Calculating Nuclear Transparency of Rho0 Meson in Hall D at JLab

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Introduction: Color Transparency

Introduced by Muller and Brodsky, 1982

- Strong force can be understood using two distinct theories at low and high energies.
- The transition from the low-energy scale to the high-energy scale has not been definitively established.
- Color transparency (CT), a key prediction of (QCD) is used to investigate the transition from nucleon-meson degree of freedom to that of quark-gluon degree of freedom

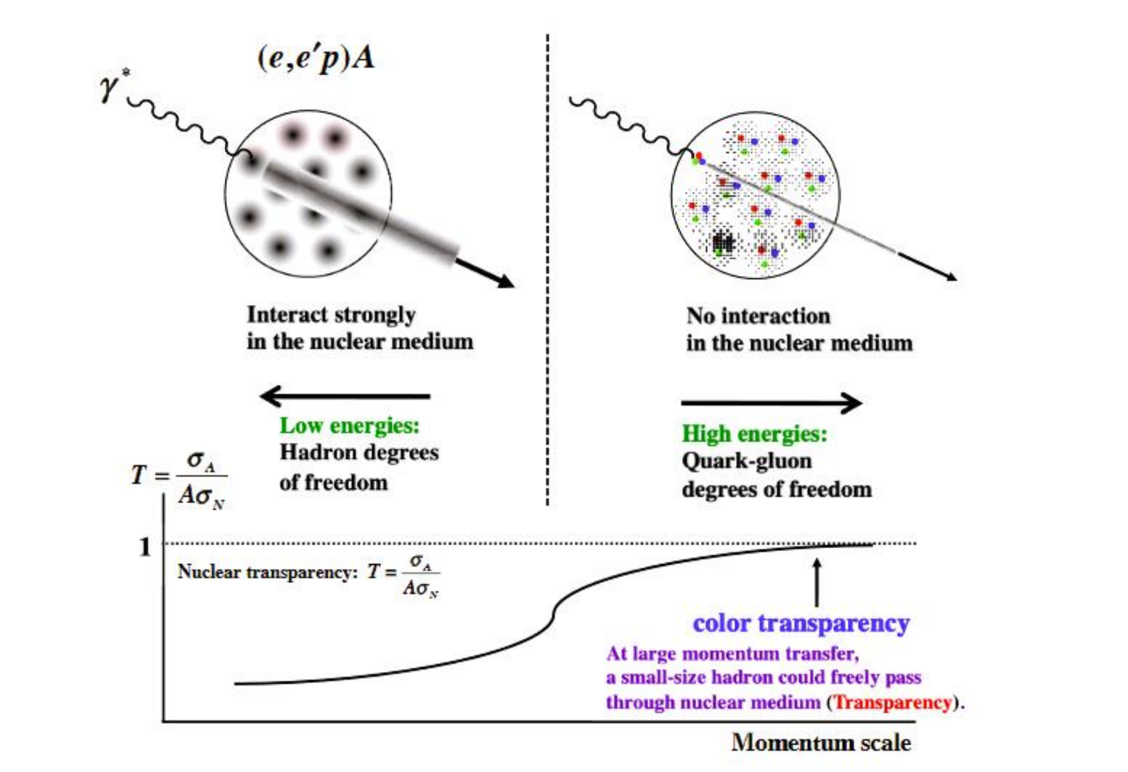
- Color transparency refers to the suppression of final state interactions of hadrons with the nuclear medium.
- This occurs in exclusive processes at high momentum transferred squared.

- Squeezing: At high momentum transfer the preferential selection of small configuration of quarks. :- Point like Configuration(PLC)
- Freezing: The PLC maintains its small size enough to cross the nucleus before it returns to regular size.
- Color-screening: Reduced interaction with hadrons in the surrounding nuclear medium.

Introduction: Nuclear Transparency

Nuclear Transparency is an observable to search for CT

- Nuclear Transparency is defined as the ratio of the cross section per nucleon for a process in the nucleus to that of a free nucleon.
- The onset of CT would involve the rise in the nuclear transparency as a function of energy.
- The onset of CT indicates the transition from nucleon-meson(low energies) picture to quark-gluon picture (high energies)



Kumano, S. Physics,4,565-577(2022)

$$Nuclear\ Transparency = T_A = \frac{\sigma_A}{A\sigma_N} \quad \begin{matrix} (nuclear\ cross\ section) \\ (free\ cross\ section\ of\ nucleon) \end{matrix}$$

.

Previous experiments

CT is well established at high energies.

Baryons:
A(p,2p): BNL
A(e,e' p): SLAC, JLAB ☹

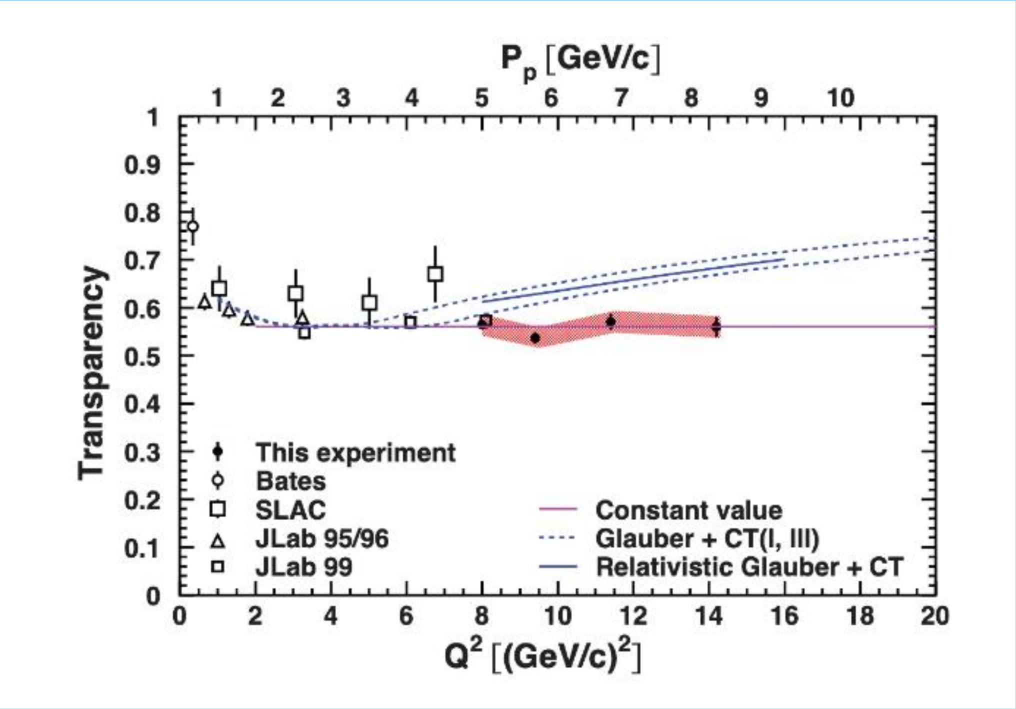
Mesons
A(π, di_jet): FNAL
A(γ, π^-p):Jlab
A(e, eπ^+):Jlab
A(e, eρ^0):DESY & JLab ☺

Study of CT at JLab:
E94139 : Quasi_elastic A(e,e',p) electron scattering on nuclei
E94104 : Pion photoproduction in Hall A
E01107 : Pion electroproduction in Hall A
E02110 : Rho0 meson electroproduction in Hall B
E1206107: Quasi elastic A(e,e',p) electron scattering on nuclei

Onset on CT has been measured in Mesons but not in Baryons

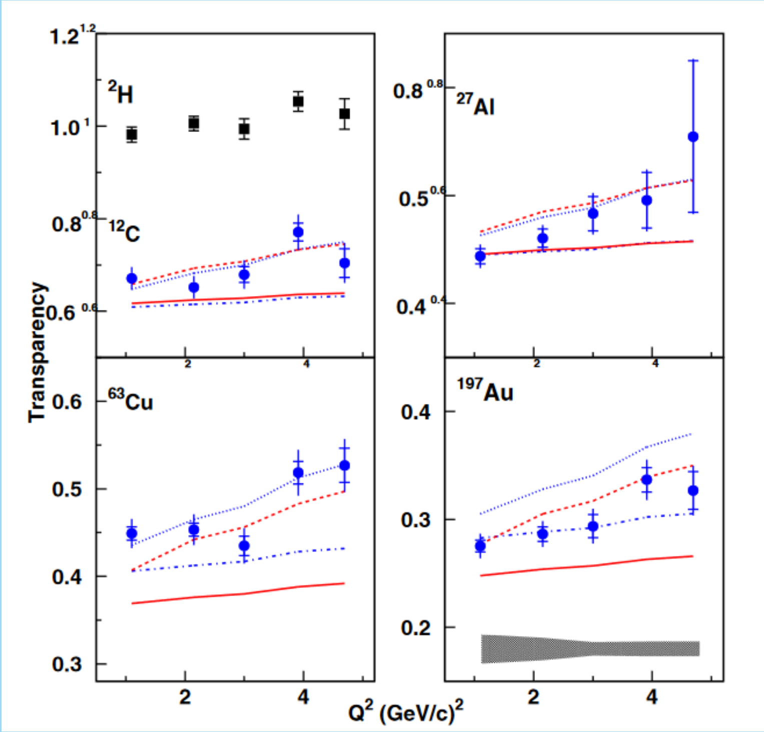
Previous experiments at JLab

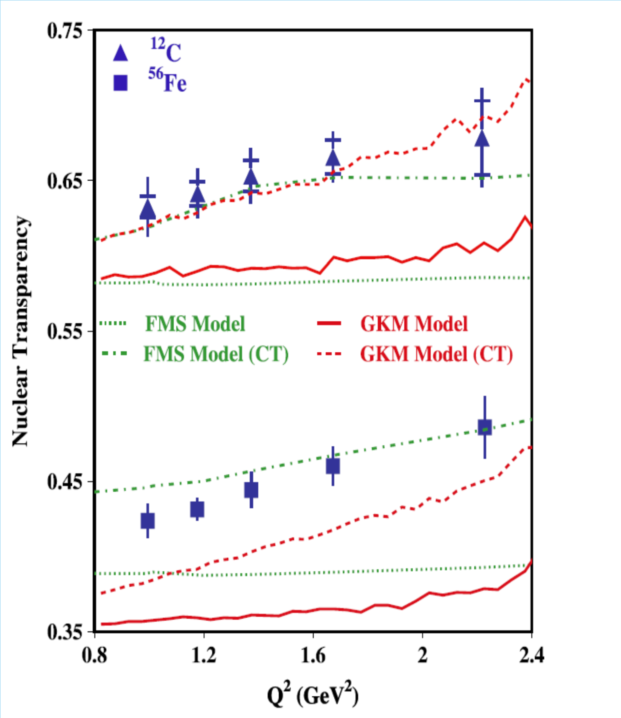
Quasielastic C(e,e',p) scattering didn't find CT in baryons



D. Bhetuwal et al., Phys. Rev. Lett.126, 082301(2021).

Pion and Rho electroproduction found onset of CT in mesons

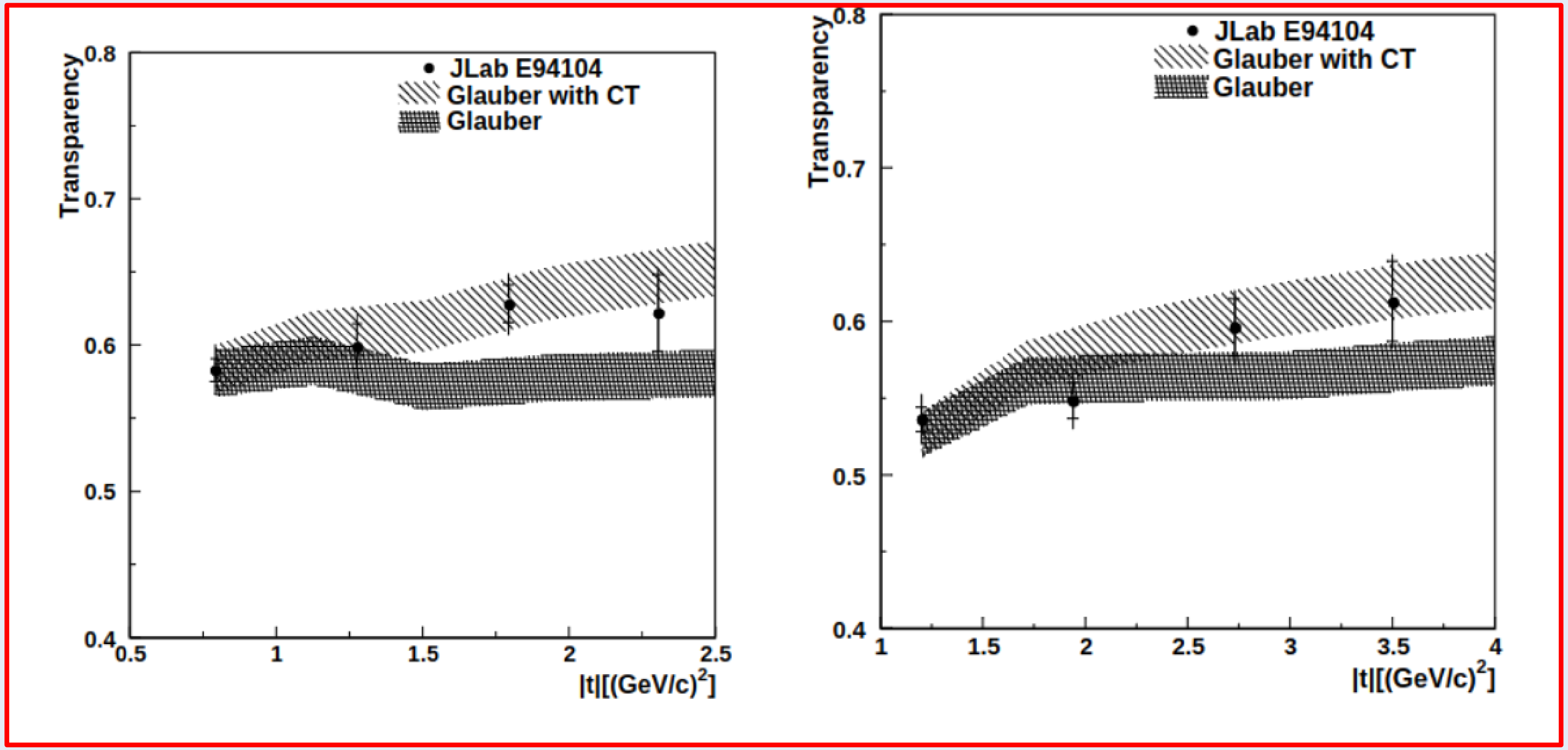




B. Clasie et al., Phys. Rev. Lett. 99, 242502(2007)
L. El Fassi et al. (CLAS), Phys. Lett. B712, 326(2012)

Previous Photoproduction experiments at JLab and Theoretical study

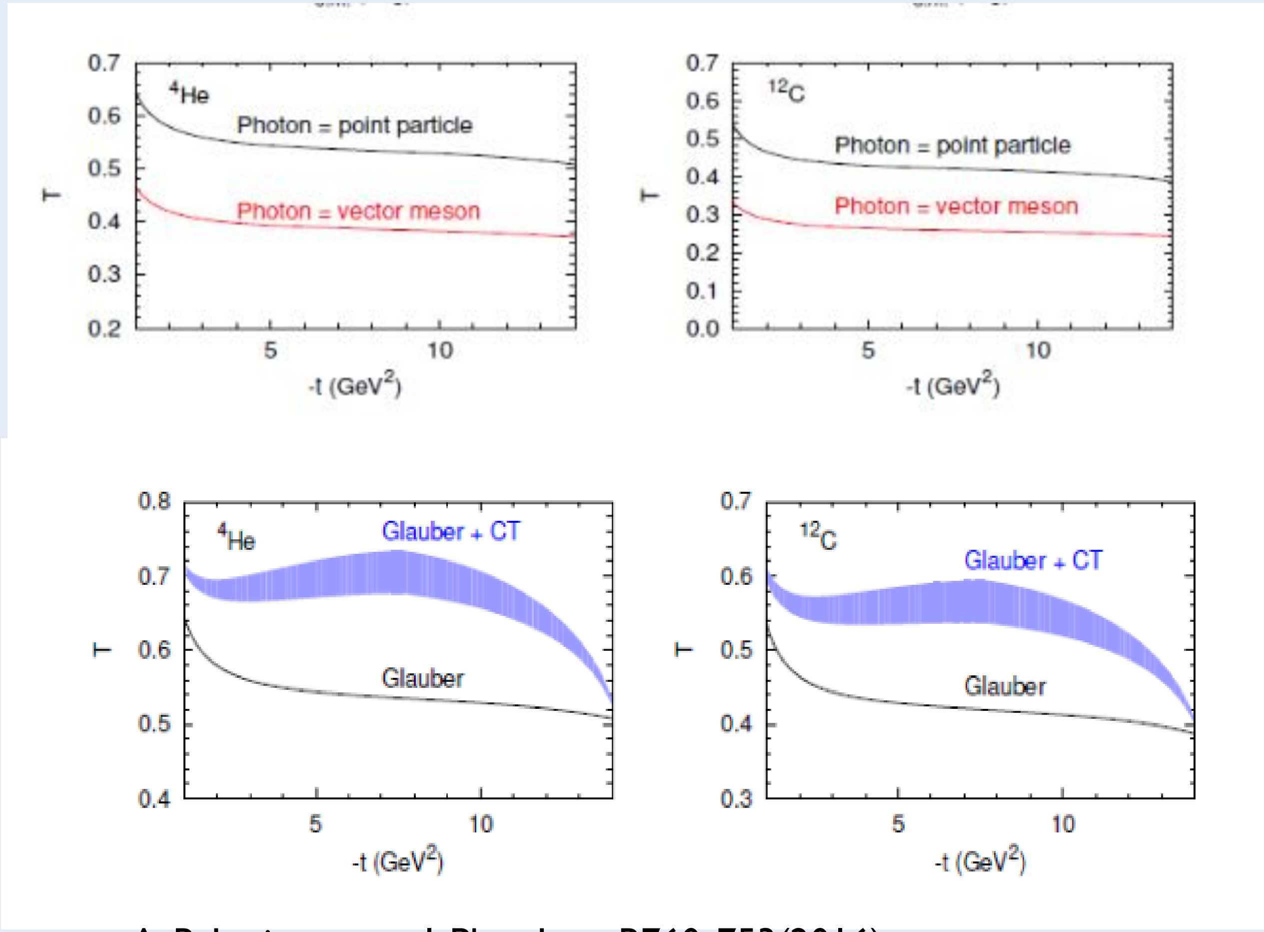
Pion photoproduction didn't find clear signature for onset of CT(uncertainty was too large)



Plot:: Nuclear Transparency of $^4He(\gamma, p, \pi^-)$ at $\theta^{\pi}_{cm} = 70°$ and $90°$ vs momentum transfer $|t|$.

D. Dutta *et al.*, Phys. Rev. C 68, 064603(2003)

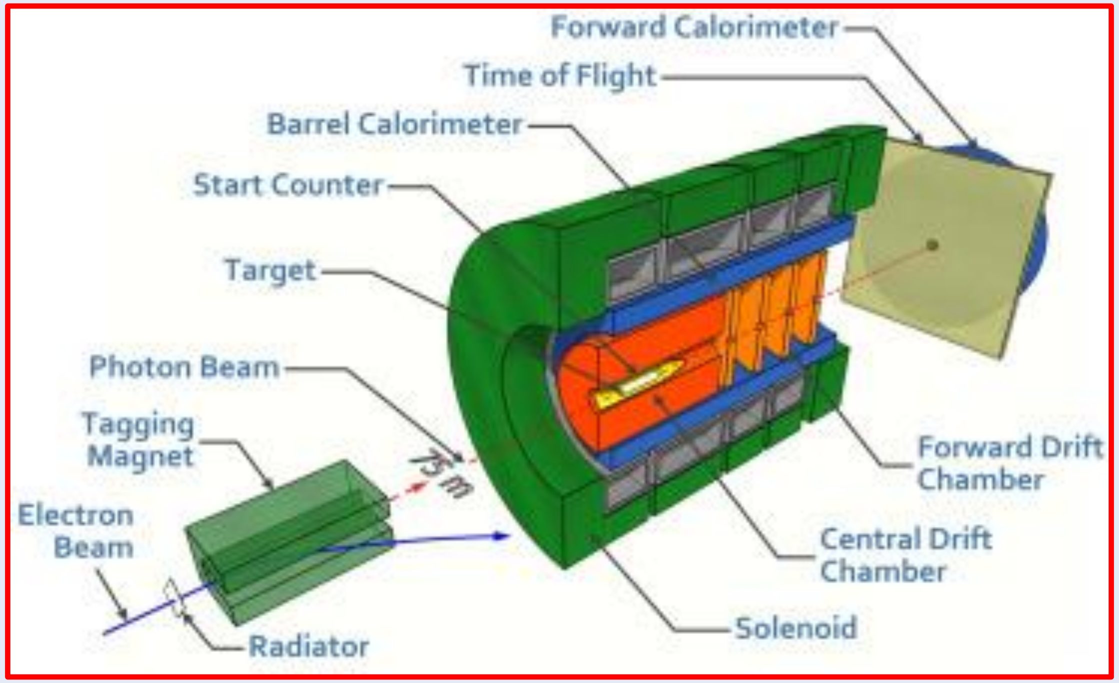
Theoretical Prediction of CT at large |t|



A. B. Larionov et al. Phys. Lett. B760, 753(2016)

- Theoretical predictions suggests a significant impact of the CT effect in photoproductions reactions at large |t|.
- More data are required for photoproduction from nuclei.
- An experiment was conducted in Hall D with additional reaction channel and an extended |t| range, including more nuclei to address this need.

Jefferson Lab Hall D

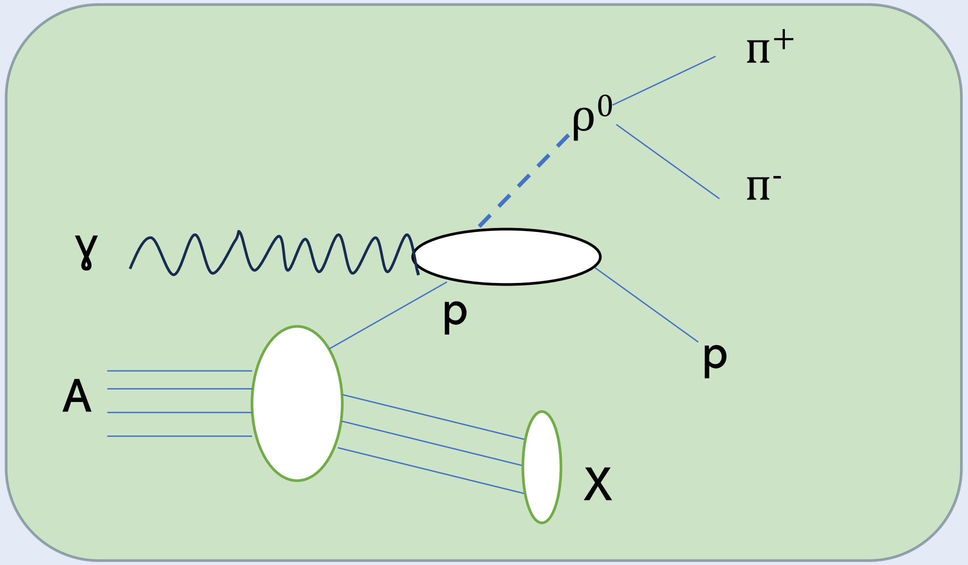


- The experiment was conducted in Nov-Dec 2021 in Hall D of Jefferson Lab.
- Used photon beam on deuterium, helium, and carbon targets.
- Primary objectives are to study short-range correlations, color transparency at large momentum transfers, and the bound structure of nucleus

S.Adhikari, et al. Nucl.Instrum.Meth.A 987,164807(2021)

Reaction of the interest

Proton Reactions	Neutron Reactions
$\gamma + p \to \pi^0 + p$	$\gamma + n \to \pi^- + p$
$\gamma + p \to \pi^- + \Delta^{++}$	$\gamma + n \to \pi^- + \Delta^+$
$\gamma + p \to \rho^0 + p$	$\gamma + n \to \rho^- + p$
$\gamma + p \to K^+ + \Lambda^0$	$\gamma + n \to K^- + \Lambda^0$
$\gamma + p \to K^+ + \Sigma^0$	$\gamma + n \to K^0 + \Sigma^0$
$\gamma + p \to \omega + p$	—
$\gamma + p \to \varphi + p$	—



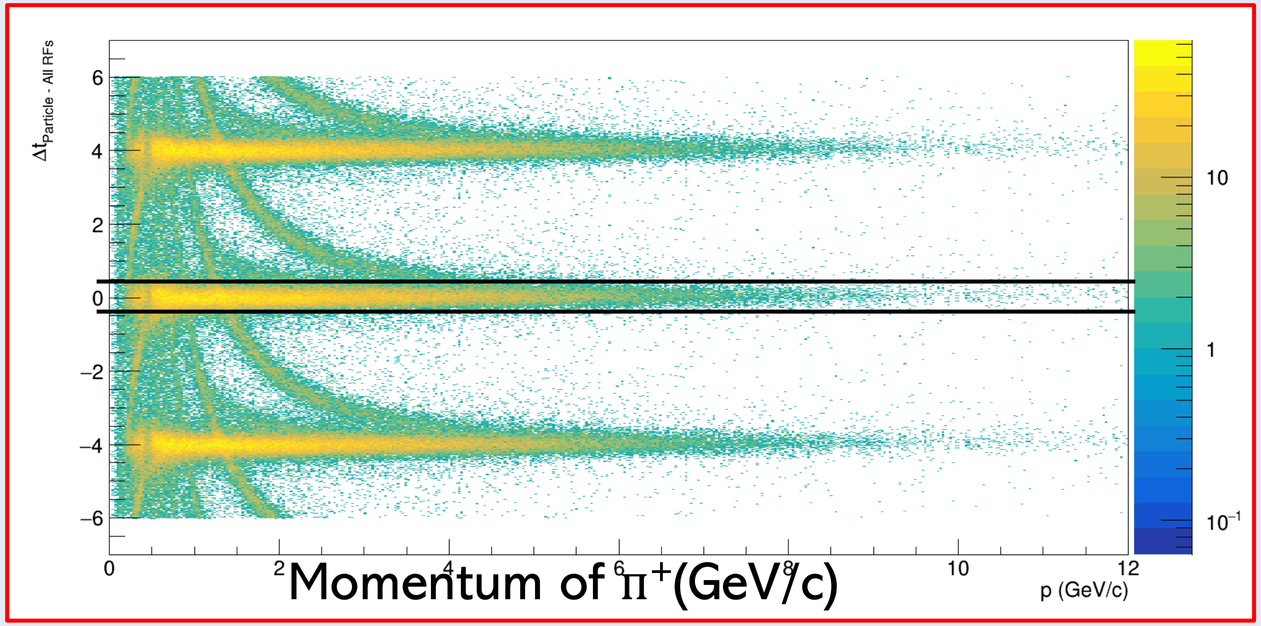
$$\gamma A \to \pi^+ \pi^- pX$$

GlueX Framework

- GlueX Analysis Library
- Reaction Filter Plugin :
- GlueX Root Analysis (Dselector)

Standard PID Timing Cuts:

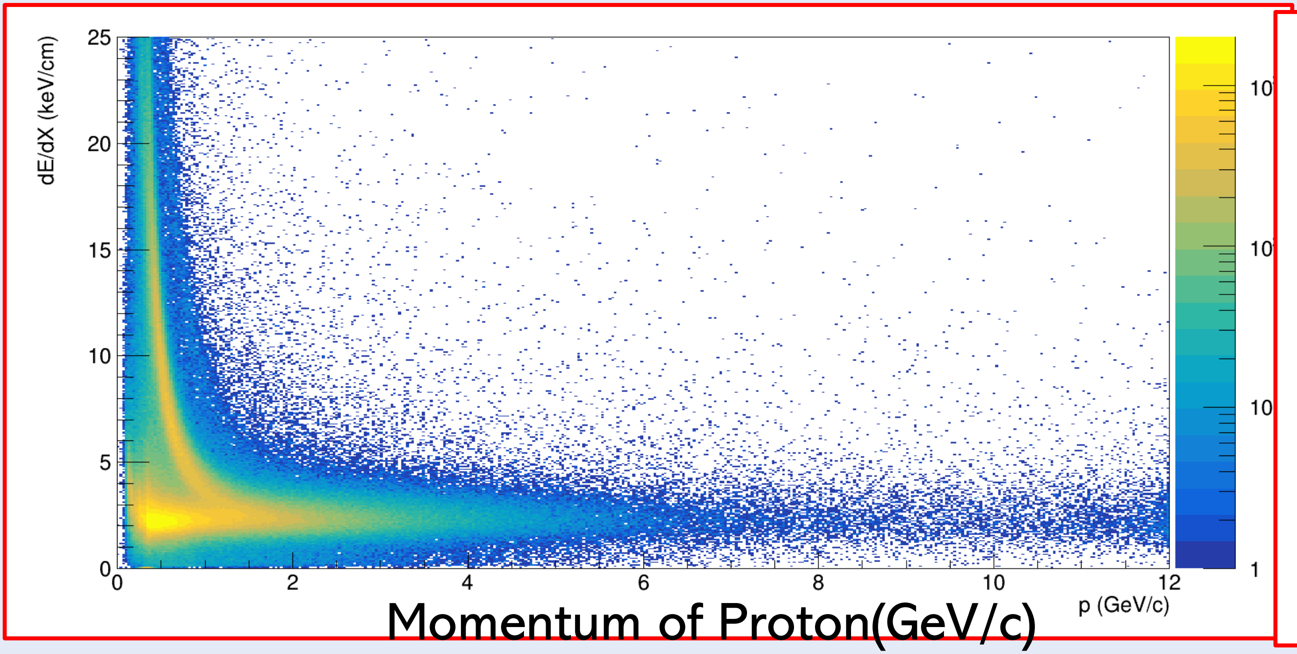
Timing cuts are applied only on the system with the best timing information available, in the order: BCAL/TOF/FCAL/SC.

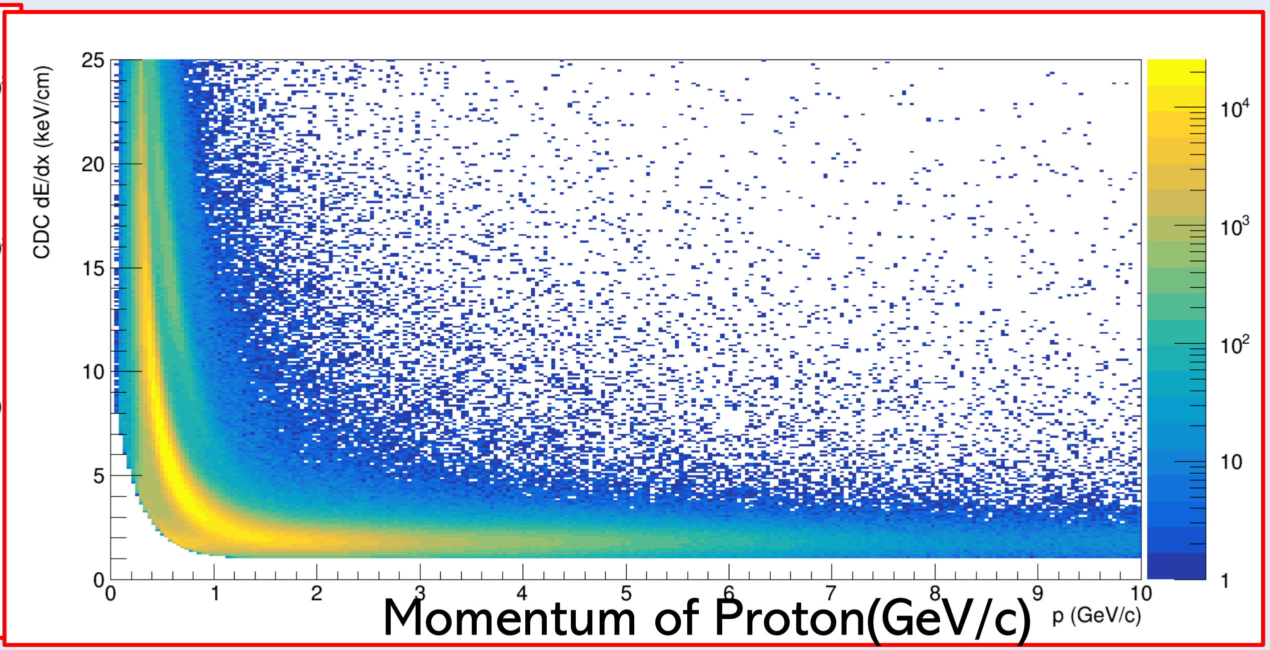


Plot: Timing of TOF detector vs. π^+ candidate momentum.

TOF can separate kaon and pions up to energies 1.9 GeV.
It is possible to identify proton with very good efficiency up to 3GeV.

Standard PID Cuts :Track Energy Loss Cut





Plot: dE/dx vs momentum of proton candidate before applying standard energy loss dE/dx cuts for single deuterium run

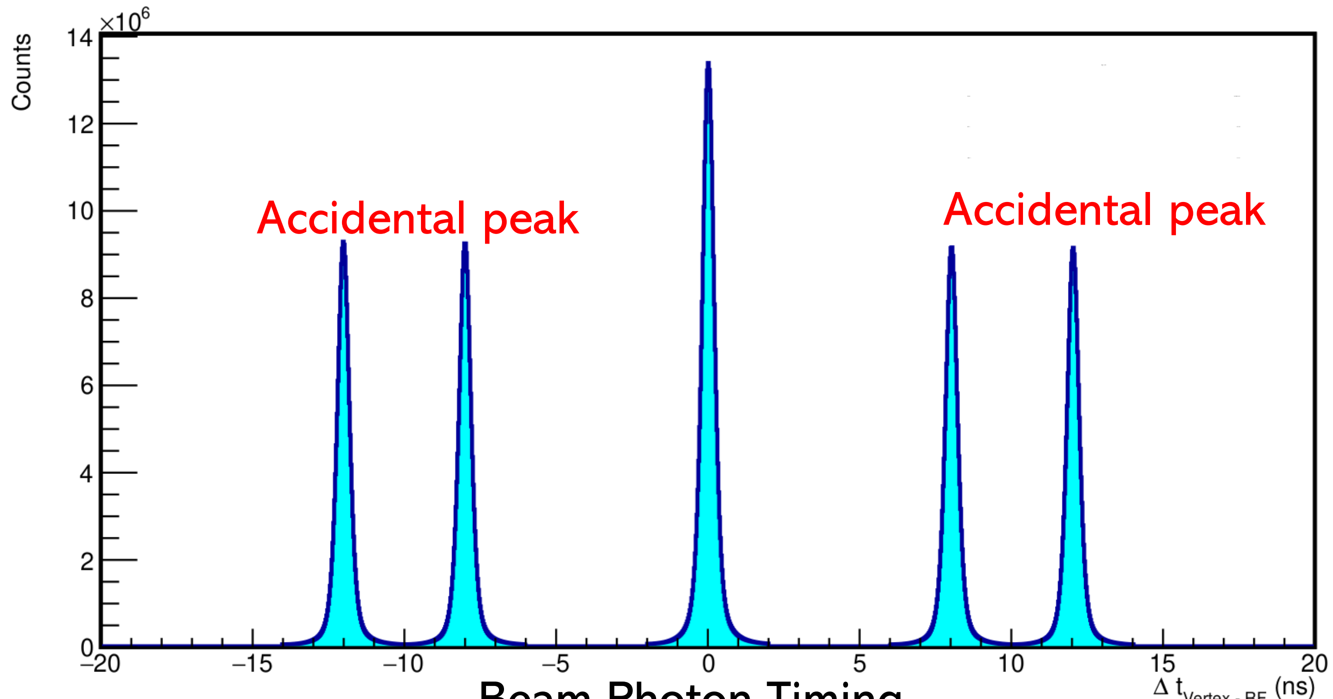
Plot: dE/dx vs momentum of proton candidate after applying standard energy loss dE/dx cuts for full deuterium run

Looking the energy deposited at CDC :: proton and pions can be separated up to energies of ~800 MeV.

Event Selection: Accidental Subtraction.

Used DSelector (GlueX Root Framework Analysis)

Prompt Peak



Plot: Accidental Subtraction

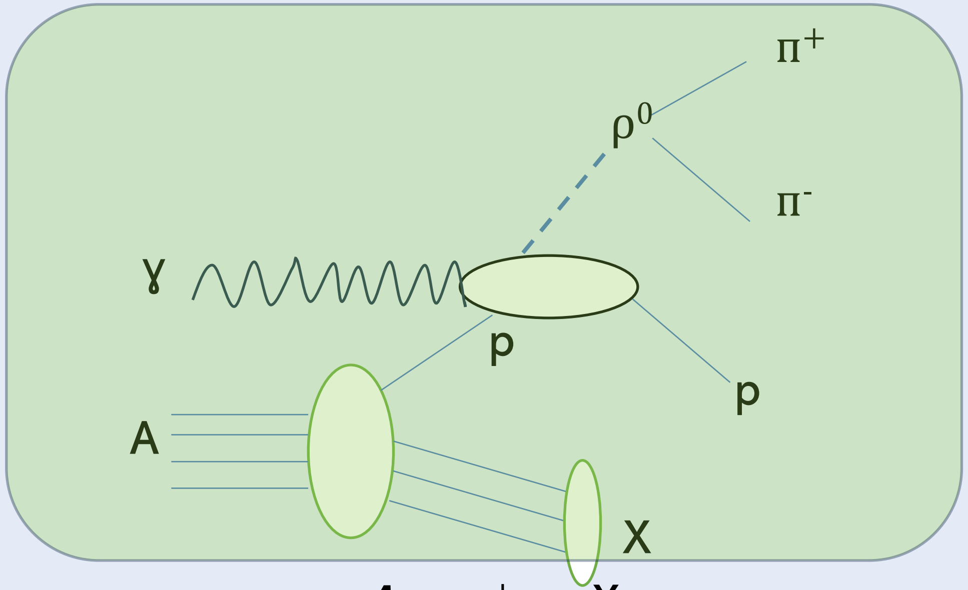
Note: Used DSelector (GlueX Root Framework Analysis)

- Beam bunches arrive every 4 ns
- Prompt beams are properly-matched photoproduced events
- Central peak also contains contribution from background coincidence
- Need to correct for accidental peak under the prompt peak
- Accidentals are scaled by ¼ , then subtracted from central peaks which statistically removes background of coincidence from the central peak

Additional Selection cuts:

- Numbers of shower tracks set to five and extra tracks were rejected.
- Beam energy : 6.5 < Eɣ < 10.8 GeV

Event Selection: Rho0 meson



$\gamma A \rightarrow \pi^+ \pi^- pX$

- Kinematic fit constraint enforce on conservation of four momentum and energy.
- Constraint on vertex: Decaying pions originates from same point in space.
- four beam bunches on each side of the primary bunch.

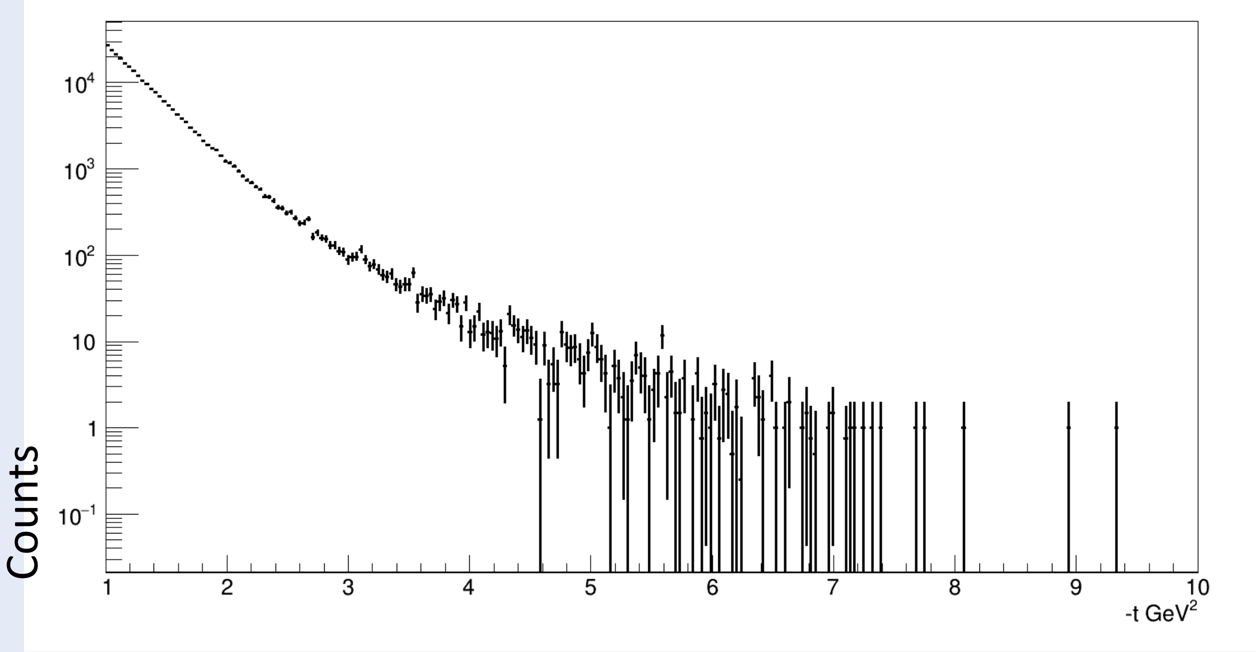
- Select on particle based hypothesis
- Fiducial cuts.
- Cuts on beam energy and Momentum Transfer
- Cut on Missing Momentum ro remove events from SRC pairs

Mandelstam Variable t

$$(\gamma A \rightarrow \pi^+\pi^- pX)$$

Mandelstam Variable "t" is defined in terms of beam photon and the final-state particles

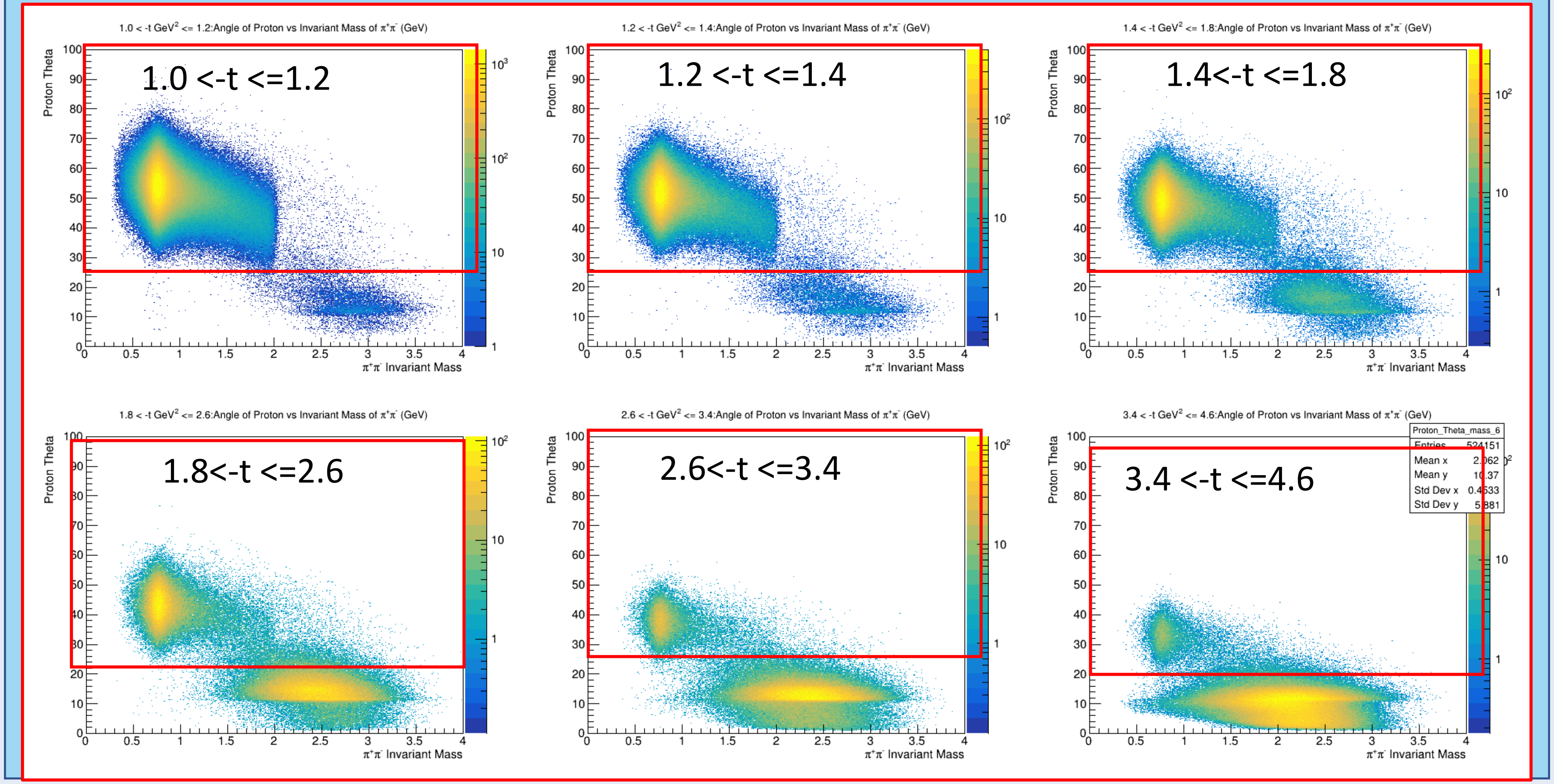
$$t = -(P_\gamma - P_{\pi^+\pi^-}),$$



|-t| GeV^2

S.N	|-t| GeV^2 Range
1	1.0 < |-t| GeV^2 ≤ 1.2
2	1.2 < |-t| GeV^2 ≤1.4
3	1.4 < |-t| GeV^2 ≤1.8
4	1.8 < |-t| GeV^2 ≤2.6
5	2.6 < |-t| GeV^2 ≤3.4
6	3.4 < |-t| GeV^2 ≤4.6

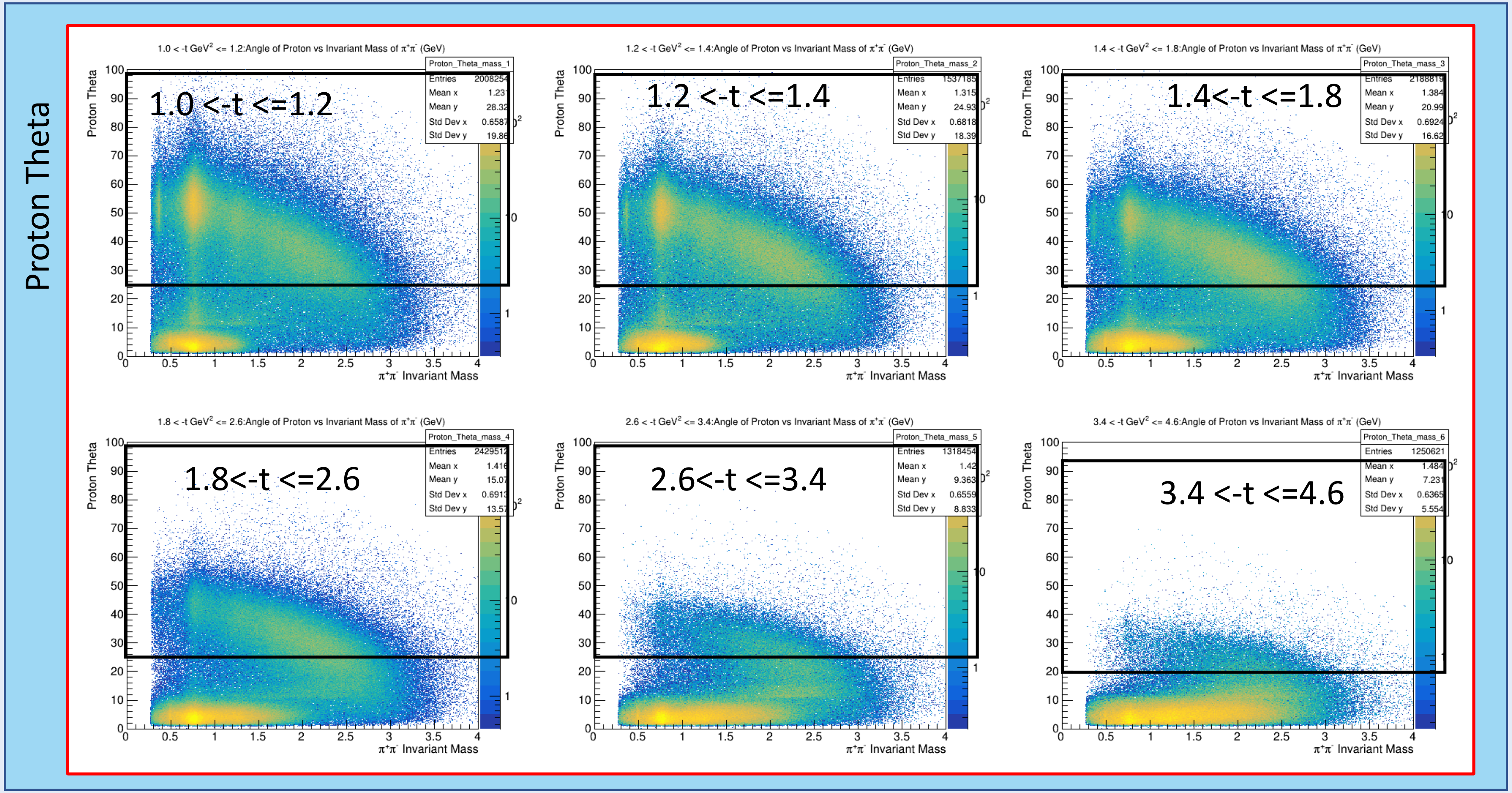
Reconstructed MC: Proton's Polar Angle vs Invariant Mass distribution



- Most of the background are from mispairing of the pions and protons .
- Events below 20 degrees polar angles results from multiple candidate of charged particles that passed the event-selection criteria.
- For this analysis we have selected events with polar angles greater than 25 degrees for |-t| ≤ 3.4 GeV² . And greater than 20 for 3.4 < |-t| ≤ 4.6 GeV² .

Plot: Reconstructed Simulation: Proton's Polar angle vs invariant mass for various bins in |-t| GeV²

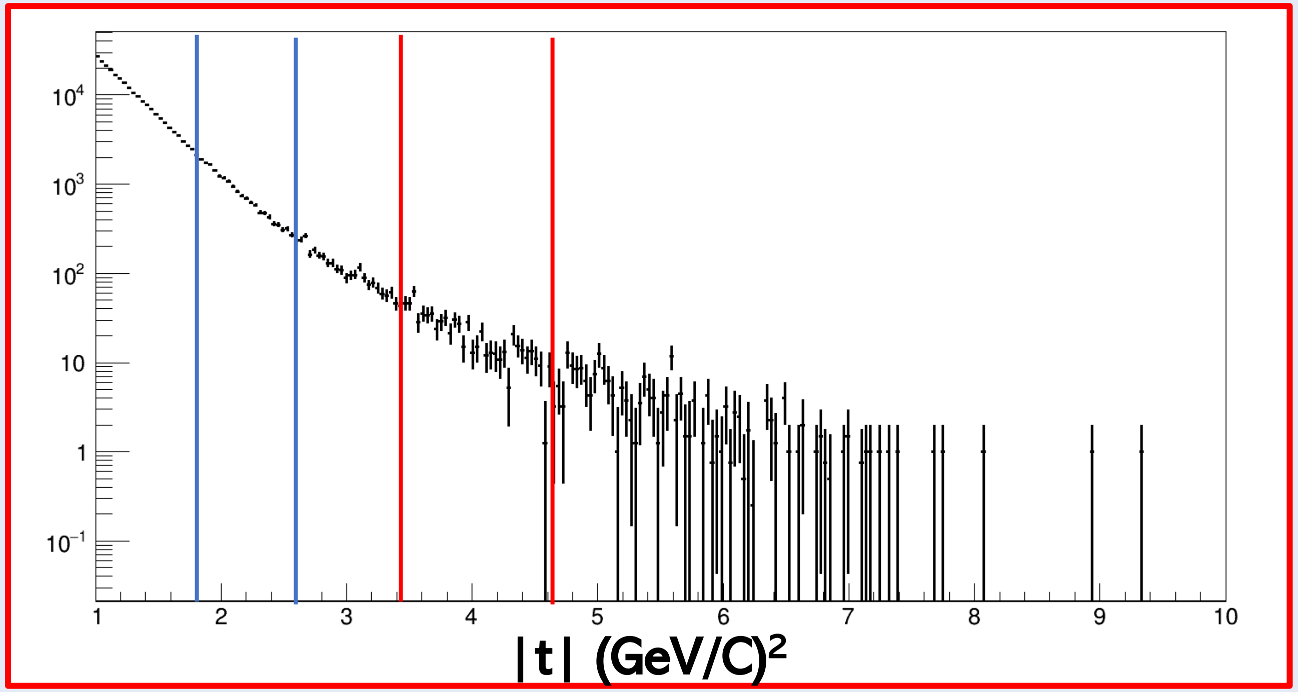
Helium Data: Proton's Polar Angle vs Invariant Mass distribution

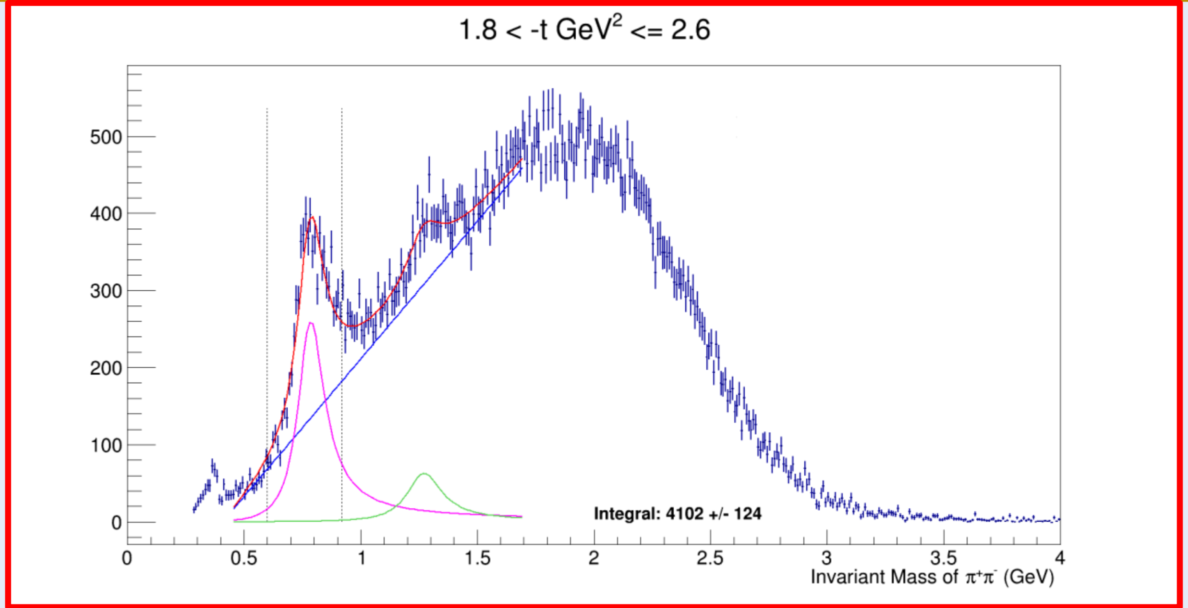


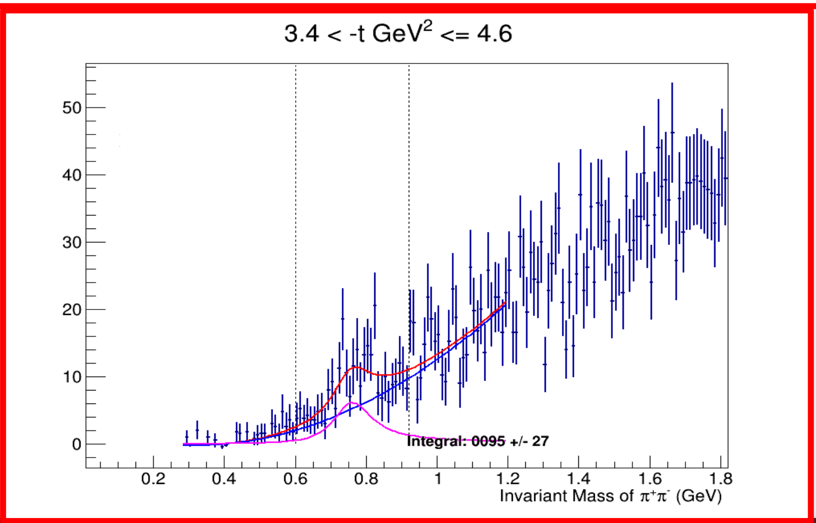
Plot: Helium Data: Proton's Polar angle vs invariant mass for various bins in |-t| GeV^2

Results: Mandelstam variable and Invariant mass of Rho0 meson

Mandelstan variable |t| in Deuterium



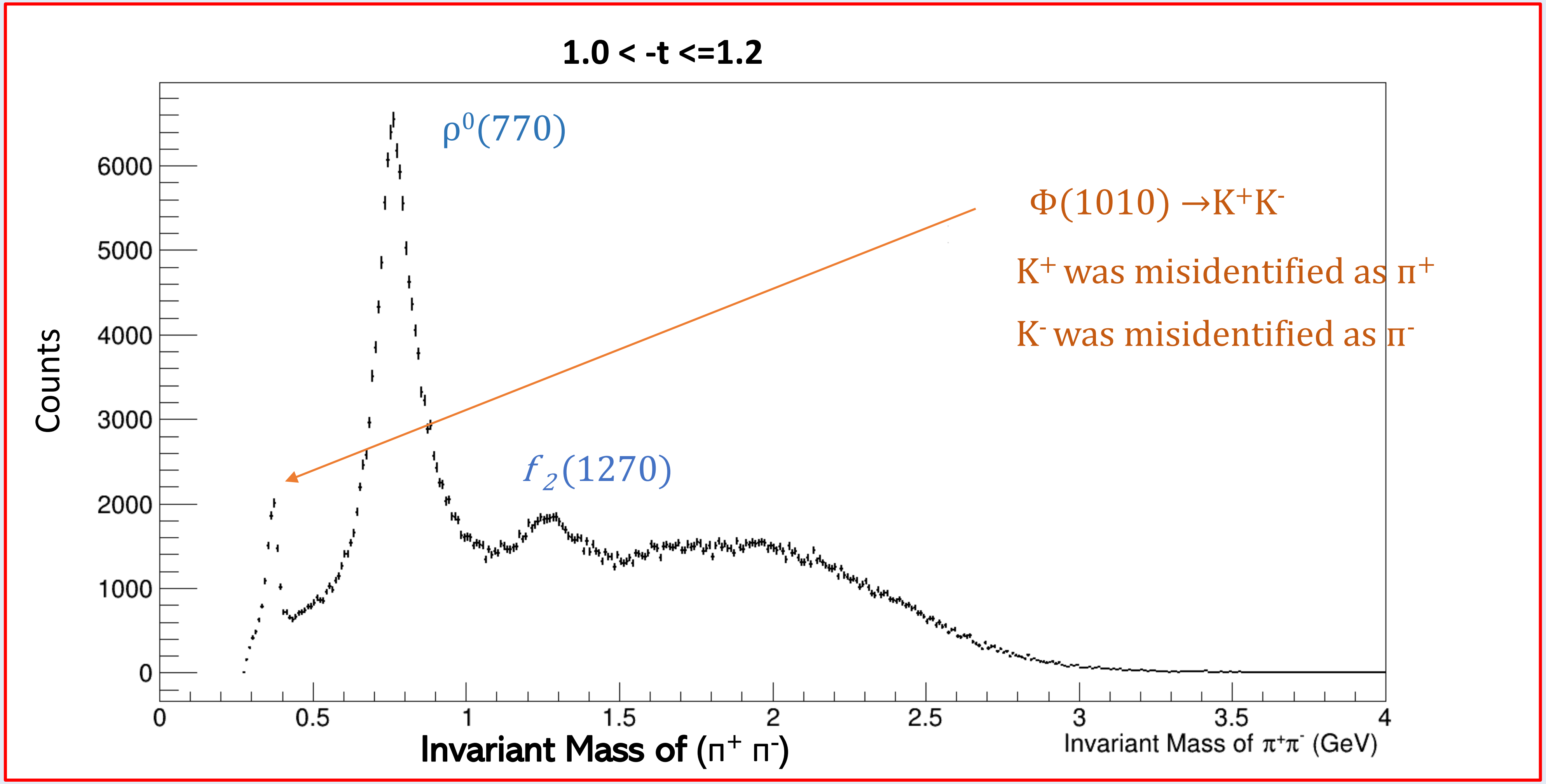




$M_{Rho} = 0.775\ GeV/c^2$

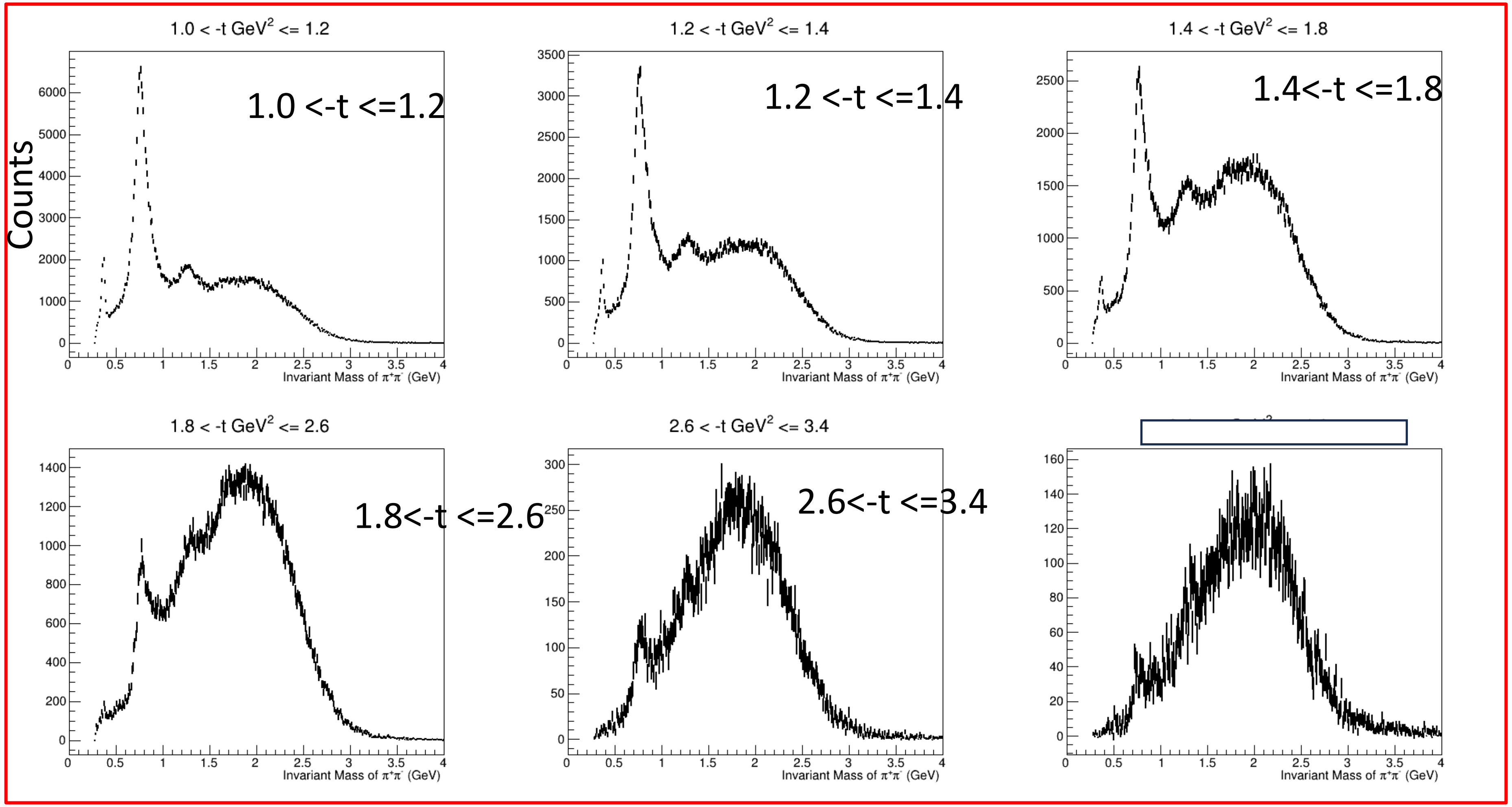
Relativistic Breit–Wigner and 2^{nd} order polynomial combination in fitting invariant mass ($\pi^+\ \pi^-$)

Helium Data: Invariant Mass Distribution



Plot: Final Invariant Mass distribution of $\pi^+\pi^-$ for $1.0 < |-t|\ \mathrm{GeV}^2 \leq 1.2$

Helium Data: Final plots of Invariant mass distribution

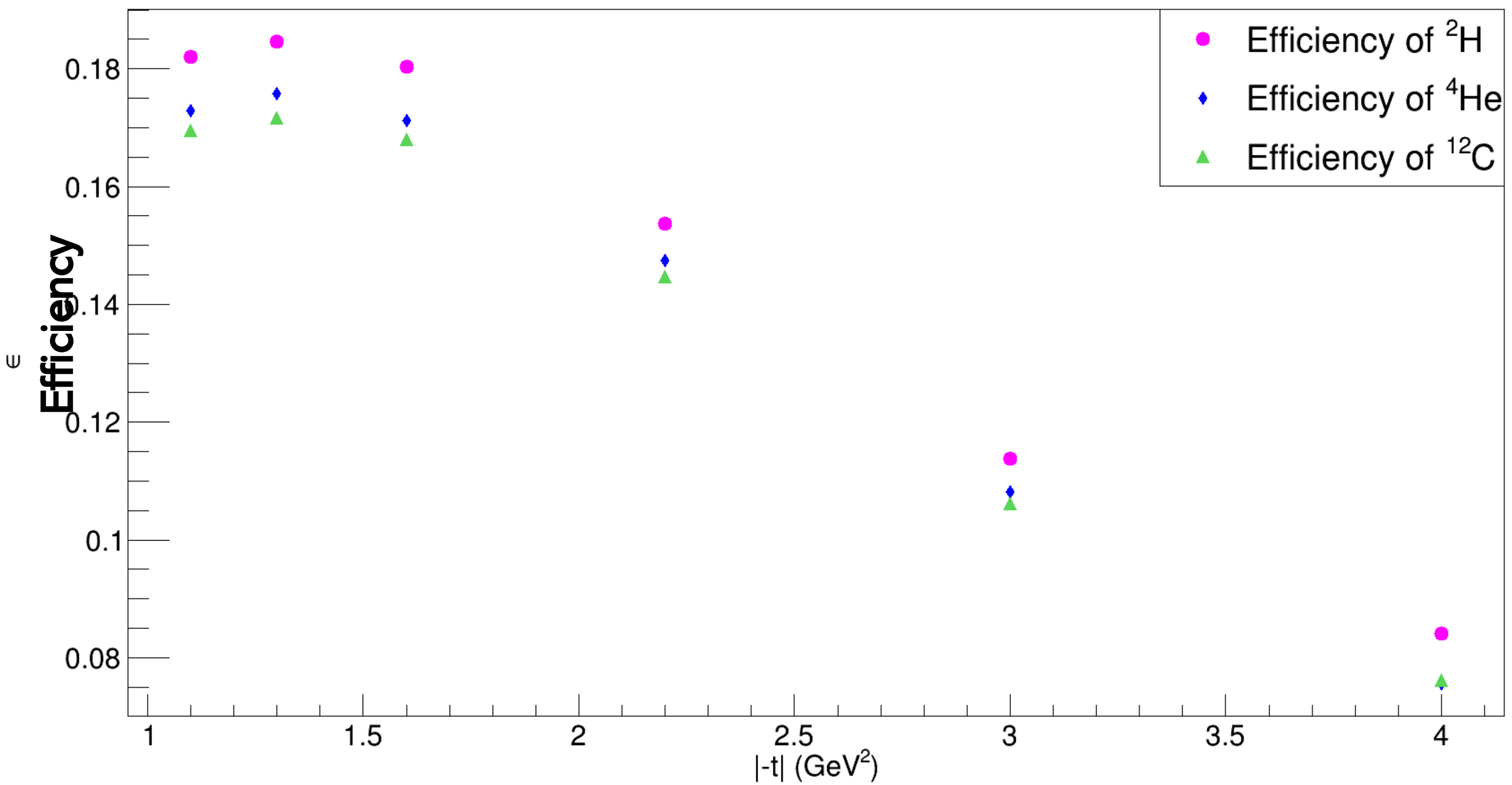


Deuterium and carbon follows similar distribution

- Challenging to model the background.
- Background modeling using Bggen Simulaton is ongoing.

Plot: Final Invariant Mass distribution of $\pi^+\pi^-$ after applying all selection criteria.

Efficiency



Plot: A plot of efficiency vs momentum distribution |-t| GeV^2

- Efficiency for deuterium is slightly higher than those for helium and carbon.
- For $1.0 < |-t|$ GeV^2 ≤ 1.2 efficiency is approximately 18%.
- For $3.4 < |-t|$ GeV^2 ≤ 4.6 efficiency is approximately 8%.

Tagged Luminosity (pb^{-1}.nucleon

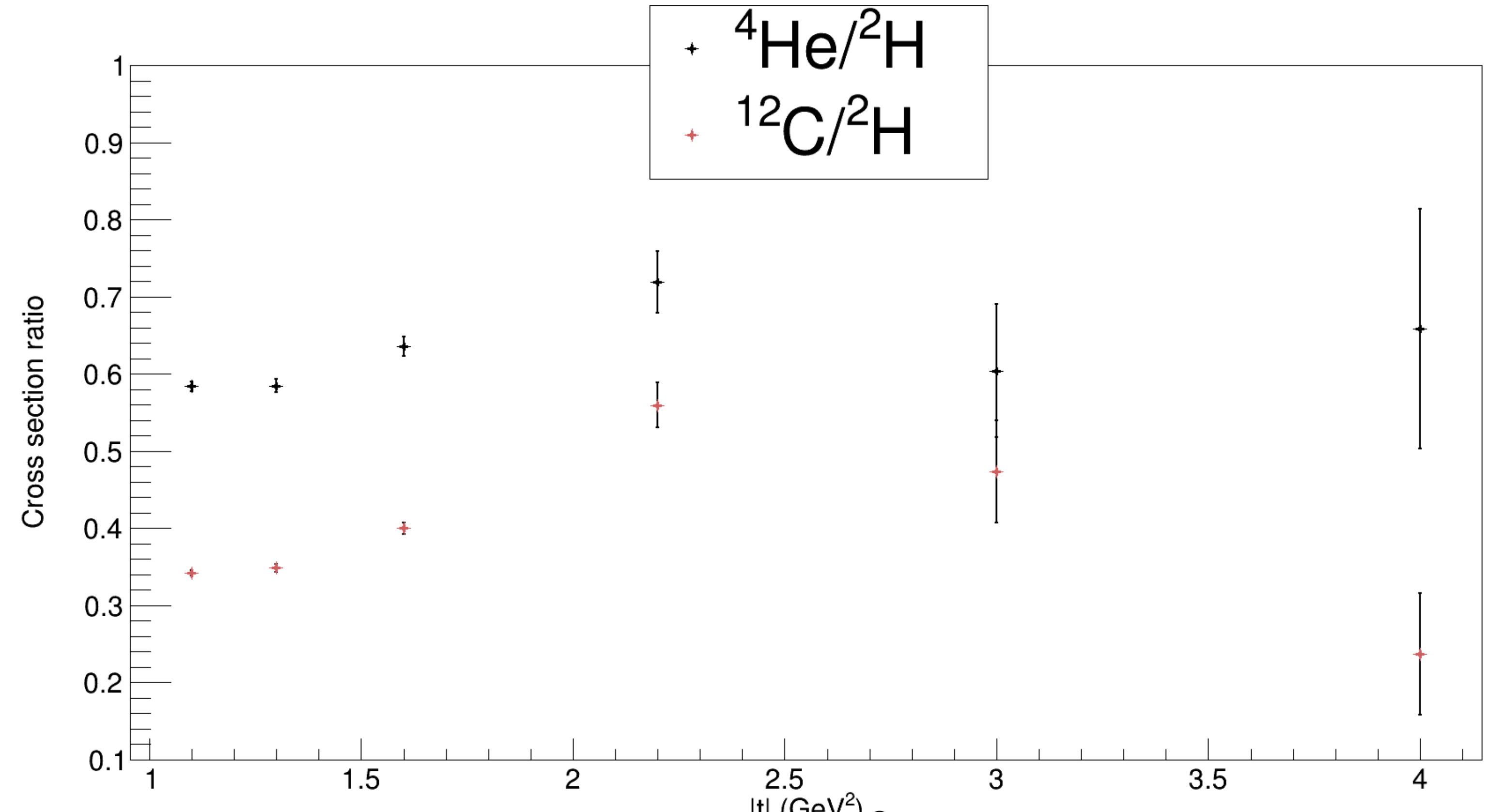
^{2}D: 33.98

^{4}He: 63.80

^{12}C: 97.93

Preliminary Nuclear Transparency

Cross Section Ratio



|- t| GeV²

Plot: Nuclear Transparency as a function of momentum transfer.

$$T(^4\text{He}) = \frac{\sigma(^4\text{He})}{\sigma(^2\text{H})}$$

$$T(^{12}\text{C}) = \frac{\sigma(^{12}\text{C})}{\sigma(^2\text{H})}$$

Only preliminary statistics uncertainty from data yield is shown.

Future works

- Study the background of data by using the background model simulation from GlueX.
- Work on systematic uncertainties associated with the cross-section ratio.
- To extract photon transparency to look for the transition of photon vector meson to that of point like configuration.
- Study the onset of CT by comparing against theoretical calculations.

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SRC/CT Collaboration

THANK YOU !

Cross Section Calculation

$$Luminosity = flux * \text{Target Length} * \text{Number Density}$$

Nucleus	Tagged Photon Flux (10^{12})	Tagged Luminosity ($pb^{-1}\cdot$nucleon)
Deuterium	13.17	33.98
Helium	30.8	63.80
Carbon	49.46	97.73

Table :Tagged flux and luminosity for each target, with beam photons having energies between 6.5 and 10.8 GeV

$$\sigma = \frac{N_{signal}}{\mathcal{L} \times \epsilon \times B(\rho^0 \to \pi^+\pi^-)}$$

$$T(^4\text{He}) = \frac{\sigma_{(^4\text{He})}}{\sigma_{(^2\text{H})}}$$

$$T(^{12}\text{C}) = \frac{\sigma_{(^{12}\text{C})}}{\sigma_{(^2\text{H})}}$$

$$\text{Number Density} = \rho_N = \frac{N_{\text{Avogadro}}(\text{particle/mole}) \times \text{target mass density}(\text{gm/cm}^3)}{\text{atomic weight of proton}(\text{gm/mole})} \times \frac{1\text{cm}^2}{1 \times 10^{24}\ \text{barns}}$$

Source: Hao Li's Dissertation (Glue X)

Detector’s Resolution

- Charged particle momentum:: 1-3%.
- Forward high momentum particle:8-9%.
- Proton.P() <250 MeV are not detected.
- Pions reconstruction:: challenging for momenta<200 MeV
- Looking the energy deposited at CDC :: proton and pions can be separated up to energies of ~800 MeV.
- TOF can separate pions and kaon up to energies ~2GeV.
- Fcal can detect photons for $E_\gamma > 100$ MeV.
- Energy is lost in calorimeter due to 11^0 gap between calorimeters.