Unveiling neutrino interactions with new electron scattering data

Julia Tena Vidal at Tel Aviv University

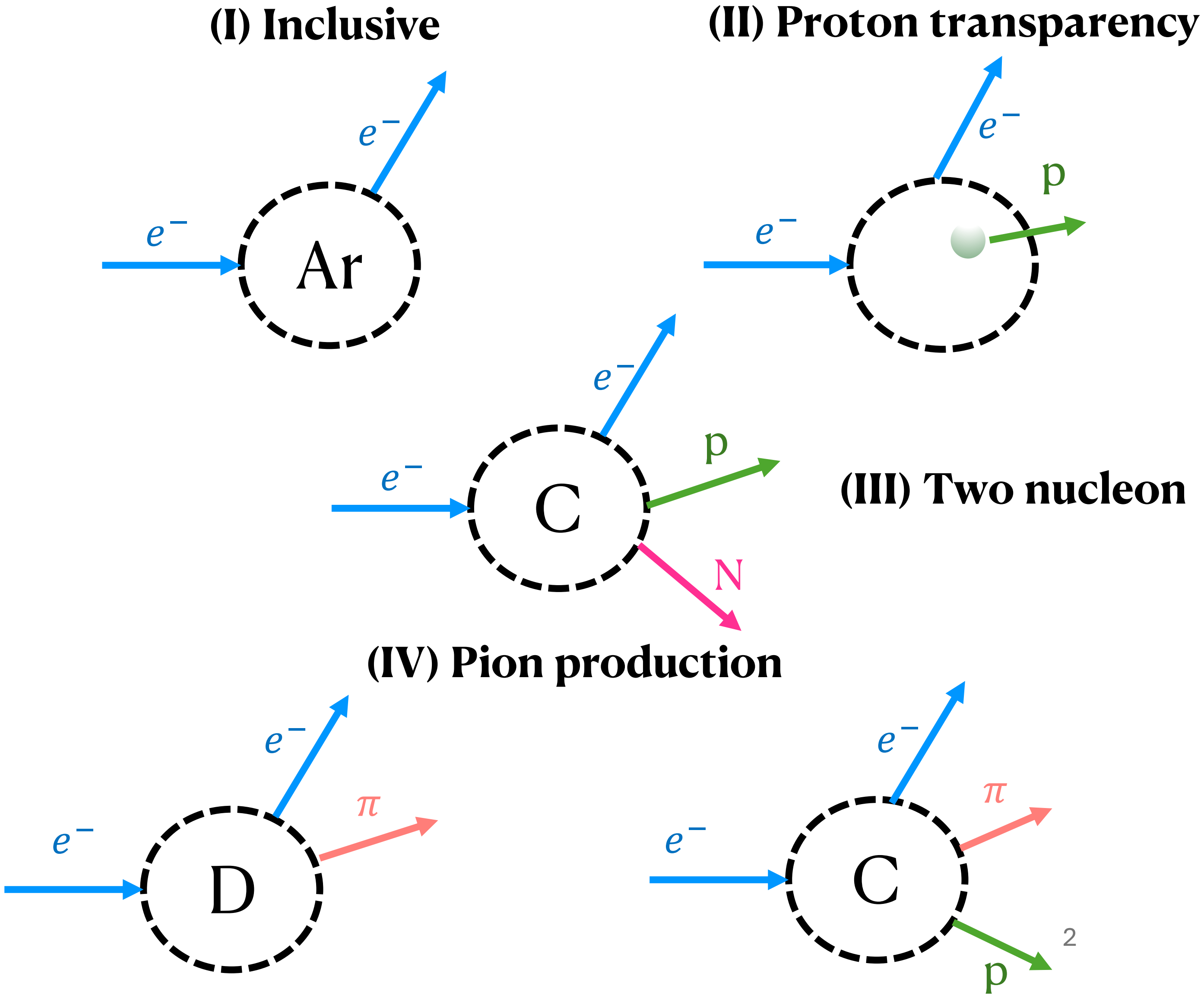
on behalf of the e4nu and CLAS collaborations

Unveiling new electron-scattering data

Huge increase in data base for **hadron electroproduction**

1-6 GeV electrons for many targets (e.g. carbon, **argon**)

New e4V measurements unveiled in this talk



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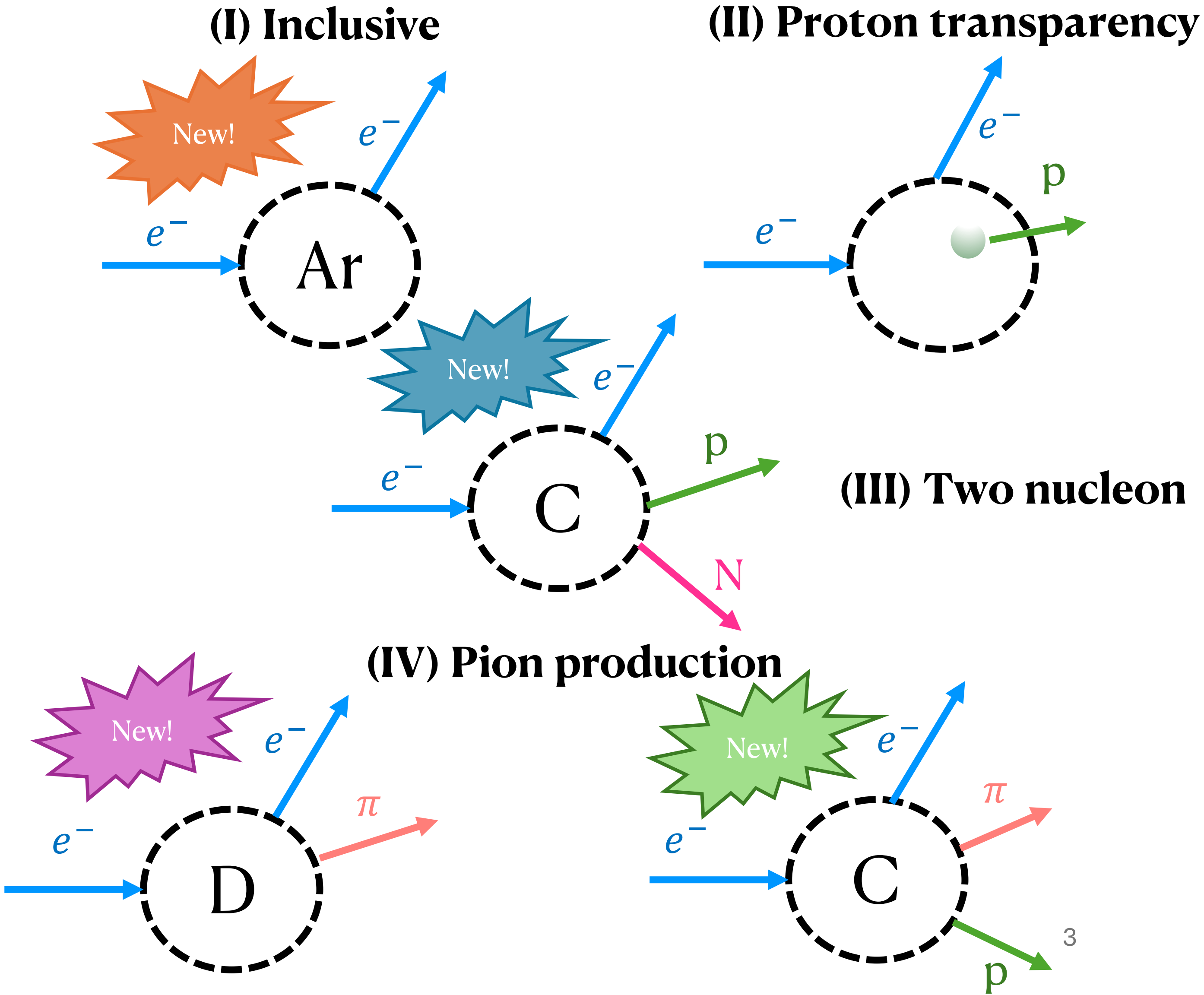


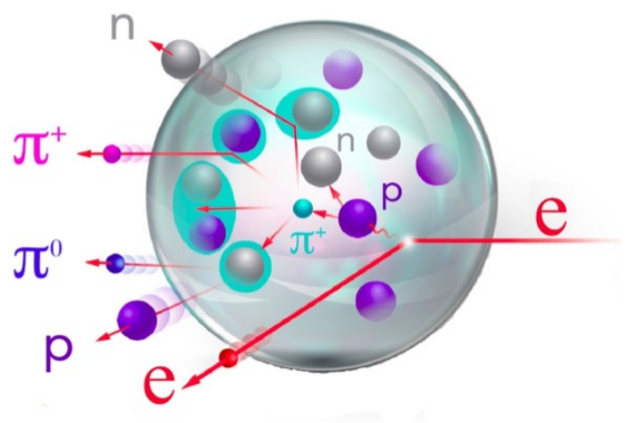
Electrons for neutrinos (e4ν)

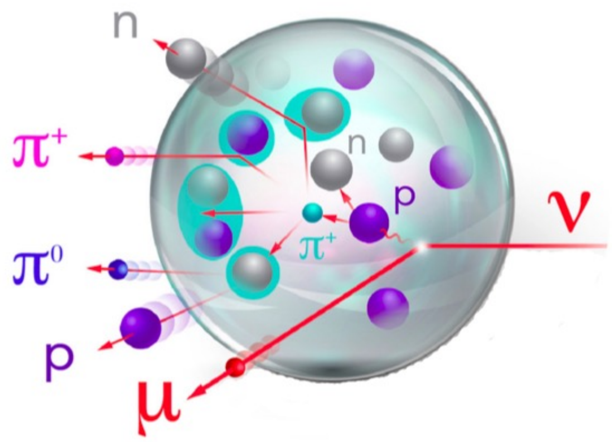
- **Same nuclear ground state**
- **Same Final State Interactions(FSI)**
- **Similar interactions with nuclei**
  - CC weak current [vector + axial]
    - $j_{\mu}^{\pm} = \bar{u}\frac{-ig_W}{2\sqrt{2}}(\gamma^{\mu} - \gamma^{\mu}\gamma^{5})u$
  - EM current [vector]
    - $j_{\mu}^{em} = \bar{u}\gamma^{\mu}u$

Useful to constrain ν –A model uncertainties

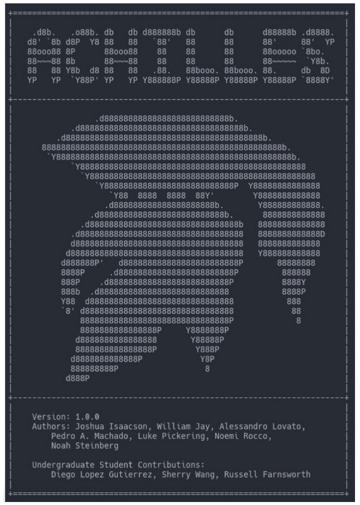
- **Monochromatic beam**
- **High statistics**

Useful to test energy reconstruction methods





Neutrino event generators need constraints



NuWro * Wrocław Neutrino Event Generator *

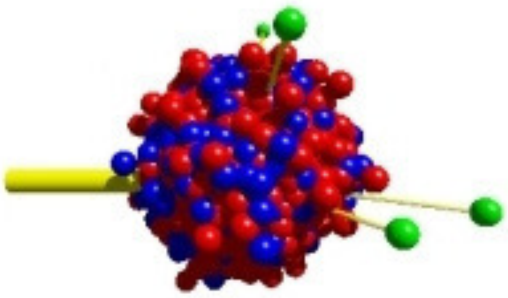
Complex theoretical picture

e-A/ν-A not always treated consistently

NEUT

Genie

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT



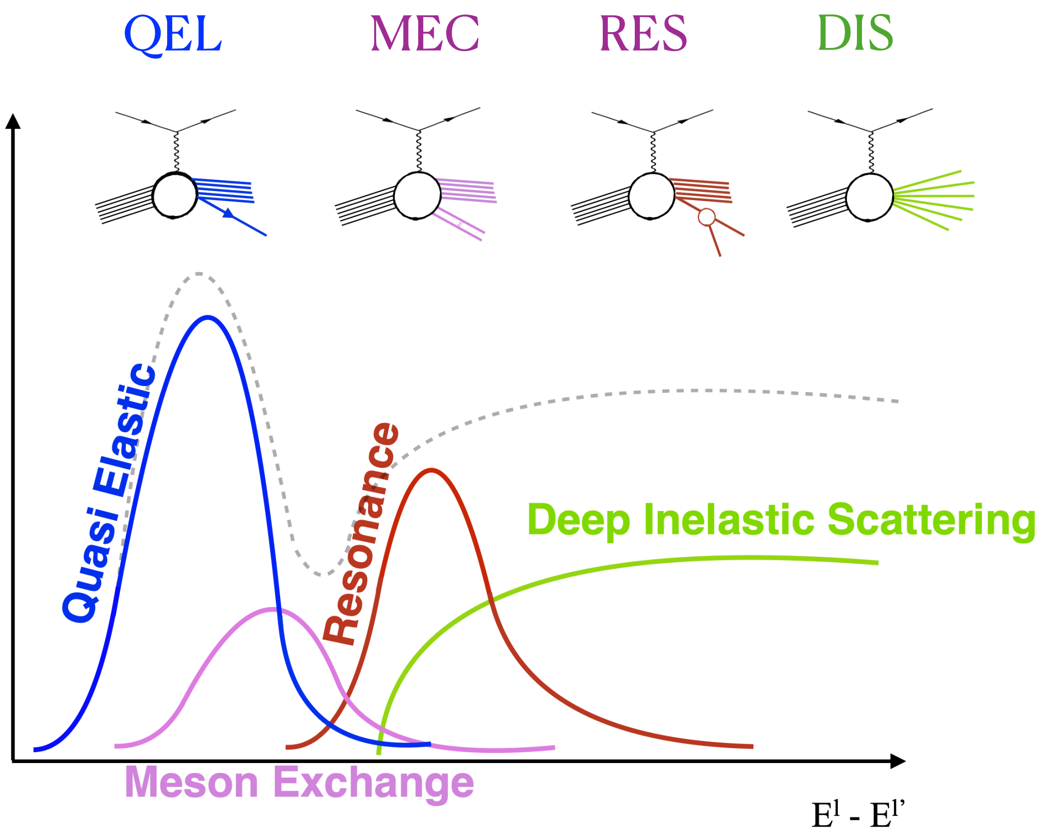
GiBUU

Neutrino event generators need constraints

Mostly inclusive models

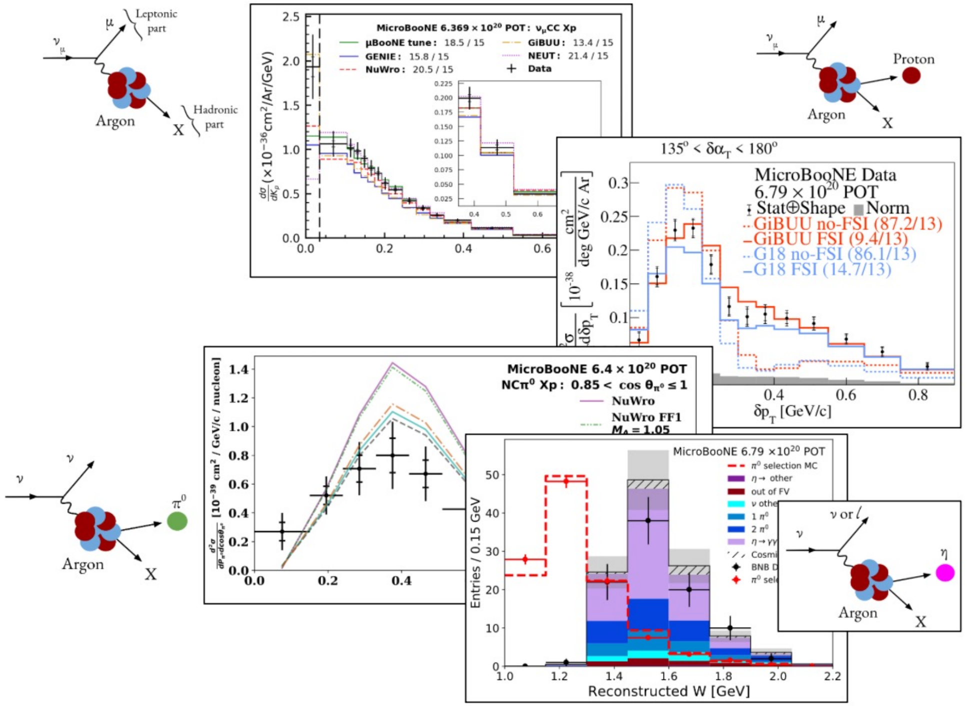
Ad-hoc hadron production – not constrained by data

Lack hadronproduction data



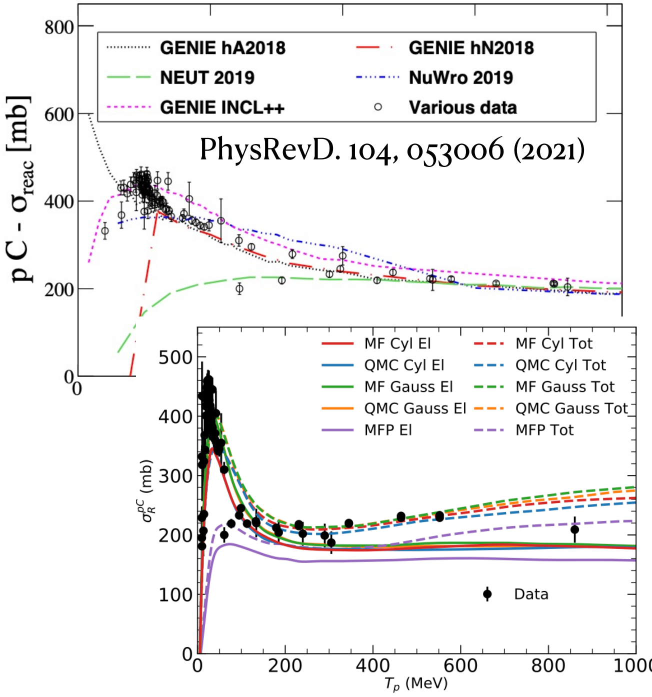
Neutrino event generators need constraints

ν-A



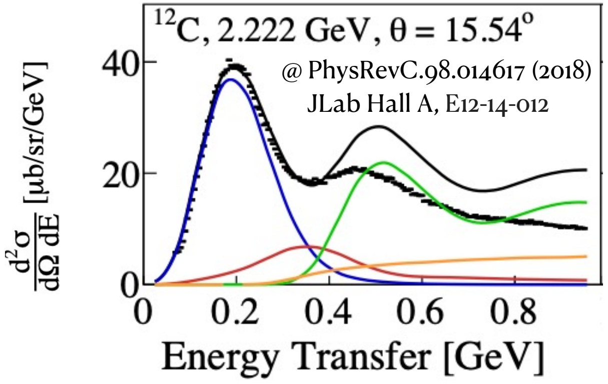
High-precision neutrino interaction measurements with MicroBooNE by Afroditi Papadopoulou

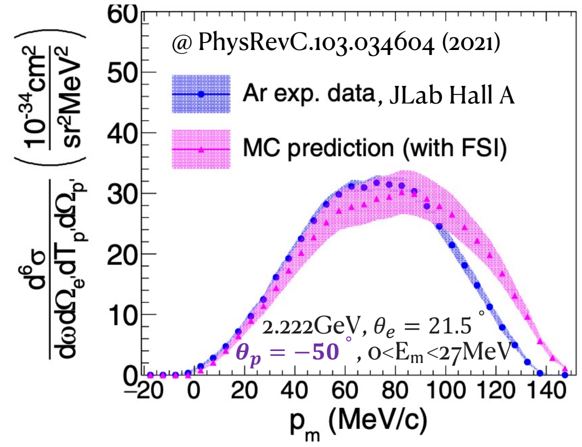
h-A



PHYSICAL REVIEW C **103**, 015502 (2021)

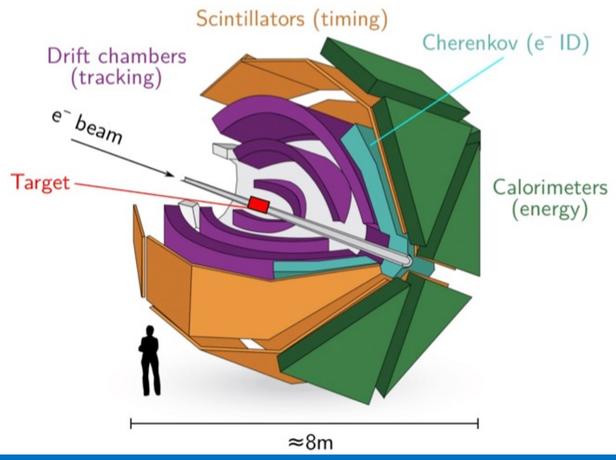
e-A

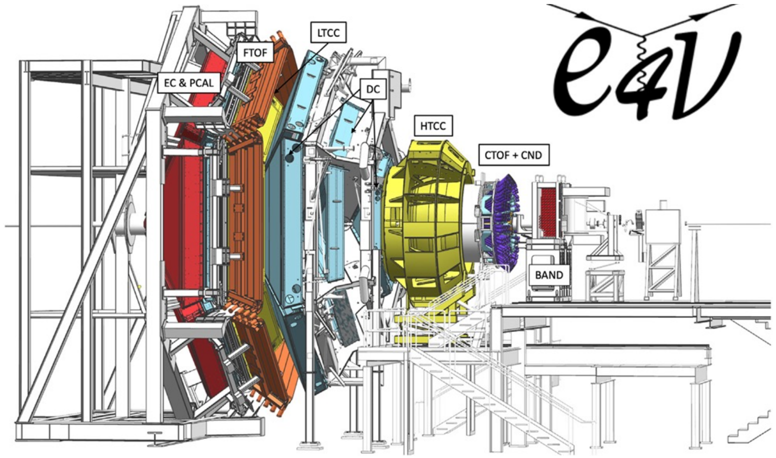




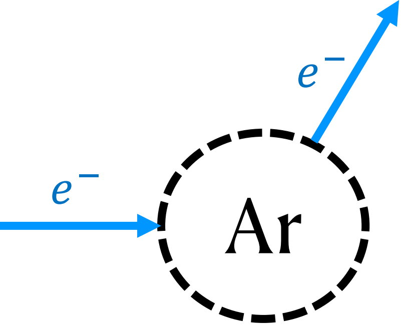
Need more exclusive data!

Hadron production with CLAS

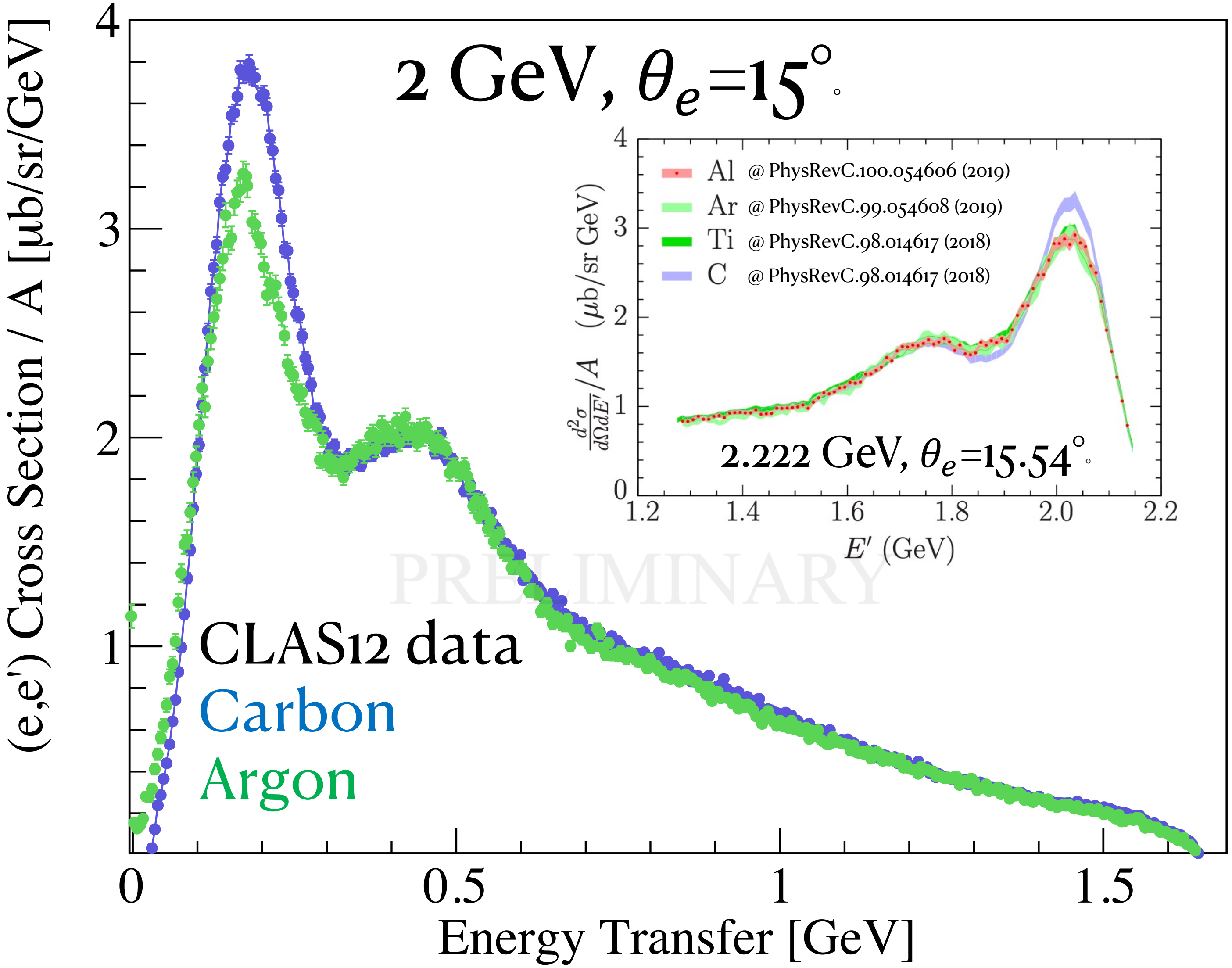




	CLAS6	CLAS12
Run years	1996-2013	2017 - ?
Luminosity	$10^{34}\ cm^{-2}s^{-1}$	$10^{35}\ cm^{-2}s^{-1}$
Targets	^{4}He, **C** & Fe	H, D, ^{4}He, **C**, (O), ^{40}**Ar** and more
Beam Energy	**1.1, 2.2, 4.4 GeV**	**(1), 2, 4, 6 GeV**
Electron acceptance	$\theta_e > 15°$	$\theta_e > 5°$
Solid angle coverage	$\sim 2\pi$	$\sim 3\pi$
Magnetic field	✓	✓
Particle thresholds	150 (300) MeV/c for $\pi^{\pm}$ (p/γ)	200 (400) MeV/c for $\pi^{\pm}$ (p/n)
Events	**~10M C(e,e') events**	**~100M ^{40}Ar (e,e') events**



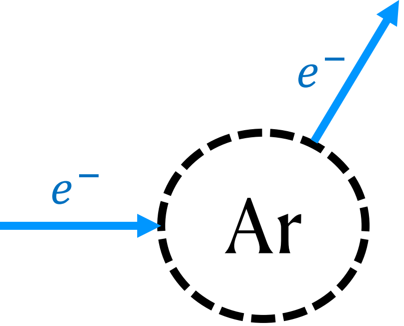
New Inclusive on C and Ar



Matan Goldenberg

Consistent with previous measurements

Different nuclear structure!



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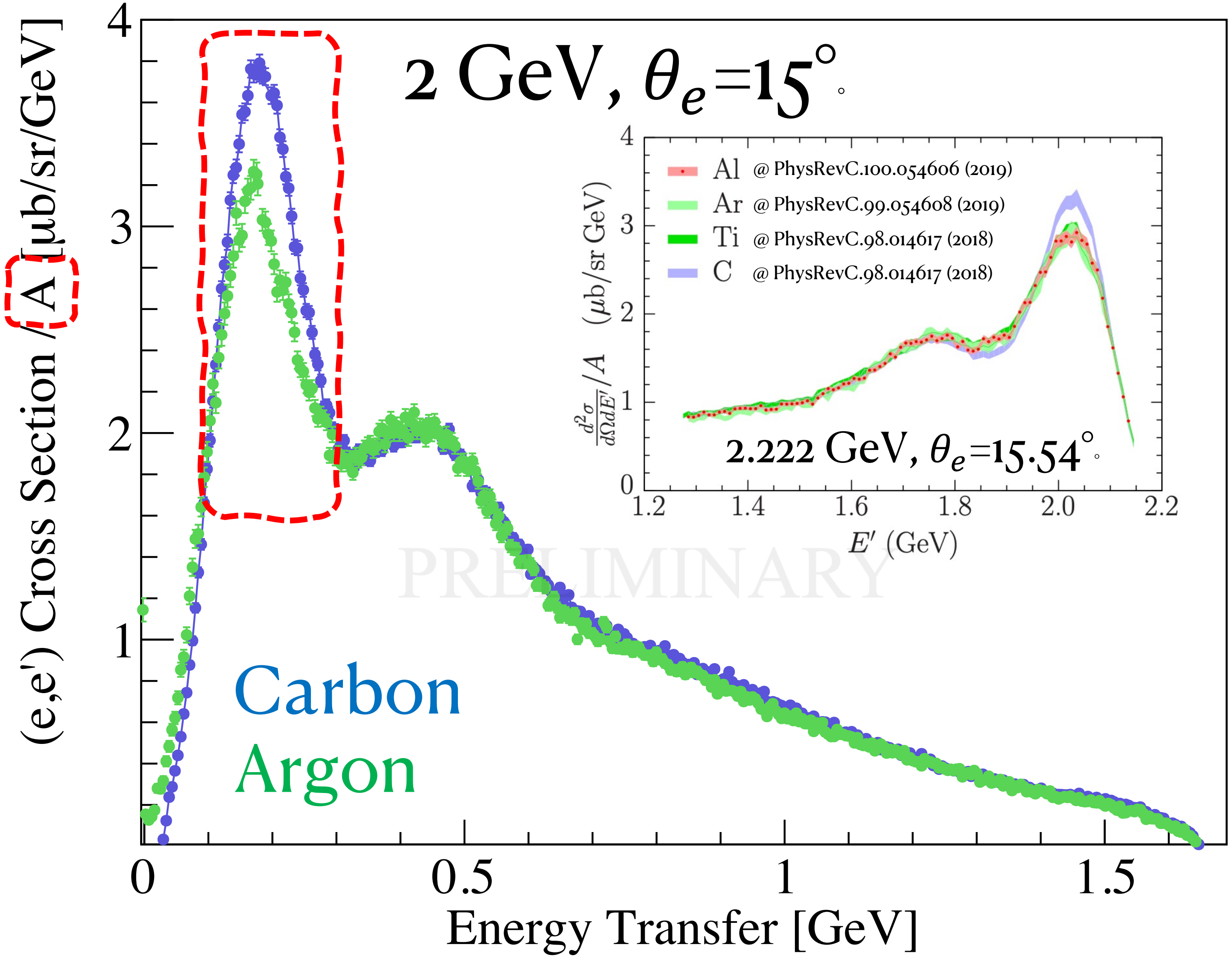

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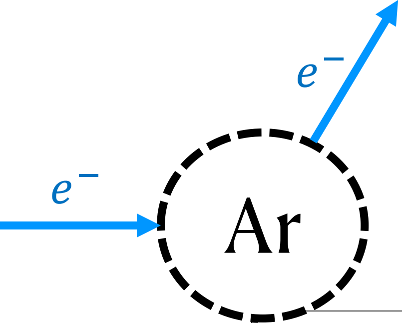
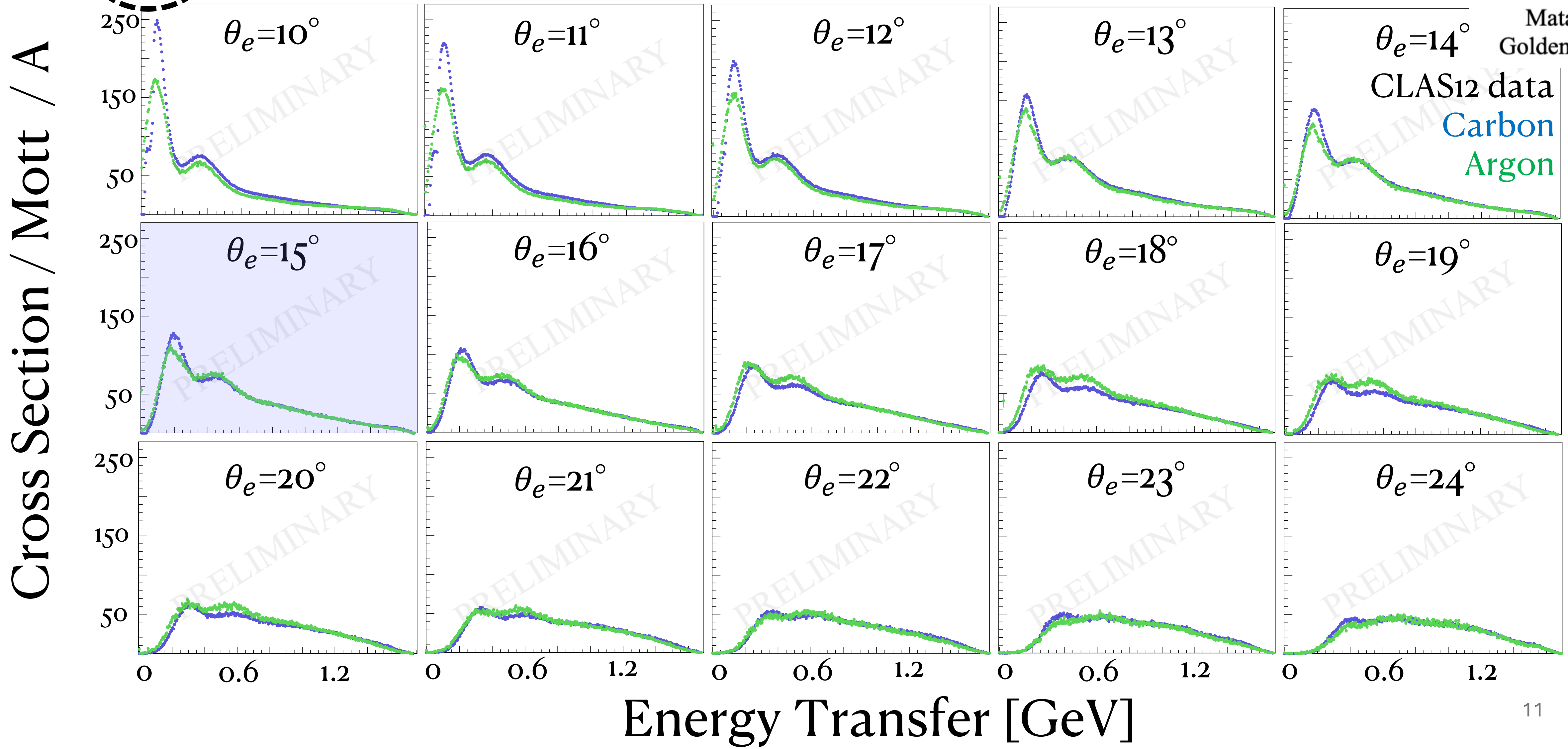
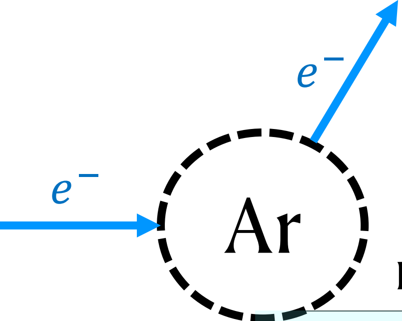


Unprecedented angular coverage

2 GeV on C & Ar


Matan Goldenberg



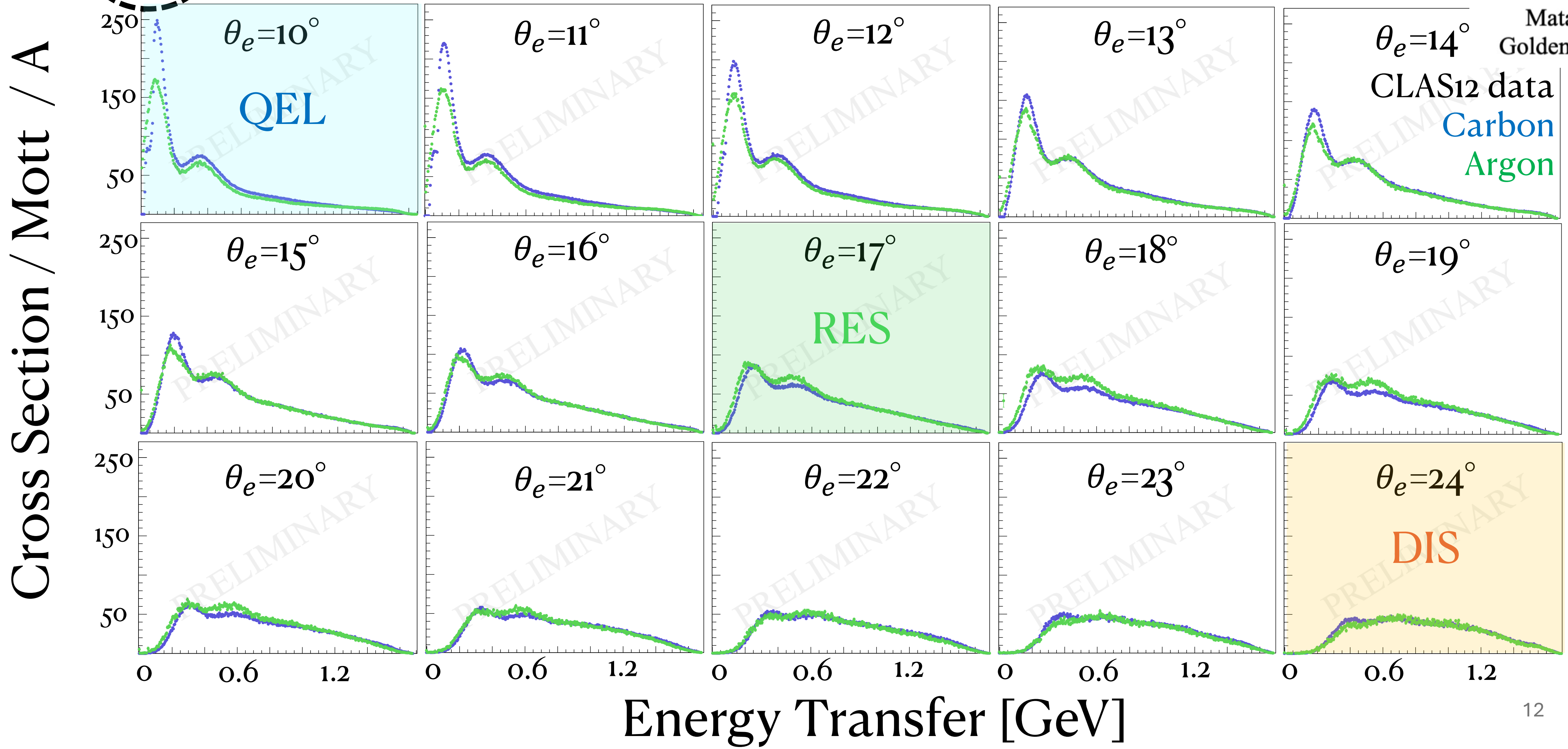


Unprecedented angular coverage

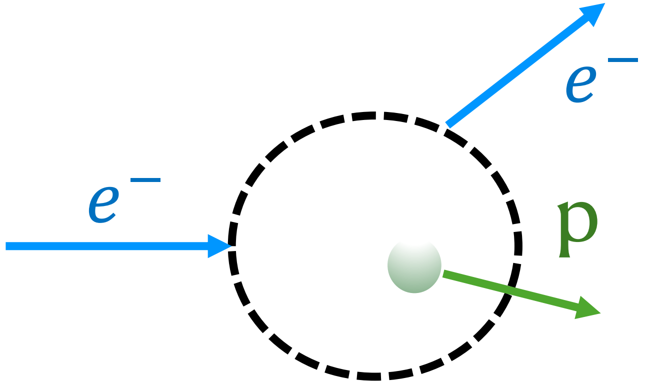
2 GeV on C & ^{40}Ar

Matan Goldenberg

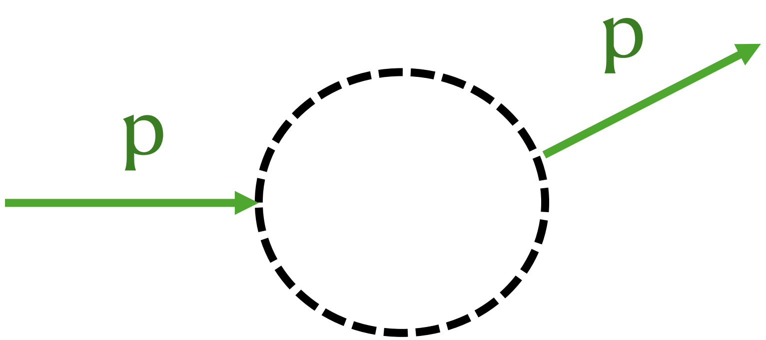
Dominated by



Proton transparency



Transparency



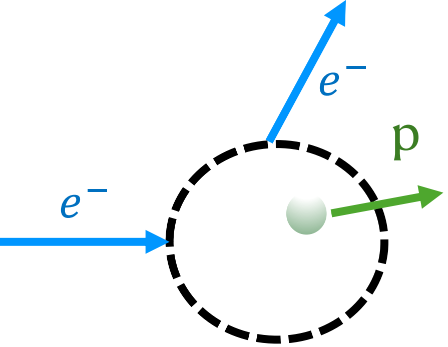
h-A data

Noah Steinberg

- Probability that a struck proton leaves the nucleus without significant re-scattering
- Complement to hadron nucleus interaction
- Study proton FSI similarly to neutrino scattering

Sensitive to both FSI and nuclear structure (PRD **104** 053006 (2021))

Strong need for new data, especially at low proton momentum



Measuring proton transparency


Noah Steinberg

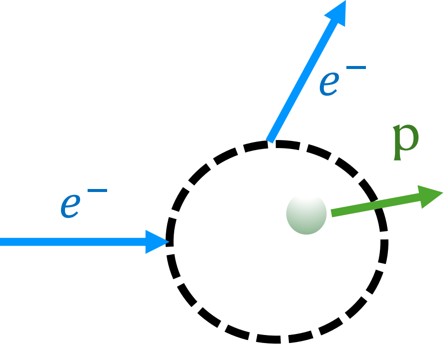
Define a more data driven transparency analysis informed by theory

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

Using MC to determine QE dominated regions and correct for other contributions

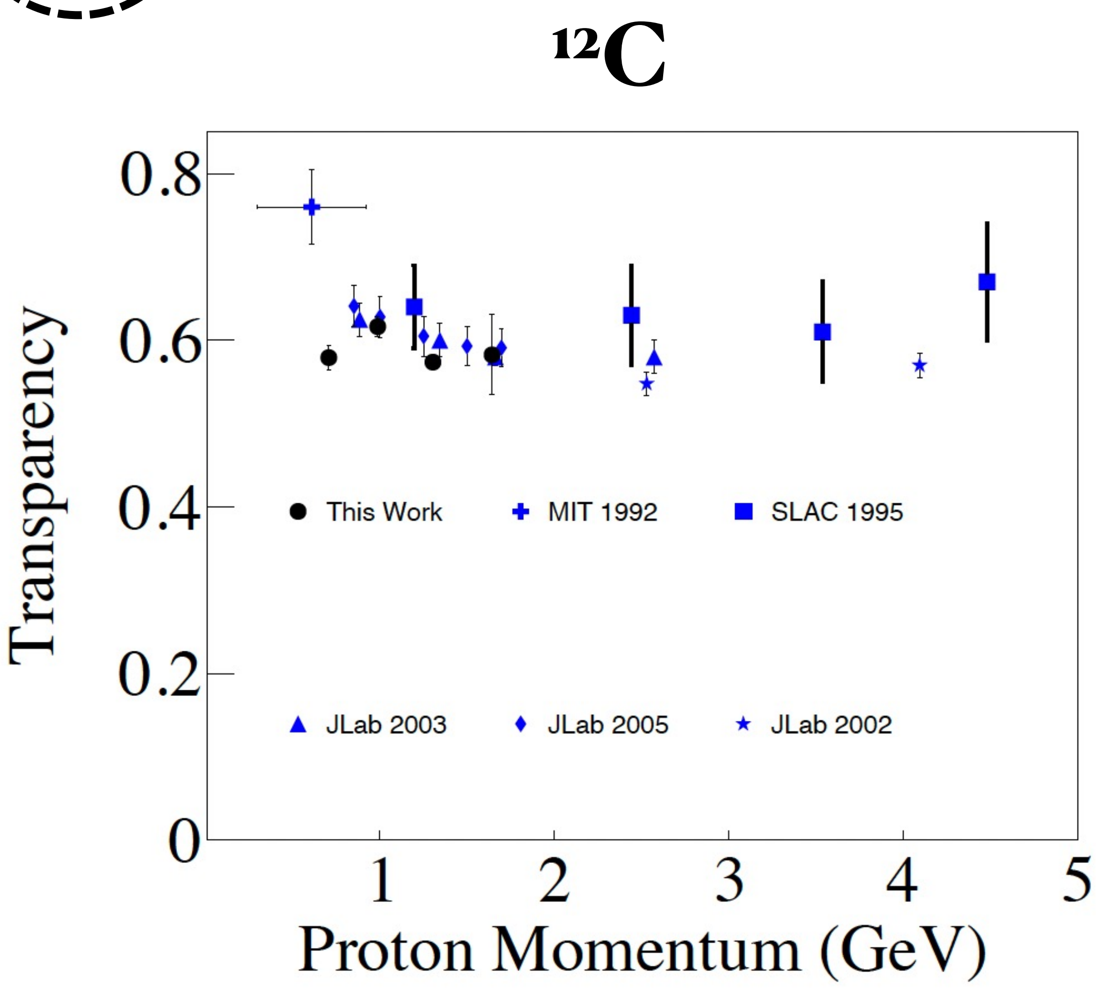
Most previous transparency analyses measured

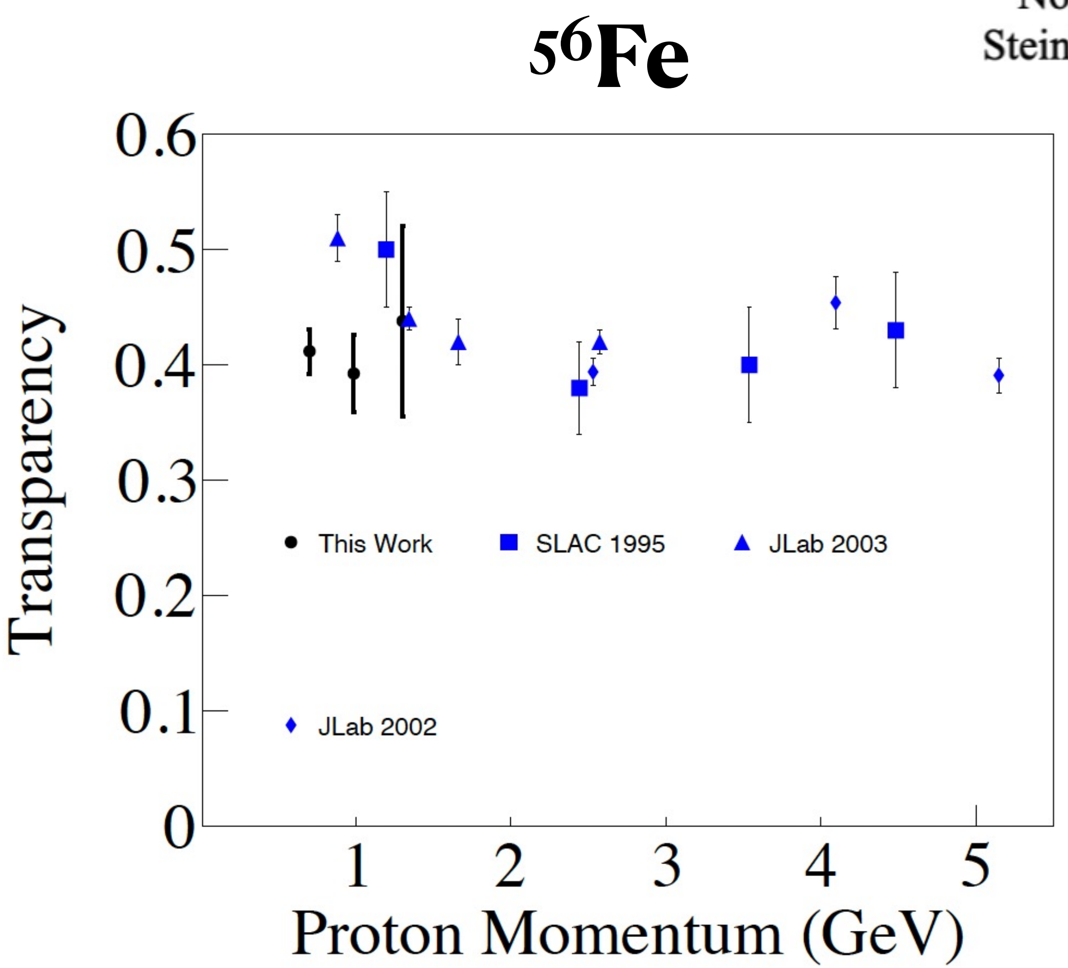
$$\mathbf{T_A} = (e,e'1p)_{\mathbf{0\pi}} / (e,e'1p)_{PWIA}$$

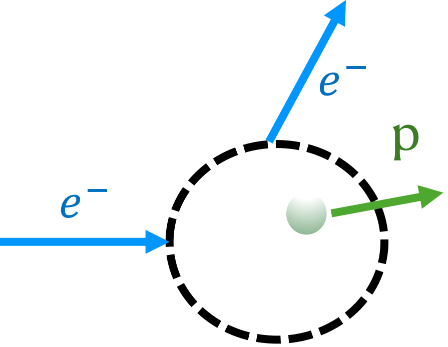


Compatible with previous data

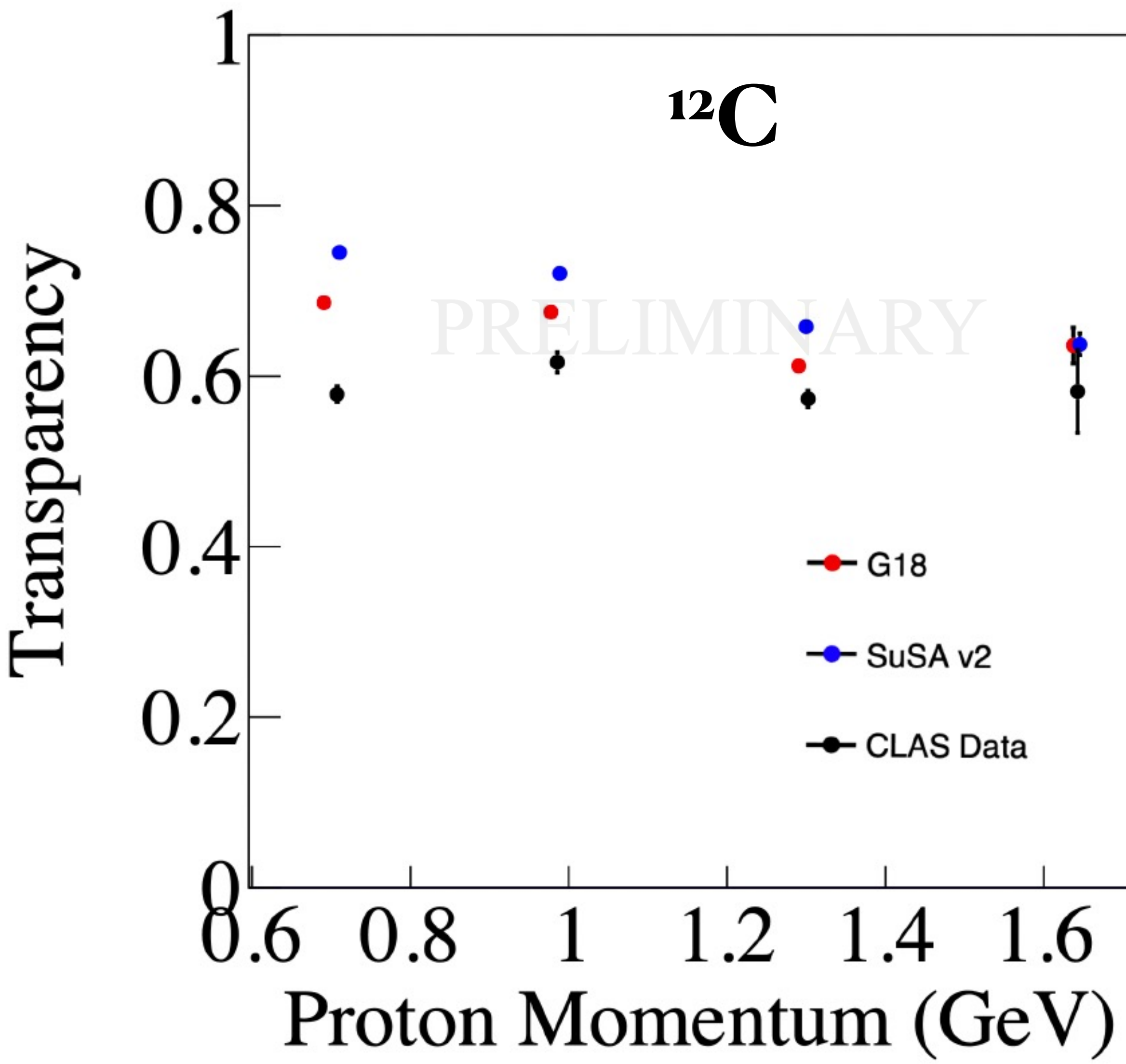
Noah Steinberg







Data not described by GENIE



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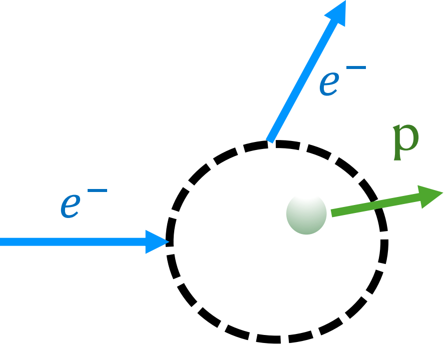

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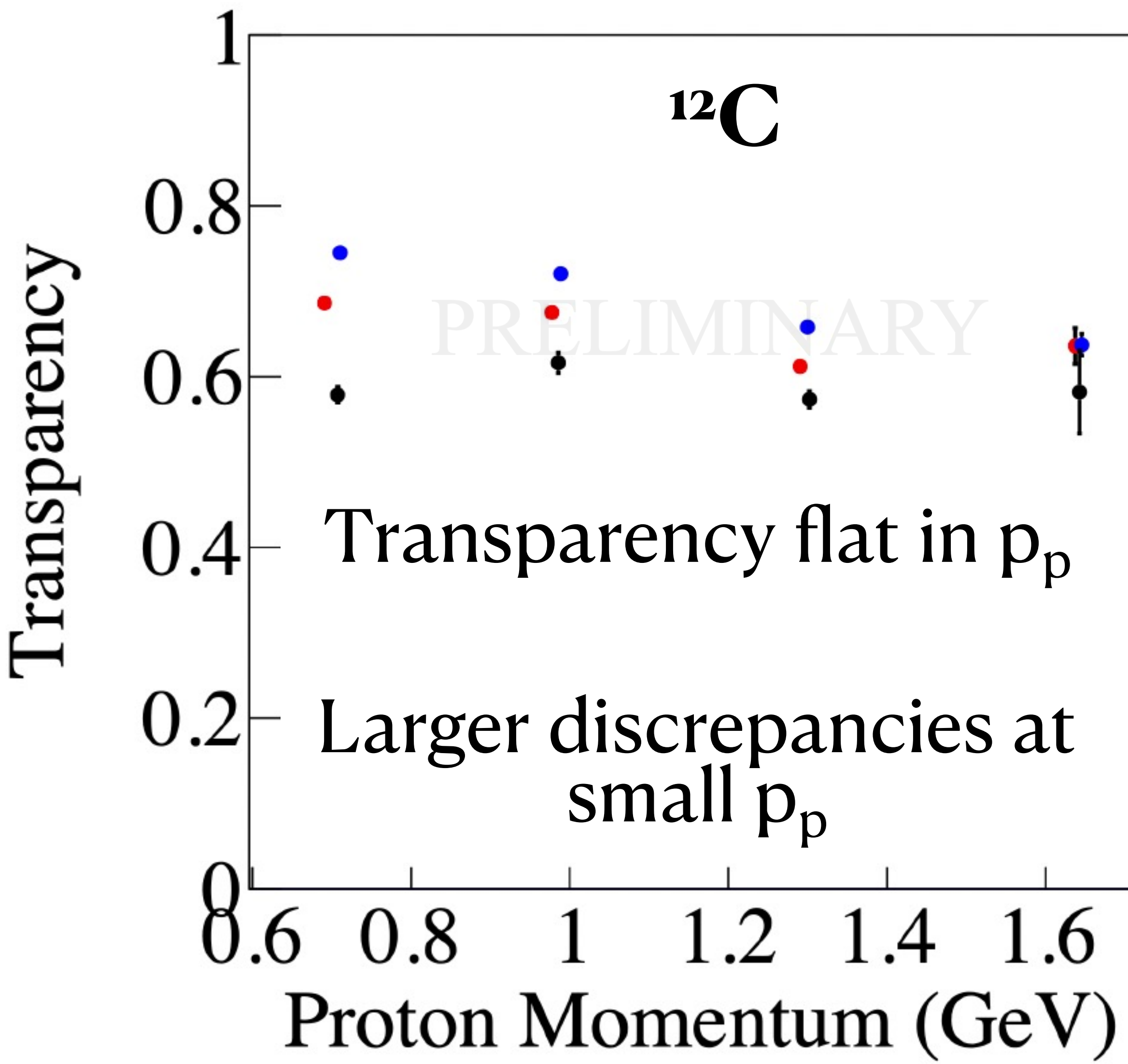
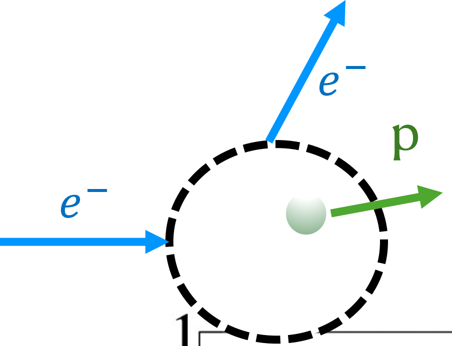


Transparency flat in p_p

Larger discrepancies at small p_p



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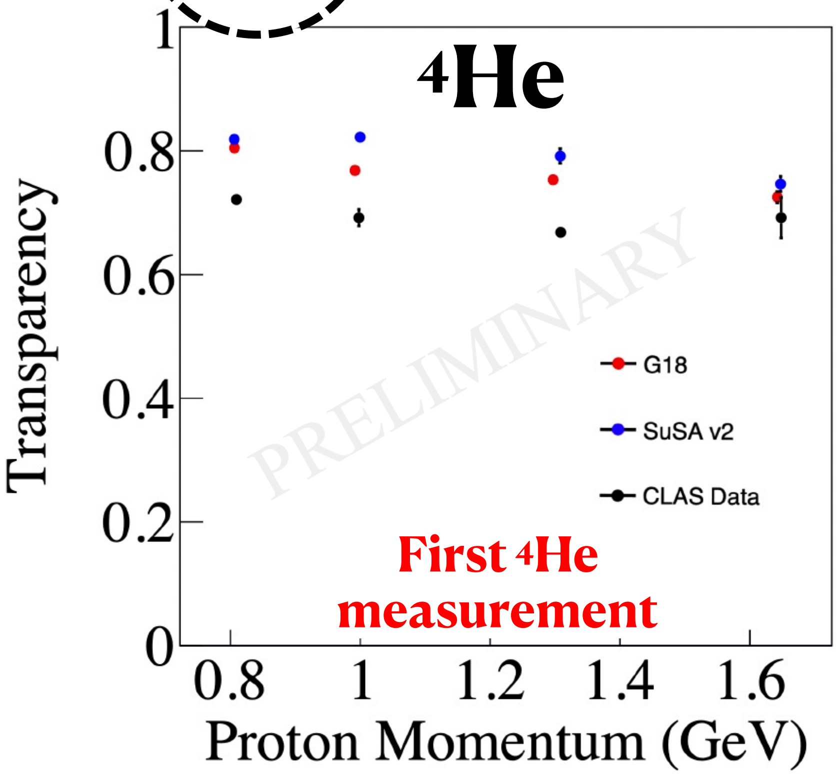
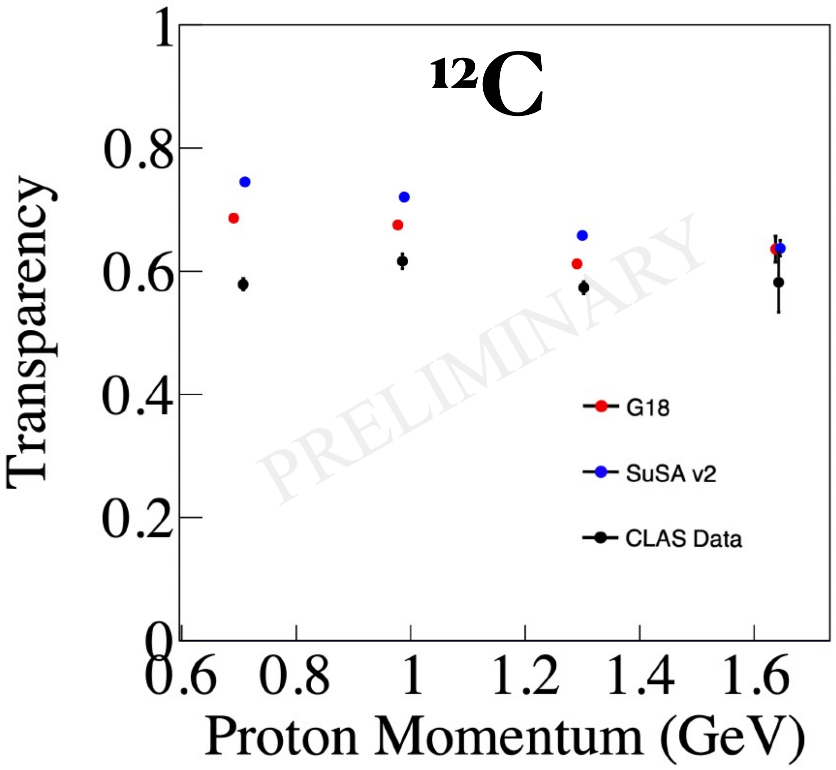
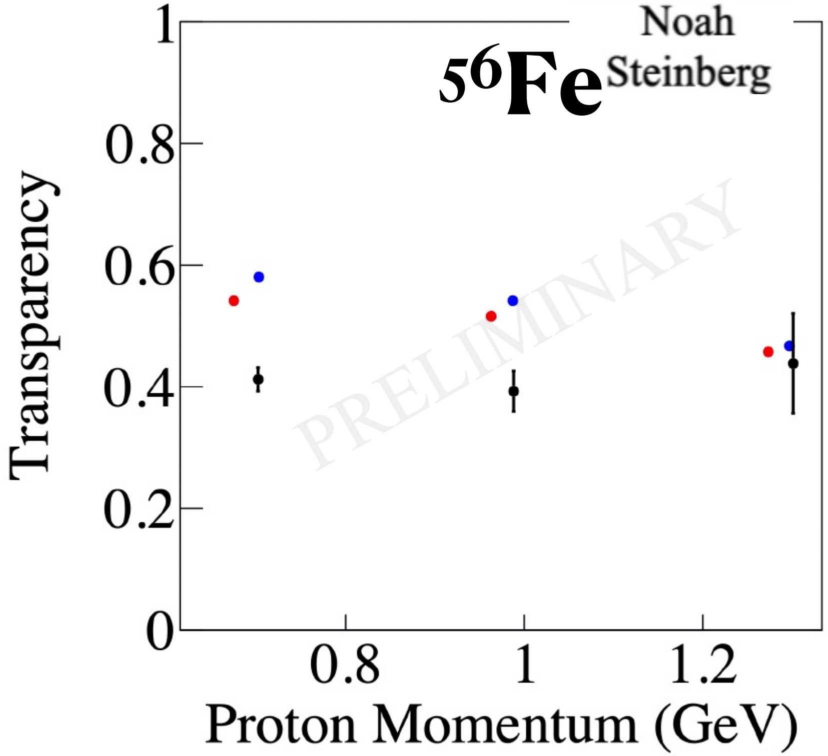


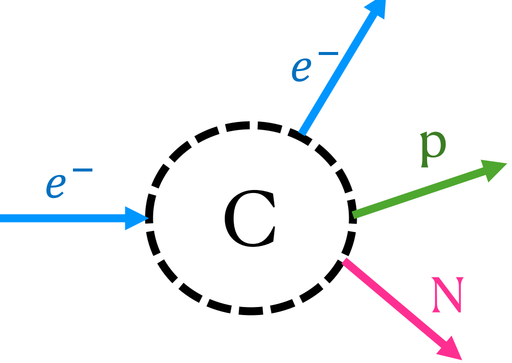




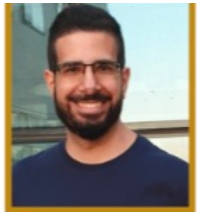
Transparency decreases with A

Simple nuclear models don't describe data – Spectral Function preferred

No evidence of problems with GENIE FSI



First two nucleon analysis

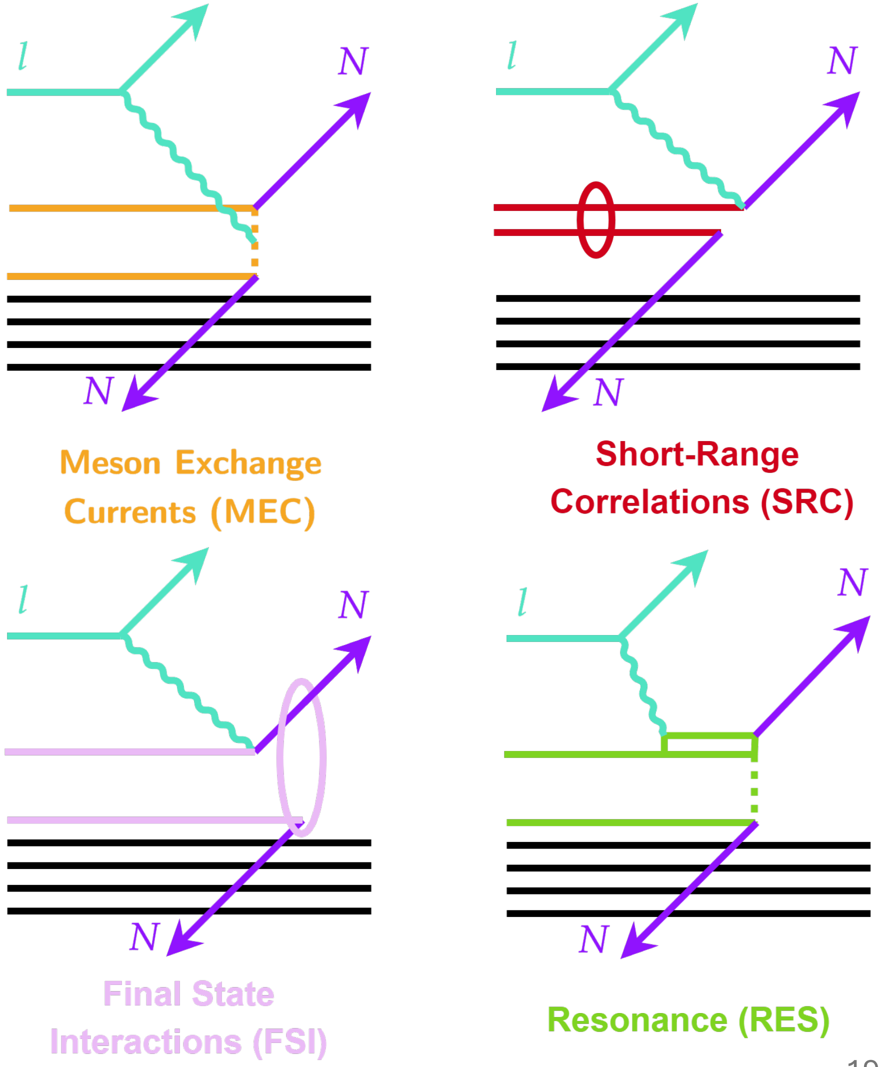


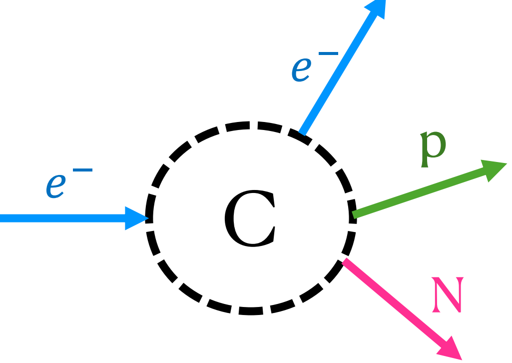
See Alon Sportes poster!

2p vs 1n1p, 0π and 0γ

- New sensitivity to nuclear effects
  - **Different processes contribute**
  - **Easily separated with kinematics**
- Background to 1p0π topology

Direct implications to neutrino experiments





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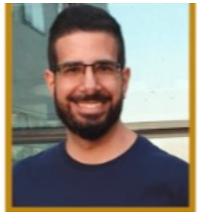

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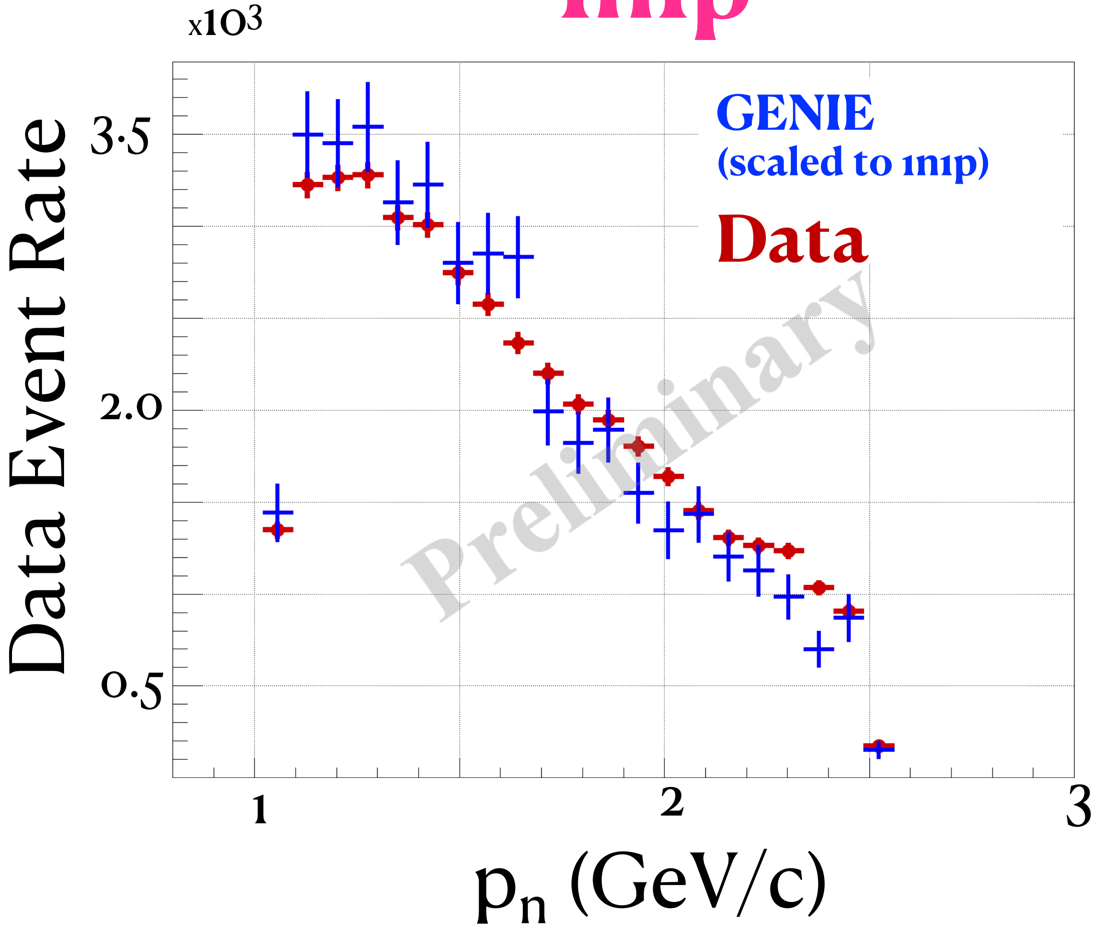
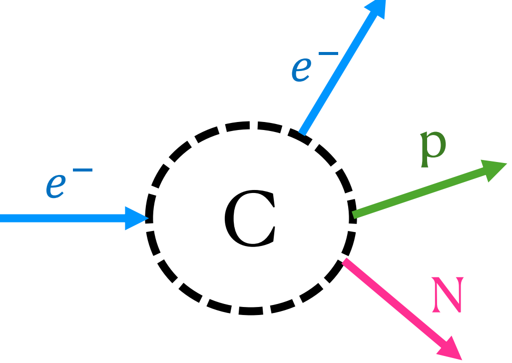
2p vs **1n1p**, 0π and 0γ

- 6 GeV on Carbon with CLAS12
- More targets and energies to come
- Particle thresholds
  - 200 (400) MeV/c for $\pi^{\pm}$ (p/n)
  - No Background subtraction

First direct look at neutrons

1n1p





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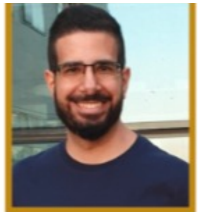

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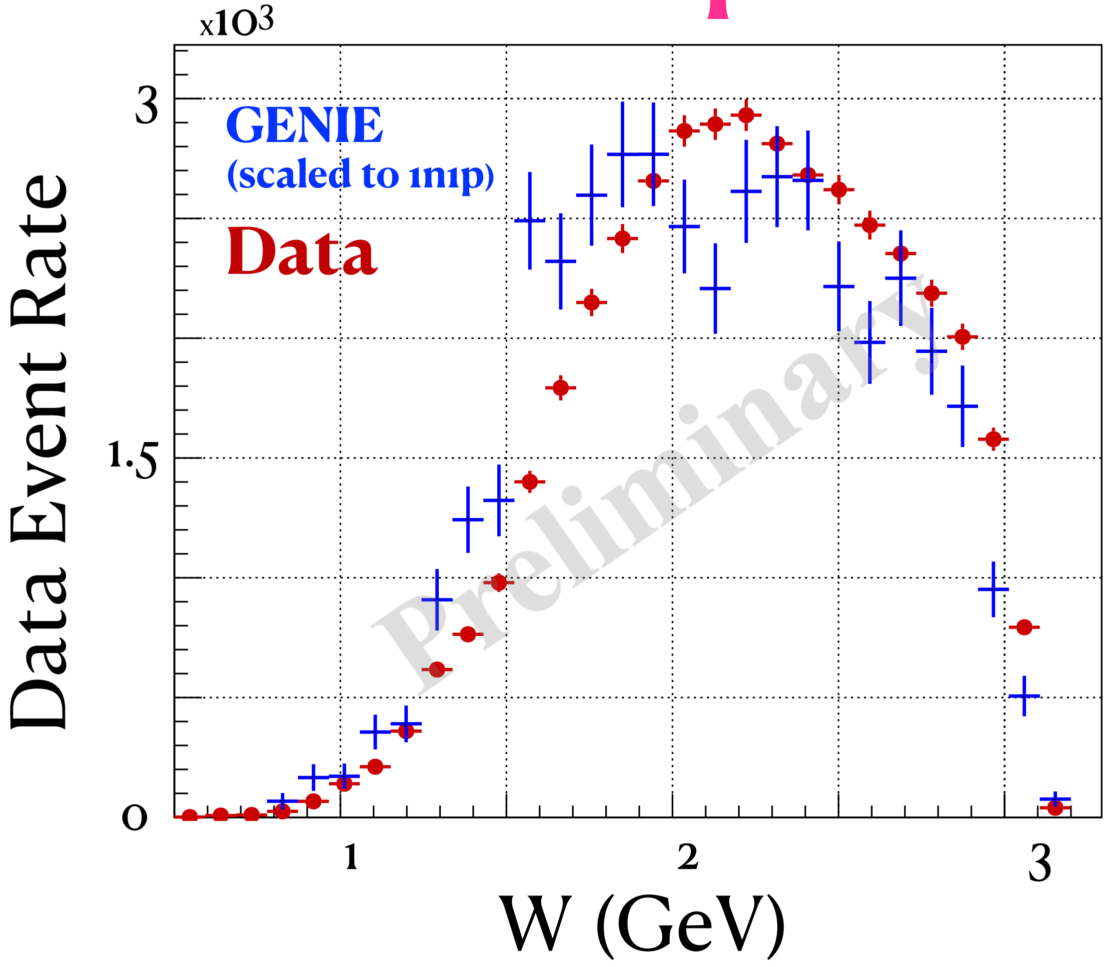
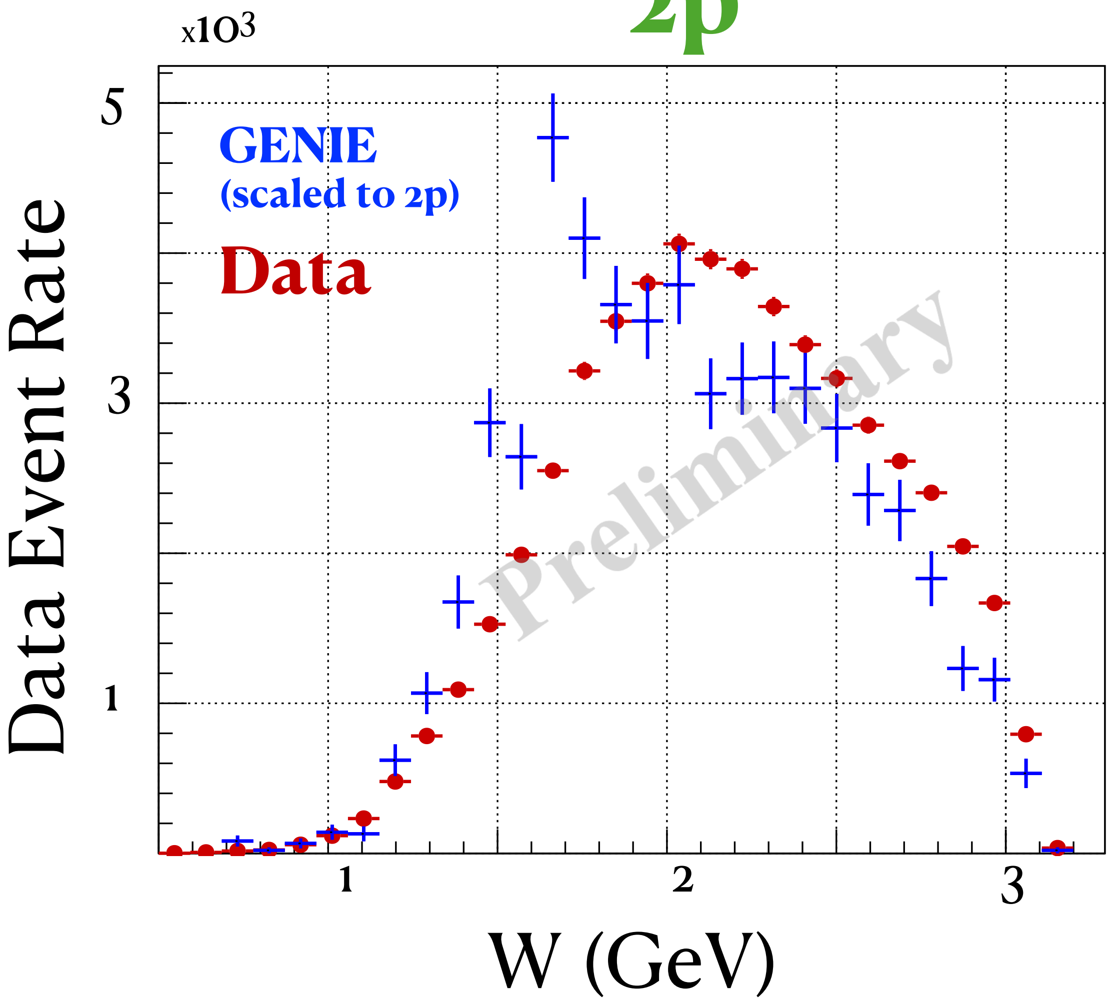
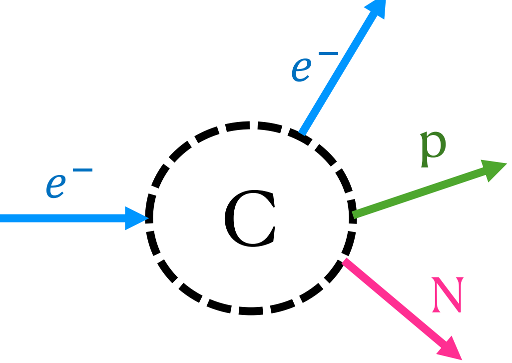
C @ 6 GeV

1n1p



2p





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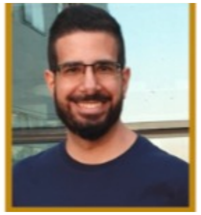

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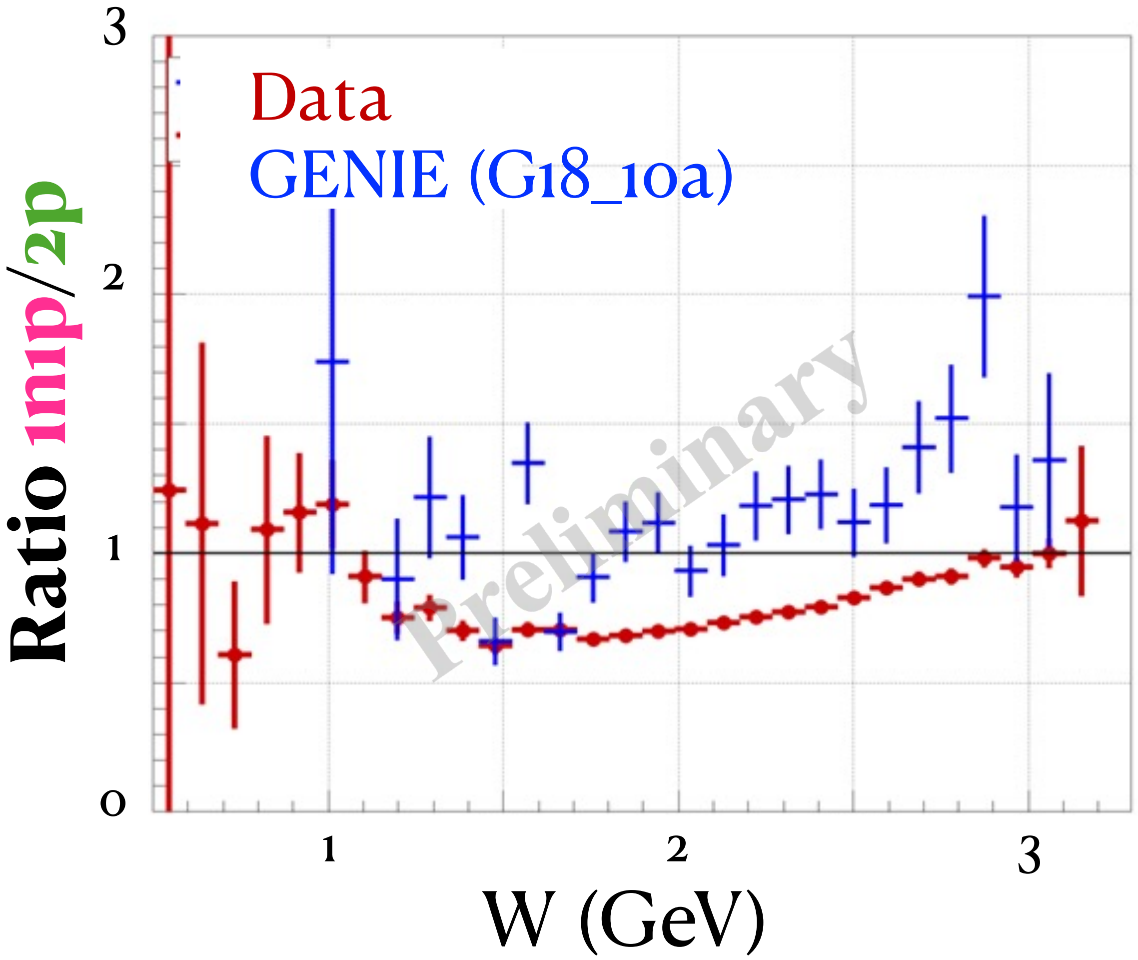
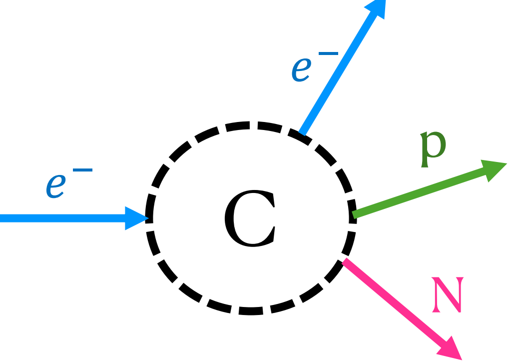


Ratio over-predicted

Different trend than data



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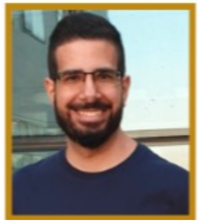

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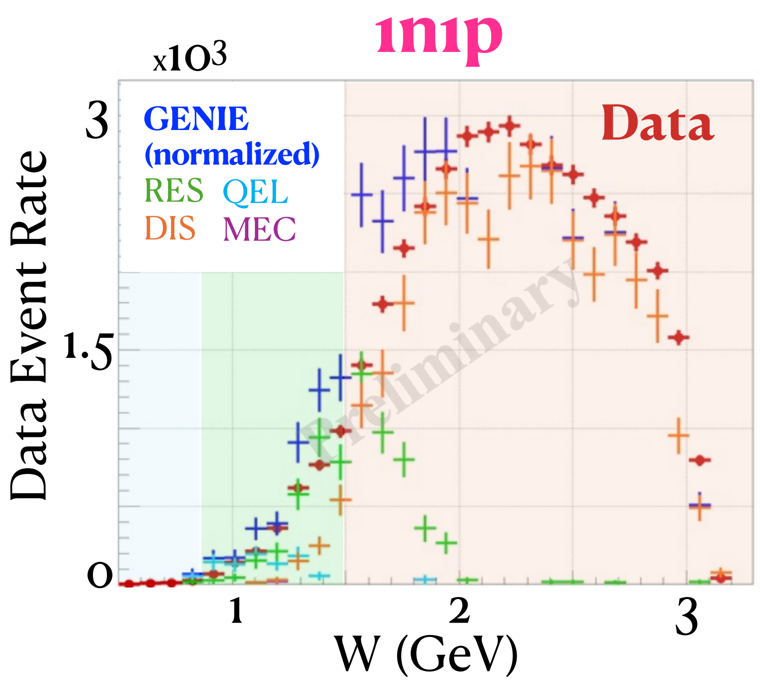
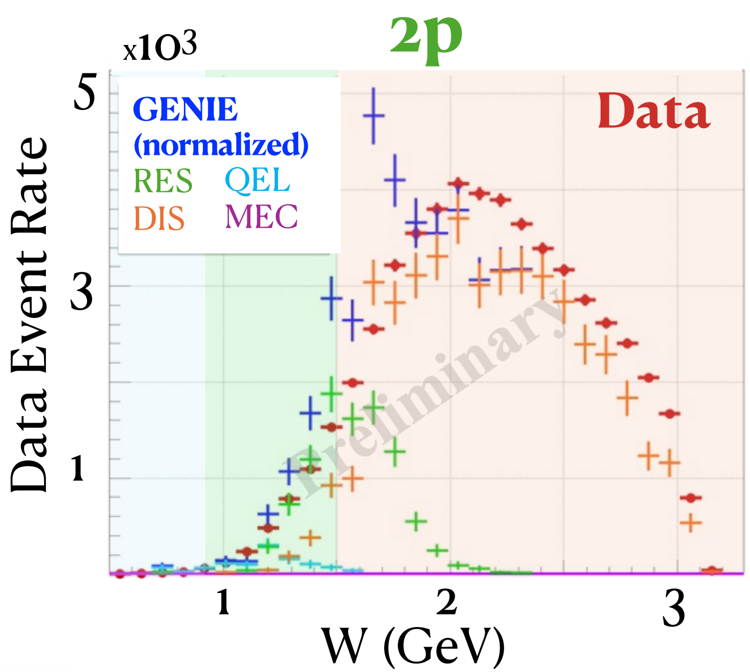
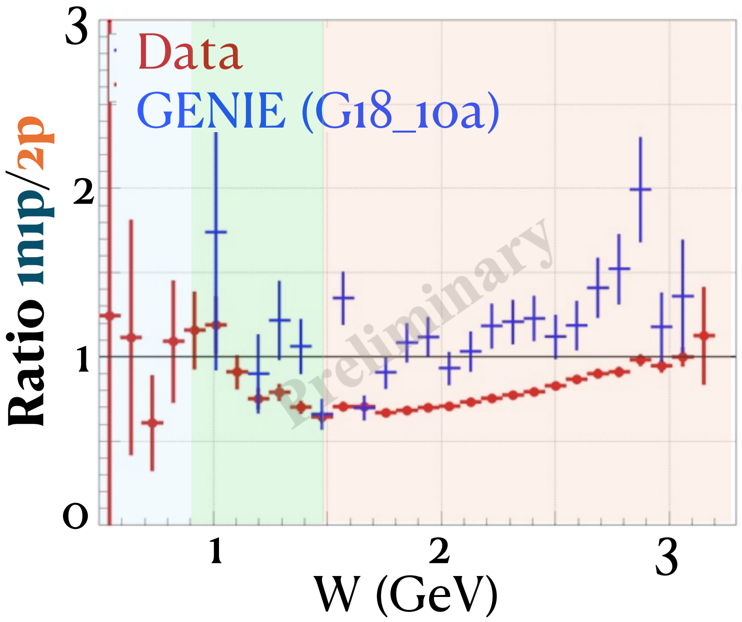
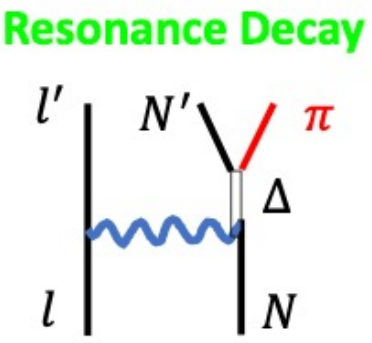






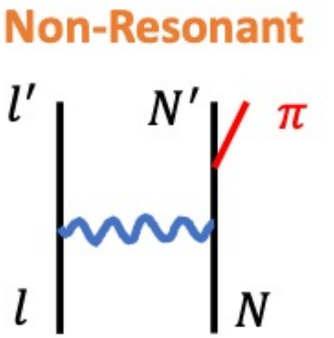
- Statistically inconclusive
- Ratio decreases when RES dominates – more 2p
- Ratio increases when DIS dominates – more 1n1p

Pion production in GENIE



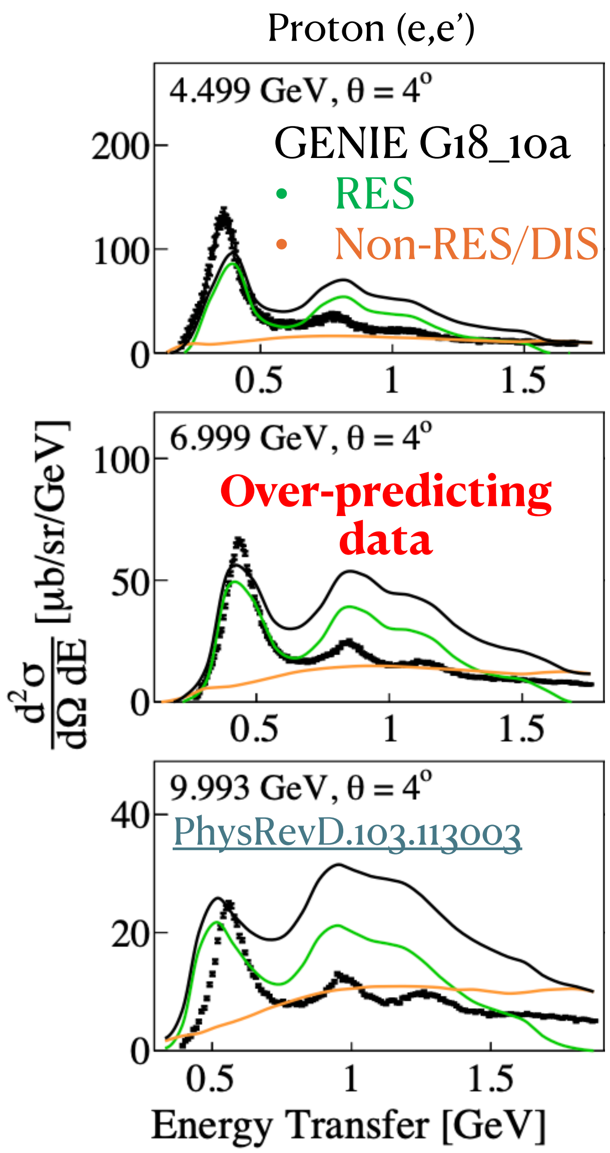
GENIE RES model

- Berger-Sehgal to model each resonance
  - Model predicts momentum transfer
  - Resonance decayed into hadrons
- No interference between RES (& Non-RES)

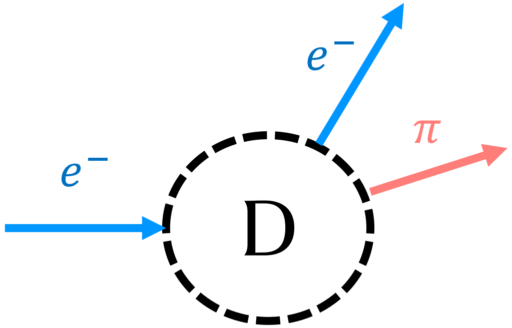


GENIE Non-RES model

- DIS model (Bodek-Yang) @ W<1.7 GeV
- Scaled with ad-hoc free parameters
- **Not tuned to electron data**



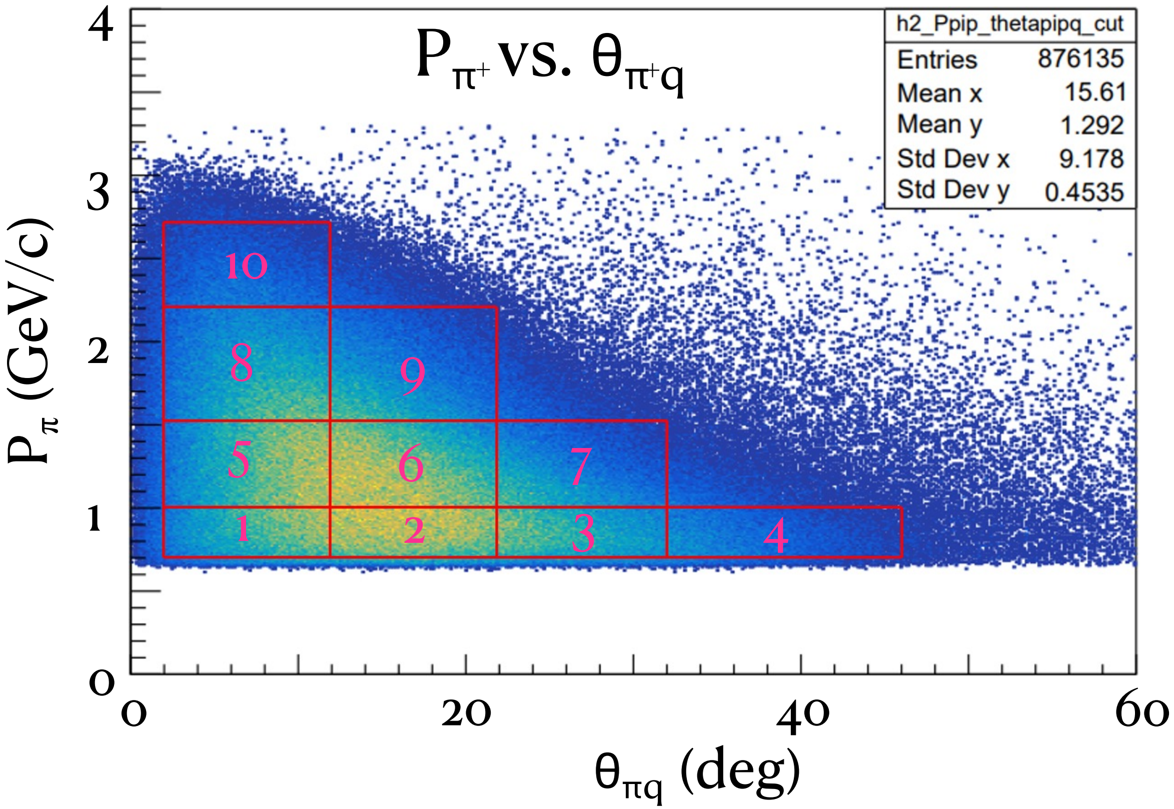
D(e,e' $\pi^{\pm}$) cross-section



by Caleb Fogler

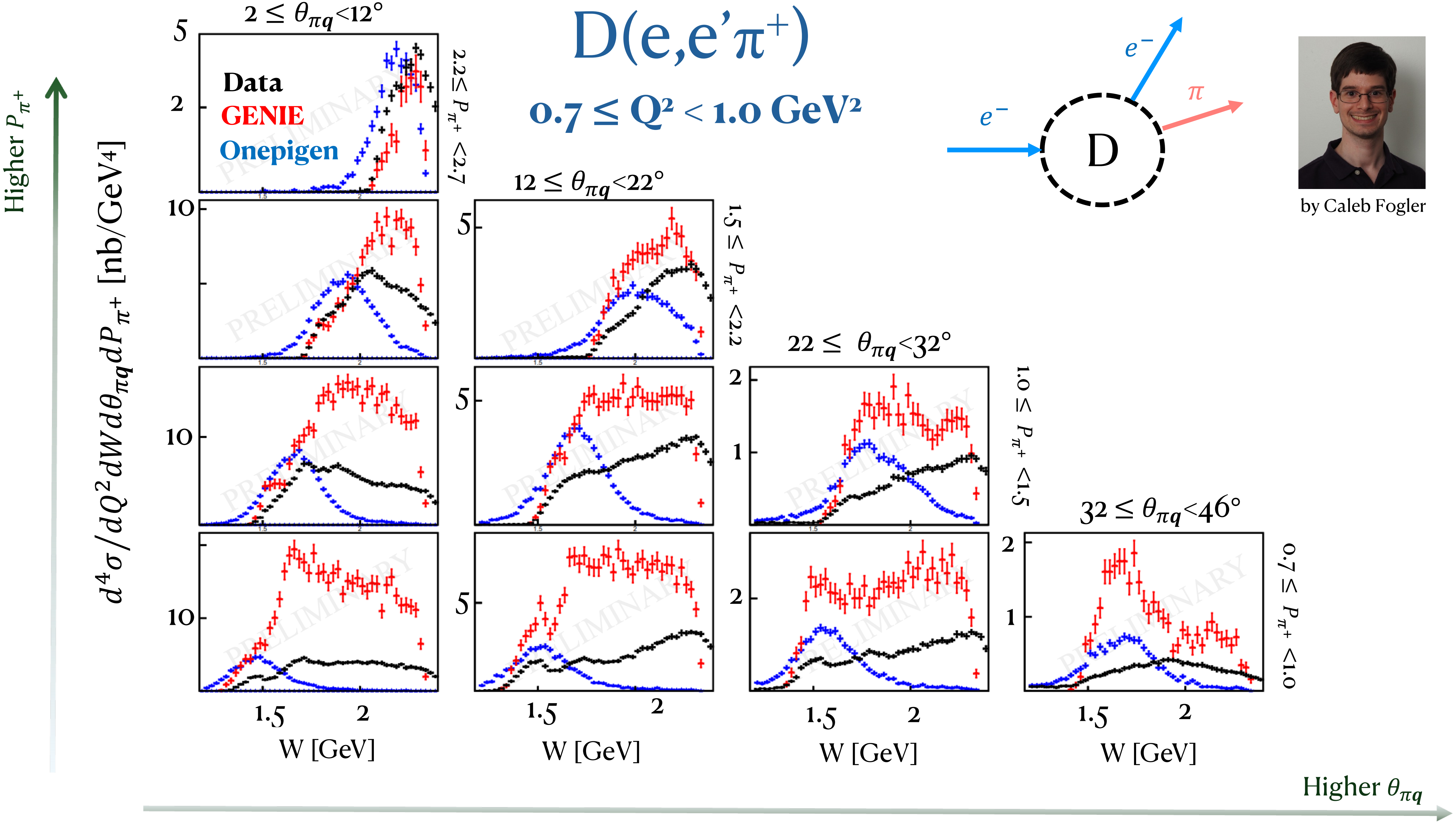
- CLAS12 forward detector
- Deuterium @ 4.2 GeV
- Multi-differential
  - Q^2, W, P_π, $\theta_{\pi q}$
- Compared against
  - GENIE (G18_10a)
  - OnePiGen
    - Single pion event generator
    - MAID2007 model

$0.7 \leq Q^2 < 1.0$ GeV²



D(e,e'π+)

$0.7 \leq Q^2 < 1.0$ GeV²



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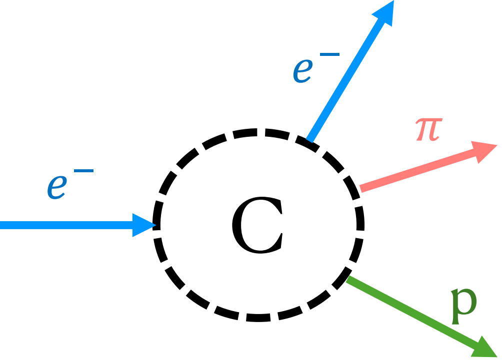


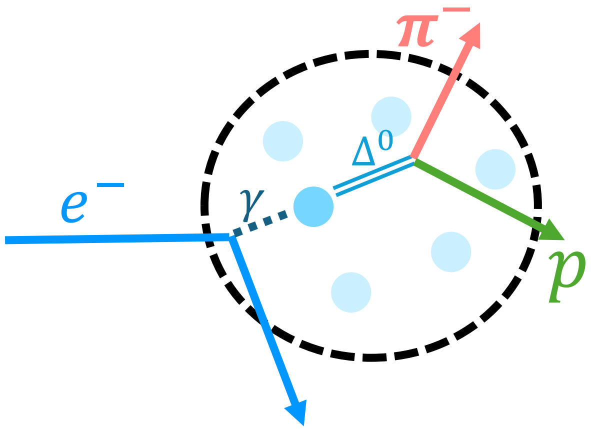
C(e,e'1p1$\pi^{\mp}$) cross-section

by Julia Tena Vidal

First look at

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

with no detected γ any number of neutrons

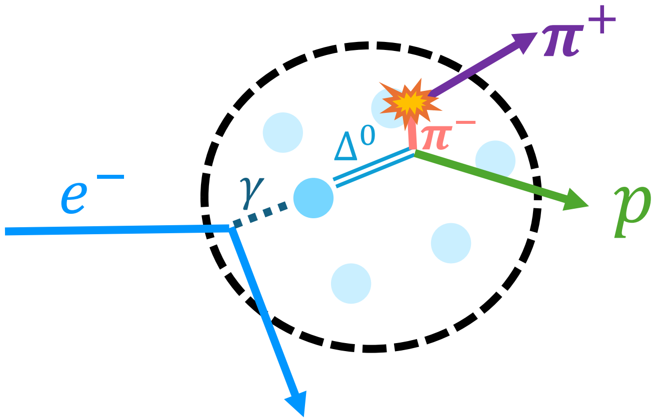


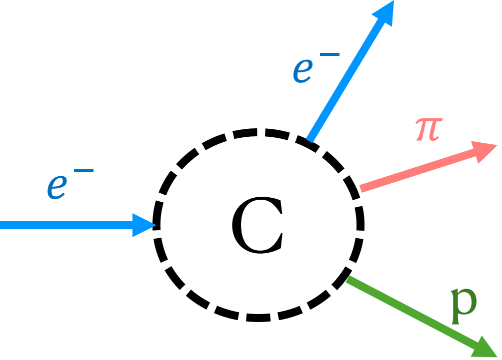
possible at the free nucleon level

Contain $\pi^{\mp}$ below 150 MeV & π^0 below 300 MeV

1.1, 2.2 and 4.4 GeV on C

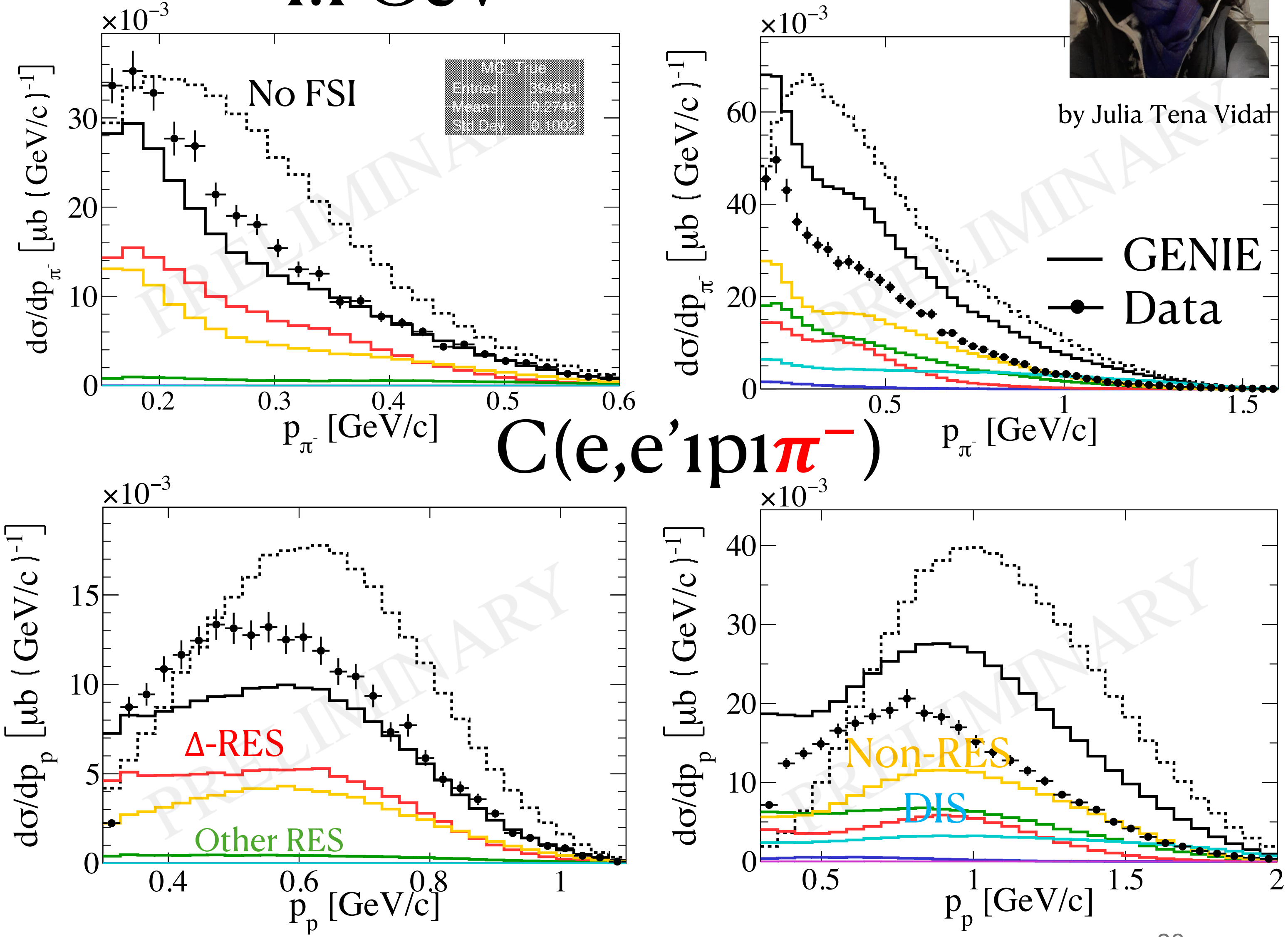
needs two or more nucleons → undetected particles (FSI!)





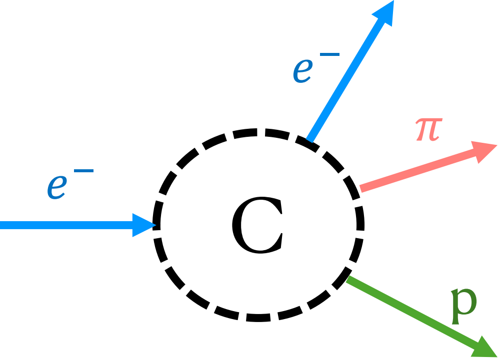
Hadron kinematics


by Julia Tena Vidal



Testing (e,e') models made exclusive

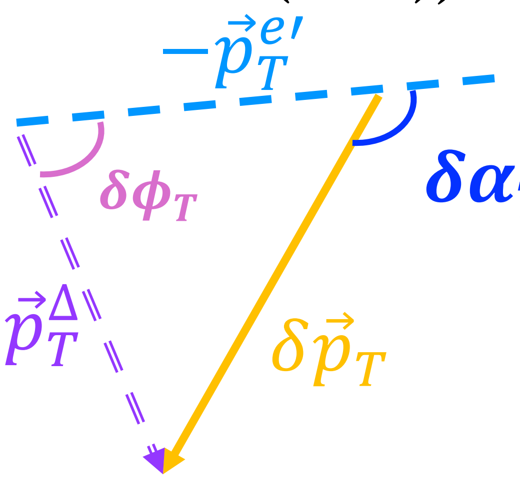
- Wrong normalization
  - Due to untuned non-RES
- Pion momentum shape agrees with GENIE
  - FSI essential
- Incorrect low proton momentum shape



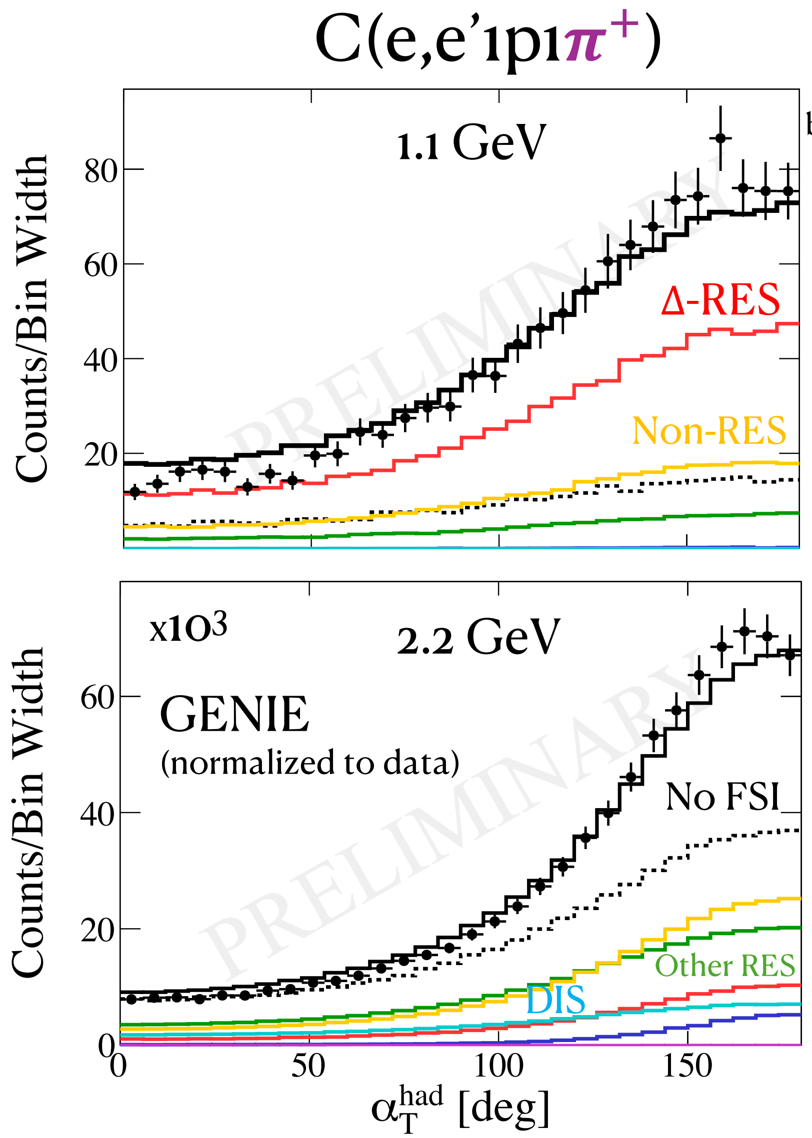
Nuclear effects

by Julia Tena Vidal

Transverse Kinematic Invariance (TKI), Boosting angle:



$$\delta\alpha_T = \cos^{-1}\left(\frac{-\vec{p}_T^{e'}\cdot\delta\vec{p}_T}{|\vec{p}_{e'}^{T}||\delta\vec{p}_T|}\right)$$



Most sensitive to FSI

- Excellent shape description at all energies

e4nu unveils electron-nucleus interactions

- Huge increase in data base for **electron hadroproduction**
- CLAS can measure many particle final states with magnetic field
- 1-6 GeV electrons for many targets (e.g. carbon, **argon**)

Analyses of (e,e'), and 1 and 2 nucleon and $\pi^{\mp}$ production data in progress

Significant impact on neutrino physics

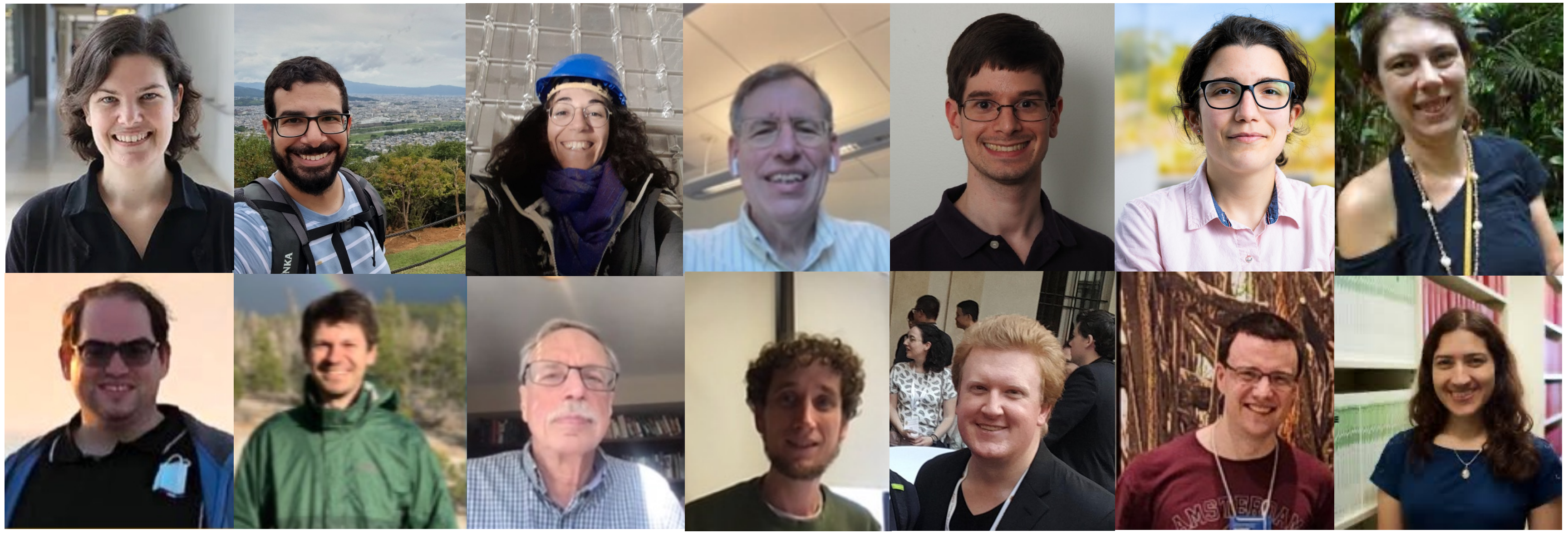
Very high statistics (~100M events) and known beam energy, provides...

- Best constraints on **nuclear structure and FSI** models
- **Vector** part of the **vector**+axial nuclear response

Event generators benefit greatly from these new data

Thank you for your attention!

Adi Ashkenazi Alon Sportes Julia Tena Vidal Larry Weinstein Caleb Fogler A.Papadopoulou Cheryl Patrick



Matan Goldelberg Noah Steinberg Steven Dytman Brandon Eberly Josh Barrow Steven Gardiner Minerva Betancourt

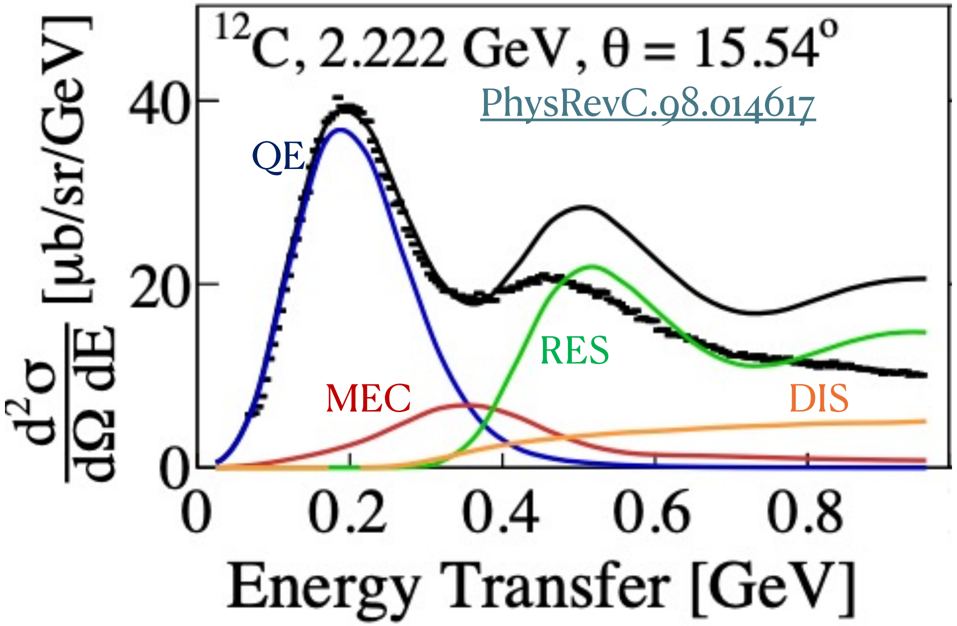
More data on the way…
New collaborators welcome to maximize impact!

The GENIE event generator

http://tunes.genie-mc.org

- **ν-A, $e^{\pm}$-A and h-A event generator**
  - From MeV to PeV, all targets
  - All interaction mechanisms and targets
- **Full description for electrons**
  - Originally developed for neutrinos
  - **Common code** for ν-A, e^{-}-A processes

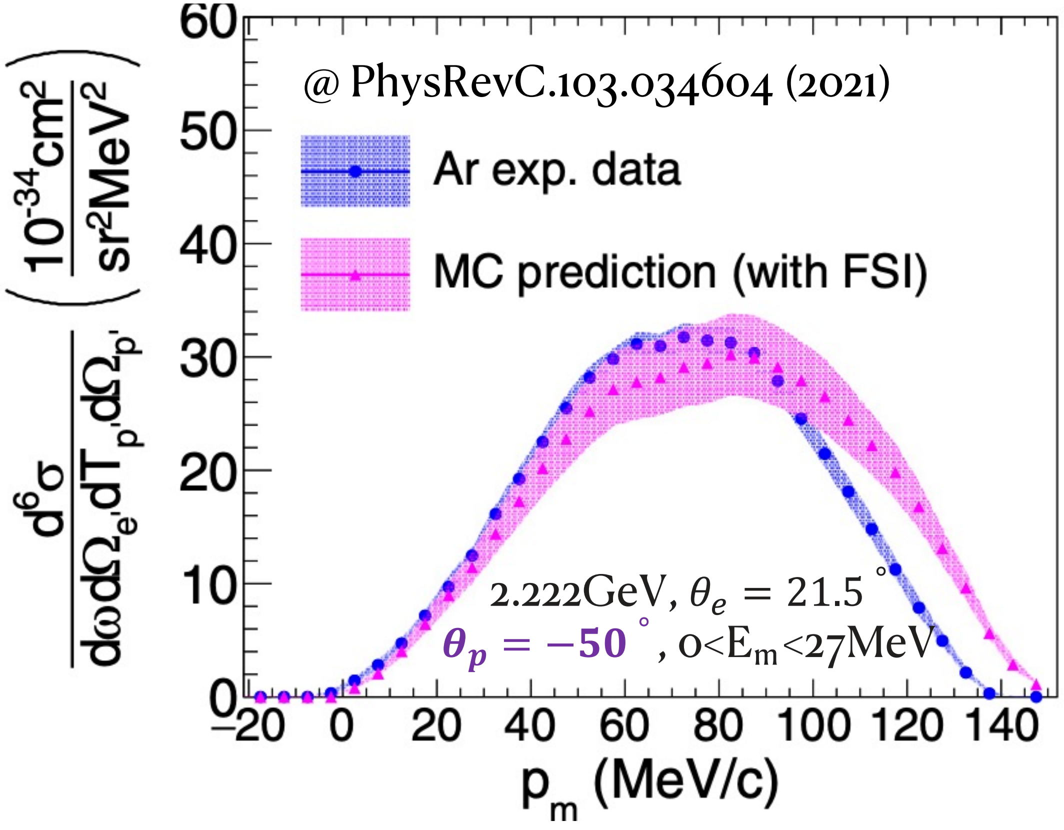
GEM21_11a (SuSAv2), e-[12]C data



Generators need hadron production data

- Many assumptions from (e,e') to (e,e'X) – **description not guaranteed**
  - Common with neutrinos
- **Lacking exclusive hadron production measurements!**
  - Growing interest in the electron community
    - limited to specific kinematics
  - Big effort in the neutrino community
    - But more difficult

(e,e'p)



High quality new data gives additional constraints to simulation

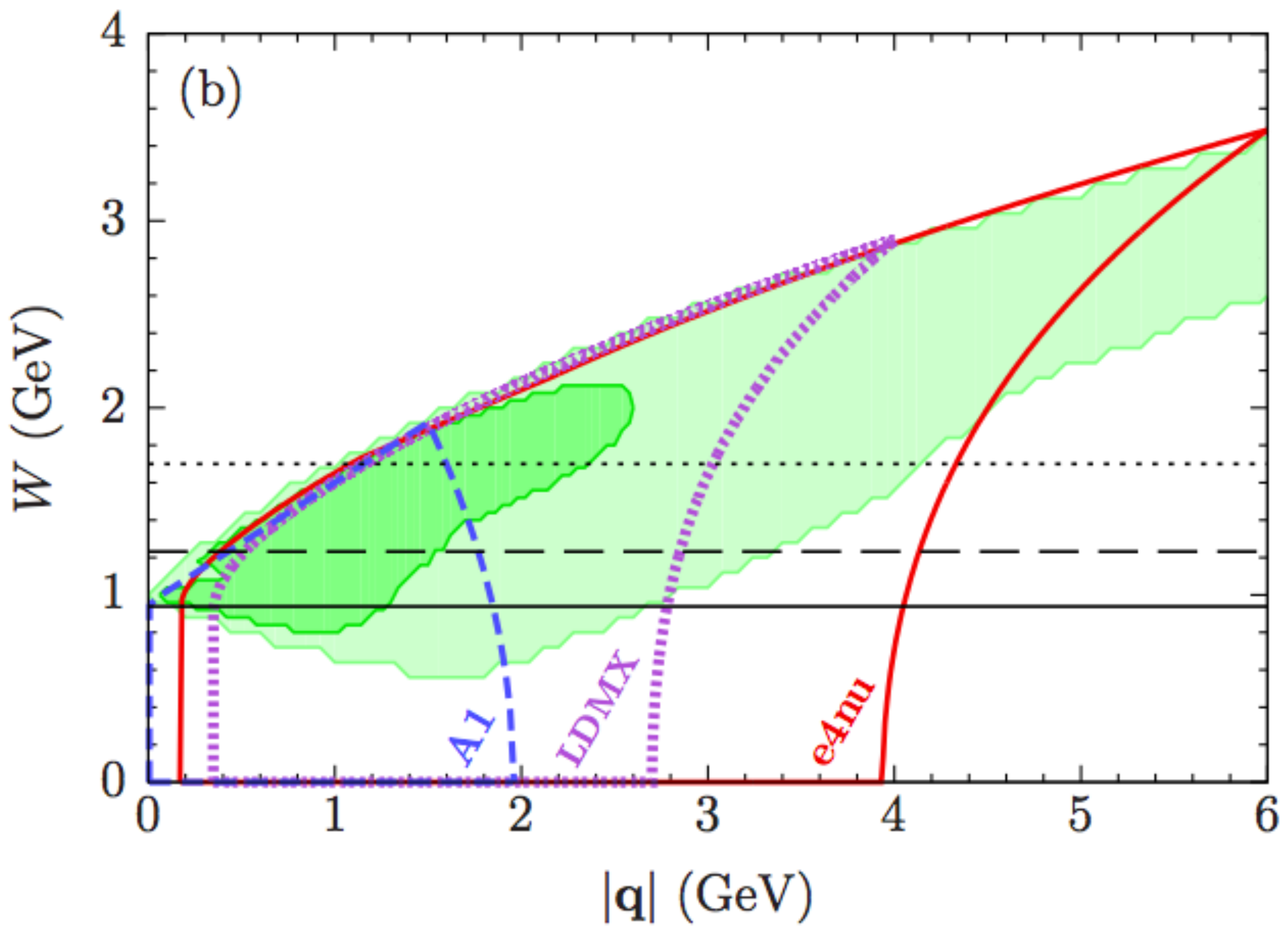
Complementary efforts

Collaborations	Kinematics	Targets	Scattering	Publications
E12-14-012 (JLab) (Data collected: 2017) Jefferson Lab	$E_e = 2.222$ GeV $\theta_e = 15.5, 17.5, 20.0, 21.5$ $\theta_p = -39.0, -44.0, -44.5, -47.0, -50.0$	Ar, Ti Al, C	(e, e') $(e, e'p)$	Phys. Rev. C **99**, 054608 Phys.Rev.D **105** 112002
e4nu/CLAS (JLab) (Data collected: 1999, 2022) Jefferson Lab	$E_e = 1, 2, 4, 6$ GeV $\theta_e > 5$	H, D, He, C, Ar, ^{40}Ca, ^{48}Ca, Fe, Sn	(e, e') e, p, n, π, γ in the final state	Nature **599**, 565 Phys.Rev.D **103** 113003
	Only effort with data already taken and expected exclusive measurements, best coverage			
A1 (MAMI) (Data collected:2020) (More data planned)	$E_e = 1.6$ GeV	H, D, He C, O, Al Ca, Ar, Xe	(e, e') 2 additional charged particles	
LDMX (SLAC) (Planned)	$E_e = 4.0$ GeV $\theta_e < 40$		(e, e') e, p, n, π in the final state	
eALBA (Planned)	$E_e = 500$ MeV - few GeV	C, CH Be, Ca	(e, e')	

Adaptation from Proceedings of the US Community Snowmass2021

arXiv:2203.06853v1 [hep-ex]

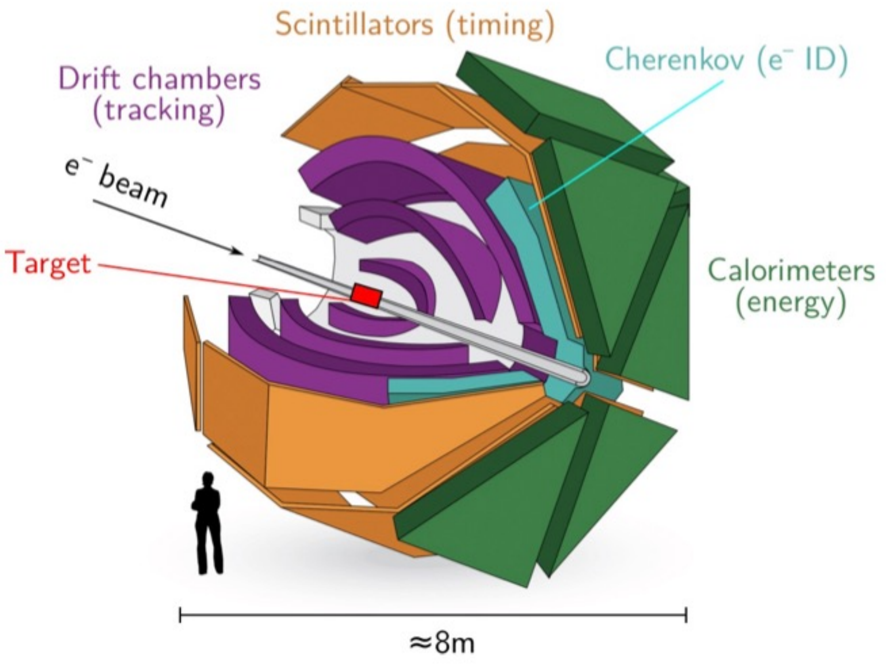
e4nu and DUNE

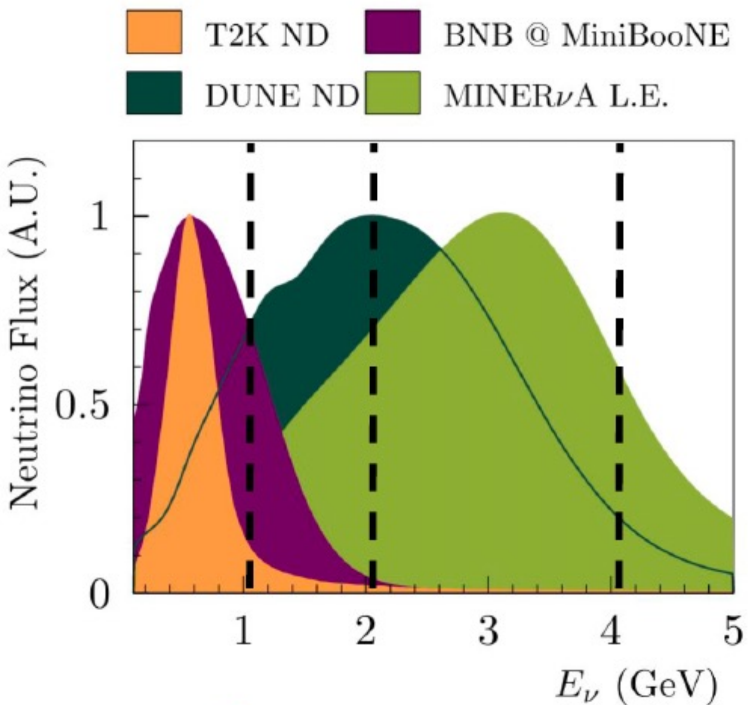


arXiv:2203.06853v1 [hep-ex] A NF06 Contributed White Paper

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





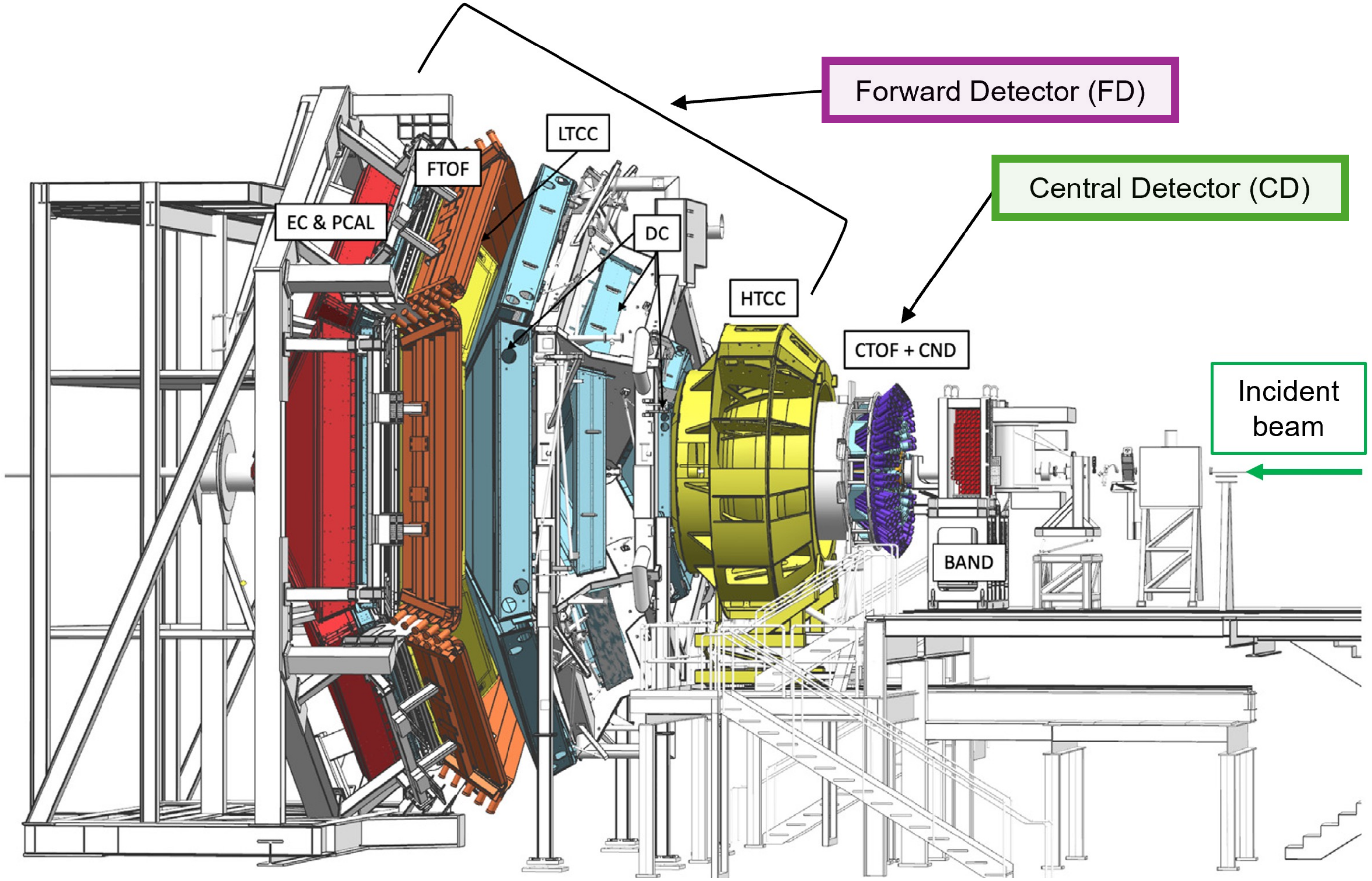
CLAS12 – sub-systems in the FD and CD

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)

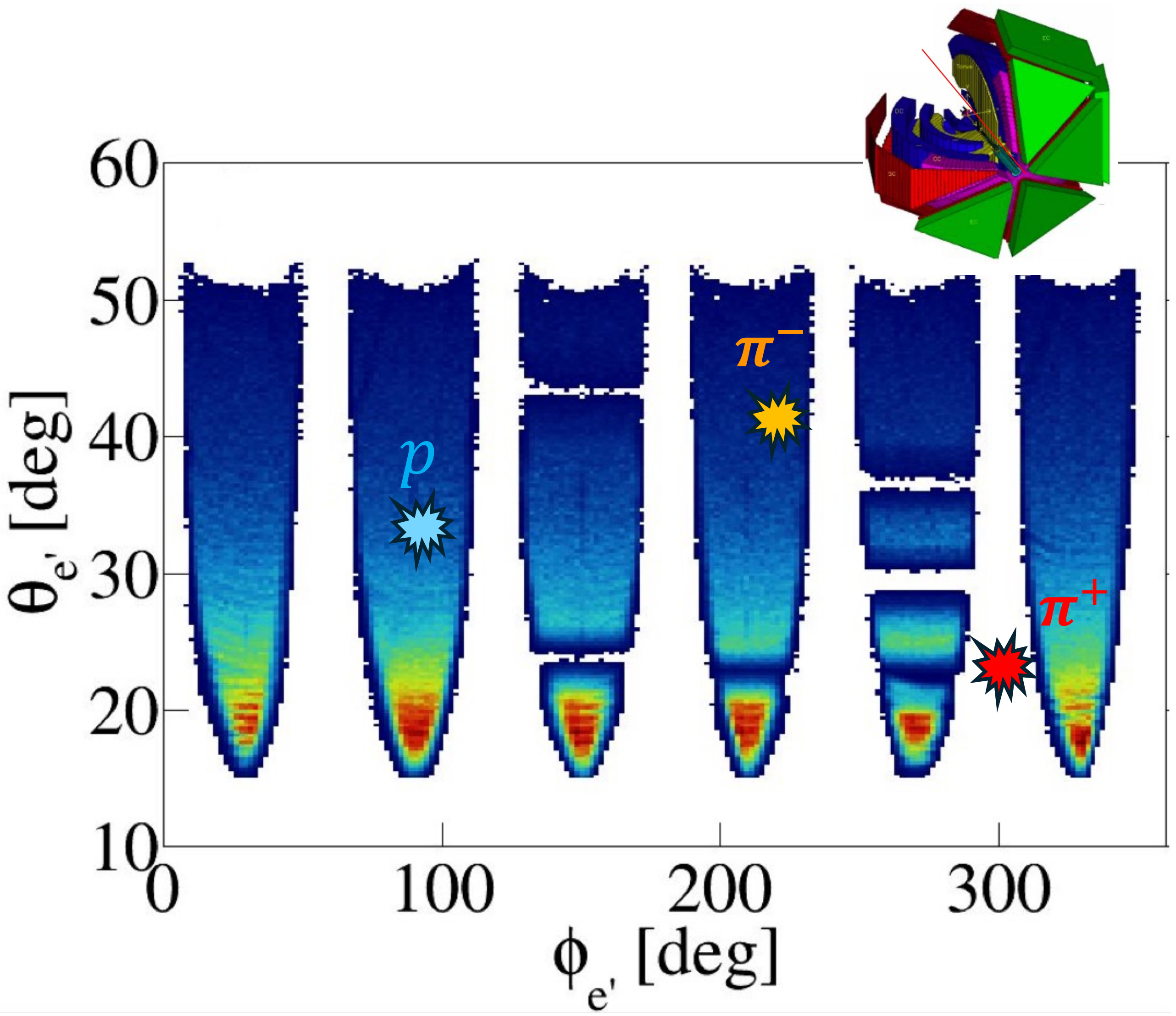


https://doi.org/10.1016/j.nima.2020.163419

Generalizing Background Subtraction

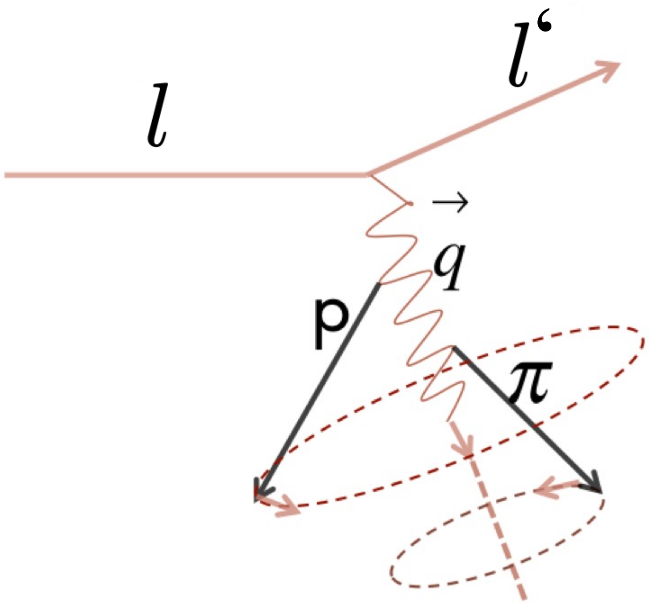
Not full "4π" coverage

- Gaps between the sectors
- Gaps within a sector
- **"Data driven" background subtraction**
- Multi-particle correction



Data Driven Background Subtraction

- Using measured (e,e'1p1π) events
- Rotate p,π around **q**
- Determine event acceptance
- Subtract (e,e'1p1π) contribution



Julia
Tena Vidal

e4nu 1p0π Event Selection

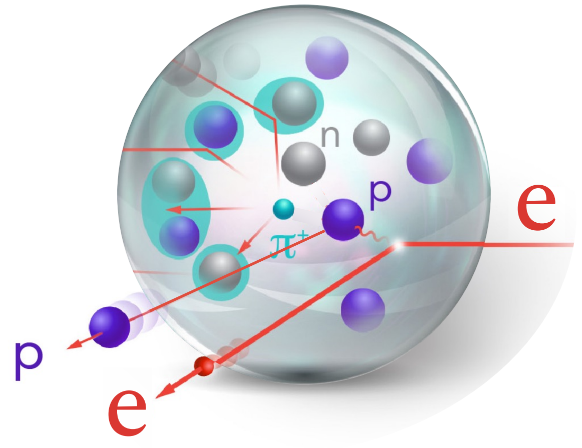
Focus on Quasi Elastic events:

1 proton above 300 MeV/c

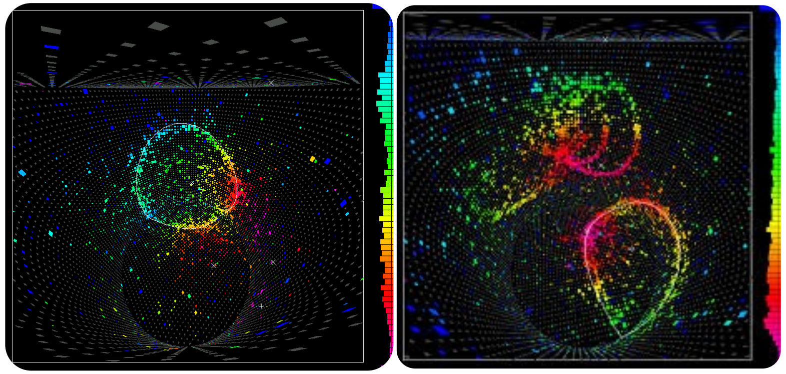
no additional hadrons above detection threshold:

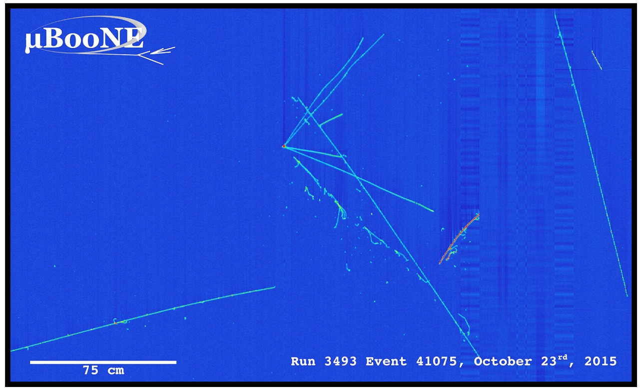
150 MeV/c for $P_{\pi^{+/-}}$

500 MeV/c for P_{π^0}



Incoming (e,e')0π Energy Reconstruction





Cherenkov detectors:

Assuming QE interaction

Using lepton only

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

Tracking detectors:

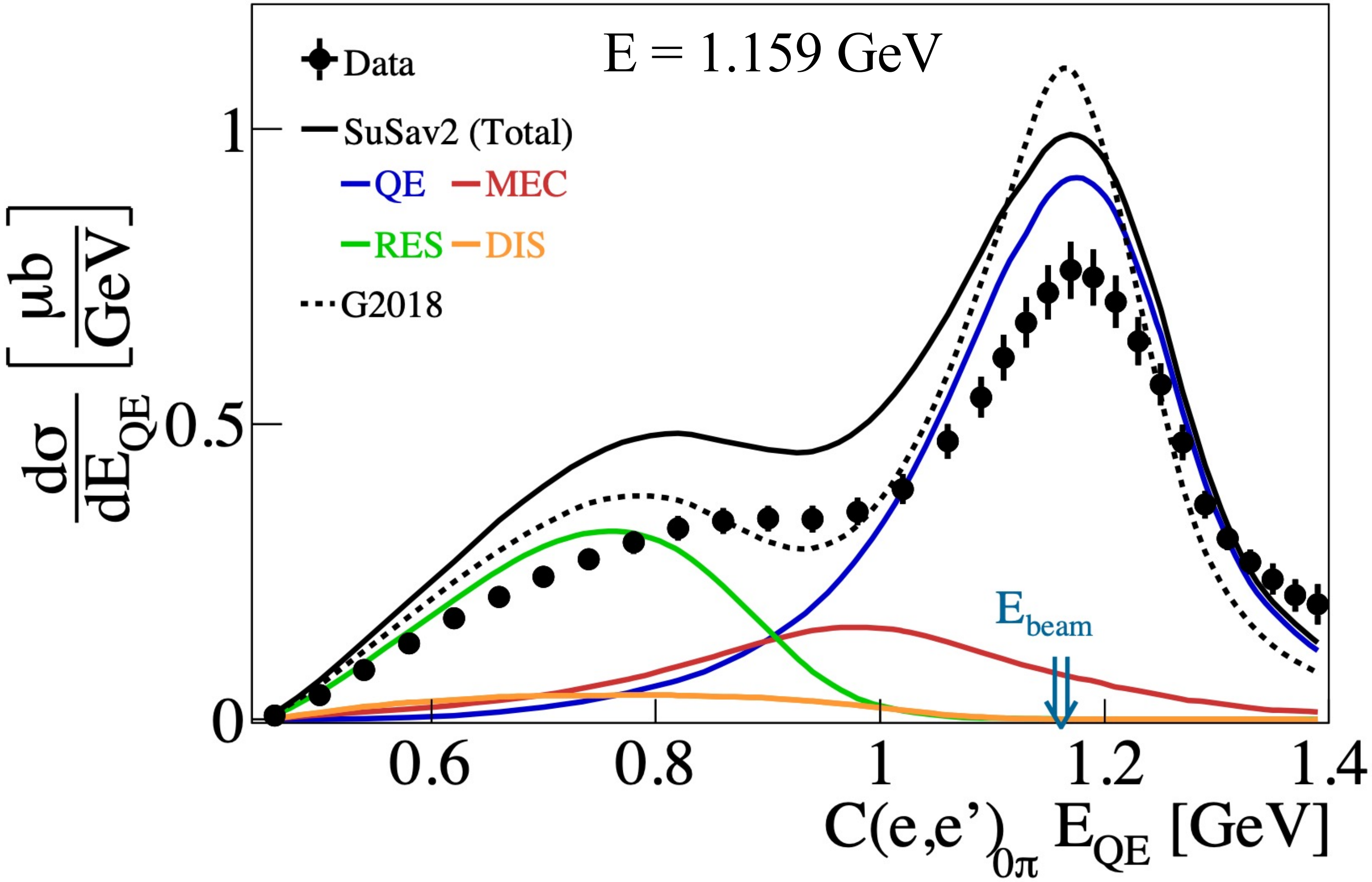
Calorimetric sum

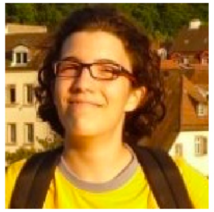
Using All detected particles

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

ϵ is the nucleon separation energy ~ 20 MeV

Incoming Energy Reconstruction



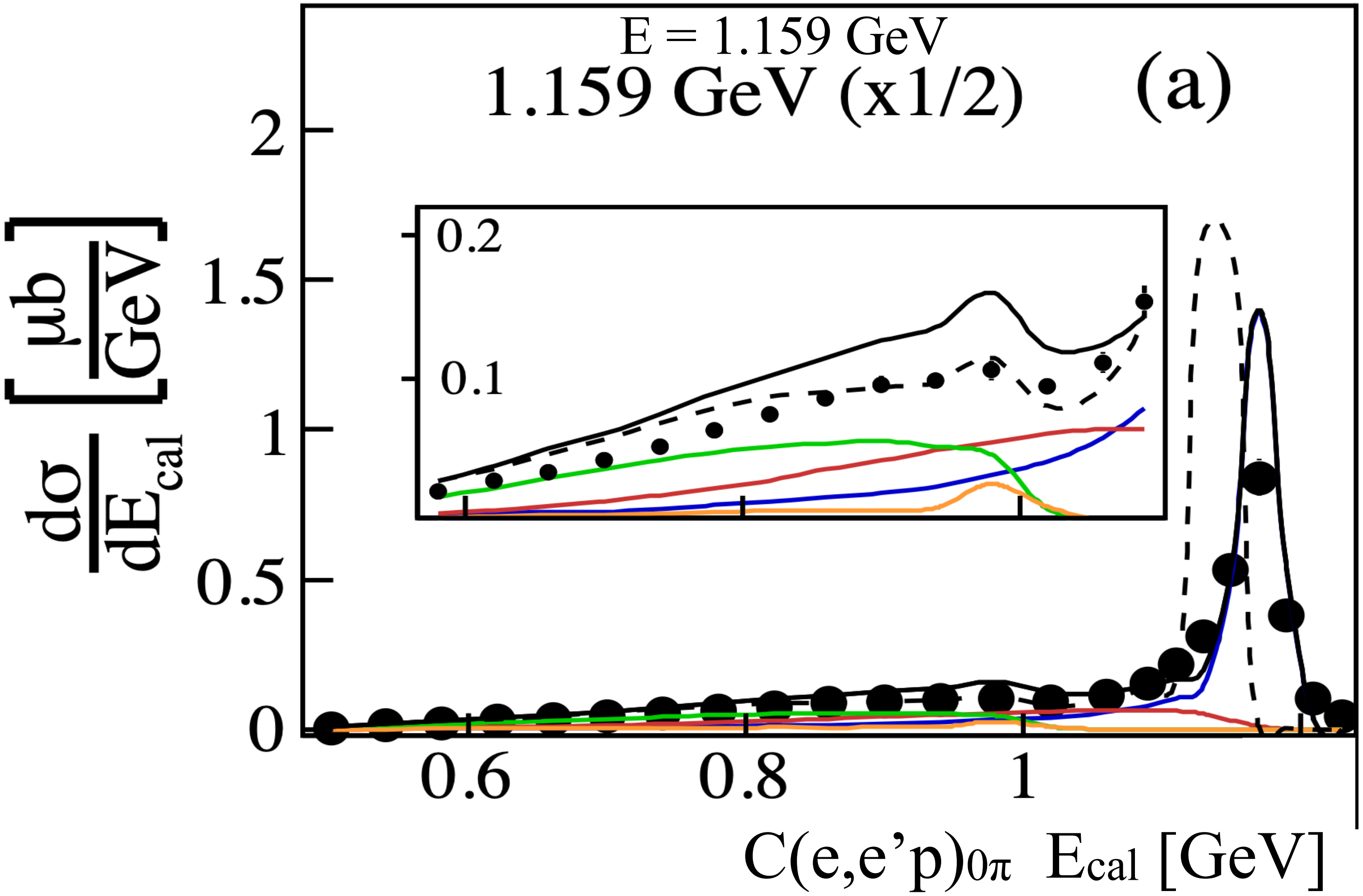


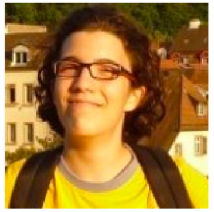
Afroditi Papadopoulou

Mariana Khachatryan

Nature **599**, 565 (2021)

Incoming Energy Reconstruction



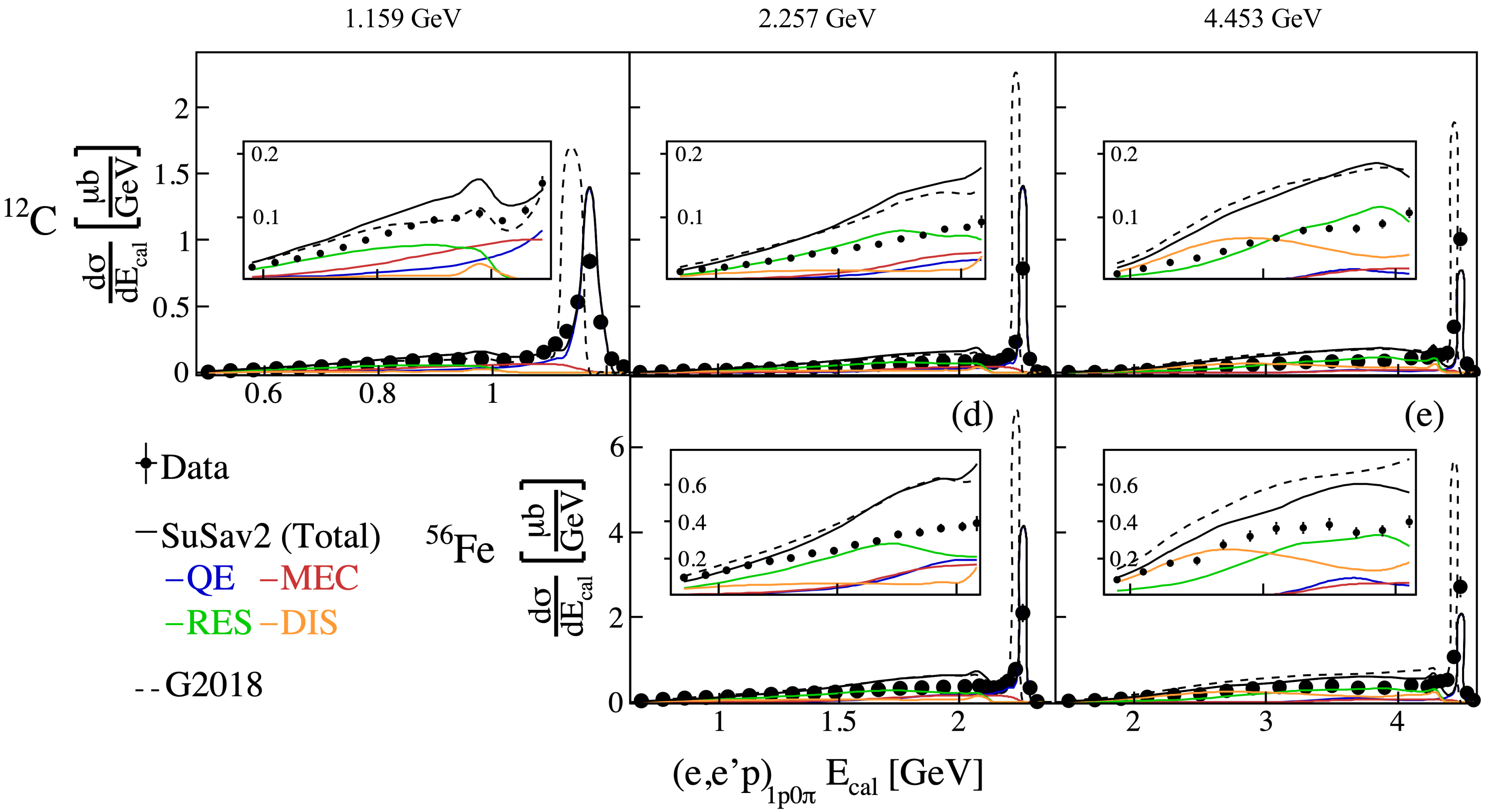


Afroditi Papadopoulou

Mariana Khachatryan

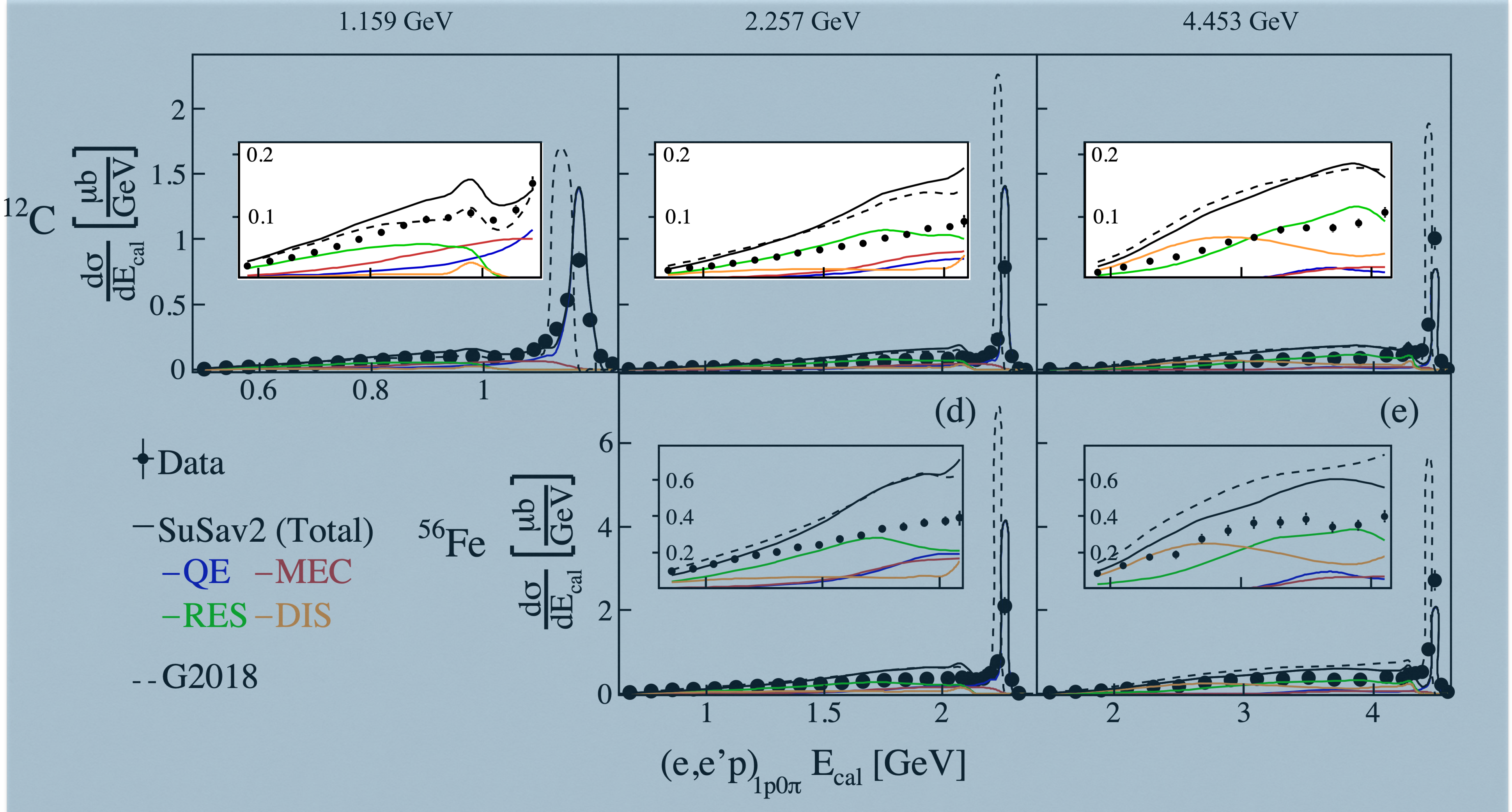
Nature **599**, 565 (2021)

Reconstructed (e,e'p)1p0π Calorimetric Energy



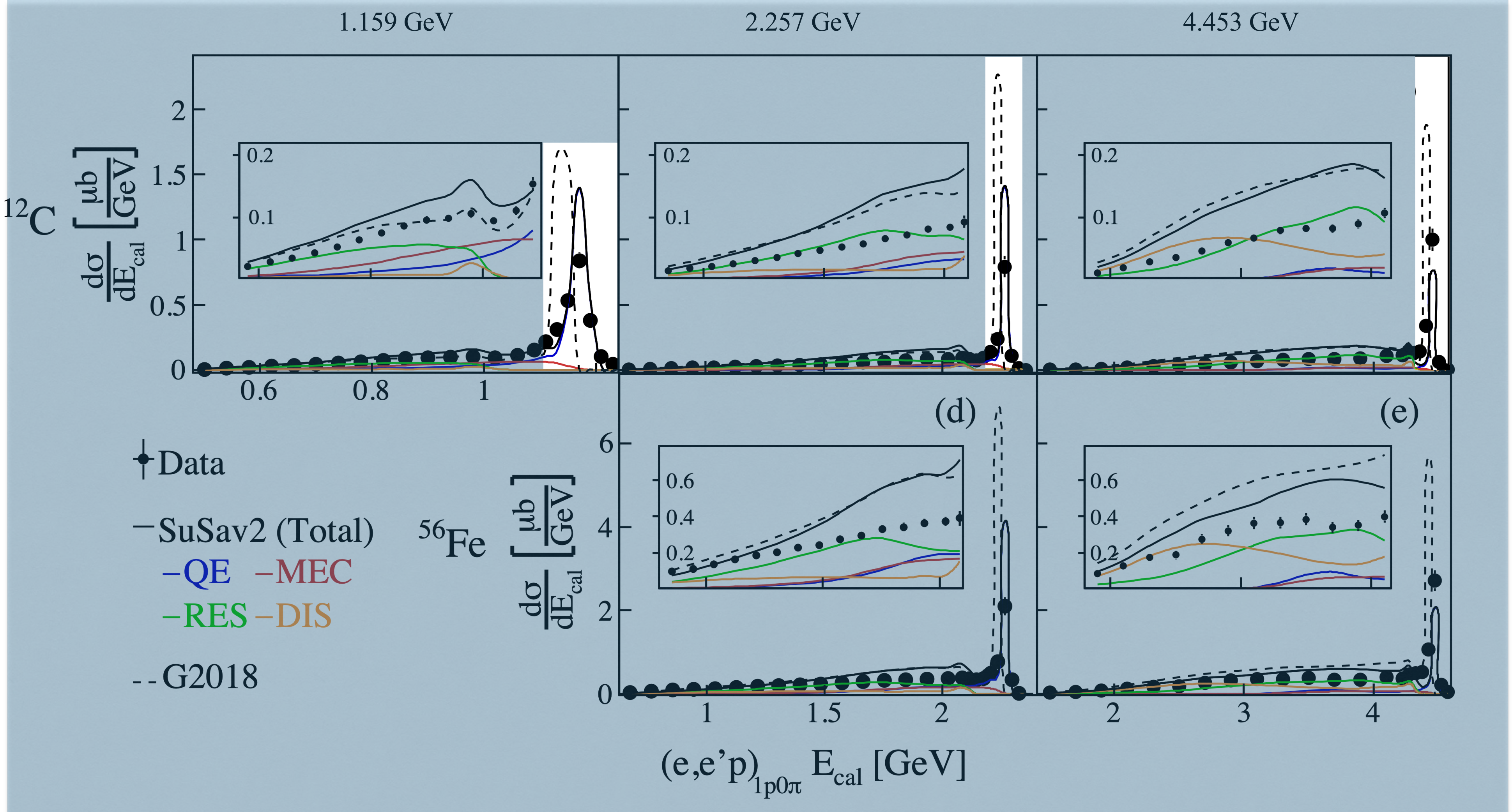
Nature **599**, 565 (2021)

Reconstructed (e,e'p)1p0π Calorimetric Energy



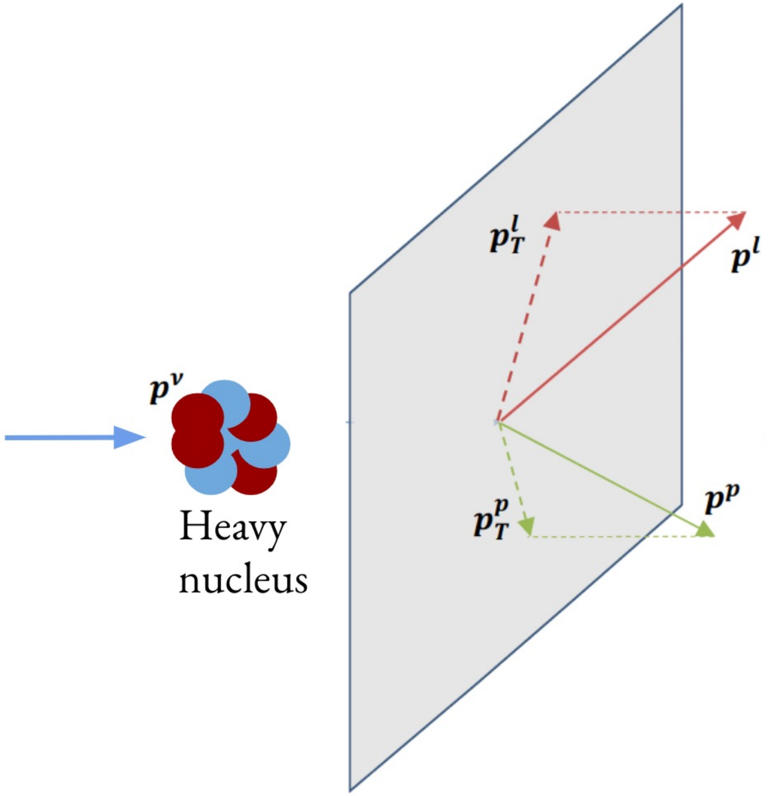
Nature **599**, 565 (2021)

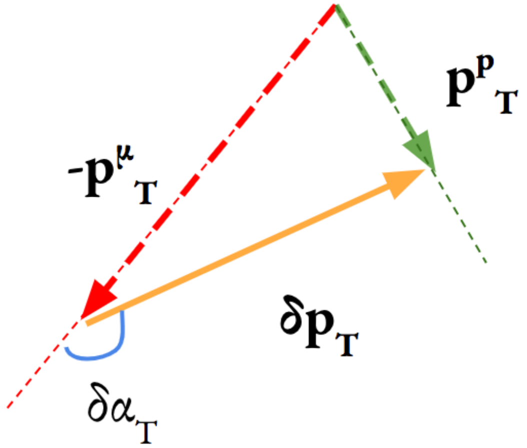
Reconstructed (e,e'p)1p0π Calorimetric Energy



Nature **599**, 565 (2021)

Focusing on different reaction mechanisms
Standard Transverse Variables





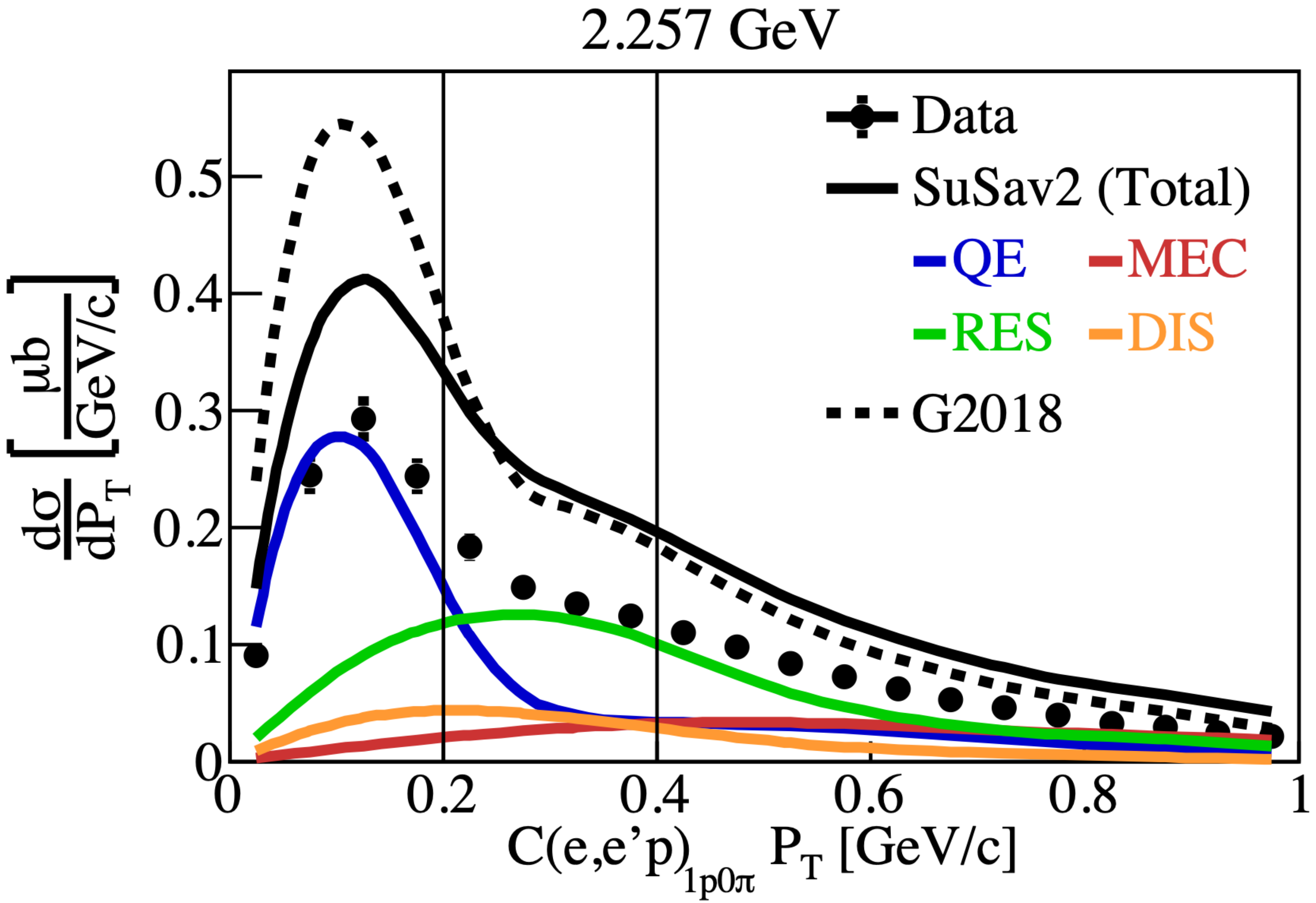
$\vec{P_T} = \vec{P_T^{e'}} + \vec{P_T^{p}}$

Sensitive to
hit nucleon momentum

$\delta\alpha_T$

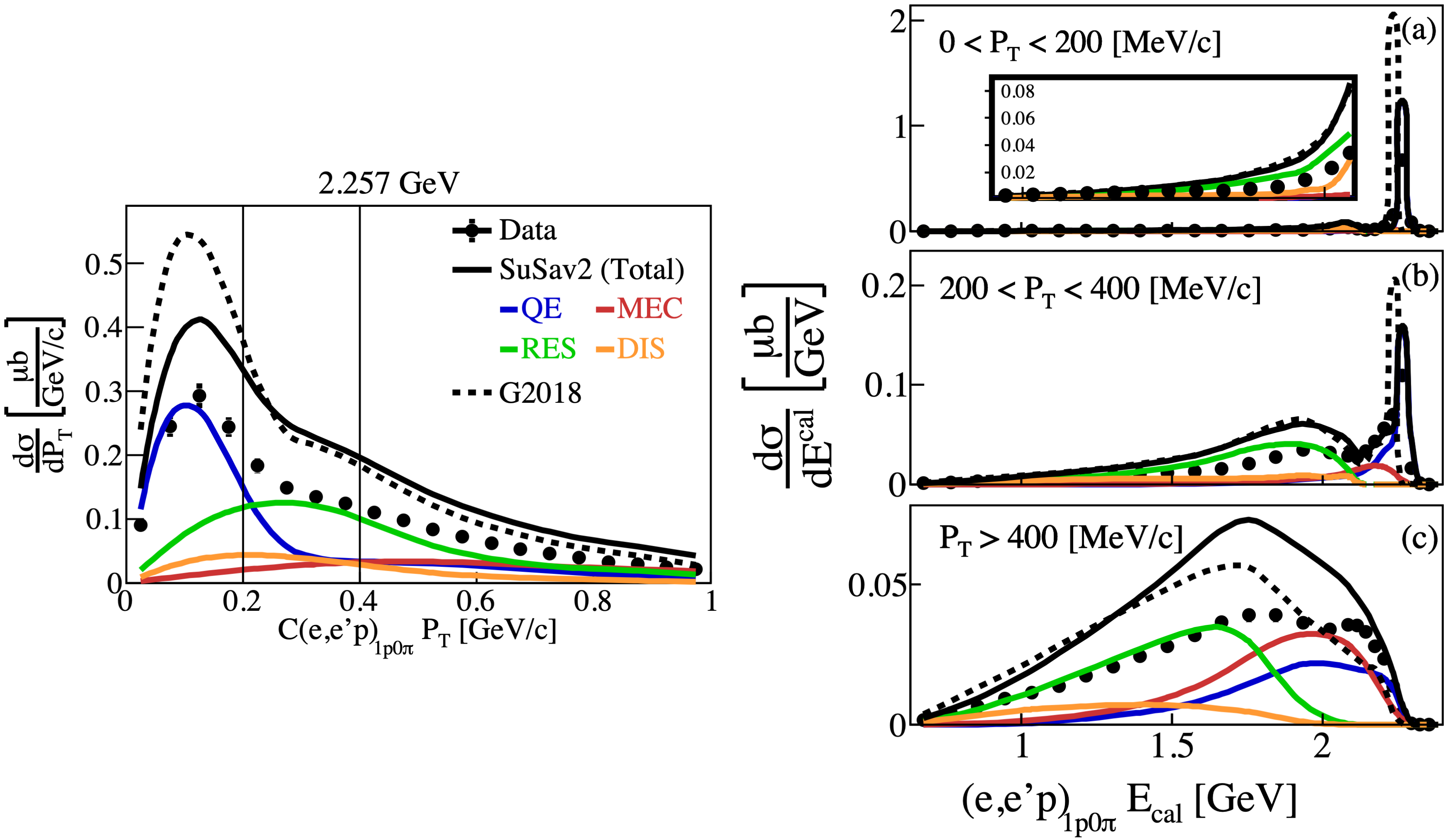
Sensitive to
Final State Interactions

Transverse missing momentum



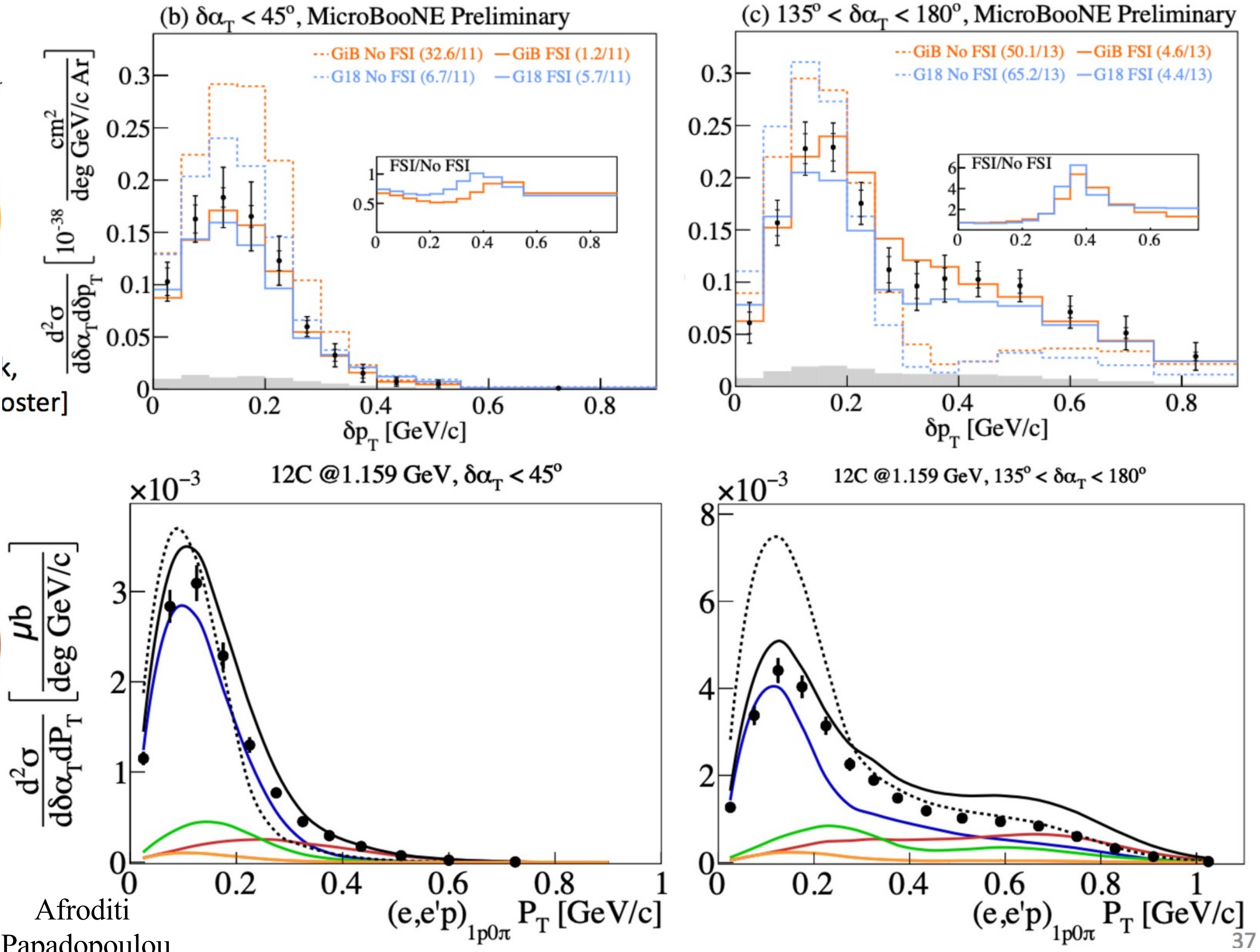
Nature **599**, 565 (2021)

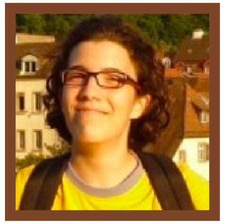
pT sensitivity to interaction mechanisms



Nature **599**, 565 (2021)

MC vs. (e,e'p) Transverse Variables

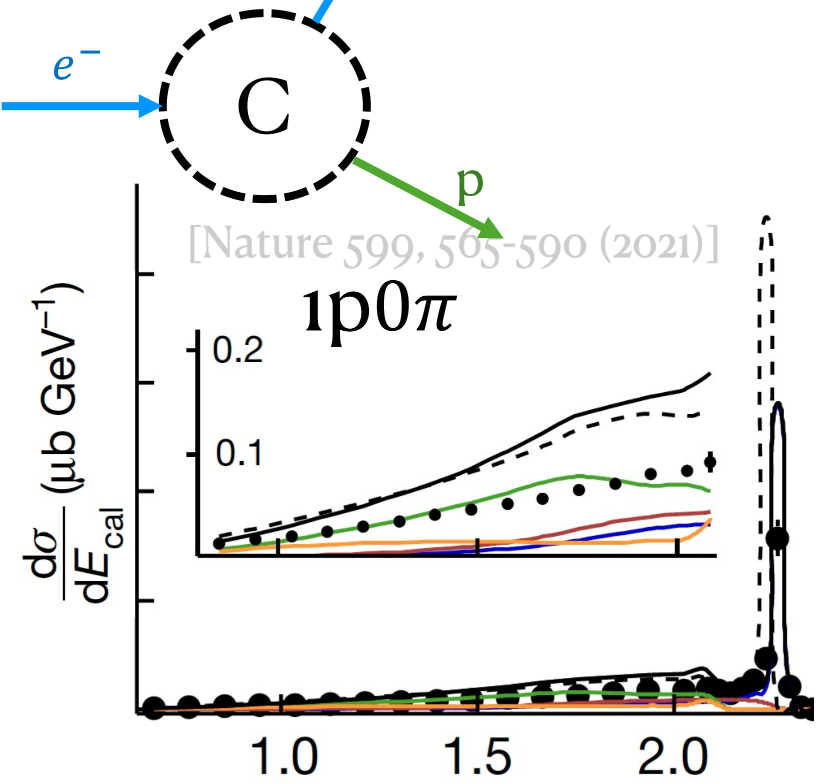




Afroditi Papadopoulou @ ANL

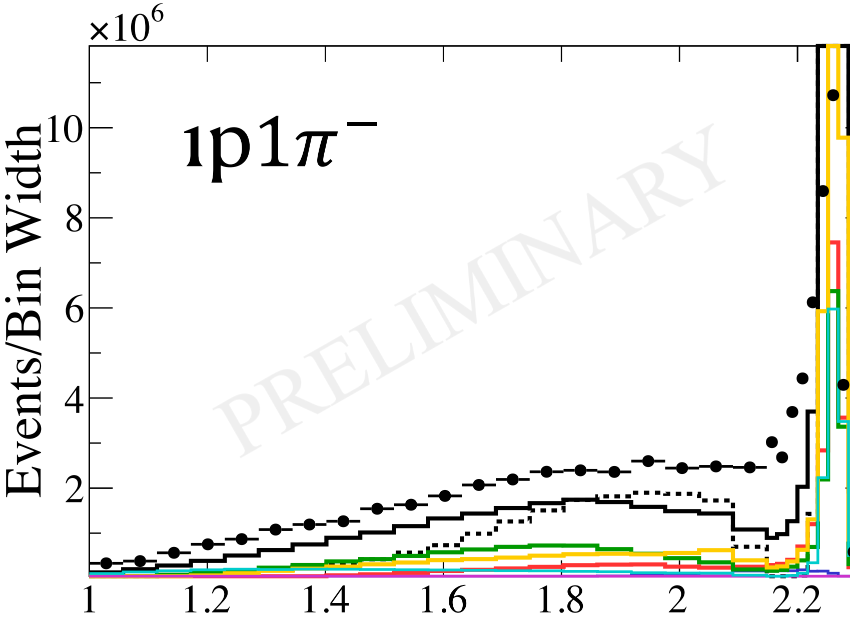
arXiv:2301.03700 [hep-ex]

Beam energy reconstruction

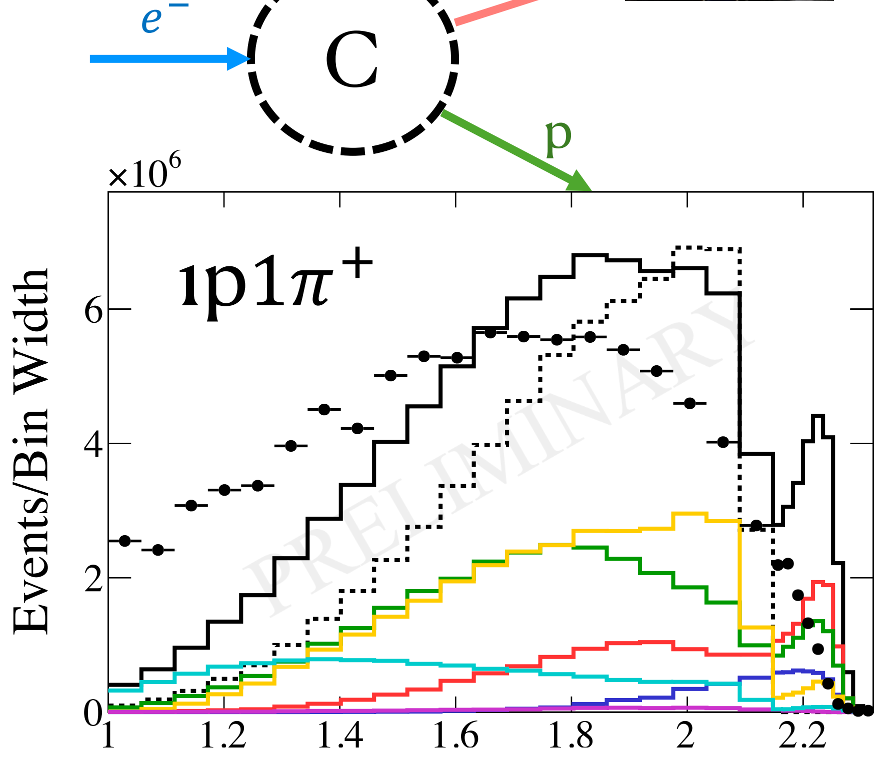


$E_{Cal} = E_{e'} + T_p + \varepsilon_p$

2.2 GeV on Carbon

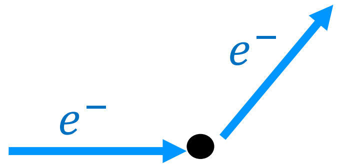


$E_{Cal} = E_{e'} + E_{\pi} + T_p + \varepsilon_p$



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

Peak reconstructed if measured particles are full final state
Tail due to missing particles, not well described



Mott Cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\alpha^2}{4E_e^2 \sin^4 \theta_{e'}/2} \cos^2 \theta_{e'}/2$$

- α: fine-structure constant
- E_e : beam energy
- $\theta_{e'}$: outgoing electron scattering angle

2N analysis – goal and event selection

Goal: comparing **2p** and **1n1p**

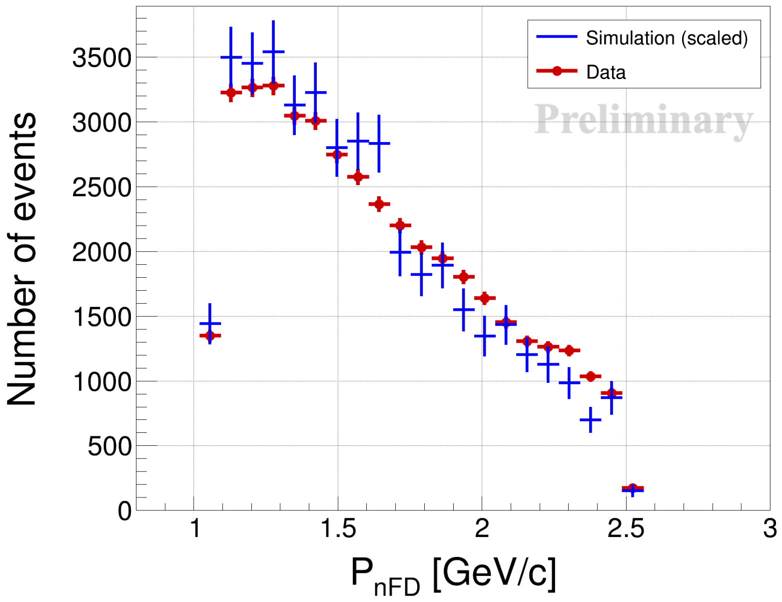
Full signal selection (based on detector constraints!):

Particles		Sub-detector	Momentum thresholds* [GeV/c]	2p	1n1p
e^-		FD	None	One electron	
$\pi^{\pm}$		CD & FD	0.2	No charged pions	
γ		FD	0.3	No photons	
Nucleons	p	FD	0.4	One proton ($\equiv pFD$)	None
		CD		One proton ($\equiv pCD$)	One proton ($\equiv pCD$)
	n	FD	0.4 lower & E_{beam}/c upper	Any number of neutrons; all of them are ignored	Any number of neutrons; considering only the *leading* ($\equiv nFD$)
Anything else		CD & FD	None	Ignored; no constraints	

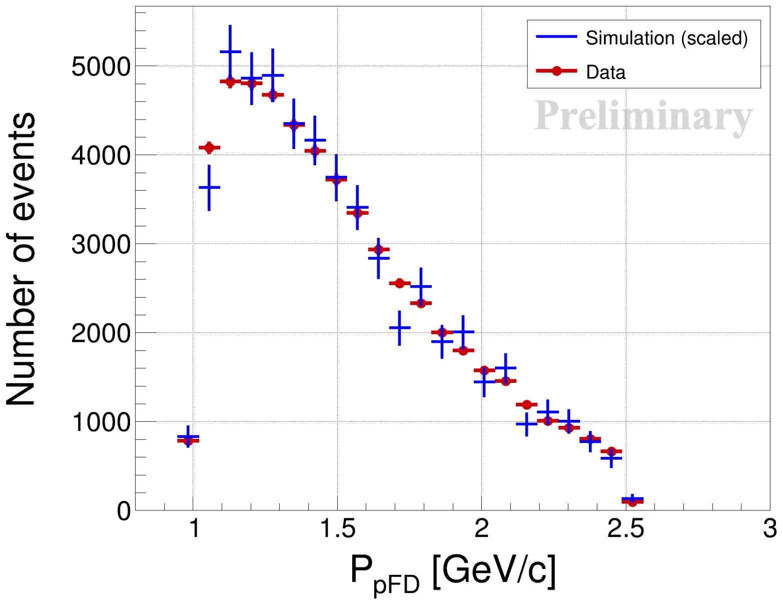
*Refined thresholds will be used in future analyses

FD nucleon momenta

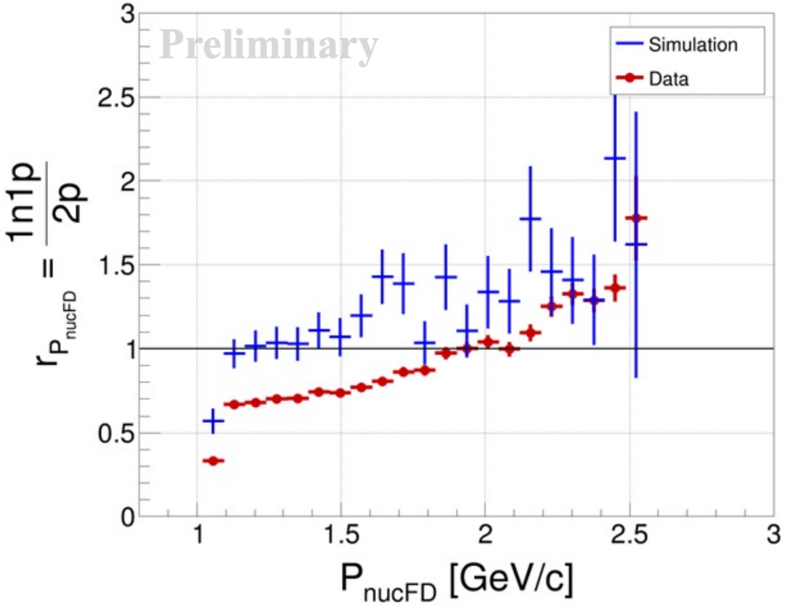
FD neutron momentum in 1n1p



FD proton momentum in 2p



FD nucleon momentum ratio

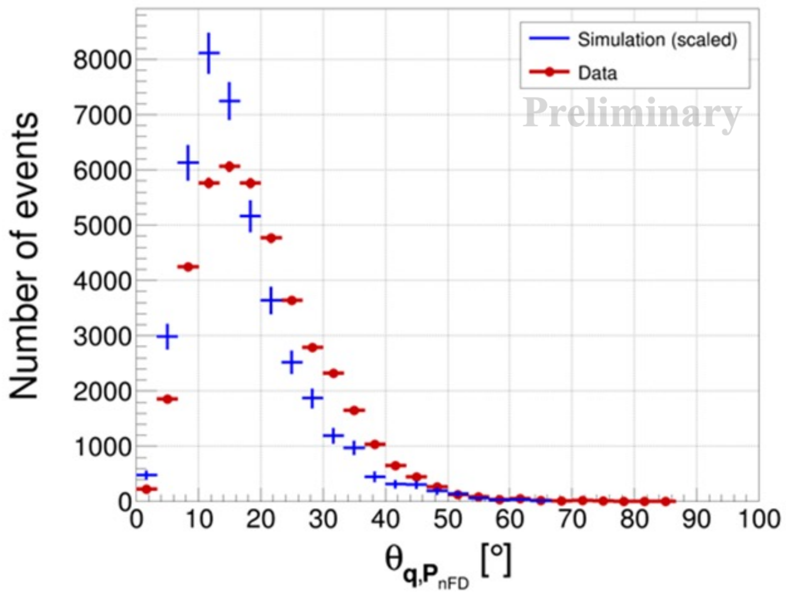


nFD = FD neutron	pFD = FD proton	$nucFD$ = FD nucleon

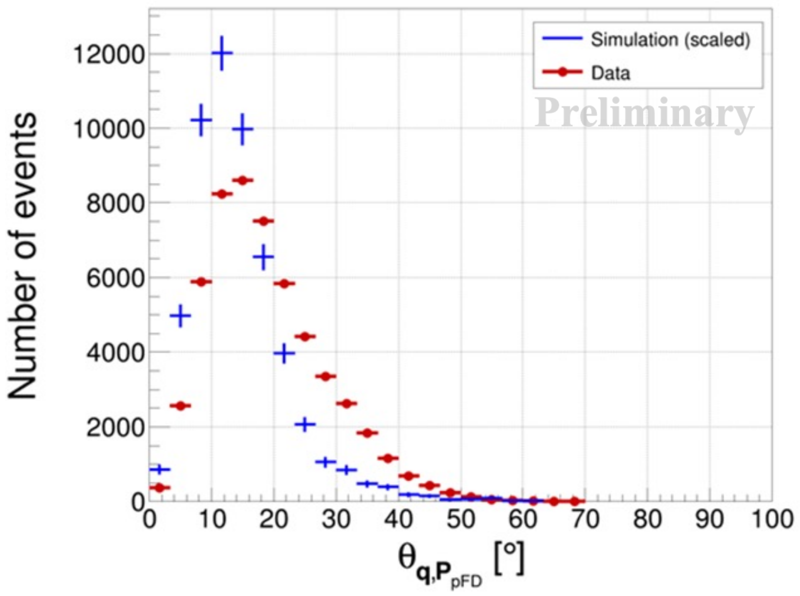
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Opening angle between $\boldsymbol{q}$ and $\boldsymbol{P}_{nucFD}$ $(\boldsymbol{\theta}_{\boldsymbol{q},\boldsymbol{P}_{nucFD}})$

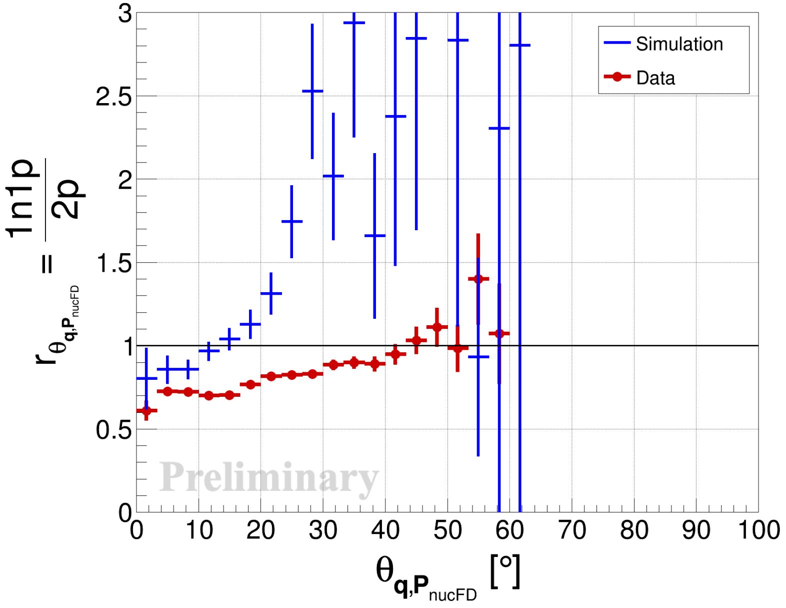
$\theta_{q,P_{nFD}}$ in 1n1p



$\theta_{q,P_{pFD}}$ in 2p



$\theta_{q,P_{nucFD}}$ distribution ratio

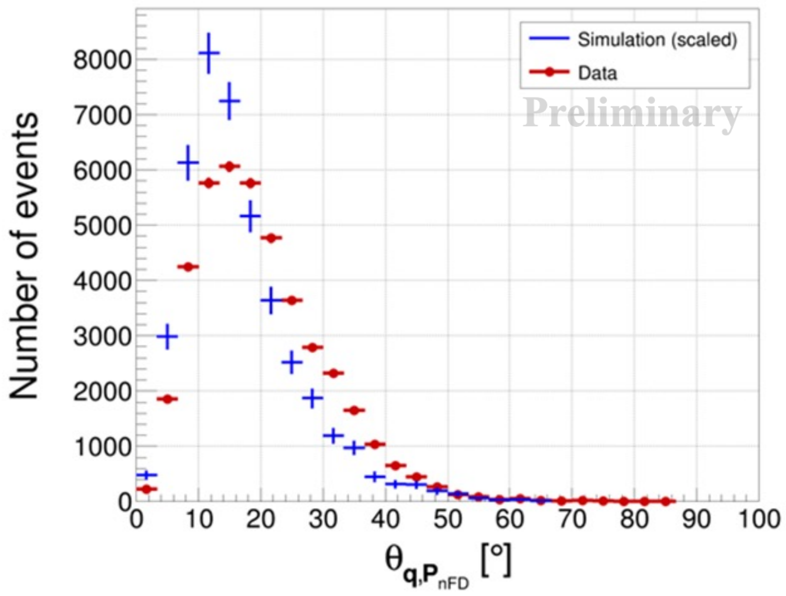


- $\theta_{q,P_{nucFD}}$ – inversely related to $|\boldsymbol{P}_{nucFD}|$

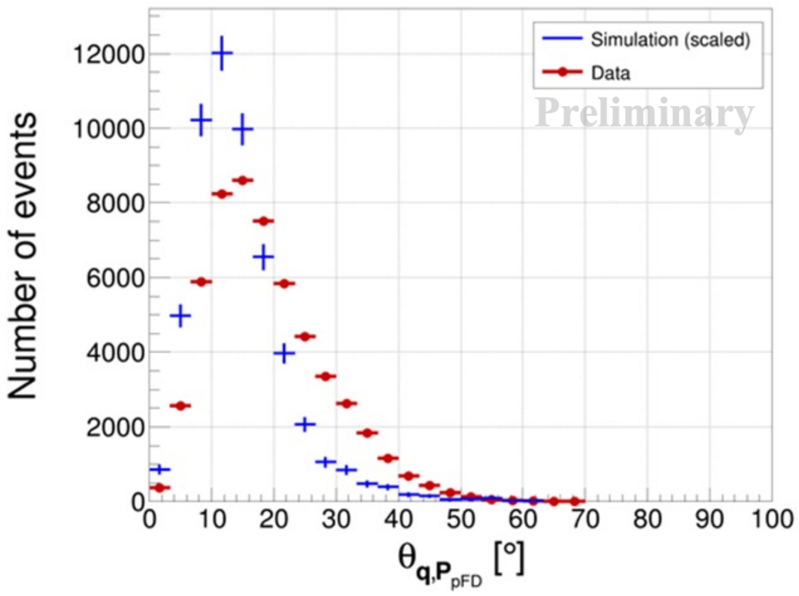
nFD = FD neutron	pFD = FD proton	$nucFD$ = FD nucleon

Opening angle between $\boldsymbol{q}$ and $\boldsymbol{P}_{nucFD}$ ($\boldsymbol{\theta}_{\boldsymbol{q},\boldsymbol{P}_{nucFD}}$) – zoom-out

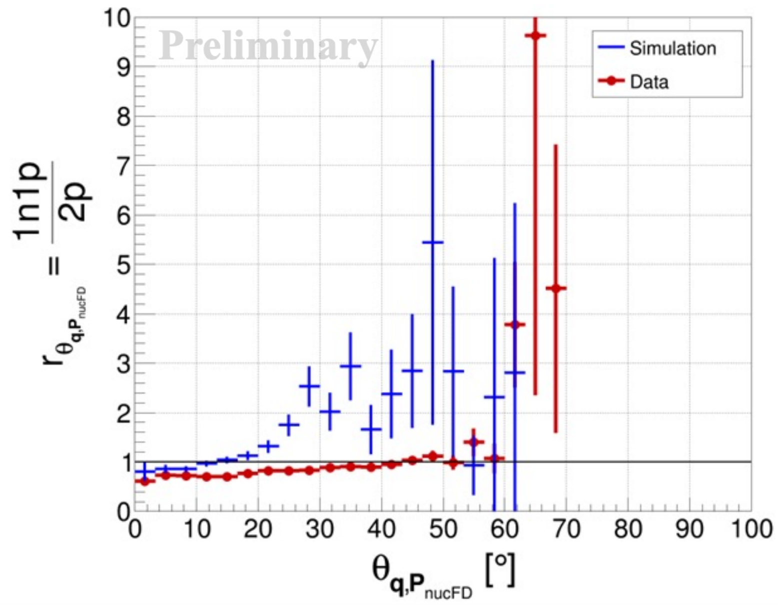
$\boldsymbol{\theta}_{\boldsymbol{q},\boldsymbol{P}_{nFD}}$ in 1n1p



$\boldsymbol{\theta}_{\boldsymbol{q},\boldsymbol{P}_{pFD}}$ in 2p



$\boldsymbol{\theta}_{\boldsymbol{q},\boldsymbol{P}_{nucFD}}$ distribution ratio



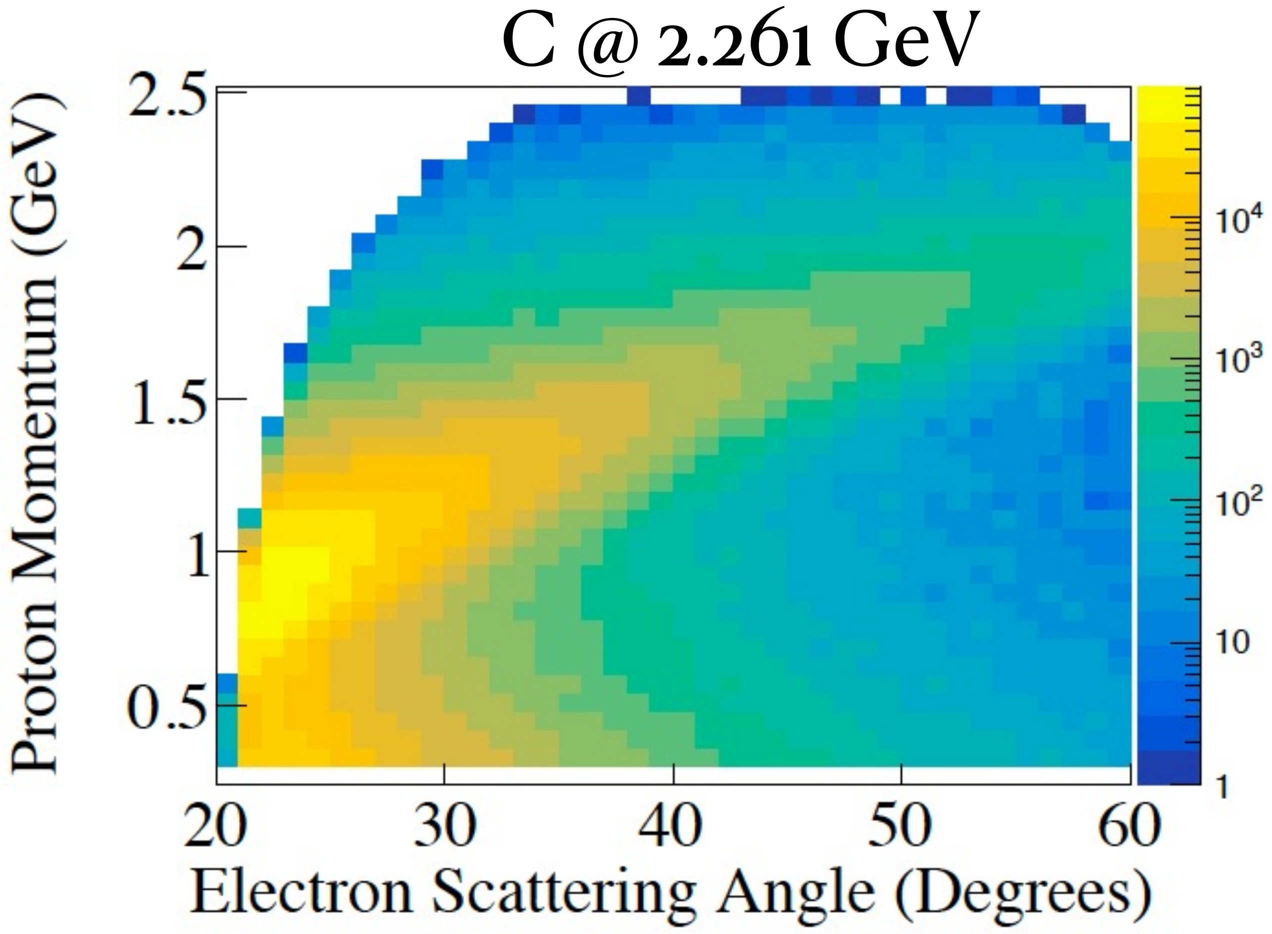
- $\theta_{\boldsymbol{q},\boldsymbol{P}_{nucFD}}$ – inversely related to $|\boldsymbol{P}_{nucFD}|$

nFD = FD neutron	pFD = FD proton	$nucFD$ = FD nucleon

[12]C simulation and data at $E_{beam} \simeq 6$ GeV

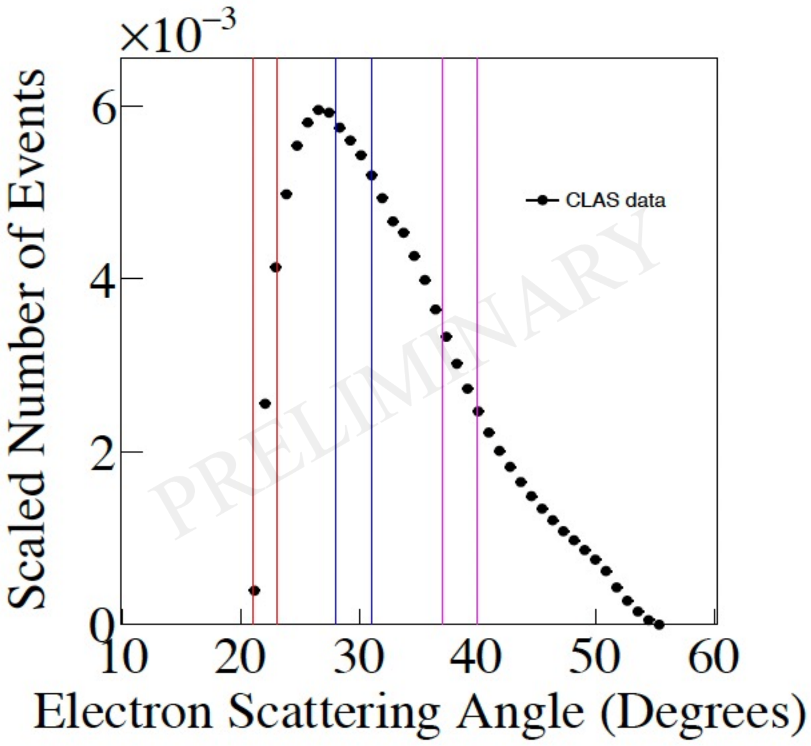
New Results – Nuclear Transparency

- Take advantage of lepton-hadron correlations in QEL scattering
- Slice data in θ_e to pick out regions of Pp

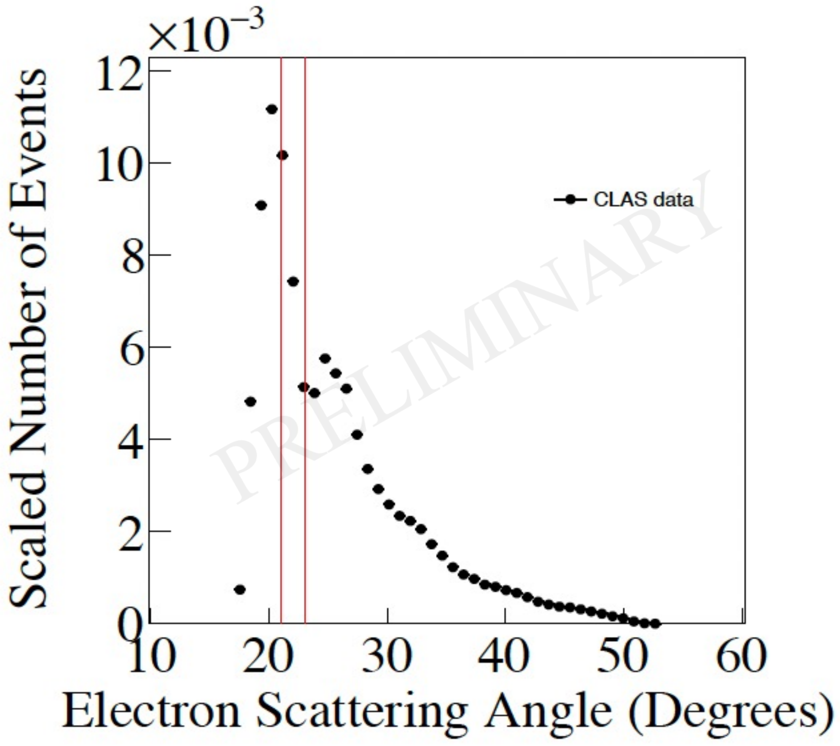


New Results – Nuclear Transparency

C @ 2.261 GeV



C @ 4.4261 GeV

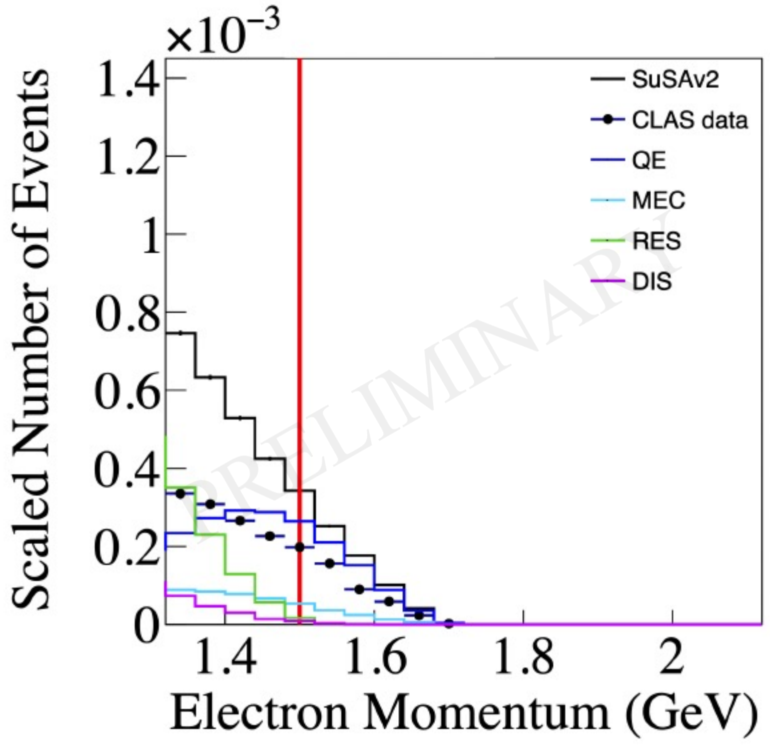


New Results – Nuclear Transparency

- Take advantage of lepton-hadron correlations in QEL scattering
- Slice data in θ_e to pick out regions of Pp

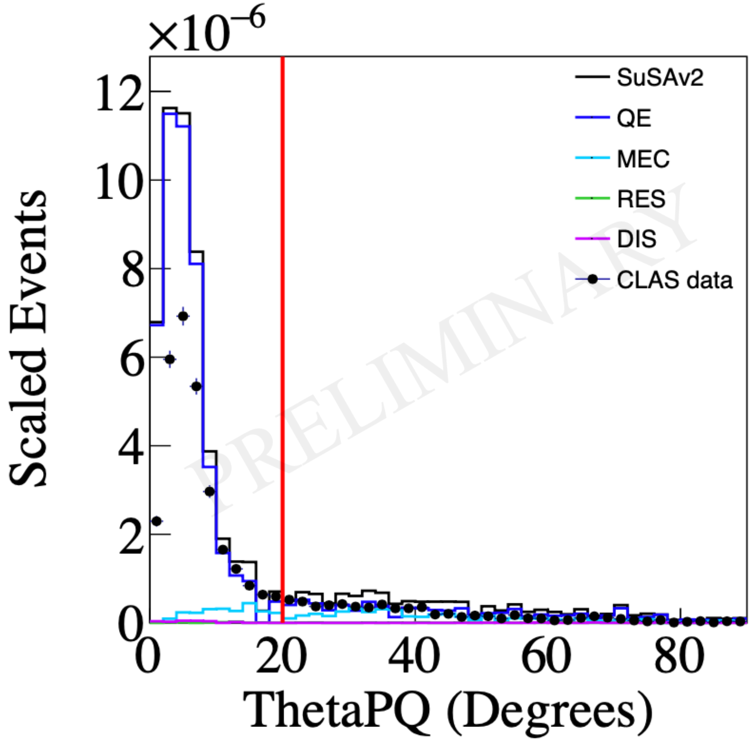
  - Cut on ω to pick QE dominated regions

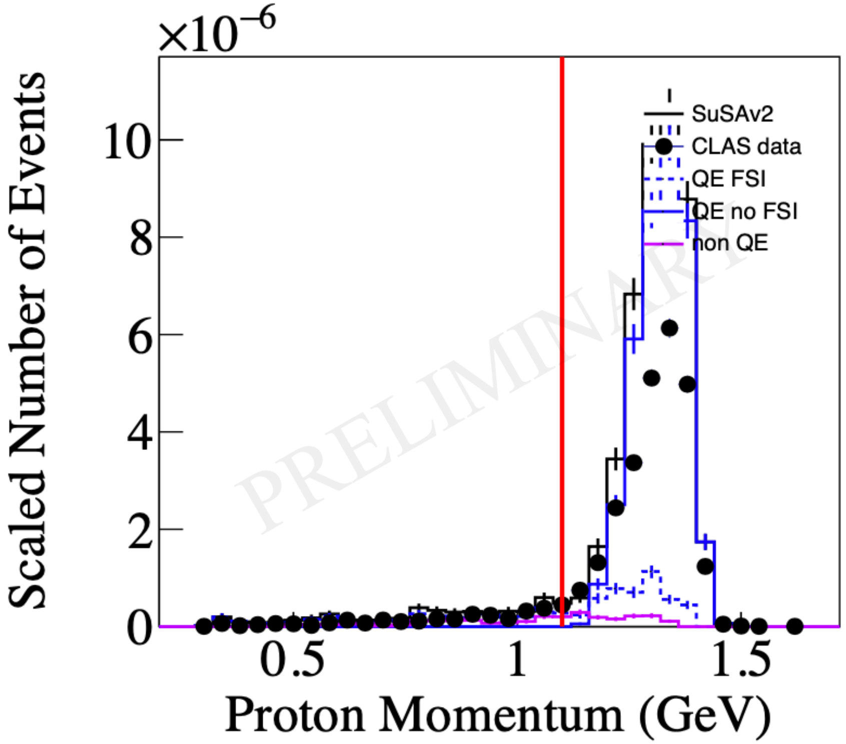
2.261 e-^{12}C
37 deg < θ_e < 40 deg



New Results – Nuclear Transparency

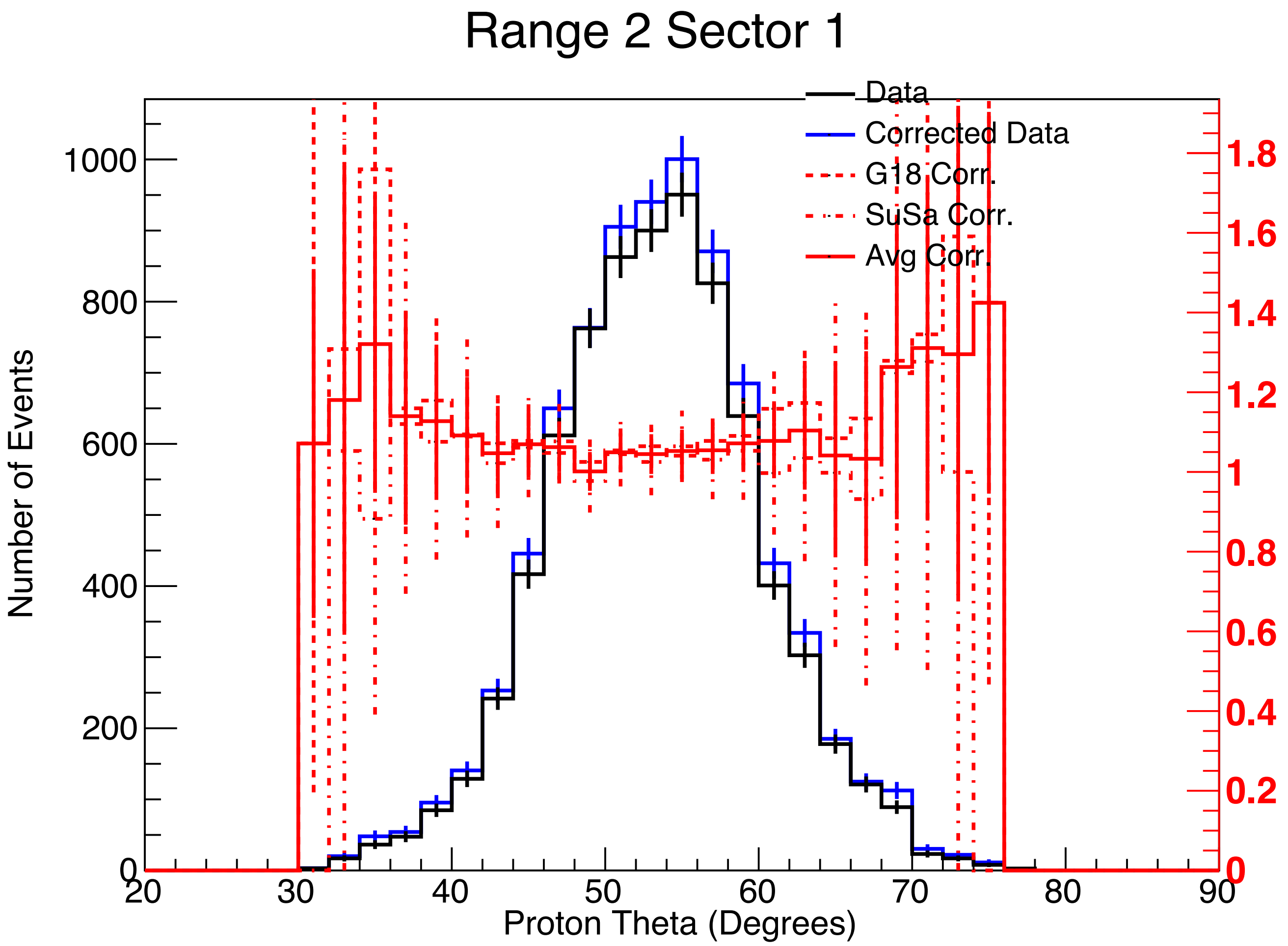
- (e,e'p) is a subset of (e,e') cut on θ_{pq} and $\mathbf{P}_p$ to isolate QE and minimal FSI regions





Where is the acceptance correction working? Proton theta distributions

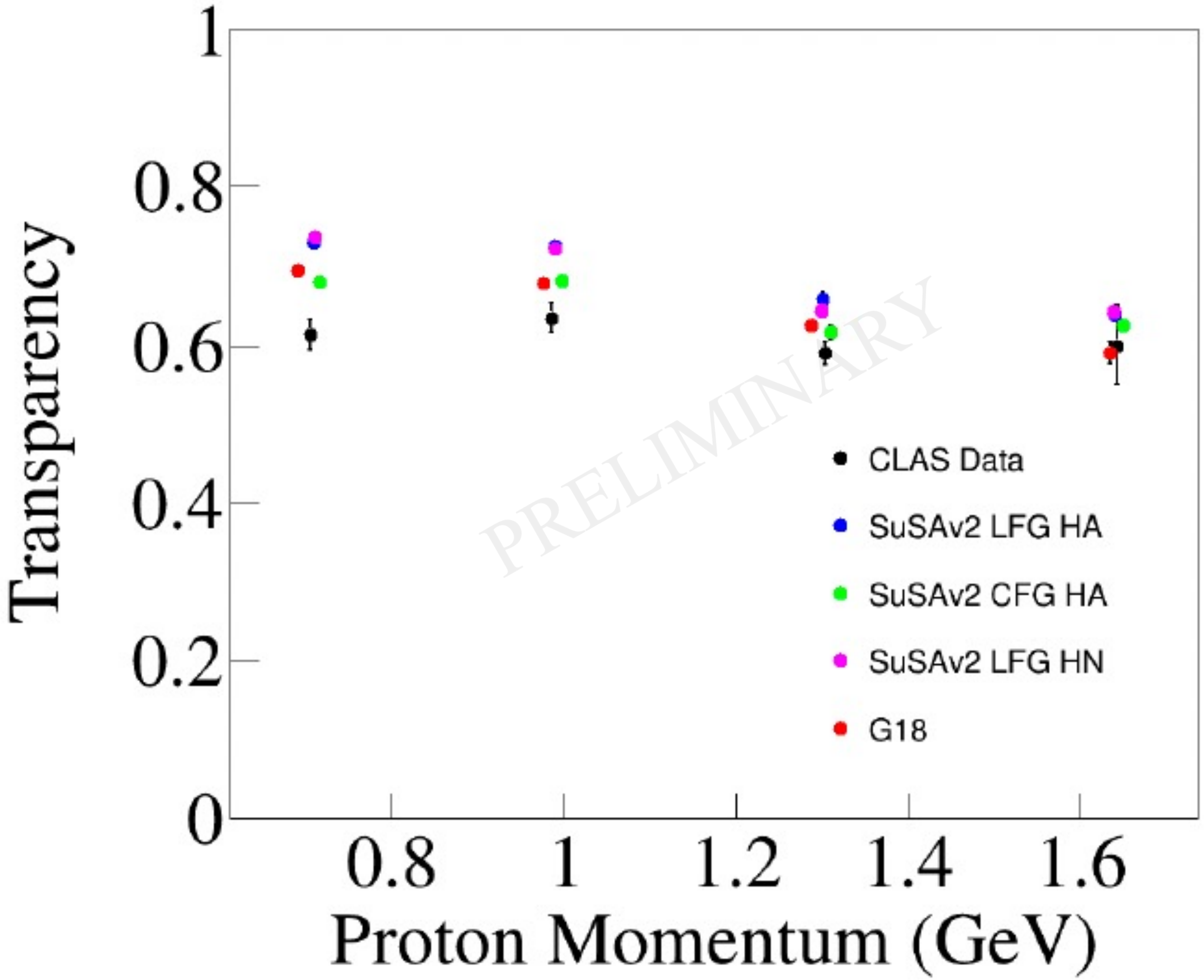
Black: Uncorrected Data
Blue: Acceptance Corrected Data
Red: Acceptance Correction Facto



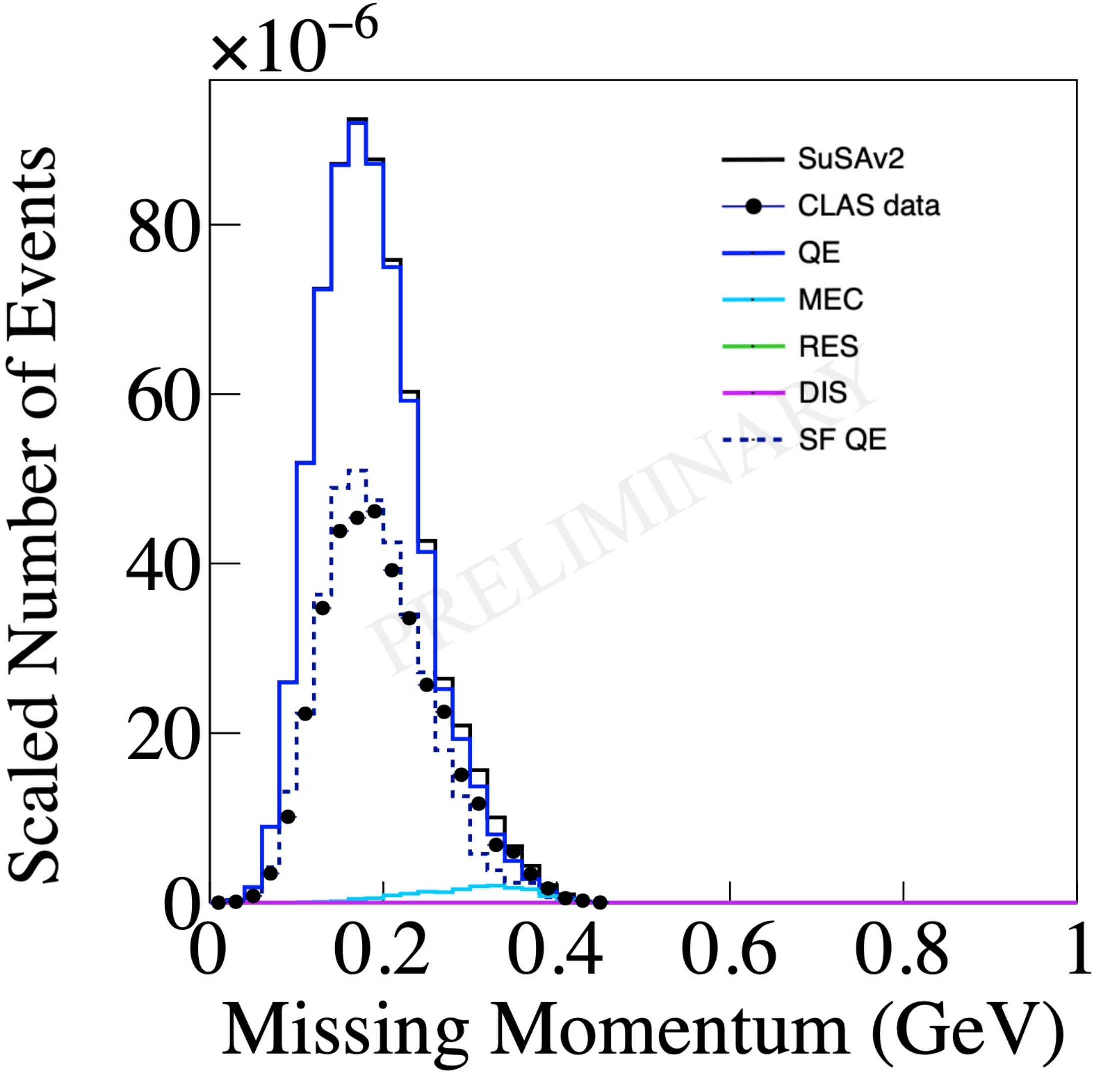
Proton Transparency - Systematics

helium % error	Stat.	Bkgd Subt.	2p2h norm.	Acceptance	Cut	Sector	SRC	Total
2.261 GeV Range 1	0.1	0.34	0.07	0.11	0.65	0.1	2.0	2.14
2.261 GeV Range 2	0.26	0.36	0.07	0.15	1.36	1.8	2.0	3.1
2.261 GeV Range 3	0.66	0.42	0.12	0.50	0.88	0.1	2.0	2.4
4.461 GeV Range 4	1.1	0.84	0.11	0.56	1.8	4.4	2.0	5.4
carbon % error	Stat.	Bkgd Subt.	2p2h norm.	Acceptance	Cut	Sector	SRC	Total
2.261 GeV Range 1	0.23	0.54	0.56	0.37	2.76	0.77	2.0	3.6
2.261 GeV Range 2	0.30	0.37	0.53	0.31	2.03	1.7	2.0	3.5
2.261 GeV Range 3	1.1	0.49	0.89	0.56	2.79	0.1	2.0	3.8
4.461 GeV Range 4	4.0	1.0	1.1	0.5	0.83	7.1	2.0	8.6
iron % error	Stat.	Bkgd Subt.	2p2h norm.	Acceptance	Cut	Sector	SRC	Total
2.261 GeV Range 1	1.4	0.62	0.74	0.58	2.83	4.1	2.0	5.7
2.261 GeV Range 2	2.3	0.64	1.0	0.41	3.79	8.03	2.0	9.4
2.261 GeV Range 3	4.4	0.56	1.1	0.64	3.36	18.0	2.0	19.0

Proton Transparency



Proton Transparency – Spectral Function

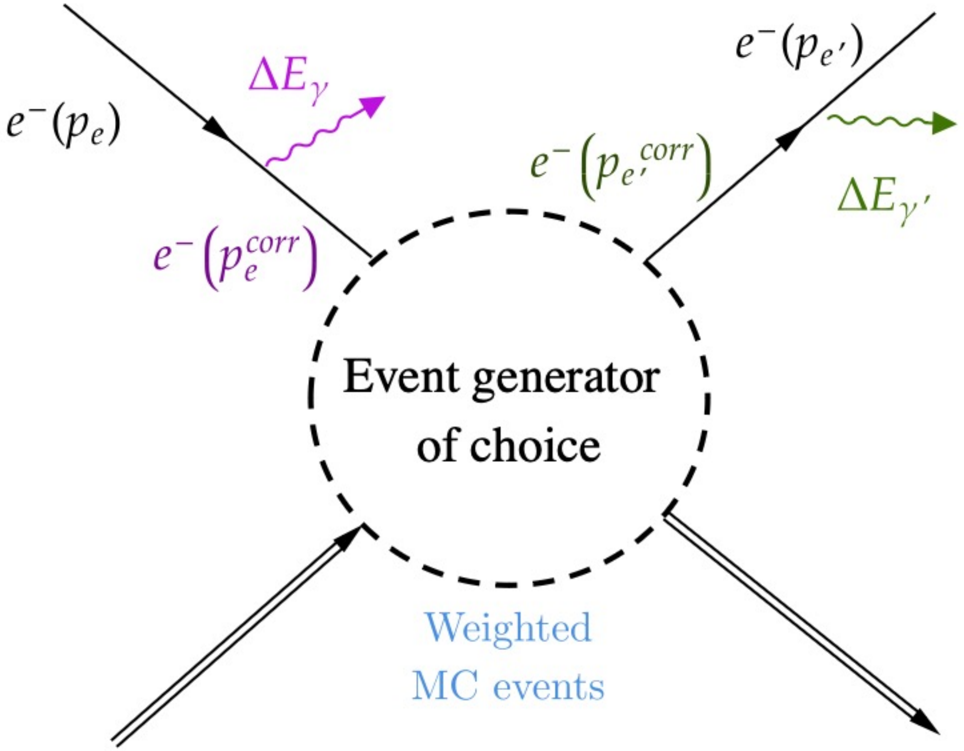


1p1π systematics

Not yet included (*)

Systematic Error	1.1 GeV	2.2 GeV	4.4 GeV
Acceptance correction	<3 %	<2 %	<2 %
Bkg. Closure Test	<6 % (*)	<10 % (*)	<15 % (*)
Geometrical Acceptance	(*)	(*)	(*)
XSec Angular dependence	1 %	1 %	1 %
Photon identification cuts	0.5 %	0.5 %	2 %
Sector-to-Sector	<1 %	<5 %	<6 %
Normalization	1 %	1 %	1 %
Radiative correction	5 %	5 %	5 %
Total	**<7 %**	**< 15 %**	**< 17 %**

Radiative Correction



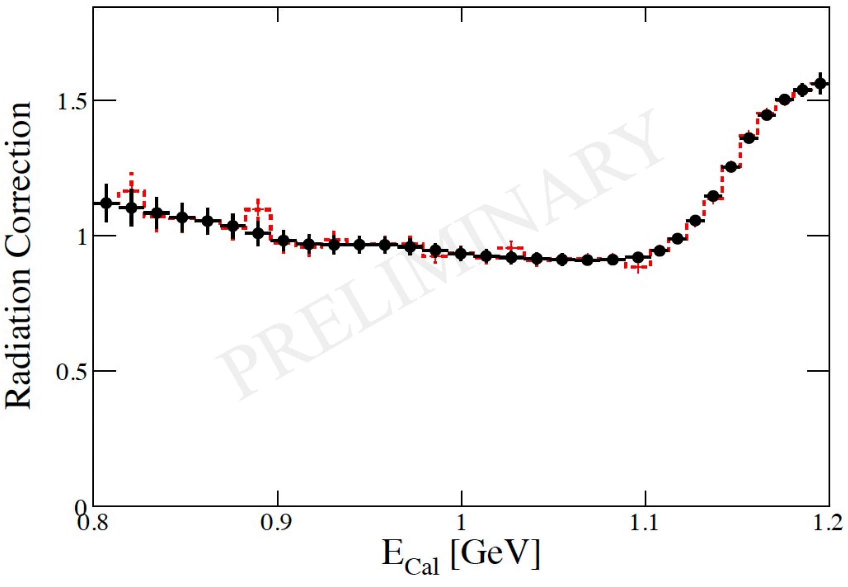
emMCRadCorr

Accounts for [PhysRevC.64.054610]:

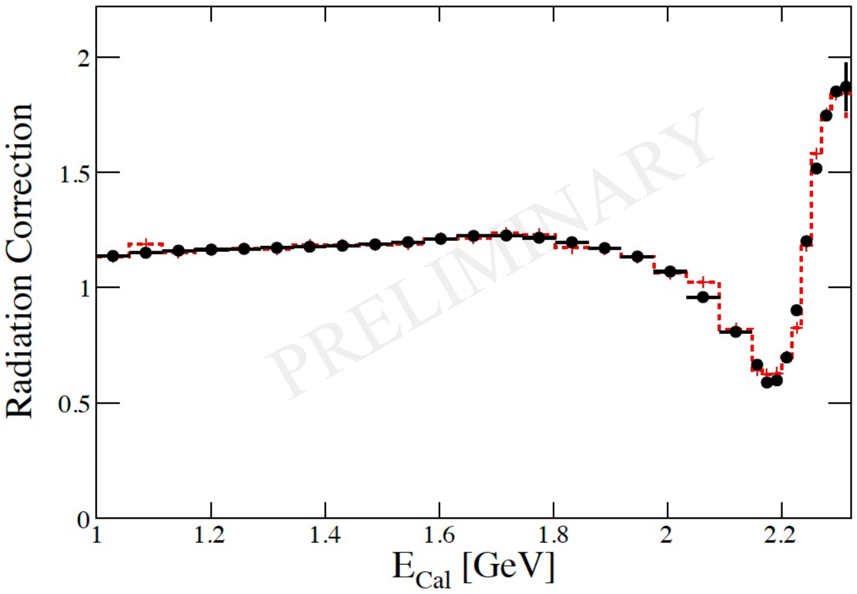
- Incident electron radiation
  - changes the incident flux
- Outgoing electron radiation
  - changes the observed energy transfer
- Vertex corrections
  - change the cross section (i.e., the weight) of the event
- Peaking approximation
  - Radiation emitted in the direction of travel
- Internal & external bremsstrahlung effects
- Neglects radiation by the emitted hadrons

Radiative Correction – 1p1π^-

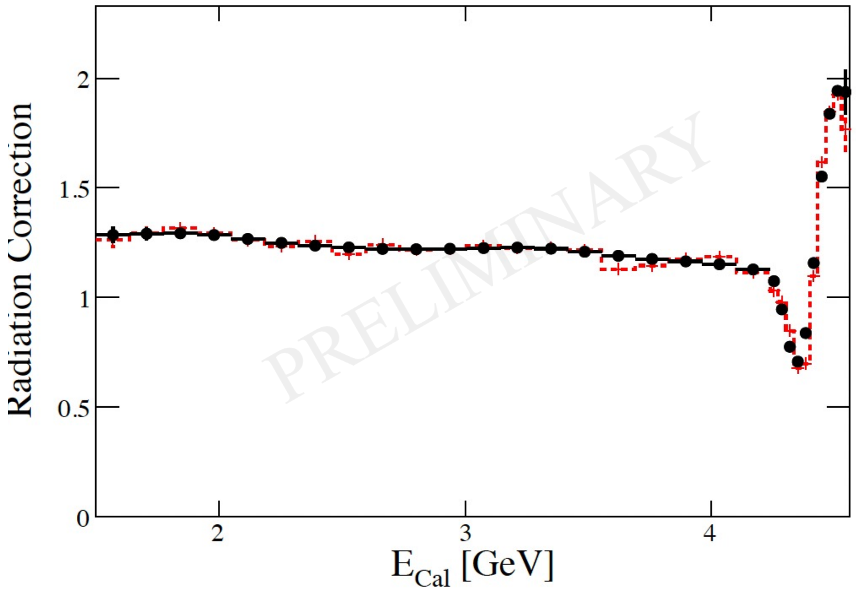
1.1 GeV



2.2 GeV



4.4 GeV



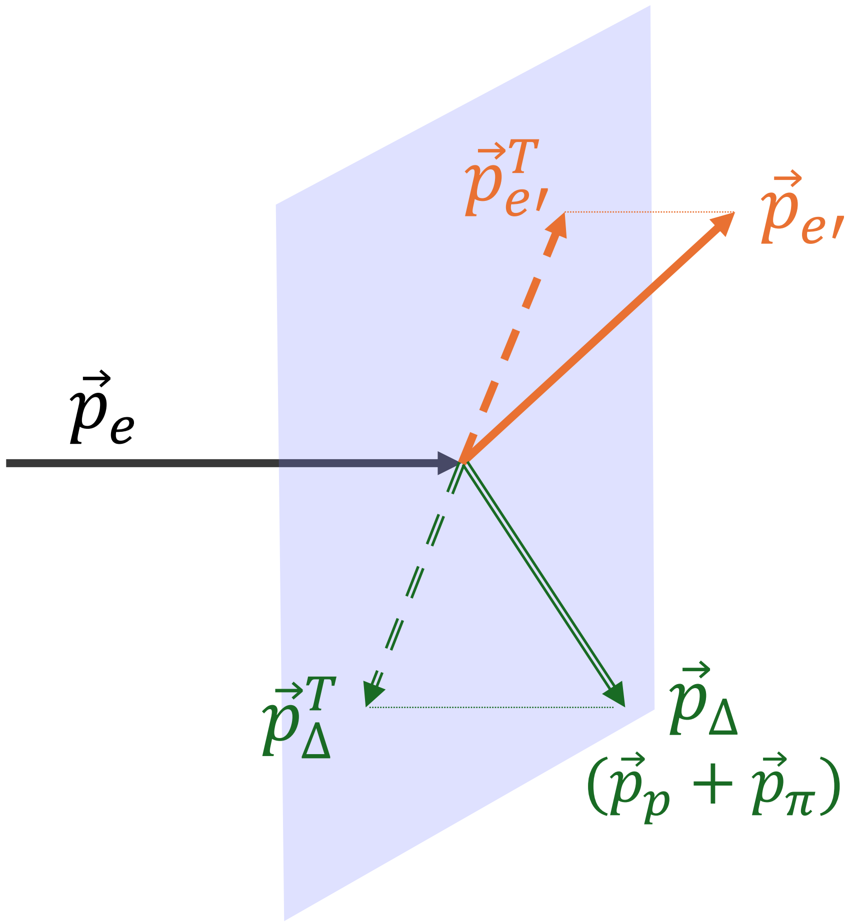
Includes a 5 % systematic from pion radiation
Propagated to the data systematics
Using smooth distributions

Pion production nuclear effects

Free nucleon

- No missing transverse momentum!

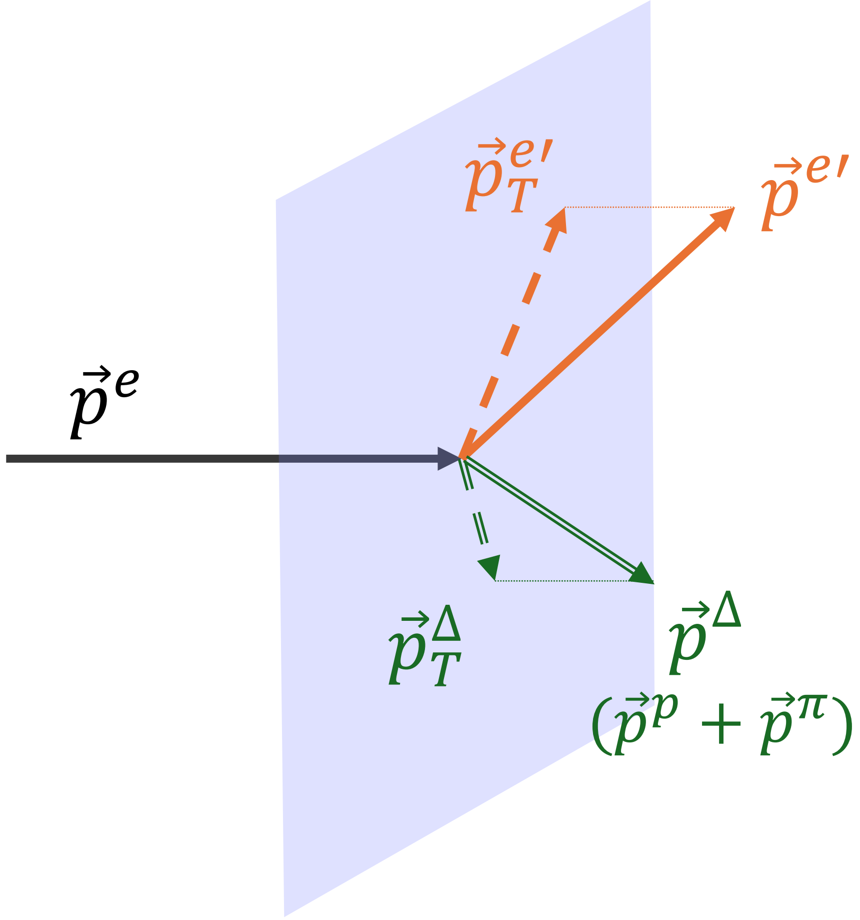
$$\delta\vec{p}_T = \left|\vec{p}_T^{\,e'} + \vec{p}_T^{\,\Delta}\right| = 0$$

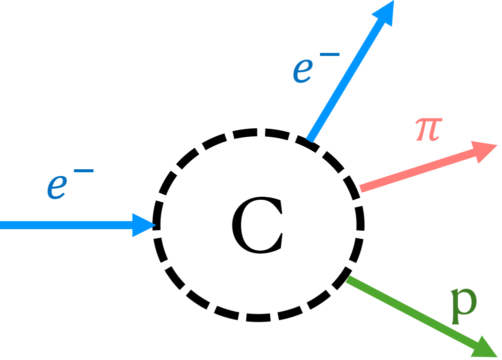


Pion production nuclear effects

Nucleus $\delta\vec{p}_T > 0$

- Nuclear structure
- Final state interactions



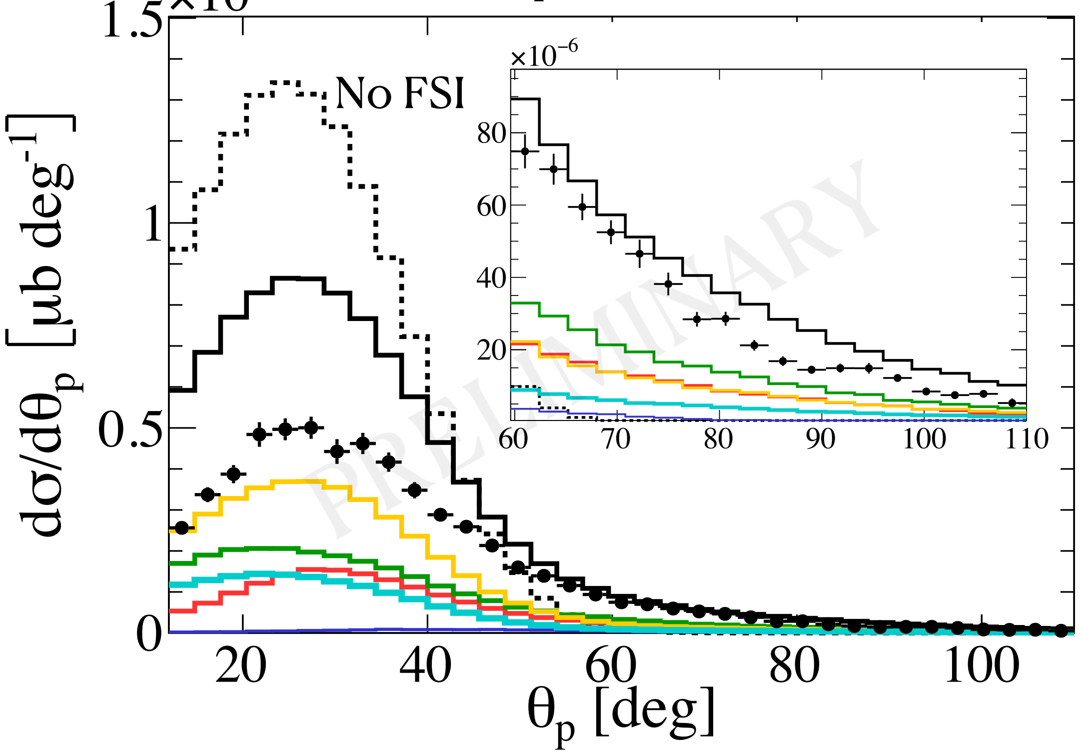


Hadron kinematics

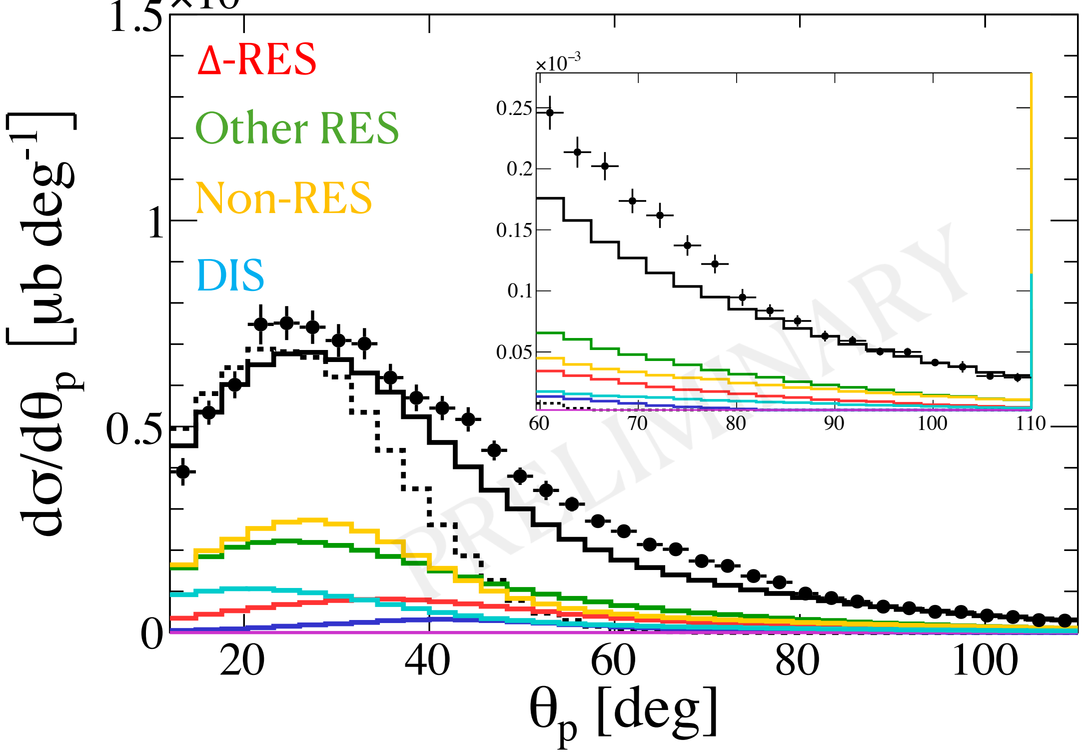
by Julia Tena Vidal

Good angular description for pions and protons

C(e,e'1p1π^-) @ 2.2 GeV

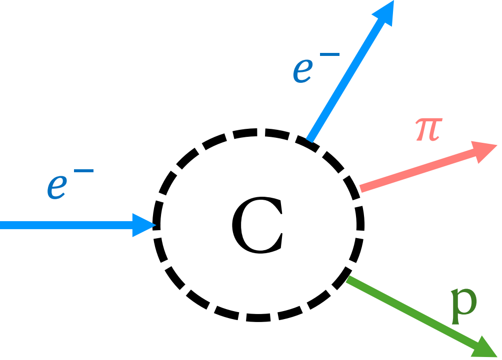


C(e,e'1p1π^+) @ 2.2 GeV



High θ_p possible only due to FSI

(e,e'1p1π^+) more sensitive to dynamics → more shape change due to FSI



Nuclear effects

by Julia Tena Vidal

Free nucleon

$$\delta\vec{p}_T = \left|\vec{p}_T^{\,e'} + \vec{p}_p + \vec{p}_\pi\right| = 0$$

Nucleus $\delta\vec{p}_T > 0$

- Nuclear structure
- Reaction mechanisms
- Final state interactions