Probing neutrino physics using A(e,e'pN) RGM data

Alon Sportes (alonsportes@mail.tau.ac.il)

Supervisor: Dr. Adi Ashkenazi

TEL AVIV UNIVERSITY

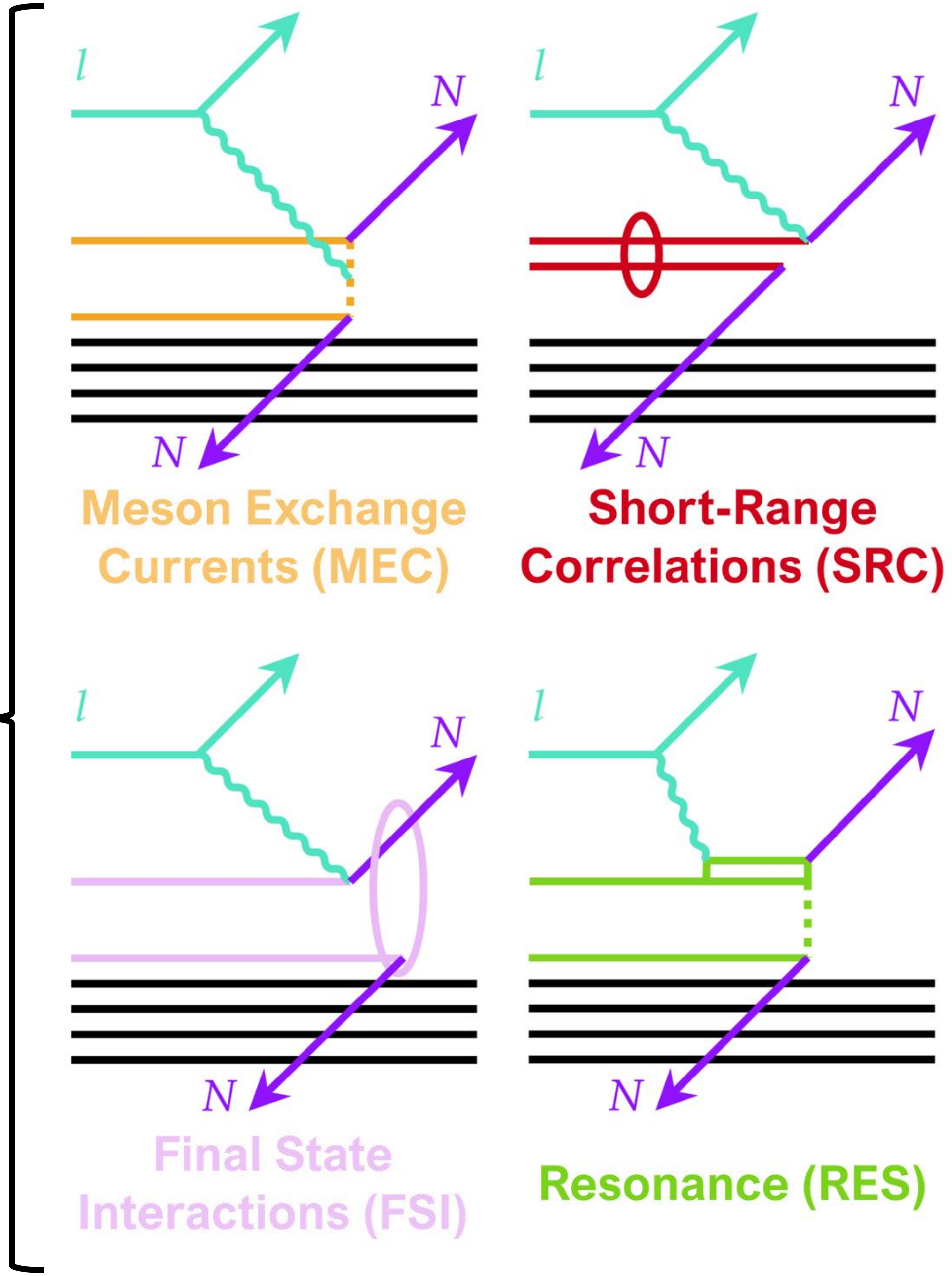
Motivation

The $e4\nu$ collaboration:

- **General:** constrain neutrino-nuclei interaction modeling using electron scattering data
- **This analysis:** two nucleon knockout

Why 2N?

- 1p reasonably well understood, quasielastic
- **2N – many reaction mechanisms**
  - Background to 1p
  - Not yet well-constrained
  - Neutron detection is hard

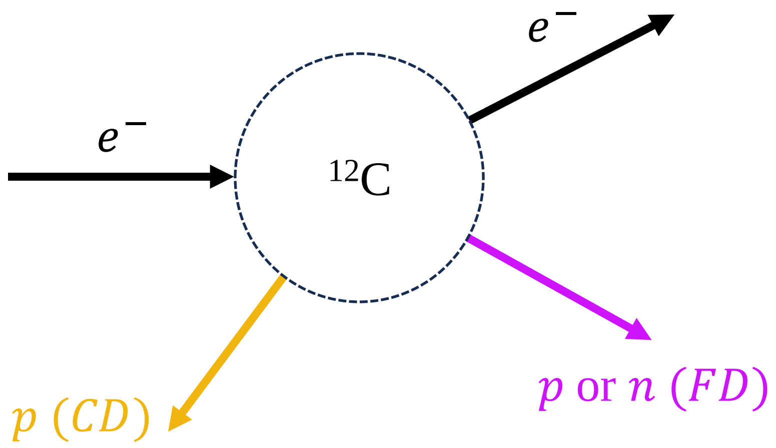


→ Compare 2p (or (e,e'pp)) and 1n1p (or (e,e'np)) topologies

Event selection

Signal selection:

- **2p:** one proton in the FD ($\equiv pFD$) and one in the CD ($\equiv pCD$)
- **1n1p:** *leading* neutron in the FD ($\equiv nFD$) and one proton in the CD ($\equiv pCD$)
  - Detect in ECAL, veto with PCAL
- No charged pions, photons; no limit on neutrons



Cuts:

- Identical proton and neutron acceptance cuts
- $\theta_{nucFD} \leq 32°$, $1 \leq P_{nucFD} \leq 2.5$ GeV/c ($nucFD = pFD, nFD$)

Corrections:

- MC-based:
  - Neutron momentum correction and resolution
  - Proton and neutron detection efficiencies
- Smearing proton momentum by neutron momentum resolution
- Applying weights based on efficiency maps

2N comparison in analysis

Ratio of 1n1p to 2p:

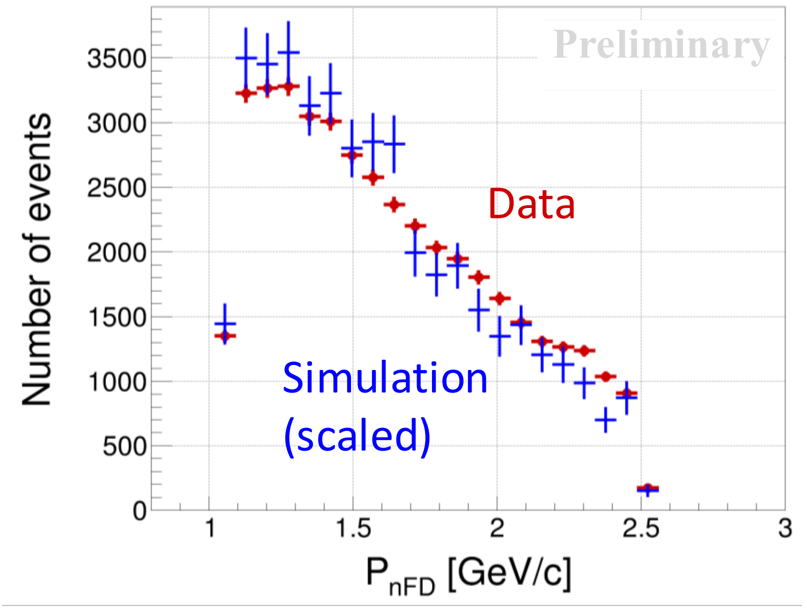
- 6 GeV ^{12}C data (run 015188)
- Compare to GENIE event generator
  - Simulates neutrino-nucleus interactions and can also simulate electron interactions
  - Reaction mechanisms – quasielastic, MEC, resonance, DIS
  - GENIE does not simulate SRC
- Understand 2N knockout mechanisms

Caveats:

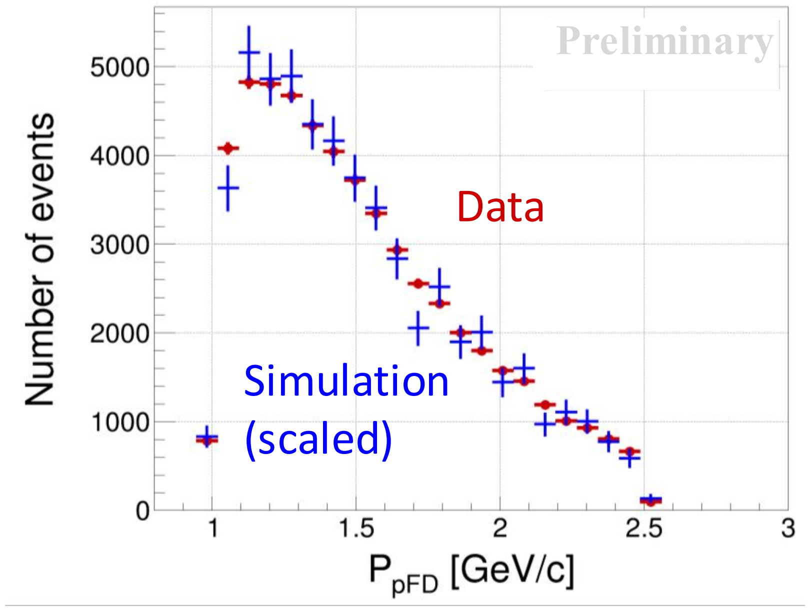
- Low statistics!
- **2N events (data):** 2p: 50K; 1n1p: 30K
  - 2p:1n1p $\neq$ 1 $\Rightarrow$ only ratio trend matters!

FD nucleon momenta

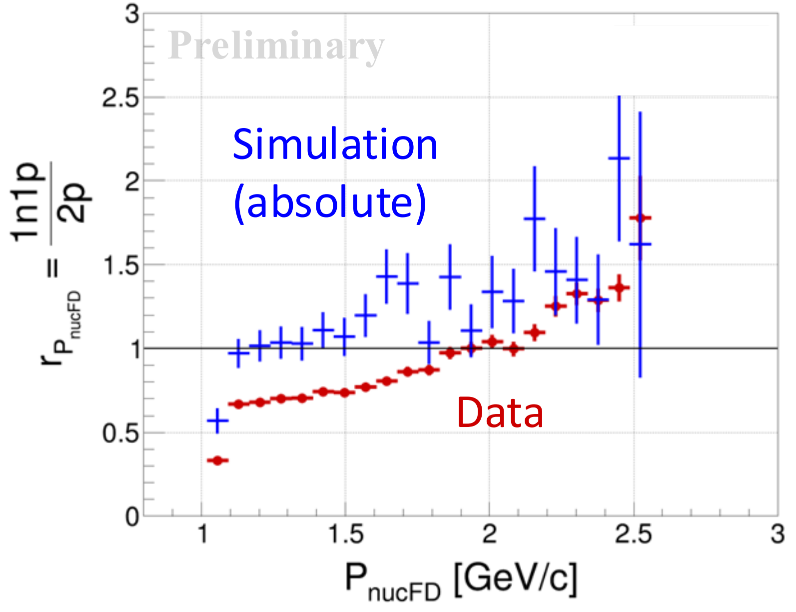
1n1p (shape only comparison)



2p (shape only comparison)



1n1p/2p ratio



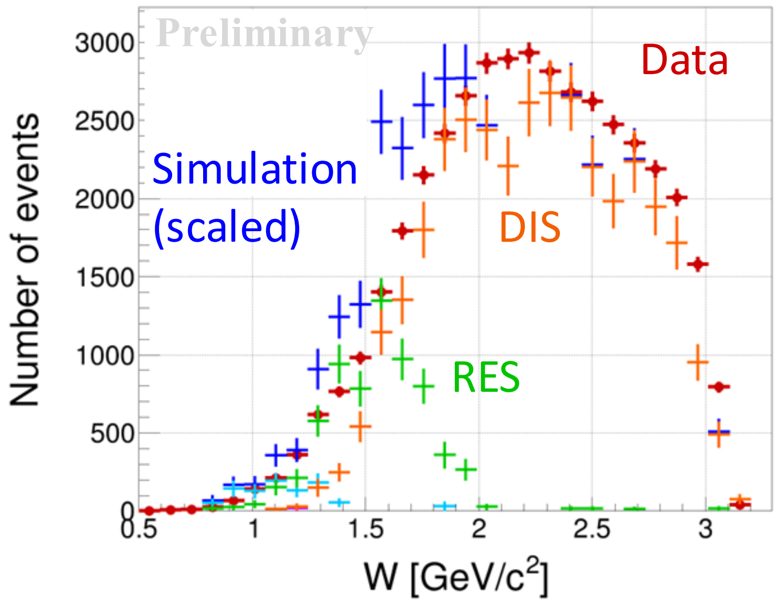
Great shape agreement
1n1p/2p ratio increases with nucleon momentum
Magnitude disagreement

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

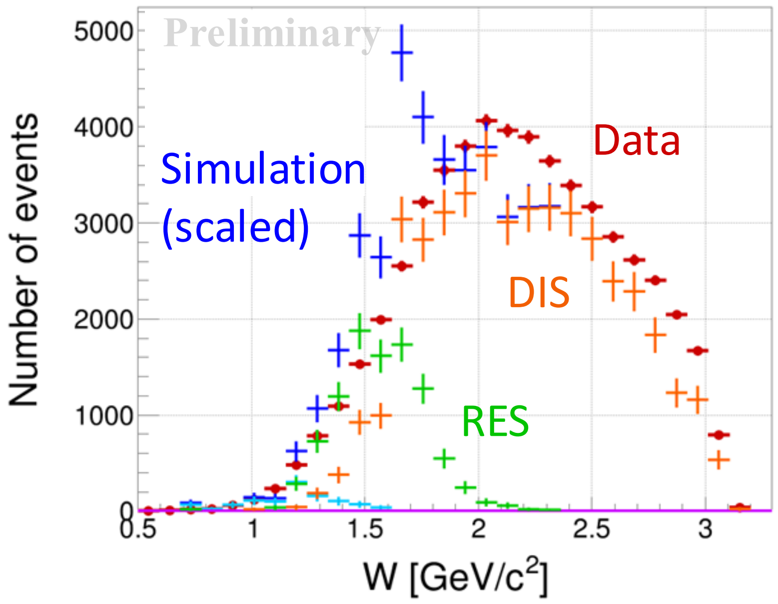
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Hadronic mass (W)

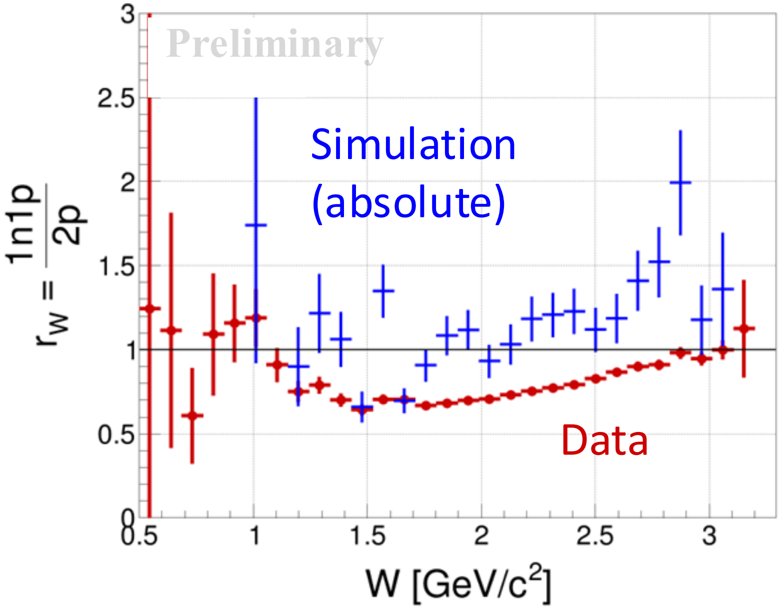
1n1p (shape only comparison)



2p (shape only comparison)



1n1p/2p ratio



Where:

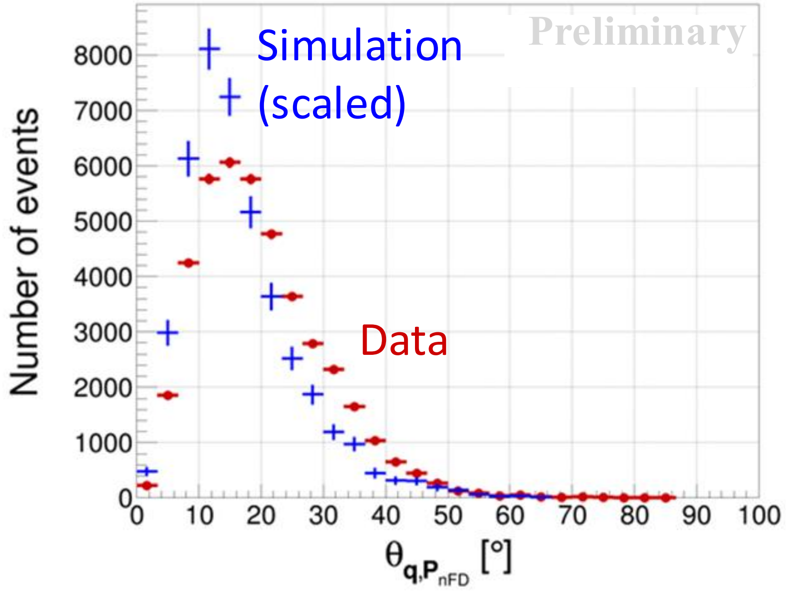
- $W = \sqrt{(\omega + m_p)^2 - |\boldsymbol{q}|^2}$
- $\boldsymbol{q} = \boldsymbol{P}_{beam} - \boldsymbol{P}_e$; m_p – proton mass; $\omega = E_{beam} - E_e$

Dominated by DIS and resonance
OK shape agreement
Ratio smaller for resonance

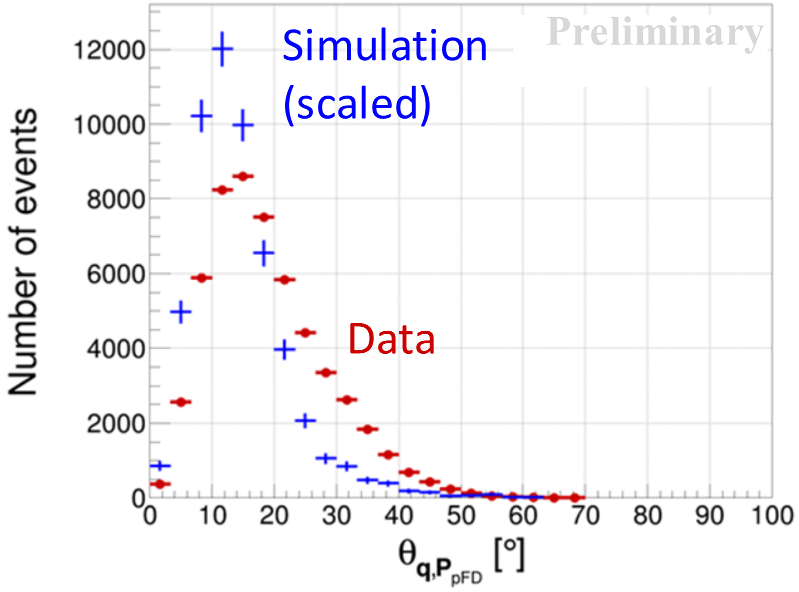
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Opening angle between q and P_{nucFD} ($\theta_{q,P_{nucFD}}$)

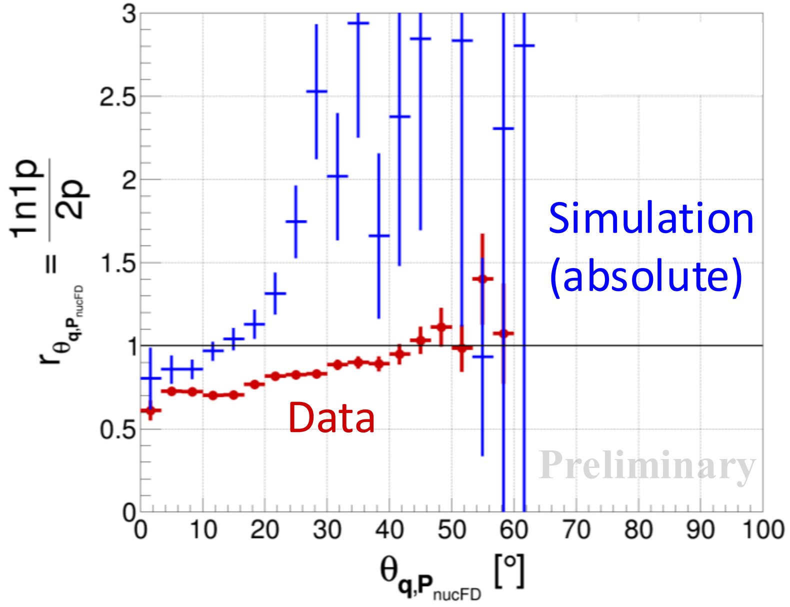
1n1p (shape only comparison)



2p (shape only comparison)



1n1p/2p ratio



1n1p is wider than 2p in simulation, not as much in the data
Data broader than simulation

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

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

Summary

- First analysis of 2N topologies for improving neutrino modeling

- Interesting differences between 2p and 1n1p data
- **Models sensitive to:**
  - Reaction mechanisms
  - Nuclear models
  - FSI

- **Future:**
  - Higher-statistics
  - More targets and energies
  - Measure neutron detection efficiency
  - Correct for undetected extra particles
  - Central detector neutron reconstruction

- Publish!

Backup

Reco cuts – particle identification

	Identify by…		Detector	Lower cut	Upper cut	Momentum threshold
e^-	Sampling Fraction (SF) cut		FD-ECAL	0.2	0.28	–
	#photo-electrons (N_{phe}) cut		FD-HTCC	2	–	
	β cut		FD	–	1.2	
	ECAL edge (V & W coordinates) cut		FD-PCAL	14 cm	–	
p	χ^2 cut		CD & FD	$-3\sigma_{CD/FD}$	$3\sigma_{CD/FD}$	400 MeV/c
	Fake protons handling	Identical CTOF hit position veto	CD-CTOF	–	–	
		Double detection in CD & FD veto	CD & FD			
$\pi^\pm$	χ^2 cut		CD & FD	$-3\sigma_{CD/FD}$	$3\sigma_{CD/FD}$	200 MeV/c
n	**Neutron definition:** neutrons and/or "photons" (i.e., PDG of 2112 or 22), without a PCAL hit and with ECIN and/or ECOUT hit		FD-ECAL	–	–	400 MeV/c & upper th. is E_{beam}/c
	Neutron ECAL veto: cut on the distance to charged particle's track		FD-ECAL	100 cm	–	
γ	**Photon definition:** photons (according to the PDG) with a PCAL hit		FD-ECAL	–	–	300 MeV/c

Reco cuts – event selection

About samples:

- **Target & beam energy:** ^{12}C (4-foil) at ~6 GeV
- **MC simulation:** GENIE; G18_02a_00_000; 24M events
- **Date:** RG-M data; run 015188

Preselection cuts: in the top table.

Event selection procedure: in the bottom table.

Preselection cut	Detector	Lower cut	Upper cut
V_z^{part} (only charged particles)	FD	-8 cm	3 cm
	CD	-7 cm	2 cm
Vertex correlation (dV_z) between V_z^{part} and V_z^e	–	-5 cm	4 cm
DC edge	DC (FD)	10 cm	–

2p	1n1p
PID (previous slide)	
One id.* electron	
No other id. charged hadrons	
Any number of: neutrals in the CD & particles with pdg = 0	
No id. FD photons (no FD photons or π^0)	
Any number on FD neutrons	
One id. Proton ∈ FD & another ∈ CD	*Leading* id. Neutron ∈ FD & one proton ∈ CD
Accounting for detector effects	

*id. particle = particle that passes PID and above mom. th.

Truth-Level (LT) cuts

Momentum thresholds: like reco cuts - see upper table.

Angle association: $5° \leq \theta \leq 40° \Longrightarrow$ FD particle; $40° \leq \theta \leq 135° \Longrightarrow$ CD particle

Efficiency calculation:

$$\epsilon_{eff} = \frac{\text{rec. variable}[(\text{Rec. cuts}) + (\text{TL cuts})]}{\text{TL variable}[(\text{TL cuts})]}$$

Event selection: bottom table.

	Momentum threshold
e^-	-
p	0.4 GeV/c
$\pi^\pm$	0.2 GeV/c
π^0	About 0.58 GeV/c*
n	0.4 GeV/c to E_{beam}/c
γ	0.3 GeV/c

		2p	**1n1p**
Number of id. proton in the FD		One id. proton	None
Number of id. proton in the CD		One id. proton	One id. proton
Forward-going neutrons	Number of id. neutrons in the FD	Any number of id. neutrons	
	Status in analysis	All of them are ignored	Looking only at the leading neutron
Constraints on other particles		A single electron	
		No id. charged pions	
		No id. π^0 in the FD	
		No id. γ in the FD	
		No other particles whatsoever	

*From direct calculation using the photon's momentum threshold.

Accounting for detector effects

Initial selection: 2p and 1n1p selection (slides 10 & 11)

Additional selection via FD nucleon vetoes (*by order*):

- **FD proton (2p):**
  1. *Fiducial cuts*: taking good detection regions for pFD and nFD using generated acceptance maps
  2. *Proton smearing*: momentum smearing by neutron resolution according to linear fit to resolution width.
  3. *Kinematical cuts*: after smearing, to look at regions with the highest efficiency:

$$\theta_{nucFD} \leq 32° \text{ and } 1 \leq P_{nucFD} \leq 2.5 \text{ [GeV/c]}$$

- **FD neutron (1n1p):**
  1. *Kinematical cuts*
  2. *Neutron momentum correction*: according to linear fit to resolution mean.
  3. *Kinematical cuts*
  4. *Fiducial cuts:* taking good detection regions for pFD and nFD using generated acceptance maps

Applying weights: surviving events were weighted by the acceptance & efficiency of the FD nucleons. Weights were calculated with:

- **2p:** pFD momentum *before* smearing
- **1n1p:** nFD momentum *after* correction

2N analysis – goal and event selection

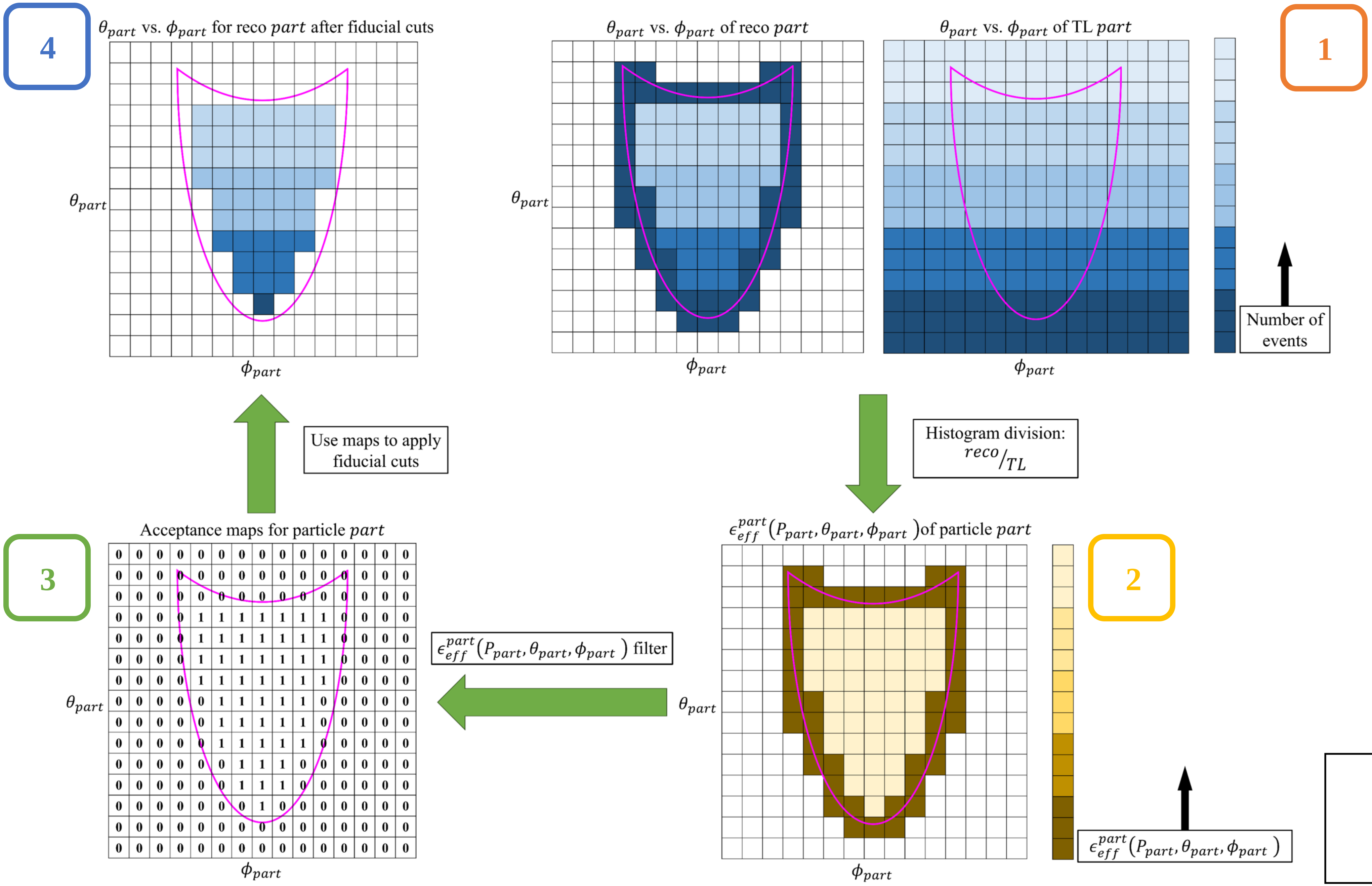
Goal: comparing **2p** and **1n1p**

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	
π^0		FD	None	No neutral pions (applied through photons)	
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

Fiducial cuts application

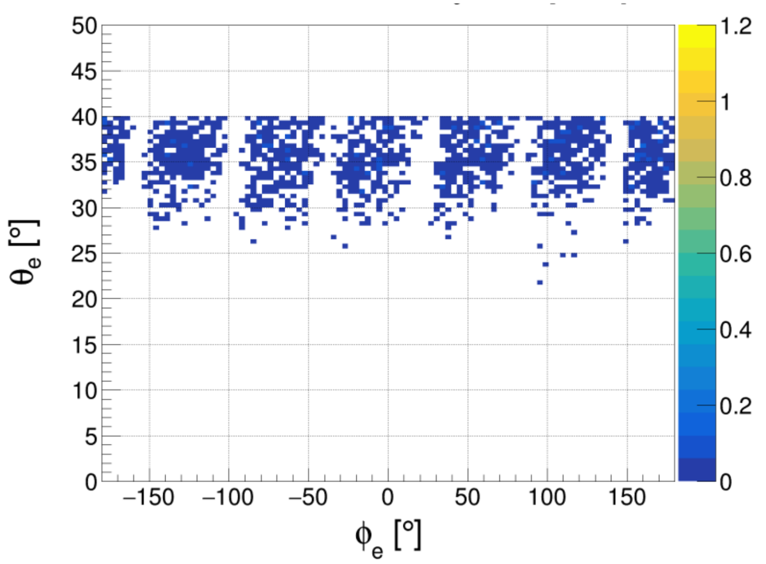


0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	1	1	1	1	1	1	0	0	0	0
0	0	0	0	1	1	1	1	1	1	1	0	0	0	0
0	0	0	0	1	1	1	1	1	1	1	0	0	0	0
0	0	0	0	1	1	1	1	1	1	1	0	0	0	0
0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

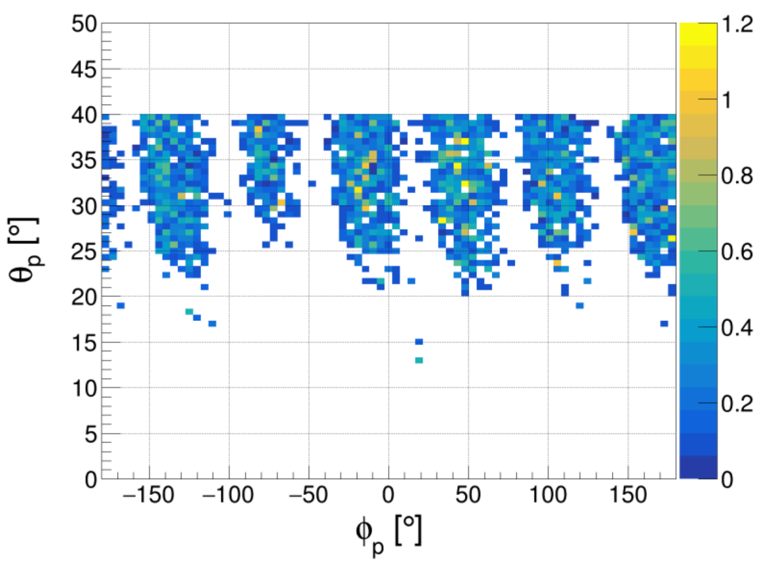
Back

Acceptance efficiency – results*

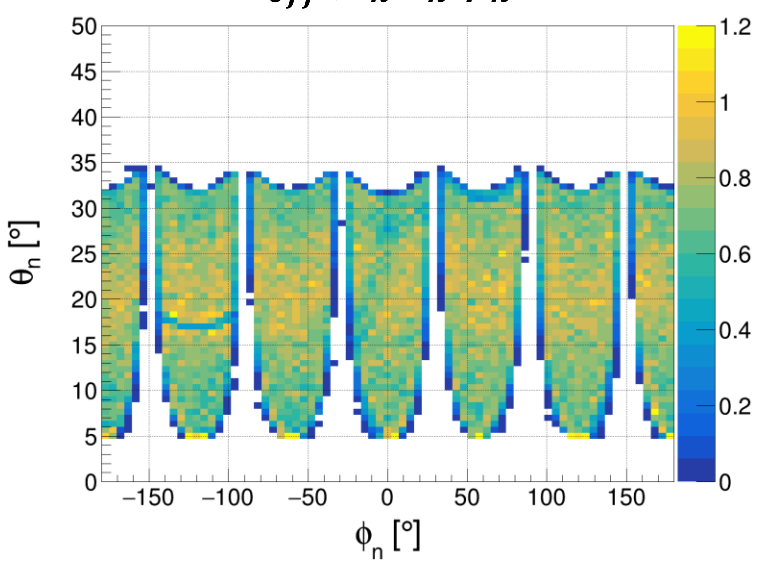
Electron $\epsilon_{eff}(P_e, \theta_e, \phi_e)$



FD protons $\epsilon_{eff}(P_p, \theta_p, \phi_p)$



Leading FD neutron $\epsilon_{eff}(P_n, \theta_n, \phi_n)$



Acceptance efficiency definition:

$$\epsilon_{eff}^{part}(P_{part}, \theta_{part}, \phi_{part}) = \frac{\text{Reco } \theta_{part} \text{ vs. } \phi_{part} \text{ histogram of particle } part}{\text{Truth } \theta_{part} \text{ vs. } \phi_{part} \text{ histogram of particle } part}$$

$part = e, p, n$

P_{part} – corresponds to the momentum slice

Back

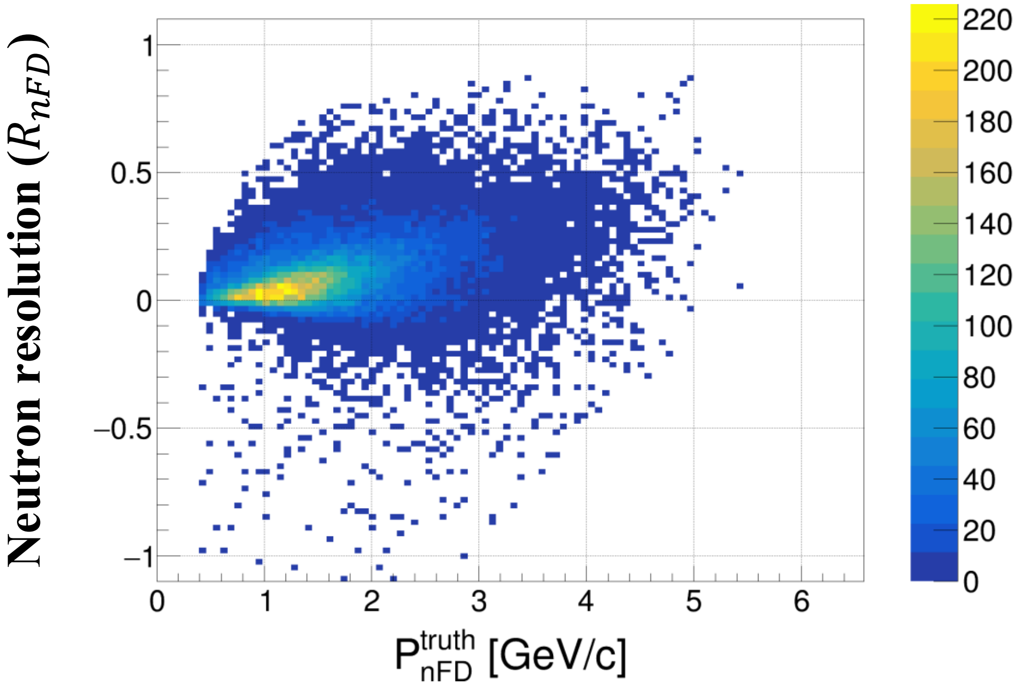
*based of events with a single reconstructed electron

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

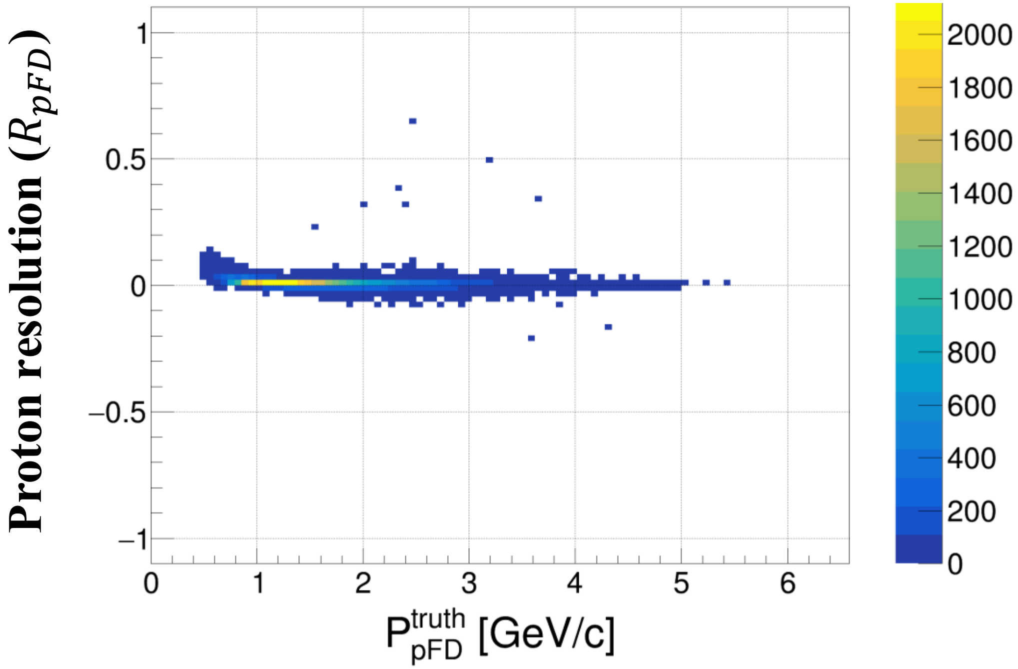
^{12}C simulation at $E_{beam} \simeq 6$ GeV

CLAS12 – nucleon momentum resolution in the FD

Neutron resolution vs. P_{nFD}^{truth} for 1n



Proton resolution vs. P_{pFD}^{truth} for 1p



Resolution (R_{part}) definition:

$$R_{part} = \frac{P_{part}^{truth} - P_{part}^{reco}}{P_{part}^{truth}}$$

$part = pFD, nFD$

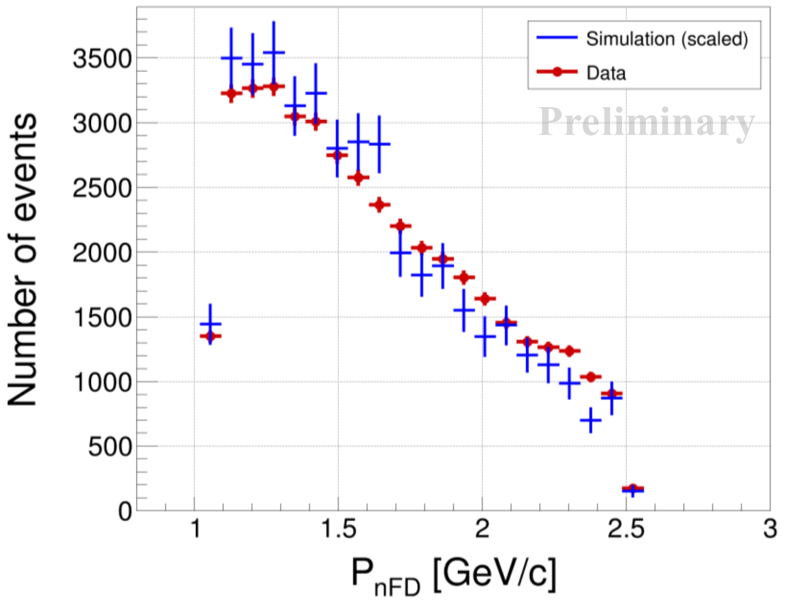
Back

Color axis = number of events

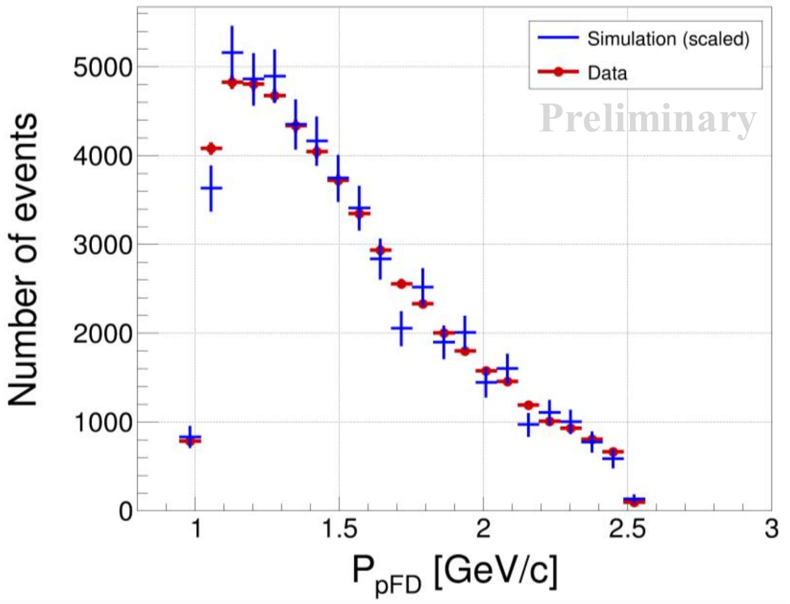
^{12}C simulation at $E_{beam} \simeq 6$ GeV

FD nucleon momenta – zoom-out

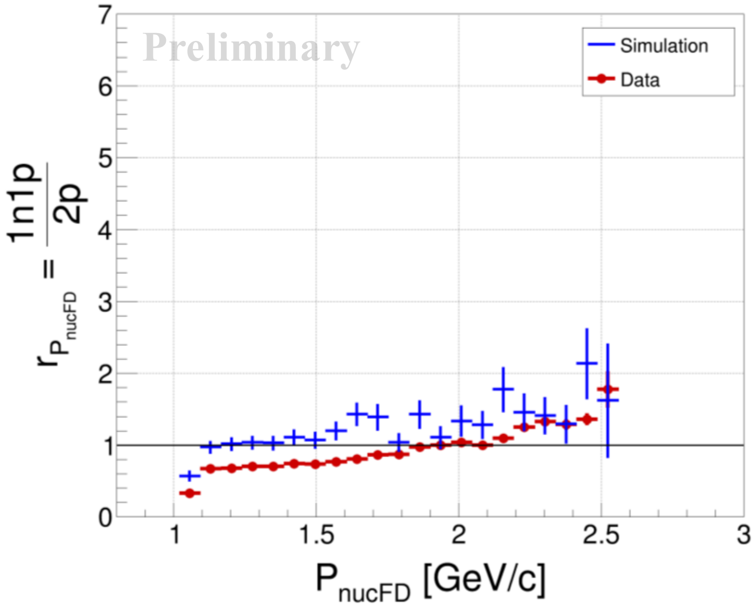
FD neutron momentum in 1n1p



FD proton momentum in 2p



FD nucleon momentum ratio



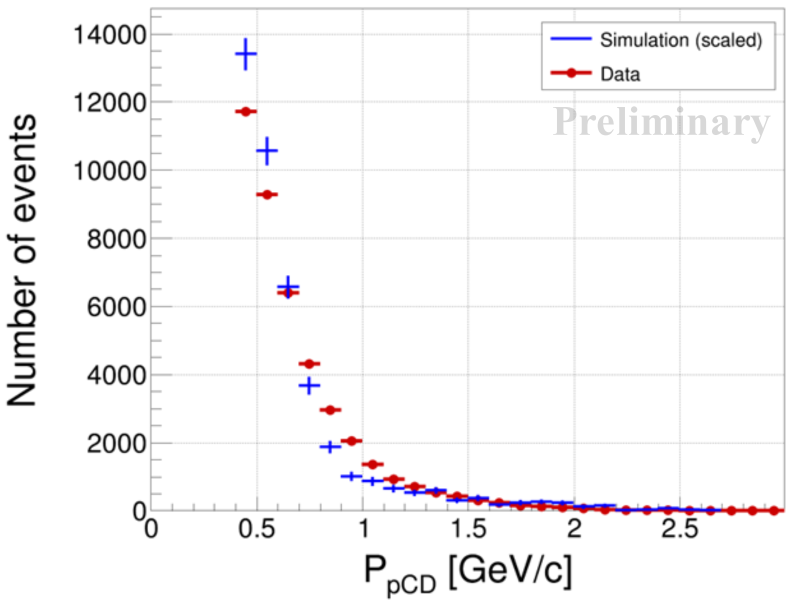
Back

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

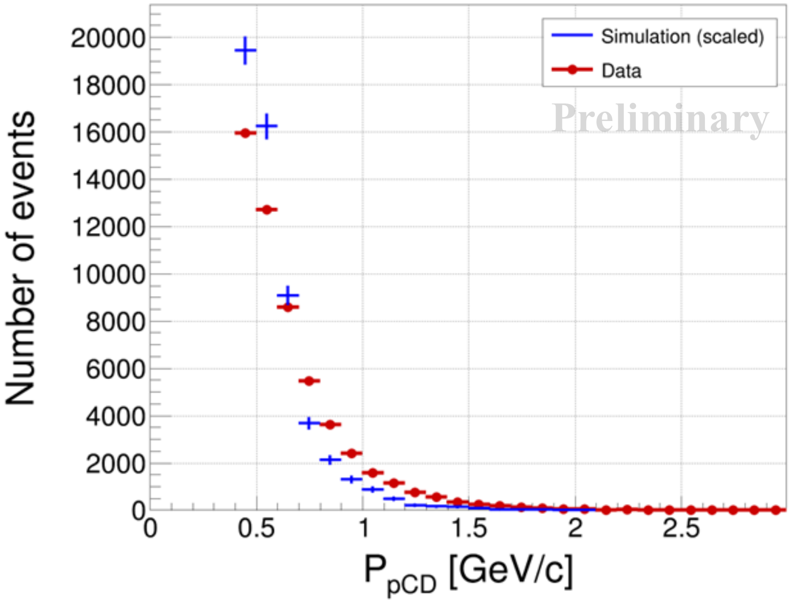
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

CD proton momenta – zoom-out

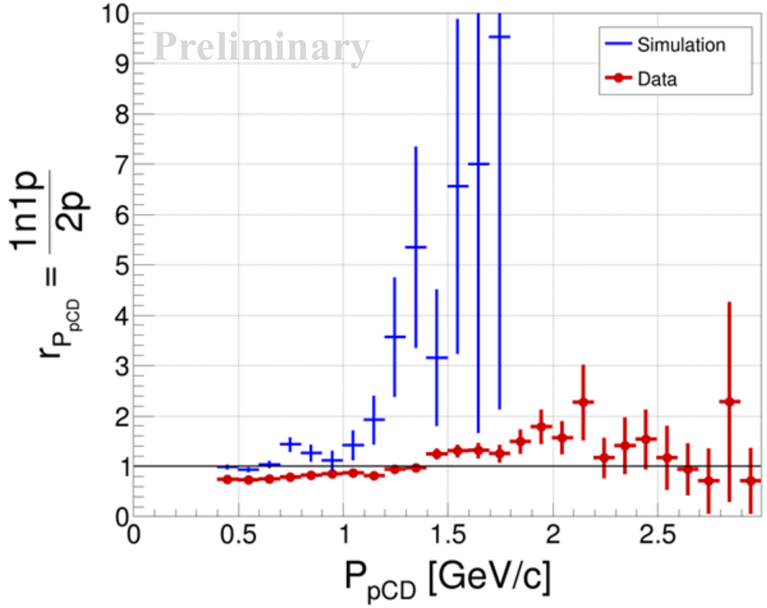
CD proton momentum in 1n1p



CD proton momentum in 2p



CD proton momentum ratio

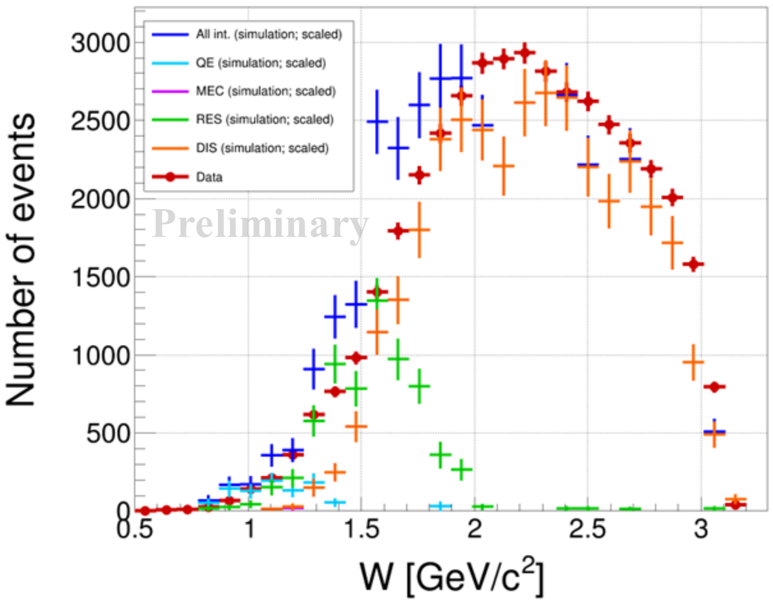


Back

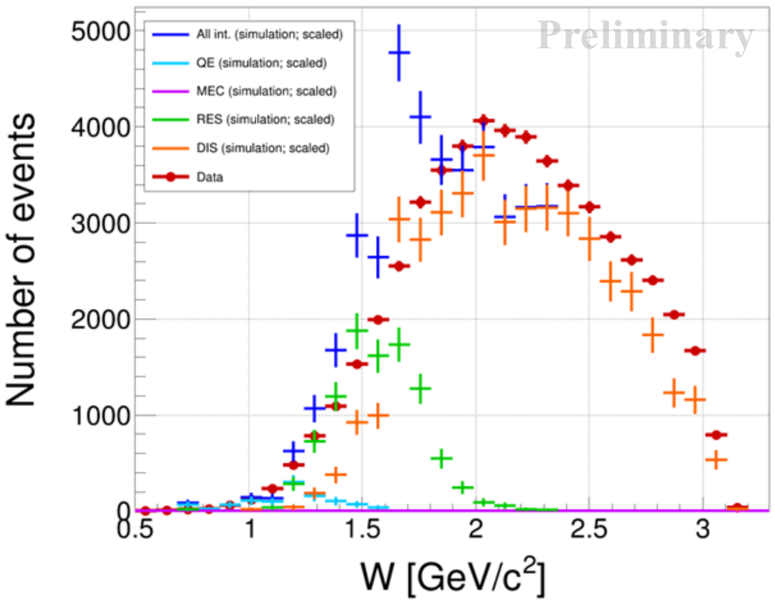
pCD = CD proton

Hadronic mass – zoom-out

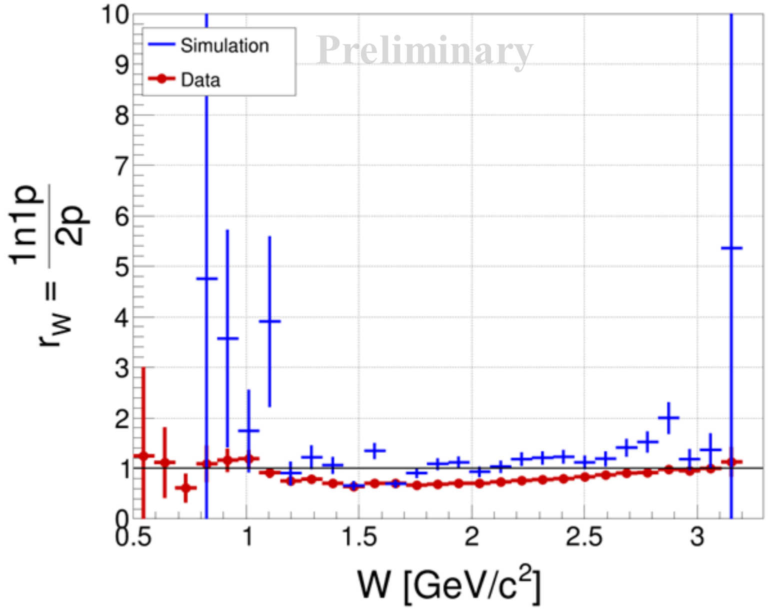
W **in 1n1p**



W **in 2p**



W **distribution ratio**



Where:

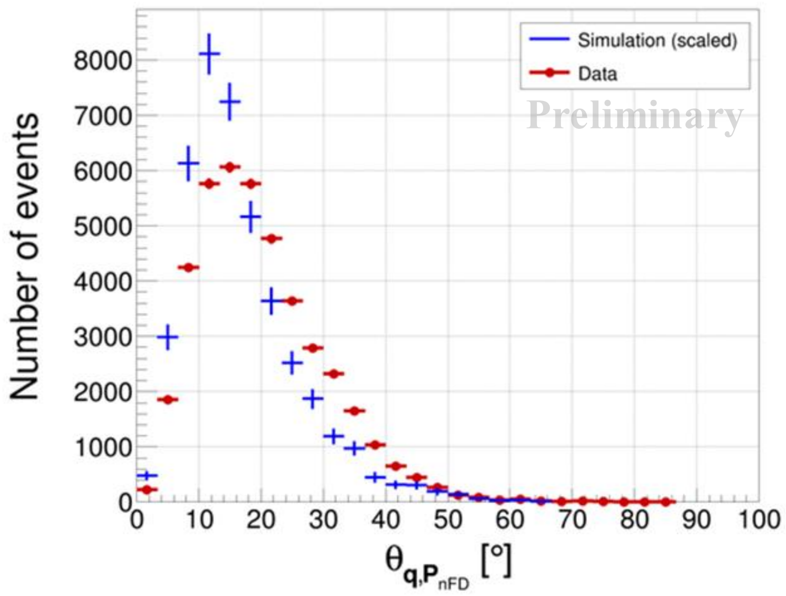
- $W = \sqrt{\left(\frac{\omega}{c^2} + m_p\right)^2 - \frac{|\boldsymbol{q}|^2}{c^2}}$
- $\boldsymbol{q} = \boldsymbol{P}_{beam} - \boldsymbol{P}_e$; $m_p -$ proton mass; $\omega = E_{beam} - E_e$

Back

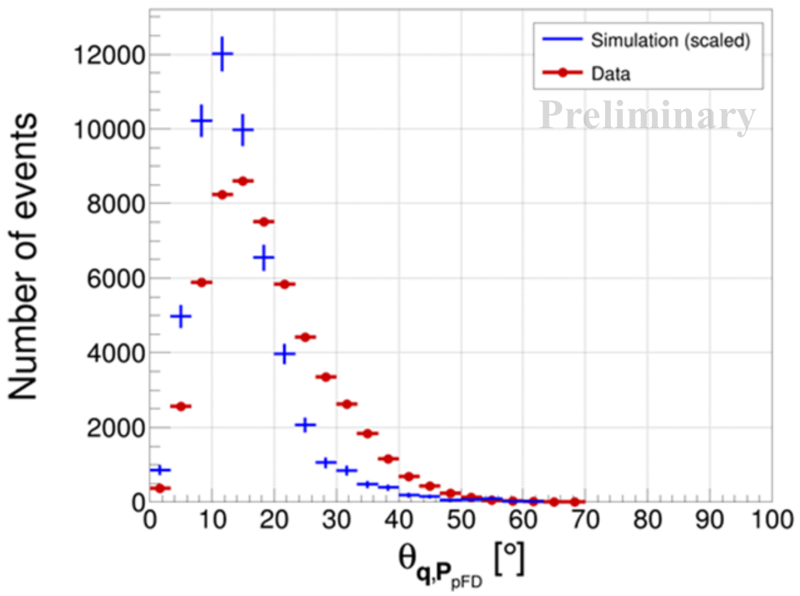
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Opening angle between q and P_{nucFD} ($\theta_{q,P_{nucFD}}$) – zoom-out

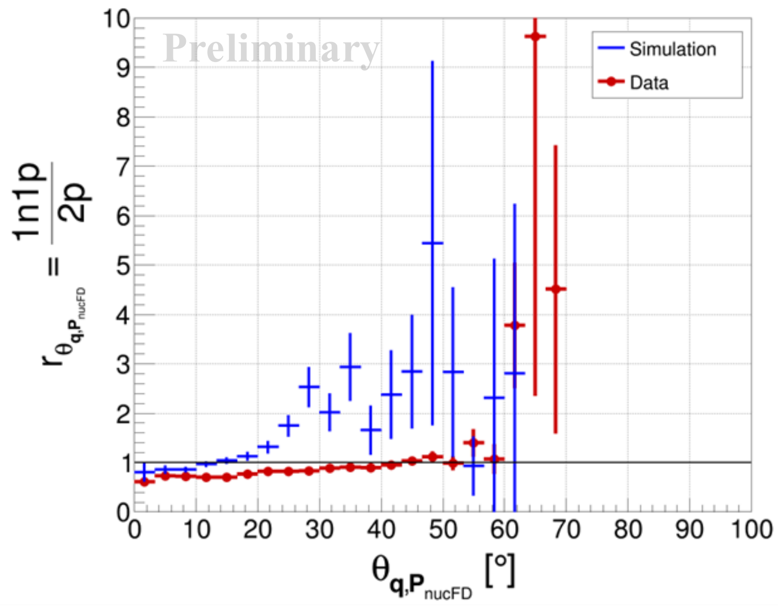
$\theta_{q,P_{nFD}}$ in 1n1p



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



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



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

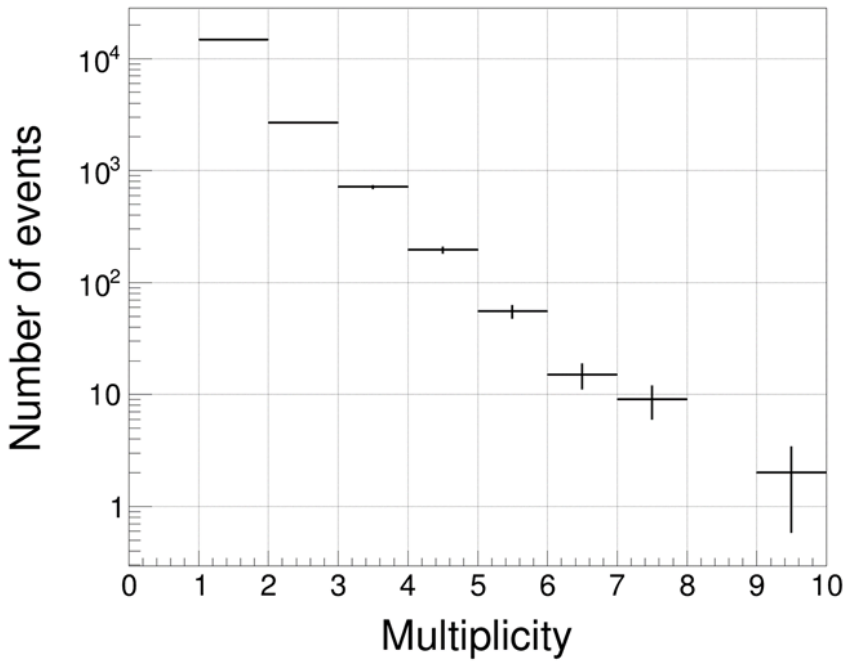
Back

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

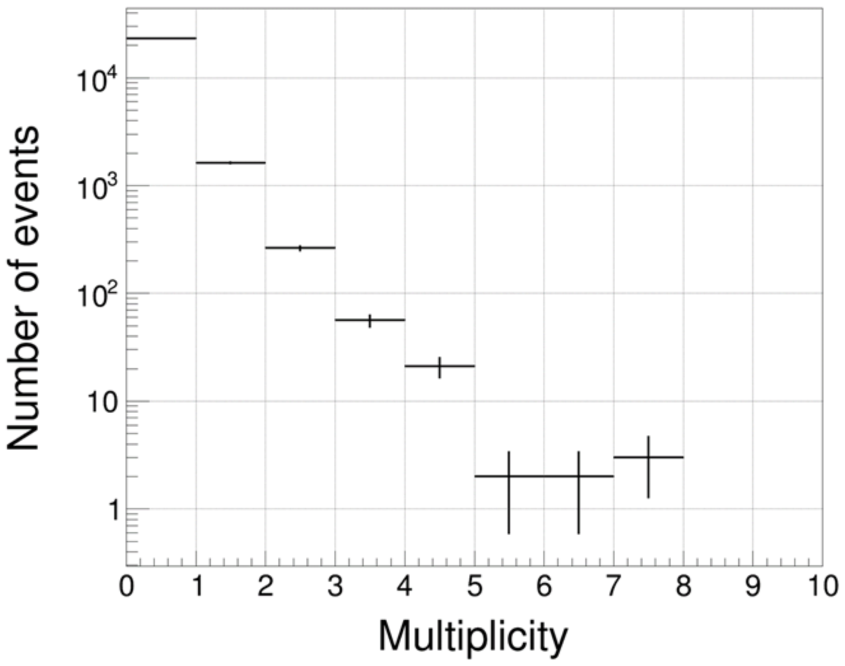
[12]C simulation and data at $E_{beam} \simeq 6$ GeV

FD neutron multiplicity

Multiplicity of FD neutrons in 1n1p



Multiplicity of FD neutrons in 2p



Contributions from higher multiplicity:

- **In 2p (multiplicity $\neq 0$):** $\approx$7.8% of 2p events
- **In 1n1p (multiplicity > 1):** $\approx$20% of 1n1p events

Back to: "Event selection & additional constraints"

Back to: "2N analysis – goal and event selection"

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

GENIE models

GENIE tune: G18_02a_00_000

Models: see table

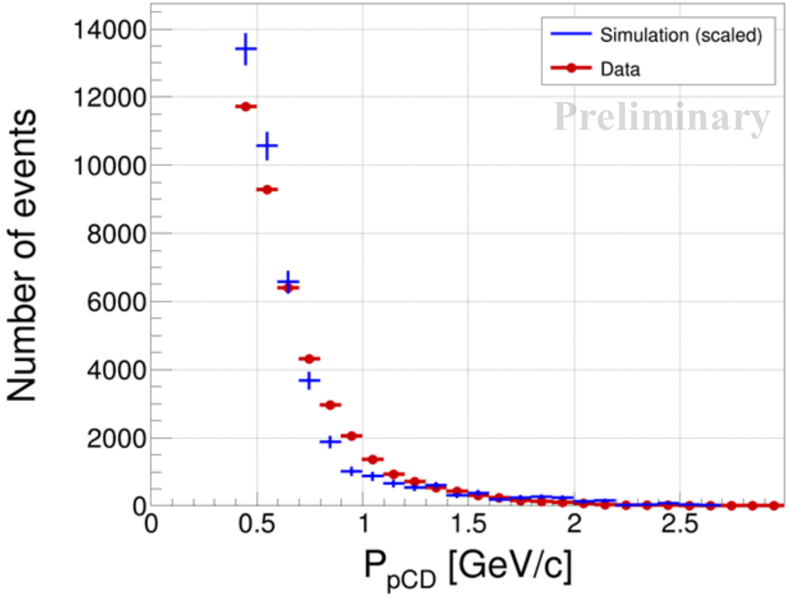
Nucler model		Local Fermi gas
Reaction mechanisms	**Quasielastic**	Rosenbluth
	MEC	Empirical MEC
	Resonance	Berger-Sehgal
	DIS	Bodek-Yang
FSI		hA

Back to:
"2N comparison in analysis"

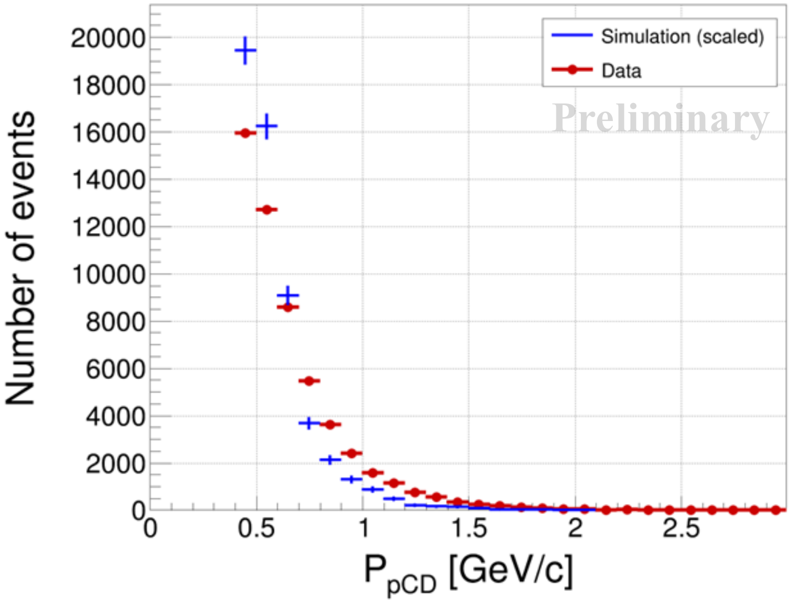
^{12}C simulation at $E_{beam} \simeq 6$ GeV

CD proton momenta

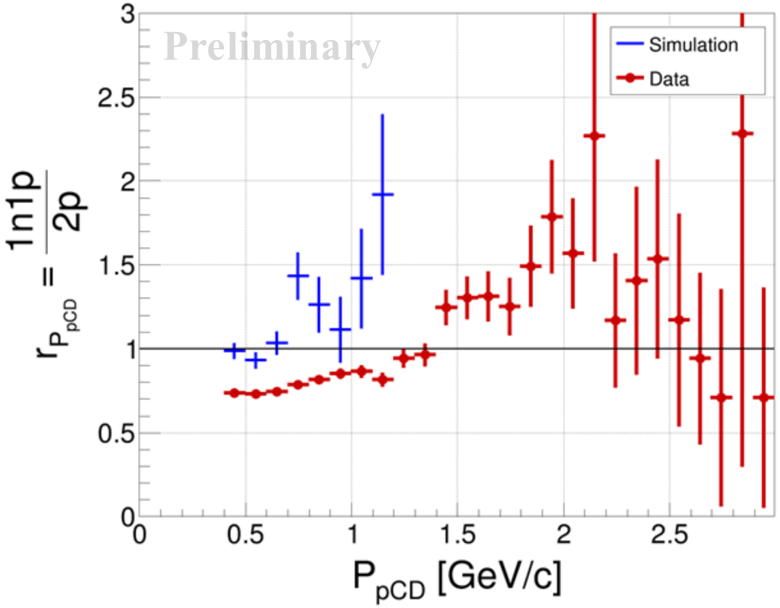
CD proton momentum in 1n1p



CD proton momentum in 2p



CD proton momentum ratio

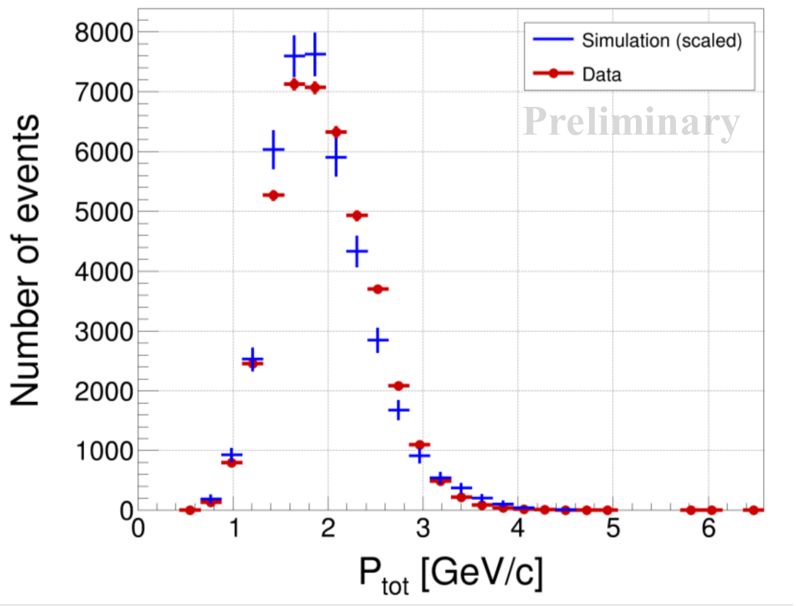


pCD = CD proton

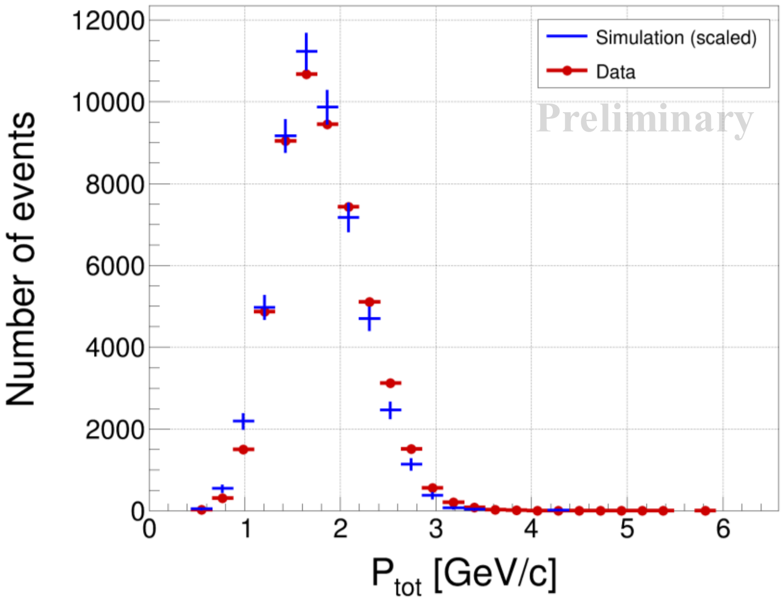
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Total nucleon momentum (P_{tot})

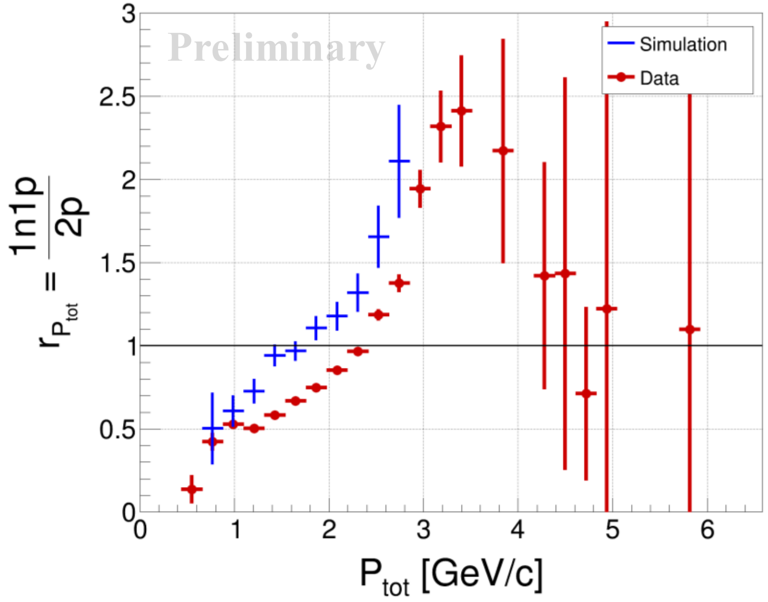
P_{tot} in 1n1p



P_{tot} in 2p



P_{tot} distribution ratio



Where:

- $P_{tot} = P_{nucFD} + P_{pCD}$

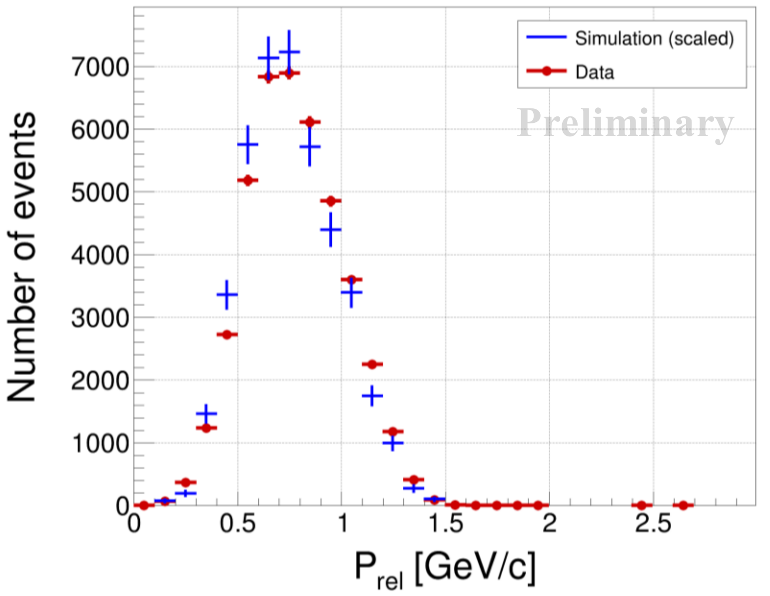
Zoom-out

$nucFD$ = FD nucleon

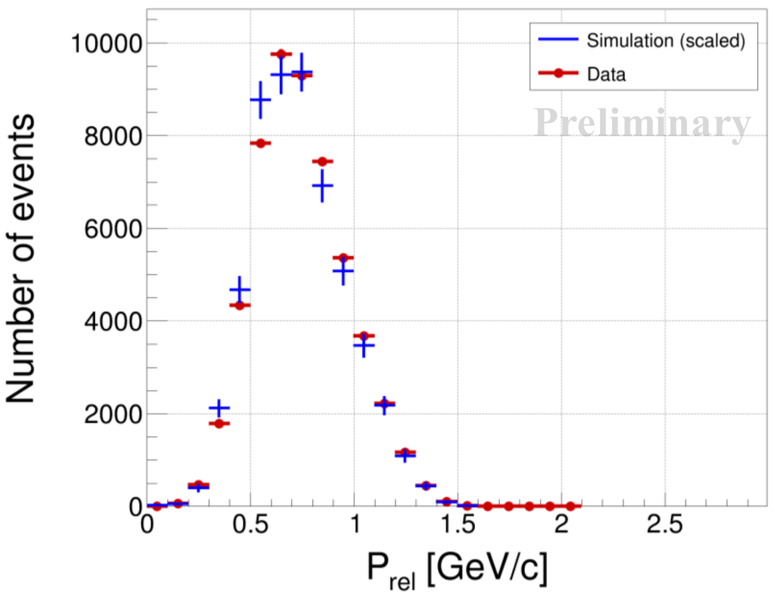
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Relative nucleon momentum (P_{rel})

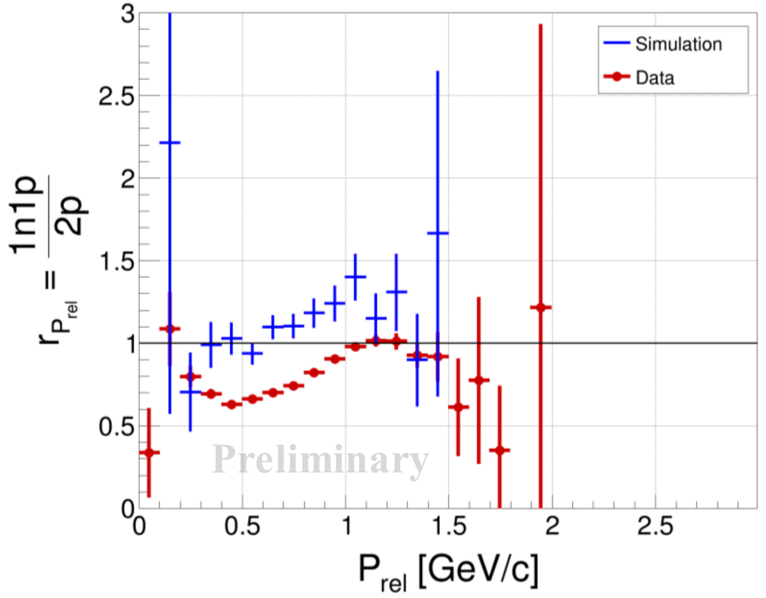
P_{rel} in 1n1p



P_{rel} in 2p



P_{rel} distribution ratio



Where:

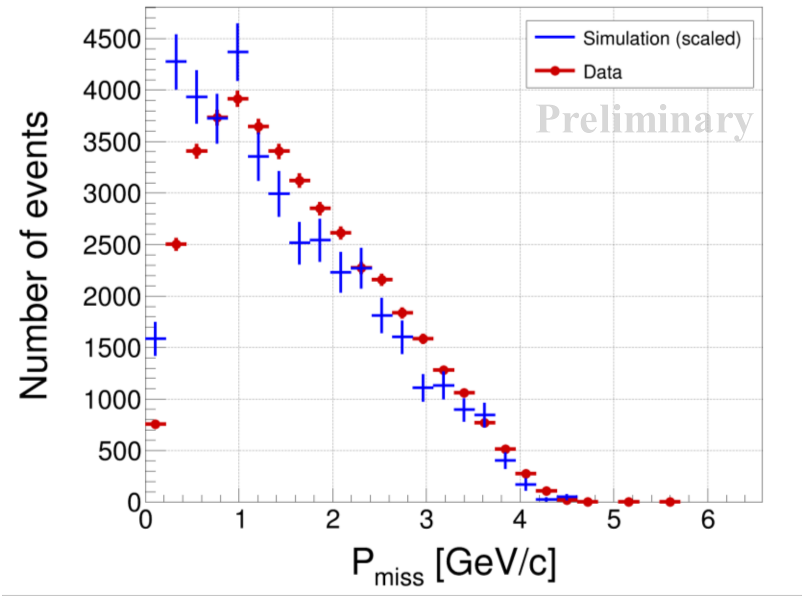
- $\boldsymbol{P_{rel}} = (\boldsymbol{P_1} - \boldsymbol{P_2})/2$
- $\boldsymbol{P_1}$ ($\boldsymbol{P_2}$) is the leading (sub-leading) nucleon

Zoom-out

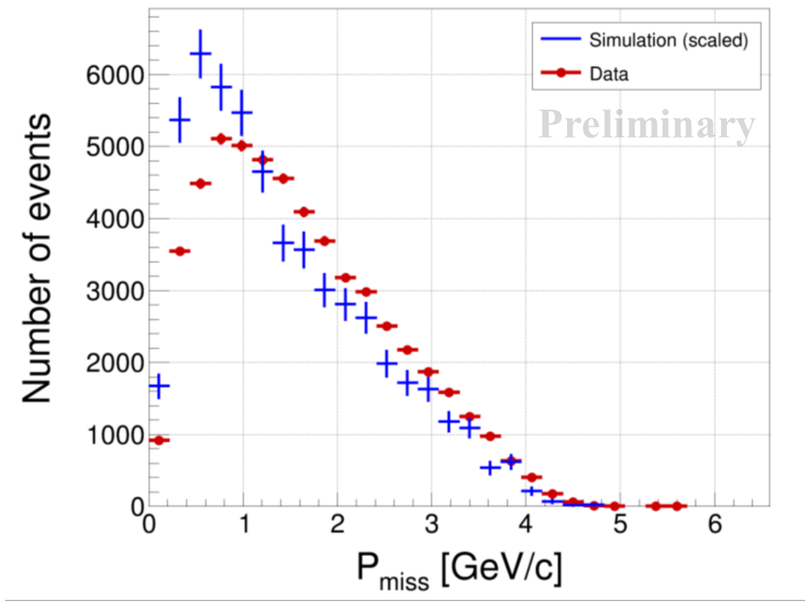
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Missing momentum (P_{miss})

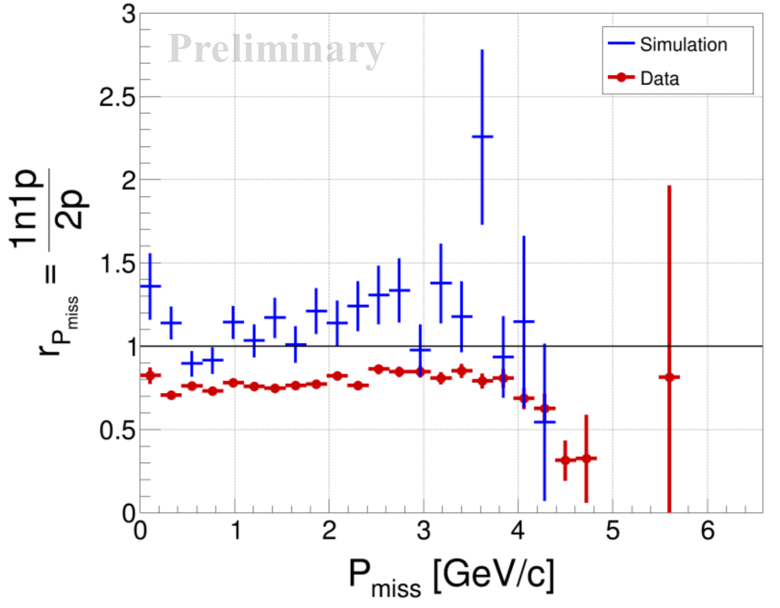
P_{miss} in 1n1p



P_{miss} in 2p



P_{miss} distribution ratio



Where:

- $P_{miss} = P_{tot} - q$
- $q = P_{beam} - P_e$

Zoom-out

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

Hadronic mass illustration in 1n1p

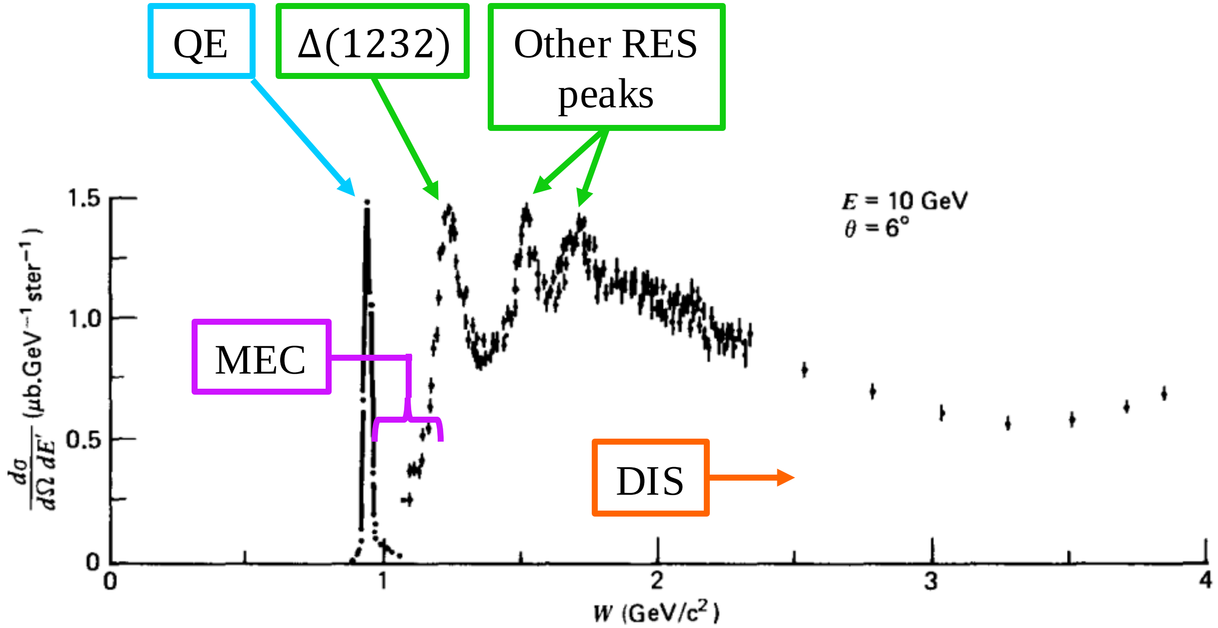
Hadronic mass (*W*):

$$W = \sqrt{\left(\frac{\omega}{c^2} + m_p\right)^2 - \frac{|\boldsymbol{q}|^2}{c^2}}$$

ω – energy transfer

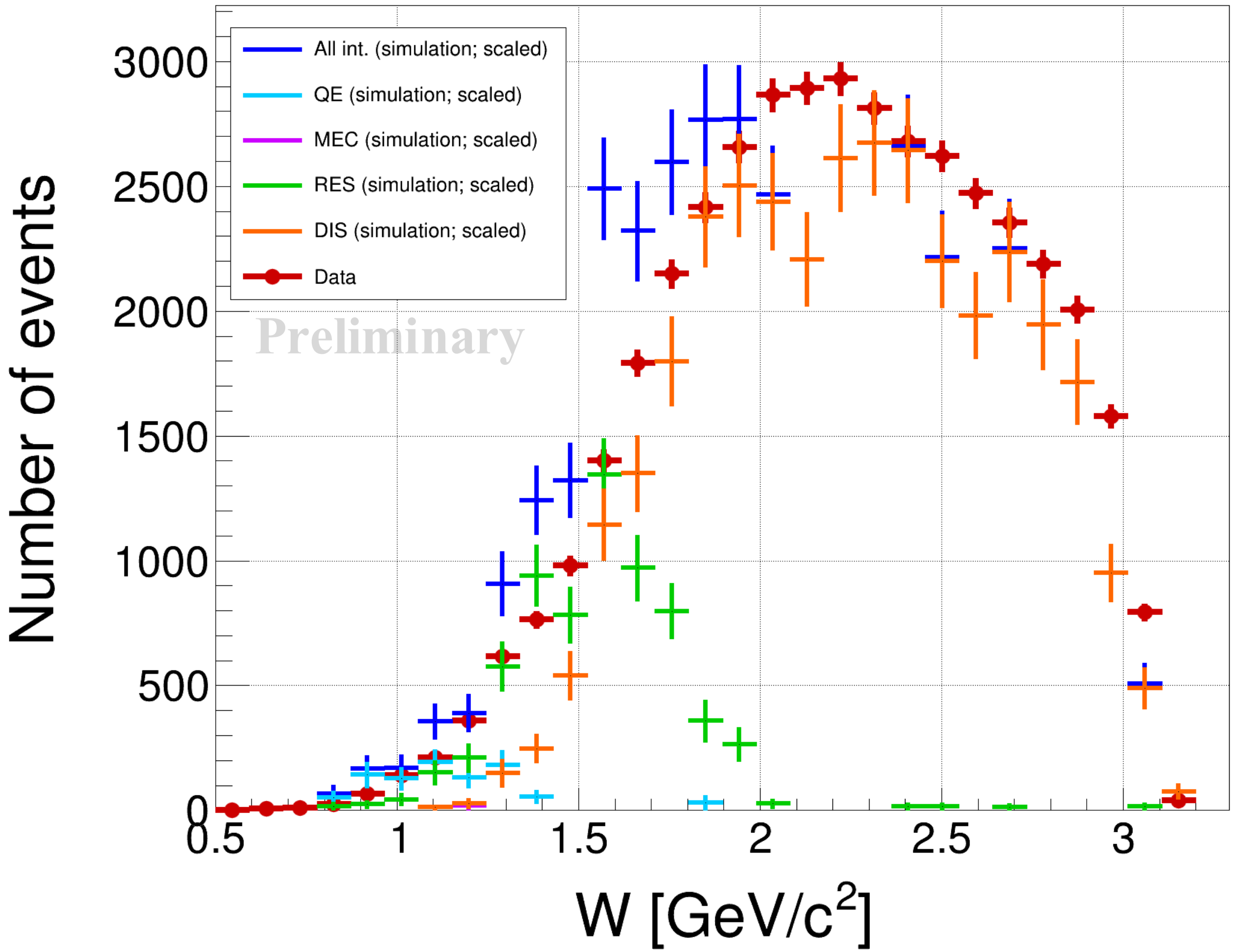
m_p – proton mass

$\boldsymbol{q}$ – three-momentum transfer



Halzen, F., & Martin, A. D. (1984). Quarks and Leptons: An Introductory Course in Modern Particle Physics

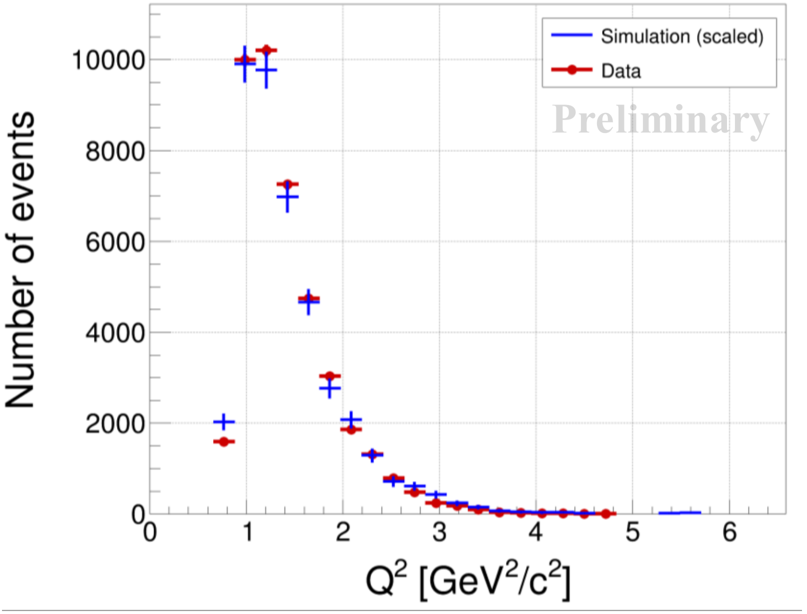
W in 1n1p



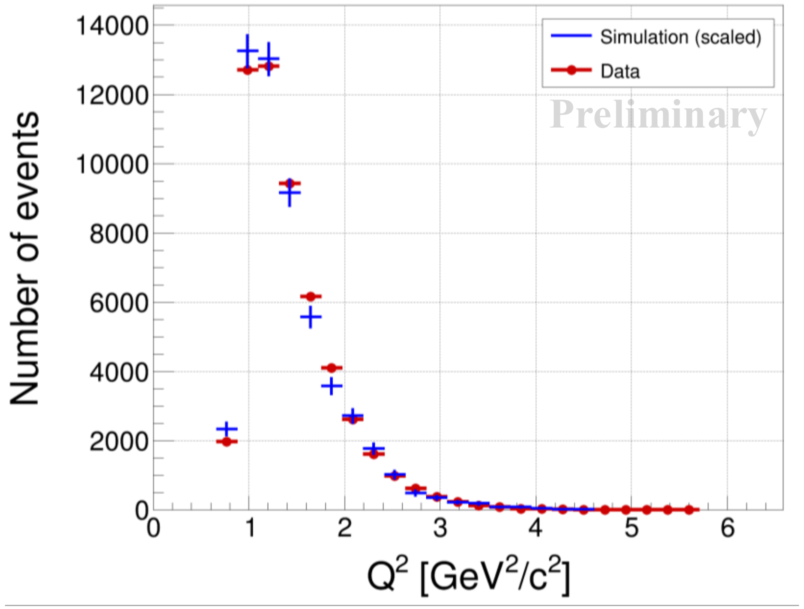
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Four-momentum squared (Q^2)

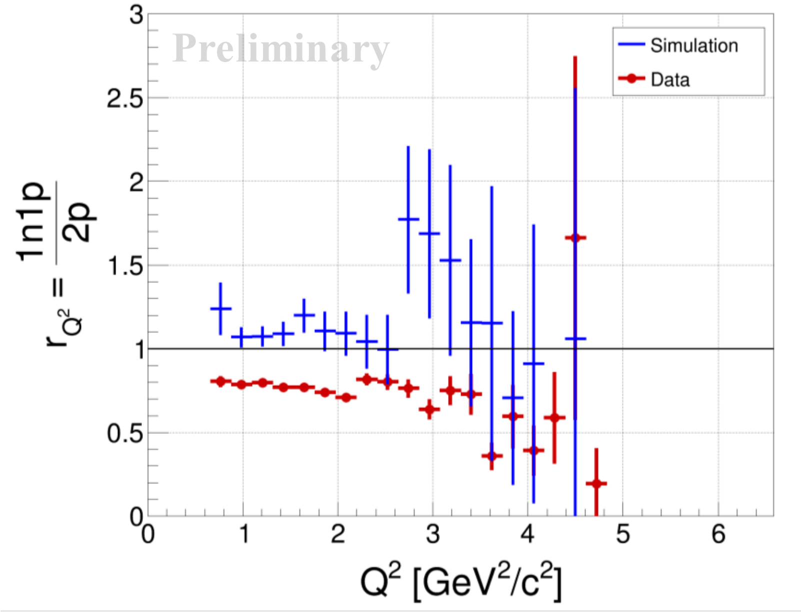
Q^2 in 1n1p



Q^2 in 2p



Q^2 distibution ratio



Where:

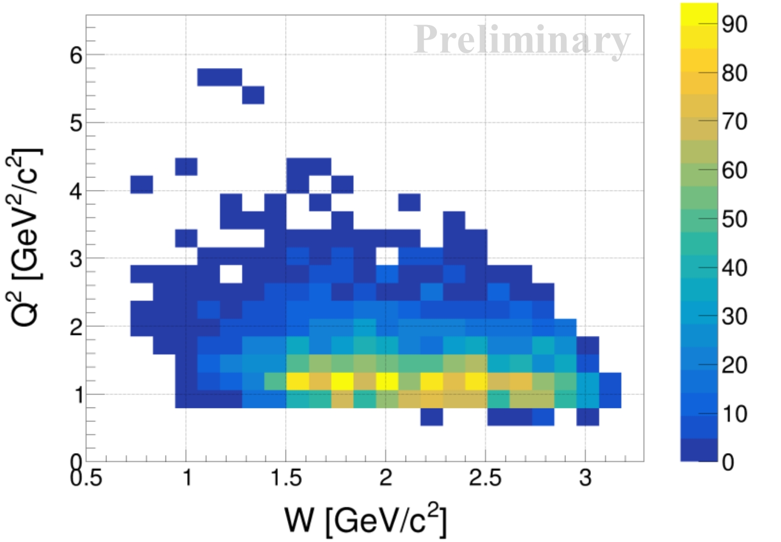
- $\boldsymbol{Q}^2 = \left|\boldsymbol{q}^2 - \omega^2\right|$
- $\boldsymbol{q} = \boldsymbol{P}_{beam} - \boldsymbol{P}_e; \omega = E_{beam} - E_e$

Zoom-out

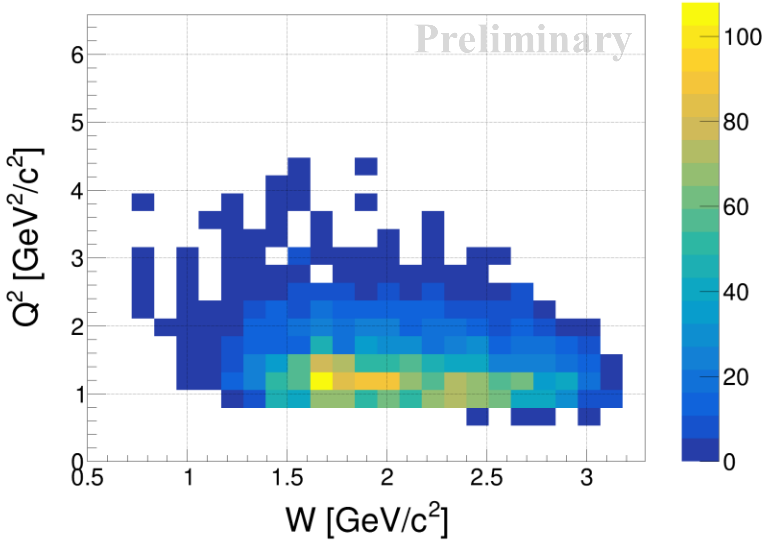
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Q^2 vs. W in simulation and data

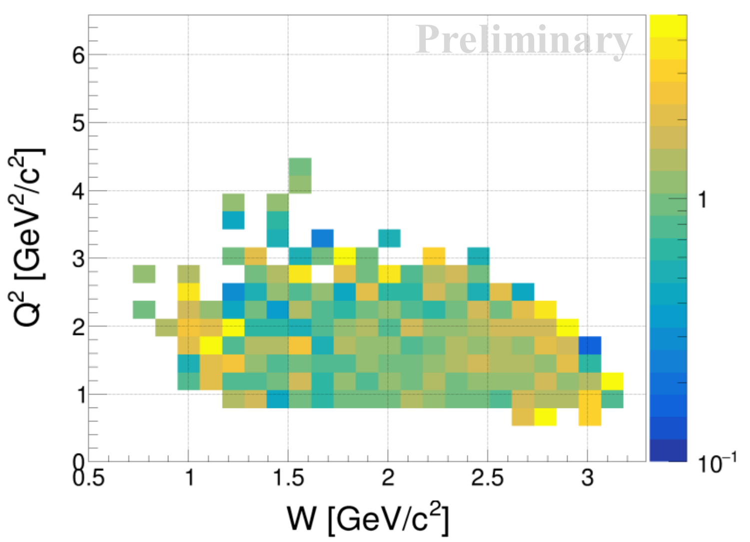
Q^2 vs. W in 1n1p (sim.)



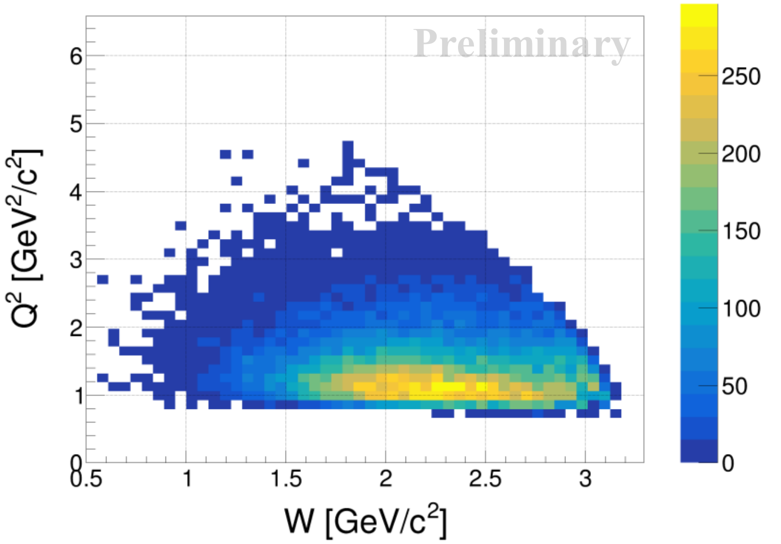
Q^2 vs. W in 2p (sim.)



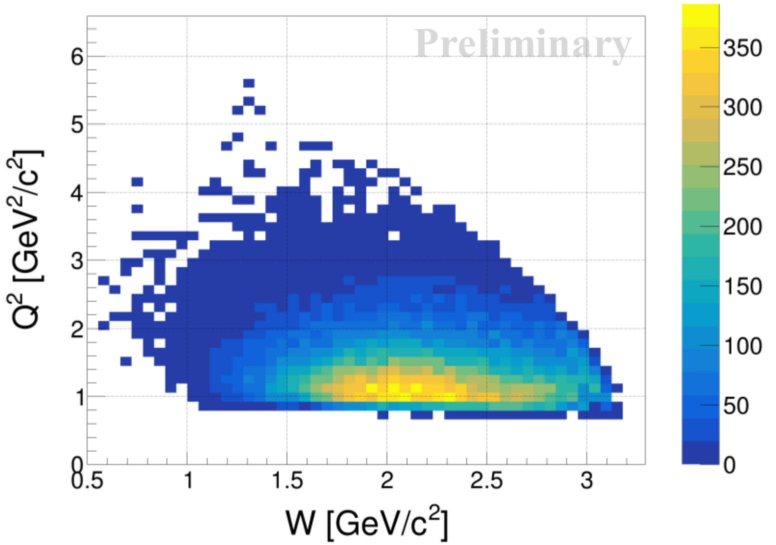
Q^2 vs. W distribution ratio (sim.)



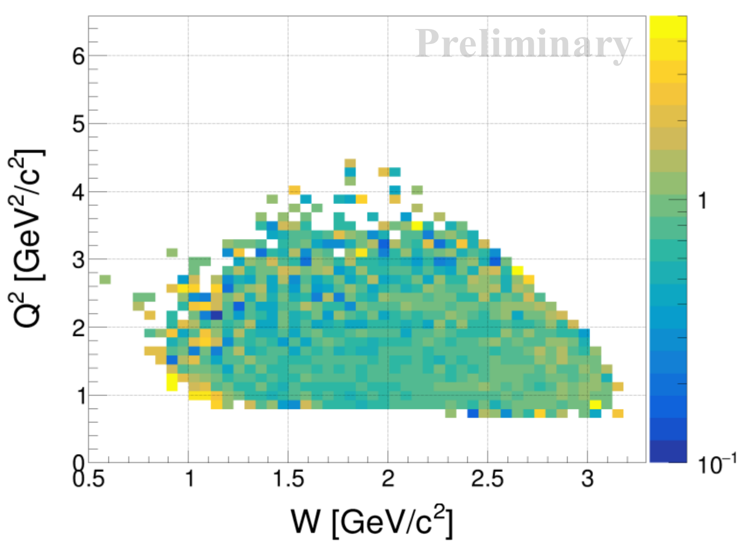
Q^2 vs. W in 1n1p (data)



Q^2 vs. W in 2p (data)



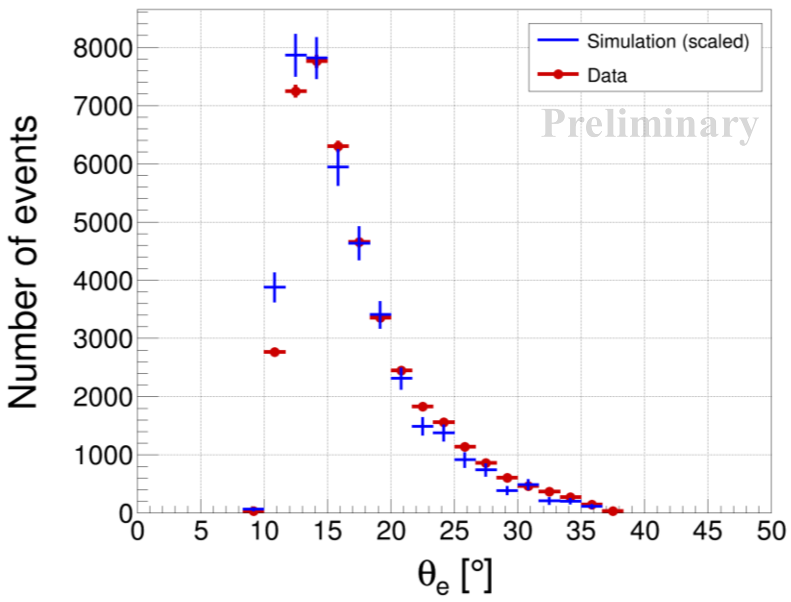
Q^2 vs. W distribution ratio (data)



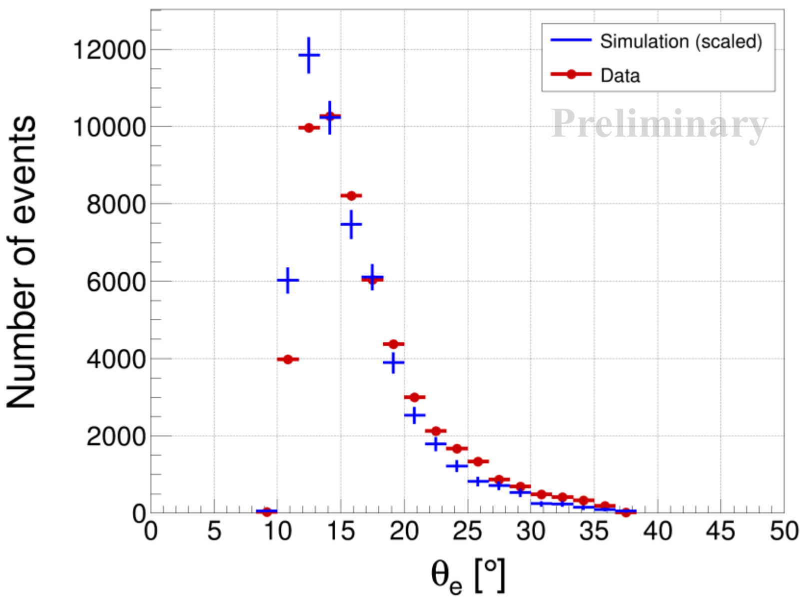
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Electron scattering angle

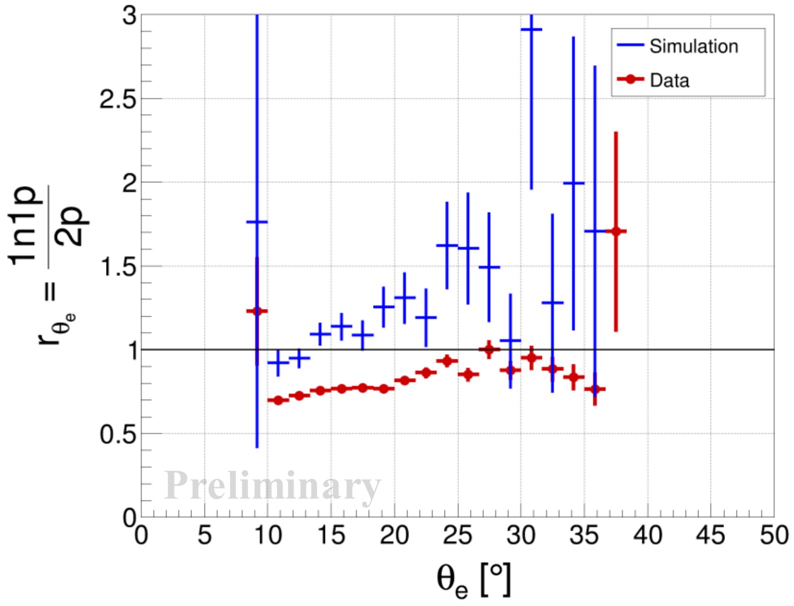
θ_e in 1n1p



θ_e in 2p



θ_e distribution ratio

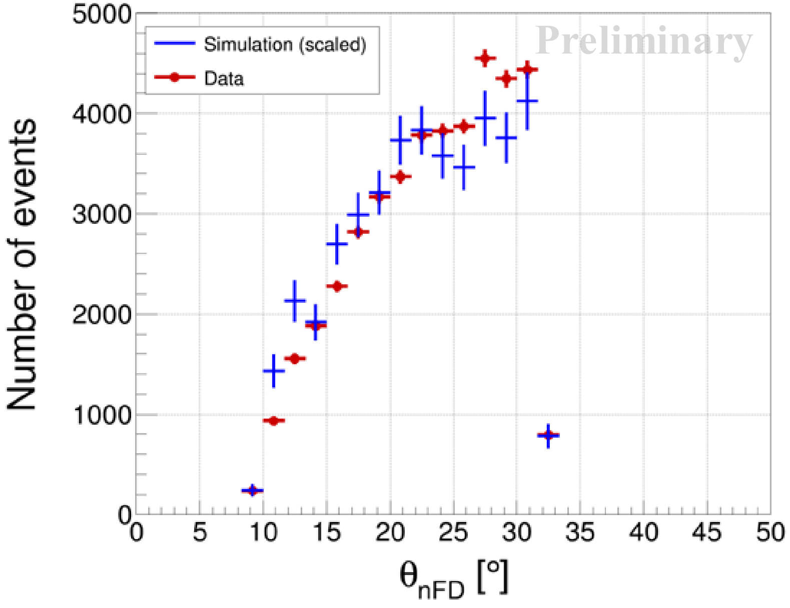


Zoom-out

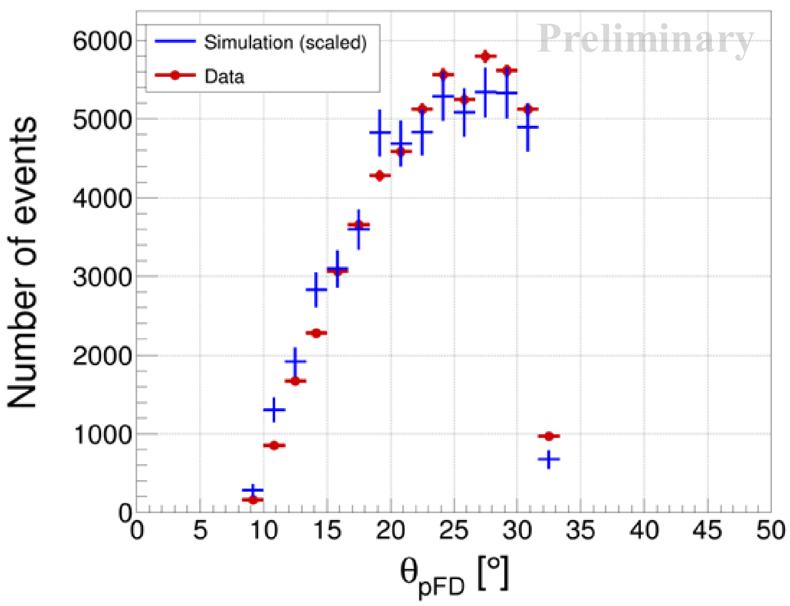
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Scattering angles of FD nucleons

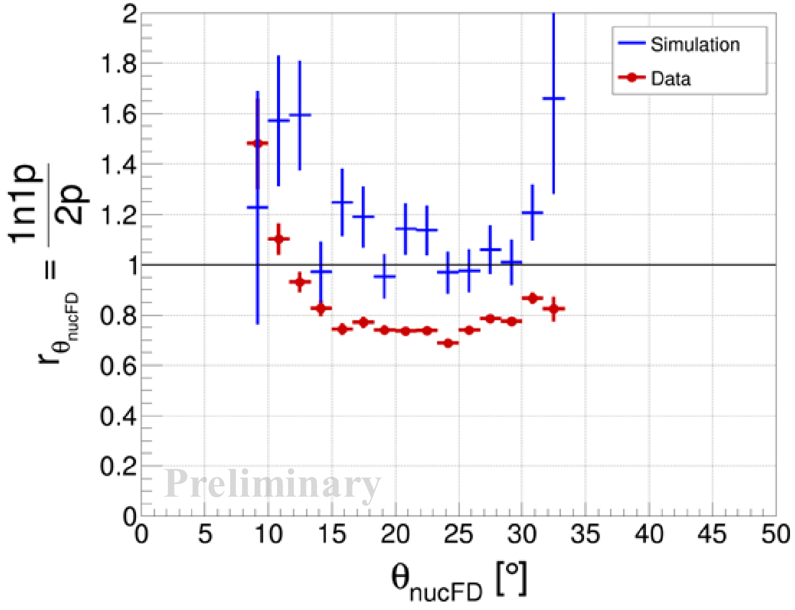
θ_{nFD} in 1n1p



θ_{pFD} in 2p



θ_{nucFD} distribution ratio

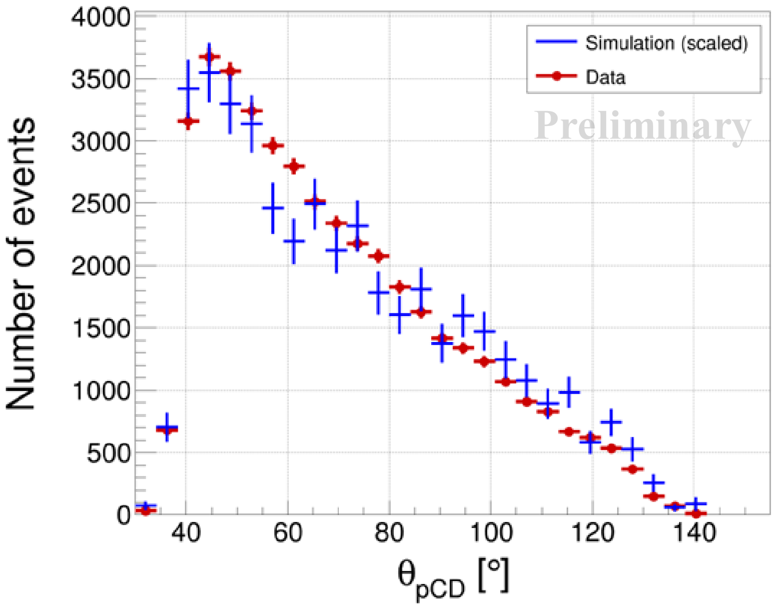


Zoom-out

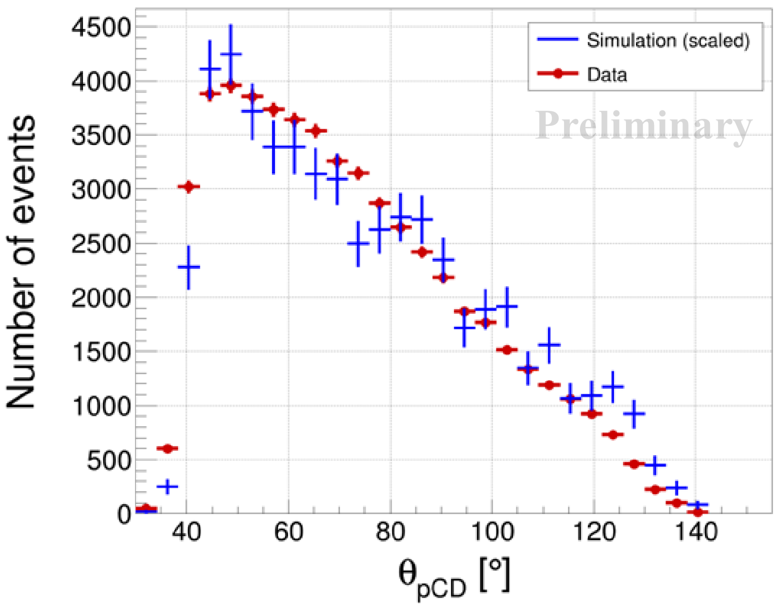
nFD = FD neutron	pFD = FD proton	$nucFD$ = FD nucleon

Scattering angles of CD protons

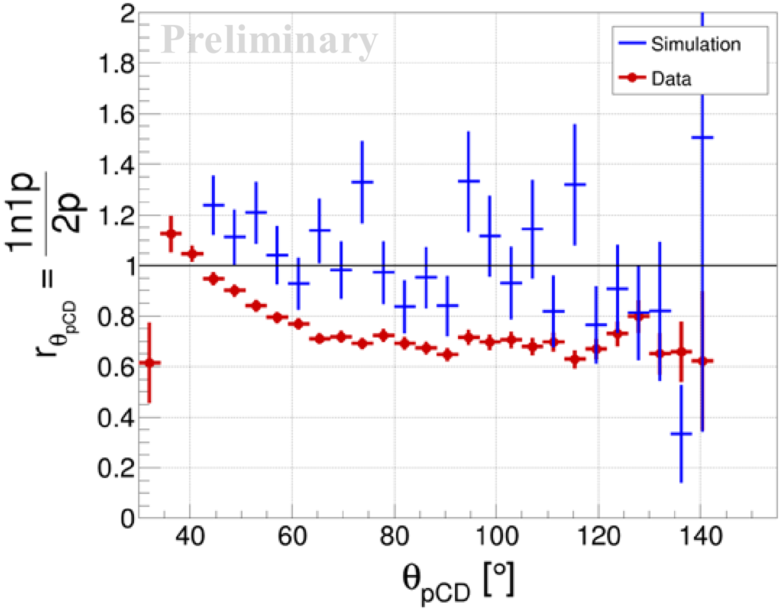
θ_{pCD} in 1n1p



θ_{pCD} in 2p



θ_{pCD} distribution ratio



Zoom-out

pCD = CD proton

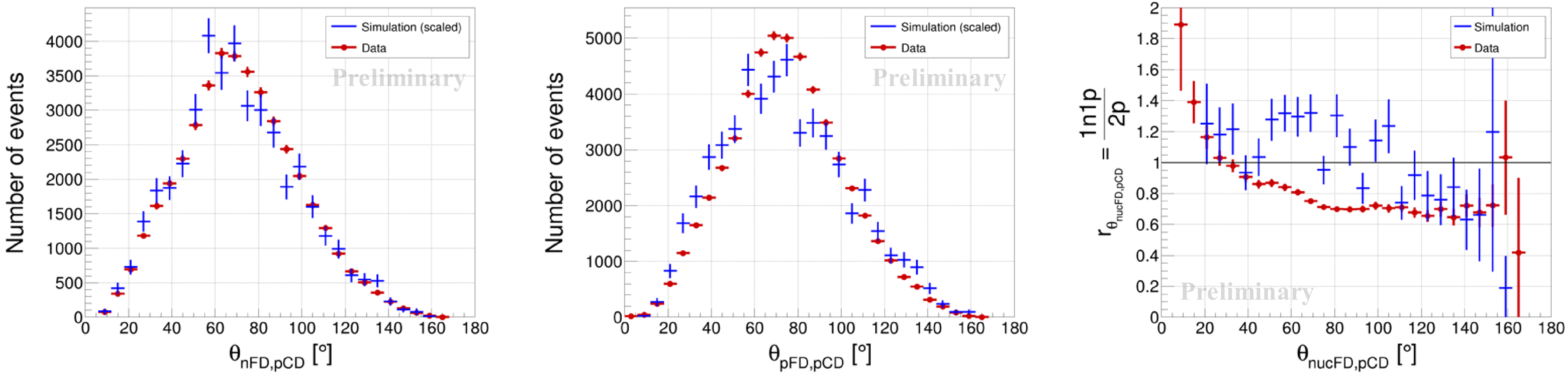
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Opening angles between FD and CD nucleon momenta ($\theta_{nucFD,pCD}$)

$\theta_{nFD,pCD}$ in 1n1p

$\theta_{pFD,pCD}$ in 2p

$\theta_{nucFD,pCD}$ distribution ratio



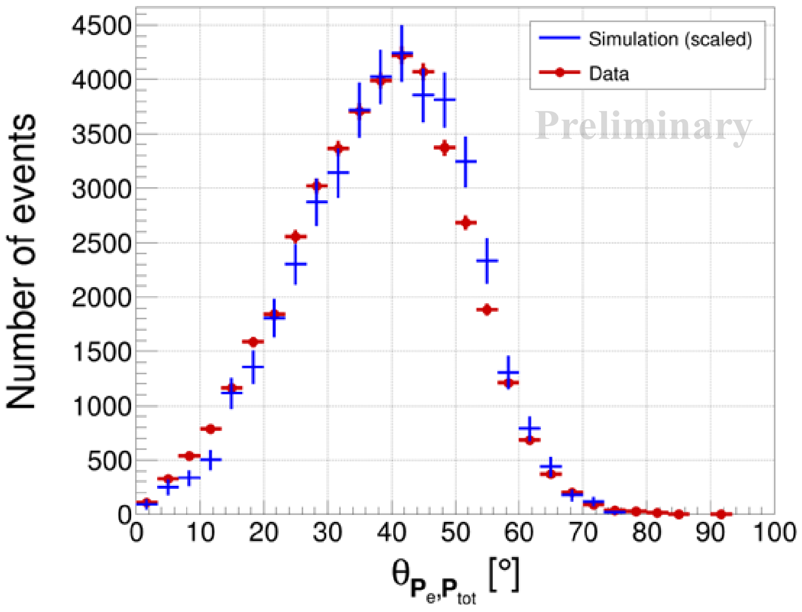
Zoom-out

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

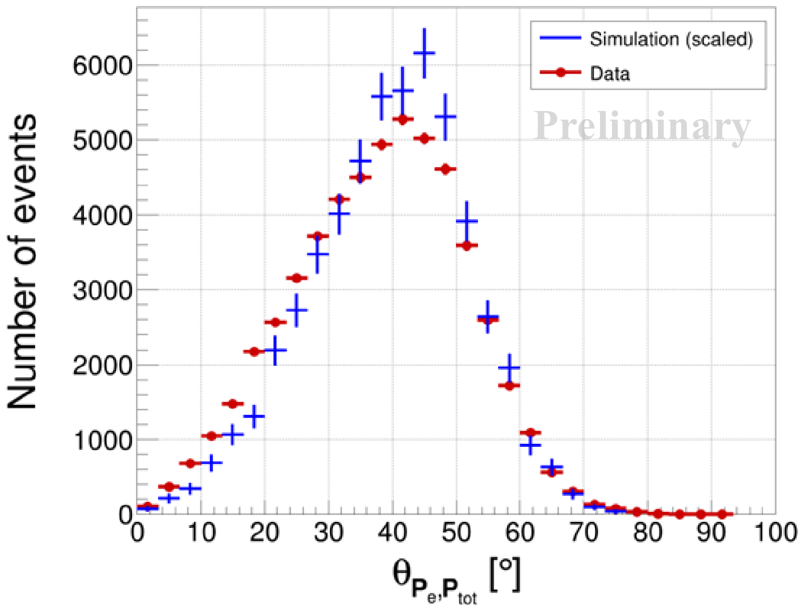
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Opening angles between P_e and P_{tot} ($\theta_{P_e,P_{tot}}$)

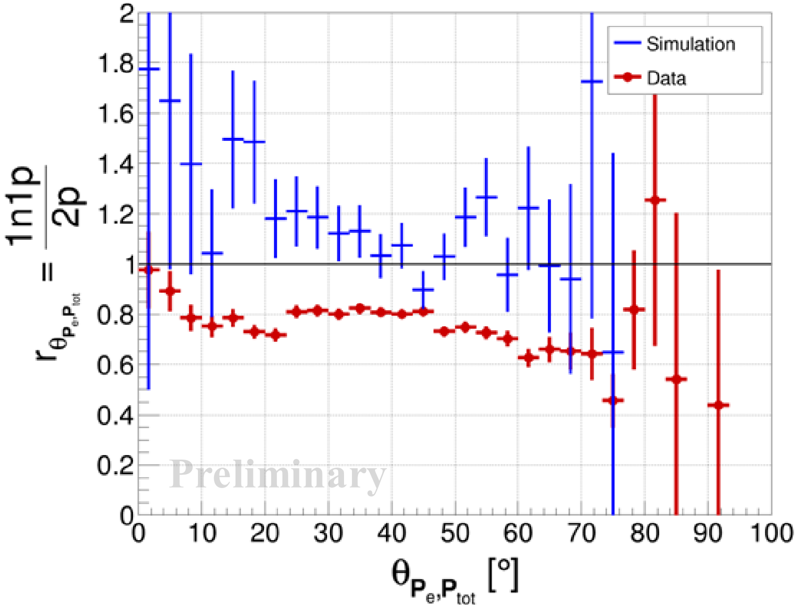
$\theta_{P_e,P_{tot}}$ in 1n1p



$\theta_{P_e,P_{tot}}$ in 2p



$\theta_{P_e,P_{tot}}$ distribution ratio



Where:

- $P_{tot} = P_{nucFD} + P_{pCD}$

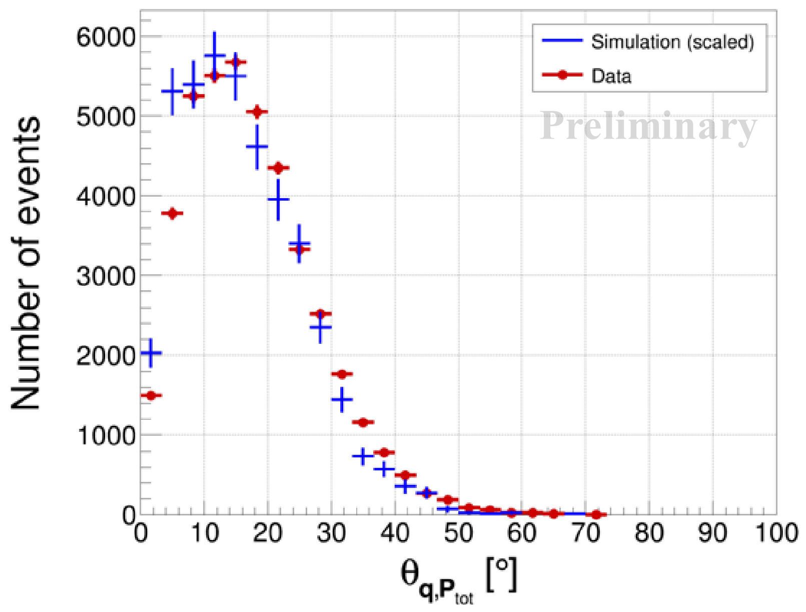
Zoom-out

$nucFD$ = FD nucleon

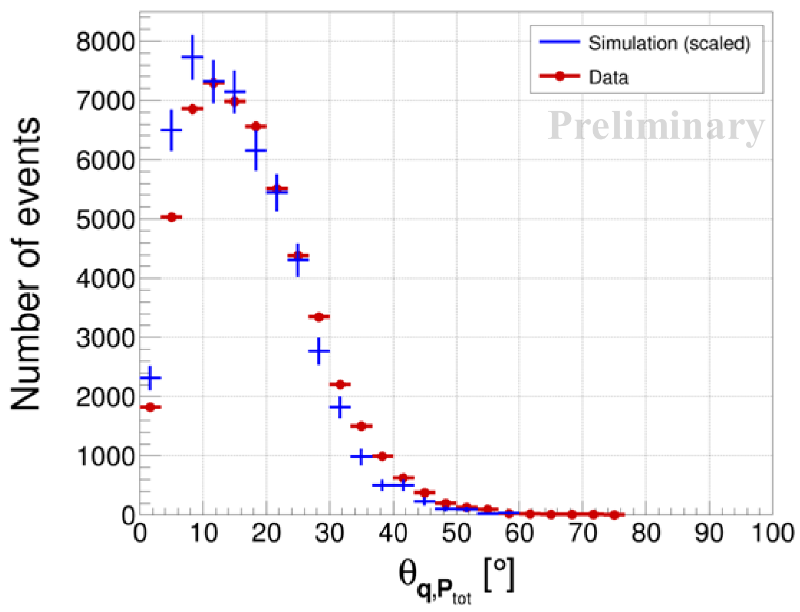
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Opening angles between q and P_{tot} ($\theta_{q,P_{tot}}$)

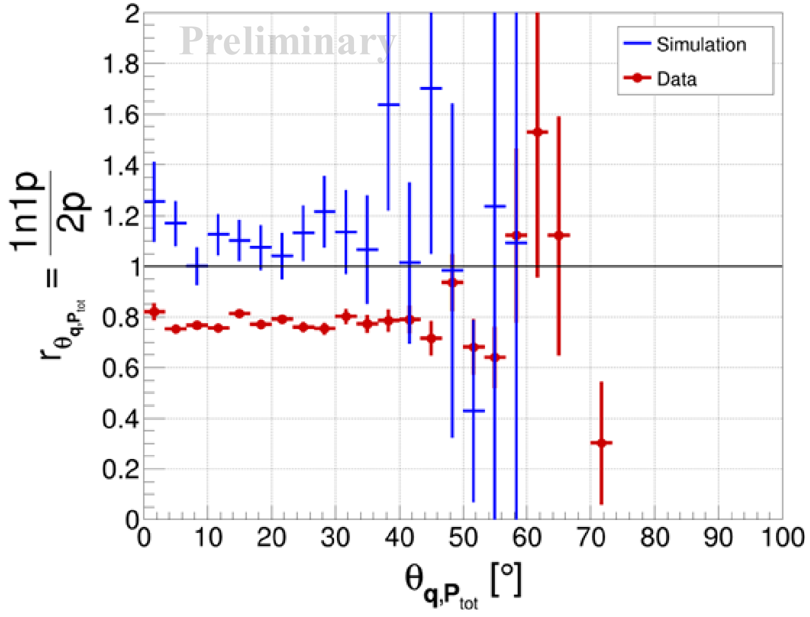
$\theta_{q,P_{tot}}$ in 1n1p



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



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



Where:

- $\boldsymbol{P_{tot} = P_{nucFD} + P_{pCD}}$
- $\boldsymbol{q = P_{beam} - P_e}$

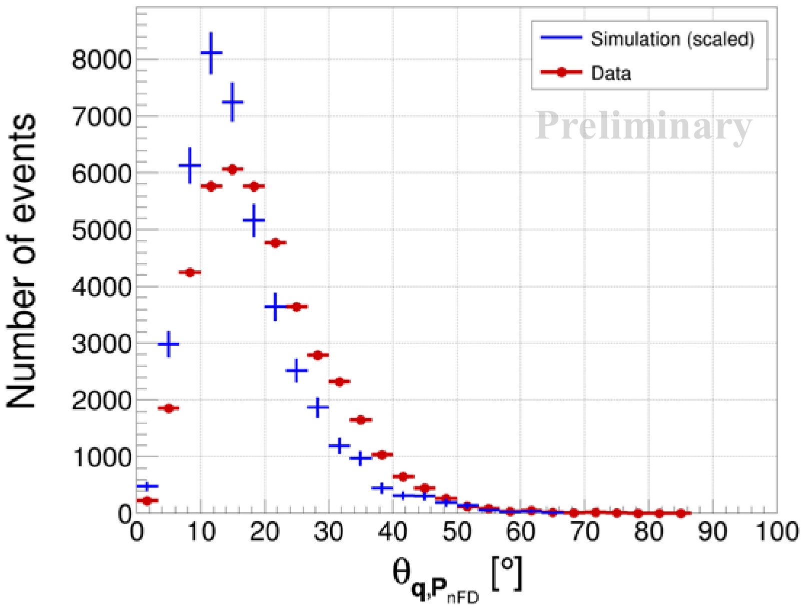
Zoom-out

$nucFD$ = FD nucleon

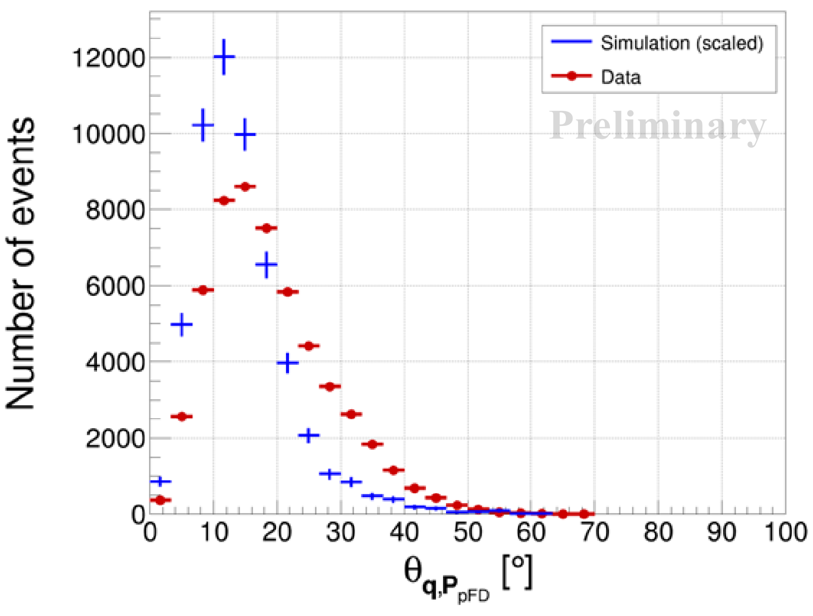
[12]C simulation and data at $E_{beam} \simeq 6$ GeV

Opening angles between q and P_{nucFD} ($\theta_{q,P_{nucFD}}$)

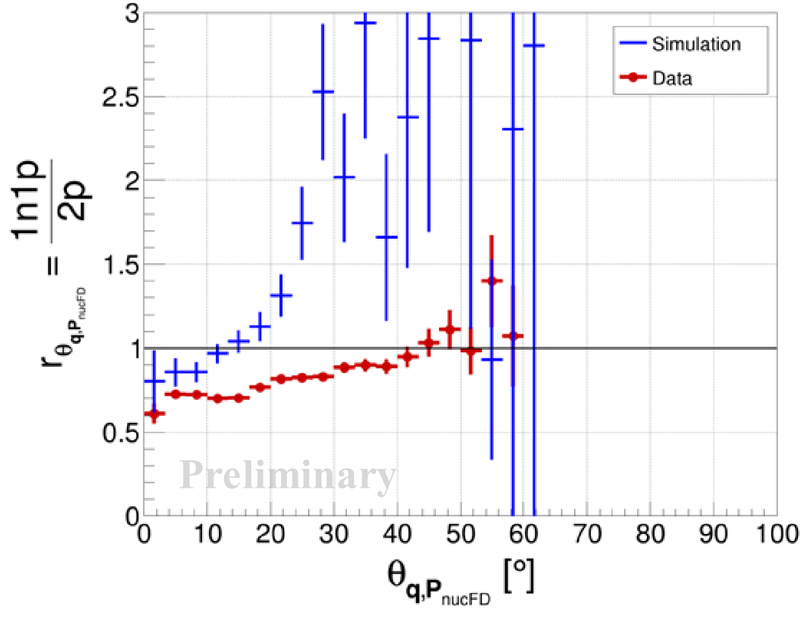
$\theta_{q,P_{nFD}}$ in 1n1p



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



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



Where:

- $q = P_{beam} - P_e$

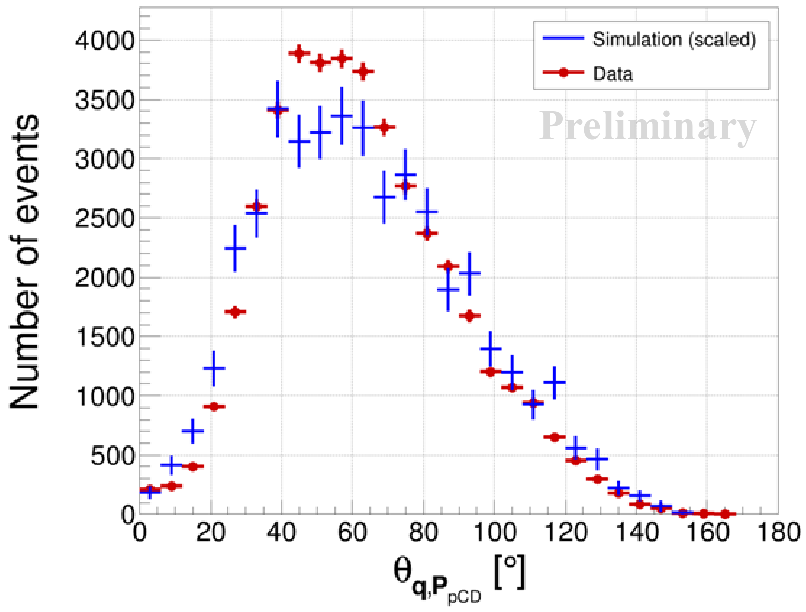
Zoom-out

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

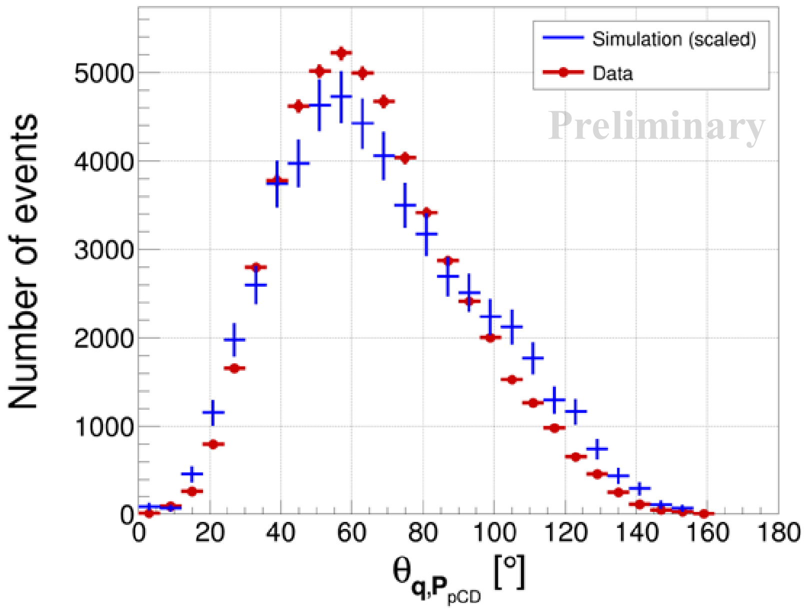
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Opening angles between q and P_{pCD} ($\theta_{q,P_{pCD}}$)

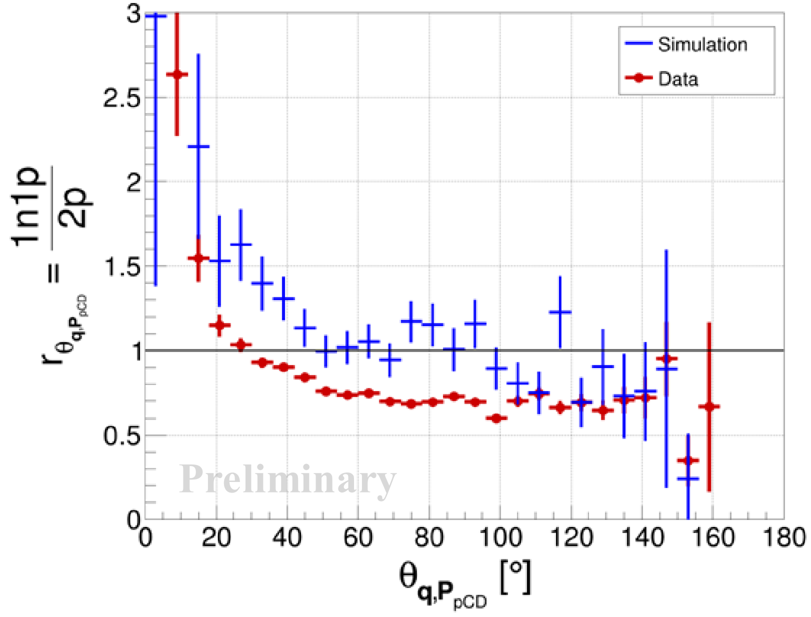
$\theta_{q,P_{pCD}}$ in 1n1p



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



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



Where:

- $q = P_{beam} - P_e$

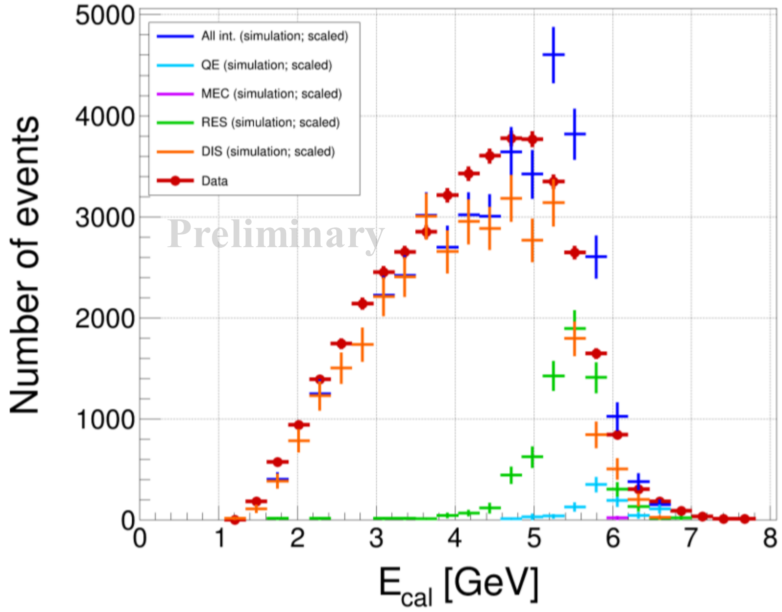
Zoom-out

pCD = CD proton

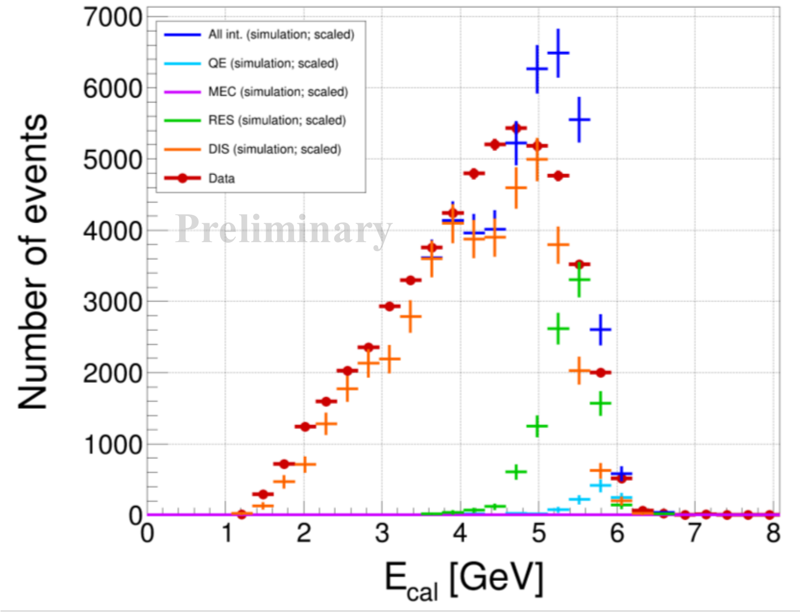
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Reconstructed energy E_{cal}

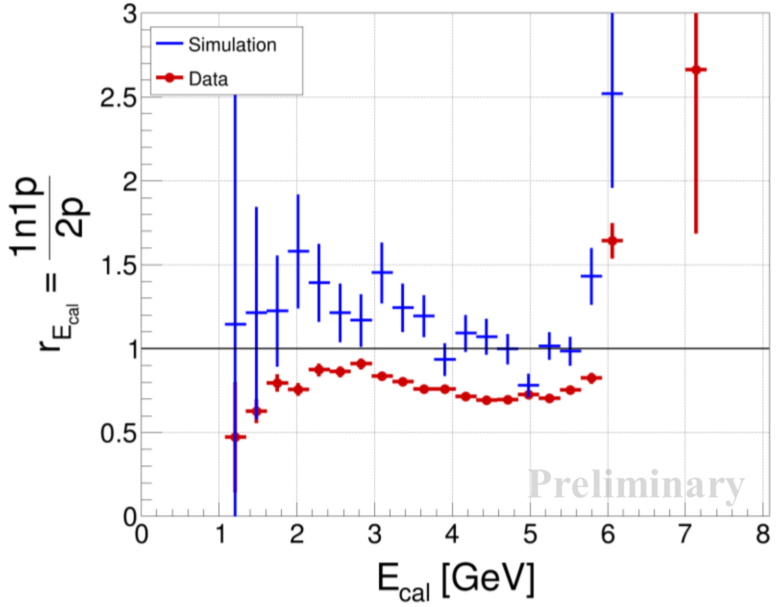
E_{cal} in 1n1p



E_{cal} in 2p



E_{cal} distibution ratio



Where:

- $E_{cal} = E_e + T_{nucFD} + T_{pCD}$
- $T_{nuc\ i} \equiv E_{nuc\ i} - m_{nuc\ i}$ is the kinematic energy of the nucleon i

Zoom-out

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

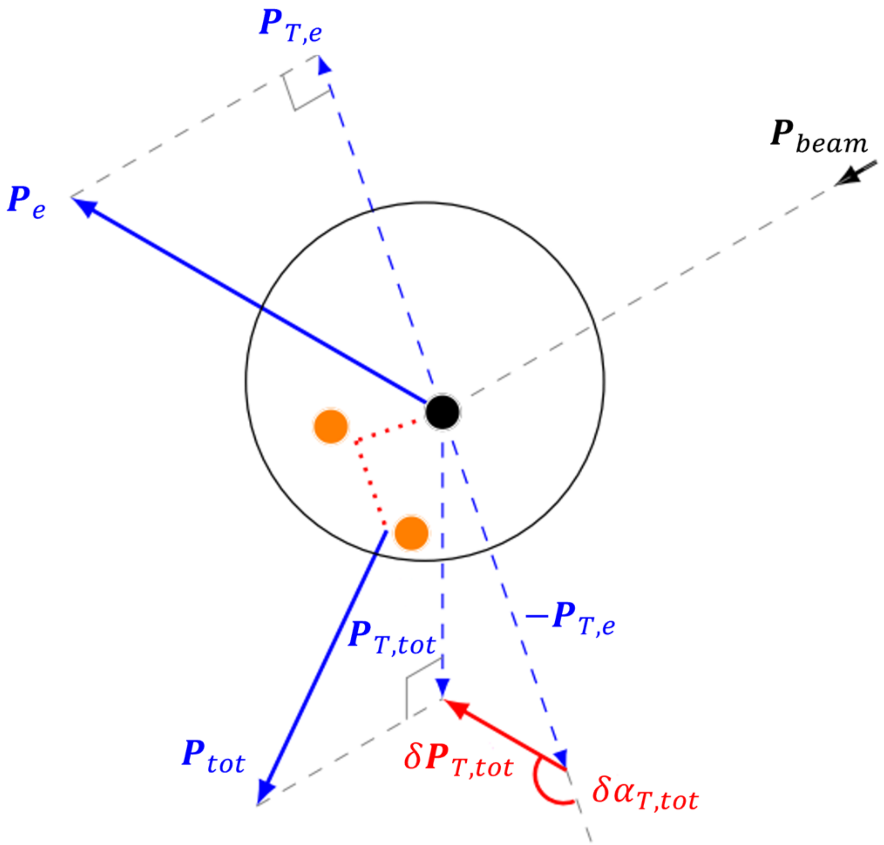
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Transverse kinematic imbalance (TKI) variables

Definitions of TKI variables:

$$\delta \boldsymbol{P}_{T,tot} = \left\| \boldsymbol{P}_{T,e} + \boldsymbol{P}_{T,tot} \right\|$$

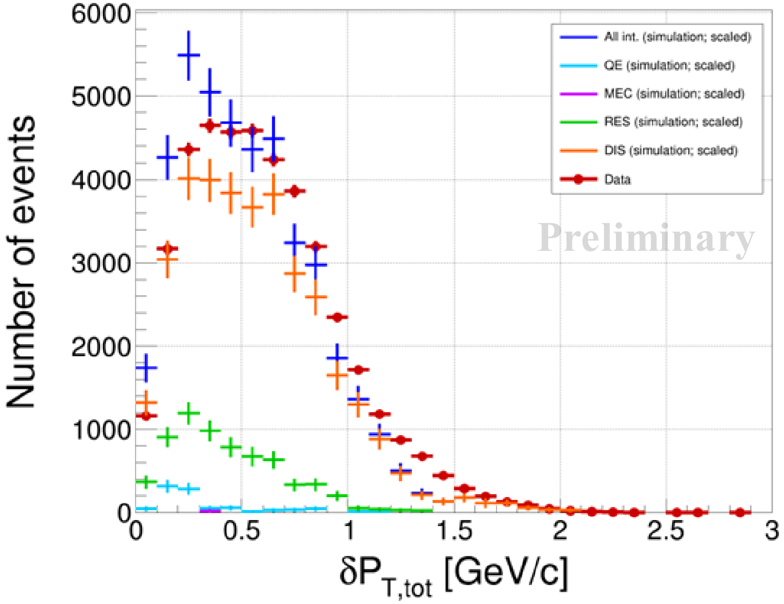
$$\delta\alpha_{T,tot} = \cos^{-1}\left[\frac{\left(-\boldsymbol{P}_{T,e}\right)\cdot \delta\boldsymbol{P}_{T,tot}}{\left\|\boldsymbol{P}_{T,e}\right\|\left\|\delta\boldsymbol{P}_{T,tot}\right\|}\right]$$



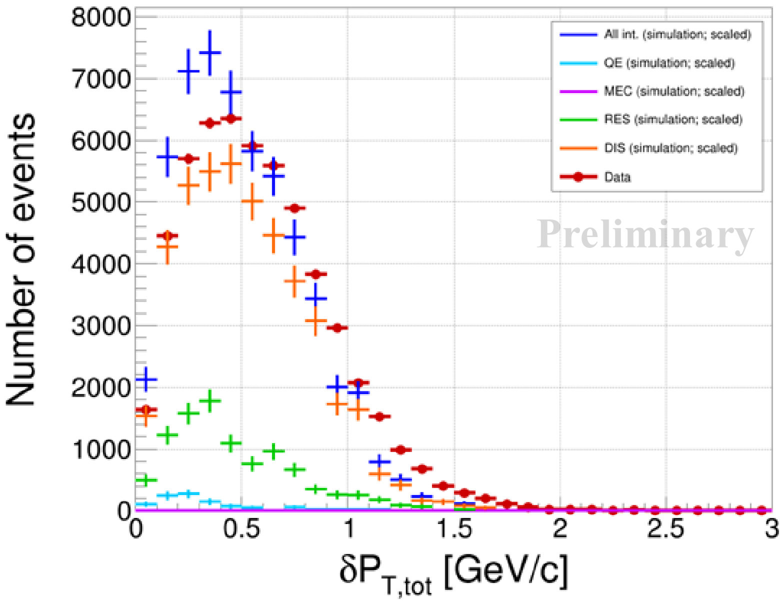
https://doi.org/10.1103/PhysRevD.102.072007

TKI variables – $\delta P_{T,tot}$

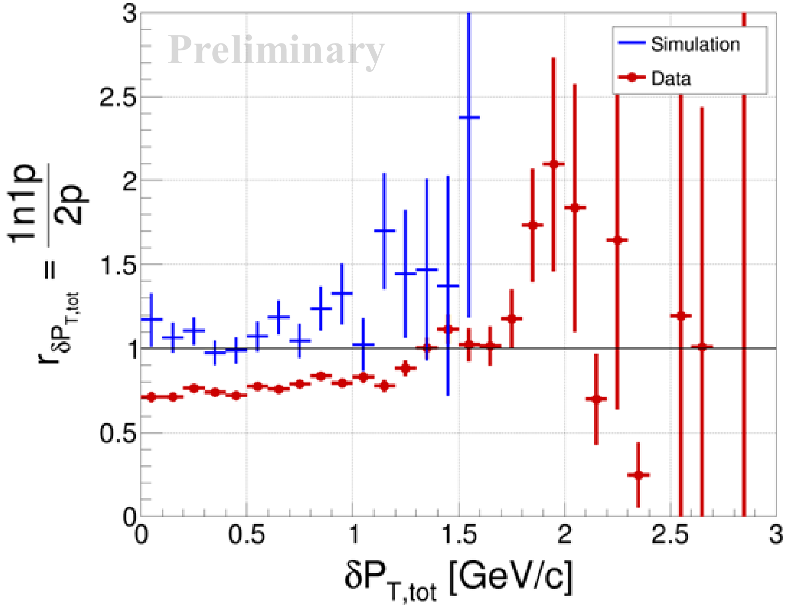
$\delta P_{T,tot}$ in 1n1p



$\delta P_{T,tot}$ in 2p



$\delta P_{T,tot}$ distibution ratio



Where:

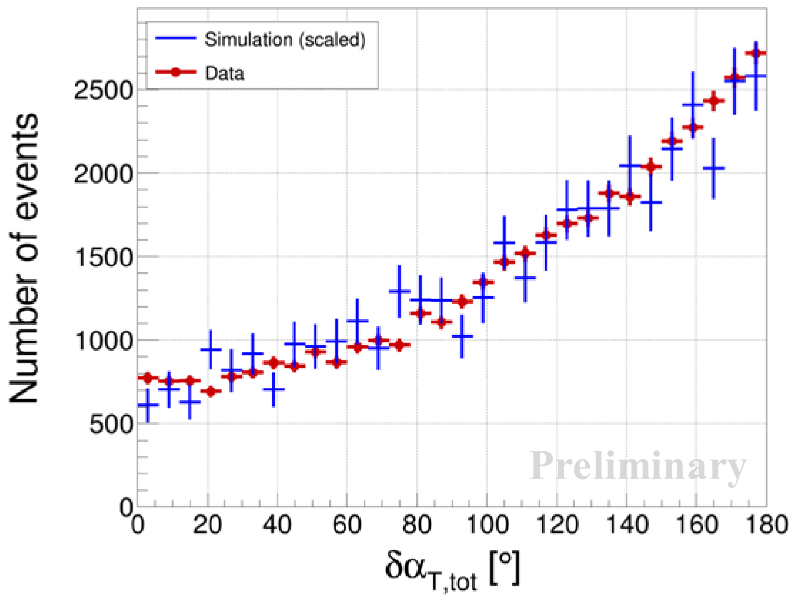
- $\delta \boldsymbol{P}_{T,tot} = \left\| \boldsymbol{P}_{T,e} + \boldsymbol{P}_{T,tot} \right\|$

Zoom-out

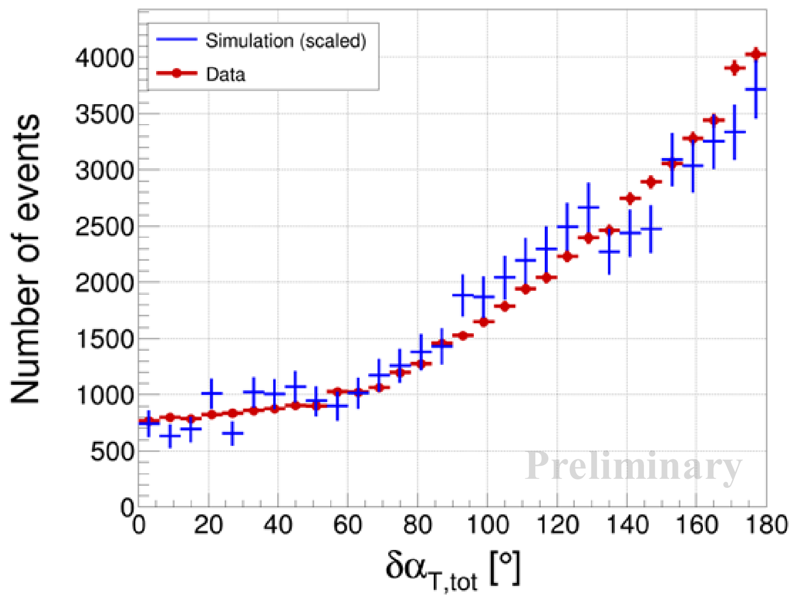
[12]C simulation and data at $E_{beam} \simeq 6$ GeV

TKI variables – $\delta\alpha_{T,tot}$

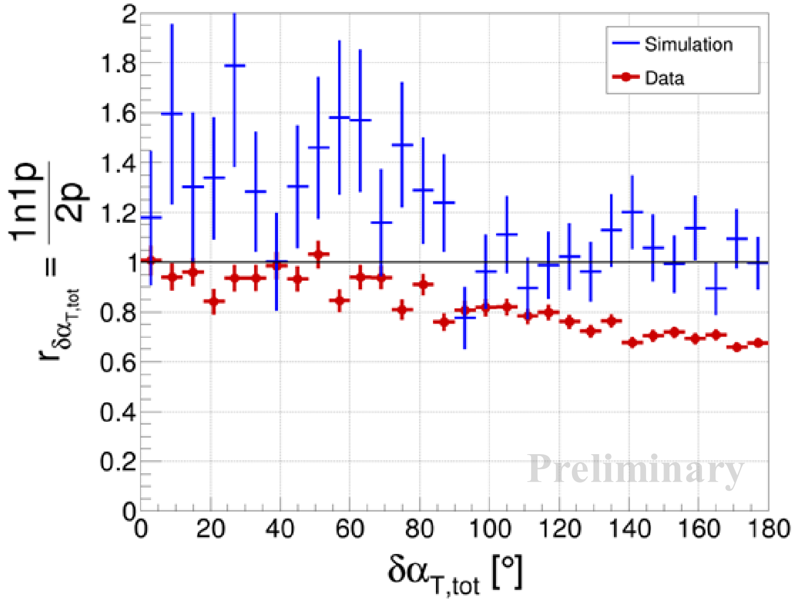
$\delta\alpha_{T,tot}$ in 1n1p



$\delta\alpha_{T,tot}$ in 2p



$\delta\alpha_{T,tot}$ distibution ratio



Where:

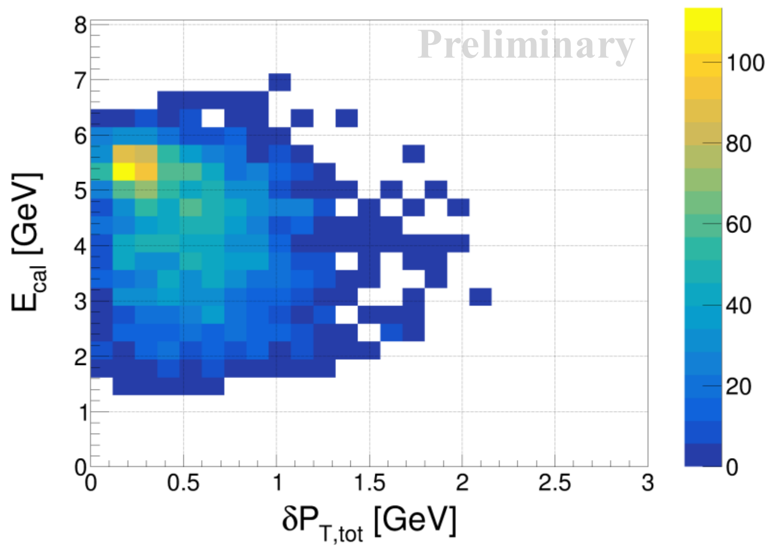
- $\delta\alpha_{T,tot} = \cos^{-1}\left[\frac{(-\boldsymbol{P}_{T,e})\cdot\delta\boldsymbol{P}_{T,tot}}{\|\boldsymbol{P}_{T,e}\|\|\delta\boldsymbol{P}_{T,tot}\|}\right]$

Zoom-out

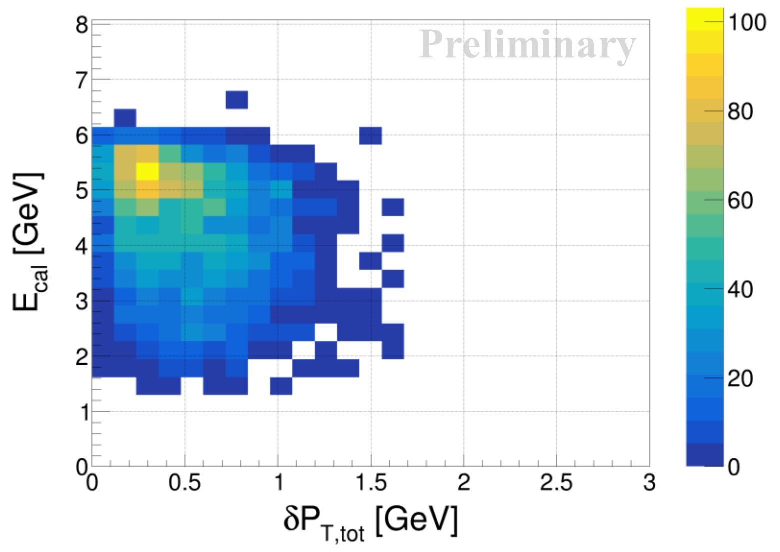
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

$\delta P_{T,tot}$ vs. E_{cal} in simulation and data

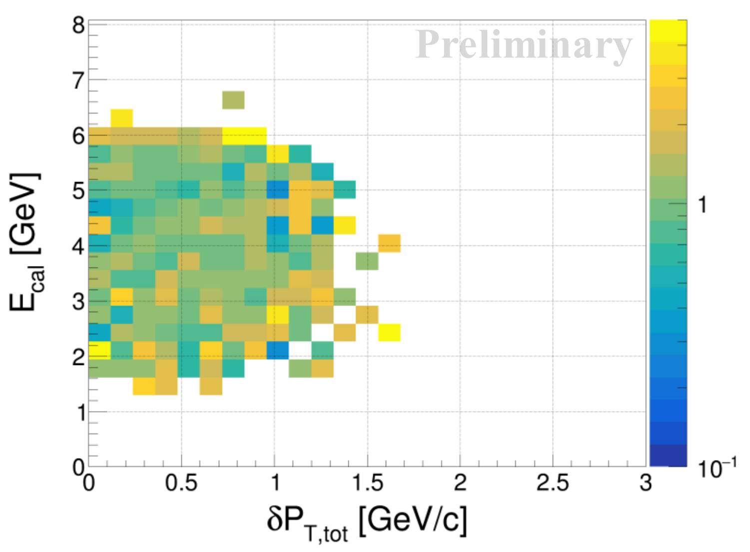
$\delta P_{T,tot}$ vs. E_{cal} in 1n1p (sim.)



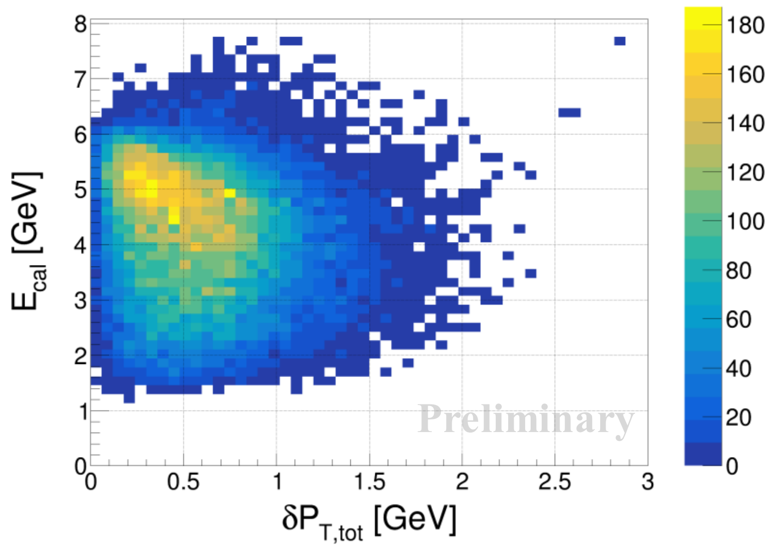
$\delta P_{T,tot}$ vs. E_{cal} in 2p (sim.)



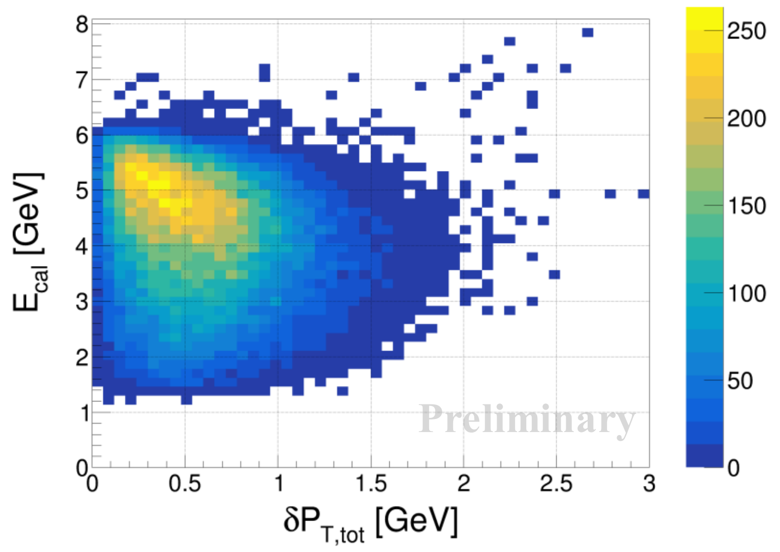
$\delta P_{T,tot}$ vs. E_{cal} 1n1p/2p ratio (sim.)



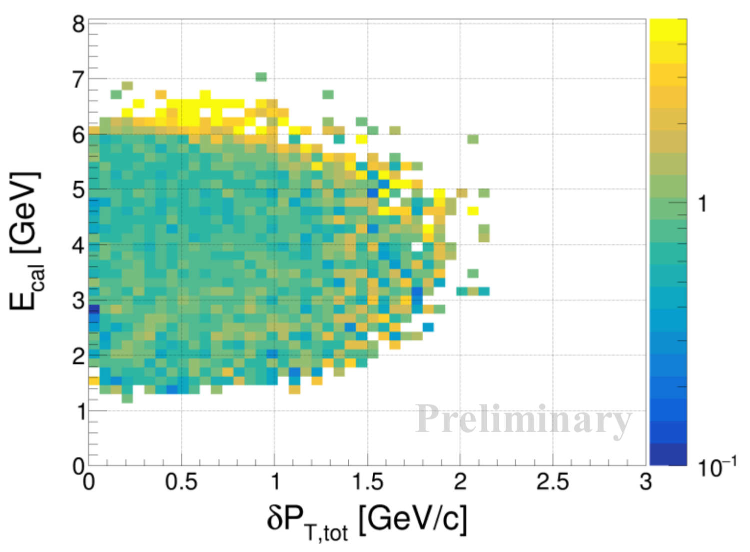
$\delta P_{T,tot}$ vs. E_{cal} in 1n1p (data)



$\delta P_{T,tot}$ vs. E_{cal} in 2p (data)



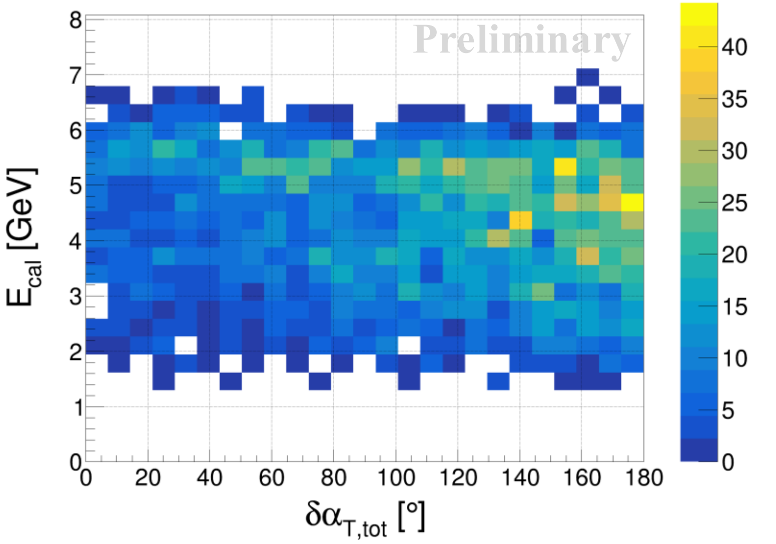
$\delta P_{T,tot}$ vs. E_{cal} 1n1p/2p ratio (data)



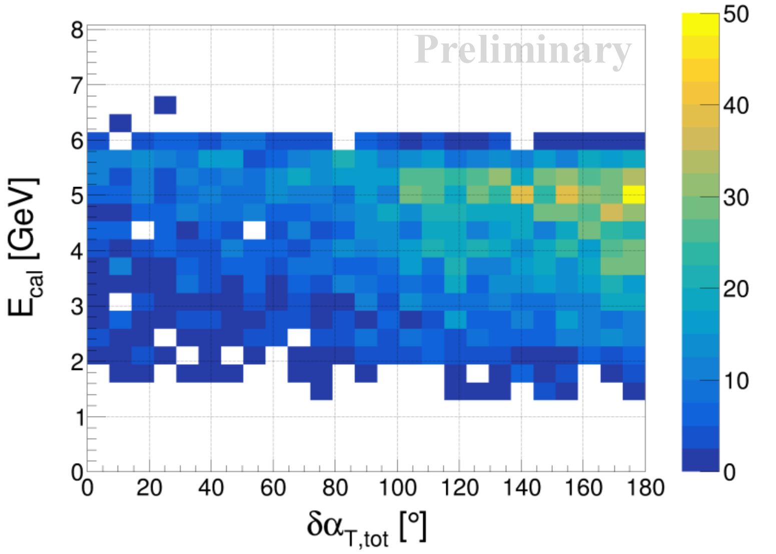
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

$\delta\alpha_{T,tot}$ vs. E_{cal} in simulation and data

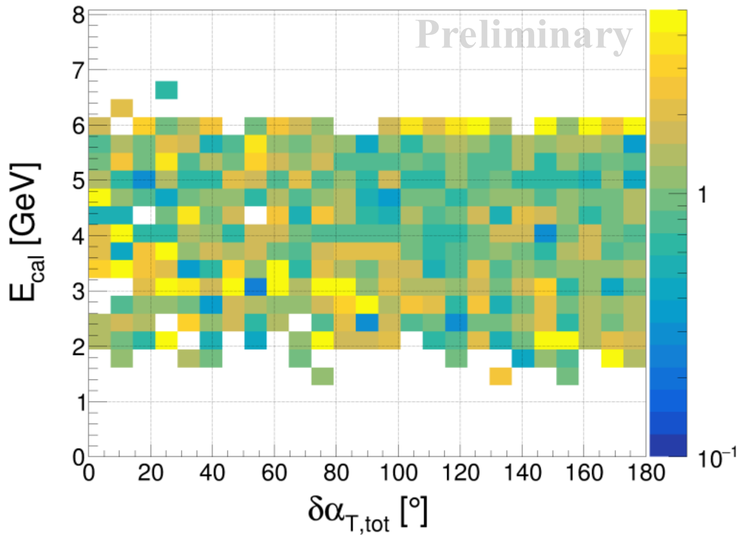
$\delta\alpha_{T,tot}$ vs. E_{cal} in 1n1p (sim.)



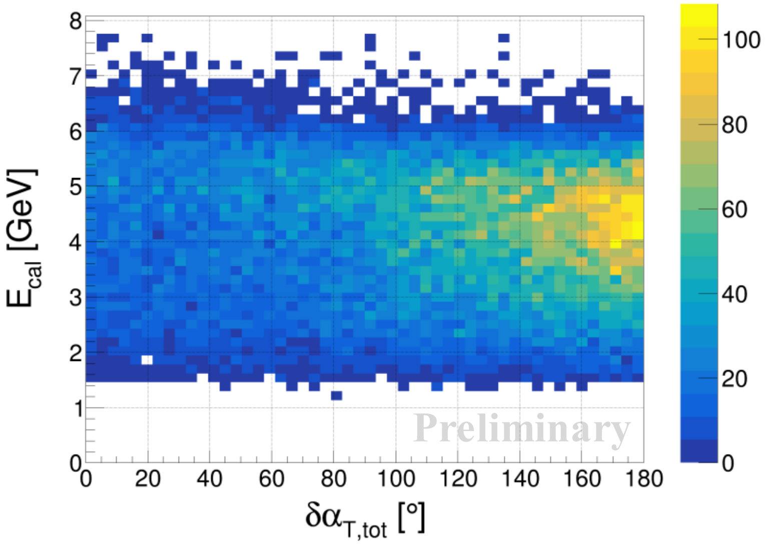
$\delta\alpha_{T,tot}$ vs. E_{cal} in 2p (sim.)



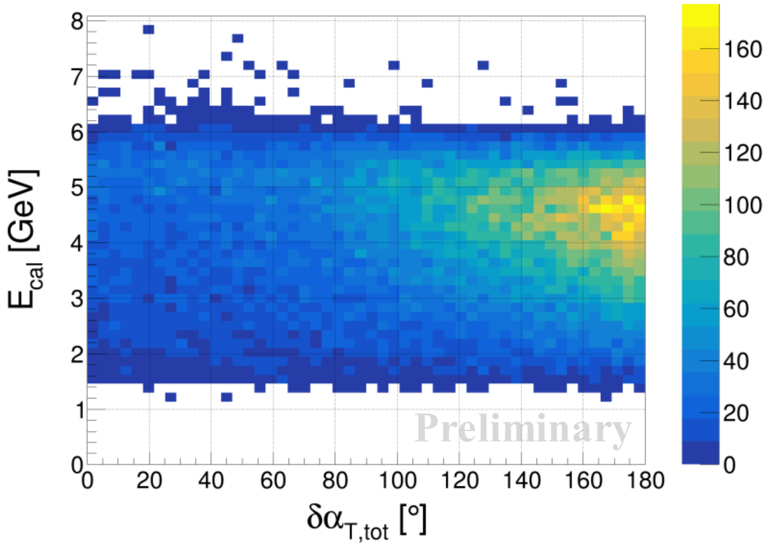
$\delta\alpha_{T,tot}$ vs. E_{cal} 1n1p/2p ratio (sim.)



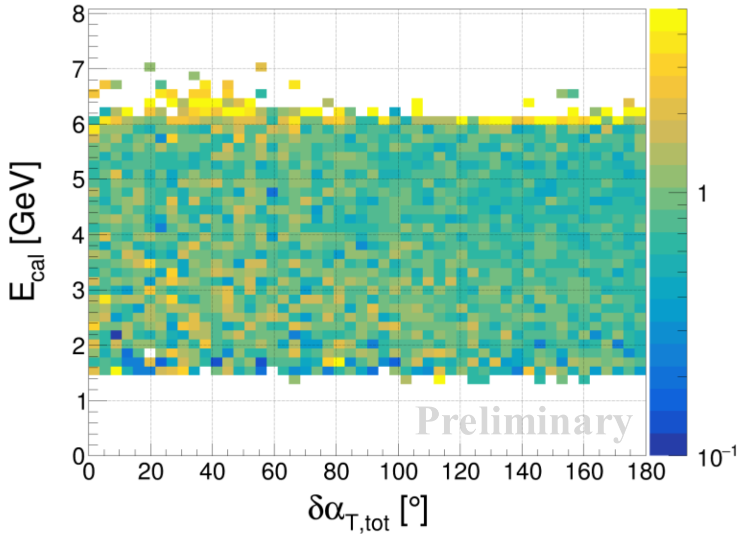
$\delta\alpha_{T,tot}$ vs. E_{cal} in 1n1p (data)



$\delta\alpha_{T,tot}$ vs. E_{cal} in 2p (data)



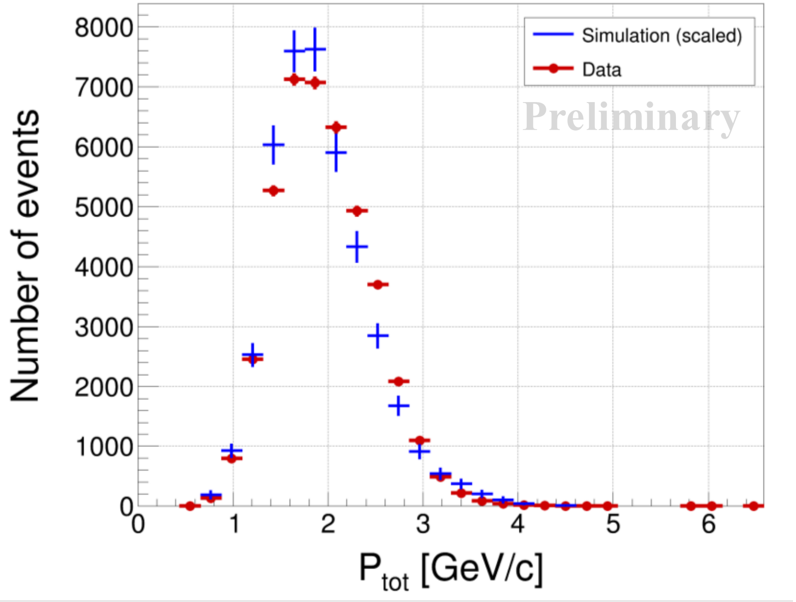
$\delta\alpha_{T,tot}$ vs. E_{cal} 1n1p/2p ratio (data)



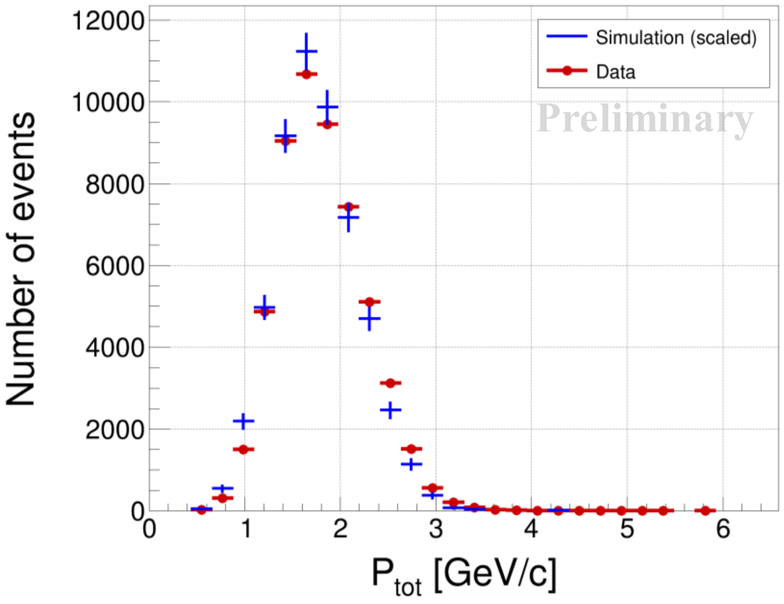
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Total nucleon momentum (P_{tot}) – zoom-out

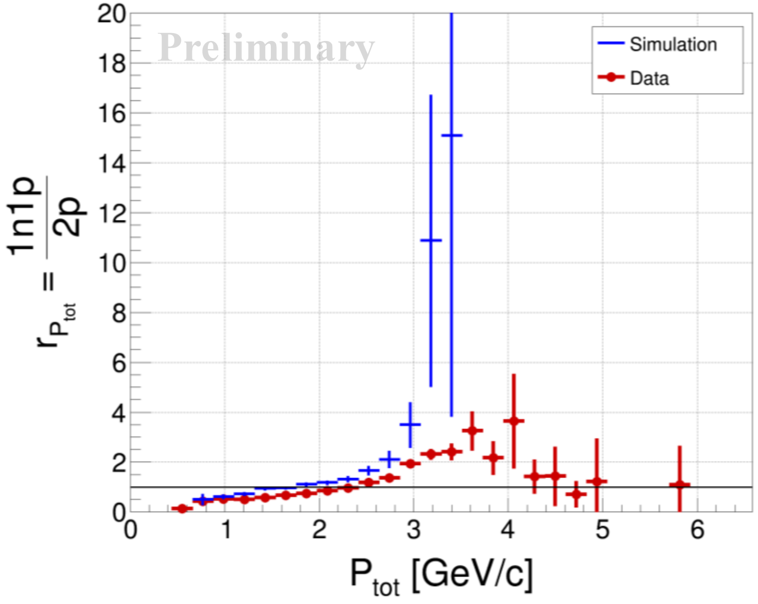
P_{tot} in 1n1p



P_{tot} in 2p



P_{tot} distribution ratio



Where:

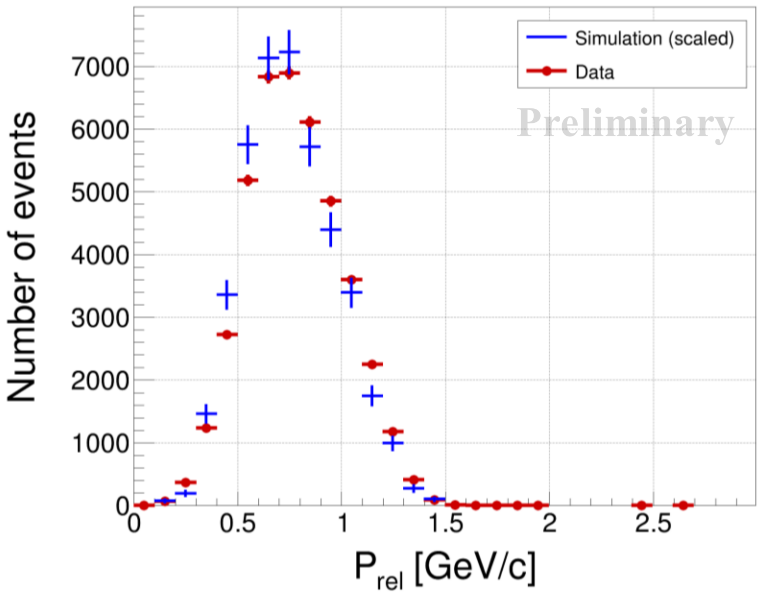
- $P_{tot} = P_{nucFD} + P_{pCD}$

Back

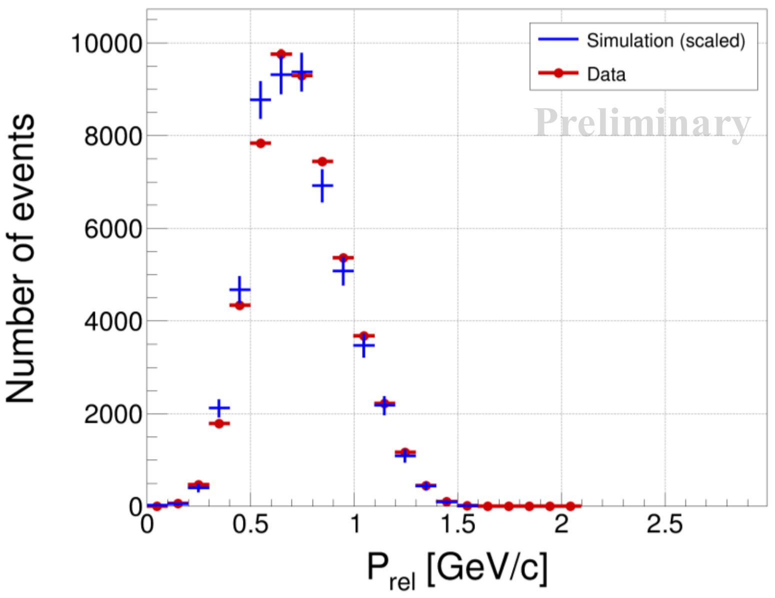
$nucFD$ = FD nucleon

Relative nucleon momentum (P_{rel}) – zoom-out

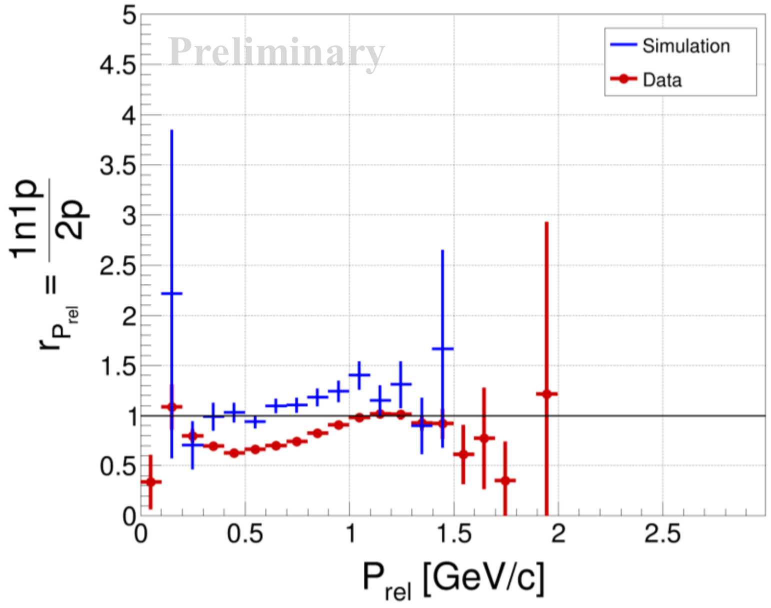
P_{rel} in 1n1p



P_{rel} in 2p



P_{rel} distribution ratio



Where:

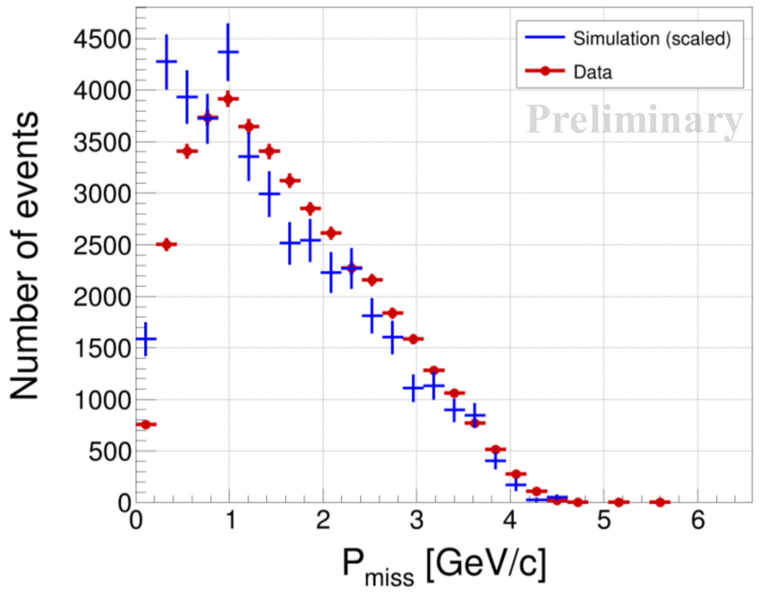
- $\boldsymbol{P_{rel} = (P_1 - P_2)/2}$
- $\boldsymbol{P_1}$ ($\boldsymbol{P_2}$) is the leading (sub-leading) nucleon

Back

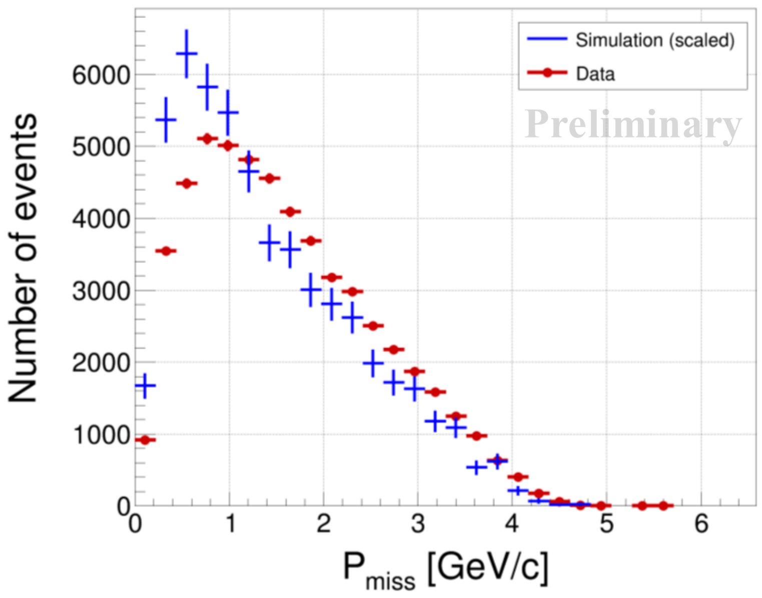
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Missing momentum (P_{miss}) – zoom-out

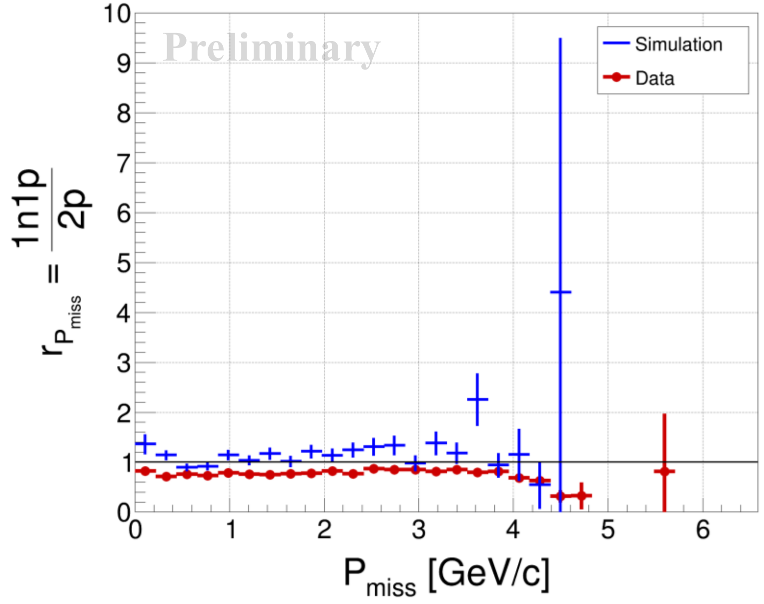
P_{miss} in 1n1p



P_{miss} in 2p



P_{miss} distribution ratio



Where:

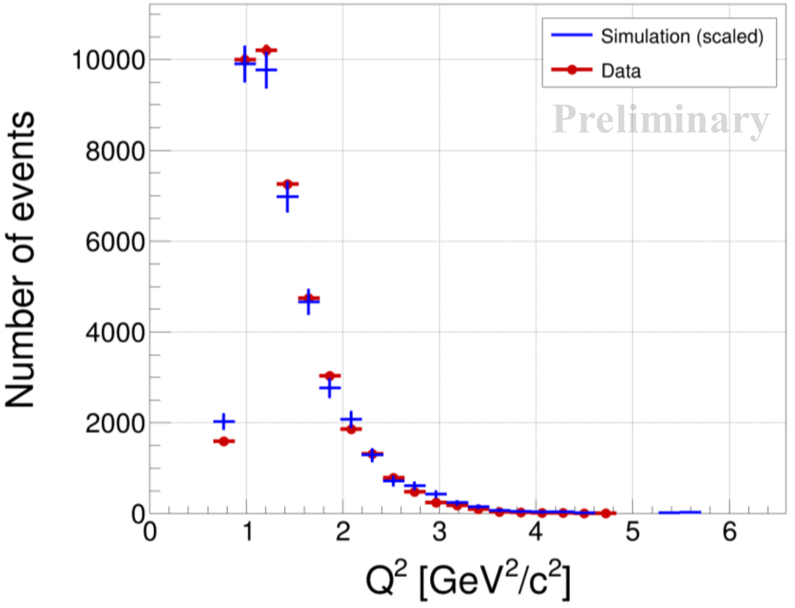
- $P_{miss} = P_{tot} - q$
- $q = P_{beam} - P_e$

Back

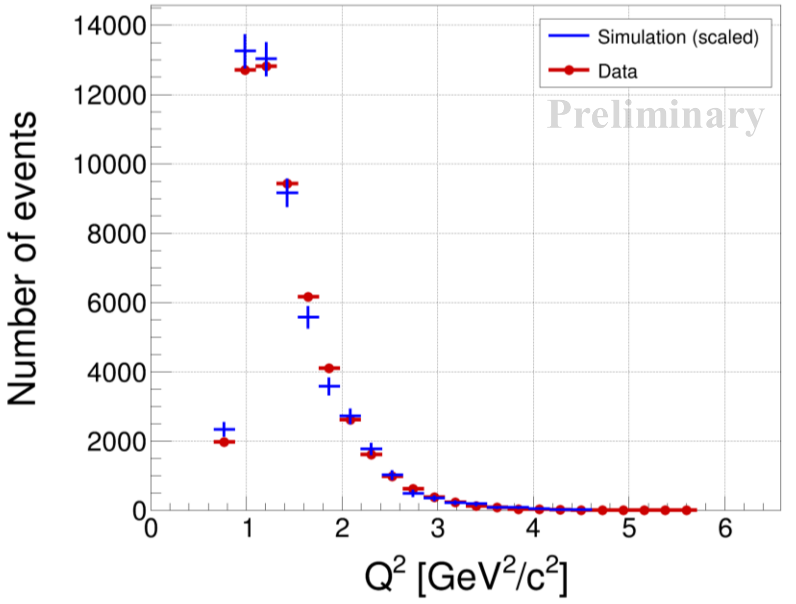
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Four-momentum squared (Q^2) – zoom-out

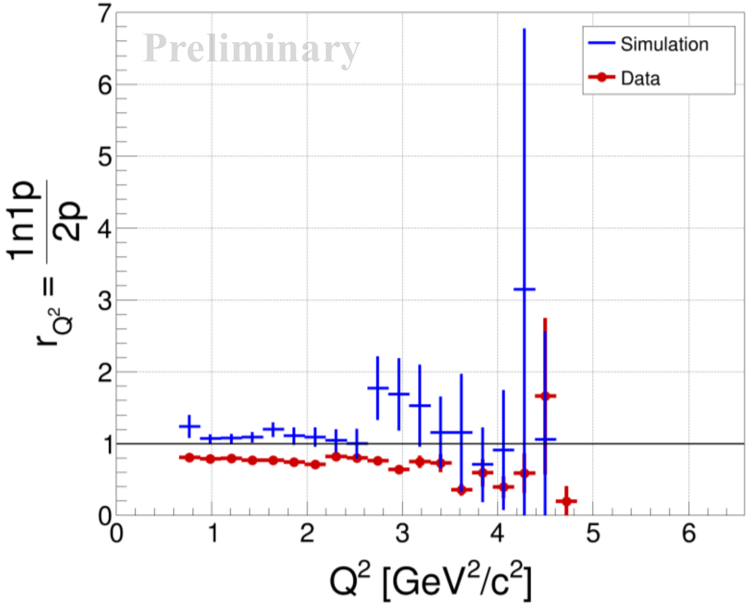
Q^2 in 1n1p



Q^2 in 2p



Q^2 distibution ratio



Where:

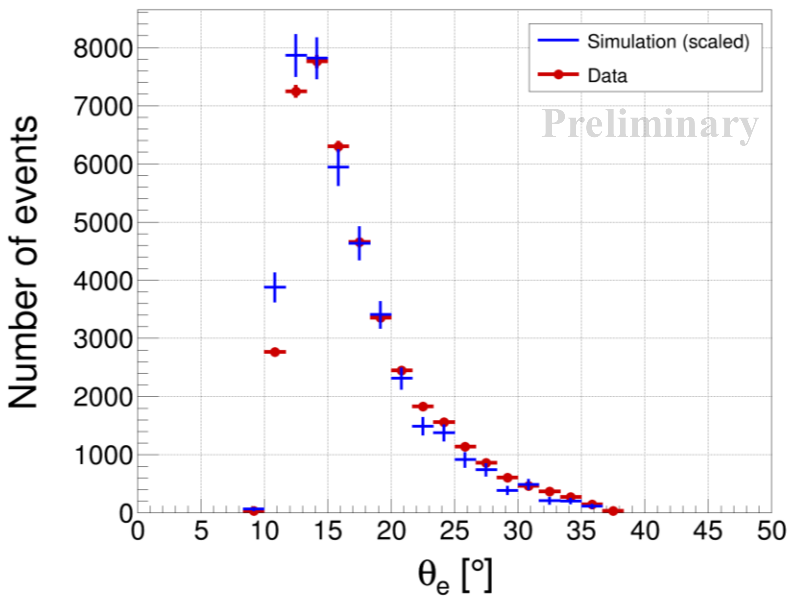
- $Q^2 = |q^2 - \omega^2|$
- $q = P_{beam} - P_e; \omega = E_{beam} - E_e$

Back

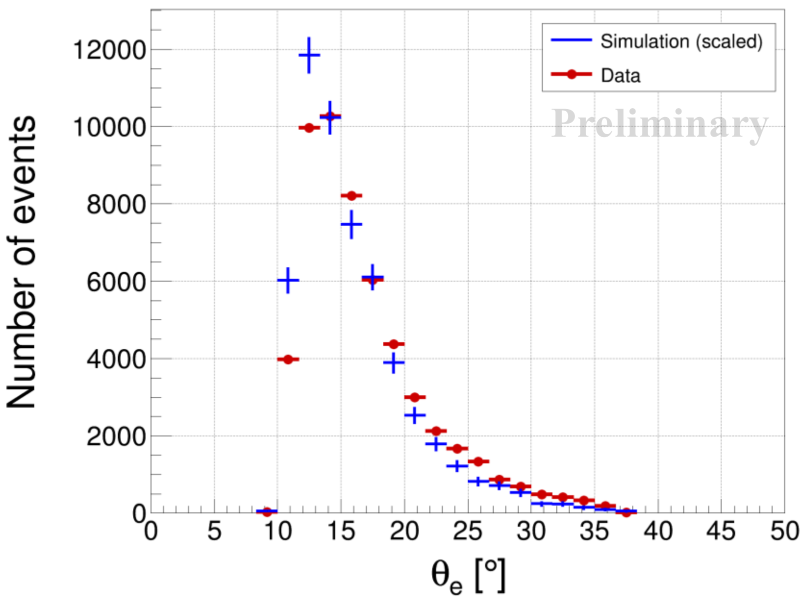
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Electron scattering angle – zoom-out

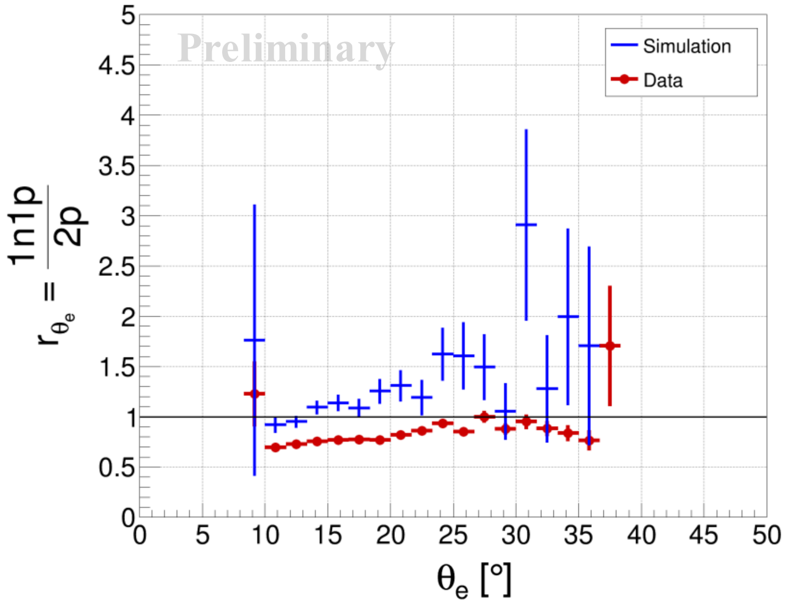
θ_e in 1n1p



θ_e in 2p



θ_e distribution ratio

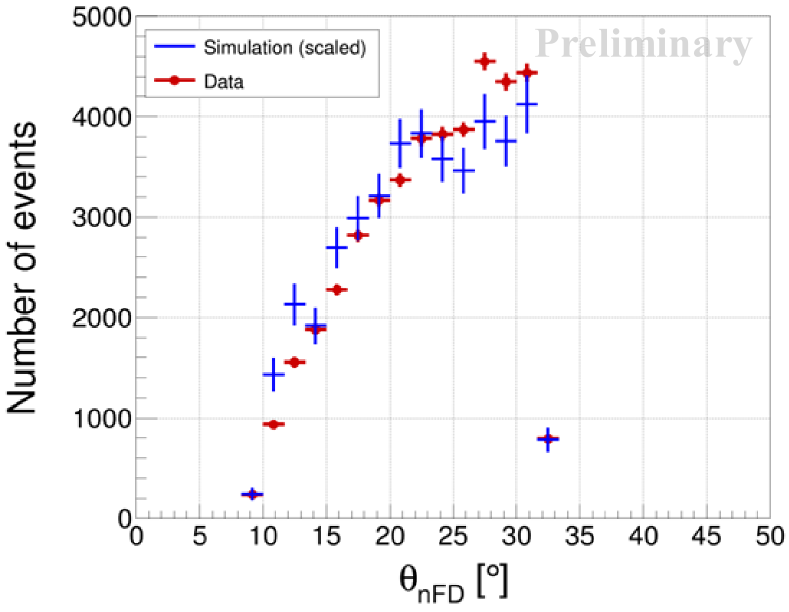


Back

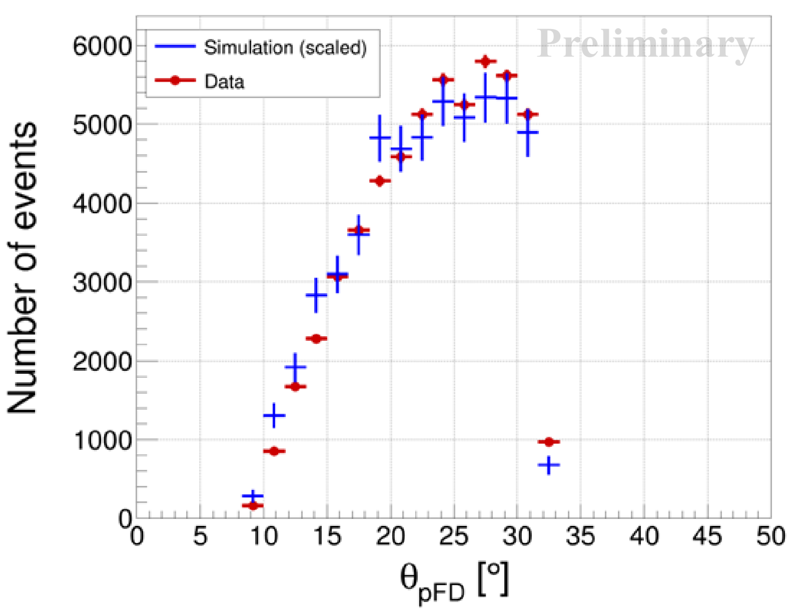
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Scattering angles of FD nucleons – zoom-out

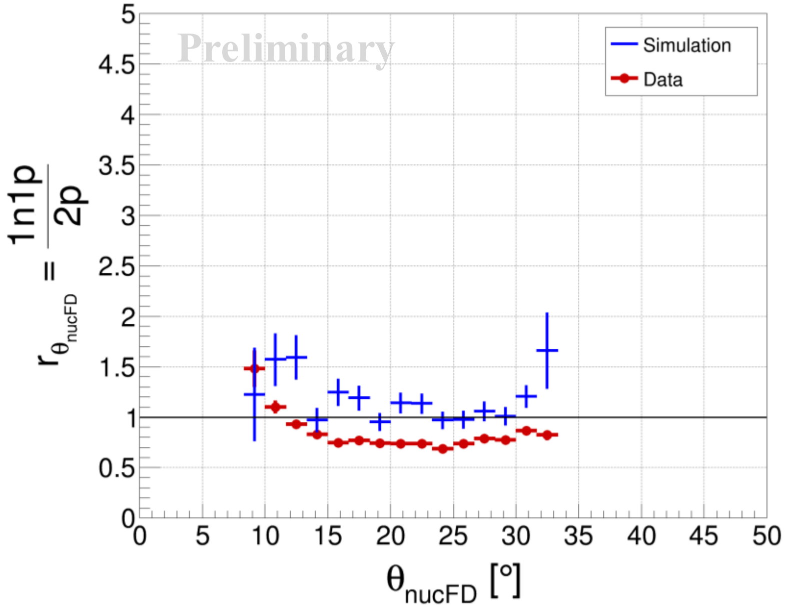
θ_{nFD} in 1n1p



θ_{pFD} in 2p



θ_{nucFD} distribution ratio



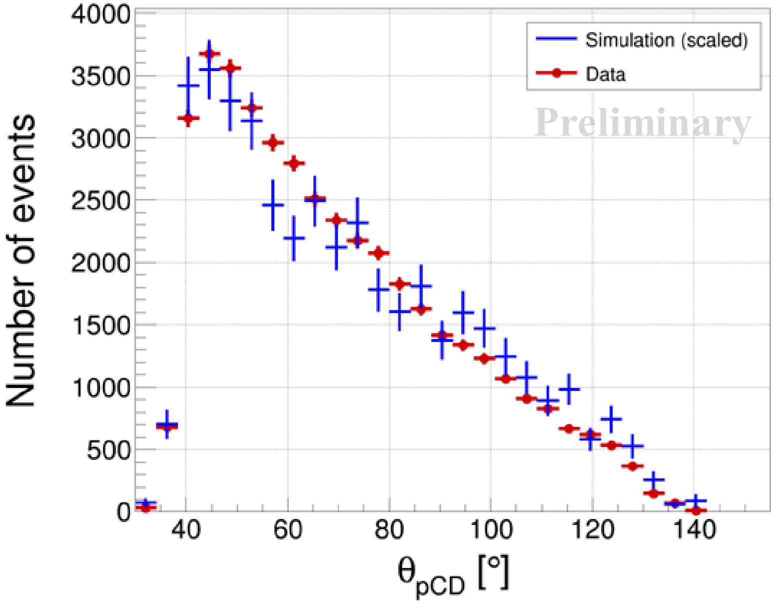
Back

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

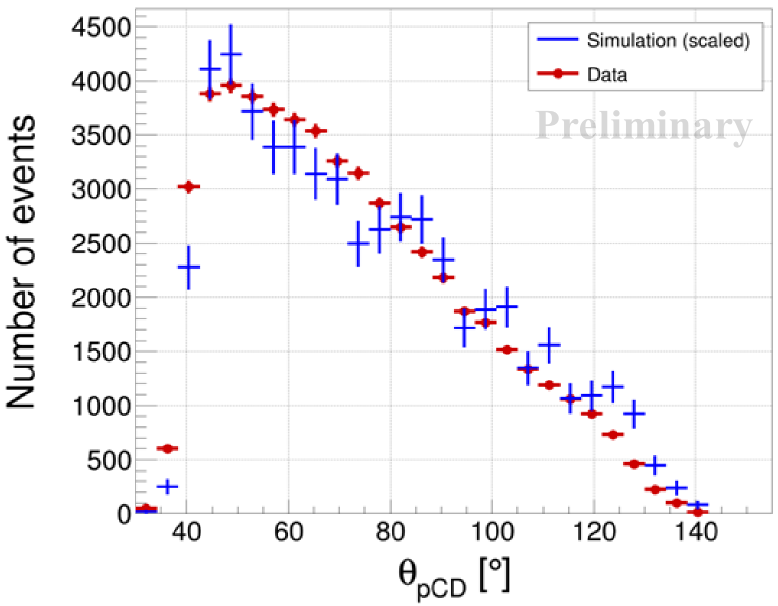
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Scattering angles of CD protons – zoom-out

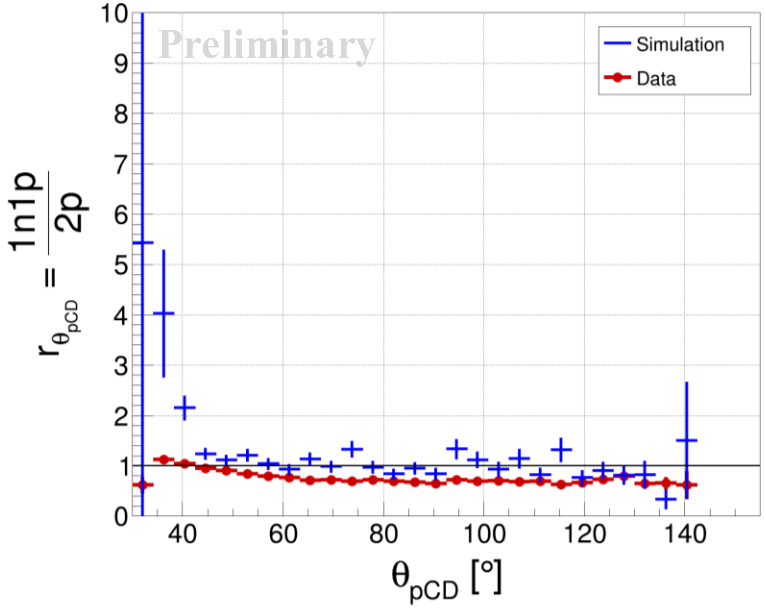
θ_{pCD} in 1n1p



θ_{pCD} in 2p



θ_{pCD} distribution ratio



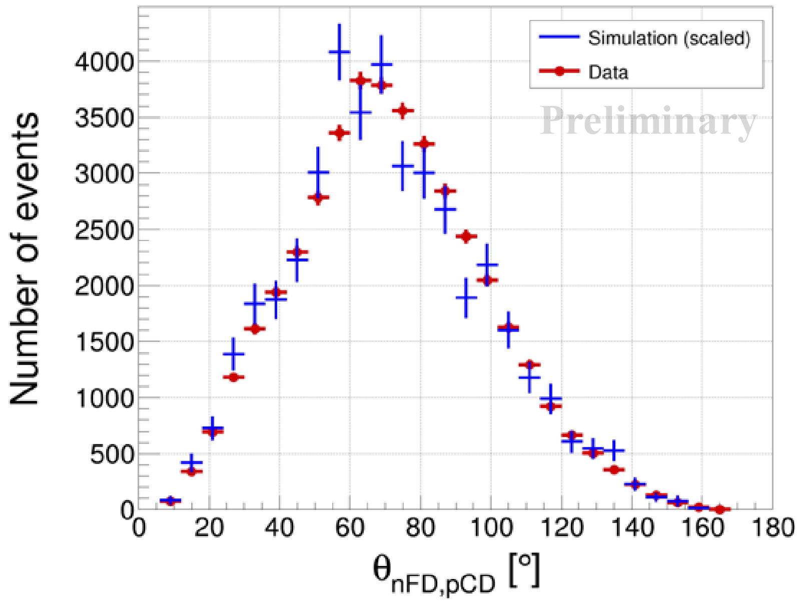
Back

pCD = CD proton

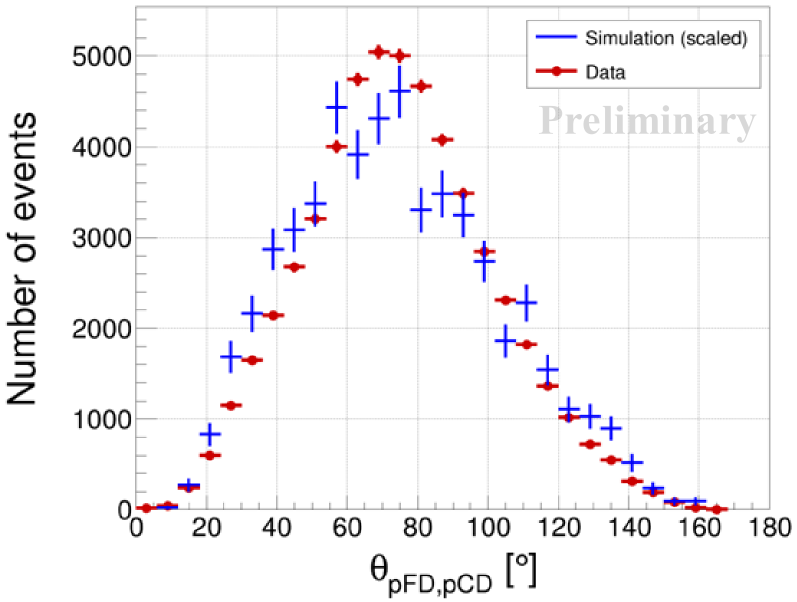
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Opening angles between FD and CD nucleon momenta ($\theta_{nucFD,pCD}$) – zoom-out

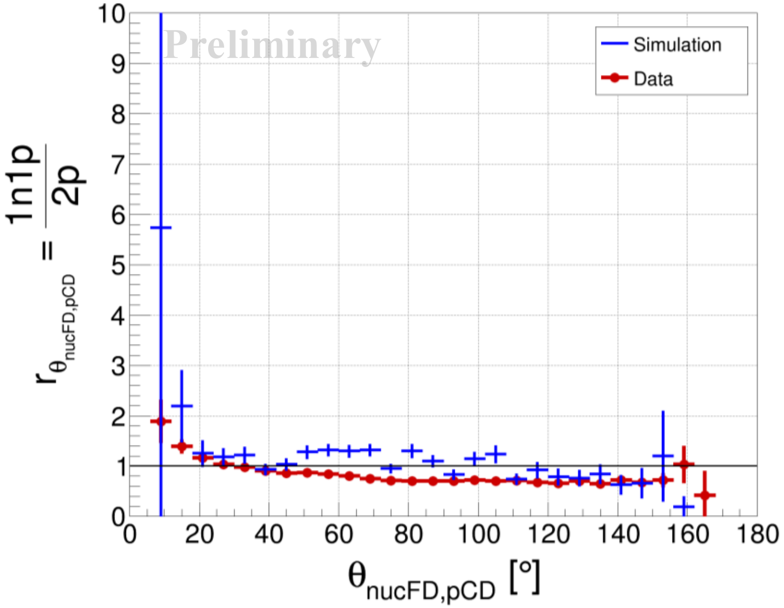
$\theta_{nFD,pCD}$ in 1n1p



$\theta_{pFD,pCD}$ in 2p



$\theta_{nucFD,pCD}$ distribution ratio

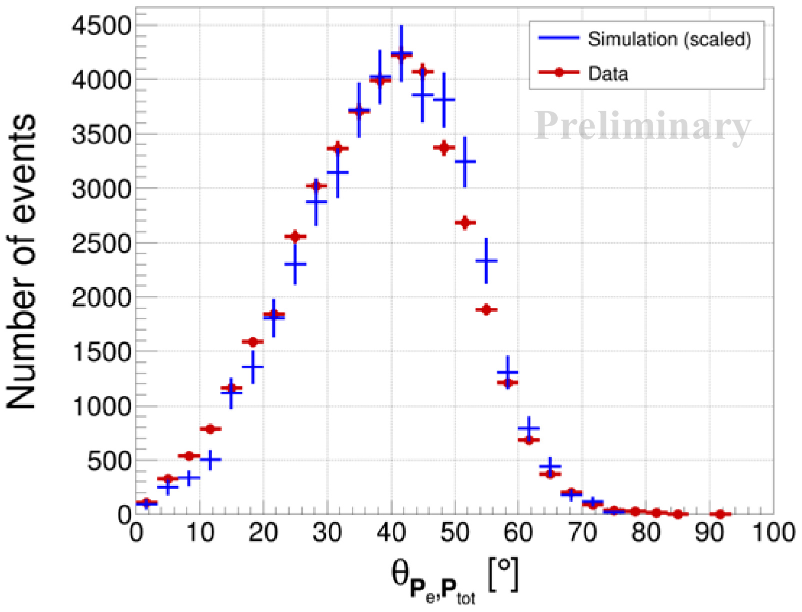


Back

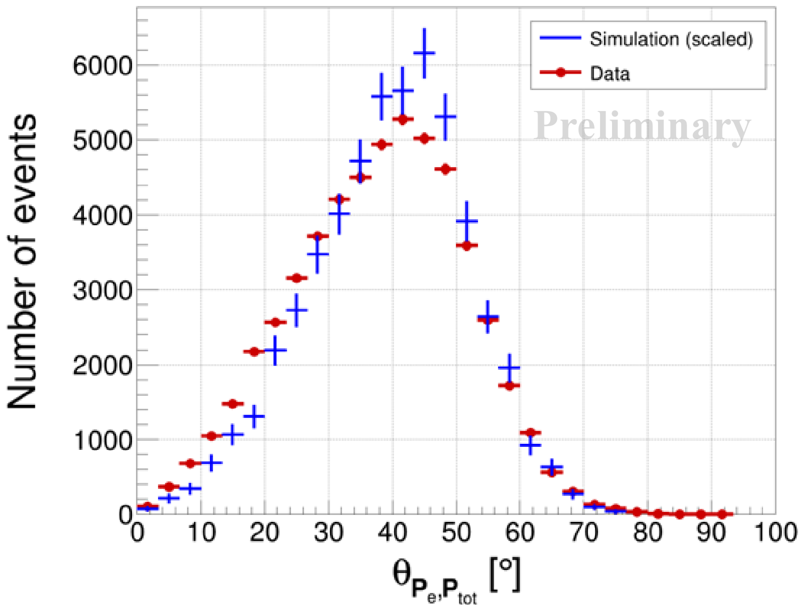
nFD = FD neutron	pFD = FD proton	pCD = CD proton	$nucFD$ = FD nucleon

Opening angles between P_e and P_{tot} ($\theta_{P_e,P_{tot}}$) – zoom-out

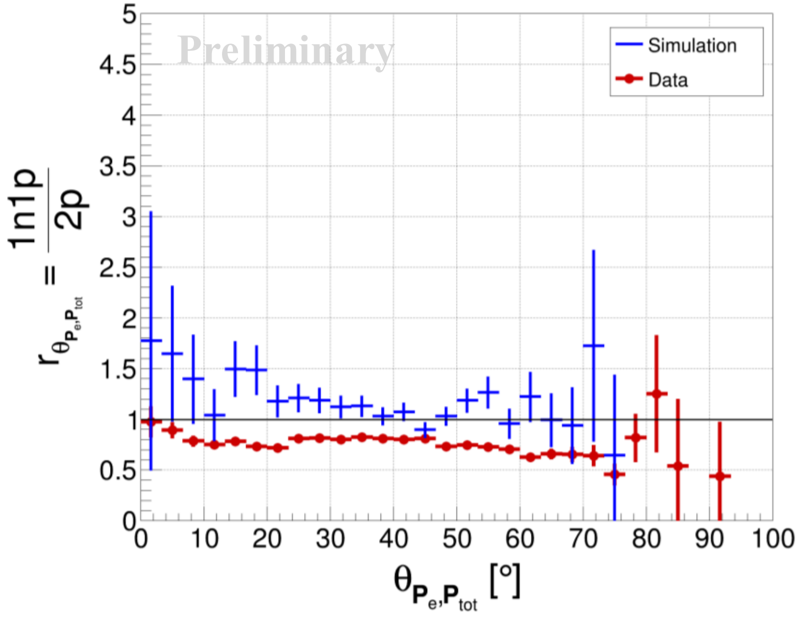
$\theta_{P_e,P_{tot}}$ in 1n1p



$\theta_{P_e,P_{tot}}$ in 2p



$\theta_{P_e,P_{tot}}$ distribution ratio



Where:

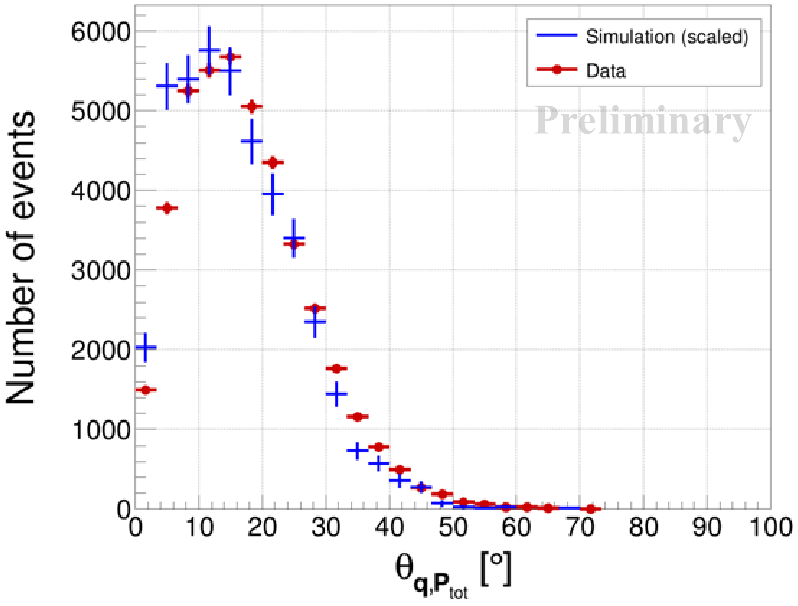
- $P_{tot} = P_{nucFD} + P_{pCD}$

Back

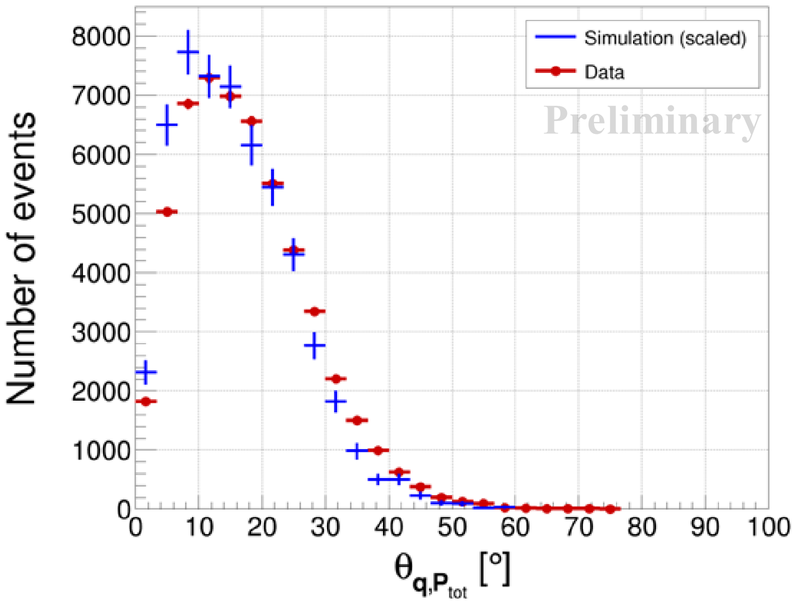
$nucFD$ = FD nucleon

Opening angles between q and P_{tot} ($\theta_{q,P_{tot}}$) – zoom-out

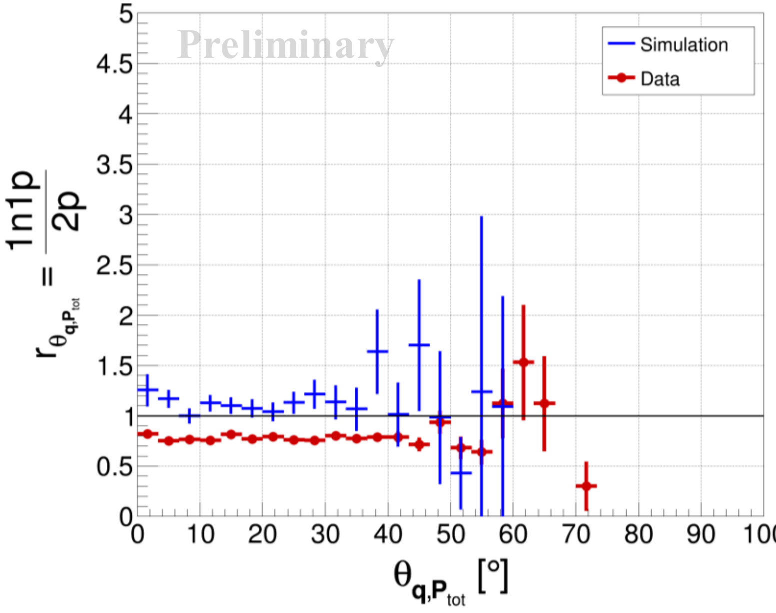
$\theta_{q,P_{tot}}$ in 1n1p



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



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



Where:

- $\boldsymbol{P}_{tot} = \boldsymbol{P}_{nucFD} + \boldsymbol{P}_{pCD}$
- $\boldsymbol{q} = \boldsymbol{P}_{beam} - \boldsymbol{P}_{e}$

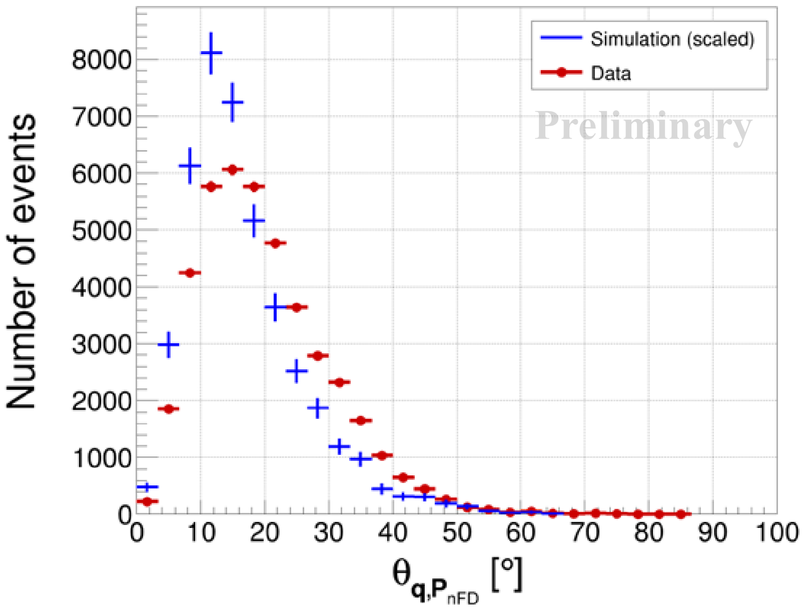
Back

$nucFD$ = FD nucleon

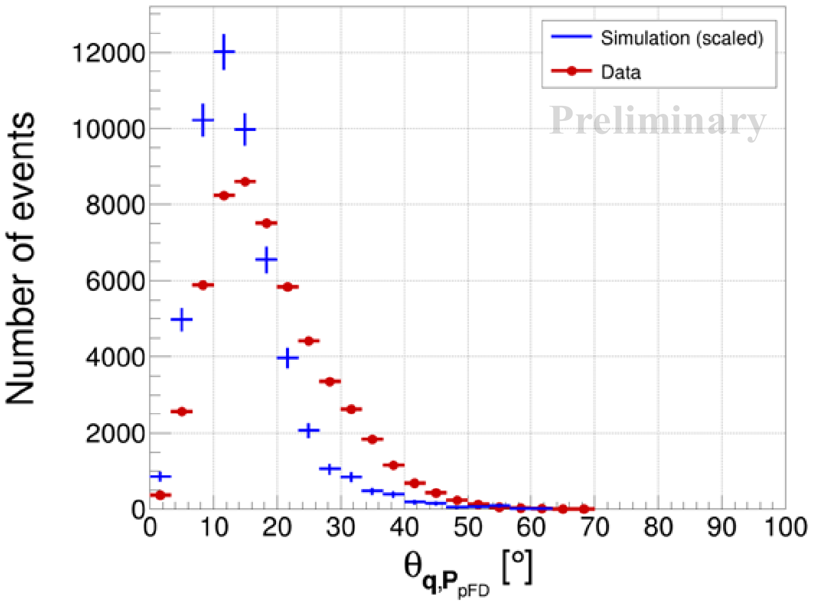
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Opening angles between q and P_{nucFD} ($\theta_{q,P_{nucFD}}$) – zoom-out

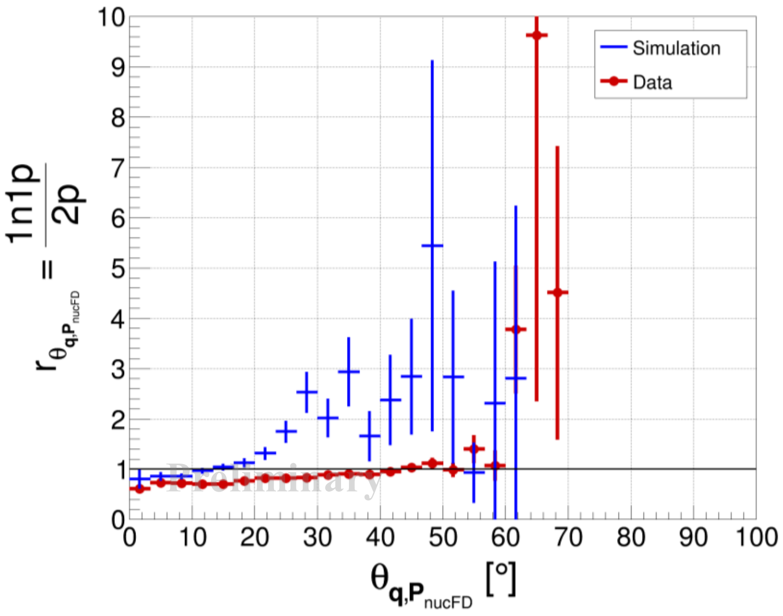
$\theta_{q,P_{nFD}}$ in 1n1p



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



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



Where:

- $q = P_{beam} - P_e$

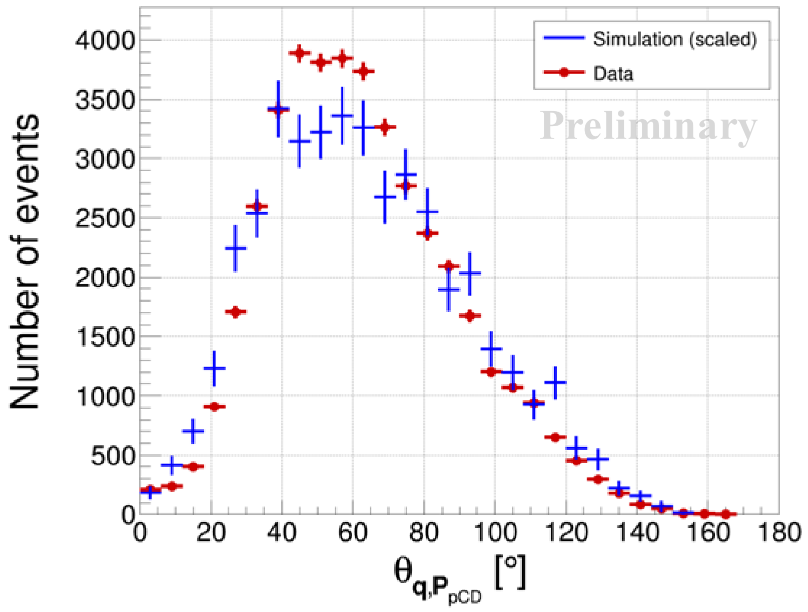
Back

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

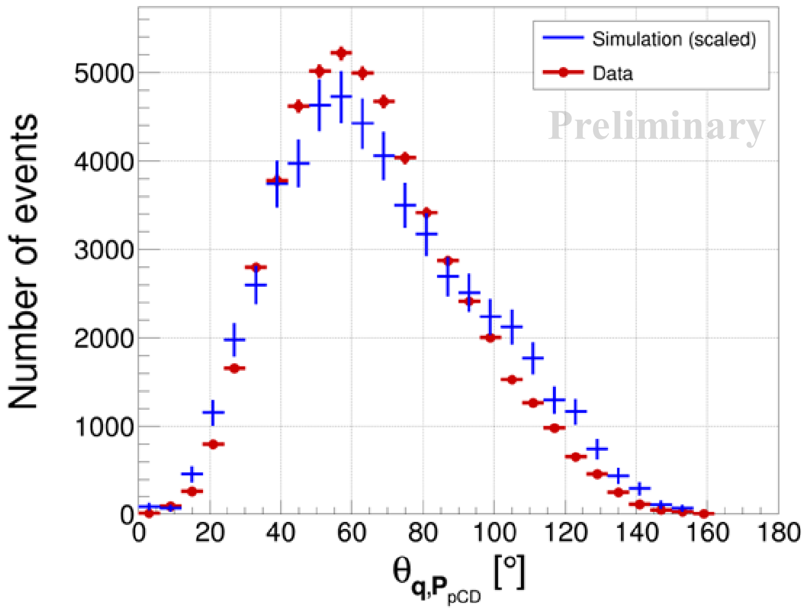
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Opening angles between q and P_{pCD} ($\theta_{q,P_{pCD}}$) – zoom-out

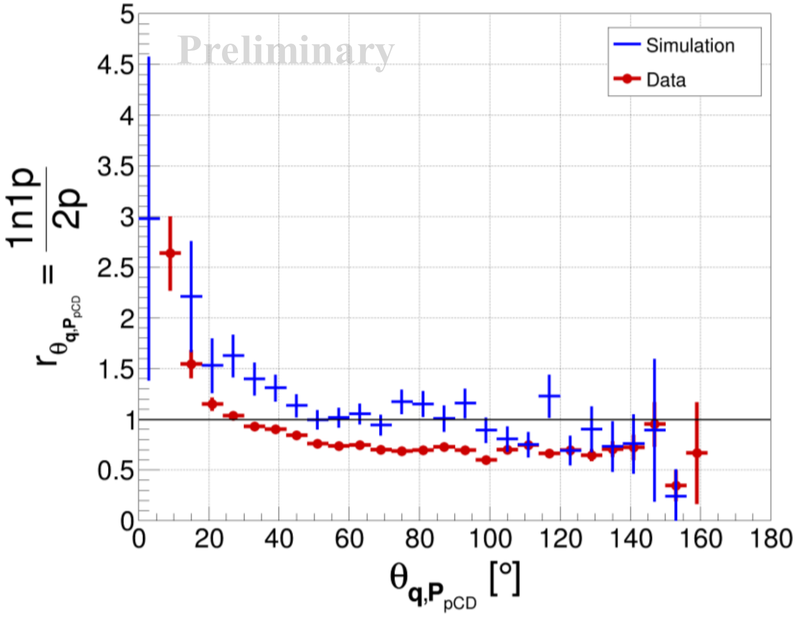
$\theta_{q,P_{pCD}}$ in 1n1p



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



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



Where:

- $q = P_{beam} - P_e$

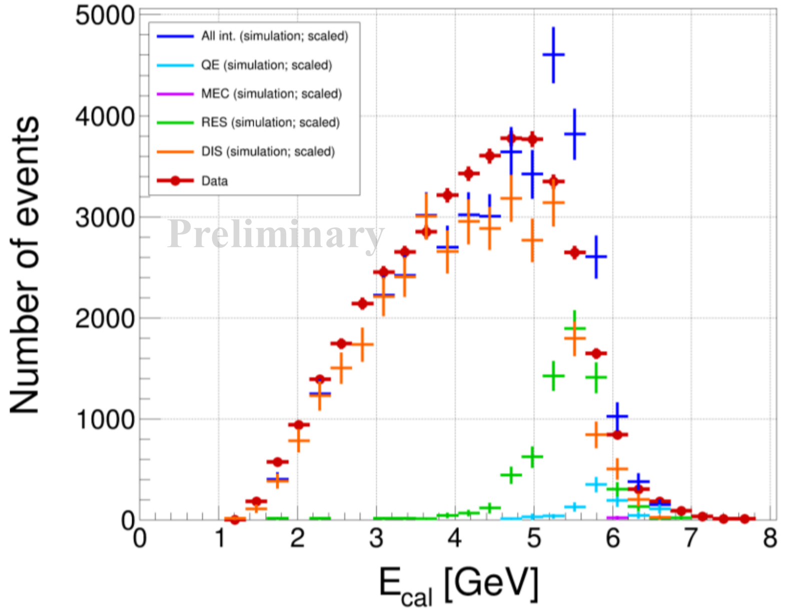
Back

pCD = CD proton

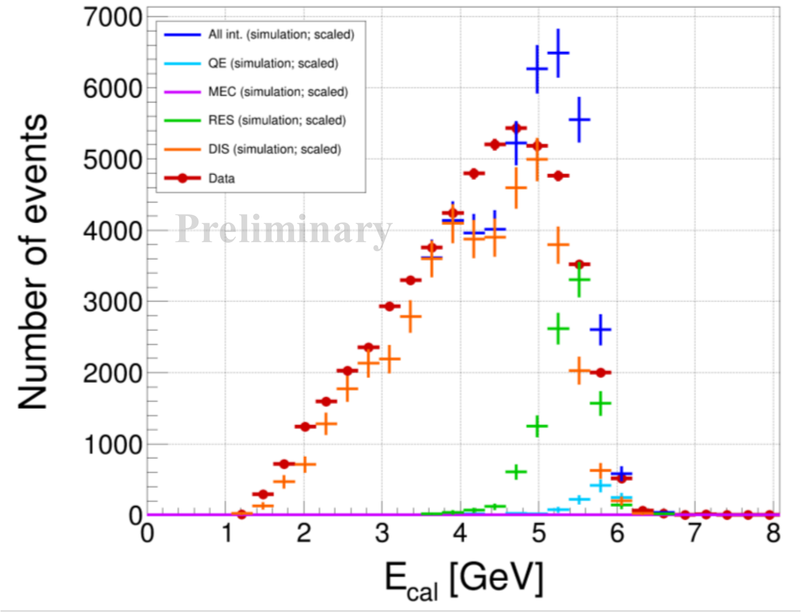
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

Reconstructed energy E_{cal} – zoom-out

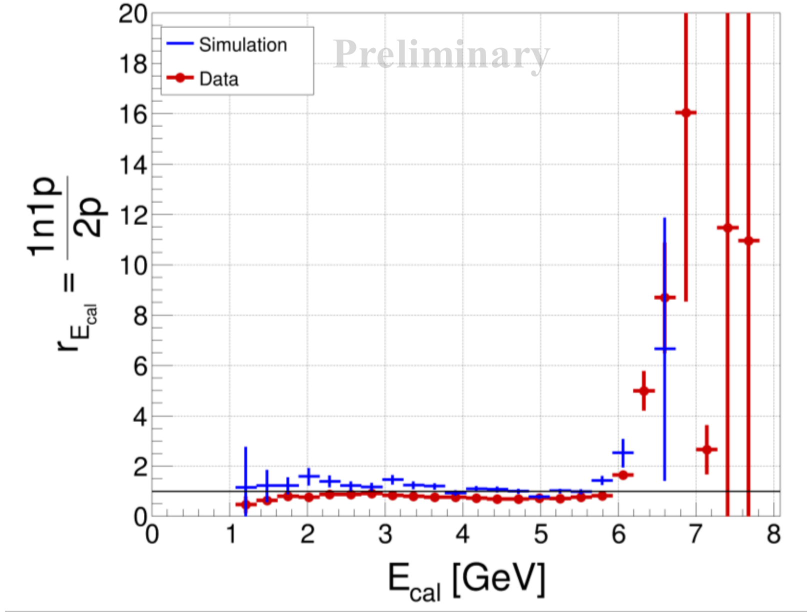
E_{cal} in 1n1p



E_{cal} in 2p



E_{cal} distibution ratio



Where:

- $E_{cal} = E_e + T_{nucFD} + T_{pCD}$
- $T_{nuc\ i} \equiv E_{nuc\ i} - m_{nuc\ i}$ is the kinematic energy of the nucleon i

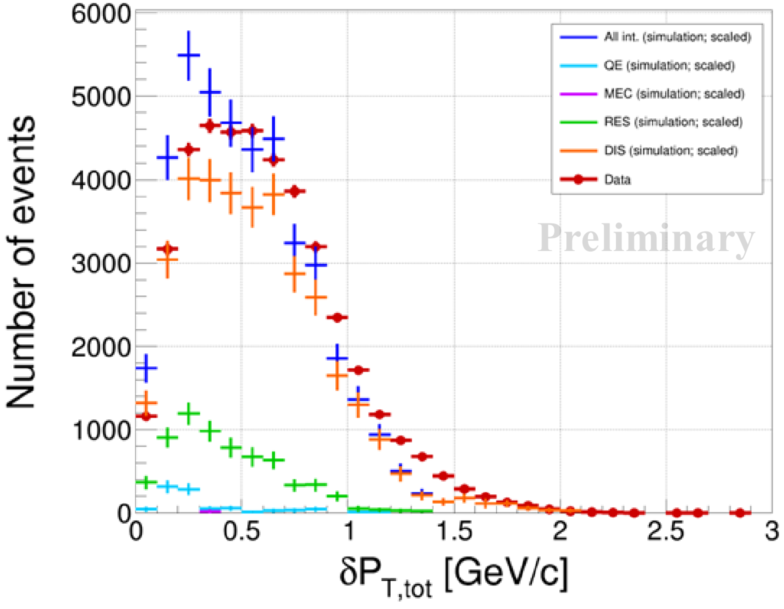
Back

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

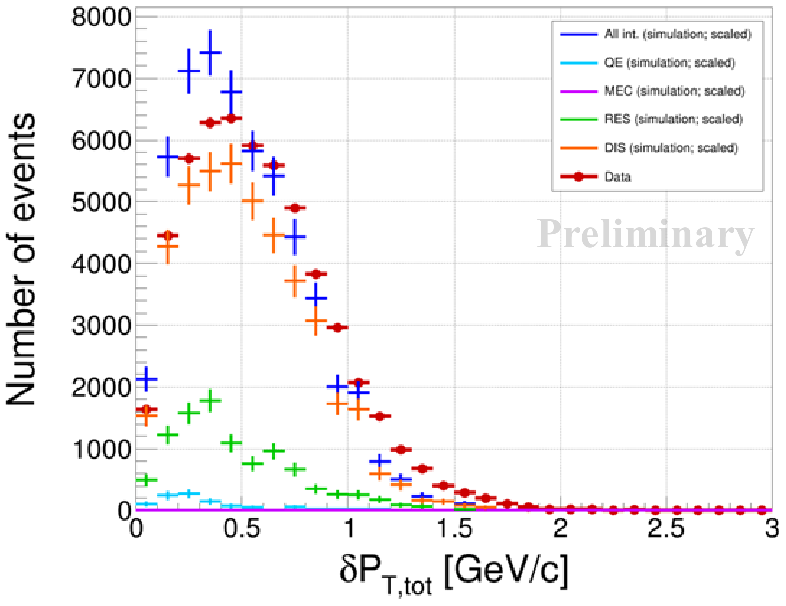
[12]C simulation and data at $E_{beam} \simeq 6$ GeV

TKI variables – $\delta P_{T,tot}$ – zoom-out

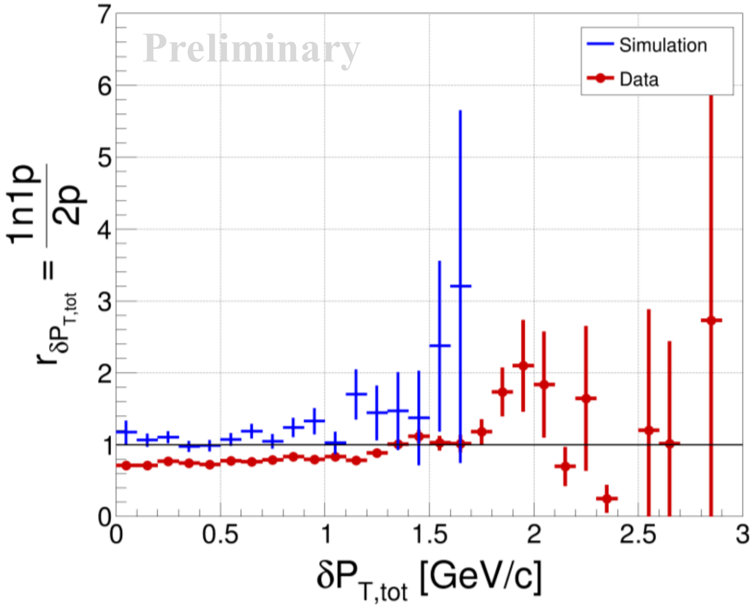
$\delta P_{T,tot}$ in 1n1p



$\delta P_{T,tot}$ in 2p



$\delta P_{T,tot}$ distibution ratio



Where:

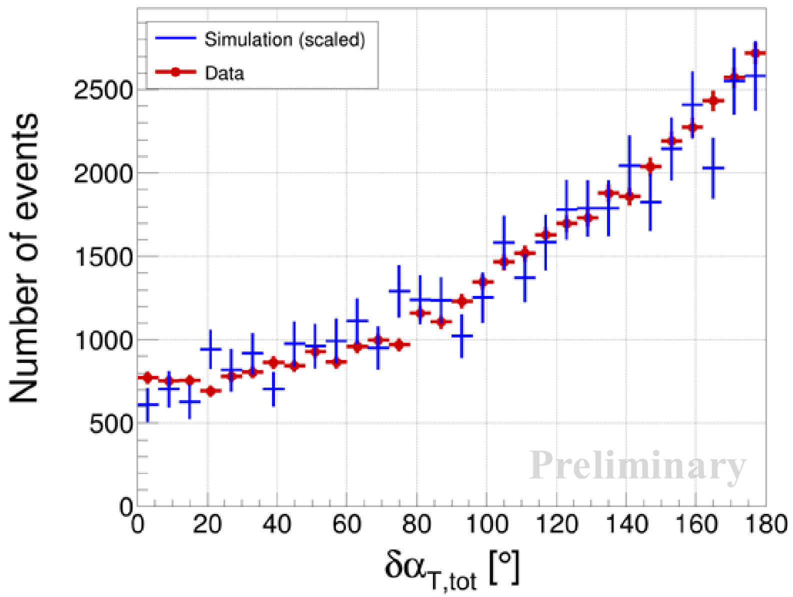
- $\delta P_{T,tot} = \left\| P_{T,e} + P_{T,tot} \right\|$

Back

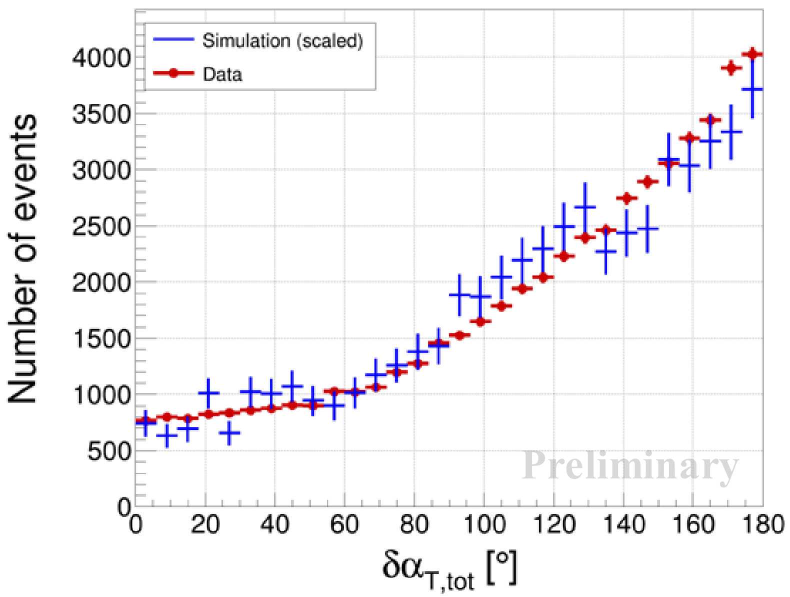
^{12}C simulation and data at $E_{beam} \simeq 6$ GeV

TKI variables – $\delta\alpha_{T,tot}$ – zoom-out

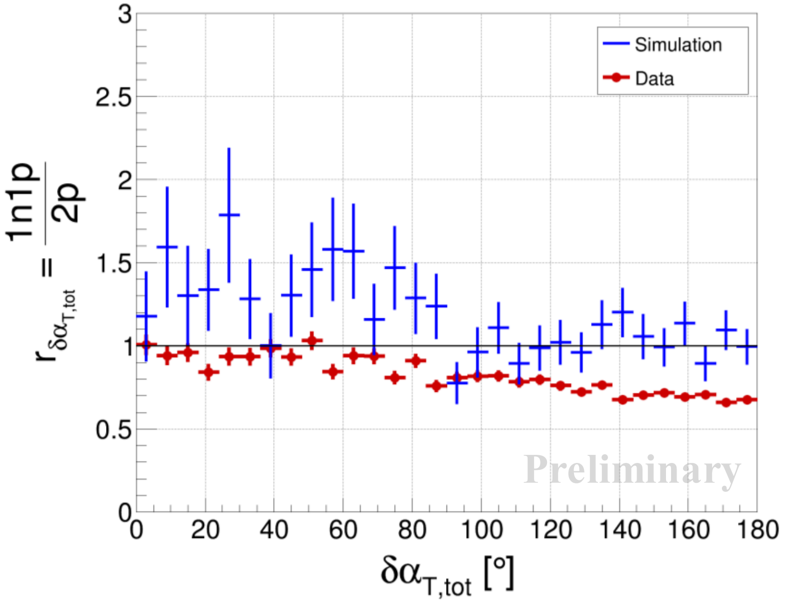
$\delta\alpha_{T,tot}$ in 1n1p



$\delta\alpha_{T,tot}$ in 2p



$\delta\alpha_{T,tot}$ distibution ratio



Where:

- $\delta\alpha_{T,tot} = \cos^{-1}\left[\frac{(-\boldsymbol{P}_{T,e})\cdot\delta\boldsymbol{P}_{T,tot}}{\|\boldsymbol{P}_{T,e}\|\|\delta\boldsymbol{P}_{T,tot}\|}\right]$

Back

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