Semi-exclusive pion production measurements with CLAS6 data

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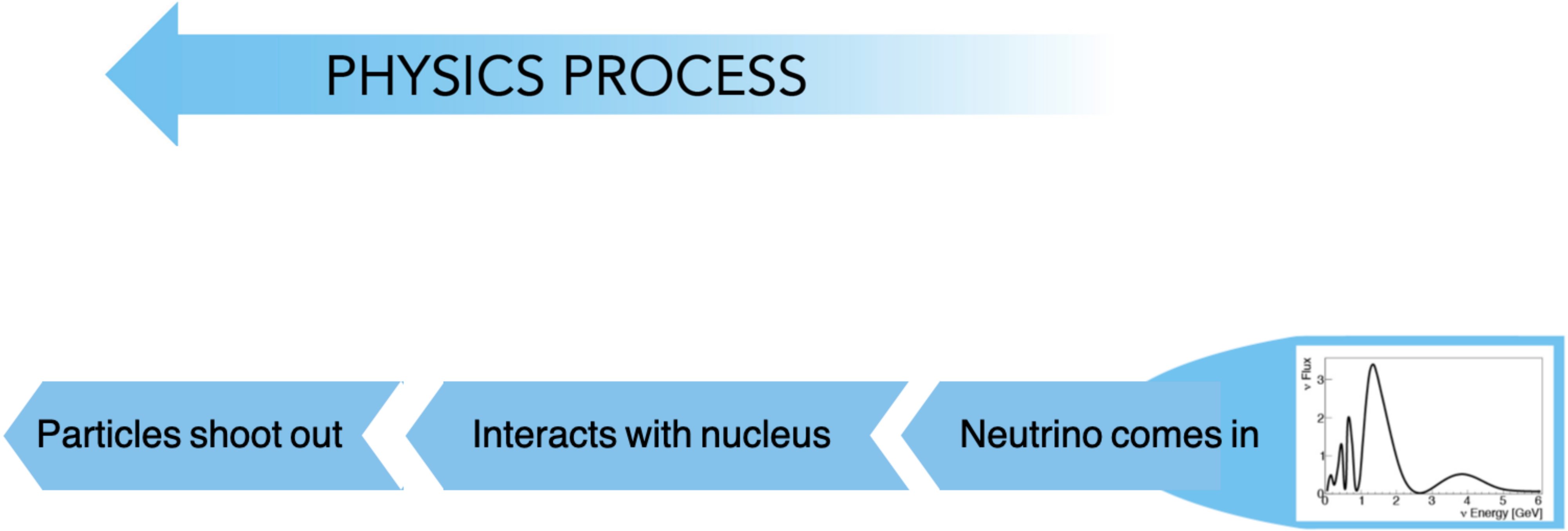
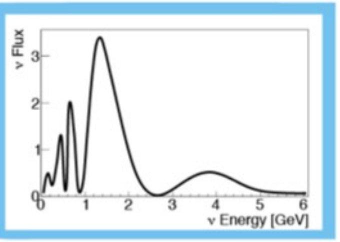
On behalf of the e4nu Collaboration

Introduction to neutrino physics



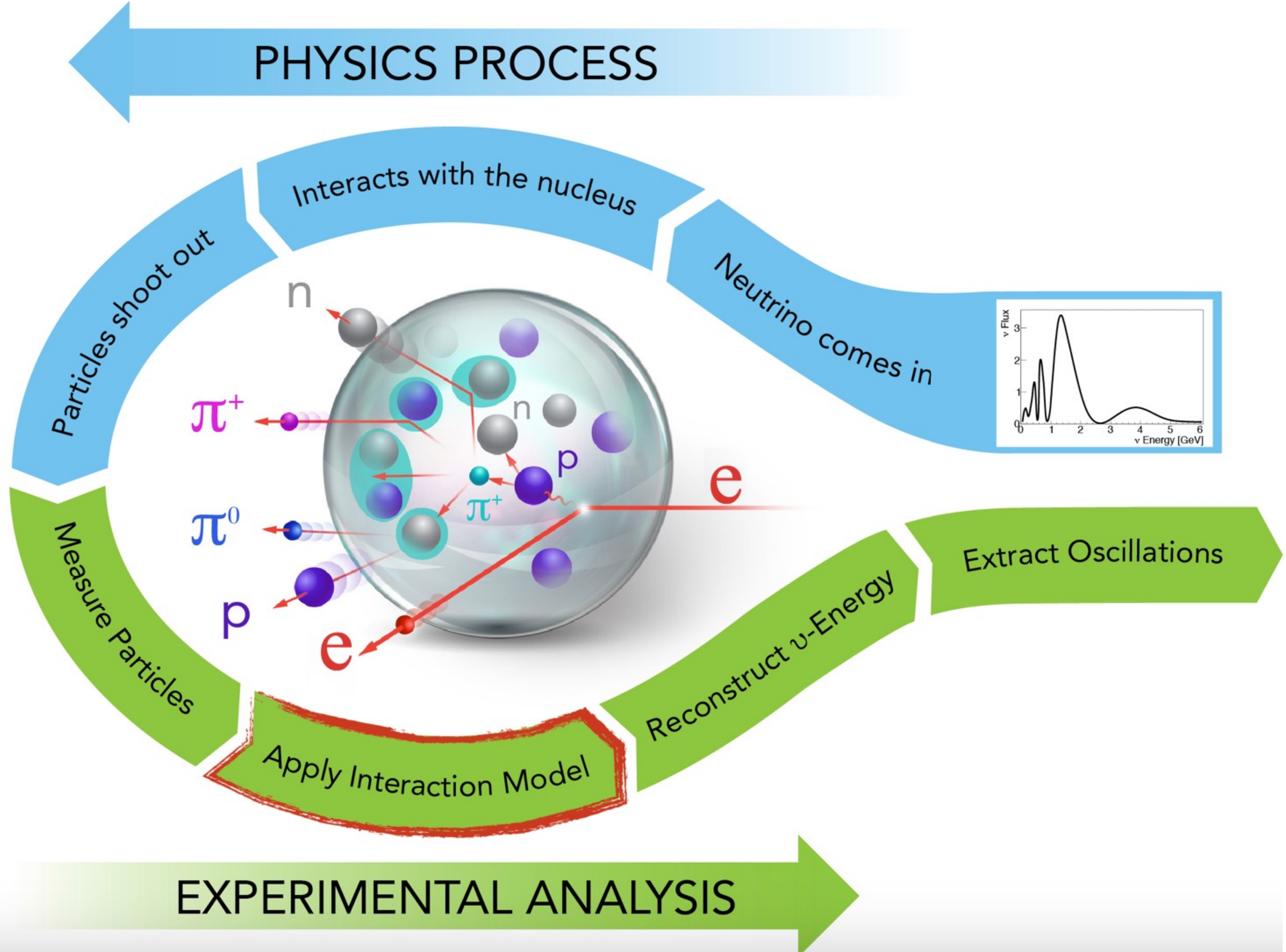
PHYSICS PROCESS

Particles shoot out ← Interacts with nucleus ← Neutrino comes in



Measure Particles → Apply Interaction Model → Reconstruct ν-Energy → Extract Oscillations

EXPERIMENTAL ANALYSIS

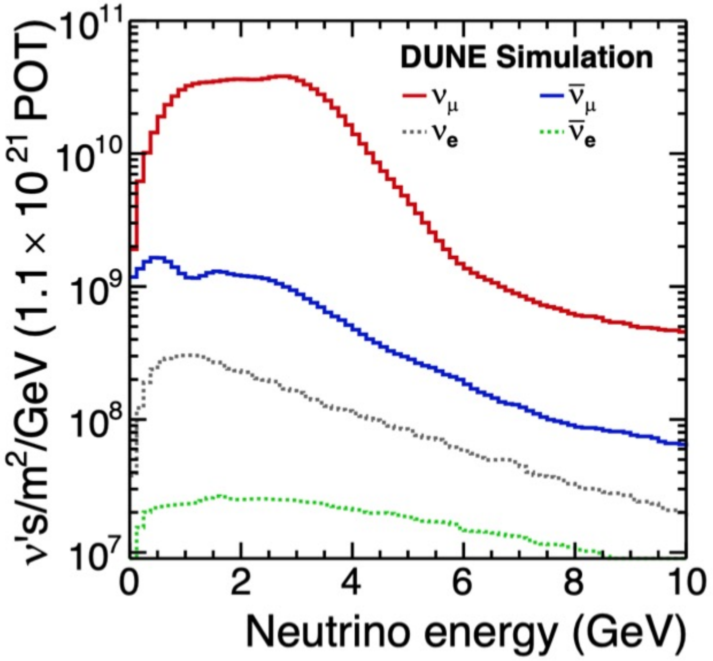


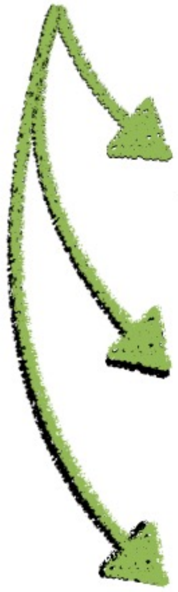
PHYSICS PROCESS
Interacts with the nucleus
Particles shoot out
Neutrino comes in
ν Flux
ν Energy [GeV]
n
n
p
π^+
π^+
π^0
p
e
e
Measure Particles
Apply Interaction Model
Reconstruct υ-Energy
Extract Oscillations
EXPERIMENTAL ANALYSIS

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





Improve theory

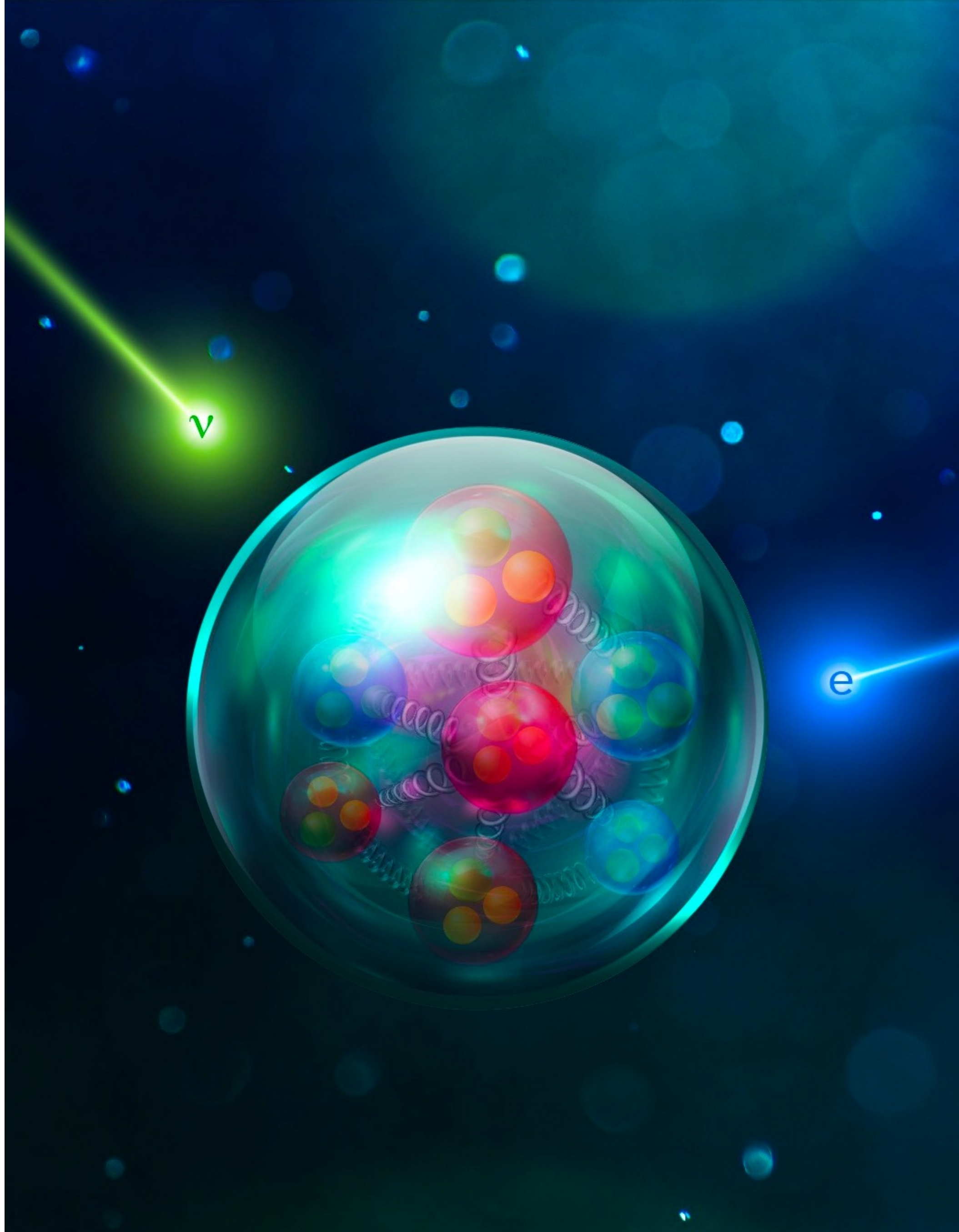
Use near detector

Use external constraints
e scattering

Electrons for neutrinos

Using electron scattering data to reduce neutrino oscillation systematic uncertainties

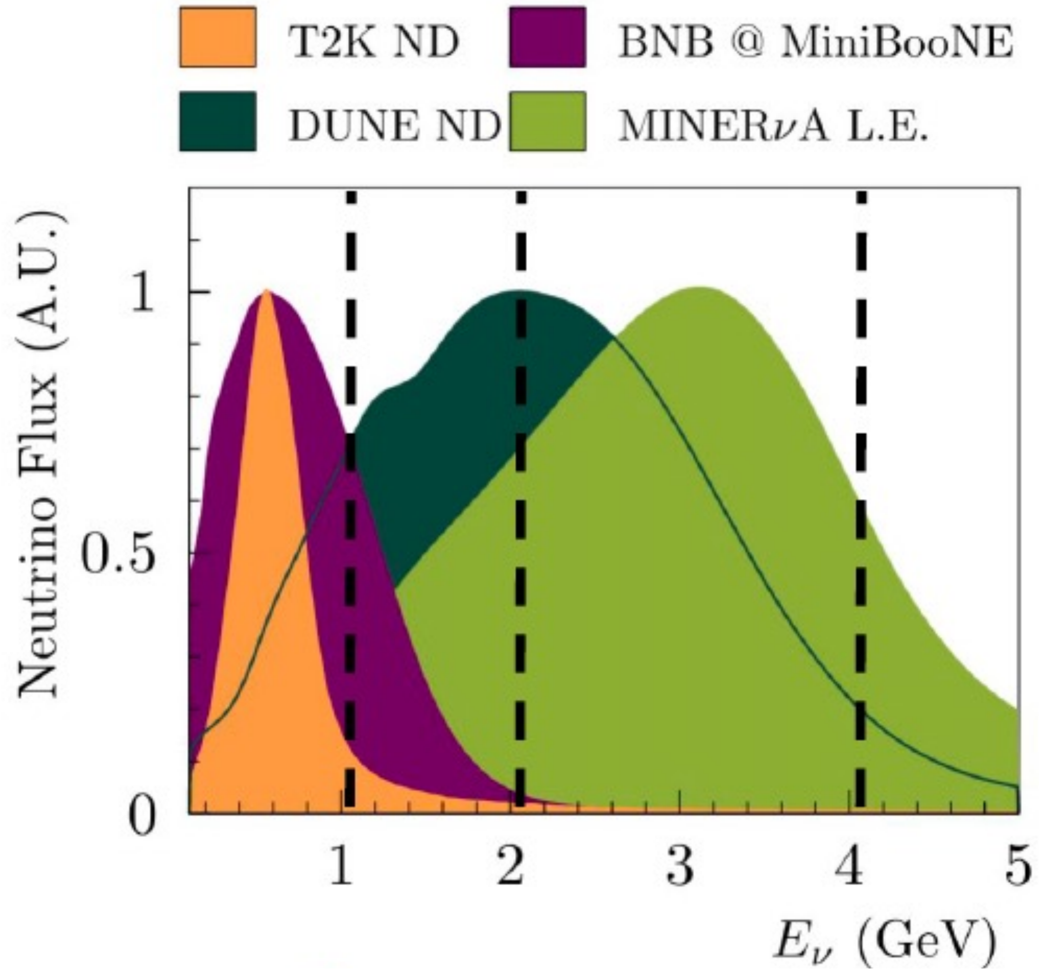
- High statistics & well-known beam
- Identical nuclear effects and final state interactions
- Similar interaction to neutrinos (**vector** vs **vector**+axial)



visit: www.e4nu.com

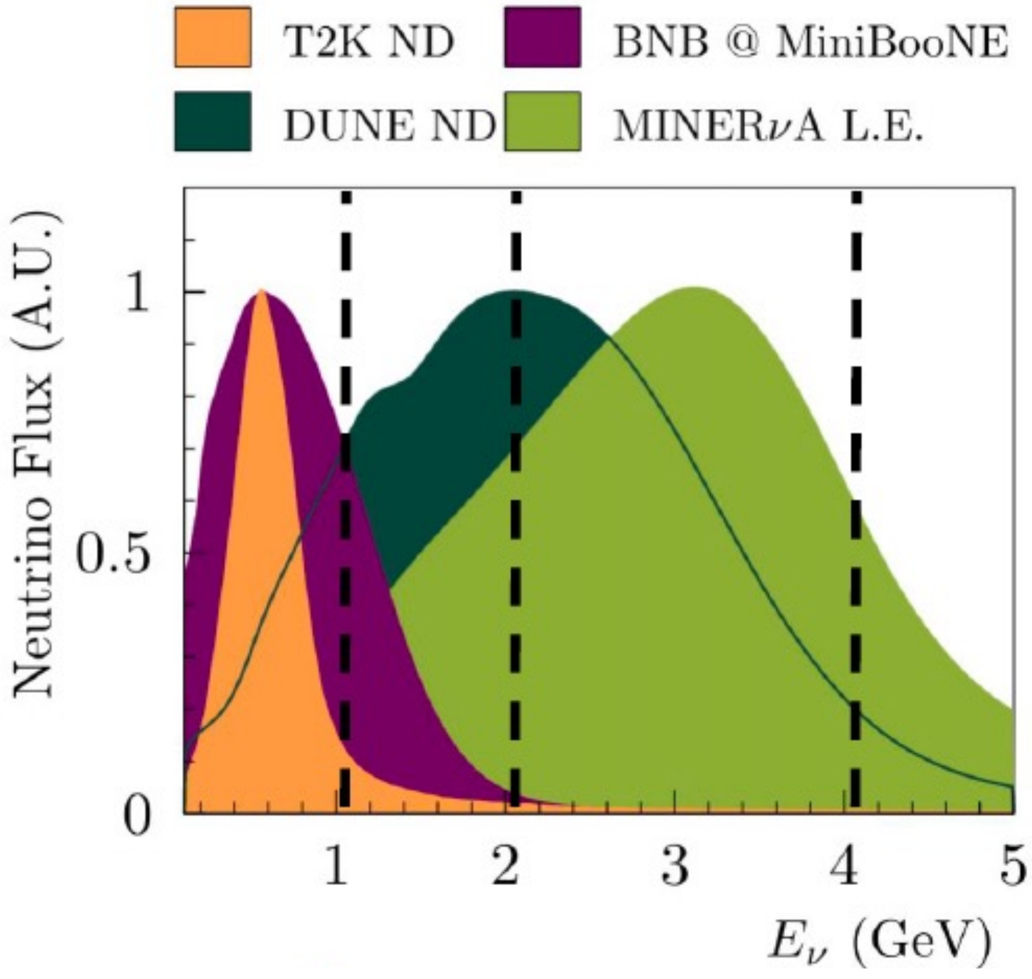
e4ν Data-Mining with CLAS6

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



e4ν analyses with CLAS data

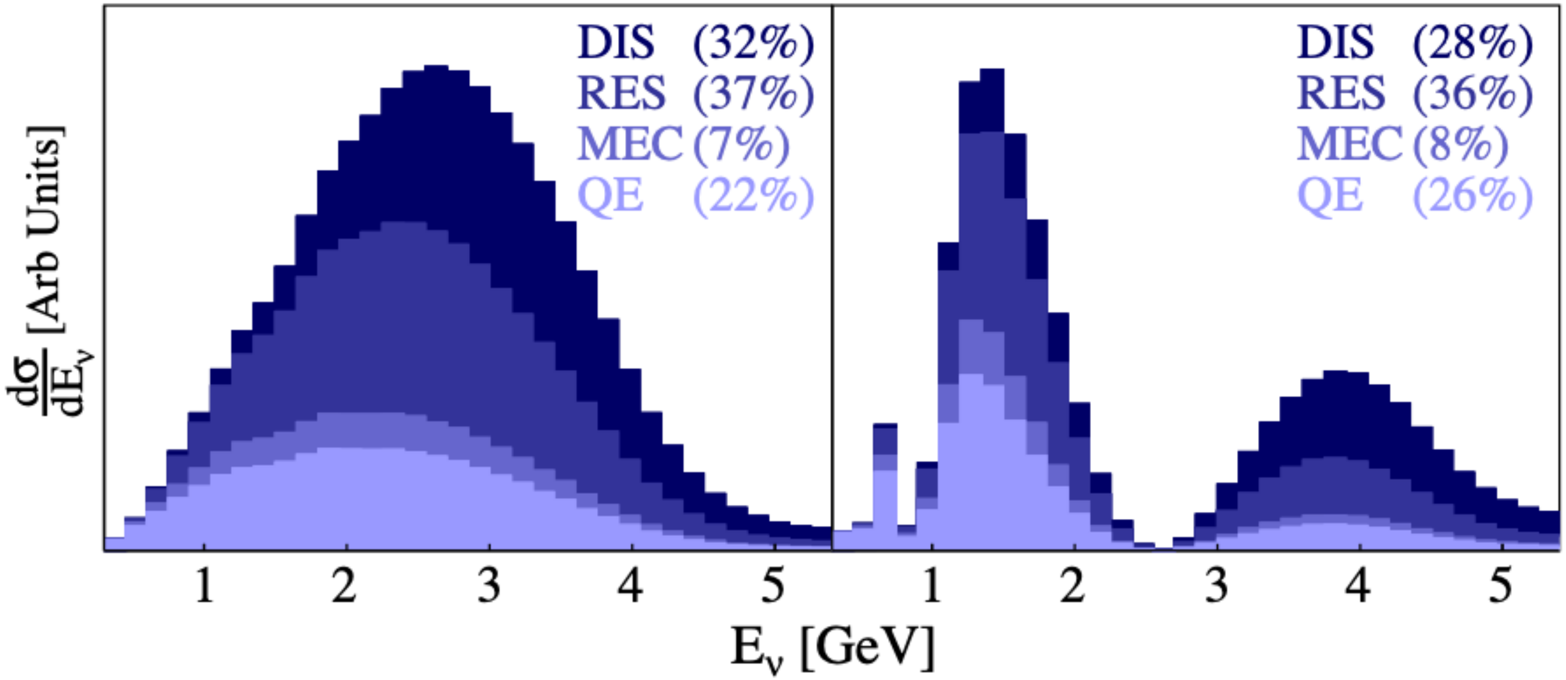
- **e4nu analysis with CLAS6 data:**
  - (e,e'1p0π) analysis, Nature 599, 565-590 (2021)
  - Transparency analysis approved by CLAS by Noah Steinberg
  - **(e,e'1p1π) single-differential cross-section analysis with CLAS6**, by J.Tena Vidal (ongoing)
- **e4nu analysis with CLAS12 data:**
  - **(e,e'1π) analysis with CLAS12, by Caleb Folger** (presenting later today)



Pion production in neutrino experiments

DUNE will be dominated by pion production events

(RES+DIS)



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).

Semi-inclusive pion production with CLAS6
(1) Signal definition

In this analysis we study two different topologies:

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

- Hall-B e2a experiment data, April 15 to May 27, 1999
- We use the same particle thresholds from previous analyses:

$$p_e > \begin{cases} 0.4\ GeV\ at\ 1.161 GeV \\ 0.55\ GeV\ at\ 2.261 GeV \\ 1.1\ GeV\ at\ 4.461 GeV \end{cases}$$

$$p_p > 0.3\ GeV$$
$$p_\gamma > 0.3\ GeV$$
$$p_{\pi^\pm} > 0.15\ GeV$$

$$15\ deg < \theta_e < 45\ deg$$
$$\theta_p > 12\ deg$$
$$\theta_\gamma > 8\ deg$$
$$\theta_{\pi^\pm} > 12\ deg$$

- and Q^2 min of 0.1, 0.4 & 0.8 GeV^2 at 1, 2 & 4 GeV respectively

Semi-inclusive pion production with CLAS6 (1) Signal definition – Physics interpretation

In this analysis we study two different topologies:

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

- **On free nucleon**
  - $e^- + p \rightarrow e^- + \Delta^+$, $\Delta^+ \rightarrow n + \pi^+$ and $\Delta^+ \rightarrow p + \pi^0$
  - $e^- + n \rightarrow e^- + \Delta^0$, $\Delta^0 \rightarrow n + \pi^0$ and $\boldsymbol{\Delta^0} \rightarrow \boldsymbol{p} + \boldsymbol{\pi^-}$
  - Higher W resonances decay in multiple pions
    - Contribute to $\mathbf{1p1\pi^-}$ and $\mathbf{1p1\pi^+}$ due to momentum thresholds and detector gaps
  - The same final state can be produced after non-resonant processes and DIS

Semi-inclusive pion production with CLAS6 (1) Signal definition – Physics interpretation

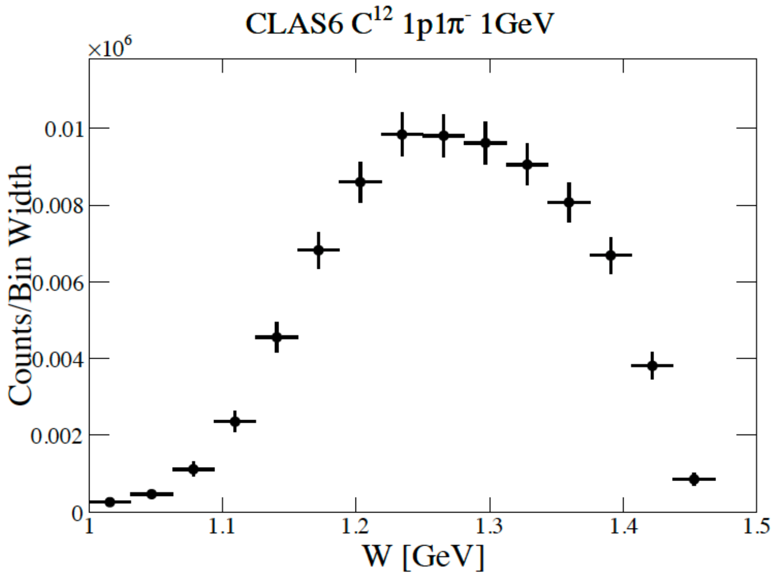
In this analysis we study two different topologies:

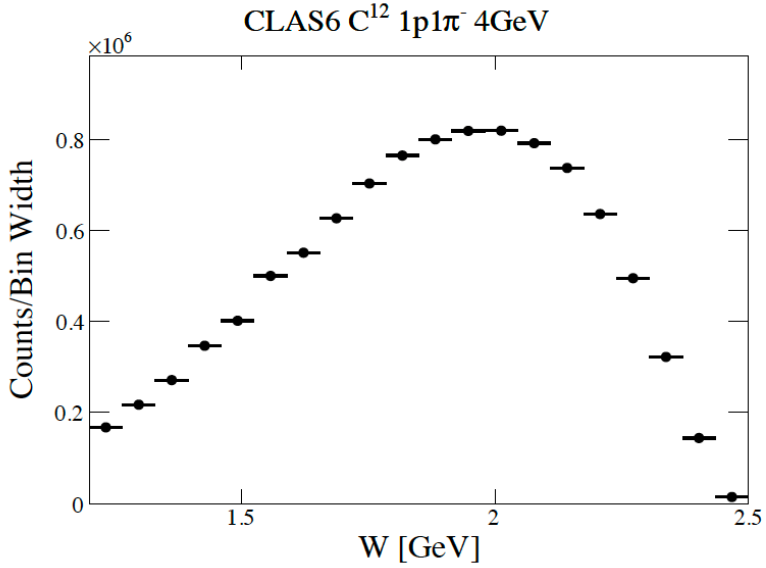
- $\mathbf{1p1\pi^-}0\pi^+0\gamma$ any number of neutrons
- $\mathbf{1p1\pi^+}0\pi^-0\gamma$ any number of neutrons

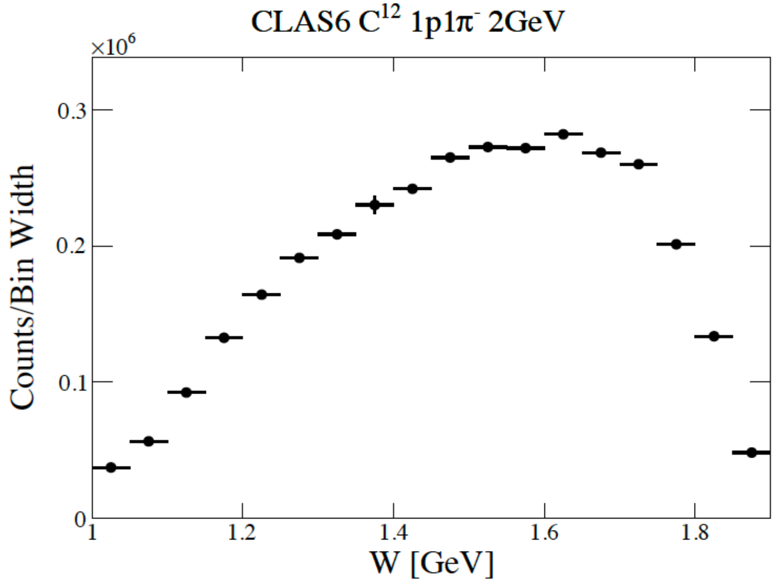
- **On nuclei**
  - FSI opens more possibilities: $\mathbf{1p1\pi^+}$ is possible due to charge exchange
  - $\mathbf{1p1\pi^+}$ sample is more sensitive to FSI

Semi-inclusive pion production with CLAS6 (2) Selection of $1p1\pi^-$ events

Raw data:







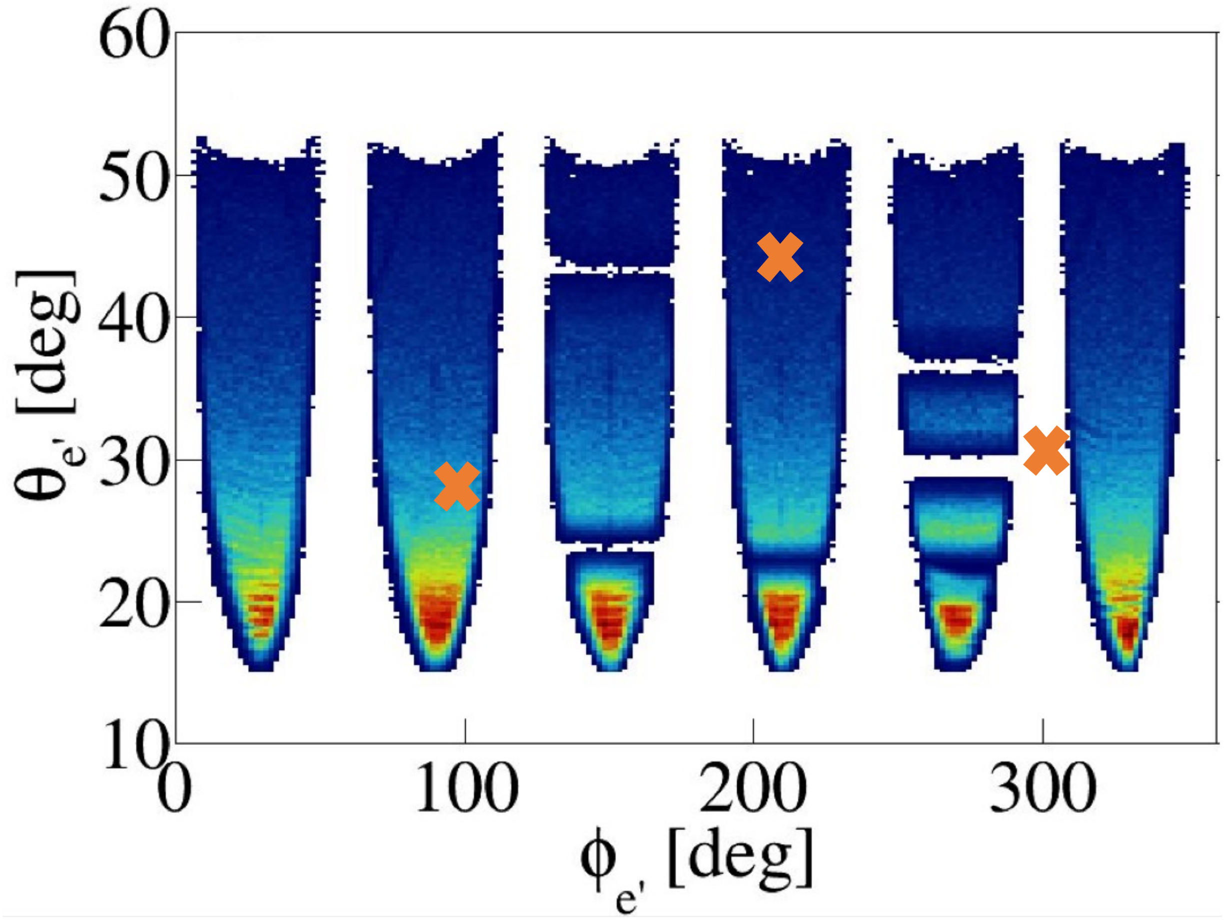
Delta dominated

Multi-pion production

Higher W resonances

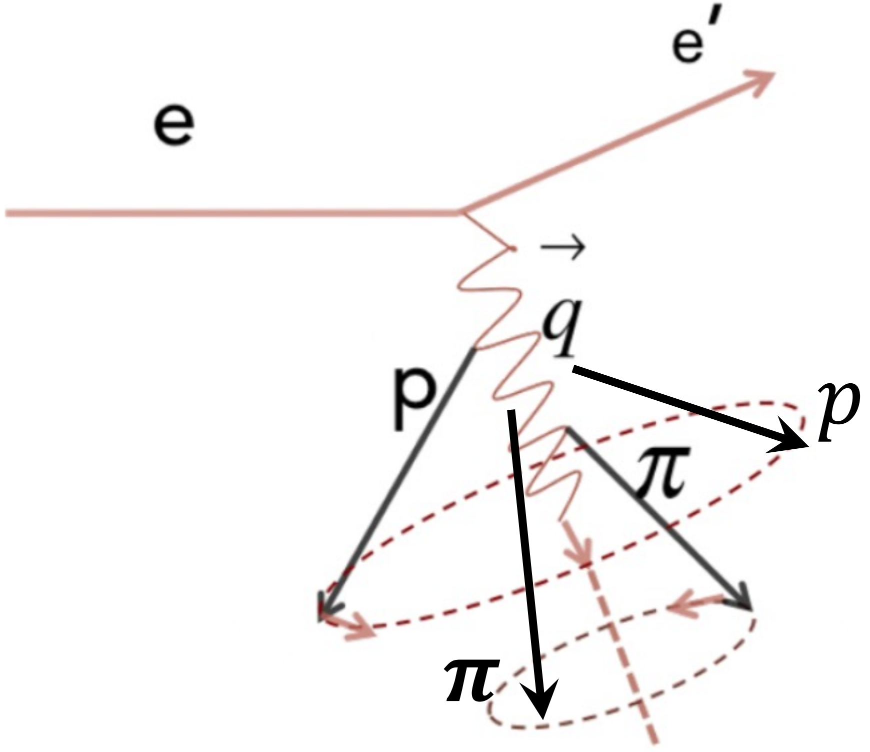
Semi-inclusive pion production with CLAS6 (3) Background subtraction

- Non-(e,e'1p1$\pi^{\pm}$) events can be selected due to detector gaps
- We use a **data-driven** method to correct for background events



Semi-inclusive pion production with CLAS6 (3) Background subtraction

- Consider a contained background event
  - i.e. 2p2π in the fiducial
- **Rotate the event N times around the q-vector**
  - 1% cross-section dependence
  - Included as systematic uncertainty

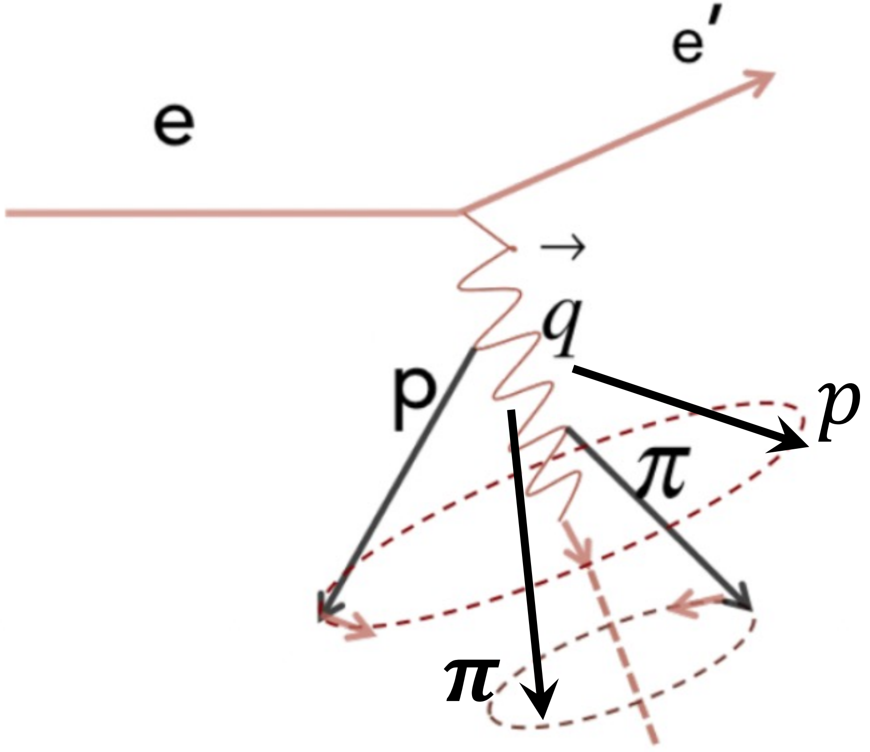


Semi-inclusive pion production with CLAS6
(3) Background subtraction

- Calculate the **probability** of the event to be reconstructed as
  - i.e. $2p1\pi$, $1p2\pi$ and $1p1\pi$
  - We add a pseudo-event with **weight *w*** and the new particle content after rotation

$$w = -\frac{N_{mf}}{N_{mi}} w_i$$

  - N_{mf}: number of counts with $m_f < m_i$
  - w_i: initial event weight

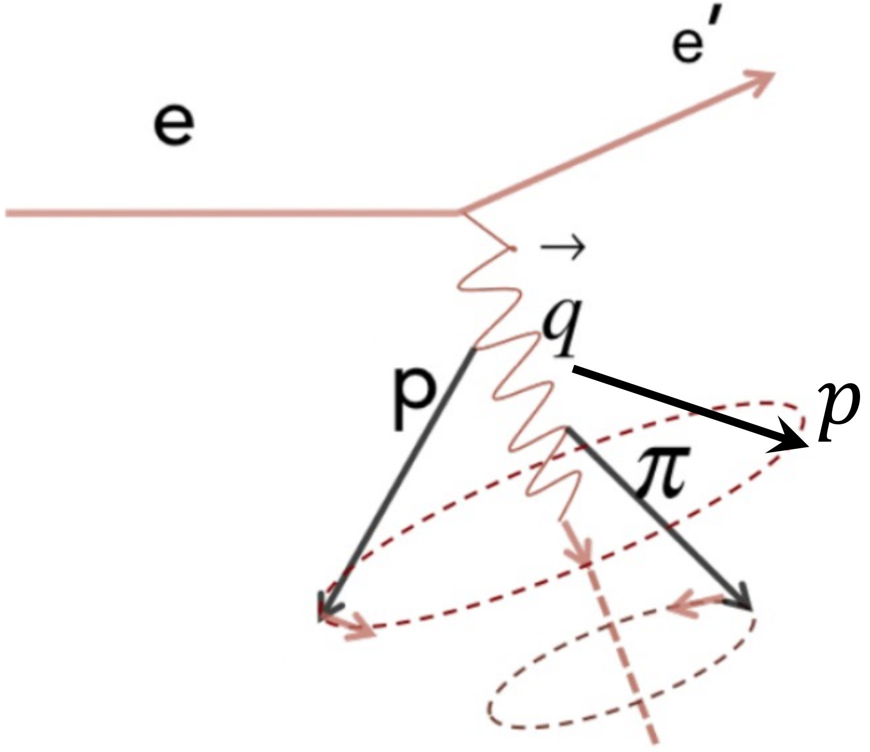


Semi-inclusive pion production with CLAS6 (3) Background subtraction

- **Repeat for lower multiplicity events**
  - i.e. $2p1\pi$ and $1p2\pi$
- Calculate the weight for the event to be reconstructed as
  - $1p1\pi$ (our signal definition)

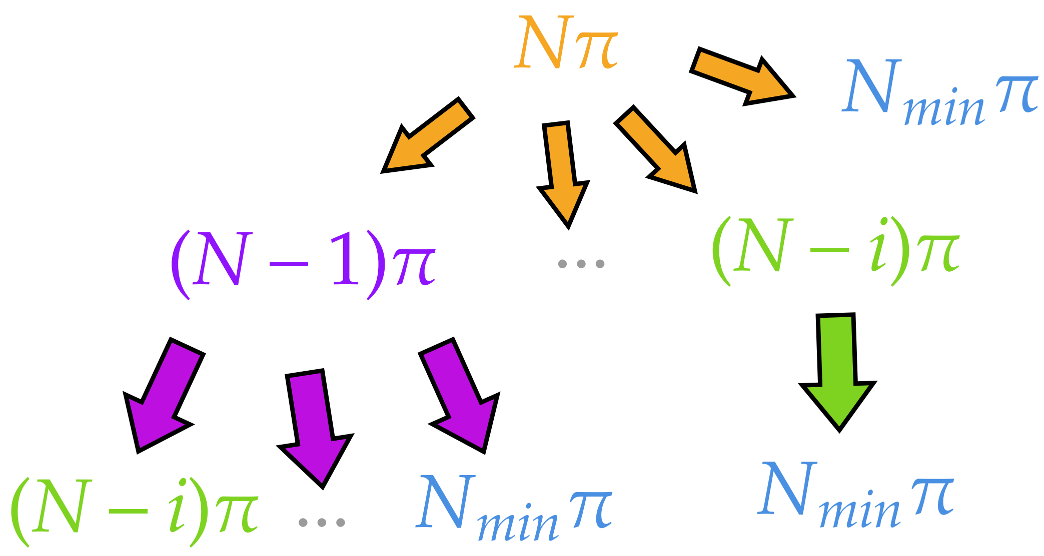
$$w = +\frac{M_{mf'}}{M_{mf}}\frac{N_{mf}}{N_{mi}}w_i$$

  - **Repeat until we only have signal events**

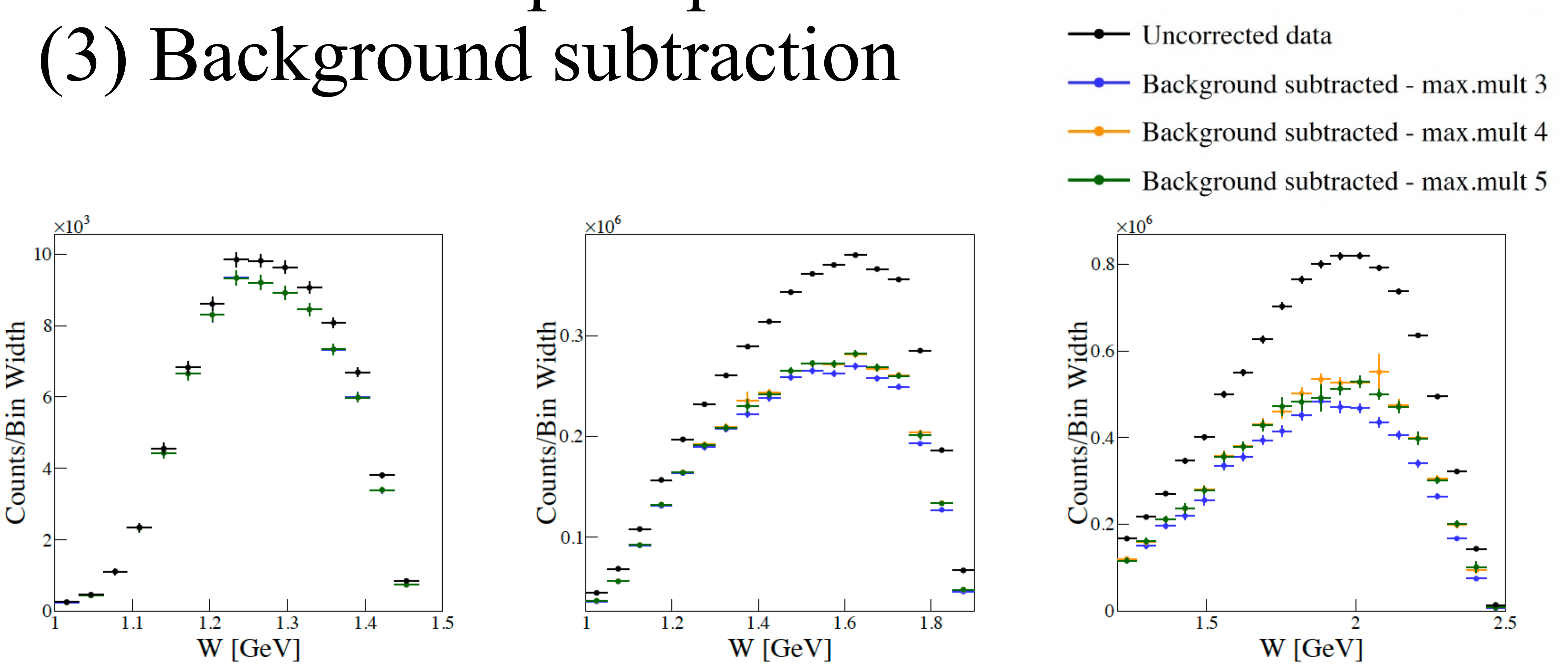


Semi-inclusive pion production with CLAS6
(3) Background subtraction

- The method can be easily generalized to any signal definition
- We classify events given their multiplicity:
  - Number of signal particles in the event
- We calculate the weight for every event with $m > m_{signal}$
  - All permutations considered by the algorithm
  - Correct weight assigned to each event
- The initial multiplicity is configurable



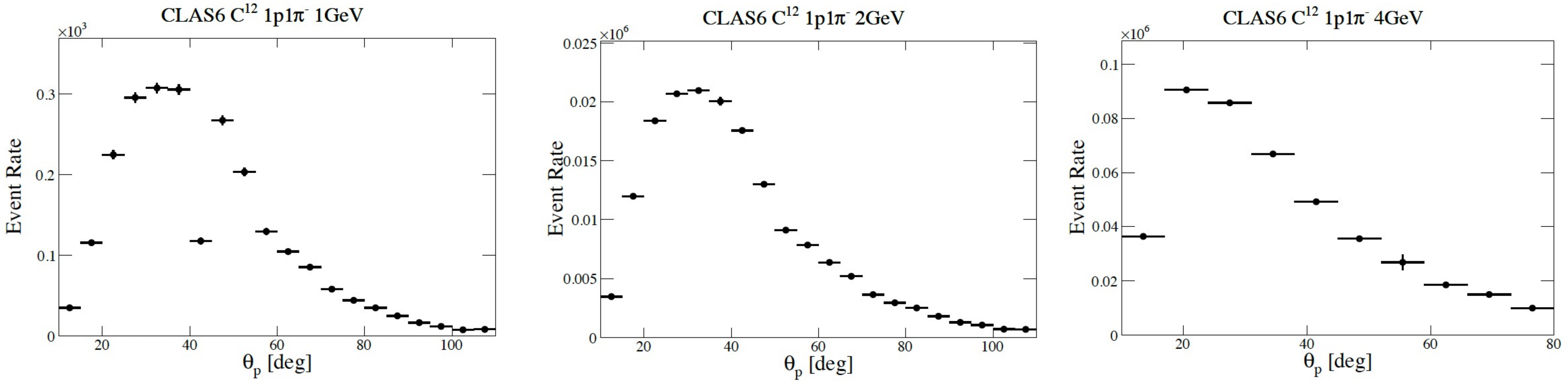
Semi-inclusive pion production with CLAS6
(3) Background subtraction



(a) Carbon at 1.1 GeV (b) Carbon at 2.2 GeV (c) Carbon at 4.4 GeV

Semi-inclusive pion production with CLAS6
(4) Correct for detector acceptance

We need to correct for the imperfect geometrical acceptance:



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

Semi-inclusive pion production with CLAS6 (4) Correct for detector acceptance

- We must correct the data for detector effects to obtain a **detector-independent cross-section** measurement
- We use **MC simulations** to compute the acceptance correction
  - MC simulation without detector effects
    - "True MC"
  - MC simulation with detector effects and no background events
    - "True reconstructed MC"
- **We apply an overall per-bin scaling factor to the data:**

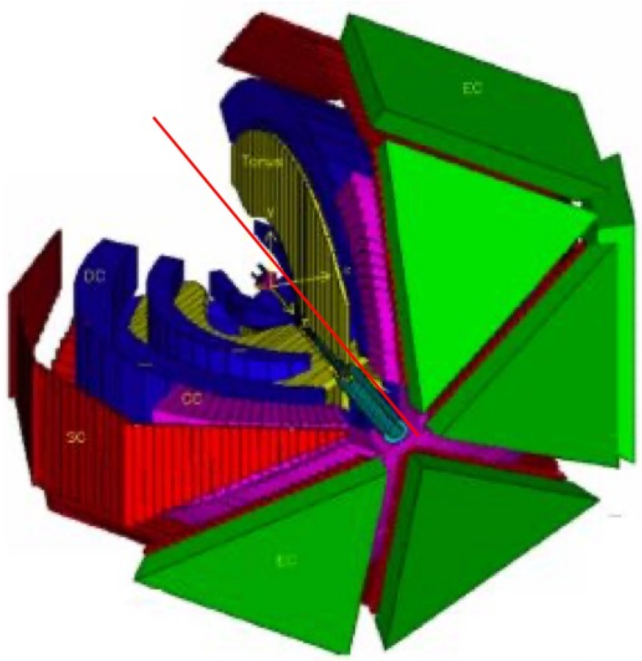
$$\alpha_{acc,i} = \frac{True\ MC\ events\ ith{-}bin}{True\ Reconstructed\ MC\ events\ ith{-}bin}$$

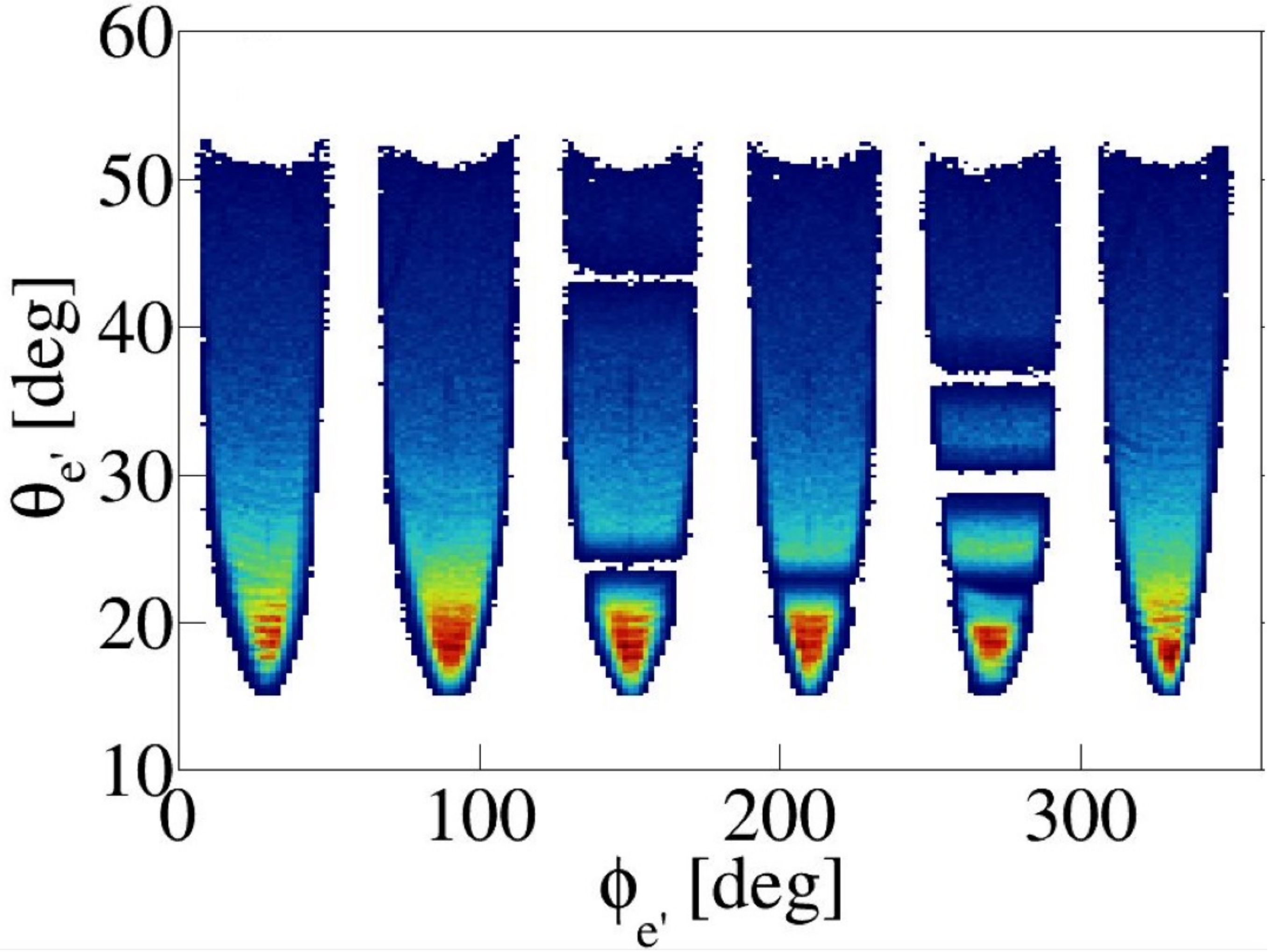
Semi-inclusive pion production with CLAS6
(4) Correct for detector acceptance

- We use **MC simulations** to compute the acceptance correction
  - MC simulation without detector effects
    - “True MC”
  - MC simulation with detector effects and no background events
    - “True reconstructed MC”

Detector effect	True MC	True Rec. MC
Particle thresholds	✓	✓
Momentum smearing	✓	✓
Fiducial Volume	✗	✓
Particle detection efficiency	✗	✓

(4) Correct for detector acceptance
Fiducial cuts for **electrons**, pions and protons

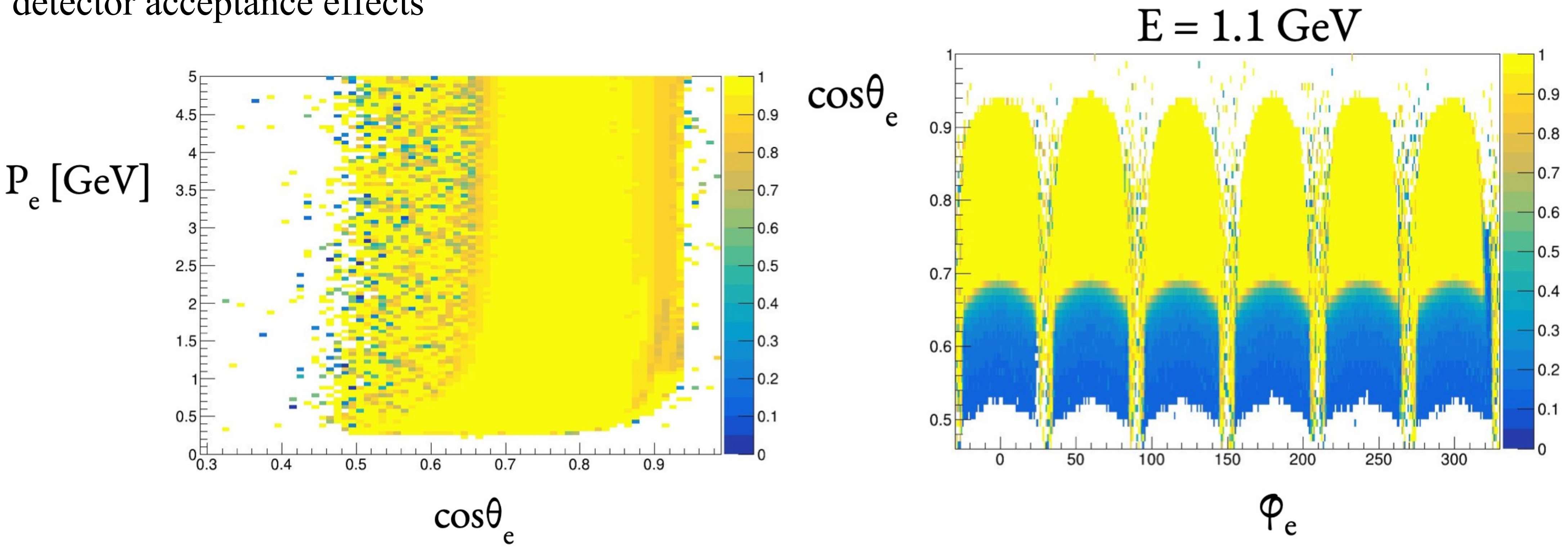




(*) Re-used from previous analysis

(4) Correct for detector acceptance
Detector acceptance maps

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



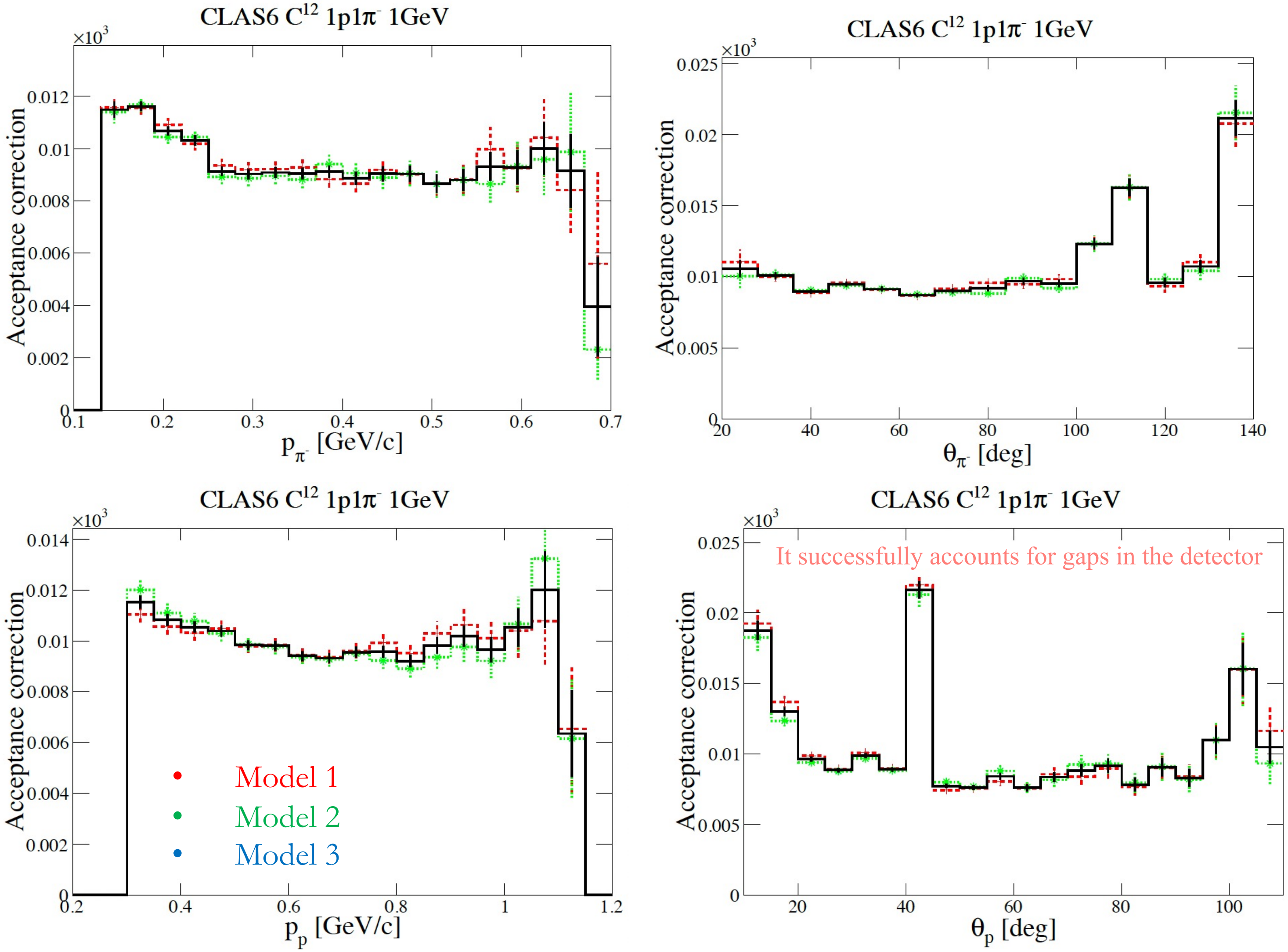
(*) Re-used from previous analysis

Semi-inclusive pion production with CLAS6
(4) Correct for detector acceptance

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

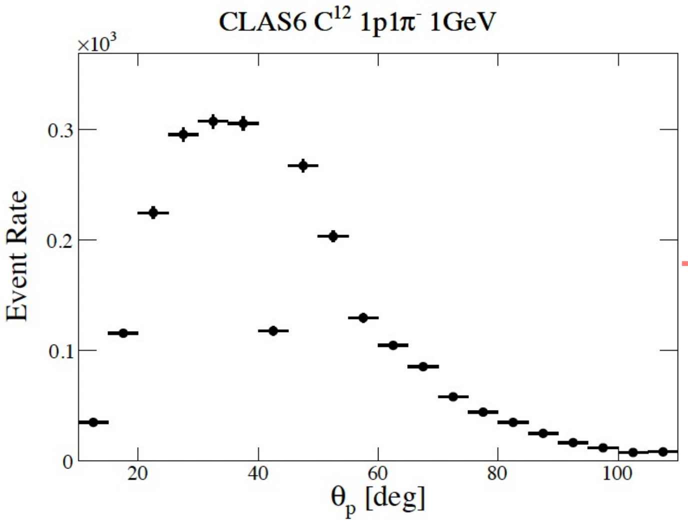
$$\alpha_{acc} = \frac{True\ MC\ events\ ith{-}bin}{True\ Reconstructed\ MC\ events\ ith{-}bin}$$

Detector effect	True MC	True Rec.
Thresholds	✓	✓
Smearing	✓	✓
Fiducial	✗	✓
Efficiency maps	✗	✓



Semi-inclusive pion production with CLAS6
(4) Correct for detector acceptance

Successfully correcting for detector gaps



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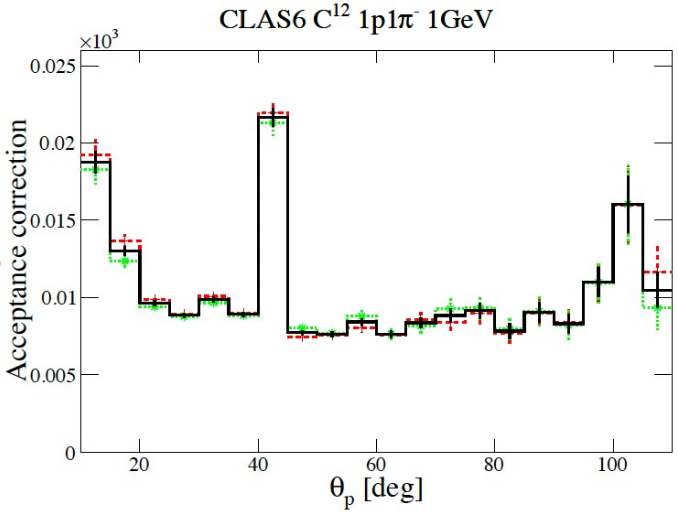

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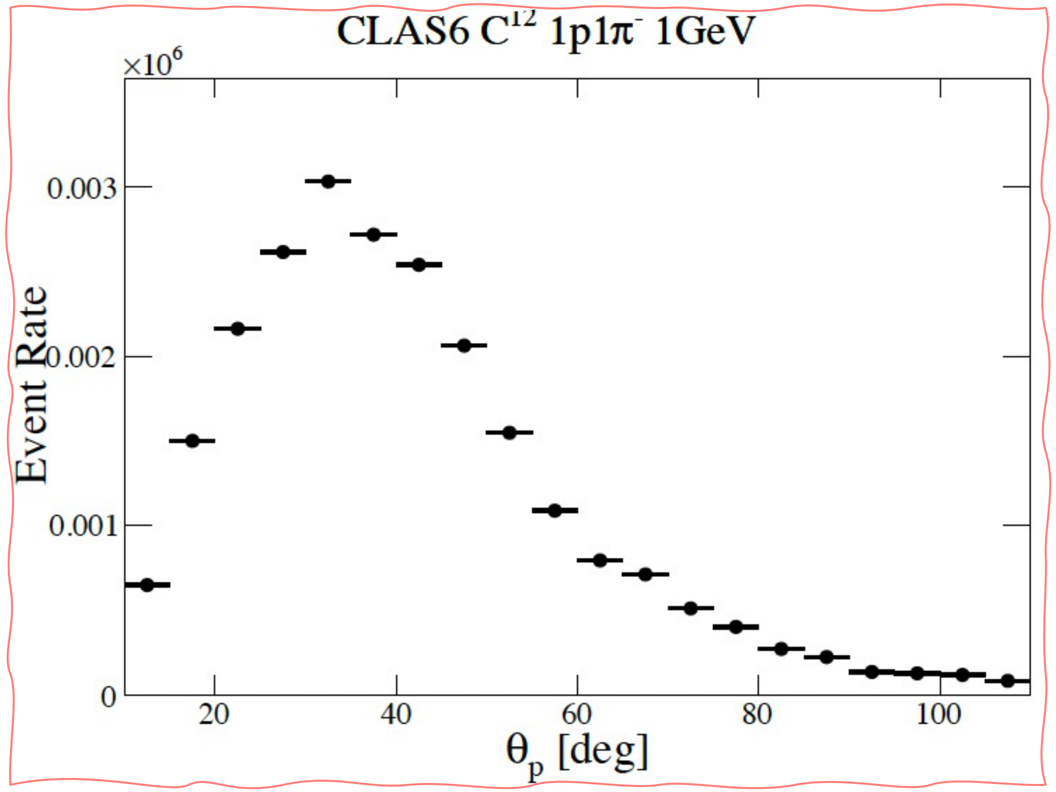
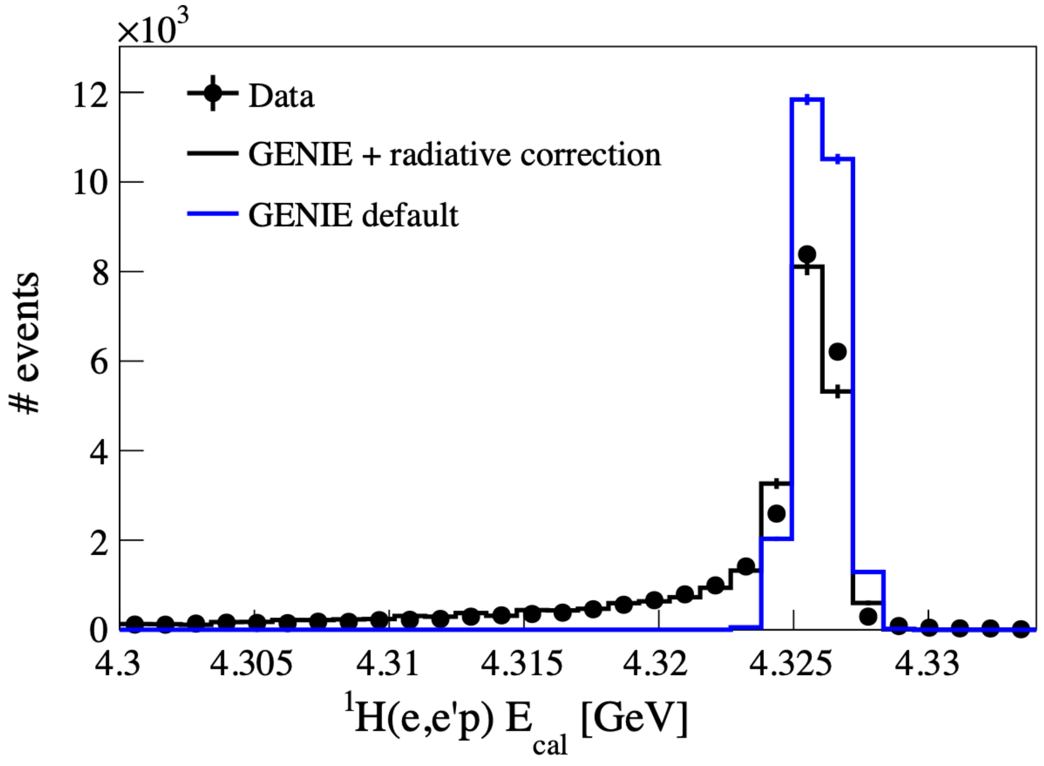


Semi-inclusive pion production with CLAS6
(5) Next steps

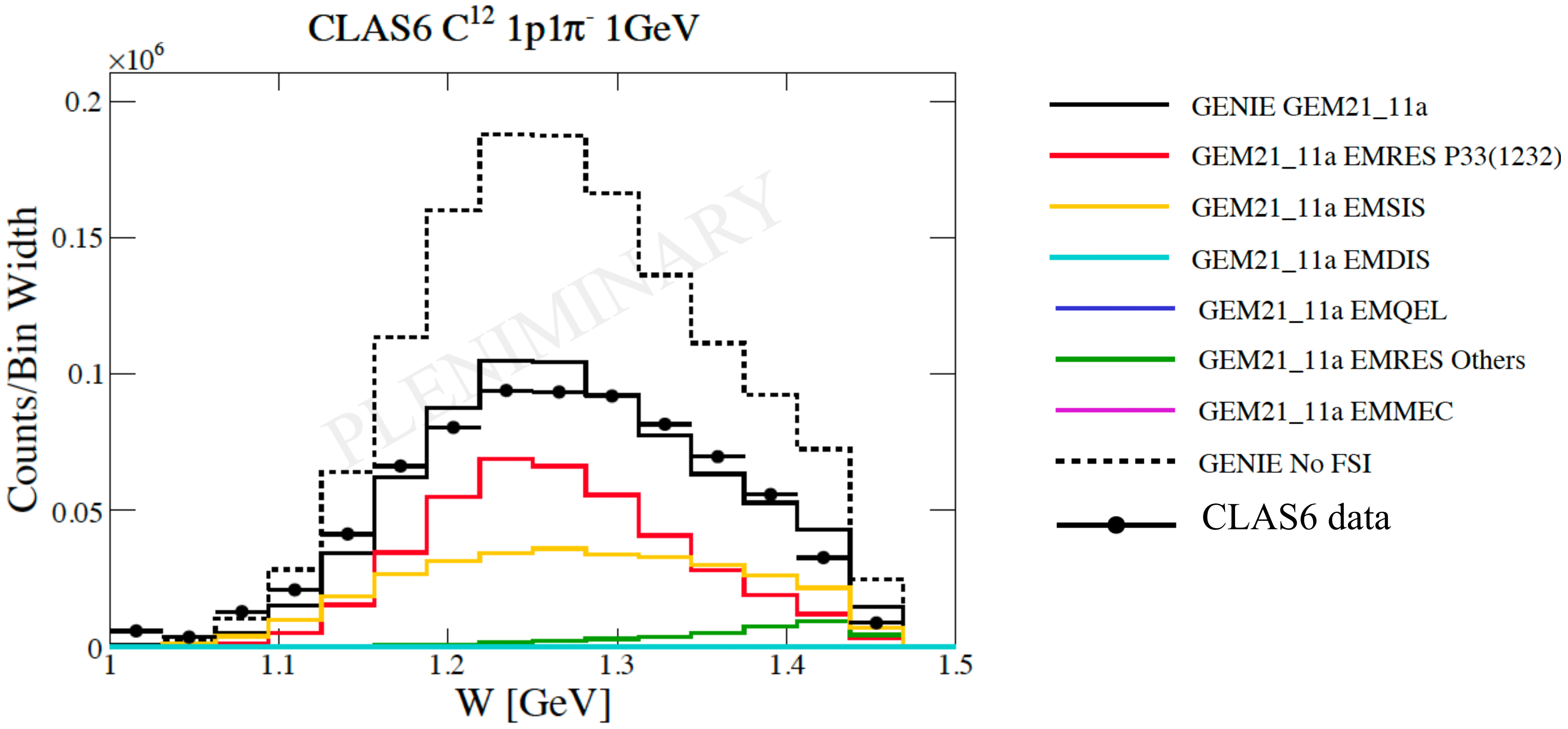
- **Systematic uncertainties – Ongoing work**
  - Re-using some of the pre-stablished uncertainties
  - **Re-calculating background subtraction uncertainties** with the new method
- **Radiative corrections – Ongoing work**
  - MC simulation does not account for radiative effects
  - We add radiative effects the same way as Jefferso Lab SIMC event generator
    - Data correction factor



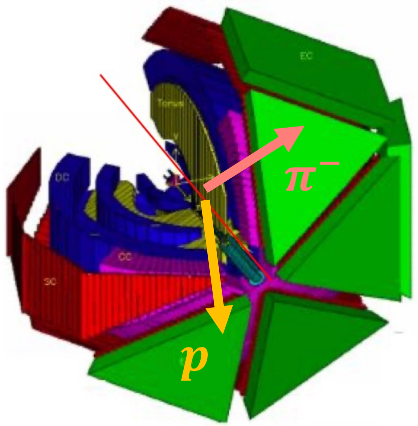
This is ongoing work; it is not included in the results shown in this talk

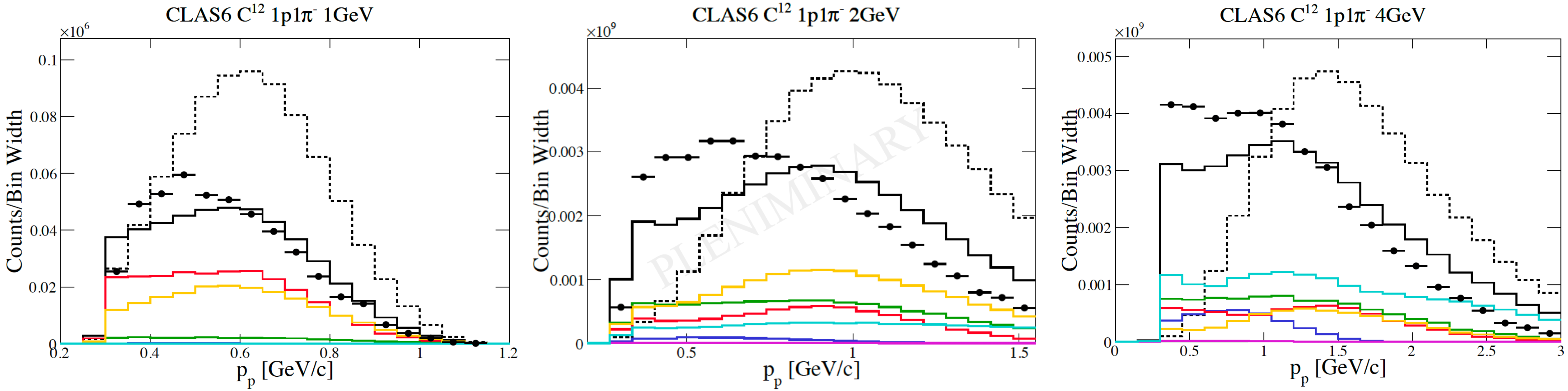
Showing corrected event rate (acceptance corrected) – shape only comparison

Semi-inclusive pion production with CLAS6 (6) Event Rate Comparisons



Semi-inclusive pion production (7) Final state kinematics

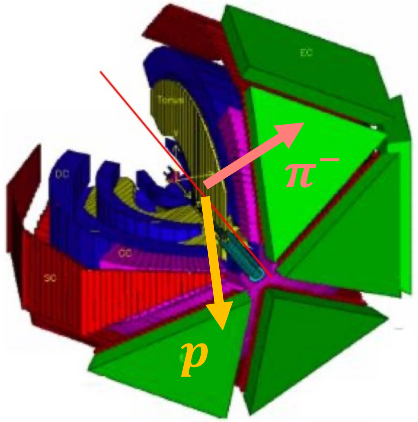


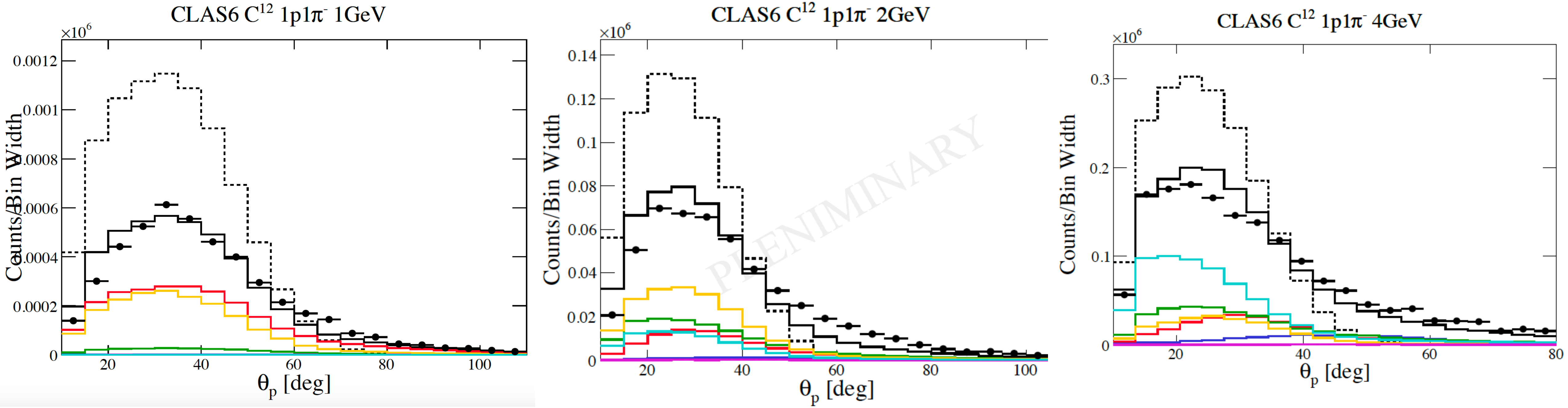


Low energy protons are not described by MC

Data/MC peak position is shifted – sensitive to FSI

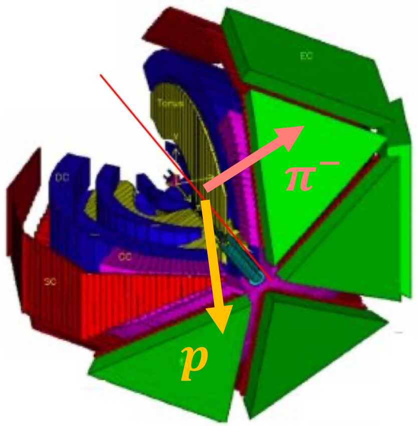
Semi-inclusive pion production
(7) Final state kinematics

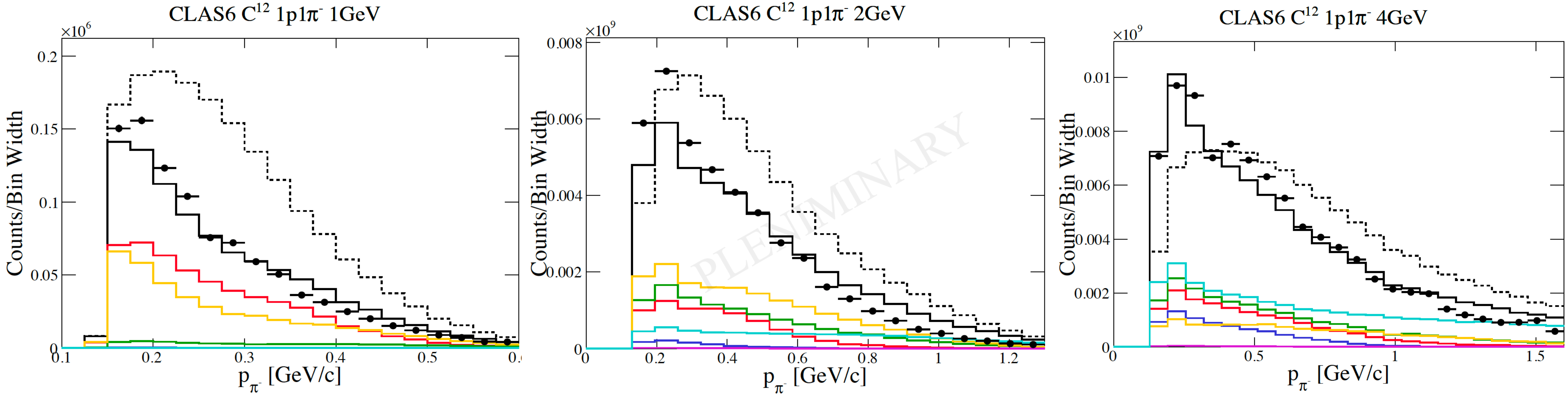




Angular shape in good agreement with MC
High θ_p possible only due to FSI

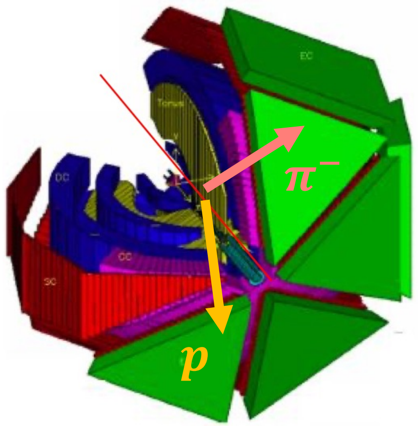
Semi-inclusive pion production (7) Final state kinematics

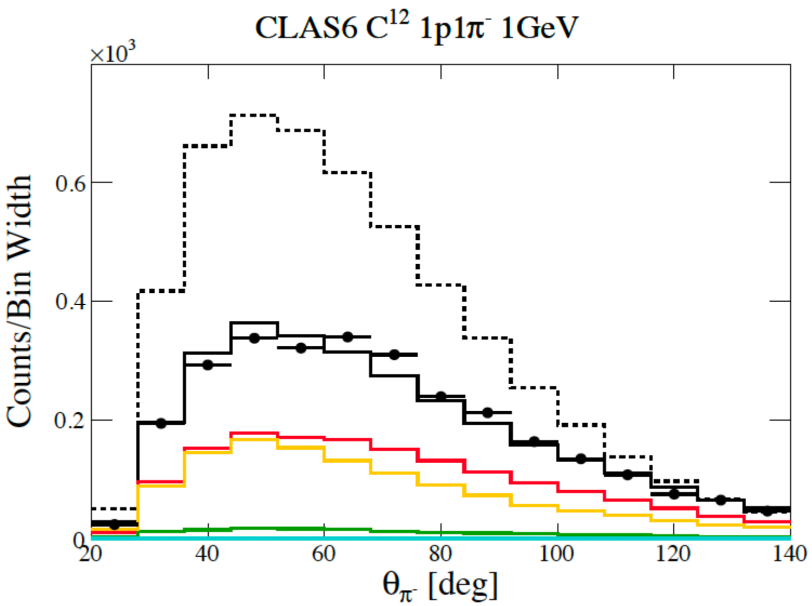


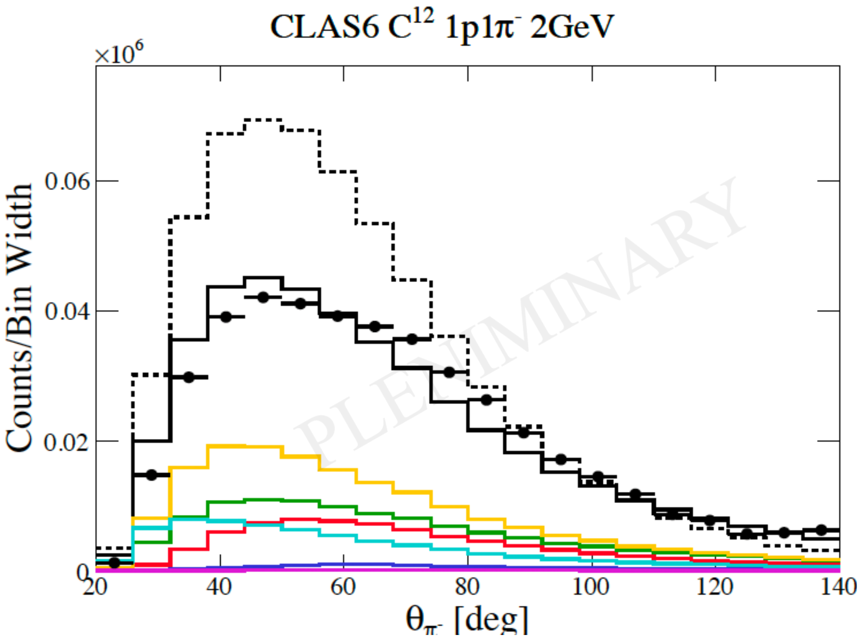


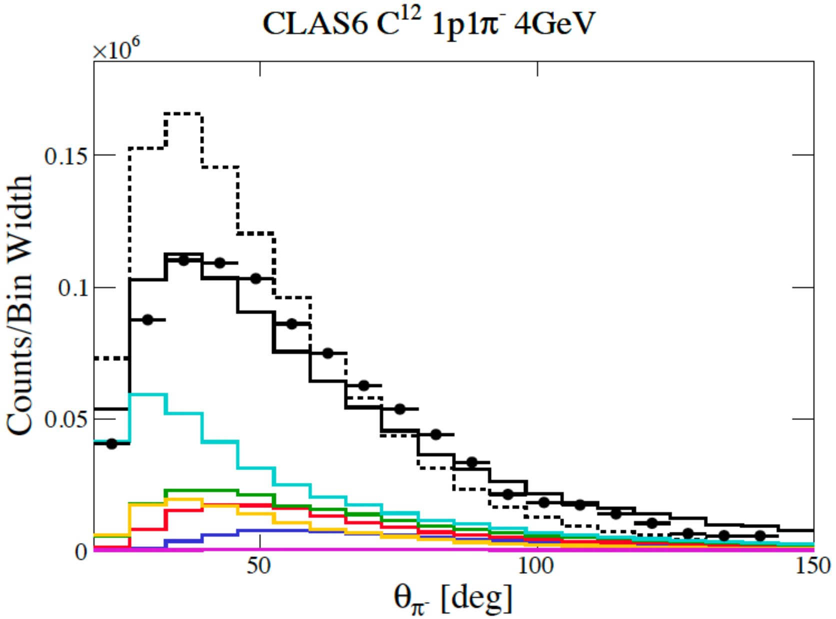
Pion momenta shape distribution well described by MC
Prediction with FSI shows correct shift when compared to data

Semi-inclusive pion production
(7) Final state kinematics



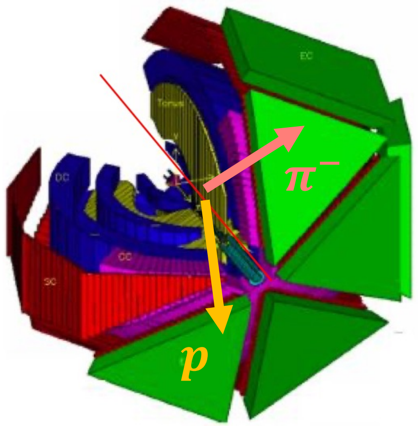




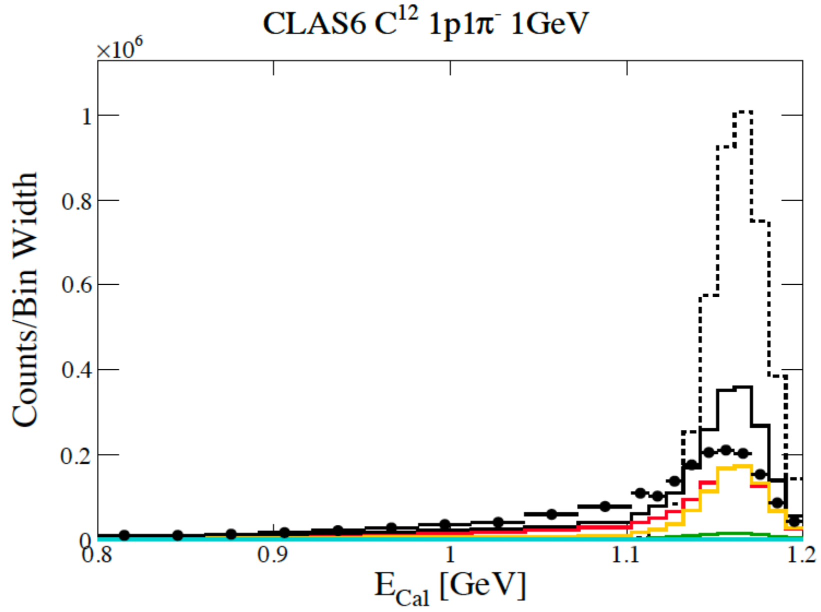


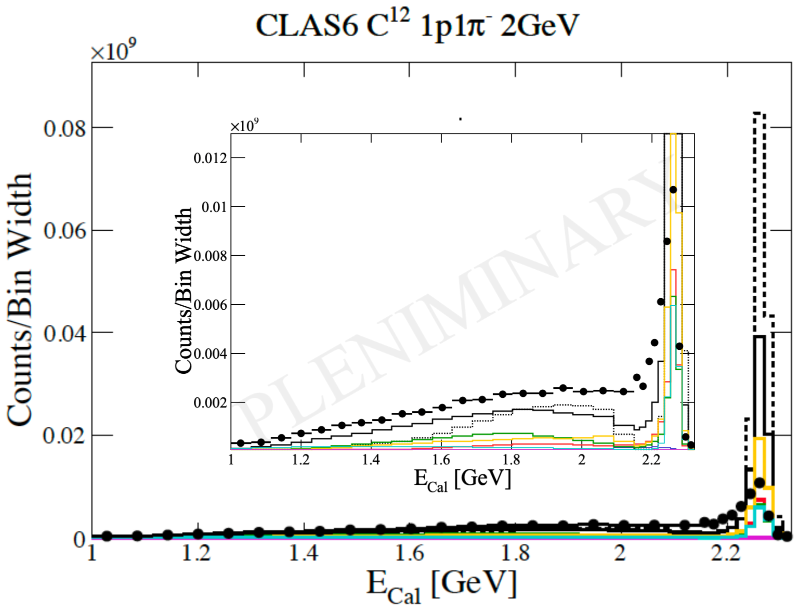
Angular shape in good agreement with MC

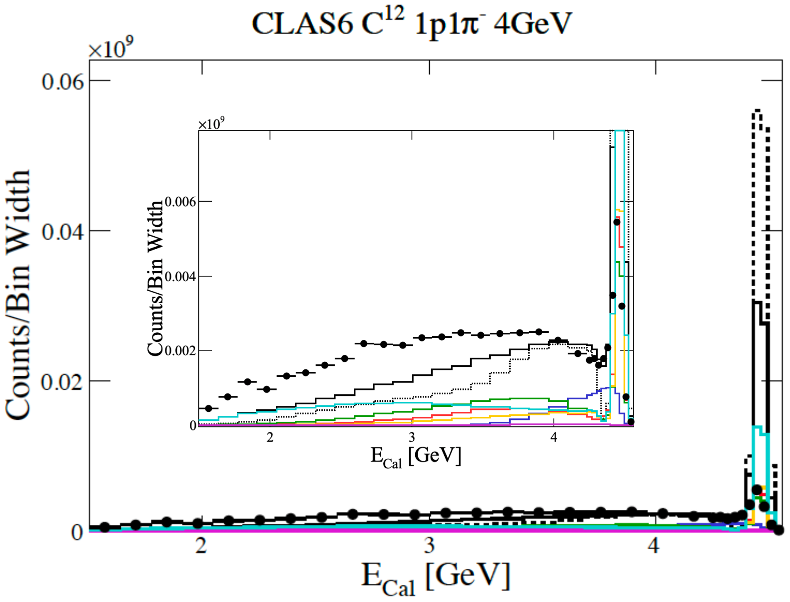
Semi-inclusive pion production
(8) Reconstructed beam energy



$$E_{Cal} = E_{e'} + E_{\pi} + T_p + \varepsilon_p$$



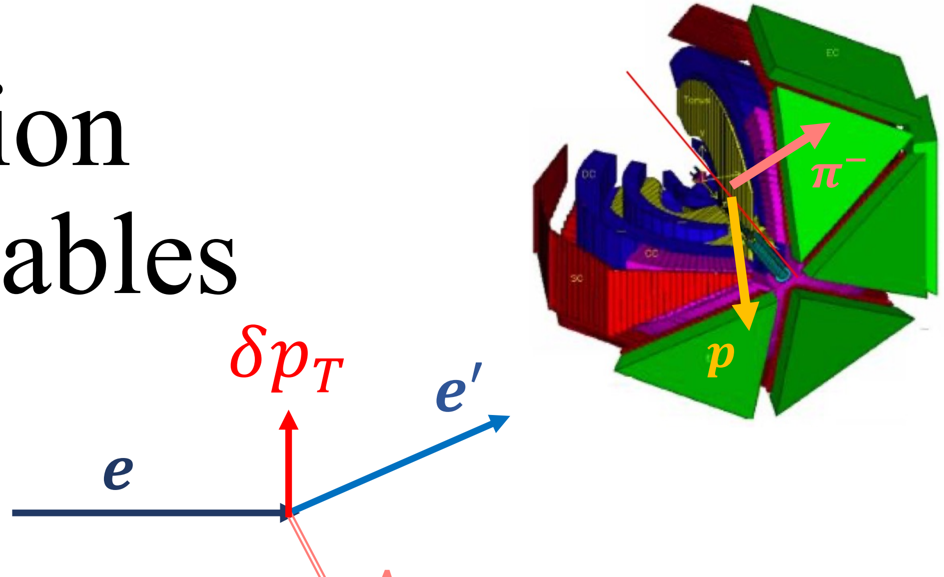




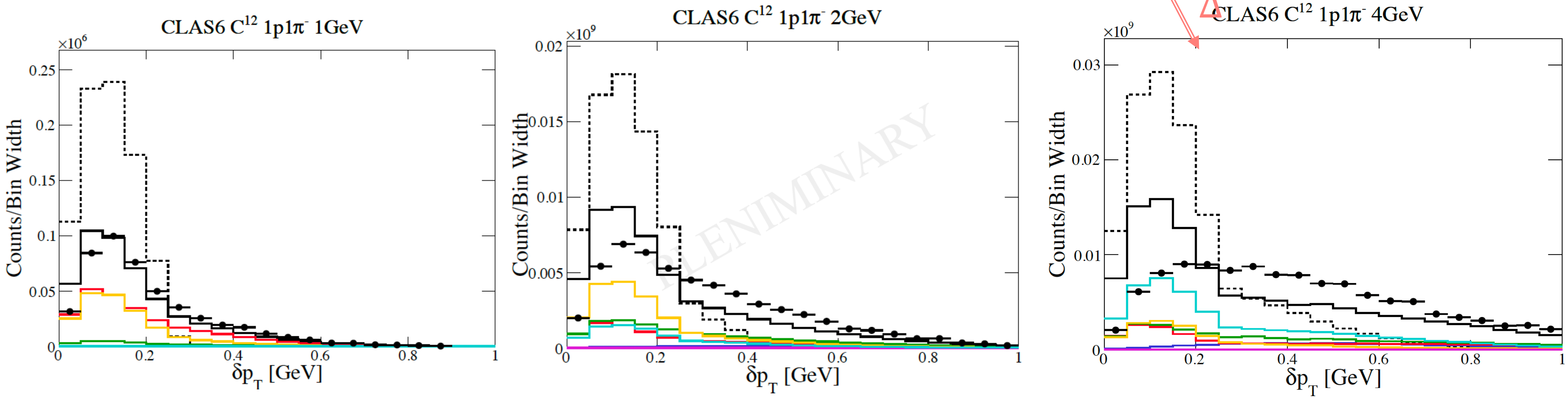
Calorimetric energy reconstruction can reconstruct beam energy

Big bias observed in the method

Semi-inclusive pion production
(9) Transverse Invariant Variables



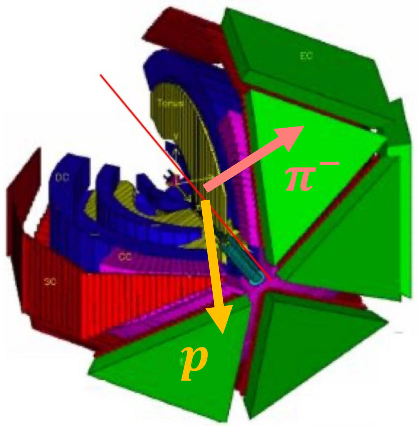
$$\delta p_T = |p_{e'} + p_{\pi} + p_p|$$

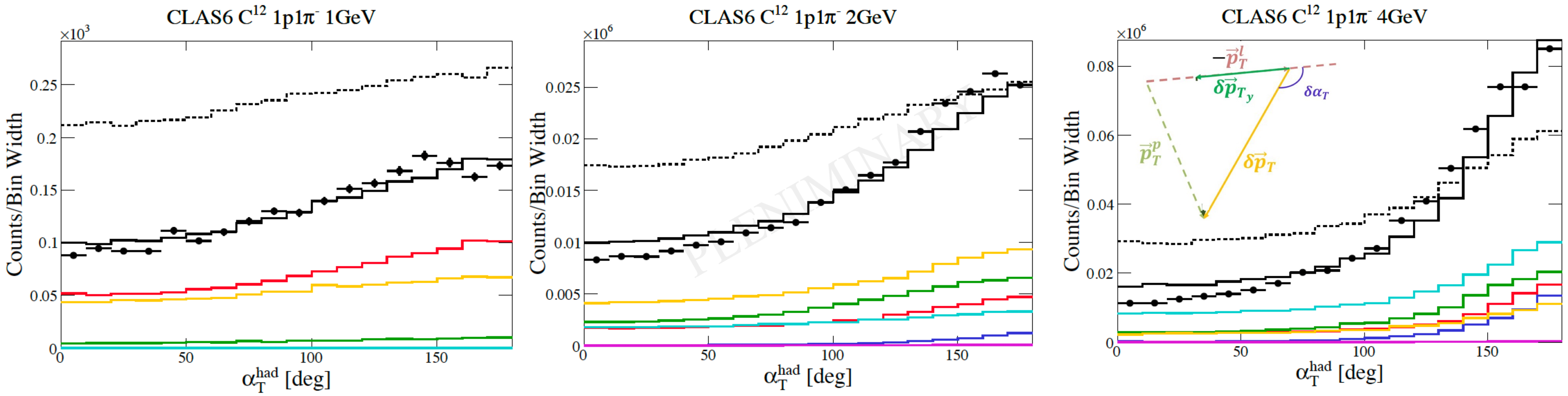


δp_T is sensitive to the nuclear model and FSI

High δp_T data dominated by FSI event

Semi-inclusive pion production
(9) Transverse Invariant Variables

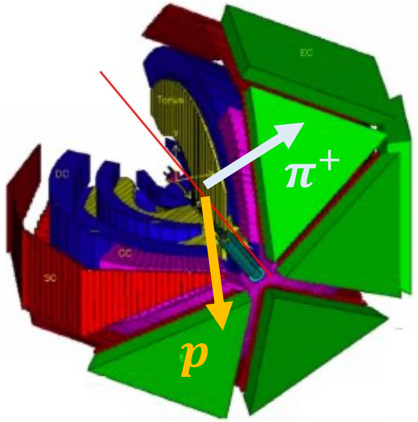


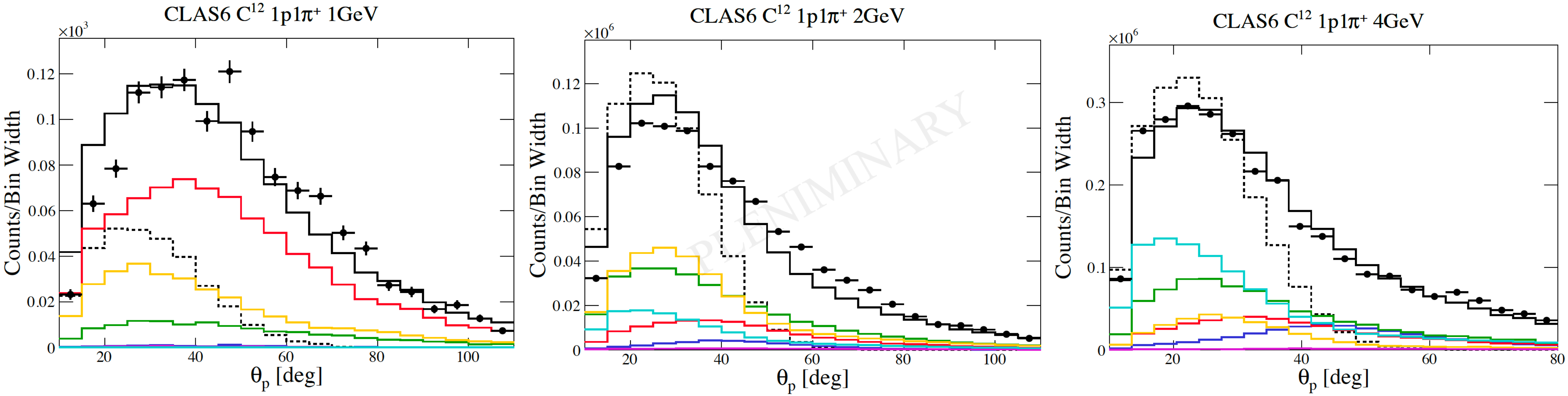


$\delta\alpha_T$ is sensitive to mostly FSI

Excellent shape description of the data for all beam energies

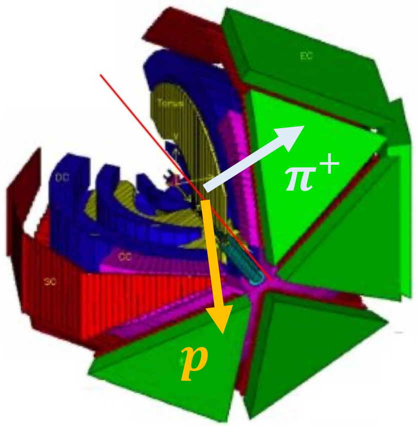
Semi-inclusive pion production (10) Final state kinematics

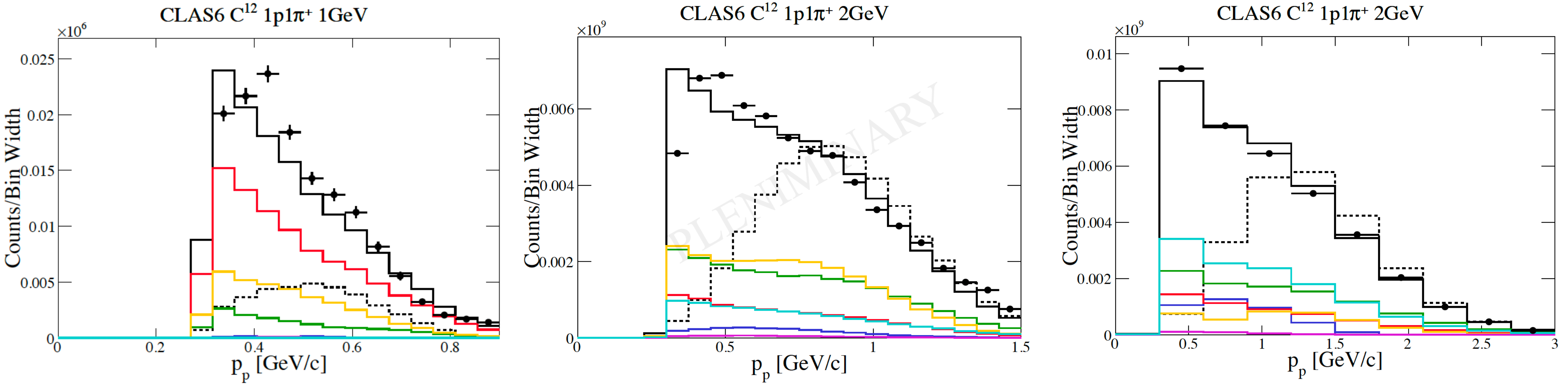




$(e, e'1p1\pi^+)$ sample most sensitive to FSI
specially at 1GeV

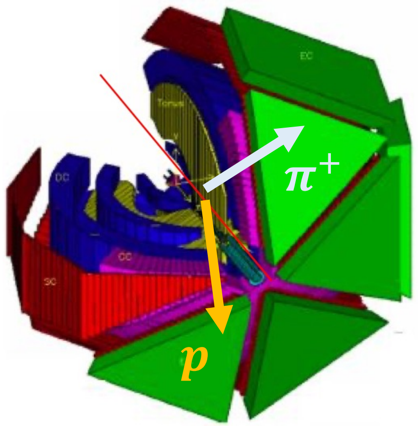
Semi-inclusive pion production (10) Final state kinematics



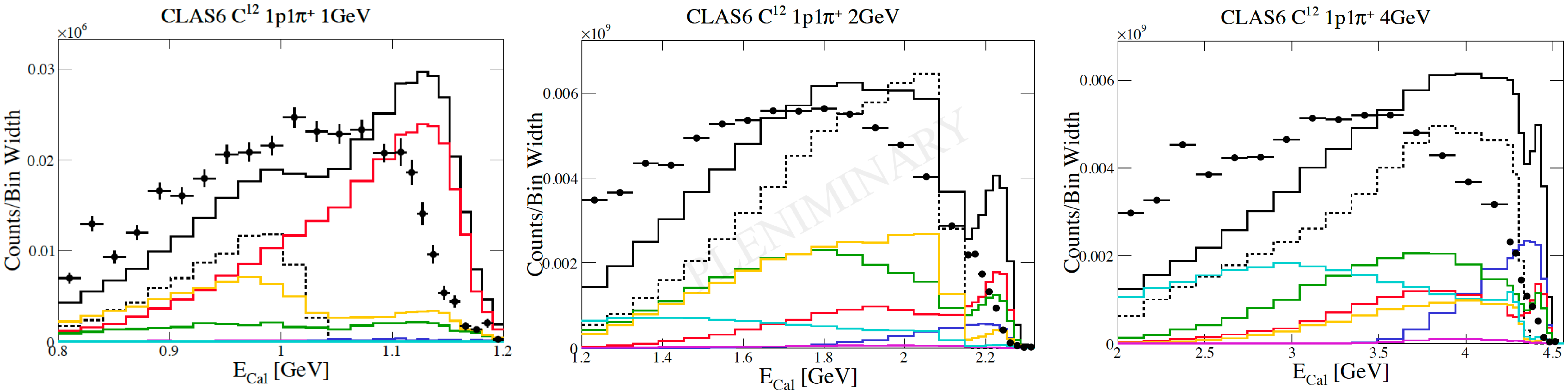


Good description of the proton momentum for $(e, e'1p1\pi^+)$ events

Semi-inclusive pion production (11) Reconstructed beam energy

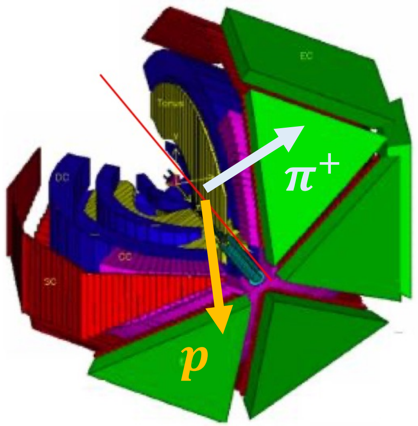


$$E_{Cal} = E_{e'} + E_{\pi} + T_p + \varepsilon_p$$

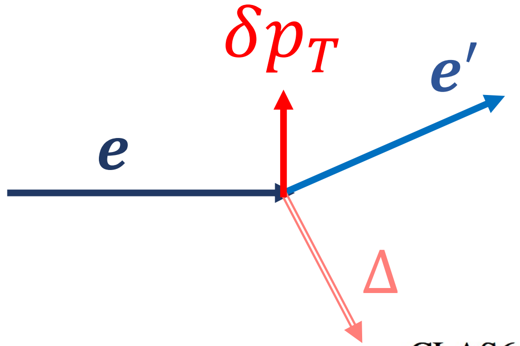


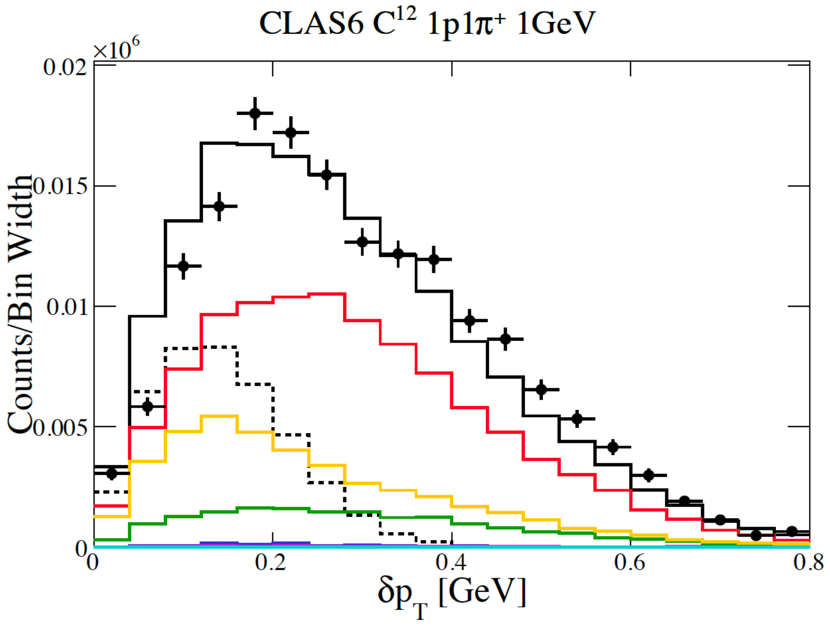
Method not sufficient to predict the beam energy
We always have undetected particles

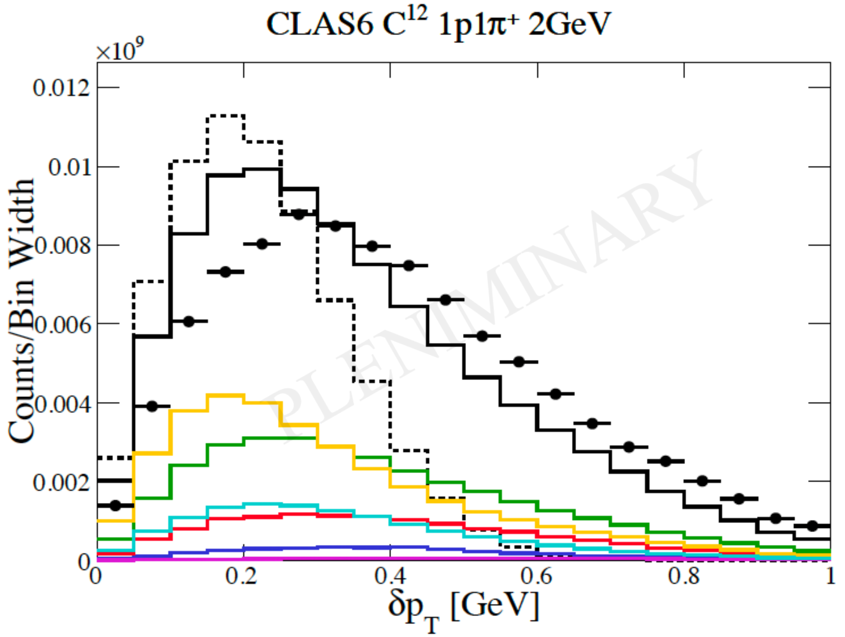
Semi-inclusive pion production (12) Transverse Invariant Variables

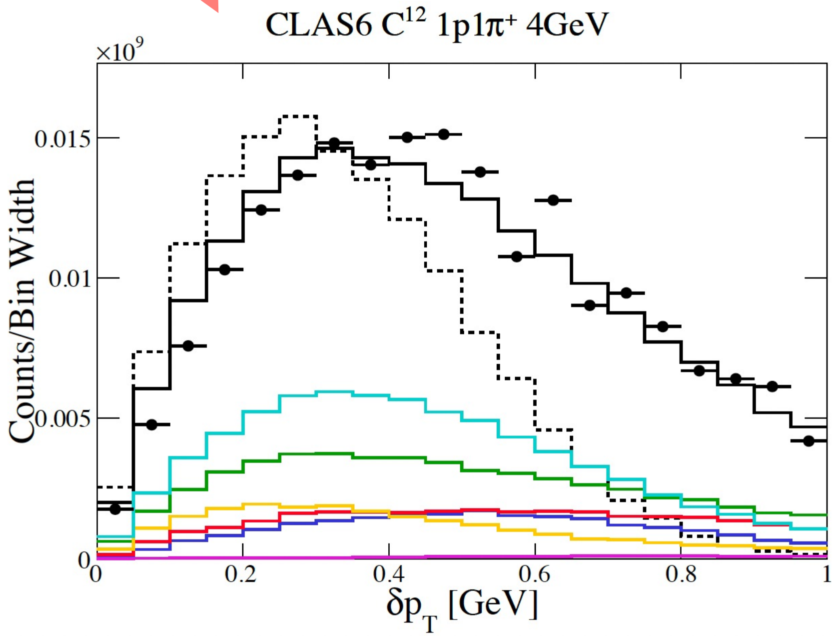


$$\delta p_T = |\boldsymbol{p}_{e'} + \boldsymbol{p}_{\pi} + \boldsymbol{p}_{p}|$$



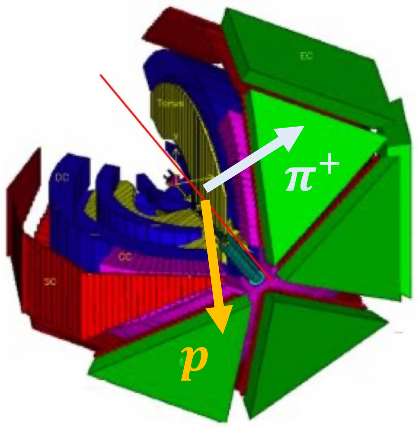


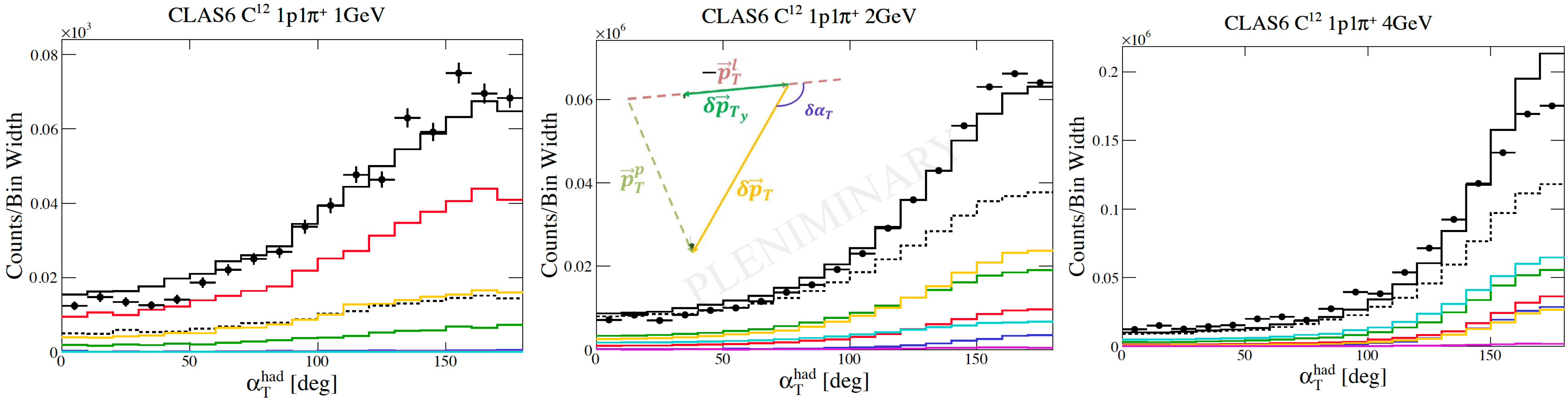




Improved shape description in $(e, e'1p1\pi^+)$ events

Semi-inclusive pion production
(12) Transverse Invariant Variables





$\delta\alpha_T$ is sensitive to mostly FSI

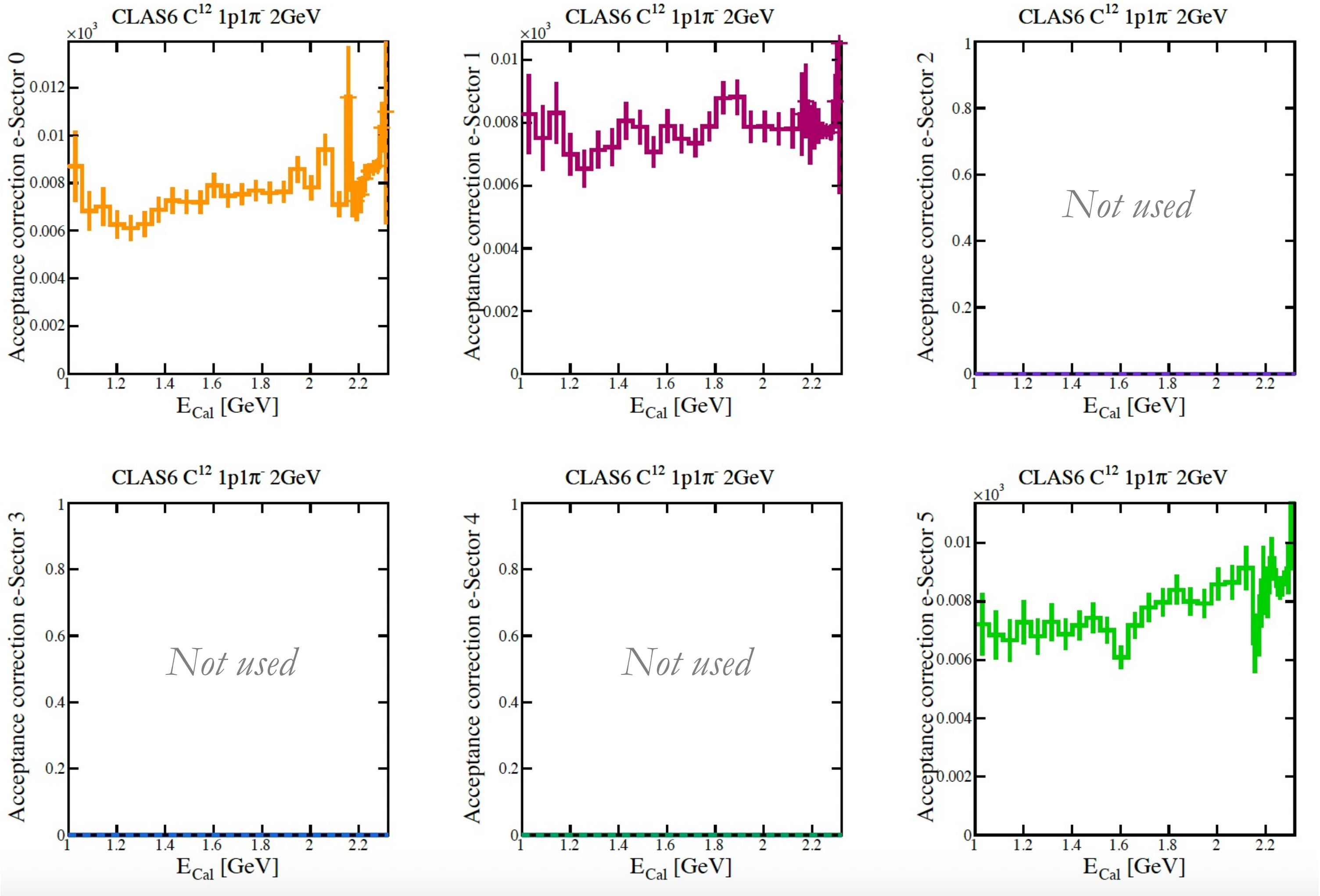
Excellent shape description of the data for all beam energies

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
  - Generalized background subtraction method available for future analyses
  - Focus on single-differential cross-section
  - Crucial input for the modelling of pion production in the nuclear media
- **Next steps for the analysis**
  - Systematic uncertainties
    - Focus on new background subtraction method systematics
  - Radiative correction
  - Cross-section measurement

Backup slides

Acceptance correction per sector

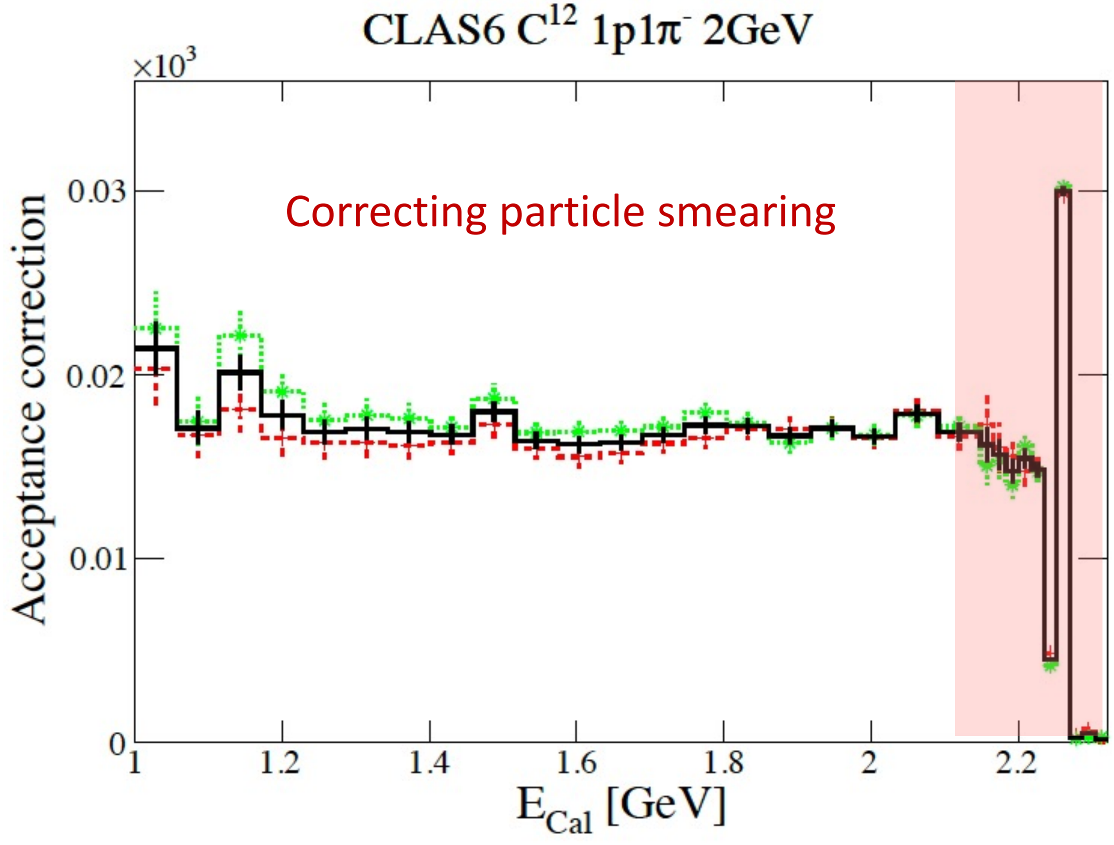


Acceptance correction

(*) 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	✗	✓



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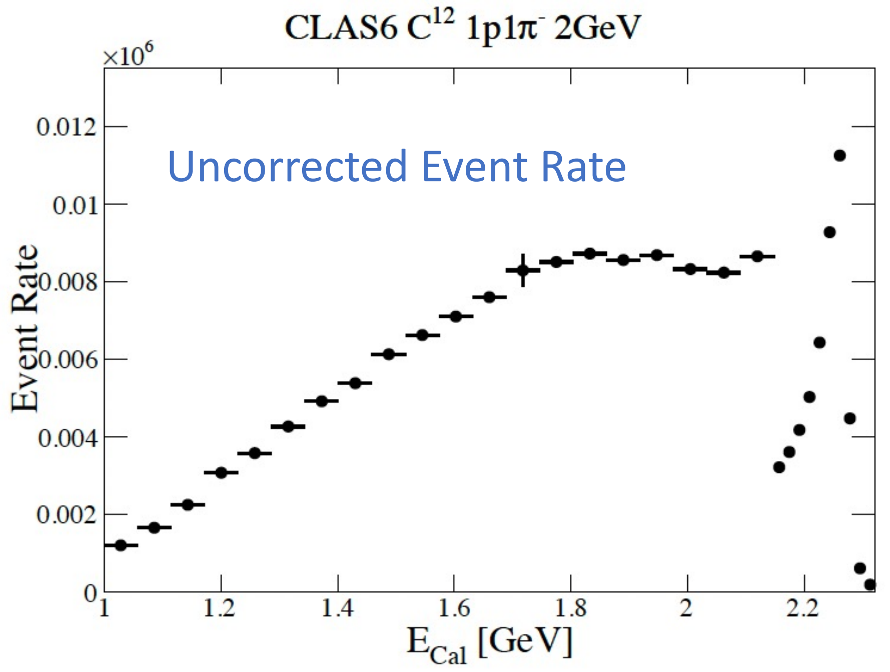

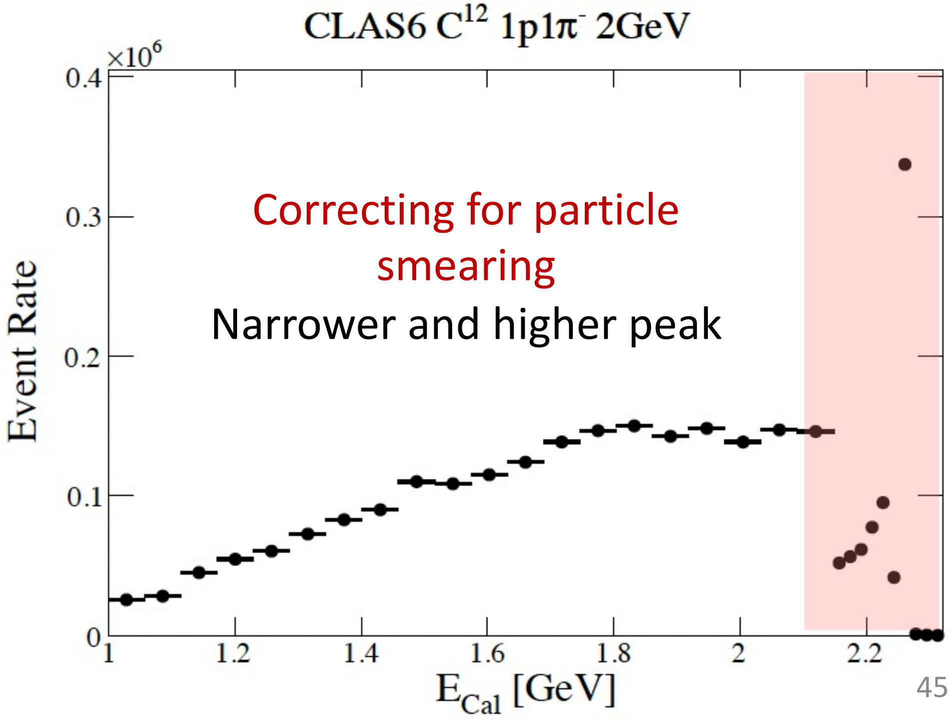

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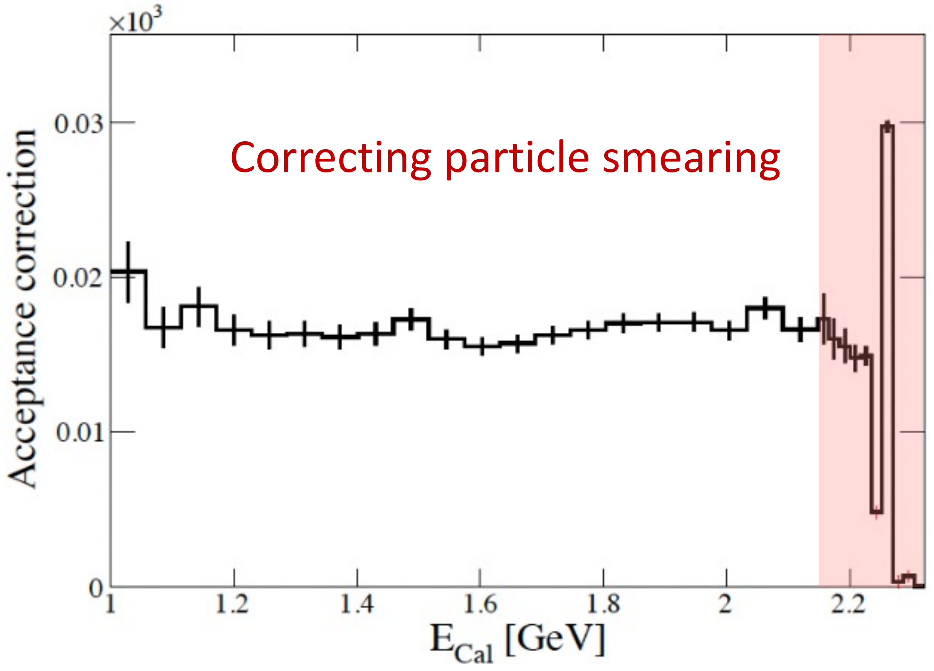
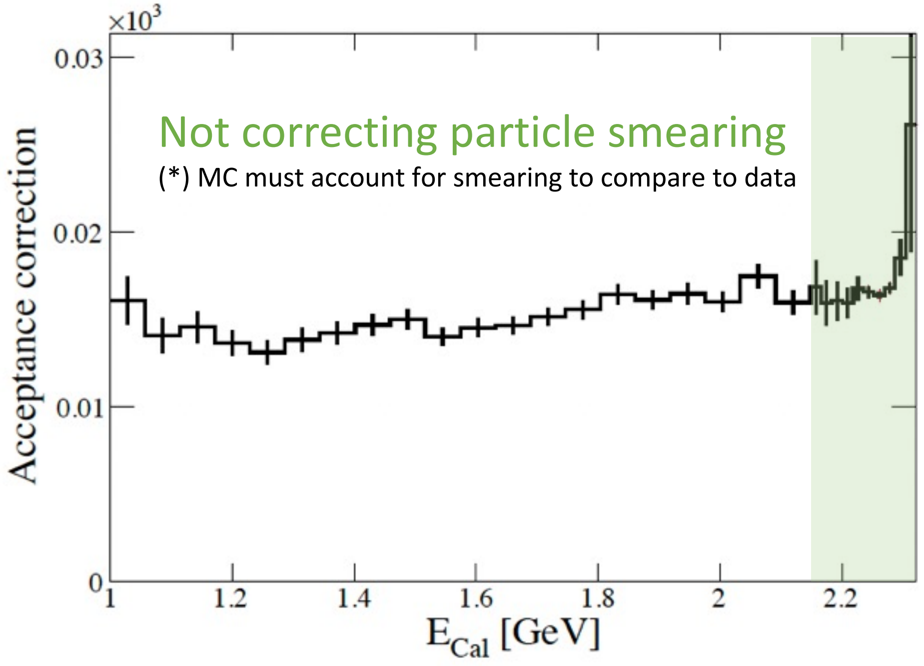
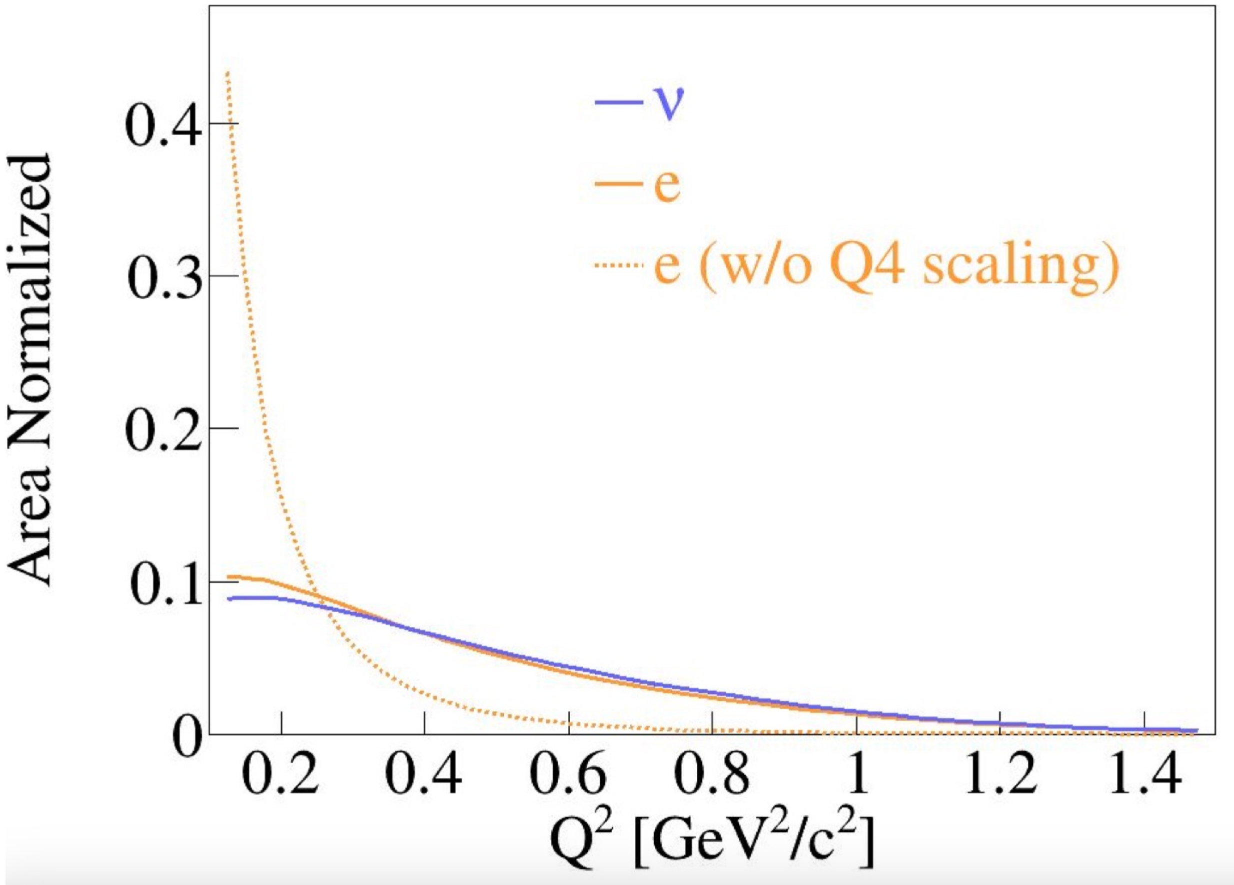


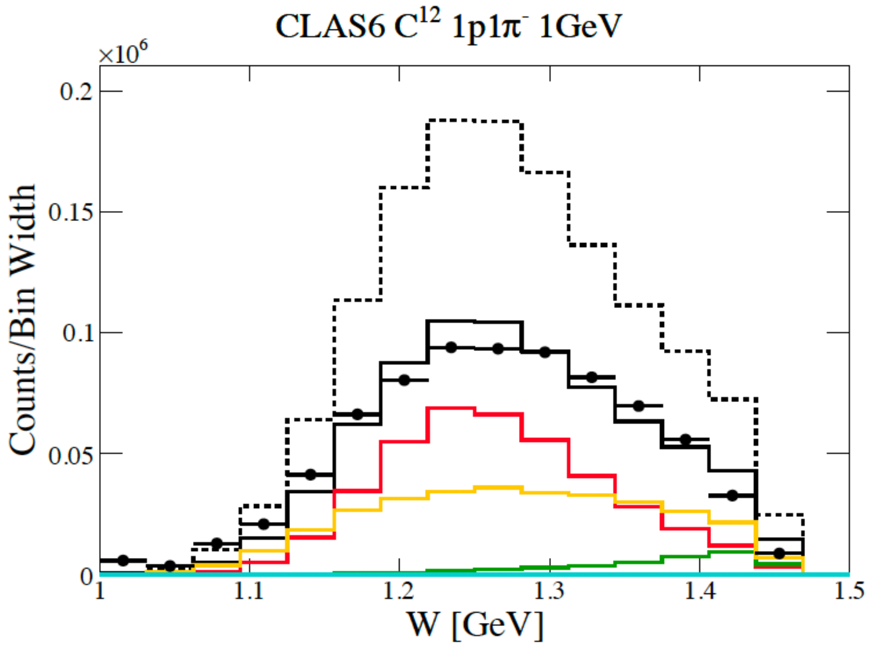


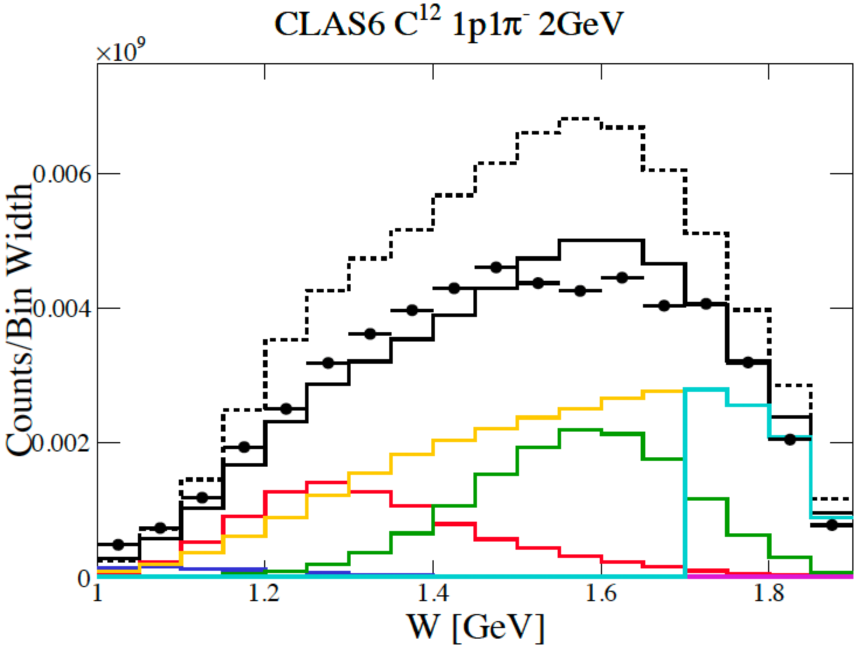
Q4 Scaling



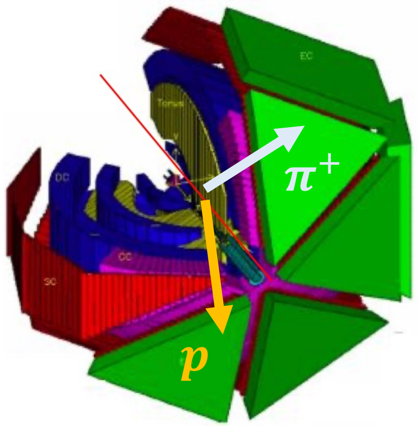
ν
e
e (w/o Q4 scaling)
Area Normalized
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Q2 [GeV2/c2]

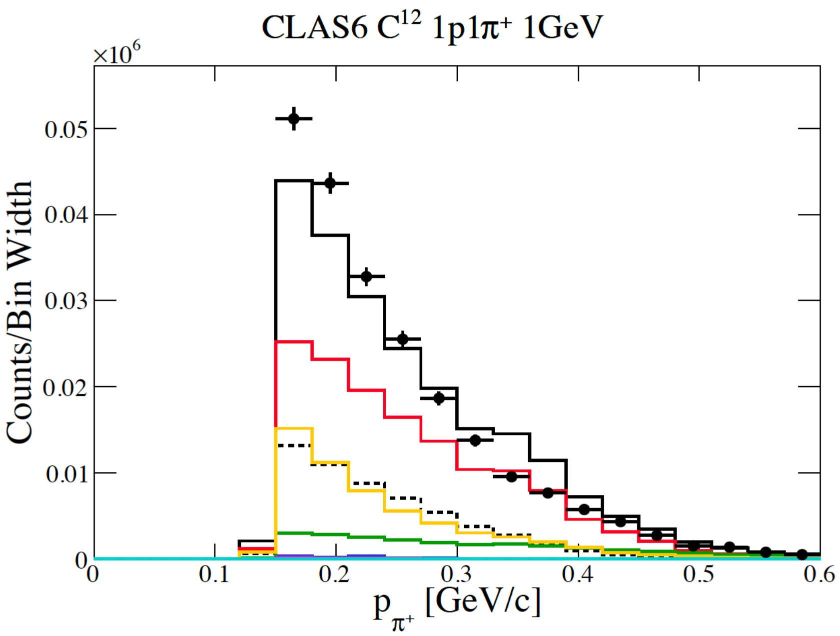
Semi-inclusive pion production with CLAS6 (6) Final state kinematics

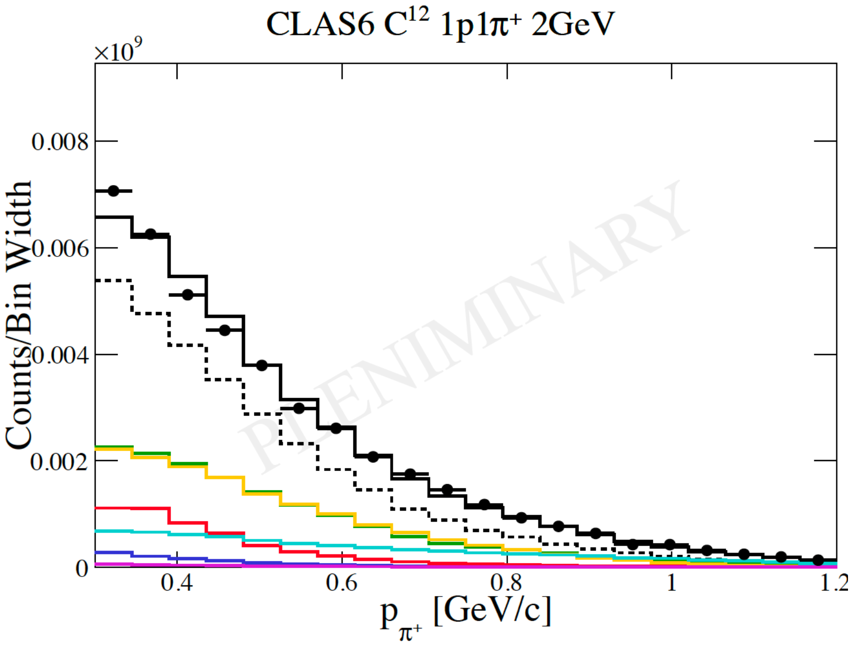


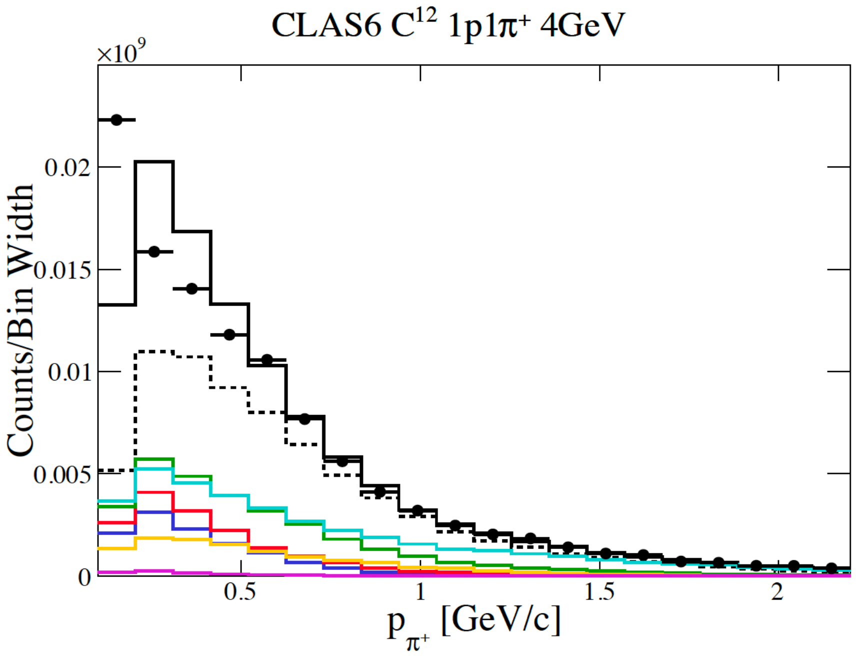


Semi-inclusive pion production (10) Final state kinematics









Semi-inclusive pion production
(10) Final state kinematics