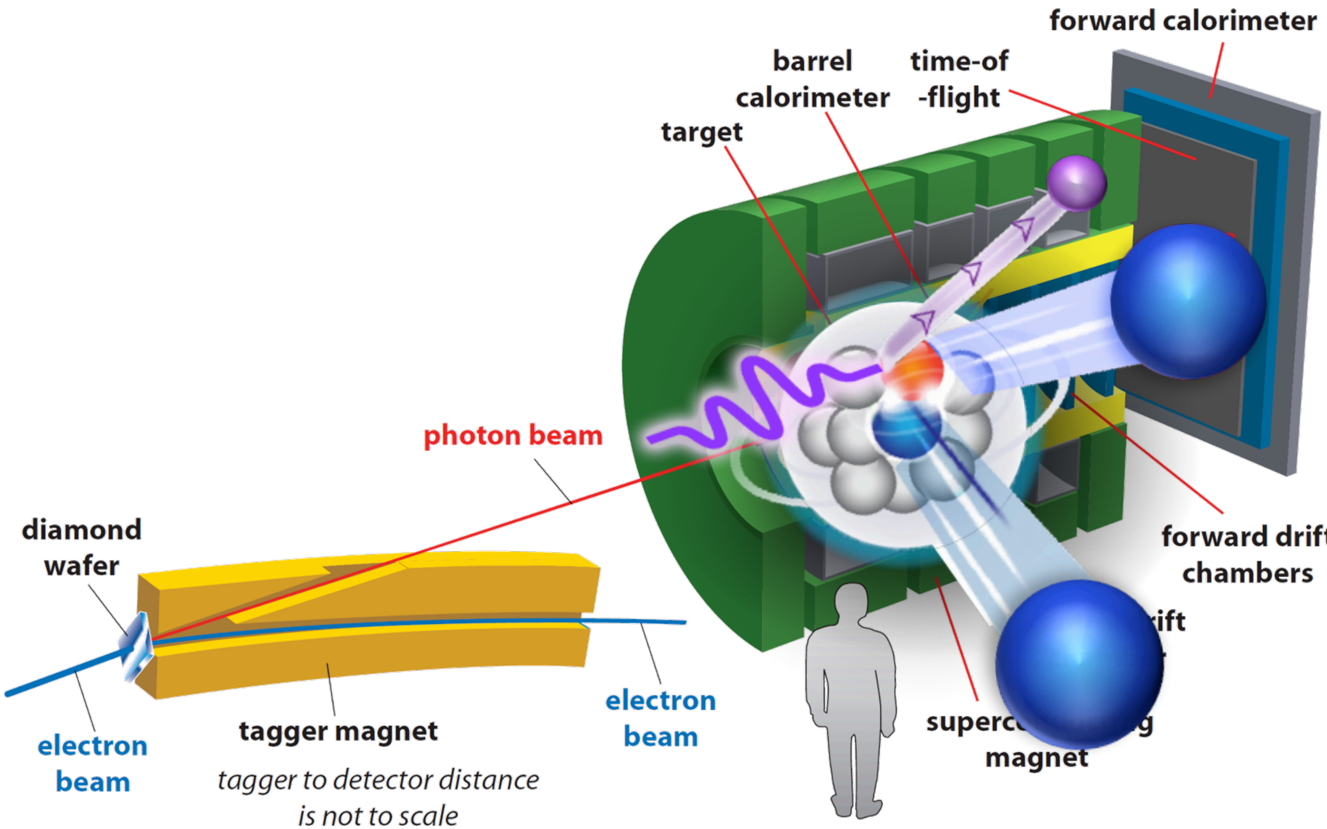
Probing QCD in the nuclear medium with real photons and nuclear targets at GlueX



Jefferson Lab
Thomas Jefferson National Accelerator Facility

Maria Patsyuk

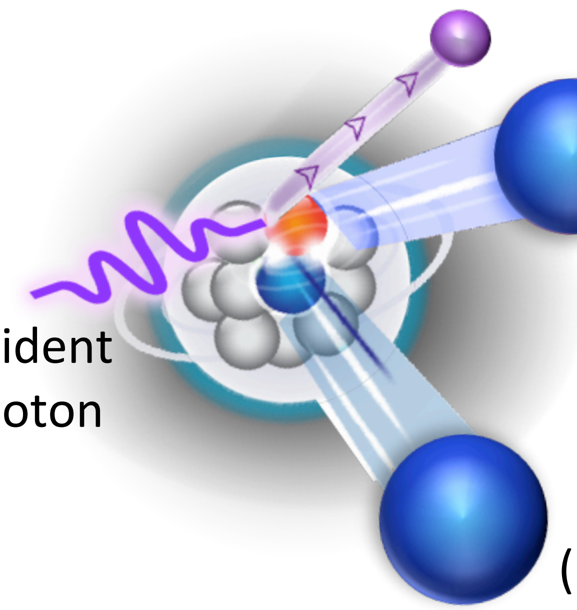
Photonuclear reactions

Fundamental QCD:

1. Photon Transparency
2. Color Transparency

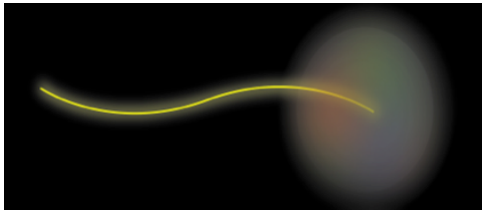
Nuclear Structure:

3. Short-Range Correlations

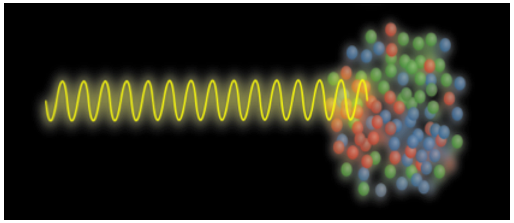


Transparency in photonuclear reactions

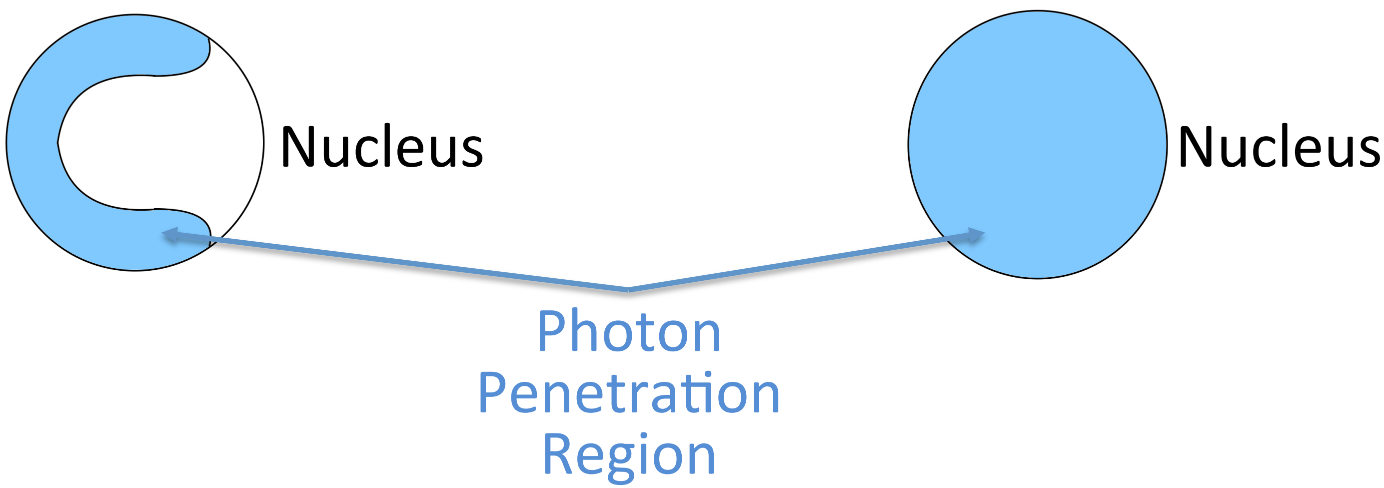
Probe Energy



Photon = superposition of moderate mass mesons

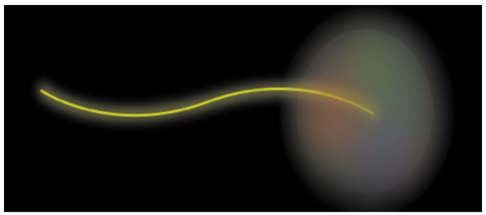


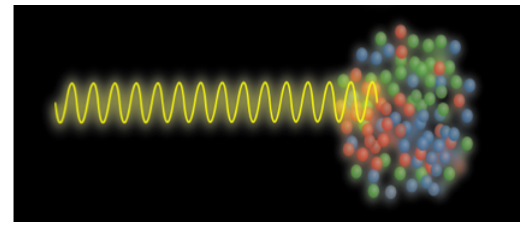
Photon = point-like particle



Transparency in photonuclear reactions

Probe Energy





Photon = superposition of moderate mass mesons

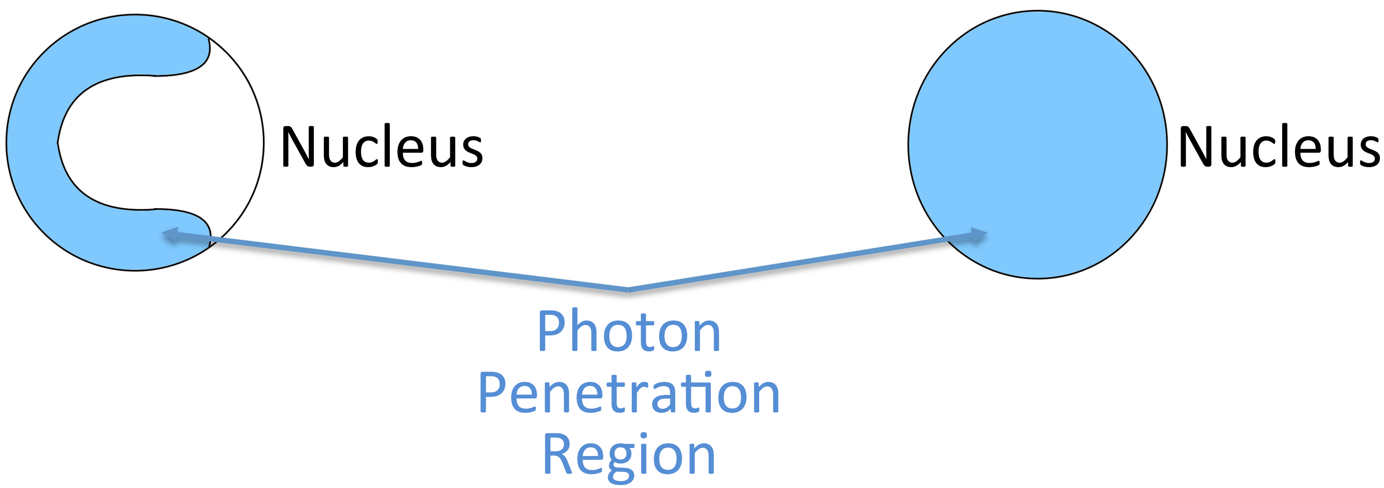
Photon = point-like particle

Transition expected at |t| ~ 2 GeV^2.
May depend on quark composition (π vs. η), spin (π vs. ρ),
Probed via transparency and A-dependence: $T = \sigma_{\gamma A} / A\sigma_{\gamma N}$

Transparency in photonuclear reactions

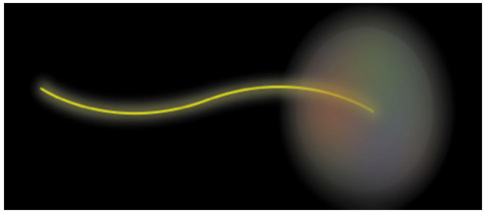
Photon = superposition of moderate mass mesons

Photon = point-like particle

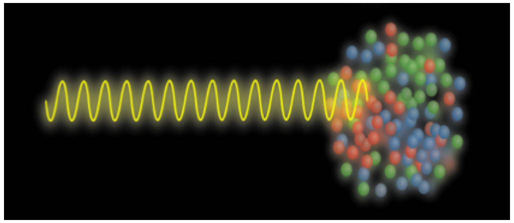


Transparency in photonuclear reactions

Probe Energy



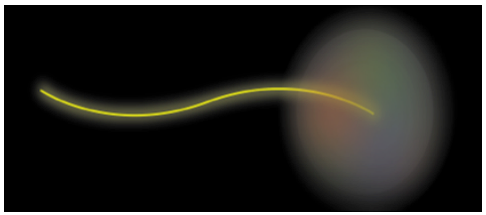
Photon = superposition of moderate mass mesons



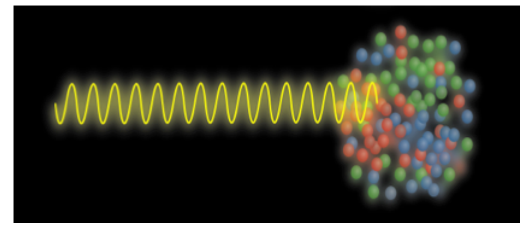
Photon = point-like particle

Transparency in photonuclear reactions

Probe Energy



Photon = superposition of moderate mass mesons



Photon = point-like particle

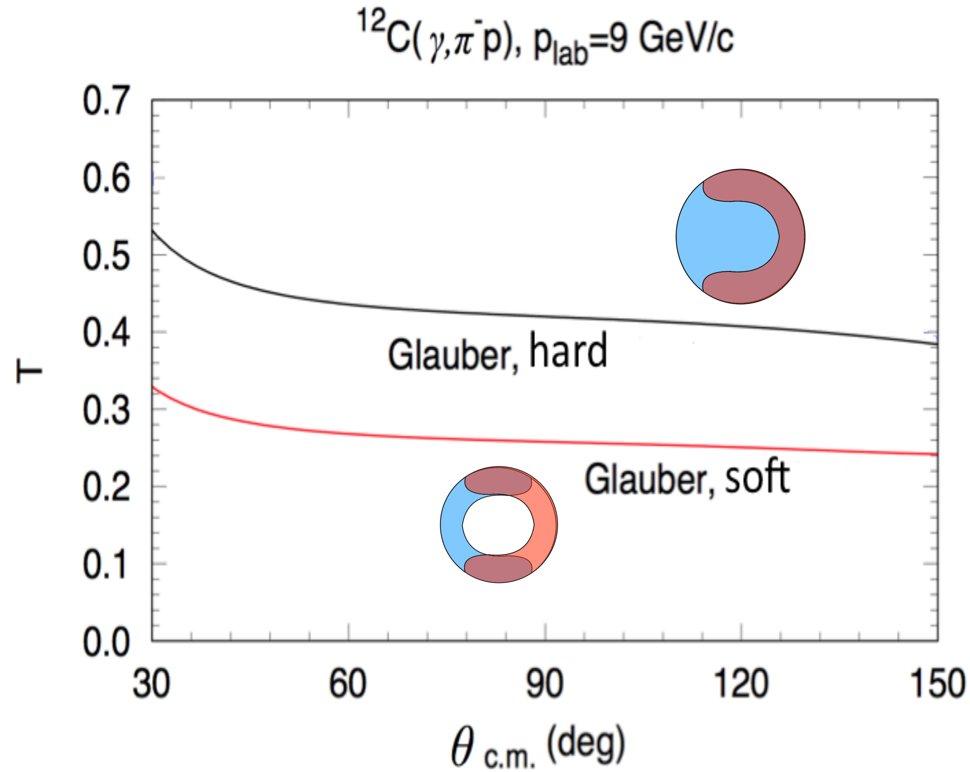
Meson+Baryon escape region

+ At very high |t|, Photon selects nucleons in compact configurations → color transparency (CT)

Photon transparency / photon structure in QCD?

Two Observables that can separate hard/soft interactions:

1. 'Absolute' transparency for a given nucleus
2. A-dependency (i.e. ratio for different nuclei)

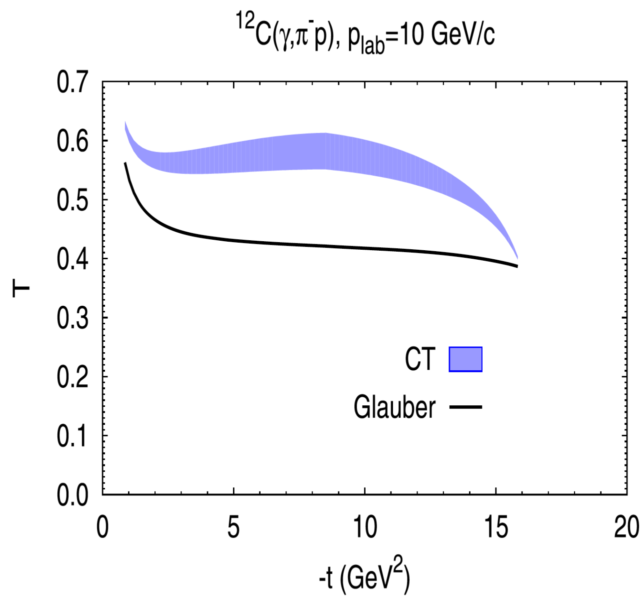


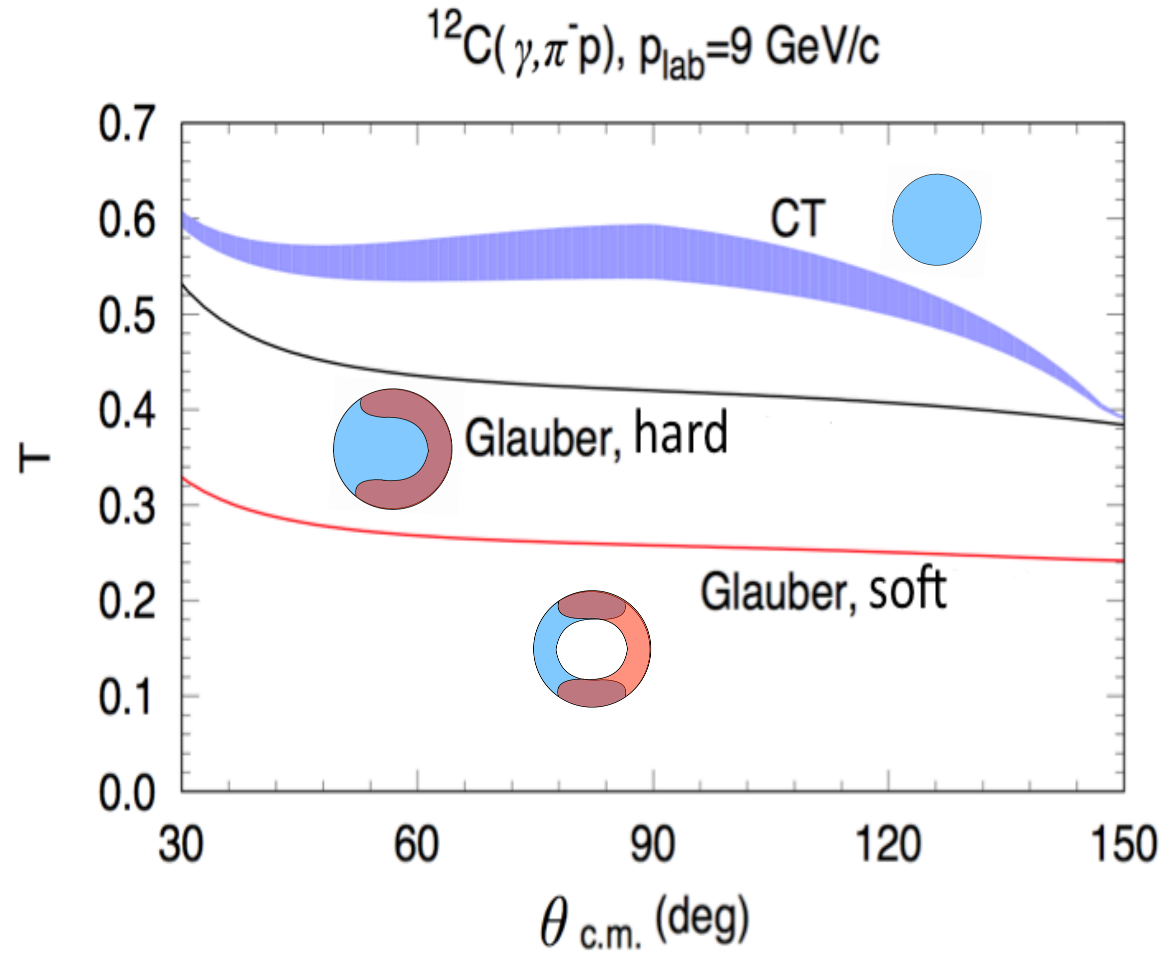
$T = \sigma_{\gamma A} / A\sigma_{\gamma N}$

A. Larionov and M. Strikman, Physics Letters 2016 + private communication

Nuclear (color) transparency

Large effect !



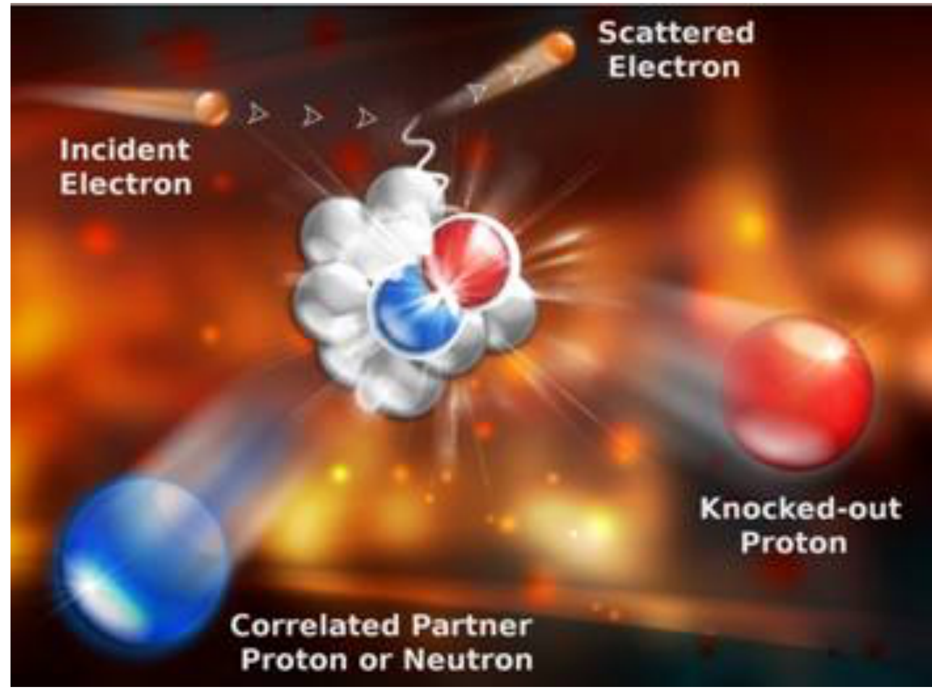


A. Larionov and M. Strikman, Physics Letters 2016 + private communication

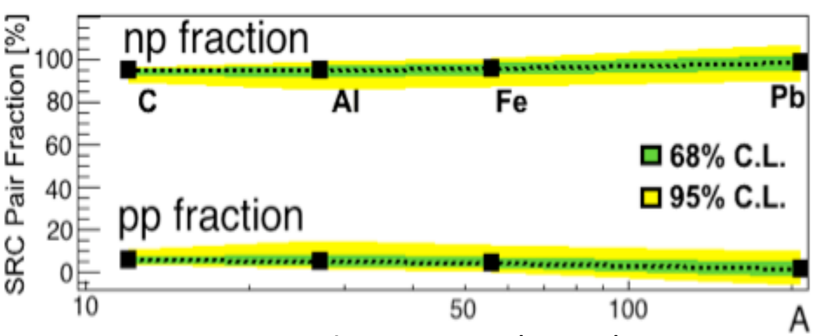
Short-Range Correlations

Nucleons form pairs with high relative momentum and low c.m. momentum compared to k_F – **SRC pairs**

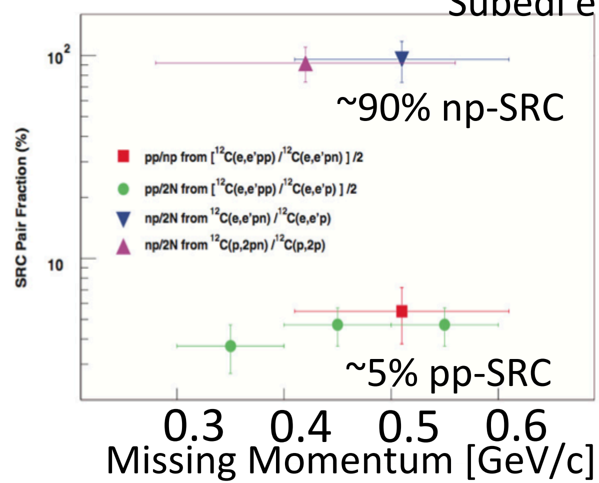
Very strong short-range interaction between nucleons → **sub-nucleon structure of SRC-nucleons might be modified compared to a free nucleon**

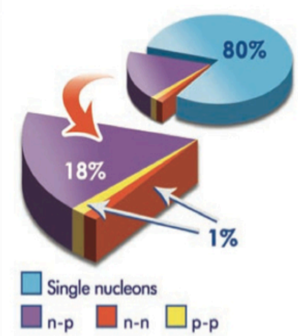


Subedi et al., Science (2008)



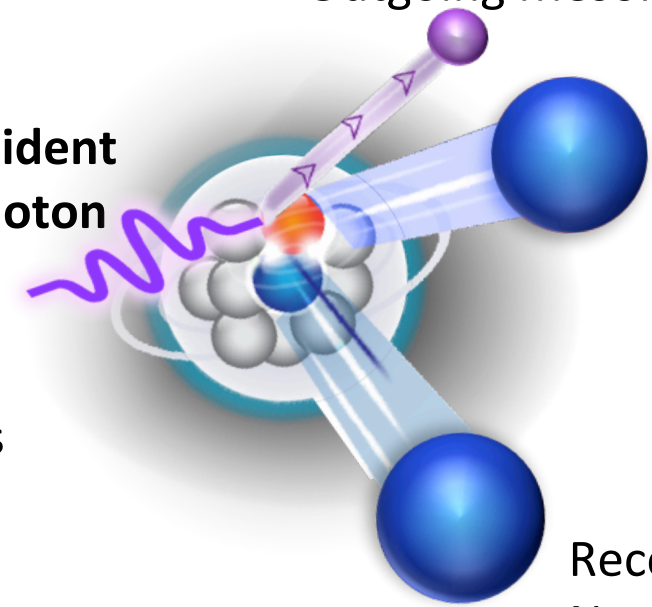
Hen et al., Science (2014)





Why photons for SRC?

Exclusive scattering of a real photon on a nucleus



- Complements the set of different probes (verification of reaction mechanism)
- Hard reactions
- γp scattering ($\sigma \sim s^{-7}$) selects mostly forward going high momentum nucleons (SRC)
- Interact with neutron leading to charged final state ($\gamma\, n \rightarrow \pi^-\, p$)

Reactions of interest

Exclusive Proton Reactions	Exclusive Neutron Reactions
$\gamma + p \rightarrow \pi^0 + p$	$\gamma + n \rightarrow \pi^- + p$
$\gamma + p \rightarrow \pi^- + \Delta^{++}$	$\gamma + n \rightarrow \pi^- + \Delta^{++}$
$\gamma + p \rightarrow \rho^0 + p$	$\gamma + n \rightarrow \rho^- + p$
$\gamma + p \rightarrow K^+ + \Lambda^0$	$\gamma + n \rightarrow K^0 + \Lambda^0$
$\gamma + p \rightarrow K^+ + \Sigma^0$	$\gamma + n \rightarrow K^0 + \Sigma^0$
$\gamma + p \rightarrow \omega + p$	x
$\gamma + p \rightarrow \phi + p$	x
…	…

Targets:

D

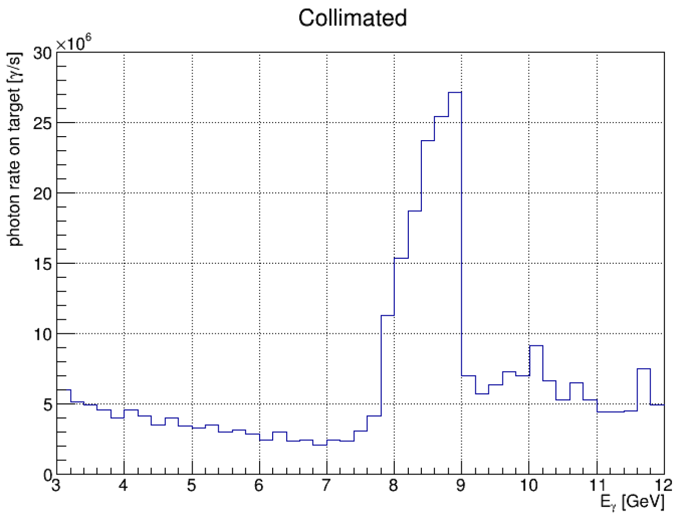
^{4}He

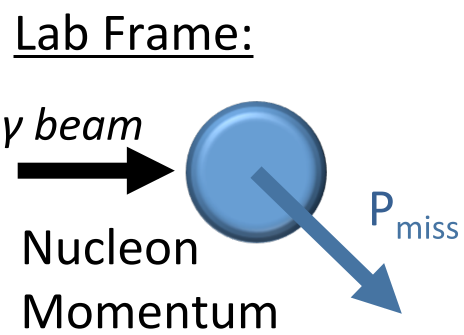
^{12}C

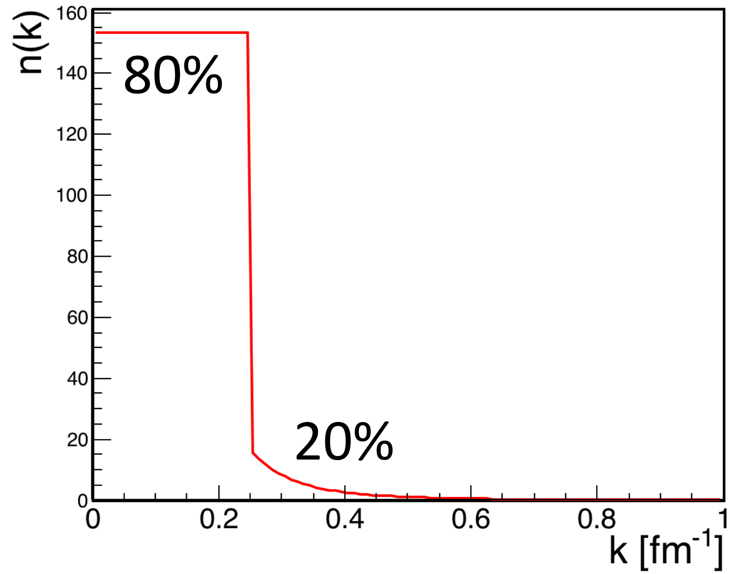
^{40}Ca

Kinematical Simulation

1. Raffle a nucleon from a correlated Fermi-Gas model and a photon from the GlueX beam:





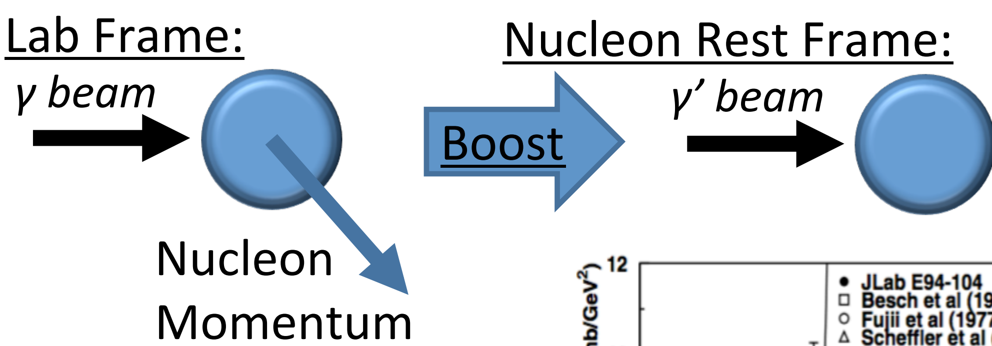


Kinematical Simulation

1. Raffle a nucleon from a correlated Fermi-Gas model and a photon from the GlueX beam

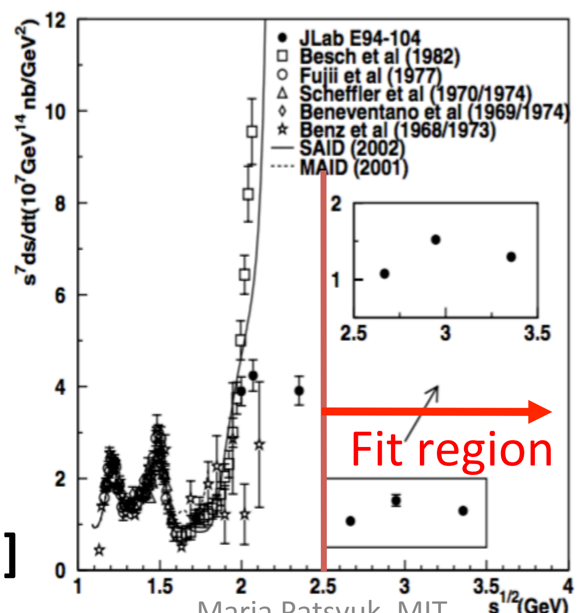
2. Get the cross-section for (γ n → π^-p) elastic scattering:

$$\left.\frac{d\sigma}{dt}\right|_{\theta_{c.m.}} = \left(C \times E_\gamma^{-7}\right) \times f(\theta_{c.m.})$$



[Phys. Rev. Lett. 91(2), 022003 (2003)]

[Phys. Rev. D 14, 679 (1976)]



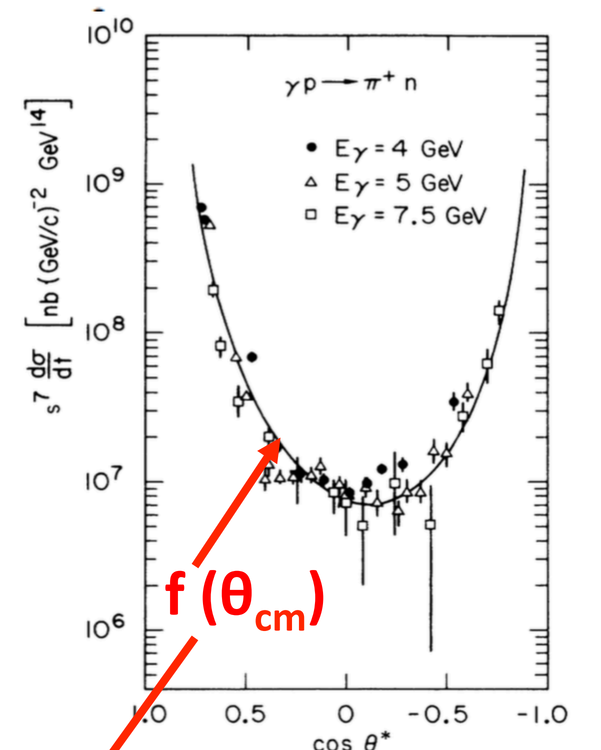


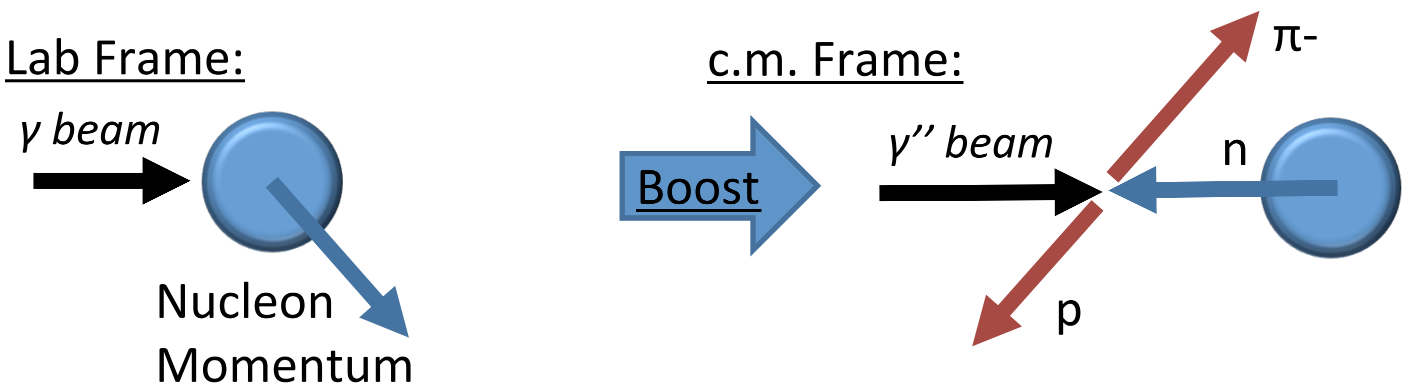
FIG. 6. $s^7\,d\sigma/dt$ versus $\cos\theta^*$ for the reaction $\gamma p \to \pi^+ n$. The solid line shows the empirical function $(1-z)^{-5}(1+z)^{-4}$ where ($z=\cos\theta^*$), which is an empirical fit to the angular distribution.

Kinematical Simulation

1. Raffle a nucleon from a correlated Fermi-Gas model and a photon from the GlueX beam

2. Get the cross-section for $(\gamma\, n \rightarrow \pi^- p)$ elastic scattering

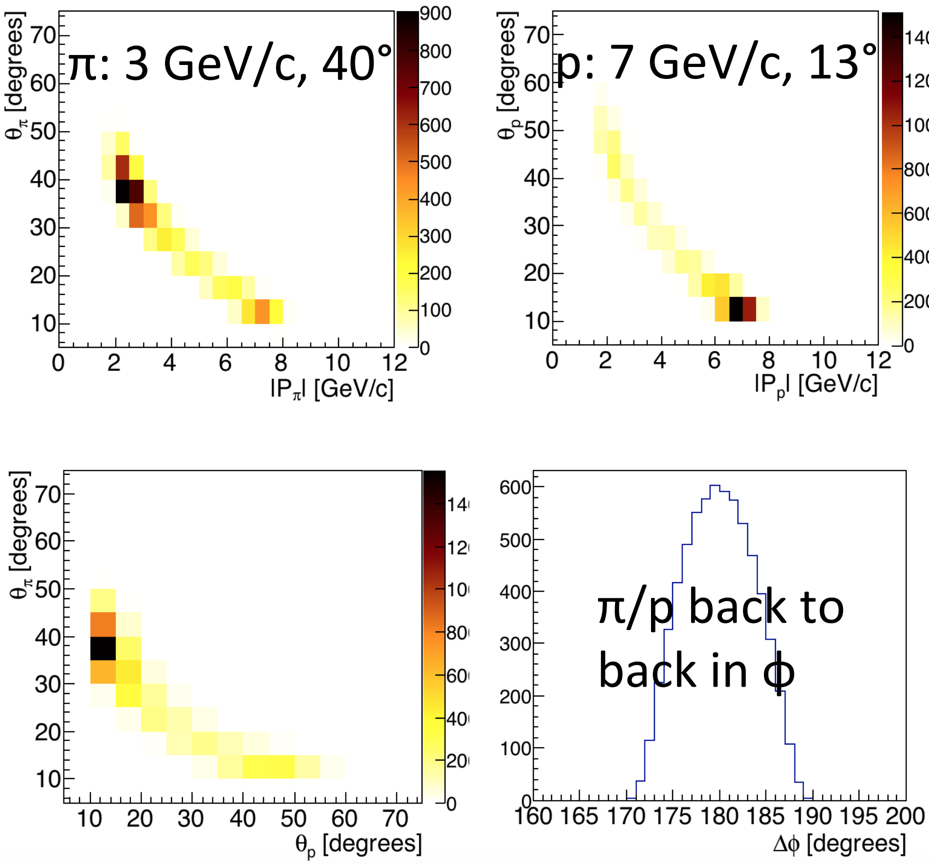
3. Boost to the c.m. and do scattering for angles of $40^o - 140^o$. Keep only events with $|t|,|u| > 2\ GeV^2$



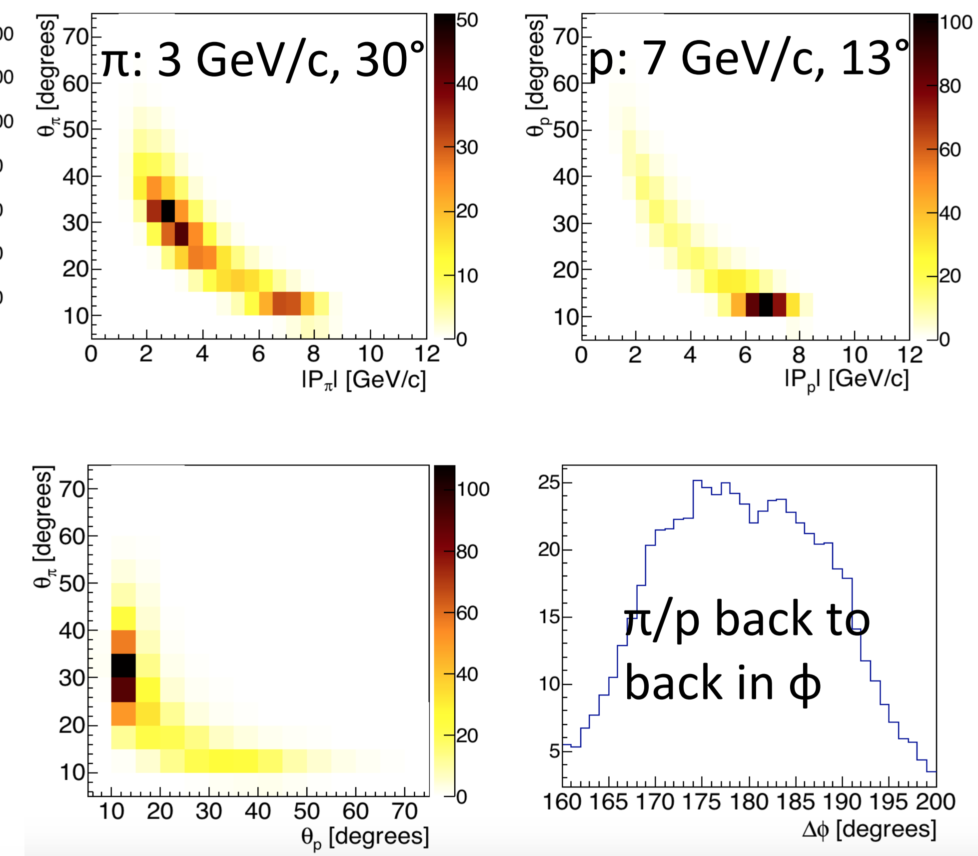
4. Boost back to the laboratory frame

Event selection for two regimes of interest

Mean Field (MF):
$P_{miss} < 0.25$ GeV/c



SRC:
$P_{miss} > 0.3$ GeV/c, $\theta_{recoil} < 160°$



Detection Efficiency Simulations

γ + n → π^- + p

(smallest expected rate)

40 days of beam, 4 targets

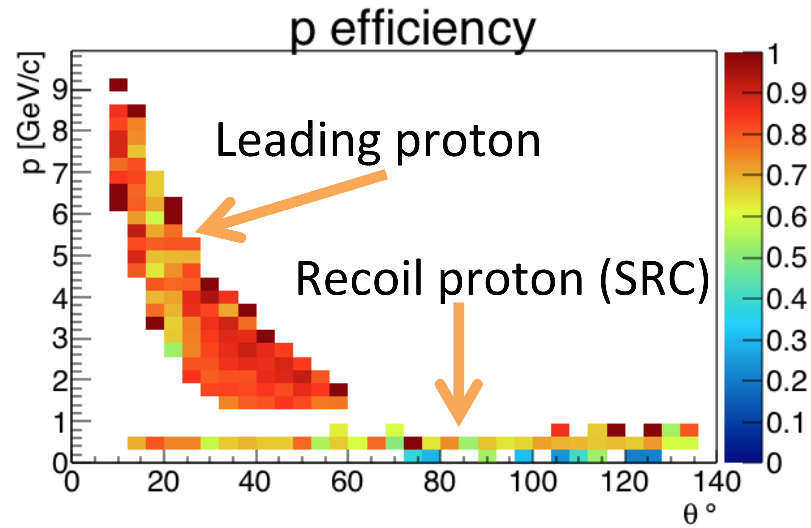
Detection efficiency:

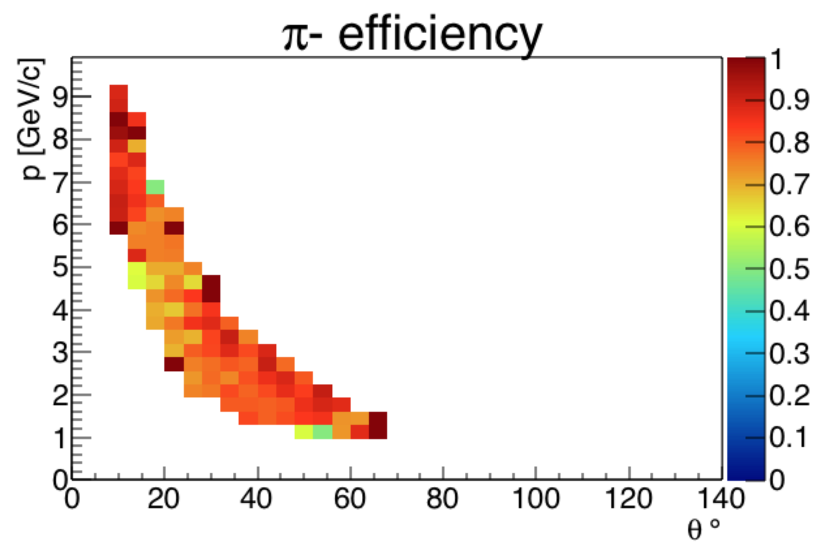
80% → each of leading particles

65% → recoil proton (SRC)

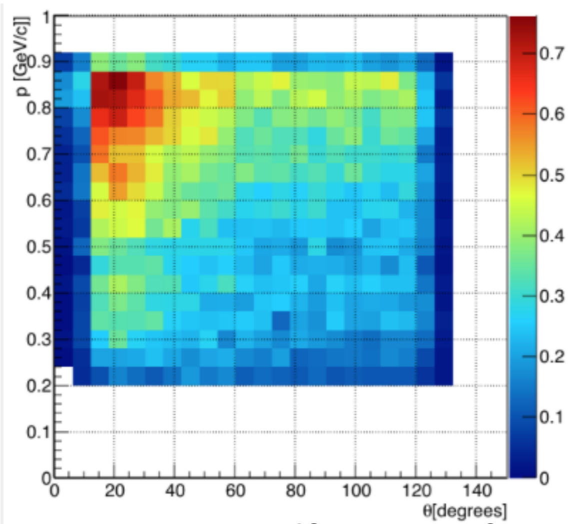
30% → reconstruction of ρ^0

Nuclear attenuation: $\sigma \sim A^{-1/3}$

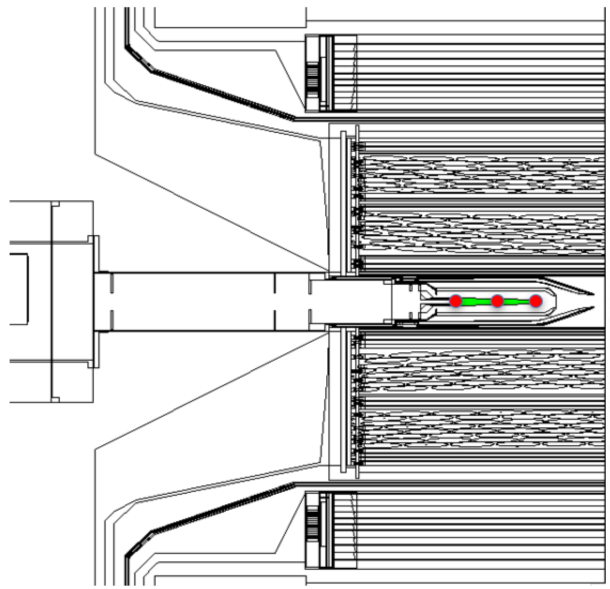


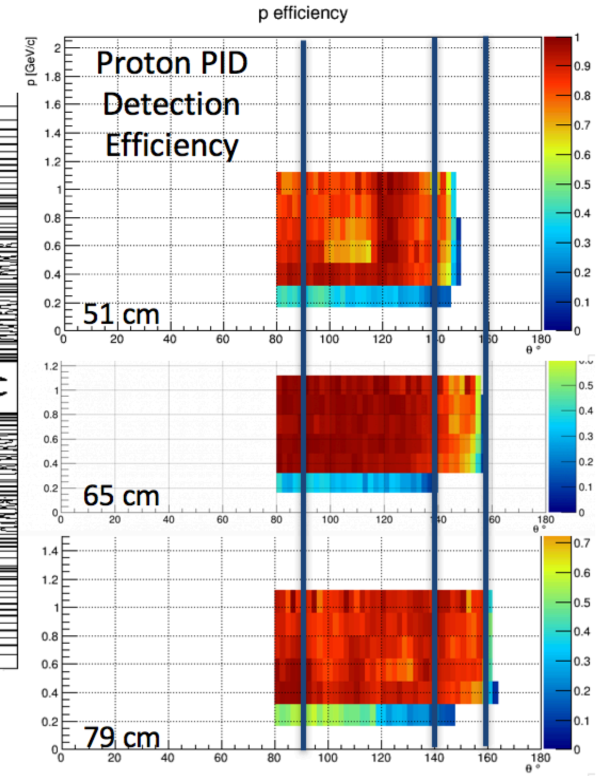


Detection Efficiency Simulations

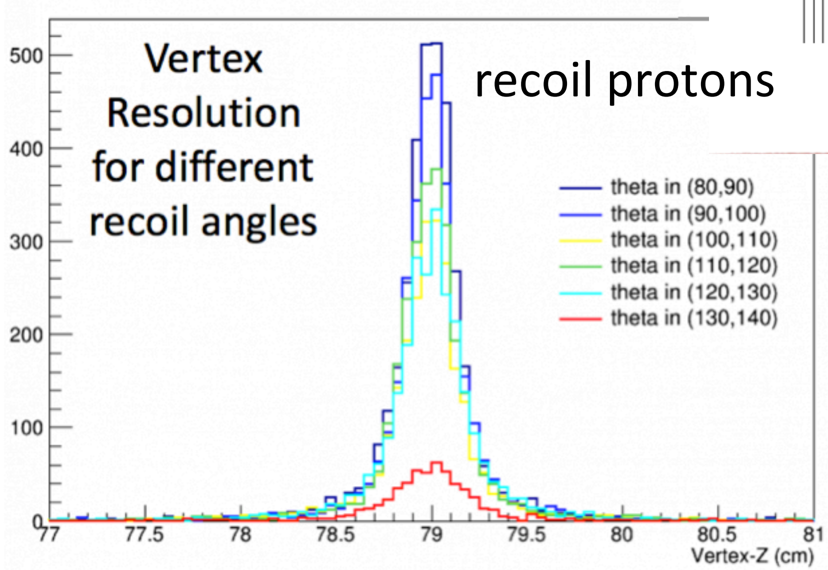


Detection efficiency for neutrons vs. angle and p

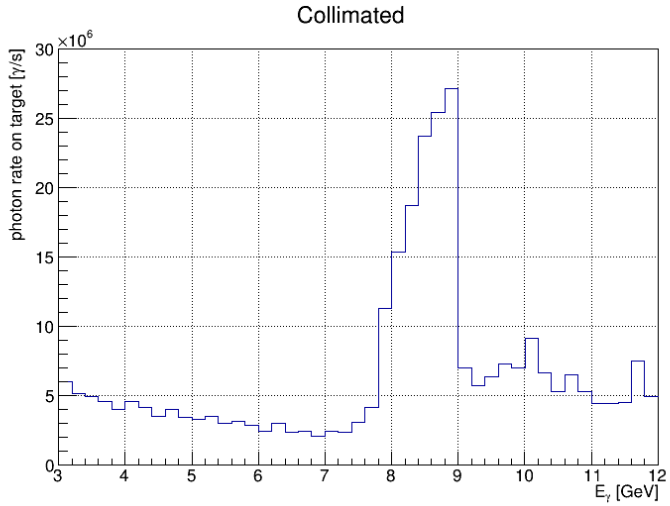


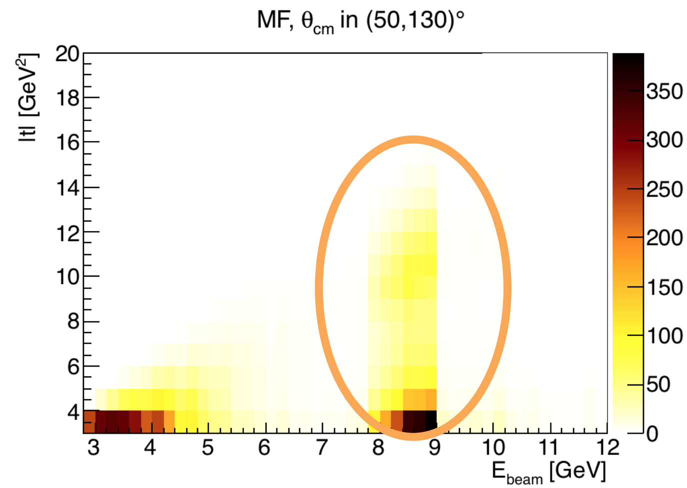


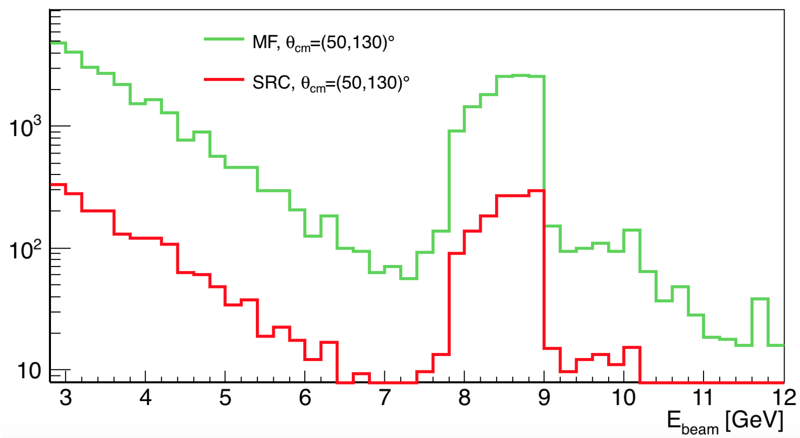
Detection efficiency for recoil protons vs. angle and p for 3 target locations

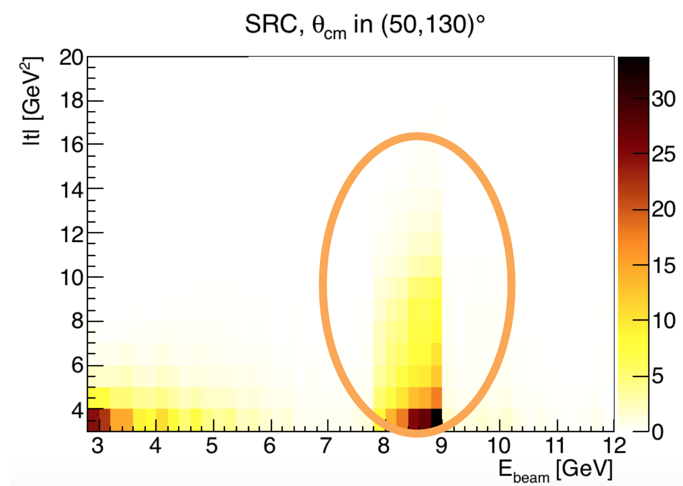


High |t| = Diamond Radiator



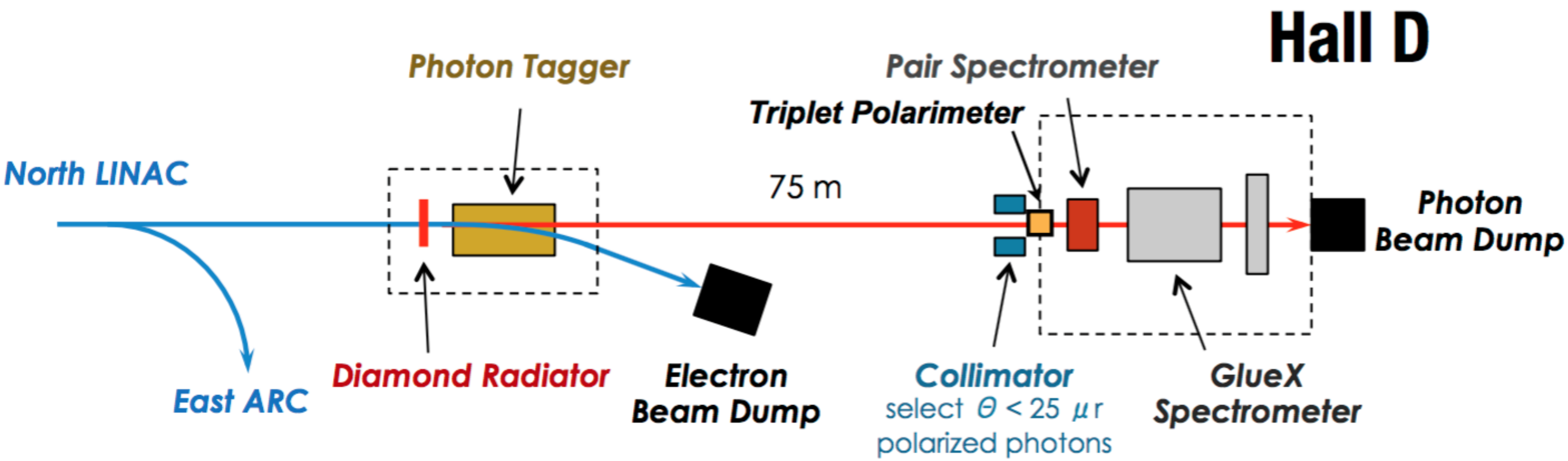


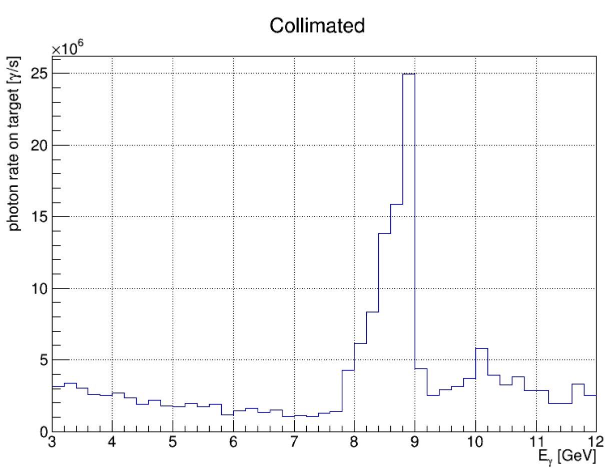




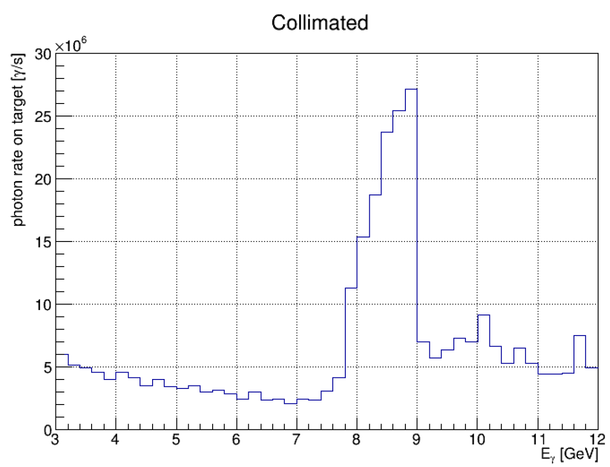
Can not use the whole photon spectrum because of tagger occupancy.
Coherent peak [8.4, 9.1] GeV, 5 mm collimator – optimized collimation efficiency and high |t| values

Beam optimization: collimator, radiator

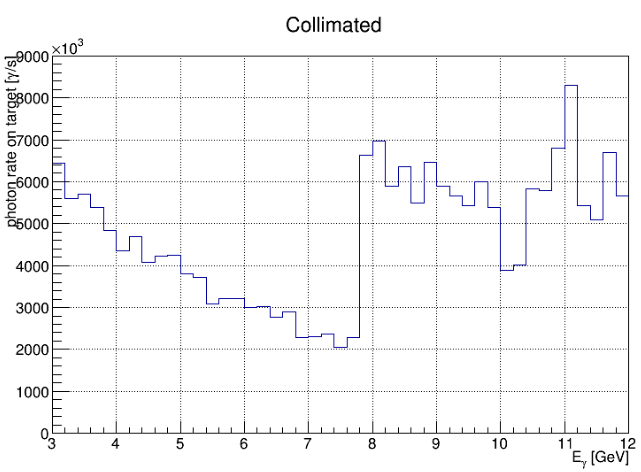




Collimator diameter 3.4 mm



Collimator diameter 5 mm



Amorphous spectrum

Rate optimization for a set of targets

Prioritized list of factors limiting the event rates:

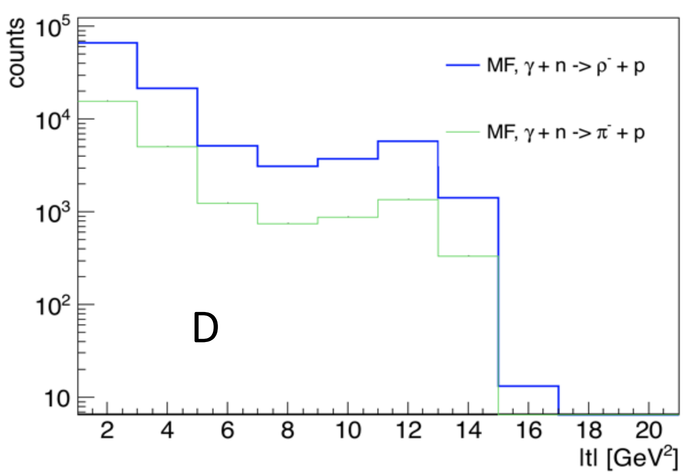
1. GlueX detector capabilities: limited flux on target of 2 10^7 photons/s
2. Target thickness → electromagnetic background ~ X0
3. Neutron background ~ n_cm * A
4. Coincidental rate in the tagger (up to 8% for this flux)

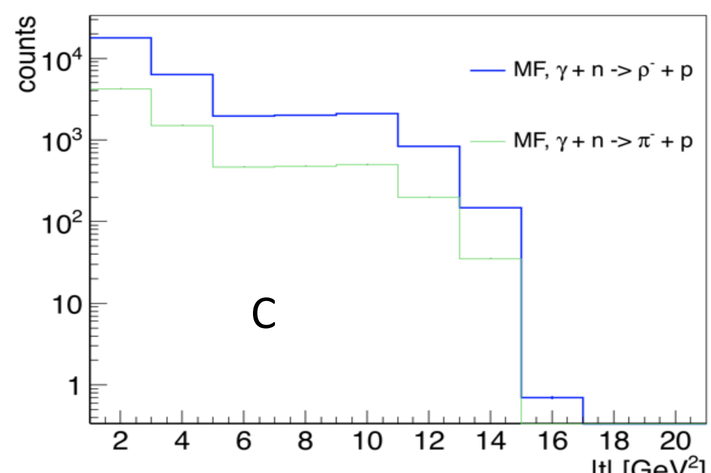
Target	Thickness [cm] / %X0	Atoms/cm3	Em bkg rel. to GlueX	Neutron bkg rel. to GlueX
D	30 / 4.1	1.51 10^{24}	0.5	0.5
^{4}He	30 / 4	5.68 10^{23}	0.5	0.5
^{12}C	1.9 / 7	1.45 10^{23}	1	0.6
^{40}Ca	0.73 / 7	1.70 10^{23}	1	1.1
LH	30 / 3.4	1.28 10^{24}	1	1

Event rates for all targets / reactions

Rates for the reactions with the smallest and largest cross section

Target	$\gamma + n \rightarrow \pi^- + p$		$\gamma + n \rightarrow \rho^- + p$		PAC days
	MF	SRC	MF	SRC	
D	12,500	750	50,000	3,200	5
^{4}He	12,000	3,000	50,000	13,000	8
^{12}C	7,300	2,300	31,000	10,000	10
^{40}Ca	2,600	900	11,000	3,500	14
Calibration, commissioning and overhead:					3
Total PAC Days:					**40**



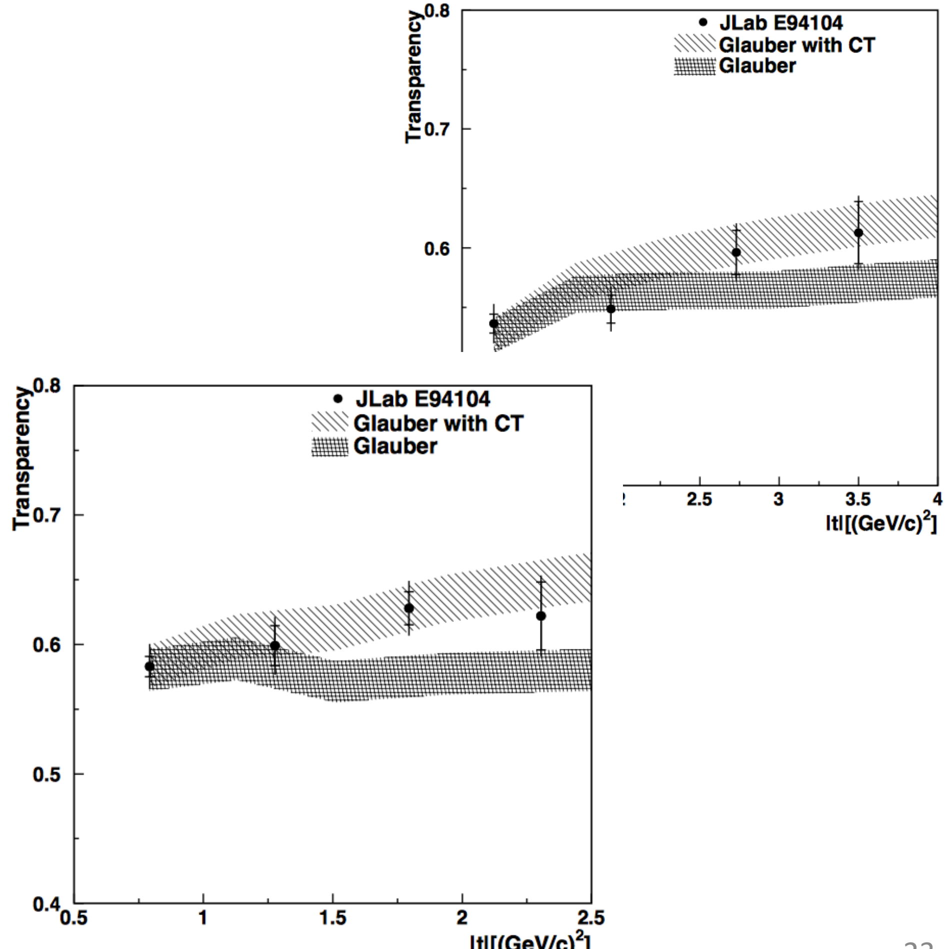


PHYSICAL REVIEW C **68**, 021001(R) (2003)

Nuclear transparency with the $\gamma n \rightarrow \pi^- p$ process in ^{4}He

D. Dutta,[1,2] F. Xiong,[2] L. Y. Zhu,[2] J. Arrington,[3] T. Averett,[4,5] E. Beise,[6] J. Calarco,[7] T. Chang,[8] J. P. Chen,[5] E. Chudakov,[5] M. Coman,[9] B. Clasie,[2] C. Crawford,[2] S. Dieterich,[10] F. Dohrmann,[3,*] K. Fissum,[11] S. Frullani,[12] H. Gao,[1,2] R. Gilman,[5,10] C. Glashausser,[10] J. Gomez,[5] K. Hafidi,[3] J.-O. Hansen,[5] D. W. Higinbotham,[2] R. J. Holt,[3] C. W. de Jager,[5] X. Jiang,[10] E. Kinney,[13] K. Kramer,[4] G. Kumbartzki,[10] J. LeRose,[5] N. Liyanage,[5] D. Mack,[5] P. Markowitz,[9] K. McCormick,[10] Z.-E. Meziani,[14] R. Michaels,[5] J. Mitchell,[5] S. Nanda,[5] D. Potterveld,[3] R. Ransome,[10] P. E. Reimer,[3] B. Reitz,[5] A. Saha,[5] E. C. Schulte,[3,8] J. Seely,[2] S. Širca,[2] S. Strauch,[10] V. Sulkosky,[4] B. Vlahovic,[15] L. B. Weinstein,[16] K. Wijesooriya,[3] C. F. Williamson,[2] B. Wojtsekhowski,[5] H. Xiang,[2] W. Xu,[2] J. Zeng,[17] and X. Zheng[2]
(Jefferson Lab E94104 Collaboration)

E_γ	$\|t\|$	T (^{4}He)	Uncertainties		
GeV	(GeV/c)^2		Statistical		point-to-point systematic
			$\theta^\pi_{cm}=70°$		
1.648	0.79	0.583	0.008		0.015
2.486	1.28	0.599	0.015		0.015
3.324	1.79	0.628	0.013		0.016
4.157	2.31	0.622	0.026	~5%	0.017
			$\theta^\pi_{cm}=90°$		
1.648	1.20	0.553	0.008		0.015
2.486	1.94	0.559	0.012		0.015
3.324	2.73	0.602	0.019		0.016
4.157	3.50	0.614	0.026	~5%	0.017



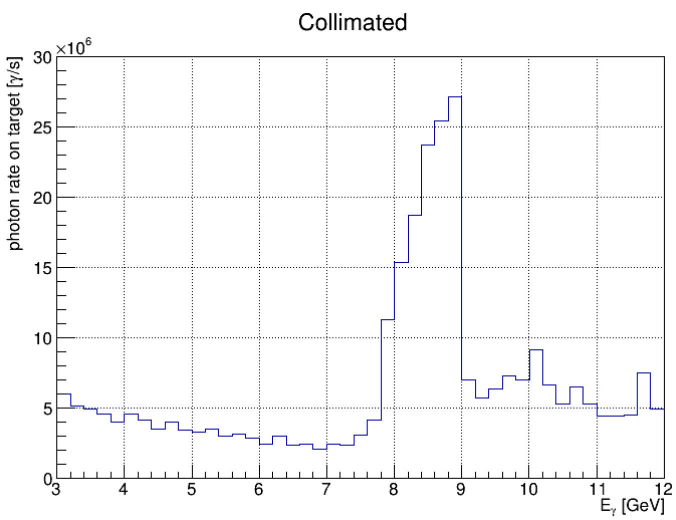
Summary

- GlueX experiment has a unique beam for photon and nuclear transparency studies, as well as SRC physics
- LOI submitted to PAC 44 includes:
  - (Color) transparency studies
  - Search for SRC pairs
  - In medium modifications of nucleon structure
- Event rates are enough to do excellent physics!

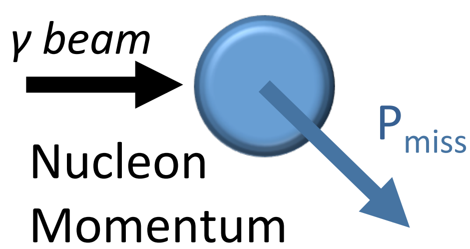
Backups

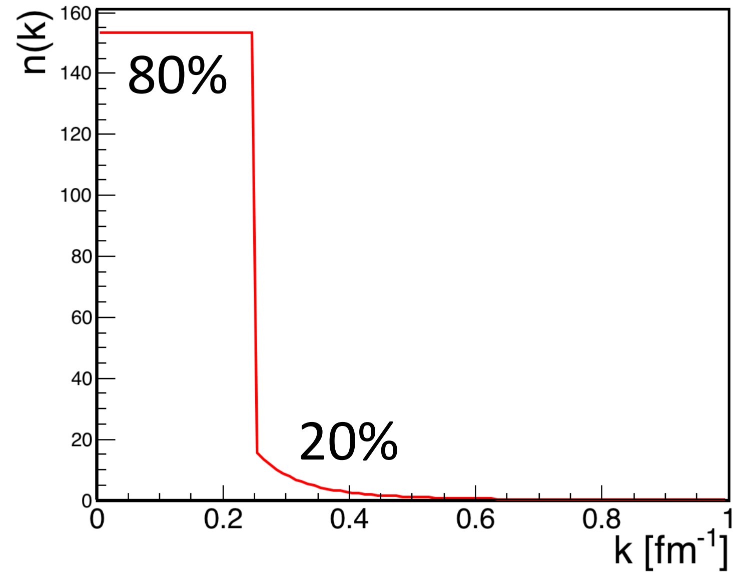
Kinematical Simulation

1. Raffle a nucleon from a correlated Fermi-Gas model and a photon from the GlueX beam:

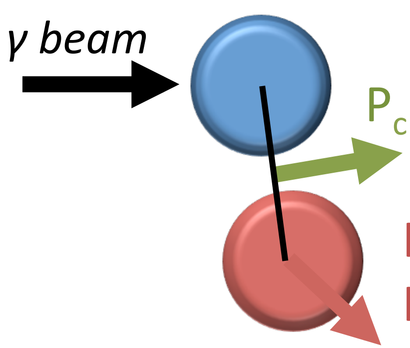


Lab Frame:





Lab Frame:



P_{cm} (gaus (0, 140 MeV/c), gaus(0, 140 Mev/c), gaus(0, 140 MeV/c))

If (P_{miss} > 250 MeV/c) $P_{recoil} = P_{cm} - P_{miss}$

If (P_{miss} < 250 MeV/c) $P_{recoil} = 0$

Factor transforming dσ/dt into dσ/dΩ

$$t = (\mathcal{P}_\gamma - \mathcal{P}_\pi)^2 = -2\mathcal{P}_\gamma \mathcal{P}_\pi + m_\pi^2$$

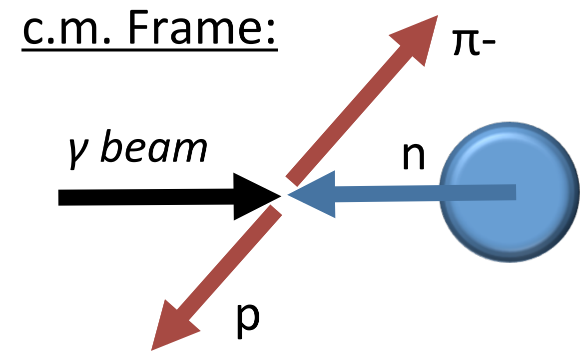
E_i, k_i - center of mass energy and momentum in the initial state.
E_f, k_f - center of mass energy and momentum in the final state.
In the center of mass system:

$$t = -2E_iE_f + 2k_ik_f \cos\theta_{cm} + m_\pi.$$

$$dt = 2k_ik_f d\cos\theta_{cm}$$

$$\frac{d\sigma}{d\cos\theta_{cm}} = 2k_ik_f \frac{d\sigma}{dt}$$

$$\frac{d\sigma}{d\Omega_{cm}} = \frac{2k_ik_f}{2\pi}\frac{d\sigma}{dt}$$



$$k_i = \frac{s - 0.94^2}{2\sqrt{s}}$$

$$k_f = \frac{\sqrt{(s - (0.938 - 0.140)^2) \cdot (s - (0.938 + 0.140)^2)}}{4s}$$

S for scattering on a moving SRC pair/MF inside a nucleus

$$s = (E_\gamma + E_N)^2 - P^2_{miss,X} - P^2_{miss,Y} - (P_{miss,Z} + E_\gamma)^2,$$

where nucleon energy (E_N) is the following:

- **MF**: $P_{miss} < k_F$ (250 MeV);

$$E_N = 0.94 - 0.015 - \frac{P^2_{miss}}{2(A-1)0.94}$$

- **moving SRC**: $P_{miss} > k_F$, (250 MeV) $P_{cm} > 0$;

$$E_N = 2 \cdot 0.94 - \sqrt{0.94^2 + P^2_{recoil}};$$

Limitations to get physical results

The natural limitations: light-cone momentum fraction (α) of the struck nucleon should be positive:

$$\alpha_{recoil} = \frac{\sqrt{0.94^2 + P_{recoil}^2} - P_{recoil,Z}}{0.94}; \tag{12}$$

$$\alpha_{cm} = \frac{2 \cdot 0.94 - P_{cm,Z}}{0.94} \approx 2; \tag{13}$$

$$\alpha_{miss} = P_{LC,cm} - P_{LC,recoil} > 0. \tag{14}$$

Also, $P_{miss} < 0.75$ GeV/c; $s > (m_N + m_\pi)^2$.