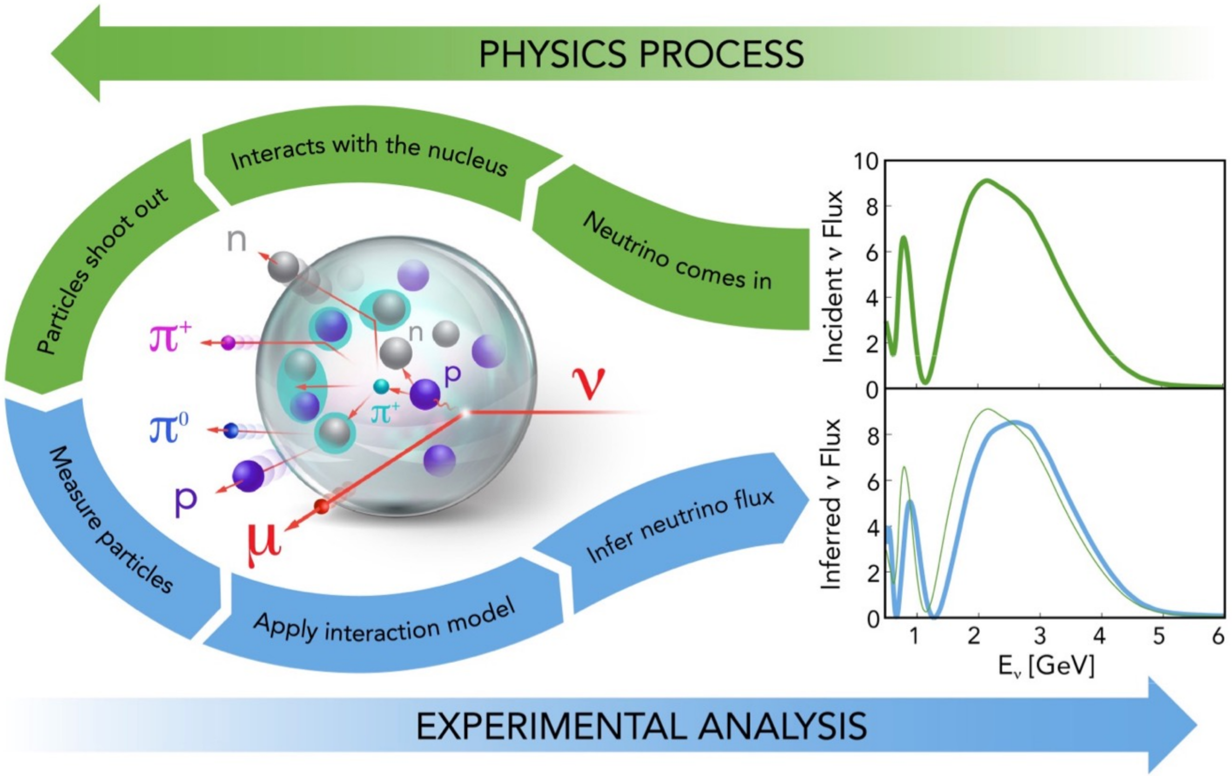
Electrons for Neutrinos

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

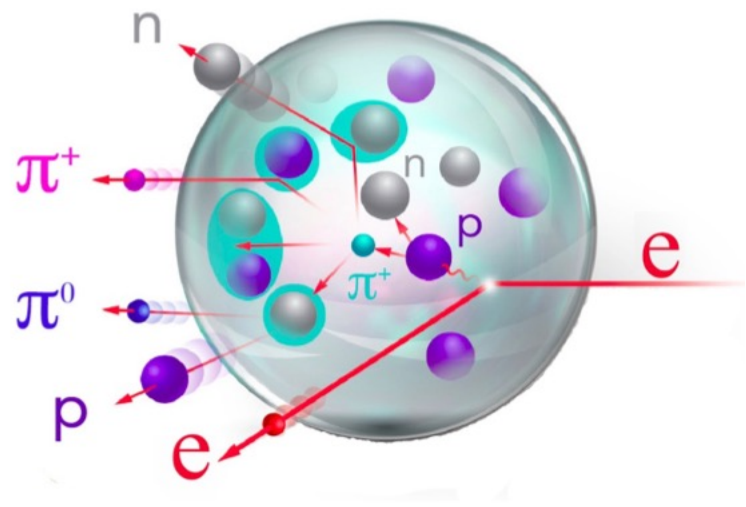


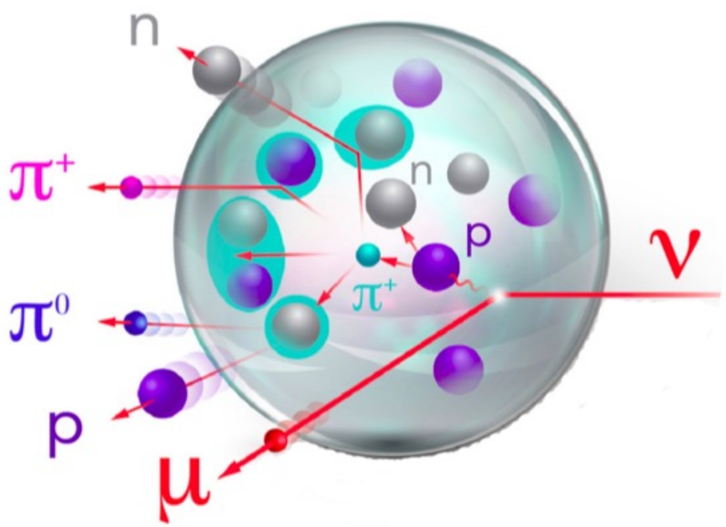
- **Unprecedented accuracy** in cross section models required by next generation neutrino oscillation experiments

Electrons for neutrinos

- 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**
- **Monochromatic** beam
- High statistics

High quality constrains for ν/e^--event generators





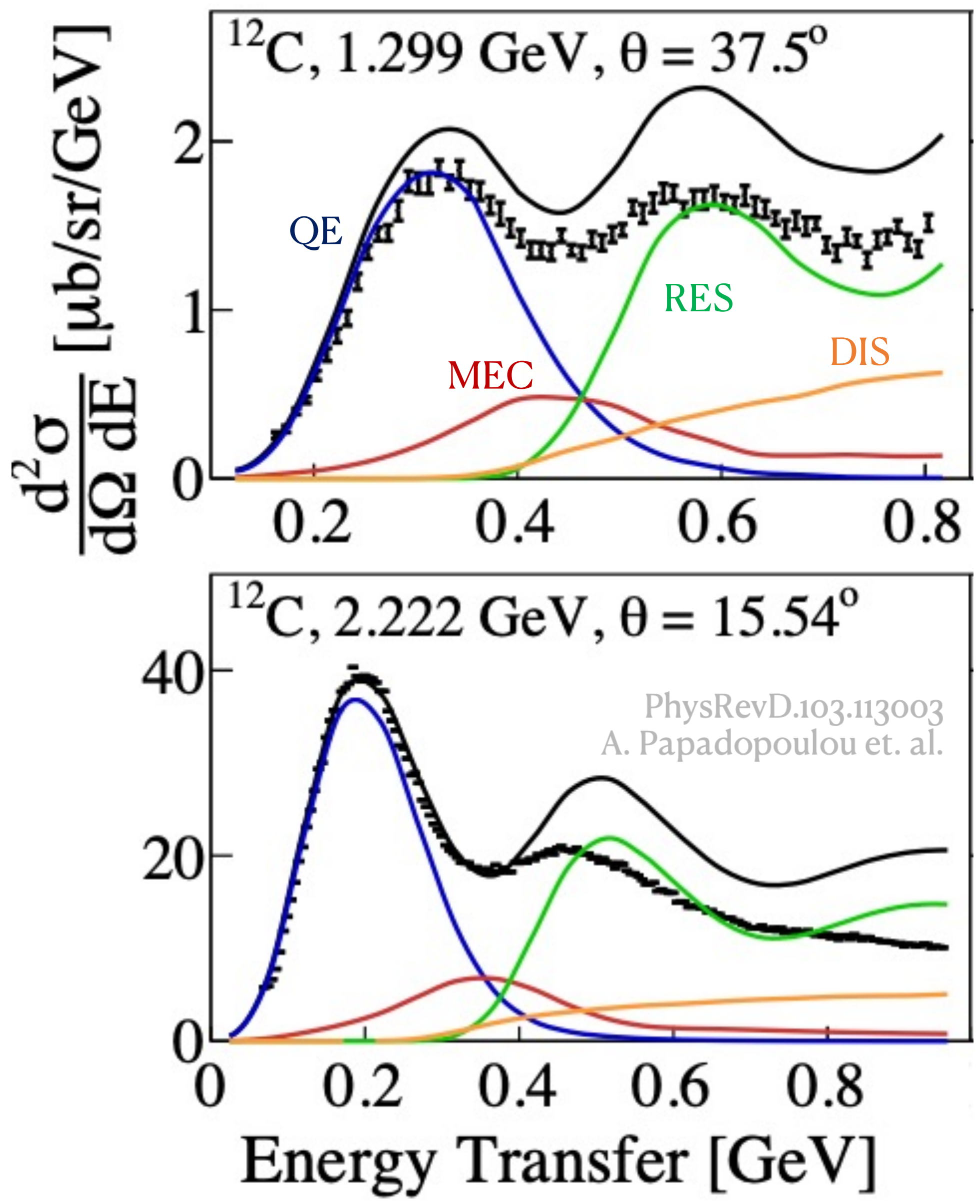
GENIE

http://tunes.genie-mc.org

- ν-A, $l^{\pm}$-A and h-A event generator
  - MeV to PeV, all targets
- **Full description for electrons**
  - Common code for ν-A, e^{-}-A processes
  - Many models available

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)	Bodek-Yang

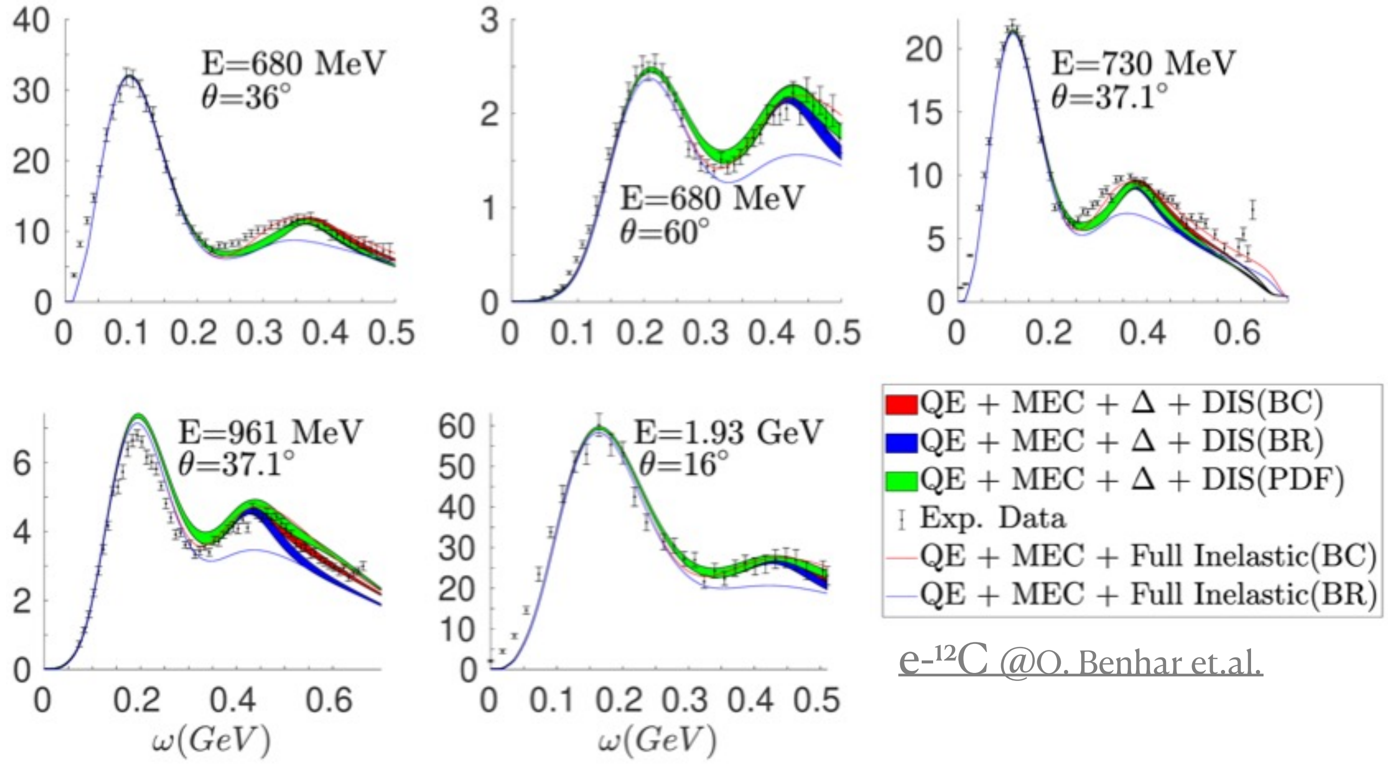
GEM21_11a (SuSAv2), e-^{12}C data



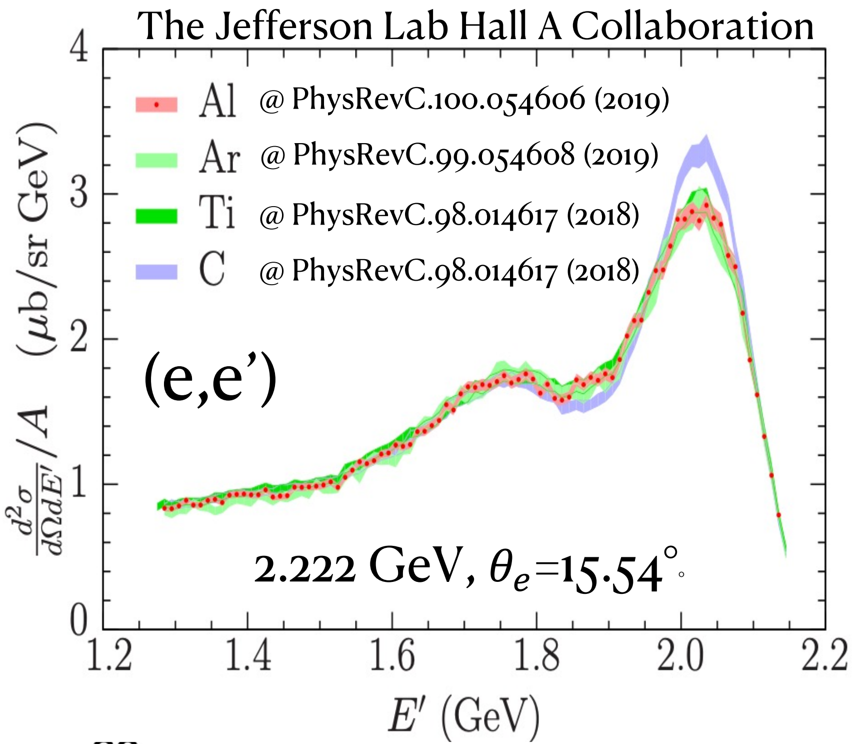
Inclusive measurements

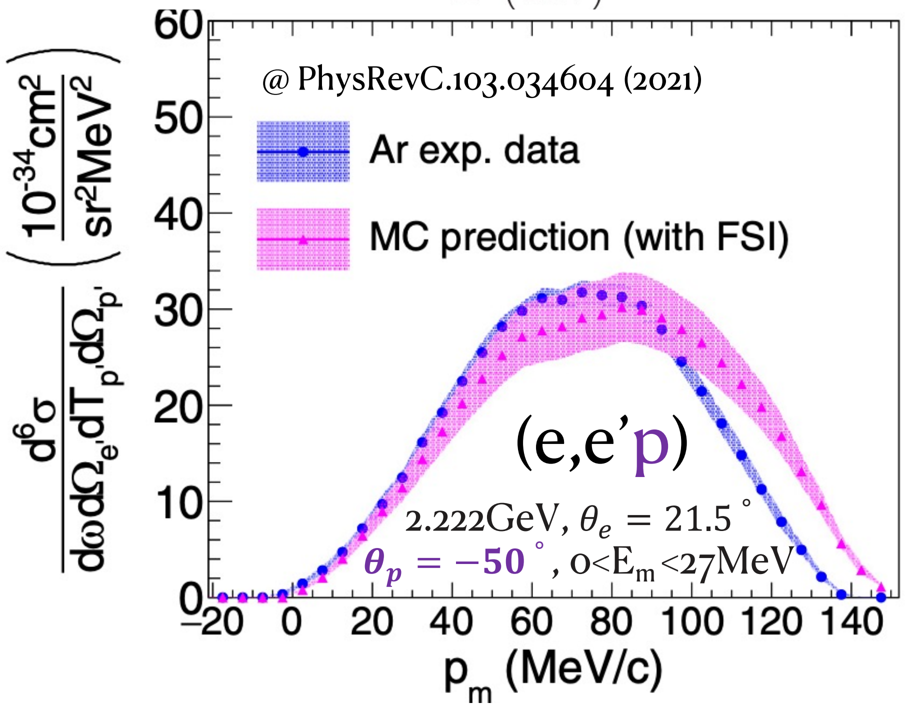
- Most electron-scattering measurements are inclusive
- Exclusive measurements are limited to specific kinematics
- **Lacking exclusive hadron production measurements**

SuSAv2 model extension to inelastic regime



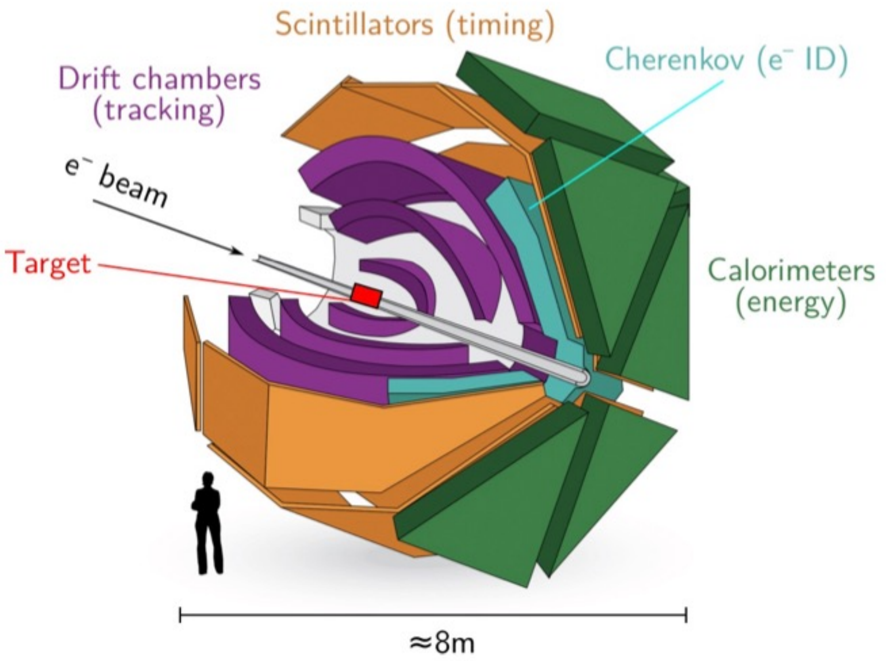
e-^{12}C @O. Benhar et.al.

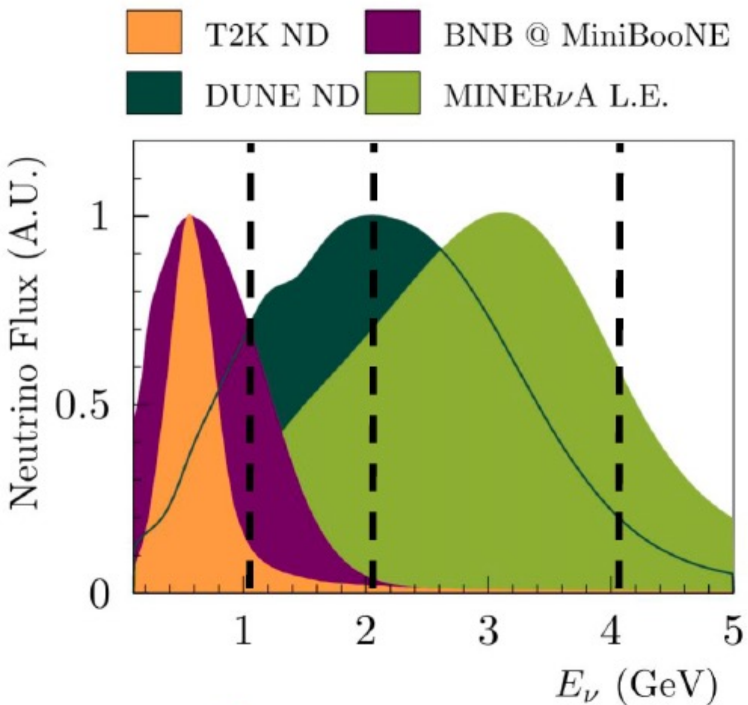




Hadron production with CLAS6

- Large acceptance @ $\theta_e > 15°$
- ~"2π" 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
- ~10M C(e,e') events



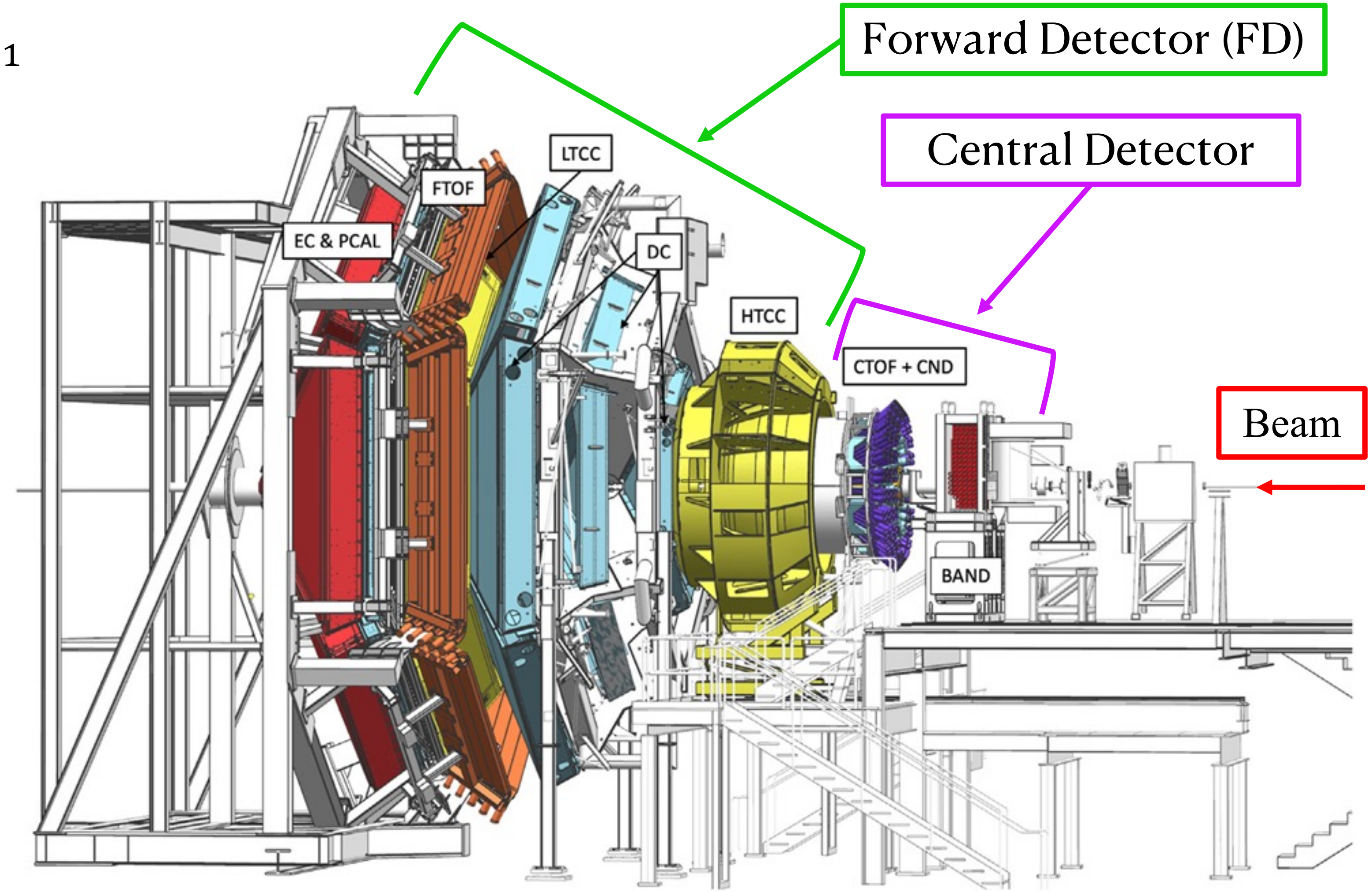


The CLAS12 detector

- **Maximal luminosity:** $10^{35}\ cm^{-2}s^{-1}$
  - **10 times larger than CLAS6**
- **Large acceptance (~4π)**
  - 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
- ~10^{8} (e,e') ^{40}Ar events
  - See backup slides by J.Barrow



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

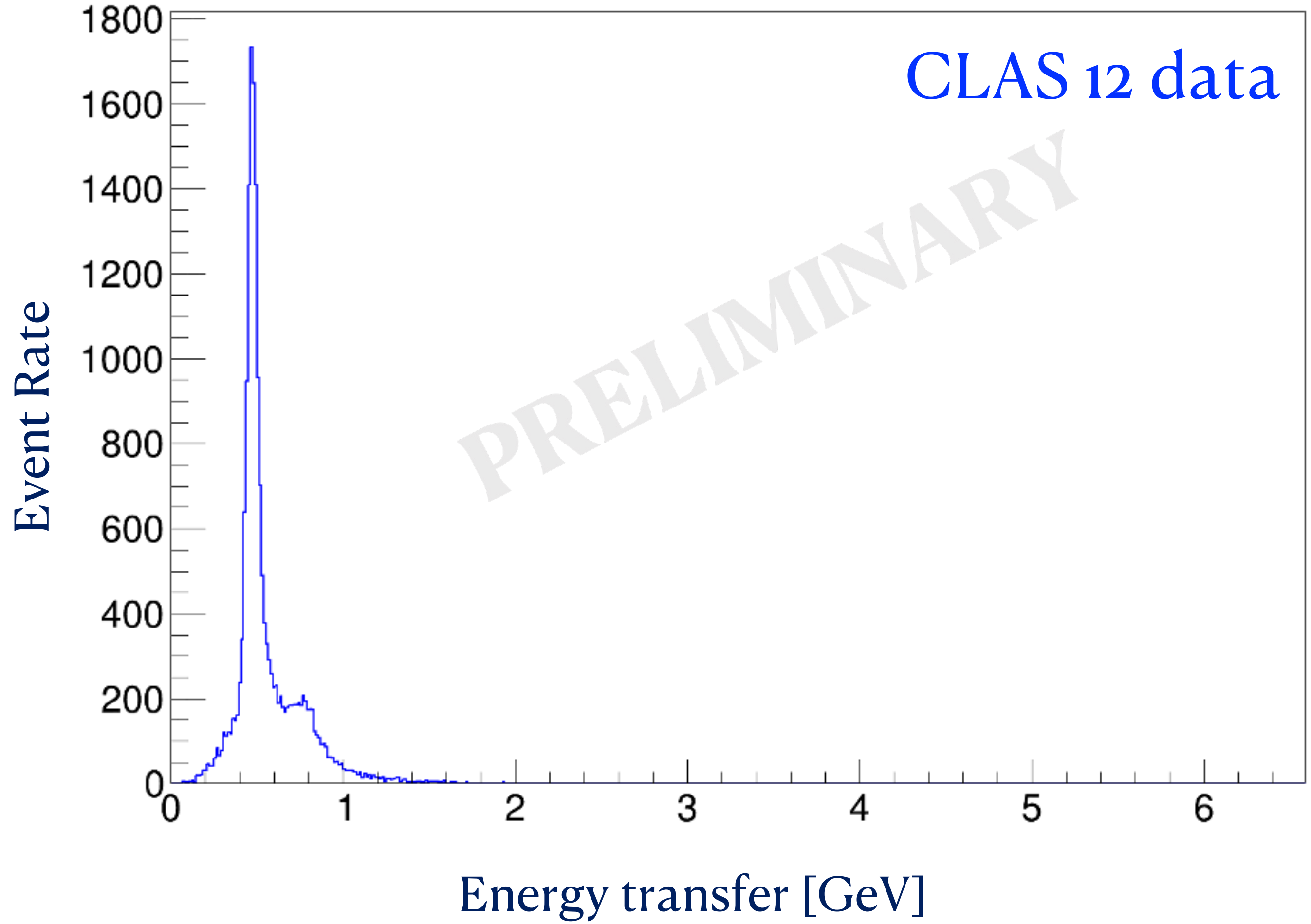
Jefferson Lab

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

Matan Goldenberg

^{2}H at 6GeV

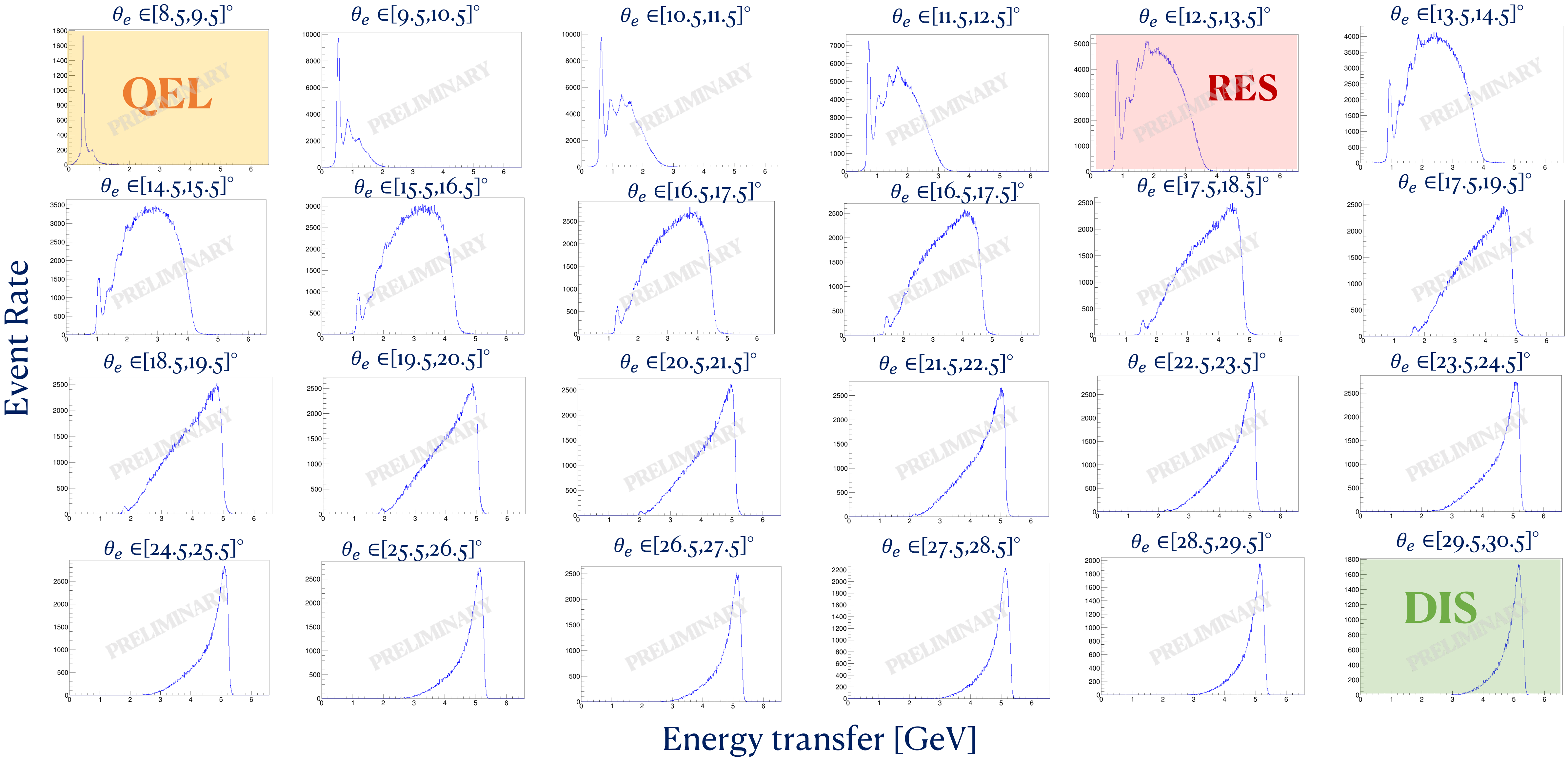
$\theta_e \in [10.5, 39.5]^\circ$ with 1° steps



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


Matan Goldenberg

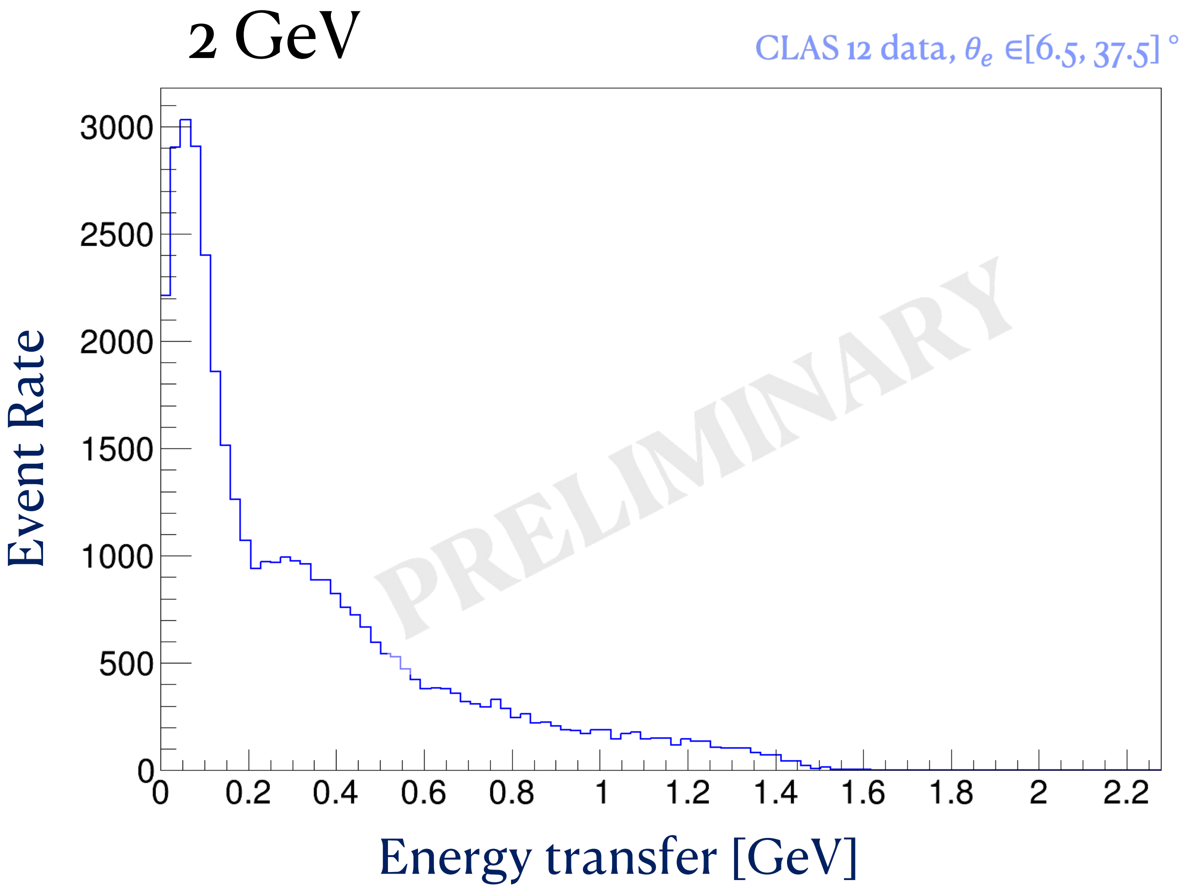
Can choose kinematics to focus on specific reaction mechanisms

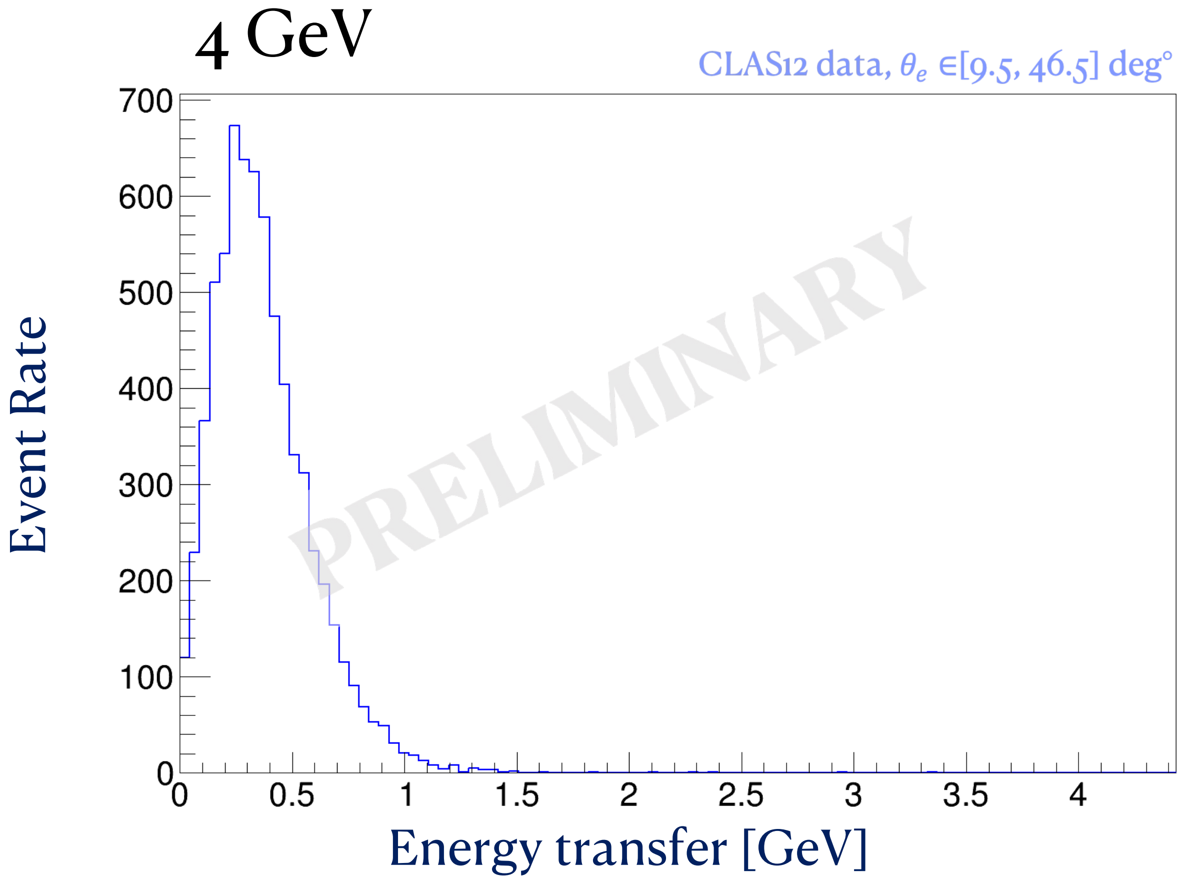


Inclusive (e,e') at multiple angles and targets

Matan Goldenberg

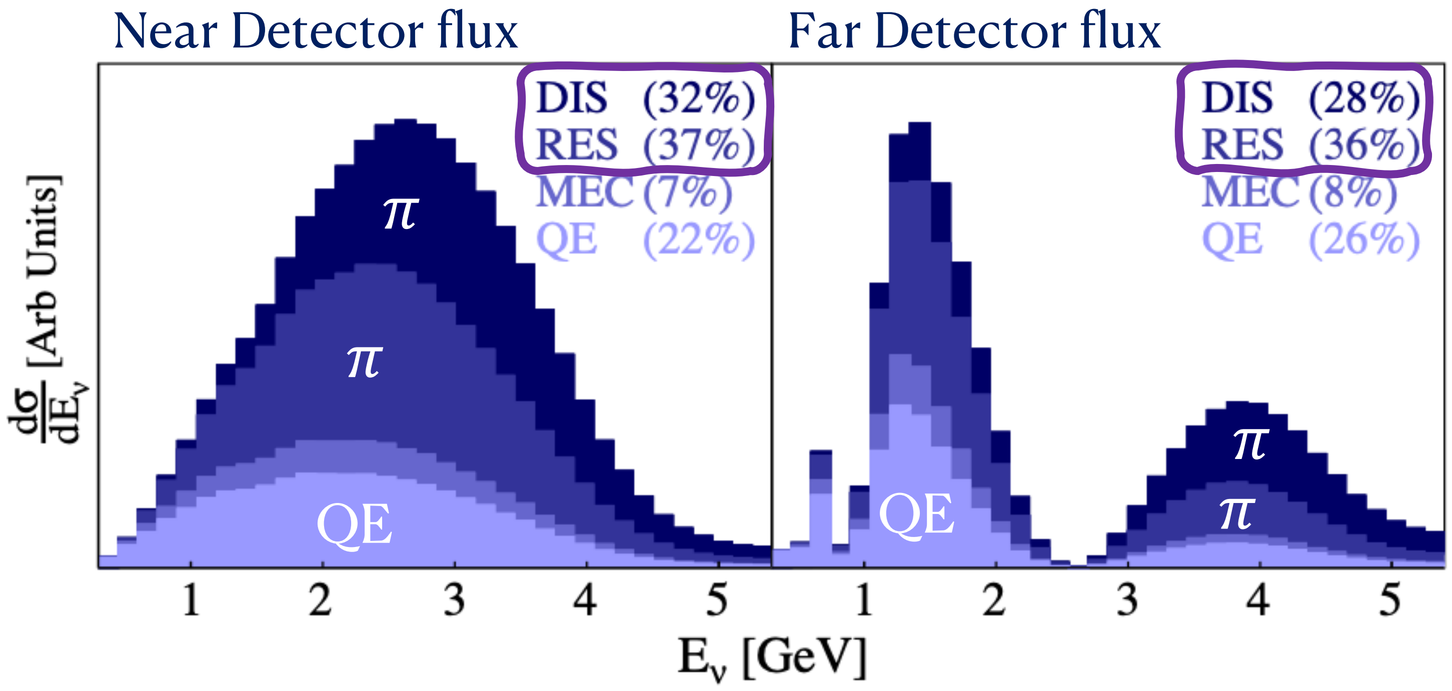
^{40}Ar





Pion production dominated era

DUNE will be dominated by pion production events



New precise data crucial to validate and improve models

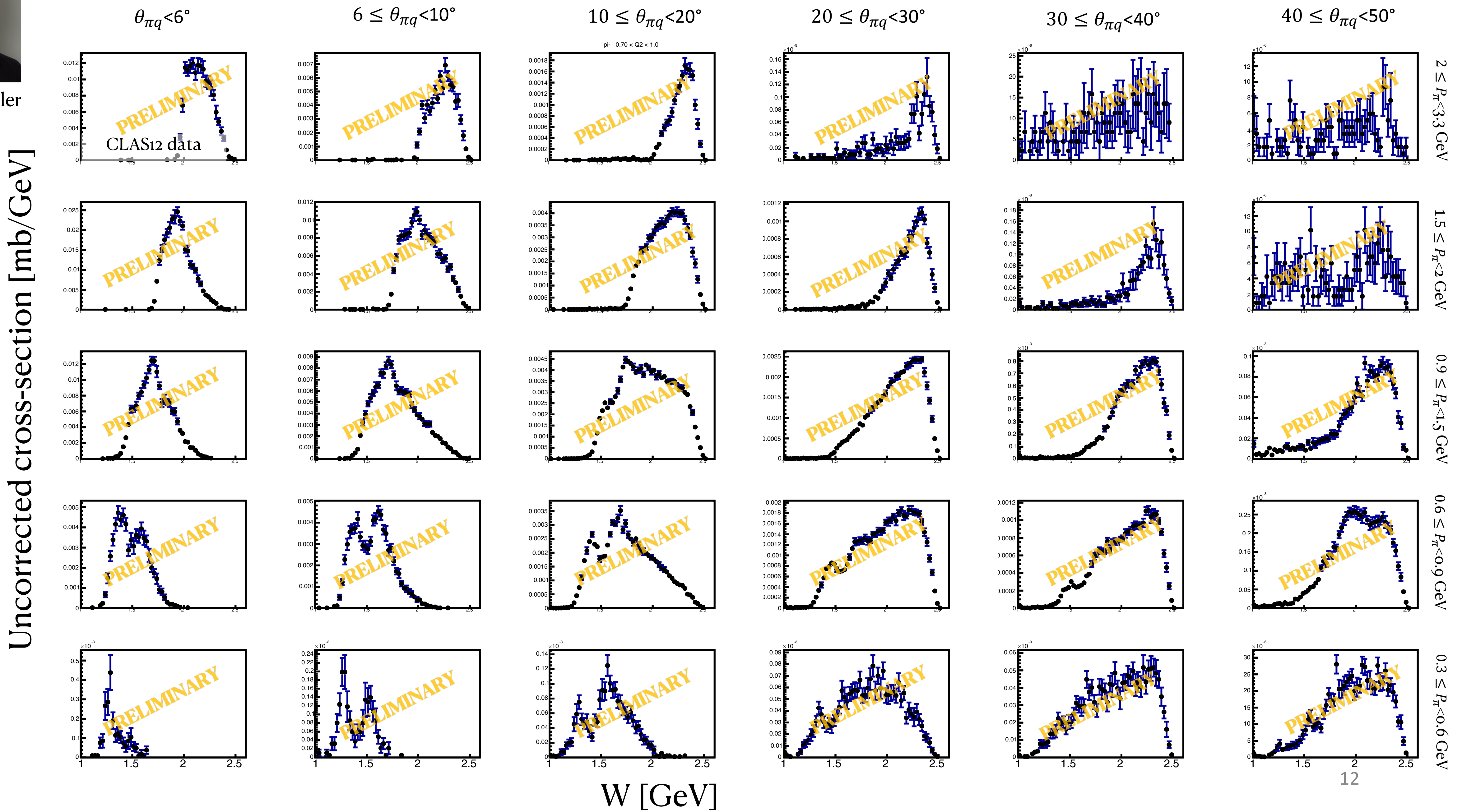
by Caleb Fogler

$^2H(e,e'\pi^-)$ at 4 GeV

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

More Q^2 slices available

^{40}Ar measurement to come

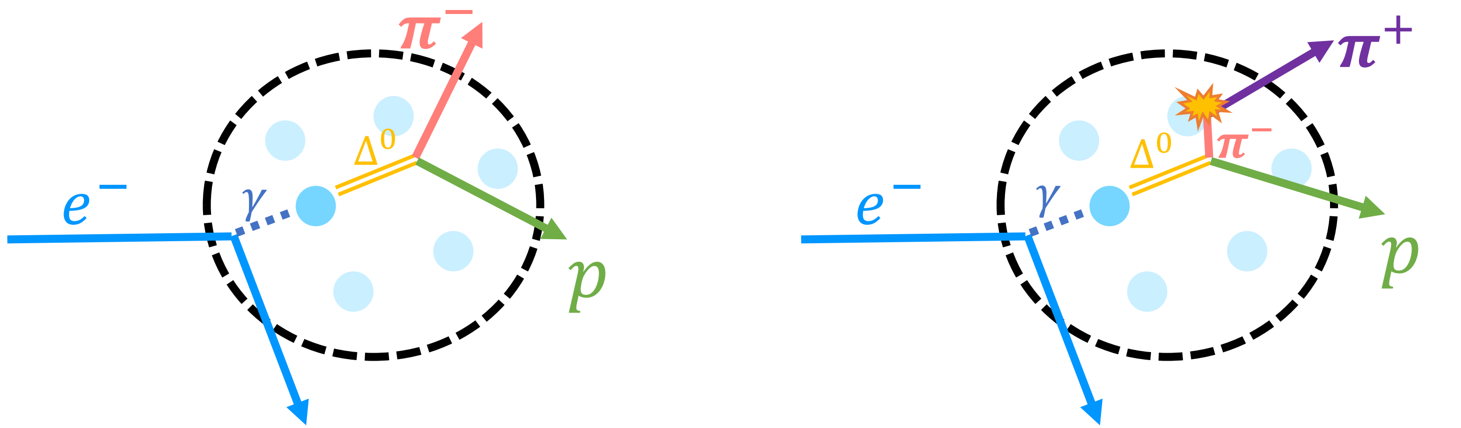


Exclusive pion production

- First e4nu electron-scattering pion production analysis:

  $1p1\pi^-$ and $1p1\pi^+$

  with no detected γ any number of neutrons
- **1.1, 2.2 and 4.4 GeV** e2a CLAS6 data
- ^{12}C (^{4}He and ^{56}Fe to come)
- $1p1\pi^-$: possible at the free nucleon level
- $1p1\pi^+$: needs two or more nucleons → undetected particles (FSI!)

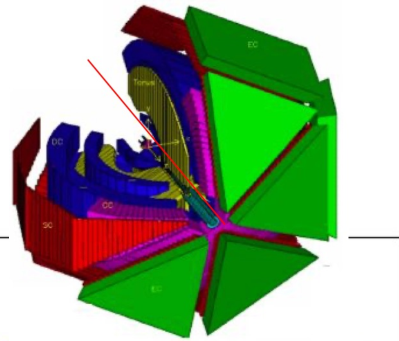


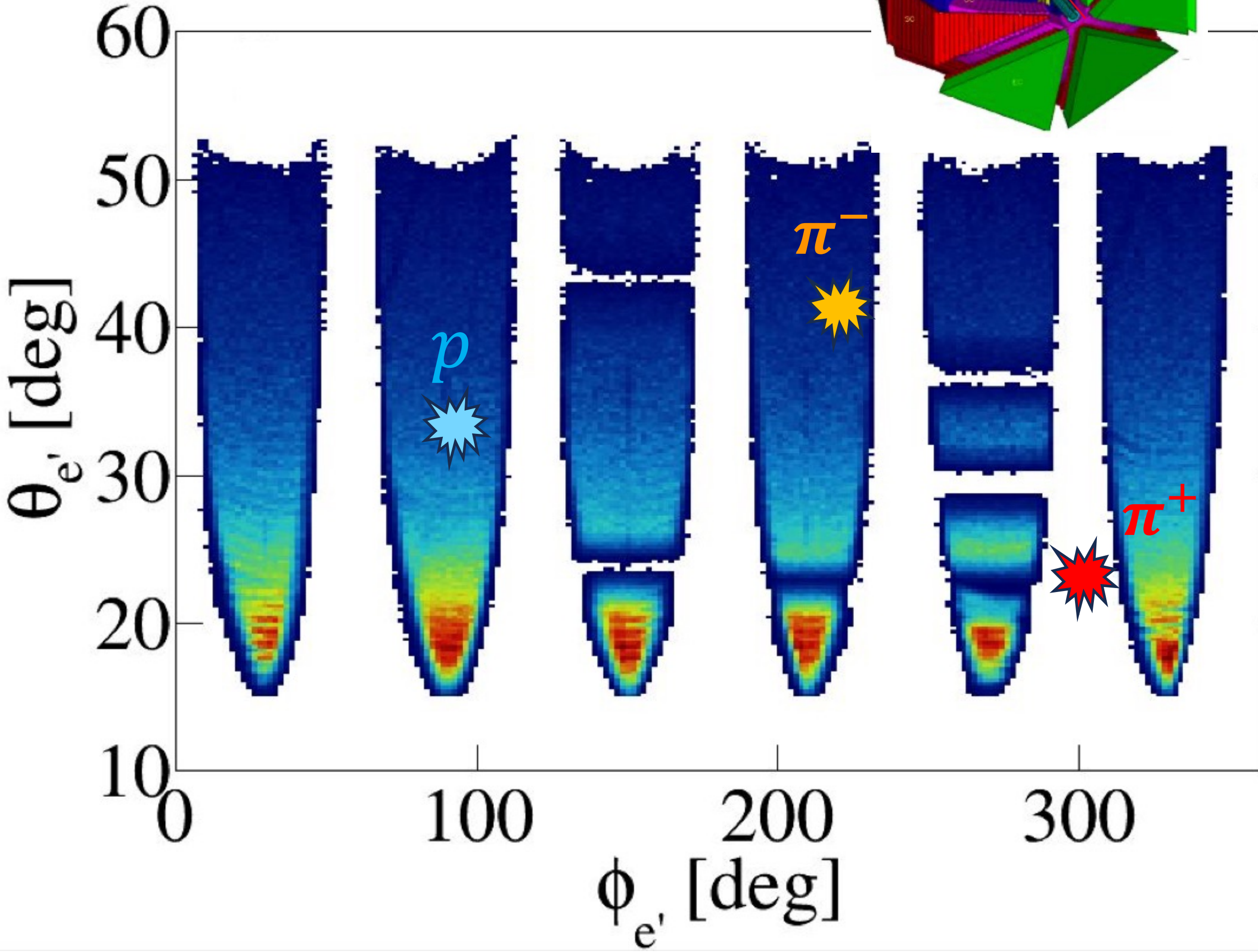
1p1$\pi^{\pm}$ analysis: background contamination

- **Particles below threshold**
  - p_p and $p_\gamma > 300\ MeV$
  - $p_{\pi^\pm} > 150\ MeV$
  - $\theta_p > 12\ deg$
  - $\theta_\gamma > 8\ deg$
  - $\theta_{\pi^\pm} > 12\ deg$
  - Data not corrected for this
  - Same cuts applied to simulation

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

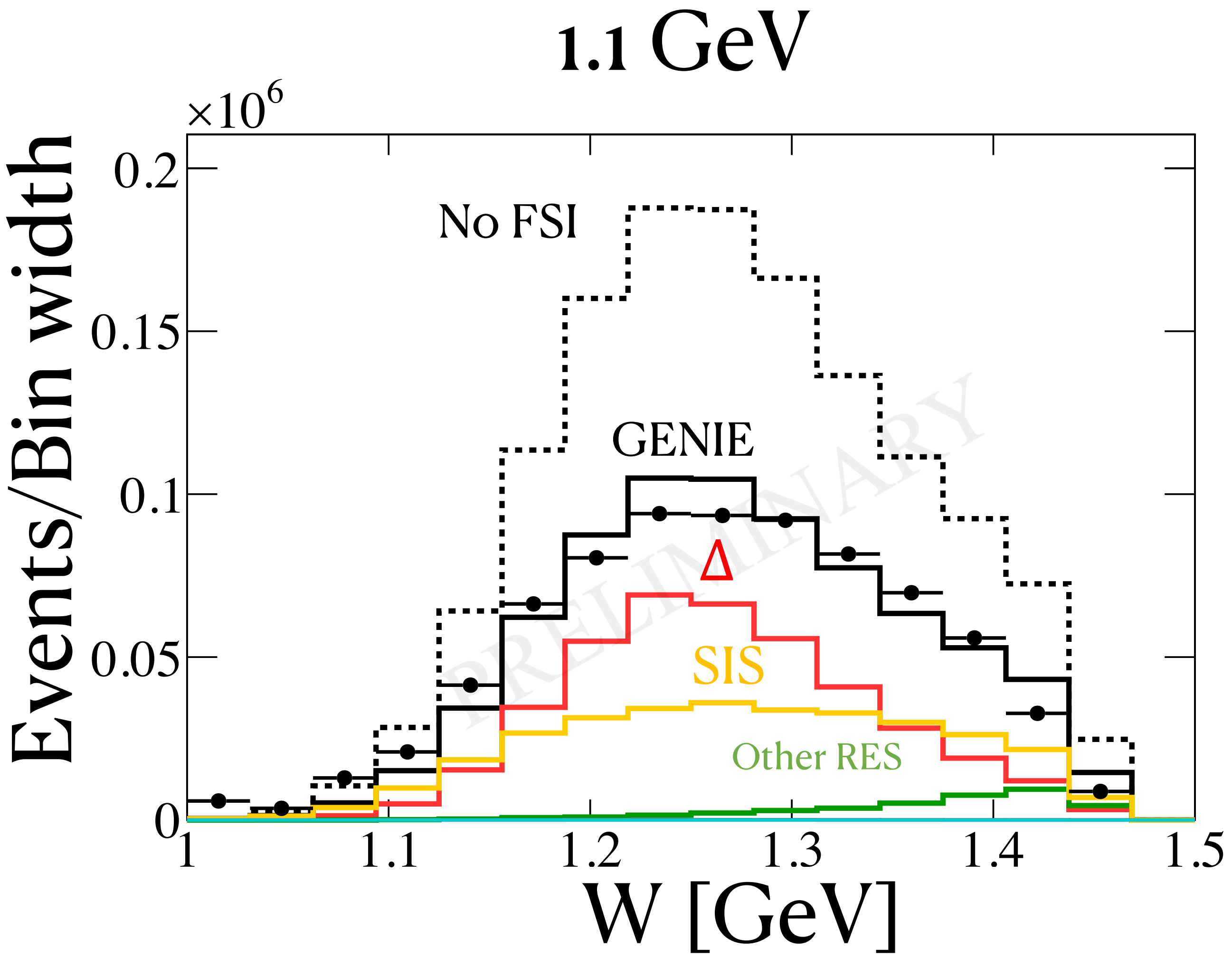
- **Not full "4π" coverage**
  - Gaps between the sectors
  - Gaps within a sector
  - **"Data driven" background subtraction**
    - Multi-particle correction



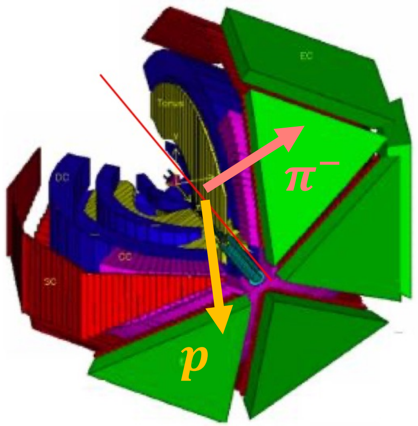


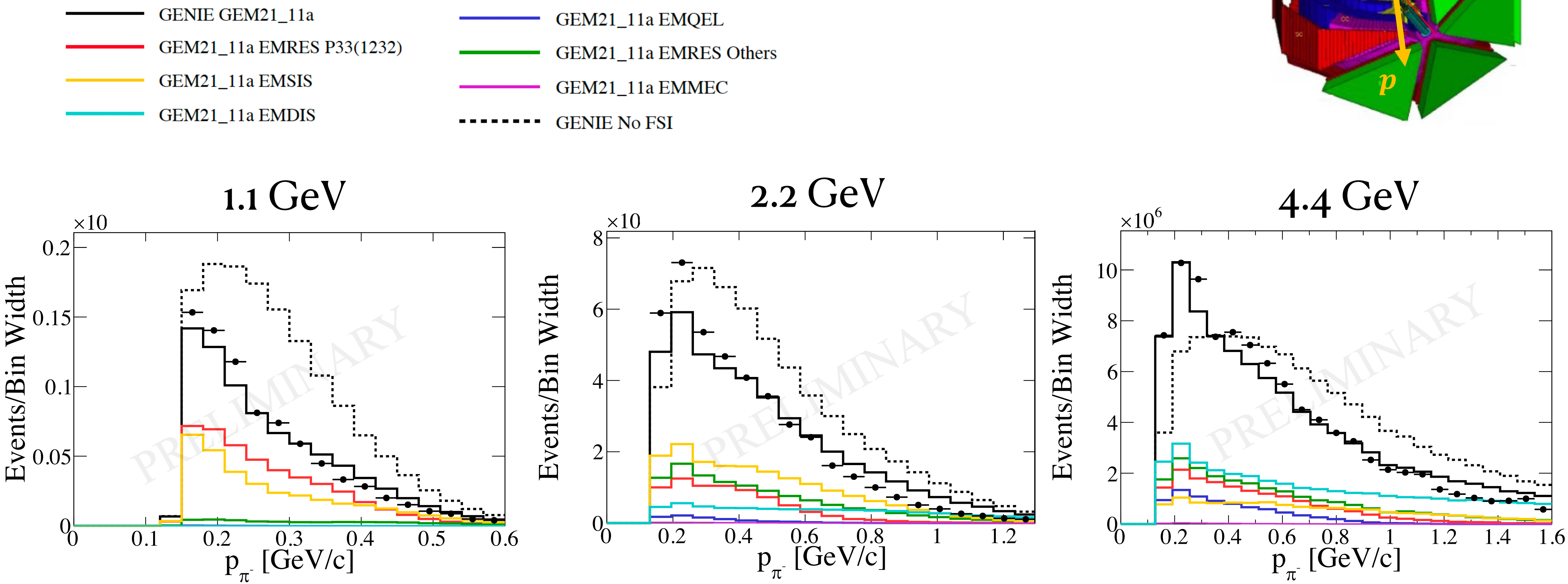
C(e,e'1pπ^-)

- Shape-only comparison
  - GENIE normalized to data
  - Using GEM21_11a
  - QEL+2p2h: SuSAv2
  - RES: Berger-Sehgal
  - SIS+DIS: Bodek-Yang
  - FSI: hA
- Data corrected for bkg. events, e/p/$\pi^{\pm}$ acceptance and detection eff.
  - Not radiative corrected yet
  - Only statistical errors



C(e,e'1pπ⁻) – Pion momentum

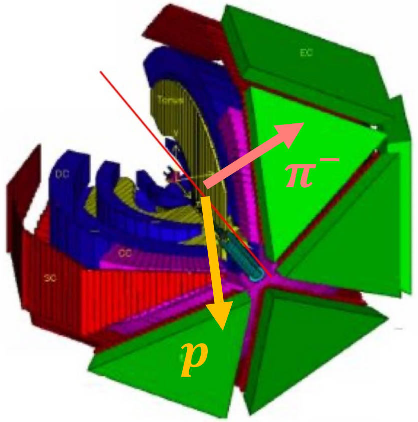


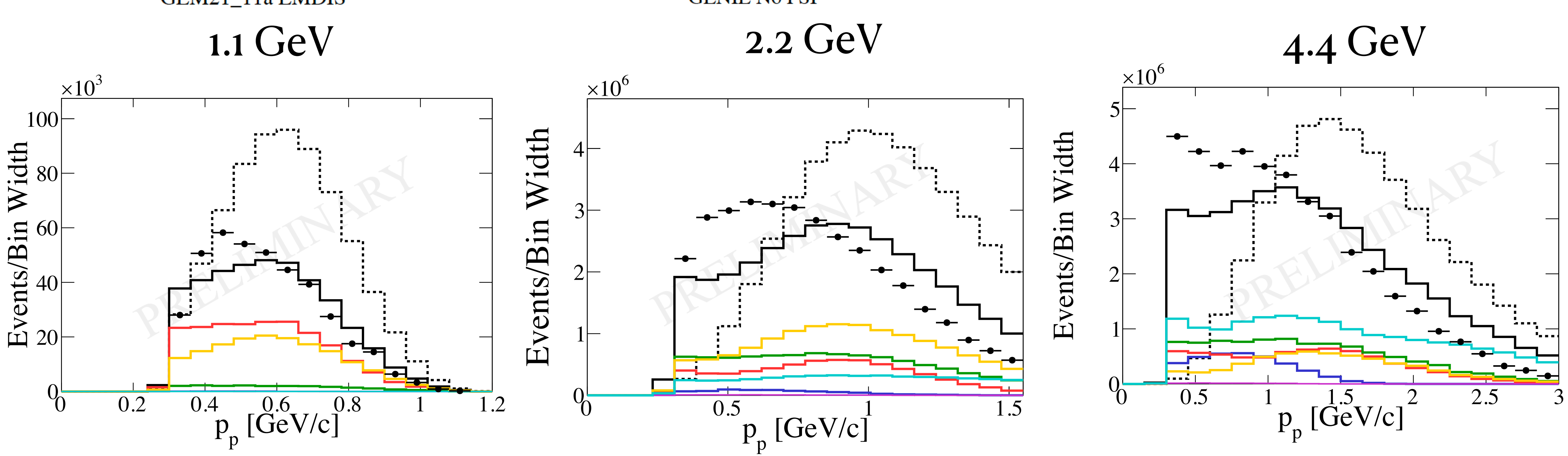


Shape well described by GENIE

FSI needed

C(e,e'1pπ⁻) – Proton momentum

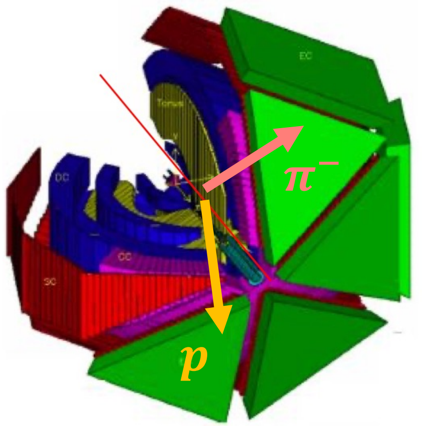


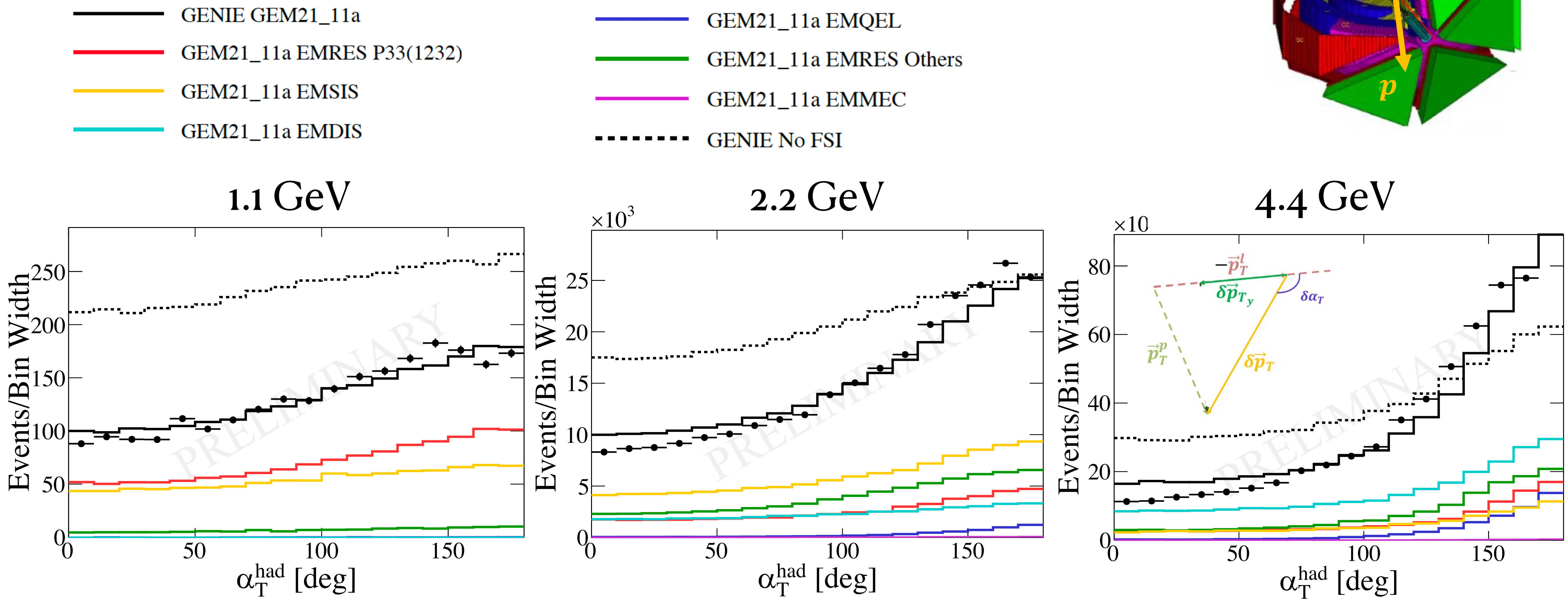


Low momentum protons are not described by MC

Sensitive to FSI

C(e,e'1pπ^-) – Transverse boosting angle

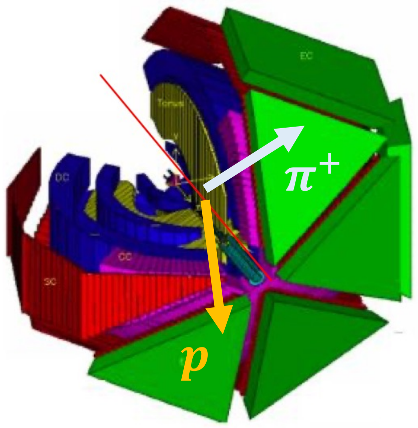


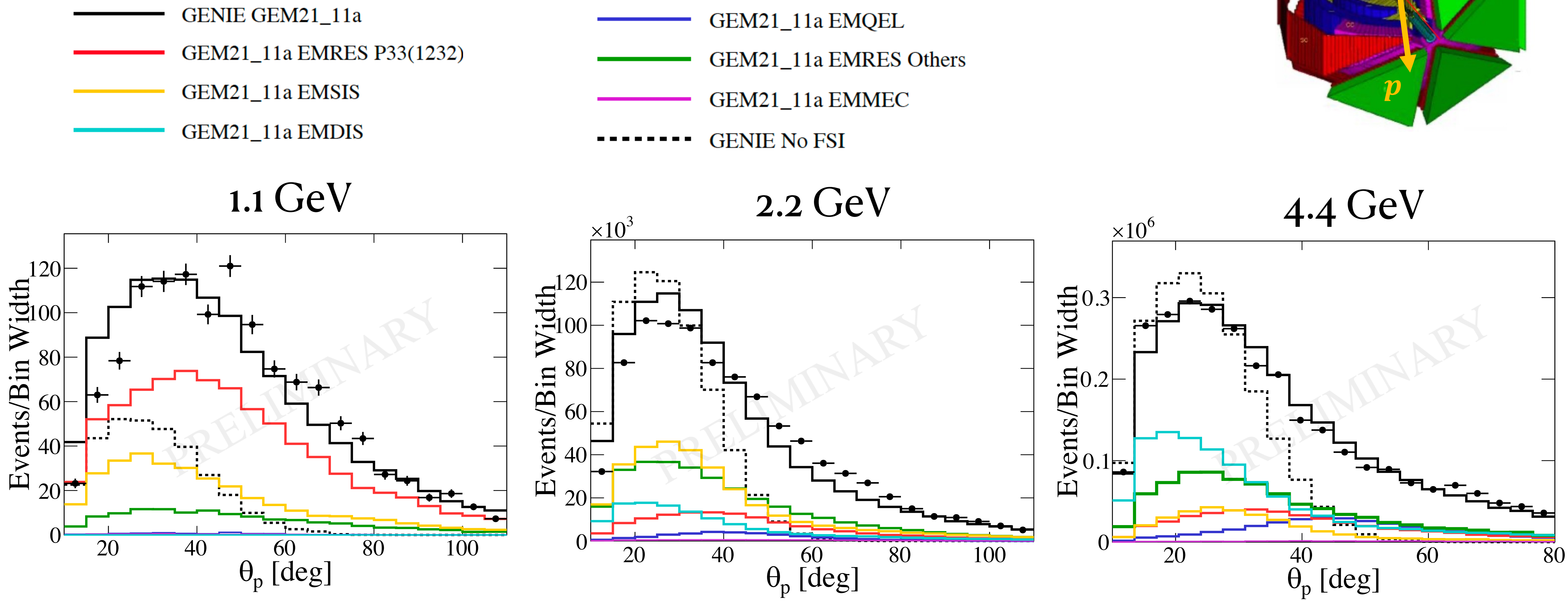


$\delta\alpha_T$ is sensitive to mostly FSI

Excellent shape description

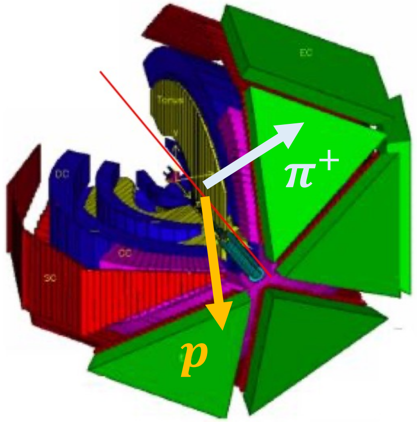
C(e,e'1pπ⁺) – Proton angle





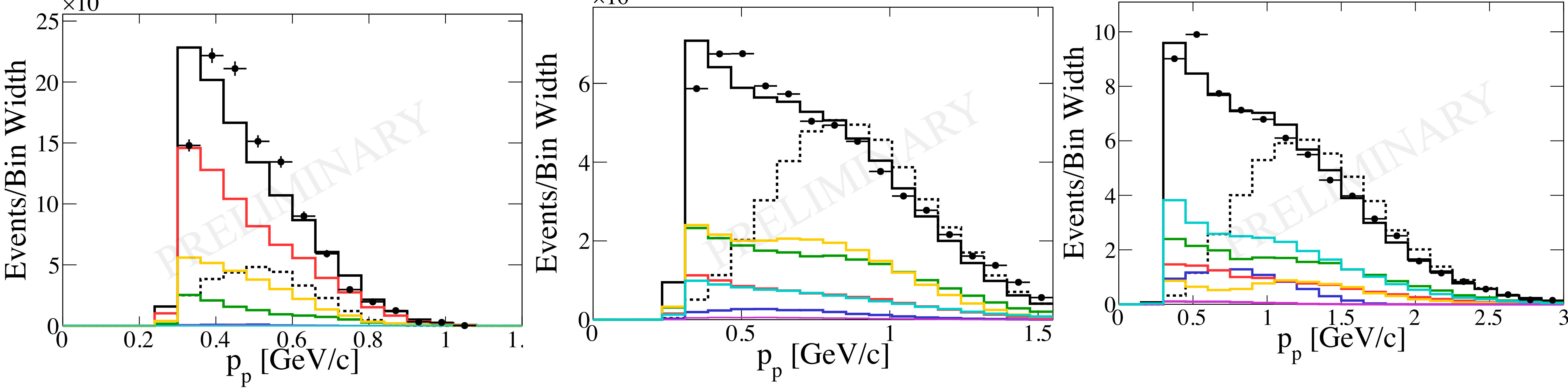
FSI crucial to describe data
Most events due to FSI

C(e,e'1pπ$^+$) - proton momentum



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

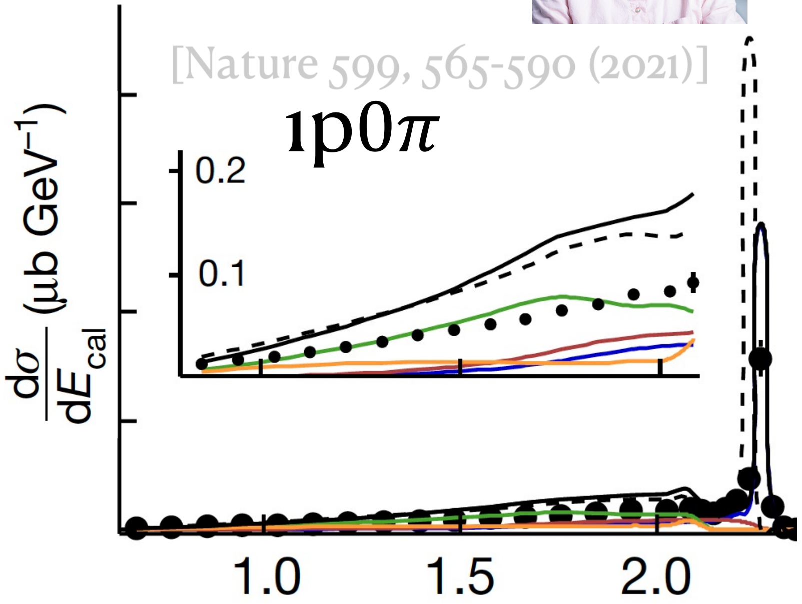
1.1 GeV — **2.2 GeV** — **4.4 GeV**



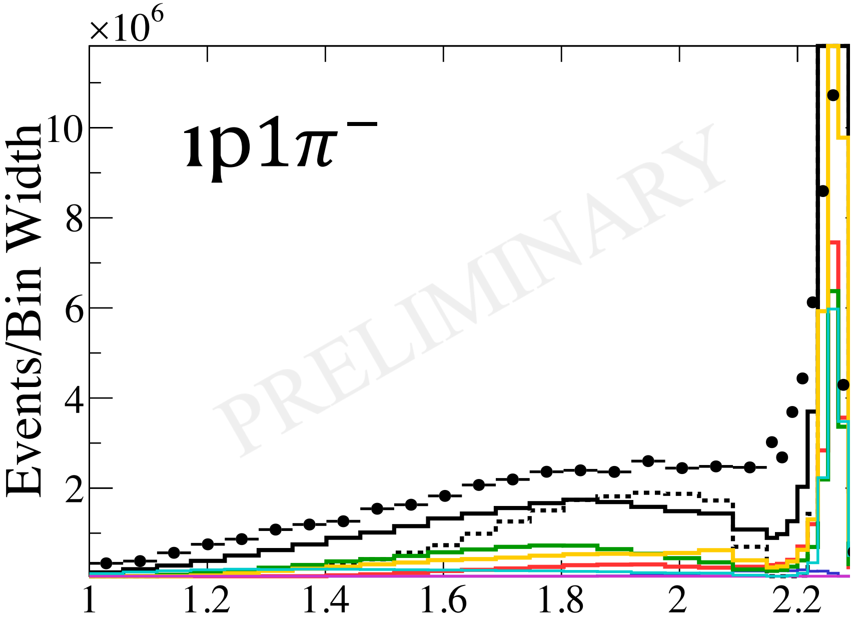
Good shape description

Beam energy reconstruction

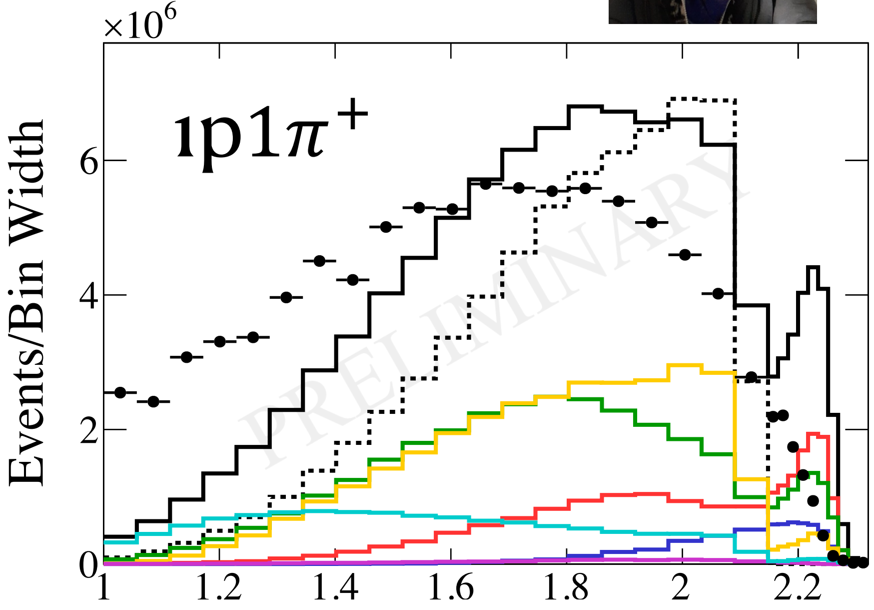
2.2 GeV on Carbon



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



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



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

Peak reconstructed if measured particles are full final state

Tail due to missing particles, not well described

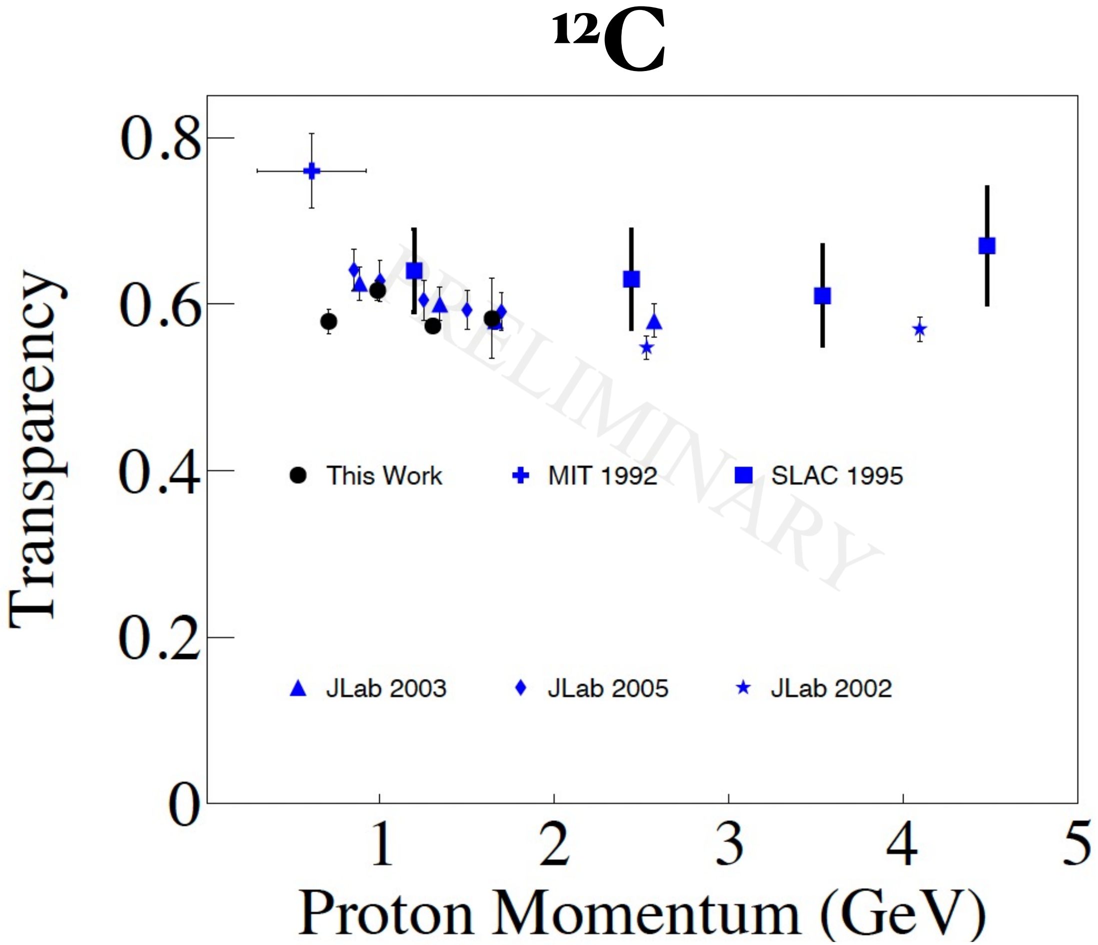
Proton transparency

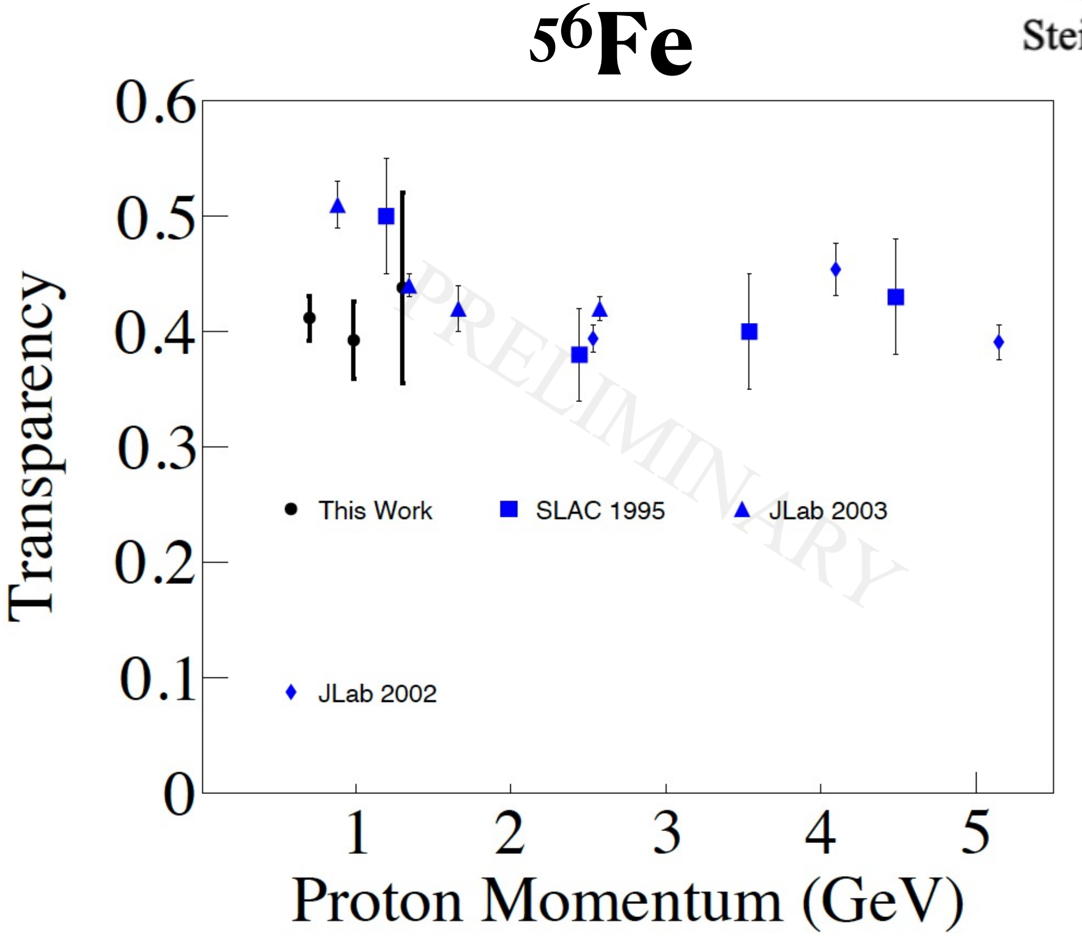
- New proton **transparency measurement** on ^{4}He, ^{12}C and ^{56}Fe
  - Probability that a struck proton leaves the nucleus without significant re-scattering
  - Study proton FSI similarly to neutrino scattering
- All previous transparency analysis measure (e,e'p)exp/$(e,e'p)_{PWIA}$
- **Define a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

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

- **N(e,e'p)0π:** selected 1p0π events from CLAS6
  - Background subtracted, radiative, acceptance and efficiency corrections
- **$N(e,e')_{QE}$:** inclusive QEL event rate
  - Use GENIE to determine QE dominated regions

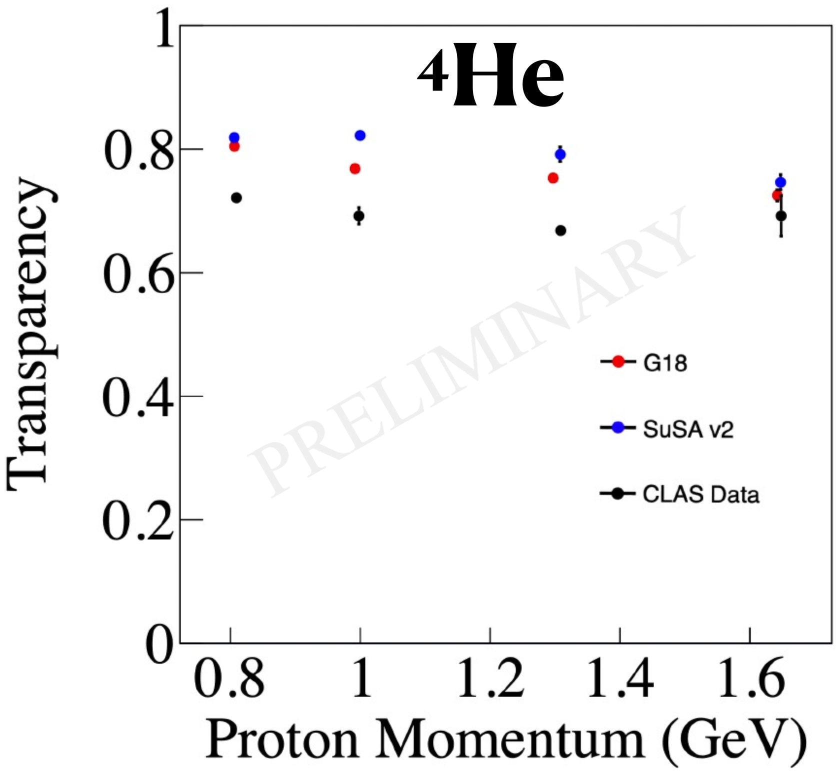
Proton transparency

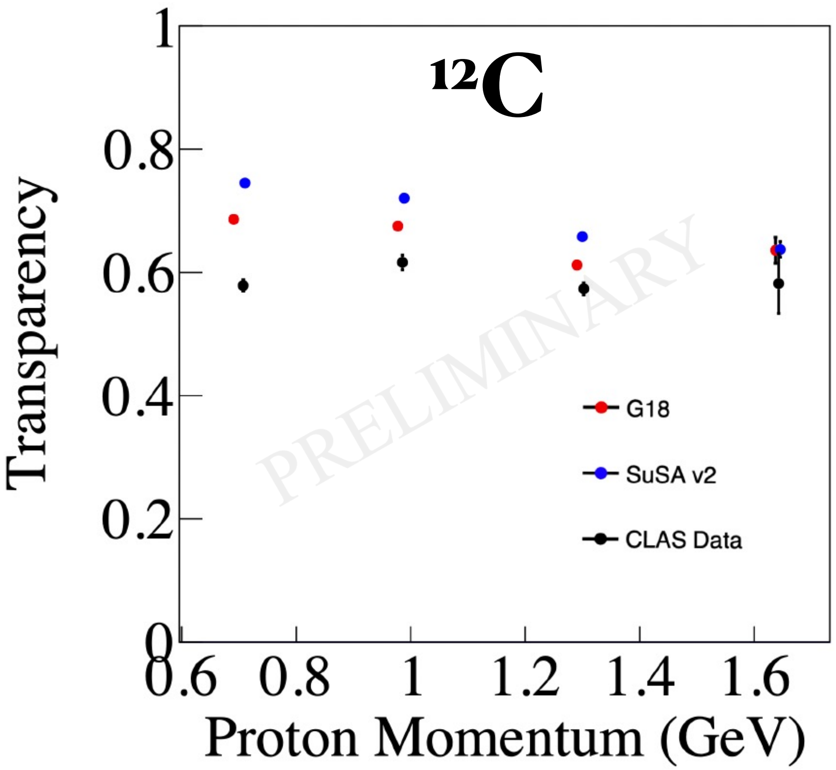


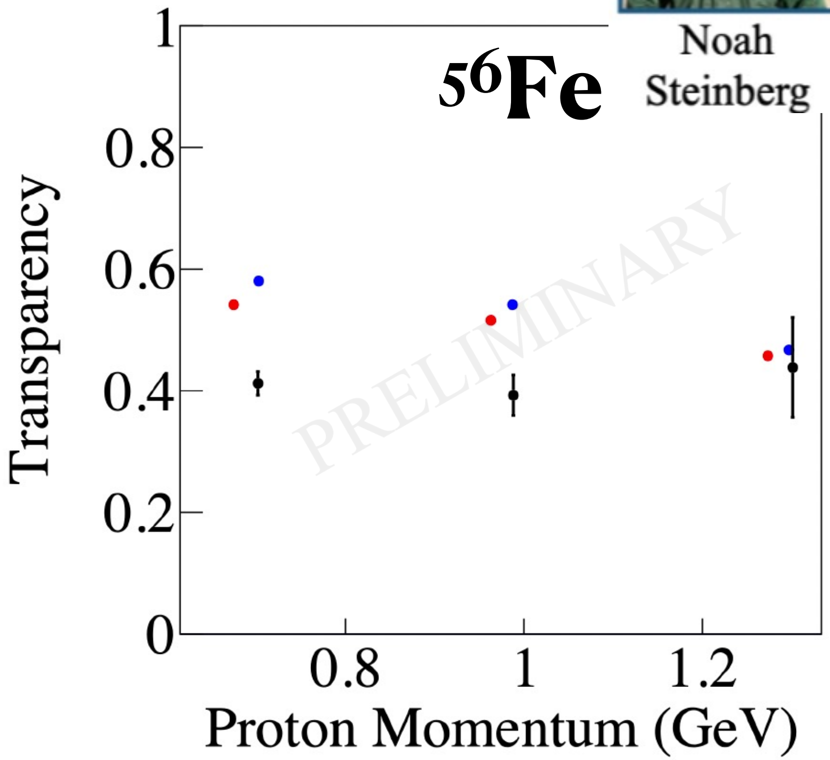


Compatible with previous data

Proton transparency







Noah Steinberg

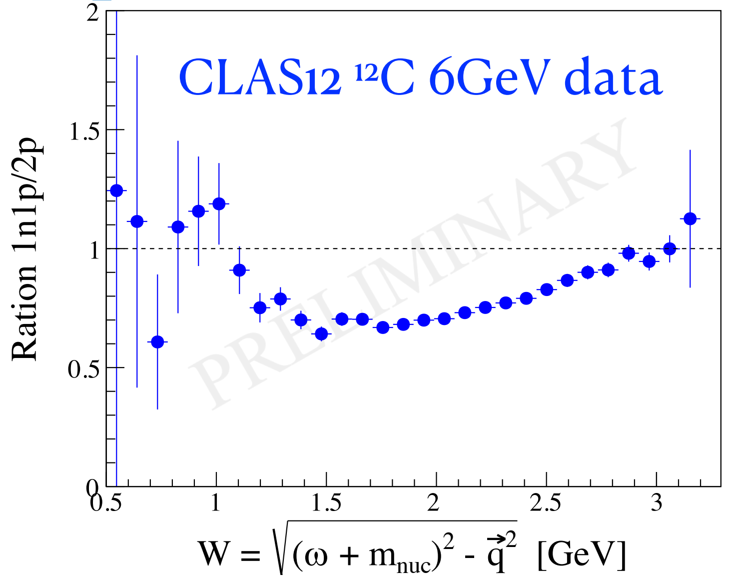
- **First transparency measurement on ^{4}He**
- Transparency flat in p_p decreases with A
- Data to MC differences larger at small p_p, grow with A
  - MC **very sensitive** to nuclear structure models

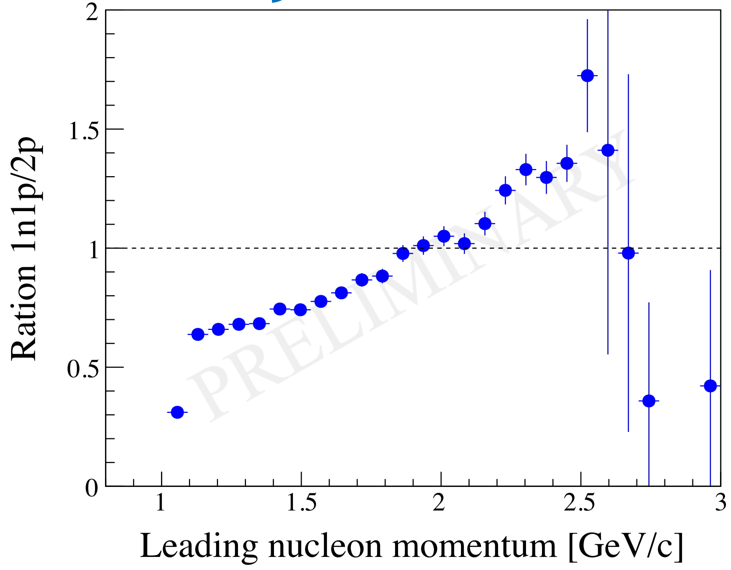
Publication soon!

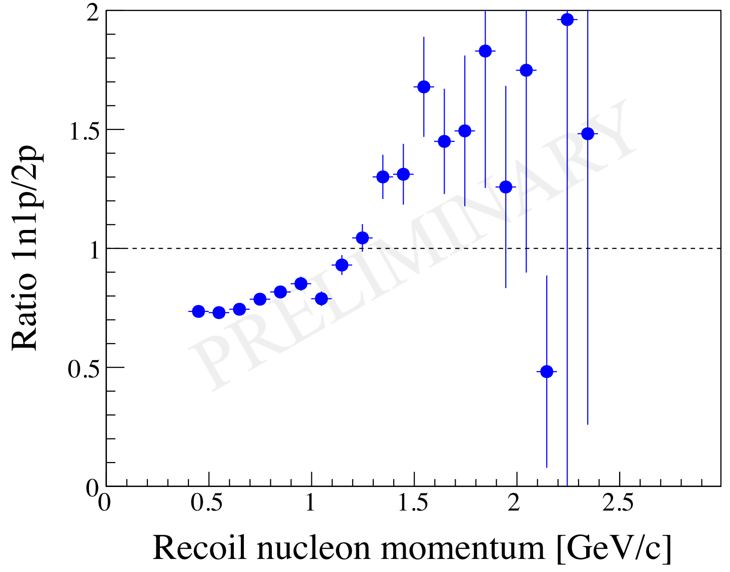
First 2p and 1n1p knockout analysis

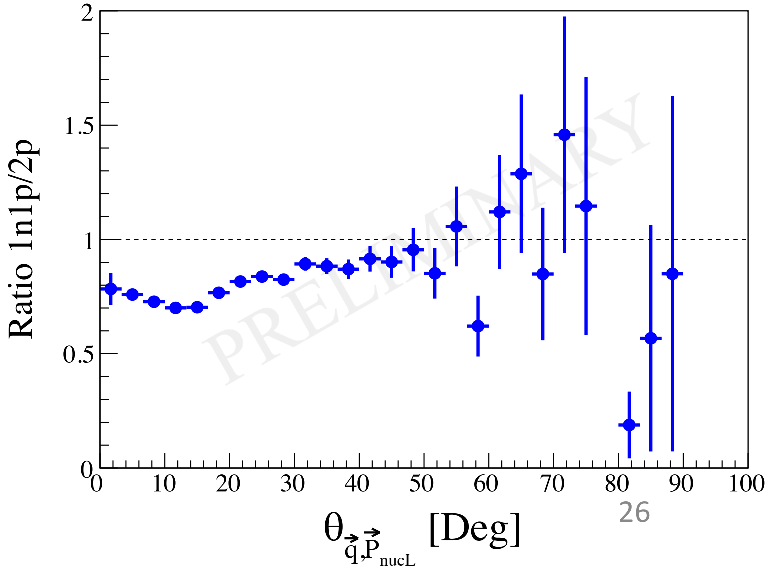
- Selecting 1n1p or 2p events with no visible pions in the final state

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









Conclusions

- e4nu provides **important input for ν-A interactions**
  - Huge increase in data base for **hadron electroproduction**
  - New sensitivity to nuclear structure/FSI
  - Significant improvement to **event generators**
- **Many channels available** for 1-6 GeV electrons (e.g. carbon, argon)
  - Unprecedented wide kinematic coverage for inclusive scattering
  - New and unique pion-proton coincidence data studies FSI, $\Delta(1232)$
  - New proton transparency data studies FSI and nuclear structure
  - New 1n1p/2p electroproduction gives new sensitivity to reaction mechanisms
  - Many other channels available for new collaborators

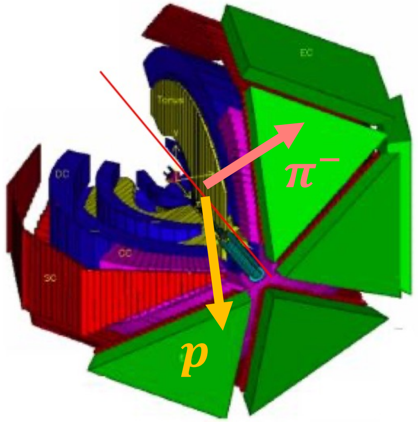
Thank you

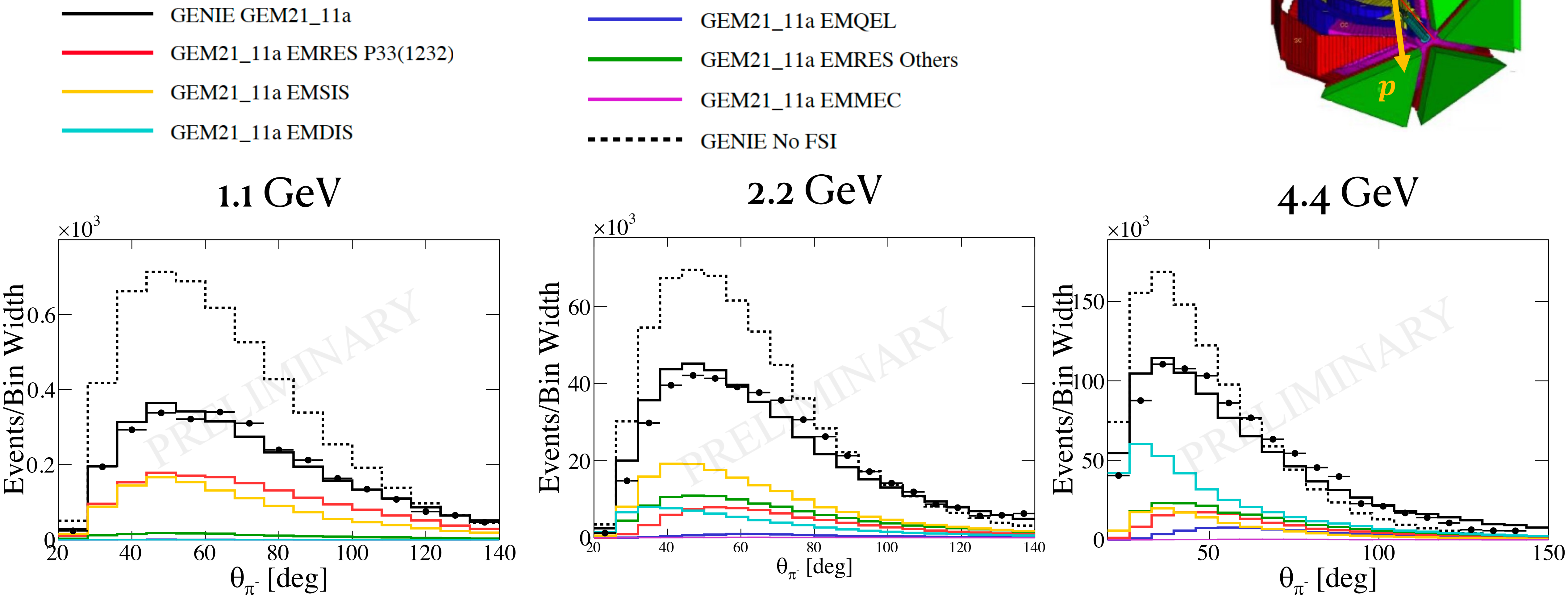
New collaborators are welcome!

e4nu at NuINT24

Backup slides

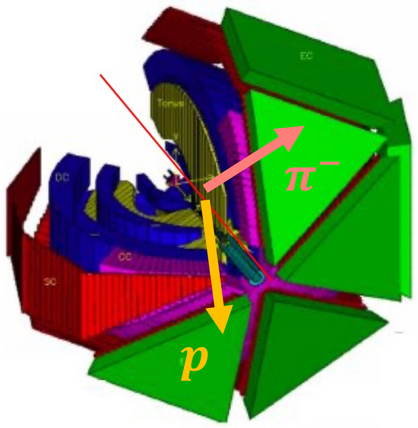
C(e,e'1pπ⁻) – Pion angle

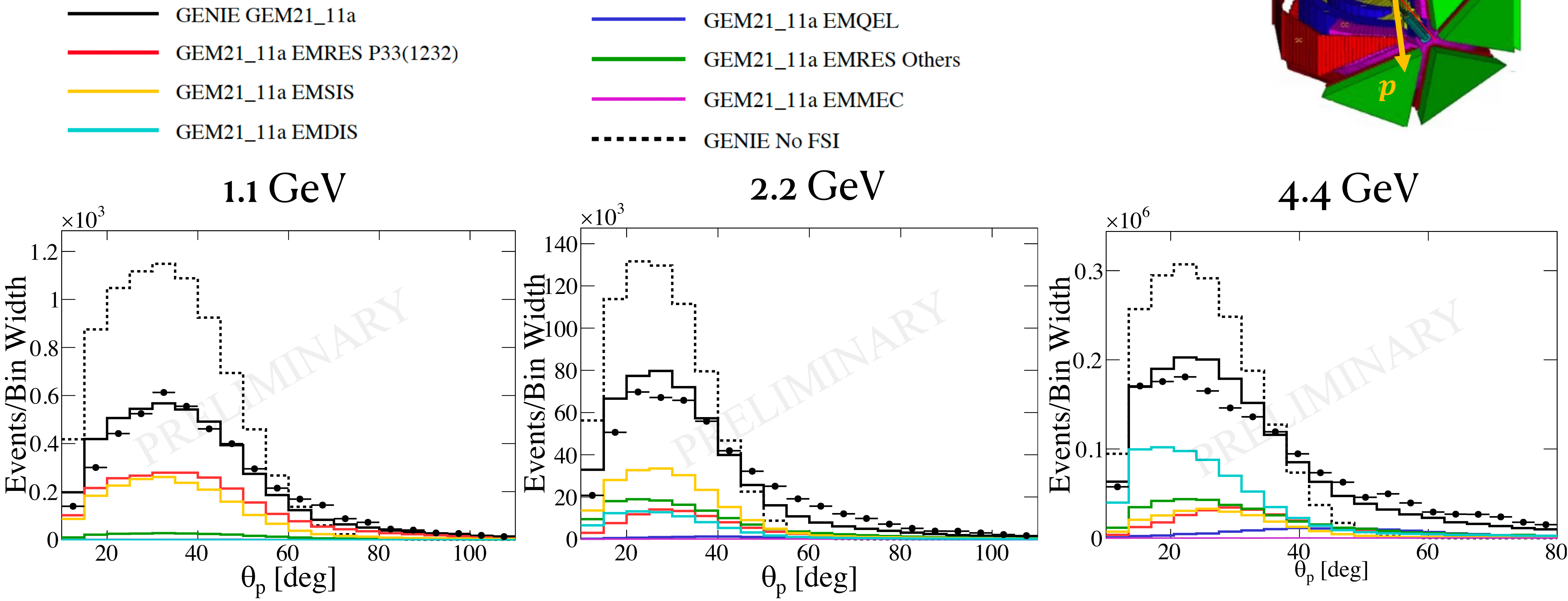




Angular shape in good agreement with GENIE

C(e,e'1pπ^-) – Proton angle

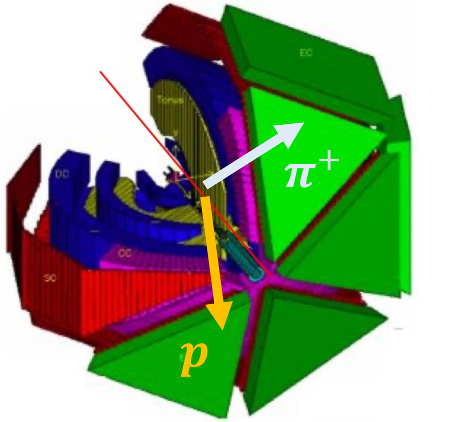


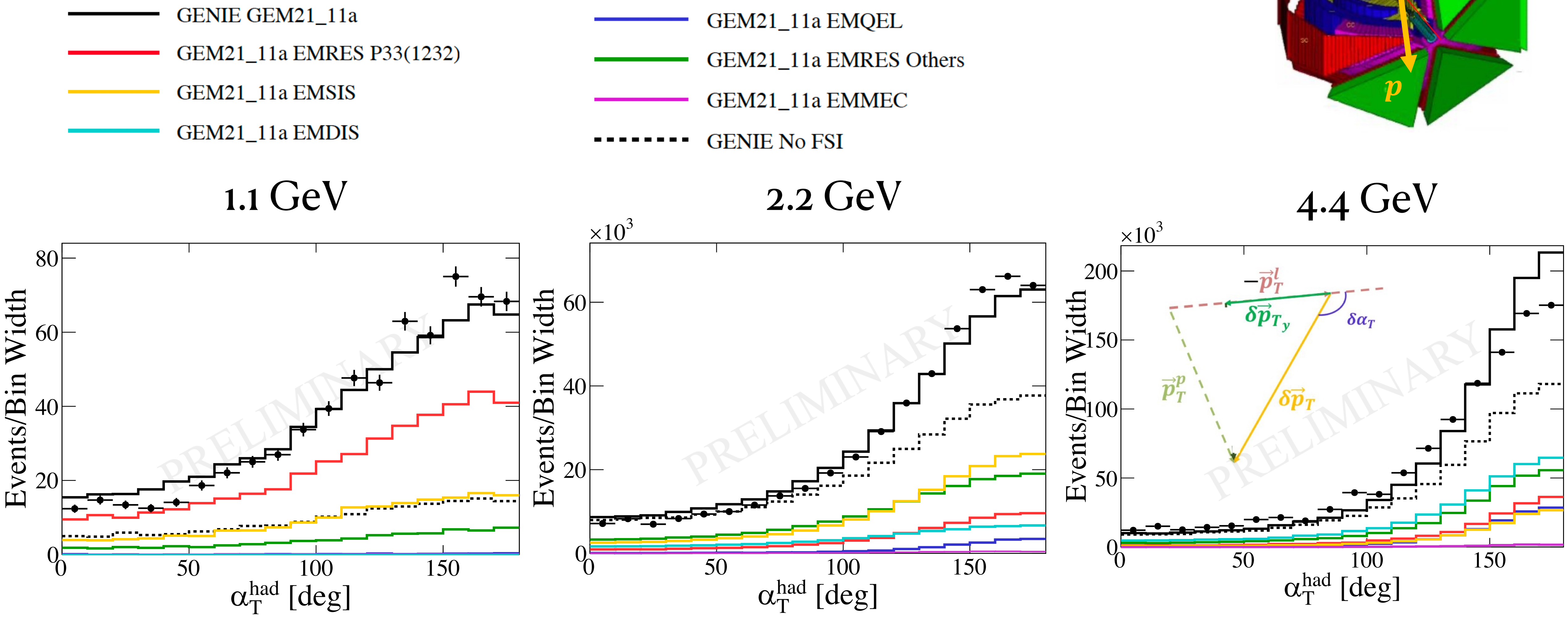


Angular shape in good agreement with MC

High θ_p possible only due to FSI

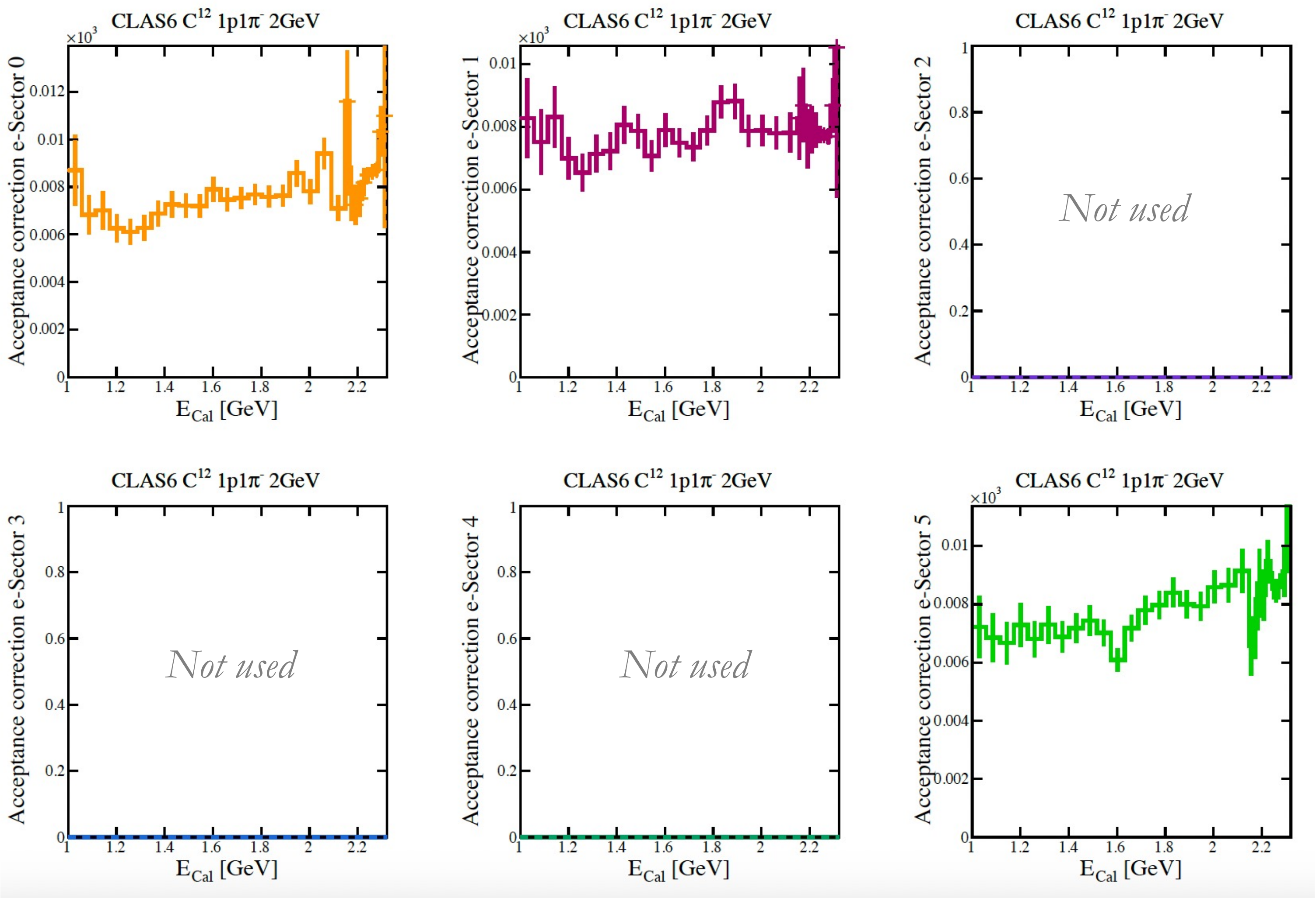
C(e,e'1pπ⁺) – Transverse boosting angle



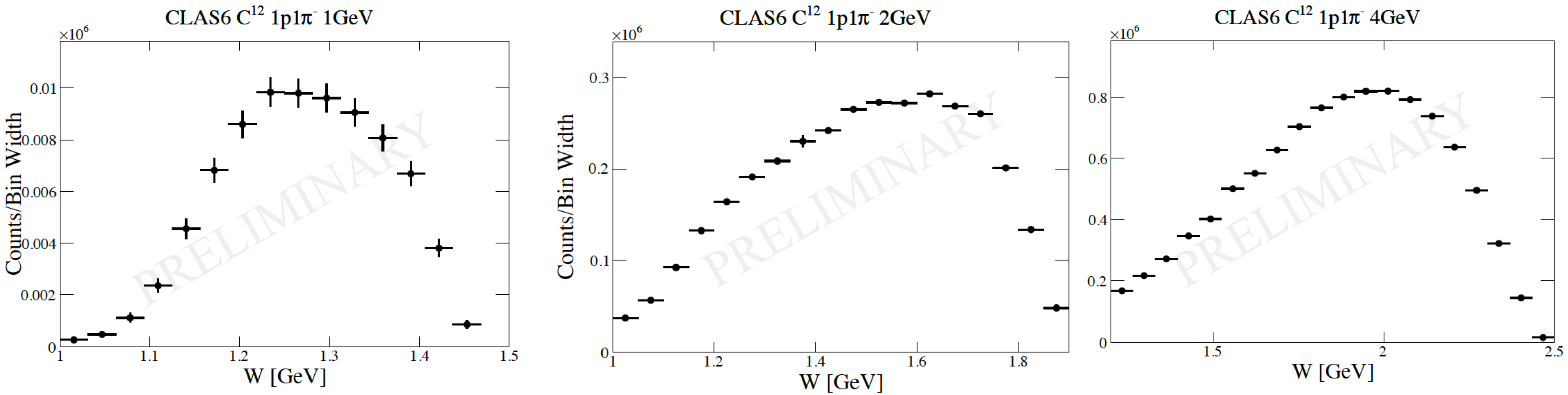


GENIE with FSI predicts correct rise

Acceptance correction per sector



Pion production analysis - Raw data



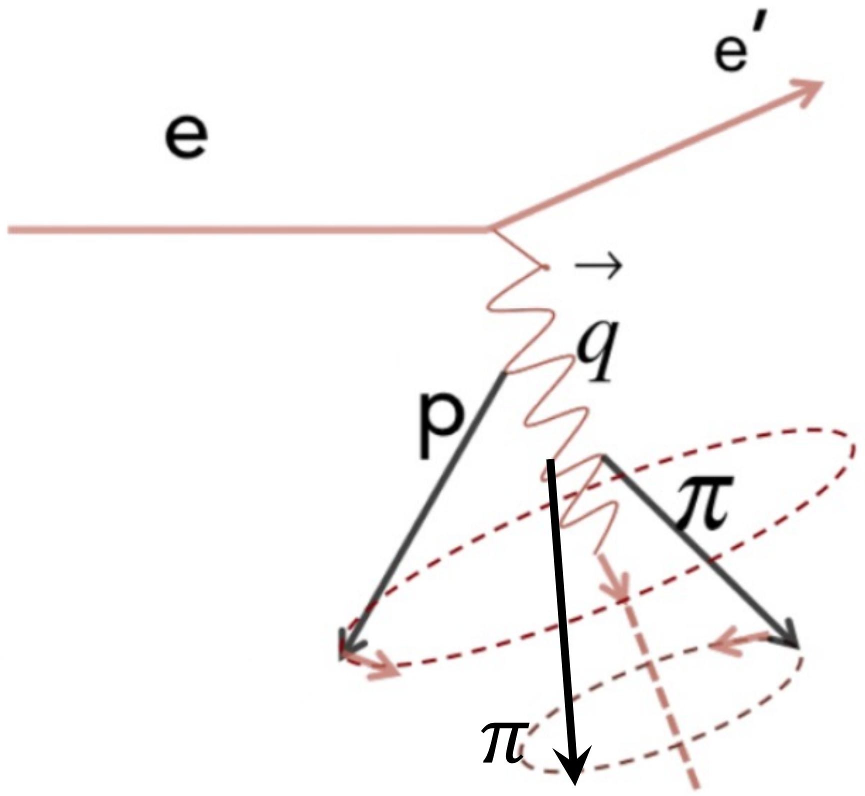
Delta dominated

Higher W resonances

Multi-pion production

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

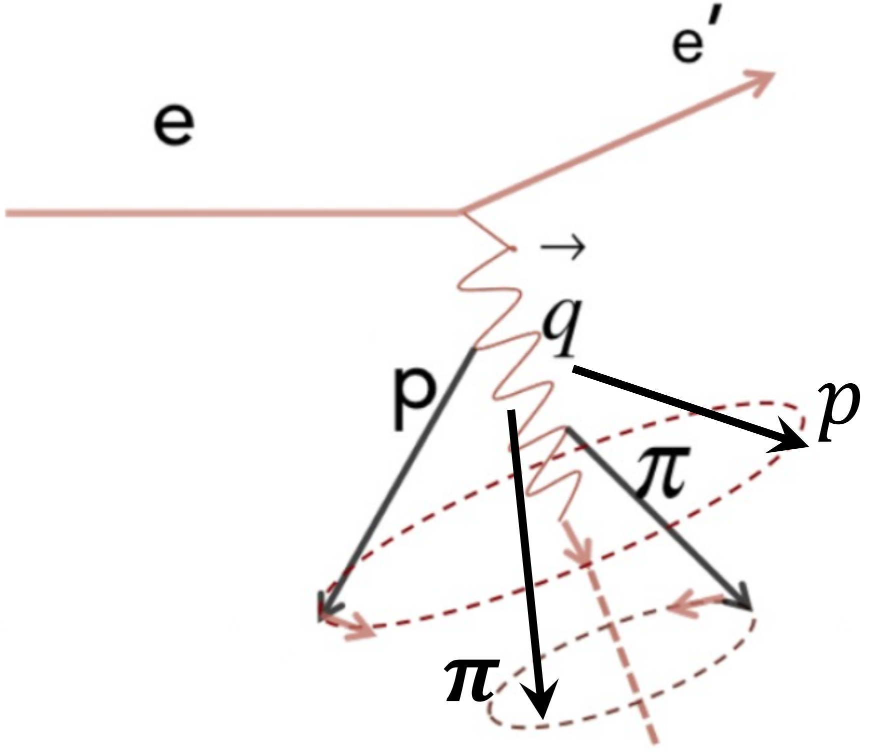


Background subtraction

- 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

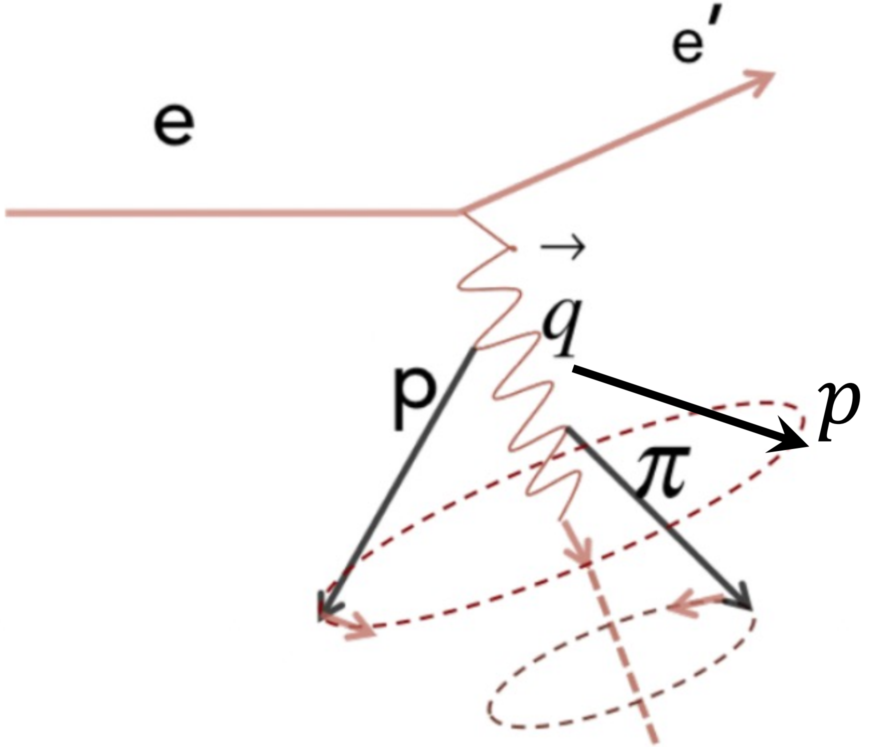


Background subtraction

- **Repeat for lower multiplicity events**
    - i.e. 2p1π and 1p2π
- Calculate the weight for the event to be reconstructed as
    - 1p1π (our signal definition)

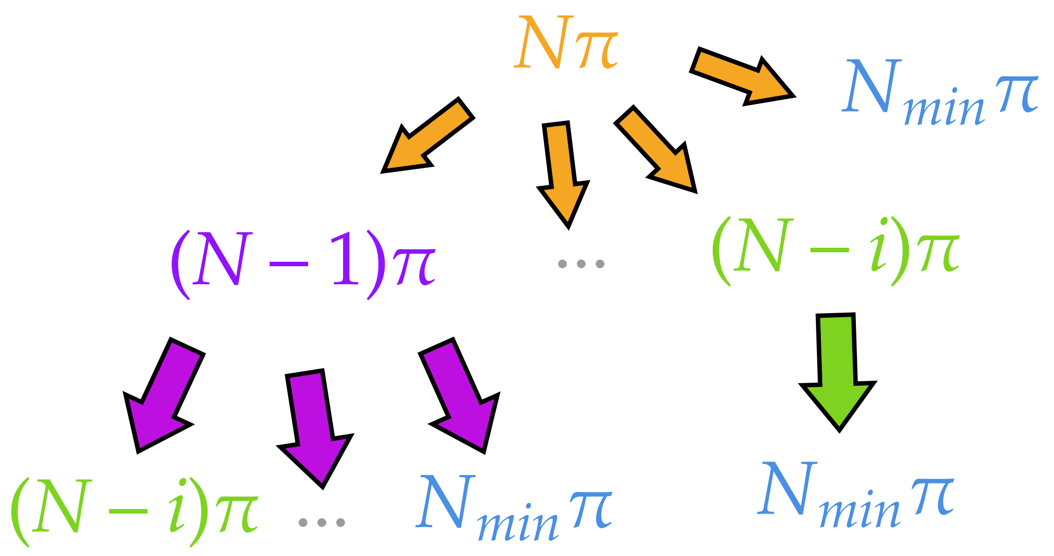
$$w = + \frac{M_{mf'}}{M_{mf}} \frac{N_{mf}}{N_{mi}} w_i$$

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

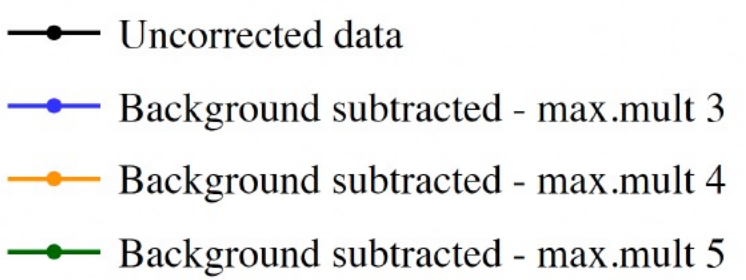


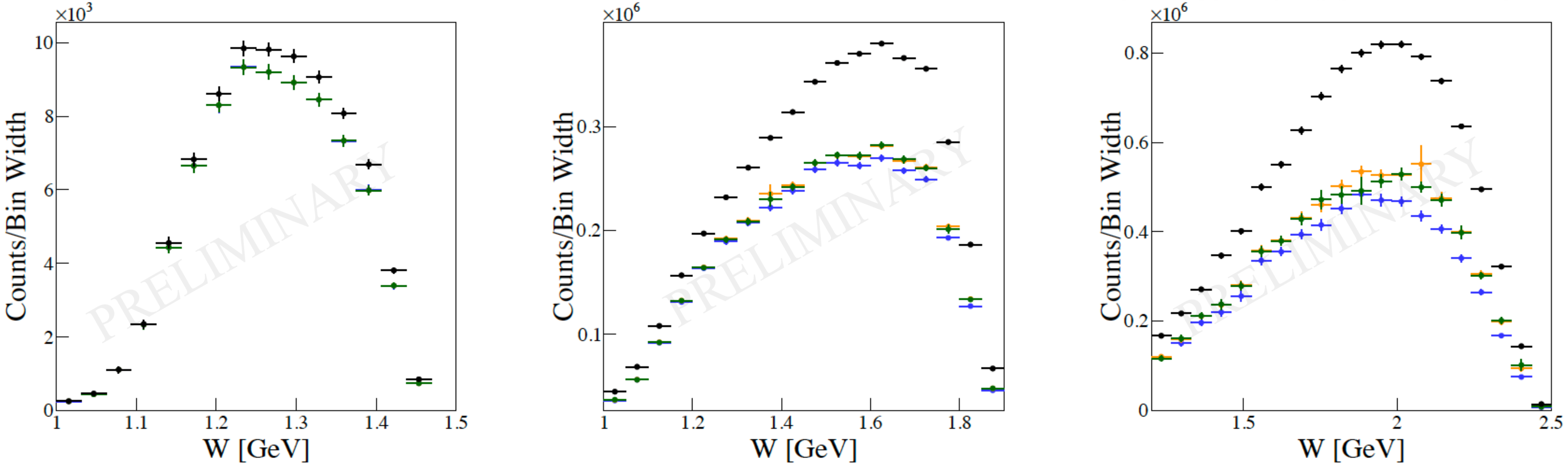
Background subtraction

- 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



Background subtraction





(a) Carbon at 1.1 GeV

(b) Carbon at 2.2 GeV

(c) Carbon at 4.4 GeV

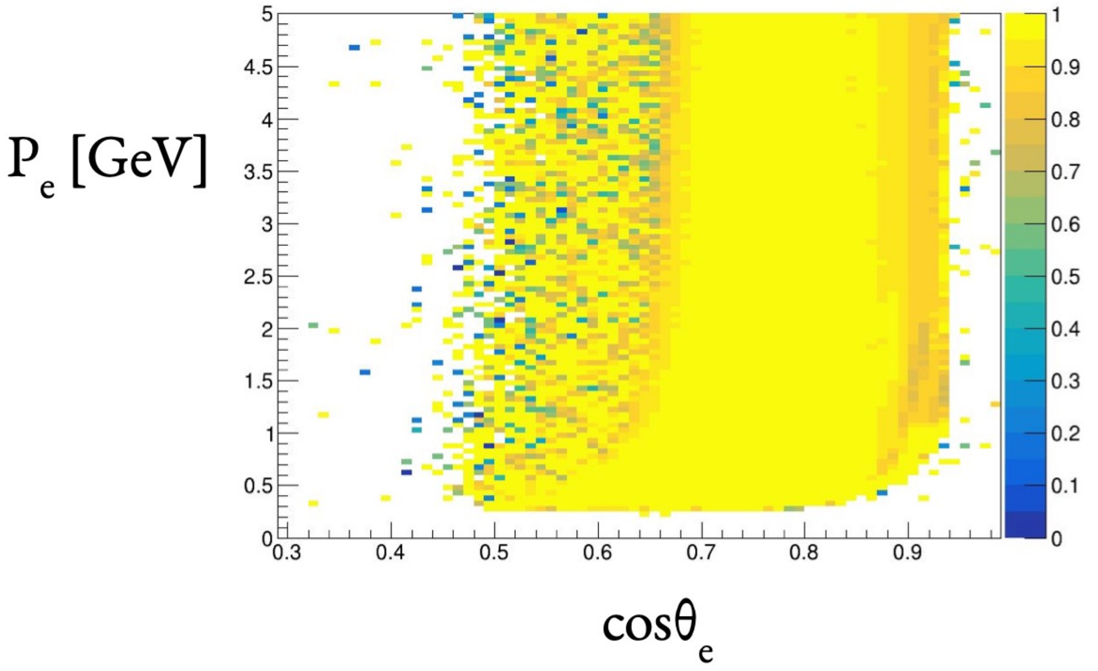
Correct for detector acceptance

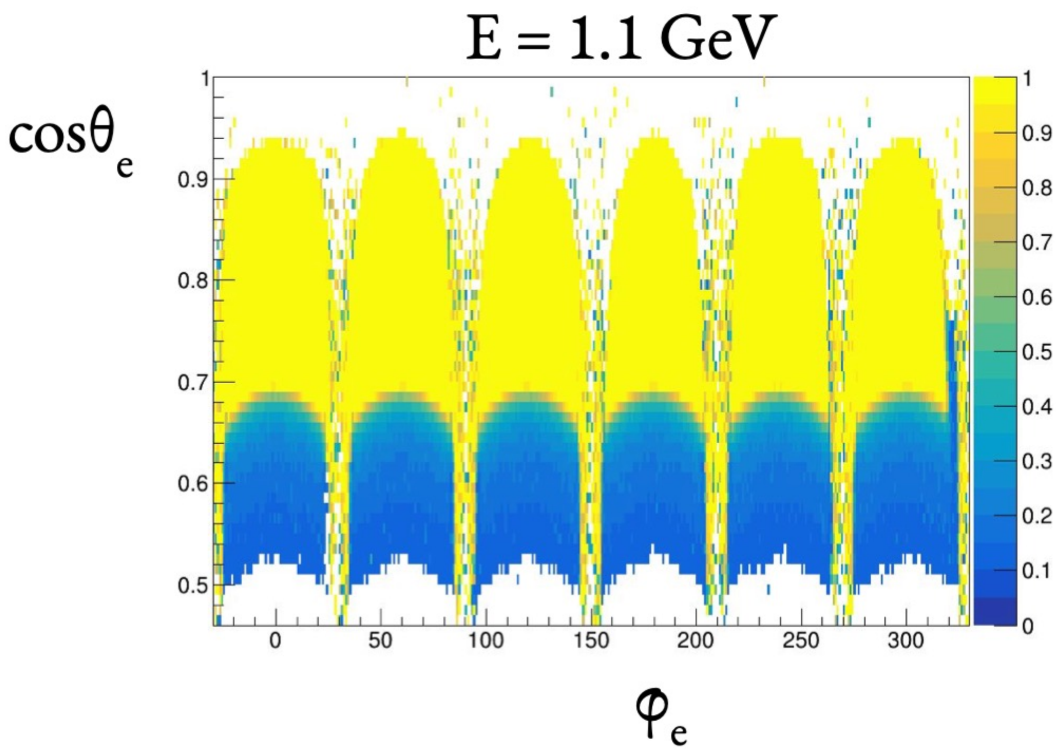
- We must correct the data for detector effects to obtain a **detector-independent cross-section** measurement
- We use **MC simulations** to compute the acceptance correction
  - MC simulation without detector effects
    - "True MC"
  - MC simulation with detector effects and no background events
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

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

Detector acceptance maps

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

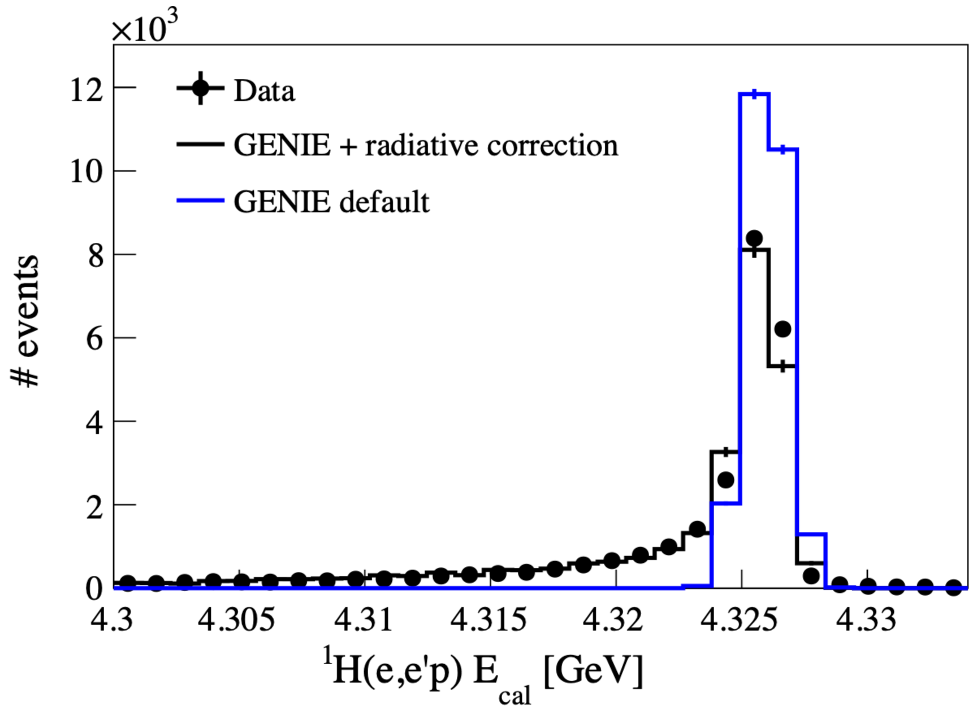




(*) Re-used from previous analysis

Radiative corrections

- MC simulation does not account for radiative effects
- We add radiative effects the same way as Jefferson Lab SIMC event generator
    - Data correction factor
- Implementation generalized for all interaction mechanisms

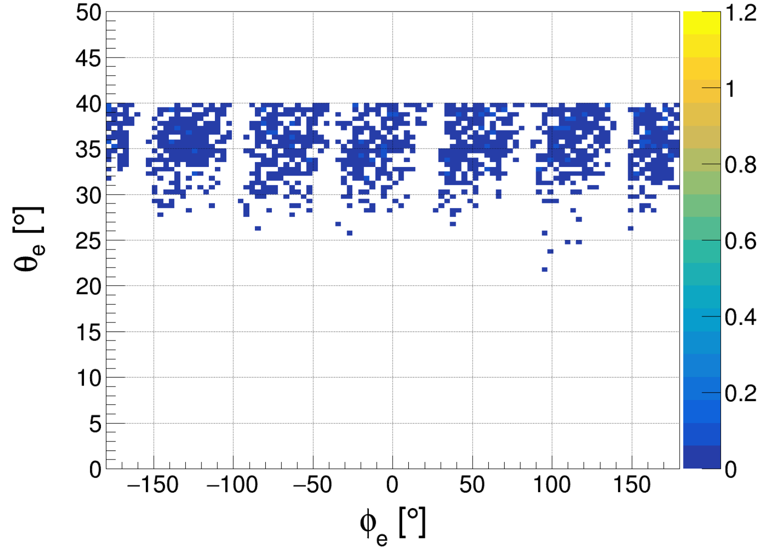


This is ongoing work; it is not included in the results shown in this talk

CLAS12 – acceptance

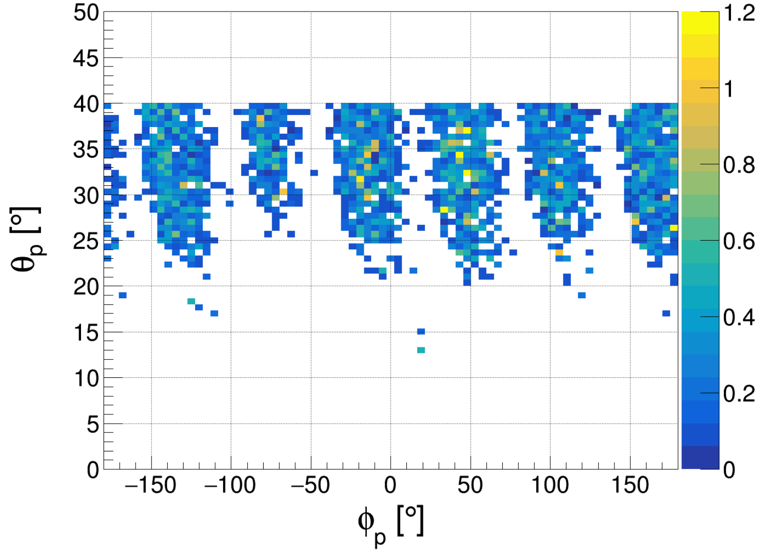
Electron

$\epsilon_{eff}(\theta_e, \phi_e)$ **in** (e, e')



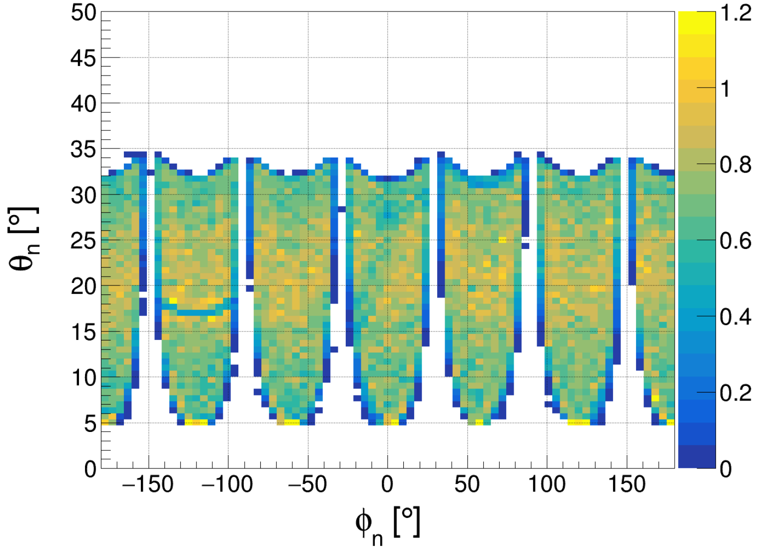
FD protons

$\epsilon_{eff}(\theta_p, \phi_p)$ **in** (e, e')



Leading FD neutron

$\epsilon_{eff}(\theta_n, \phi_n)$ **in** (e, e')



FD acceptance:

- **Polar angle:** $5° \leq \theta \leq 35°$ (up to 45° in some sub-systems)
- **Azimuthal angle:** from 50% at $\theta = 5°$ to 90% at $\theta = 40°$

CD acceptance:

- **Polar angle:** $35° \leq \theta \leq 125°$
- **Azimuthal angle:** full range

$$\epsilon_{eff}(\theta, \phi) = \frac{Observed}{Expected}$$

Leading FD neutron = the neutron with the highest momentum magnitude in the FD

^{12}C simulation at $E_{beam} \simeq 6$ GeV

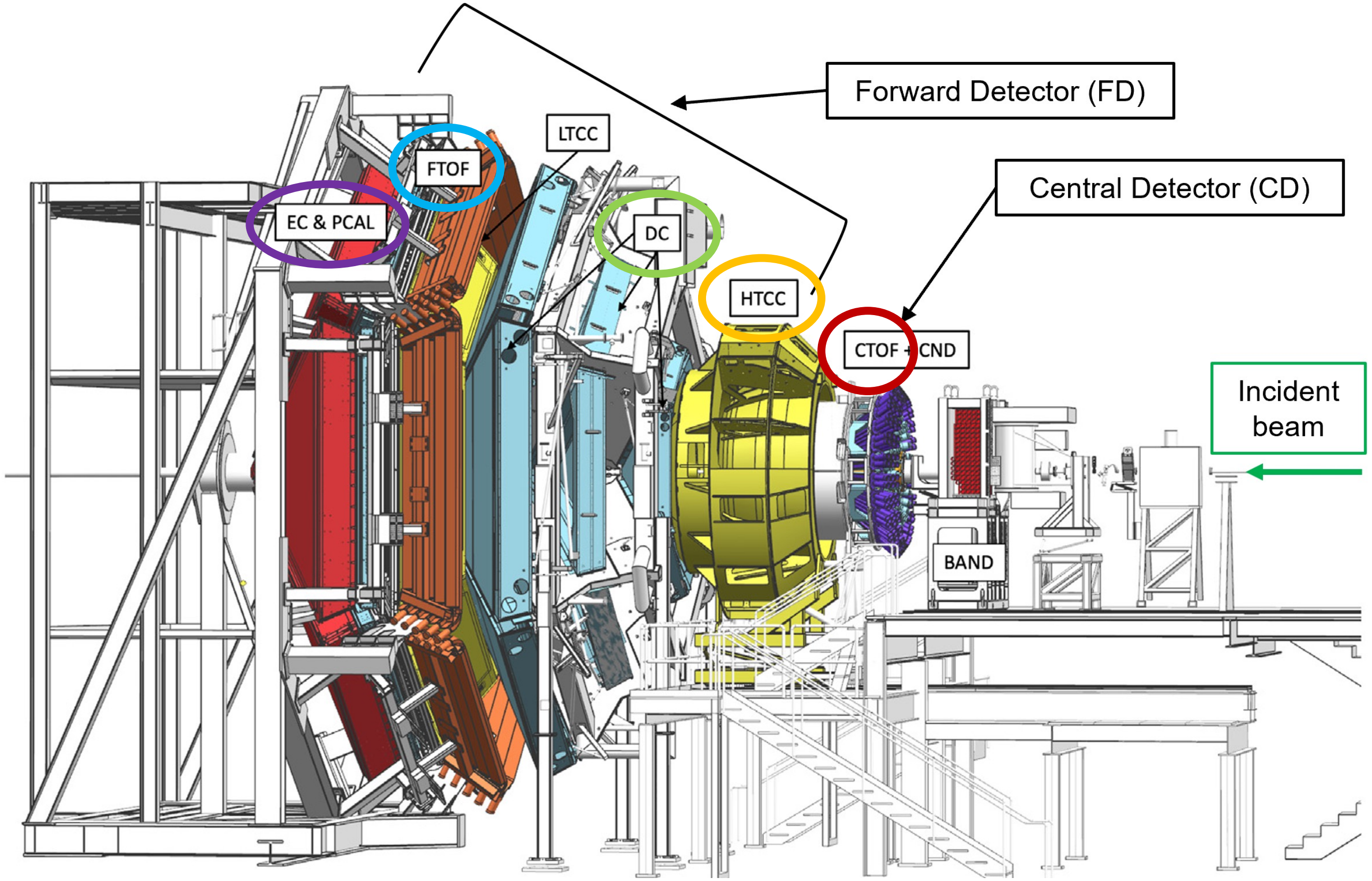
CLAS12 – sub-systems in the FD and CD

Forward Detector (FD):

- High Threshold Cherenkov Counter (HTCC)
- Drift Chambers (DC)
- Low Threshold Cherenkov Counter (LTCC)
- Forward Time-Of-Flight detector (FTOF)
- Ring Imaging Cherenkov detector (RICH)
- Electromagnetic Calorimeters (EC & PCAL)

Central Detector (CD):

- Central Vertex Tracker (CVT)
- Central Time-Of-Flight (CTOF)
- Central Neutron Detector (CND)
- Back Angle Neutron Detector (BAND)



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

Back to:
The CLAS12 detector

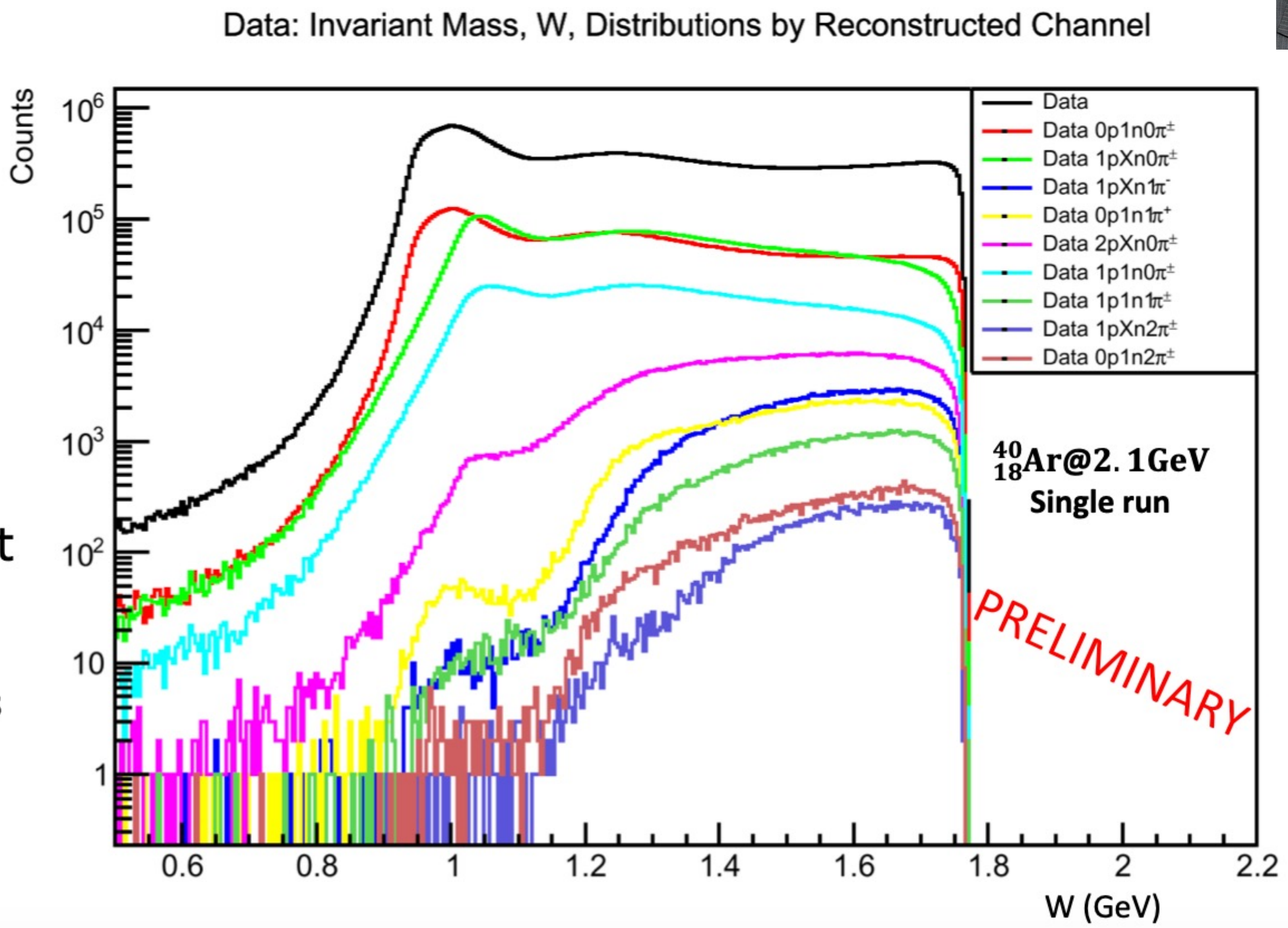
CLAS12 statistics

J.Barrow

Energy (GeV)	Q^2 Threshold	Channels with Expected Counts ($\times 10^6$)				
		$1pXn0\pi^{\pm}$	$2pXn0\pi^{\pm}$	$1pXn1\pi^{-}$	$1pXn2\pi^{\pm}$	$1p1n0\pi^{\pm}$
2.07	~ 0	~400	~20	~7	~0.6	~100
4.03	~ 0.1	~90	~20	~3	~0.6	~20
5.99	~ 0.4	~20	~5	~3	~2	~6

CLAS12 ^{40}Ar statistics

- W approximated off the standing proton
- Shapes are reasonable
- $\sim 5\ \mathrm{MeV}$ bins
  - Statistics look good!
- Problems w/GENIE prevent comparisons at high ω
  - Radiative effects dominate
  - Cut: $\omega \lesssim 1.2\ \mathrm{GeV}$



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CLAS12 ^{40}Ar statistics

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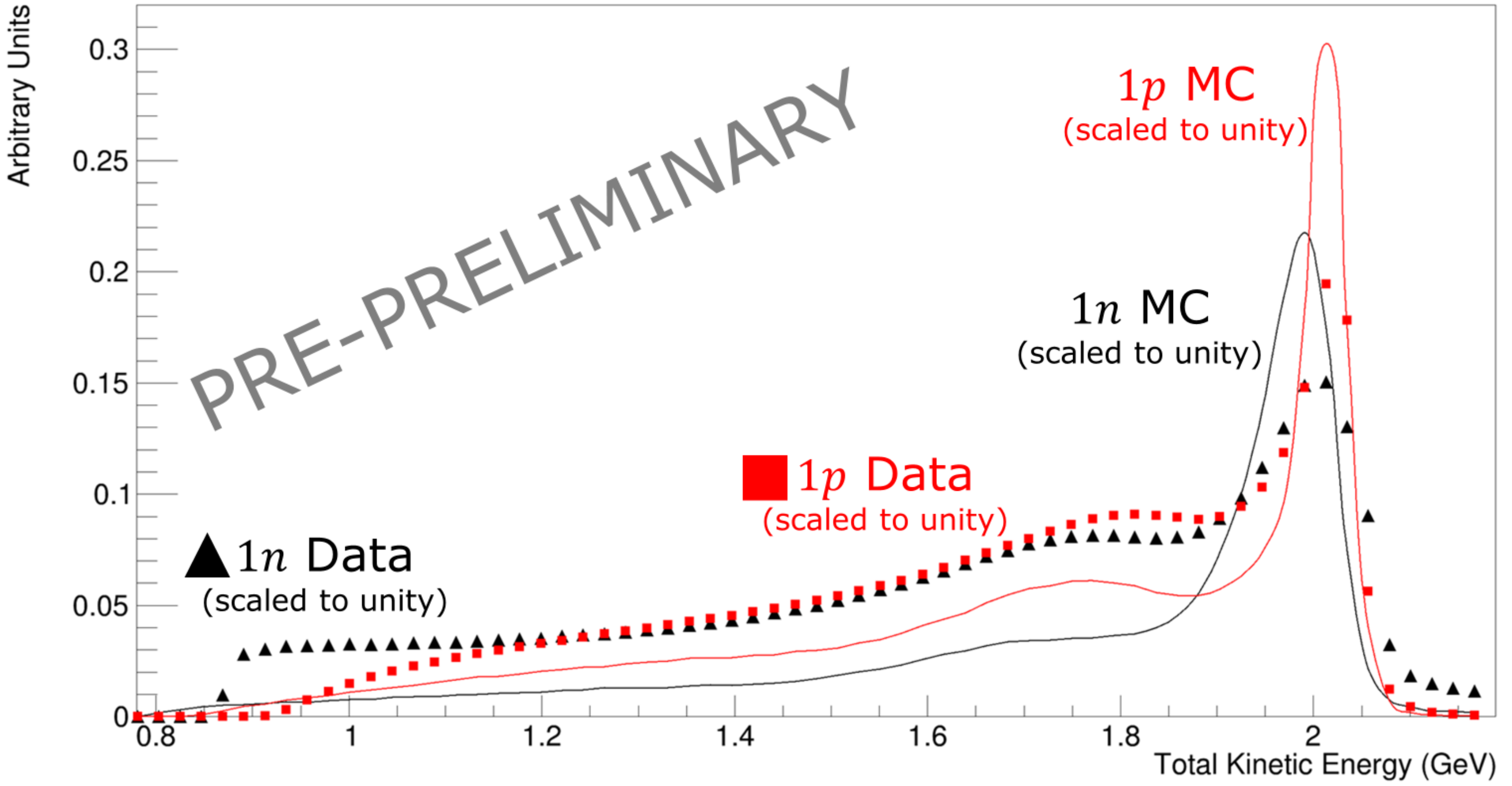

CLAS12 ^{40}Ar statistics

J.Barrow