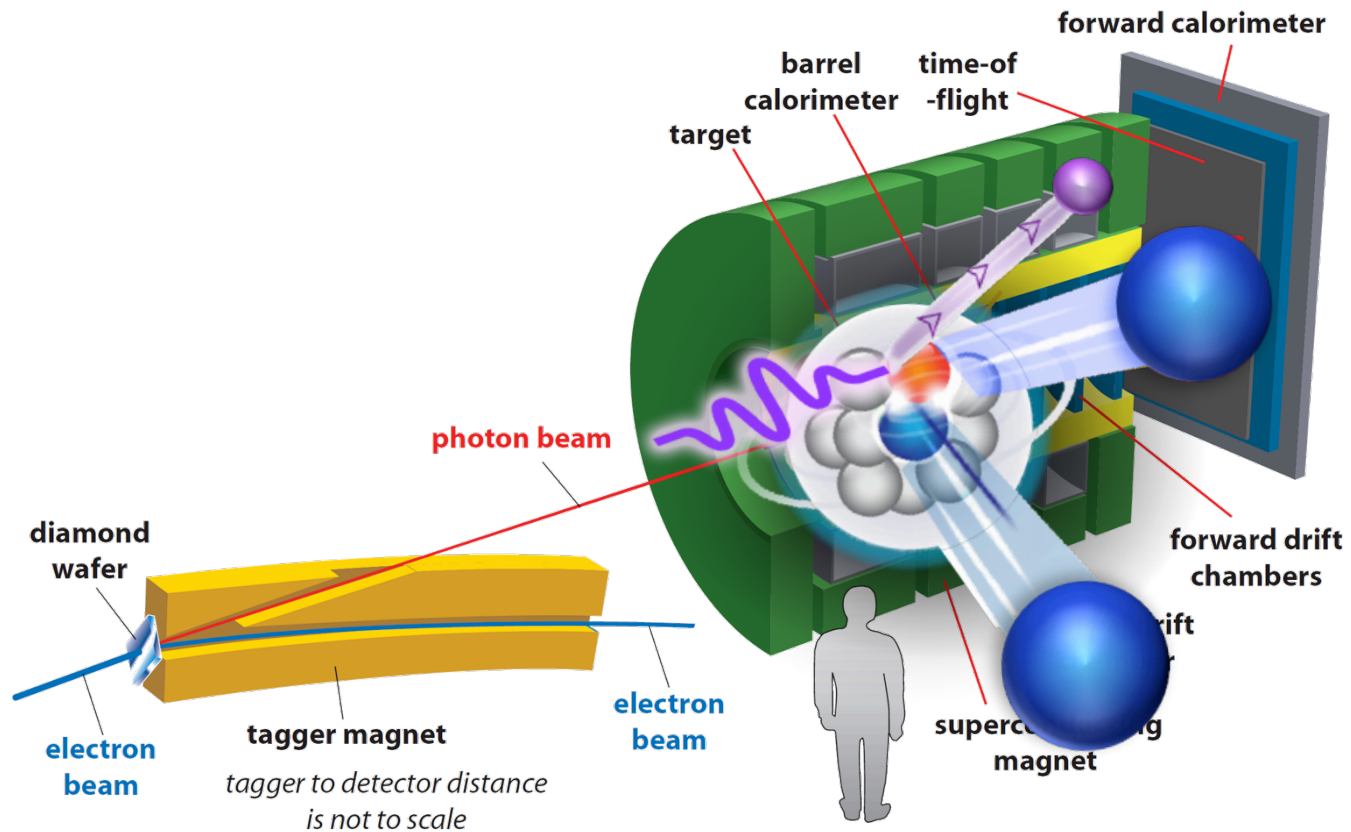


Probing QCD in the nuclear medium with real photons and nuclear targets at GlueX



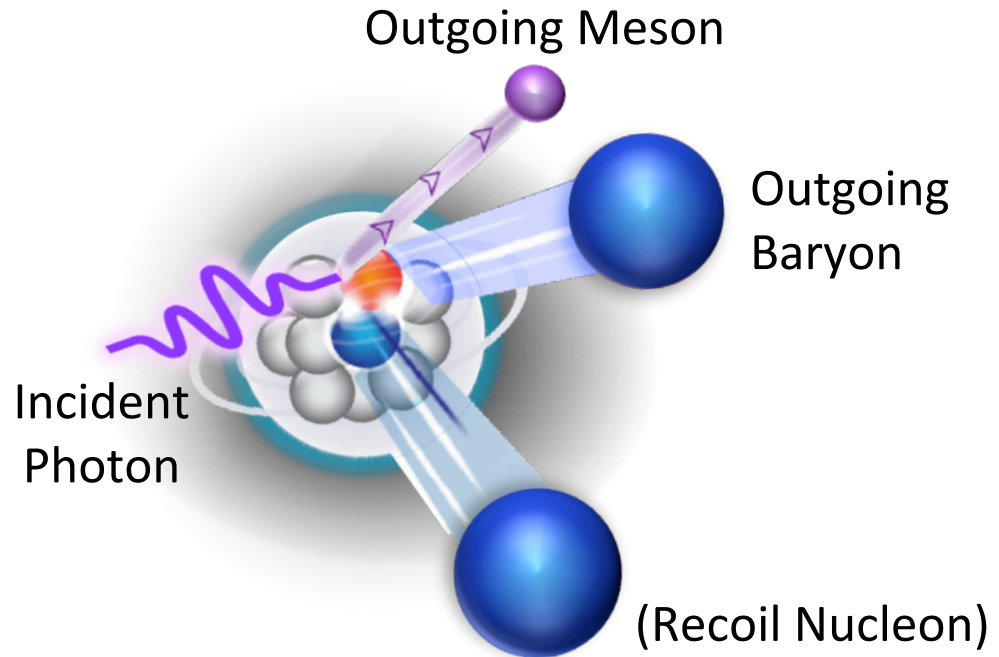
Photonuclear reactions

Fundamental QCD:

1. Photon Transparency
2. Color Transparency

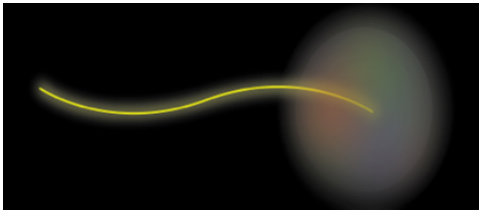
Nuclear Structure:

3. Short-Range Correlations

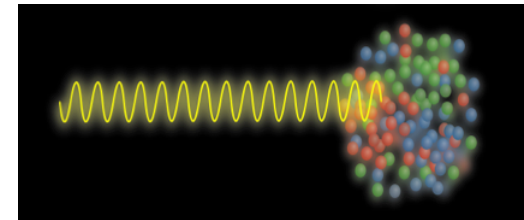


Transparency in photonuclear reactions

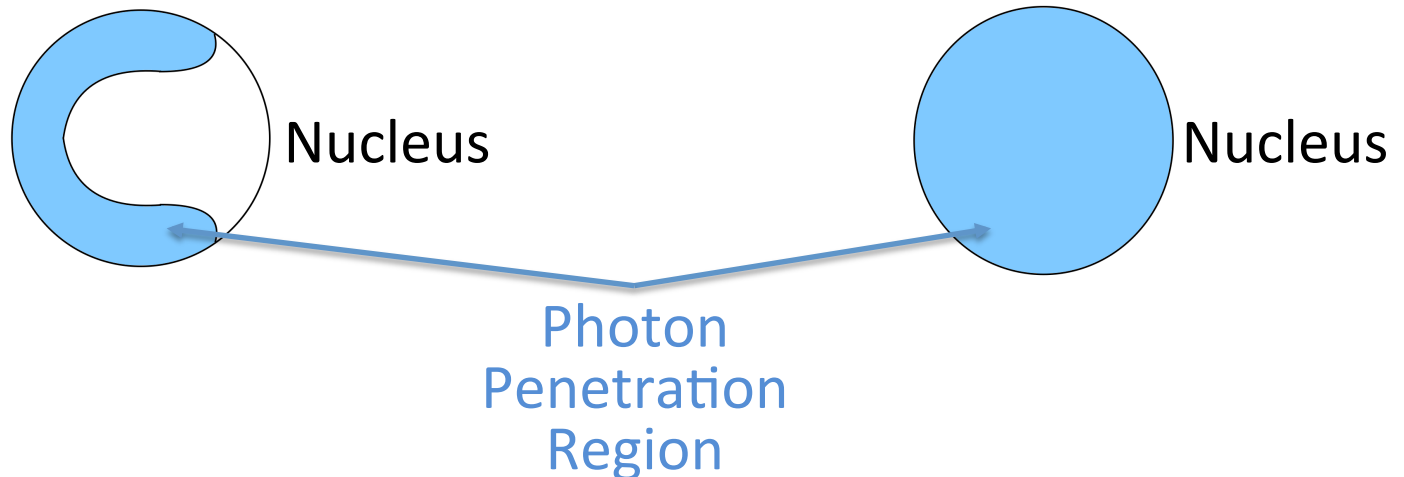
Probe Energy 



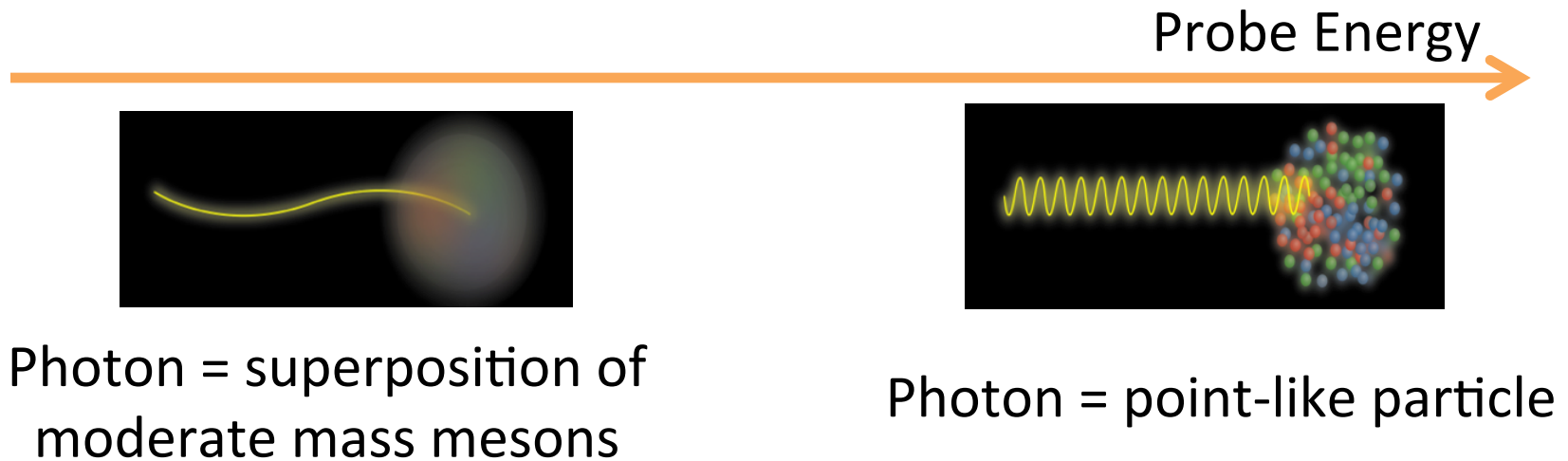
Photon = superposition of moderate mass mesons



Photon = point-like particle



Transparency in photonuclear reactions



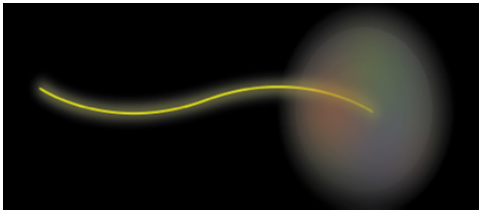
Transition expected at $|t| \sim 2 \text{ GeV}^2$.

May depend on quark composition (π vs. η), spin (π vs. ρ),

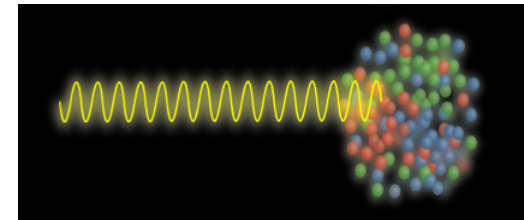
Probed via transparency and A-dependence: $T = \sigma_{\gamma A} / A\sigma_{\gamma N}$

Transparency in photonuclear reactions

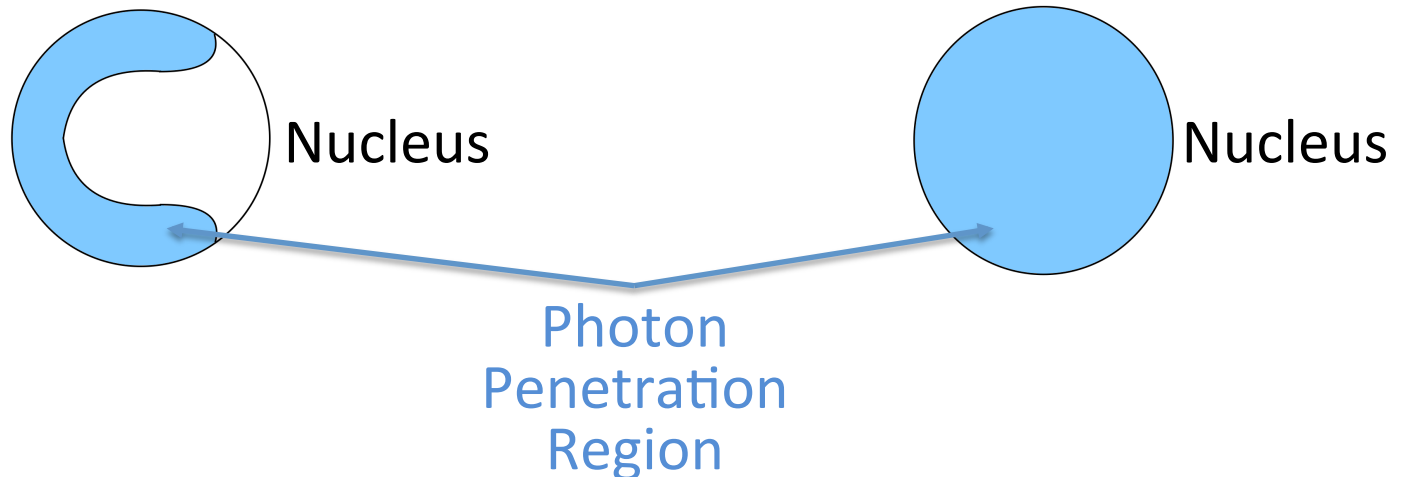
Probe Energy 



Photon = superposition of moderate mass mesons

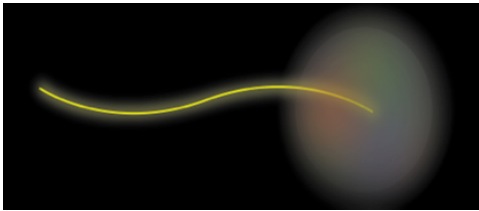


Photon = point-like particle

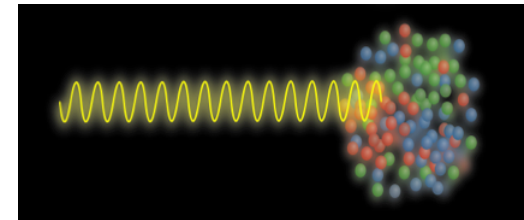


Transparency in photonuclear reactions

Probe Energy 



Photon = superposition of moderate mass mesons

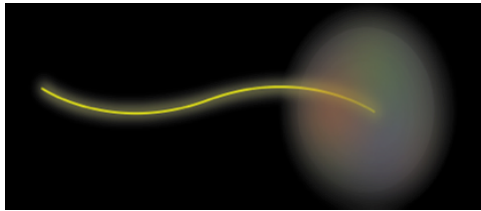


Photon = point-like particle

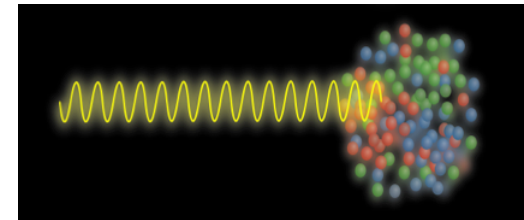


Transparency in photonuclear reactions

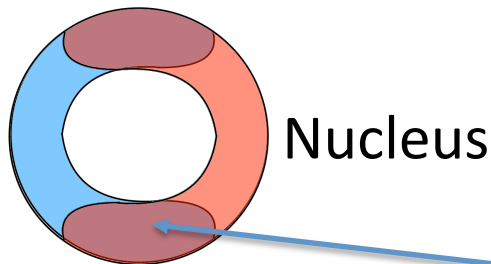
Probe Energy 



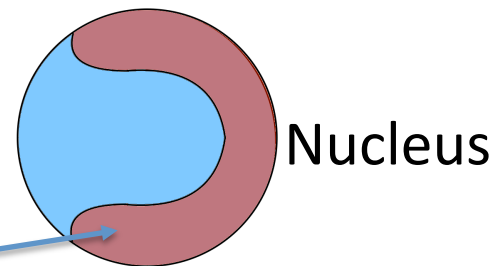
Photon = superposition of moderate mass mesons



Photon = point-like particle



Meson+Baryon
escape region



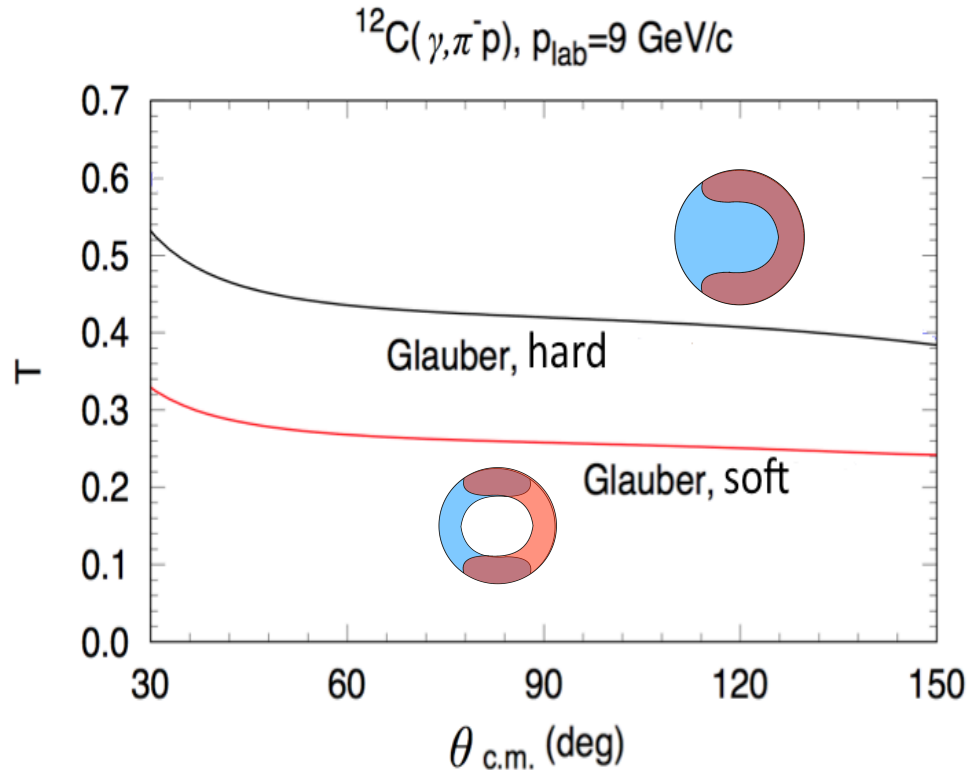
+ At very high $|t|$, Photon selects nucleons in compact configurations
→ color transparency (CT)

Photon transparency / photon structure in QCD?

Two Observables that can
separate hard/soft interactions:

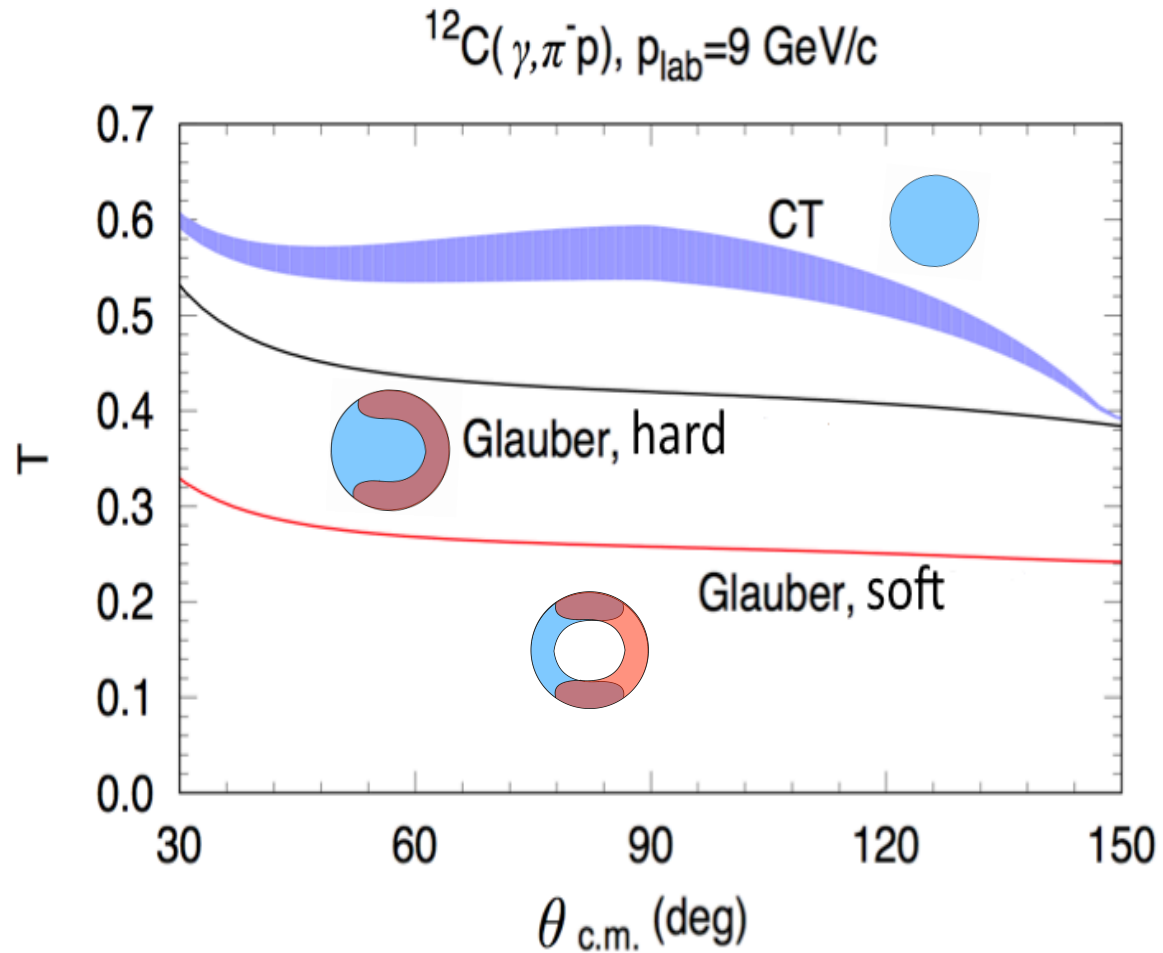
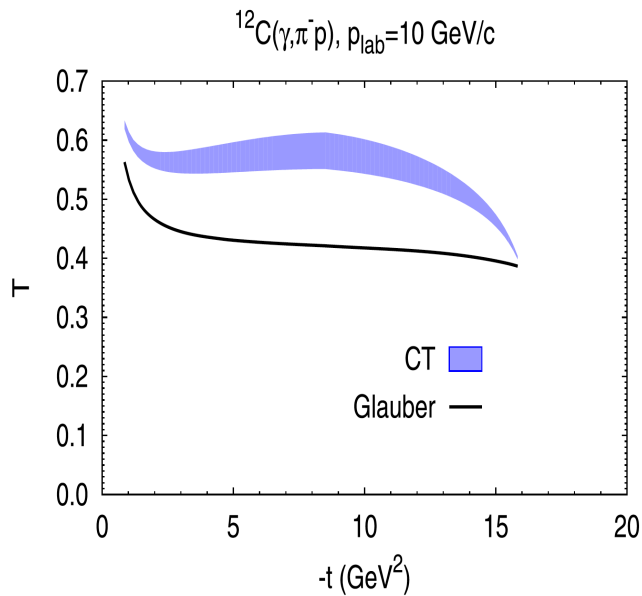
1. 'Absolute' transparency for a given nucleus
2. A-dependency (i.e. ratio for different nuclei)

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



Nuclear (color) transparency

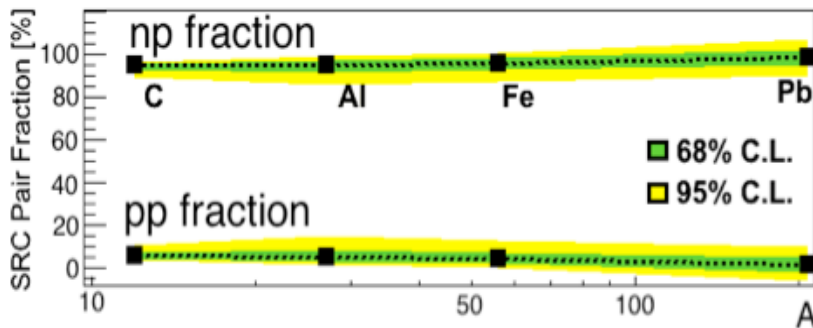
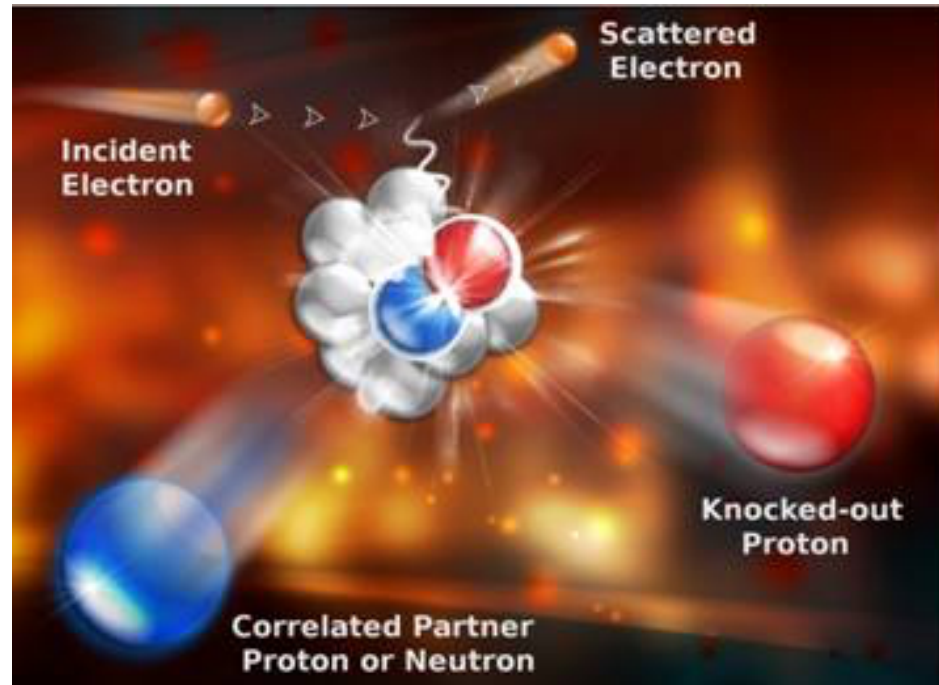
Large effect !



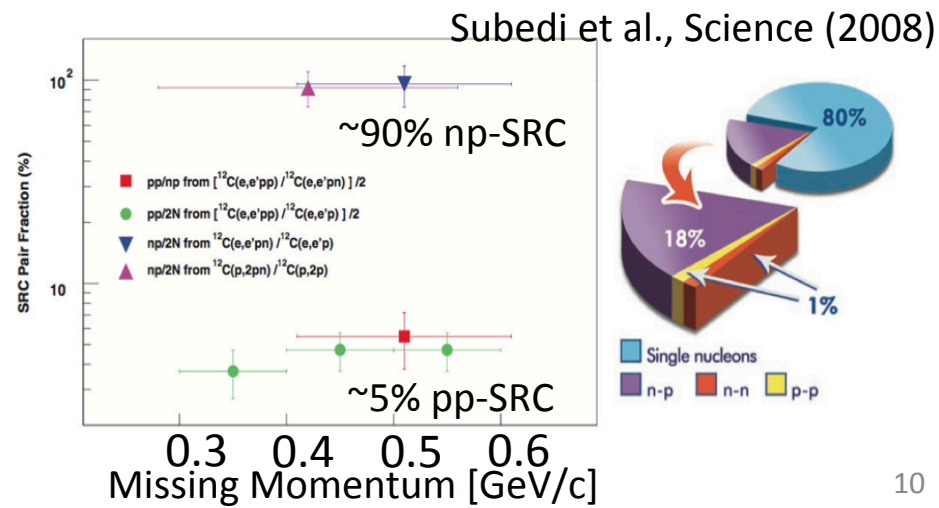
Short-Range Correlations

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**

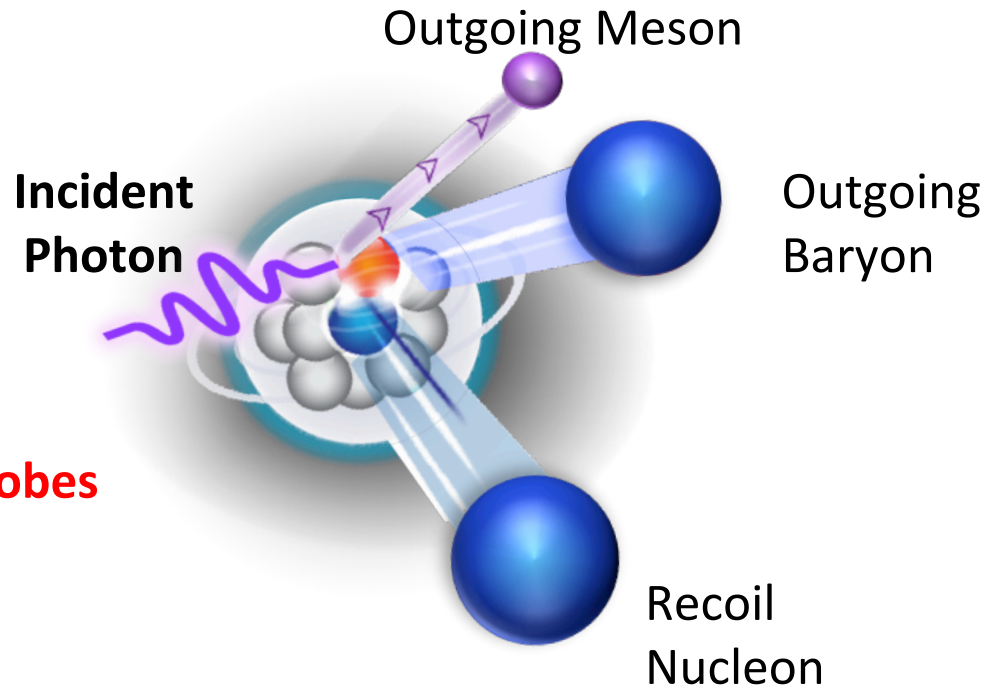


Hen et al., Science (2014)



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

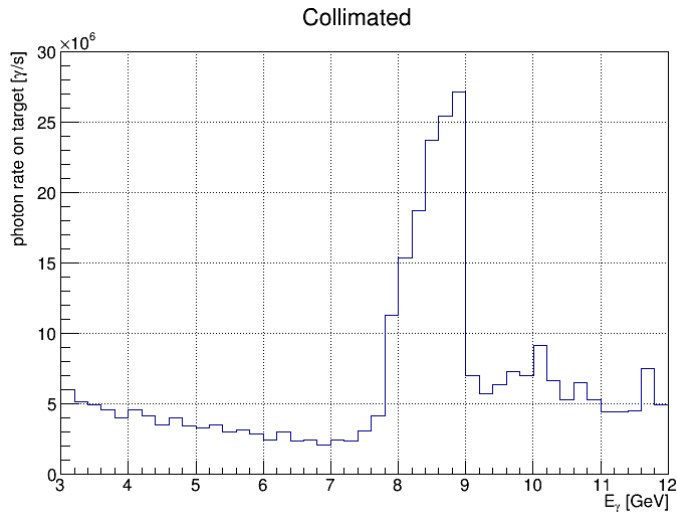
⁴He

¹²C

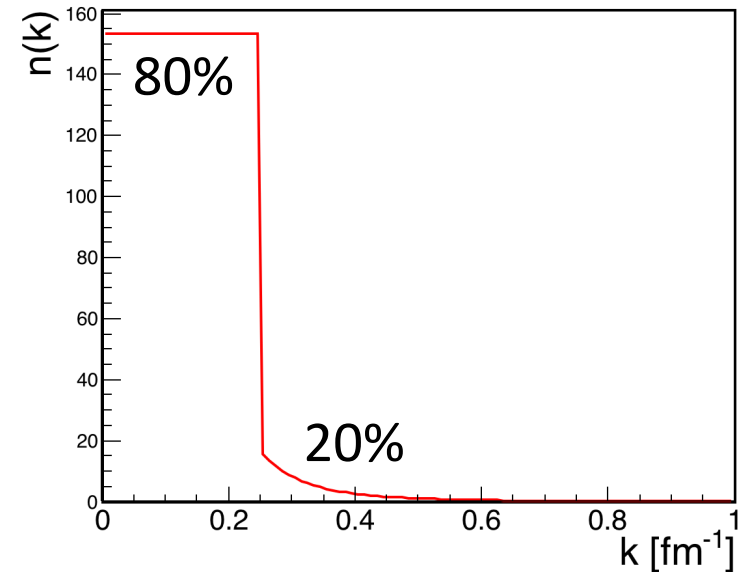
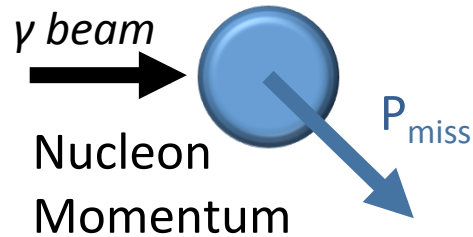
⁴⁰Ca

Kinematical Simulation

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



Lab Frame:

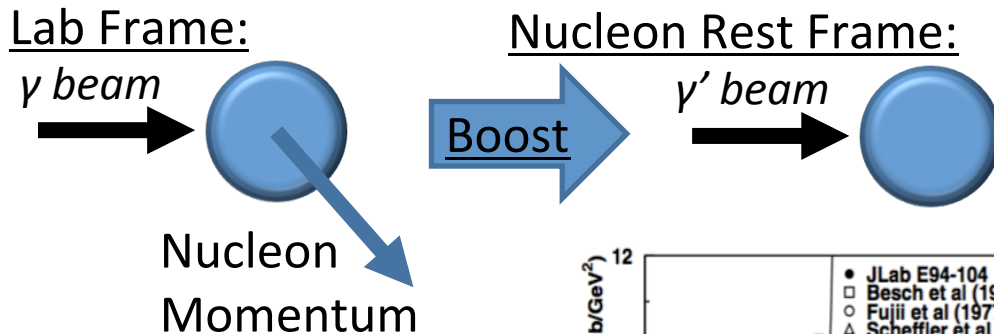


Kinematical Simulation

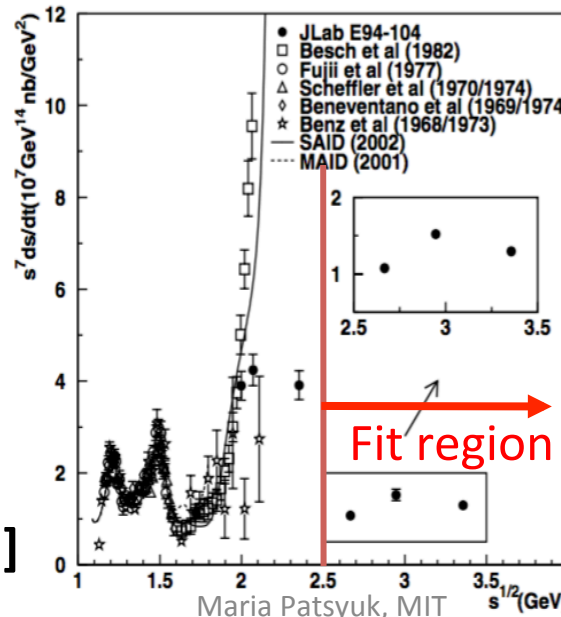
1. Raffle a nucleon from a correlated Fermi-Gas model and a photon from the GlueX beam

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

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



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



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

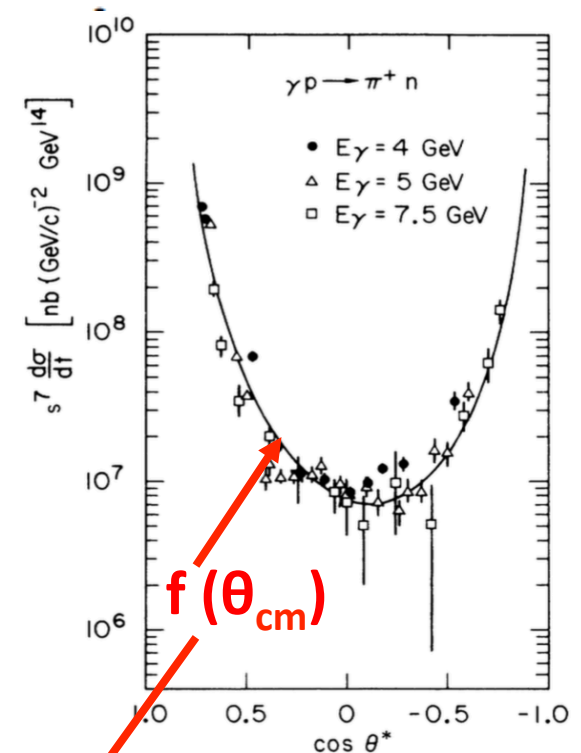
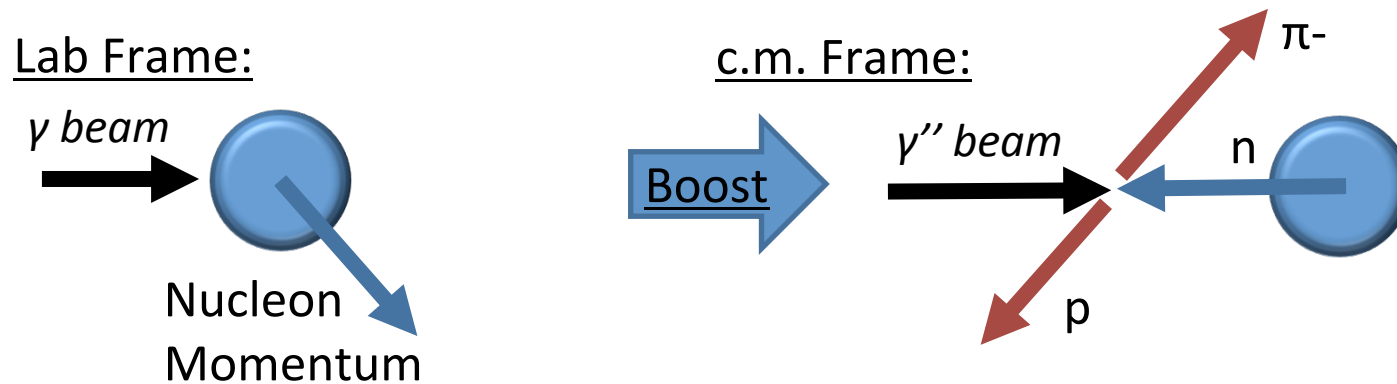


FIG. 6. $s^7 d\sigma/dt$ versus $\cos\theta^*$ for the reaction $\gamma p \rightarrow \pi^+ n$. The solid line shows the empirical function $(1-z)^{-5}(1+z)^{-4}$ where $(z = \cos\theta^*)$, which is an empirical fit to the angular distribution.

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 $40^\circ - 140^\circ$. Keep only events with $|t|, |u| > 2 \text{ GeV}^2$

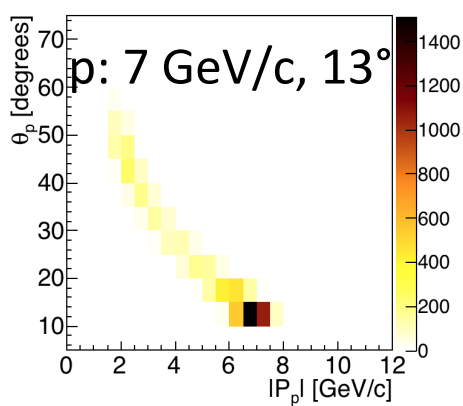
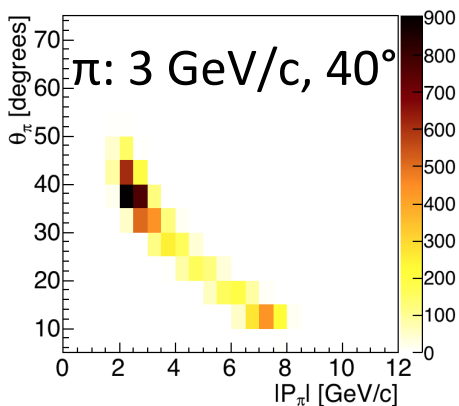


4. Boost back to the laboratory frame

Event selection for two regimes of interest

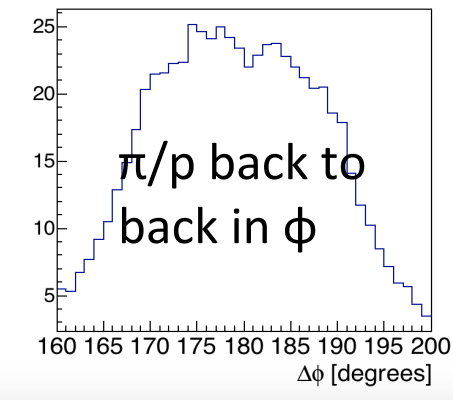
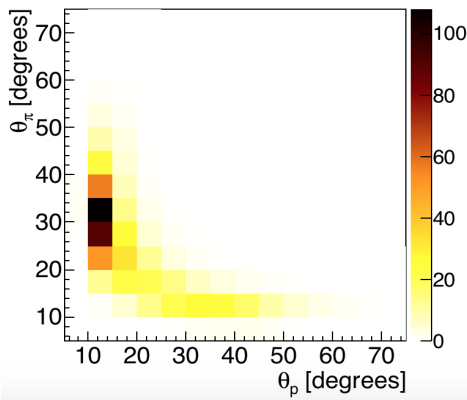
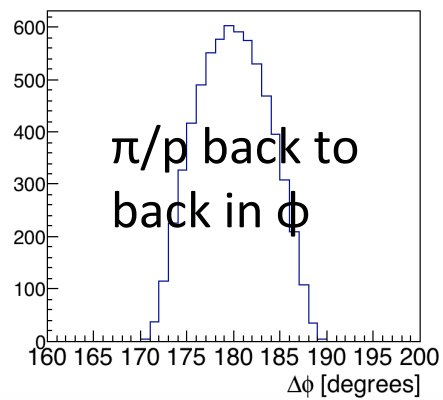
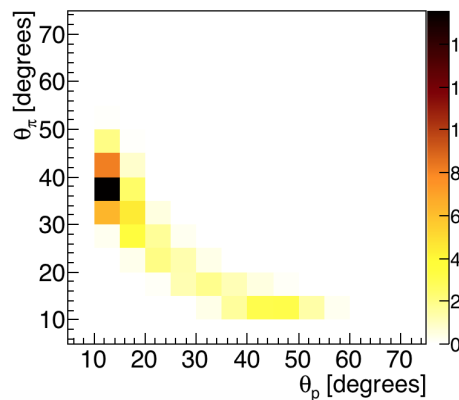
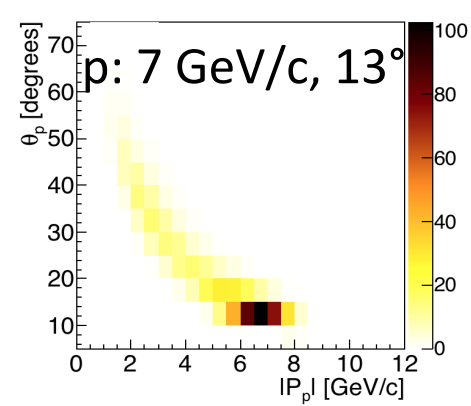
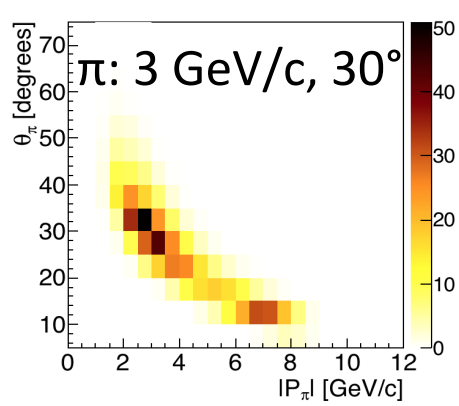
Mean Field (MF):

$P_{\text{miss}} < 0.25 \text{ GeV}/c$



SRC:

$P_{\text{miss}} > 0.3 \text{ GeV}/c, \theta_{\text{recoil}} < 160^\circ$



Detection Efficiency Simulations



(smallest expected rate)

40 days of beam, 4 targets

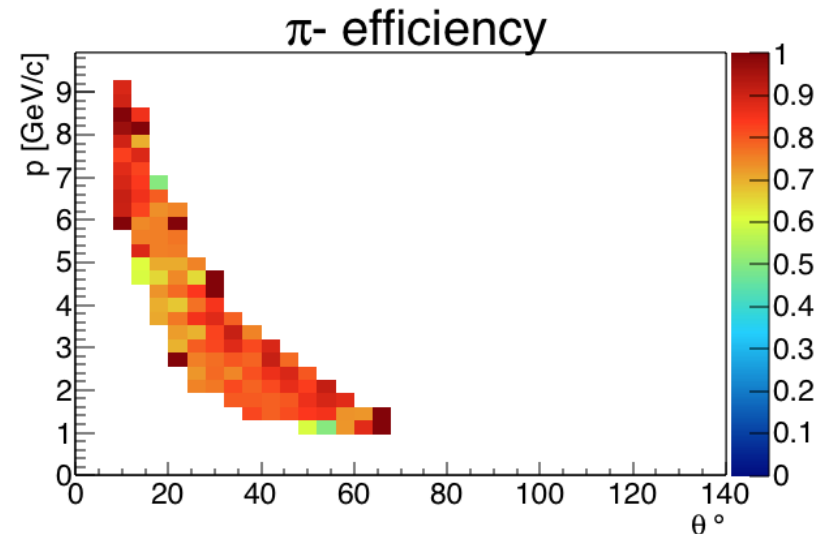
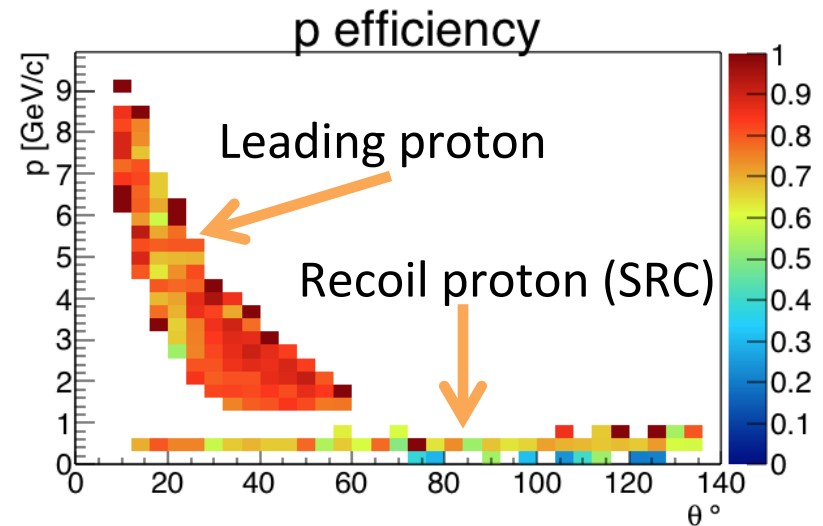
Detection efficiency:

80% \rightarrow each of leading particles

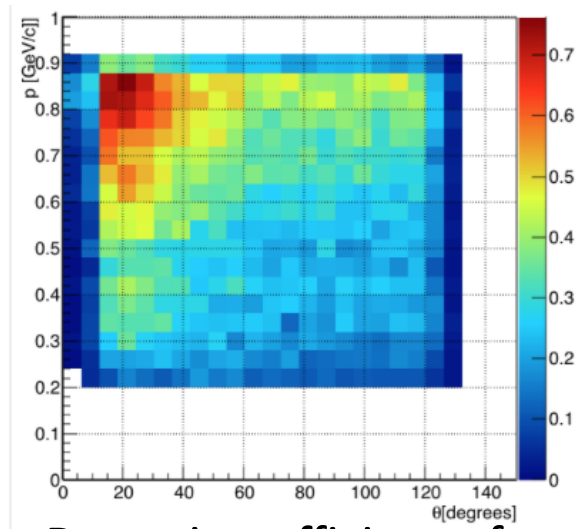
65% \rightarrow recoil proton (SRC)

30% \rightarrow reconstruction of ρ^0

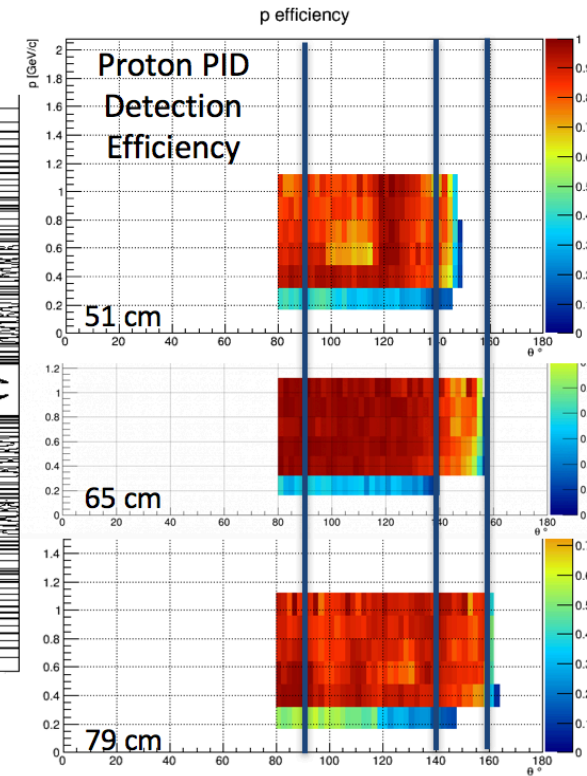
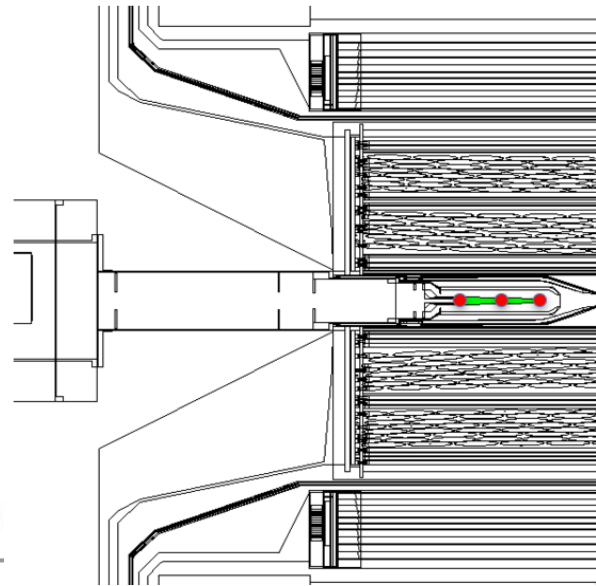
Nuclear attenuation: $\sigma \sim A^{-1/3}$



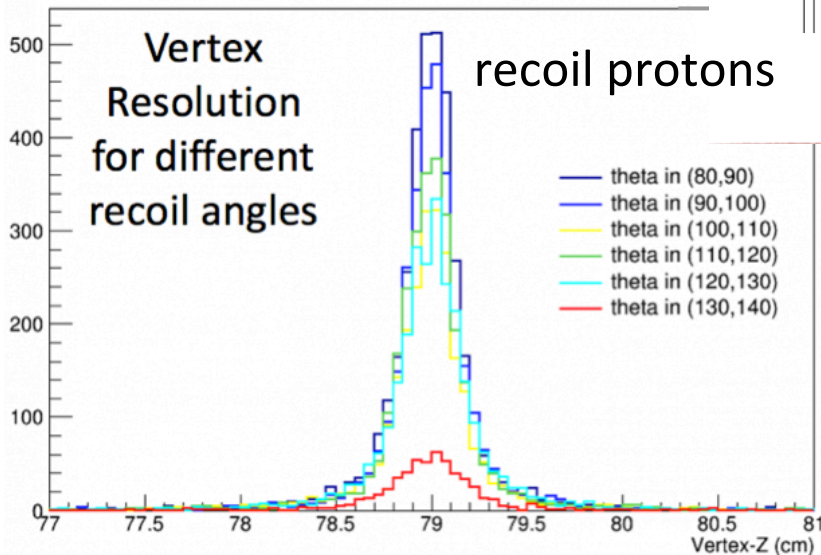
Detection Efficiency Simulations



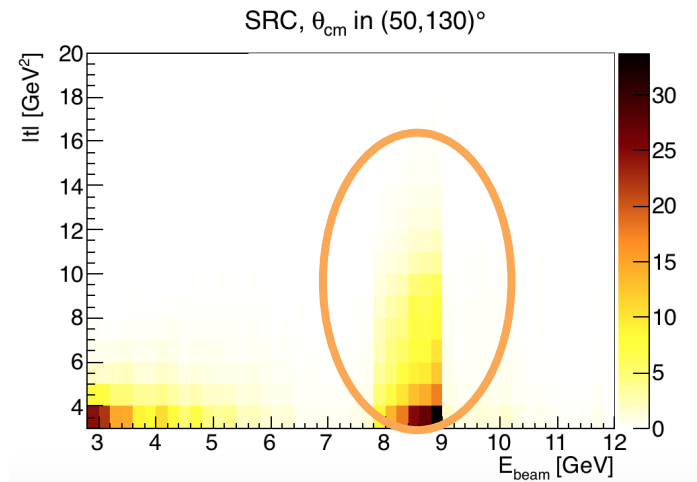
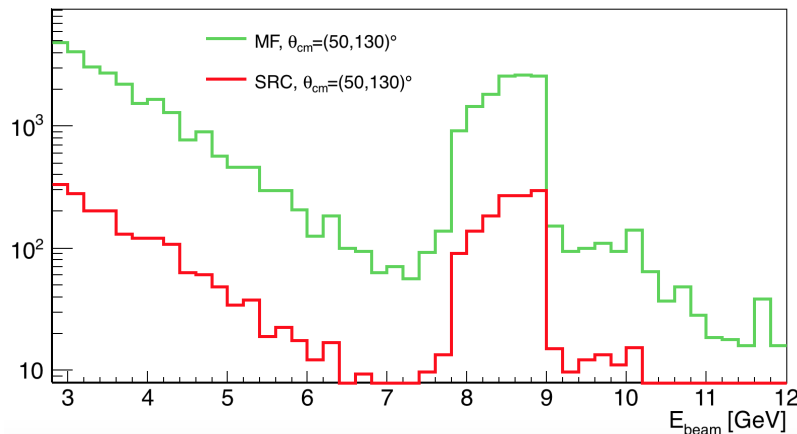
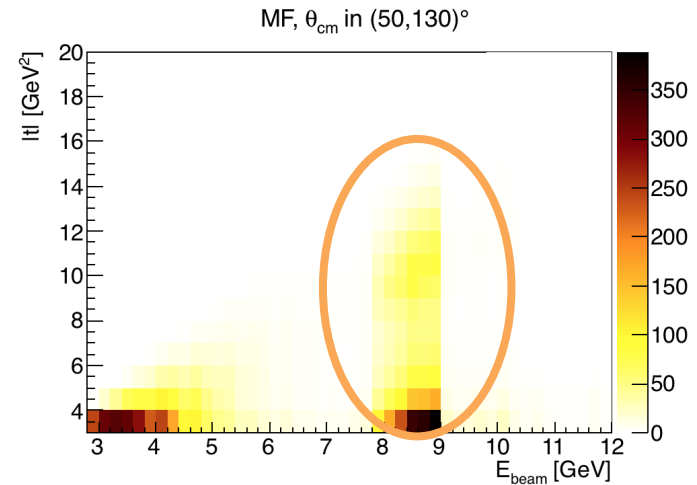
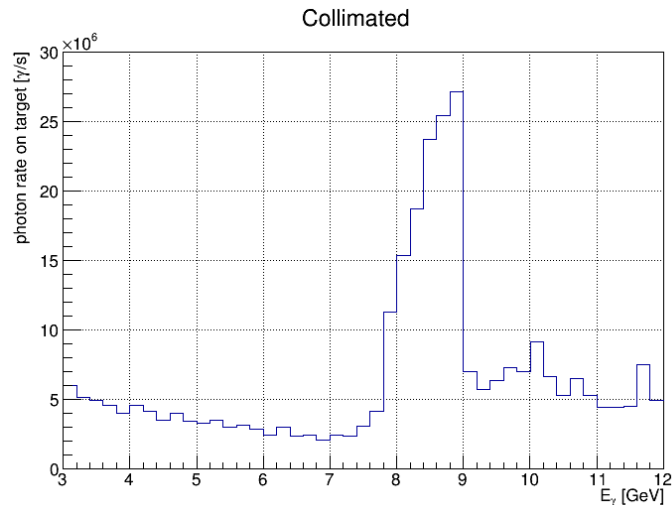
Detection efficiency for neutrons vs. angle and p



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

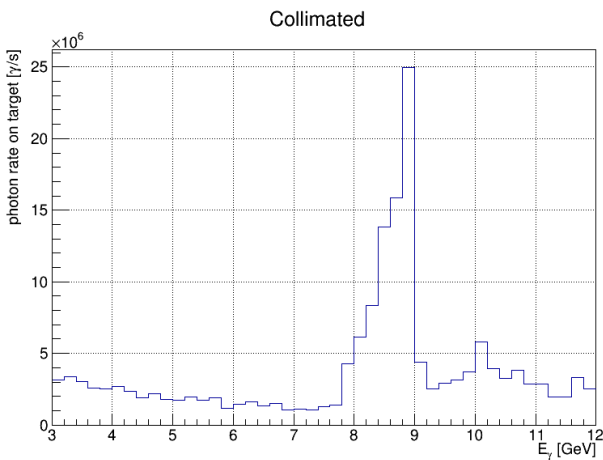
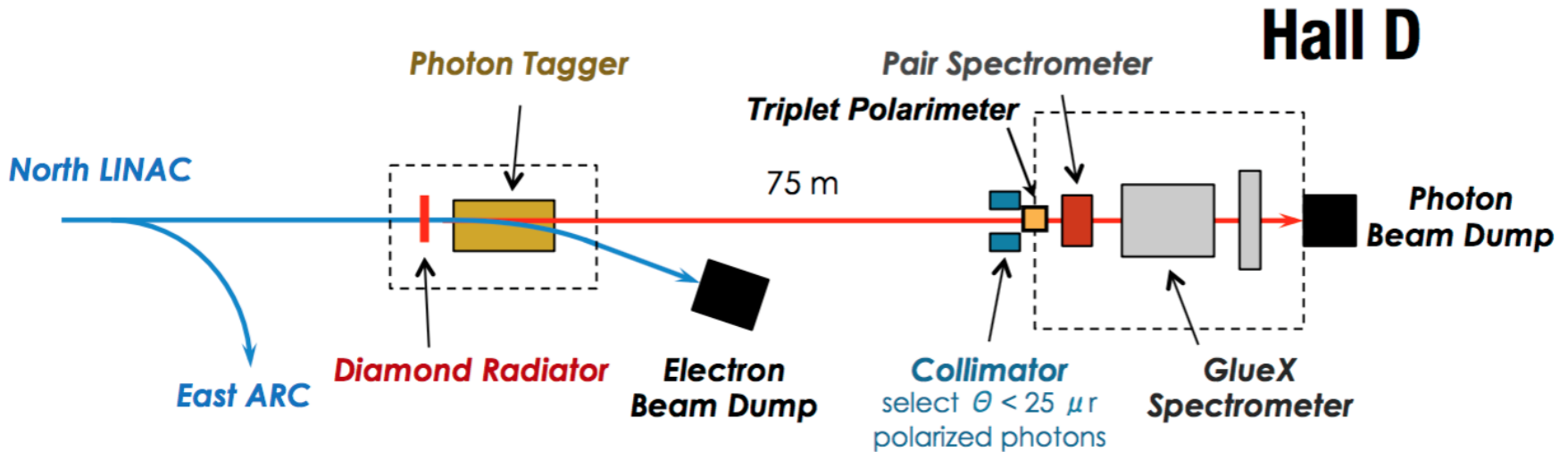


High $|t|$ = Diamond Radiator

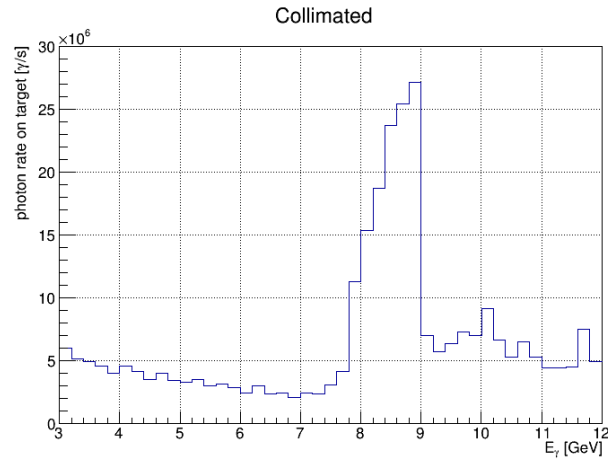


Can not use the whole photon spectrum because of tagger occupancy.
Coherent peak [8.4, 9.1] GeV, 5 mm collimator – optimized collimation efficiency and high $|t|$ values

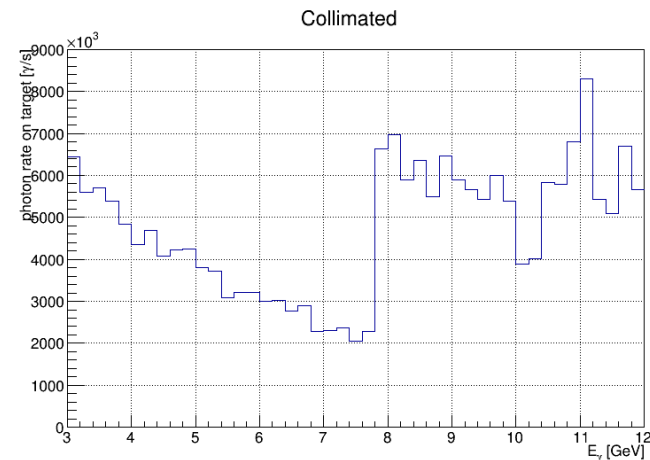
Beam optimization: collimator, radiator



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:

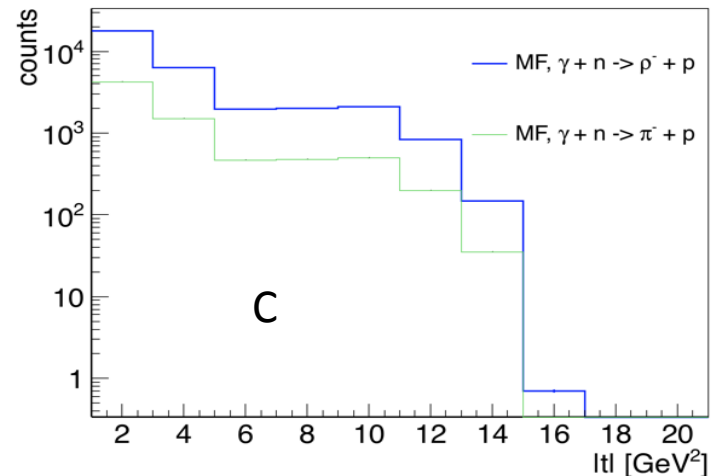
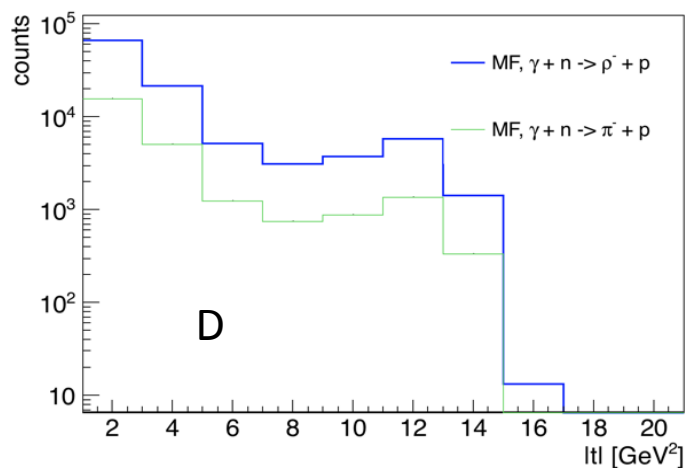
1. GlueX detector capabilities: limited flux on target of $2 \cdot 10^7$ photons/s
2. Target thickness \rightarrow electromagnetic background $\sim X_0$
3. Neutron background $\sim n_{\text{cm}} \cdot A$
4. Coincidental rate in the tagger (up to 8% for this flux)

Target	Thickness [cm] / %X0	Atoms/cm ³	<u>Em bkg</u> rel. to <u>GlueX</u>	<u>Neutron</u> bkg rel. to <u>GlueX</u>
D	30 / 4.1	$1.51 \cdot 10^{24}$	0.5	0.5
⁴ He	30 / 4	$5.68 \cdot 10^{23}$	0.5	0.5
¹² C	1.9 / 7	$1.45 \cdot 10^{23}$	1	0.6
⁴⁰ Ca	0.73 / 7	$1.70 \cdot 10^{23}$	1	1.1
LH	30 / 3.4	$1.28 \cdot 10^{24}$	1	1

Event rates for all targets / reactions

Rates for the reactions with the smallest and largest cross section

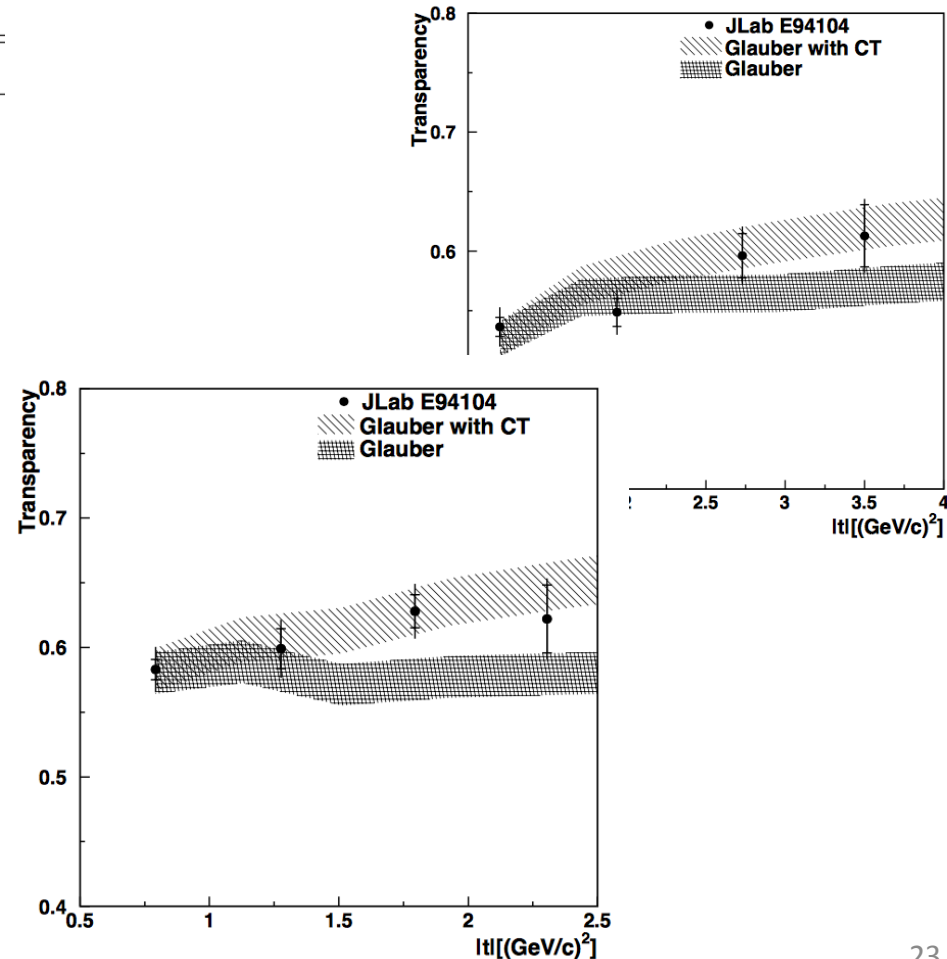
Target	$\gamma + n \rightarrow \pi^- + p$		$\gamma + n \rightarrow \rho^- + p$		PAC days
	MF	SRC	MF	SRC	
D	12,500	750	50,000	3,200	5
^4He	12,000	3,000	50,000	13,000	8
^{12}C	7,300	2,300	31,000	10,000	10
^{40}Ca	2,600	900	11,000	3,500	14
Calibration, commissioning and overhead:					3
Total PAC Days:	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



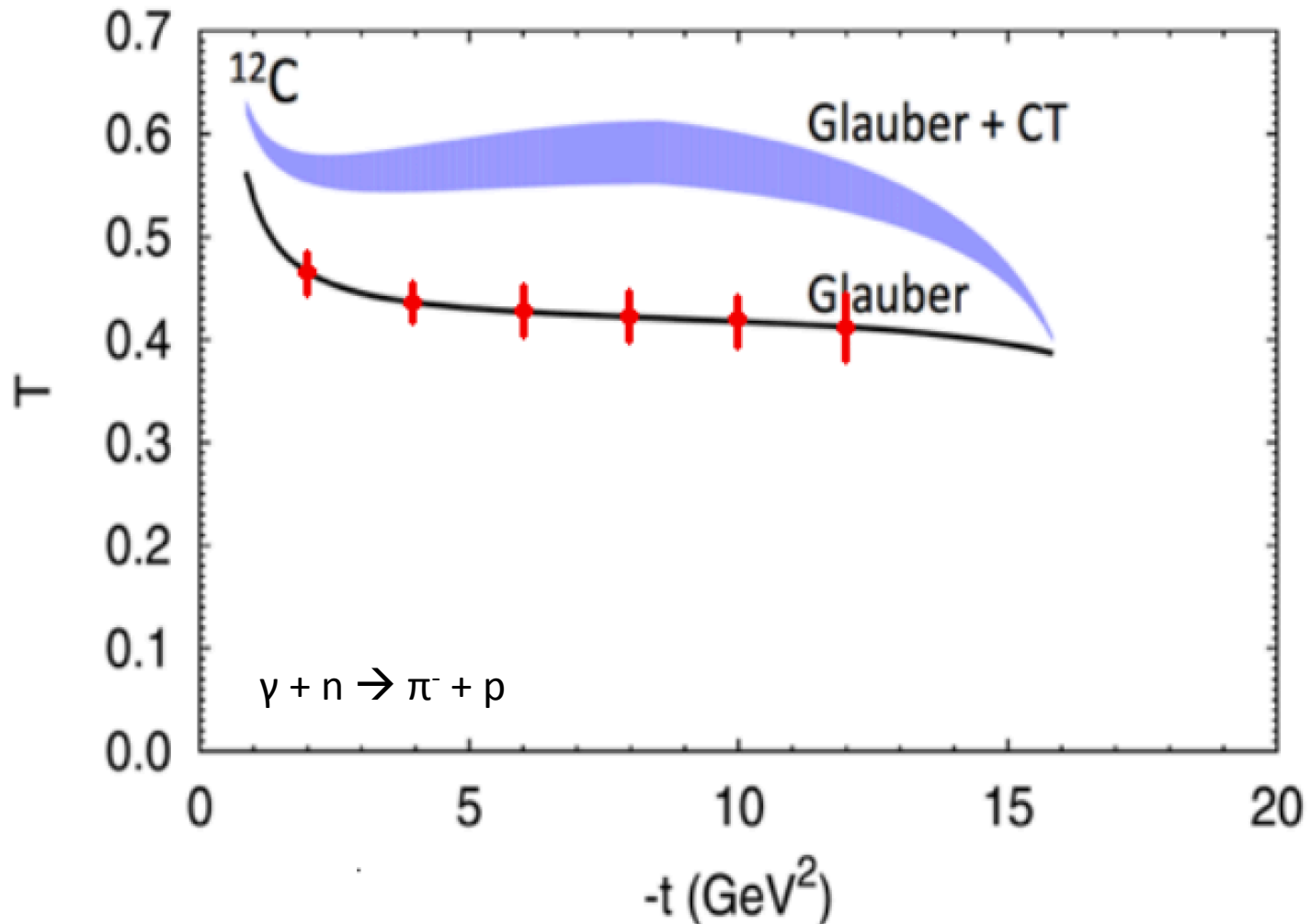
Nuclear transparency with the $\gamma n \rightarrow \pi^- p$ process in ${}^4\text{He}$

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. Glashauser,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. Zheng²
 (Jefferson Lab E94104 Collaboration)

E_γ	$ t $	T (${}^4\text{He}$)	Uncertainties	
GeV	$(\text{GeV}/c)^2$		Statistical	point-to-point systematic
			$\theta_{cm}^\pi = 70^\circ$	
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 $\sim 5\%$	0.017
			$\theta_{cm}^\pi = 90^\circ$	
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 $\sim 5\%$	0.017



GlueX Predictions



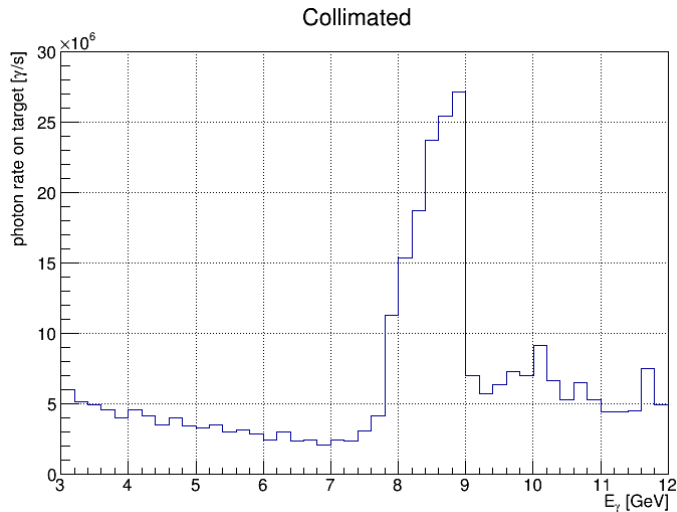
Summary

- 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!

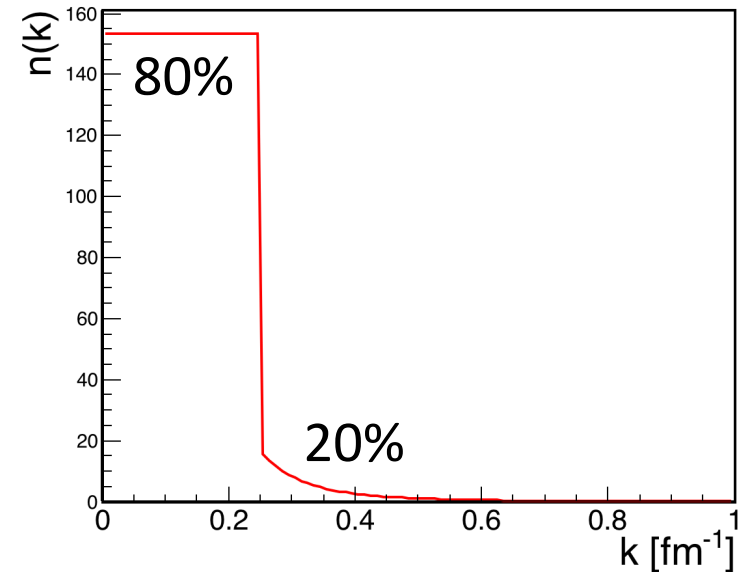
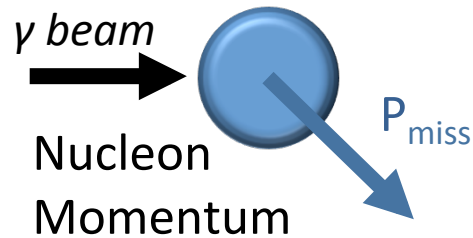
Backups

Kinematical Simulation

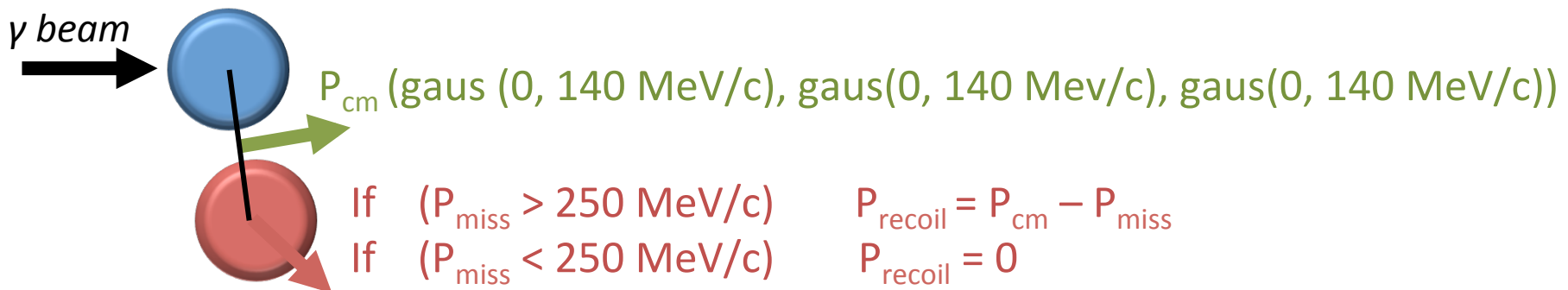
1. Raffle a nucleon from a correlated Fermi-Gas model and a photon from the GlueX beam:



Lab Frame:



Lab Frame:



Factor transforming $d\sigma/dt$ into $d\sigma/d\Omega$

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

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.

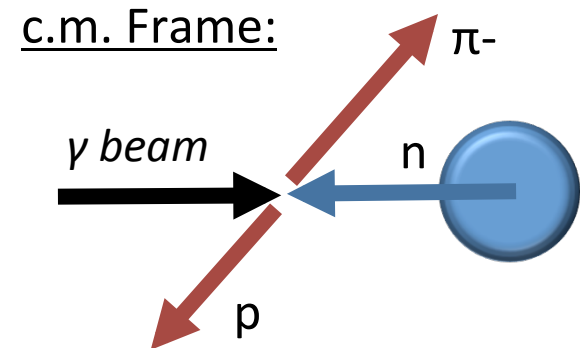
In the center of mass system:

$$t = -2E_i E_f + 2k_i k_f \cos \theta_{cm} + m_\pi^2.$$

$$dt = 2k_i k_f d \cos \theta_{cm}$$

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

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



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

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

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

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

where nucleon energy (E_N) is the following:

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

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

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

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

Limitations to get physical results

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

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

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

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

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