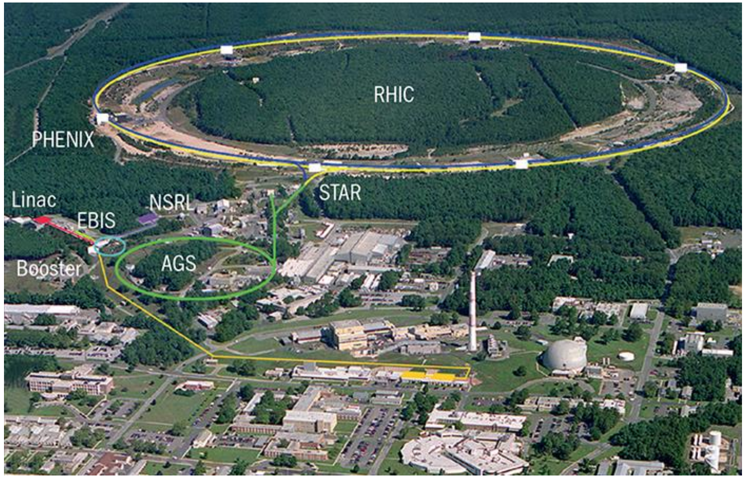
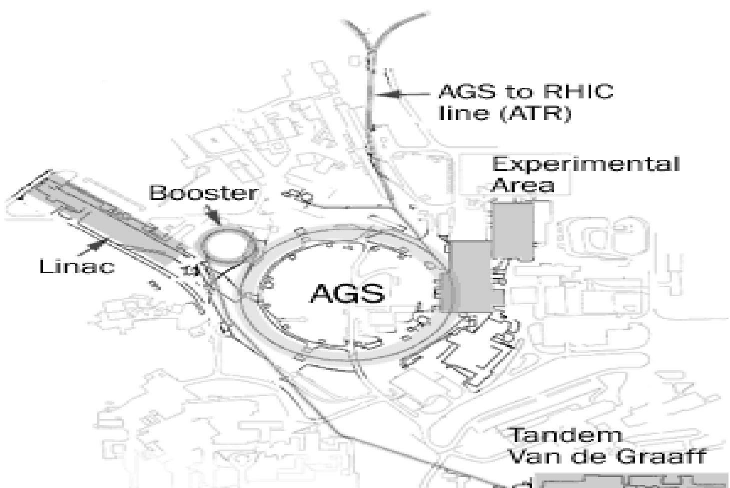
Hard Deuteron and 3He Photodisintegration

Misak Sargsian
Florida International University, Miami

Photoproduction Studies on the Deuteron and Helium-3 in Hall D
FIU, April 20, 2026

Alternating Gradient Synchrotron (AGS)





Build in 1960

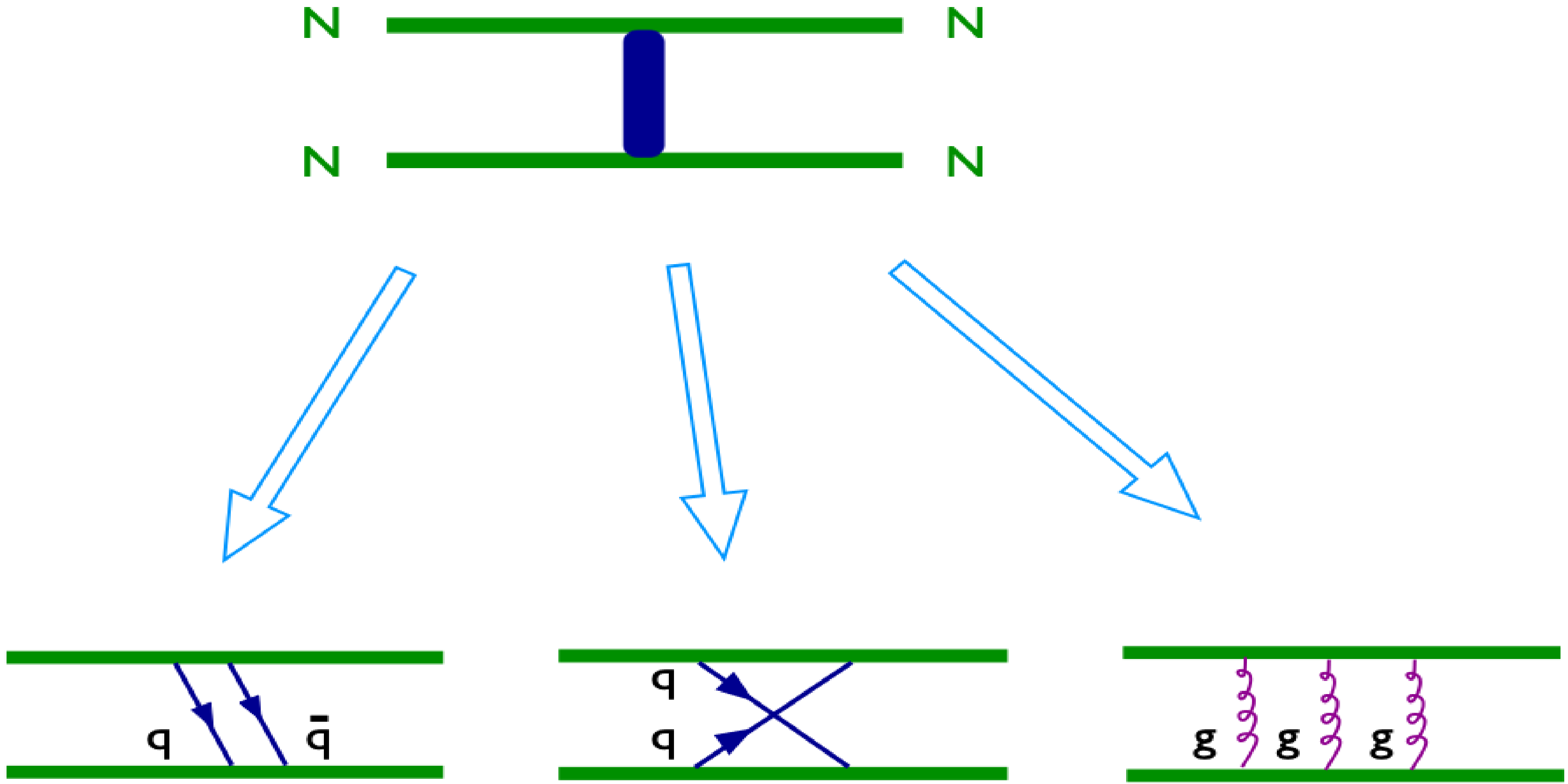
Max Proton Energy 33 GEV

Meson-baryon reactions	
1	$\pi^+ p \to p\pi^+$
2	$\pi^- p \to p\pi^-$
3	$K^+ p \to pK^+$
4	$K^- p \to pK^-$
5	$\pi^+ p \to p\rho^+$
6	$\pi^- p \to p\rho^-$
7	$K^+ p \to pK^{*+}$
8	$K^- p \to pK^{*-}$
9	$K^- p \to \pi^- \Sigma^+$
10	$K^- p \to \pi^+ \Sigma^-$
11	$K^- p \to \Lambda \pi^0$
12	$\pi^- p \to \Lambda K^0$
13	$\pi^+ p \to \pi^+ \Delta^+$
14	$\pi^- p \to \pi^- \Delta^+$
15	$\pi^- p \to \pi^+ \Delta^-$
16	$K^+ p \to K^+ \Delta^+$
Baryon-baryon reactions	
17	$pp \to pp$
18	$\bar{p}p \to p\bar{p}$
19	$\bar{p}p \to \pi^+\pi^-$
20	$\bar{p}p \to K^+K^-$

PRD, 49, 1994

- First Color Transparency Measurements

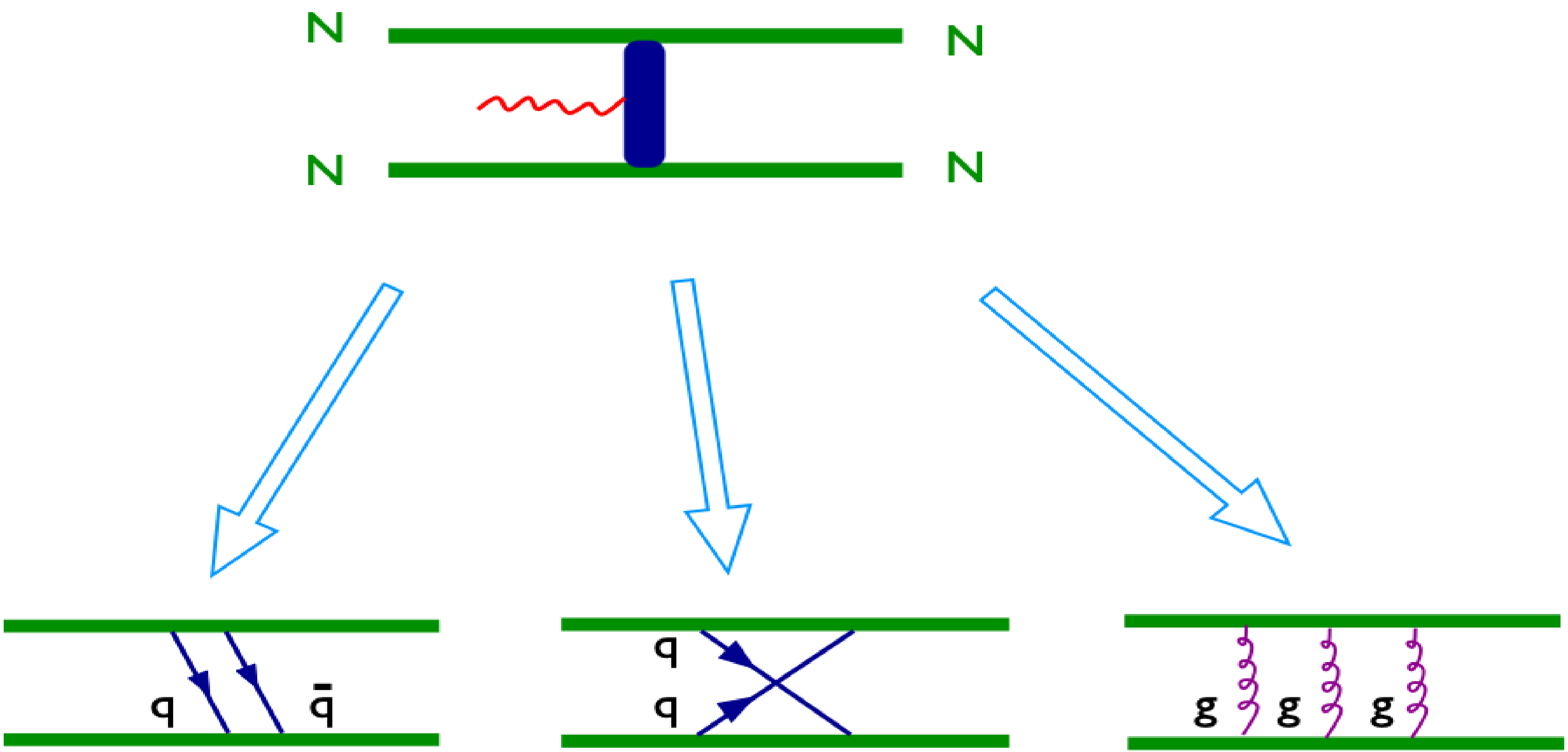
A.S Caroll et al, PRL, 1988



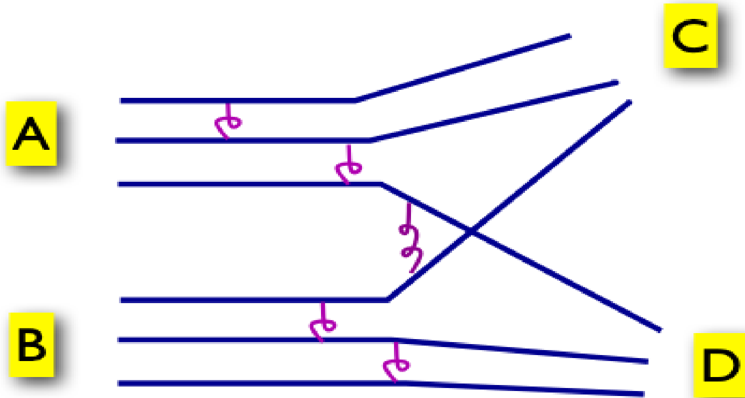
-Can be Studied in Hard Exclusive NN Scattering Reactions

-Last Experiments were done at early 90's at AGS, BNL

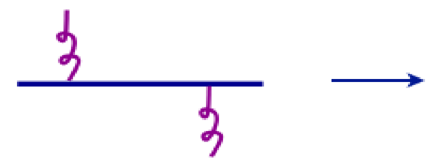
- High Energy Break up of two nucleons in Nuclei



Consider A+B→C + D



$$f(\frac{t}{s})$$



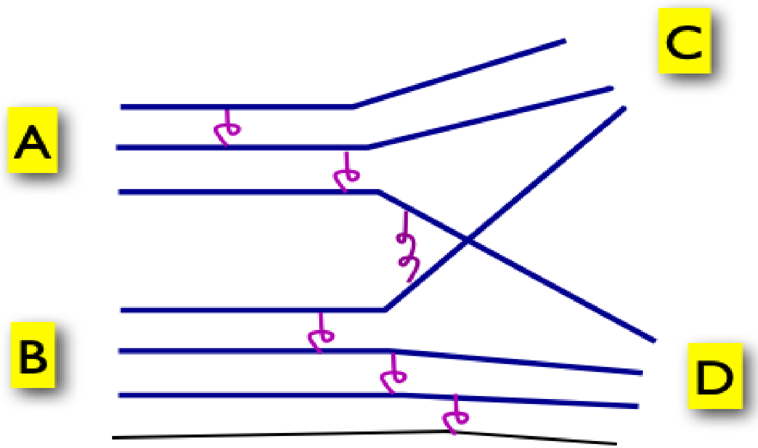
$$\frac{1}{s}$$

$$A \sim F(\frac{t}{s}) \frac{1}{s^{\frac{n_A+n_B+n_C+n_D}{2}-2}}$$

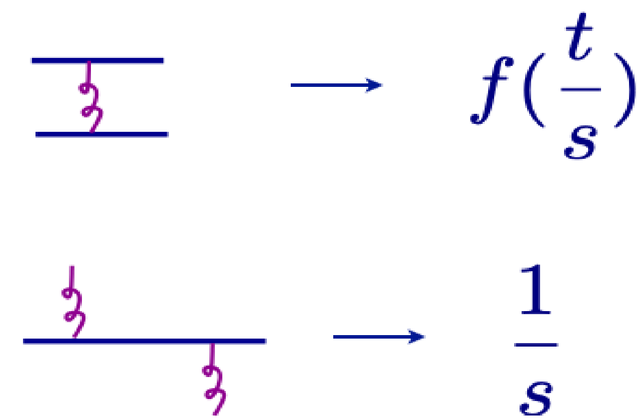
Brodsky, Farrar 1975
Matveev, Muradyan, Takhvelidze, 1975

$$\frac{d\sigma}{dt} \approx \frac{|A|^2}{s^2} = F^2(\frac{t}{s}) \frac{1}{s^{n_A+n_B+n_C+n_D-2}}$$

Consider A+B→C + D



additional $\frac{1}{s}$

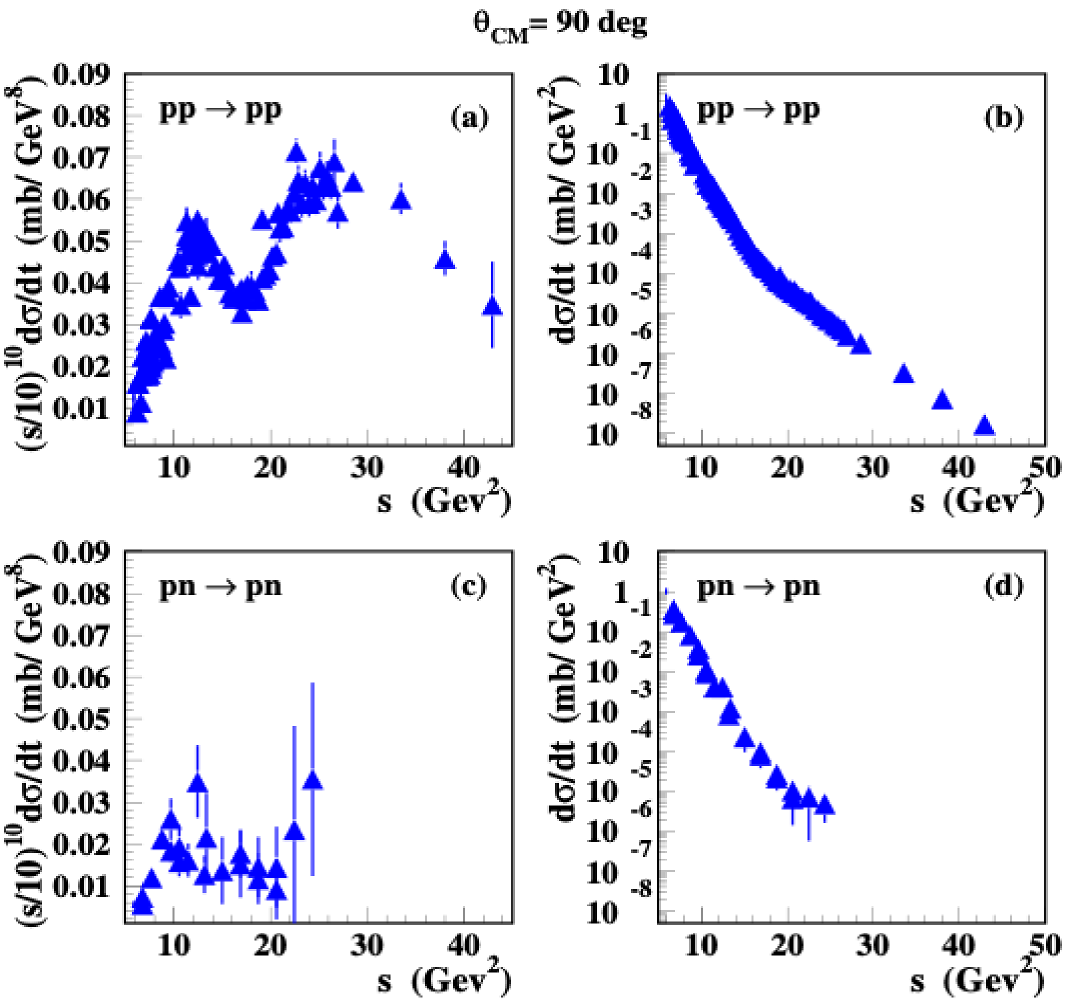


$$A \sim F(\frac{t}{s}) \frac{1}{s^{\frac{n_A+n_B+n_C+n_D}{2}-2}}$$

Brodsky, Farrar 1975
Matveev, Muradyan, Takhvelidze, 1975

$$\frac{d\sigma}{dt} \approx \frac{|A|^2}{s^2} = F^2(\frac{t}{s}) \frac{1}{s^{n_A+n_B+n_C+n_D-2}}$$

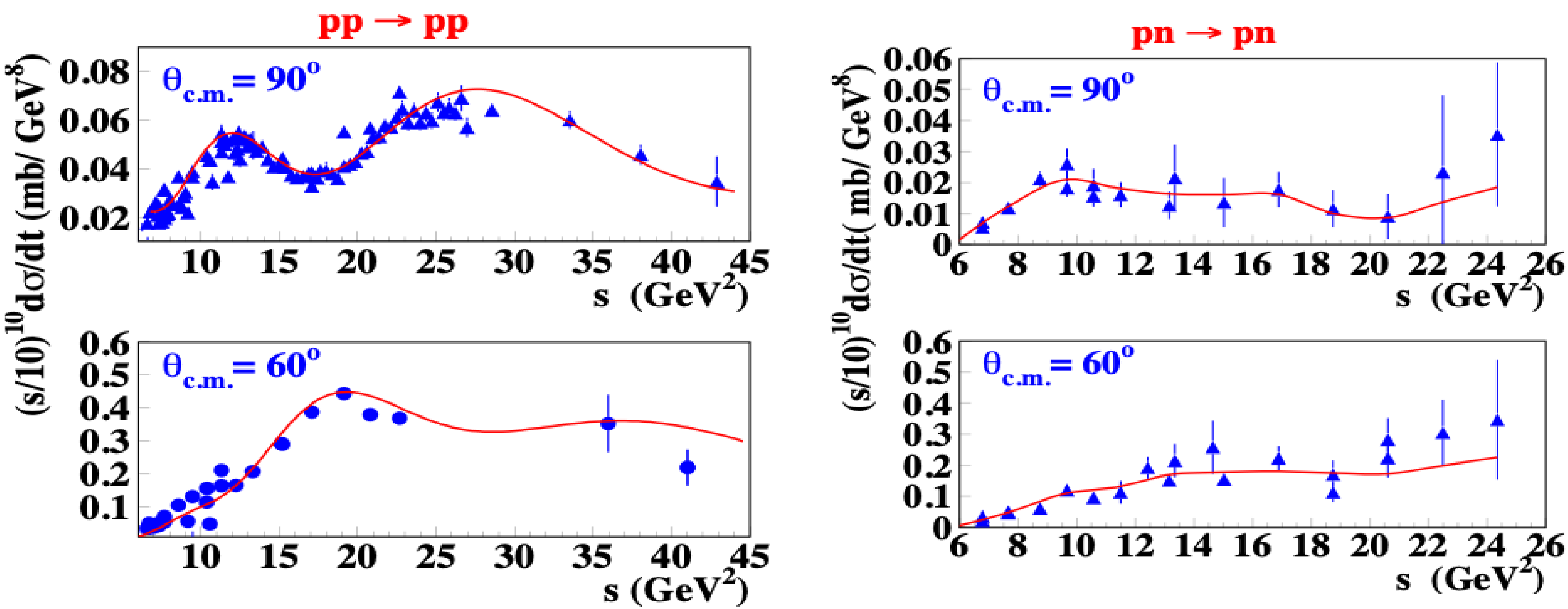
Hard Elastic NN Scattering



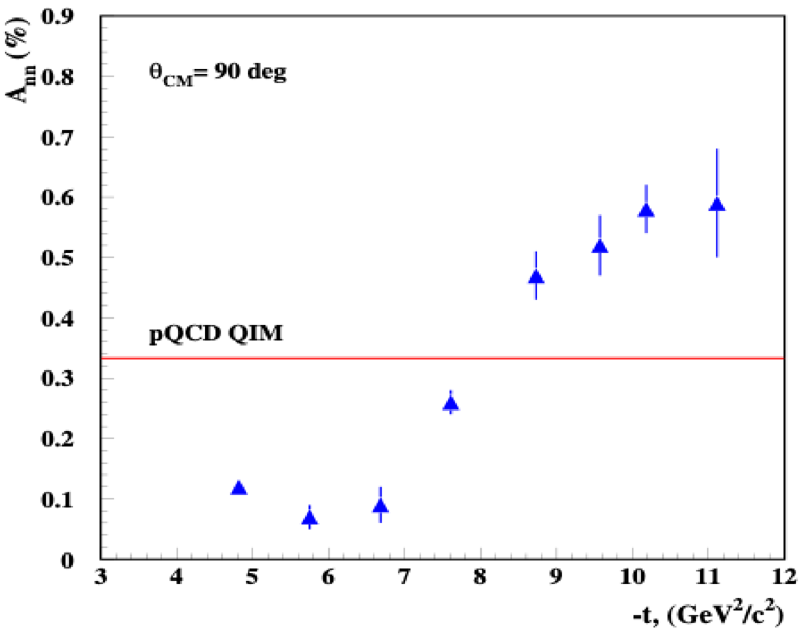
$$\frac{d\sigma^{ab\to cd}}{dt} = s^{-(n_a+n_b+n_c+n_d-2)}F(\theta_{cm})$$

$$\frac{d\sigma^{NN}}{dt} = s^{-10}F(\theta_{cm})$$

- Oscillatory Energy Dependence of Hard Elastic NN Scattering



- Anomalous Polarization Asymmetries in Hard pp Scattering

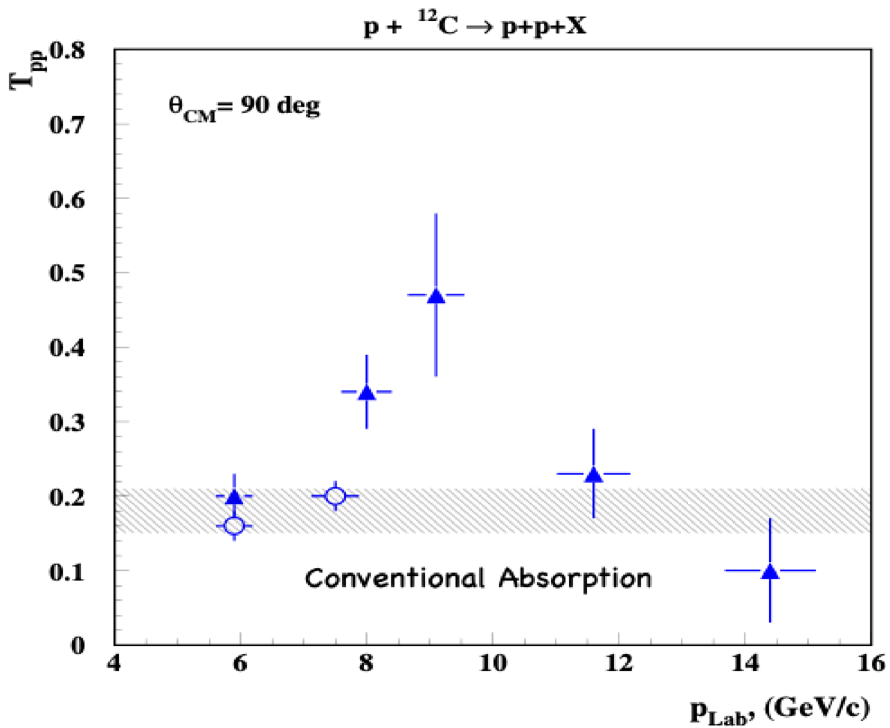


$$p_{lab} = 11.75 \text{ GeV/c}$$

$$\sigma_{\uparrow\uparrow} \approx 4\sigma_{\uparrow\downarrow}$$

Crabb et al PRL 1978,
Crosbie et al, PRD 1981

- Color Transparency in Hard pA Scattering

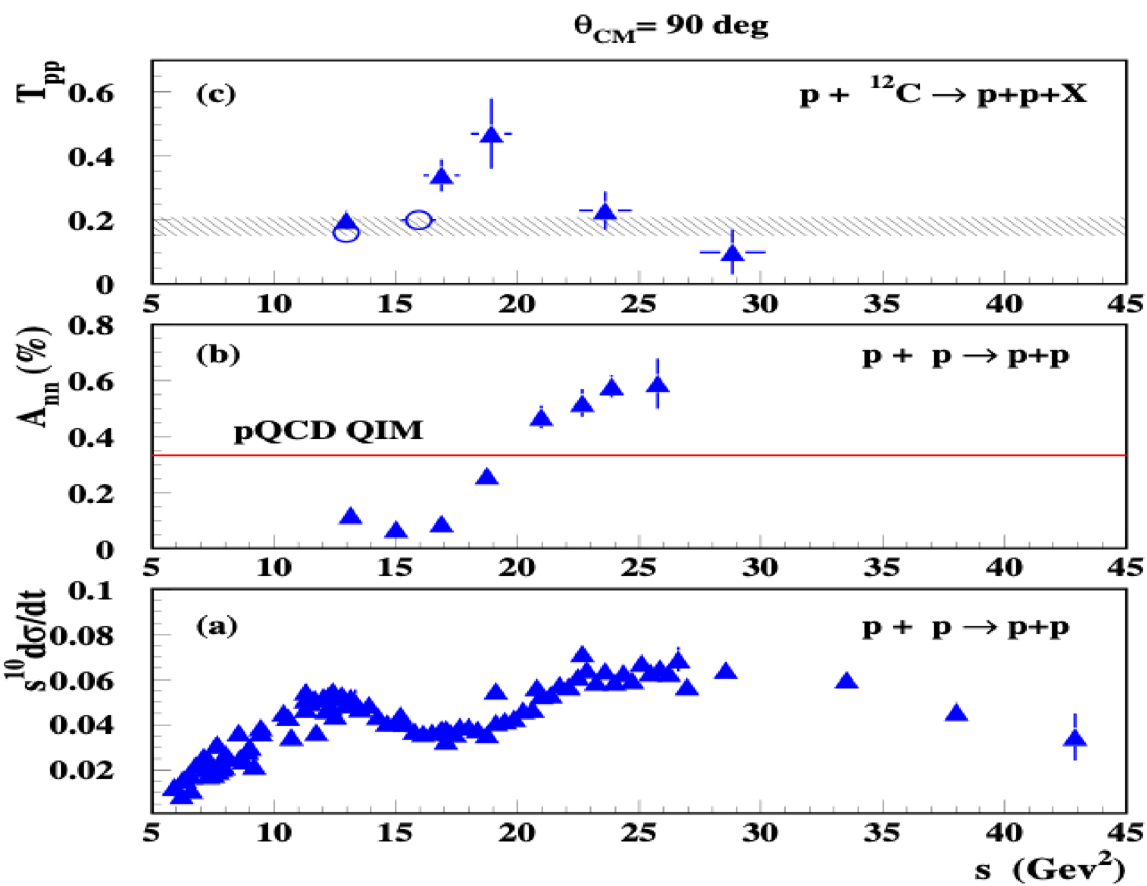


$$p + A \rightarrow p + p + X$$

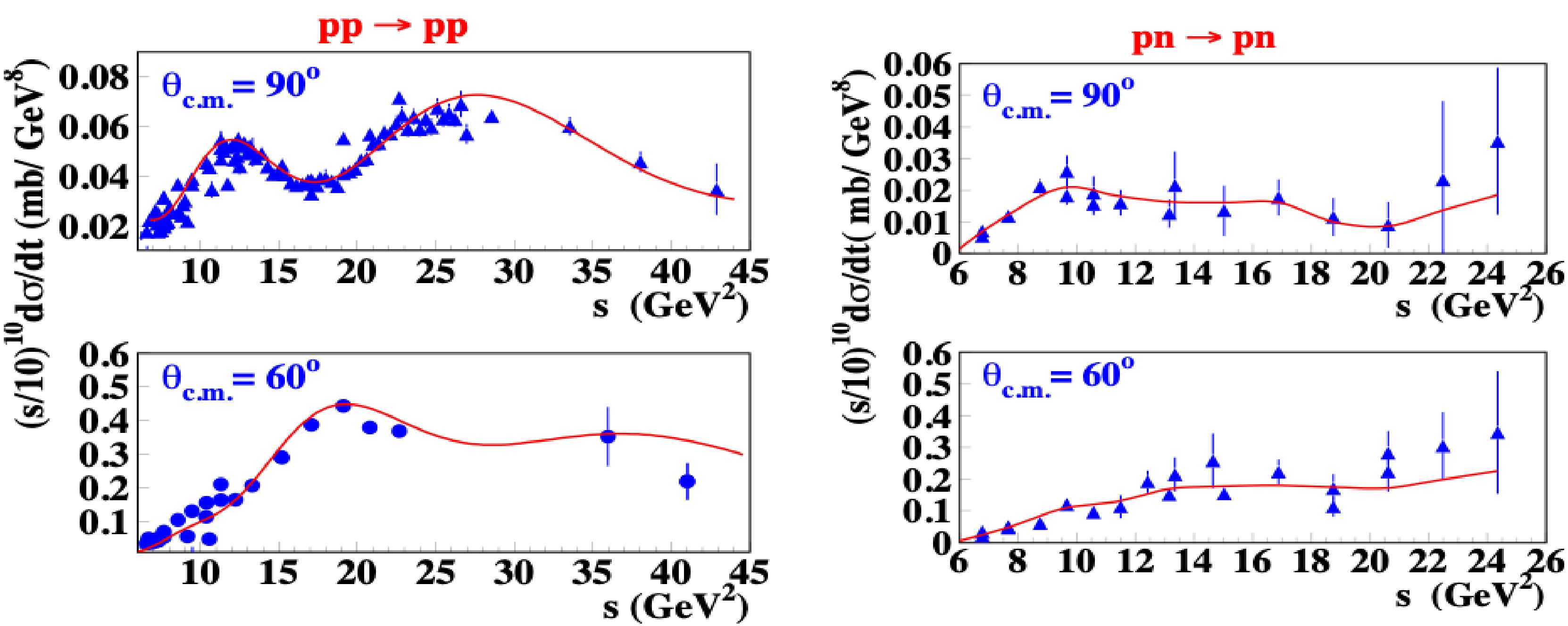
$$p + p_{bound} \rightarrow p + p \quad at \quad \theta_{cm} = 90^0$$

Mardor et al, PRL 1998
Aclander et al PRC 2004

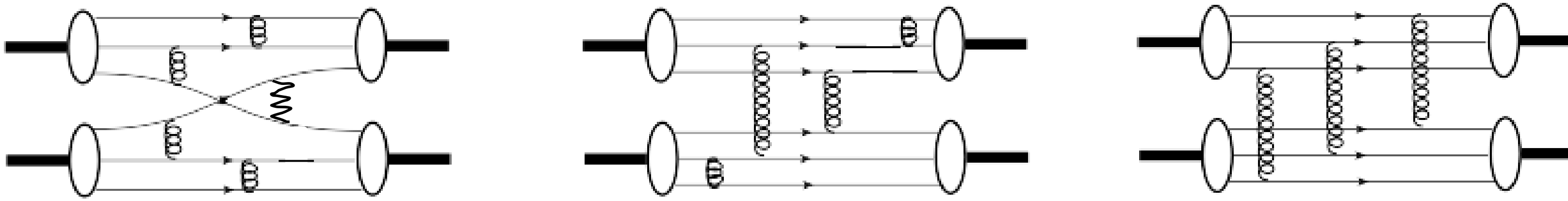
- Oscillations Superimposed



- Oscillatory Energy Dependence of Hard Elastic NN Scattering

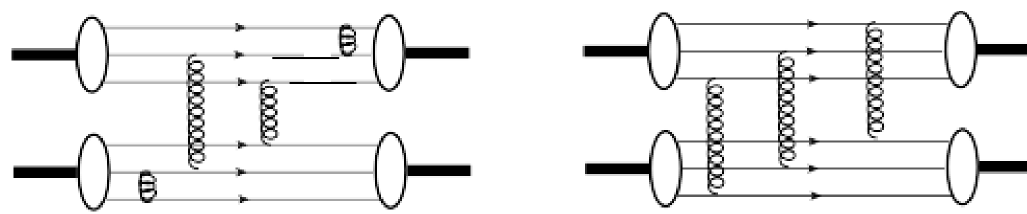


pp -> pp



(a) (b) (c)

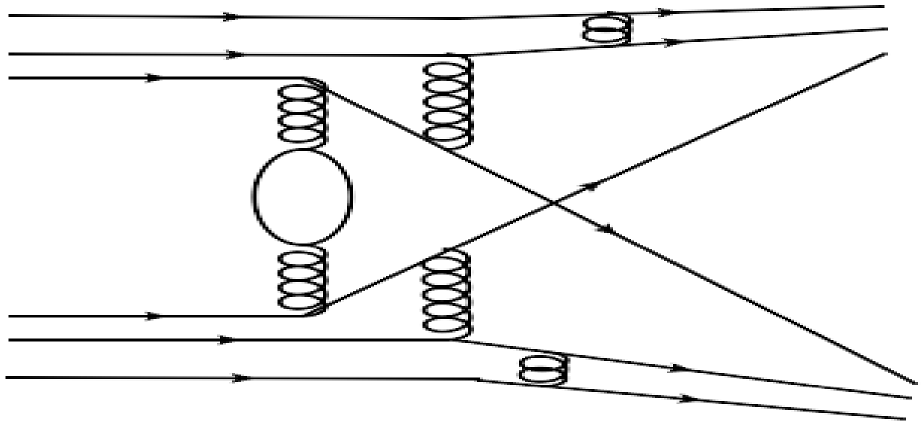
$p\bar{p}$ -> $p\bar{p}$



(b) (c)

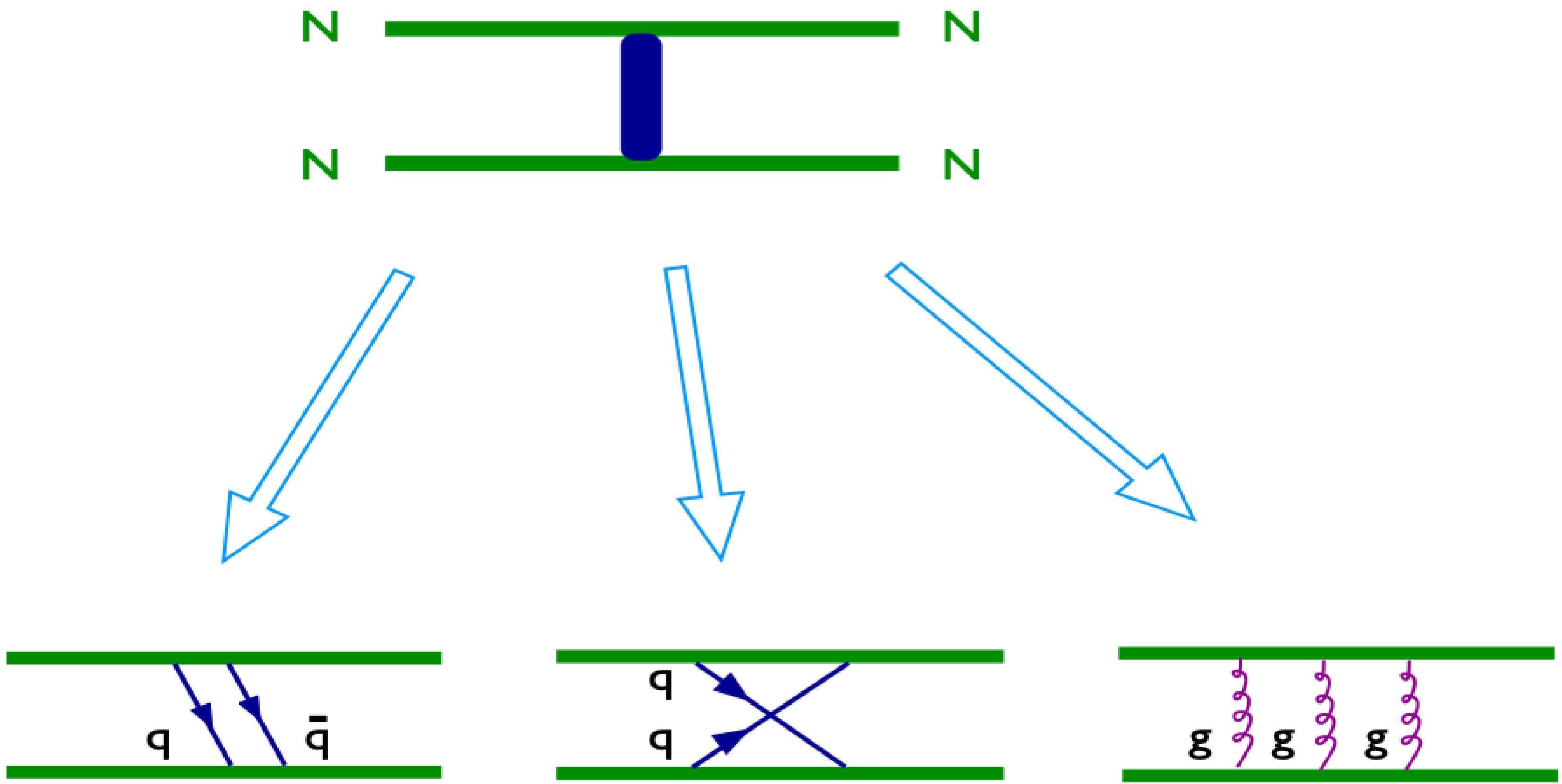
$$\frac{\sigma_{\bar{p}p}}{\sigma_{pp}} \approx \frac{1}{40}$$ at 90^0 CM

$$\frac{\sigma_{\bar{p}p}}{\sigma_{pp}} \approx 1.7$$ at 0^0



Brodsky, De Teramond, PRL 1988

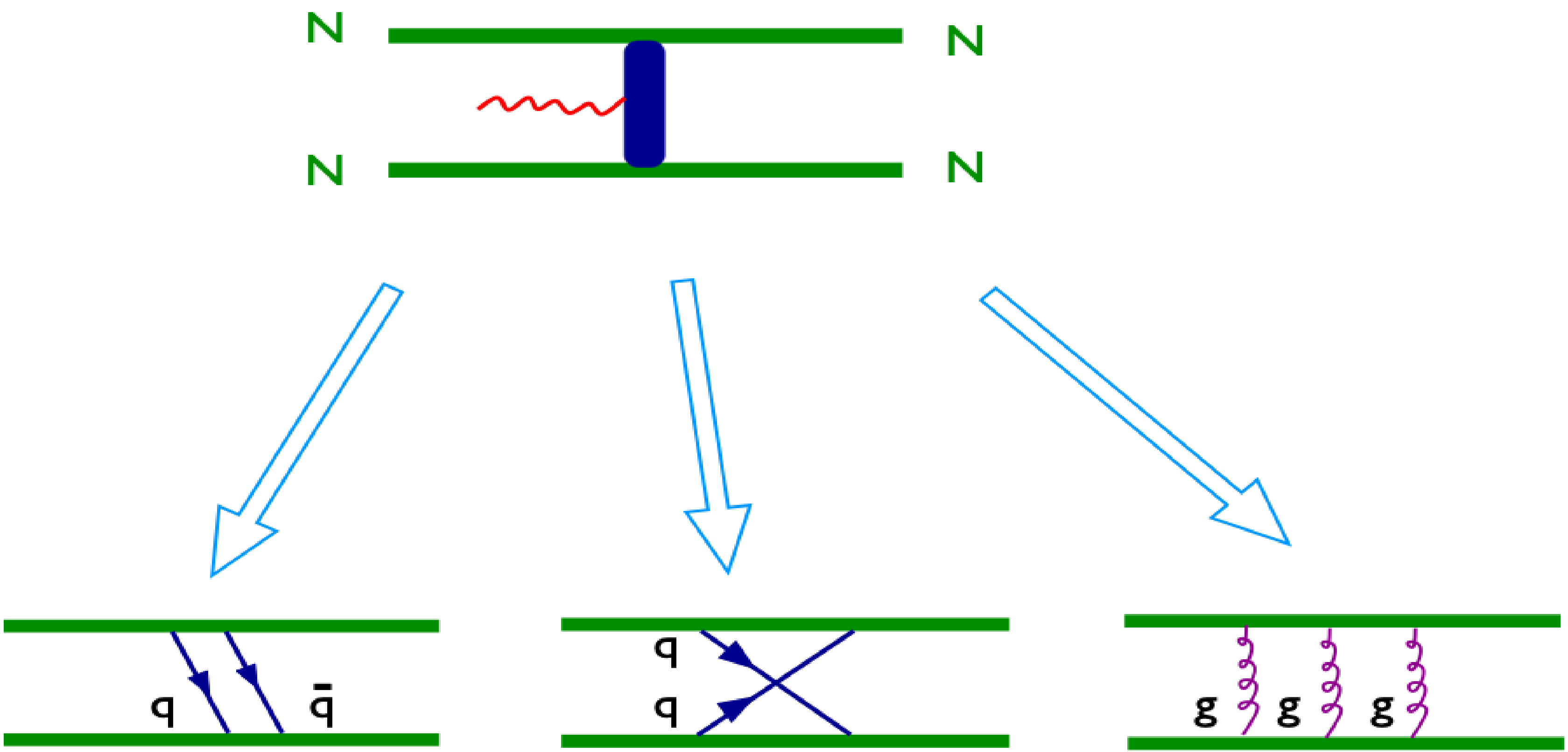
Interpreted in terms of two J=L=S=1, B=2 resonance structure
Associated with the strange- and charmed – particle production at thresholds



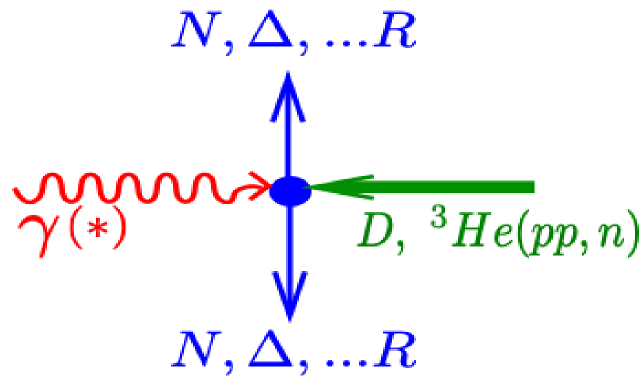
-Can be Studied in Hard Exclusive NN Scattering Reactions

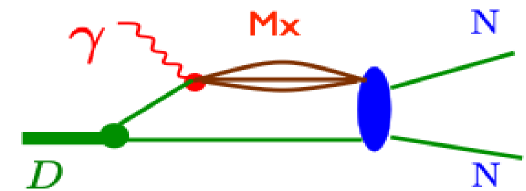
-Last Experiments were done at early 90's at AGS, BNL

- High Energy Break up of two nucleons in Nuclei



- **Large CM angle disintegration of nuclei:**





$$s = (k_\gamma + p_d)^2 = 2M_d E_\gamma + M_d^2$$

Brodsky, Chertock, 1976

Holt, 1990

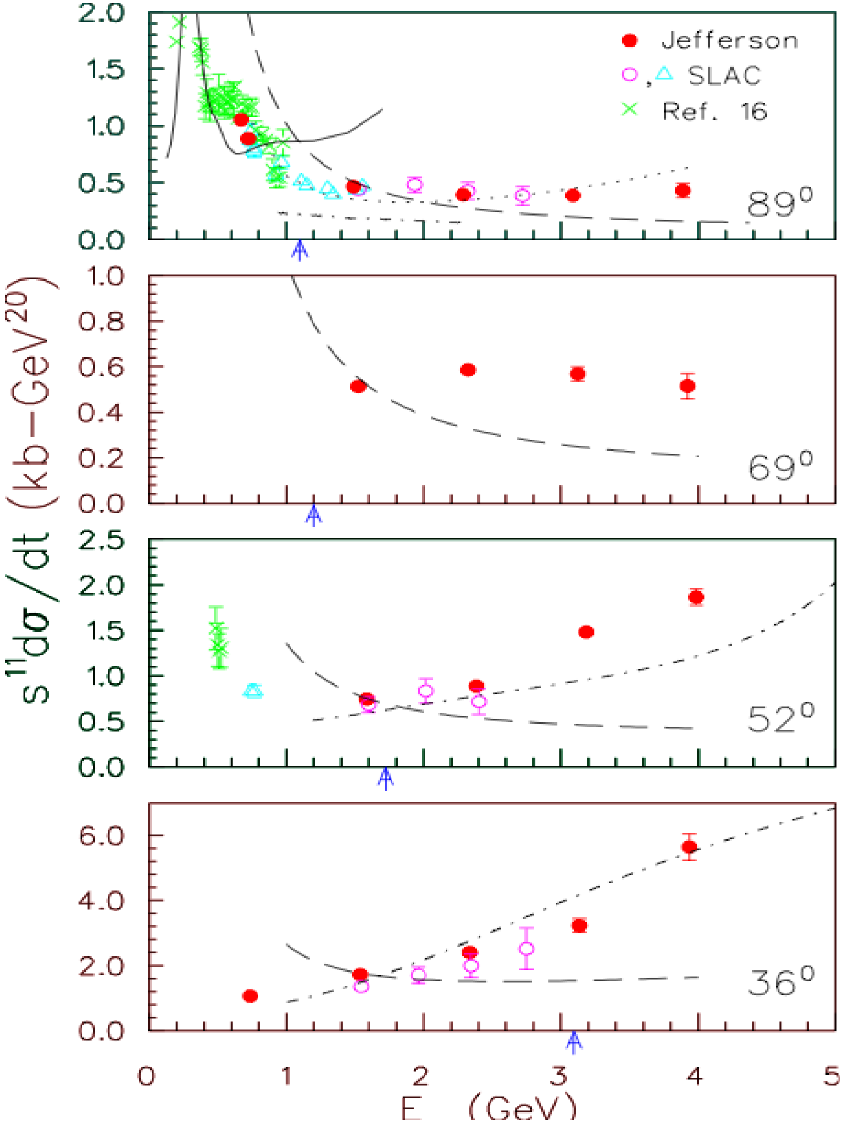
Gilman, Gross, 2002

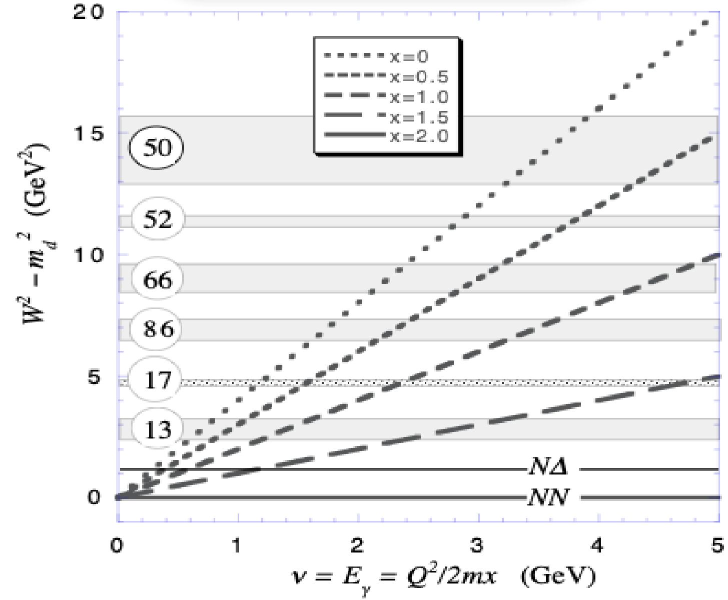
$$t = (k_\gamma - p_N)^2 = [cos\theta_{cm} - 1]\frac{s - M_d^2}{2}$$

$$E_\gamma = 2\ \mathrm{GeV},\ s = 12\ \mathrm{GeV}^2,\ t\,|_{90^0} \approx -4\ \mathrm{GeV}^2,\ M_x = 2\ \mathrm{GeV}$$

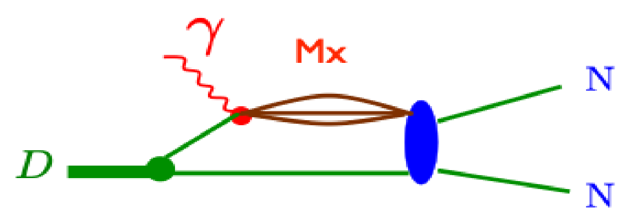
$$E_\gamma = 12\ \mathrm{GeV},\ s = 41\ \mathrm{GeV}^2,\ t\,|_{90^0} \approx -18.7\ \mathrm{GeV}^2,\ M_x = 4.4\ \mathrm{GeV}$$

$\gamma d \rightarrow pn$

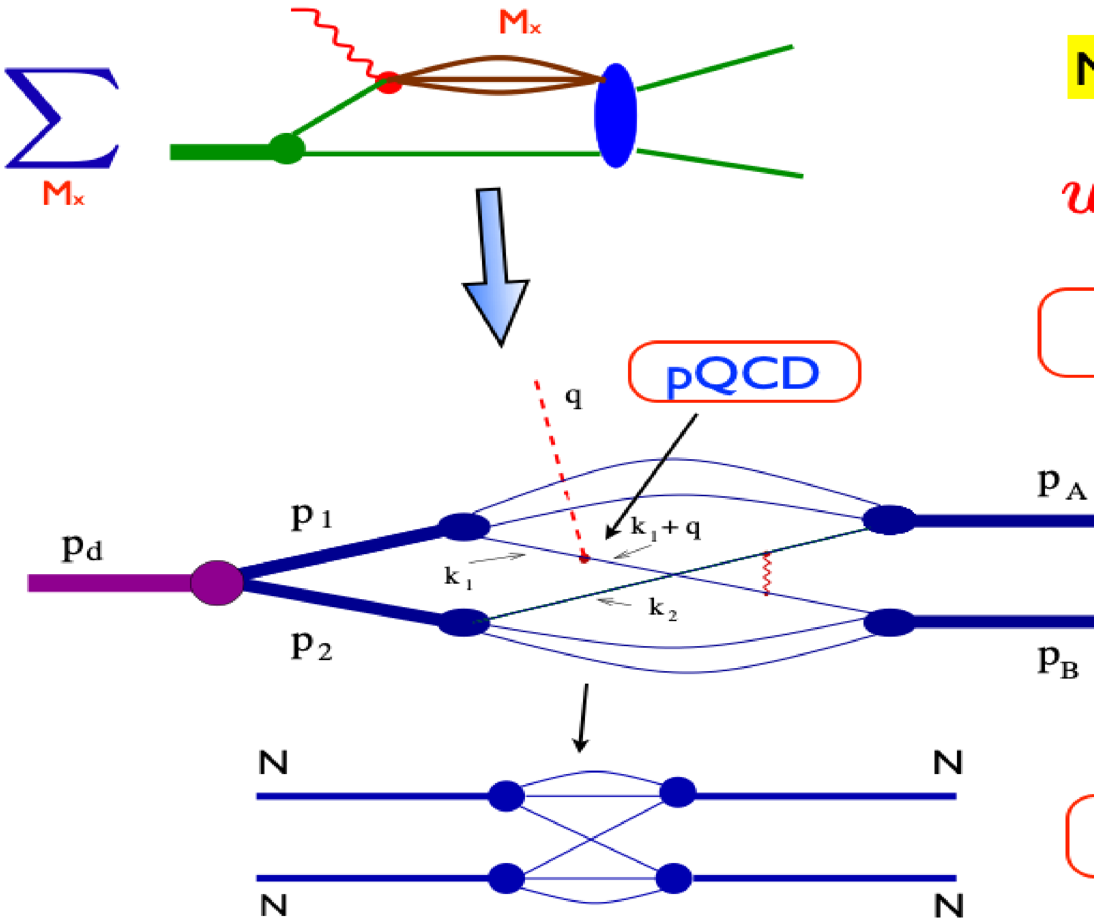




Gilman, Gross, 2002



Hard Rescattering Mechanism

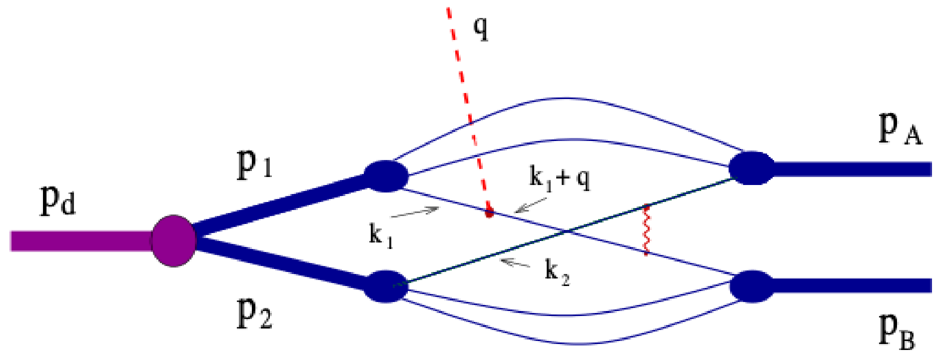


Mmax=w > 2 GeV

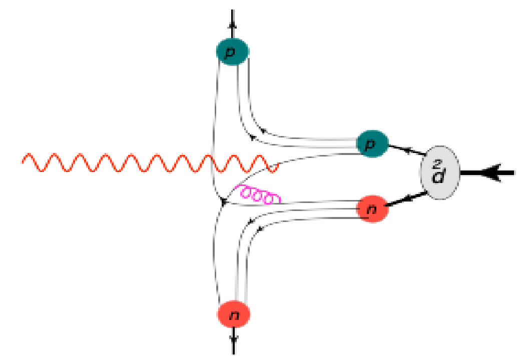
$$w \sim \sqrt{2E_\gamma m_N}$$

$$E_\gamma \geq 2.5 \text{ GeV}$$

NN -amplitude



Frankfurt, Miller, MS, Strikman
PRL 2000



$$T = -\sum_{e_q} \int \left(\frac{\psi_N^\dagger(x_2', p_{B\perp}, k_{2\perp})}{x_2'} \bar{u}(p_B - p_2 + k_2) \; [-igT_c^F \gamma^\nu] \right.$$

$$\left. \frac{u(k_1+q)\bar{u}(k_1+q)}{(k_1+q)^2 - m_q^2 + i\epsilon} \; [-ie_q \epsilon^\perp \cdot \gamma^\perp] \; u(k_1) \frac{\psi_N(x_1, p_{1\perp}, k_{1\perp})}{x_1} \right)$$

$$\left\{ \frac{\psi_N^\dagger(x_1', p_{A\perp}, k_{1\perp})}{x_1'} \bar{u}(p_A - p_1 + k_1) \; [-igT_c^F \gamma_\mu] \; u(k_2) \frac{\psi_N(x_2, p_{2\perp}, k_{2\perp})}{x_2} \right\}$$

$$G^{\mu\nu} \frac{\Psi_d(\alpha, p_\perp)}{1-\alpha} \frac{dx_1}{1-x_1} \frac{d^2 k_{1\perp}}{2(2\pi)^3} \frac{dx_2}{1-x_2} \frac{d^2 k_{2\perp}}{2(2\pi)^3} \frac{d\alpha}{\alpha} \frac{d^2 p_\perp}{2(2\pi)^3}, \qquad ($$

We use the reference frame where
$p_d = (p_{d0}, p_{dz}, p_\perp) \equiv (\frac{\sqrt{s'}}{2} + \frac{M_d^2}{2\sqrt{s'}}, \frac{\sqrt{s'}}{2} - \frac{M_d^2}{2\sqrt{s'}}, 0)$,
with $s = (q + p_d)^2$, $s' \equiv s - M_D^2$,
and the photon four-momentum is $q = (\frac{\sqrt{s'}}{2}, -\frac{\sqrt{s'}}{2}, 0)$.

-The knocked-out quark propagator.

$$(k_1 + q)^2 - m_q^2 = x_1 s' \left[\left(1 + \frac{1}{s'} (M_d^2 - \frac{m_n^2 + p_\perp^2}{1-\alpha}) \right) \alpha - \frac{x_1 m_R^2 + k_\perp^2 + m_q^2(1-x_1)}{(1-x_1)x_1 s'} - \frac{p_\perp^2 - 2p_\perp k_{1\perp}}{x_1 s'} \right] \quad (1)$$

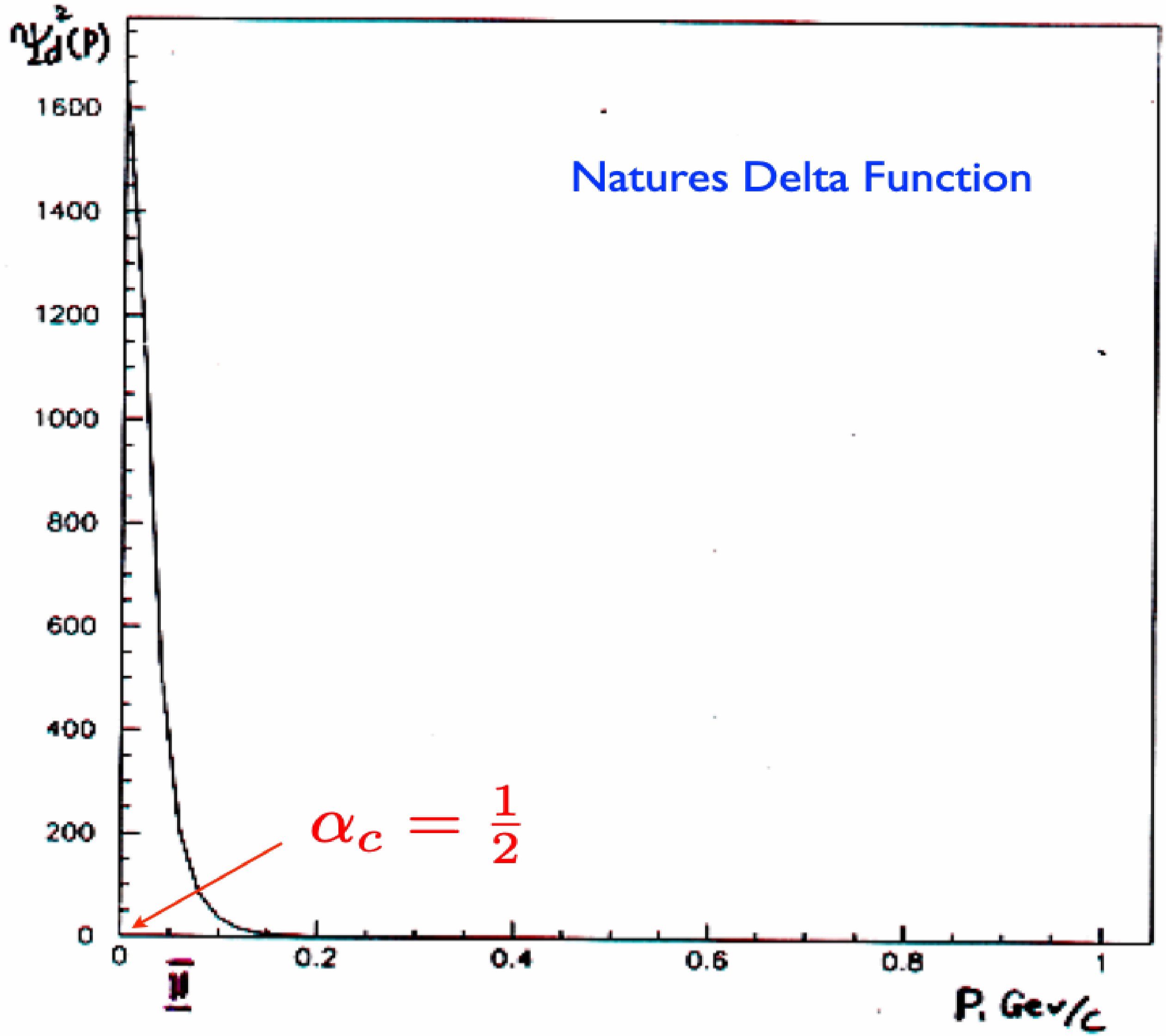
-We are concerned with momenta such that $p_\perp^2 \ll m_N^2 \ll s'$ and $\alpha \sim \frac{1}{2}$ so we neglect terms of order $p_\perp^2, m_N^2/s' \ll 1$ to obtain:

$$(k_1 + q)^2 - m_q^2 + i\epsilon \approx x_1 s' (\alpha - \alpha_c + i\epsilon),$$

$$\alpha_c \equiv \frac{x_1 m_R^2 + k_{1\perp}^2}{(1-x_1)x_1 \tilde{s}}. \quad \text{looking for } \alpha_c \sim \tfrac{1}{2} \text{ contribution} \quad (2)$$

Here $\tilde{s} \equiv s'(1 + \frac{M_d^2}{s'})$ and m_R is the recoil mass of the spectator quark-gluon system of the first nucleon.

- The integration over $k_{1\perp}$ in the region $k_{1\perp}^2 \sim \frac{(1-x_1)x_1\tilde{s}}{2} \gg x_1 m_R^2$ does provide $\alpha_c = \frac{1}{2}$.



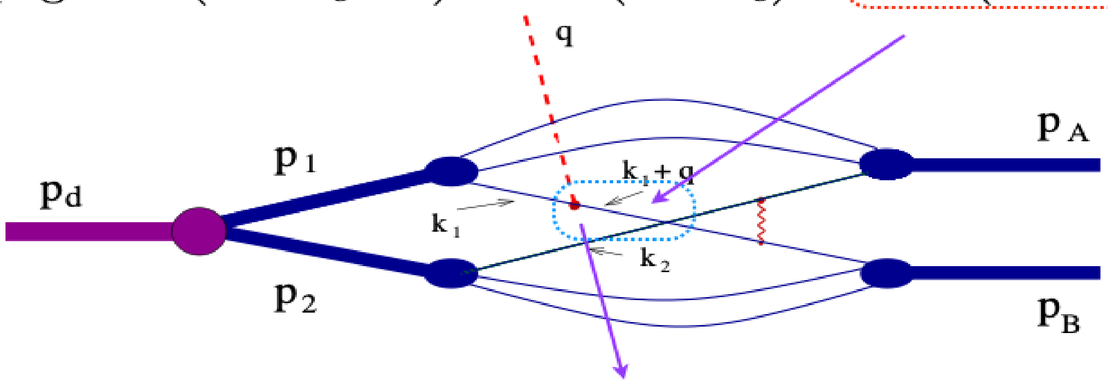
$\Psi_d^2(P)$
1600
1400
1200
1000
800
600
400
200
0
0
0.2
0.4
0.6
0.8
1
P, Gev/c
Natures Delta Function
$\alpha_c = \frac{1}{2}$

$$x_1 = (1 - \frac{m_R^2}{\alpha_c s'}) \to 1$$

- Keeping only the imaginary part of the quark propagator (eikonal approximation) leads to $\alpha = \alpha_c$ and corresponds to keeping the contribution from the soft component of the deuteron wave function.

Next we calculate the photon-quark hard scattering vertex– $\bar{u}(k_1+q)[\gamma_\perp]u(k_1)$ and use Eq. (2) to integrate over α

-By taking into account only second term in the decomposition of struck quark propagator: $(\alpha - \alpha_c + \epsilon)^{-1} \equiv \mathcal{P}(\alpha - \alpha_c)^{-1} - i\pi\delta(\alpha - \alpha_c)$:



$$\bar{u}^\beta(k_1+q)\left[-ie\epsilon^\mu(\lambda_\gamma)\gamma_\mu\right]u^\alpha(k_1) = ie_q 2\sqrt{2E_2E1}(-\lambda_\gamma)\delta^{\beta,\alpha}\delta^{\lambda_\gamma,\alpha}$$

$$\langle \lambda_A, \lambda_B \mid A \mid \lambda_\gamma, \lambda_D \rangle = \sum_{(\eta_1,\eta_2),(\xi_2),(\lambda_1,\lambda_2)} \int \frac{e_q\sqrt{2}}{x_1\sqrt{s'}} \sqrt{[1-(1-\alpha_c)x_1](1-\alpha_c)x_1}$$
$$\left\{ \frac{\psi_N^{\dagger\lambda_B,\eta_2}(p_B, x_2', k_{2\perp})}{x_2'} \bar{u}_{\eta_2}(p_B - k_2)[-igT_c^F\gamma^\nu]\cdot u_{\lambda_\gamma}(p_1 - k_1 + q) \frac{\psi_N^{\lambda_1,\lambda_\gamma}(p_1, x_1, k_{1\perp})}{x_1} \times \right.$$
$$\left. \frac{\psi_N^{\dagger\lambda_A,\eta_1}(p_B, x_1', k_{1\perp})}{x_1'} \bar{u}_{\eta_1}(p_A - k_1)[-igT_c^F\gamma^\mu] u_{\xi_2}(p_2 - k_2) \frac{\psi_N^{\lambda_2,\xi_2}(p_2, x_2, k_2)}{x_2} G^{\mu,\nu}(r) \frac{dx_1}{1-x_1} \frac{d^2k_{1\perp}}{2(2\pi)^3} \frac{dx_2}{1-x_2} \frac{d^2k_{2\perp}}{2(2\pi)^3} \right\}$$
$$\frac{\Psi^{\lambda_D,\lambda_1,\lambda_2}(\alpha, p_\perp)}{(1-\alpha)\alpha} \frac{d^2p_\perp}{4(2\pi)^2}. \qquad (1)$$

$$A_{pn}^{QIM} = \int \frac{\psi_N^\dagger(x_2', p_{B\perp}, k_{2\perp})}{x_2'} \bar{u}(p_B - p_2 + k_2)\left[-igT_c^F\gamma^\nu\right] u(k_1 + q) \frac{\psi_N(x_1, p_{1\perp}, k_{1\perp})}{x_1}$$
$$\frac{\psi_N^\dagger(x_1', p_{F\perp}, k_{1\perp})}{x_1'} \bar{u}(p_A - p_1 + k_1)\left[-igT_c^F\gamma_\mu\right] u(k_2) \frac{\psi_N(x_2, p_{2\perp}, k_{2\perp})}{x_2} \cdot G^{\mu\nu}$$
$$\times \frac{dx_1}{1-x_1} \frac{d^2k_{1\perp}}{2(2\pi)^3} \frac{dx_2}{1-x_2} \frac{d^2k_{2\perp}}{2(2\pi)^3} \qquad (1)$$

Frankfurt, Miller, Sargsian, Strikman, Phys.Rev. Lett 2000

$$\langle \lambda_A, \lambda_B, | A_{Q_i} | \lambda_\gamma, \lambda_D \rangle = \sum_{(\eta_1,\eta_2),(\xi_2),(\lambda_1,\lambda_2)} \int \frac{eQ_i f(\theta_{cm})}{\sqrt{2s'}} \times$$

$$\langle \eta_2, \lambda_B | \langle \eta_1, \lambda_A | A^i_{QIM}(s, l^2) | \lambda_1, \lambda_\gamma \rangle | \lambda_2 \xi_2 \rangle \times \Psi^{\lambda_D,\lambda_1,\lambda_2}(\alpha_c, p_\perp) \frac{d^2 p_\perp}{(2\pi)^2} (1)$$

Notation used $| \lambda_{nucleon}, \lambda_{quark} \rangle$

Assuming $\lambda_1 = \lambda_\gamma$

Brodsky, Carlson, Lipkin Phys.Rev.D 1979
Farrar, Gottlieb, Sivers, Thomas Phys.Rev.D 1979

NN ⇨ NN

$$\langle a'b' | A^{NN}_{QIM} | ab \rangle = \frac{1}{2} \langle a'b' | \sum_{i\in a\ ,\ j\in b} [I_i I_j + \vec{\tau}_i \cdot \vec{\tau}_j] F_{i,j}(s,t) | ab \rangle$$

SU(6)

γ np ⇨ np

$$\langle a'b' | A^{Q}_{QIM} | ab \rangle \,|_{a,b\in D} = \frac{1}{2} \langle a'b' | \sum_{i\in a\ ,\ j\in b} [I_i I_j + \vec{\tau}_i \cdot \vec{\tau}_j](Q_i + Q_j) F_{i,j}(s,t) | ab \rangle = (Q_u + Q_d) \langle a'b' | A^{pn}_{QIM} | ab \rangle$$

$$(Q_u + Q_d) \langle a'b' | A^{pn}_{QIM} | ab \rangle = \frac{1}{3} \langle a'b' | A^{pn} | ab \rangle .$$

$$A^{pn}_{QIM} \approx A_{pn}$$

$$\langle p_{\lambda_A}, n_{\lambda_B} \mid A \mid \lambda_\gamma, \lambda_D \rangle = \sum_{\lambda_2} \frac{f(\theta_{cm})}{3\sqrt{2s'}} \times$$
$$(\langle p_{\lambda_A}, n_{\lambda_B} | A_{pn}(s, t_n) | p_{\lambda_\gamma}, n_{\lambda_2} \rangle - \langle p_{\lambda_A}, n_{\lambda_B} | A_{pn}(s, u_n) | n_{\lambda_\gamma} p_{\lambda_2} \rangle)$$
$$\int \Psi^{\lambda_D, \lambda_\gamma, \lambda_2}(\alpha_c, p_\perp) \frac{d^2 p_\perp}{(2\pi)^2} \qquad (1)$$

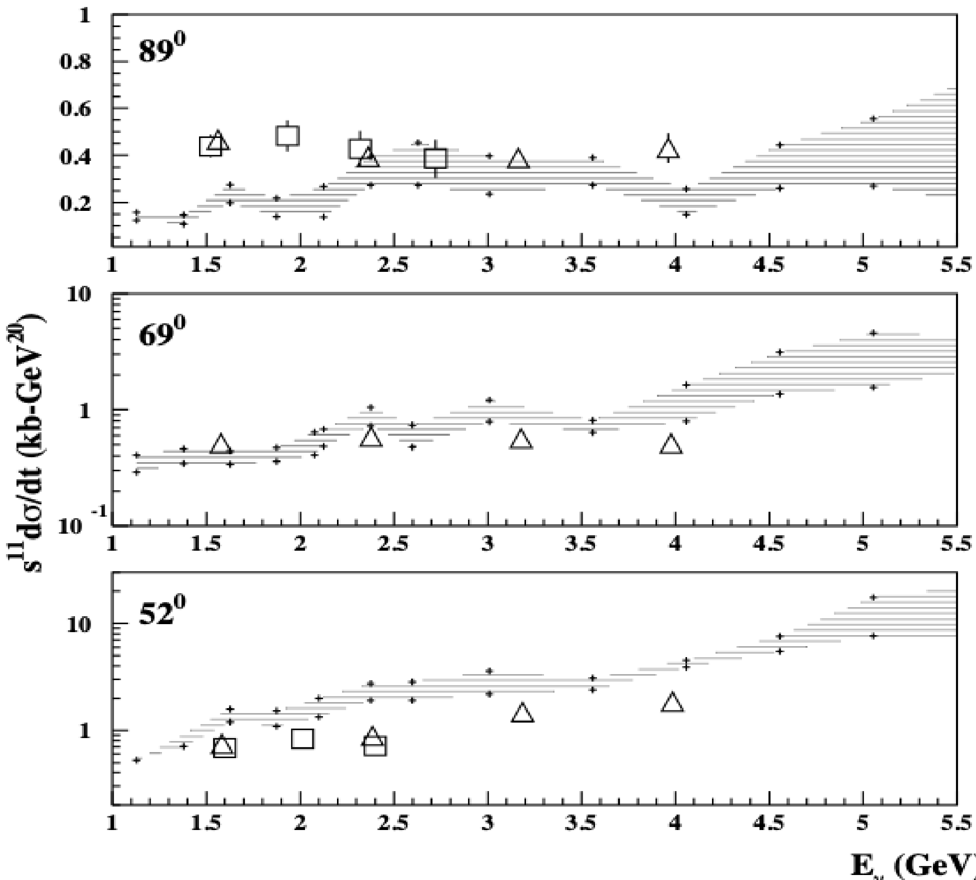
$$\Psi^{\lambda_D, \lambda_1 \lambda_2} = (2\pi)^{\frac{3}{2}} \Psi_{NR}^{J_D, \lambda_1, \lambda_2} \sqrt{m} = [u(k) + w(k)\sqrt{\tfrac{1}{8}} S_{12}] \xi_1^{\lambda_D, \lambda_1, \lambda_2}$$

$$\frac{d\sigma^{\gamma d \to pn}}{dt} = \frac{8\alpha}{9} \pi^4 \cdot \frac{1}{s'} C(\frac{\tilde{t}}{s}) \frac{d\sigma^{pn \to pn}(s, \tilde{t})}{dt} \left| \int \Psi_d^{NR}(p_z = 0, p_\perp) \sqrt{m_N} \frac{d^2 p_\perp}{(2\pi)^2} \right|^2,$$

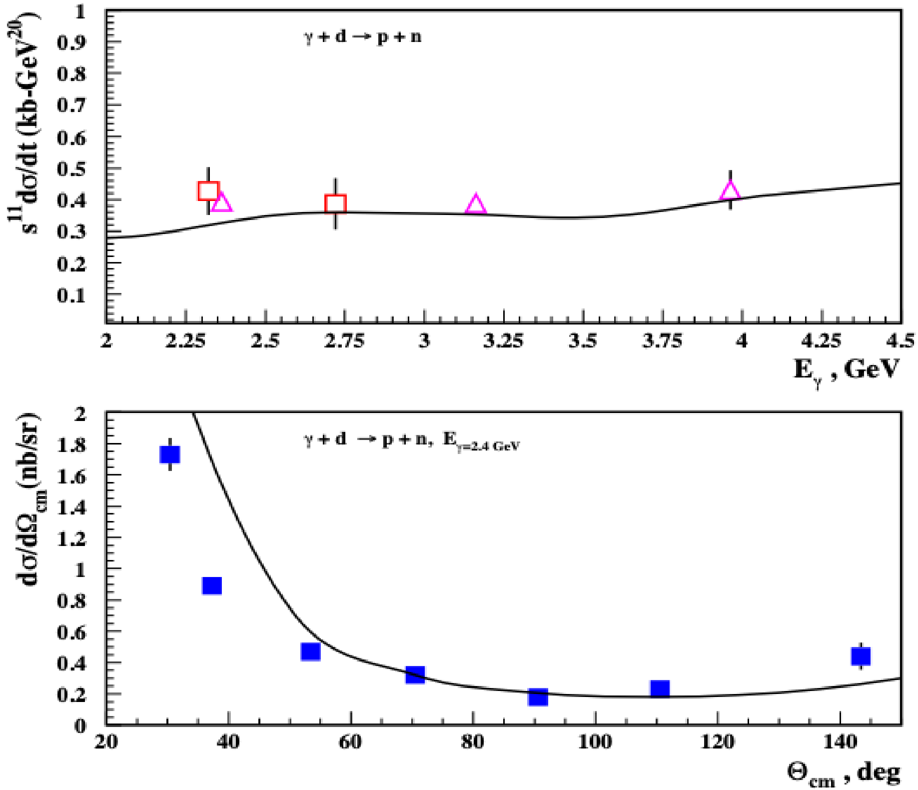
$$C(\tfrac{\tilde{t}}{s}) \mid_{\theta_{cm}=90} = 1$$

Frankfurt, Miller, M.S. Strikman
PRL 2000

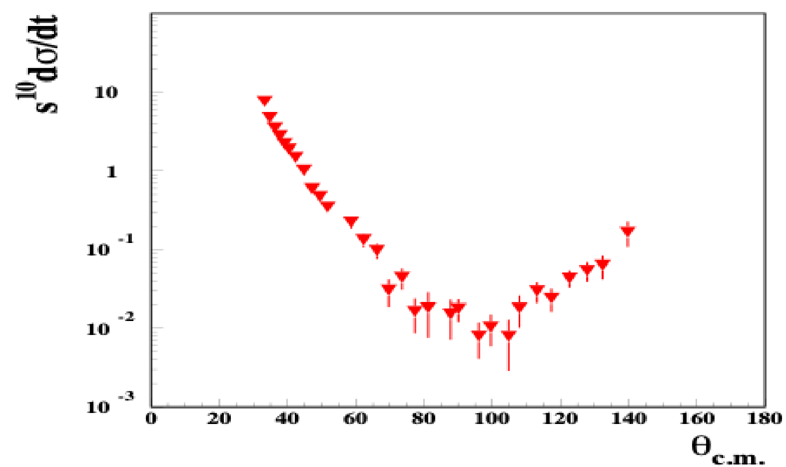
$$\frac{d\sigma^{\gamma d\to pn}}{dt} = \frac{8\alpha}{9}\pi^4 \cdot \frac{1}{s'} C(\frac{\tilde{t}}{s}) \frac{d\sigma^{pn\to pn}(s,\tilde{t})}{dt} \left| \int \Psi_d^{NR}(p_z=0,p_\perp)\sqrt{m_N}\frac{d^2p_\perp}{(2\pi)^2} \right|^2,$$



$\gamma + d \to p + n$



$pn \to pn$



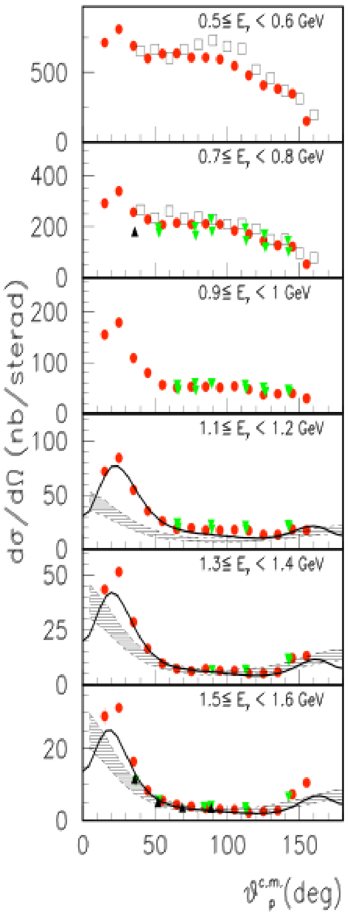


FIG. 7: (Color) Angular distributions of the deuteron photodisintegration cross section measured by the CLAS (full/red circles) in the incident photon energy range 0.50 – 1.70 GeV. Results from Mainz [26] (open squares, average of the measured values in the given photon energy intervals), SLAC [5, 6, 7] (full/green down-triangles), JLab Hall A [10] (full/blue squares) and Hall C [8, 9] (full/black up-triangles) are also shown. Error bars represent the statistical uncertainties only. The solid line and the hatched area represent the predictions of the QGS [18] and the HRM [27] models, respectively.

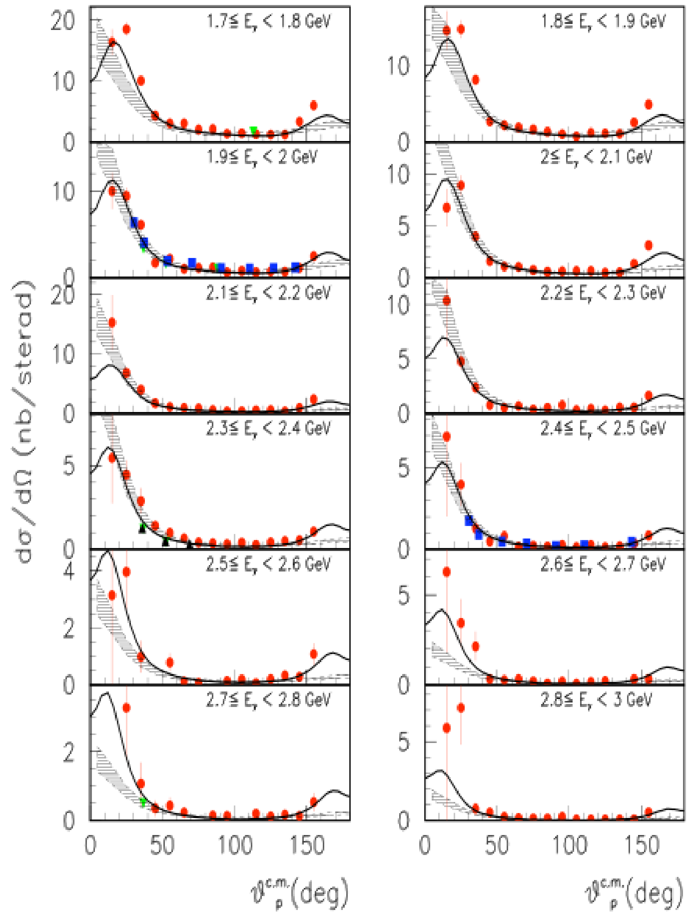


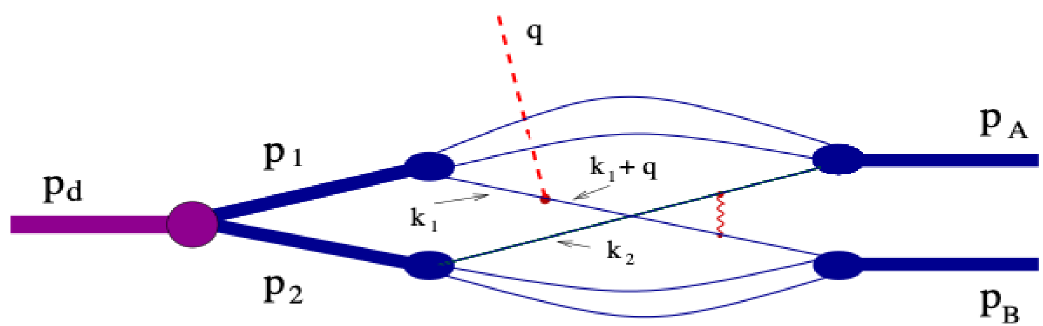
FIG. 8: (Color) Same as Fig. 7 for photon energies 1.7 – 3.0 GeV.

Specifics of Hard Rescattering Model

Helicity Selection Rule

- Photon selects nucleon in the nucleus with helicity = to its own

- Due to dominance of Helicity Conserving amplitudes in NN scattering, photon helicity will propogate to the helicty of one of the final nucleons.

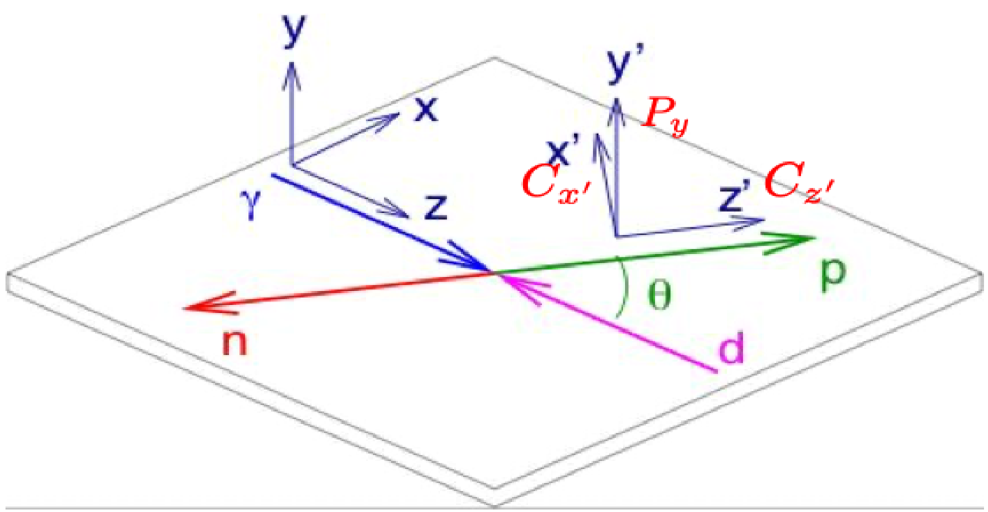


Polarization Observables

$$\langle p_{\lambda_A}, n_{\lambda_B} \mid A \mid \lambda_\gamma, \lambda_D \rangle = \sum_{\lambda_2} \frac{f(\theta_{cm})}{3\sqrt{2s'}} \times$$

$$\left(\langle p_{\lambda_A}, n_{\lambda_B} | A_{pn}(s, t_n) | p_{\lambda_\gamma}, n_{\lambda_2} \rangle - \langle p_{\lambda_A}, n_{\lambda_B} | A_{pn}(s, u_n) | n_{\lambda_\gamma} p_{\lambda_2} \rangle \right)$$

$$\int \Psi^{\lambda_D, \lambda_\gamma, \lambda_2}(\alpha_c, p_\perp) \frac{d^2 p_\perp}{(2\pi)^2}$$



Gilman, Gross, 2002

$$P_y = -\frac{2Im\left\{\phi_5^\dagger[2(\phi_1+\phi_2)+\phi_3-\phi_4]\right\}}{2|\phi_1|^2+2|\phi_2|^2+|\phi_3|^2+|\phi_4|^2+6|\phi_5|^2}$$

$$C_{x'} = \frac{2Re\left\{\phi_5^\dagger[2(\phi_1-\phi_2)+\phi_3+\phi_4]\right\}}{2|\phi_1|^2+2|\phi_2|^2+|\phi_3|^2+|\phi_4|^2+6|\phi_5|^2}$$

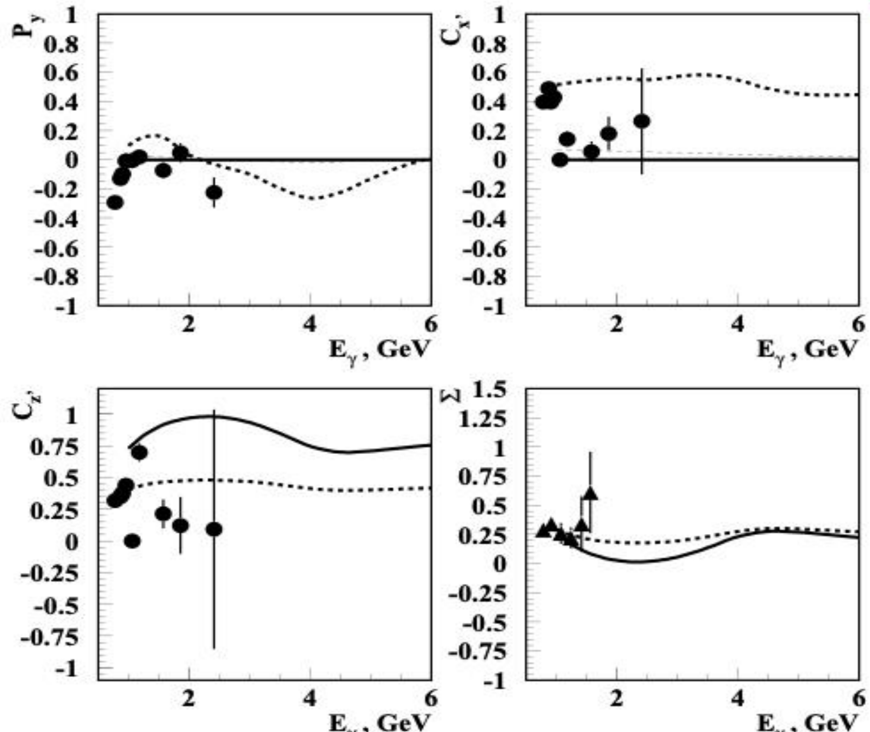
$$C_{z'} = \frac{2|\phi_1|^2-2|\phi_2|^2+|\phi_3|^2-|\phi_4|^2}{2|\phi_1|^2+2|\phi_2|^2+|\phi_3|^2+|\phi_4|^2+6|\phi_5|^2}$$

$$\Sigma = \frac{2Re\left[|\phi_5|^2-\phi_3^\dagger\phi_4\right]}{2|\phi_1|^2+2|\phi_2|^2+|\phi_3|^2+|\phi_4|^2+6|\phi_5|^2},$$

$$\begin{aligned}
\phi_1(s,t_n,u_n) &= \langle +,+ \mid A_{pn} \mid +,+ \rangle \\
\phi_2(s,t_n,u_n) &= \langle +,+ \mid A_{pn} \mid -,- \rangle \\
\phi_3(s,t_n,u_n) &= \langle +,- \mid A_{pn} \mid +,- \rangle \\
\phi_4(s,t_n,u_n) &= \langle +,- \mid A_{pn} \mid -,+ \rangle \\
\phi_5(s,t_n,u_n) &= \langle +,+ \mid A_{pn} \mid +,- \rangle. \qquad (1)
\end{aligned}$$

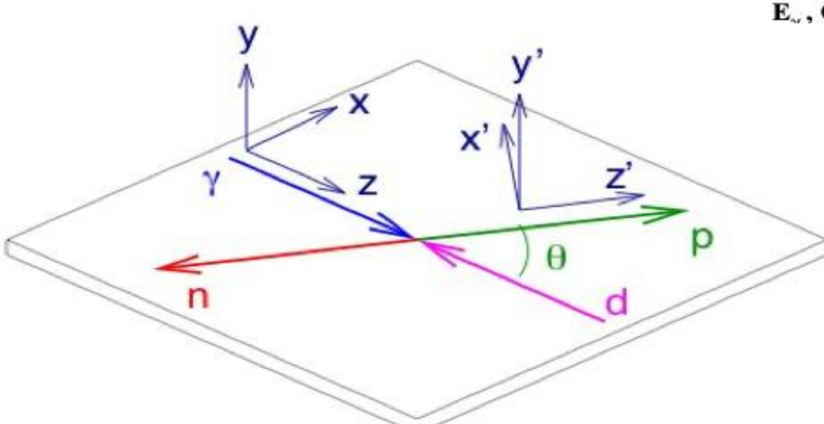
$$|\phi_1| \geq |\phi_3|, |\phi_4| > |\phi_5| > |\phi_2|.$$

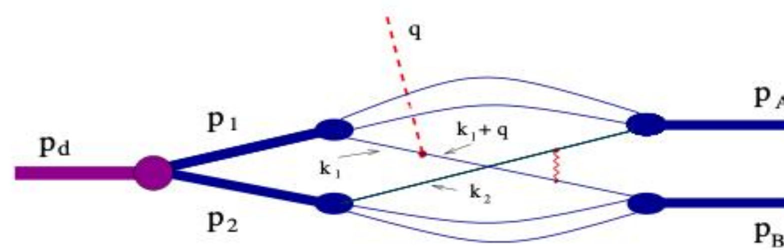
Sargsian, Phys. Lett. B 2004

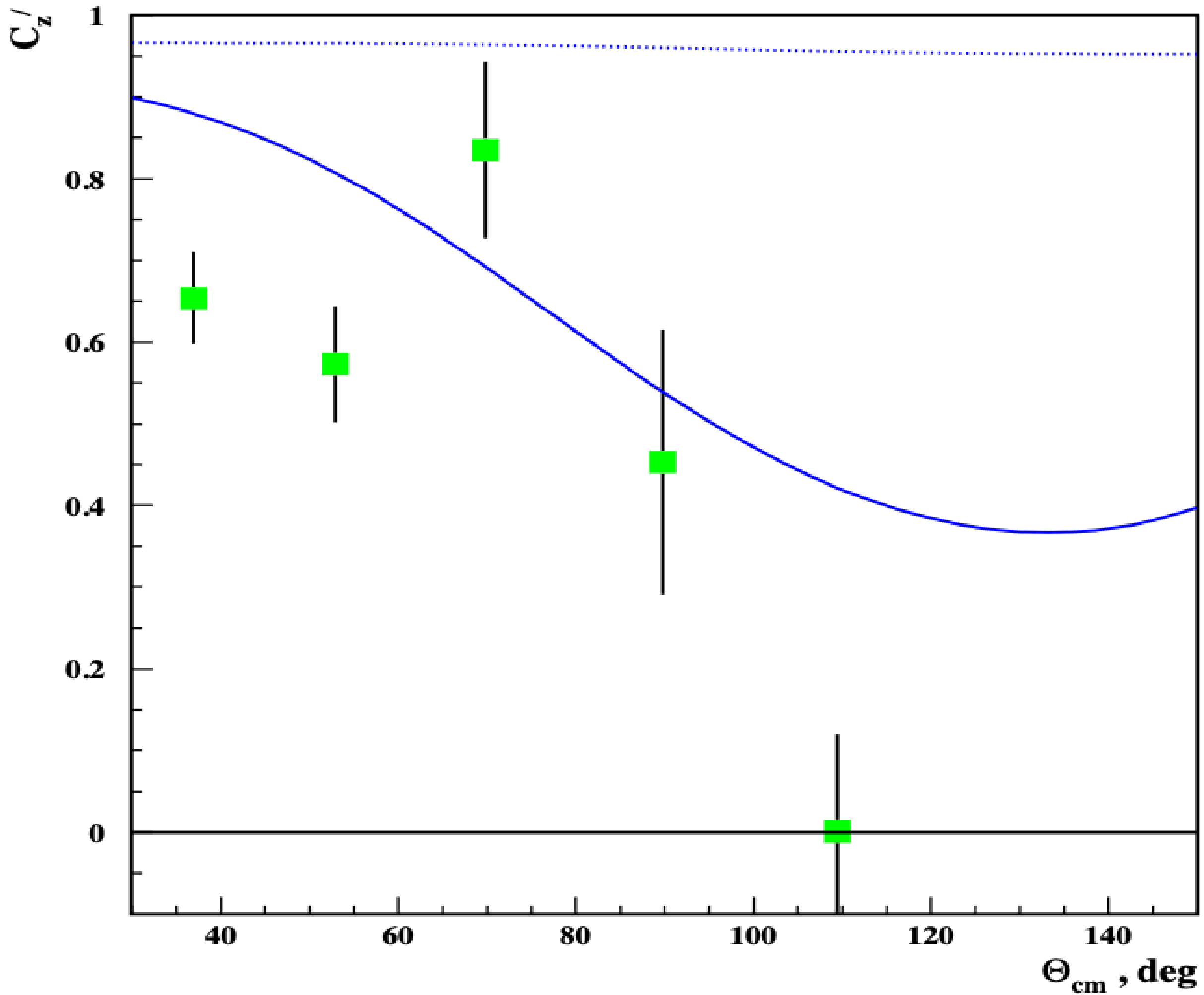


$$C_{z'} = 0.5 \div 1.0$$

Data, JLab 2002





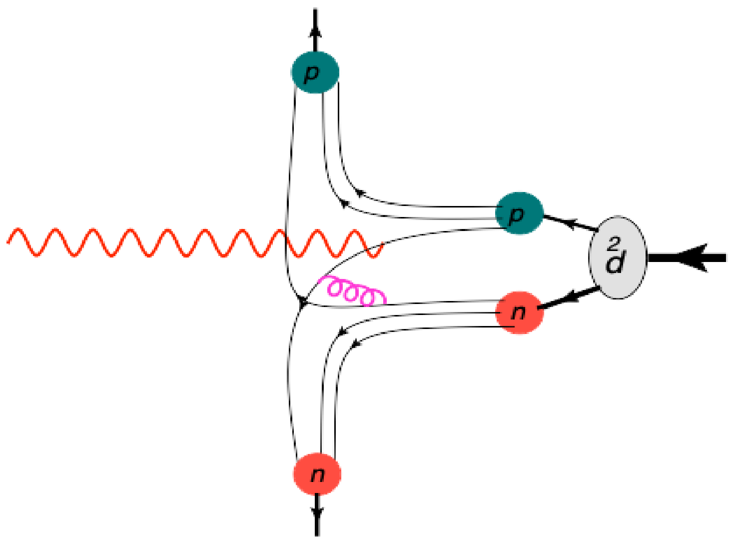


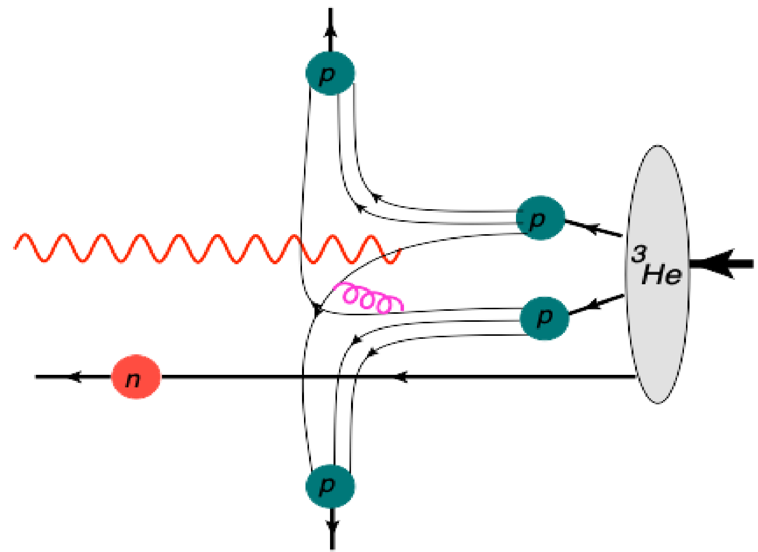
Jiang et al, PRL2007

Break up of pn from the deuteron

Break up of pp from Helium 3

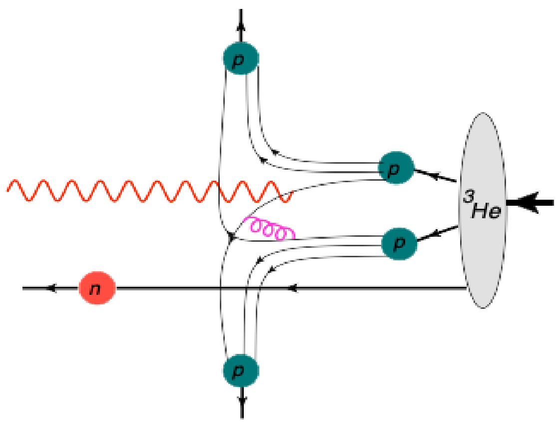
Brodsky, Frankfurt, Gilman, Hiller, Miller
Piasetzky, M.S., Strikman
Phys. Lett. B 2004

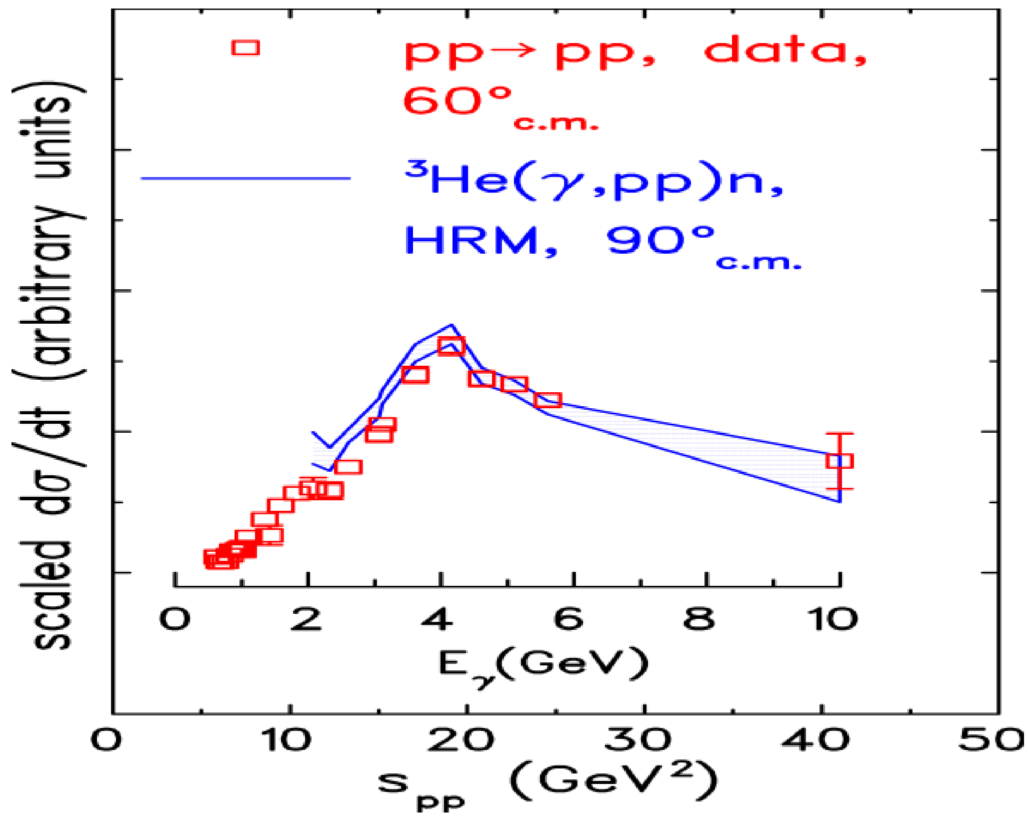




Break up of pp from Helium 3

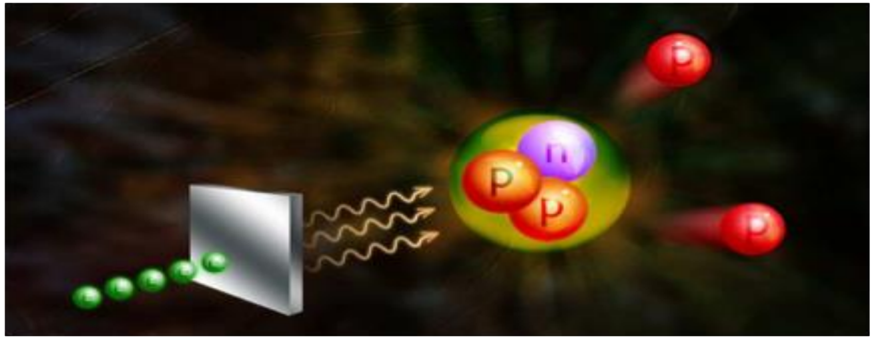
Brodsky, Frankfurt, Gilman, Hiller, Miller
Piasetzky, M.S., Strikman
Phys. Lett. B 2004





Hard photodisintegration of ^{3}He into p-p, p-n, and p-d pairs

The Jefferson Lab Hall A Collaboration



W. Boeglin, P. Markowitz
Florida International University, Miami, FL 33199 USA

G. Ron
Hebrew University of Jerusalem, Jerusalem, Israel

D.W. Higinbotham (spokesperson), B. Sawatzky, S. Wood
Jefferson Lab, Newport News, VA 23606 USA

W. Bertozzi, S. Gilad
Massachussetts Institute of Technology, Cambridge, MA 02139 USA

L. Weinstein
Old Dominion University, Norfolk, VA 23529 USA

L. El Fassi, R. Gilman (spokesperson), S. Leighton
G. Kumbartzki, R. Ransome, Y. Zhang
Rutgers University, Piscataway, NJ 08854-8019 USA

D. Anez, A.J. Sarty
St. Mary's University, Halifax, Nova Scotia B3H 3C3 CANADA

N. Bubis, O. Hen, I. Korover, E. Piasetzky,
I. Pomerantz (spokesperson and contact person), R. Shneor
Tel Aviv University, Tel Aviv, Israel

S. Širca, M. Mihovilovič
University of Ljubljana, Jadranska 19, 1000 Ljubljana, SLOVENIA

S. Strauch (spokesperson), Y. Ilieva
University of South Carolina, Columbia, South Carolina 29208, USA

G. Jin, R. Lindgren, B.E. Norum
University of Virginia, Charlottesville, Virginia 22904, USA

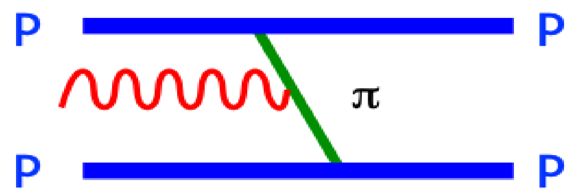
Info from Lower Energies

- Hard Photodisintegration of pp pair: $\gamma + {}^3He \longrightarrow pp + n$

What is known?

for $E_\gamma \leq 0.5 GeV$

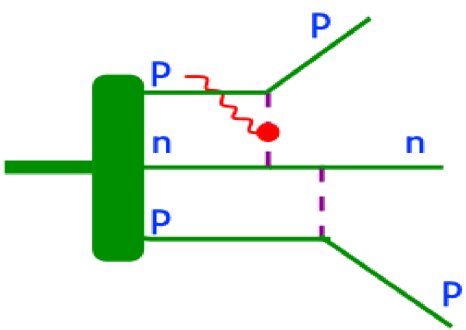
$\sigma_{\gamma pp} \ll \sigma_{\gamma pn}$



~ 0

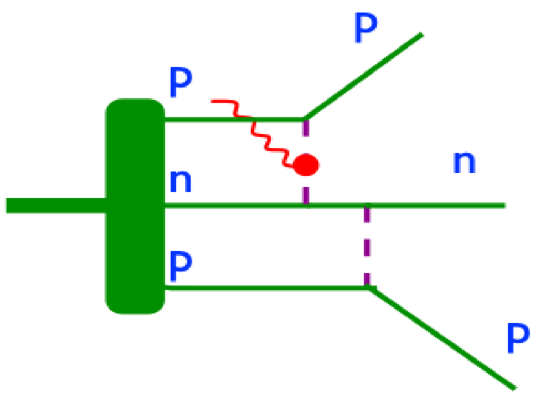
Laget, Nucl.Phys. 1989

- Three Body Processes are Dominant

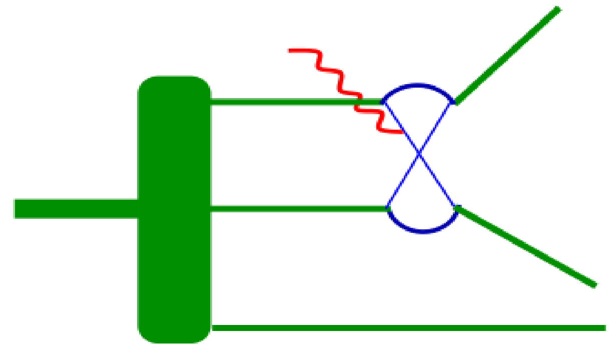


$$\frac{\sigma(\gamma^3 He \rightarrow pp)}{\sigma(\gamma^3 He \rightarrow pn)} \approx 1\%$$

(I) Transition from 3-step to 2-step processes



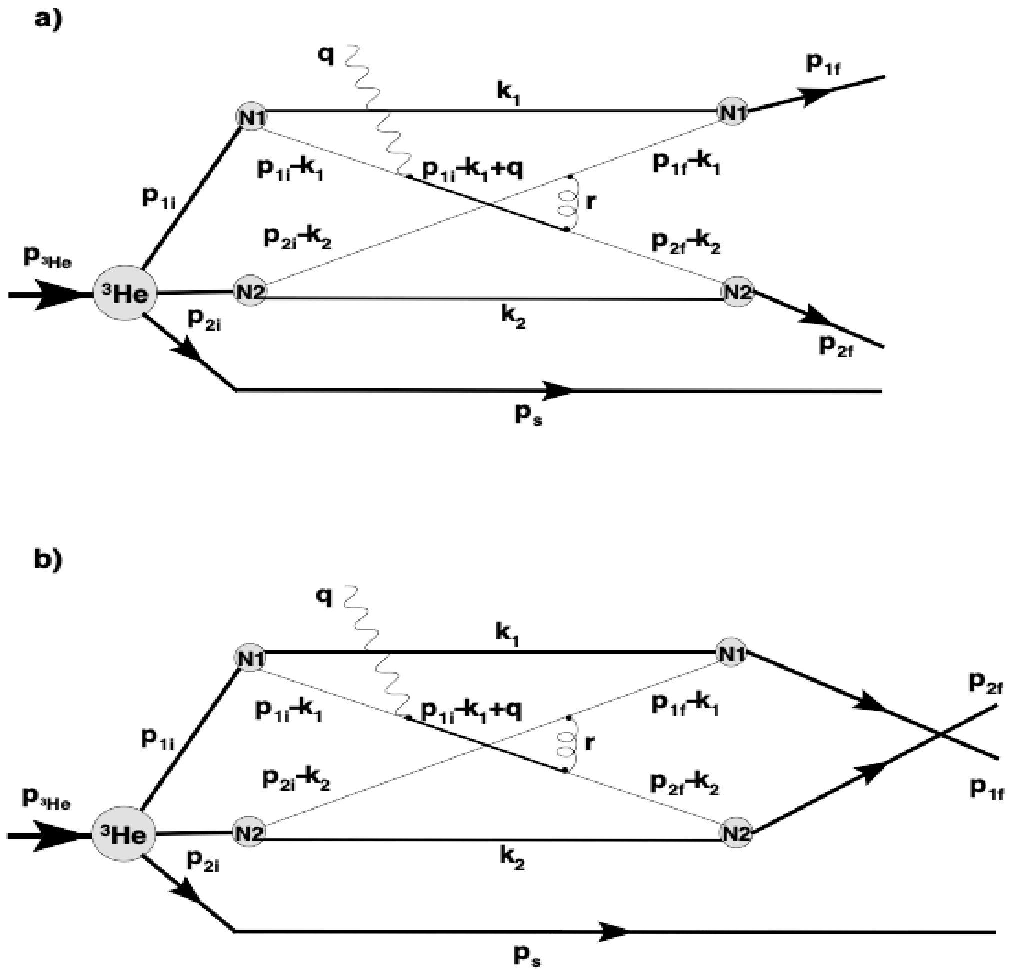
$\sim s^{-13}$



$\sim s^{-11}$

Considering $\gamma + ^3He \rightarrow (NN) + N$

M. S., C.Granados
Phys. Rev. C 2009



$$
\begin{aligned}
<+,+|T_{NN}^{QIM}|+,+> &= \phi_1 \\
<+,+|T_{NN}^{QIM}|+,-> &= \phi_5 \\
<+,+|T_{NN}^{QIM}|-,-> &= \phi_2 \\
<+,-|T_{NN}^{QIM}|+,-> &= \phi_3 \\
<+- |T_{NN}^{QIM}| -+> &= -\phi_4 .
\end{aligned} \tag{1}
$$

$$
|\bar{\mathcal{M}}|^2 = \frac{(e)^2 2(2\pi)^6}{2s'_{NN}} \frac{1}{2} \left[2Q_F^2|\phi_5|^2 S_0 + Q_F^2(|\phi_1|^2 + |\phi_2|^2) S_{12} + (|Q_1\phi_3 + Q_2\phi_4|^2 + |Q_1\phi_4 + Q_2\phi_3|^2) S_{34} \right] ,
$$

$$
Q_F = Q_1 + Q_2 = \frac{N_{uu}(Q_u + Q_u) + N_{dd}(Q_d + Q_d) + N_{ud}(Q_u + Q_d)}{N_{uu} + N_{dd} + N_{ud}}
$$

$\phi_3 \approx -\phi_4$ For pp

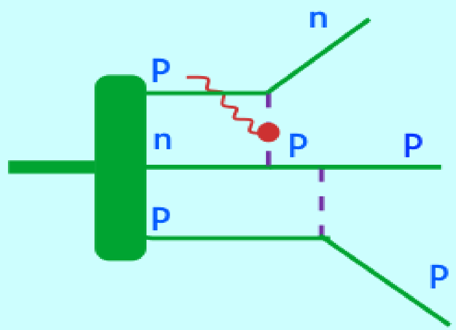
$$\frac{d\sigma}{dt\frac{d^3p_s}{E_s}} = \alpha Q^2_{F,PP} 16\pi^4 S^{pp}_{34}(\alpha = \frac{1}{2}, \vec{p}_s) \frac{2C^2\beta^2}{1+2C^2} \frac{s_{NN}(s_{NN}-4m_N^2)}{(s_{NN}-p^2_{NN})^2(s-M^2_{^3He})} \times \frac{d\sigma^{pp\to pp}(s_{NN},t_N)}{dt}, \qquad \beta = \frac{2(|\phi_3|-|\phi_4|)}{|\phi_1|} \quad (1)$$

$$\frac{\sigma(\gamma^3He\to pp)}{\sigma(\gamma^3He\to pn)} \approx 0.1 \quad \text{at 4GeV}$$

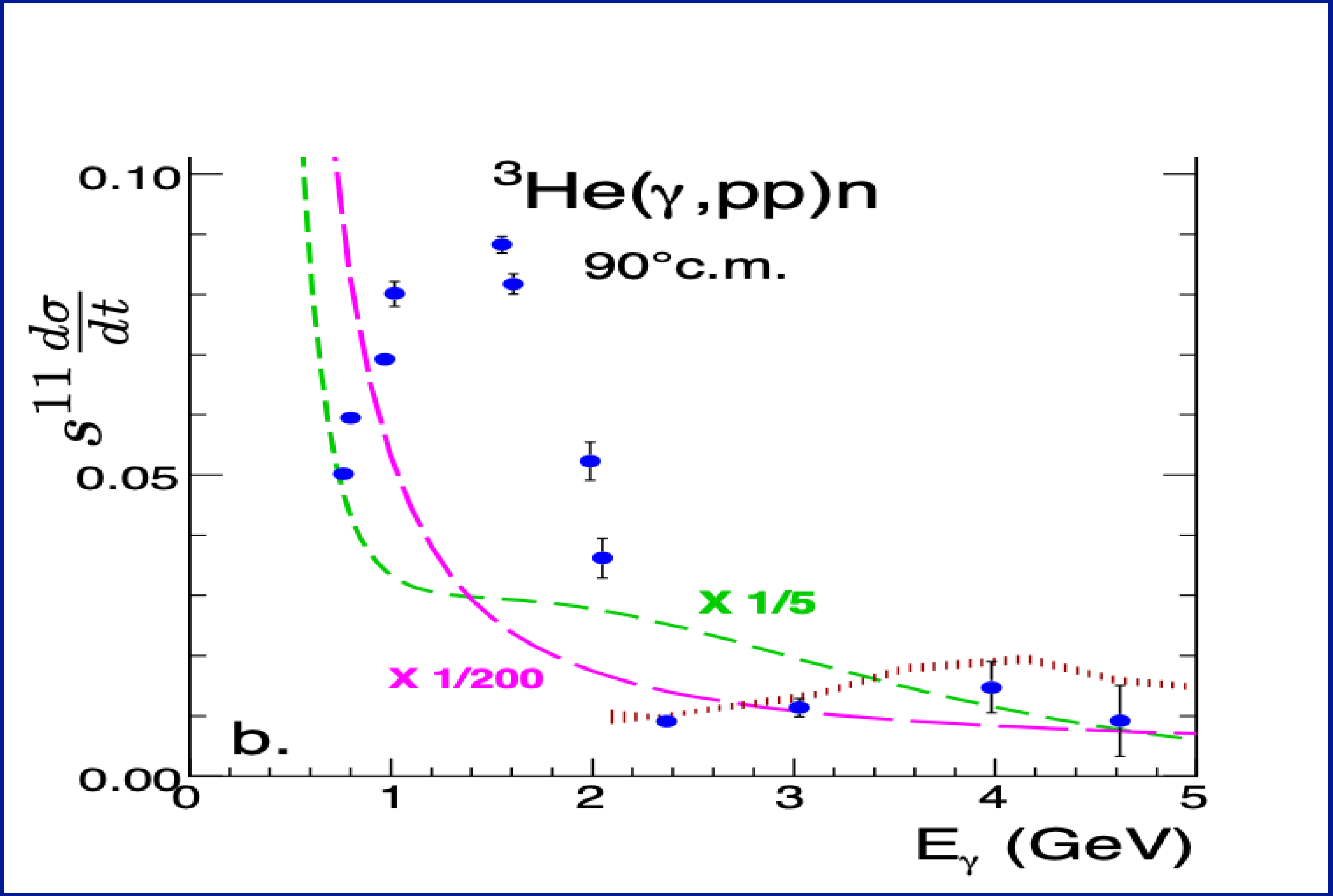
Meson Exchange Picture

$$\frac{\sigma(\gamma^3He\to pp)}{\sigma(\gamma^3He\to pn)} \approx 0.01 \quad \text{at 0.5 GeV}$$

J-M.Laget, Nucl.Phys. 1989

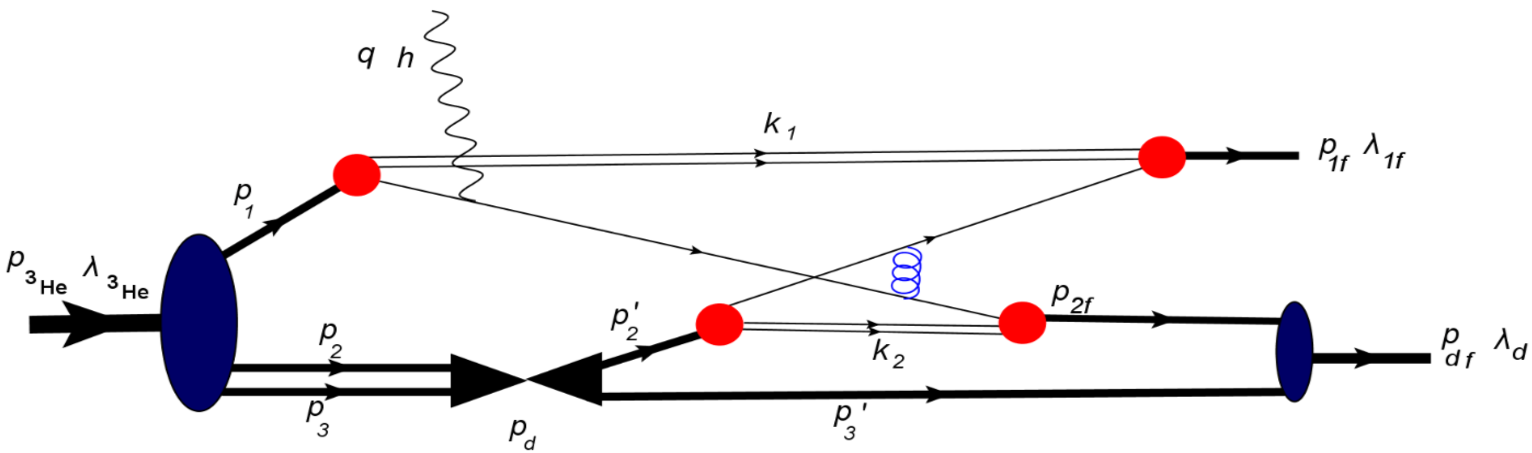


Pomerantz, et al,
Phys. Lett. B 2010



Hard Photodisintegration of 3He into pd pairs

D. Maheswari, M. Sargsian
Phys. Rev. C 2017



$$\mathcal{M}^{\lambda_{df},\lambda_{1f};\lambda_{3\mathrm{He}},h} = \sum_{\lambda'_d} \int \chi_d^{*\lambda'_d} (-i\Gamma^\dagger_{DNN}) \frac{i(\not{p}_{2f} + m)}{p_{2f}^2 - m_N^2 + i\epsilon} \frac{i(\not{p}'_3 + m)}{p_3'^2 - m_N^2 + i\epsilon} \frac{i(\not{p}'_2 + m)}{p_2'^2 - m_N^2 + i\epsilon}$$

$$A: \qquad i\frac{\Gamma_{DNN}\chi_d^{\lambda_d}\chi_d^{*\lambda_d}}{p_d^2 - m_d^2 + i\epsilon}(-i)\Gamma^\dagger_{DNN} \frac{i(\not{p}_3 + m)}{p_3^2 - m_N^2 + i\epsilon} \frac{i(\not{p}_2 + m)}{p_2^2 - m_N^2 + i\epsilon} \frac{i(\not{p}_1 + m)}{p_1^2 - m_N^2 + i\epsilon}$$

$$i\Gamma_{^3\mathrm{He}}\chi_{^3\mathrm{He}}^{\lambda_{3\mathrm{He}}} \frac{d^4p'_2}{(2\pi)^4} \frac{d^4p_3}{(2\pi)^4} \frac{d^4p'_3}{(2\pi)^4}$$

$$N1: \int \chi_{p_{1f}}(-i)\Gamma^\dagger_{N1} \frac{i(\not{p}_{1f} - \not{k}_1 + m)}{(p_{1f} - k_1)^2 - m_q^2 + i\epsilon}\left[-igT_c^\beta\gamma_\mu\right] \frac{iS(k_1)}{k_1^2 - m_s^2 + i\epsilon}$$

$$\frac{i(\not{p}_1 - \not{k}_1 + m_q)}{(p_1 - k_1)^2 - m_q^2 + i\epsilon} i\Gamma_{n1} \frac{d^4k_1}{(2\pi)^4}$$

$$N2: \int (-i)\Gamma^\dagger_N \frac{i(\not{p}_{2f} - \not{k}_2 + m_q)}{(p_{2f} - k_2)^2 - m_q^2 + i\epsilon} \frac{iS(k_2)}{k_2^2 - m_s^2 + i\epsilon} \frac{i(\not{p}'_2 - \not{k}_2 + m_q)}{(p'_2 - k_2)^2 - m_q^2 + i\epsilon} i\Gamma_{n2'} \frac{d^4k_2}{(2\pi)^4}$$

$$\gamma: -igT_c^\alpha\gamma_\nu \frac{i(\not{p}_1 + \not{q} - \not{k}_1 + m_q)}{(p_1 - k_1 + q)^2 - m_q^2 + i\epsilon}\left[-ie\gamma^\mu\epsilon_h^\mu\right]$$

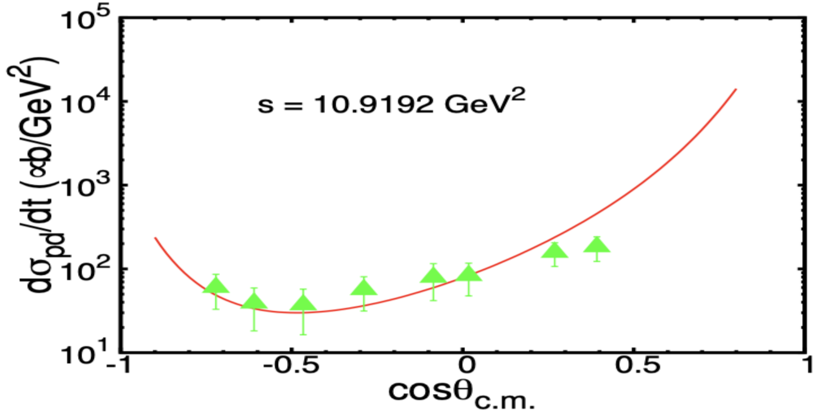
$$g: \frac{id_{\mu\nu}\delta_{\alpha\beta}}{q_q^2}.$$

$$\mathcal{M}^{\lambda_{df},\lambda_{1f};\lambda_{^3\mathrm{He}},h} = \frac{3}{4}\frac{1}{\sqrt{s'_{^3\mathrm{He}}}}\sum_i eQ_i(h)\sum_{\substack{\lambda_d\\ \lambda_2,\lambda_3}}\int \mathcal{M}_{pd}^{\lambda_{df},\lambda_{1f};\lambda_d,h}(s,t_N)\frac{\Psi_d^{\dagger\lambda_d:\lambda_2,\lambda_3}(\alpha_3,p_{3\perp},\beta_d,p_{d\perp})}{1-\alpha_3}$$
$$\times \quad \Psi_{^3\mathrm{He}}^{\lambda_{^3\mathrm{He}}:h,\lambda_2,\lambda_3}(\beta_1=1/3,p_{1\perp},\beta_2,p_{2\perp})\frac{d^2p_{d\perp}}{(2\pi)^2}\frac{d\beta_3}{\beta_3}\frac{d^2p_{3\perp}}{2(2\pi)^3}. \tag{15}$$

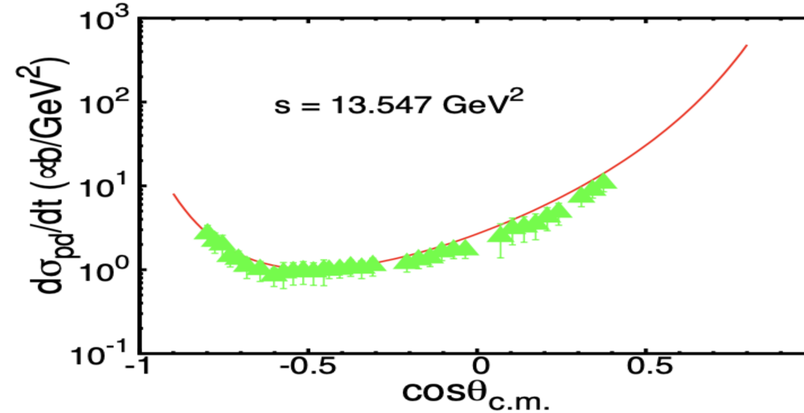
$$\mathcal{M}^{\lambda_{df},\lambda_{1f};\lambda_{^3\mathrm{He}},h} = \frac{3}{4}\frac{eQ_{eff}(h)}{\sqrt{s'_{^3\mathrm{He}}}}\sum_{\lambda_d}\mathcal{M}_{pd}^{\lambda_{df},\lambda_{1f};\lambda_d,h}(s,t_{pd})\int \Psi_{^3\mathrm{He}/d}^{\lambda_{^3\mathrm{He}}:\lambda_1,\lambda_d}(\beta_1=1/3,p_{1\perp})\frac{d^2p_{1\perp}}{(2\pi)^2}.$$

$$\frac{d\sigma}{dt} = \frac{9}{32}\frac{e^2Q_{eff}^2}{s'_{^3\mathrm{He}}}\left(\frac{s'_N}{s'_{^3\mathrm{He}}}\right)\frac{d\sigma_{pd}}{dt}(s,t_{pd})S_{^3\mathrm{He}/d}(\beta_1=1/3),$$

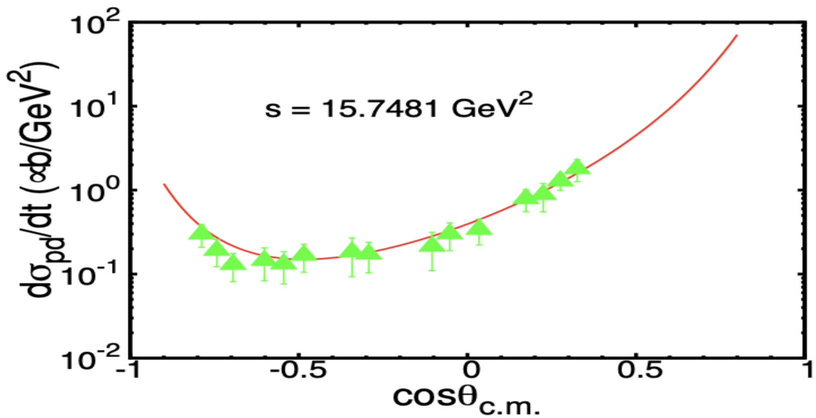
where $s'_N = s - m_N^2$.


s = 10.9192 GeV^2
dσ_{pd}/dt (∝b/GeV^2)
cos$\theta_{c.m.}$
10^5
10^4
10^3
10^2
10^1
-1
-0.5
0
0.5
1

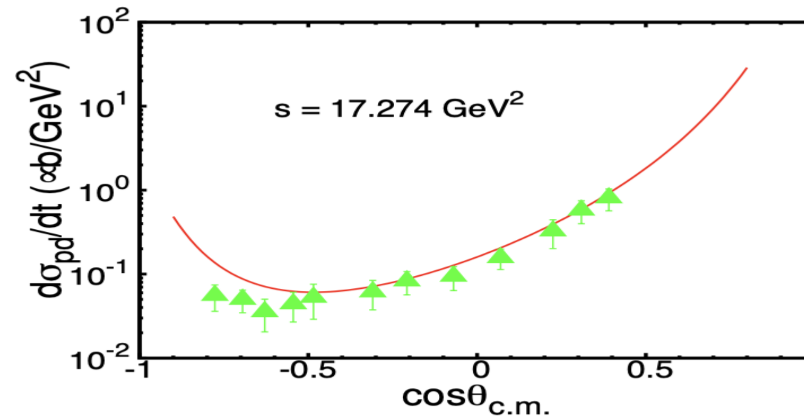
(a)


s = 13.547 GeV^2
dσ_{pd}/dt (∝b/GeV^2)
cos$\theta_{c.m.}$
10^3
10^2
10^1
10^0
10^{-1}
-1
-0.5
0
0.5
1

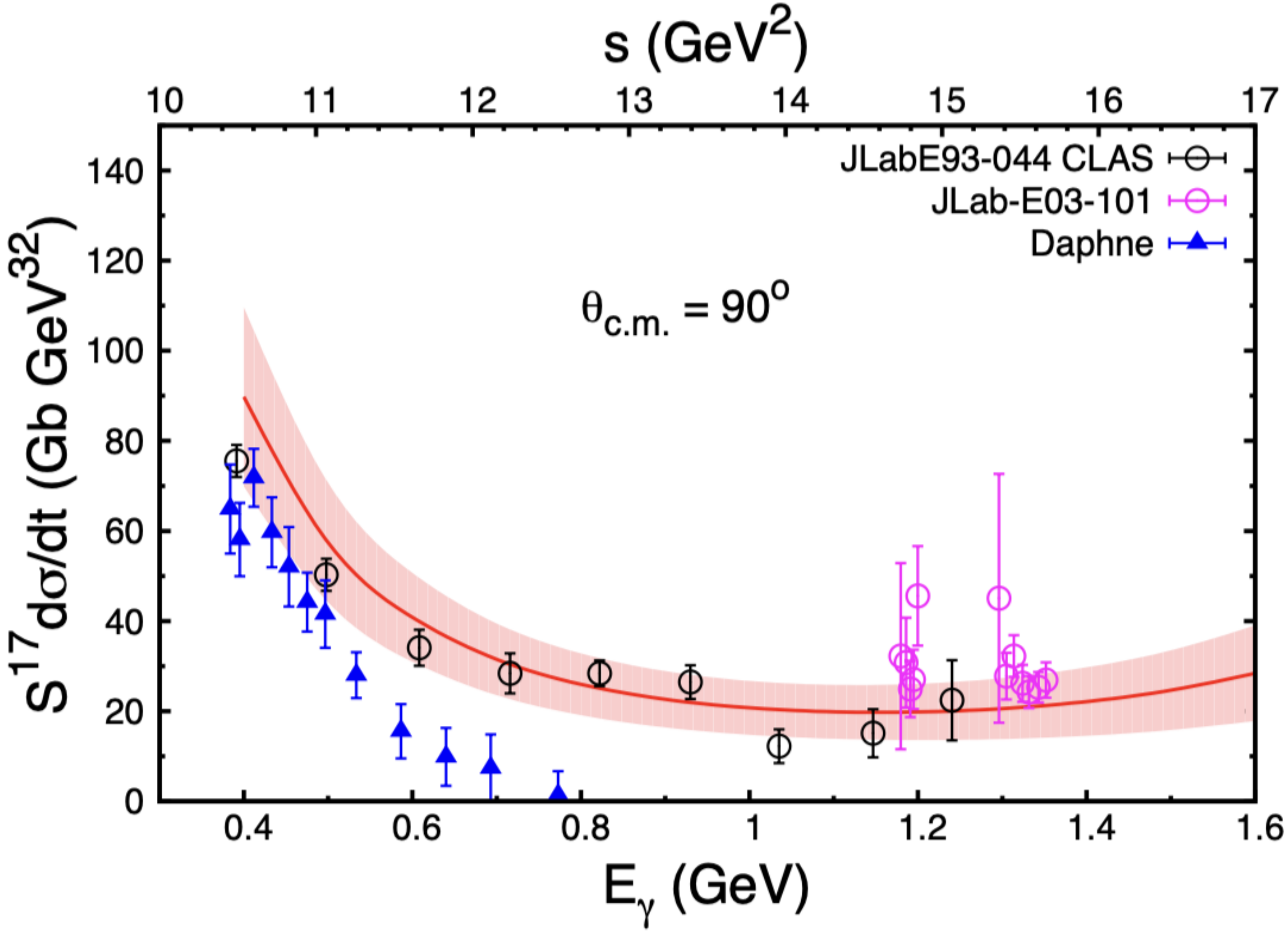
(b)


s = 15.7481 GeV^2
dσ_{pd}/dt (∝b/GeV^2)
cos$\theta_{c.m.}$
10^2
10^1
10^0
10^{-1}
10^{-2}
-1
-0.5
0
0.5
1

(c)


s = 17.274 GeV^2
dσ_{pd}/dt (∝b/GeV^2)
cos$\theta_{c.m.}$
10^2
10^1
10^0
10^{-1}
10^{-2}
-1
-0.5
0
0.5
1

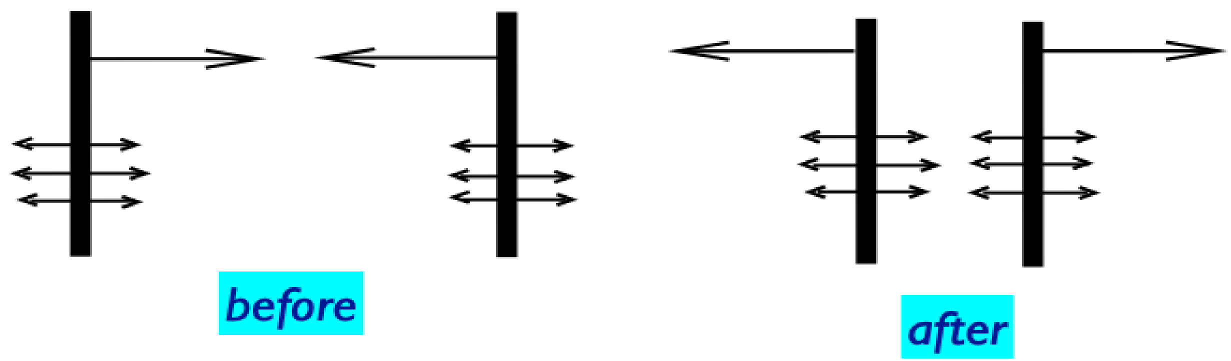
(d)

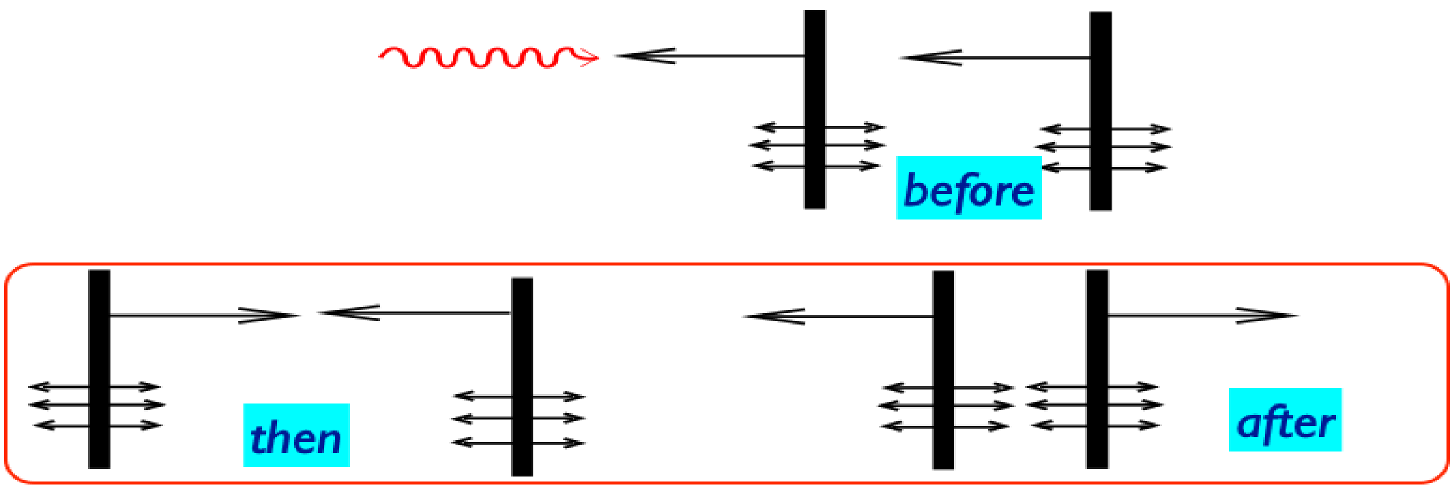


s (GeV^2)
10
11
12
13
14
15
16
17
JLabE93-044 CLAS
JLab-E03-101
Daphne
$\theta_{c.m.} = 90^o$
$S^{17}d\sigma/dt$ (Gb GeV^{32})
0
20
40
60
80
100
120
140
0.4
0.6
0.8
1
1.2
1.4
1.6
E_γ (GeV)

What's Next: Studying Hard Hadronic Processes

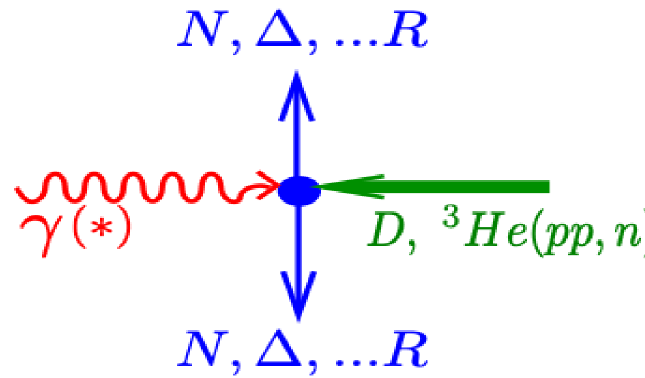
Baryon-Baryon Scattering





What's Next:

1. Studying Hard Hadronic Processes



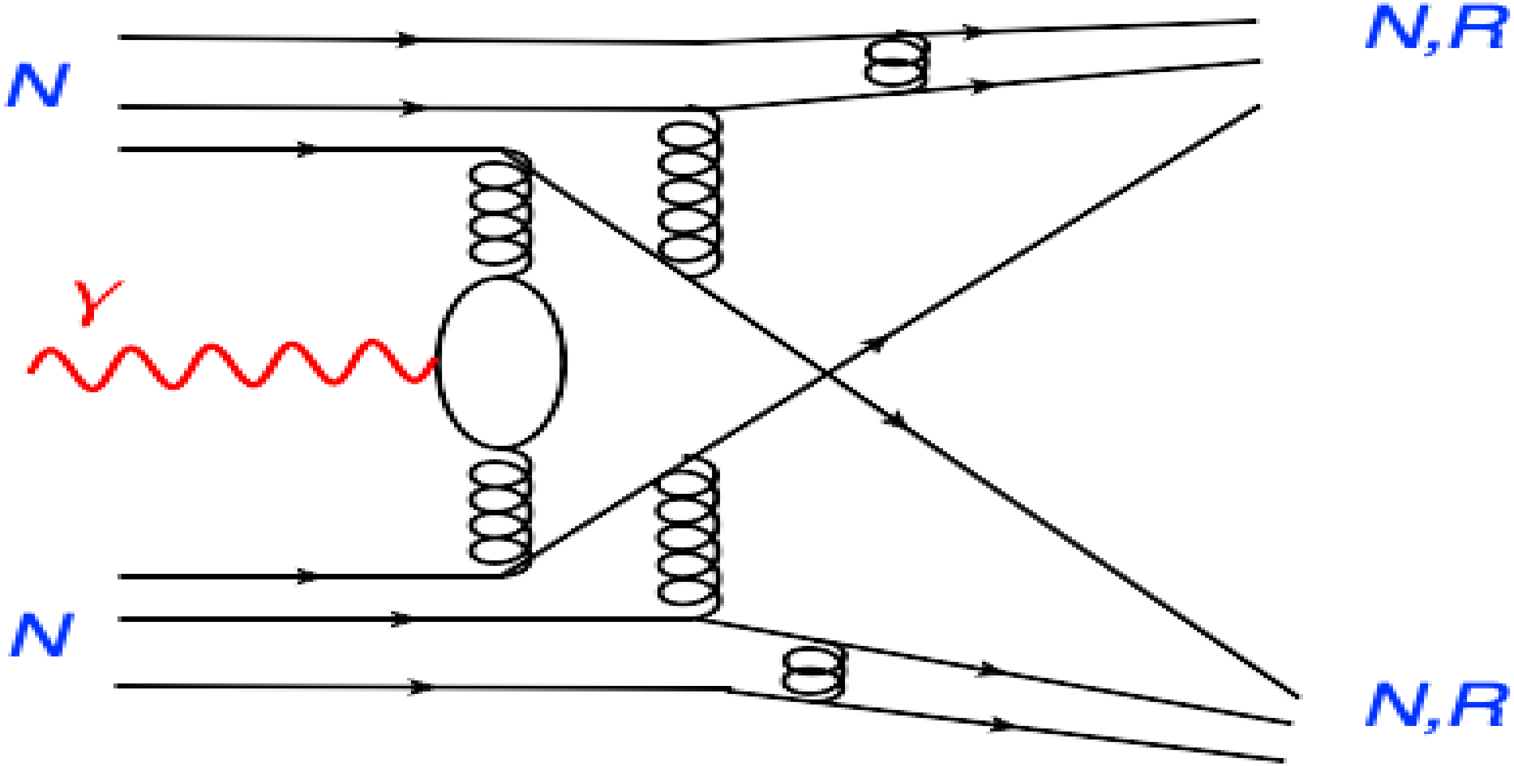
Break - up reactions to the deuteron break-up of other 2Baryons

$$\gamma + d \to \Delta + \Delta$$

M. S., and C.Granados
Phys. Rev. C 2011

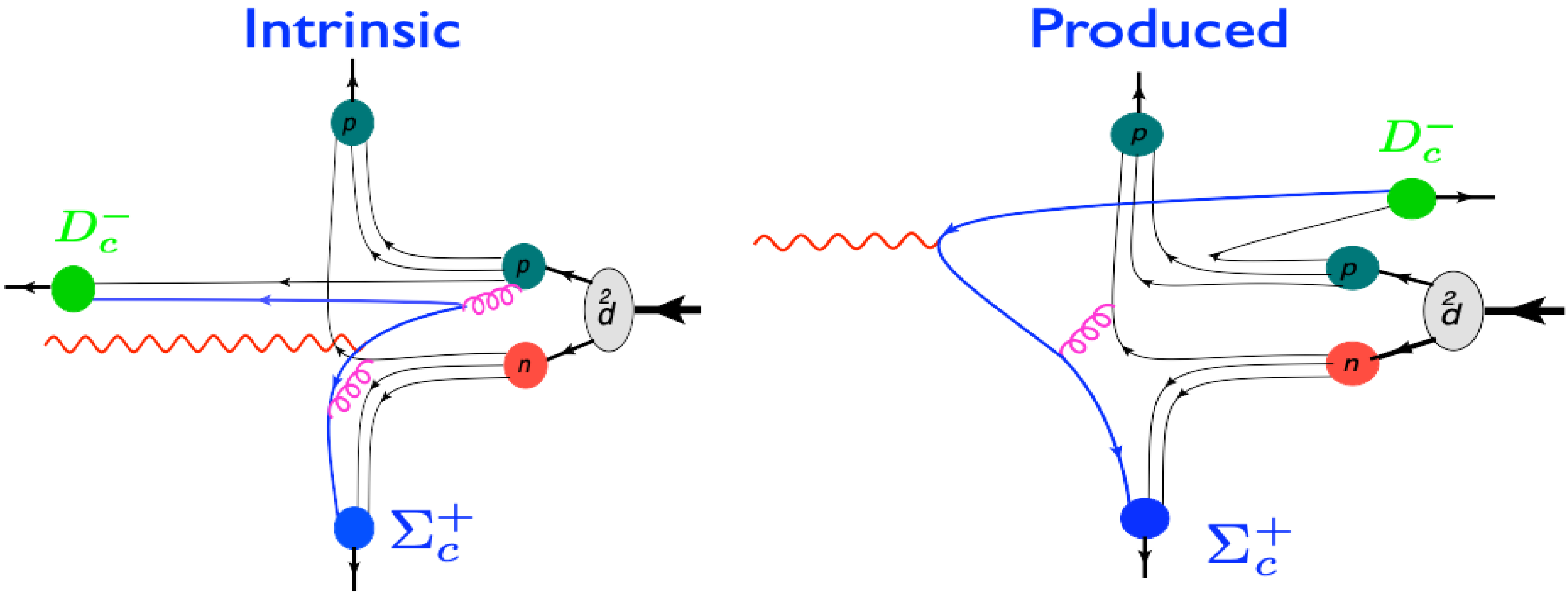
Extraction of hard Baryonic Helicity Amplitudes from Polarized measurement

2. Probing $(s\bar{s})$ or $(c\bar{c})$ component of the nucleon

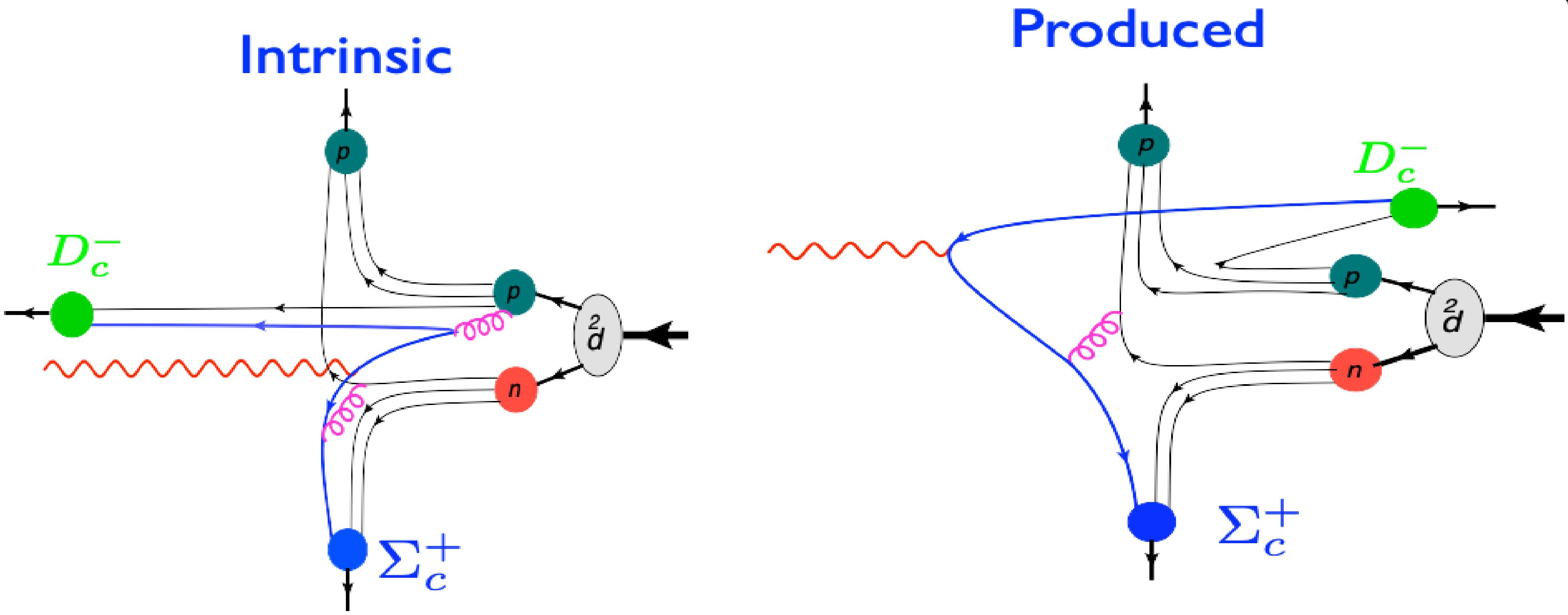

N
γ
N
N,R
N,R

Studying $c\bar{c}$ component in the deuteron

$$\gamma + d \rightarrow p + \Sigma_c^+ + D_c^-$$



Kinematics $\gamma + d \rightarrow p + \Sigma_c^+ + D_c^-$



target fragmentation D_c^- midrapidity $p\Sigma_c^+$ current fragmentation D_c^-

$p_t = 2GeV/c$ $s = 412\ \mathrm{GeV}^2$

Outlook

- (Jlab 4-6 GeV): Experimentally established adequacy of QCD degrees of freedom **in hard break-up of light nuclei**

- (Jlab 4-6 GeV): Hard Rescattering Mechanism is consistent with major **observations of the break-up reactions**

- (Jlab 4-6 GeV): Indicating the possibility of using these reaction to study **hard hadronic interactions**

- (Jlab 12 GeV): More accurate measurements to study the substructure of hard pp and pn interaction

- (Jlab 12 GeV): Studying Hard break-up of light-nuclei into baryonic resonances

$$\Delta\Delta,\ N\Sigma K,\ N\Sigma_c D$$