Semi-exclusive pion production measurements with CLAS6 data

Julia Tena Vidal
Tel Aviv University
On behalf of the e4nu Collaboration

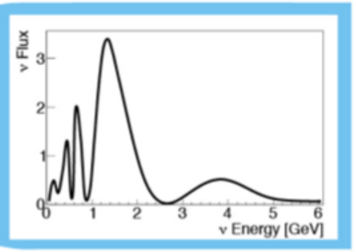
Introduction to neutrino physics

PHYSICS PROCESS

Particles shoot out

Interacts with nucleus

Neutrino comes in



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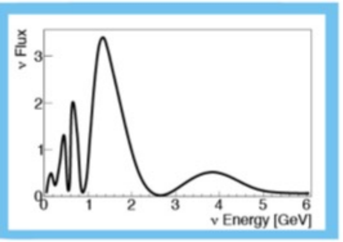


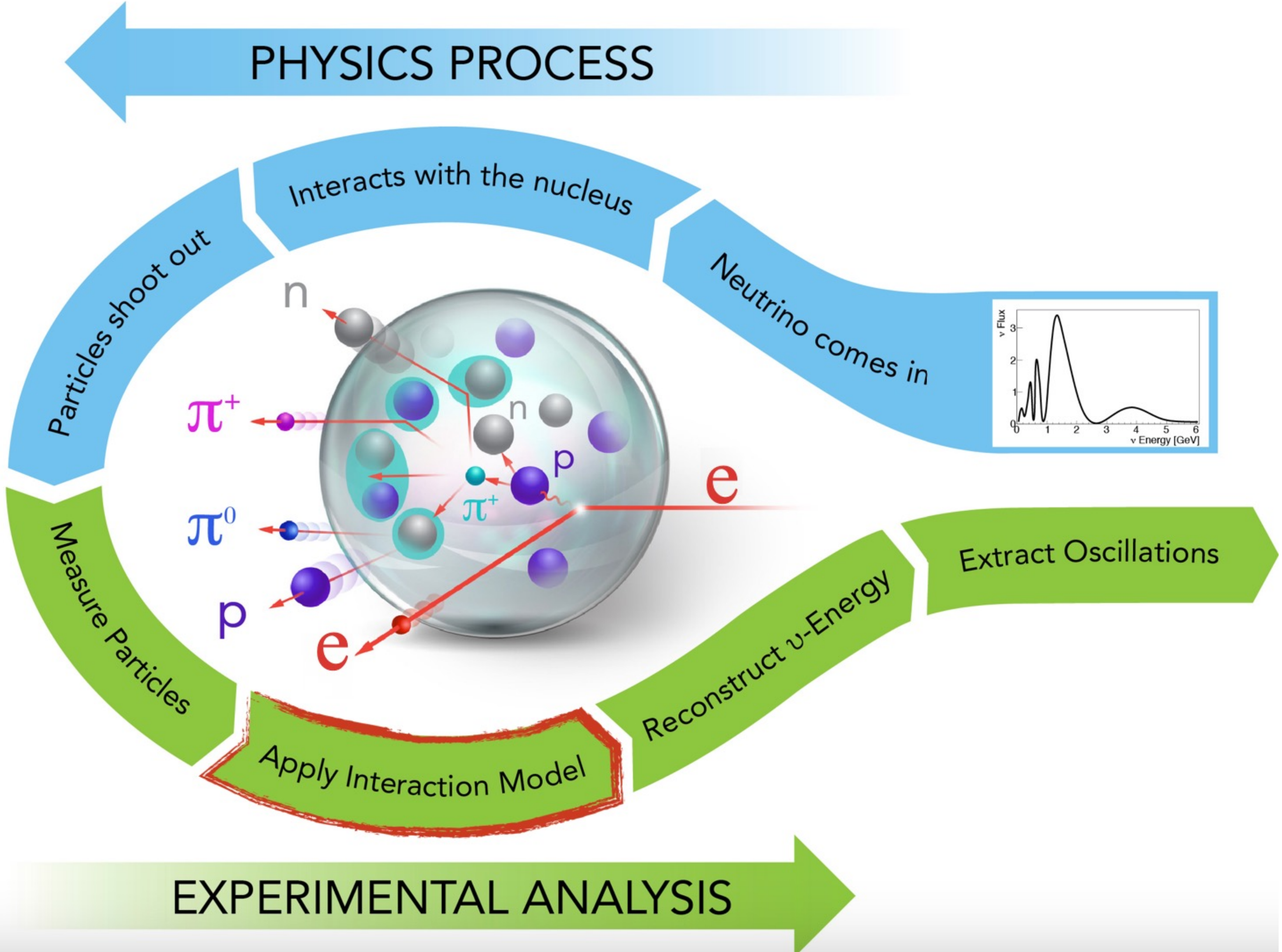
Measure Particles

Apply Interaction Model

Reconstruct ν-Energy

Extract Oscillations

EXPERIMENTAL ANALYSIS



PHYSICS PROCESS

Neutrino comes in

Interacts with the nucleus

Particles shoot out

Measure Particles

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EXPERIMENTAL ANALYSIS

The challenge
Next generation high precision

$$N(E_{rec}, L) \propto \int \Phi(E, L)\sigma(E) f_{\sigma}(E, E_{rec}) dE$$

Measurement

Incoming true flux

Modelling input

The challenge
Next generation high precision

$$N(E_{rec}, L) \propto \int \Phi(E, L)\sigma(E) f_{\sigma}(E, E_{rec}) dE$$

Measurement

Incoming true flux

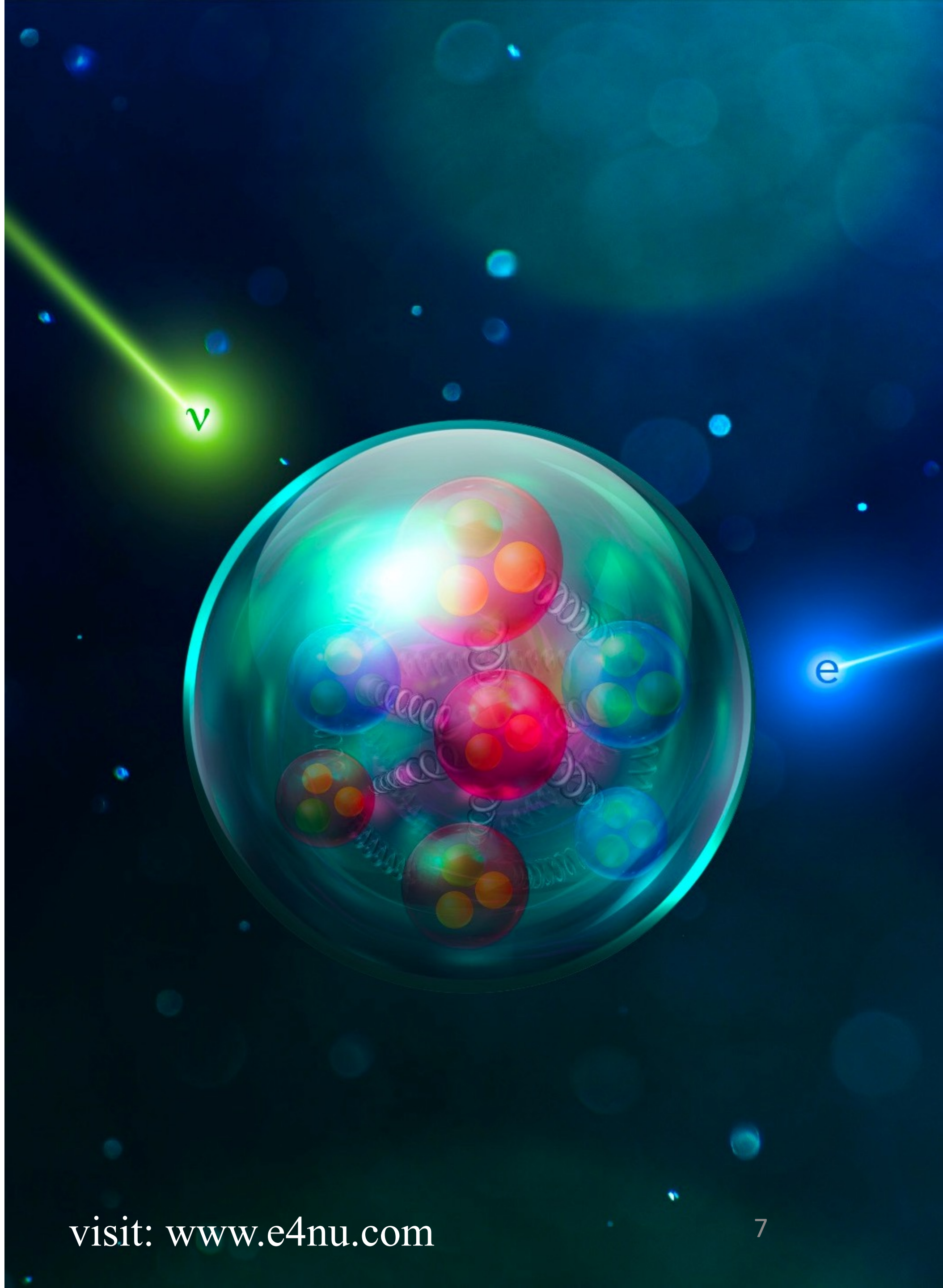
Modelling input

- Improve theory
- Use near detector
- Use external constraints
  e scattering

Electrons for neutrinos

- **Using electron scattering data to reduce neutrino oscillation systematic uncertainties**
  - Test neutrino energy reconstruction
  - Constrain lepton-nucleus interaction models

  - Identical nuclear effects and final state interactions
  - Similar interaction to neutrinos (vector vs vector+axial)

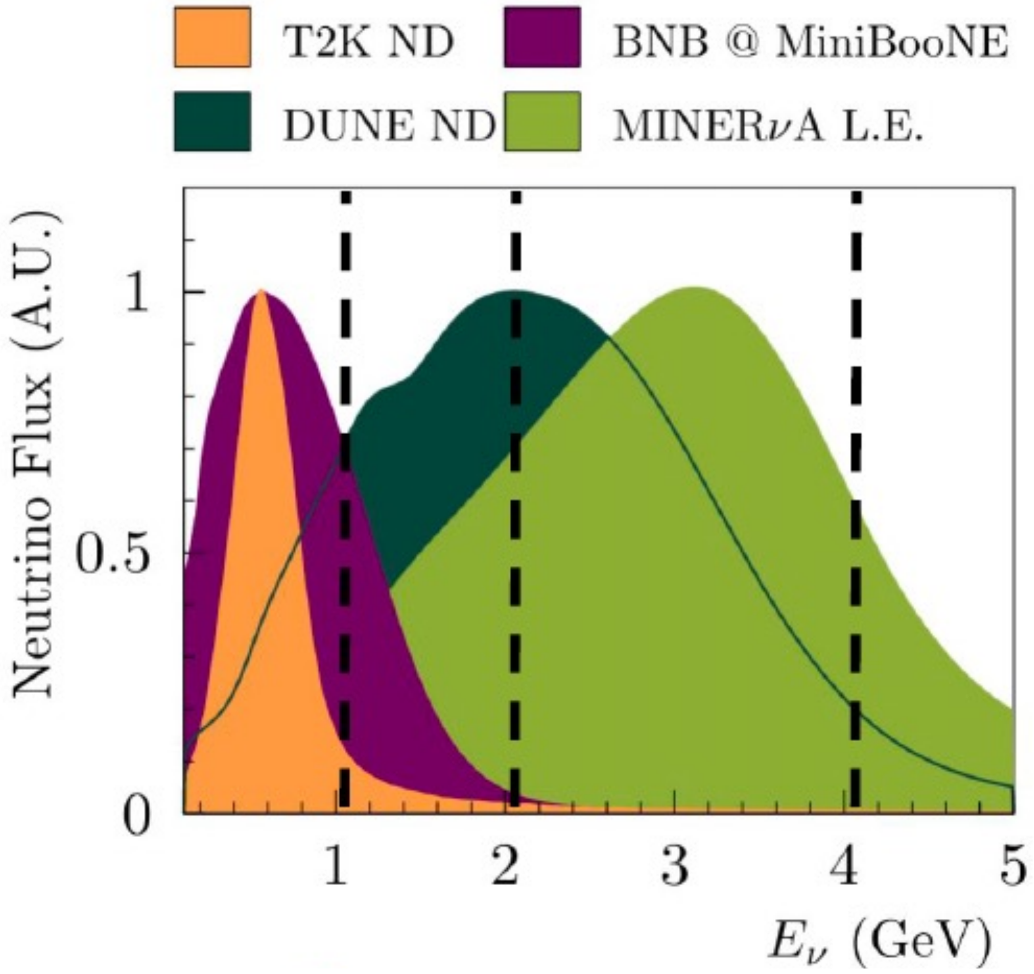


visit: www.e4nu.com

CLAS6 data analysis in e4nu

e4ν Data-Mining with CLAS6

- Large acceptance @ $\theta_e > 15°$
- Charged particle threshold comparable to neutrino tracking detectors
- Beam energies: 1, 2 & 4 GeV
- Targets: ^4He, ^{12}C, ^{56}Fe



Electron-beam energy reconstruction for neutrino oscillation measurements

Nature **599**, 565–570 (2021)

- e4nu already published an analysis with CLAS6 data
- Measured (e,e’1p0π) cross-section
  - C, Fe and He
  - 1.159, 2.257 and 4.453 GeV
- Focused on quantifying bias due to electron-energy reconstruction
  - Using same methods used in the neutrino community
  - Most events aren’t reconstructed at the correct beam energy
  - MC Generators fail to predict the data

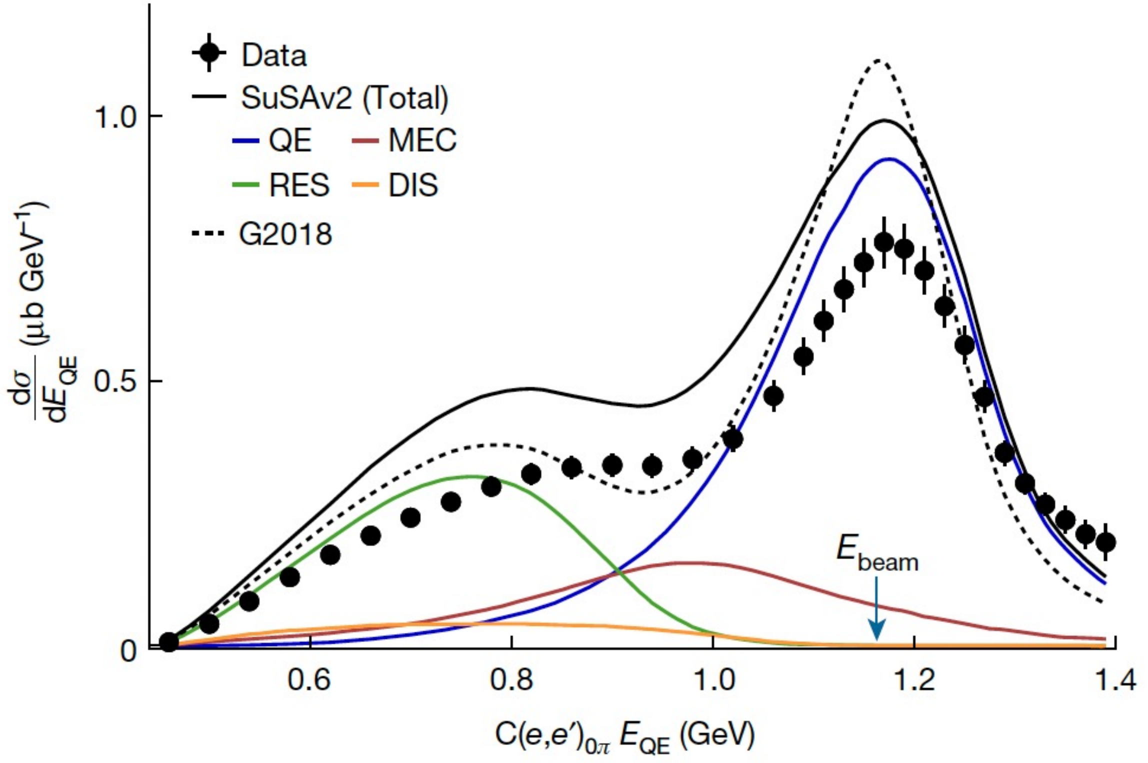
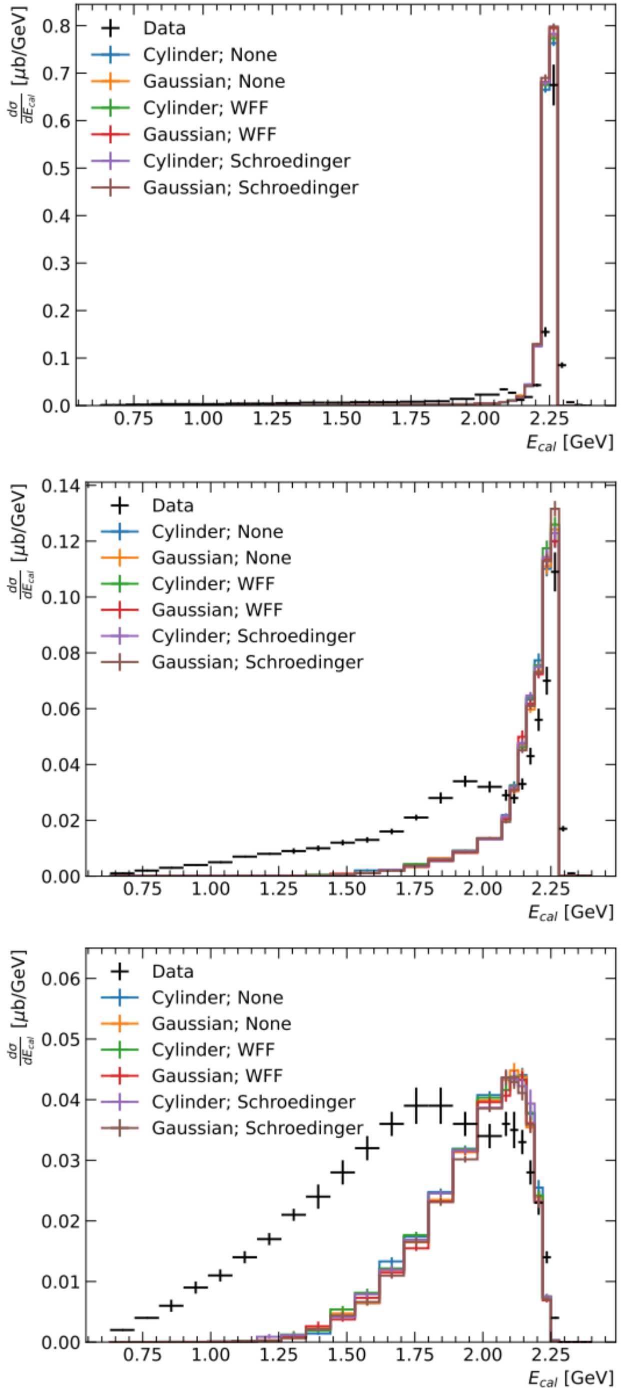


Fig.1 The 1.159 GeV C(e,e’1p0π) cross-section as a function of the reconstructed electron energy under the quasi-elastic hypothesis. The data is compared against two GENIE MC predictions.

CLAS6 data analysis in e4nu

- High impact results in the neutrino community
    - Benchmarking new models and generators, such as ACCHILES
    - arXiv: 2205.06378 (2022)
- The **same datasets** are being used for additional analyses of interest for the neutrino community
- Transparency measurement
    - Lead by Noah Steinberg @ FNAL - Under review
    - Same analysis code and sample as (e,e'1p0π) analysis
        - CLAS6 data He, C, and Fe at 2 and 4 GeV
- Measurement of **semi-exclusive pion production** with CLAS6 data
    - Lead by Julia Tena Vidal @ Tel Aviv University
    - New analysis code, same sample as (e,e'1p0π) analysis



Pion production and neutrino experiments

- Accelerator based neutrino experiments use wide-beam neutrino fluxes
    - Need to understand all interaction mechanisms for precision measurements
- **Pion production events dominate the near-future DUNE experiment event-rate**
    - Simplistic pion production models in event generators
    - Will affect efficiency corrections, background estimation, neutrino reconstruction…
- **Background for few-GeV neutrino experiments**

Dominated by Resonant and Deep Inelastic Scattering events

Pion production processes!

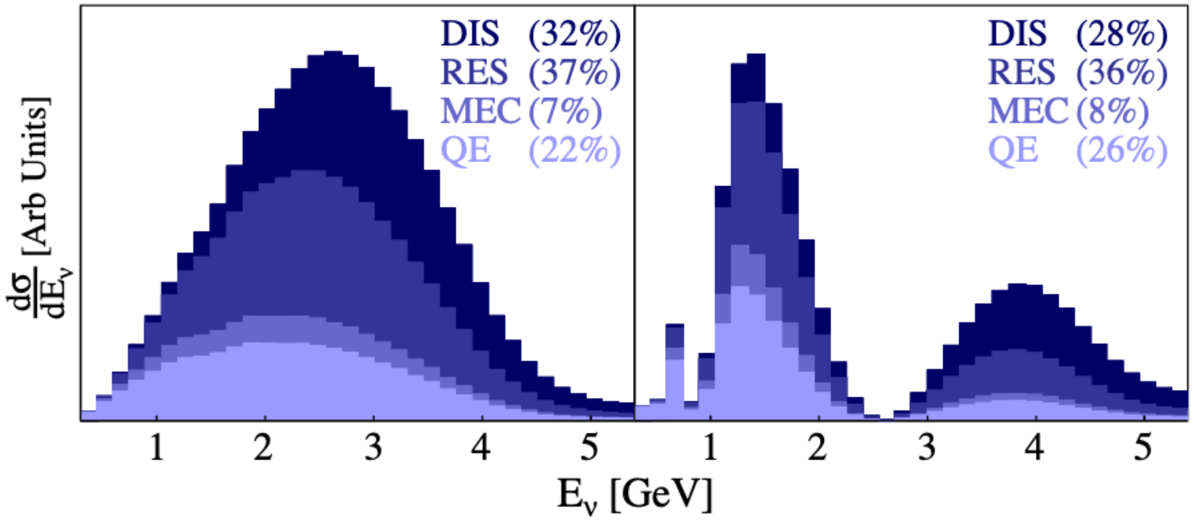


Fig.3 Charged-current cross sections as a function of neutrino energy. Cross-section is computed using the GENIE MC generator with the DUNE Near Detector flux (left) and Far Detector flux (right).

Pion Production - Physics overview

- Without nuclear effects, the following RES production mode are possible:
  - $e^- + p \rightarrow e^- + \Delta^+ \, , \Delta^+ \rightarrow n + \pi^+$ and $\Delta^+ \rightarrow p + \pi^0$
  - $e^- + n \rightarrow e^- + \Delta^0 \, , \Delta^0 \rightarrow n + \pi^0$ and $\boldsymbol{\Delta^0 \rightarrow p + \pi^-}$
  - Higher W resonances decay in multiple pions
    - Contribute due to momentum thresholds and detector gaps
  - Non-RES background and DIS will also produce pions

- With Nuclear effects:
  - More possibilities open due to FSI
  - $\boldsymbol{p + \pi^+}$ final state is possible

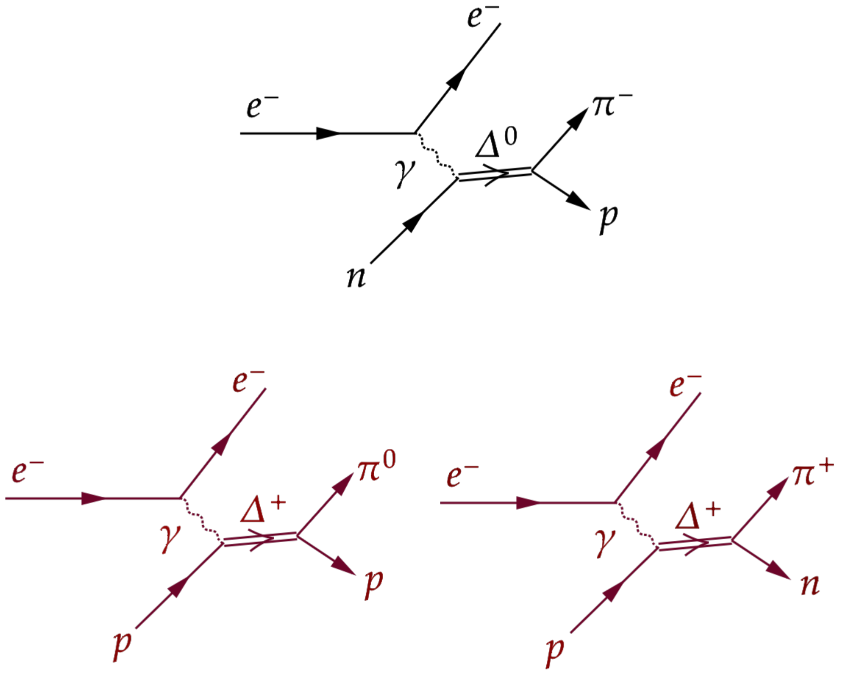


Fig.4 e-N RES production Feyman diagram the pion-production threshold. In this analysis we only look at charged particles (top diagram).

Definition of pion production topology

We are looking into different topology definitions:

- $\boldsymbol{1p1\pi}^{-}0\pi^{+}0\gamma$ any number of neutrons
- $\boldsymbol{1p1\pi}^{+}0\pi^{-}0\gamma$ any number of neutrons
- $\boldsymbol{1\pi}^{-}0\pi^{+}0\gamma$ any number of protons and neutrons
- $\boldsymbol{1\pi}^{+}0\pi^{-}0\gamma$ any number of protons and neutrons

Focus in this talk

The same analysis cuts are applied for each analysis

Using data from CLAS6 on carbon at **1.161, 2.261** and 4.461 GeV

Pion production analysis – **CLAS6 Data**

For each data event,

1. Apply momentum and angle thresholds to detected particles
2. Select signal events (i.e. $1p1\pi^-$events)
3. Remove background (*)
4. Correct for detector acceptance (*)
5. Weight events by Q4 to probe regions of the phase space that are relevant for neutrinos
6. Convert from event-rate to cross-section

(*) Explained later in the talk

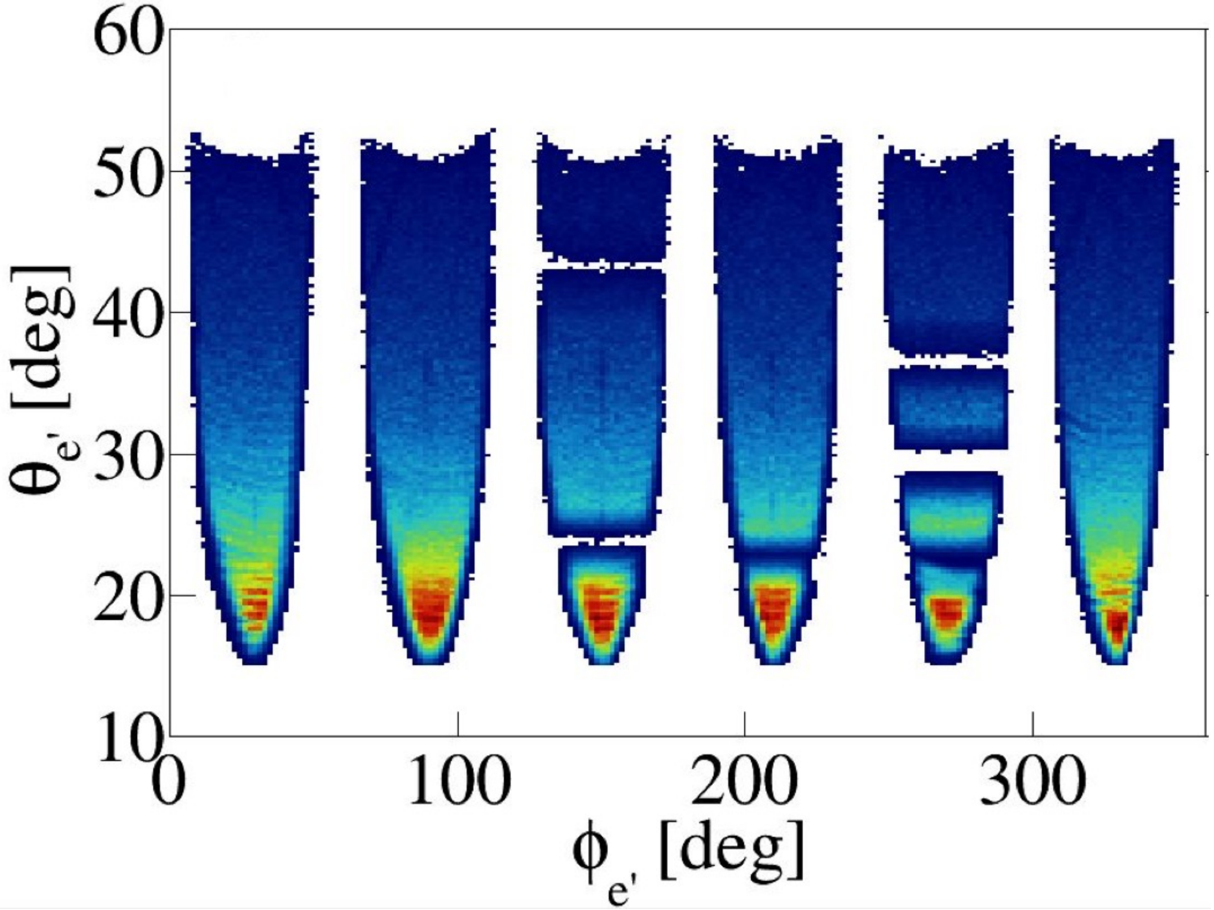
Pion production analysis
CLAS6 Monte Carlo

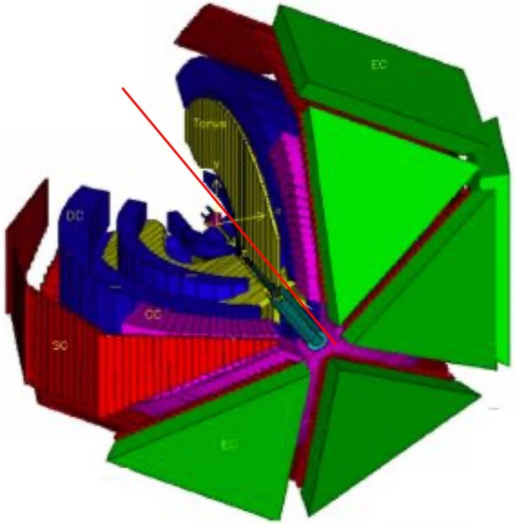
For each MC event,

1. Apply momentum and angle thresholds to detected particles
2. Weight events by Q4 to probe regions of the phase space that are relevant for neutrinos
3. Smear particle momentum according to CLAS6 simulations
4. Remove particles outside fiducial maps
5. Remove Background events (true reconstructed sample)
6. Weight events according to efficiency maps
7. Select signal events (i.e. $1p1\pi^{-}$ events)
8. Convert from event-rate to cross-section

Pion production analysis cuts
Fiducial cuts

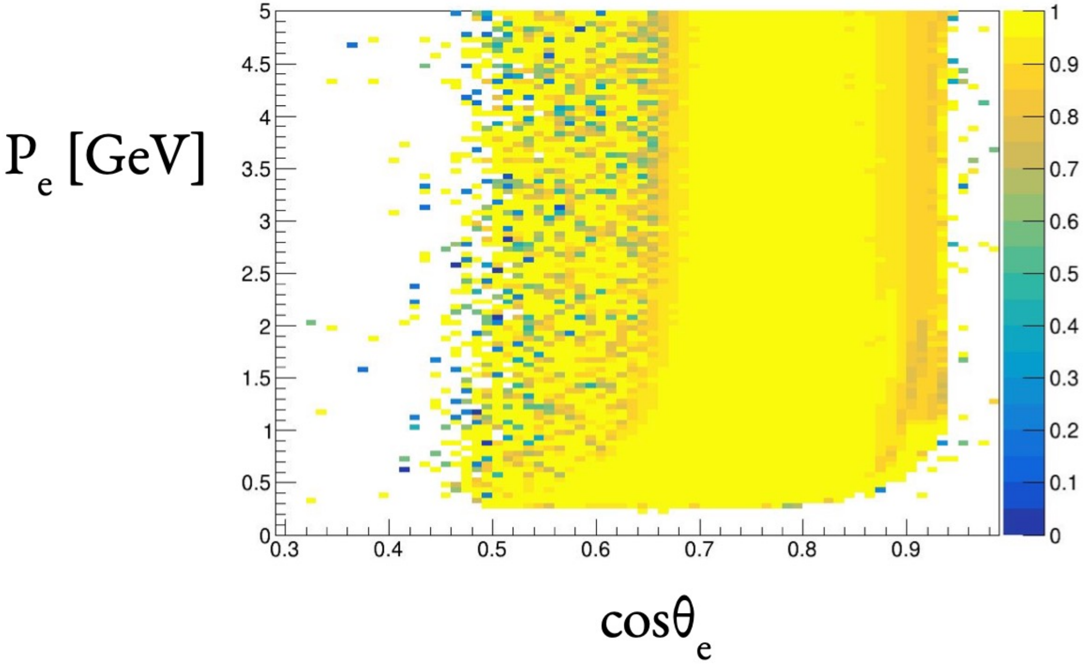
- Only applied to MC events
- Data events already in the fiducial

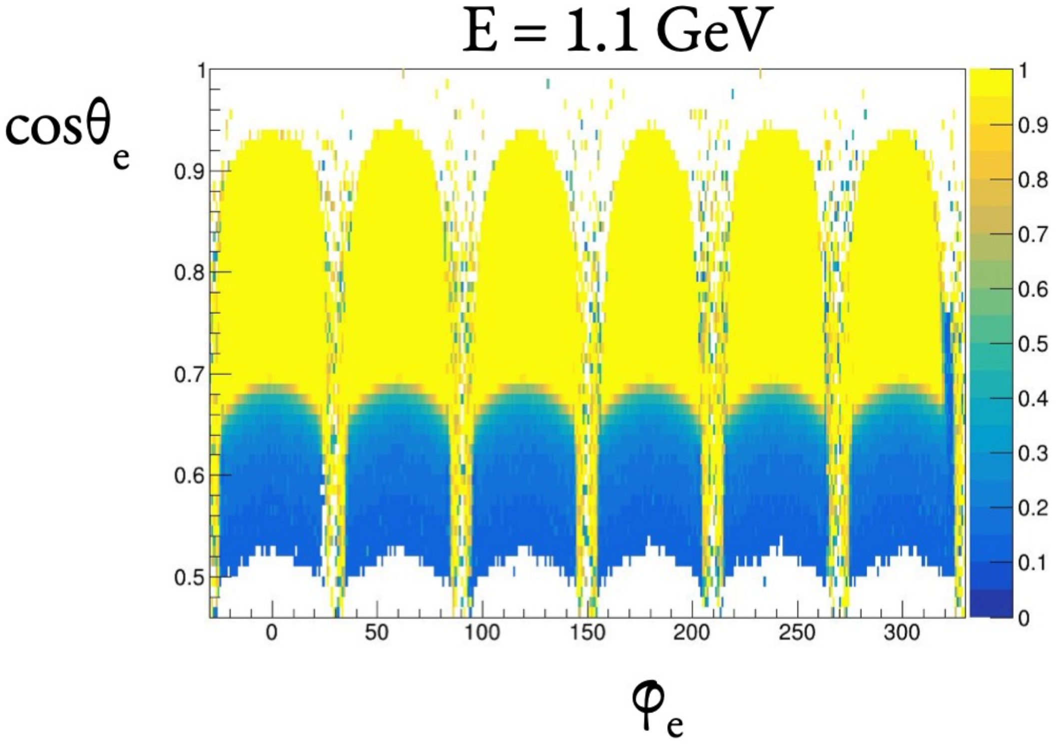




Pion production analysis cuts – Monte Carlo

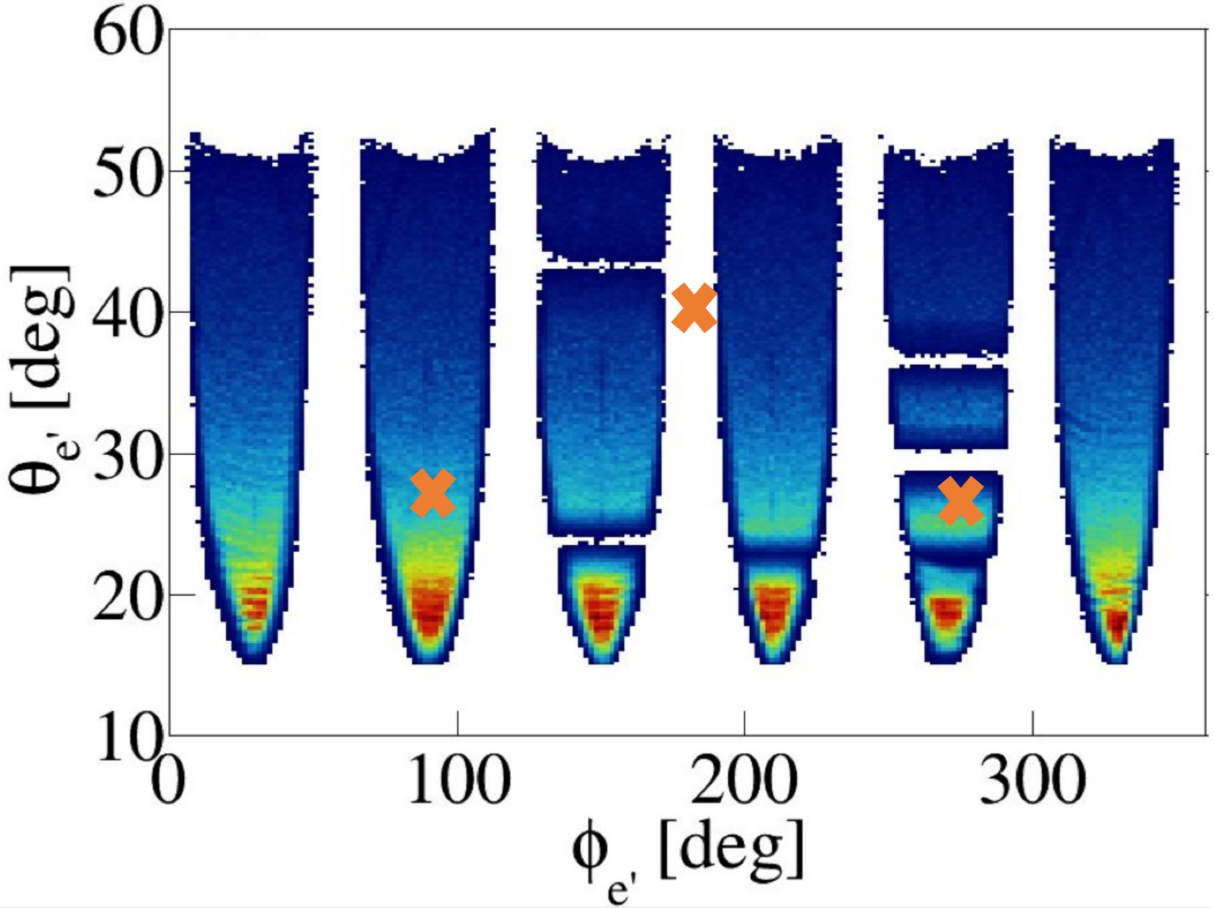
Depending on momentum and directionality, we assign an extra MC weight to account for detector acceptance effects





Background contamination

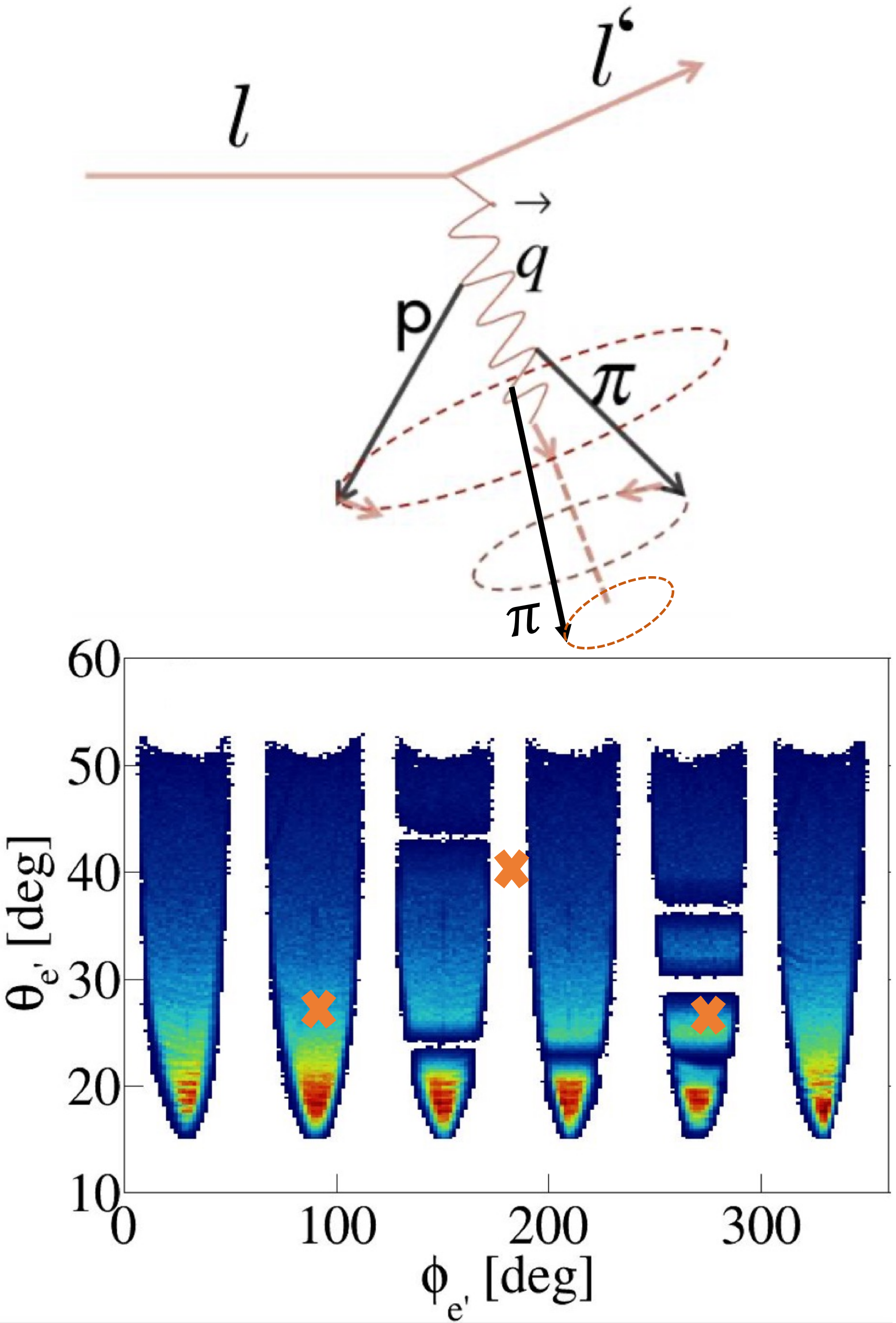
Non-(e,e'1p1π^-) events can be reconstructed as (e,e'1p1π^-) due to gaps in the detector



Data-driven background subtraction method

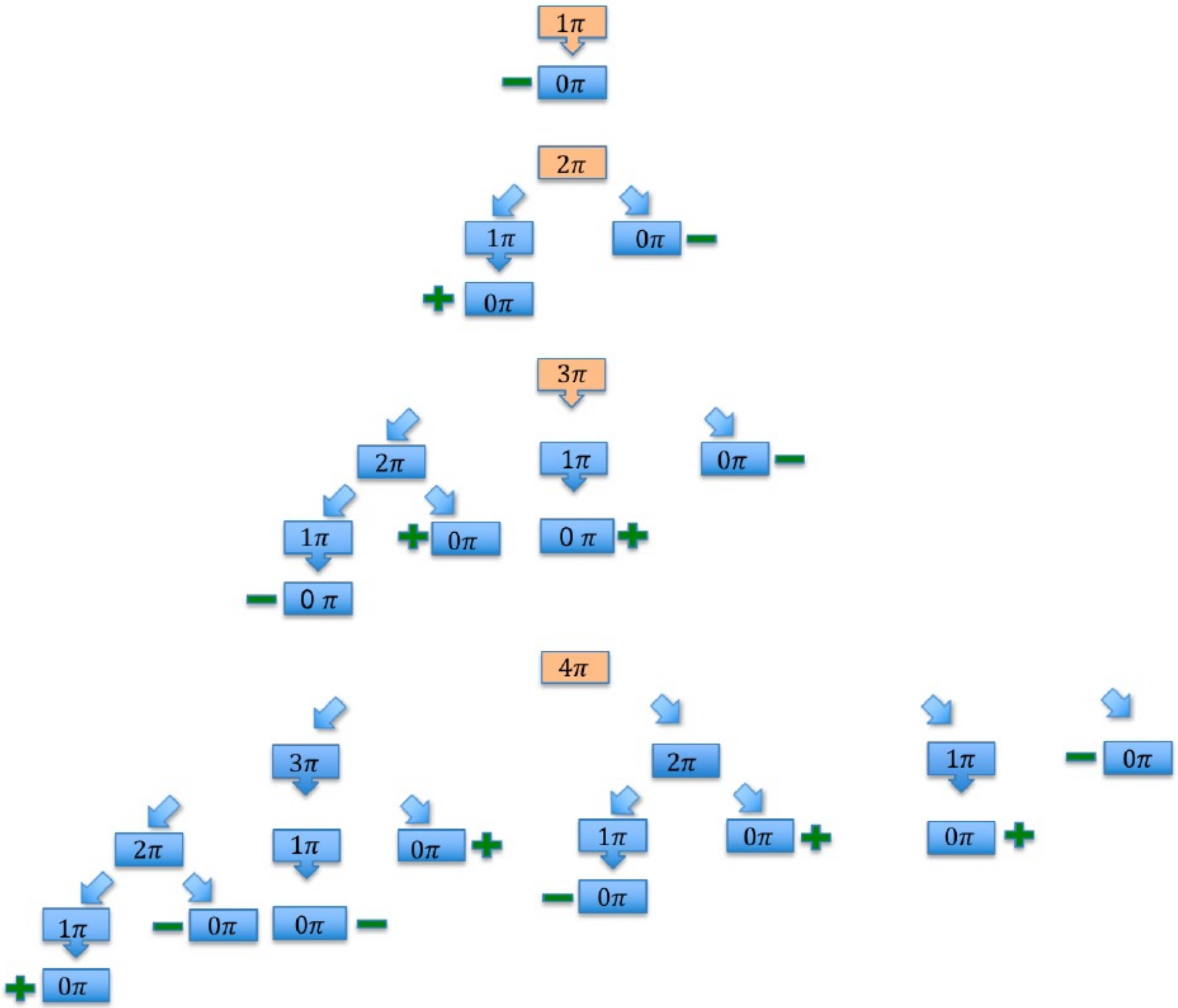
We can use detected background events to estimate the background:

- Use measured $1p2\pi^-$events
- Rotate all hadrons around q to determine detection efficiency
  - $1p2\pi^- \rightarrow 1p1\pi^-$
- Subtract undetected $1p2\pi^-$ events
- Repeat for higher multiplicities
  - $2p2\pi^- \rightarrow 1p1\pi^-$ (subtract)
  - $2p2\pi^- \rightarrow 1p2\pi^- \rightarrow 1p1\pi^-$ (add)
- This procedure was used in the (e,e’ $p0\pi$) analysis



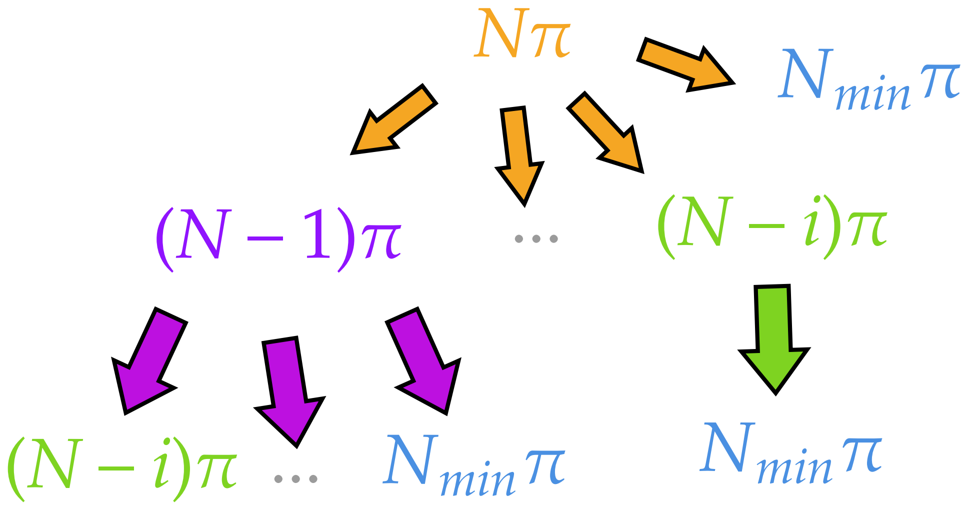
Data-driven background subtraction method

- This procedure was used in the (e,e’ $p0\pi$) analysis
  - It was **specific** to the $1p0\pi$ topology
- This logic requires **to hard-code** each possible combination by hand
  - Must re-write it for every analysis
  - Not robust
  - Easy to miss a contribution
- Not the most efficient as we start from th smallest background multiplicity



New background subtraction method

- The new code classifies the events in **"multiplicity" groups**
  - Signal multiplicity, Min. Multiplicity N_{min}
  - Background multiplicity
    - Mult N: $N\pi$ (max. mult. is configurable)
- Starting from the higher multiplicity events, calculate probability to have a smaller multiplicity $(m_f < m_i)$
  - Store pseudo-event in new "multiplicity" group
  - The new event has a weight $\omega_f = -\omega_i \frac{N^{mf}}{N^{mi}}$
- Repeat for lower multiplicity groups
  - These contain real background events and pseudo-events



$N\pi$

$N_{min}\pi$

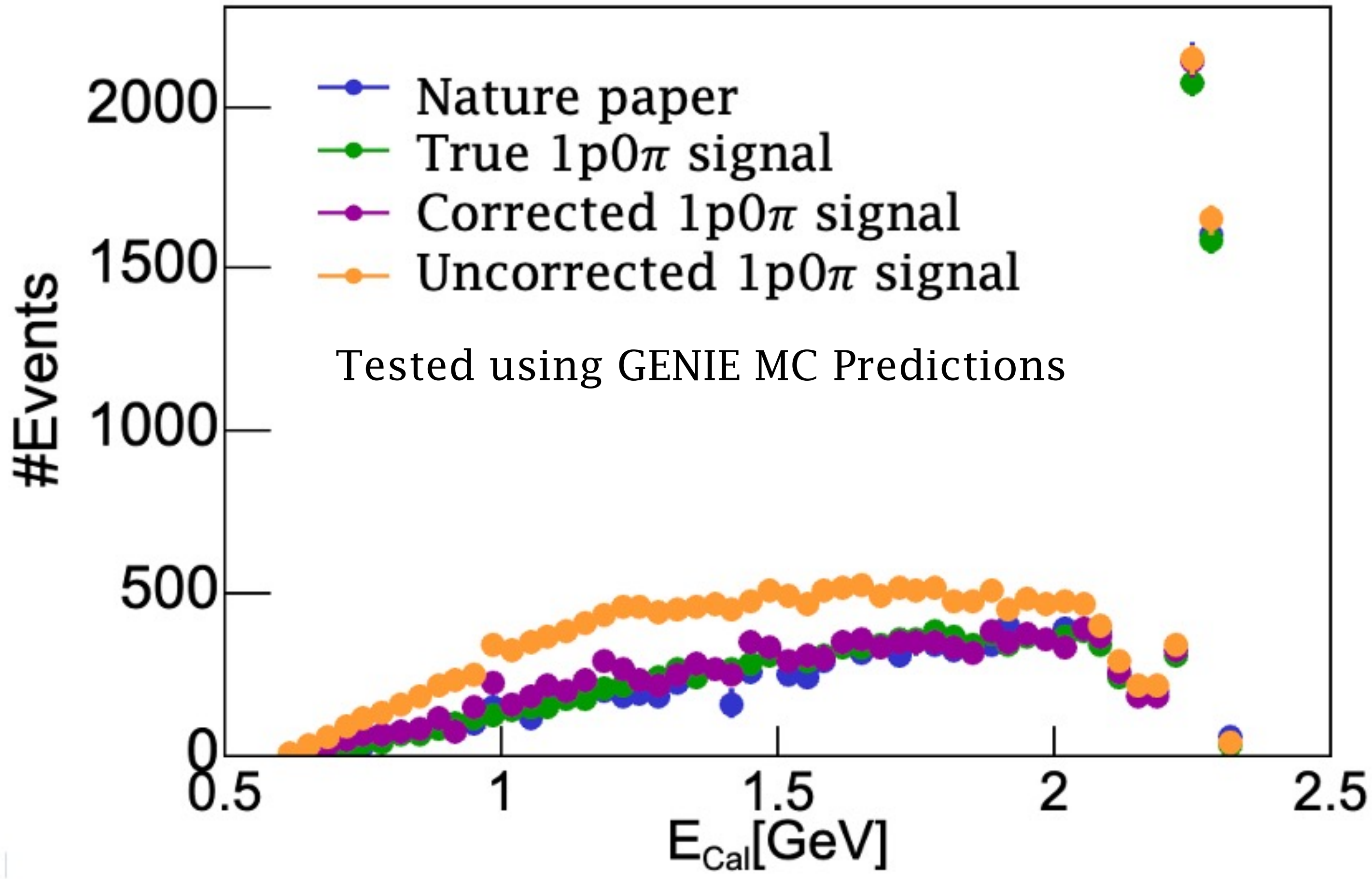
$(N-1)\pi$ … $(N-i)\pi$

$(N-i)\pi$ … $N_{min}\pi$ $N_{min}\pi$

e4nu analysis code – Validation

New code successfully reproduces previous results

$^{12}C(e,e'1p0\pi)$, 2GeV



Tested using GENIE MC Predictions

Pion production analysis – **CLAS6 Data**

For each data event,

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(*) Explained later in the talk

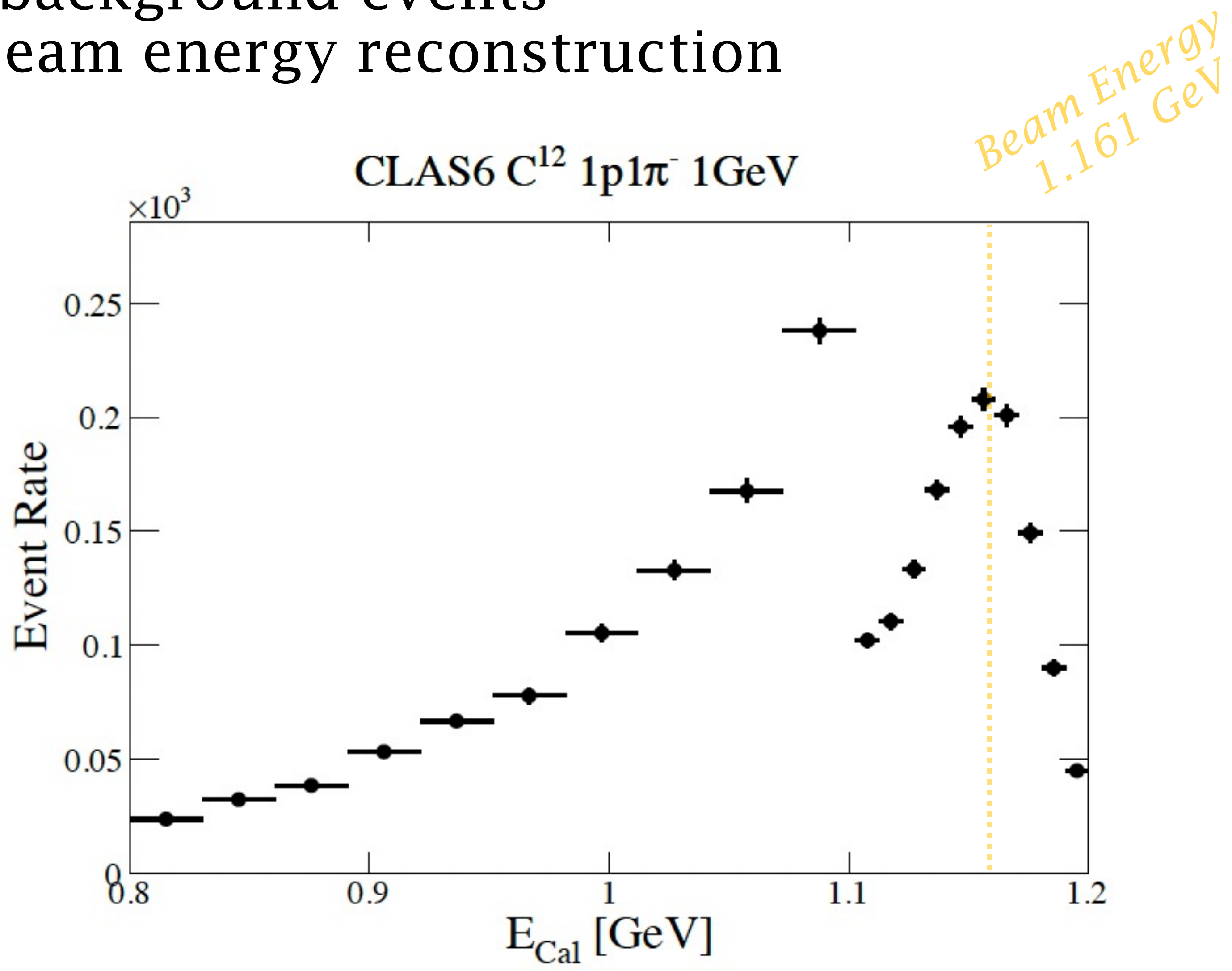
(e,e'1p1π^-) event rate
Calorimetric Beam energy reconstruction

- In neutrino experiments, the per-event neutrino energy is not known
- It is always reconstructed from the observed final state particles
- Depending on the experiment characteristics, different methods are used
- One method is to use the **calorimetric technique**
  - $E_{Cal} = E_{e'} + E_{\pi} + T_p + \varepsilon_p$,

    $E_{e'}$ and $E_{e'}$: outgoing electron and pion energy
    T_p, ε_p: proton kinetic energy and separation energy
  - Neutral particles and undetected particles are not included

(e,e’1p1π^-) event rate

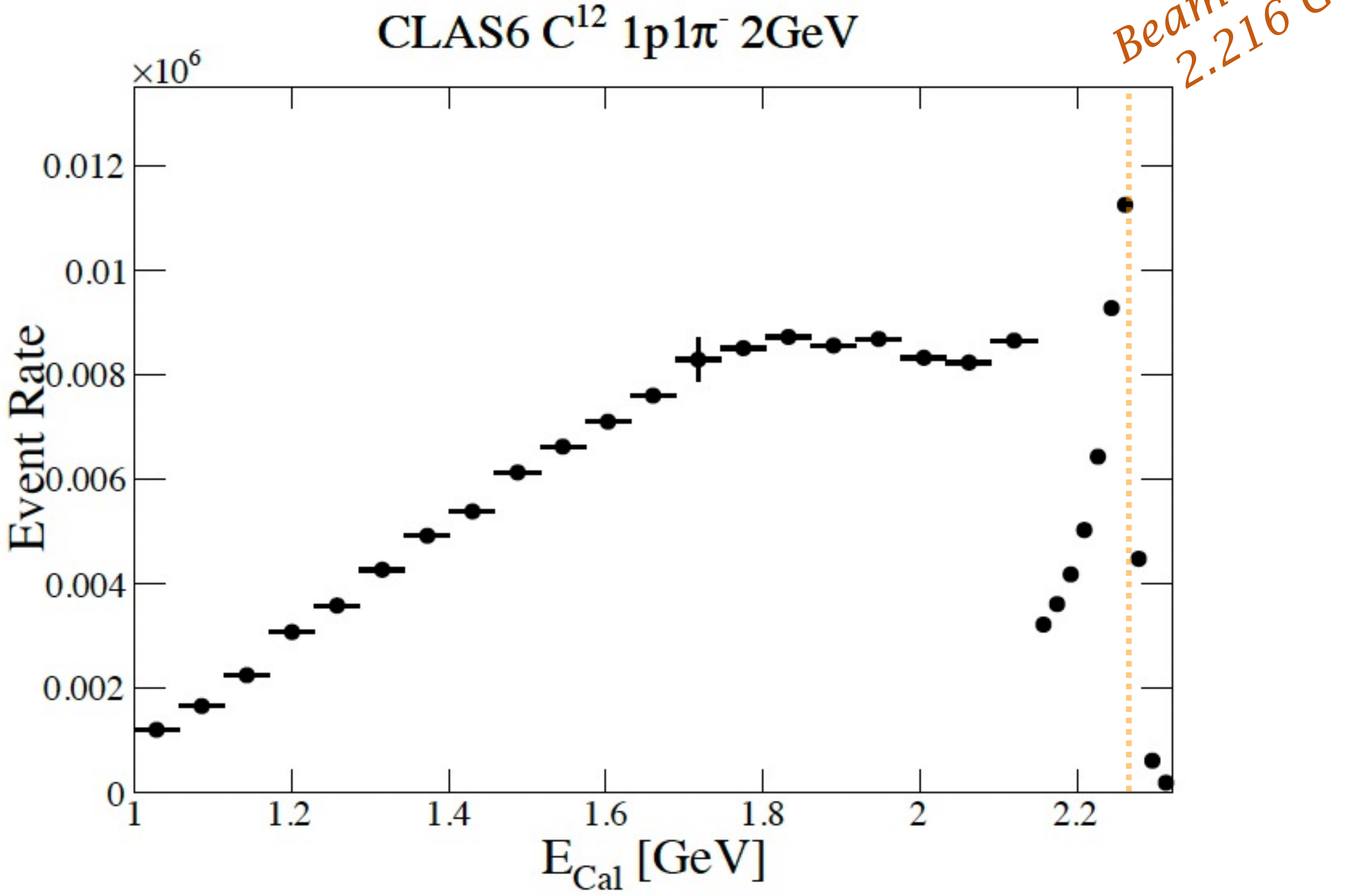
Corrected for background events
Calorimetric Beam energy reconstruction



$(e,e'1p1\pi^-)$ event rate

Corrected for background events

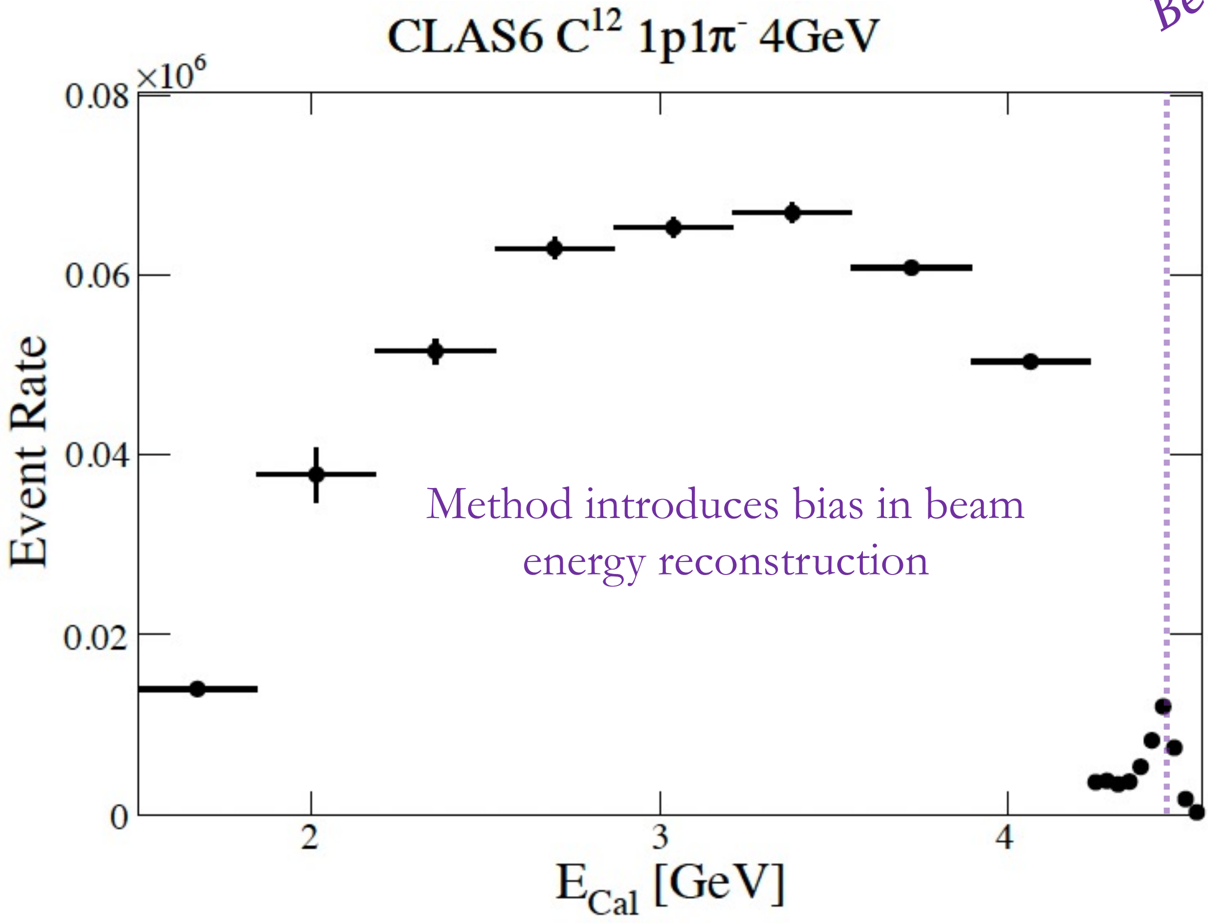
Calorimetric Beam energy reconstruction



(e,e’1p1π^-) event rate

Corrected for background events

Calorimetric Beam energy reconstruction



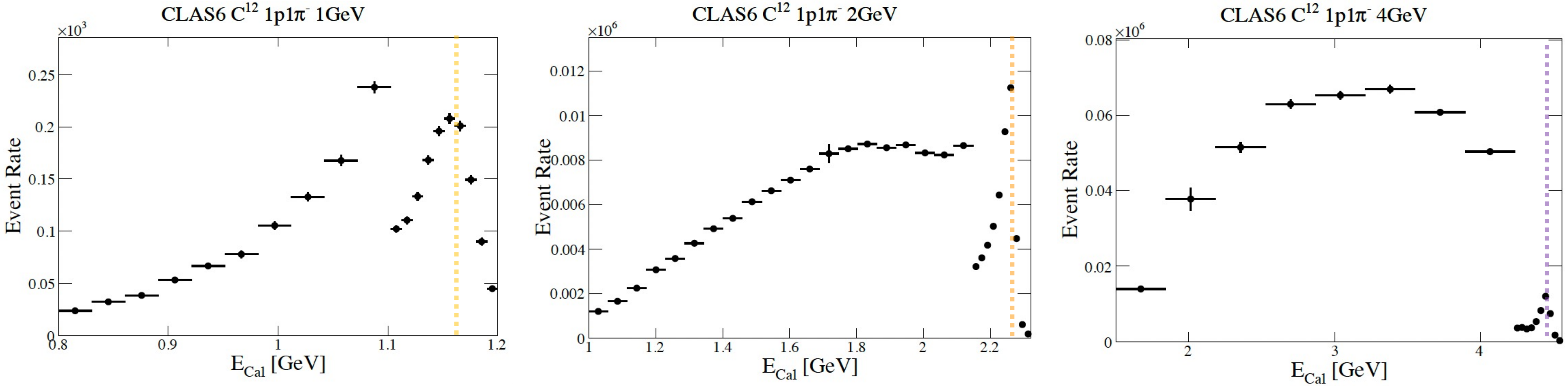
Beam Energy 4.4161 GeV

Method introduces bias in beam energy reconstruction

(e,e'1p1π^-) event rate

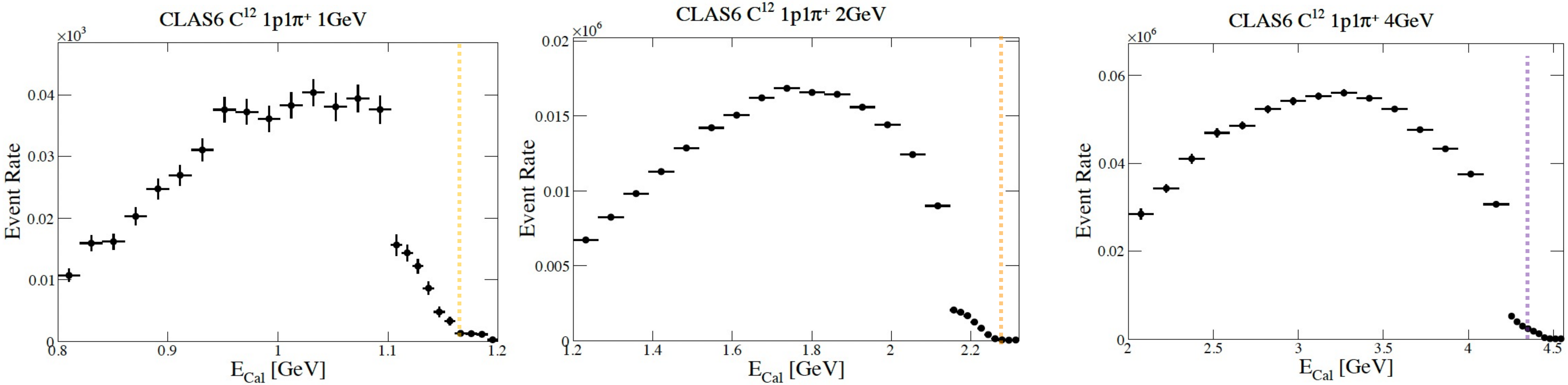
Corrected for background events

Calorimetric Beam energy reconstruction



- Larger energy reconstruction bias at high energy
- Tail events correspond to events with additional undetected particles

(e,e'1p1π^+) event rate
Corrected for background events
Calorimetric Beam energy reconstruction

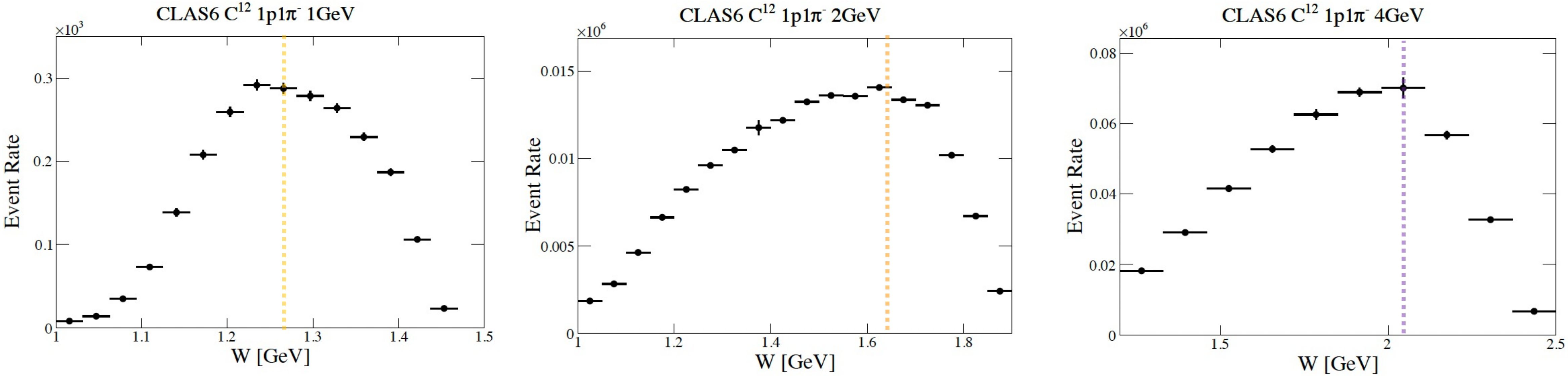


- The 1p1π^+ final state is only possible via FSI and multi-pion production events with undetected pions
- **Cannot use calorimetric method to reconstruct beam energy**

(e,e’1p1π^-) event rate
Other variables of interest

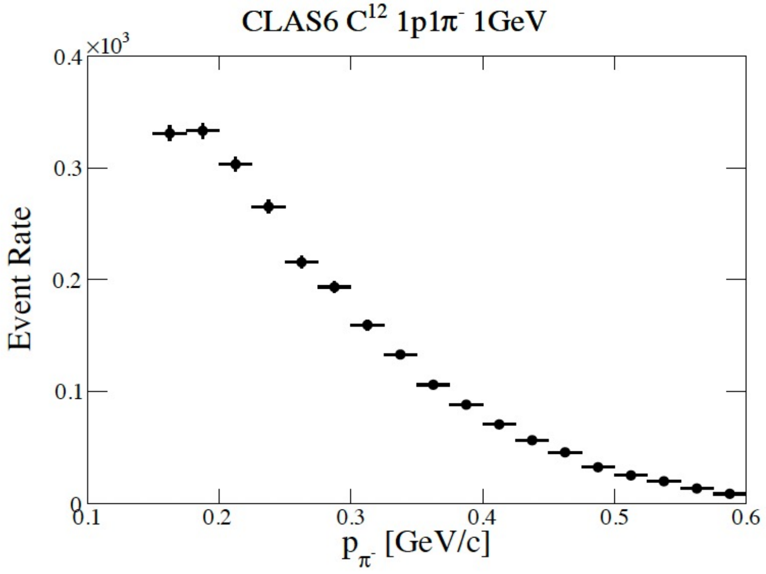
- **True event kinematics**
  - I.e. W
  - Reconstructed using known beam-energy
  - Avoids model bias
- **Outgoing particle kinematics**
  - Pion momentum and angle
  - Proton momentum and angle
- Additional variables under study
  - Focus on characterization of the nuclear environment
  - Will review it on the next presentation

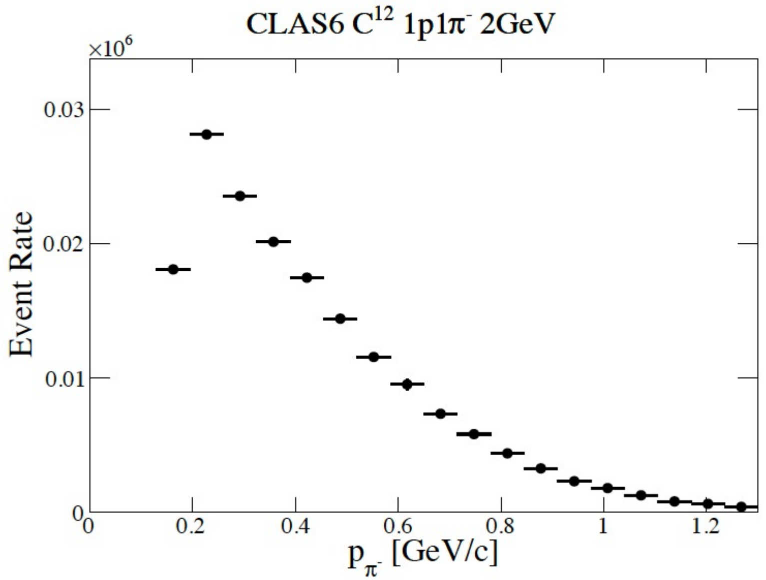
(e,e’1p1π^-) event rate
True W

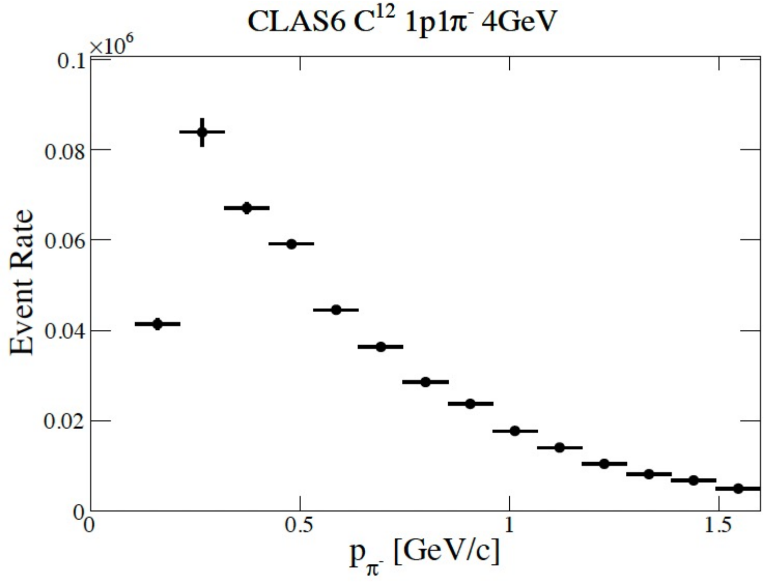


- Shift in the distribution towards higher W as beam energy increases
    - Exploring different RES/DIS region
    - Neutrino experiments cannot reconstruct this variable without bias
    - Good test of event generator physics

(e,e’1p1π^-) event rate
Background subtracted
Pion momentum

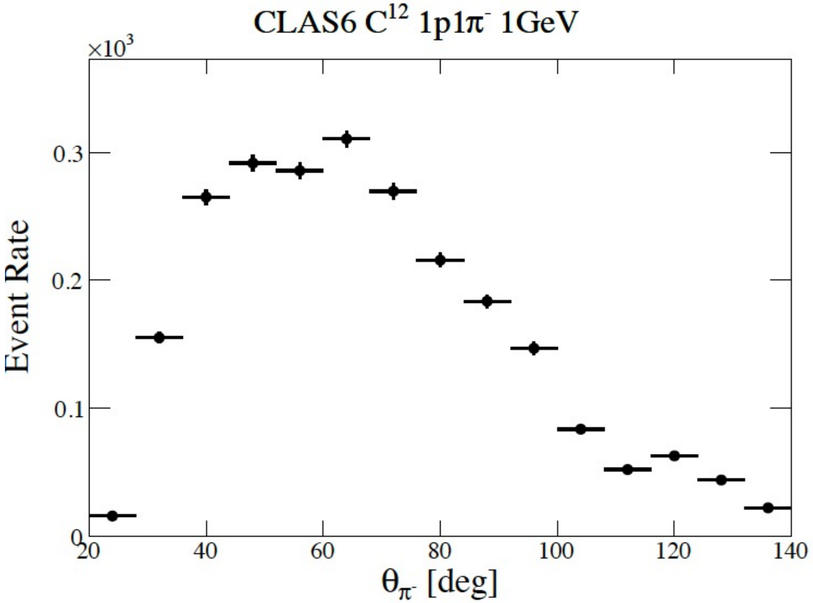


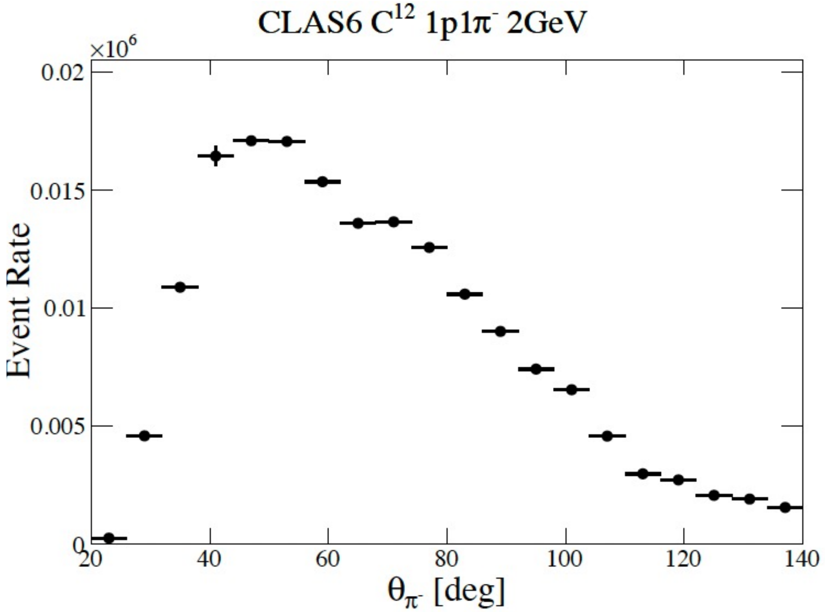


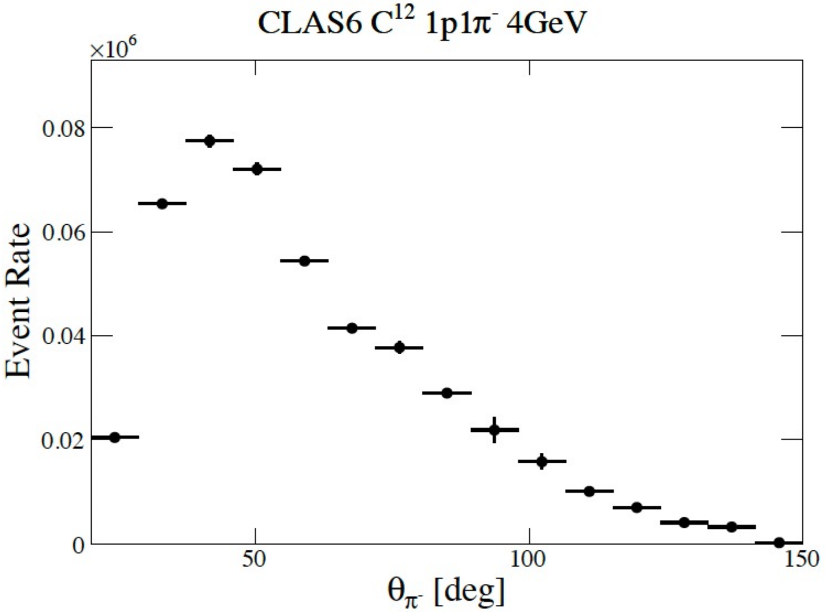


Particle threshold: $p_{\pi^{\pm}} > 0.15\ {}^{GeV}/_{c}$

(e,e’1p1π^-) event rate
Background subtracted
Pion angle

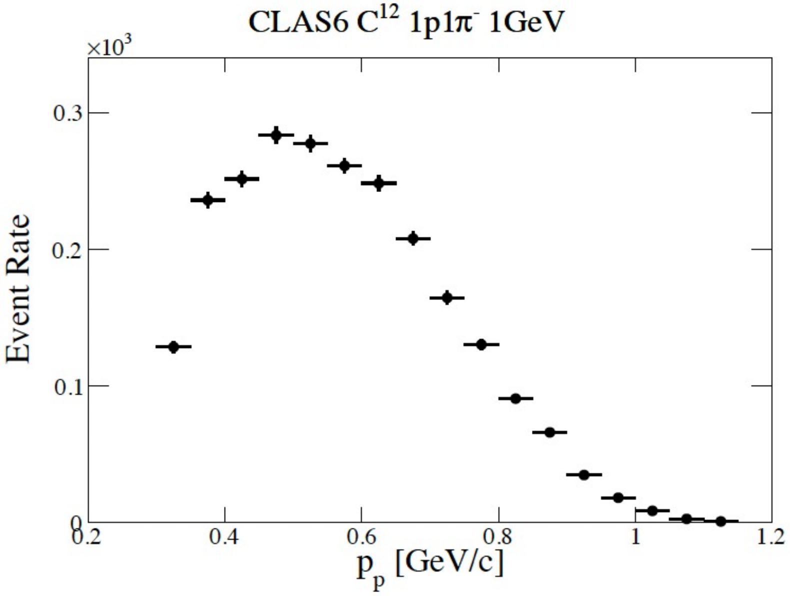


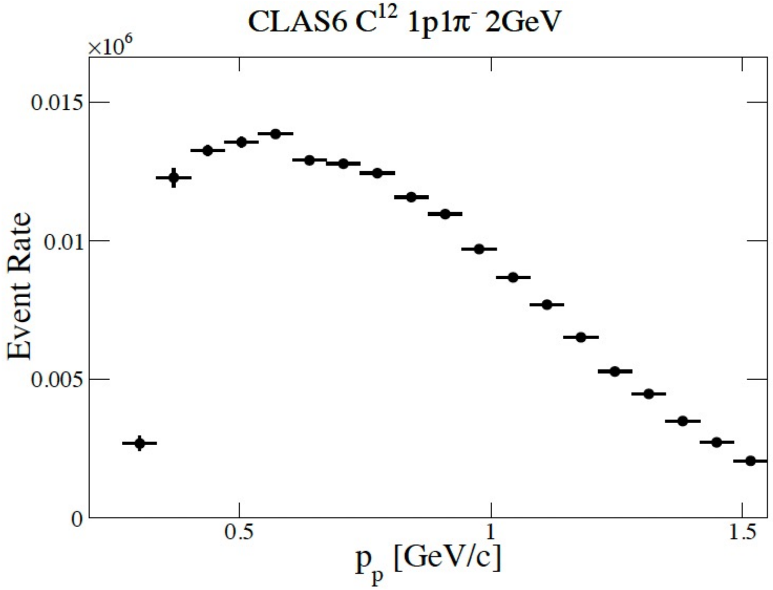


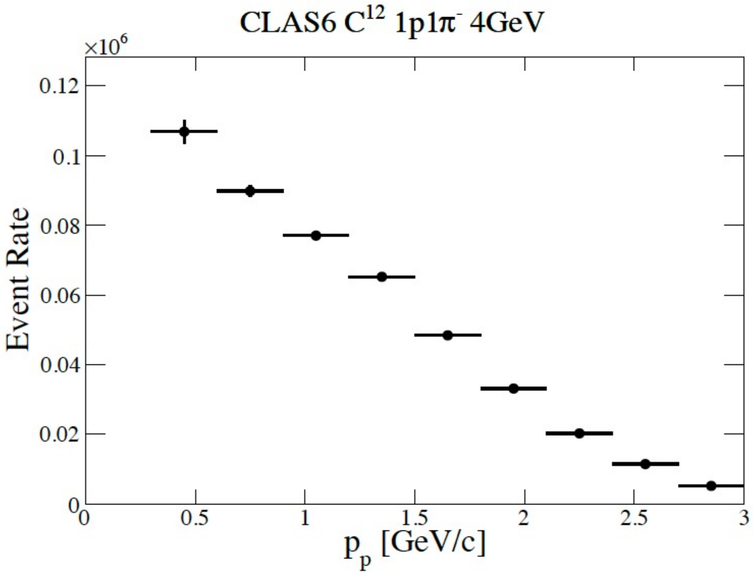


- Detector gaps show as dips in the uncorrected data distributions

(e,e'1p1π^-) event rate
Background subtracted
Proton momentum

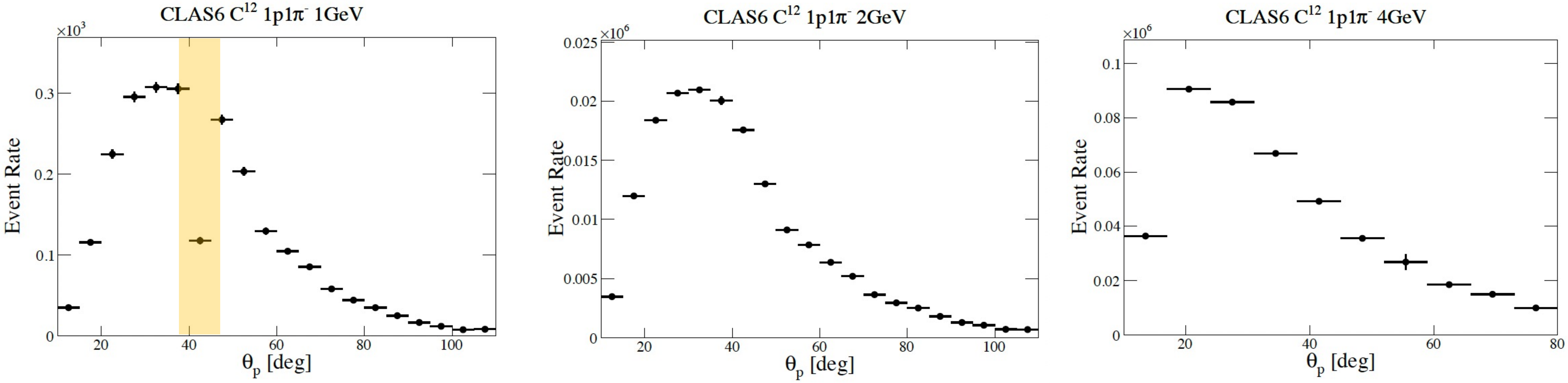






Particle threshold: $p_p > 0.3\ {}^{GeV}/_{c}$

(e,e’1p1π^-) event rate
Background subtracted
Proton angle



- **Detector gaps** show as dips in the uncorrected data distributions

Pion production analysis – **CLAS6 Data**

For each data event,

1. Apply momentum and angle thresholds to detected particles
2. Select signal events (i.e. $1p1\pi^-$ events)
3. Remove background (*)
4. **Correct for detector acceptance (*)**
5. Weight events by Q4 to probe regions of the phase space that are relevant for neutrinos
6. Convert from event-rate to cross-section

Acceptance correction

We must correct the data for detector effects to obtain a detector-independent cross-section measurement

For CLAS6 analyses, we must correct for:

- Smearing effects
- Fiducial cuts
- Detection efficiency
- Radiative corrections (Ongoing work)

Using MC prediction from GENIE to estimate correction

Detector effect	True MC	True Rec.
Thresholds	✓	✓
Scaled by Q^4	✓	✓
Smearing	✗	✓
Fiducial	✗	✓
Efficiency maps	✗	✓

We apply an overall per-bin scaling factor to the data:

$$\alpha_{acc} = \frac{True\ MC\ events\ ith-bin}{True\ Reconstructed\ MC\ events\ ith-bin}$$

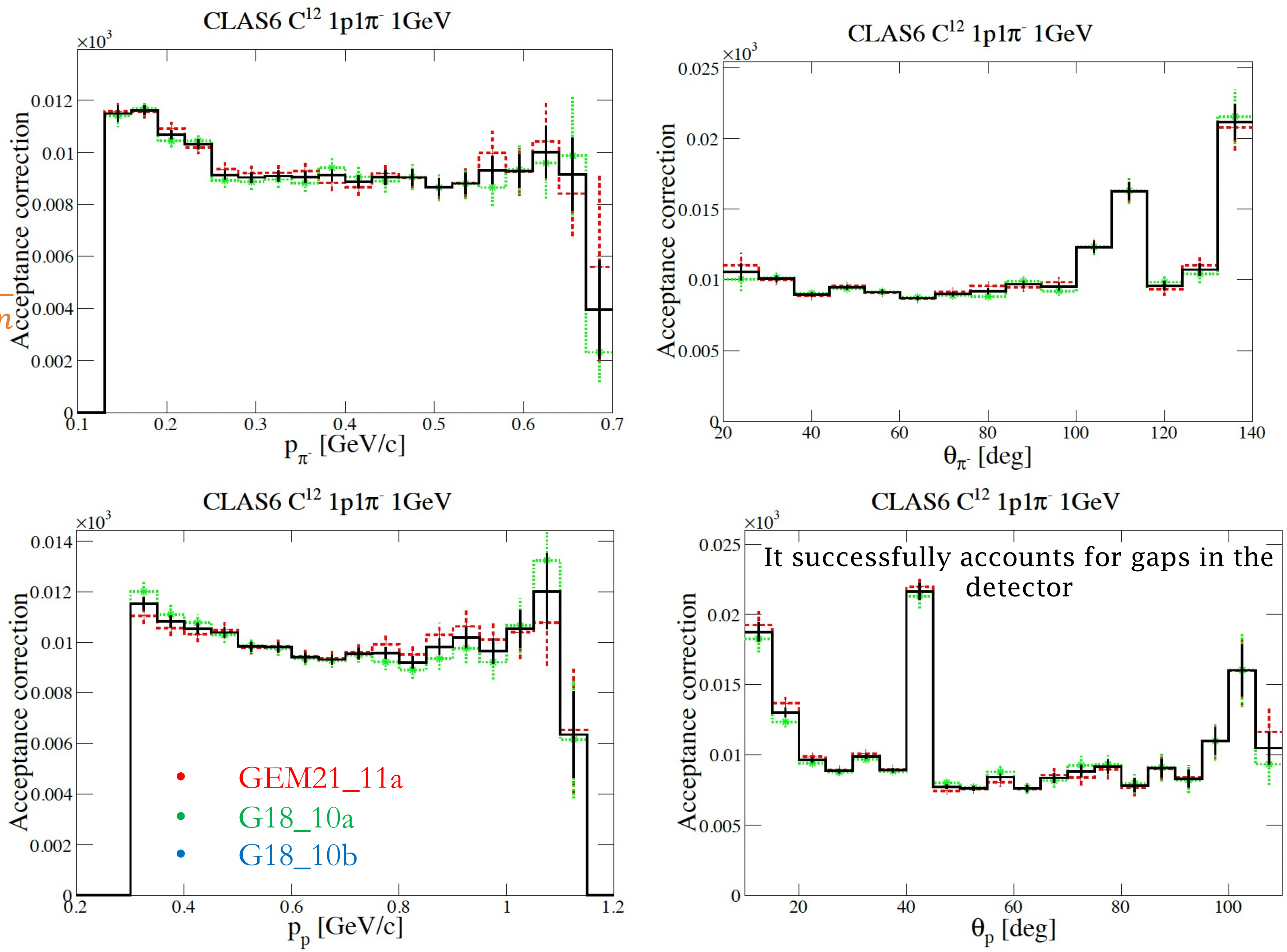
Acceptance correction

We **average** the acceptance for different models to avoid model dependencies

$$\alpha_{acc} = \frac{True\ MC\ events\ ith{-}bin}{True\ Reconstructed\ MC\ events\ ith{-}bin}$$

Detector effect	True MC	True Rec.
Thresholds	✓	✓
Scaled by Q^4	✓	✓
Smearing (*)	✗	✓
Fiducial	✗	✓
Efficiency maps	✗	✓

(*) Previous approach



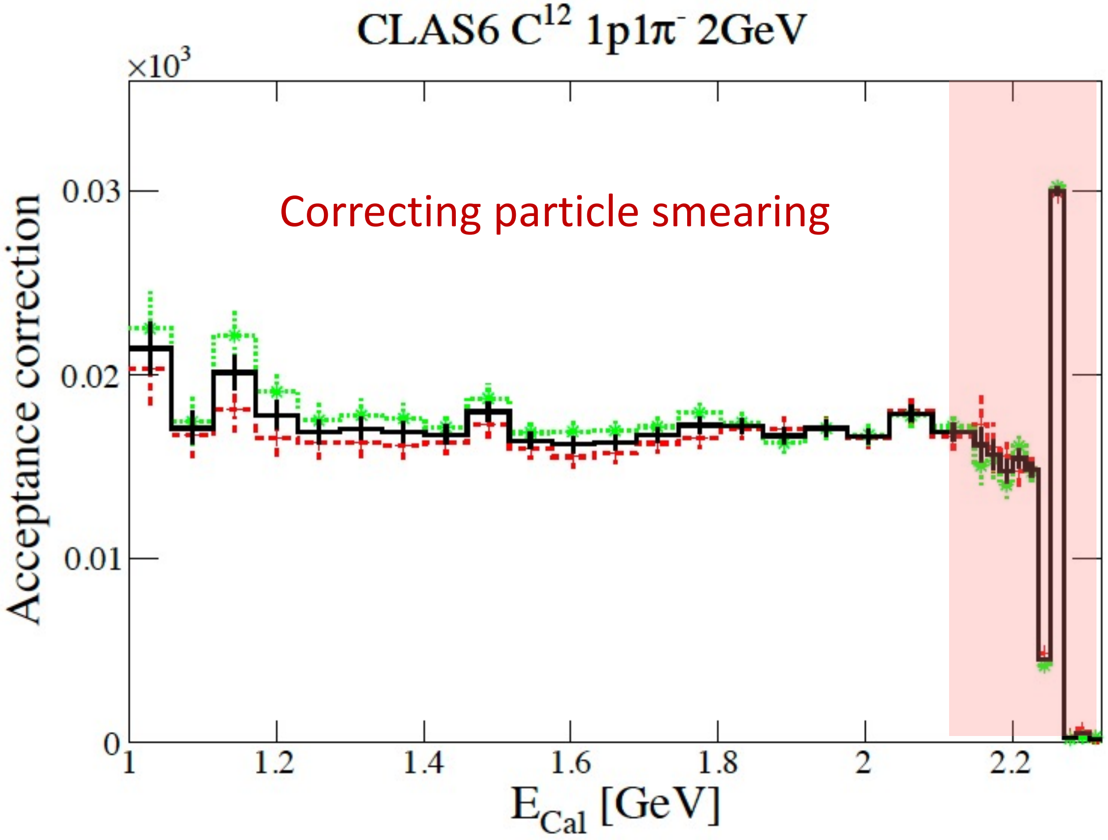
It successfully accounts for gaps in the detector

Acceptance correction

(*) Correcting for smearing biases the beam energy reconstruction

$$\alpha_{acc} = \frac{True\ MC\ events\ ith{-}bin}{True\ Reconstructed\ MC\ events\ ith{-}bin}$$

Detector effect	True MC	True Rec.
Thresholds	✓	✓
Scaled by Q^4	✓	✓
Smearing (*)	✗	✓
Fiducial	✗	✓
Efficiency maps	✗	✓



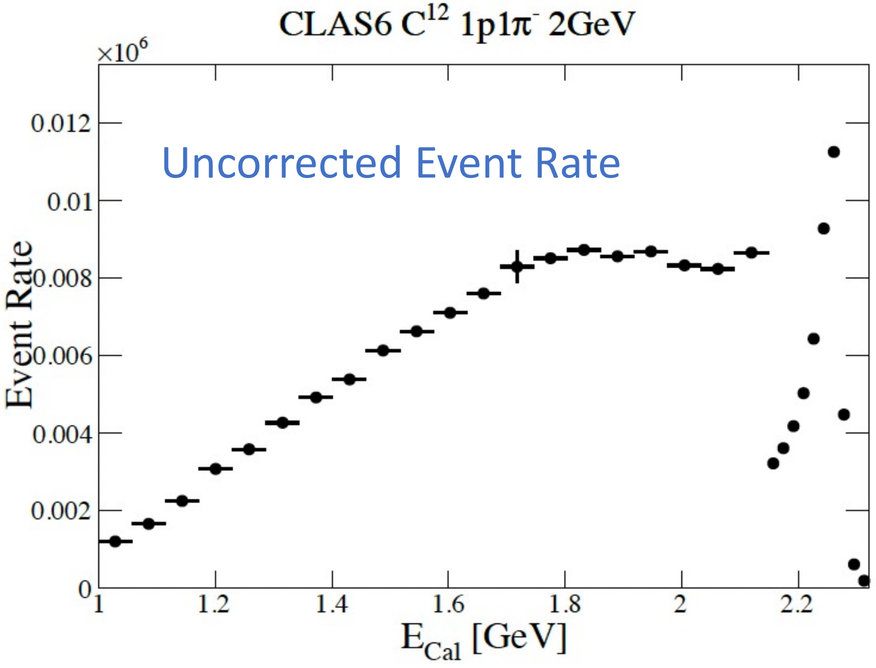
Correcting particle smearing

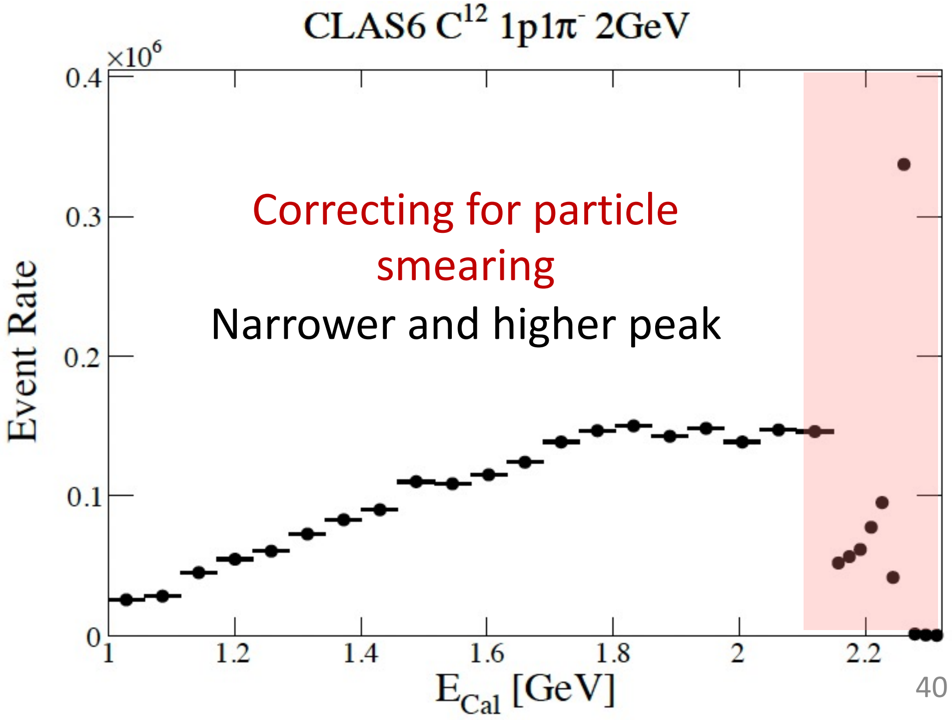
Acceptance correction

(*) Correcting for smearing biases the beam energy reconstruction

$$\alpha_{acc} = \frac{True\ MC\ events\ ith{-}bin}{True\ Reconstructed\ \ MC\ events\ ith{-}bin}$$

Detector effect	True MC	True Rec.
Thresholds	✓	✓
Scaled by Q^4	✓	✓
Smearing (*)	✗	✓
Fiducial	✗	✓
Efficiency maps	✗	✓



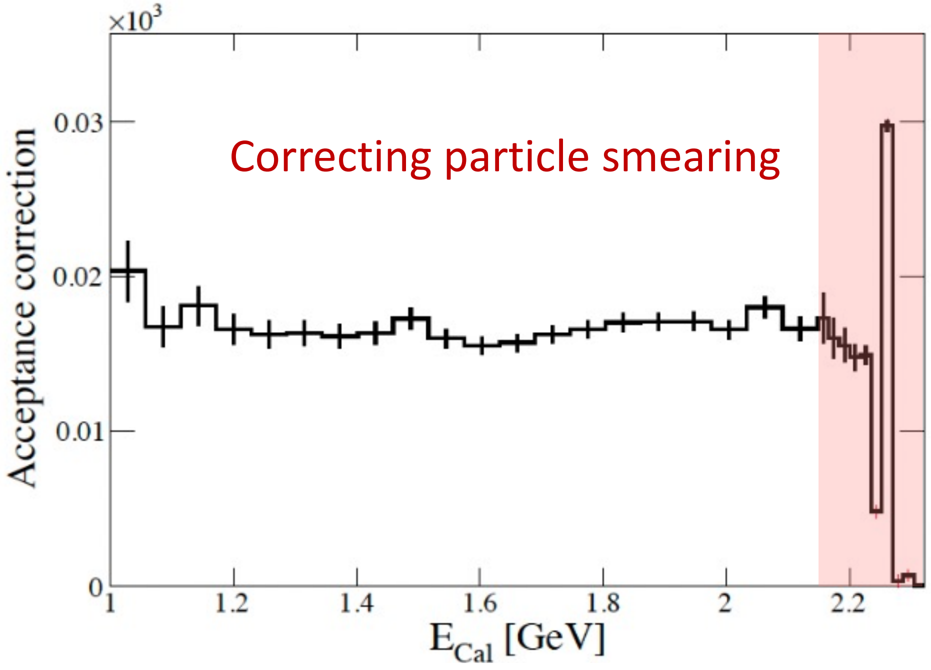


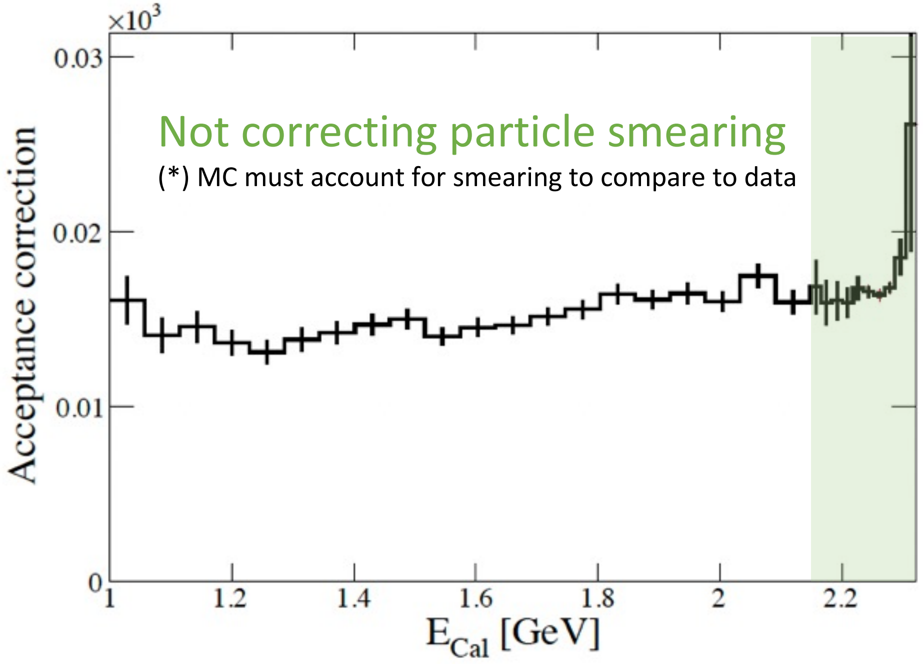
Acceptance correction

(*) Correcting for smearing biases the beam energy reconstruction

$$\alpha_{acc} = \frac{True\ MC\ events\ ith\text{-}bin}{True\ Reconstructed\ MC\ events\ ith\text{-}bin}$$

Detector effect	True MC	True Rec.
Thresholds	✓	✓
Scaled by Q^4	✓	✓
Smearing (*)	✓	✓
Fiducial	✗	✓
Efficiency maps	✗	✓


Correcting particle smearing


Not correcting particle smearing

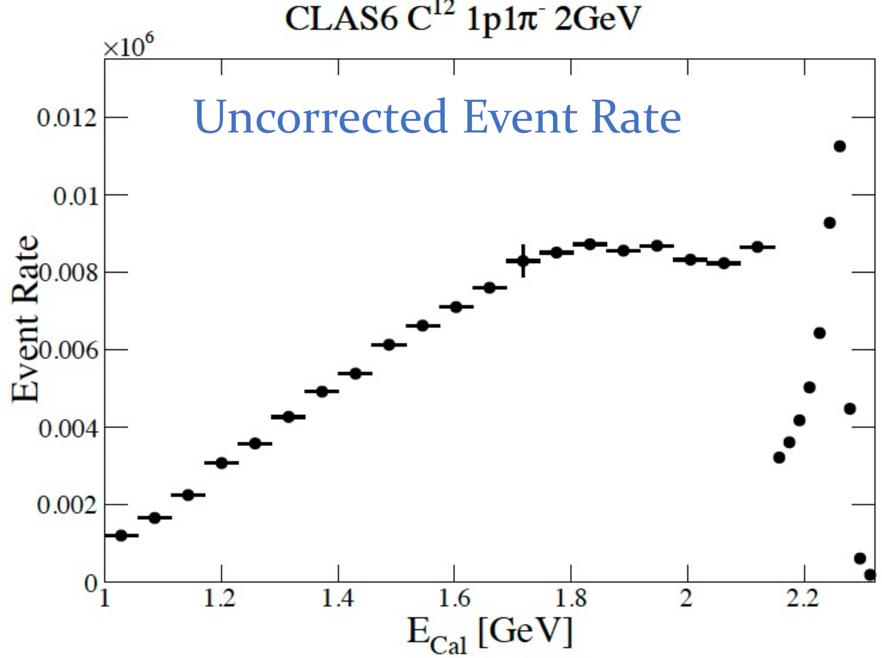
(*) MC must account for smearing to compare to data

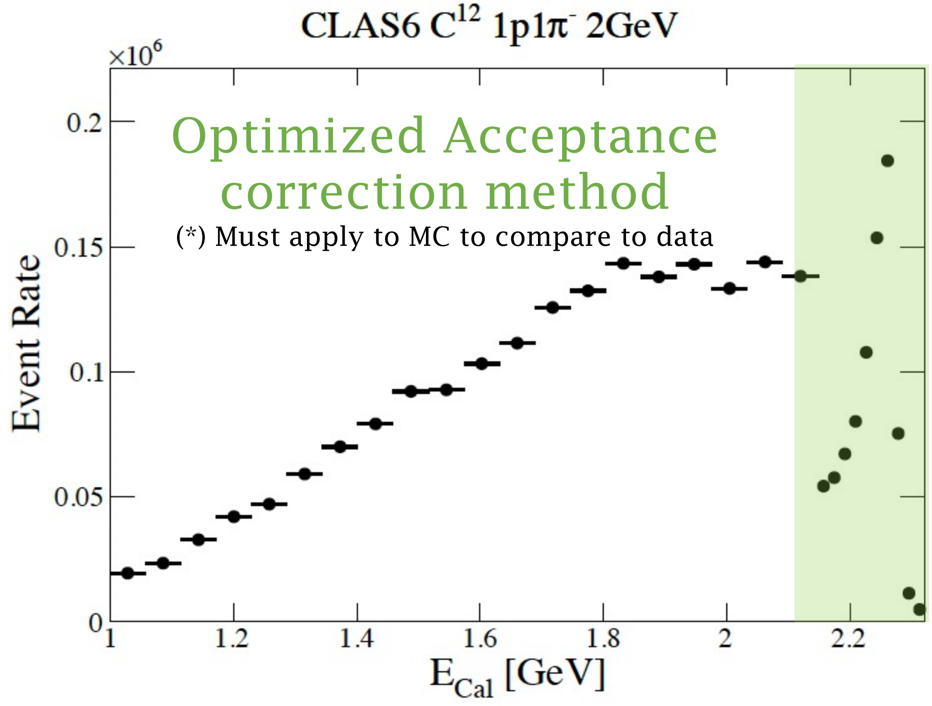
Acceptance correction

(*) Correcting for smearing biases the beam energy reconstruction

$$\alpha_{acc} = \frac{\text{True MC events ith−bin}}{\text{True Reconstructed MCevents ith−bin}}$$

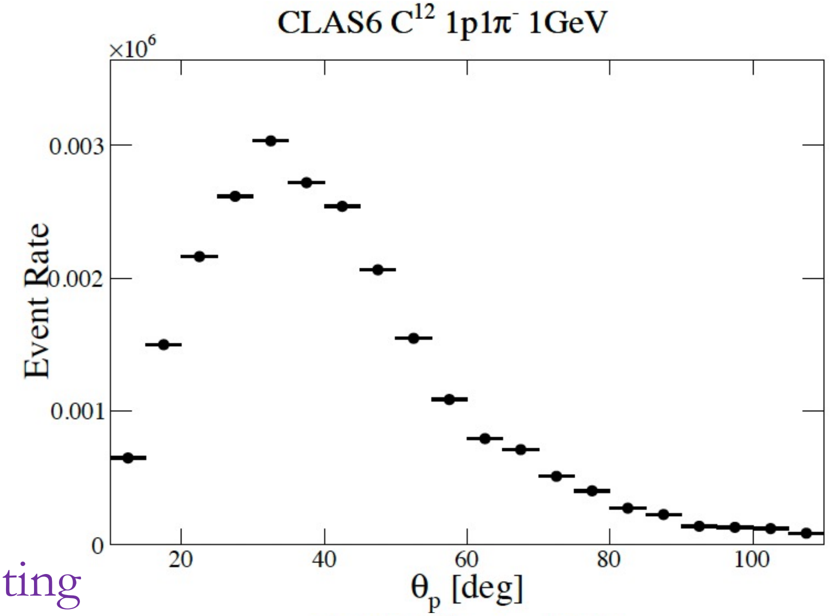
Detector effect	True MC	True Rec.
Thresholds	✓	✓
Scaled by Q^4	✓	✓
Smearing (*)	✓	✓
Fiducial	✗	✓
Efficiency maps	✗	✓

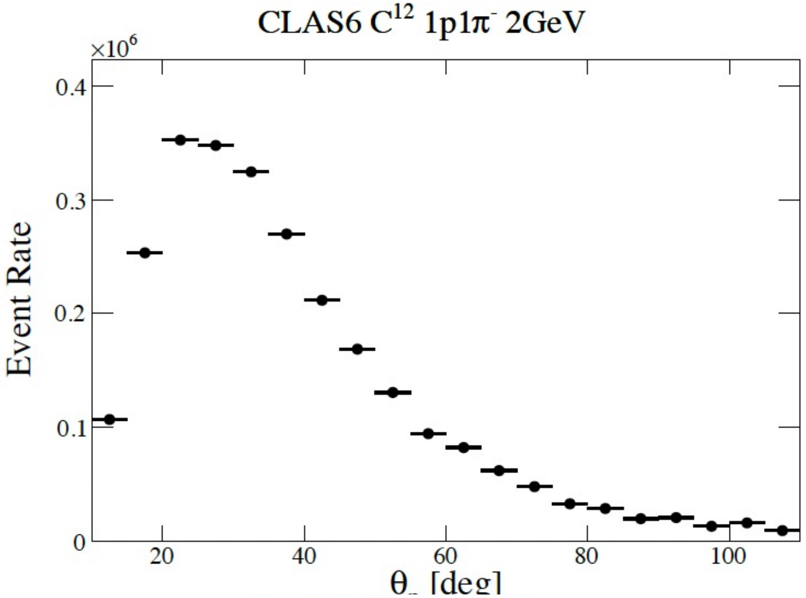

Uncorrected Event Rate


Optimized Acceptance correction method

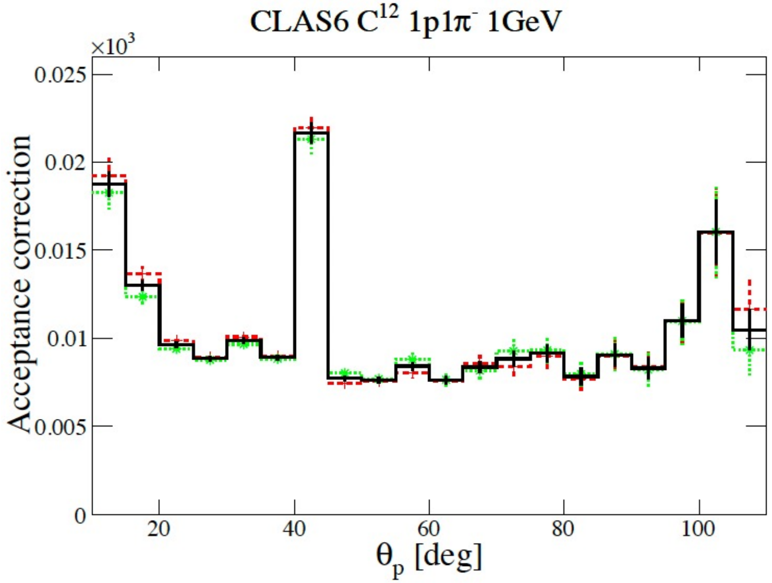
(*) Must apply to MC to compare to data

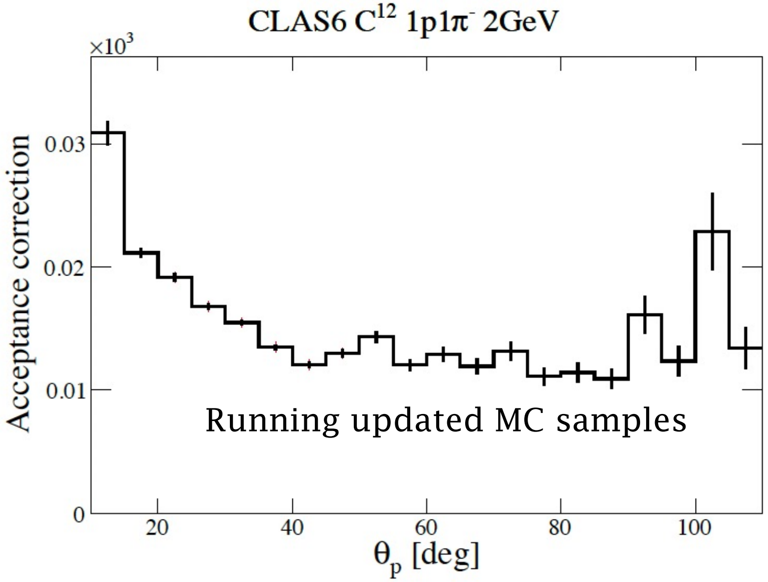
(e,e’1p1π^-) **acceptance corrected** event rate Proton momentum


CLAS6 C^{12} 1p1π^- 1GeV


CLAS6 C^{12} 1p1π^- 2GeV

Successfully correcting for detector gaps


CLAS6 C^{12} 1p1π^- 1GeV


CLAS6 C^{12} 1p1π^- 2GeV

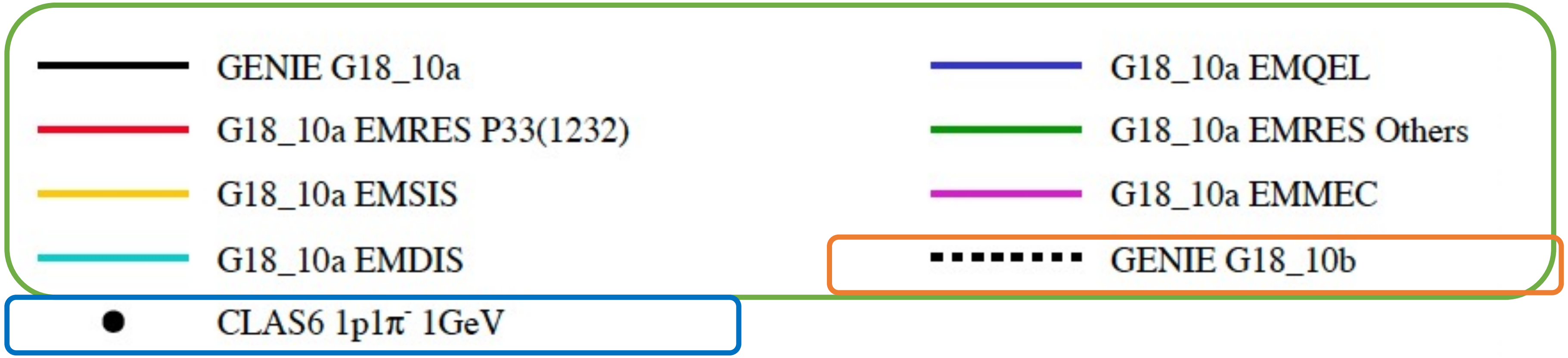
Running updated MC samples

Comparison against MC

- **Convert to cross-section**
  - Normalization factor computed within analysis code and stored in root file
  - Code already available for conversion
  - Validated against previous (e,e'1p) work
- **Correct for radiative corrections**
  - MC does not account for radiative effects
  - **Work in progress**

Overview of plotting format

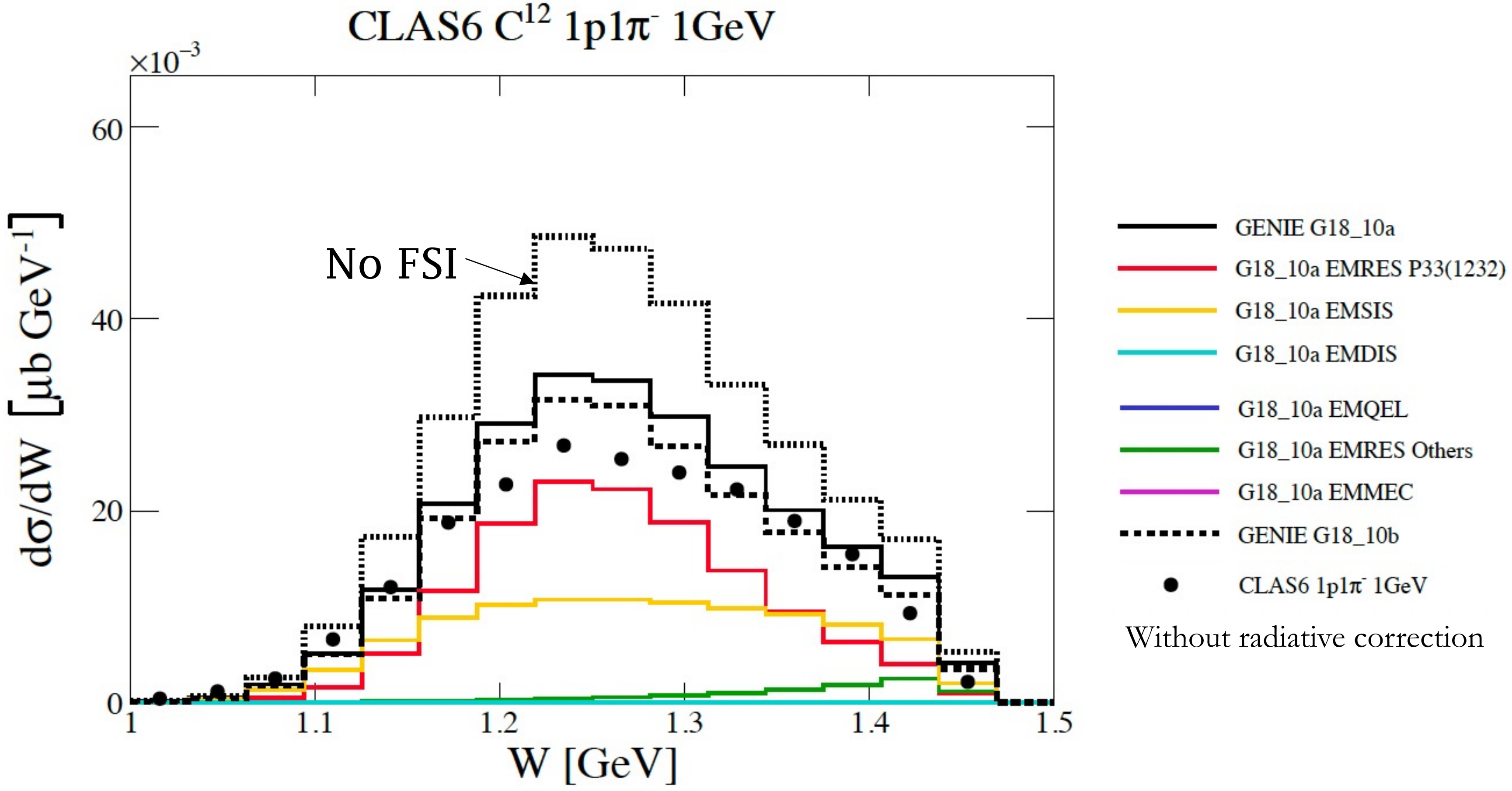
Only one model is used to compute the breakdown:



Additional models are also displayed, but the contribution to each mode is not shown

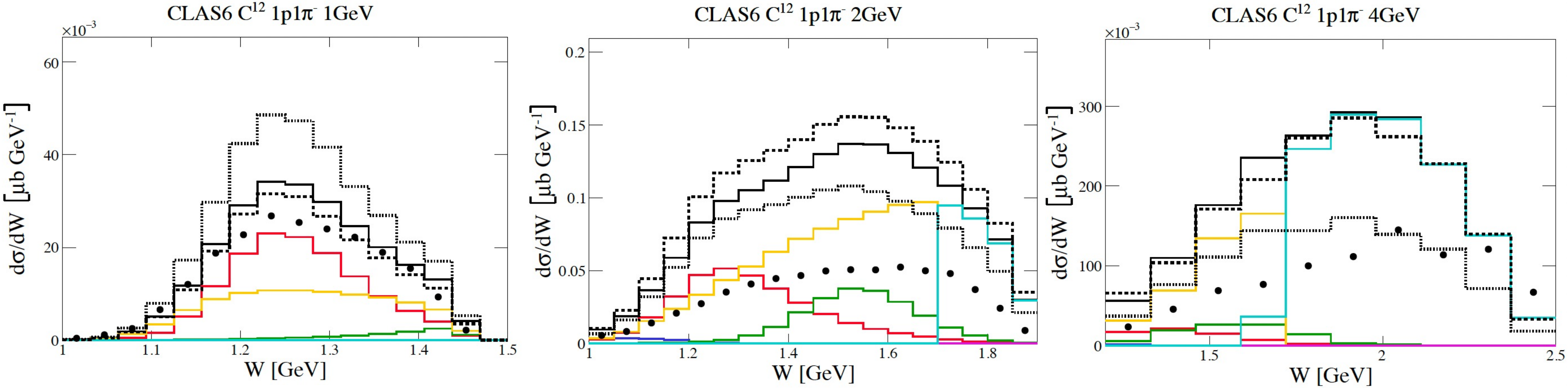
Data is always shown as black circles

C(e,e'1pπ^-) cross-section measurement



Without radiative correction

C(e,e’1pπ^-) cross-section measurement



Contribution from higher W resonances increases with beam energy

- Initial comparison confirms the expected physics
- Normalization off due to double-counting in event generator

Conclusions and next steps

- **CLAS6 data is crucial for the neutrino community**
  - Same nuclear effects, vector part of the interaction
  - Relevant energies and targets for neutrino experiments
- **New CLAS6(e,e’1p1π) analysis ongoing**
  - Required improved background subtraction method
  - Proves large bias in energy reconstruction methods
  - Extracting single-differential cross-section
- **Analysis code and methodology well established**
  - Can reproduce CLAS6(e,e’1p0π) analysis
  - Started writing up the analysis note
- **Working on systematic uncertainties and radiative corrections**

Backup slides

e4nuanalysiscode Public

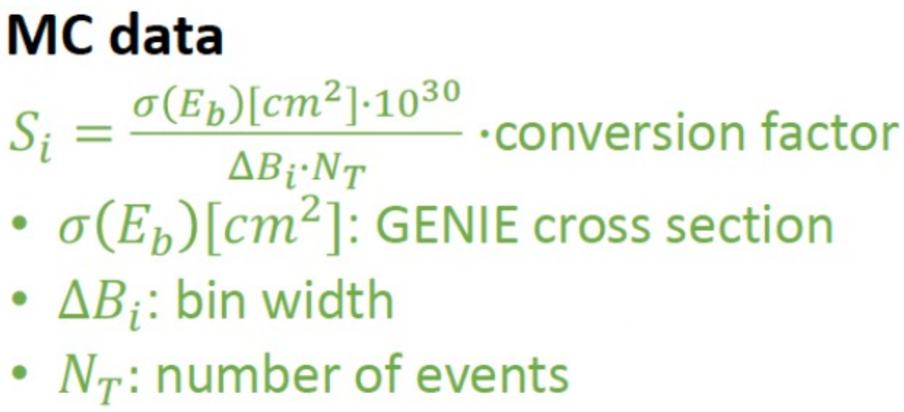
- The previous code was specific to the (e,e’1p0π) topology
  - It could not be used for new analyses
- **New code is highly configurable and topology independent**
  - It can be used to extract CLAS6 cross-sections for all topologies of interest
  - New background subtraction method
  - Outputs a single ROOT file which contains all event information for plotting
  - Plotting and validation scripts
  - Successfully reproduced previous e4nu (e,e’1p0π) results
- Can easily be used for CLAS12 analyses
- Deals with CLAS6 data and MC data simultaneously
- Available for public use in [github]()
  - Cannot be used without access to CLAS6 data files

Pion production analysis cuts

- Momentum cuts
  - $p_e > \begin{cases} 0.4\ GeV/c\ at\ 1.161 GeV \\ 0.55\ GeV/c\ at\ 2.261 GeV \\ 1.1\ GeV/c\ at\ 4.461 GeV \end{cases}$
  - $p_p > 0.3\ {}^{GeV}/_{c}$
  - $p_\gamma > 0.3\ {}^{GeV}/_{c}$
  - $p_{\pi^\pm} > 0.15\ {}^{GeV}/_{c}$
- Angle cuts:
  - $15\ deg < \theta\ _e < 45\ deg$
  - $\theta\ _p > 12\ deg$
  - $\theta\ _\gamma > 8\ deg$
  - $\theta\ _{\pi^\pm} > 12\ deg$

- Minimum Q^2:
  - $Q^2 > \begin{cases} 0.1\ {}^{GeV}/_{c}\ at\ 1.161 GeV \\ 0.4\ {}^{GeV}/_{c}\ at\ 2.261 GeV \\ 0.8\ {}^{GeV}/_{c}\ at\ 4.461 GeV \end{cases}$
  - Applied to both data and MC
  - MC produced with same Q^2 min

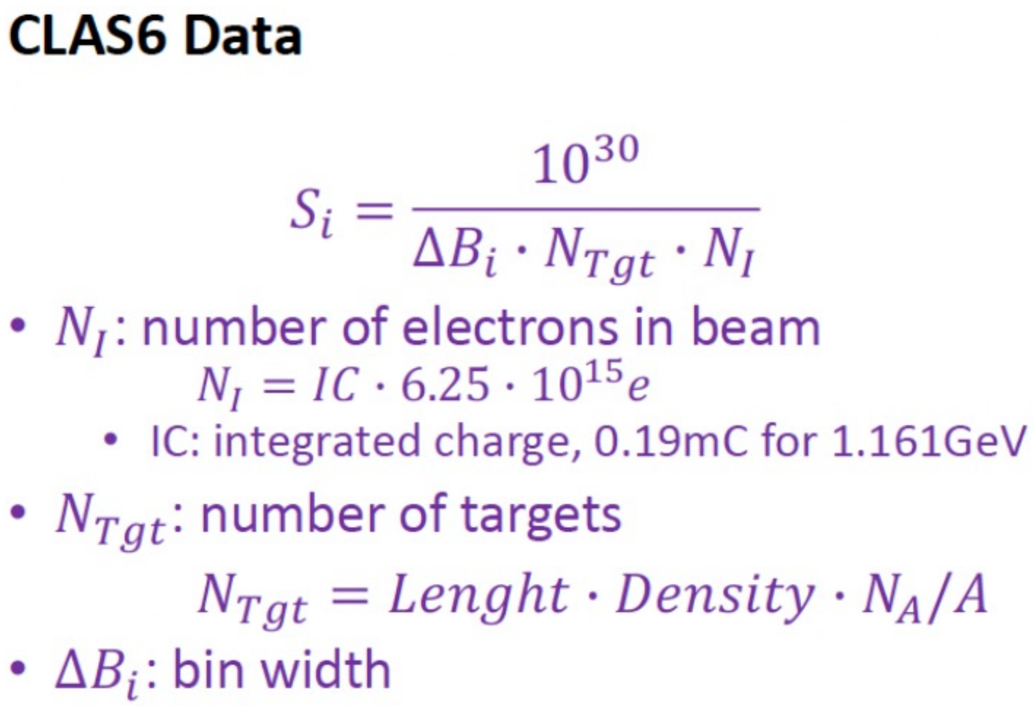
Conversion to cross-section



MC data

$S_i = \frac{\sigma(E_b)[cm^2]\cdot 10^{30}}{\Delta B_i \cdot N_T}$ ·conversion factor

- $\sigma(E_b)[cm^2]$: GENIE cross section
- ΔB_i: bin width
- N_T: number of events

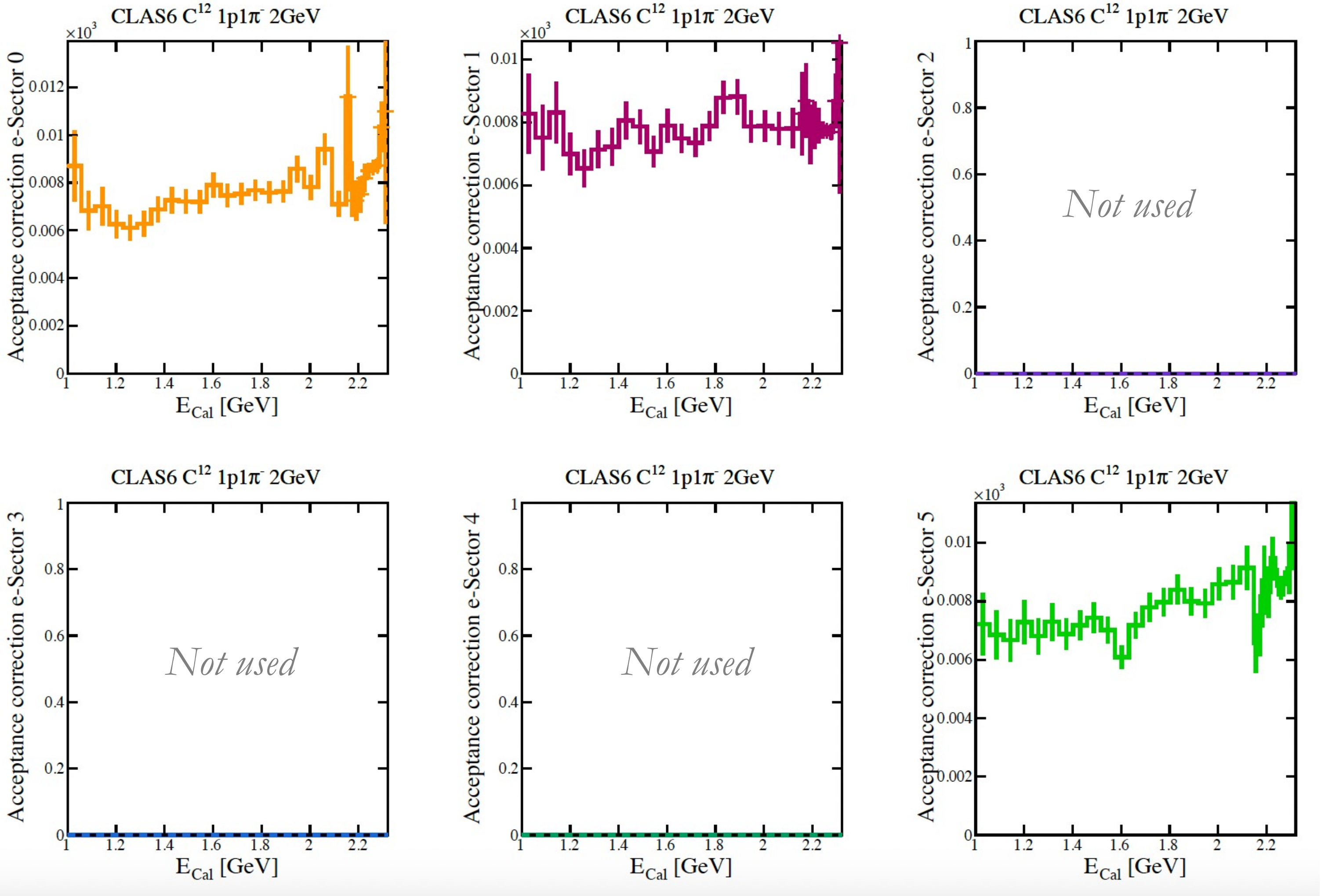


CLAS6 Data

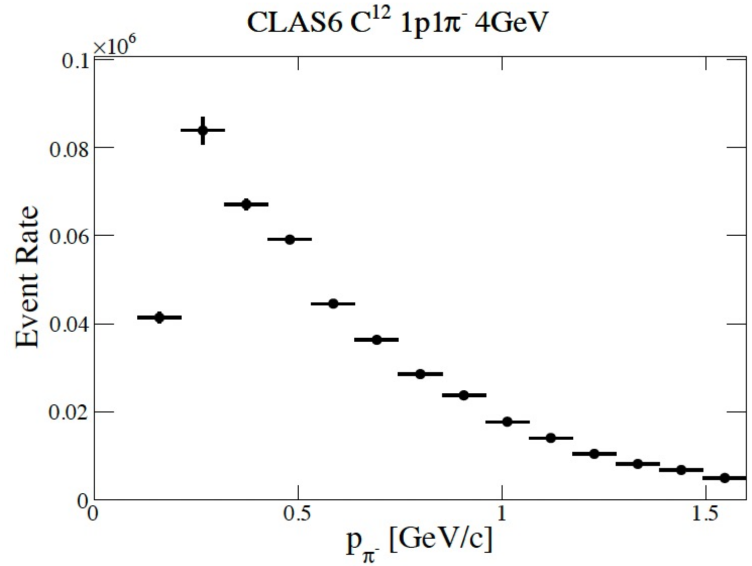
$$S_i = \frac{10^{30}}{\Delta B_i \cdot N_{Tgt} \cdot N_I}$$

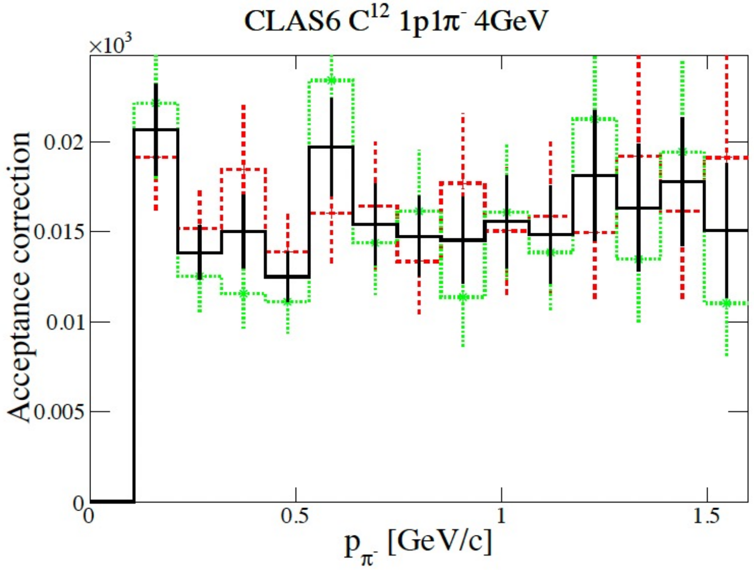
- N_I: number of electrons in beam
  $N_I = IC \cdot 6.25 \cdot 10^{15} e$
  - IC: integrated charge, 0.19mC for 1.161GeV
- N_{Tgt}: number of targets
  $N_{Tgt} = Lenght \cdot Density \cdot N_A / A$
- ΔB_i: bin width

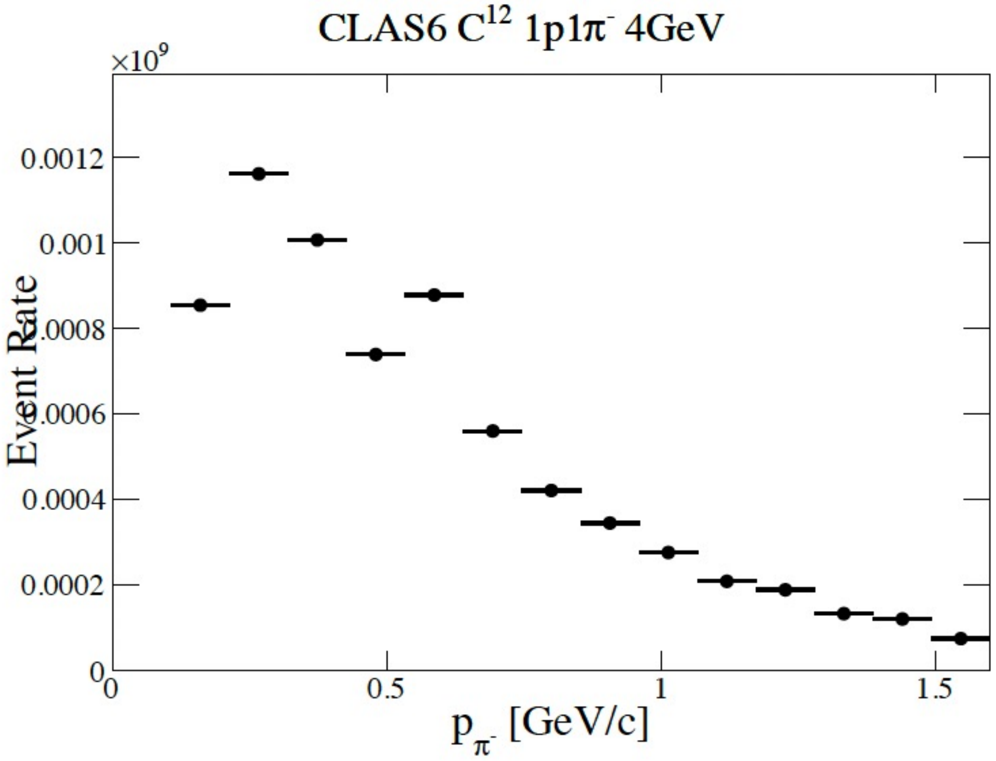
Acceptance correction per sector



(e,e’1p1π^-) event rate
True W

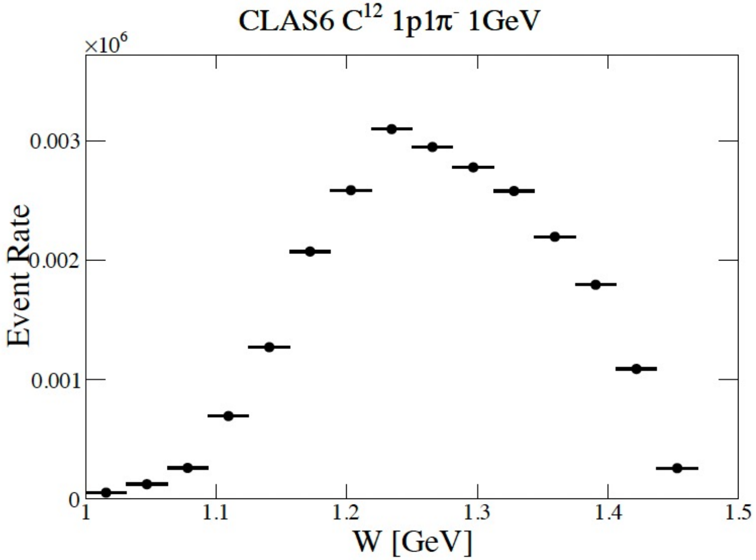


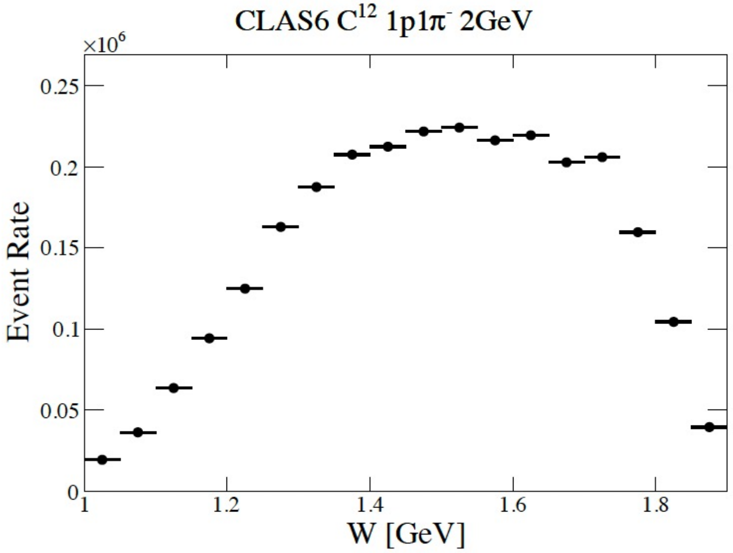


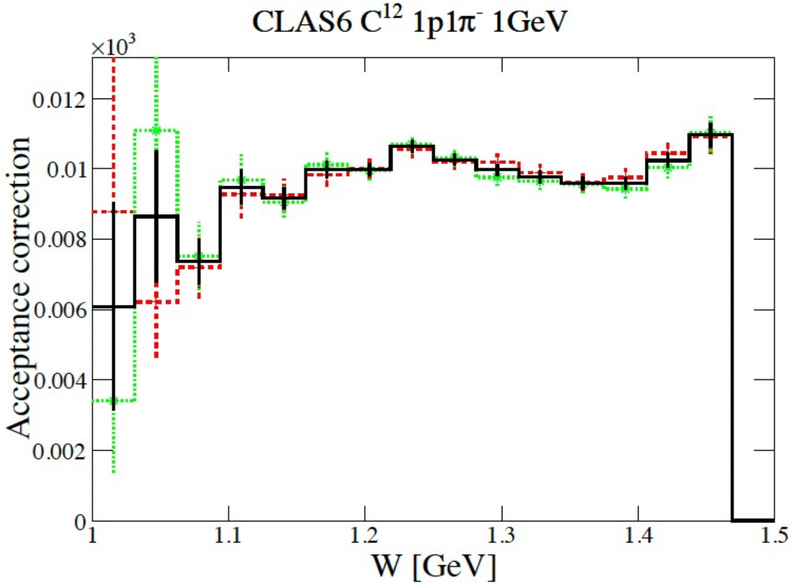


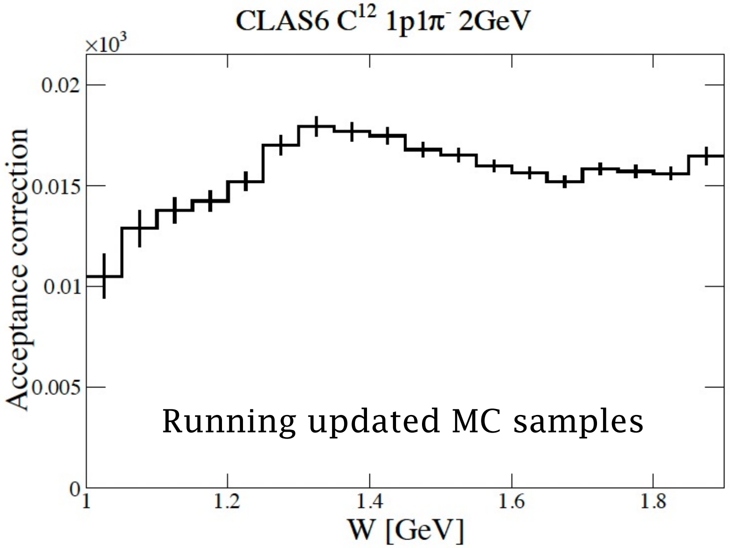
Low statistics in MC
Re-running updated samples

(e,e'1p1π^-) **acceptance corrected** event rate
True W


CLAS6 C^{12} 1p1π^- 1GeV

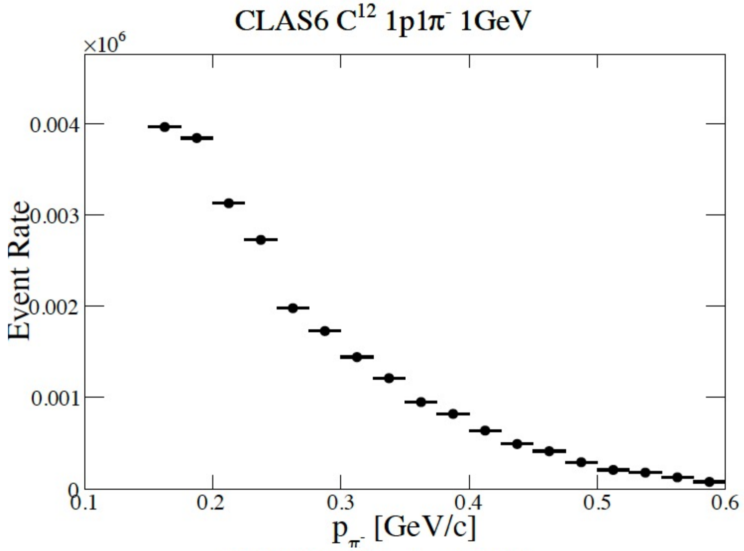

CLAS6 C^{12} 1p1π^- 2GeV

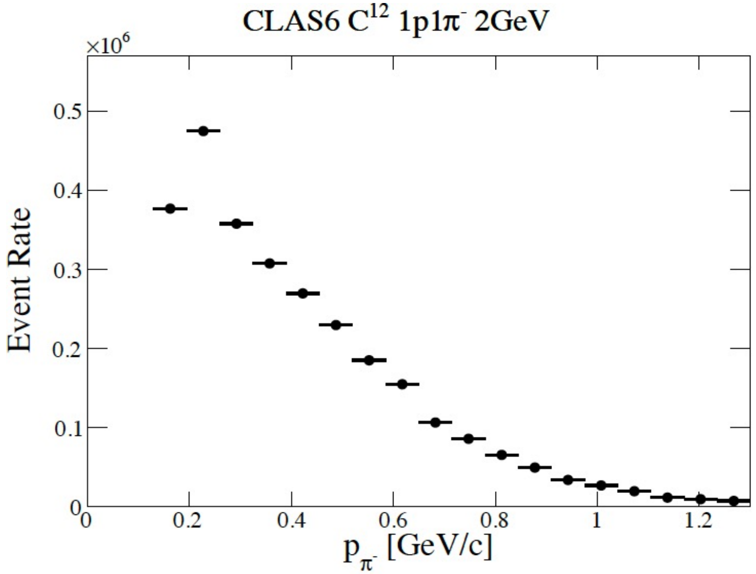

CLAS6 C^{12} 1p1π^- 1GeV

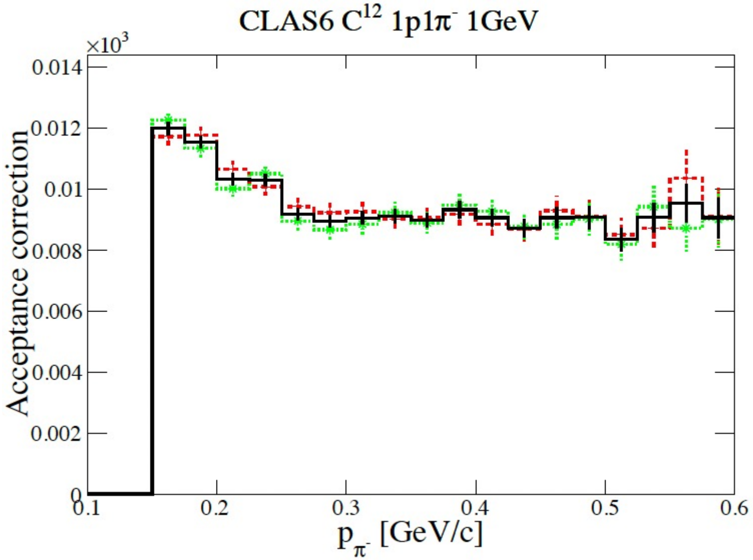

CLAS6 C^{12} 1p1π^- 2GeV

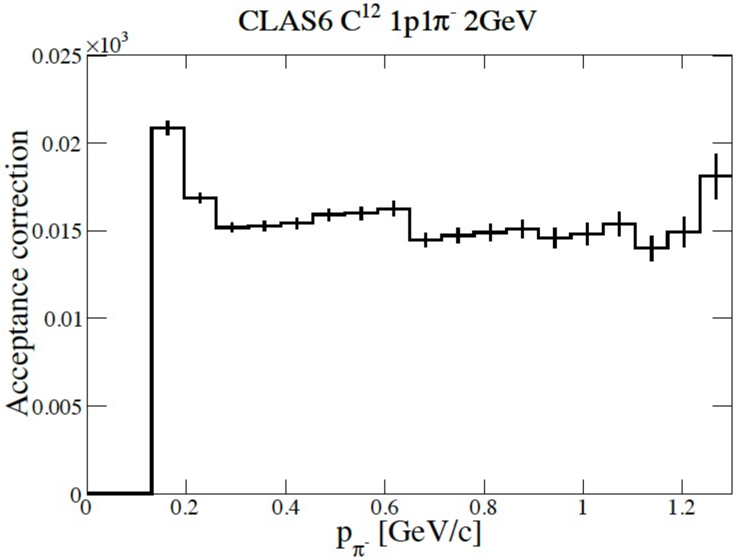
Running updated MC samples

$(e,e'1p1\pi^-)$ **acceptance corrected** event rate Pion momentum

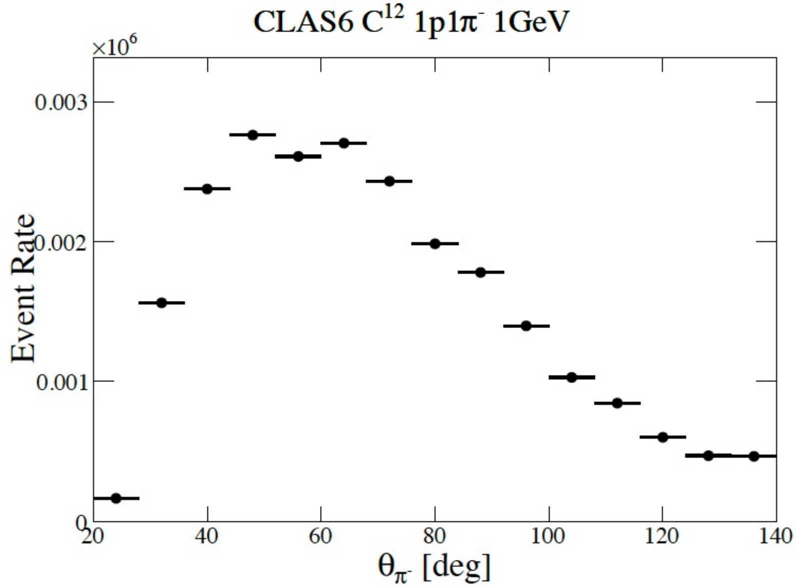


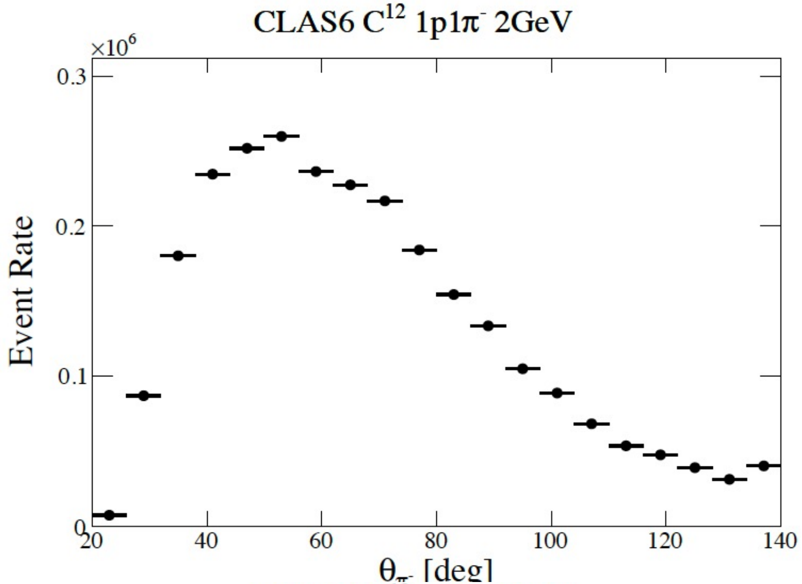


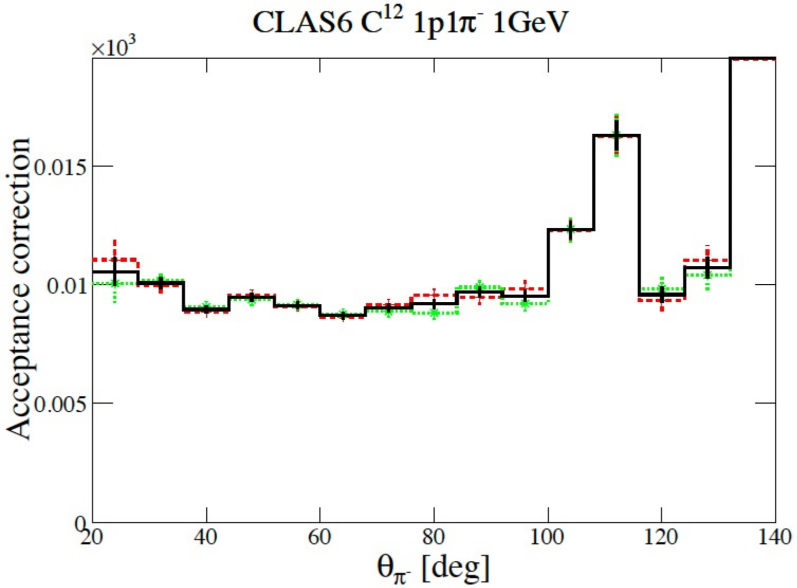


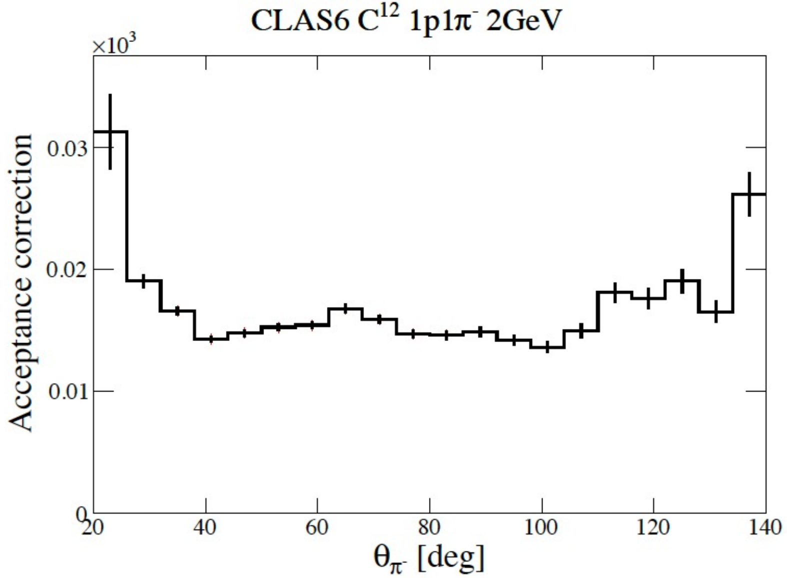


(e,e'1p1π^-) **acceptance corrected** event rate
Pion angle

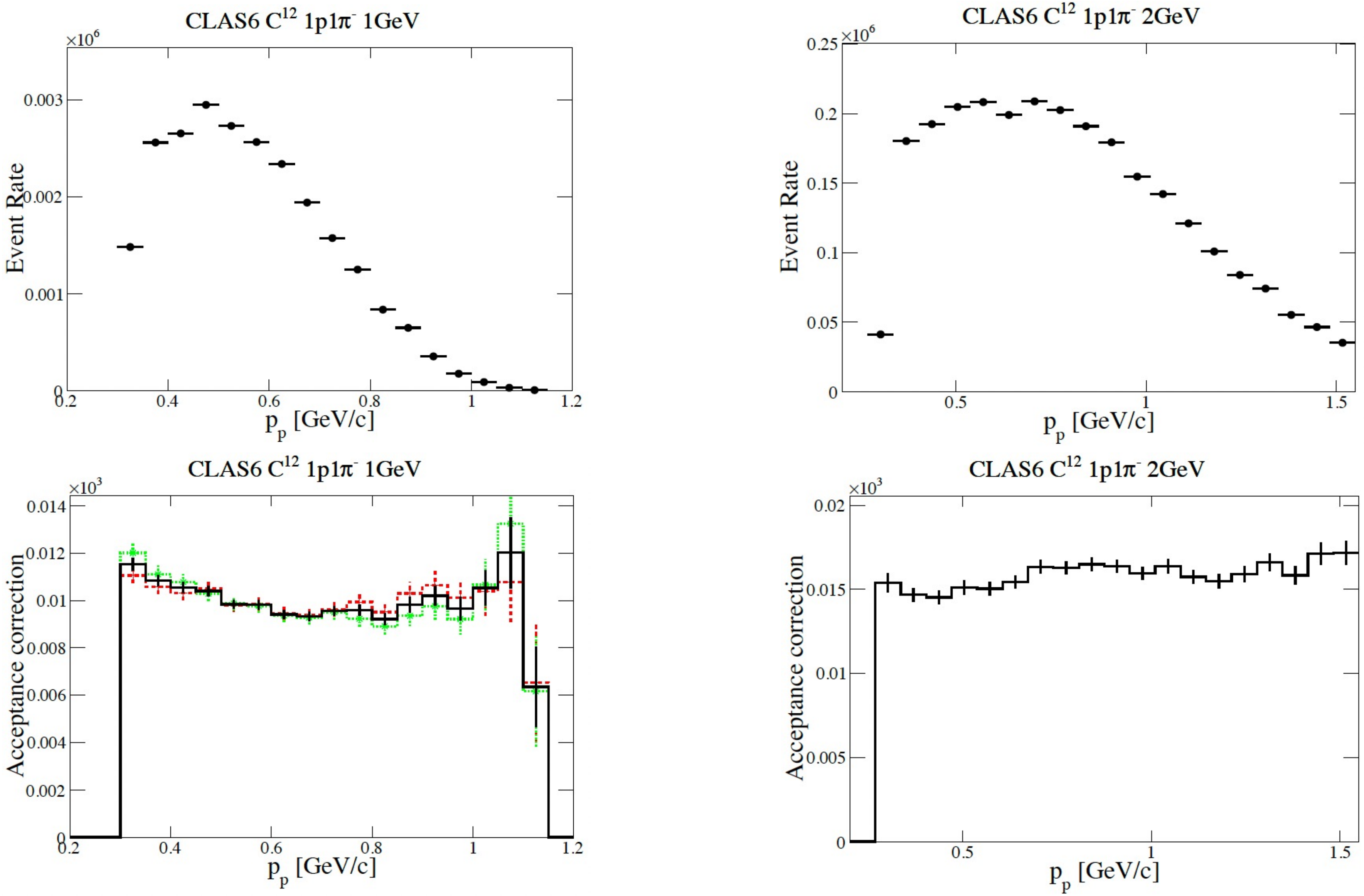

CLAS6 C^{12} 1p1π^- 1GeV


CLAS6 C^{12} 1p1π^- 2GeV

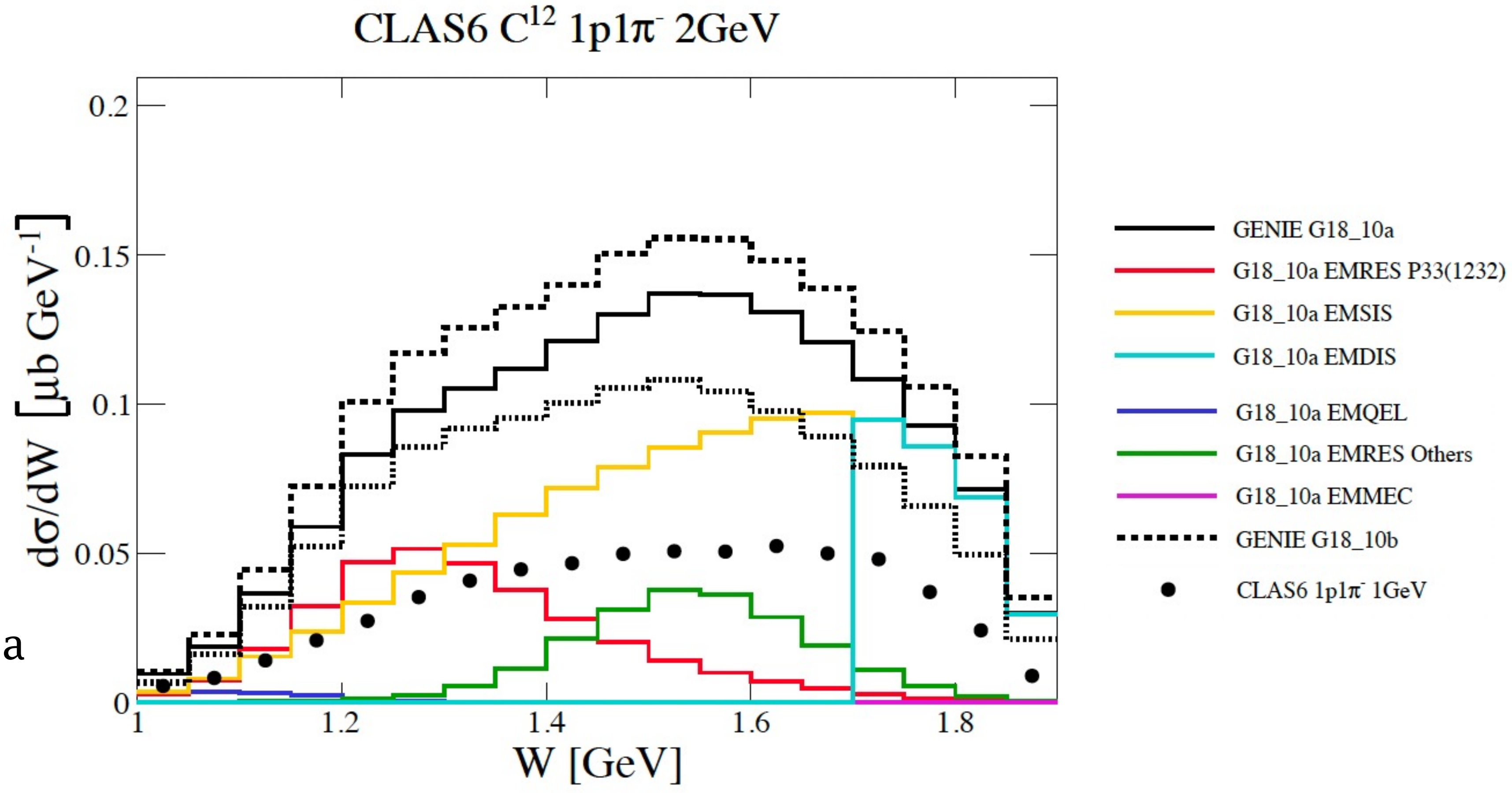

CLAS6 C^{12} 1p1π^- 1GeV


CLAS6 C^{12} 1p1π^- 2GeV

(e,e’1p1π^-) **acceptance corrected** event rate Proton momentum

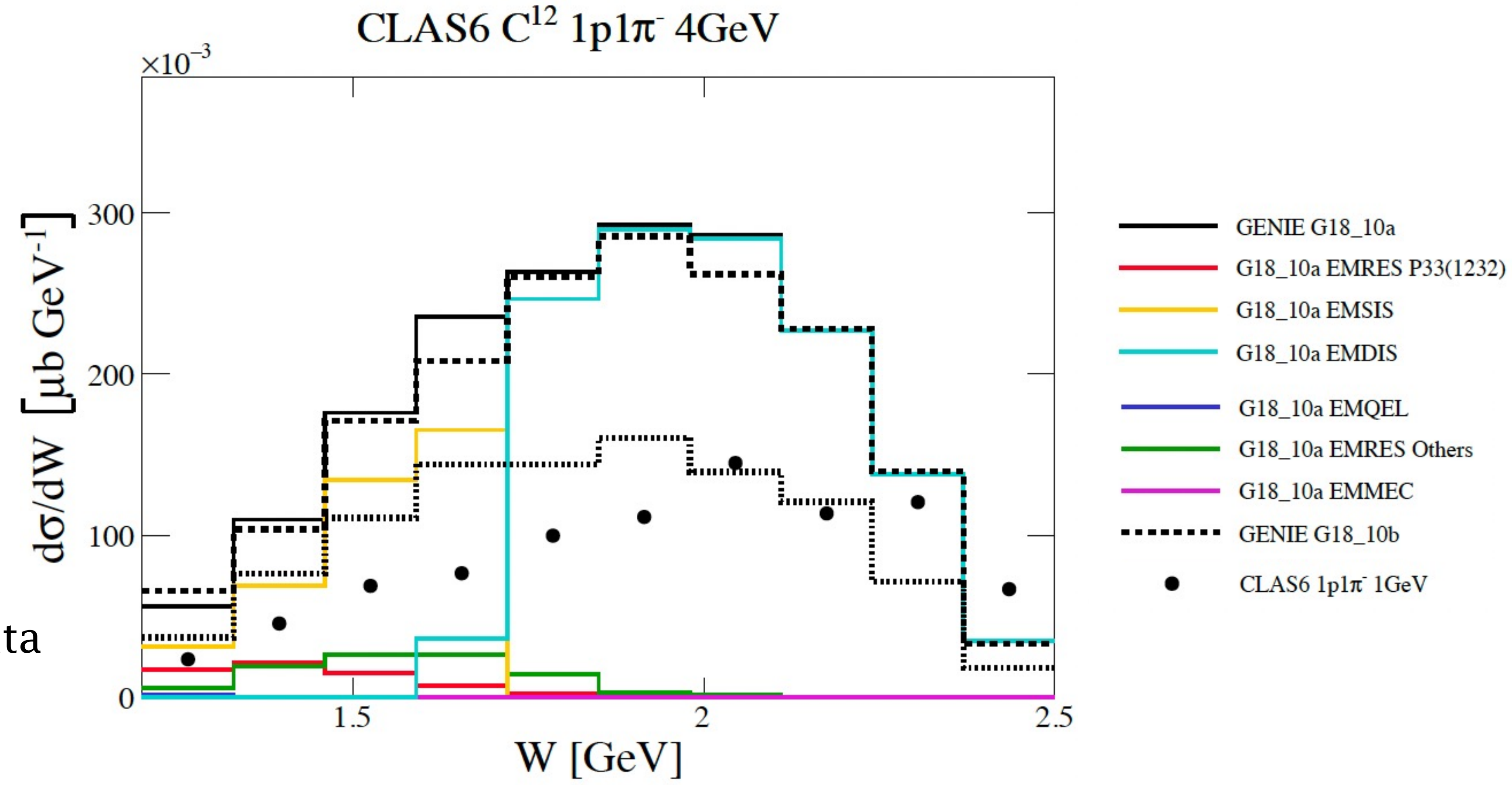


C(e,e’1pπ^-) cross-section measurement



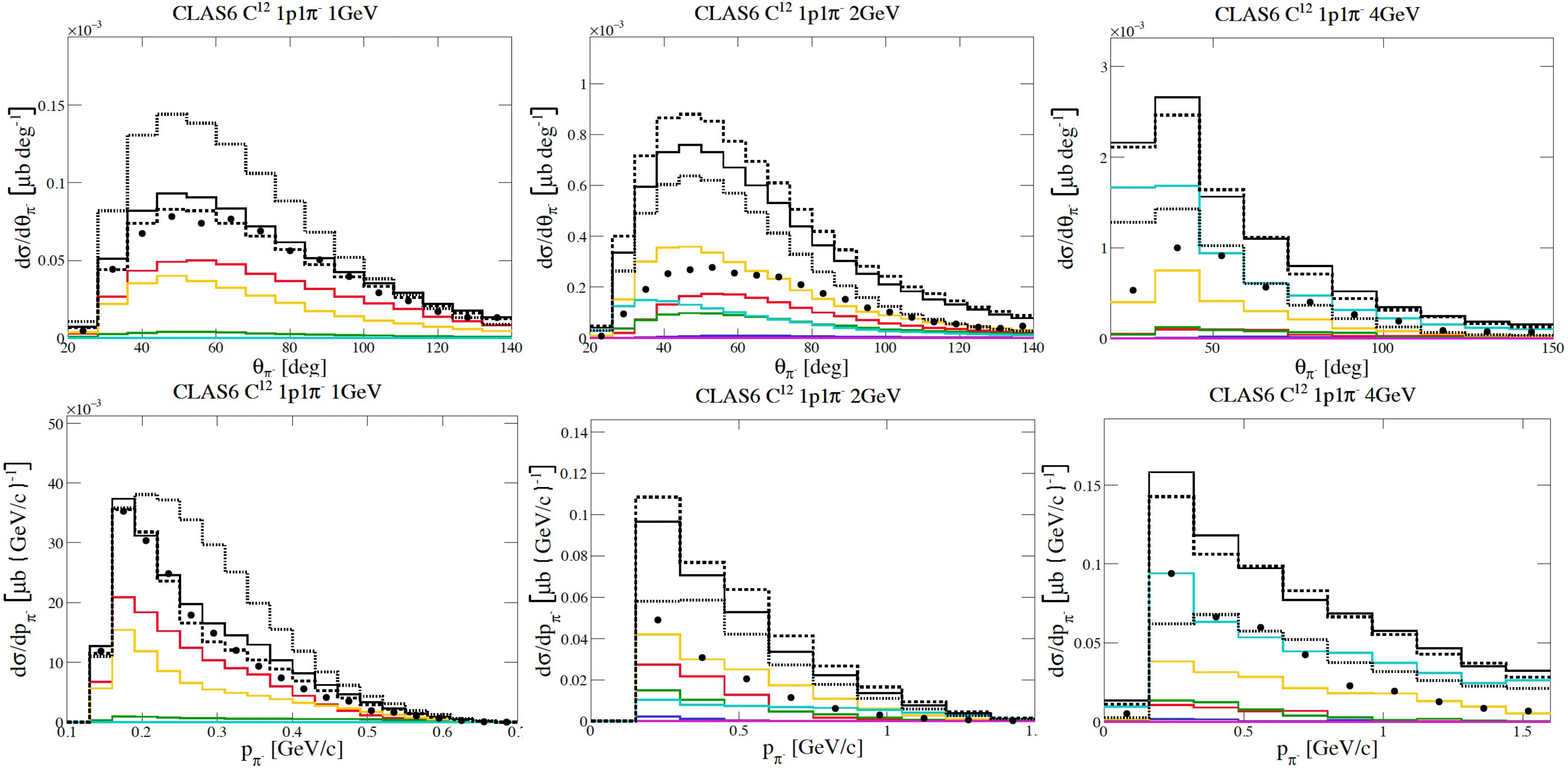
MC over-predicts data

C(e,e’1pπ^-) cross-section measurement



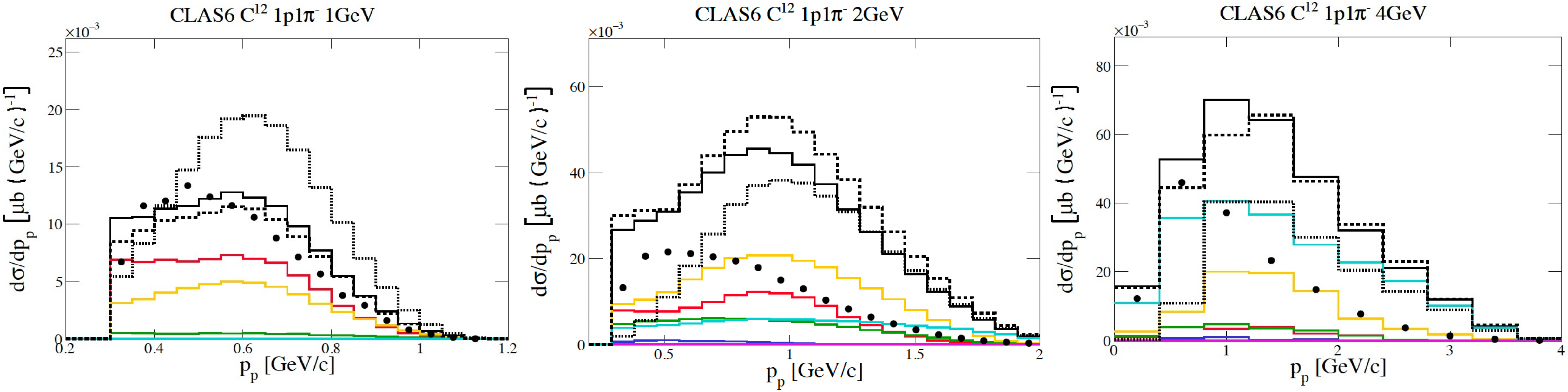
MC over-predicts data

Good description of pion kinematics distribution shape



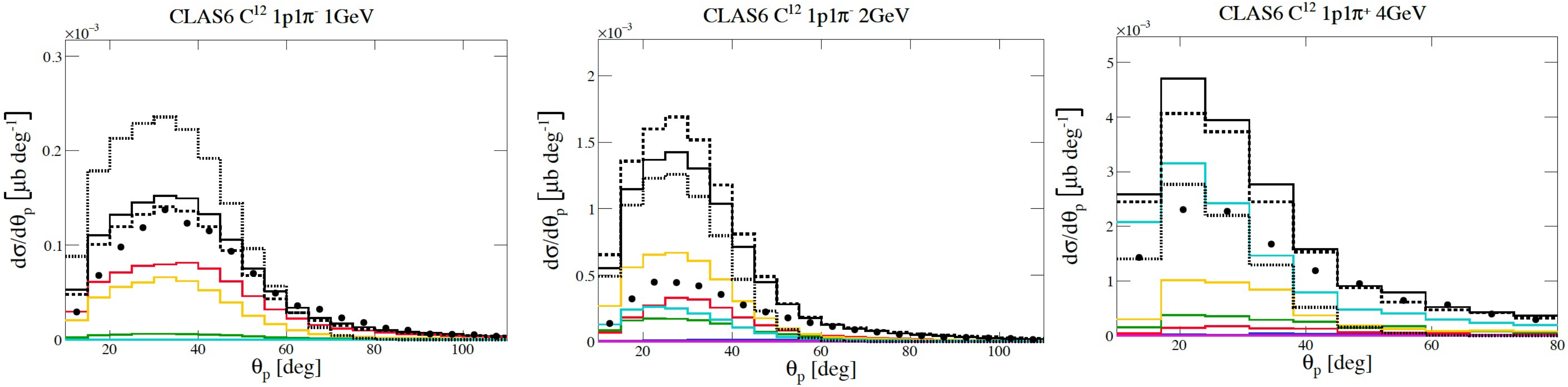
MC with FSI describes shape of the data distribution

C(e,e'1pπ^-) cross-section measurement



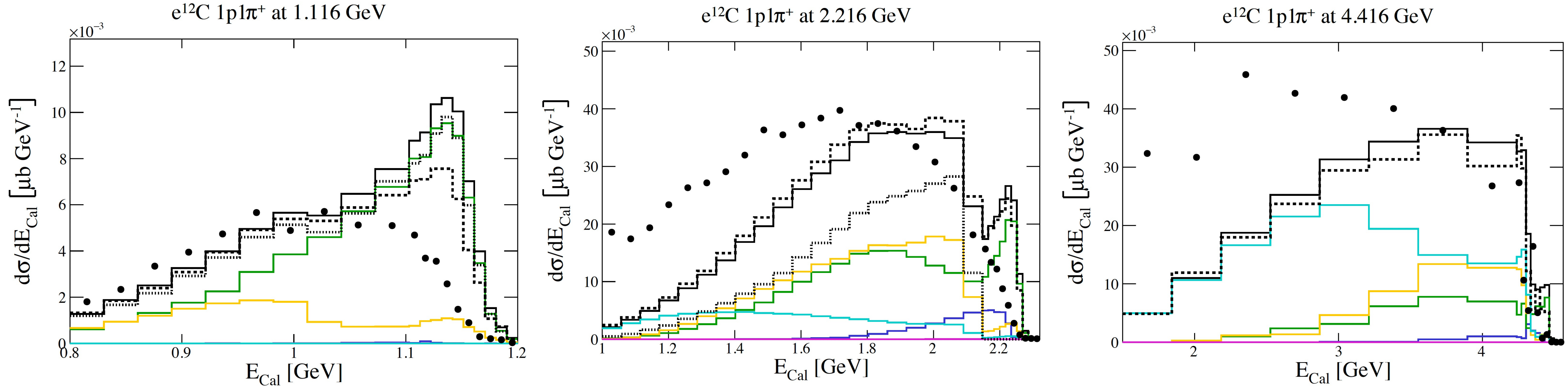
Different shape in pion momentum distribution
Data shifted to lower momentum

C(e,e'1pπ^-) cross-section measurement



Good description of tails, where FSI has a bigger impact

C(e,e'1pπ^+) cross-section measurement



Cannot reconstruct incoming neutrino energy for this topology
Missing energy due to FSI and undetected hadrons