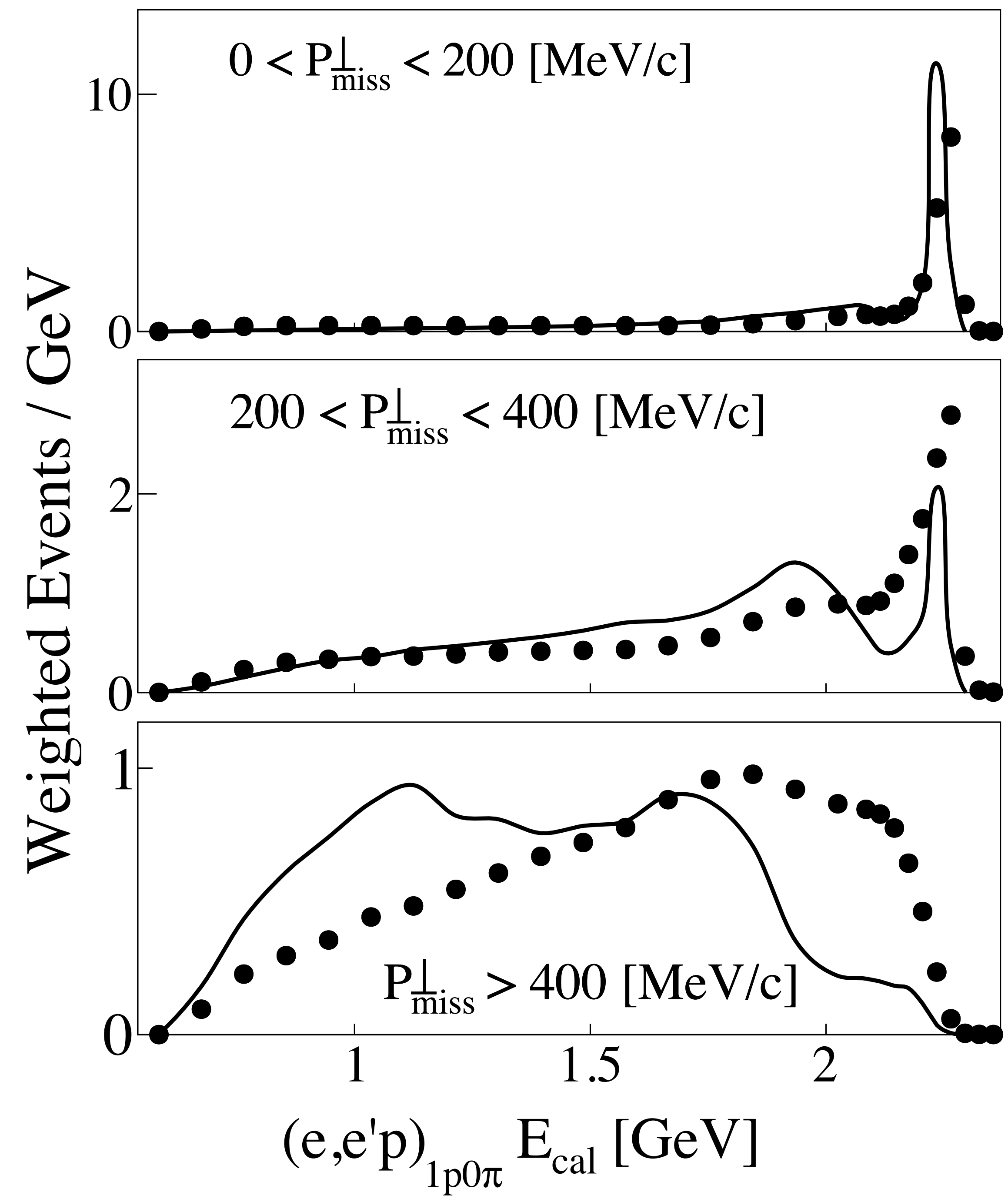


Disagreements between Data and MC



MC vs. (e,e'p) Data: $\vec{P}^{miss}_{\perp} = \vec{P}^{e'}_{\perp} + \vec{P}^{p}_{\perp}$





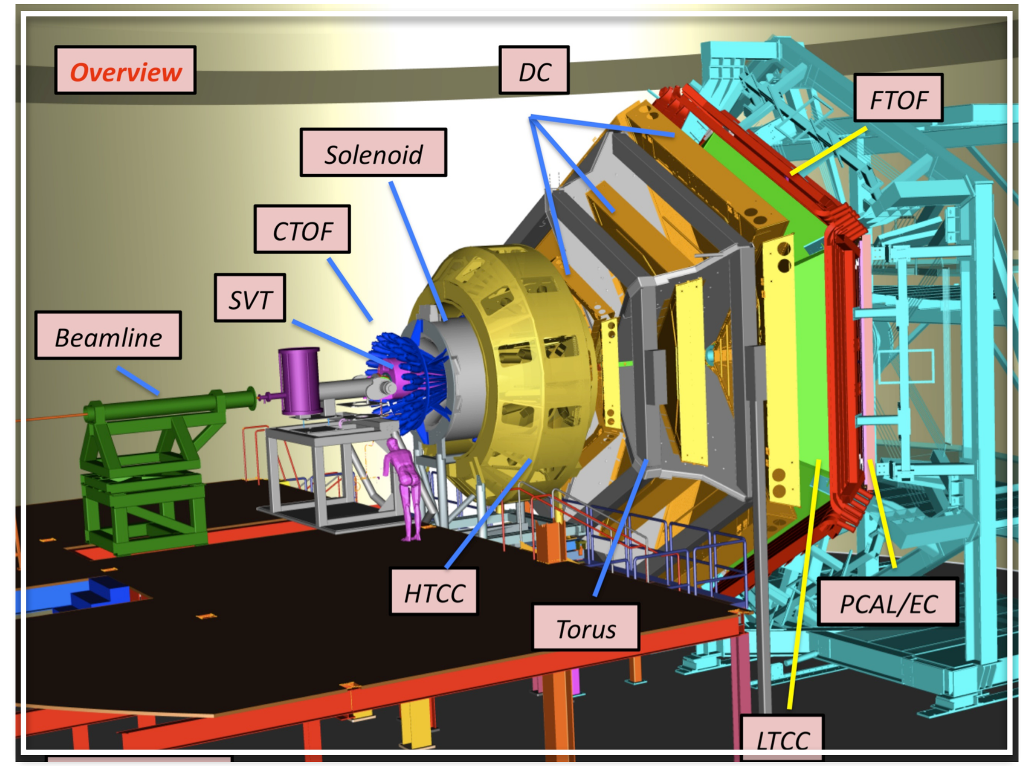
Future Plans -Approved run for CLAS12

Ten times more luminosity

Keeping the low threshold 300 MeV/c

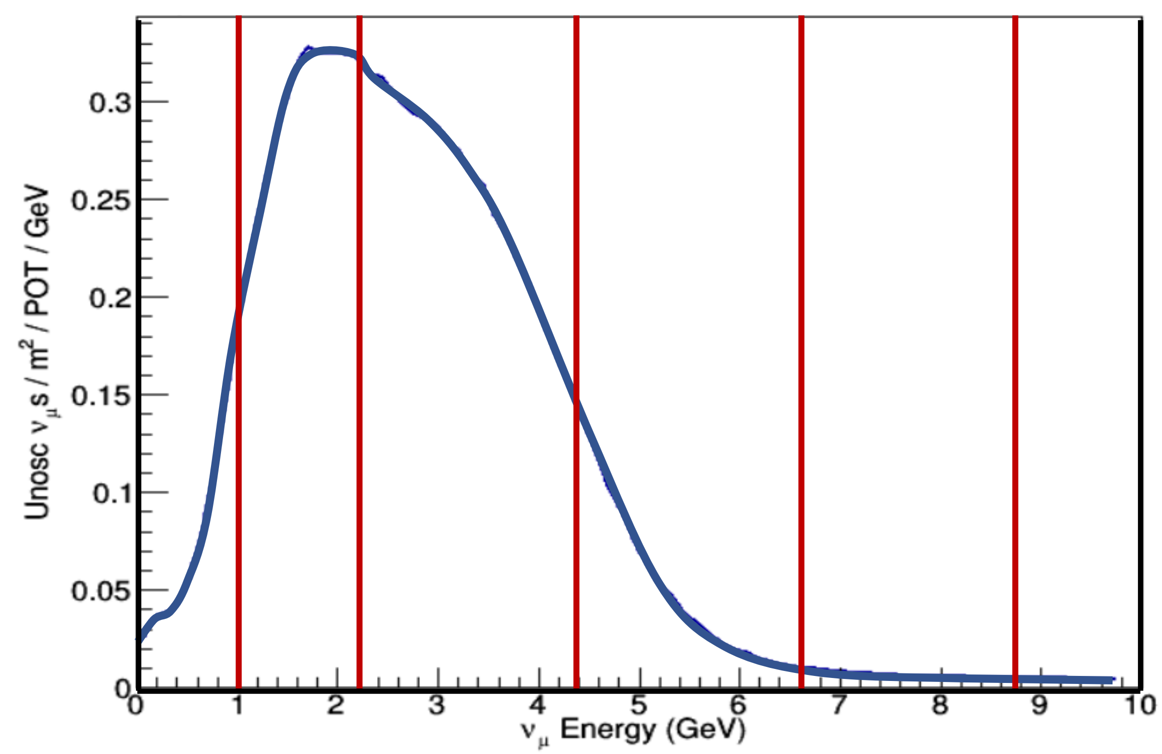
Targets: ^{2}D, ^{4}He, ^{12}C, ^{16}O, ^{40}Ar, ^{120}Sn

Incoming 1 - 7 GeV relevant for DUNE incoming flux



Overwhelming support from:

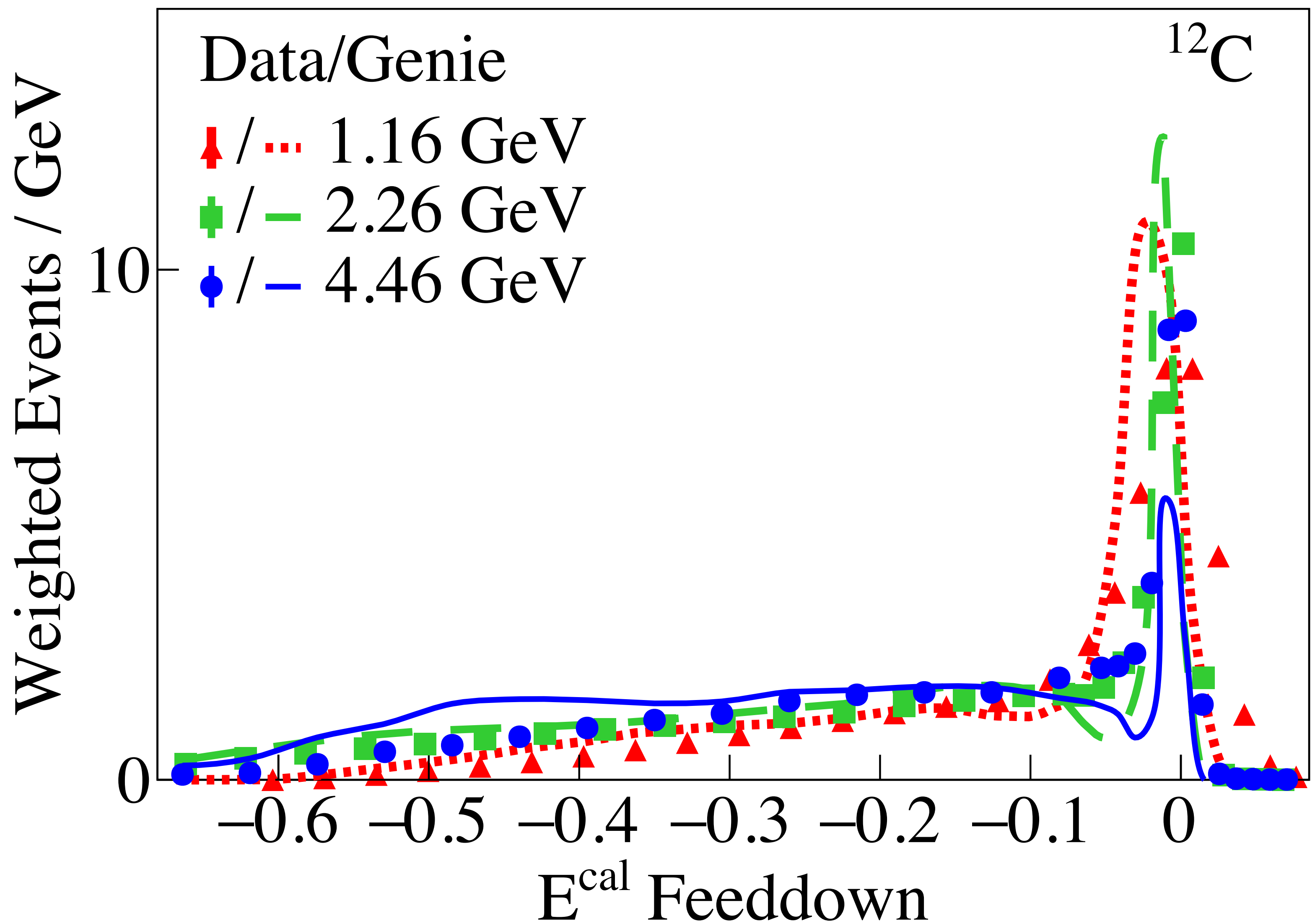
MINERvA



Implications and future plans

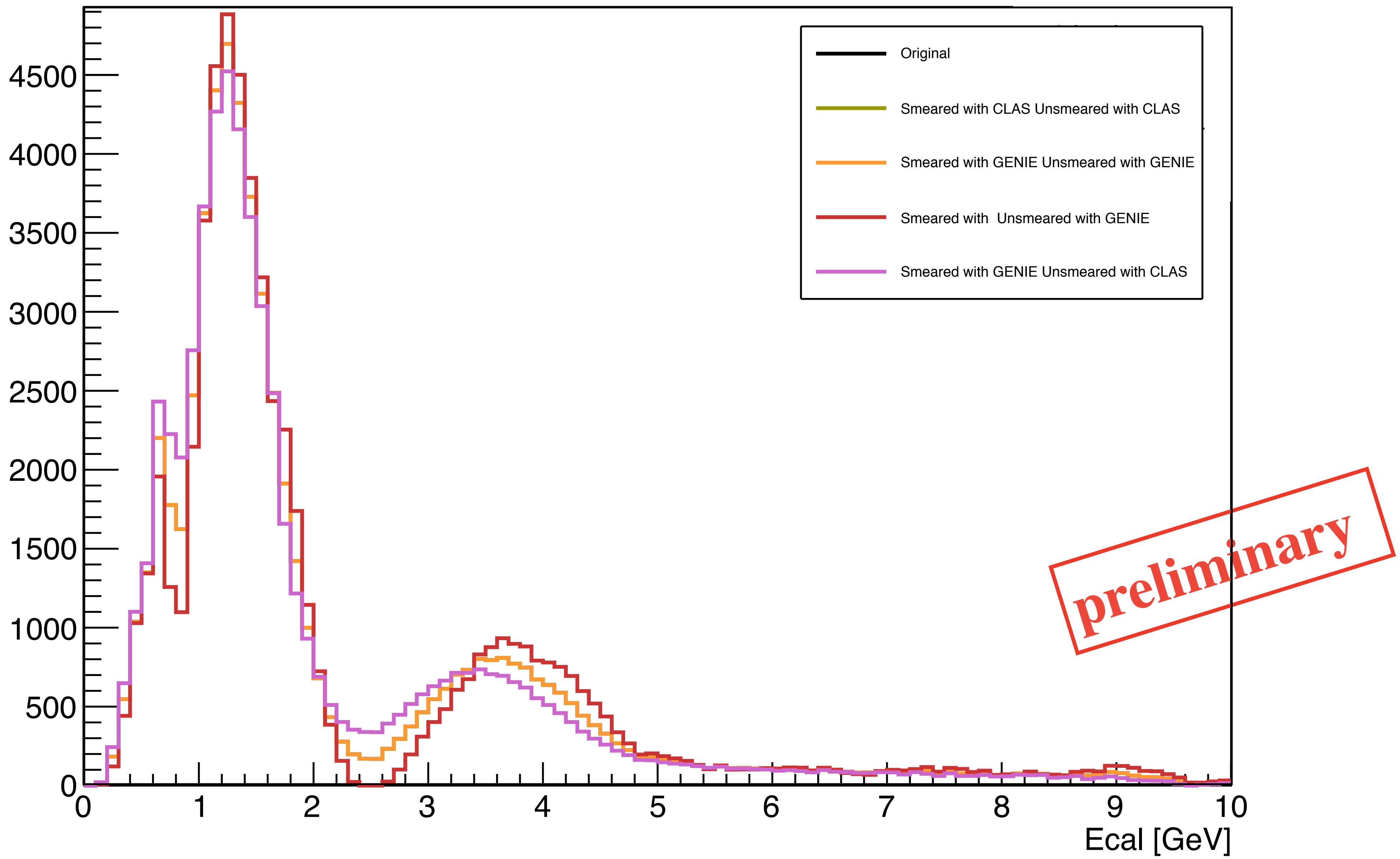
Potential implication on DUNE analysis

The expected energy at DUNE far detector as reconstructed using the energy feed down from A(e,e'p) data and simulation



Potential implication on DUNE analysis

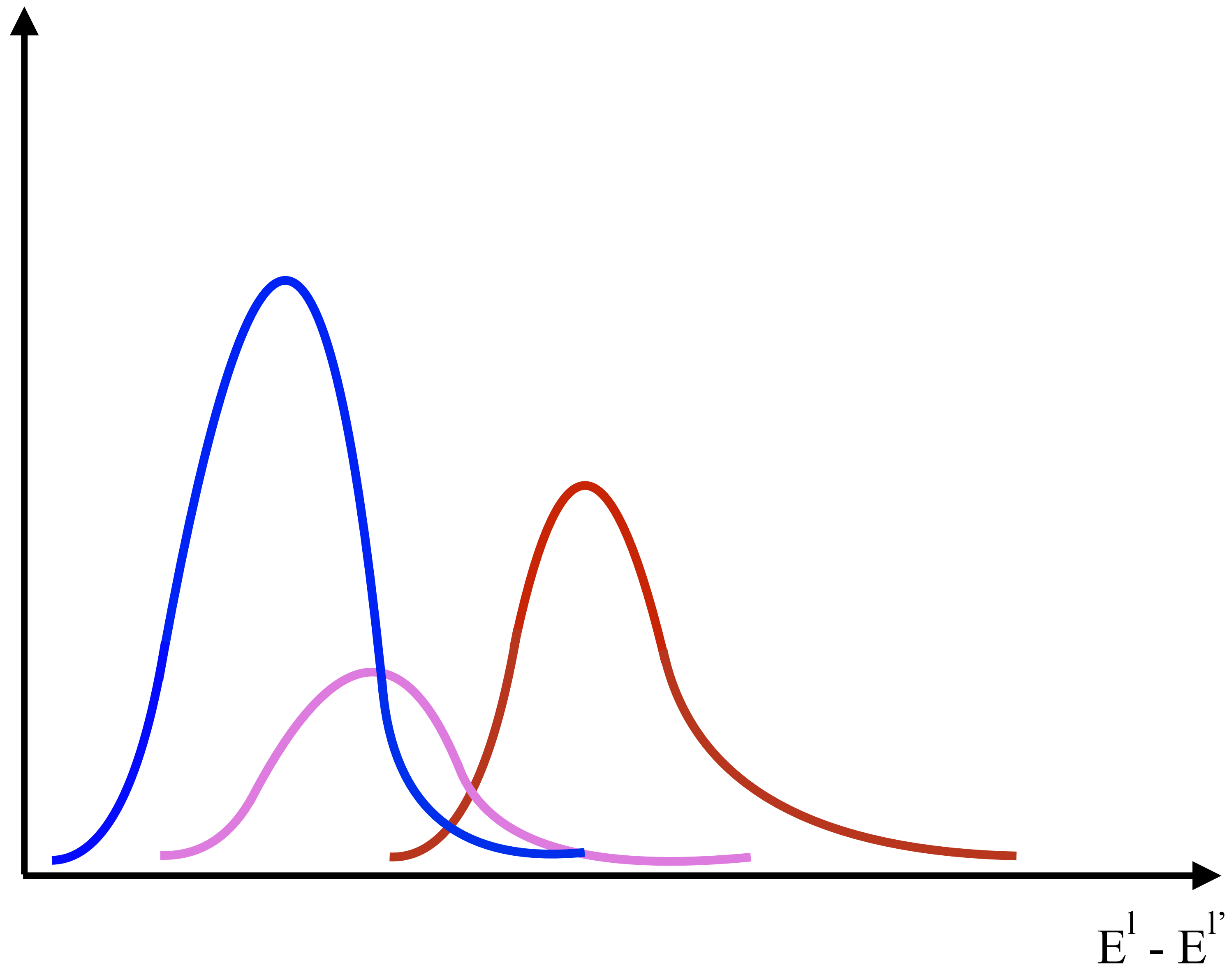
The expected energy at DUNE far detector as reconstructed using the energy feed down from A(e,e'p) data and simulation



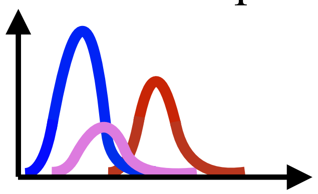
Un-modelled nuclear effects can be mistakingly considered as oscillation effects

Potential implication on DUNE analysis

A rigorous study of νA and eA interactions will have a major contribution to DUNE's ability to measure mixing parameters



Future Plans

Project	2020	2021	2022	2023	2024
μBooNE	Publish: CCQE + technical overlay papers	high statistics analysis multi-bins differential cross section		Expand phase space 	
	Finalise LArTPC detector+modelling systematics				
e4ν	Publish: QE, inclusive + Offer an electron data based tune to Genie	CLAS12 preparation & data-taking		CLAS12 analysis and publications	
		Resonances: analysis + publication			

Summary

Presenting a first CCQE differential cross section measurement in Ar with MicroBooNE,

A wide phase space electron scattering data is used to test the methods for incoming energy reconstruction and improve νA interaction modelling.

Major disagreement between data and event generators.

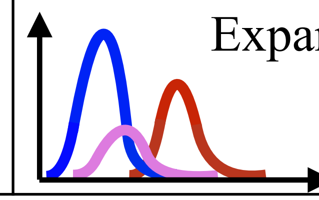
For QE-like events both leptonic and hadronic reconstructed energies have bad resolution, mostly for heavier nuclei and high missing transverse momentum

Looking forward to

- Expand the phase space and obtain new data with more relevant nuclei, energies and processes.
- Better measure and constrain systematics inside MicroBooNE
- Working on future experiments

Thank you for your attention

Future Plans

<table>
<tr><th>Project</th><th>2020</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th></tr>
<tr><td rowspan="2">μBooNE</td><td>Publish: CCQE + technical overlay papers</td><td colspan="2">high statistics analysis multi-bins differential cross section</td><td colspan="2"> Expand phase space</td></tr>
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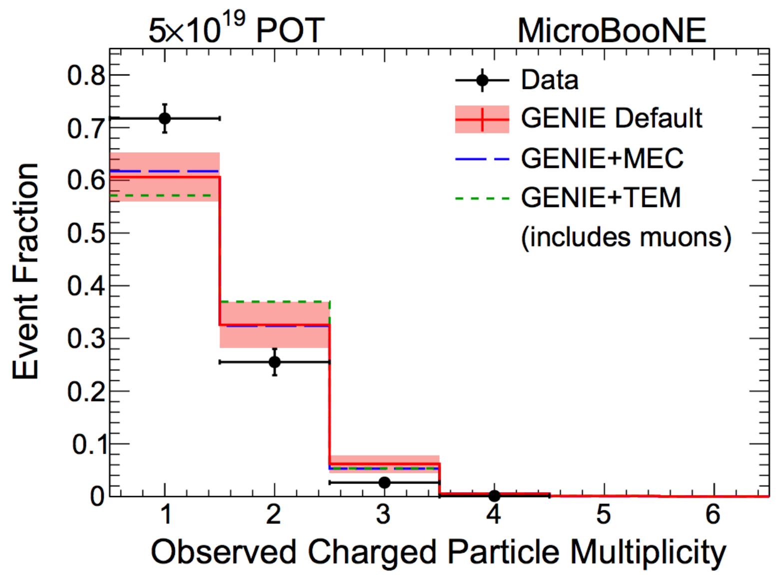
<tr><td colspan="2">Resonances: analysis + publication</td><td colspan="2"></td></tr>
<tr><td>DUNE</td><td>Joining ArgonCube Collaboration as DAQ lead
ArgonCube</td><td>R&D for a dedicated DAQ suitable for the chosen design</td><td>Commissioning a readout + DAQ prototype in local lab</td><td colspan="2">Join DAQ commissioning at Fermilab</td></tr>
</table>

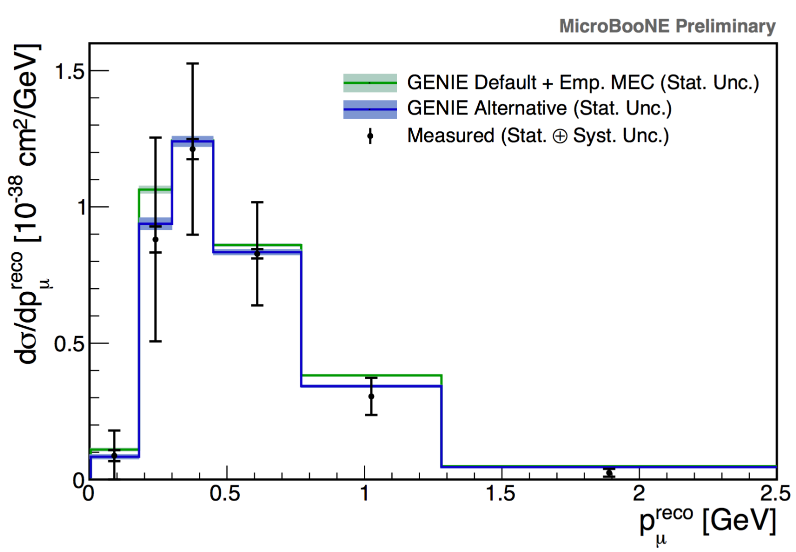
MicroBooNE First Results



Charged particle Multiplicity

First detailed measurement testing GENIE models on Argon nuclei

arXiv:1805.06887 (submitted to PRD)

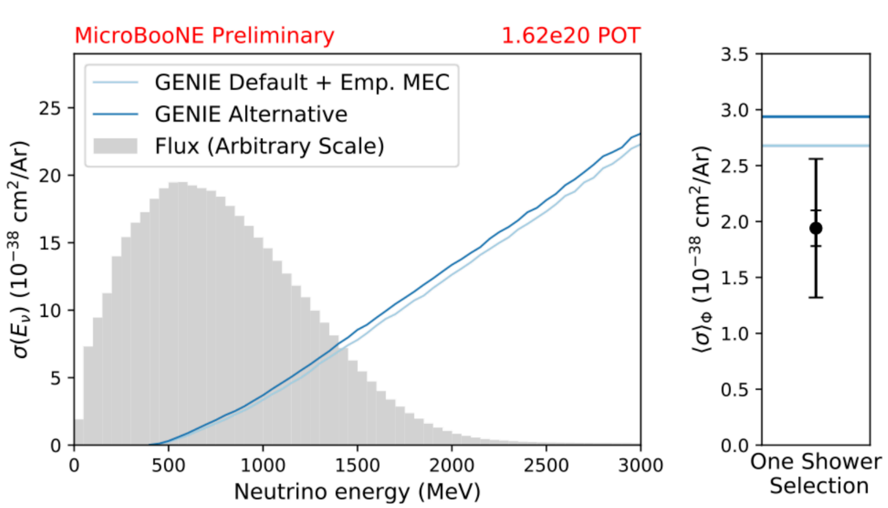


CC inclusive

good cosmic rejection

model dependencies are negligible

MICROBOONE-NOTE-1045-PUB



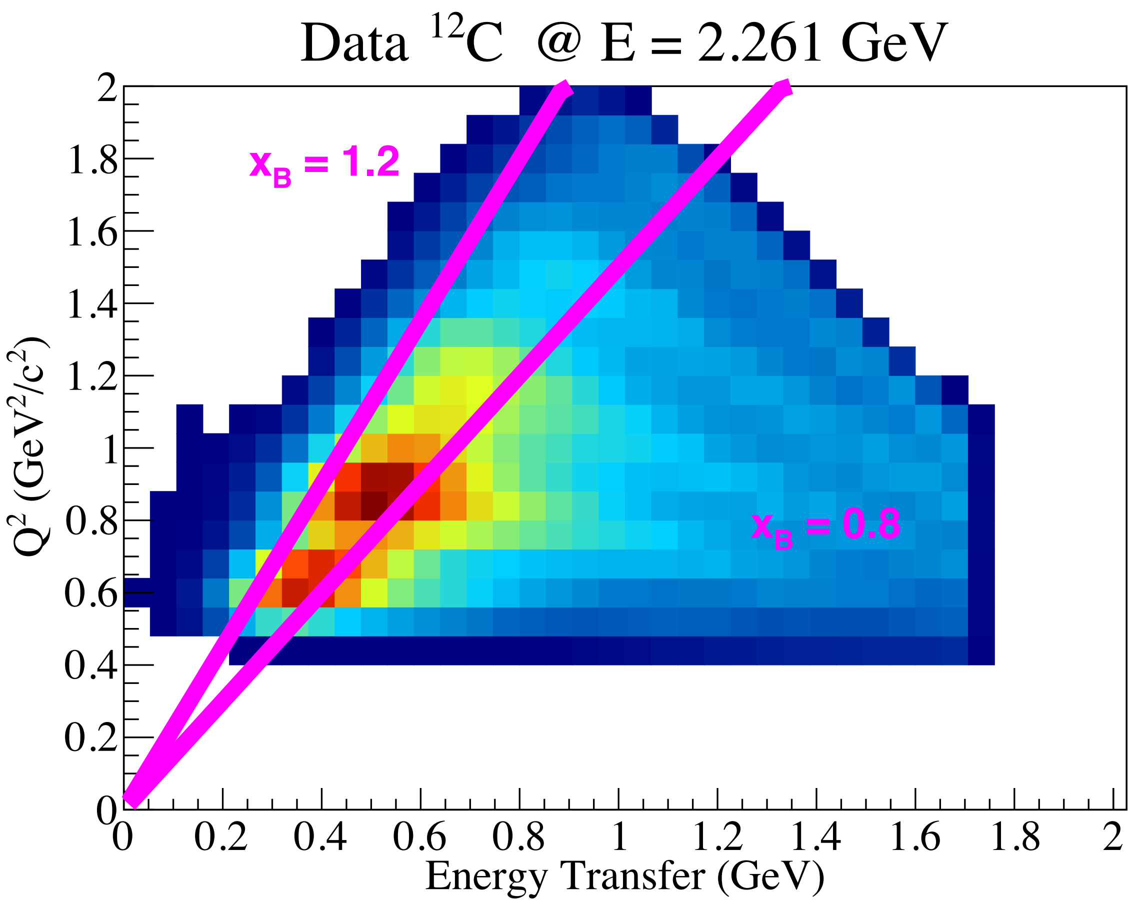
CC π^0

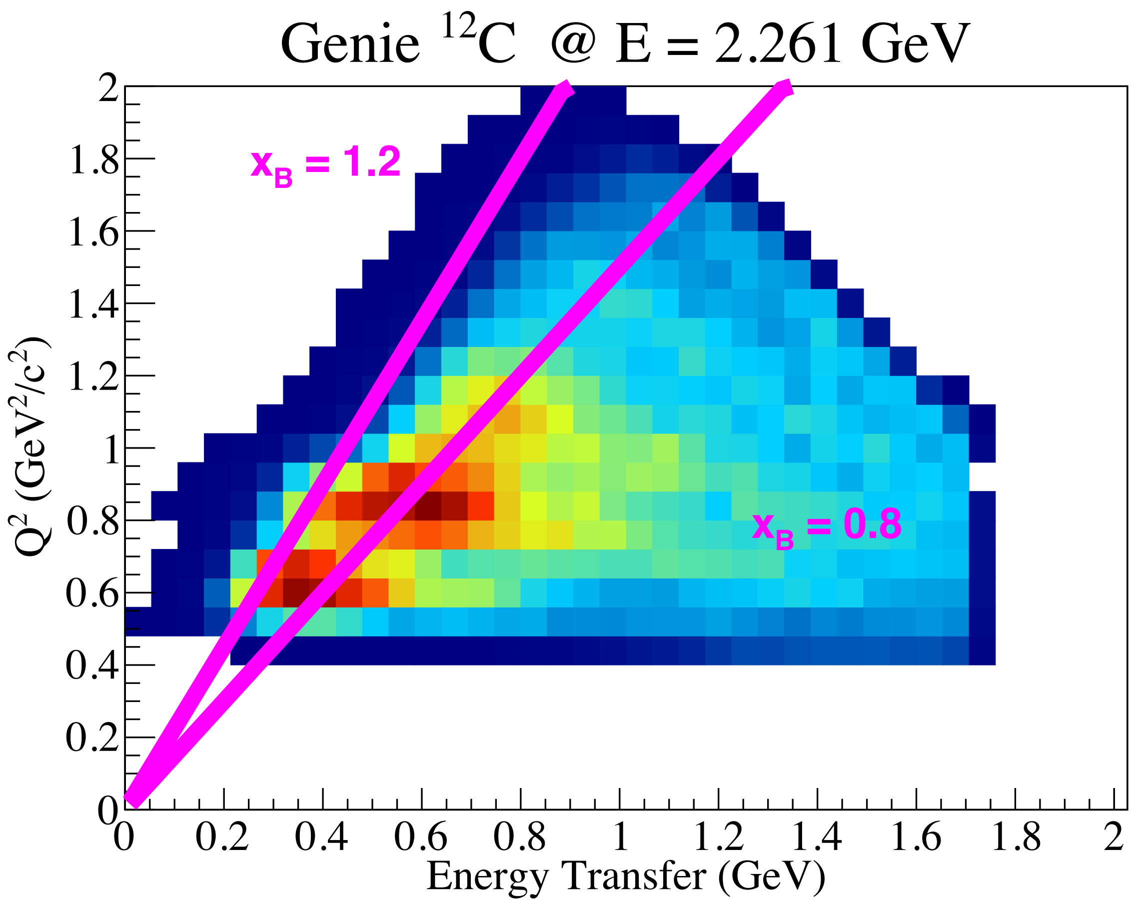
Low statistics, lower cosmic background

Model dependent

MicroBooNE–Note–1032–PUB

MC vs. (e,e'p) Data: Isolating the QE peak

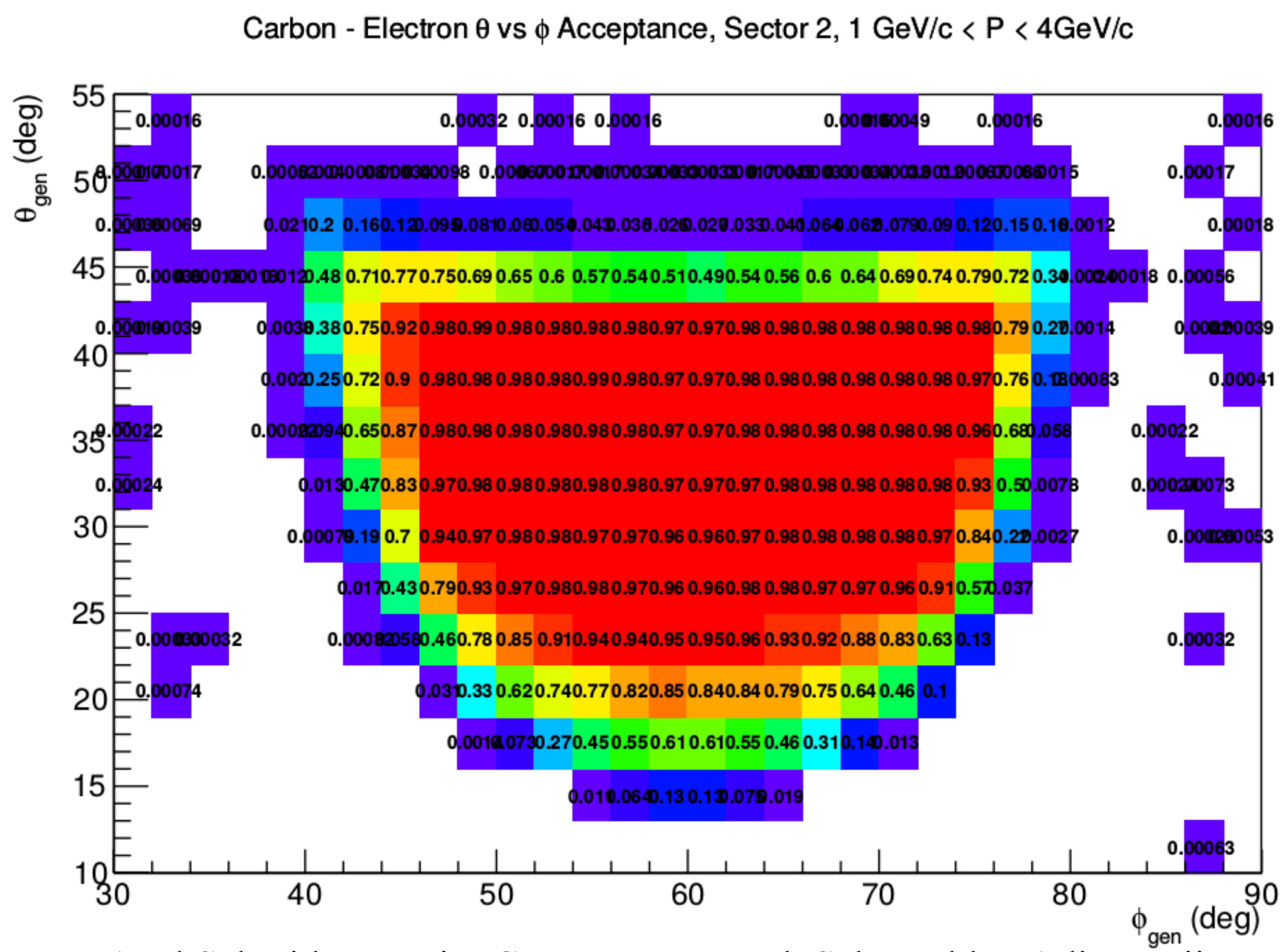




CLAS: Acceptance maps availble

CLAS has a different efficiency, which we will publish as acceptance maps for public use for each:

- Target
- Particle type
- Particle momentum



Axel Schmidt, Reynier Cruz Torres, Barak Schmookler, Adin Hrnjic

Generators - Electron mode database

	Model Name	v	e	Detailed electron mode implementation
COherent	Pion production: Rein-Sehgal, Berger-Sehgal	+	-	
Quasi **E**lastic	Factorized with Llewellyn -Smith elementary xsec: FG, LFG, BR-FG, momentum-dependent potential	+	+	FG, LFG and SF. Elementary electron-nucleon cross section calculated explicitly (includes de Forest treatment of binding energy) + an equivalent implementation to the neutrino side
	Benhar's spectral function + elastic FSI, optional effective spectral functions by A. Ankowski	+	-	
Meson **E**x**C**hange	Marteu-like model (inclusive only)	+	-	

Generators - Electron mode database

	Model Name	v	e	Detailed electron mode implementation
	Valencia model (inclusive only)	+	-	
	TEM model (inclusive only)	+	-	
	SuSAv2 (inclusive only)	+	-	
RESonance	Delta production within Adler-Rarita-Schwinger formalism, Oset, Salcedo in-medium modifications, decay parametrized using ANL, BNL data, nonresonant background extrapolated from DIS	+	-	
	Valencia model for SPP, Delta(1232) and nonresonant background	-	+	

Generators - Electron mode database

	Model Name	v	e	Detailed electron mode implementation
Deep **I**nelastic **S**cattering	Bodek-Yang model (grv94)	+	-	

Generators - Electron mode database

GiBUU	Model Name	ν	e	Detailed electron mode implementation
COherent				
Quasi **E**lastic	QE[1]	+	+	The electron σ is calculated using the formfactor BBA2003 parametrization. For the neutrino cross section, the vector form factors are extracted from the electrons ones based on CVC, the axial form factor is using the dipole form with the axial vector constant, gA, taken from β decay, and Q2 dependence tuned to neutrino data.
Meson **E**x**C**hange	SuSA	+	+	?
	Empirical	+	+	The cross section for electrons is obtained from a data analysis by Bosted and Christy, and the neutrino one is then extracted based on the relations between the e and ν structure functions used by the Lyon group[2]

Generators - Electron mode database

GiBUU	Model Name	v	e	Detailed electron mode implementation
RESonance	Phenomenological FF	+	+	For the e σ calculation, the helicity amplitudes are determined in the MAID analysis[3] For σv , the vector form factors, C_{6V} C_{5V} C_{4V} , are extracted from the electrons ones based on the CVC. $C_{5A}(0)$ is obtained by fitting the available pion production data on an elementary target. C_{3V} is taking the modified dipole form. C_{3A} is set to zero. C_{6A} can be related to C_{5A} by PCAC. C_{5A} parametrization is given in Leitner et al..
Deep **I**nelastic **S**cattering	[4]	+	?	1. lepton interacts with a nucleon, modeled by Pythia (nucleon is treated as free or bound + Fermi motion, Pauli blocking). 2. (pre-)hadrons are propagated through the surrounding nuclear medium according to the BUU transport description. This is exactly the same for e and v all other hadron-induced reactions on nuclei.

Generators - Electron mode database

Genie

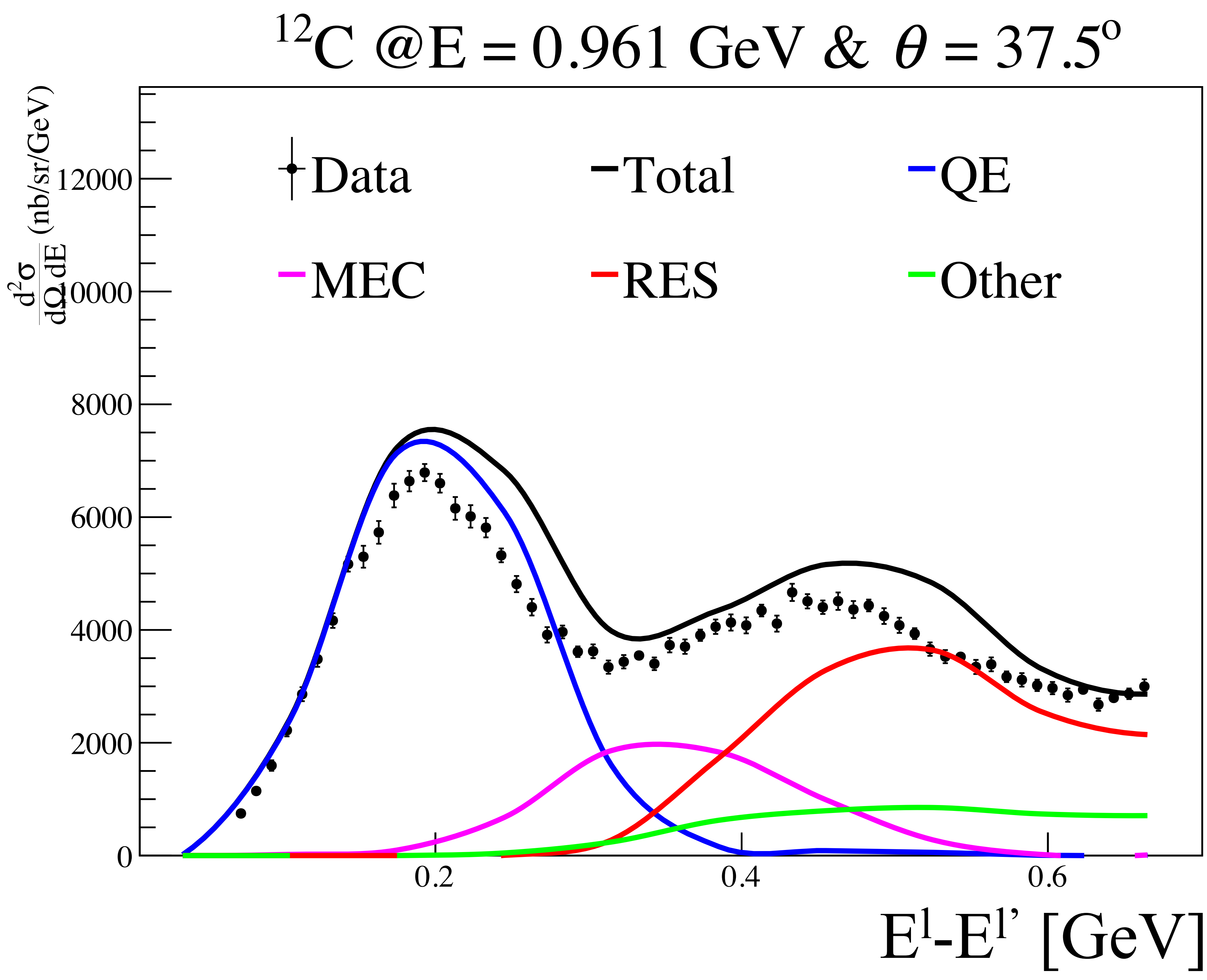
	Model Name	v	e	Detailed electron mode implementation
COherent	Ahrens	+	-	
	Coherent pion	+	-	
Quasi **E**lastic	Rosenbluth	-	+	Stand alone code only for electrons
	Llewellyn Smith	+	+	Calculating for v, if probe is electron modify coupling constants (release candidate for v3.2)
	SUSA	+	+	SDo: Works for nu and e in the same code using hadron tensor table framework (although of course the nu and e tensors are different). Inclusive model implementation.
	Nieves dipole	+	-	
	Nieves z exp	+	-	

Generators - Electron mode database

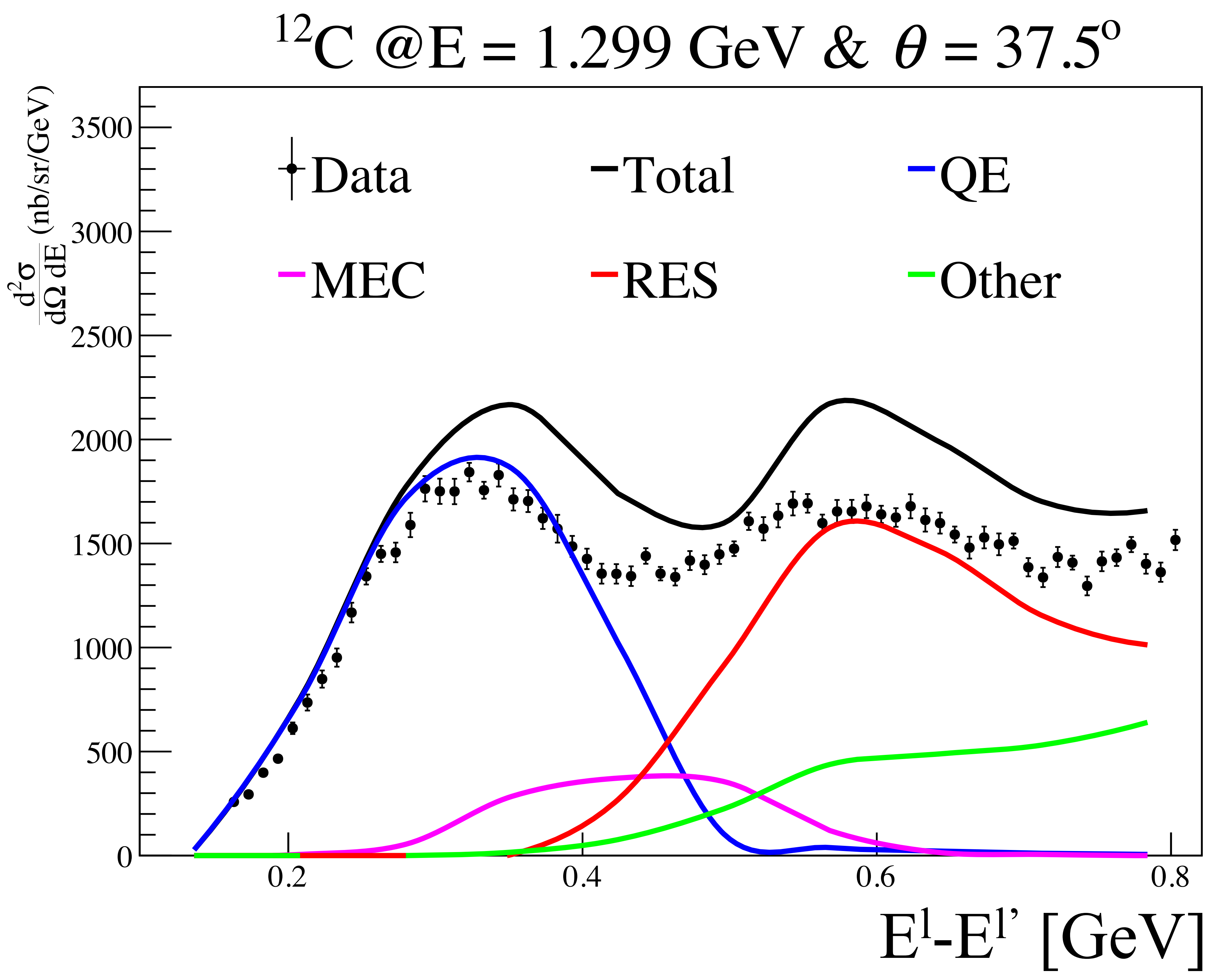
Genie

	Model Name	v	e	Detailed electron mode implementation
Meson **E**x**C**hange	Empirical Dytman model	+	+	Calculating for v, if probe is electron modify coupling constants.
	Nieves	+	-	
	SUSA	+	+	SDo: Works for nu and e in the same code using hadron tensor table framework (although of course the nu and e tensors are different). Inclusive model implementation. Can predict the different contributions from different initial state pairs for e and for nu.
RESonance	Rein Sehgal	+	+	Calculating for v, if probe is electron modify coupling constants
	Berger Sehgal	+	+	Calculating for v, if probe is electron modify coupling constants
Deep **I**nelastic **S**cattering	Bodek-Yang			

Testing neutrino generators with inclusive electron scattering data

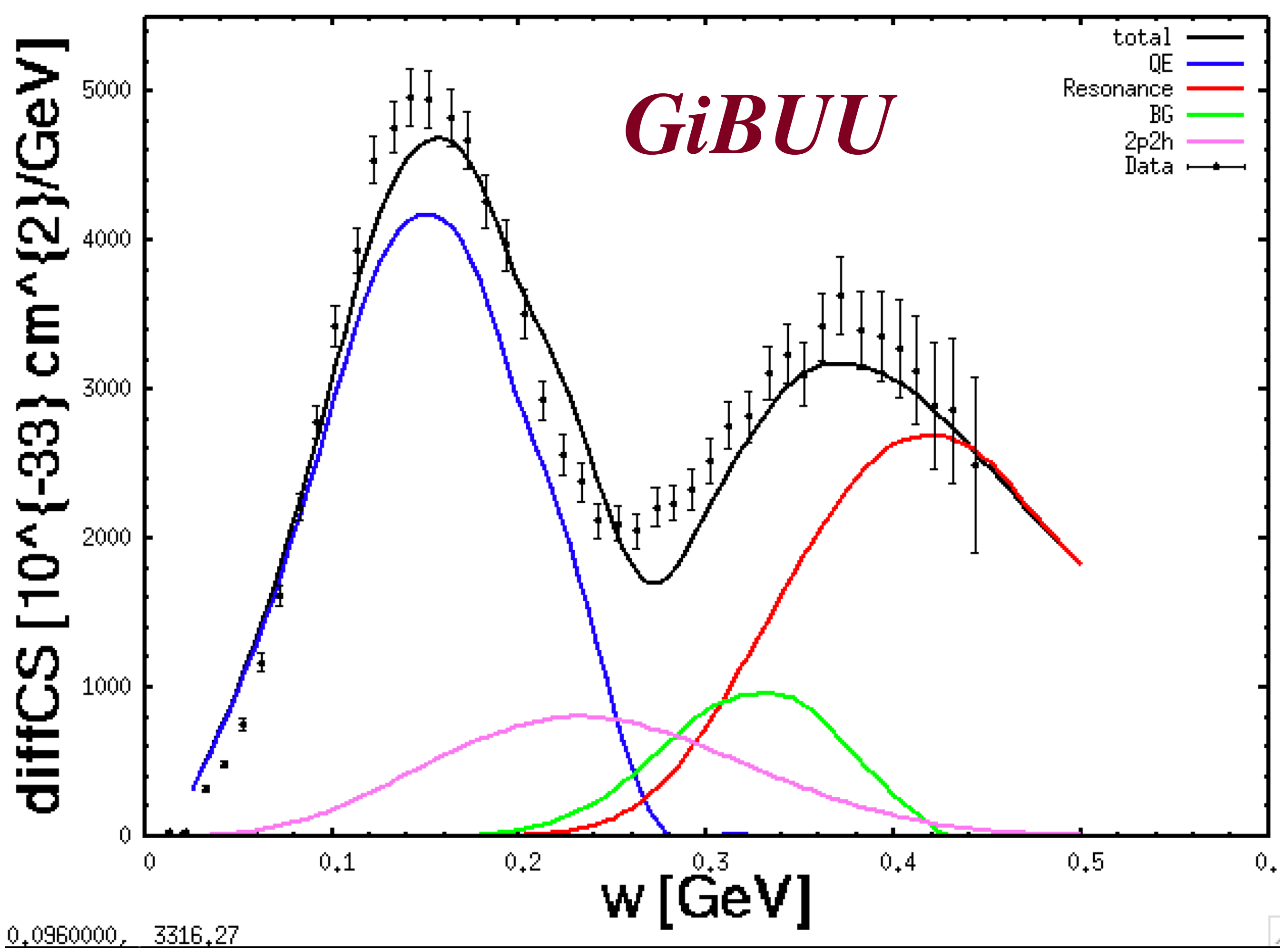


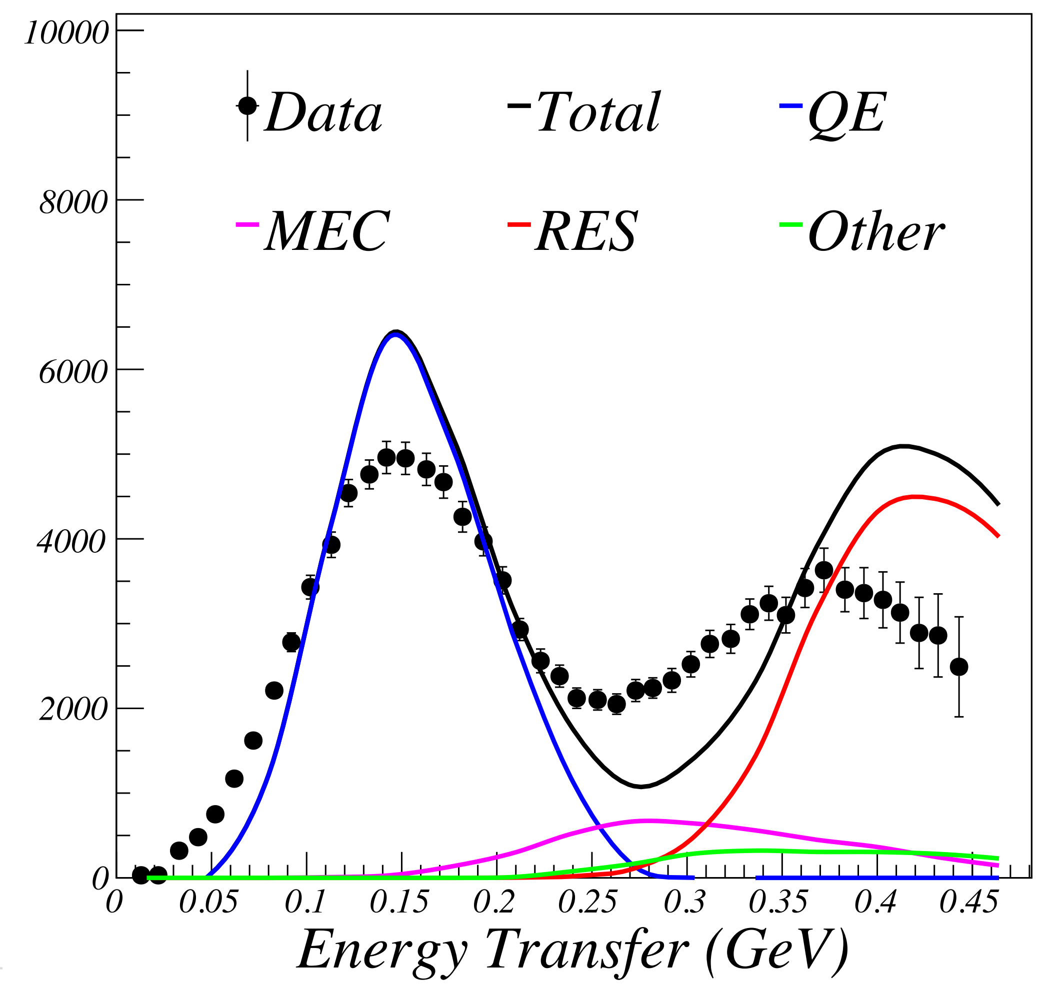
Testing neutrino generators with inclusive electron scattering data



Comparing to data

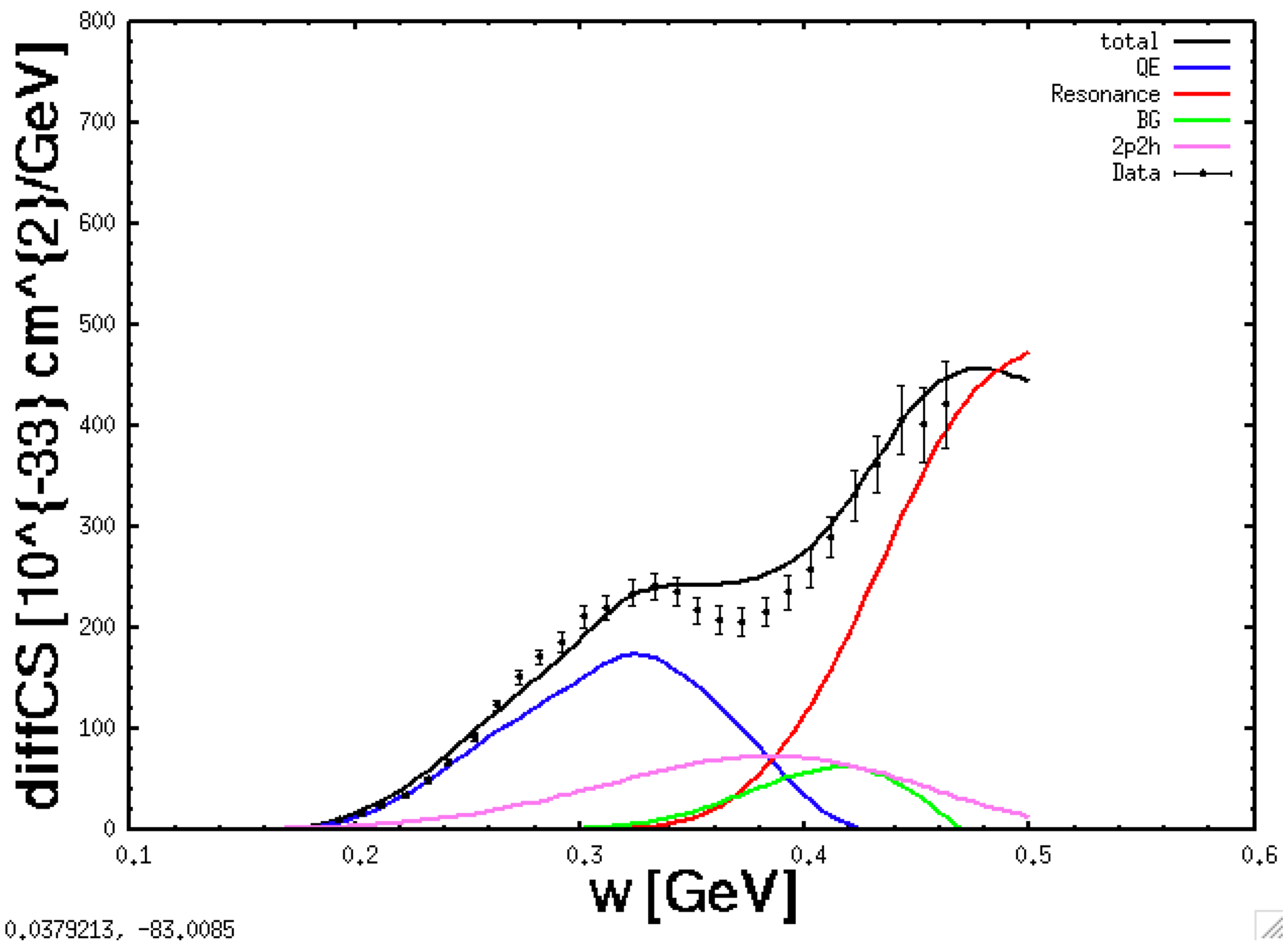
$^{12}C\ @E = 0.56\ GeV\ \&\ \theta = 60^o$

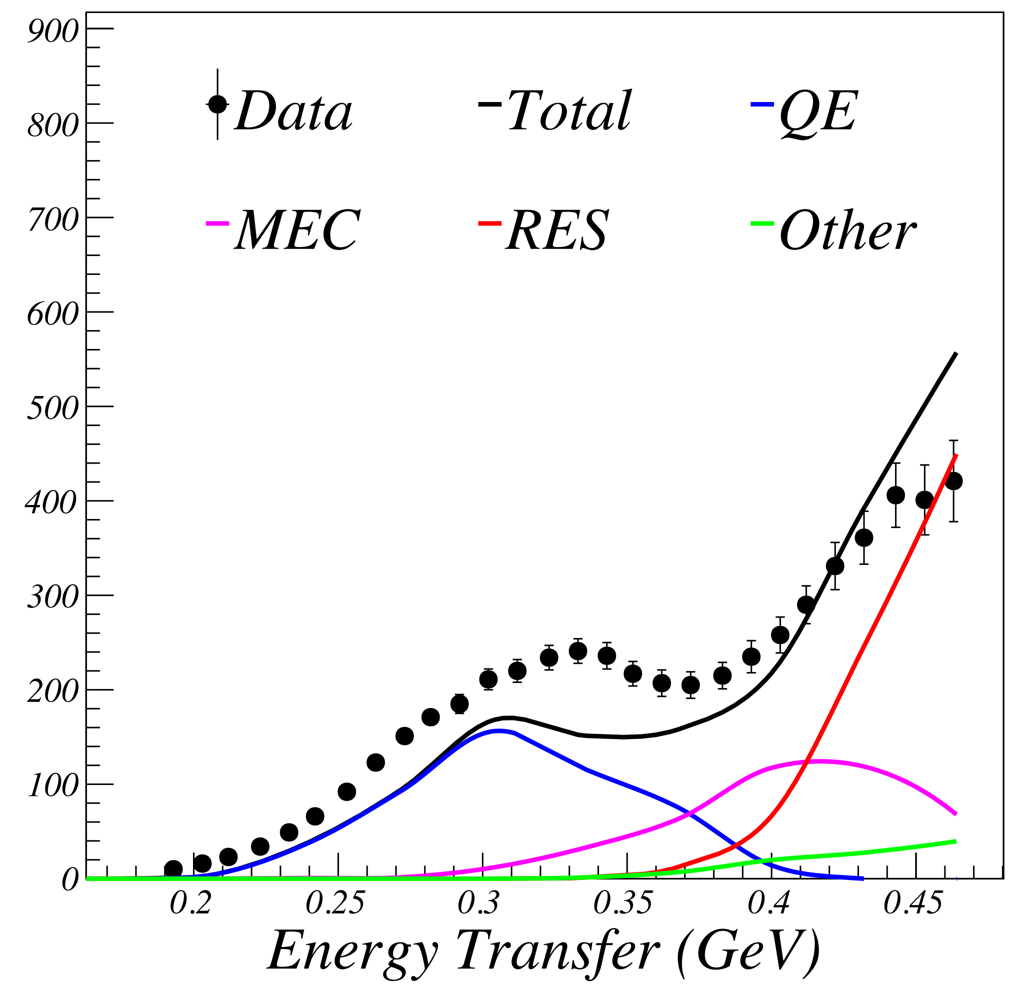




Comparing to data - Inclusive A(e,e’)

^{12}C @$E = 0.56$ GeV & $\theta = 145^o$





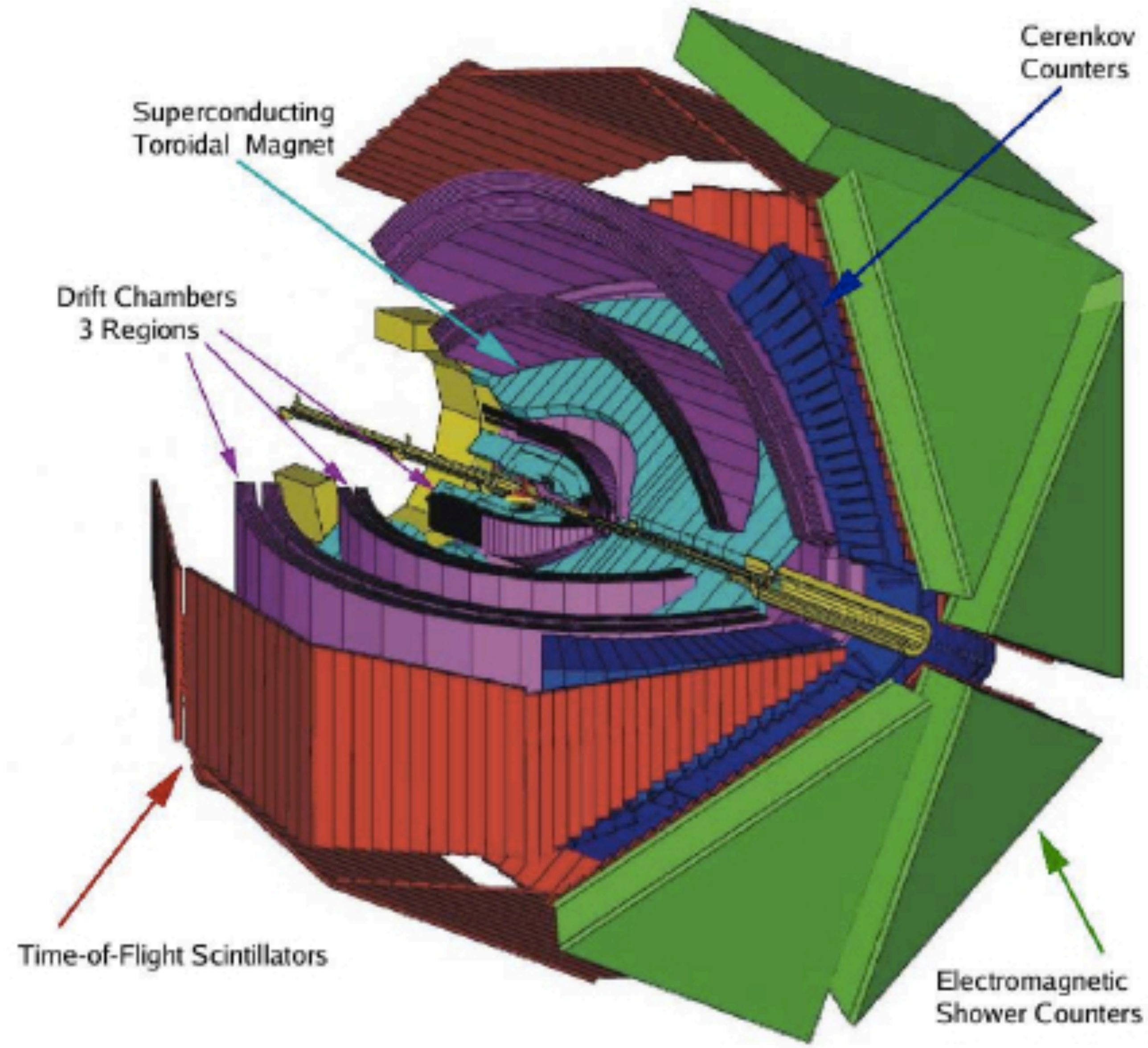
CLAS Detector

Large (~4π) acceptance

Sub detectors:

- Tracking in a toroidal field
- TOF scintillators
- Cherenkov detector
- EM calorimeter

Detection threshold: 300 MeV/c



Open Trigger

GENIE3 Simulation

Nuclear model	Local fermi gas model
QE	Lewellyn Smith for neutrino
	Rosenbluth CS for electrons
MEC	Empirical Dytman model
Resonances	Berger Sehgal
FSI	hA (data driven) + variations

GENIE is calculating each contribution separately and then summing them up

Adding radiative correction

Electron Scattering Data vs. GENIE

List of changes in GENIE

- Corrected Mott cross section expression
- Empirical MEC:
  - Added boost back to lab frame.
  - Corrected mass for cluster of particles.
  - Corrected form for dipole.
  - Corrected expression for Form Factor.
  - Try Berger Seghal, with corrected coupling constant
- RESKinematics Maximum Cross-section
  - Replaced old calculation by a GSL Minimizer.
- Switched to Local Fermi Gas Model.

A(e,e'p) Event Selection

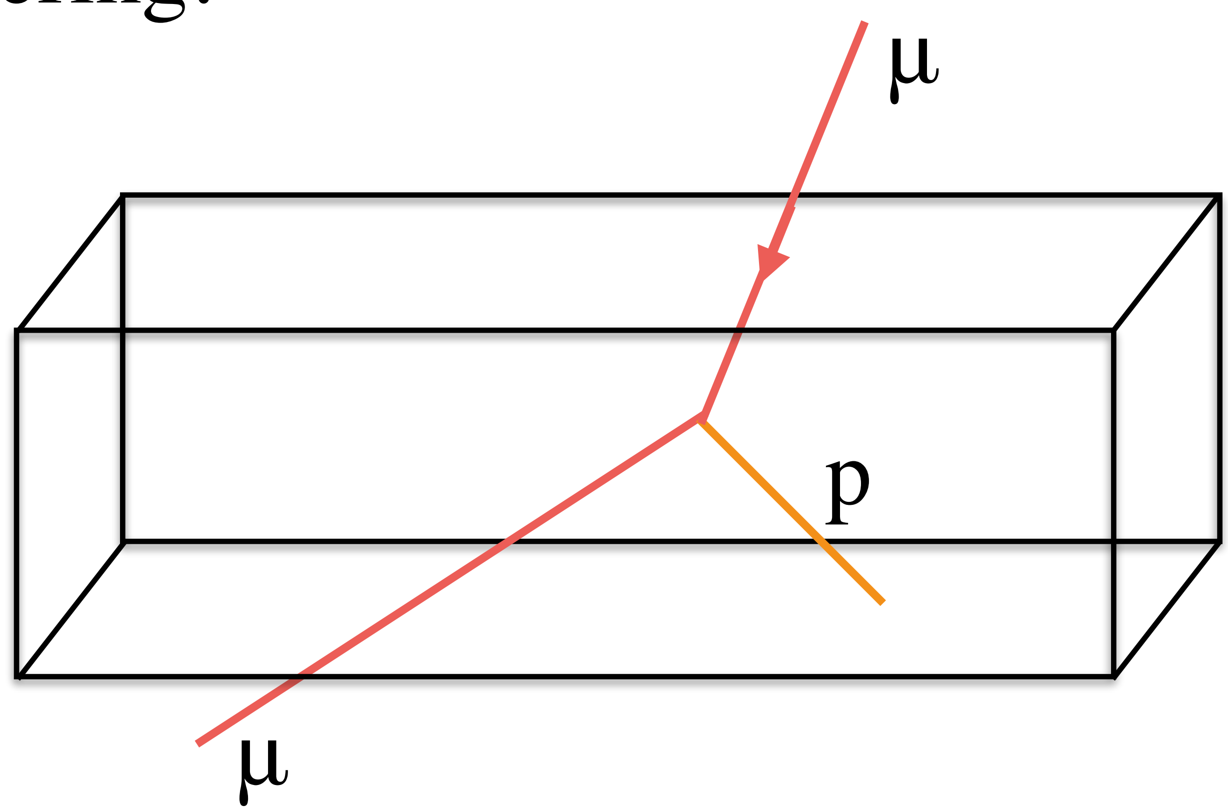
Repeat the e4nu analysis with cosmic muons inside MicroBooNE

Right now not enough events

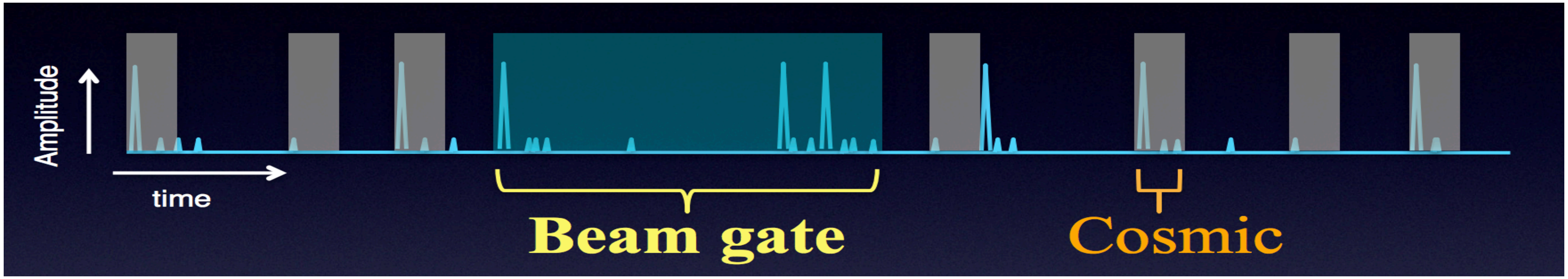
Will be possible with smart triggering.

Currently testing a joint

CRT - PMT trigger



LArTPC DAQ systems - μBooNE

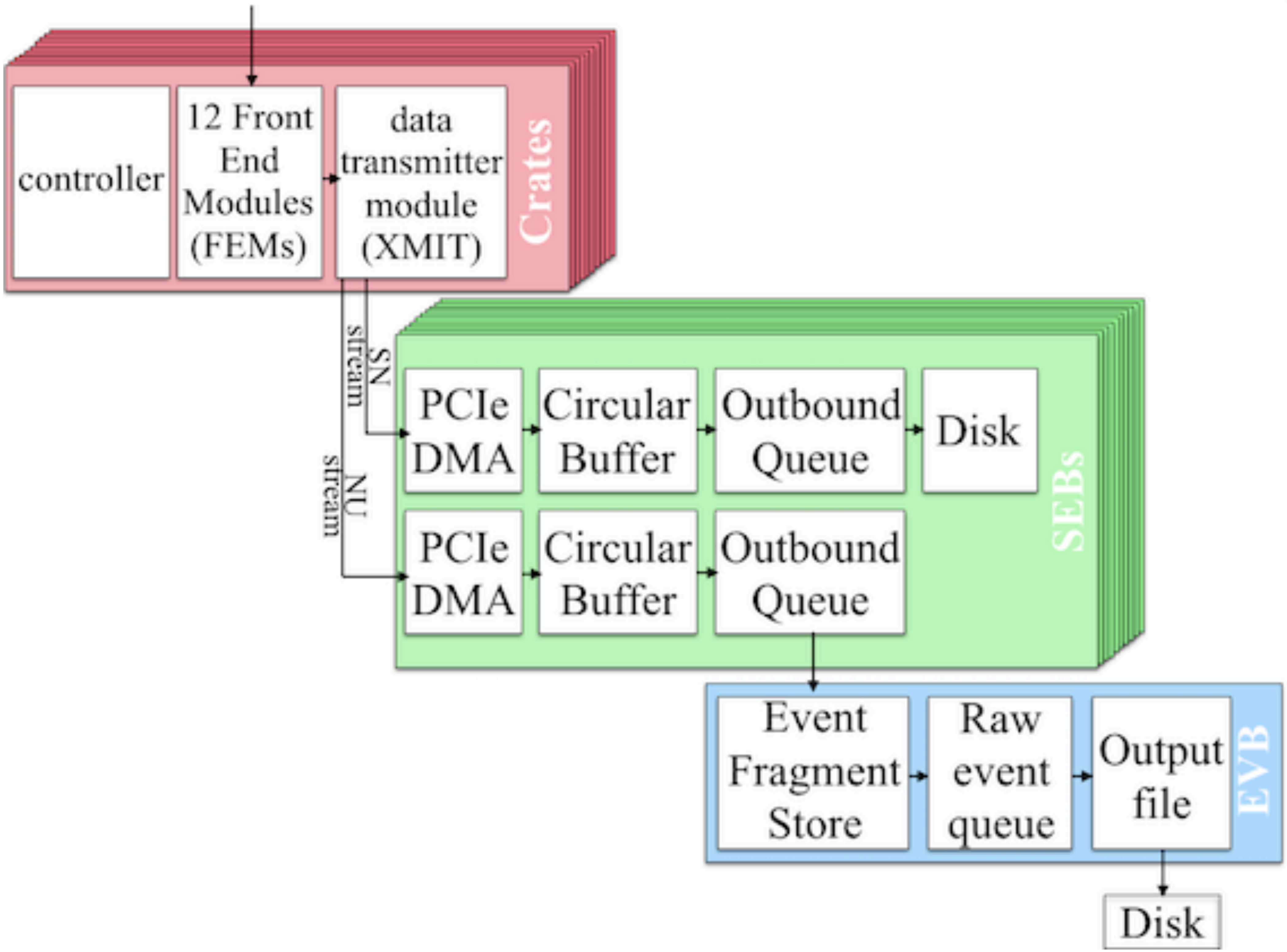


ν stream

	Rate
BNB	3.5 Hz
NUMI	0.7 Hz
EXTernal	12 Hz

In parallel a continuous SuperNova stream is saved for 24h

LArTPC DAQ systems



CCQE - Event selection

Preselection

- MicroBooNE trigger
- Pairs of tracks with close proximity (11 cm separation)
- Pandora cosmic removal pass

Cosmic BG filter

- Energy deposition profile
- Track length
- Scintillation light
- Collinearity $|\theta_{12} - 90°| \leq 55^{o}$

CCQE PS

- Vertex activity
- Coplanarity $|\Delta\phi - 180°| \leq 35^{o}$
- p_T imbalance $p_T \leq 0.35$ GeV/c

arXiv:1812.05679

CCQE - Event selection

Preselection

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Pairs of tracks with close proximity (11 cm separation)

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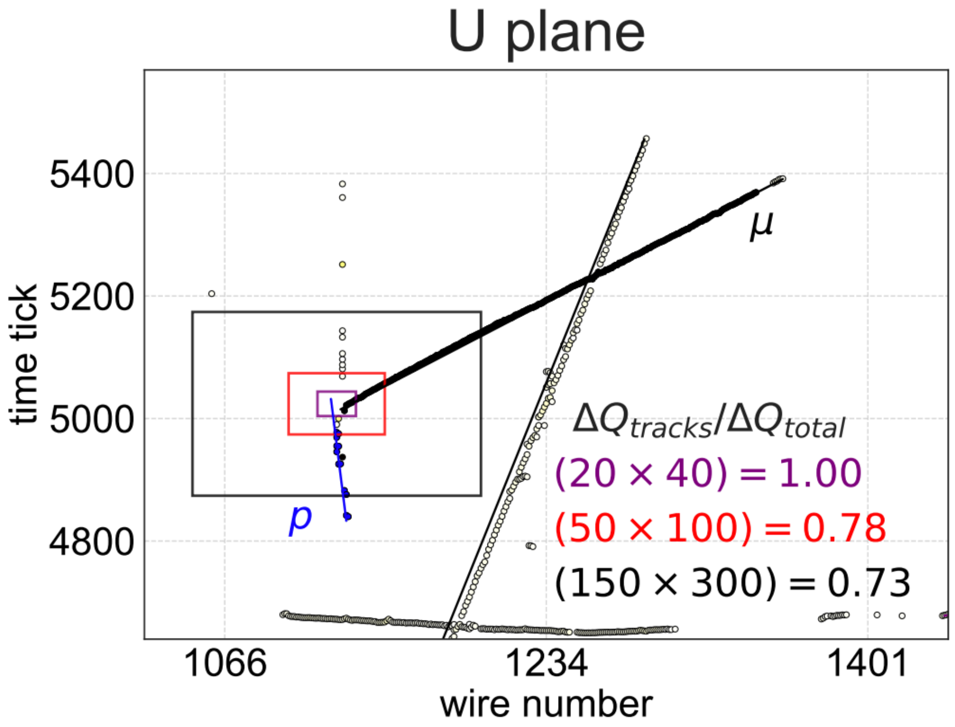

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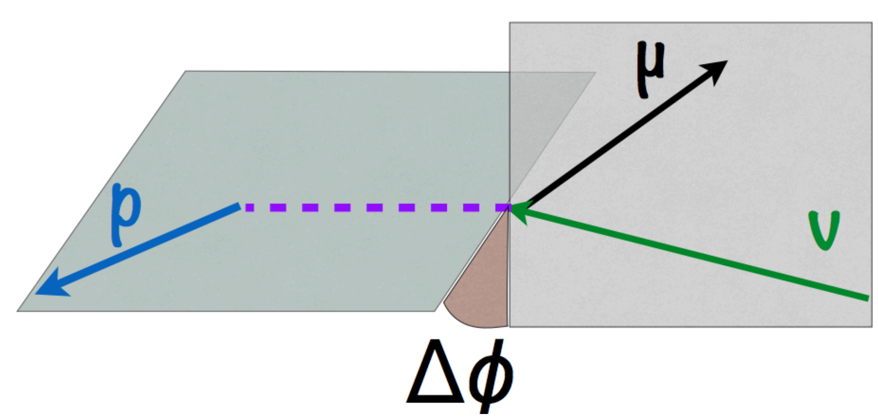

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CCQE - Event selection

Preselection

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Pandora cosmic removal pass

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Collinearity $|\theta_{12} - 90°| \leq 55^o$

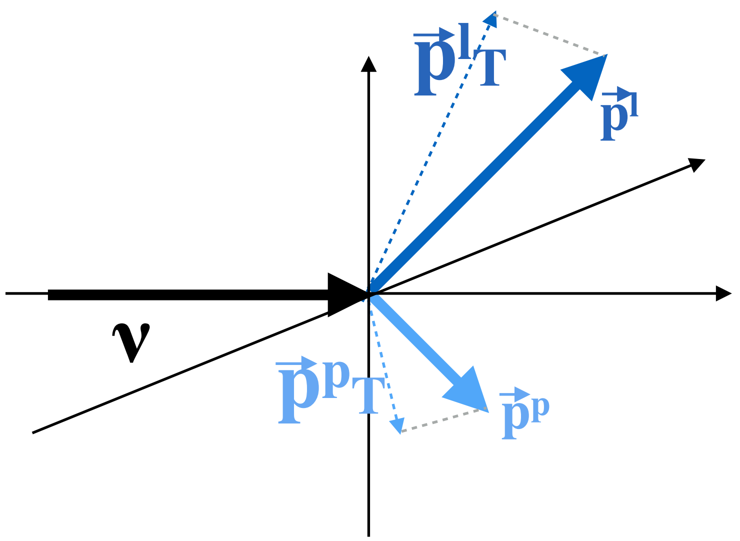
CCQE PS

Vertex activity

Coplanarity $|\Delta\phi - 180°| \leq 35^o$

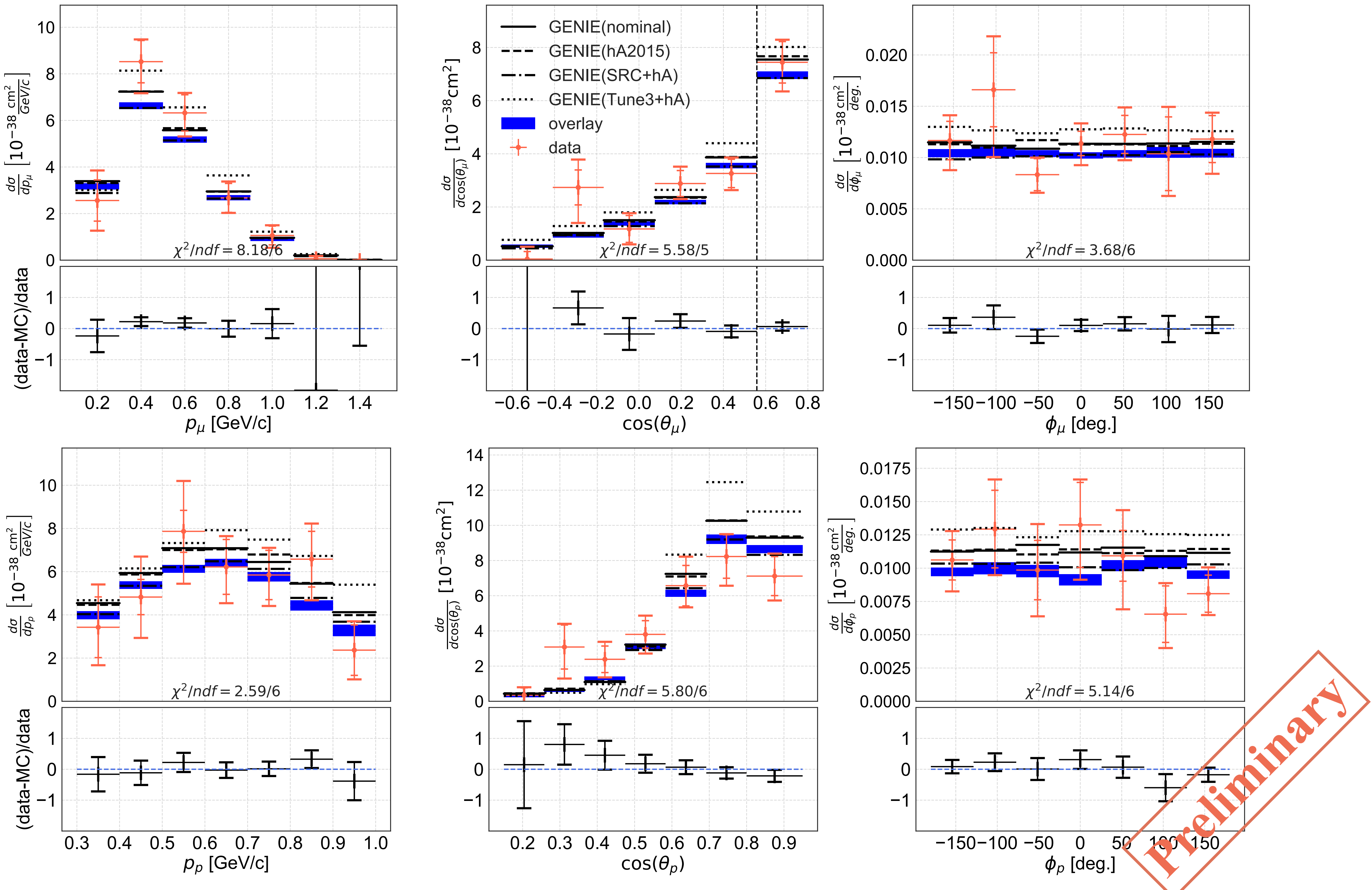
p_T imbalance $p_T \leq 0.35$ GeV/c

$$\vec{p}_T = \vec{p}^{l}_T + \vec{p}^{p}_T$$



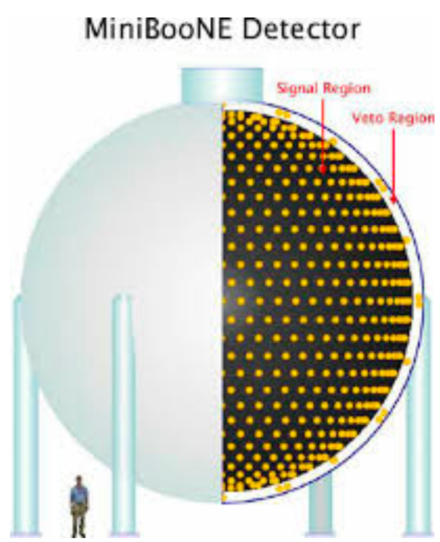
arXiv:1812.05679

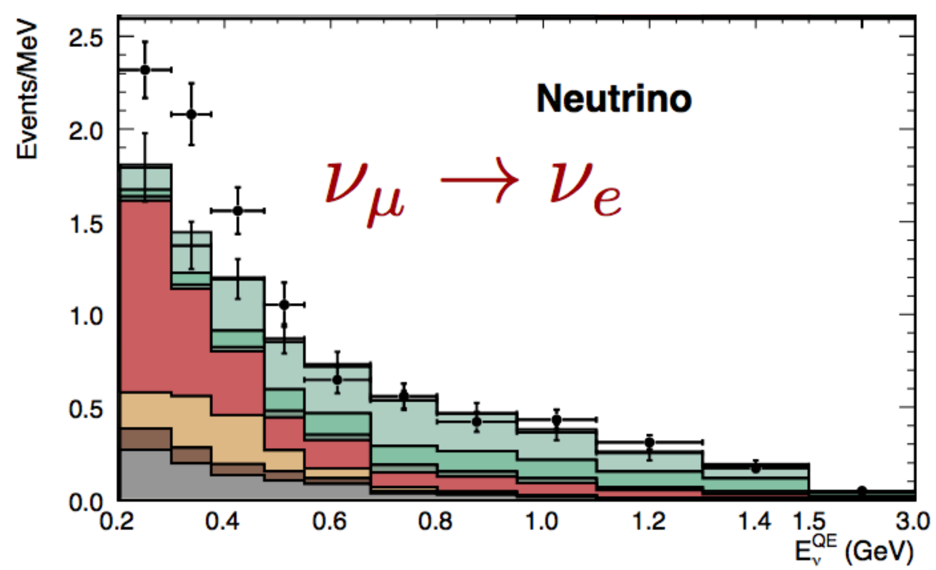
CCQE - Results



Neutrino Anomaly - Low Energy Excess

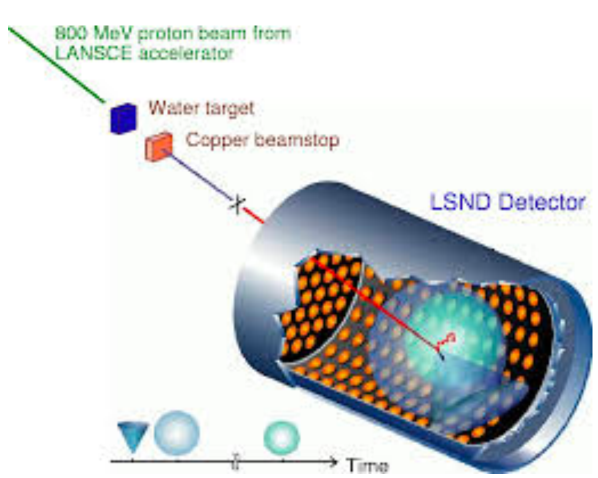
Current anomalies including the LSND and MiniBooNE low energy excess.

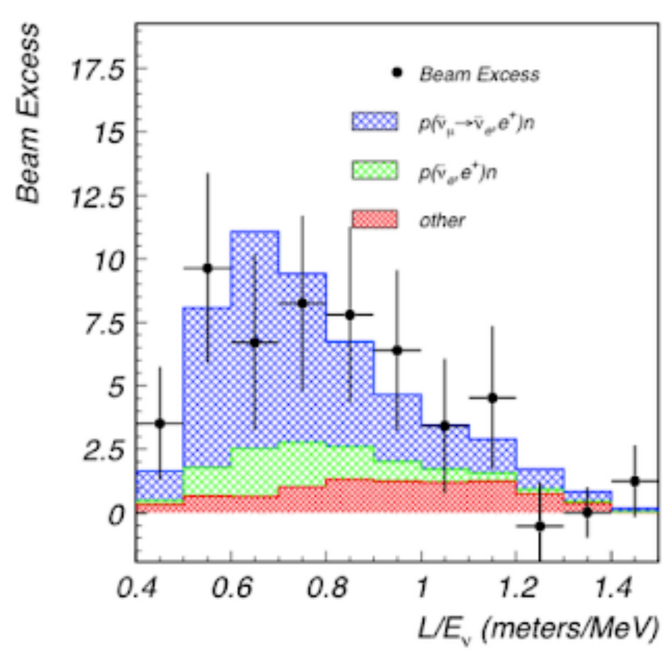




e

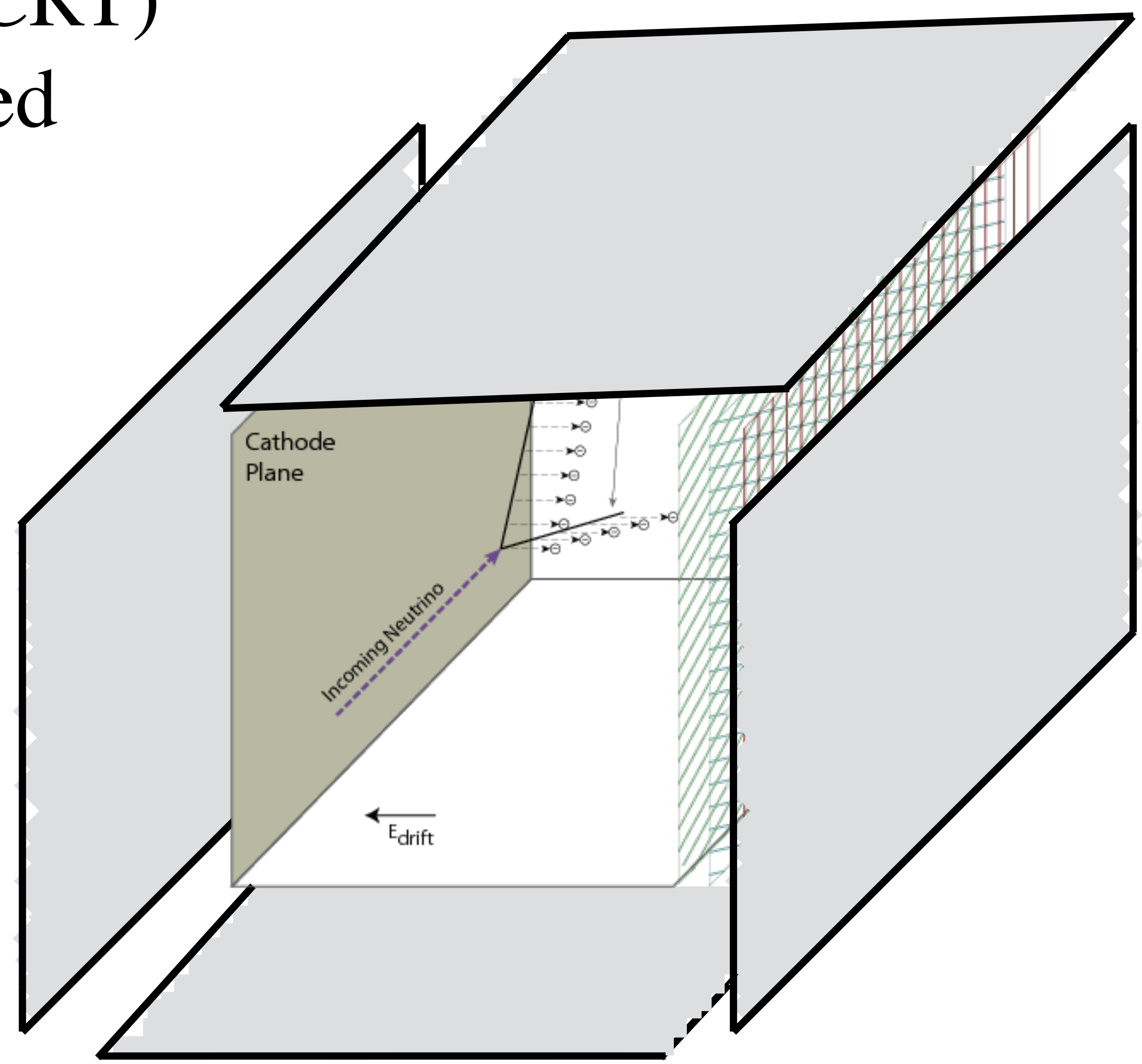
π^0





LAr TPC - MicroBooNE

As of the third run period a Cosmic Ray Tagger (CRT) has been commissioned around MicroBooNE



Overlay Workshop

For the LArTPC community

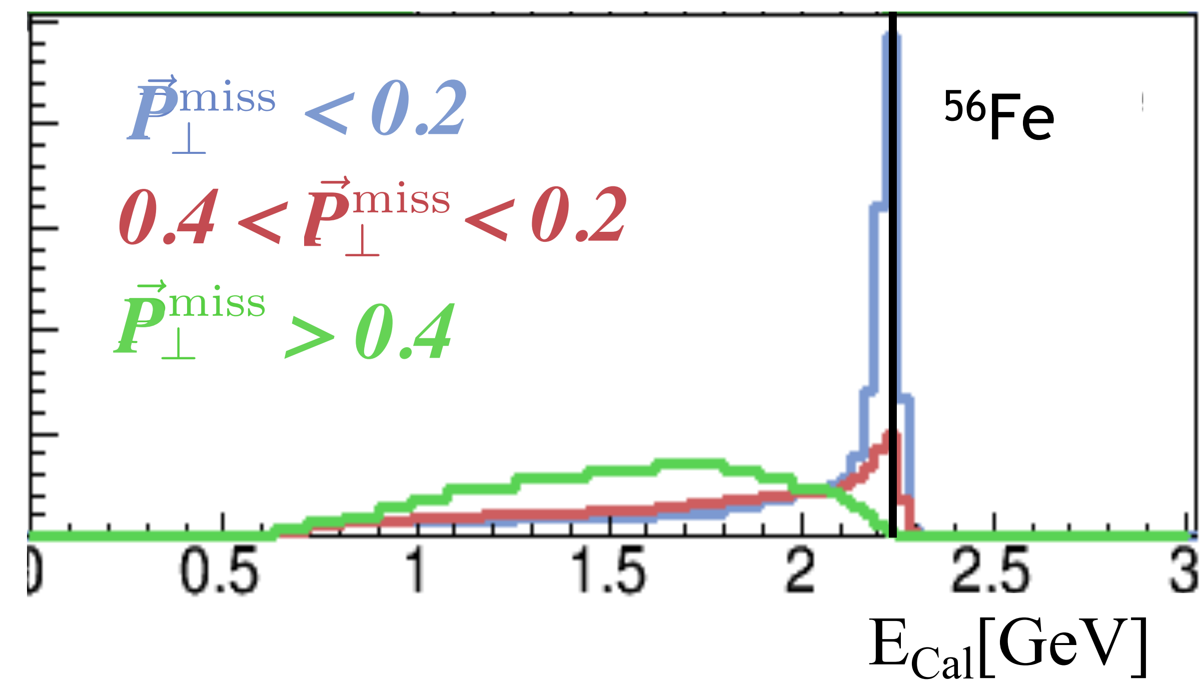
March 4th 2019 WH Fermilab

join us for a day long workshop to discuss the latest in the overlaying technique: adding simulated signals on top of collected data and help design the new generation of MC samples

Organisers: Erica Snider, Afroditi Papadopoulou, Wesley Ketchum, Adi Ashkenazi

Reconstructed Energy dependence on $\vec{P}_{\perp}^{\text{miss}}$

$$\vec{P}_{\perp}^{\text{miss}} = \vec{P}_{\perp}^{e'} + \vec{P}_{\perp}^{p}$$



Increased non QE background for higher $\vec{P}_{\perp}^{\text{miss}}$