Single-meson photoproduction off d and ^3He

Igal Jaeglé

Workshop on
Photoproduction Studies on the Deuteron and Helium-3 in Hall D

April 20, 2026

Table of contents

Existing neutron set

Proxy for a neutron target (d, ^3He, or ^4He)

- "Neutron data" is needed to disentangle the isospin composotion of the elementary strong amplitude
- Above $\mathrm{E}_{\gamma}^{\mathrm{beam}} = 2.5$ GeV, negligible to none neutron data available

The reaction of interest is

$$\gamma + d \rightarrow$$

Two possible productions:

- Nuclear Coherent (or coherent)

$$\gamma + d \rightarrow \quad \eta + d \tag{1}$$

- Nuclear Incoherent (or quasi-free)

$$\gamma + d \rightarrow \quad \eta + N^{recoil} + N^{spectator} \tag{2}$$

Nuclear effects must be taken into account and studied by comparing free proton to bound proton to validate ISI and FSI calculations

Physics Goals and Isospin Decomposition

Reaction Set (linearly polarized photon beam)

- $\gamma p \to \pi^0/\eta^{(\prime)}/\omega/\rho^0/\phi p$
- $\gamma n \to \pi^0/\eta^{(\prime)}/\omega/\rho^0/\phi n$
- Coherent $\gamma d/^3He \to \pi^0/\eta^{(\prime)}/\omega/\rho^0/\phi d/^3He$

1. Isospin decomposition

$$\mathcal{T}_p = \mathcal{T}^S + \mathcal{T}^V, \qquad \mathcal{T}_n = \mathcal{T}^S - \mathcal{T}^V$$

Measurements:

- $d\sigma_p/dt$, $d\sigma_n/dt$,$d\sigma_d/dt$,,$d\sigma_{^3He}/dt$,
- Beam asymmetry $\Sigma_p(t)$, $\Sigma_n(t)$, $\Sigma_d(t)$, $\Sigma_{^3He}(t)$,
- SDMEs for ω, $\rho^{0,\pm}$, and ϕ

Extraction:

- Magnitude ratio $|\mathcal{T}^S/\mathcal{T}^V|$
- Relative phase (via Σ)

2. Natural vs Unnatural Exchange

$$\frac{d\sigma}{dtd\phi} = \frac{1}{2\pi}\frac{d\sigma}{dt}\left(1 - P_\gamma \Sigma \cos 2\phi\right)$$

- $\Sigma \to +1$: natural parity dominance
- $\Sigma \to -1$: unnatural parity dominance
- $\Sigma(t)$ evolution $\Rightarrow$ helicity structure change

3. Coherent deuteron as isoscalar filter

$$\mathcal{T}_{d,\mathrm{coh}} \sim (\mathcal{T}_p + \mathcal{T}_n) \otimes F_d(t) \approx 2\,\mathcal{T}^S \otimes F_d(t)$$

$$\mathcal{T}_{^3He,\mathrm{coh}} \sim (2\,\mathcal{T}_p + \mathcal{T}_n) \otimes F_{^3He}(t) \approx (3\,\mathcal{T}^S + \mathcal{T}^V) \otimes F_{^3He}(t)$$

- Direct constraint on isoscalar amplitude
- Reduces neutron nuclear uncertainties
- Stabilizes global Regge fit

Momentum Transfer Evolution and Onset of Hard Scattering

Forward region: $0 \lesssim -t \lesssim 2$ **GeV**^{2}

- Exponential t-dependence
- Reggeized t-channel exchange
- Strong Σ sensitivity
- Clean isospin separation

Intermediate region: $2 \lesssim -t \lesssim 6$ **GeV**^{2}

- Possible residue zeros / curvature
- Increased helicity-flip contributions
- Test validity of single Regge framework

Diagnostics:

- Change in slope parameter $b(t)$
- Evolution of $\Sigma(t)$

Large $-t$: $6 \lesssim -t \lesssim 12$ **GeV**^{2}

- Strong suppression of coherent $\gamma d \to \eta d$
- Possible power-law behavior

$$\frac{d\sigma}{dt} \sim s^{-n} f(t)$$

- Test onset of short-distance mechanisms

Key signatures:

- Deviation from exponential behavior
- Change in polarization pattern
- Proton–neutron scaling differences

Global fit observables:

$$\{d\sigma_p, d\sigma_n, d\sigma_d, \Sigma_p, \Sigma_n, \Sigma_d\}$$

$\Rightarrow$ Isoscalar/isovector separation

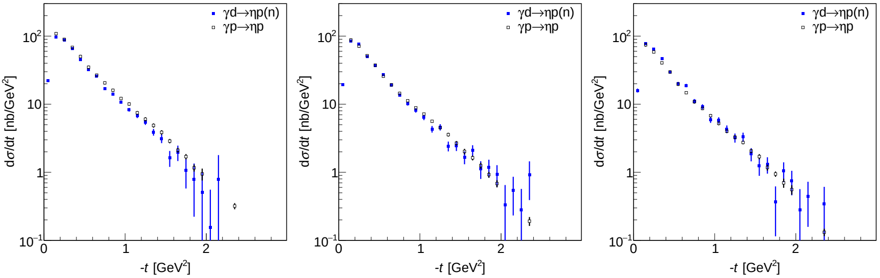
$\Rightarrow$ Natural/unnatural decomposition

$\Rightarrow$ Helicity evolution and hard-scattering onset

Comparison between SRC/CT quasi-free proton and free proton

Free proton data are final GlueX phase I resuls (Jon's results not yet published)

- $8 \leq E_\gamma \leq 9$ GeV
- $9 \leq E_\gamma \leq 10$ GeV
- $10 \leq E_\gamma \leq 10.8$ GeV



- Except for Fermi motion, all other nuclear effects appear to be negligible
- Fermi motion effect only impact differential cross section at $-t \leq 0.25\text{GeV}^2$
- A long LD2 run allows to reach larger -t

Good agreement between free and quasi-free proton

Aleksandr I. Fiks's fit

Initially A.I. Fiks used Chiang et al., PRC 68 (2003) 045202 which is very similar than Laget, PRC 72, 022202R (2005)

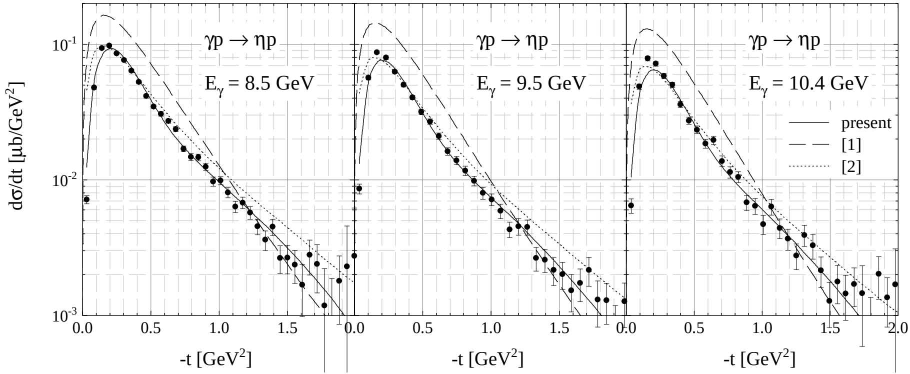
- $T(\omega)$ and $T(\rho)$ included
- Nondegenerate trajectories for π^0 => always yield a deep minimum at $-t = 0.5$ GeV^2
- Degenerate trajectories for η and η' => deep absent

Then Sibirtsev et al., EPJA 46 (2010) 359 (which has more than 2 trajectories)

- All trajectories are nondegenerate
- But this model includes the so-called 'cuts' - additional trajectories that fill these minima
- $T(\omega)$, $T(\rho)$, and $T(b_1)$ included

Aleksandr I. Fiks's fit

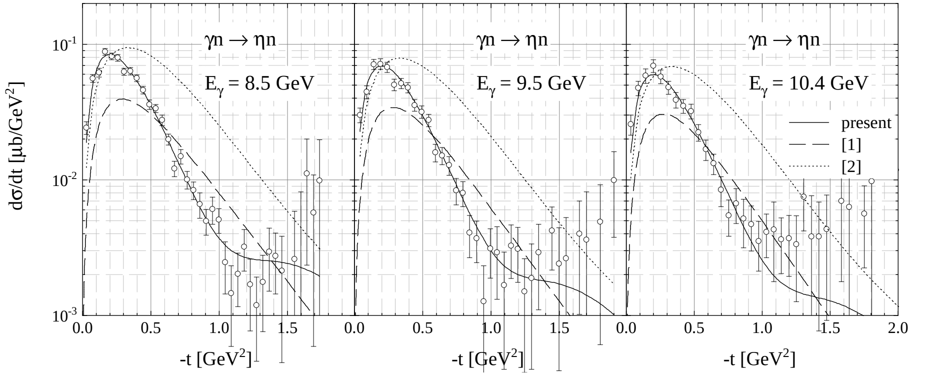
- Present, Sibirtsev et al., EPJA 46 (2010) 359, combined fit of quasi-free p, quasi-free n, and coherent
- 1, Chiang et al., PRC 68 (2003) 045202 as is or using free p data
- 2, Sibirtsev et al., EPJA 46 (2010) 359 as is or using free p data



T_S contribution very small. A long LD2 run allows to reach larger $-t$

Aleksandr I. Fiks's fit

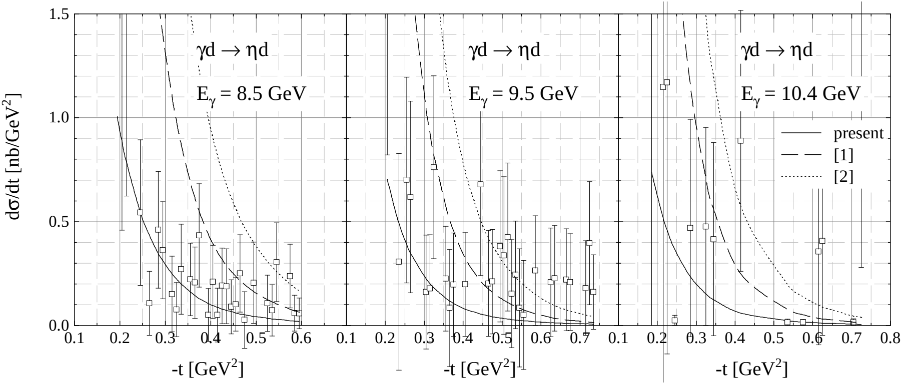
- Present, Sibirtsev et al., EPJA 46 (2010) 359, combined fit of quasi-free p, quasi-free n, and coherent
- 1, Chiang et al., PRC 68 (2003) 045202 as is or using free p data
- 2, Sibirtsev et al., EPJA 46 (2010) 359 as is or using free p data



T_S contribution very small. A long LD2 run allows to reach larger $-t$

Aleksandr I. Fiks's fit

- Present, Sibirtsev et al., EPJA 46 (2010) 359, combined fit of quasi-free p, quasi-free n, and coherent
- 1, Chiang et al., PRC 68 (2003) 045202 as is or using free p data
- 2, Sibirtsev et al., EPJA 46 (2010) 359 as is or using free p data

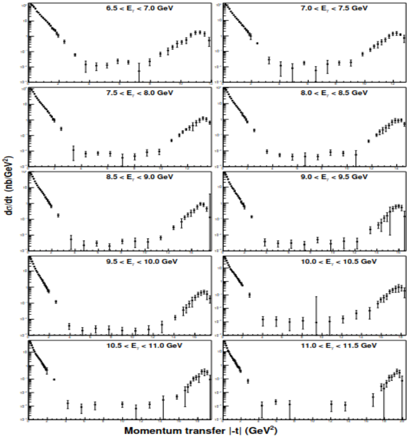


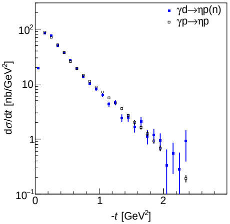
T_S contribution very small. A long LD2 run allows to reach larger *-t*

$\gamma d \rightarrow \eta n(p)$ expected statistical uncertainty

Would be roughly 3 times larger than GlueX-I $\gamma p \rightarrow \eta p$ results

- Left: results of John Zarling, $\gamma p \rightarrow \eta p$ - GlueX-I
- Right: preliminary results of SRC/CT, $\gamma d \rightarrow \eta p(n)$ and $9 \leq E_\gamma \leq 10$ GeV



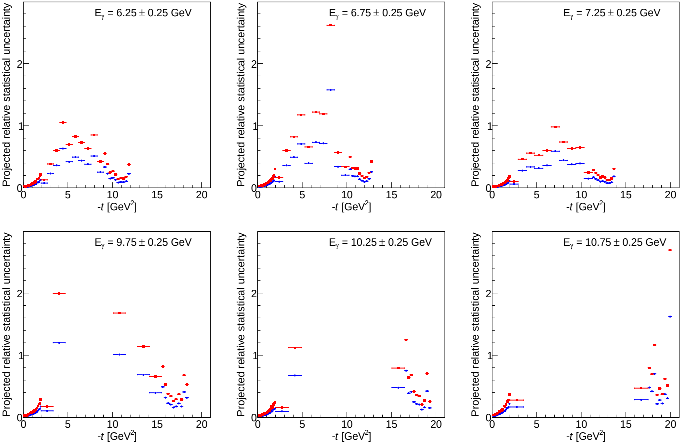


Preliminary SRC/CT results: nuclear effects are negligible, all trajectories are nondegenerate, and $\mathcal{T}^S$ contribution is much smaller than expected

$\gamma d \rightarrow \eta n(p)$ expected statistical uncertainty

To achieve a statistical uncertainty for the quasi-free proton measurement equal to that of the free proton measurement:

- Required integrated luminosity: ~ 165 pb^{-1}
- Integrated luminosity collected between 8 and 10.8 GeV (SRC/CT): 11.65 pb^{-1}
- Maintain comparable statistical uncertainties for quasi-free neutron wrt quasi-free proton measurements



Conclusion

Single meson can be measured in coincidence with a recoil proton, neutron, or deuteron

- Neutron data negligible to none
- Deuteron data are essential to disentangle isospin contributions
- Not treated here:
  - Helium-3 data set needed together with existing Helium-4 data to quantify the Strong (coherent) contributions
  - Search for exotic Coulomb processes involving a bound proton in the nuclear medium