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

PR12-17-007 (GlueX collaboration proposal)

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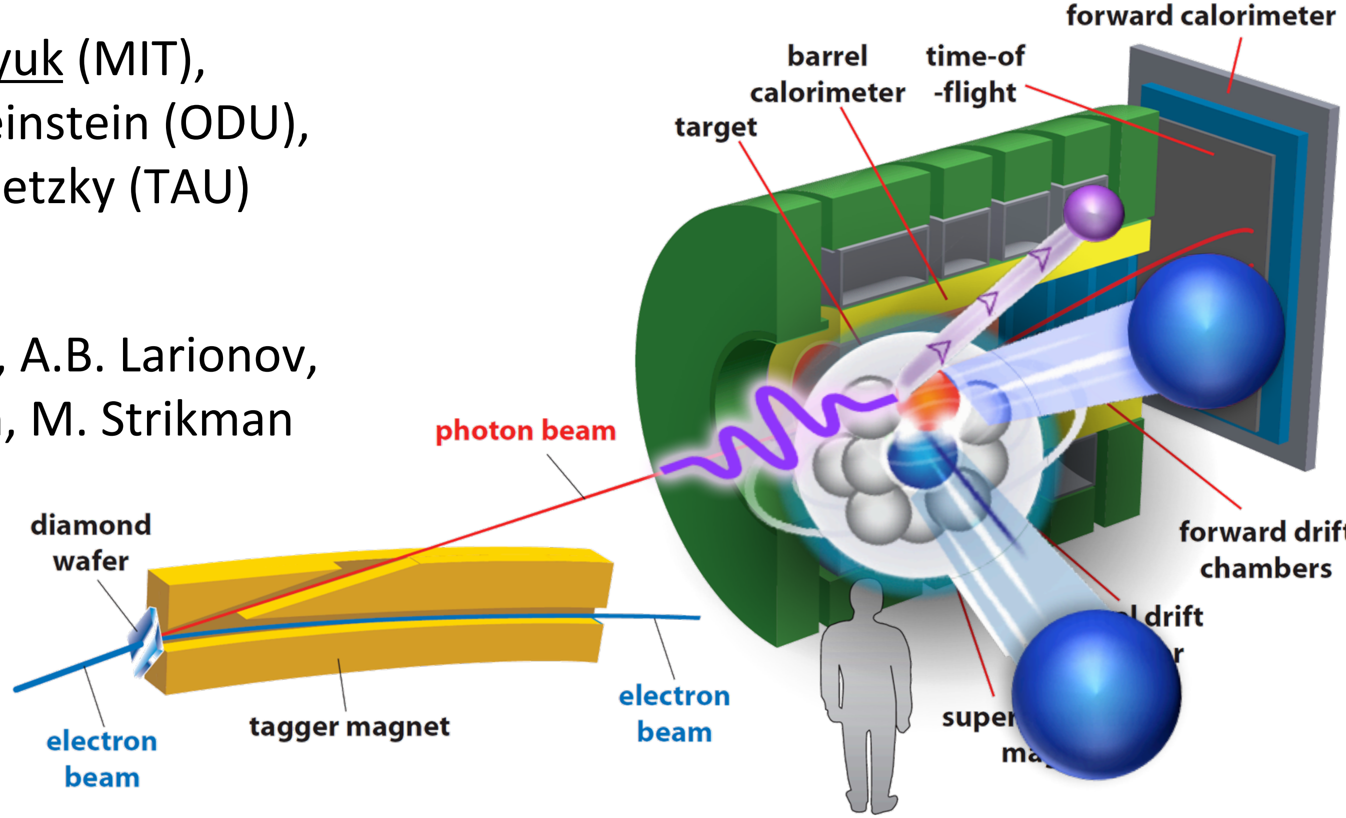

Jefferson Lab
Thomas Jefferson National Accelerator Facility
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Balanced 3 Course Meal To Start The Day

$|t| > 3\ GeV^2$ **(3) SRC**

$|t| > 3\ GeV^2$ **(2) Color Transparency**

$1 < |t| < 3\ GeV^2$ **(1) Photon Structure**

(1) Photon Structure in QCD

In production processes

Soft interaction:
Photon = **Vector Meson Pair (VM)**

Hard interaction:
Photon = **Point-Like Particle (PL)**

Regge model

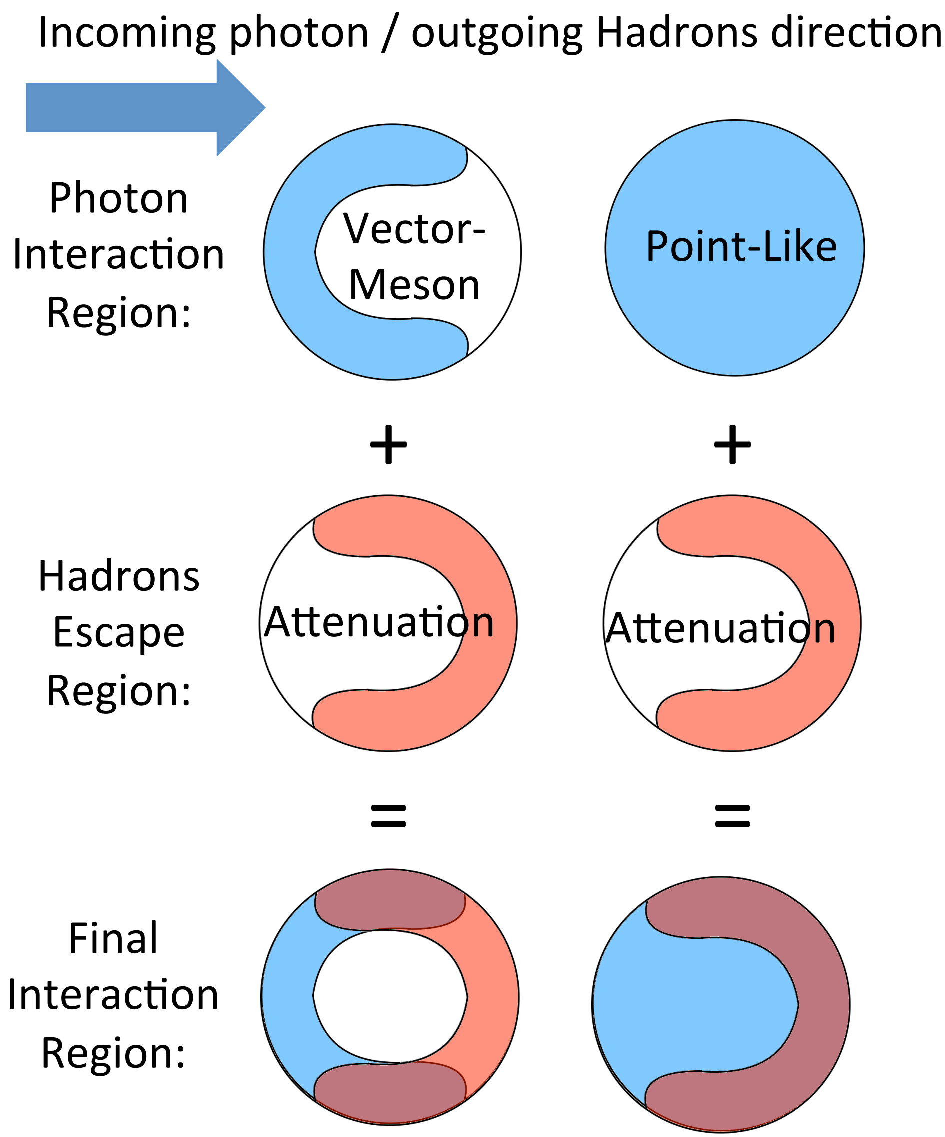
Fundamental question of the photon structure!

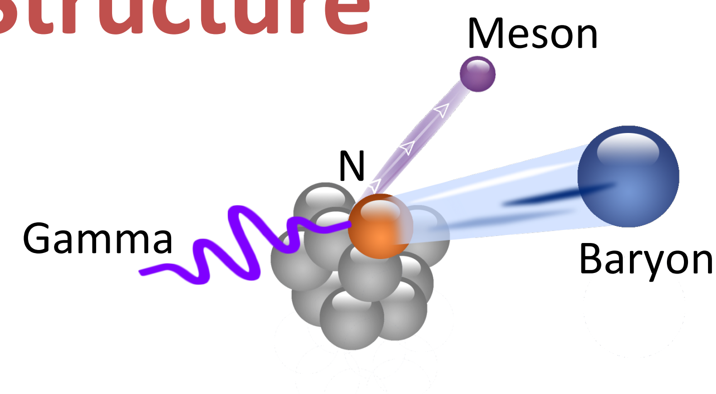
Soft-hard transition was never observed!

Soft-hard transition gives insight about the onset of QCD applicability for exclusive processes and origin of scaling behavior (constituent counting rules)

$$\frac{d\sigma}{d\Omega_{c.m.}} = \frac{1}{s^{\sum n_i - 2}} f(\cos\Theta_{c.m.})$$

Probing Photon Structure





Measurements of exclusive photoproduciton off nuclei requires:

(A) Photon penetrates the nucleus
(B) Hadrons escape the nucleus

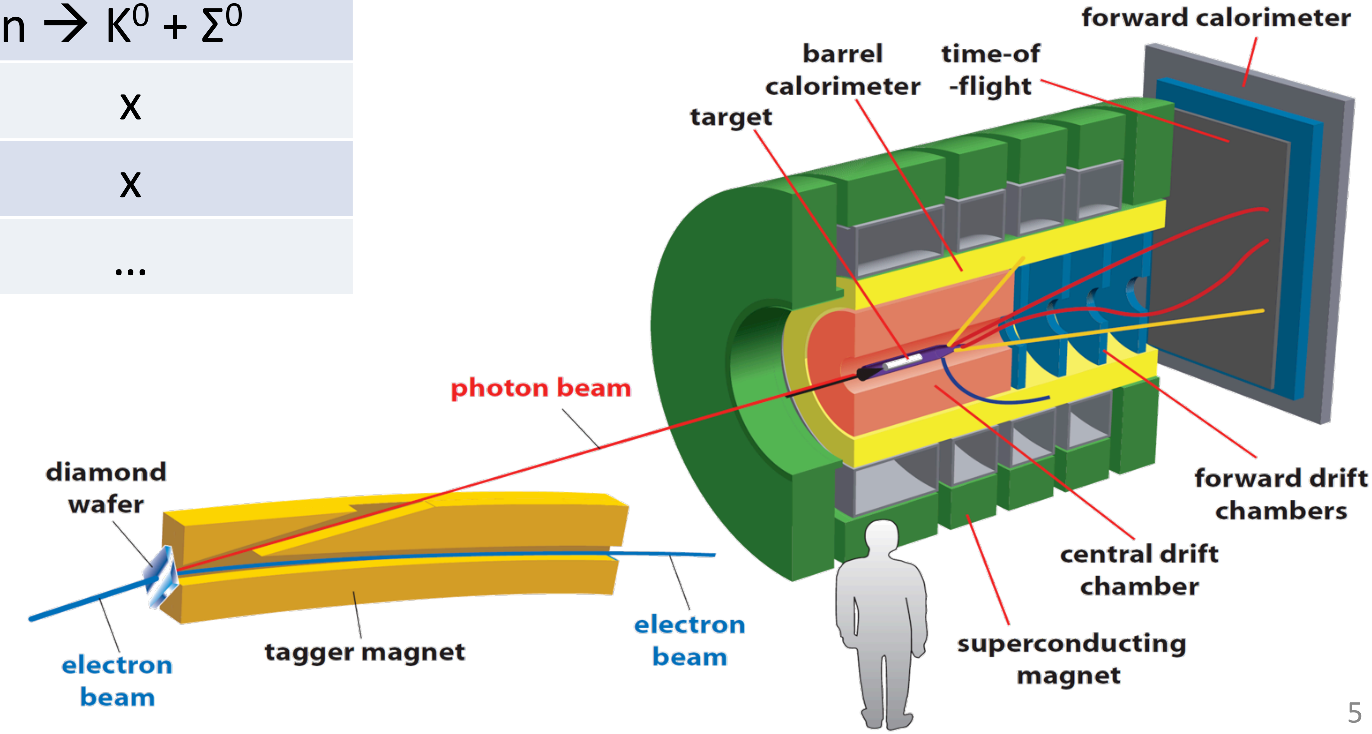
Reaction cross-section will have different value and A-dependence for Vector-Meson vs. point like photon!

Details of soft-hard transition

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
…	…

Simultaneous measurement of a wide range of final states allows probing the **quark composition** (π vs. η) and **spin** dependence (π vs. ρ) of the soft-hard transition

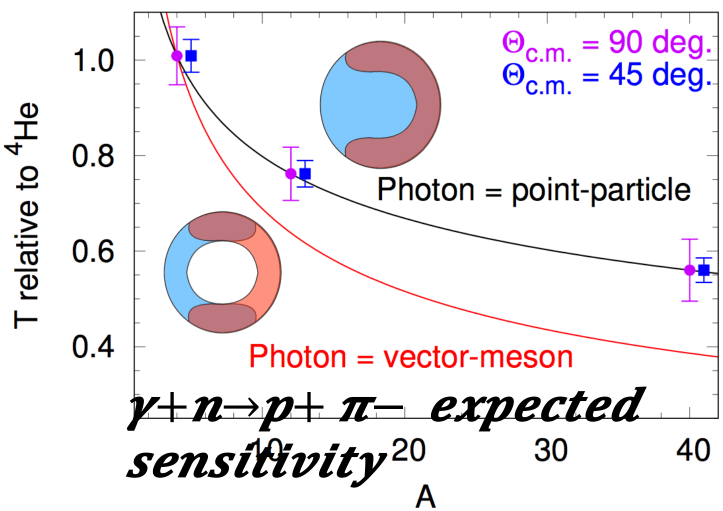
<u>**Targets:**</u>
H, D, ^{4}He, ^{12}C, ^{40}Ca



Mapping of soft-hard transition: A, |t|, |u|

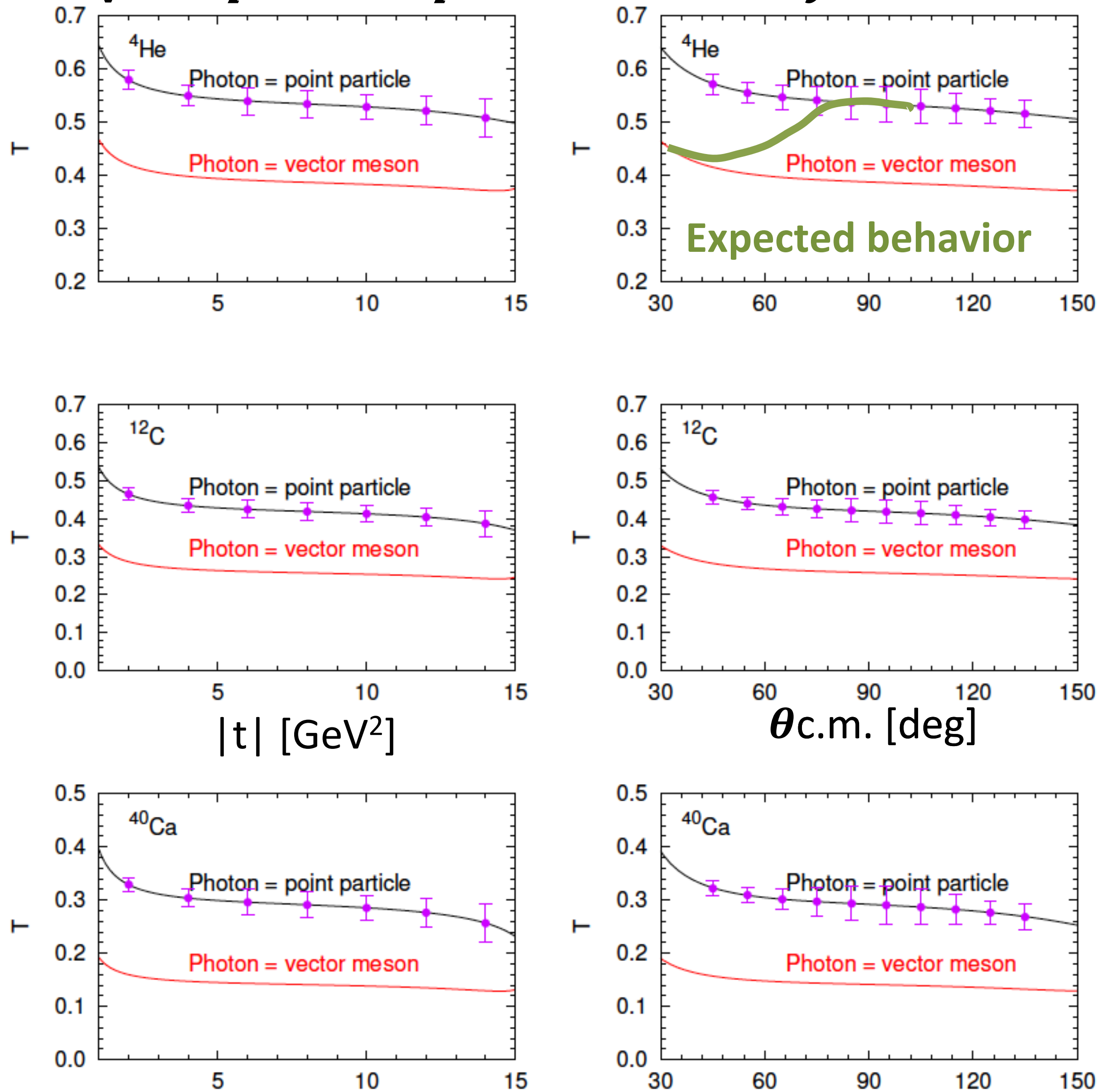
Absolute transparency and ratios for **A= 4, 12, and 40** over a wide range of **|t|** and **|u|** → detailed map of the soft-hard transition!

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



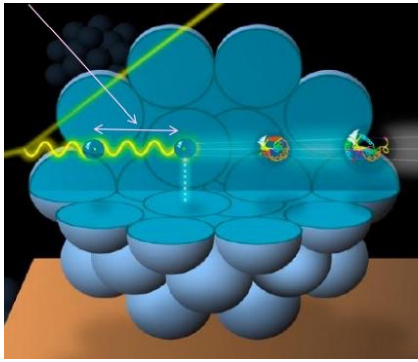
γ+n→p+ π− expected sensitivity

γ+n→p+ π− expected sensitivity



Larionov and Strikman, PLB (2016)

(2) Color Transparency

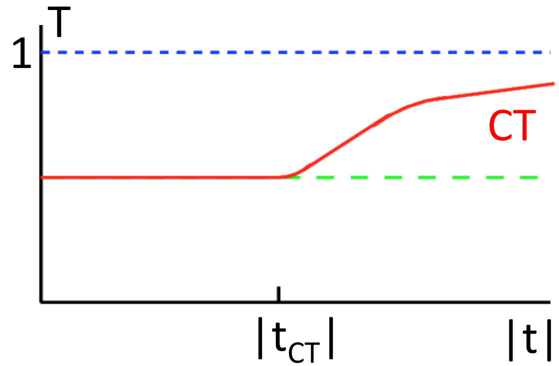


At high |t| photon couples to small transverse sized configuration of a nucleon

"**squeezing**" – defined by |t|, |u|

Fundamental QCD prediction: small sized configurations interact less with hadronic matter

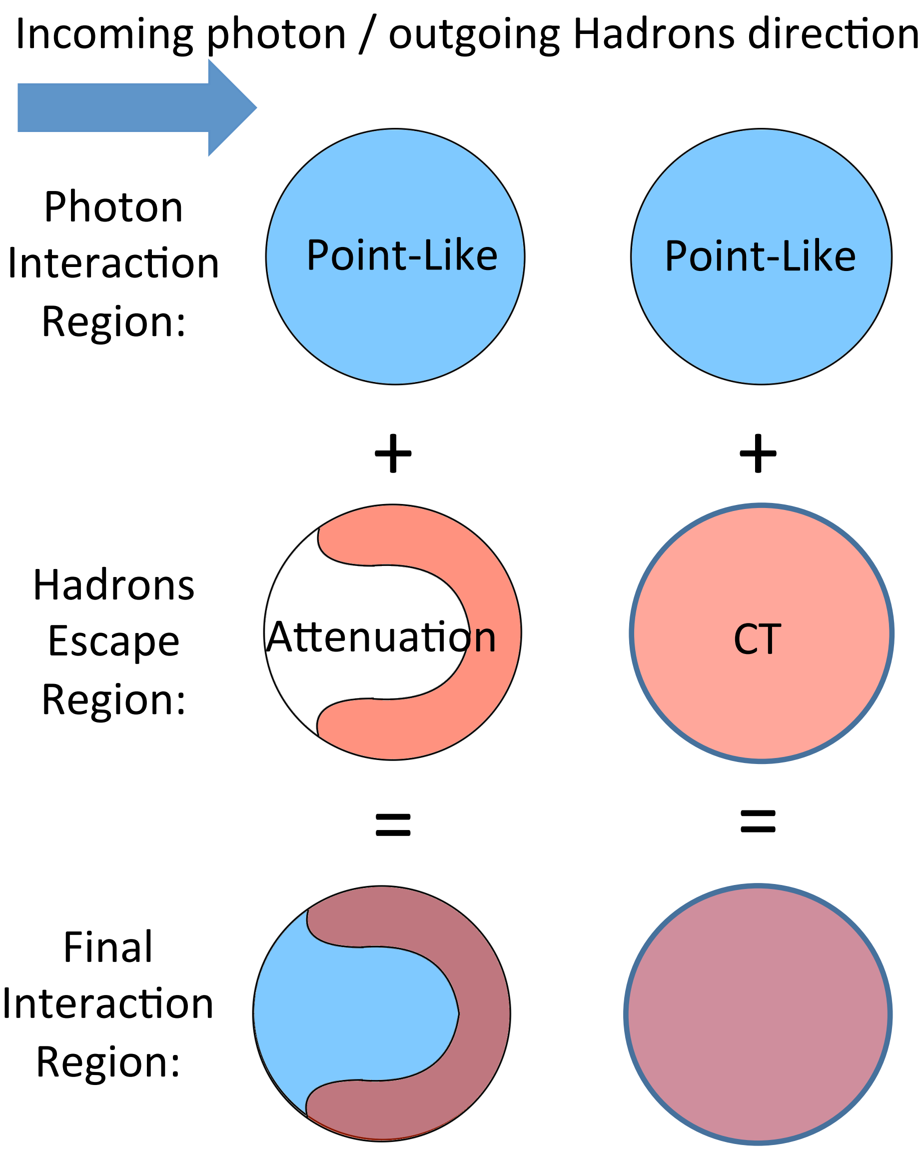
"**freezing**" – defined by energy transfer

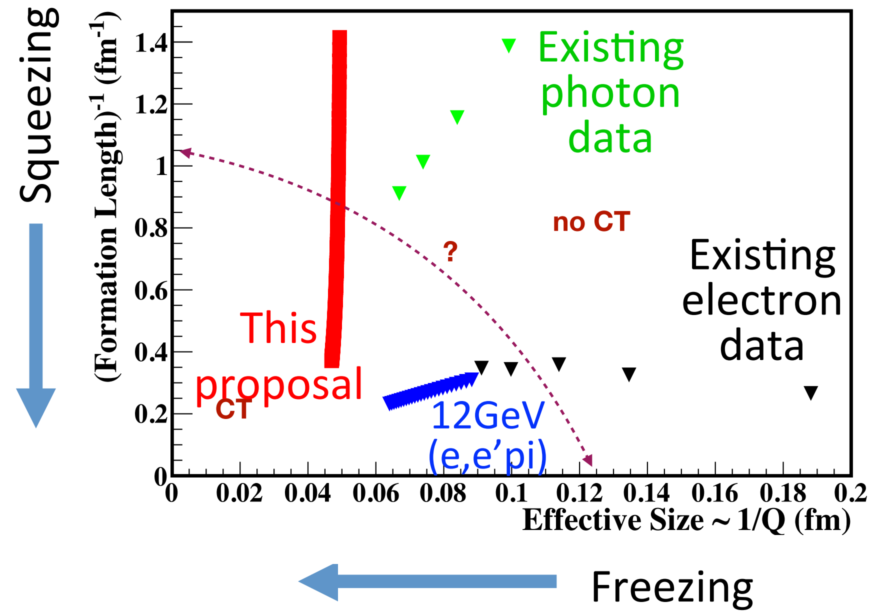


GlueX – unique machine to study CT:

high energy transfers even for moderate momentum transfers |t|!

Probing Color Transparency



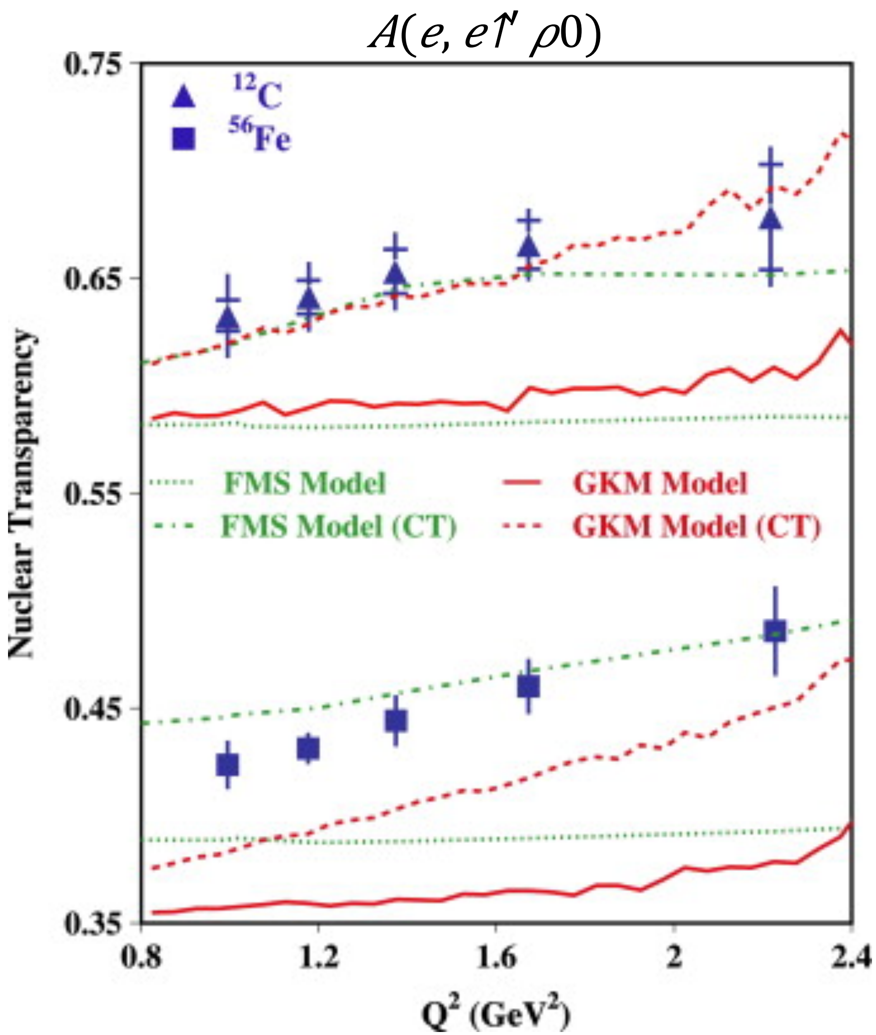


CT – is assumed for QCD factorization in GPD framework -

yet never observed for baryons!

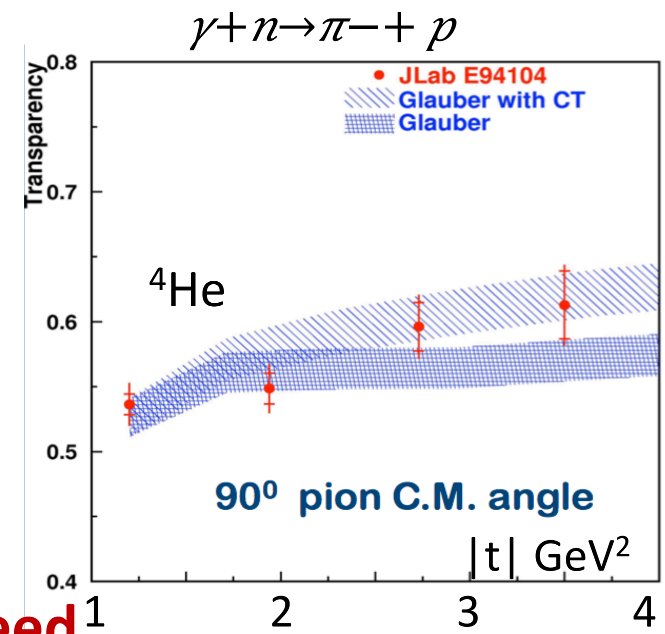
Current status of CT

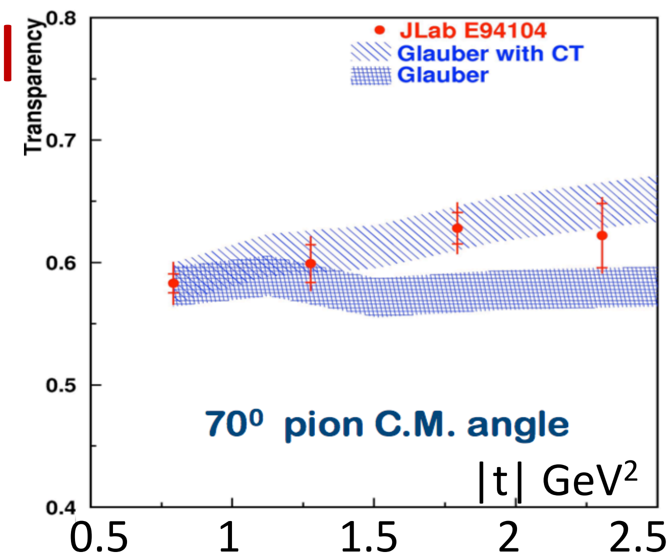
Mesons: observation



L. El-Fassi, et al., PLB 712, 326 (2012)

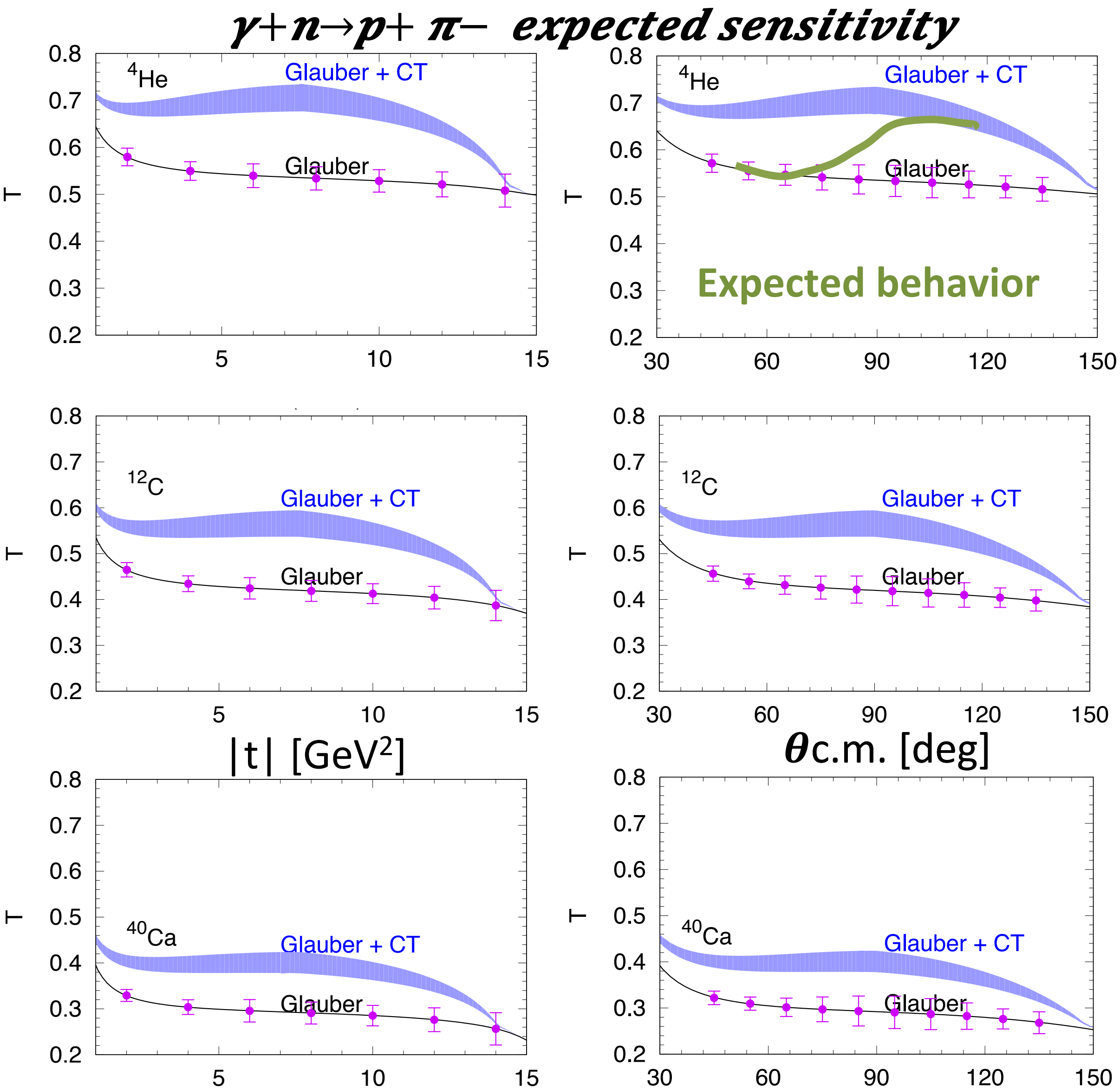
Baryons: need larger |t|





Dutta et al. PRC 68, 021001R (2003)

GlueX advantages



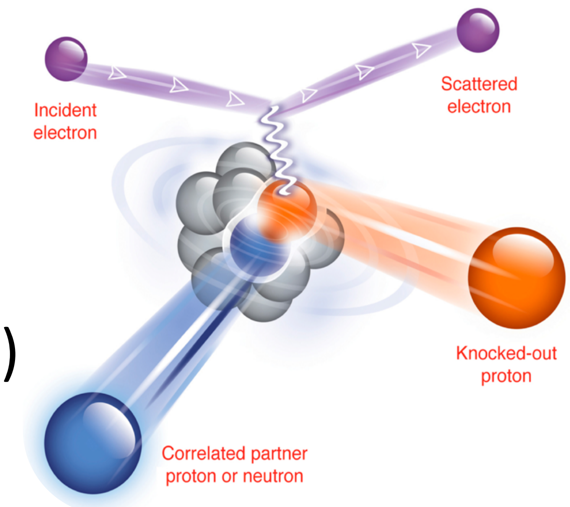
Previous measurements:
$|t| < 3.5$ GeV^2

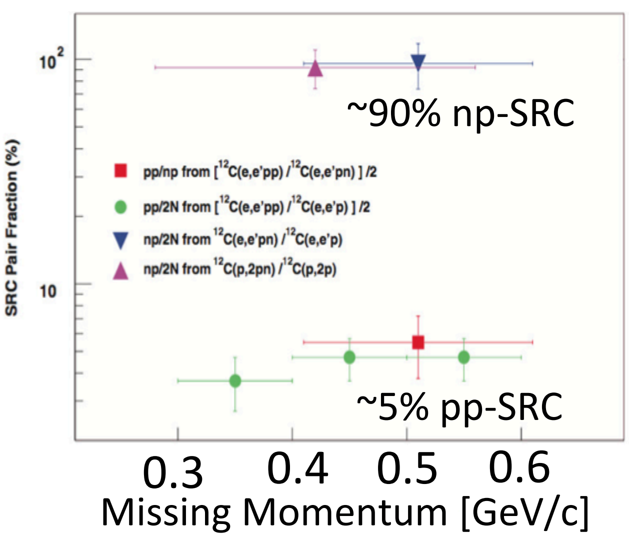
1. **Extends $|t_{max}|$ from 3.5 GeV^2 to >10 GeV^2!**
2. **Higher photon energy (enhanced "freezing")**
3. **Many baryon-meson final states**
4. **Wide c.m. angle coverage**

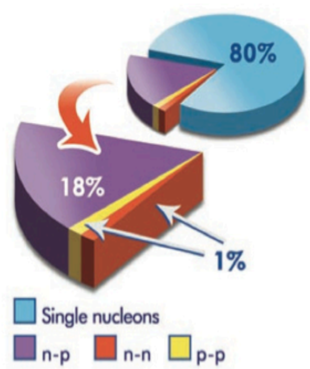
(3) Short-Range Correlations (SRC)

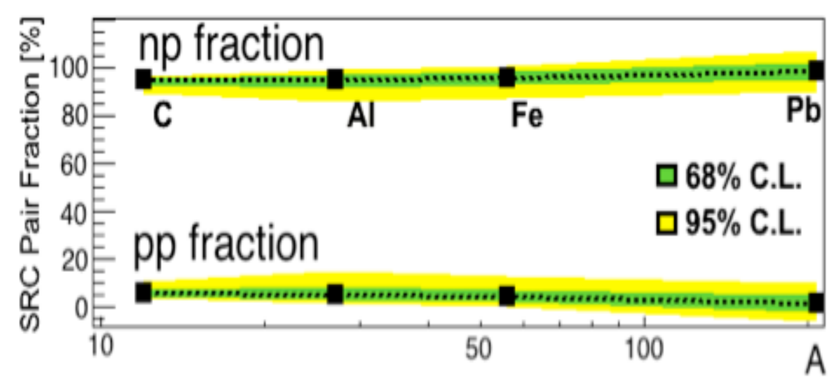
Nucleon pairs with high relative momentum and low c.m. momentum compared to k_F

Studied primarily with A(e,e'pN) and A(p,2pn) reactions









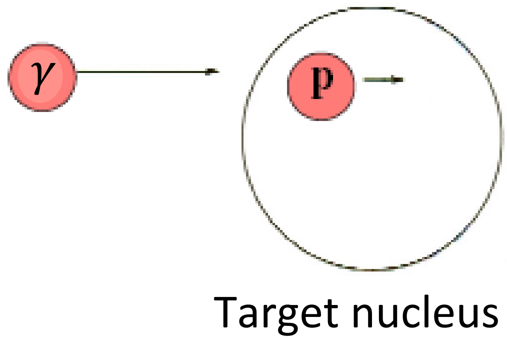
Subedi et al., Science (2008)

Hen et al., Science (2014)

Why photons ?

Interaction is more likely with high momentum forward going nucleon (SRC)

$$\frac{d\sigma}{dt} \propto s^{-7}$$



Probe independence on reaction mechanism:

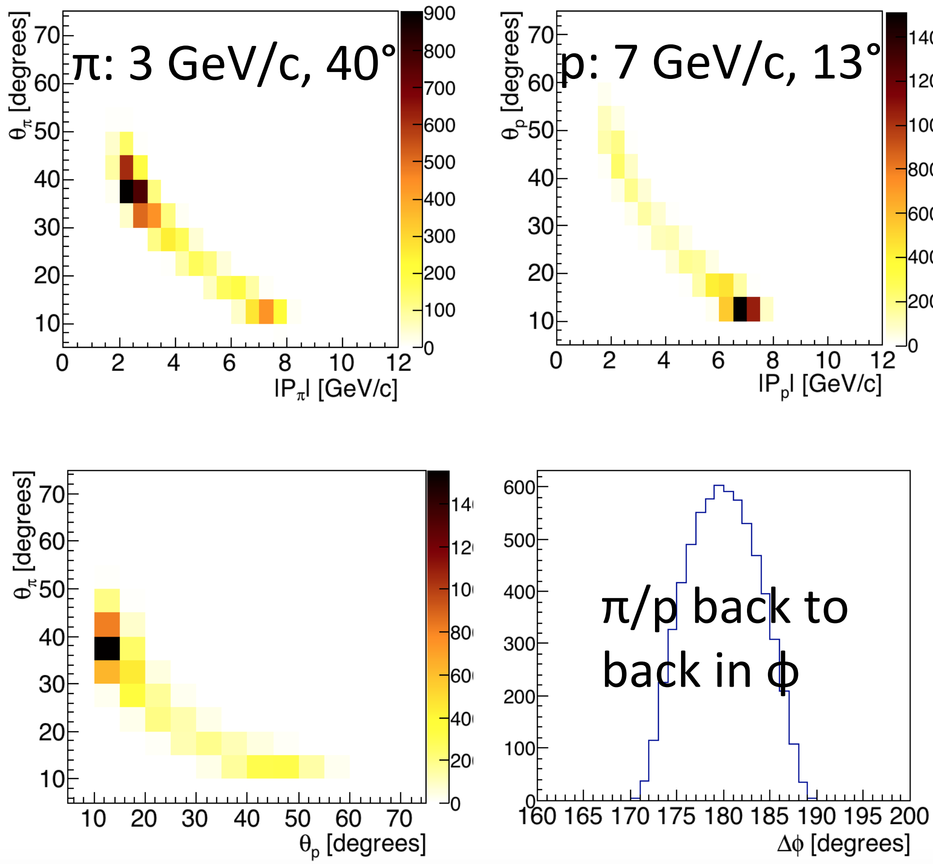
- e and p data show good consistency
- e vs. γ – different reaction mechanisms and kinematics
- Isospin structure: np/pp ratio
- Momentum transfer |t| dependence

Kinematical distributions

$\gamma + n \rightarrow \pi^- + p$ (smallest expected rate)

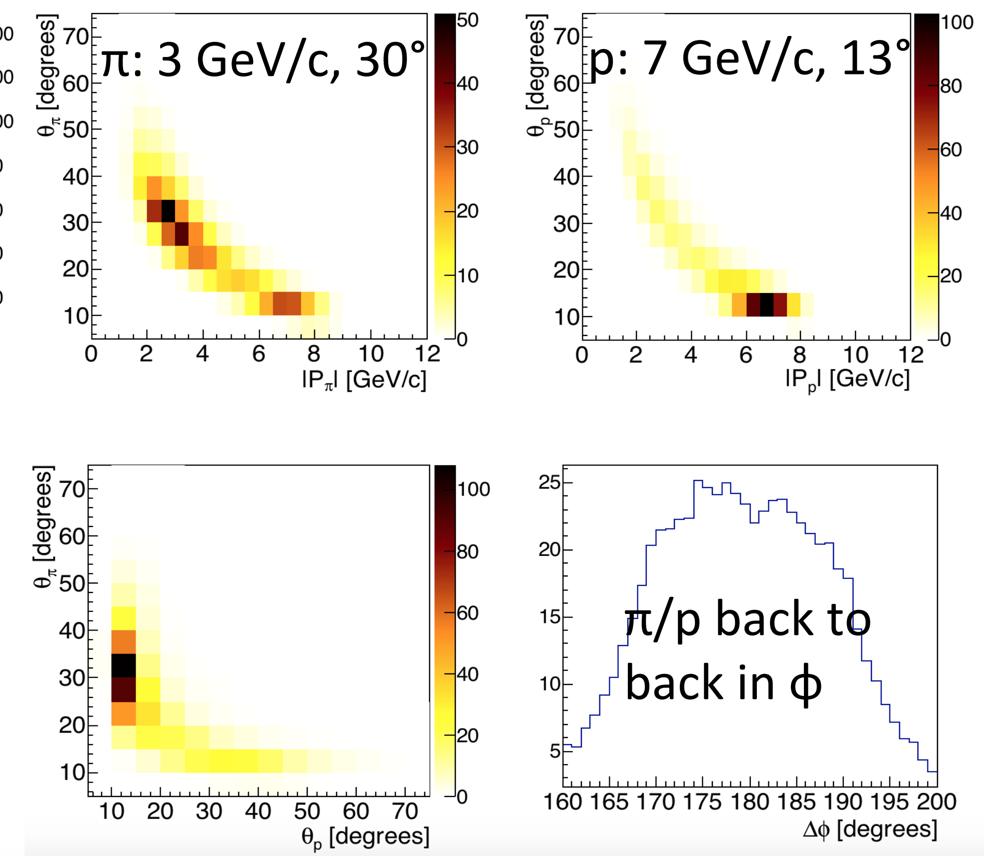
Mean Field (MF):

$P_{miss} < 0.25$ GeV/c



SRC:

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



Reconstruction of final state particles in GlueX software

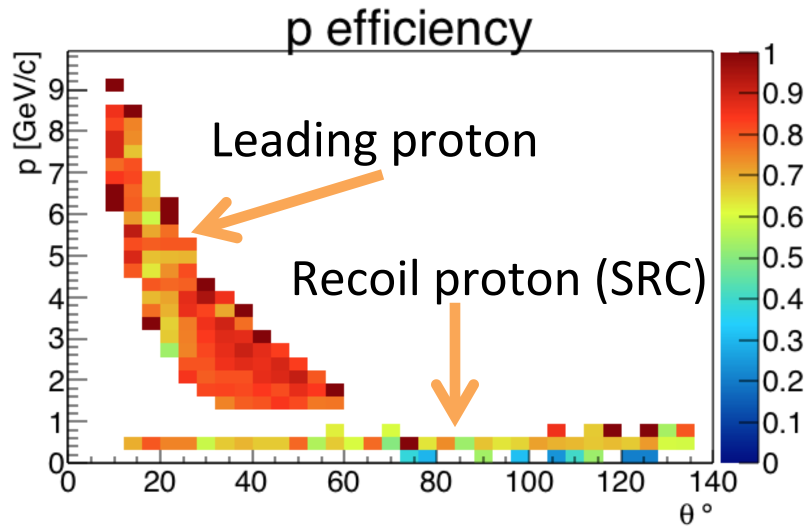
$\gamma + n \rightarrow \pi - + p$

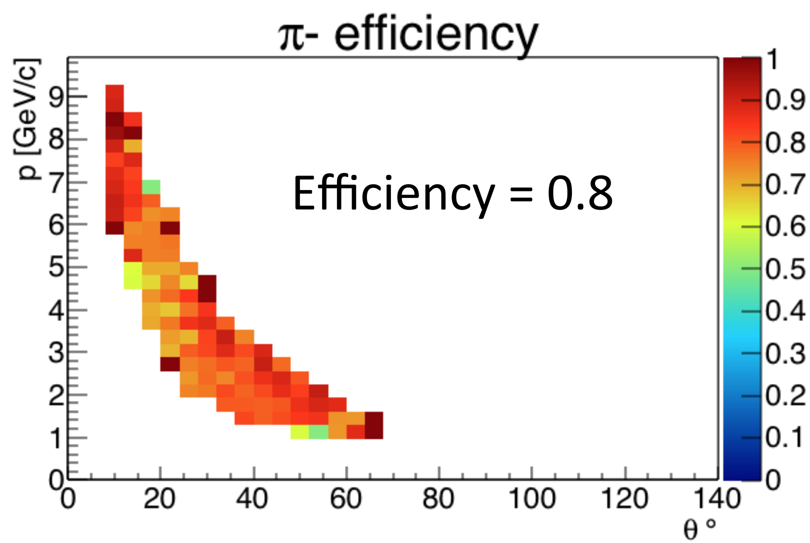
Detection efficiency:

80% → each of leading particles

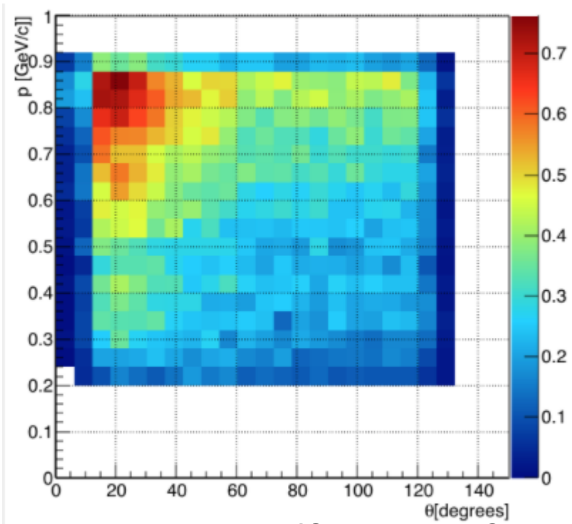
65% → recoil proton (SRC)

30% → reconstruction of ρ^0



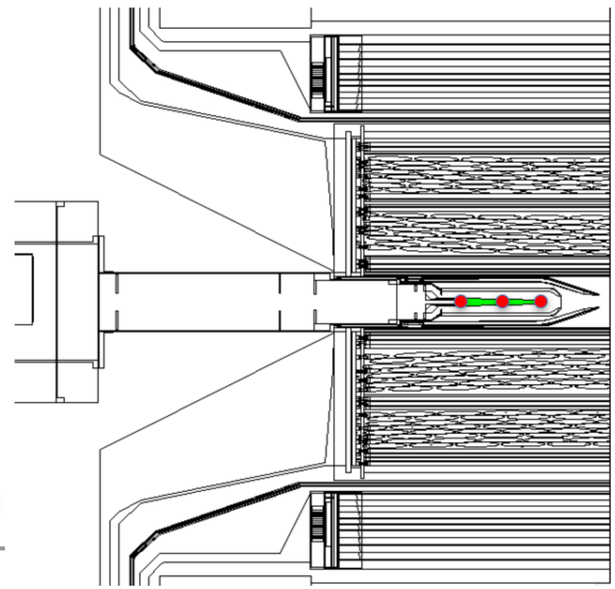


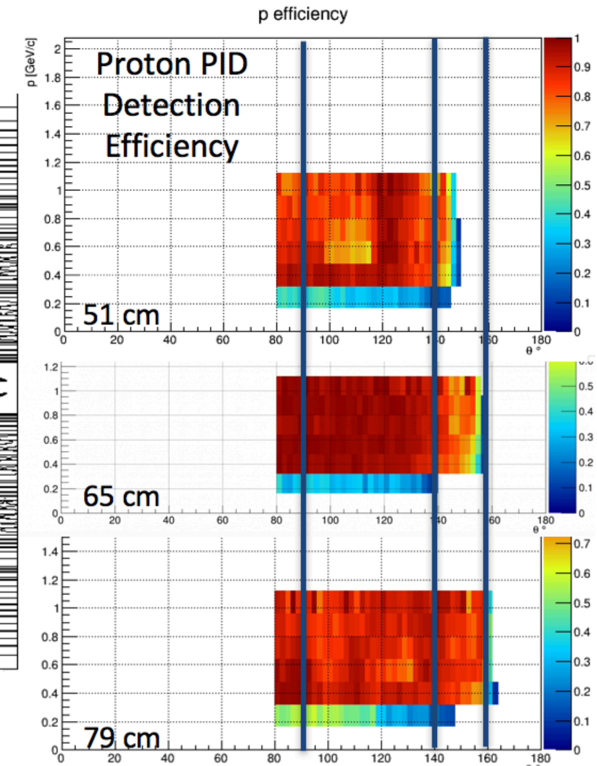
Detection efficiency for the recoil (SRC)



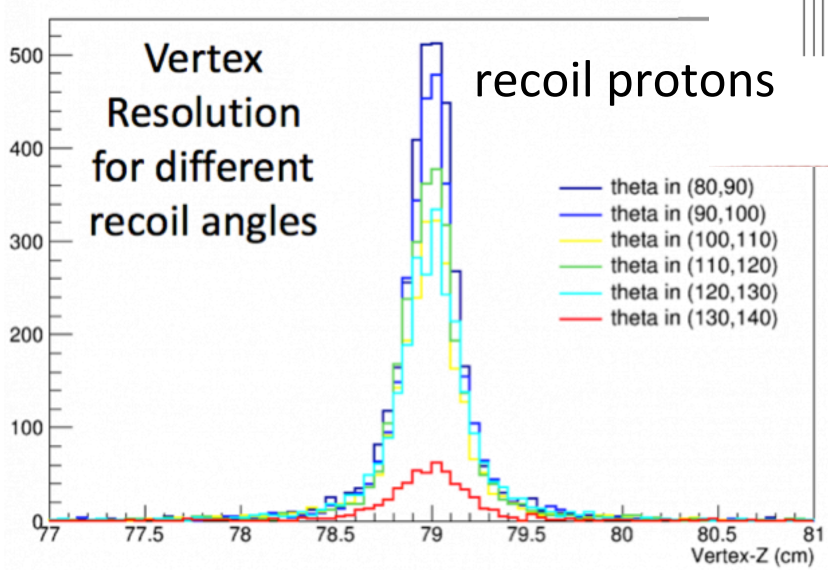
Detection efficiency for neutrons vs. angle and p

Estimated using full GlueX Geant-based software

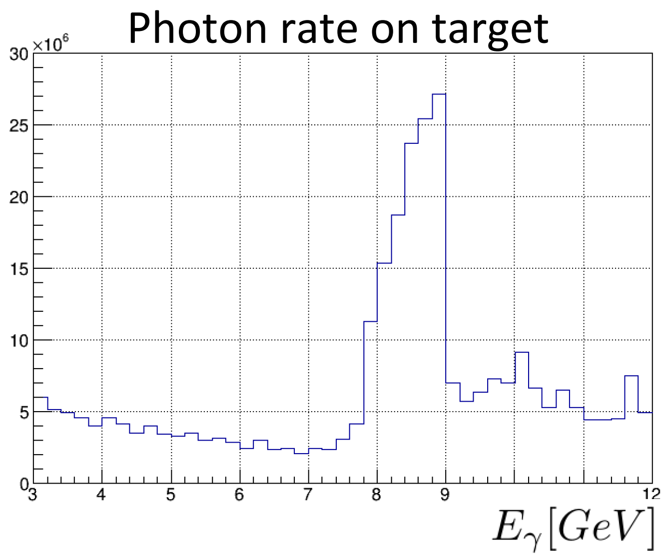


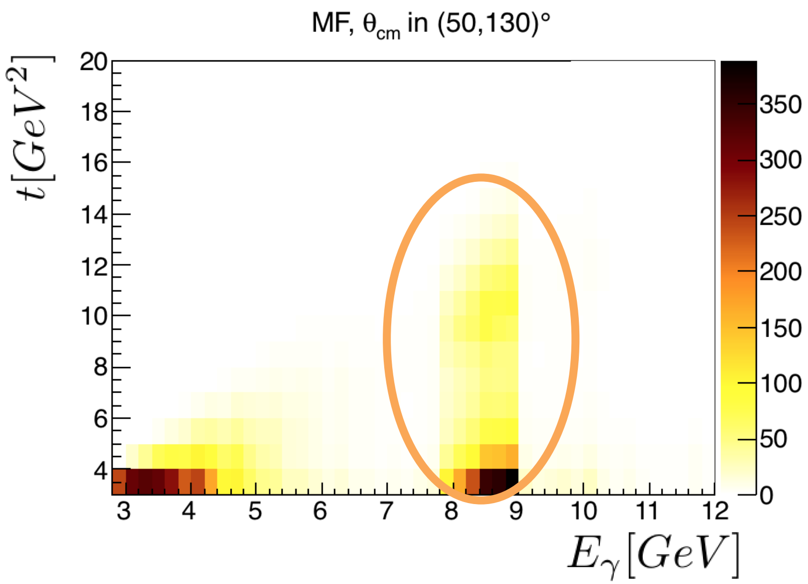


Detection efficiency for recoil protons vs. angle and p for 3 target locations



Beam conditions





Can not use the whole photon spectrum because of tagger occupancy

$$\frac{d\sigma}{dt} \propto s^{-7}, \qquad \text{need large } |t| \text{ values}$$

Coherent peak [8.4, 9.1] GeV and **5 mm collimator**

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 x 10^7 photons/s in the coherent peak
2. Target thickness → electromagnetic background ~ X_0
3. Neutron background $\propto \rho_{target} \cdot A$
4. Coincidental rate in the tagger (up to 24% for this flux)

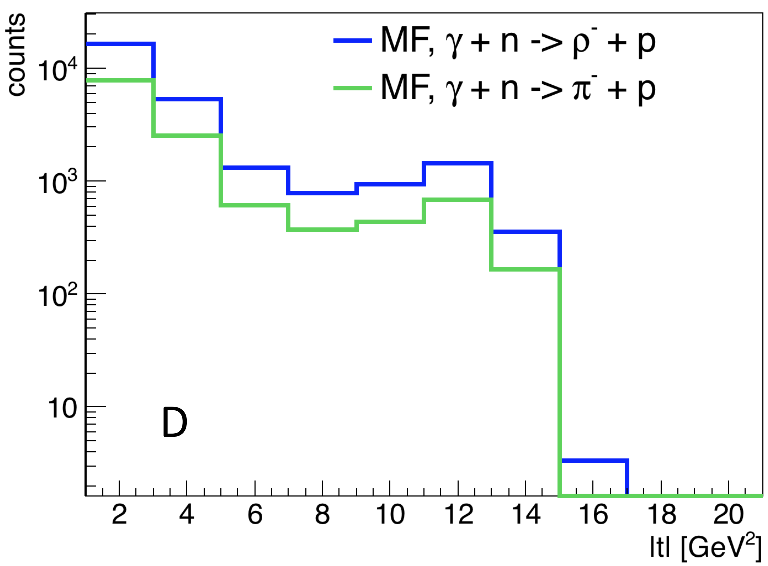
Target	Thickness [cm] / % X_0	Atoms/cm^2 for the given target thickness	EM bkg. rel. to GlueX	Neutron bkg. rel. to GlueX
D	30 / 4.1	1.51×10^{24}	0.5	1.3
^{4}He	30 / 4	5.68×10^{23}	0.5	1
^{12}C	1.9 / 7	1.45×10^{23}	1	0.8
^{40}Ca	0.73 / 7	1.70×10^{22}	1	0.3
LH	30 / 3.4	1.28×10^{24}	1	1*

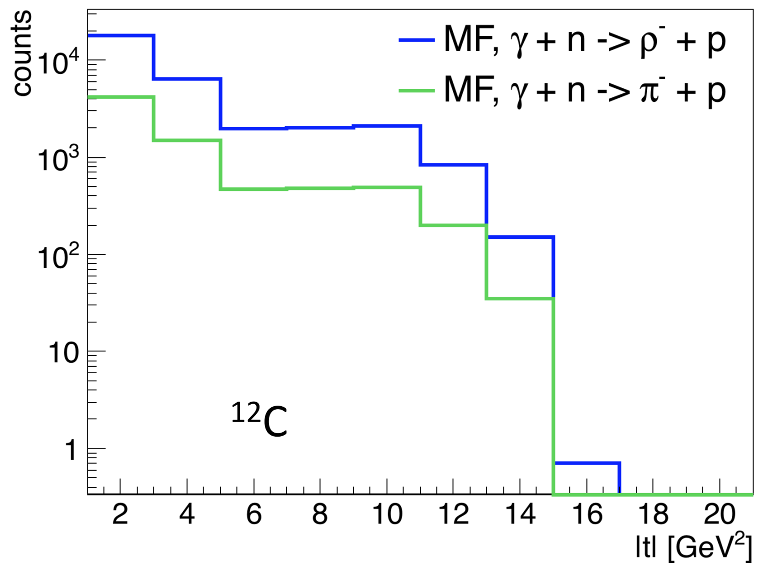
* For nominal flux in the coherent peak of 10^8 photons/s

Proposed Measurement

Event rates for reactions with the smallest and largest cross sections

Target	$\gamma + n \rightarrow \pi^- p$		$\gamma + n \rightarrow \rho^- p$		PAC Days
	MF	SRC	MF	SRC	
D	13,600	750	57,000	3,000	5
^{4}He	13,000	670	54,500	2,800	8
^{12}C	7,400	2,300	31,000	9,500	10
^{40}Ca	2,600	840	10,900	3,500	14
Calibration, commissioning, and overhead:					3
Total PAC Days:					40





Summary

- A new photonuclear program for Hall-D
- Standard GlueX conditions and no changes to the GlueX spectrometer and Hall-D beam line
- Physics focus:
  1. Photon Structure
  2. Color Transparency and SRC
  3. Many more ideas being suggested by theoreticians…

     (e.g. M. Sargsian contribution to arXiv:1704.00816)

Backups

Technical TAC:

Beam and targets:

The photon beam: similar to GlueX, at a 40% of the high-intensity GlueX (E12-13-003). The targets are different and need to be manufactured and installed. A helium target is under development for the PRIMEX experiment. Most likely, the deuterium and helium targets can be provided at moderate costs.

Background/Radiation estimates:

The discussion of the impact of the target thickness is somewhat confusing, see page 26: "Therefore, for EM background estimations, 7%X0 on nuclei is equivalent to3.5%X0 on hydrogen" The message was probably as follows: "At a 50% of the GlueX beam current one can use a twice thicker target in rad. lengths in order to have the absolute EM rate similar to GlueX."
The GlueX EM background were measured for Hydrogen target. In the case of nuclear targets the existence of neutrons in the nucleus affect the radiation length but not the EM background and the electrons density of the target is determined by the number of protons in the parget. This is the origin of the difference between the Hydrogen 3.5%X0 and nuclear 7%X0.

Page 27, Table2: the column 4 is normalized to the approved GlueX experiment E12-13- 003, while the column 5 is normalized to a factor of 2 higher luminosity (the GlueX initial design).
Correct. This is done as the current GlueX running conditions are already at the limit of the EM backgrounds while the neutron backgrounds in these conditions are not an issue so there we continue refereeing to the design spec.

Proper evaluation of the neutron (~1 MeV) background is important since neutron irradiation is damaging for the SiPMs (used in BCAL). The neutron background was estimated by scaling the results of the calculations made for helium. The neutron background from deuterium might be significantly higher – more calculations or measurements are highly desirable.

The neutron background for deuterium can indeed be somewhat higher than the scaling we assumed for the other nuclei (which was guided by the Radcon group). Since writing the proposal, the Radcon group were able to perform neutron background calculations for the deuteron target. They are presented below and show that the neutron background (> 1 MeV) is only x 1.5 – 2 higher for Deuteron target than for ^{4}He. One should also note that the main neutron damage is accumulated damage that, for GlueX, was estimated over a year of running. The proposed deuteron run time is very short (5 days) and will therefore have negligible average effect. We will naturally monitor the neutron backgrounds and if needed reduce the beam intensity for the deuteron running and increase its beam time at the expense of the solid targets.

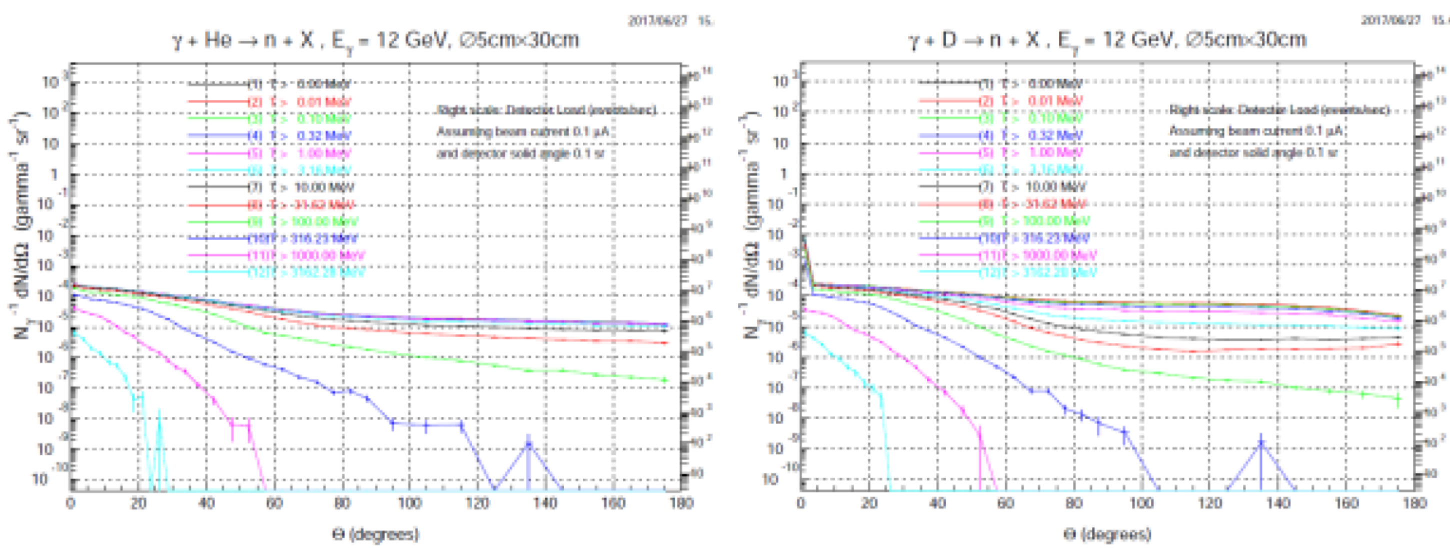


Fig. 1: Calculated neutron fluxes for a realistic Hall-D photon beam spectrum and Deuteron (right) and ^{4}He (left) targets.

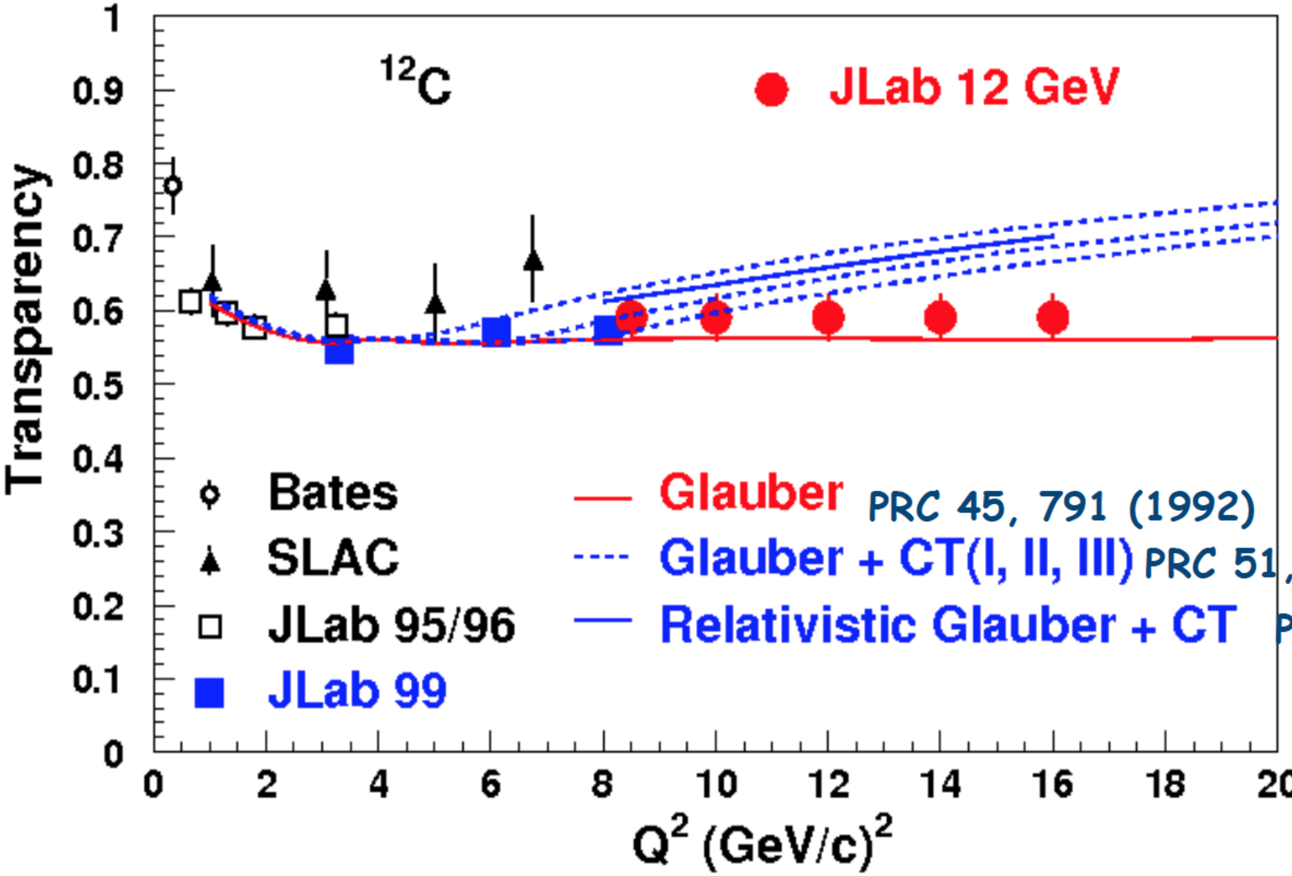
Time request:

40 days, see page 27. The changeover of a solid target to a liquid target would probably require about 24 h. It is unclear if this time is included in the beam time request. The Cover Sheet seems to contain a typo in the “Beam Requirement List” asking for 40 days for each of the 4 targets.

We apologize for the typo in the Cover Sheet. The time to change the targets is taken into account as part of the assumed 6 days (3 PAC days) overhead time.

Hadron production photon is a kind of chameleon - which can interact as a q\bar q pair (a meson) and a point -like particle (direct photon) . Understanding of interplay between these two regimes is important for detailed understanding of the photon structure which is as fundamental issue in QCD as the understanding of the structure of nucleons, pions,…- This issue was studied at HERA, but the interplay is likely to be very different at Jlab energies. In addition to gaining understanding of the photon properties, the knowledge of this interplay will **improve modeling of hadron production essential for hall D as the direct photon interactions are not described by a standard Regge model. Also comparing the processes in the kinematics where soft photon dominates and where point like photon dominates will provide important additional information about quark - gluon meson structure**. For example, large t processes select preferentially minimal Fock space components of the mesons.

A(e,e'p) @ 11 GeV JLab



PRC 45, 791 (1992)

PRC 51, 3435 (95), 50, R1296 (94)

PRC 74, R062201 (2007)

What exactly needs to be studied with a photon beam?

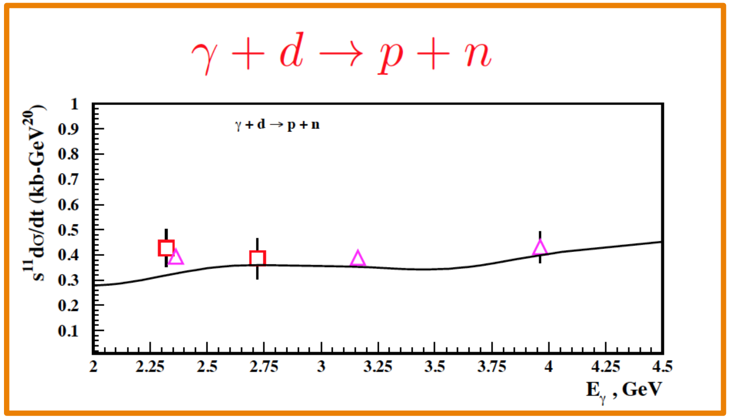
PLC: CT for baryons - no observation

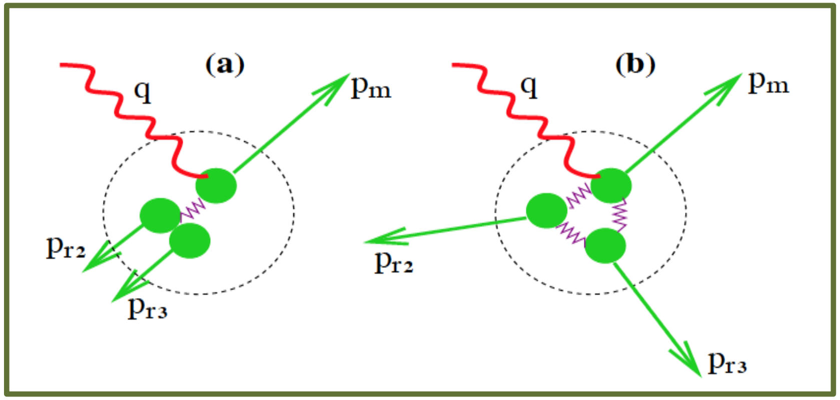
Structure of photon: transition between hadronic and partonic couplings

SRC pair counting for different probes (e, p, photon) – test of interpretation

3N – SRC – no direct observation

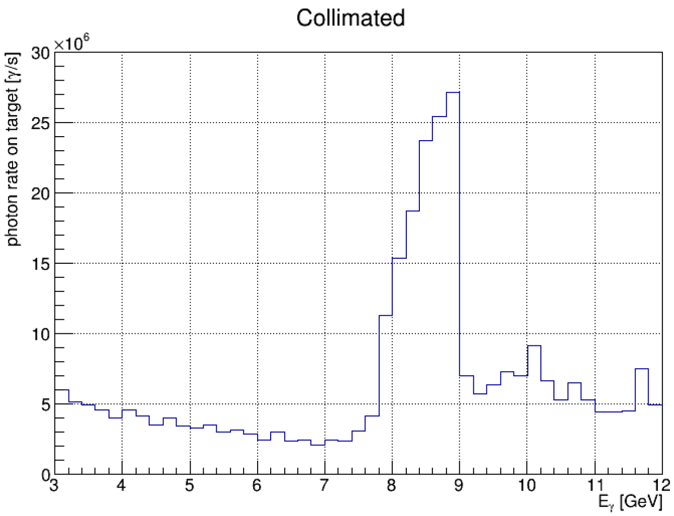
Photon disintegration of D, ^{3}He – was observed only with p,n in final state – address NN repulsive core, constituent counting rules (quark degrees of freedom?)



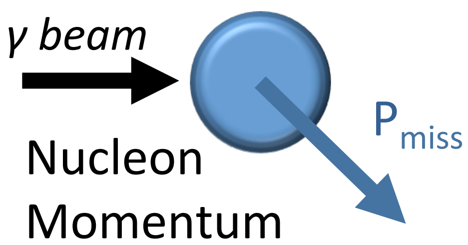


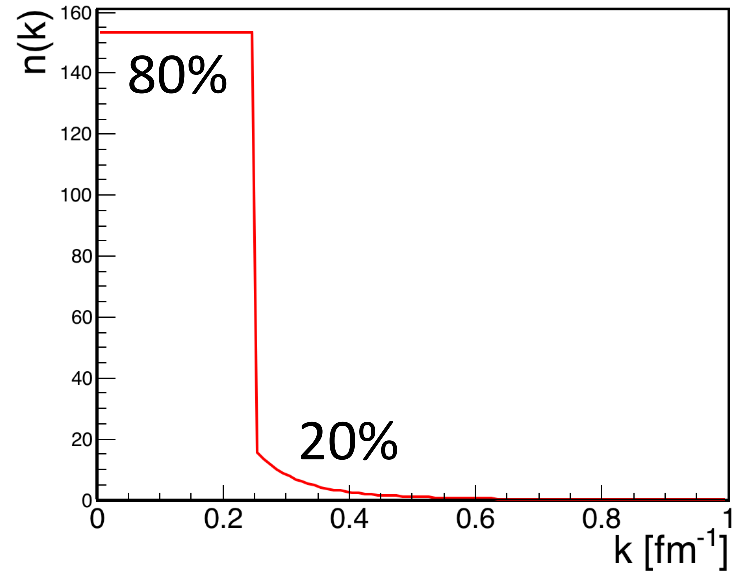
Kinematical simulation

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



Lab Frame:



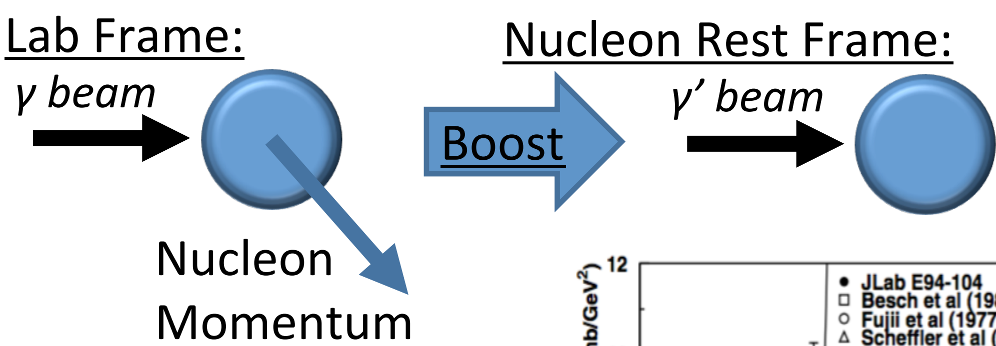


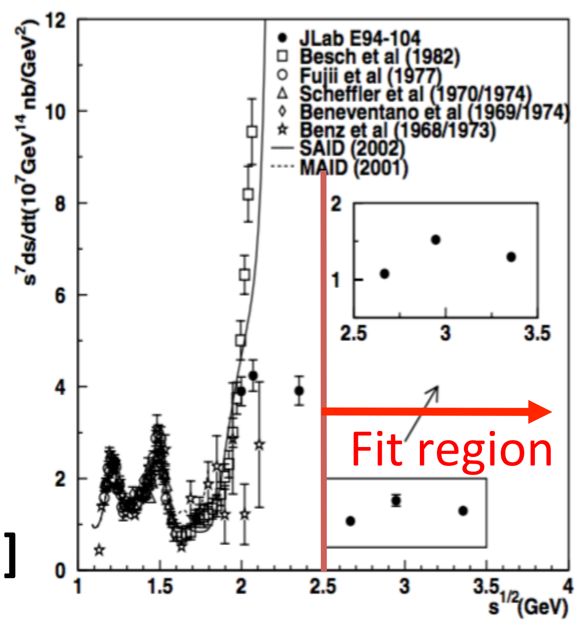
Kinematical simulation

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:

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





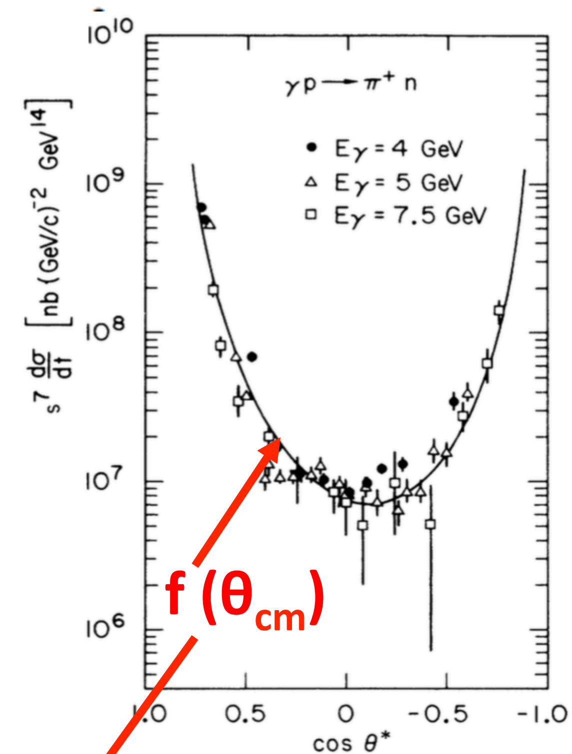


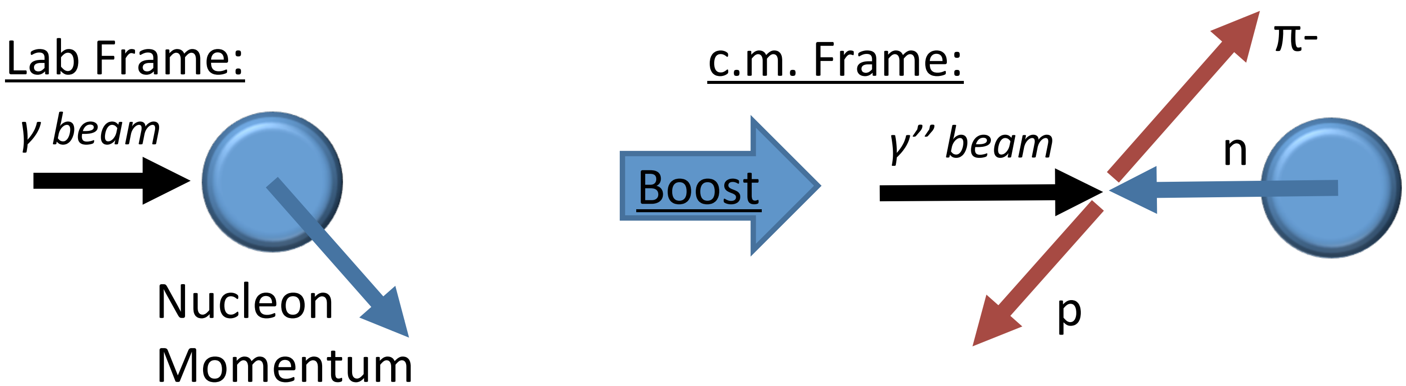
FIG. 6. $s^7\, d\sigma/dt$ versus $\cos\theta^*$ for the reaction $\gamma p \rightarrow \pi^+ n$. The solid line shows the empirical function $(1-z)^{-5}(1+z)^{-4}$ where ($z = \cos\theta^*$), which is an empirical fit to the angular distribution.

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

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

Kinematical simulation

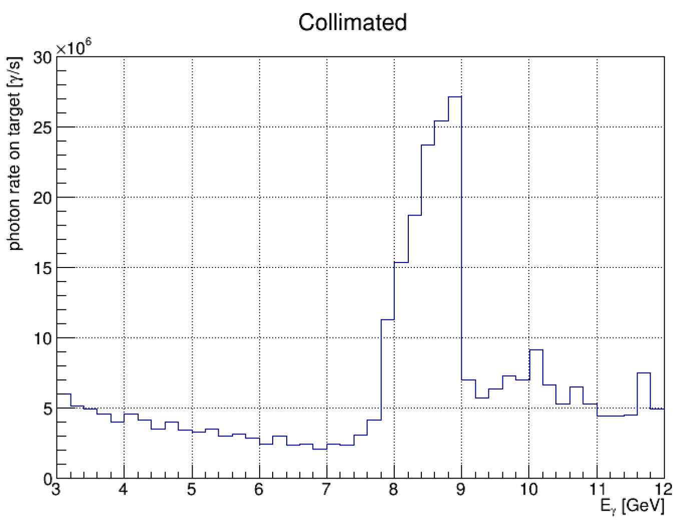
1. Raffle a nucleon from a correlated Fermi-Gas model and a photon from the GlueX beam
2. Get the cross-section for ($\gamma\, n \rightarrow \pi^- p$) elastic scattering
3. Boost to the c.m. and do scattering for angles of $40^o - 140^o$. Keep only events with $|t|,|u| > 2\ GeV^2$



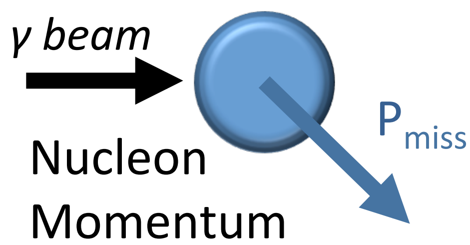
4. Boost back to the laboratory frame

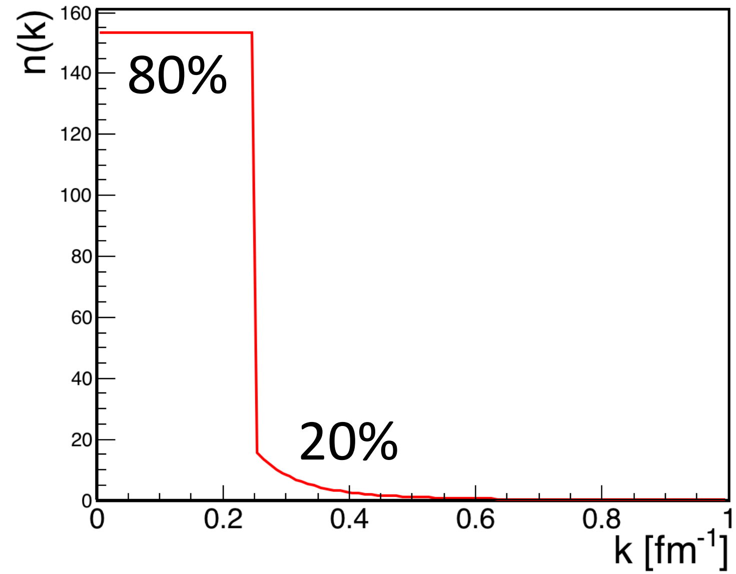
Kinematical Simulation

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

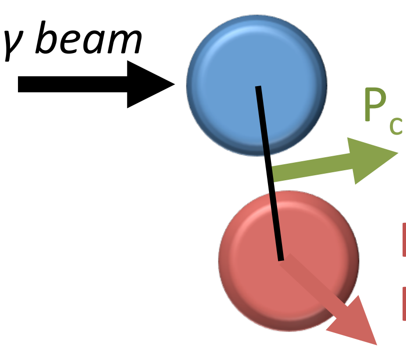


Lab Frame:





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) $P_{recoil} = 0$