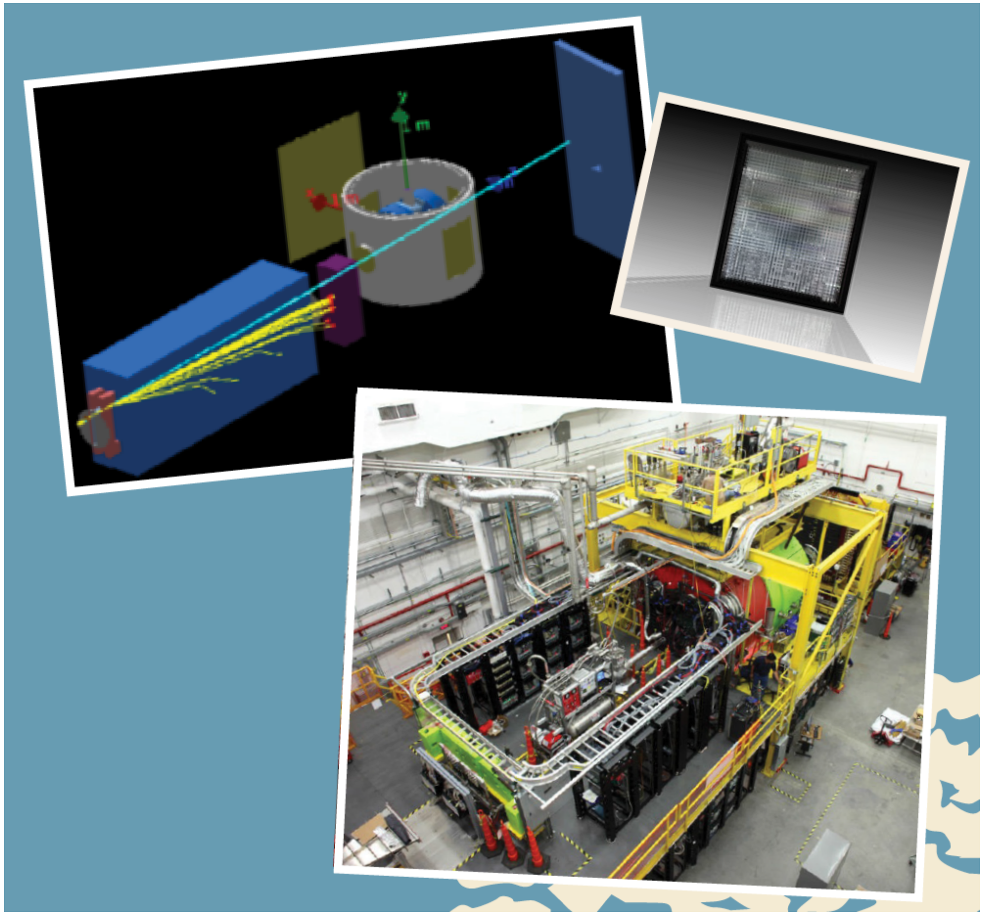
Photonuclear Reactions



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What can we study by measuring photonuclear reactions?

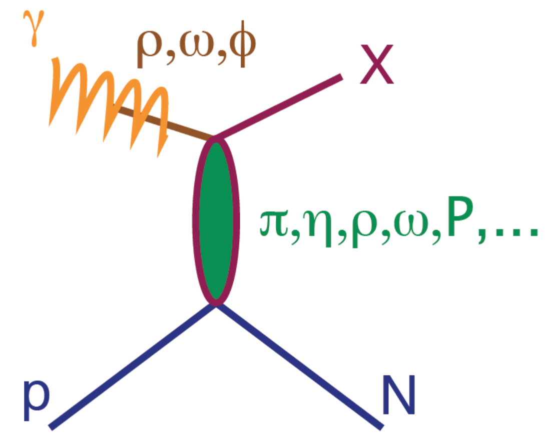
1. Photon Transparency

QCD-related

2. Color Transparency

3. Nuclear Structure
4. Medium Modifications

(1) Photon transparency / What is the photon structure in QCD?



Option I: Soft processes

Photon = superposition of hadronic states with moderate mass,
interacts only with the rim of the nucleus (Glauber approximation)

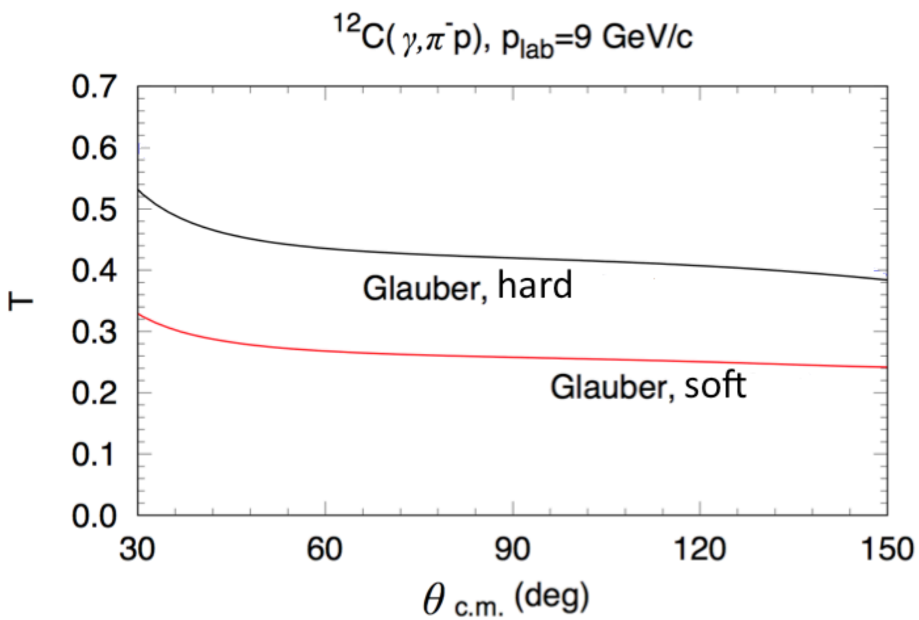
Transition at $|t| \sim 2$ GeV^2, may depend on quark composition (π vs. η), spin (π vs. ρ), A-dependency of $T = \sigma_{measured} / \sigma_{PWIA}$

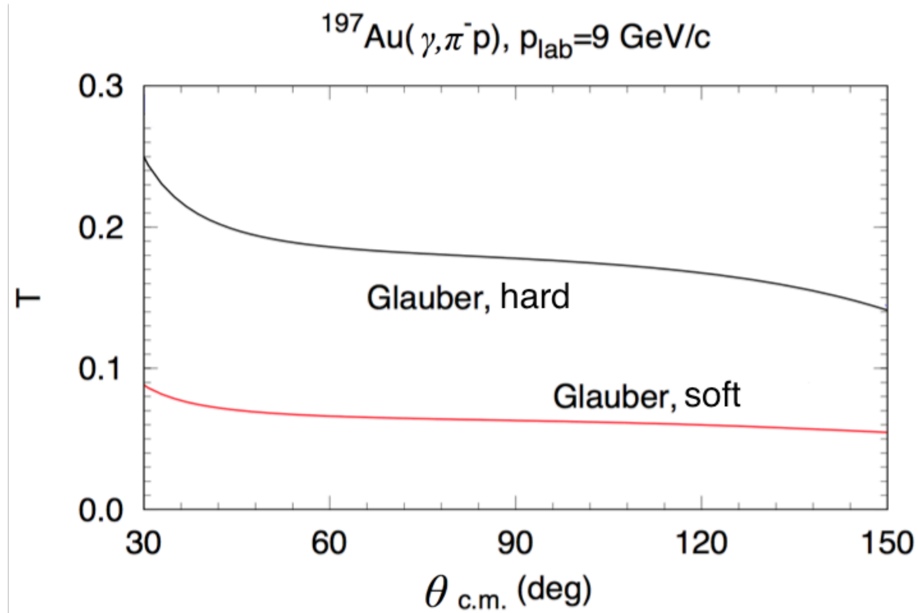
Option II: Hard processes

Photon = point-like particle,
can interact with any nucleon inside the nucleus

(1) Photon transparency / What is the photon structure in QCD?

$T = \sigma_{measured} / \sigma_{PWIA}$





<u>Two Observables that can separate hard / soft interactions:</u>

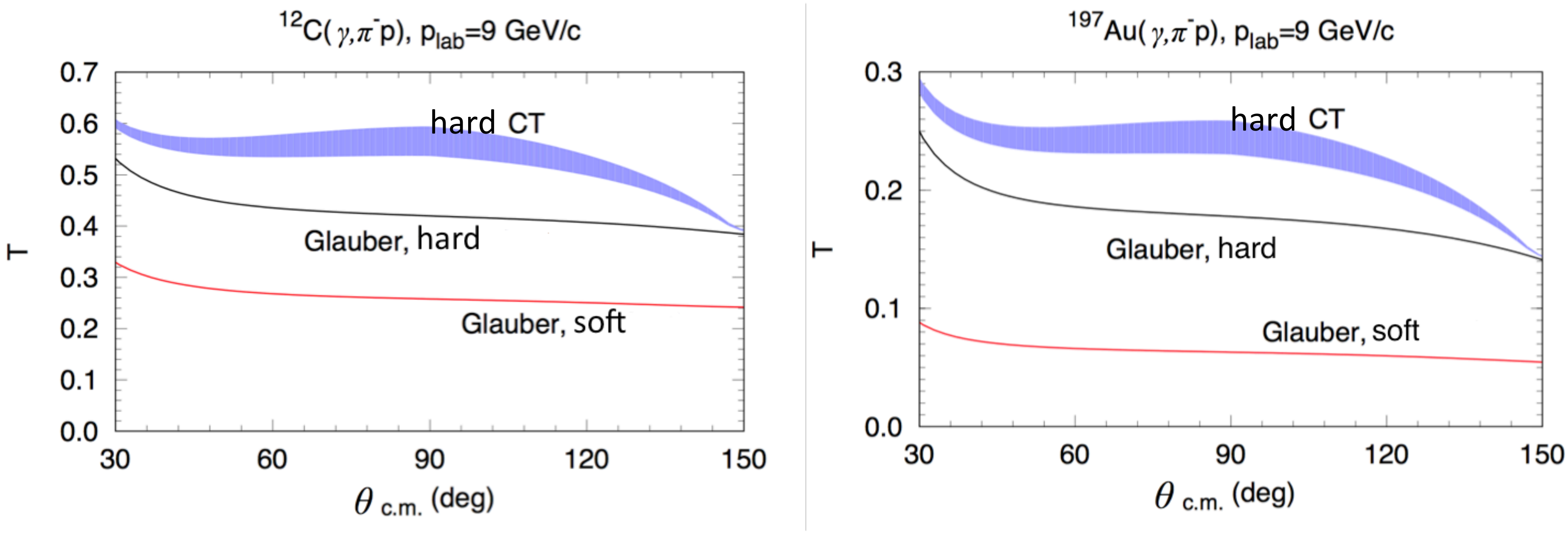
1. 'Absolute' transparency for a given nucleus
2. A-dependency (i.e. ratio for ^{197}Au and ^{12}C)

A. Larionov and M. Strikman, private communication

(2) Nuclear (color) transparency

For GlueX kinematical conditions nuclear attenuation deviates from the Glauber calculation:

$$T = \sigma_{measured} / \sigma_{PWIA}$$



Large effects !

A. Larionov and M. Strikman, private communication

(2) Nuclear (color) transparency

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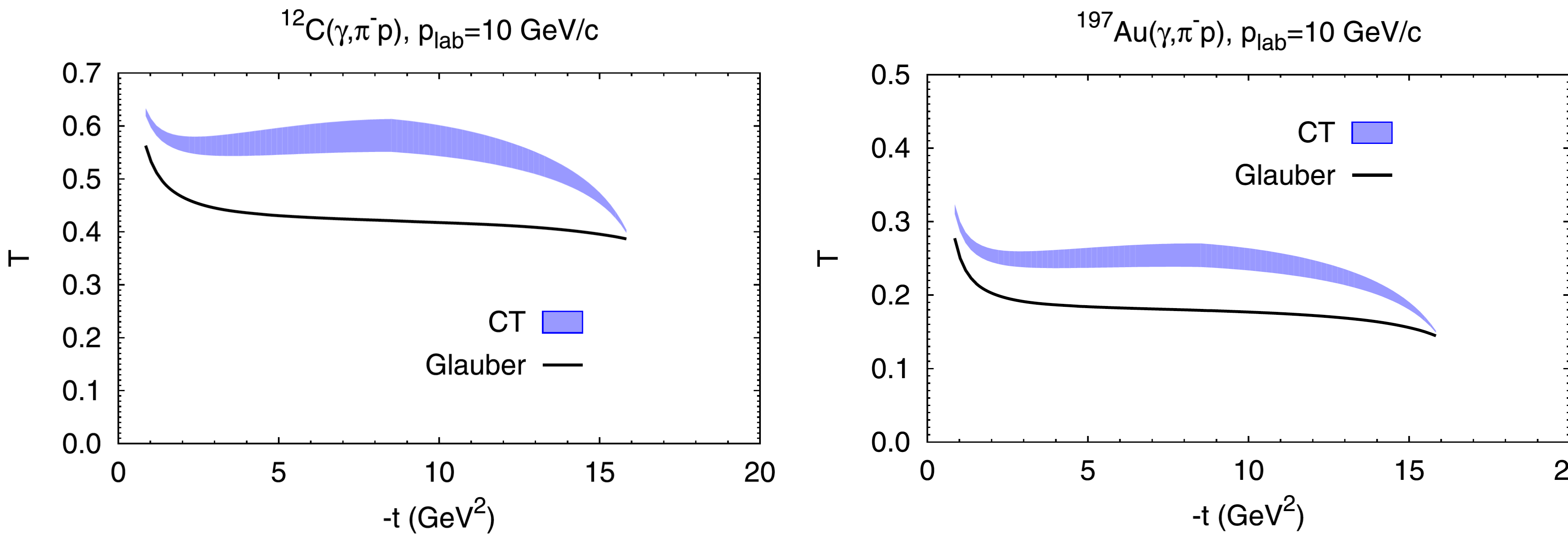


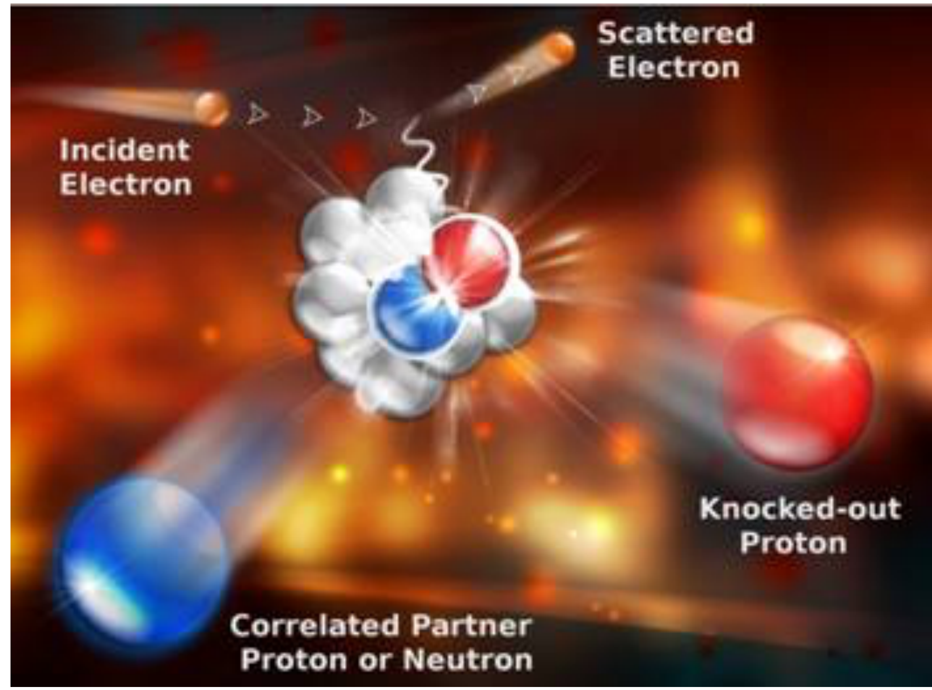
Large effects !

A. Larionov and M. Strikman, Phys. Lett. B **760**, 753 (2016)

(3) SRC – probes of nuclear structure

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**



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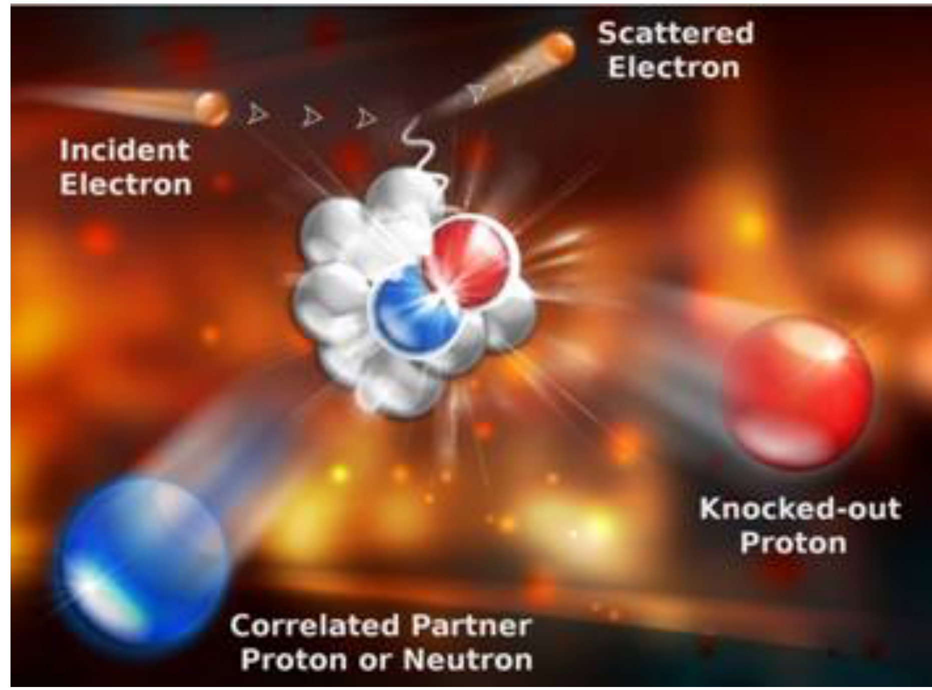
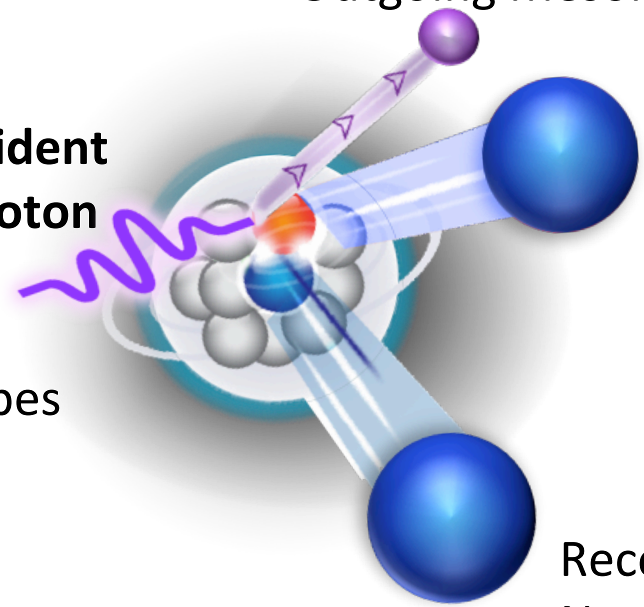


Implications:

- **Nuclear physics**: nuclear momentum distribution, nucleon-nucleon interaction
- **Particle physics**: EMC effect, ν-nucleus scattering, NuTeV anomaly
- **Astrophysics**: neutron stars, nuclear symmetry energy
- **Atomic physics**: energy sharing in IFS, contact interaction in IFS

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 ($\gamma\, n \rightarrow \pi^-\, p$)

- Probe nn SRC-pairs
- role of p vs. n in a nucleus
- map transition between mean field and SRC

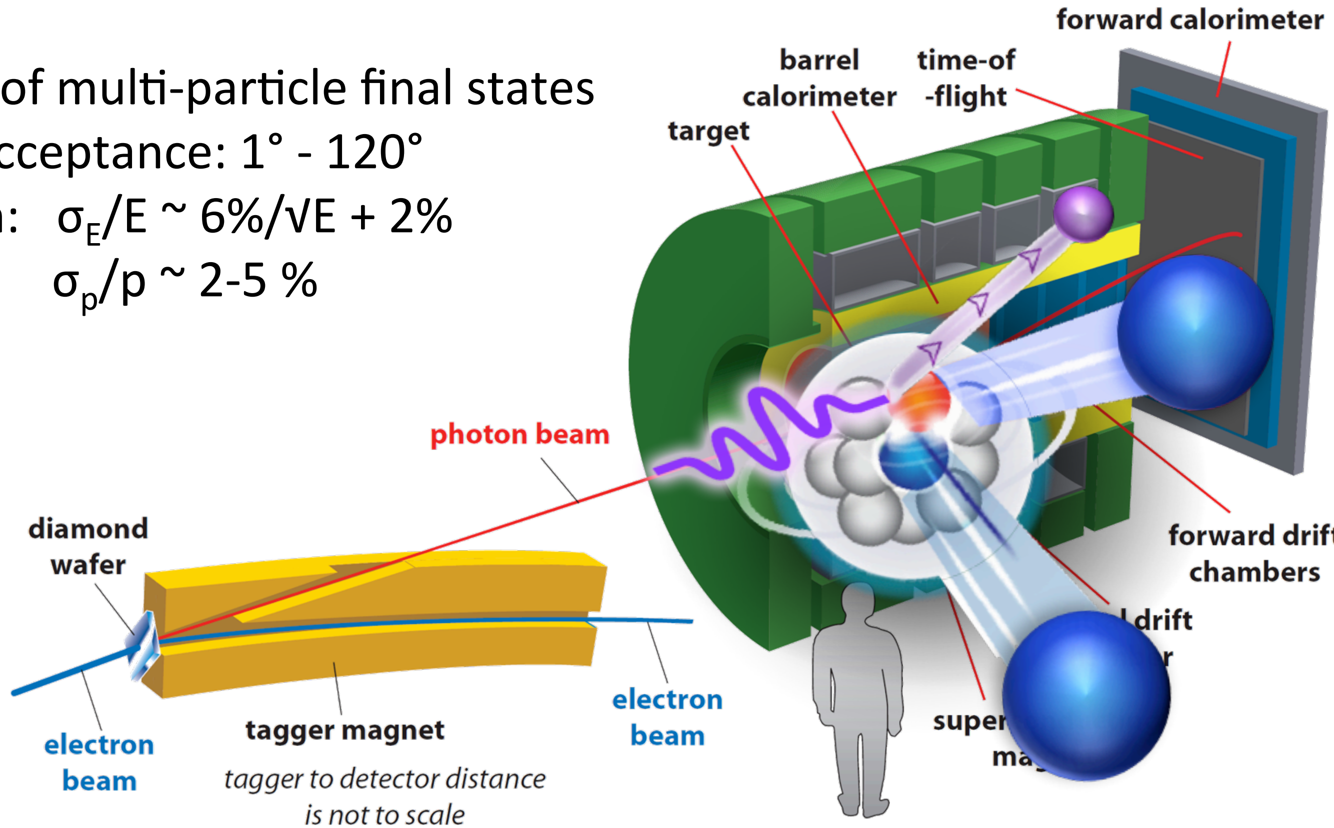
Example: GlueX

Detection of multi-particle final states

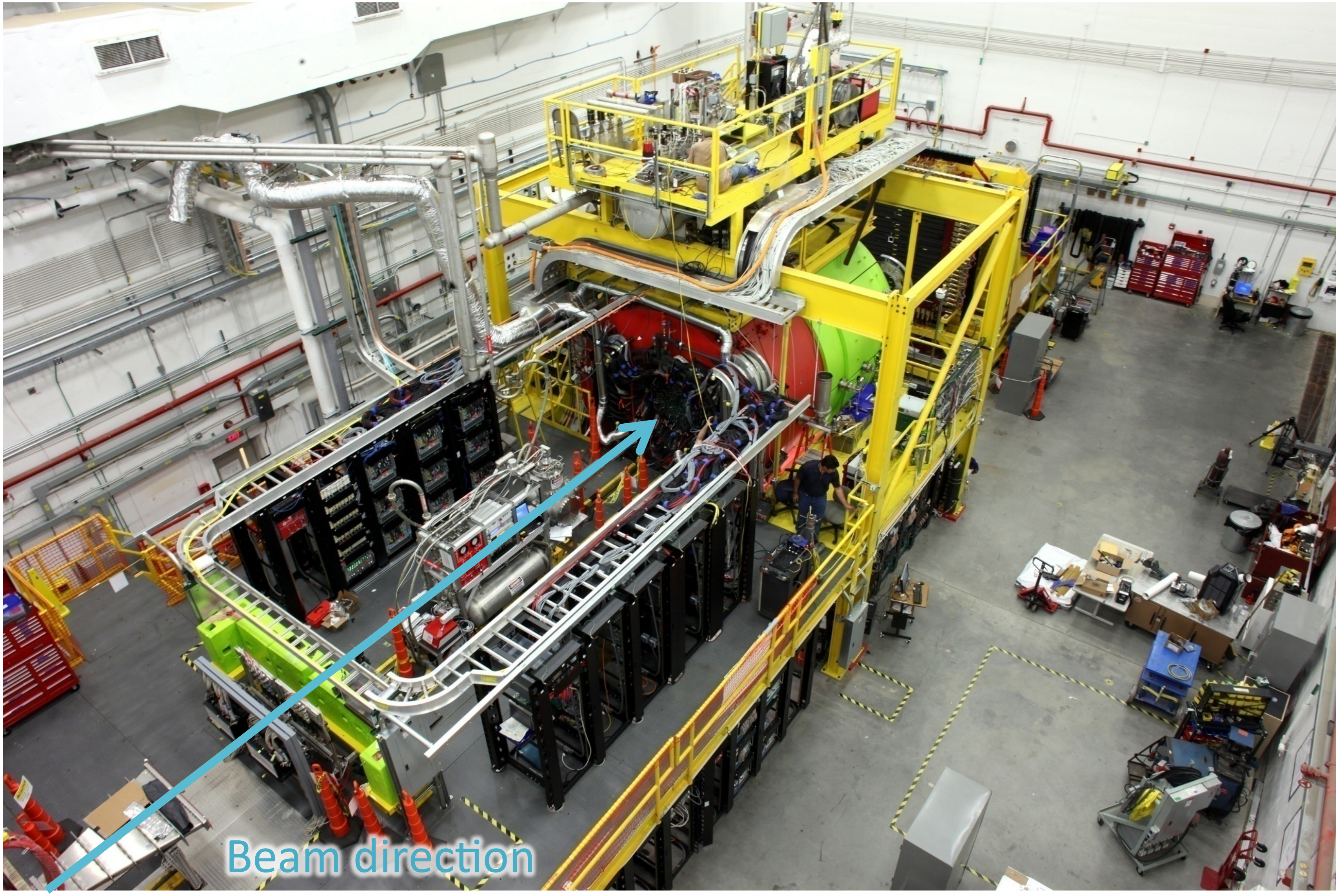
Uniform acceptance: 1° - 120°

Resolution: $\sigma_E/E \sim 6\%/\sqrt{E} + 2\%$

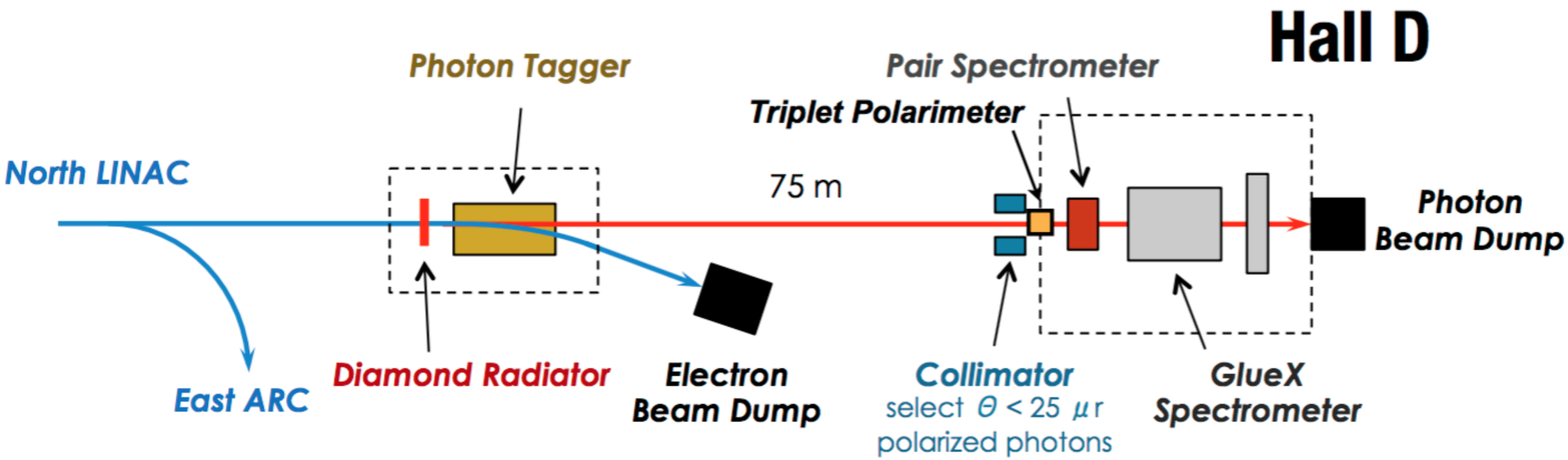
$\sigma_p/p \sim 2\text{-}5\ \%$

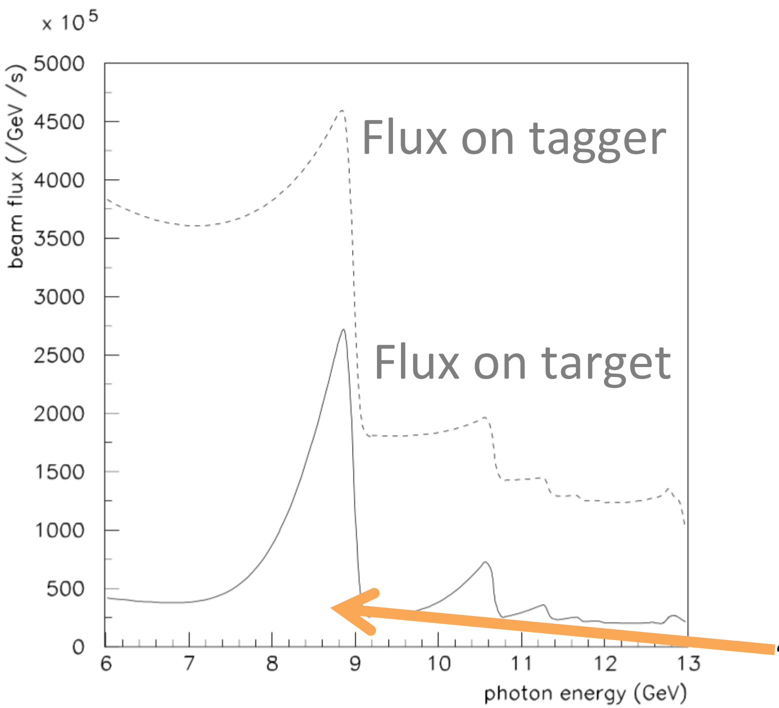


GlueX in Hall D



Beam line



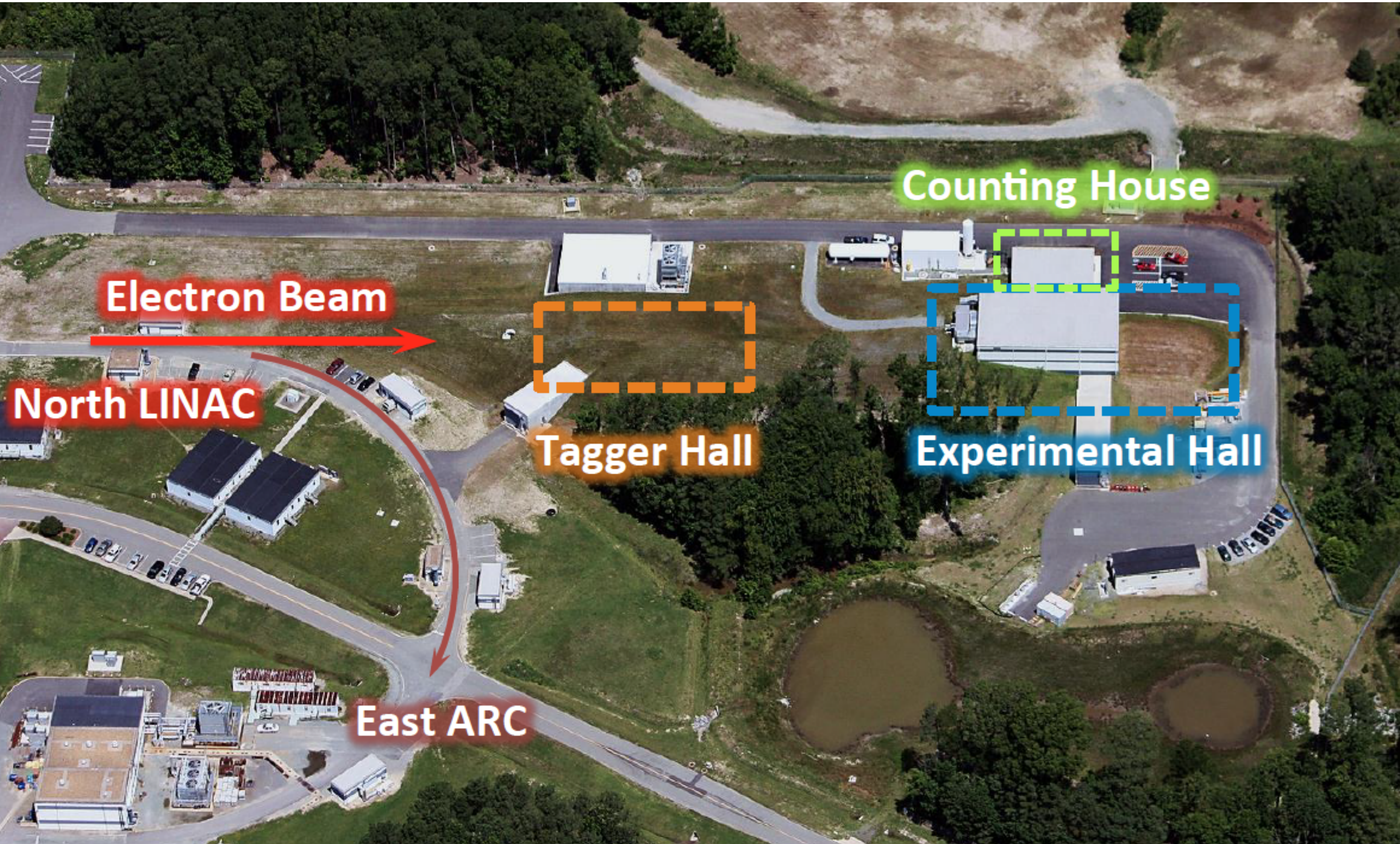


12 GeV electrons up to 2.2 μA hit a diamond radiator and produce linearly polarized bremsstrahlung photons

Intensity: up to 10^8 γ/s in coherent peak E_γ=8.4-9 GeV

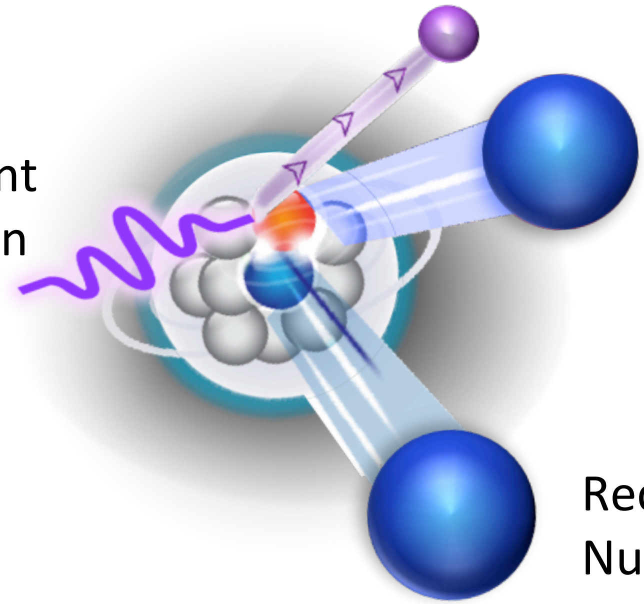
40% average polarization

Hall D Complex



GlueX : final state

Exclusive scattering of a real photon on a nucleus



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
…	…

Possible Targets:

^{2}H

^{4}He

^{12}C

^{28}Si

^{40}Ca

^{93}Nb

^{208}Pb

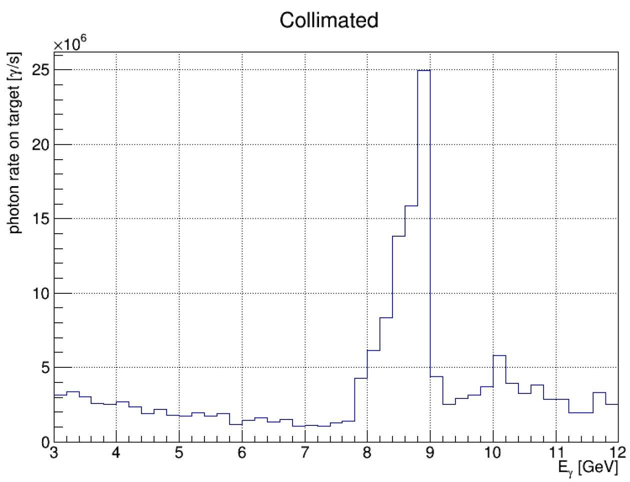
Compare properties of different hadrons at few GeV

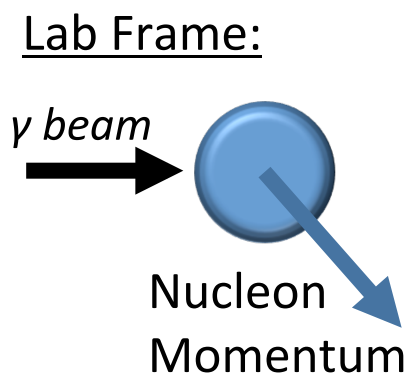
+ Possible novel observable:

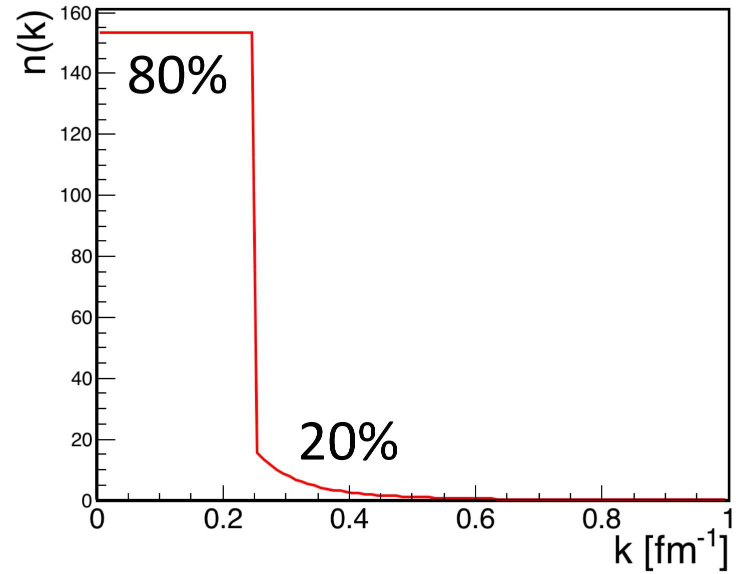
Compare branching ratios for scattering off free/bound nucleon → address **structure modifications of bound nucleons (EMC effect)**

Kinematical Simulation

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



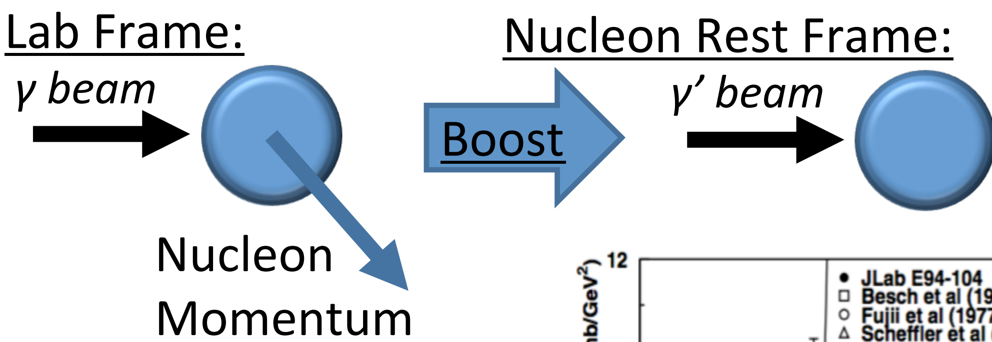


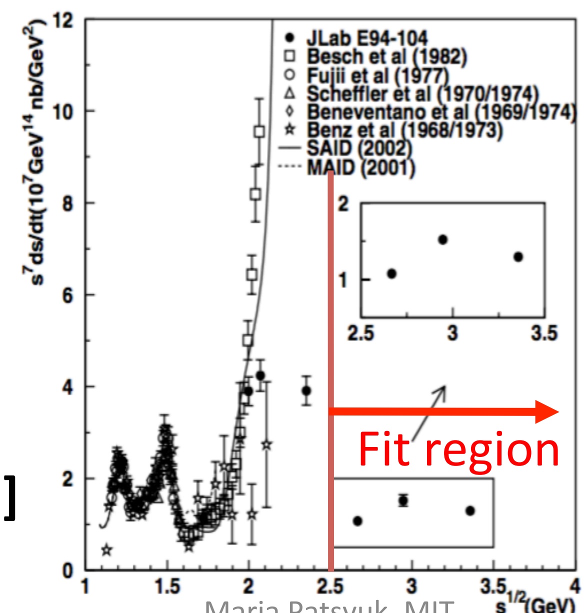


Kinematical Simulation

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

2. Boost to the nucleon rest frame and get the cross-section for (γ n → π⁻p) elastic scattering: $\left.\frac{d\sigma}{dt}\right|_{\theta_{c.m.}} = \left(C \times E_\gamma^{-7}\right) \times f(\theta_{c.m.})$





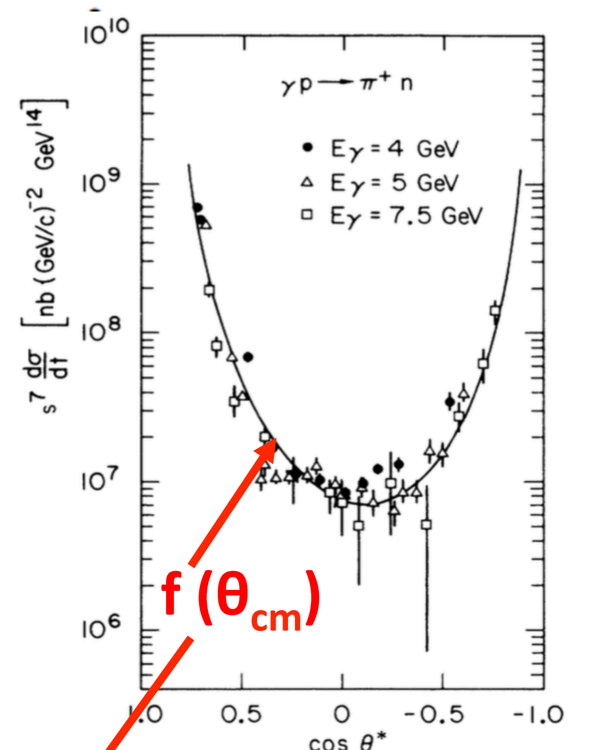


FIG. 6. $s^7 d\sigma/dt$ versus cosθ^* for the reaction $\gamma p \to \pi^+ n$. The solid line shows the empirical function $(1-z)^{-5}(1+z)^{-4}$ where $(z = \cos\theta^*)$, which is an empirical fit to the angular distribution.

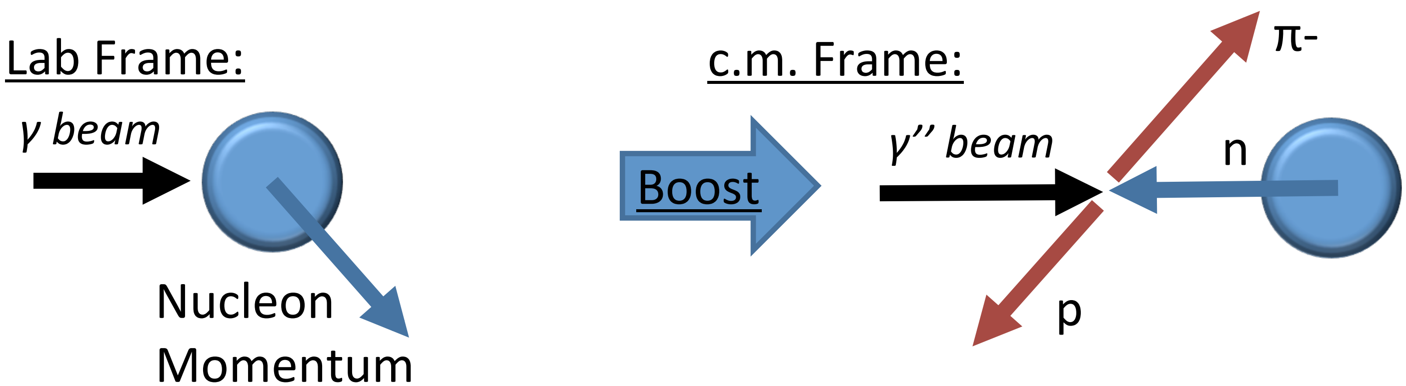
[Phys. Rev. D 14, 679 (1976)]

Kinematical Simulation

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

2. Boost to the nucleon rest frame and get the cross-section for (γ n → π^-p) elastic scattering

3. Boost to the c.m. and do scattering for angles of 50° – 130° . Keep only events with |t|,|u| > 2 GeV^2



4. Boost back to the laboratory frame

Main assumptions

γ + n → π^- + p *(smallest expected rate)*

30 days of beam, 2 g/cm^2 target density

50% detector acceptance

75% detection efficiency for the leading baryon

50% reduction rate due to transparency for the leading baryon and meson

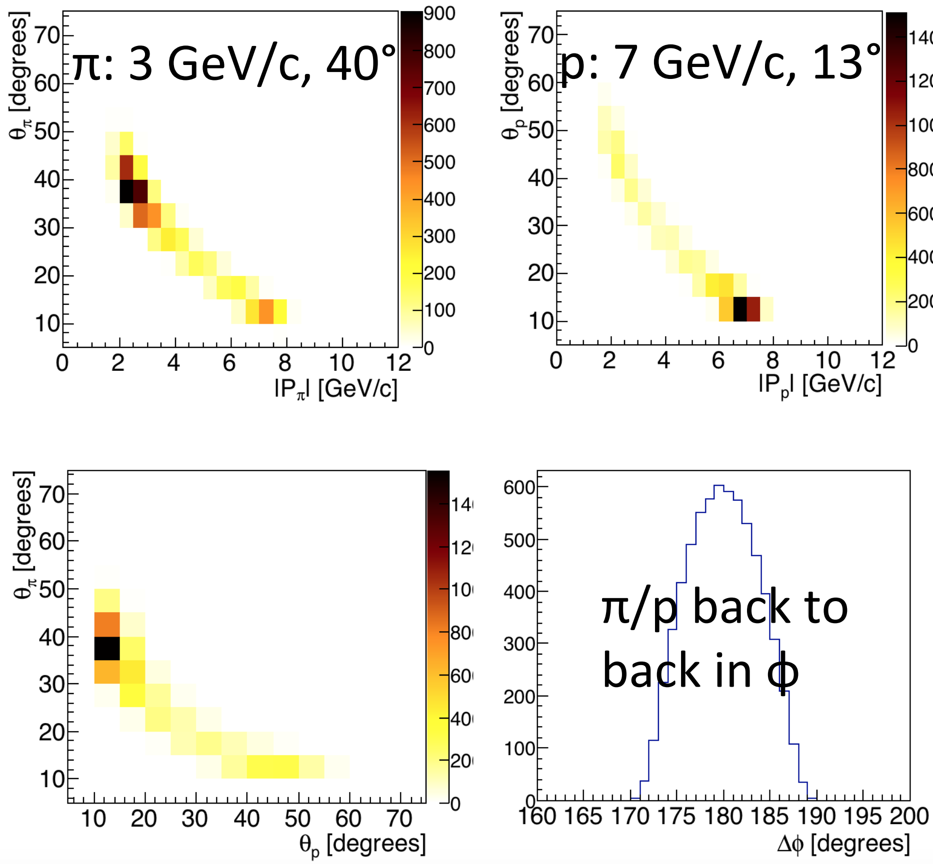
50% reduction rate due to transparency for the recoil nucleon (SRC)

80% detection efficiency for the recoil nucleon (SRC)

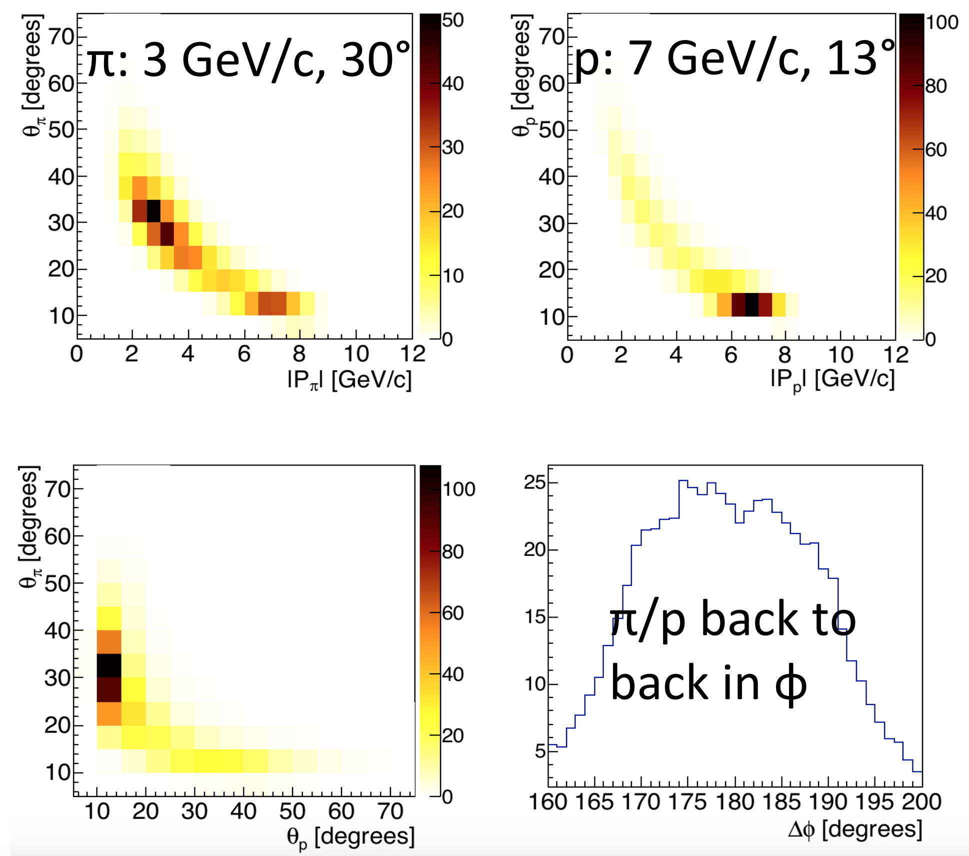
Event selection

Regimes of interest:

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

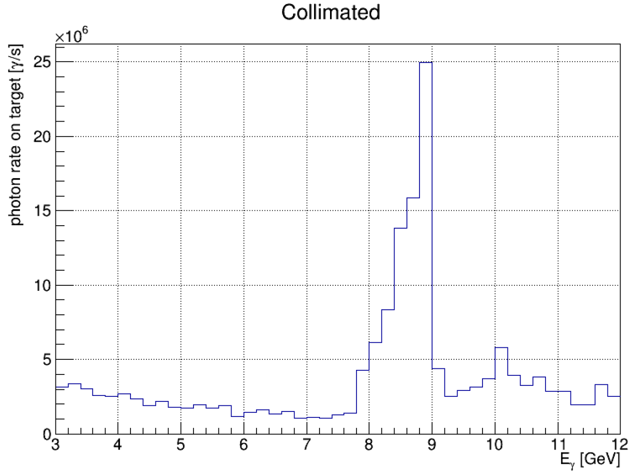


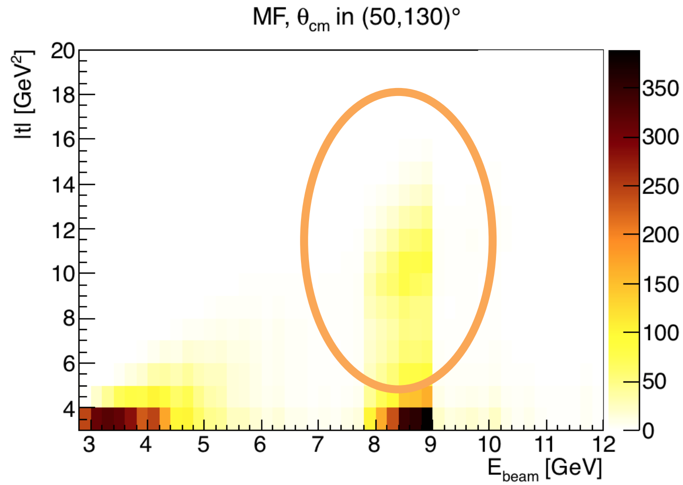
SRC:
$P_{miss} > 0.3$ GeV/c, $\theta_{recoil} < 160°$

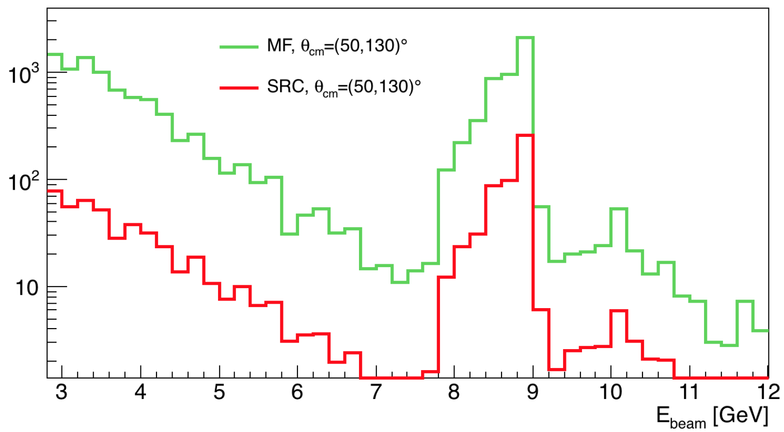


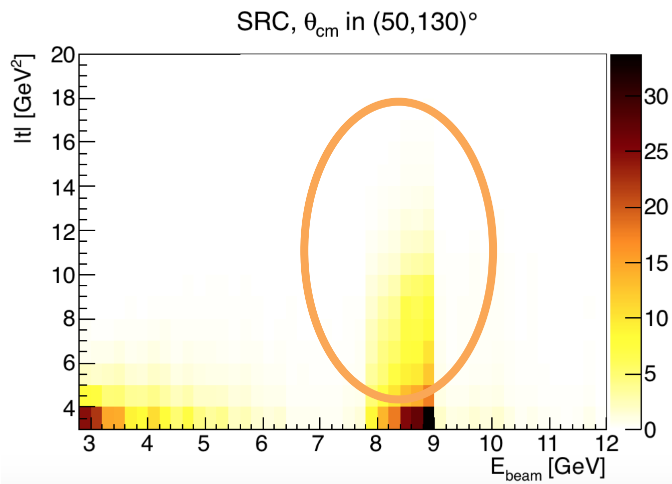
Beam optimization

Can not use the whole photon spectrum because of tagger occupancy
Coherent peak area [7.8, 9] GeV – optimized collimation efficiency and high |t| values

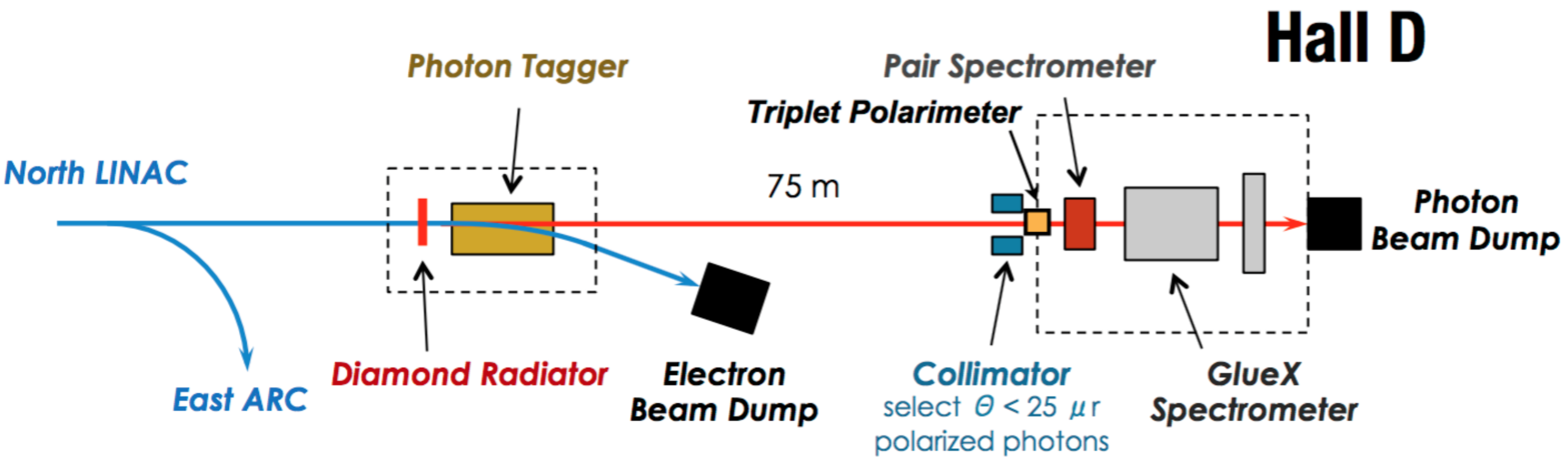




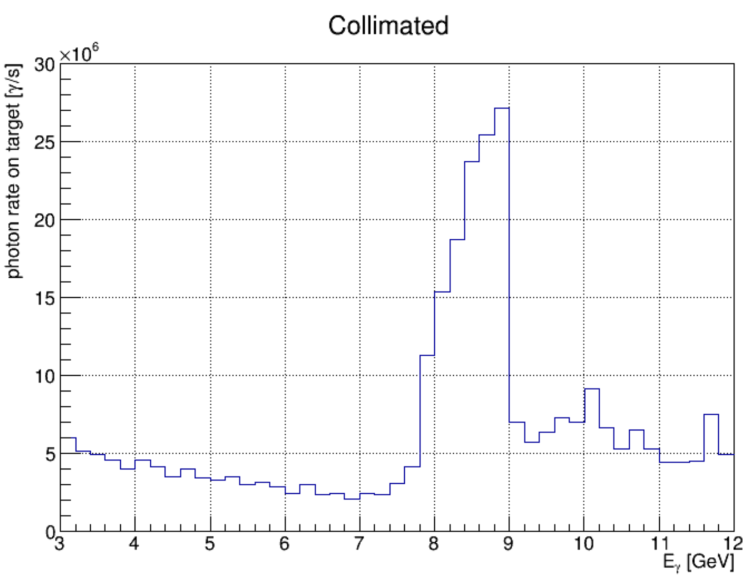




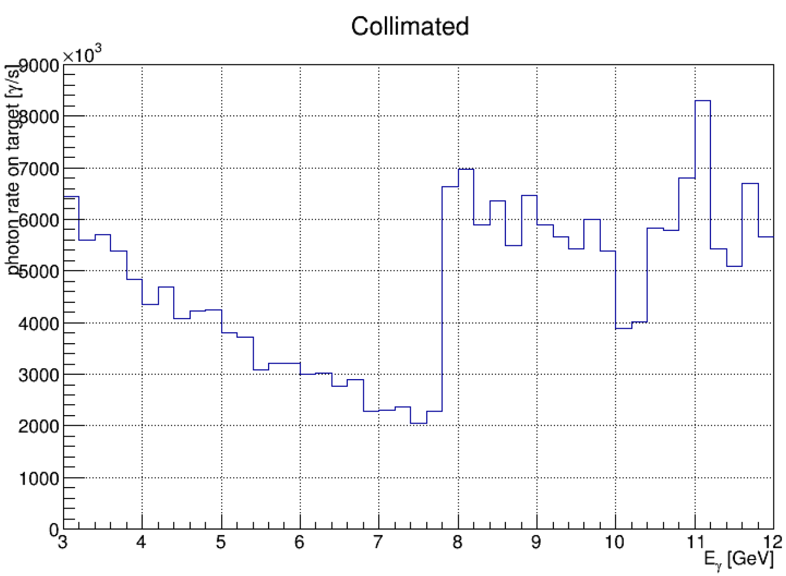
Beam optimization



Collimator diameter 5 mm (default 3.4 mm)



Amorphous spectrum

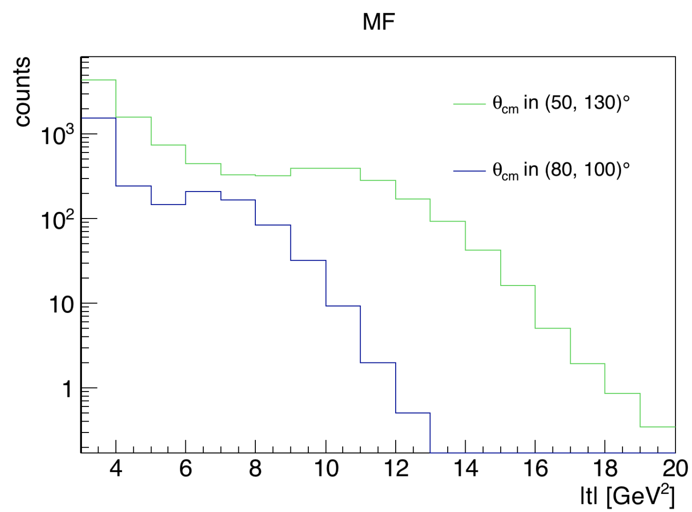


Rate estimation

30 days of running

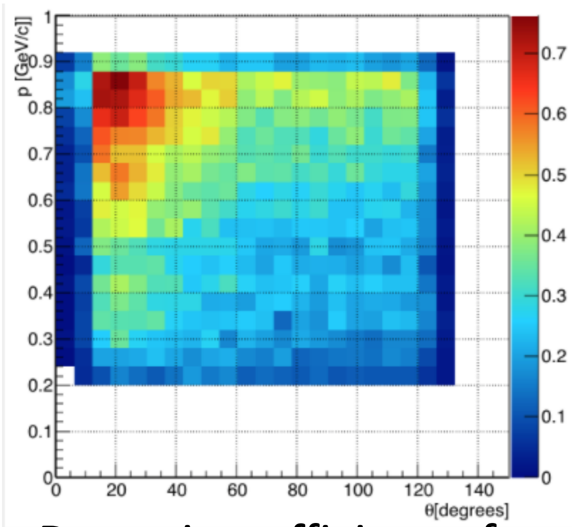
	Collimator 3.4, full spectrum	Collimator 3.4, coherent peak	Collimator 5, full spectrum	Collimator 5, coherent peak	Collimator 5, amorphous spectrum
MF	10k - 100k	4k - 40k	15k - 180k	5k - 55k	20k - 200k
SRC	0.8k - 8k	0.3k - 4k	1k - 10k	0.5k - 5k	1k - 12k

Numbers are modest, but the effects of photon and color transparency are large!!

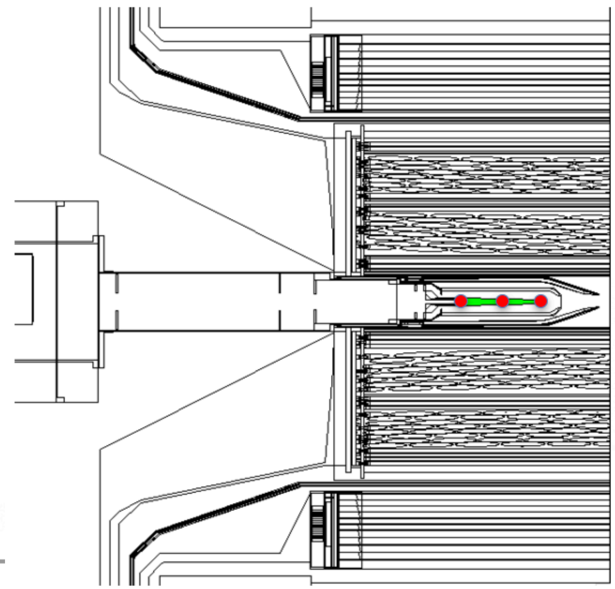


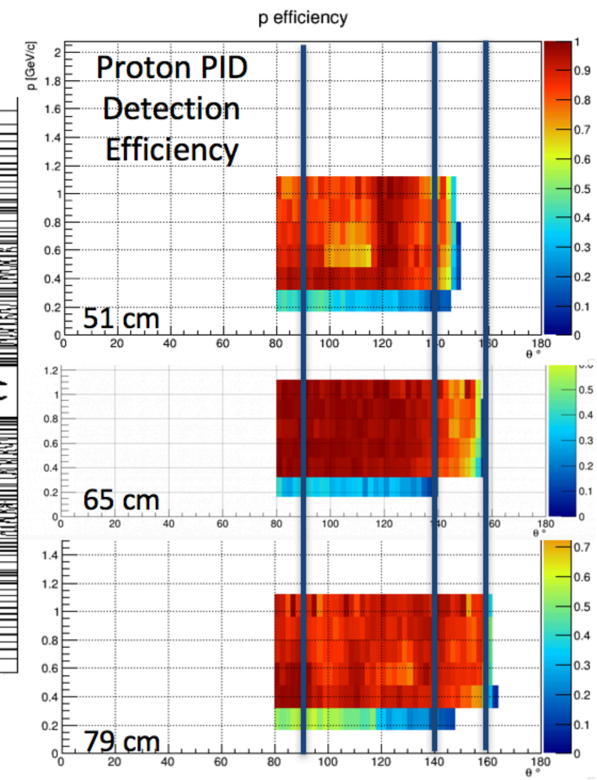
High Intensity Photon Source providing high energy high intensity tagged photon beam will help to conduct detailed studies on structure modifications of nucleons inside nucleus

MC estimation of the detector response

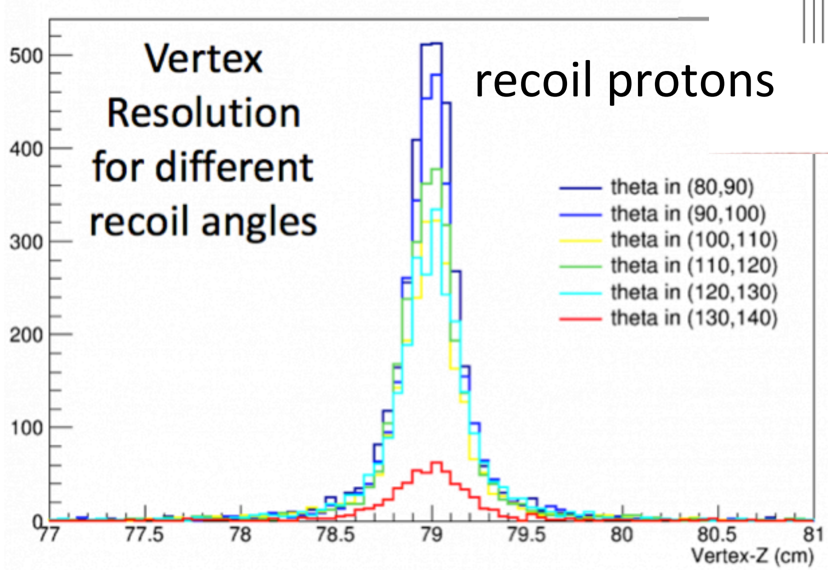


Detection efficiency for neutrons vs. angle and p





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



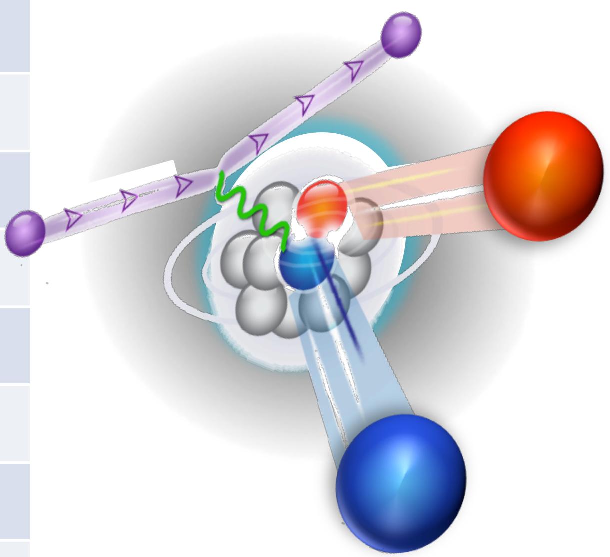
Summary

- 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 modest, but good enough to do excellent physics! New high intensity photon source will allow even more physics ☺

Backup

Reactions

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
…	…



A set of thin foil targets:

^{2}H, ^{4}He, ^{12}C, (^{27}Al), ^{28}Si, **^{40}Ca, ^{48}Ca, ^{54}Fe**, ^{93}Nb, ^{208}Pb

Modifications of nucleon structure in nuclei

A proton can be described using Fock states:

- *FREE*

$$\left|proton\right\rangle = \alpha_{PLC}\left|PLC\right\rangle + \alpha_{3qg}\left|3q+g\right\rangle ... + \alpha_{3q\pi}\left|3q+\pi\right\rangle + \alpha\left|\ \right\rangle$$

- *BOUND*

$$\left|proton^*\right\rangle = \alpha^*{}_{PLC}\left|PLC\right\rangle + \alpha^*{}_{3qg}\left|3q+g\right\rangle ... + \alpha^*{}_{3q\pi}\left|3q+\pi\right\rangle + \alpha^*\left|\ \right\rangle$$

- *SRC*

$$\left|proton^{SRC}\right\rangle = \alpha^{SRC}{}_{PLC}\left|PLC\right\rangle + \alpha^{SRC}{}_{3qg}\left|3q+g\right\rangle ... + \alpha^{SRC}{}_{3q\pi}\left|3q+\pi\right\rangle + \alpha^{SRC}\left|\ \right\rangle$$

Novel observable:

Compare branching ratios (BR) when scattering off quasi-free/bound nucleon for a set of reactions → Get an idea about relative contribution of different Fock states for quasi-free/bound nucleon

Particle identification