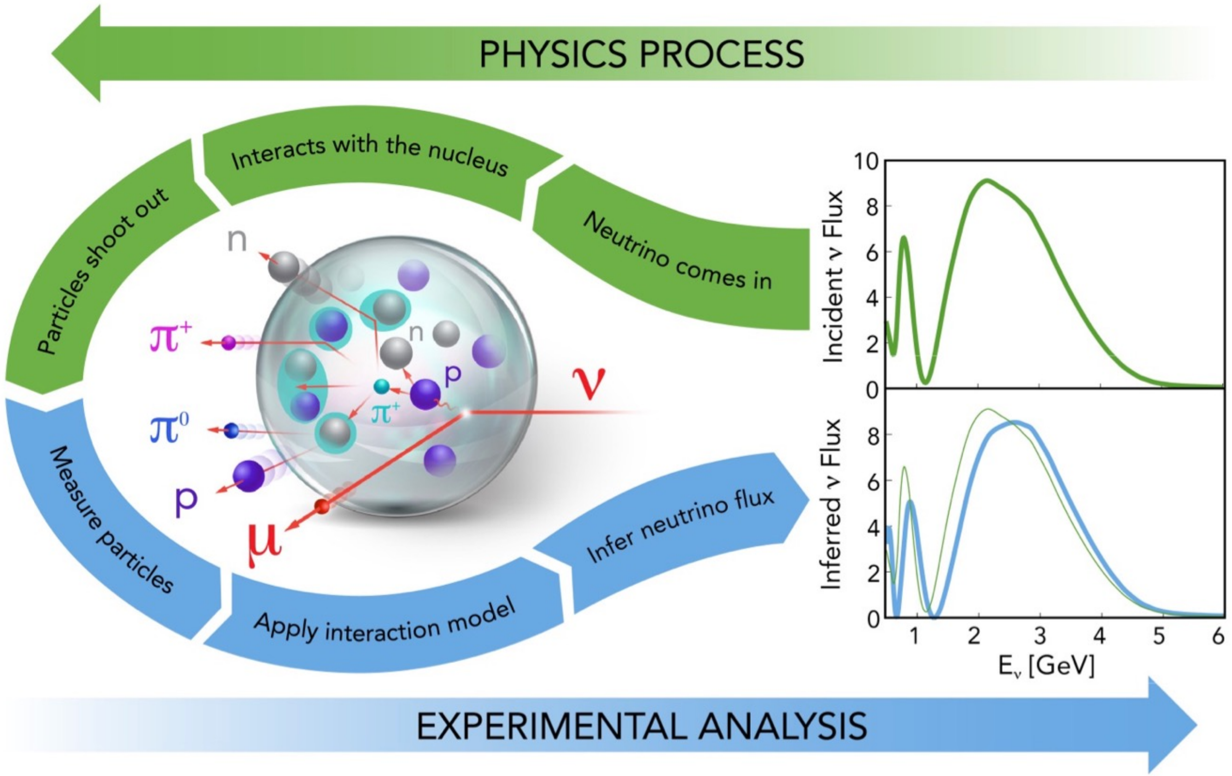
Electrons for Neutrinos

Julia Tena Vidal at Tel Aviv University
on behalf of the e4nu and CLAS collaborations

Introduction

- Global effort to improve lepton-nucleus scattering models for oscillation experiments



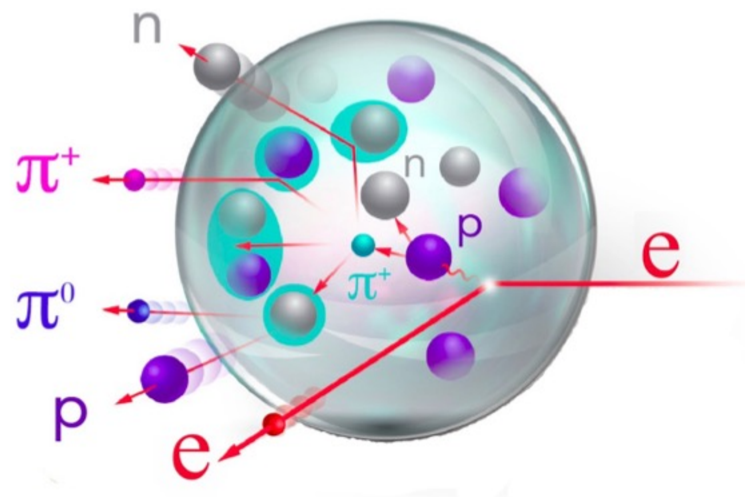
- **Unprecedented accuracy** in cross section models required by next generation neutrino oscillation experiments

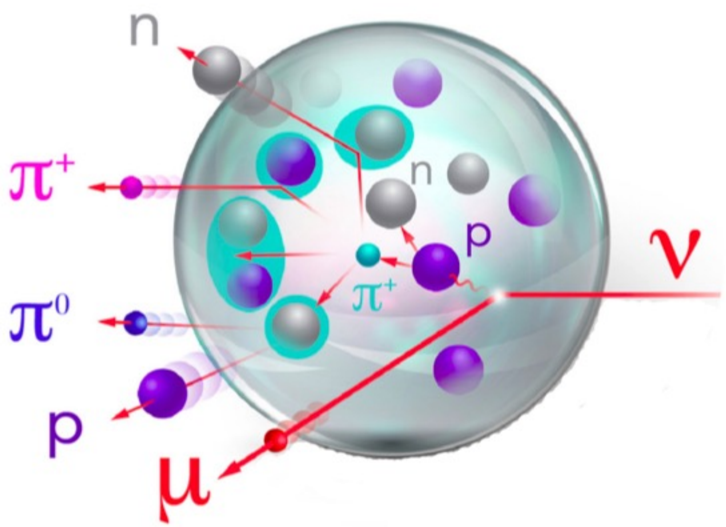
Electrons for neutrinos

- **Monochromatic** incident energy
  - Can choose kinematics focus on specific reaction mechanisms
- High statistics

- Similar interactions with nuclei
  - CC weak current [vector + axial]
    - $j_\mu^\pm = \bar{u}\frac{-ig_W}{2\sqrt{2}}(\gamma^\mu - \gamma^\mu\gamma^5)u$
  - EM current [vector]
    - $j_\mu^{em} = \bar{u}\gamma^\mu u$
- **Almost identical nuclear physics**

High quality constrains for neutrino event generators



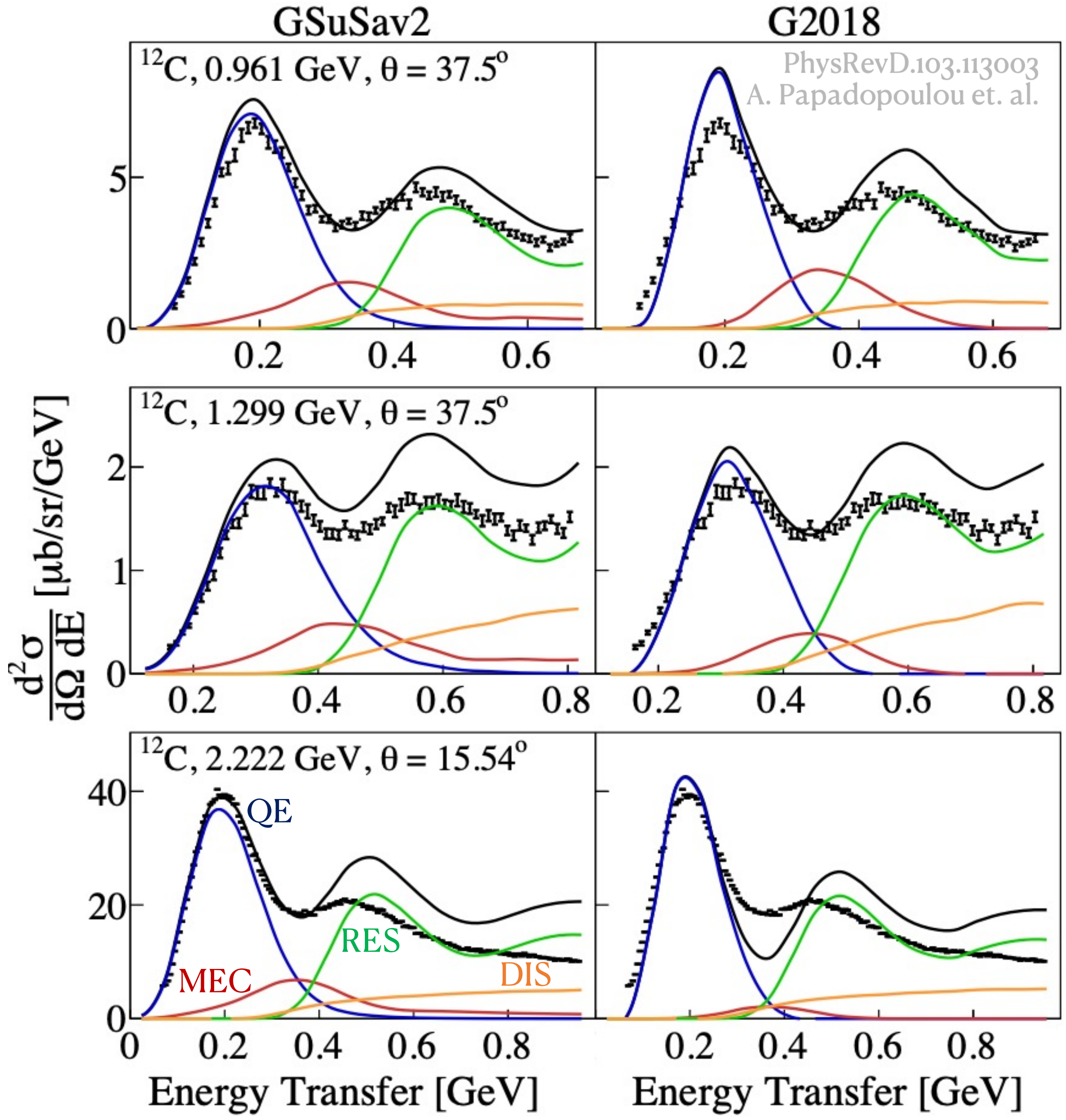


GENIE

http://tunes.genie-mc.org

- ν-A, $l^{\pm}$-A and h-A event generator
  - MeV to PeV, all flavours and targets
- Originally developed for neutrinos
- **Full description for electrons**
  - Only event generator in the market with all EM processes
  - Variety of models available
  - More comprehensive models to come

Nuclear model	LFG/RFG/CFG/SF
Final Sate Interactions (FSI)	hA/hN/INCL++/G4 (*) Identical for ν-codes
Quasielastic (QEL)	Rosenbluth/SuSAv2
2p2h (MEC)	Empirical/SuSAv2
Resonance (RES)	Berger-Sehgal
Deep Inelastic (DIS)	Bodeck-Yang

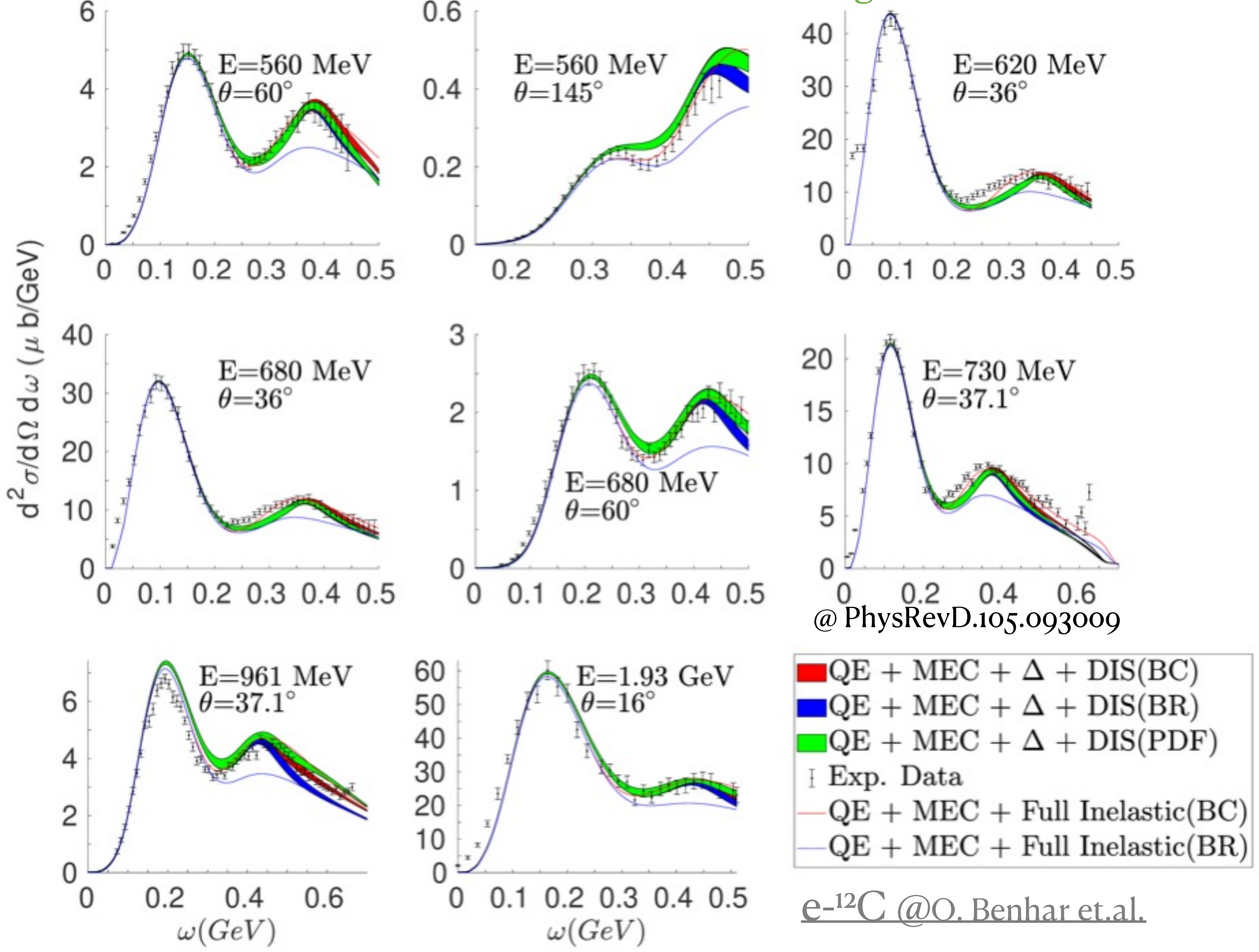


GENIE benchmarked against e-^{12}C data

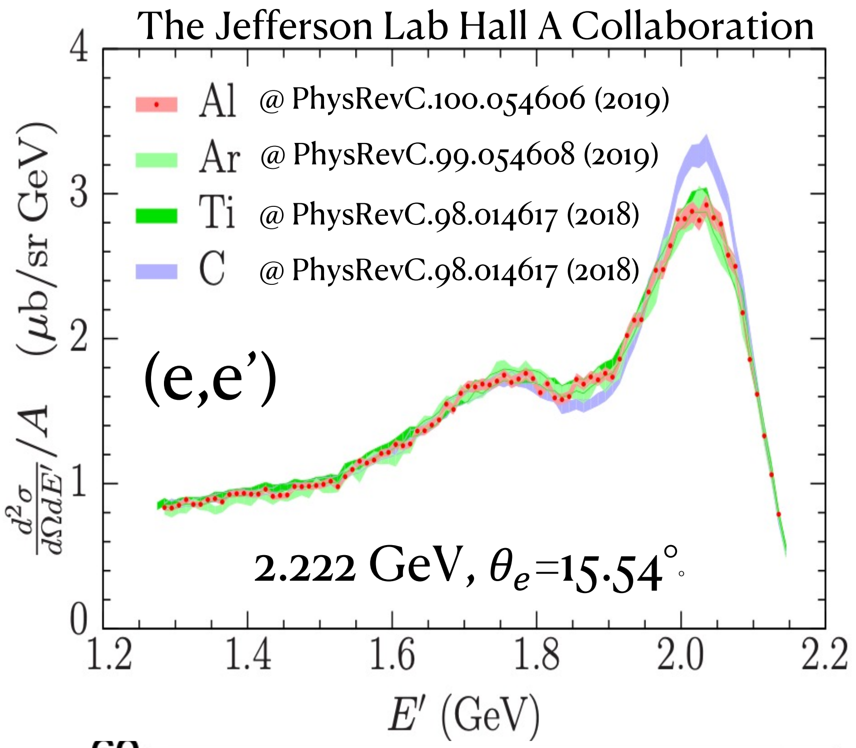
Inclusive measurements

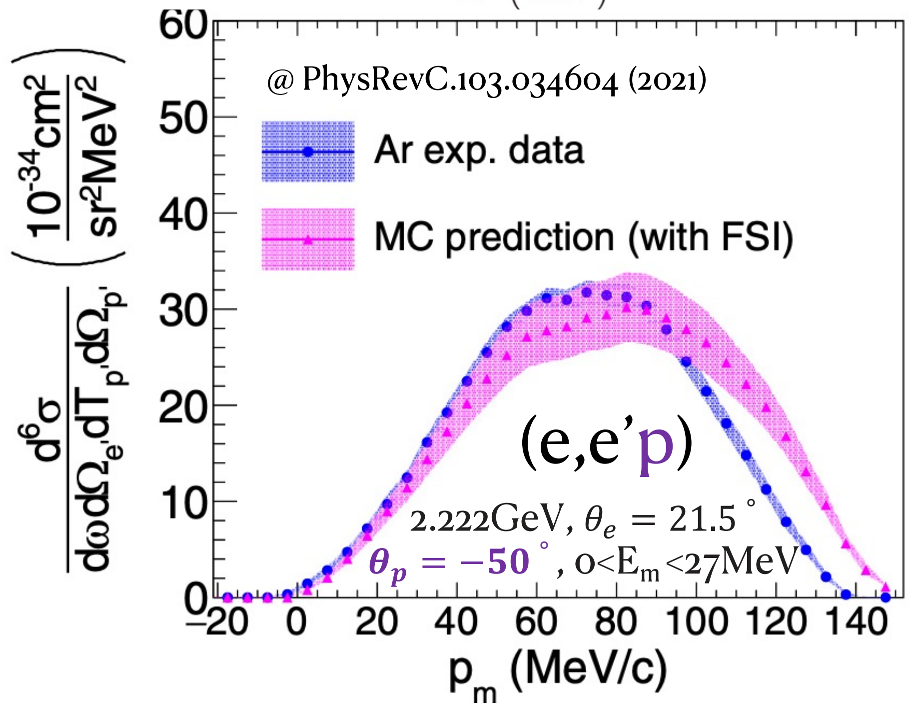
- Most electron-scattering measurements are inclusive
- Exclusive measurements are limited to specific kinematics
- **Lacking precise hadron production measurements**

SuSAv2 model extension to inelastic regime



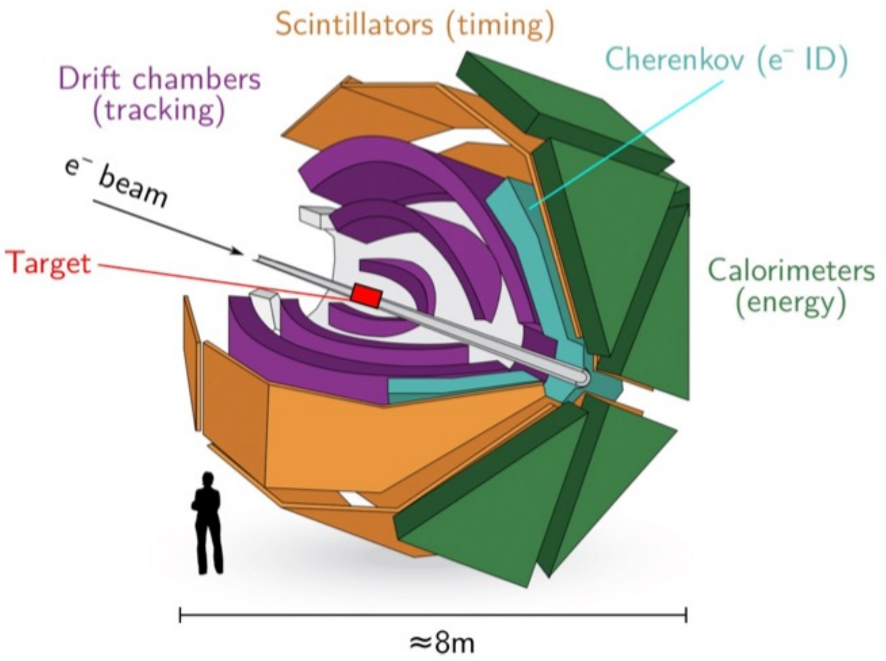
e-12C @O. Benhar et.al.

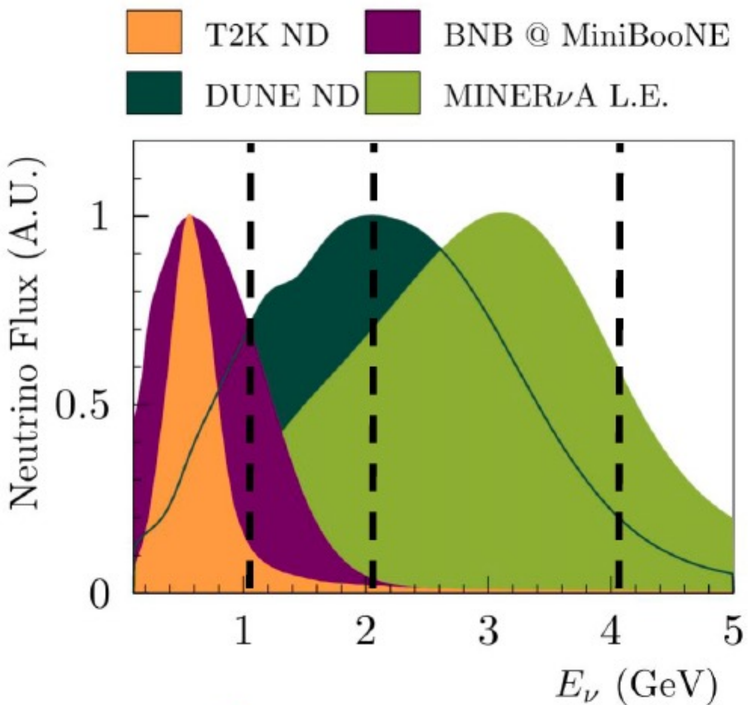




Hadron production with CLAS6

- Large acceptance @ $\theta_e > 15°$
- ~50% of "4π" coverage
- Charged particle threshold comparable to neutrino tracking detectors
  - 300 MeV/c for p and γ
  - 150 MeV/c for $\pi^{\pm}$
  - Magnetic field disentangles charge
- Beam energies of interest for ν:
  - 1.1, 2.2 & 4.4 GeV
- Targets ^{4}He, C & Fe



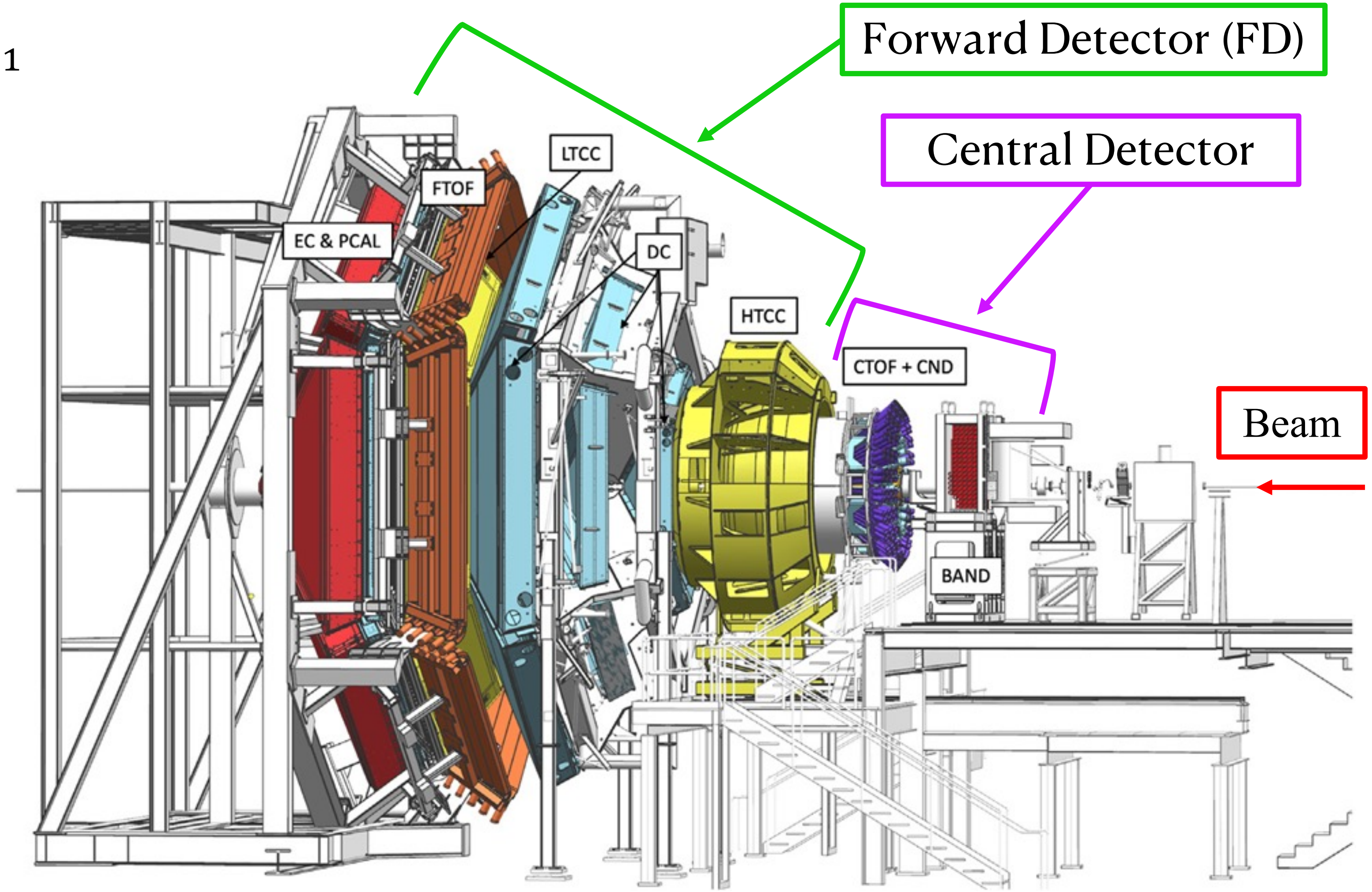


The CLAS12 detector

- **Maximal luminosity:** $10^{35}\ cm^{-2}s^{-1}$
  - **10 times larger than CLAS6**
- **Large acceptance ($\sim 4\pi$)**
  - Improved acceptance @ $\theta_e > 5°$
- **Detection thresholds:**
  - 400 MeV/c for p and n
  - 200 MeV/c for $\pi^{\pm}$
  - 300 MeV/c for γ
  - **Can detect neutrons**
- Open trigger
- Magnetic field

Acquired data:

- **Energies:** 2, 4, 6 GeV
- **Targets:** H, D, ^{4}He, ^{12}C, **^{40}Ar** and more



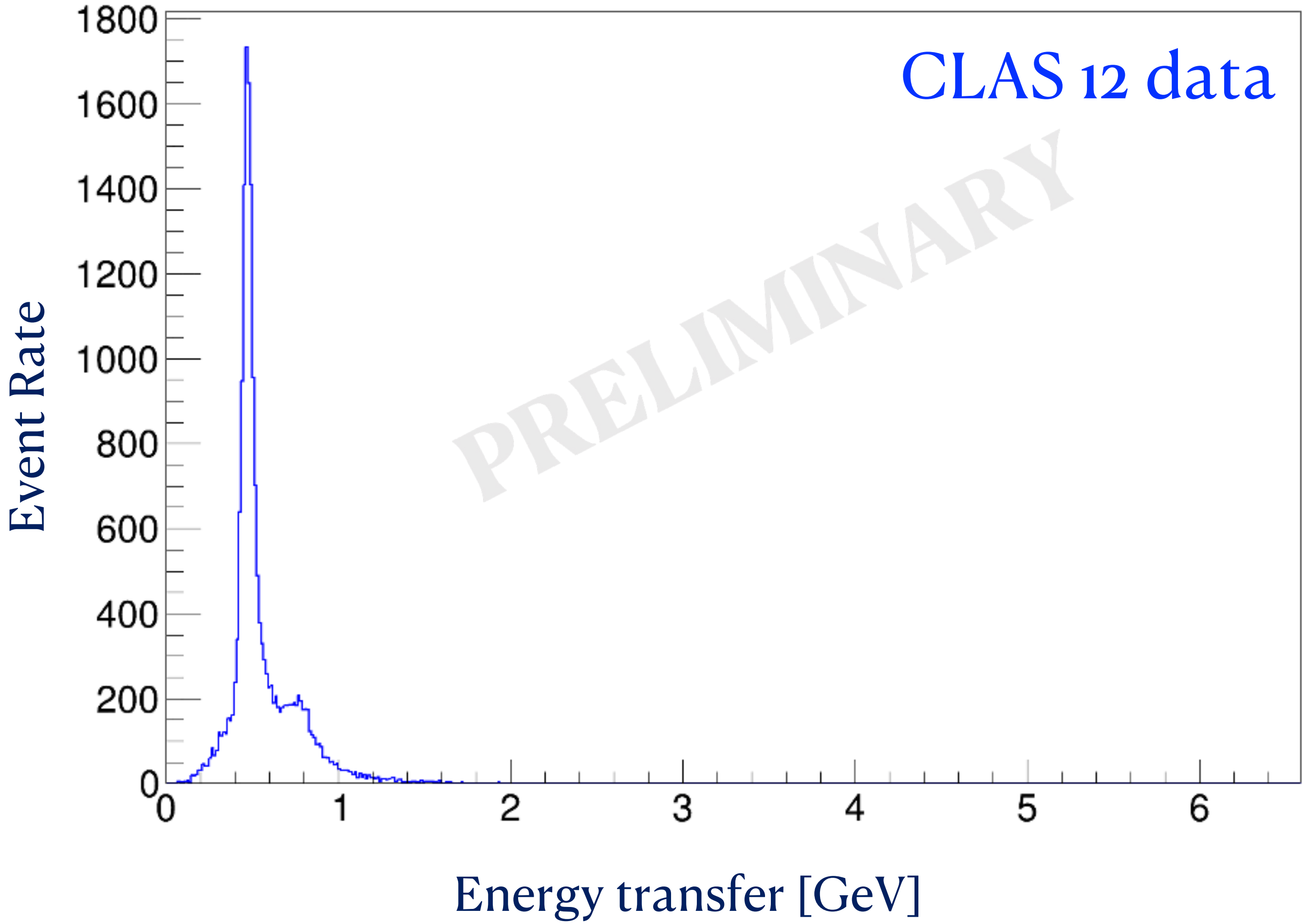
https://doi.org/10.1016/j.nima.2020.163419

Jefferson Lab

Inclusive (e,e') at multiple angles and targets

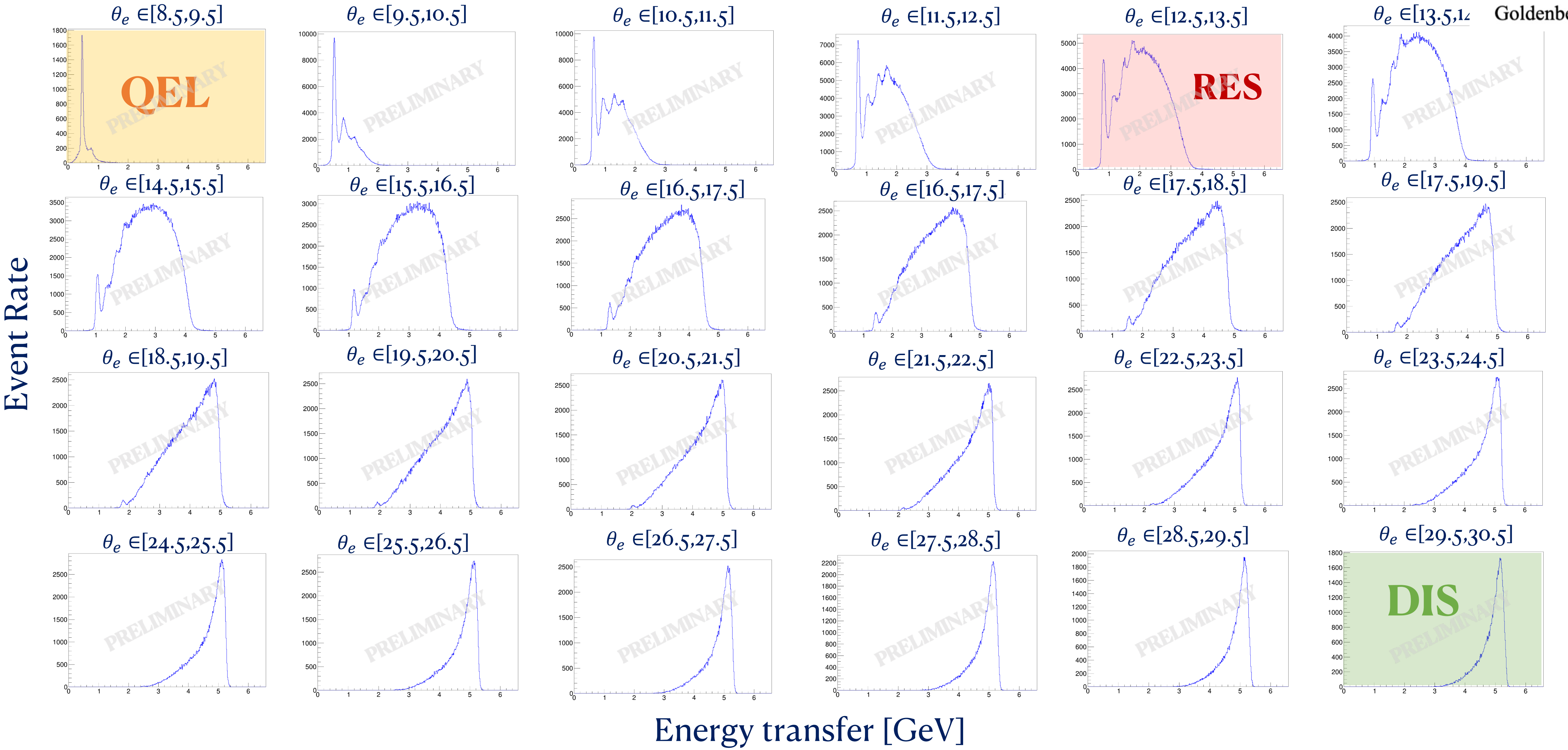
^{2}H at 6GeV

$\theta_e \in[10.5, 39.5]$ deg with 1deg steps



Inclusive (e,e’) at multiple angles and targets

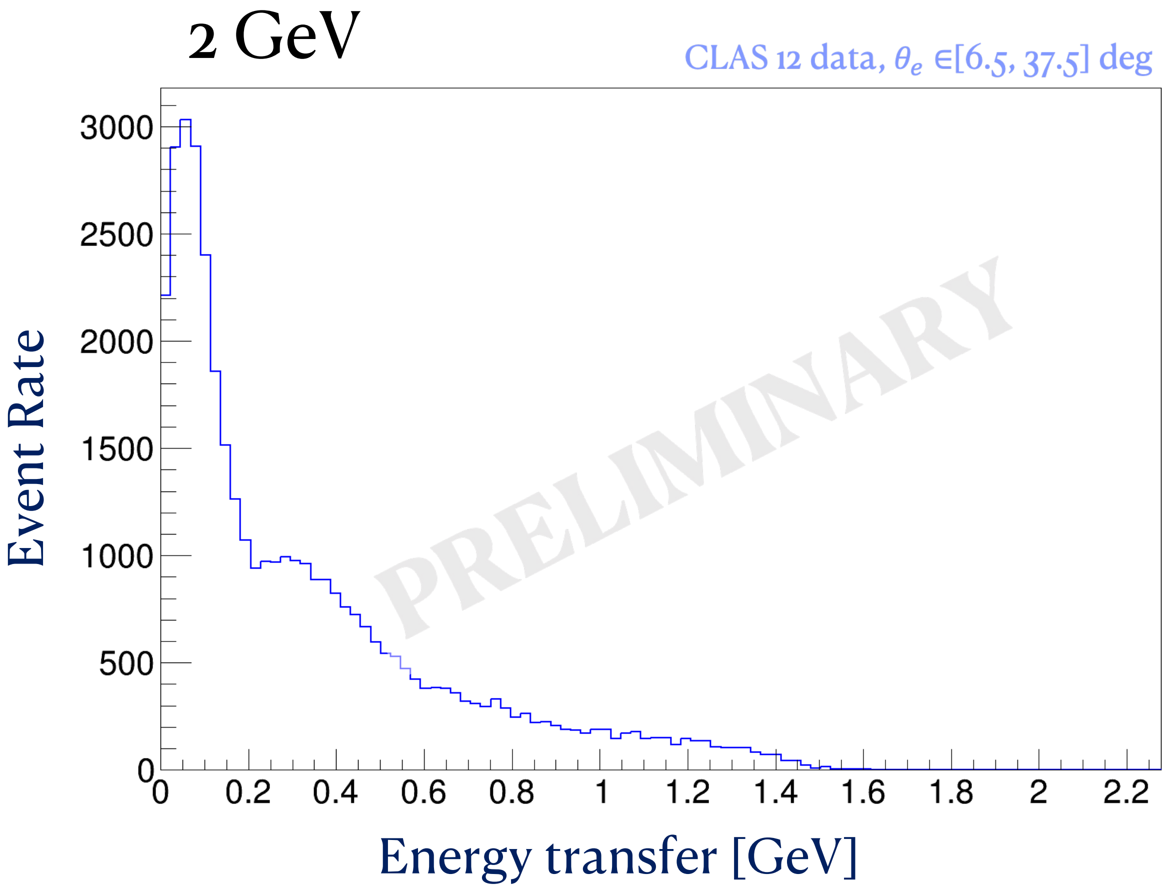
Matan Goldenberg

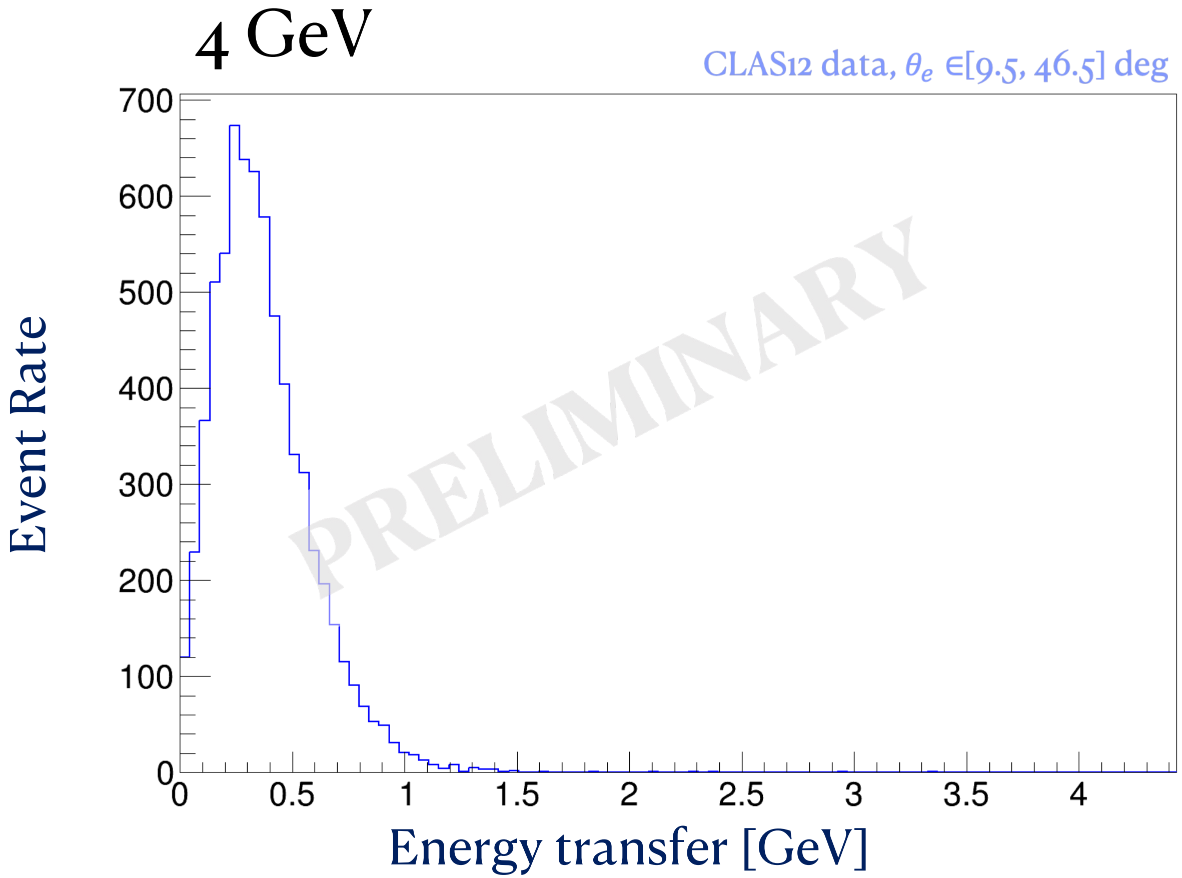


Inclusive (e,e') at multiple angles and targets

Matan Goldenberg

^{40}Ar



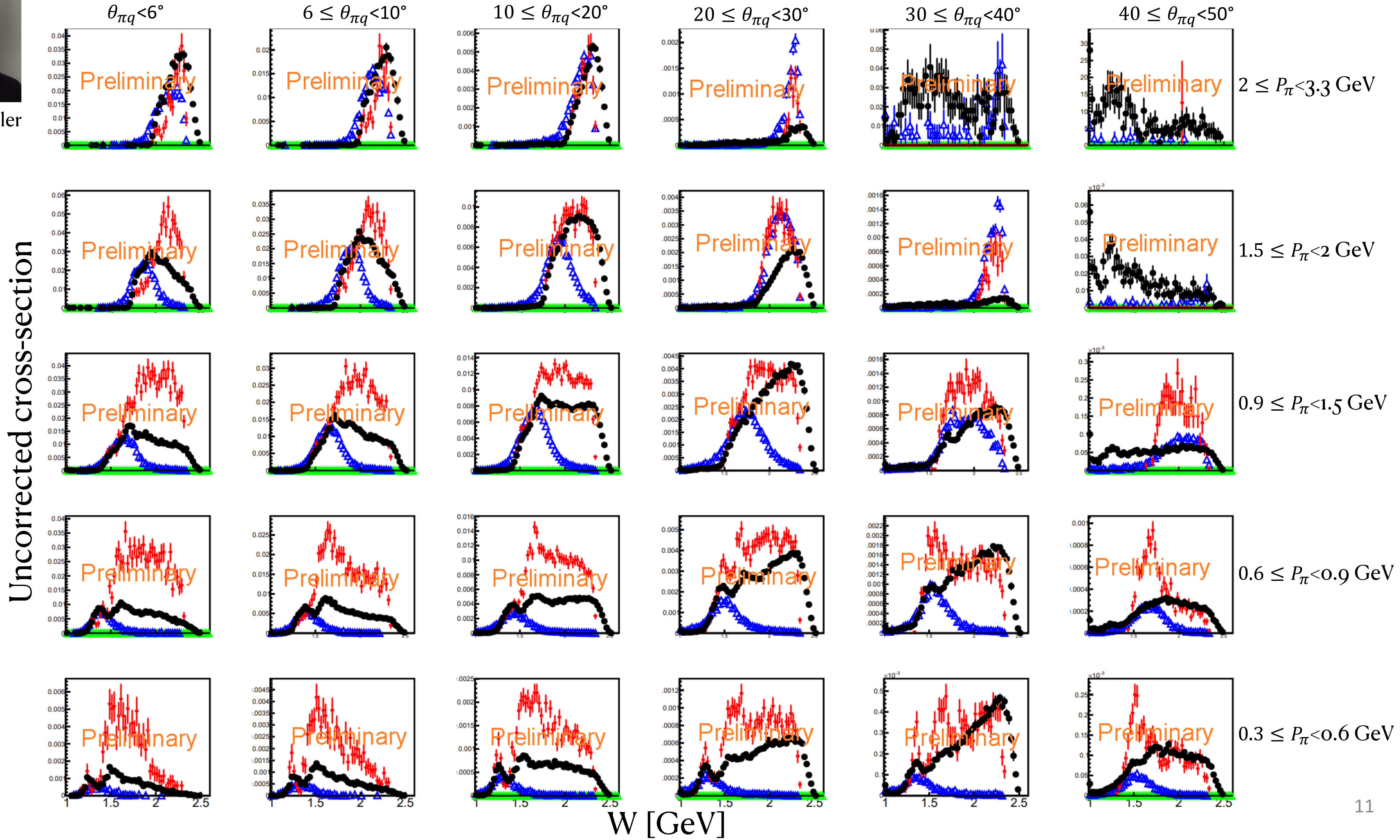


$^{2}H(e,e'\pi^{+})$ at 4 GeV

$0.7 < Q^2 < 1$ GeV^2

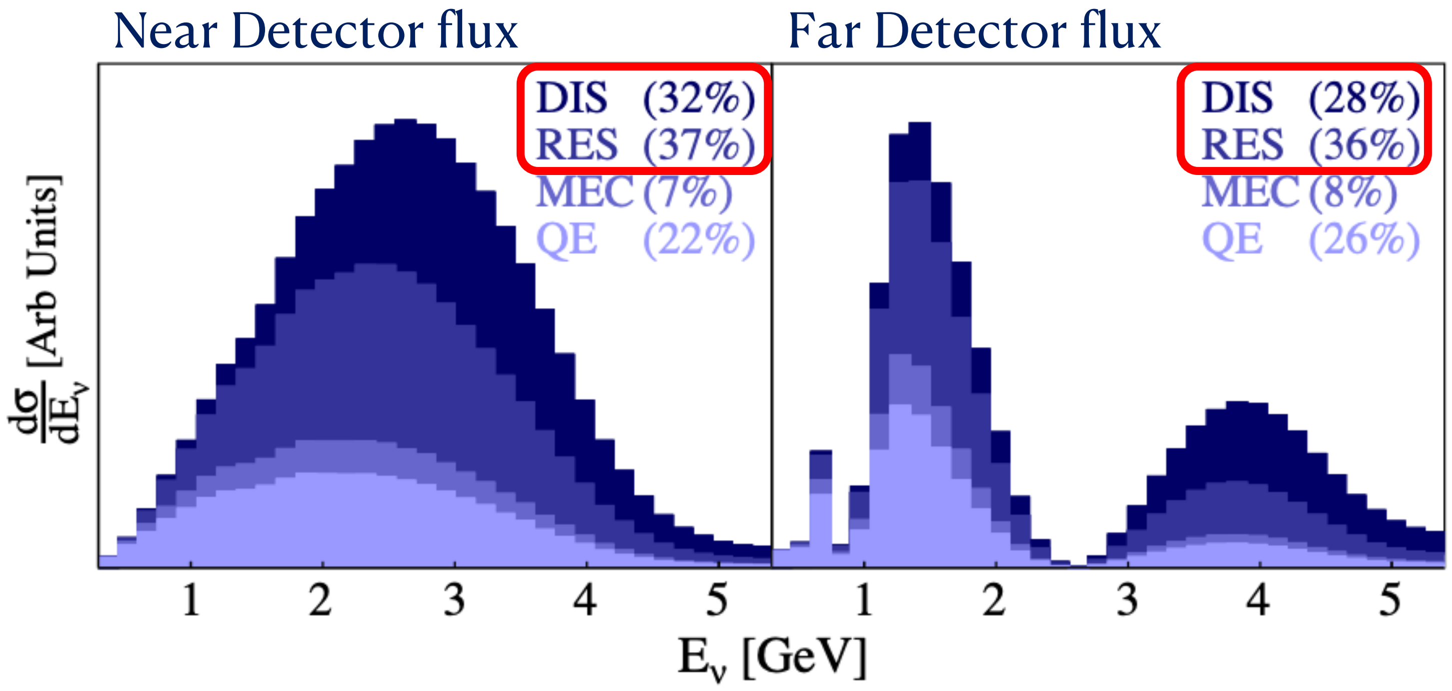
More Q^2 slices available
^{40}Ar measurement to come

by Caleb Fogler



Pion production dominated era

DUNE will be dominated by pion production events

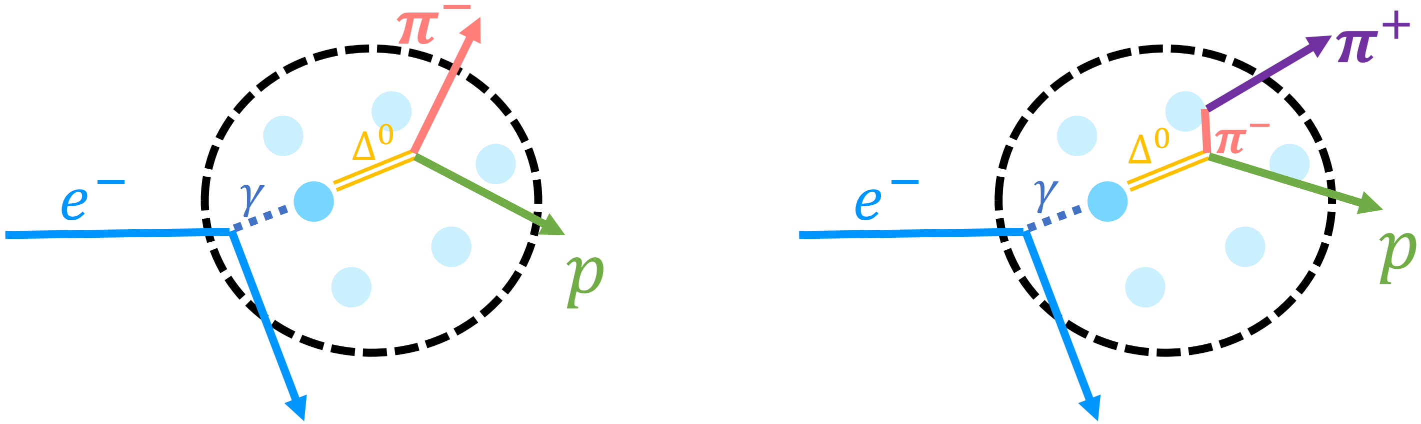


Exclusive data crucial to validate and improve models

Pion production

- First e4nu electron-scattering pion production analysis: $\mathbf{1p1\pi^-}$ and $\mathbf{1p1\pi^+}$

  with no detected γ any number of neutrons
- **1, 2 and 4 GeV** e2a CLAS6 data
- ^{12}C (^{4}He and ^{56}Fe to come)
- $\mathbf{1p1\pi^-}$: possible at the free nucleon level
- $\mathbf{1p1\pi^+}$: needs two or more nucleons → undetected particles (FSI!)

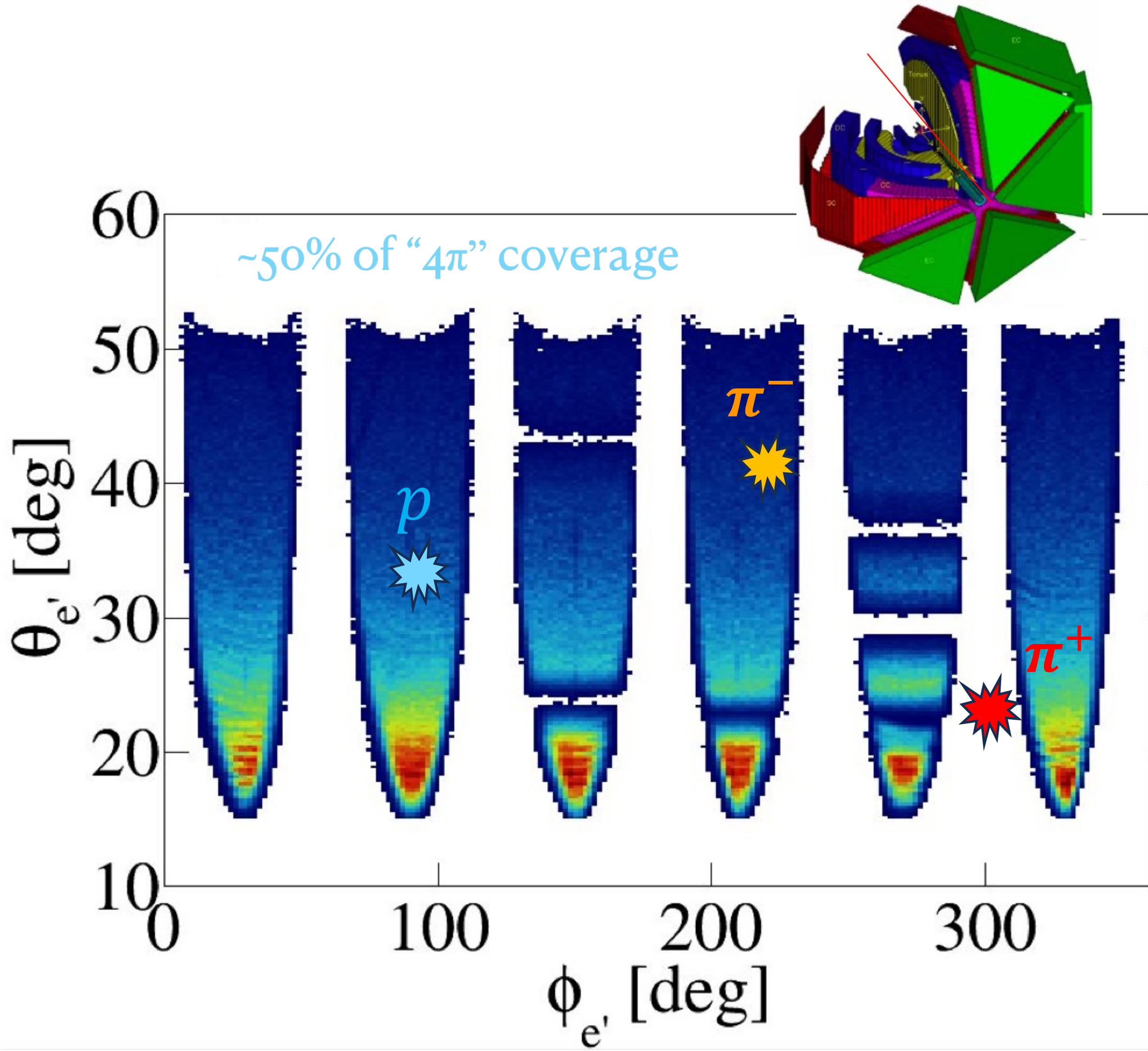


Pion production analysis with CLAS6 Background contamination

- **Particles below threshold**
  - p_p and $p_\gamma > 300\ MeV$
  - $p_{\pi^\pm} > 300\ MeV$
  - $\theta_p > 12\ deg$
  - $\theta_\gamma > 8\ deg$
  - $\theta_{\pi^\pm} > 12\ deg$
  - Data not corrected for this
  - Same cuts applied to simulation

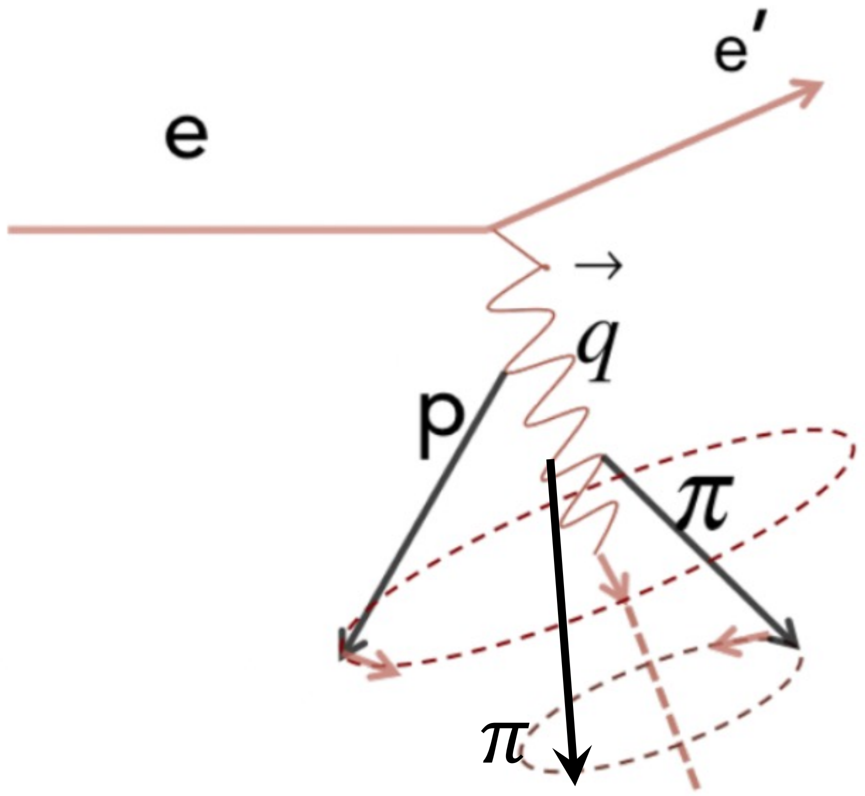
1p1$\pi^{\pm}$ analysis: background contamination

- **Not full "4π" coverage**
  - Gaps between the sectors
  - Gaps within a sector
  - **"Data driven" background subtraction**



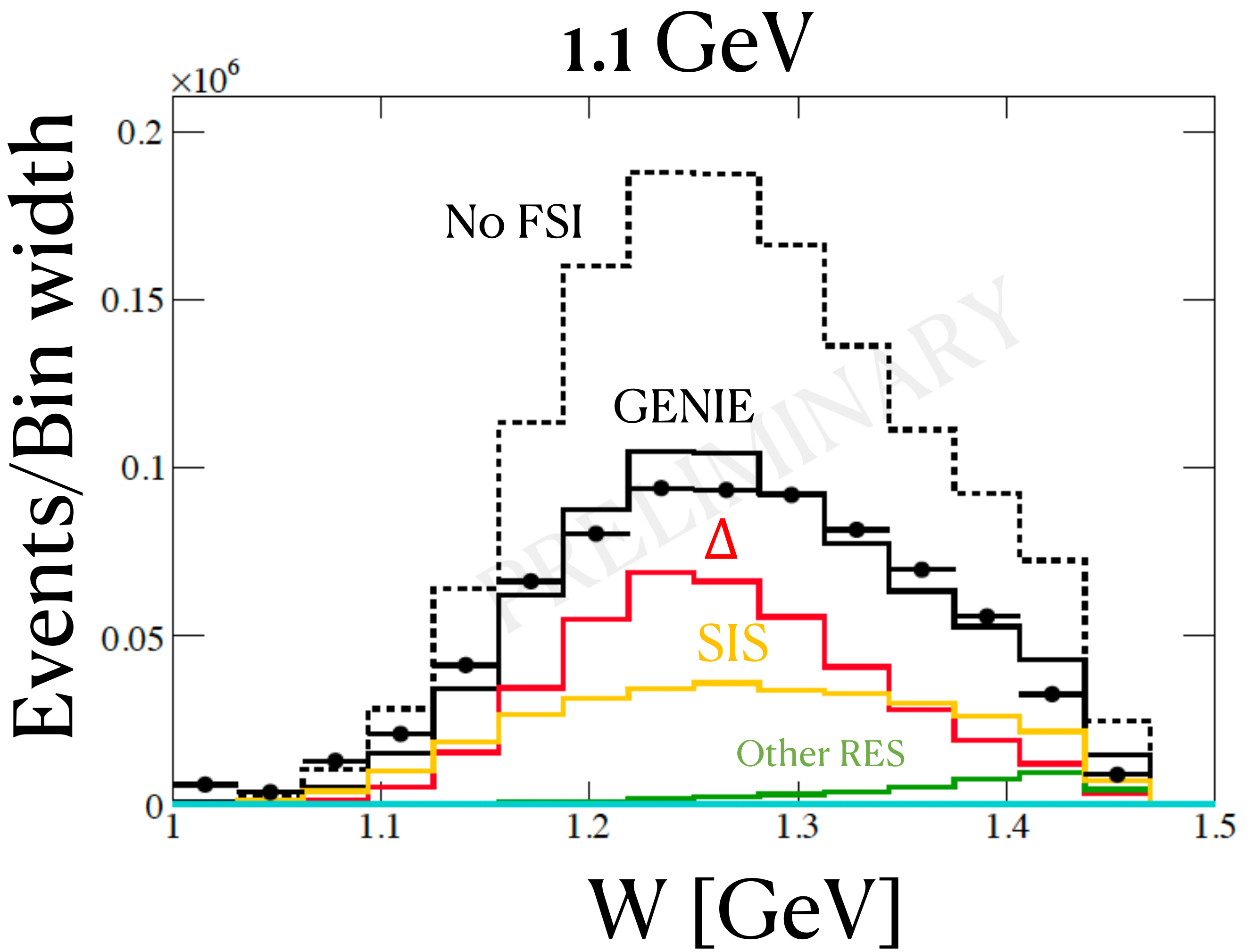
1p1$\pi^{\pm}$ analysis: background contamination

- **"Data driven" background subtraction**
  - **Rotate detected background event N times around $\vec{q}$**
    - Compute probability to be detected as signal (P_{signal})
    - Add pseudo-event weighted by P_{signal}
    - 1% $\phi_{\vec{p}\cdot\vec{q}}$-dependence on cross-section

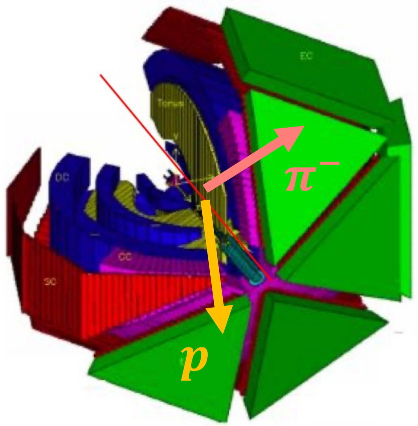


$^{12}C(e,e'1p\pi^{-})$

- GENIE normalized to data event rate
- Data corrected for bkg. events, $e/p/\pi^{\pm}$ acceptance and detection eff.
  - Not radiative corrected yet
  - Only statistical errors



$^{12}C(e,e'1p\pi^-)$ – Pion momentum



- GENIE GEM21_11a
- GEM21_11a EMRES P33(1232)
- GEM21_11a EMSIS
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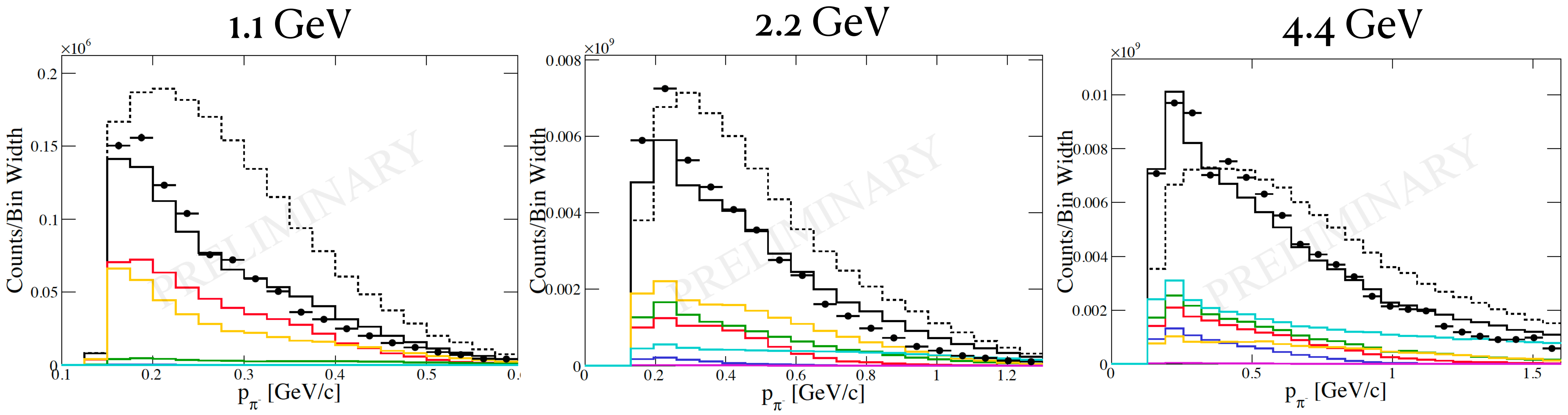
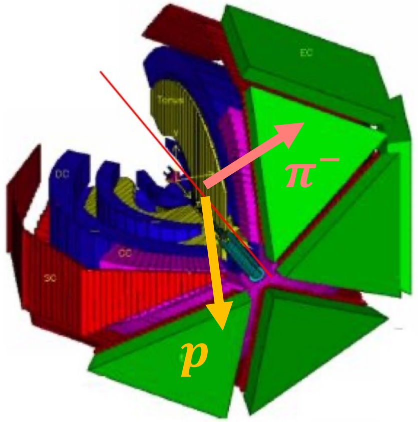
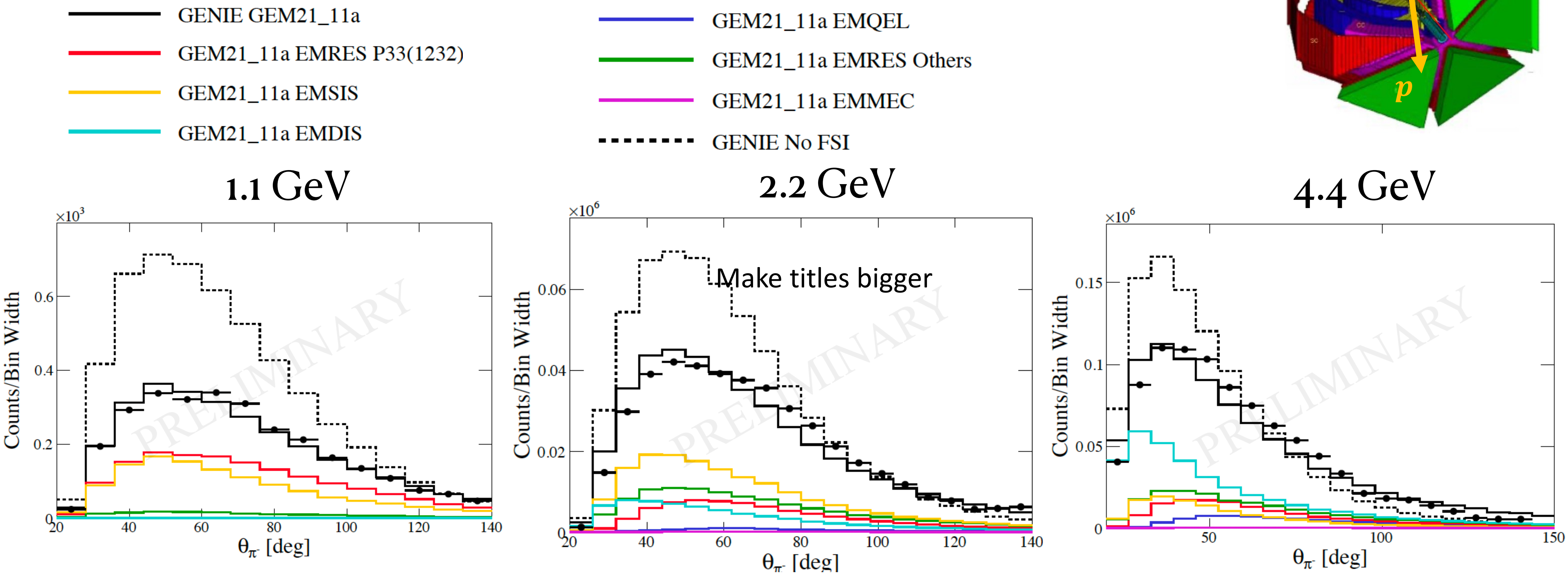
- GEM21_11a EMQEL
- GEM21_11a EMRES Others
- GEM21_11a EMMEC
- GENIE No FSI



Shape well described by GENIE
FSI needed

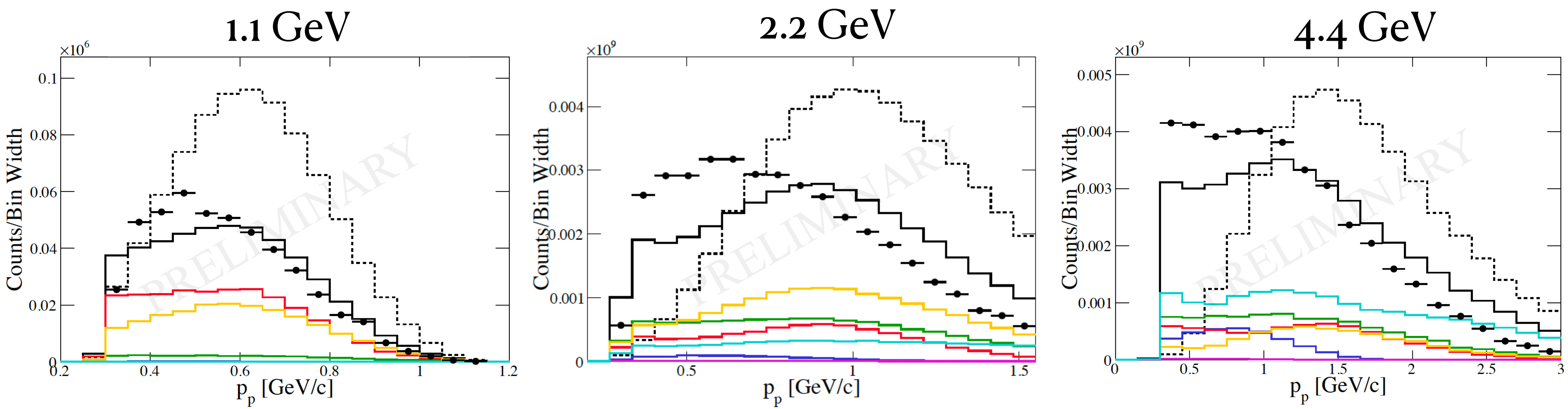
$^{12}C(e,e'1p\pi^-)$ – Pion angle

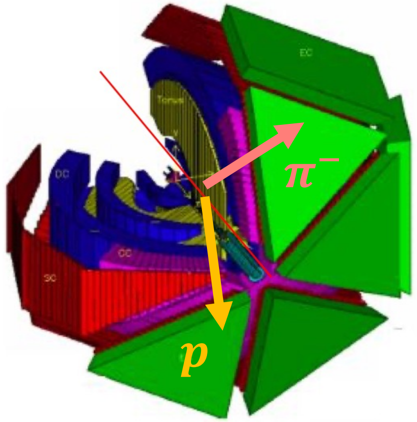




Angular shape in good agreement with GENIE

$^{12}C(e,e'1p\pi^-)$ – Proton momentum

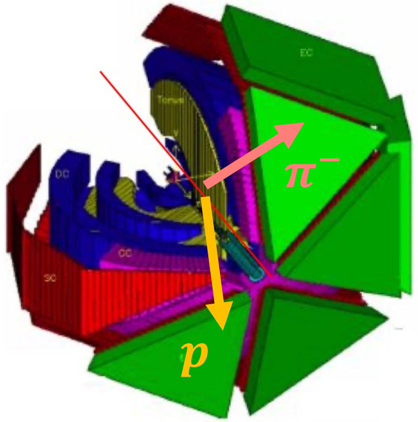


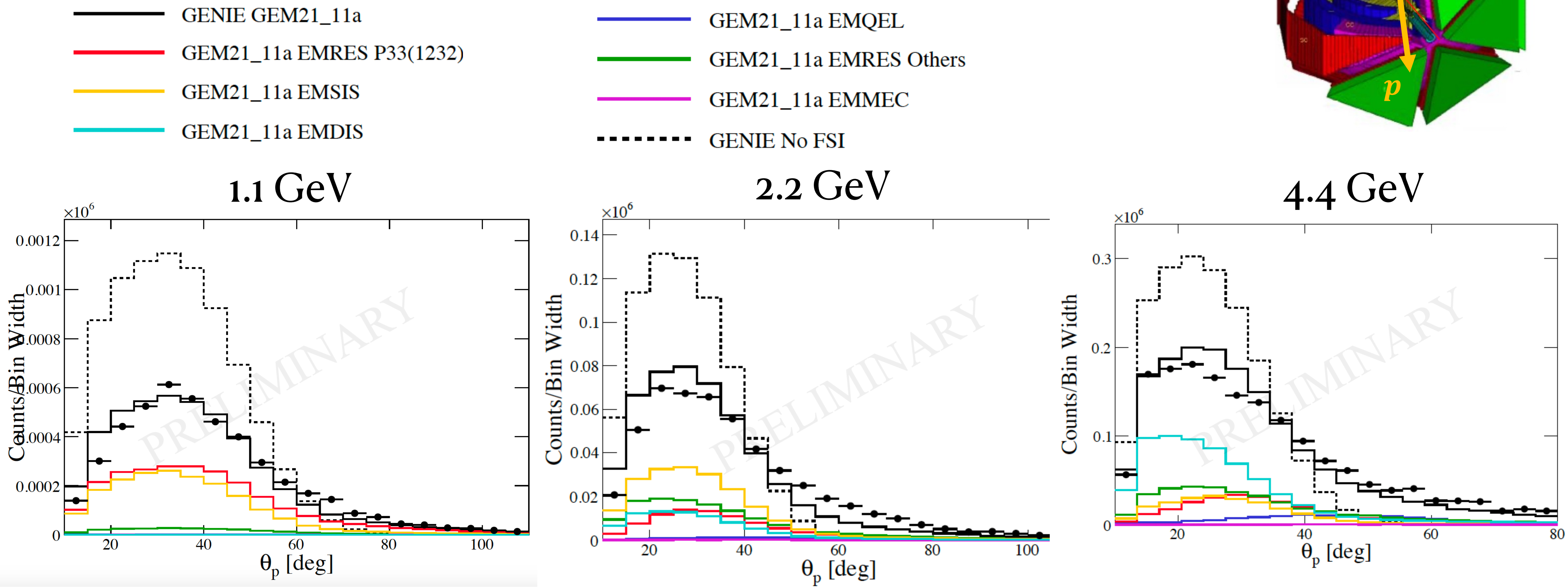


Change to 0 proton mom

Low momentum protons are not described by MC
Sensitive to FSI

$^{12}C(e,e'1p\pi^-)$ – Proton angle

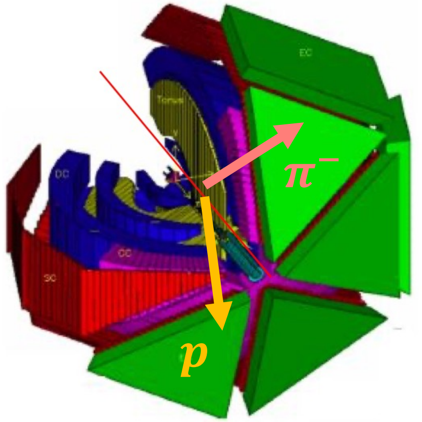




Angular shape in good agreement with MC

High θ_p possible only due to FSI

$^{12}C(e,e'1p\pi^-)$ – Transverse boosting angle



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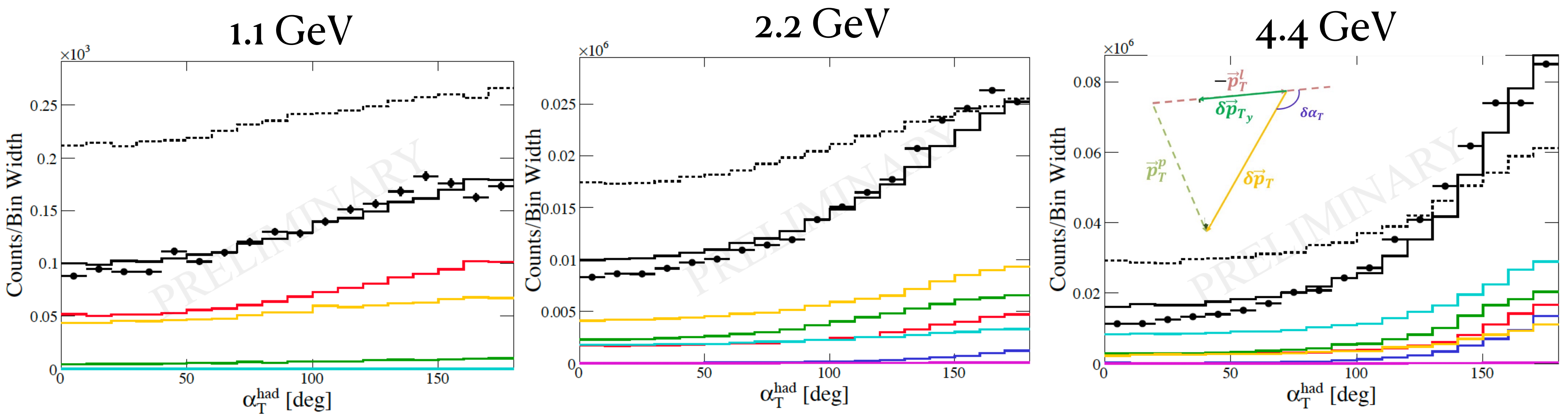
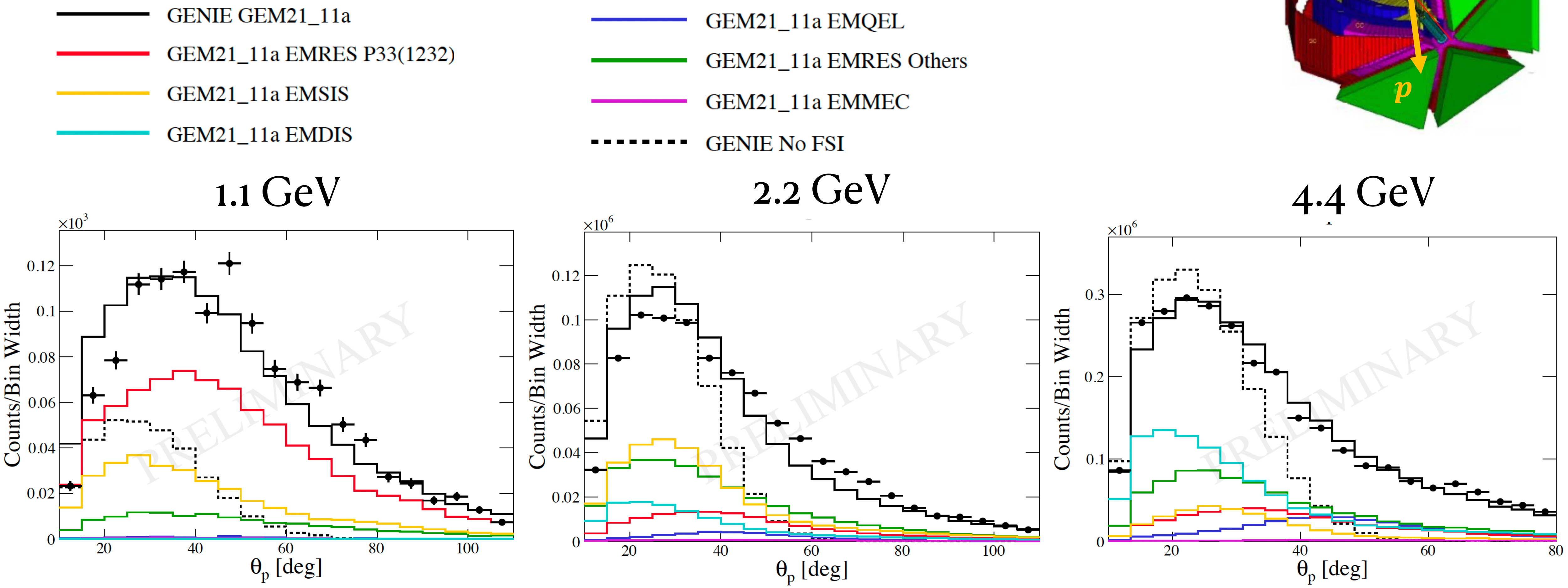
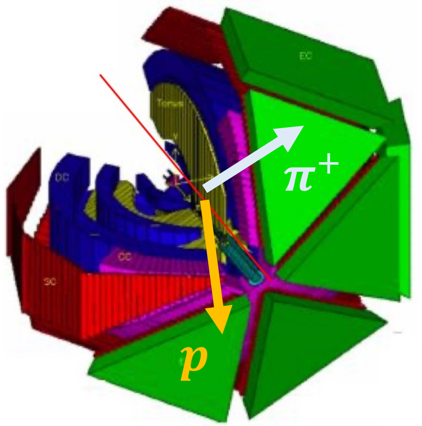


$\delta\alpha_T$ is sensitive to mostly FSI

Excellent shape description

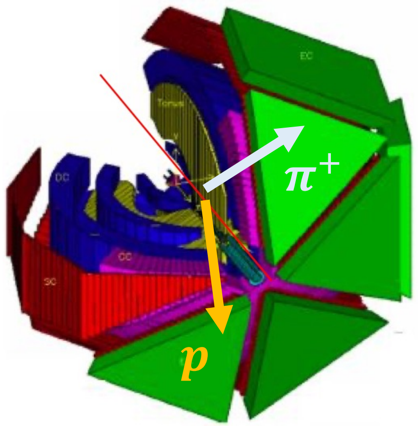
$^{12}C(e,e'1p\pi^{+})$ – Proton angle





FSI crucial to describe data

^{12}C(e,e'1pπ^+) - proton momentum



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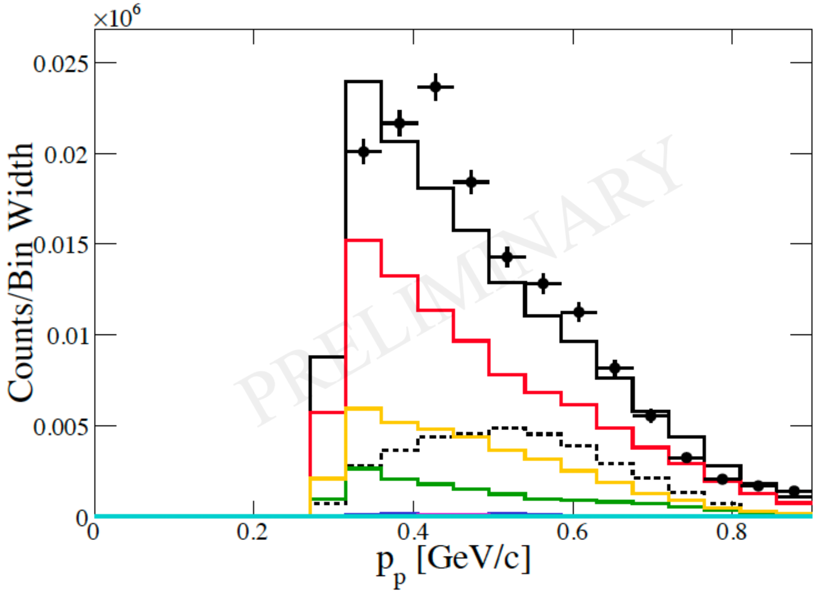
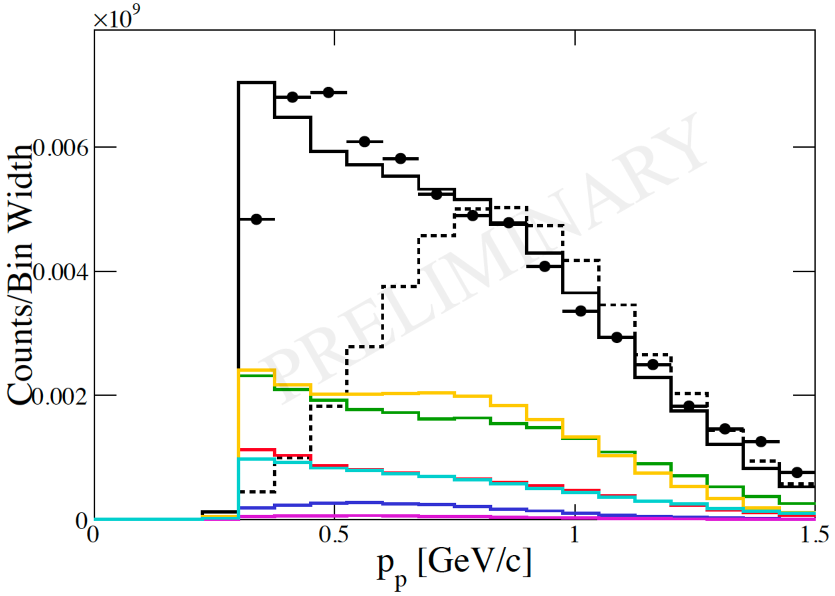
GENIE No FSI

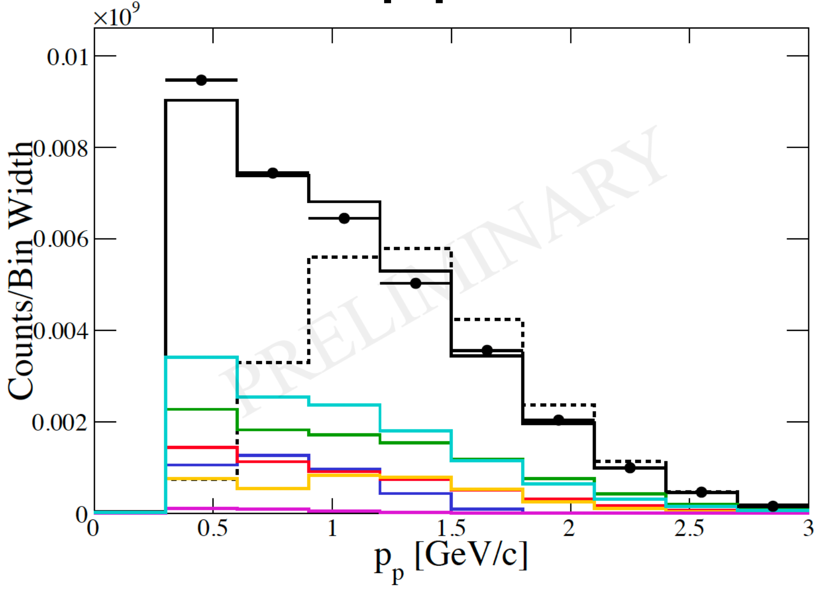
1.1 GeV



2.2 GeV

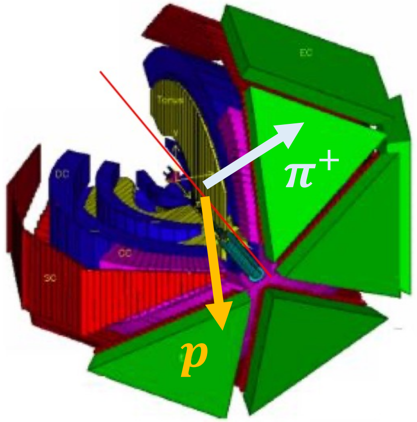


4.4 GeV



Good shape description

$^{12}C(e,e'1p\pi^-)$ – Transverse boosting angle



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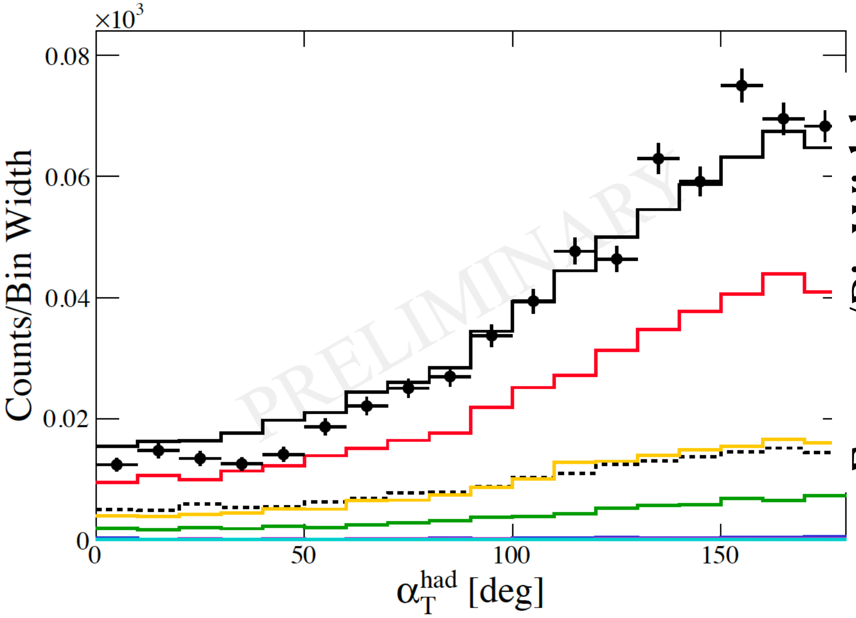
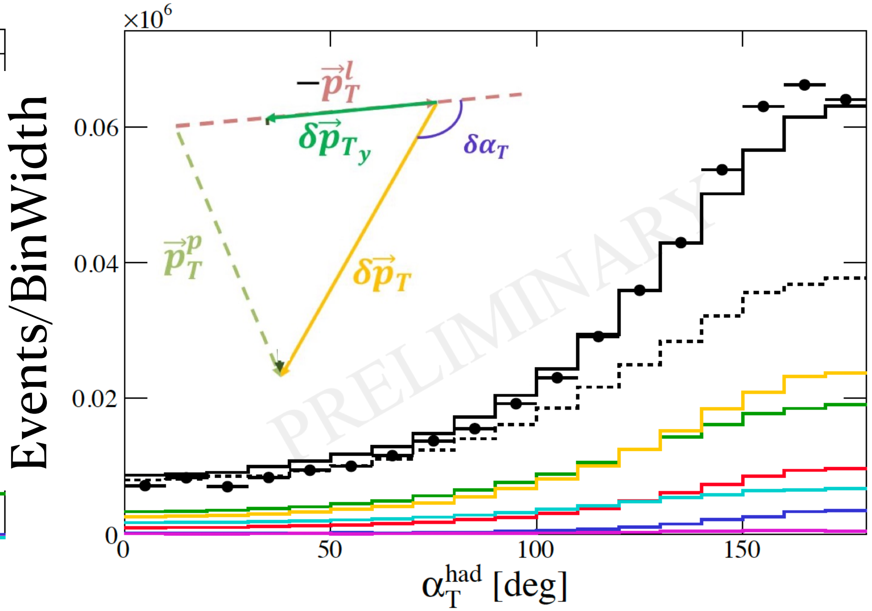
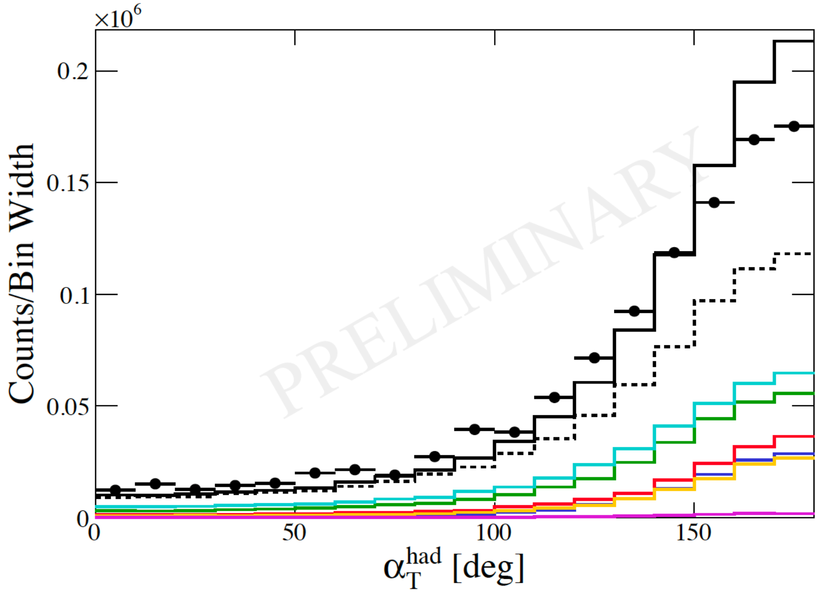


2.2 GeV

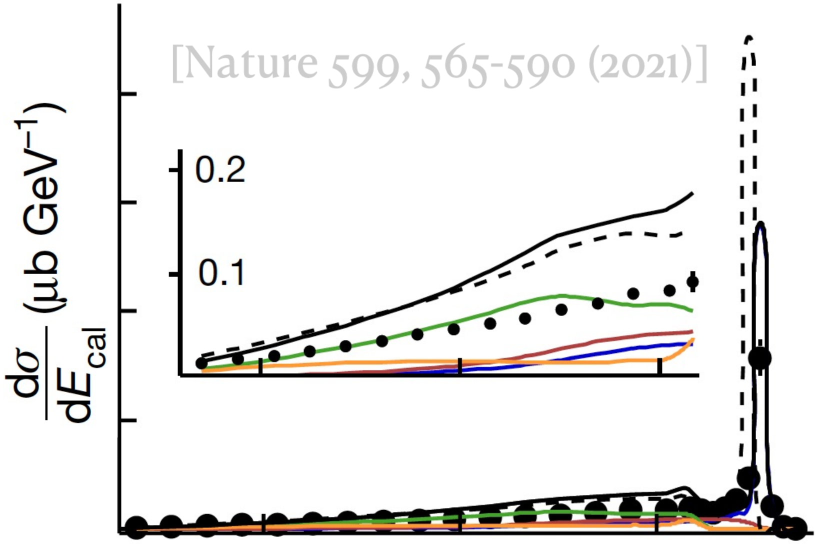


4.4 GeV



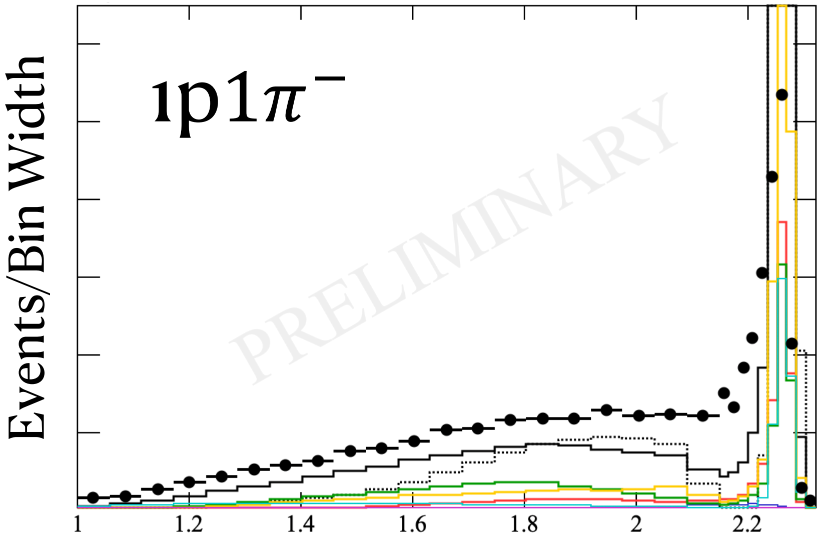
GENIE with FSI predicts correct rise

Beam energy reconstruction

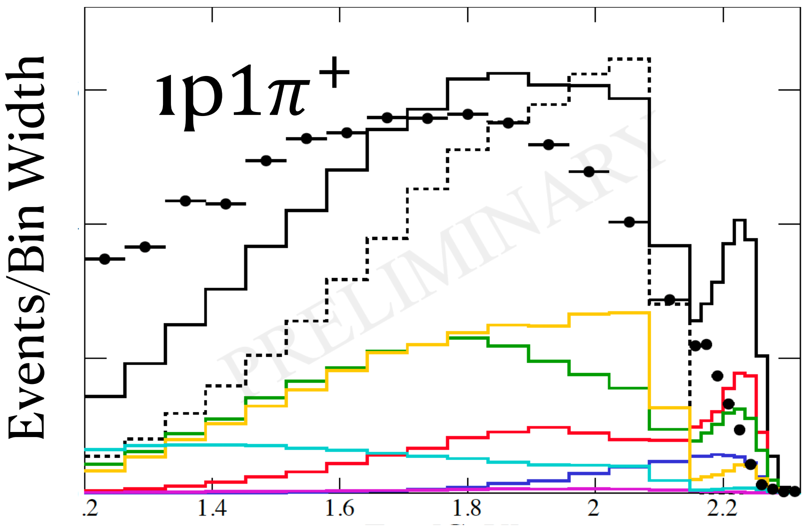


$E_{Cal} = E_{e'} + T_p + \varepsilon_p$

2 GeV on Carbon



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



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

Reconstruction method fails when FSI effects dominate

Proton transparency

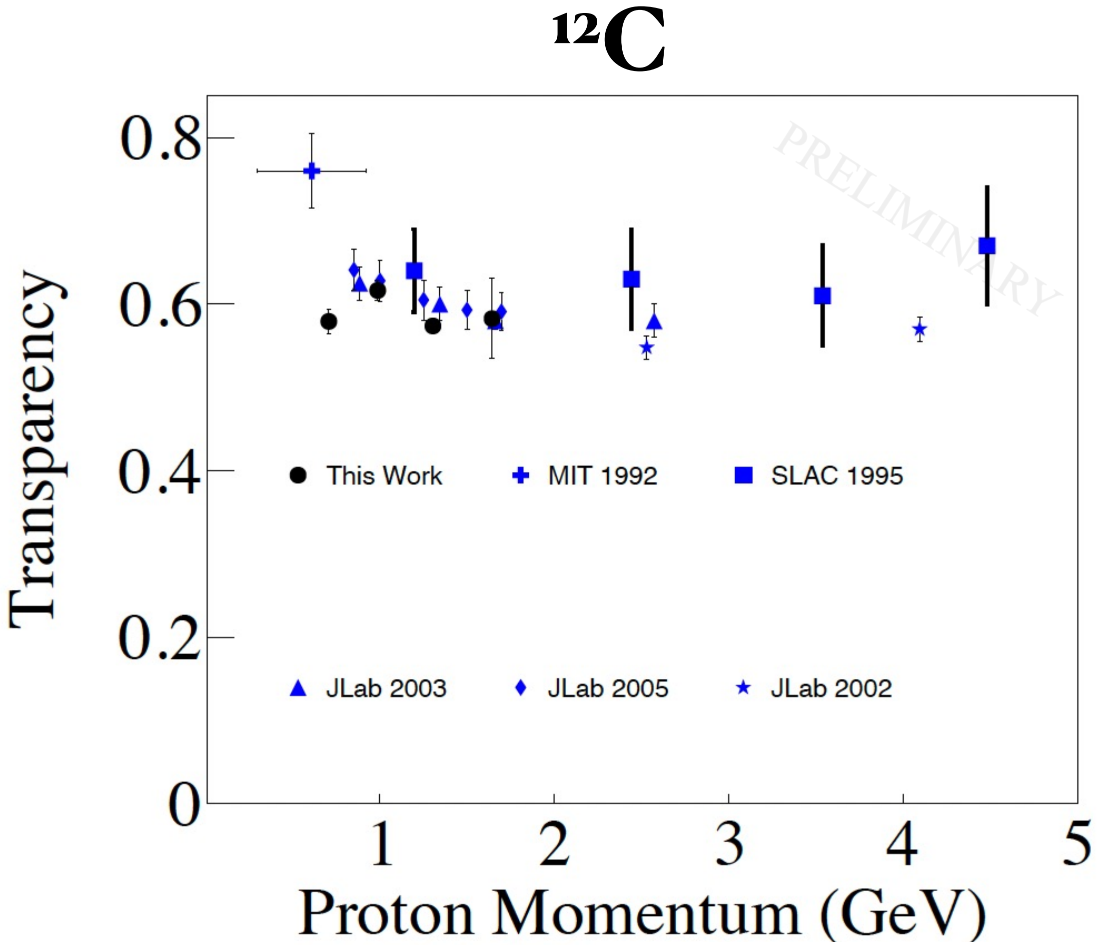
Noah Steinberg

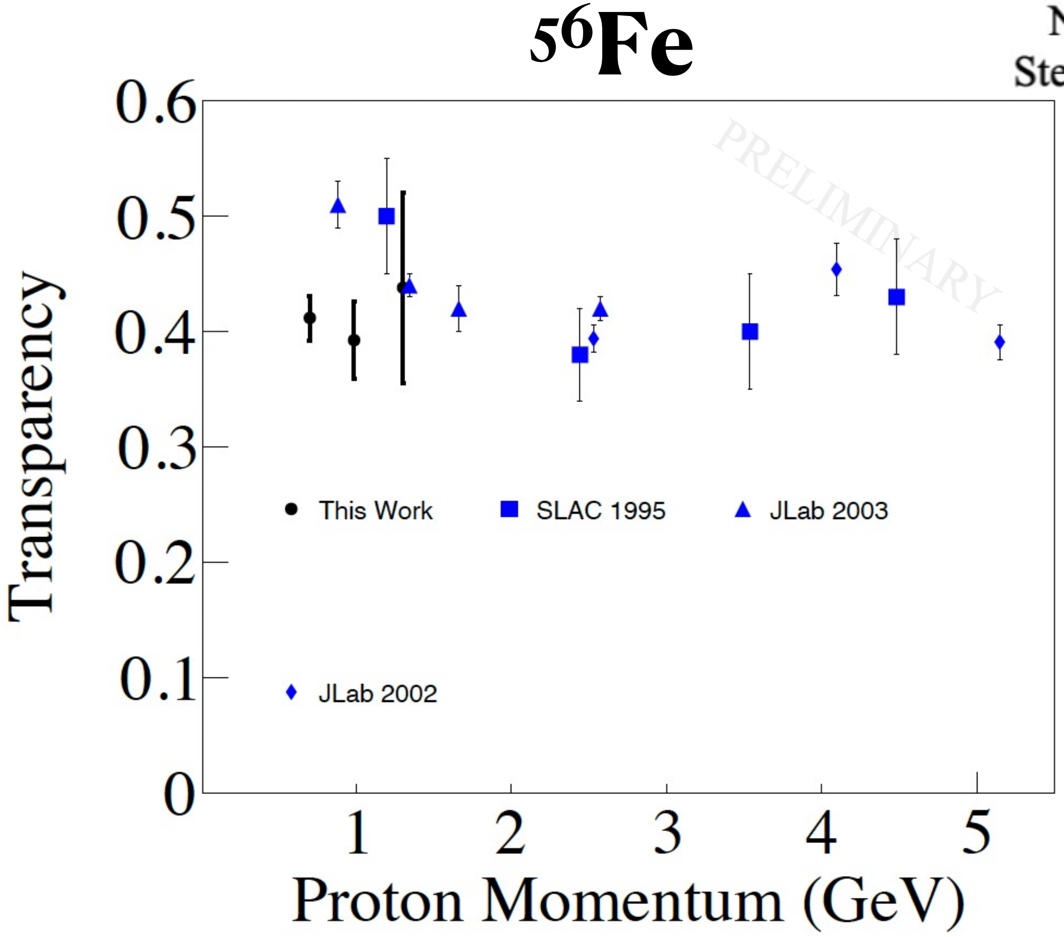
- New proton **transparency measurement** on ^{4}He, ^{12}C and ^{56}Fe
  - Probability that a struck proton leaves the nucleus without significant re-scattering
  - Study proton FSI similarly to neutrino scattering
- All previous transparency analysis measure $(e,e'p)exp/(e,e'p)_{PWIA}$
- **Define a more data driven transparency analysis informed by theory**

$$\mathbf{T_A = N(e,e'p)0\pi\, / N(e,e')_{QE}}$$

- **$N(e,e'p)0\pi$:** selected $1p0\pi$ events
  - Background subtracted, radiative, acceptance and efficiency corrections
- **$N(e,e')_{QE}$:** inclusive QEL event rate
  - Use GENIE to determine QE dominated regions

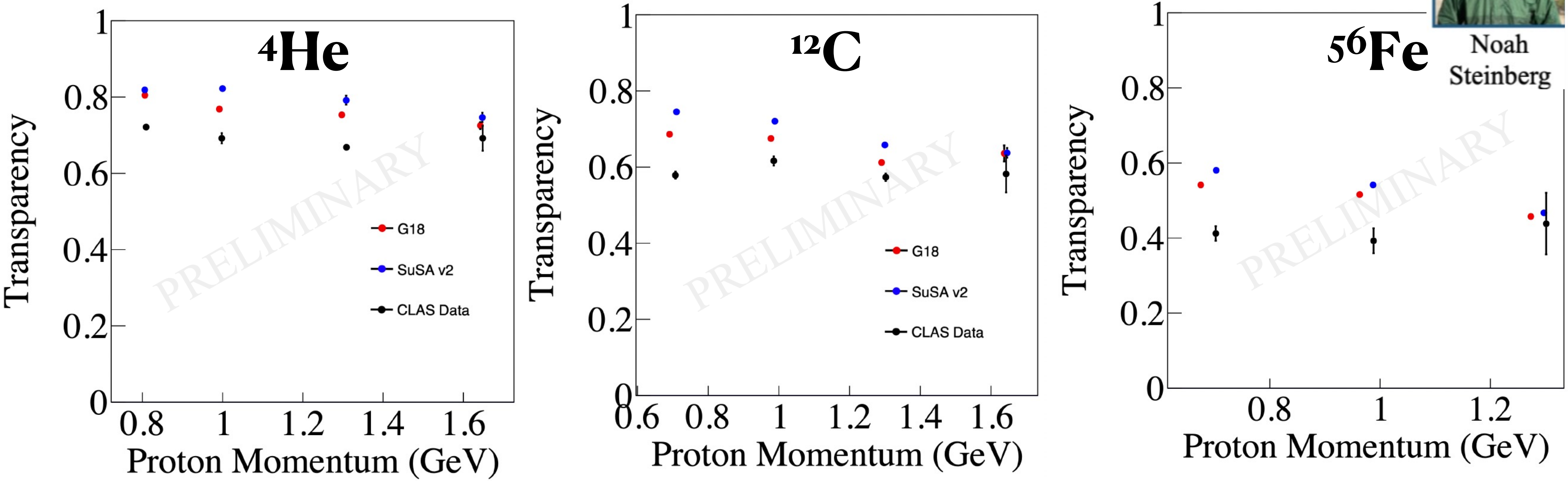
Proton transparency





Compatible with previous data

Proton transparency



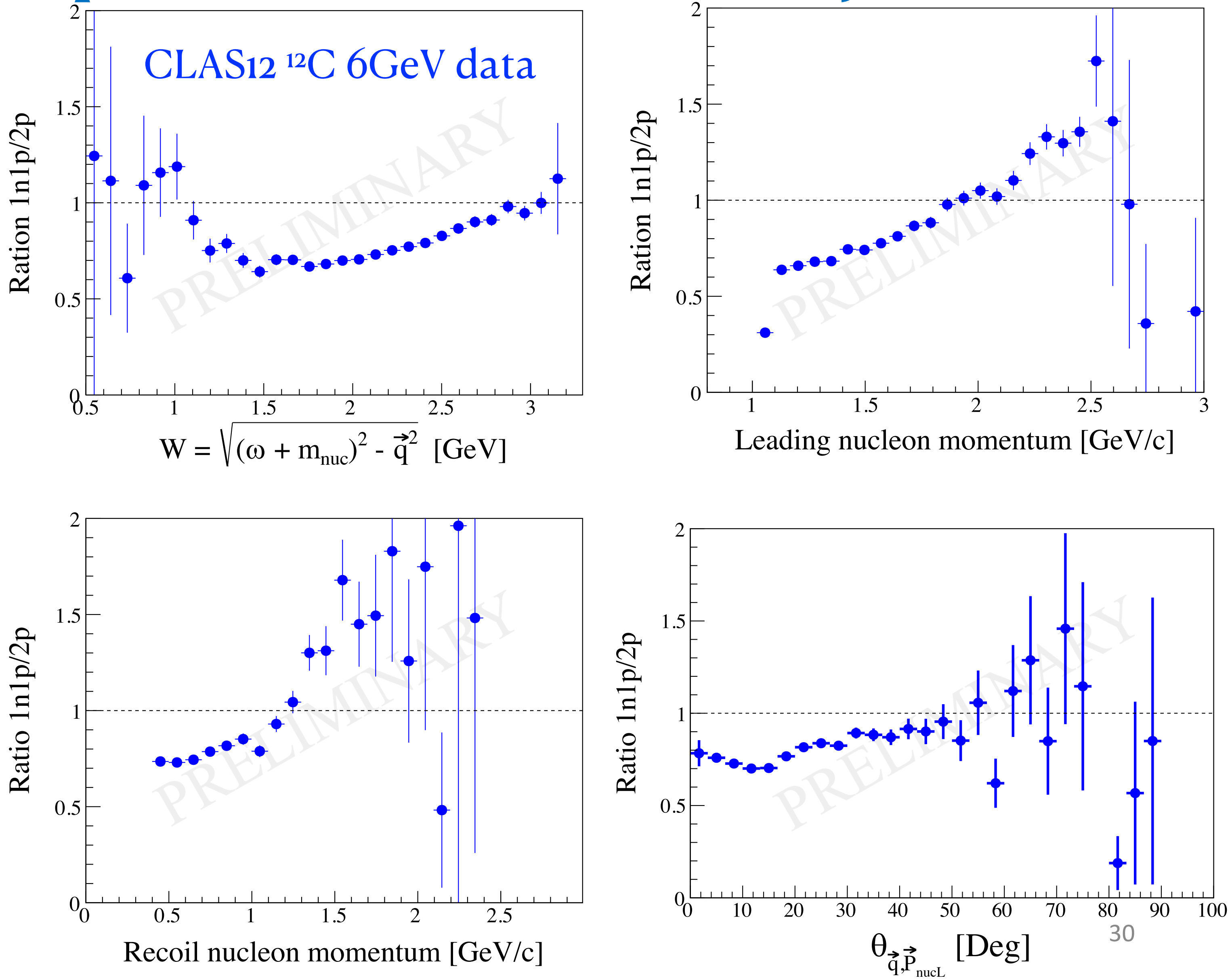
- **First transparency measurement on ^{4}He**
- Transparency flat in p_p decreases with A
- Data to MC differences larger at small p_p, grow with A
  - MC **very sensitive** to nuclear structure models

Publication soon!

First 2p and 1n1p knockout analysis

- Selecting 1n1p or 2p events with no visible pions in the final state

- 6 GeV on Carbon
- $N_{(e,e')} \sim 30M$
- $N_{(e,e'2p)} \sim 50k, \;\; N_{(e,e'1n1p)} \sim 30k$
- Will repeat analysis:
  - 2, 4 and 6GeV
  - Argon target



Conclusions

- The e4nu collaboration is building exhaustive exclusive electron-scattering cross-section library
  - CLAS6 and CLAS12 data
  - Study e-A interaction for different nuclear targets and energies
- Many measurements on its way
  - $1p1\pi^{\pm}$ analysis – pion and proton FSI in nuclear environment
  - New proton transparency measurement – FSI and nuclear model
  - $1p0\pi$ cross-section measurement (published)
  - First Argon Inclusive cross-section for many Q^2 slices
  - First two nucleon production analysis in Carbon
  - Inclusive (e,e'π) analysis on deuterium
- These data will give us new insights of nuclear effects in lepton-nucleus experiments

Conclusions

- Hadron production data of high quality valuable also for neutrino physics
- Data coming for a variety of targets, Argon
- Measurements focusing on untangling nuclear effects from cross-section

Thank you !

Join us!