Hard Photodisintegration of ^3He into *pd* pair

Dhiraj Maheswari
Florida International University
Miami, FL, USA

HUGS 2015

Outline

- Motivation
- Calculations
- Result

Motivation

- Hard scattering processes are those in which the invariant energy *s* and invariant transferred momenta $-t, -u >> m^2$

- Hard nuclear processes are important in that at sufficiently high momentum transfer, we expect the "quark-gluon" degrees of freedom in the participating hadrons to reveal.

- Quark Counting Rule: For an arbitrary hard process of the type $a + b \to c + d$

$$\frac{d\sigma}{dt} \sim \frac{1}{s^{n-2}} \qquad n = n_a + n_b + n_c + n_d$$

For Instance, if "a" is a photon, $n_a = 1$ and if "a" is a proton, $n_a = 3$

Motivation

- Following are the Hadronic and Photoproduction processes that confirms with the Quark Counting Rule

$$pp \to pp \qquad \frac{d\sigma}{dt} \sim s^{-10} \quad p\pi \to N\pi \qquad \frac{d\sigma}{dt} \sim s^{-8} \quad \gamma p \to N mesons \qquad \frac{d\sigma}{dt} \sim s^{-7}$$

- Counting Rule is significant for nuclear targets, for it may indicate sensitiveness of QCD degrees of freedom in nuclear targets where quarks are elusive.
- First nuclear process studied was the photodisintegration of deuteron

$$\gamma + d \to p + n, \qquad \frac{d\sigma}{dt} \sim s^{-11}$$

S. J. Brodsky and B. T. Chertok, The Asymptotic Form-Factors of Hadrons and Nuclei and the Continuity of Particle and Nuclear Dynamics," Phys. Rev. D 14, 3003 (1976).

The Theory

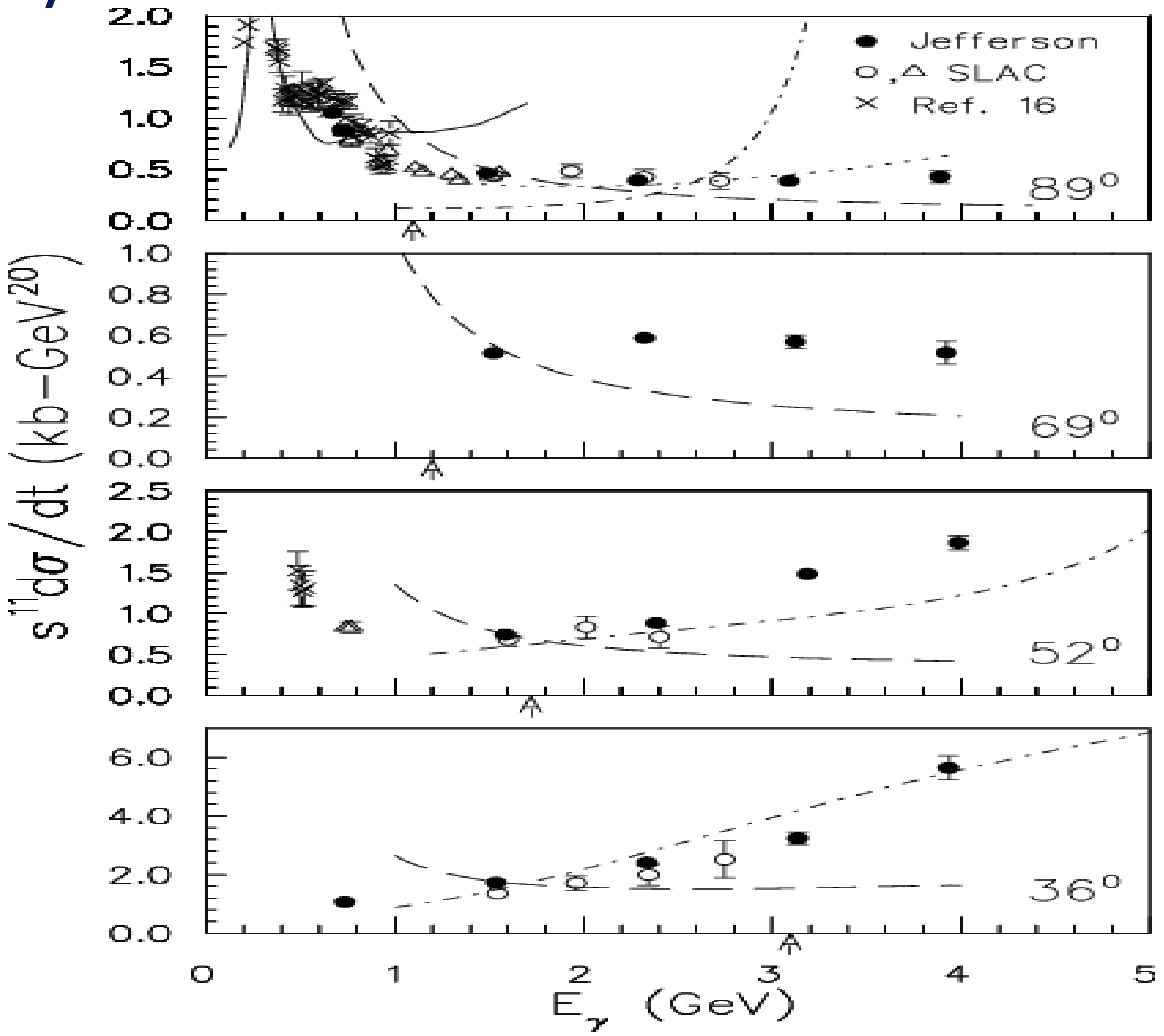
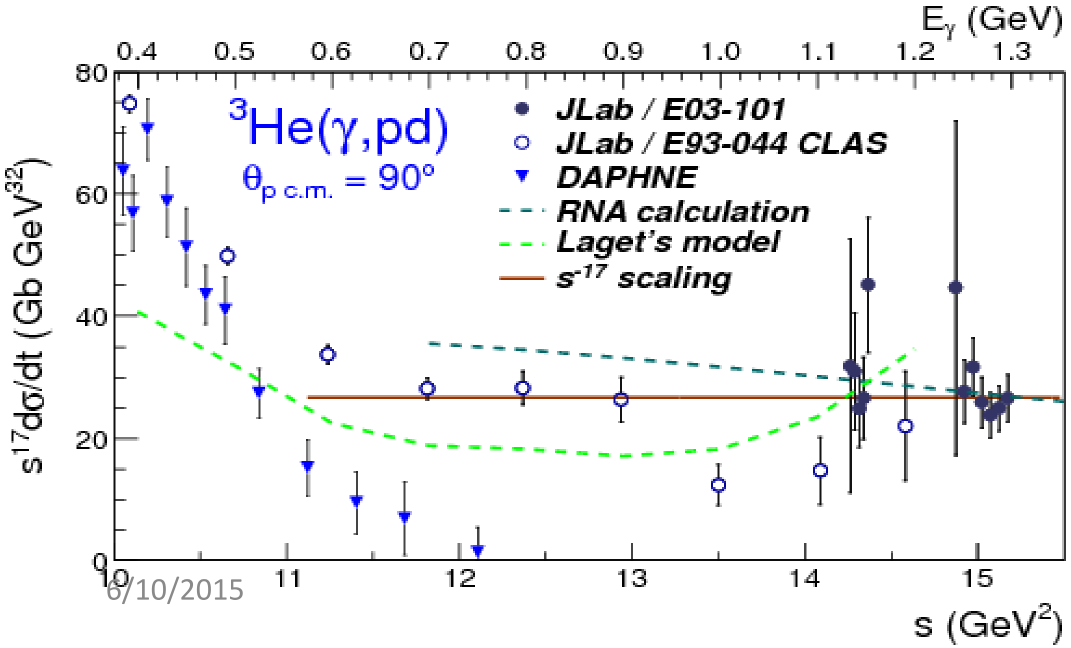


Figure: Scaled Differential Cross Section as function of Photon Energy for $\gamma + d \rightarrow p + n$

Application of Quark Counting Rule to study $\gamma + {}^3He \rightarrow p + d$

- These experiments were then extended to study the ^{3}He target, for which the onset of scaling was observed for the reaction $\gamma + {}^3He \rightarrow p + d$ at photon energy > 2 GeV and $\theta_{cm} = 90^o$
- For this reaction, the scaling can be shown to be $\frac{d\sigma}{dt} \sim s^{-17}$
- Highest power ever observed.



Even if quark-counting rules are observed, the pQCD approximation failed to describe the absolute cross sections of the processes, which indicate that even though the quark degrees of freedom are observed, the processes are still non-perturbative.

I. Pomerantz et al. [CLAS and Hall-A and Hall-A Collaborations], Hard Two body Photodisintegration of 3He," Phys. Rev. Lett. 110, no. 24, 242301 (2013) [arXiv:1303.5049 [nucl-ex]].

The Model

- Hard Rescattering Model (HRM): A non-perturbative model
- HRM was able to beautifully describe the photodisintegration of deuteron

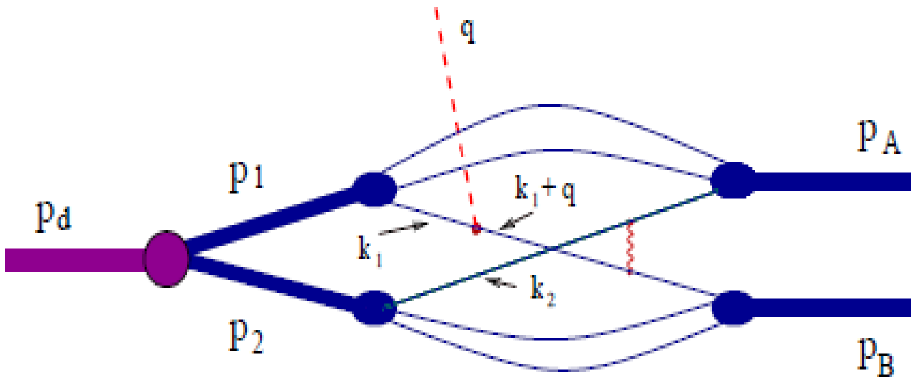
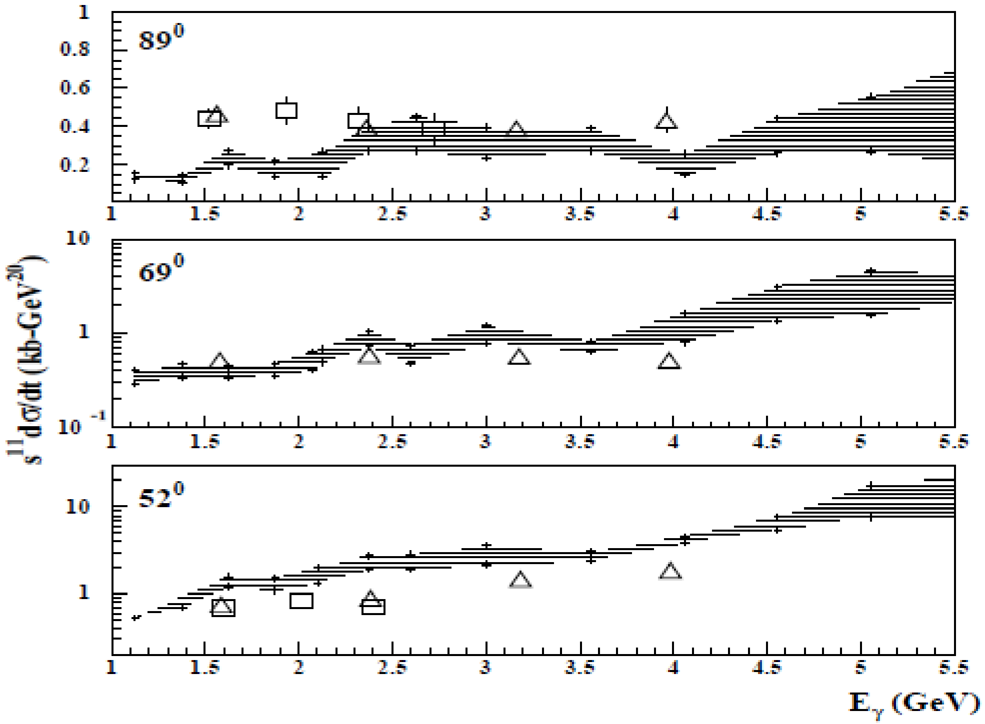


FIG. 1. Quark Rescattering diagram.



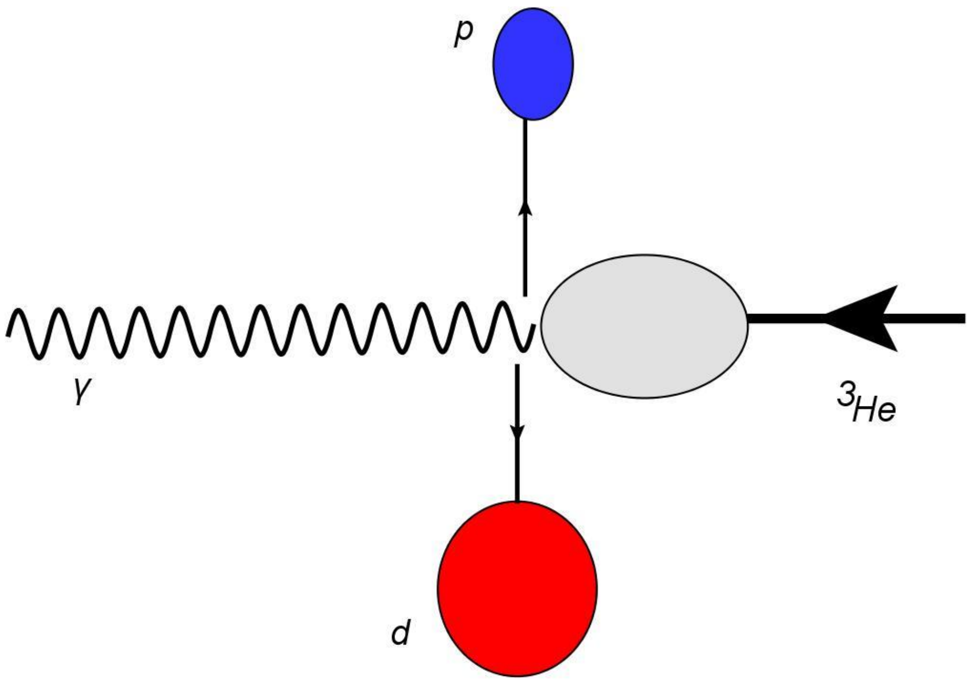
(Triangles) C. Bochna et al., Phys. Rev. Lett. 81, 4576 (1998).
(Squares) J.E. Belz et al., Phys. Rev. Lett. 74, 646 (1995).

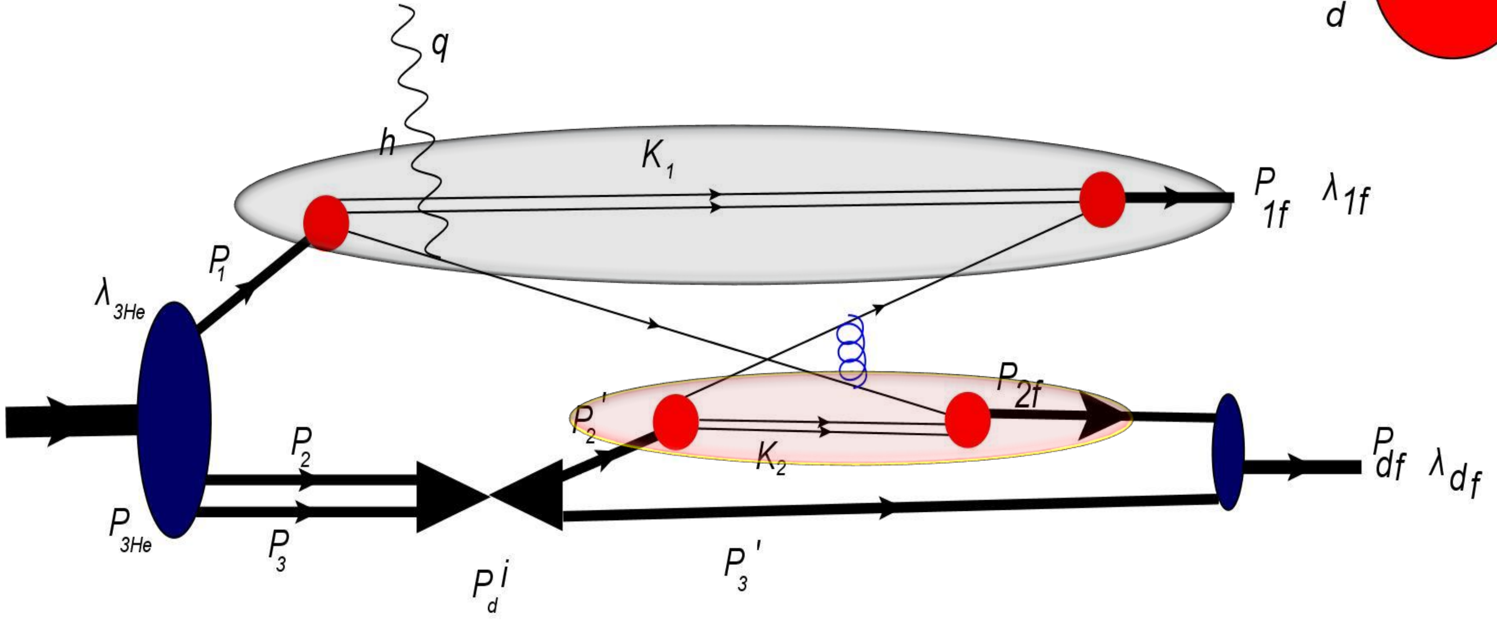
Fig: Scaled Diff. Cross Section for photodisintegration of deuteron

L. L. Frankfurt, G. A. Miller, M. M. Sargsian and M. I. Strikman, QCD rescattering and high-energy two-body photodisintegration of the deuteron," Phys. Rev. Lett. 84, 3045 (2000)

Hard Breakup of ^3He

$\gamma + ^3He \rightarrow p + d$





Reference Frame and Kinematics

- Reference Frame

$$q(+,-,\perp) = (0, \sqrt{s'}, 0)$$

$$P_{3He}(+,-,\perp) = (\sqrt{s'}, \frac{m_{3He}^2}{\sqrt{s'}}, 0) \qquad s' = s - m_{3He}^2$$

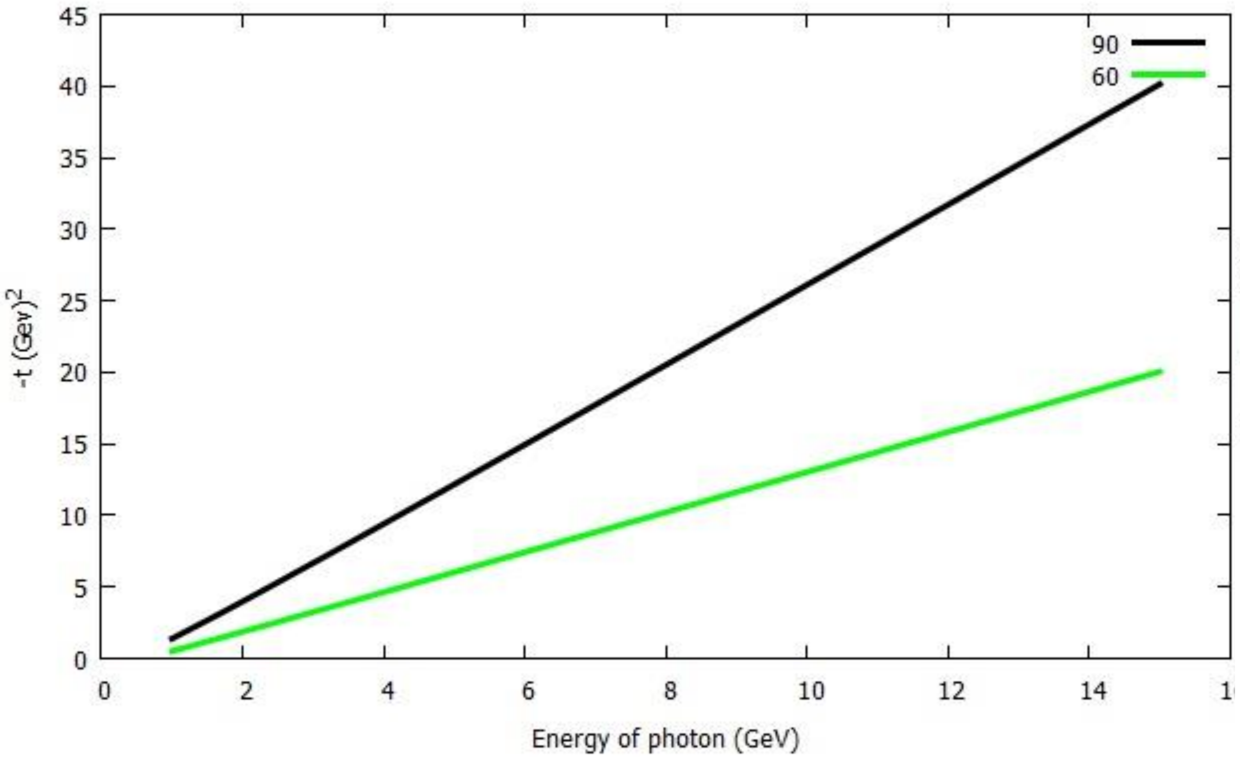


Fig: *t* as function of Photon energy

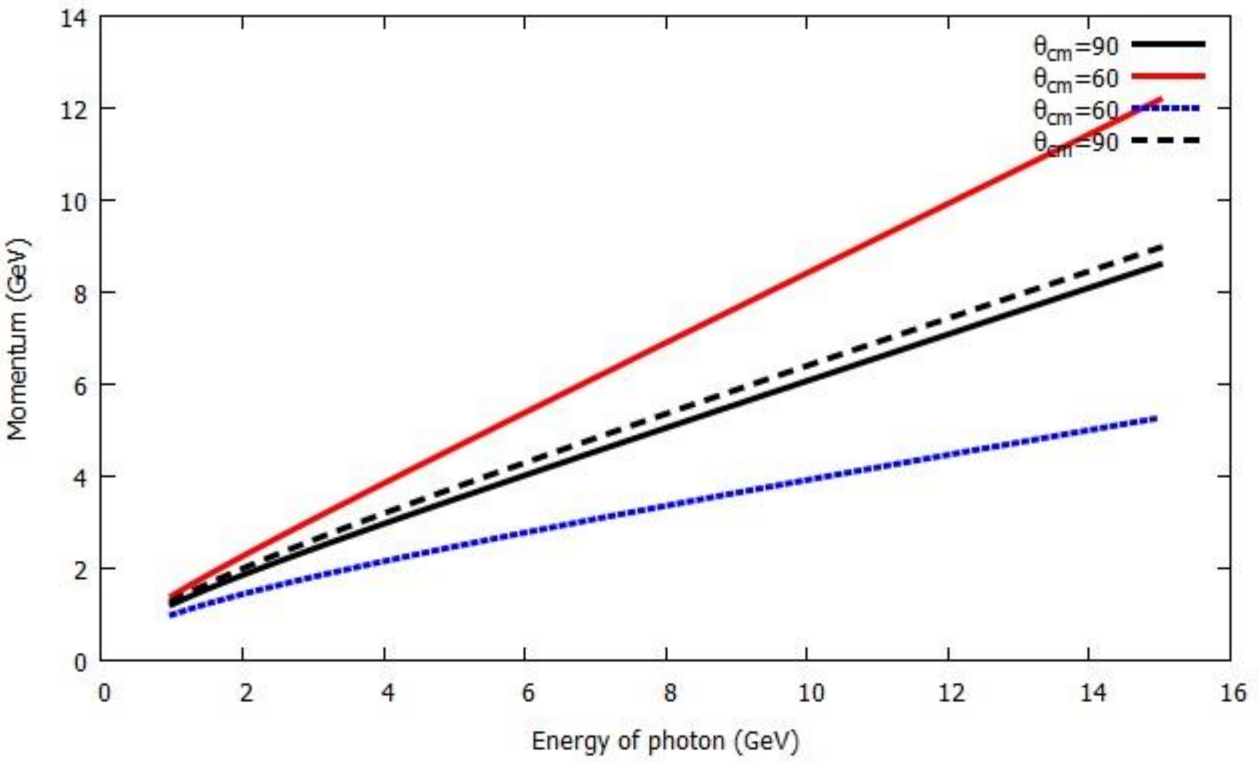


Fig: Momentum as function of Photon Energy

Amplitude of the process

$$A^{\lambda_{df},\lambda_{1f};\lambda_{3He},h} = \sum_{\lambda'_d} \int \chi_d^{*\lambda_{d'}} (-i\Gamma^{\dagger}_{dnn}) \frac{i(\not{P}_{2f}+m)}{P_{2f}^2 - m^2 + i\epsilon} \frac{i(\not{P}_{3'}+m)}{P_{3'}^2 - m^2 + i\epsilon} \frac{i(\not{P}_{2'}+m)}{P_{2'}^2 - m^2 + i\epsilon}$$

$$i\frac{\Gamma_{dnn}\chi_d^{\lambda_{d'}}\chi_d^{*\lambda_{d'}}}{p_{d'}^2 - m_d^2 + i\epsilon} (-i)\Gamma^{\dagger}_{dnn} \frac{i(\not{P}_3+m)}{P_3^2 - m^2 + i\epsilon} \frac{i(\not{P}_2+m)}{P_2^2 - m^2 + i\epsilon} \frac{i(\not{P}_1+m)}{P_1^2 - m^2 + i\epsilon}$$

$$i\Gamma_{3He}\chi_{3He}^{(s)} \frac{d^4P_2}{(2\pi)^4} \frac{d^4P_3}{(2\pi)^4} \frac{d^4P_{3'}}{(2\pi)^4}$$

$$N1: \int \chi_{p_{1f}} (-i)\Gamma^{\dagger}_{n1f} \frac{i(\not{P}_{1f} - \not{K}_1 + m)}{(P_{1f}-K_1)^2 - m^2 + i\epsilon} \left[-igT_c^{\beta}\gamma_{\mu}\right] \frac{iS(K_1)}{K_1^2 - m^2 + i\epsilon}$$

$$\frac{i(\not{P}_1 - \not{K}_1 + m)}{(P_1-K_1)^2 - m^2 + i\epsilon} i\Gamma_{n1} \frac{d^4K_1}{(2\pi)^4}$$

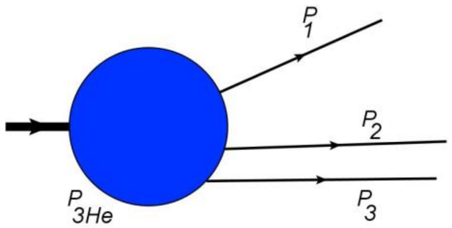
$$\gamma: -igT_c^{\alpha}\gamma_{\nu} \frac{i(\not{P}_1 + \not{q} - \not{K}_1 + m)}{(P_1 - K_1 + q)^2 - m^2 + i\epsilon} \left[-ie\gamma^{\mu}\epsilon^{\mu}\right]$$

$$N2: \int (-i)\Gamma^{\dagger}_{n2f} \frac{i(\not{P}_{2f} - \not{K}_2 + m)}{(P_{2f}-K_2)^2 - m^2 + i\epsilon} \frac{iS(K_2)}{K_2^2 - m^2 + i\epsilon} \frac{i(\not{P}_{2'} - \not{K}_2 + m)}{(P_{2'}-K_2)^2 - m^2 + i\epsilon}$$

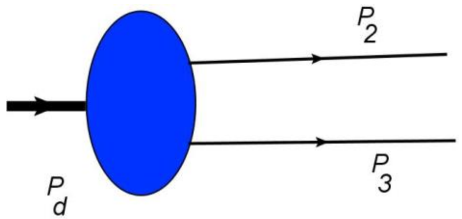
$$i\Gamma_{n2'} \frac{d^4K_2}{(2\pi)^4}$$

$$g: \frac{id_{\mu\nu}\delta_{\alpha\beta}}{q_q^2}$$

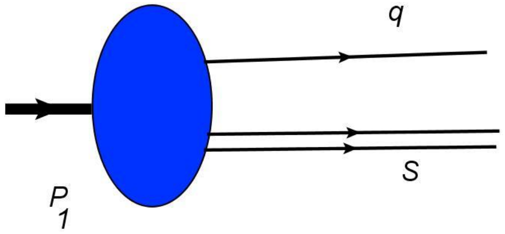
The light cone wavefunctions



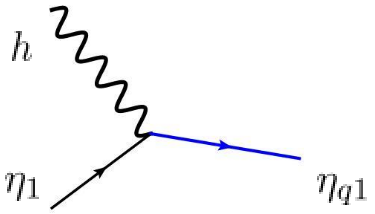
$$\Psi_{3He}^{\lambda_{3He}}(\beta_1,\lambda_1,p_{1\perp},\beta_2,p_{2\perp}\lambda_2,\lambda_3) = \frac{\bar{u}(p_3,\lambda_3)\bar{u}(p_2,\lambda_2)\bar{u}(p_1,\lambda_1)}{\left(m_{3He}^2 - \frac{m_d^2+p_{d\perp}^2}{\beta_d} - \frac{p_{1\perp}^2+m^2}{\beta_1}\right)}\Gamma_{3He}\chi_{3He}^{(s)}$$



$$\Psi_d^{\lambda_{d'}}(\alpha_3', p_{3\perp}, p_{d\perp}') = \frac{\bar{u}(p_2,\lambda_2)\bar{u}(p_3,\lambda_3)}{\left(m_d^2 + p_{d\perp}'^2 - \frac{m^2+p_{3\perp}^2}{\alpha_3'} - \frac{m^2+p_{2\perp}^2}{1-\alpha_3'}\right)}\Gamma_{dnn}\chi_d^{\lambda_{d'}}$$



$$\Psi_n^{\lambda;\eta}(X_s,K_\perp,p_\perp) = \frac{\bar{u}_q(P-K,\eta)\bar{\psi}_s(K)}{m^2+p_\perp^2 - \frac{m_s^2+K_\perp^2}{X_s} - \frac{(P-K)_\perp^2+m_q^2}{1-X_s}}\Gamma_n u(P,\lambda)$$



$$\bar{u}_{\eta_{q1}}(P_2)[ie\epsilon^\mu\gamma^\mu]u_{\eta_1}(P_1) = ieQ2\sqrt{2E_1E_2}(-h)\delta^{\eta_{q1}h}\delta^{\eta_1 h}$$

Calculations

- After defining light cone wavefunctions, the amplitude reduces to

$$A^{\lambda_{df},\lambda_{1f};\lambda_{3He},h} = -i\frac{3}{4}\pi\frac{1}{\sqrt{s'}}\sum_i eQ_i \sum_{\substack{\lambda_{d'},\lambda_{2f},\lambda_{3'}\lambda_{2'}\\ \lambda_1,\lambda_2,\lambda_3\\ \eta_{1f},\eta_{2'},\eta_{2f}}} \int \frac{\Psi_d^{\dagger\lambda_{df}}(\alpha_{2f}/\Lambda, p_{2\perp}, \alpha_3'/\Lambda, p_{3'\perp})}{1-\alpha_3'/\Lambda}$$

$$\left\{\frac{\Psi_{n2f}^{\dagger\lambda_{2f};\eta_{2f}}(X_{s2}, p_{2f\perp}, k_{2\perp})}{1-X_{s2}}\bar{u}_q(P_{2f}, K_2, \eta_{2f})[-igT_c^{\alpha}\gamma_\nu]\Big[u_q(P_1+q-K_1,h)(-h)\Big]\right.$$

$$\left.\frac{\Psi_{n1}^{\lambda_1;h}(X_1, K_{1\perp}, p_{1\perp})}{1-X_1}\right\}_1 \left\{\frac{\Psi_{n1f}^{\dagger\lambda_{1f};\eta_{1f}}(X_{s1}, K_{1\perp}, p_{1f\perp})}{1-X_{s1}}\bar{u}_q(P_{1f}-K_1, \eta_{1f})[-igT_c^{\beta}\gamma_\mu]\right.$$

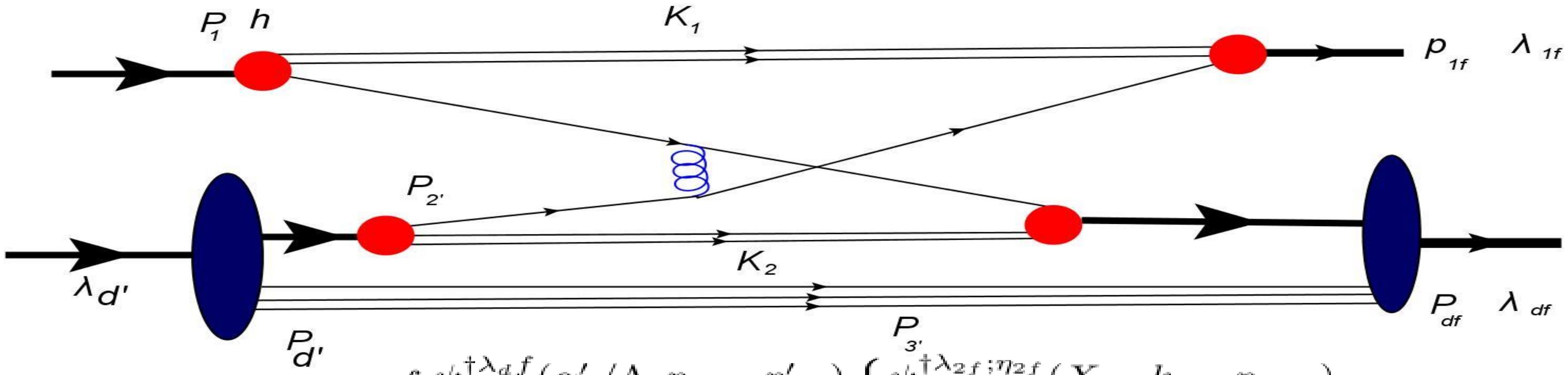
$$\left. u_q(P_{2'}-K_2, \eta_{2'})\frac{\Psi_{n2'}^{\lambda_{2'};\eta_{2'}}(X_{2'}, p_{2'\perp}, k_{2\perp})}{1-X_{2'}}\right\}_2 G^{\mu\nu}(r)\frac{\Psi_d^{\lambda_{d'}}(\alpha_3', p_{d\perp}', p_{3\perp}')}{1-\alpha_3'}$$

$$\frac{\Psi_{d'}^{\dagger\lambda_{d'}}(\alpha_3', p_{3\perp}, p_{d\perp}')}{(1-\alpha_{3'})}\Psi_{3He}^{\lambda_{3He}}(\beta_1 = 1/3, \lambda_1, p_{1_\perp}, \beta_2, p_{2_\perp}\lambda_2, \lambda_3)\frac{d^2p_{d\perp}}{(2\pi)^3}\frac{d\beta_3}{\beta_3}\frac{d^2p_{3\perp}}{(2\pi)^3}\frac{d\alpha_{3'}}{\alpha_{3'}}\frac{d^2p_{3'\perp}}{2(2\pi)^3}$$

$$\frac{dX_1}{X_1}\frac{d^2k_{1\perp}}{2(2\pi)^3}\frac{dX_{2'}}{X_{2'}}\frac{d^2k_{2\perp}}{2(2\pi)^3}$$

Calculations

- Mechanism of *pd* → *pd* process



$$A_{pd}^{\lambda_{df},\lambda_{1f};\lambda_{d'},h} = \sum_{\substack{\lambda_{d'},\lambda_{2'},\lambda_{2f},\lambda_{3'} \\ \eta_{1f},\eta_{2'},\eta_{2f}}} \int \frac{\psi_{df}^{\dagger\lambda_{df}}(\alpha_3'/\Lambda, p_{df\perp}, p_{3\perp}')}{1-\alpha_3'/\Lambda} \left\{ \frac{\psi_{n2f}^{\dagger\lambda_{2f};\eta_{2f}}(X_{s2}, k_{2\perp}, p_{2f\perp})}{1-X_{s2}} \right.$$

$$\left. \bar{u}_q(P_{2f}-K_2,\eta_{2f})[-igT_c^{\alpha}\gamma_\nu]u_q(P_1-K_1,h)\frac{\Psi_{n1}^{h;h}(X_1,K_{1\perp},p_{1\perp})}{1-X_1} \right\}_1 G^{\mu\nu}(r)$$

$$\left\{ \frac{\Psi_{n1f}^{\dagger\lambda_{1f};\eta_{1f}}(X_{s1},K_{1\perp},p_{1f\perp})}{1-X_{s1}} \bar{u}_q(P_{1f}-K_1,\eta_{1f})[-igT_c^{\beta}\gamma_\mu]u_q(P_2'-K_2,\eta_{2'}) \right.$$

$$\left. \frac{\psi_{n2'}^{\lambda_{2'};\eta_{2'}}(X_{2'},k_{2\perp},p_{2\perp}')}{1-X_{2'}} \right\}_2 \frac{\psi_d^{\lambda_{d'}}(\alpha_3',p_{d\perp},p_{3\perp}')}{1-\alpha_{3'}} \frac{1}{2}\frac{dX_1}{X_1}\frac{d^2k_{1\perp}}{(2\pi)^3}\frac{1}{2}\frac{dX_{2'}}{X_{2'}}\frac{d^2k_{2\perp}}{(2\pi)^3}\frac{d\alpha_{3'}}{\alpha_{3'}}\frac{d^2p_{3'\perp}}{2(2\pi)^3}$$

Final Amplitude for $\gamma + {}^3He \rightarrow p + d$

$$A^{\lambda_{df},\lambda_{1f};\lambda_{3He},h} = i\pi\frac{3}{\sqrt{s'}}\frac{1}{((2\pi)^3)^2}\sum_i eQ_i h A_{pd}^{\lambda_{df},\lambda_{1f};\lambda_{d'},h} \sum_{h,\lambda_{d'}} \int \Psi_{{}^3He/d}^{\lambda_{3He},\lambda_1,\lambda_{d'}}(P_1,h)d^2p_{1\perp}$$

Results

- The Differential CS: $\frac{d\sigma^{\gamma 3He}}{dt} = \frac{1}{2}\frac{\alpha}{32}\frac{1}{((2\pi)^3)^3}\frac{s_{\gamma 3He}-(m_d-m_p)^2}{s'^2}\frac{d\sigma^{pd}}{dt}S_{3He/d}$

$$\frac{d\sigma^{pd}}{dt} = \frac{1}{16\pi}\frac{1}{(s_{pd}-(m_d+m_p)^2)(s_{pd}-(m_d-m_p)^2)}|\overline{A_{pd}}|^2$$

$$S_{3He/d} = \frac{1}{2}\sum_{\lambda_{3He}}\sum_{\lambda_1,\lambda_{d'}}\int |\Psi_{3He/d}^{\lambda_{3He},\lambda_1,\lambda_{d'}}(P_1,\lambda_1)|^2 d^2P_{1\perp}$$

$$\Psi_{3He/d}^{\lambda_{3He},\lambda_1,\lambda_{d'}}(P_1,\lambda_1) = \sum_{\lambda_2,\lambda_3,\lambda_{d'}}\int \Psi_{d'}^{\lambda_{d'}\dagger}(P_{rel})\Psi_{3He}^{\lambda_{3He}}(P_1,\lambda_2,\lambda_3,P_{rel})d^3P_{rel}$$

$$\Psi_{{}^3He/d}^{\lambda_{3He};LC}(P_1,\lambda_1,\lambda_{d'}) = \sqrt{2m_d}(2\pi)^{3/2}\Psi_{{}^3He/d}^{\lambda_{3He};NR}(P_1,\lambda_1,\lambda_{d'}) \qquad P_{rel} = P_3 - P_2$$

THANK YOU!!!