Hard Photo-disintegration & Polarization Effects

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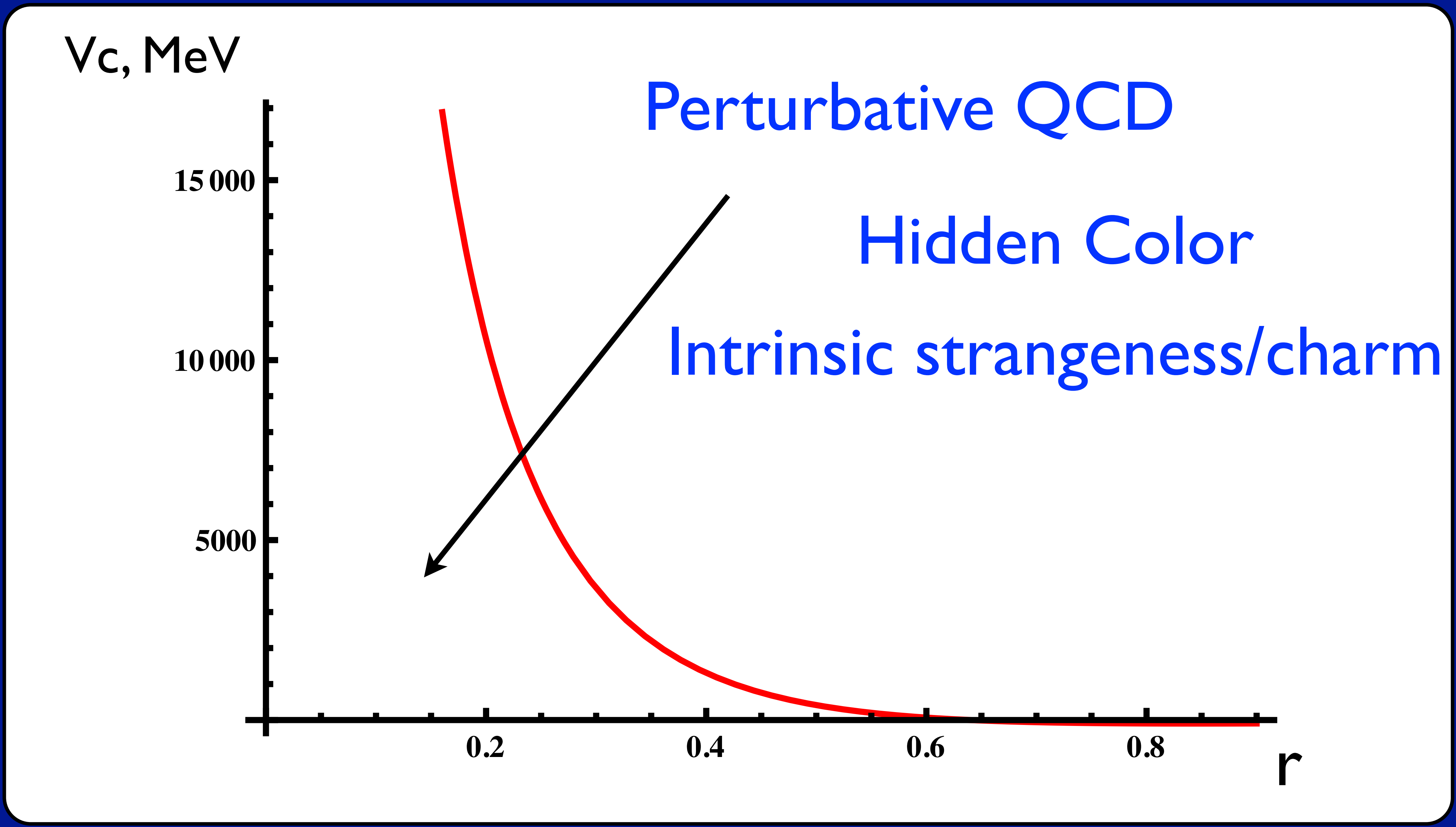
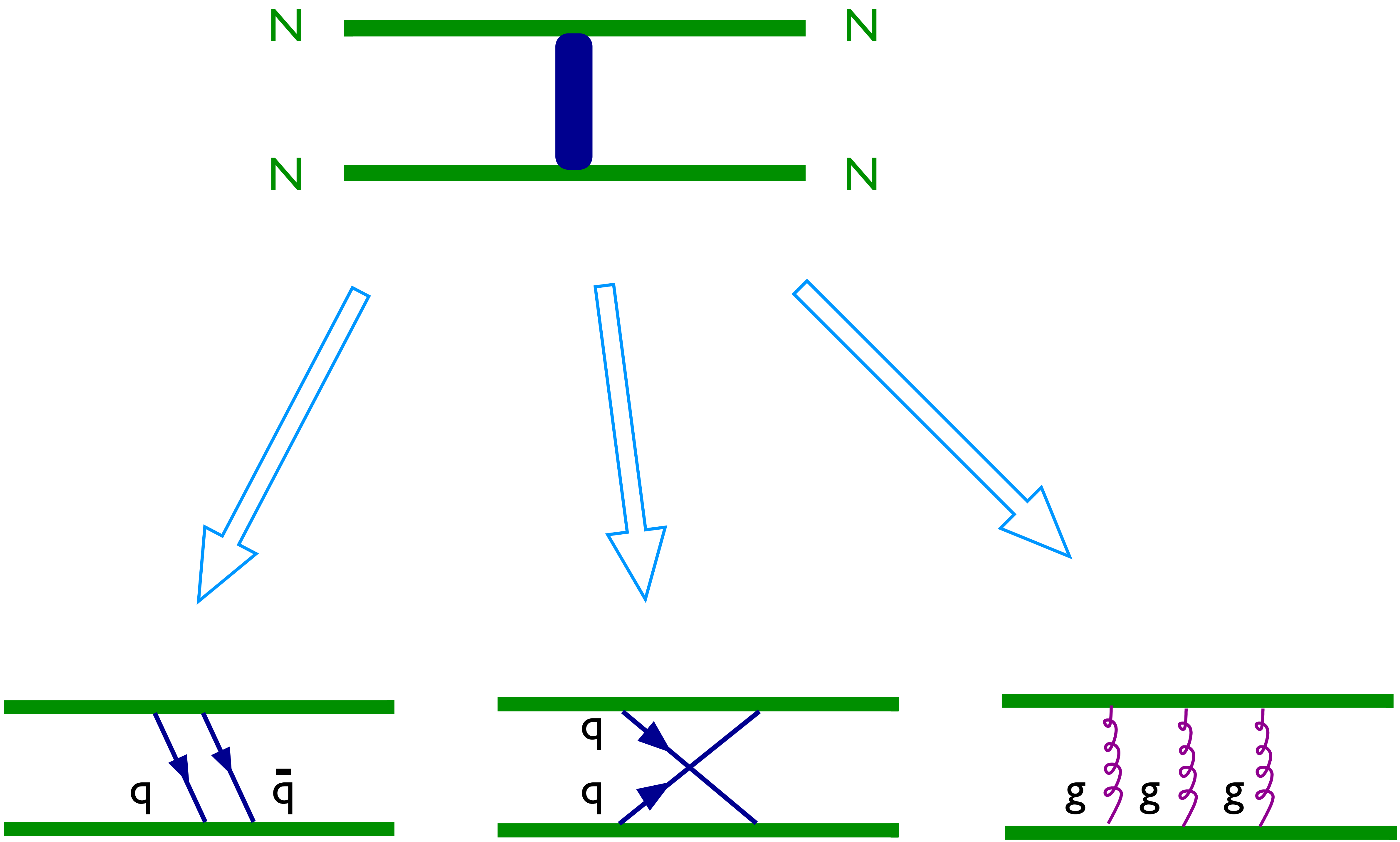
Nuclear Photodisintegration with GlueX
April 28-29, 2016 , JLab, Newport News, VA

NN interaction at core distances

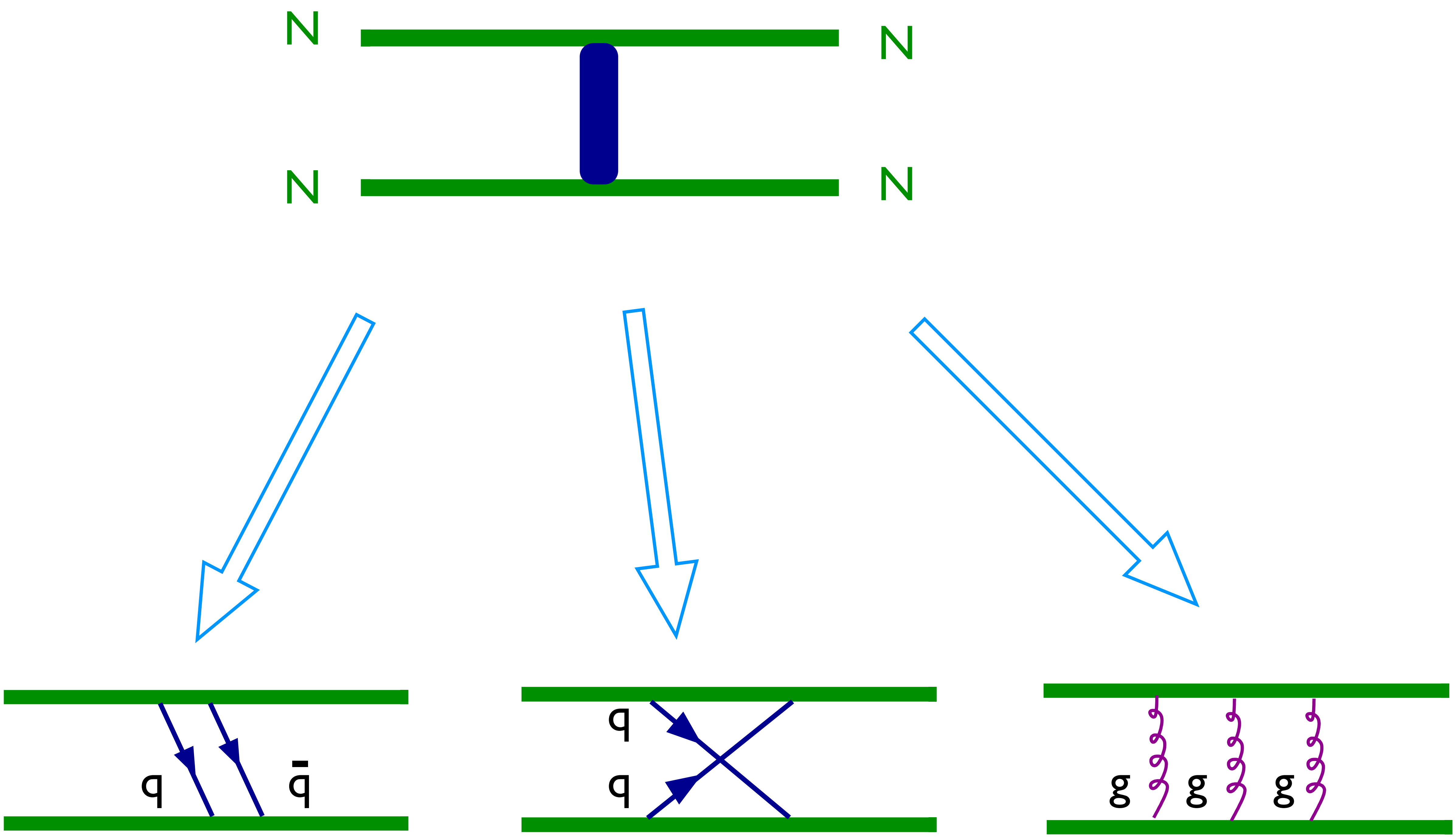




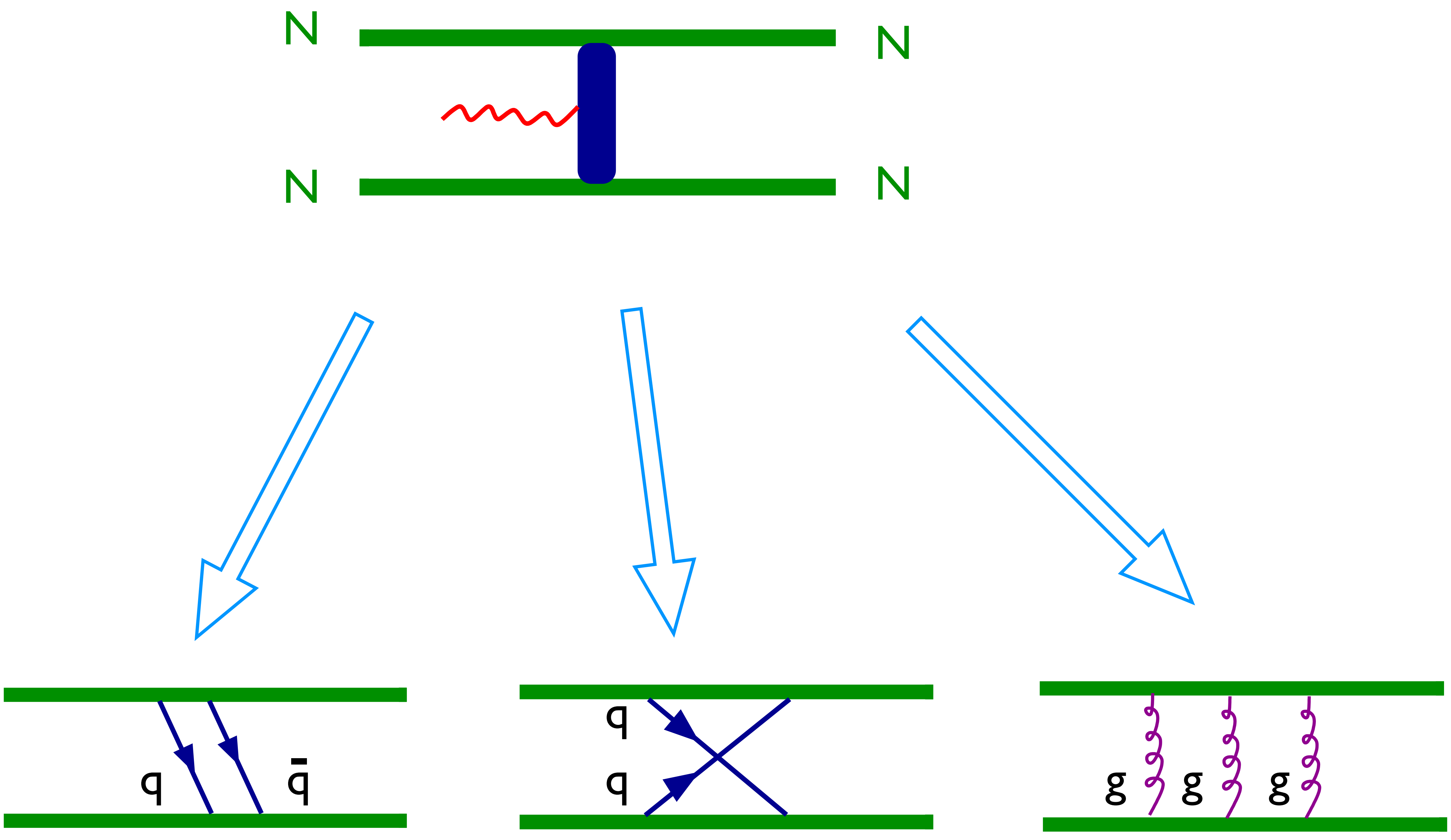
-Can be Studied in Hard Exclusive NN Scattering Reactions

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

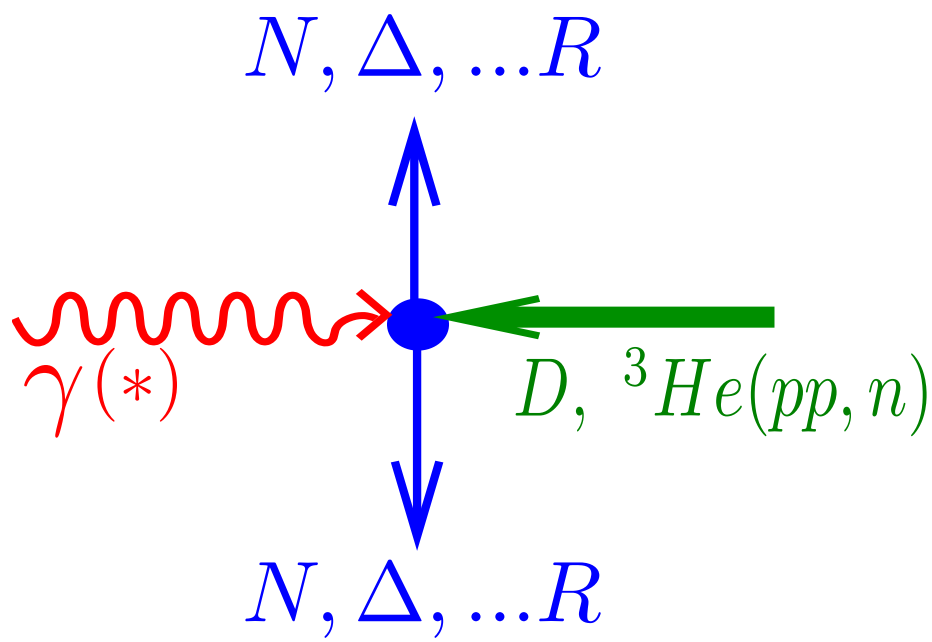
- High Energy Break up of two nucleons in Nuclei

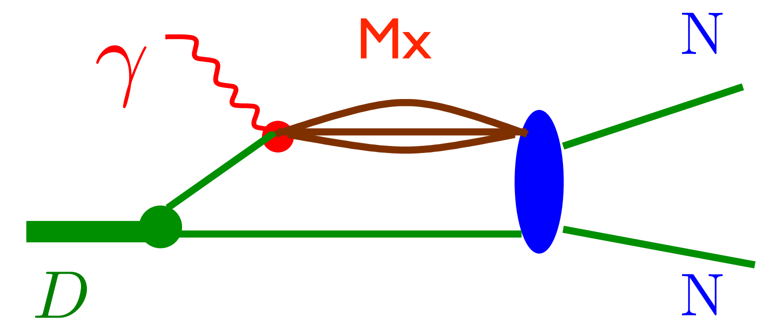


- High Energy Break up of two nucleons in Nuclei



- Large CM angle disintegration of nuclei:





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

Brodsky, Chertock, 1976

Holt, 1990

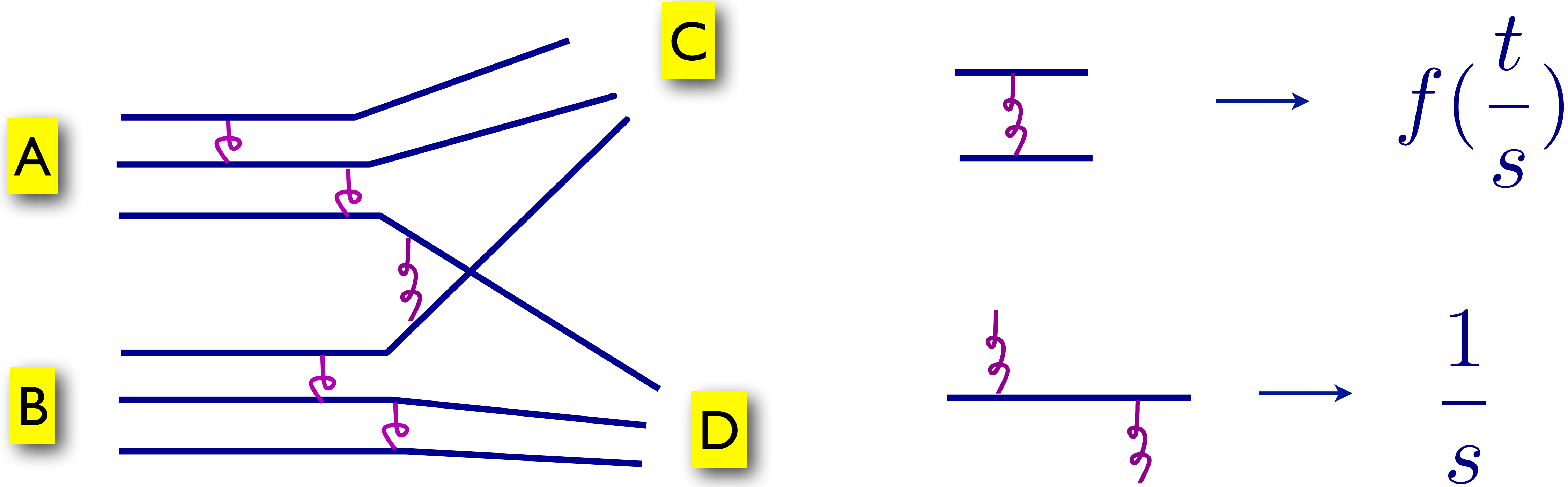
Gilman, Gross, 2002

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

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

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

Consider A+B→C + D

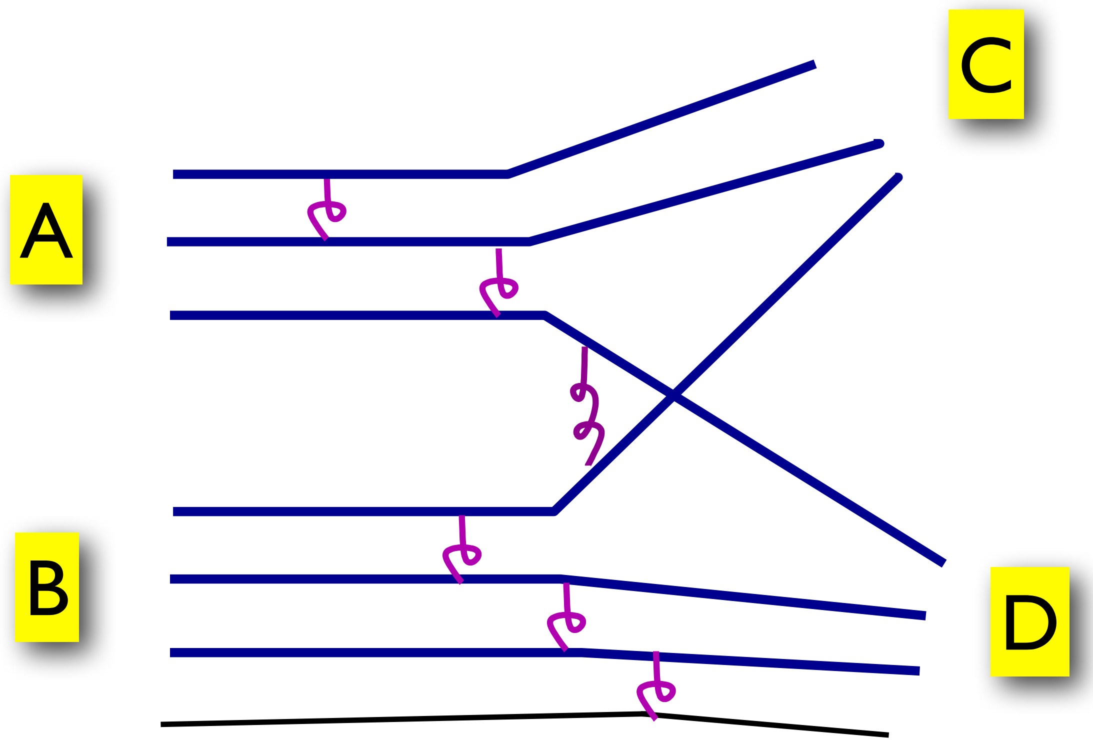


$$A \sim F(\frac{t}{s}) \frac{1}{s^{\frac{n_A+n_B+n_C+n_D}{2}-2}}$$

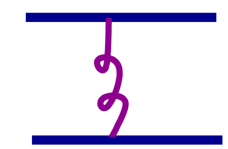
Brodsky, Farrar 1975
Matveev, Muradyan, Takhvelidze, 1975

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

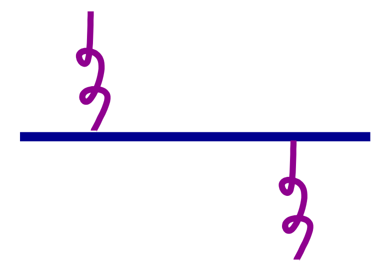
Consider A+B→C + D



additional $\frac{1}{s}$



$$\longrightarrow \quad f\left(\frac{t}{s}\right)$$



$$\longrightarrow \quad \frac{1}{s}$$

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

Brodsky, Farrar 1975
Matveev, Muradyan, Takhvelidze, 1975

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

$\gamma d \rightarrow pn$

scaling

Exclusive large-momentum-transfer scattering

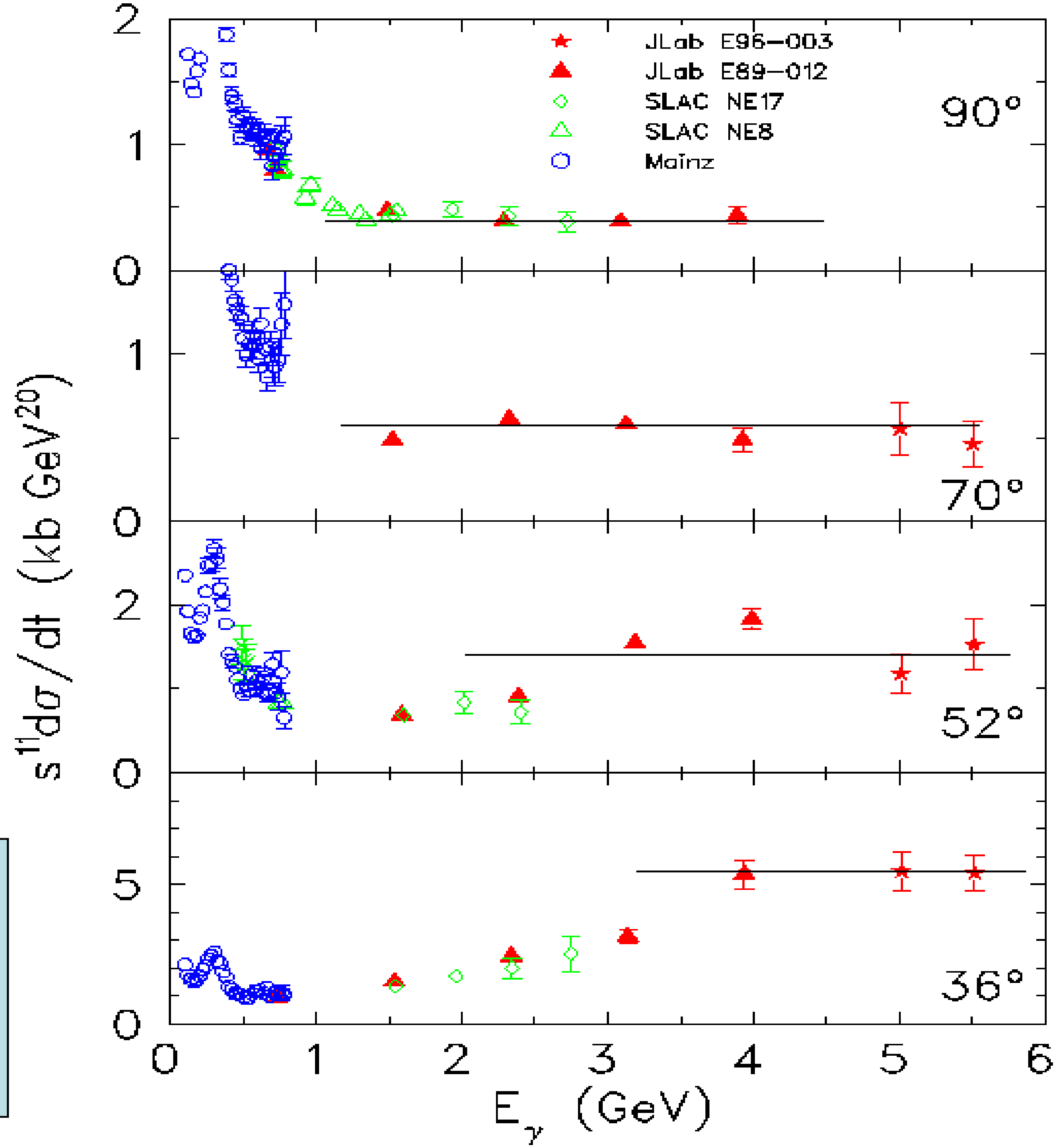
•Dimensional counting rule:

$$\frac{d\sigma}{dt}_{AB\rightarrow CD} \propto S^{-(N=n_A+n_B+n_C+n_D-2)} f(\tfrac{t}{s})$$

For

$$\gamma\ d \rightarrow p\,(high\ p_t)\ +\ n\,(high\ \ p_t)$$

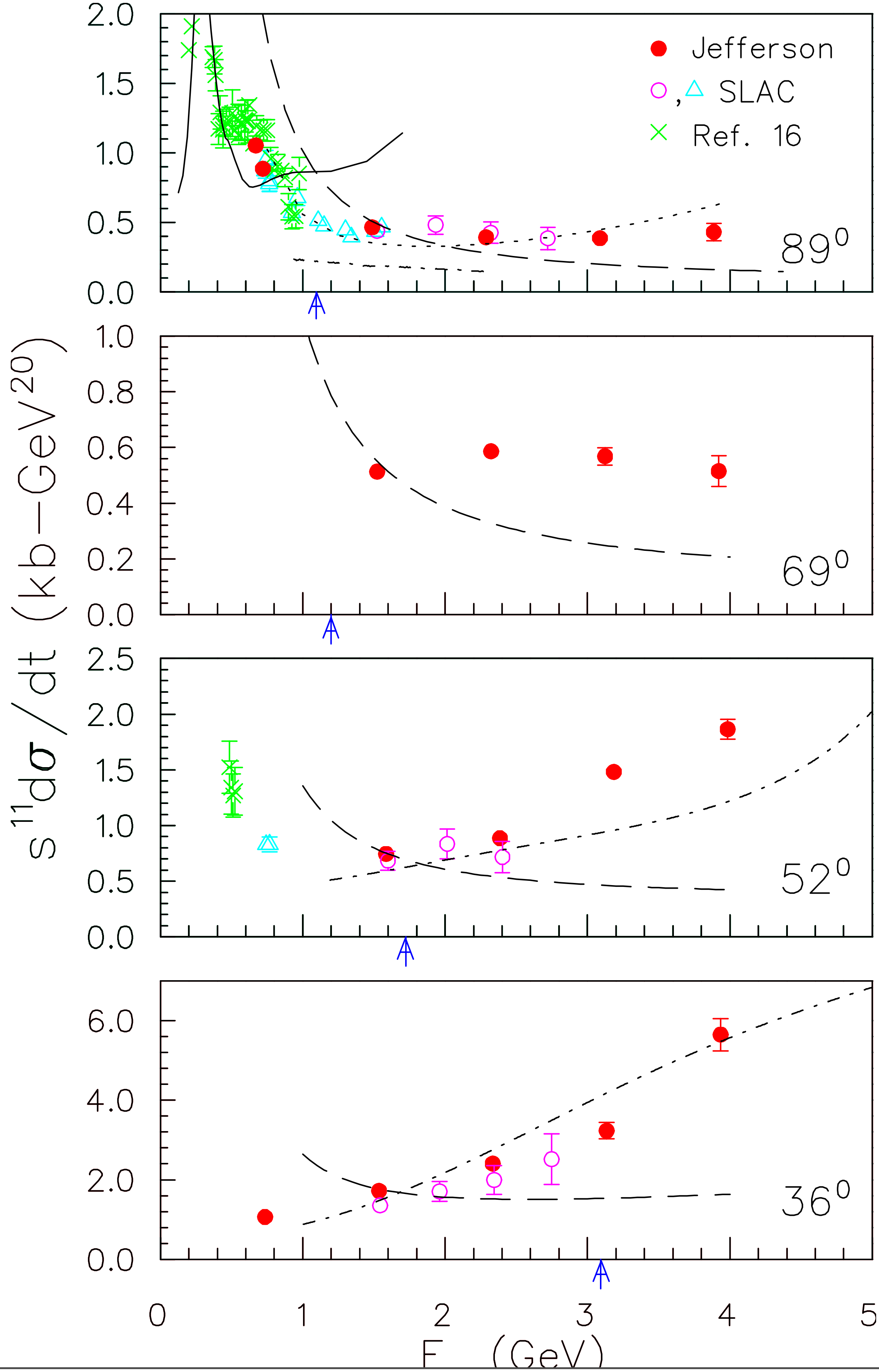
N = 1 + 6 + 3 + 3 – 2 = 11

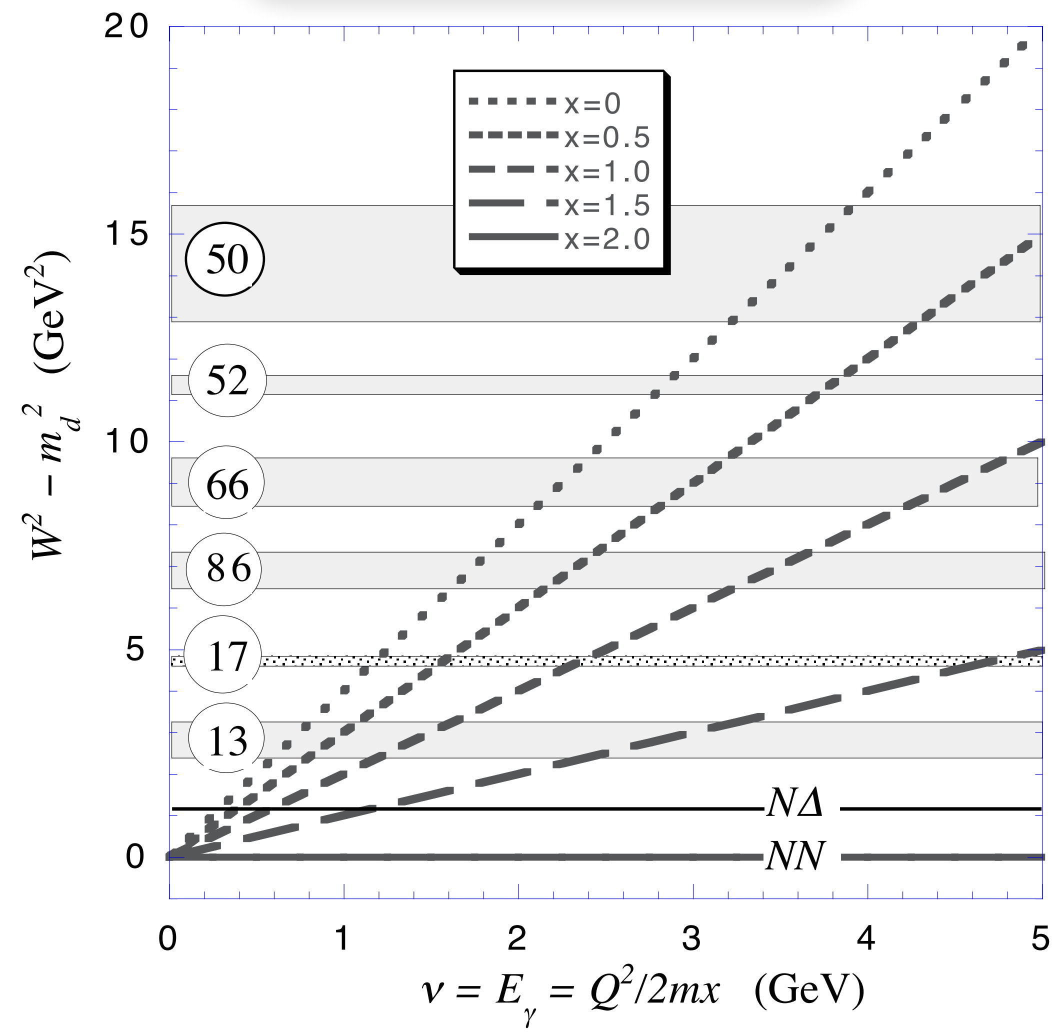


Notice:

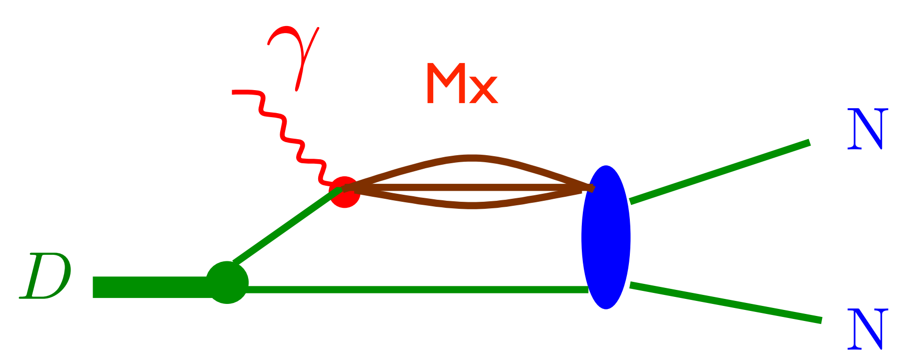
$$\frac{d\sigma}{dt}(E_\gamma = 1\,\text{GeV/c}) / \frac{d\sigma}{dt}(E_\gamma = 4\,\text{GeV/c}) \approx 10^4$$

$\gamma d \rightarrow pn$

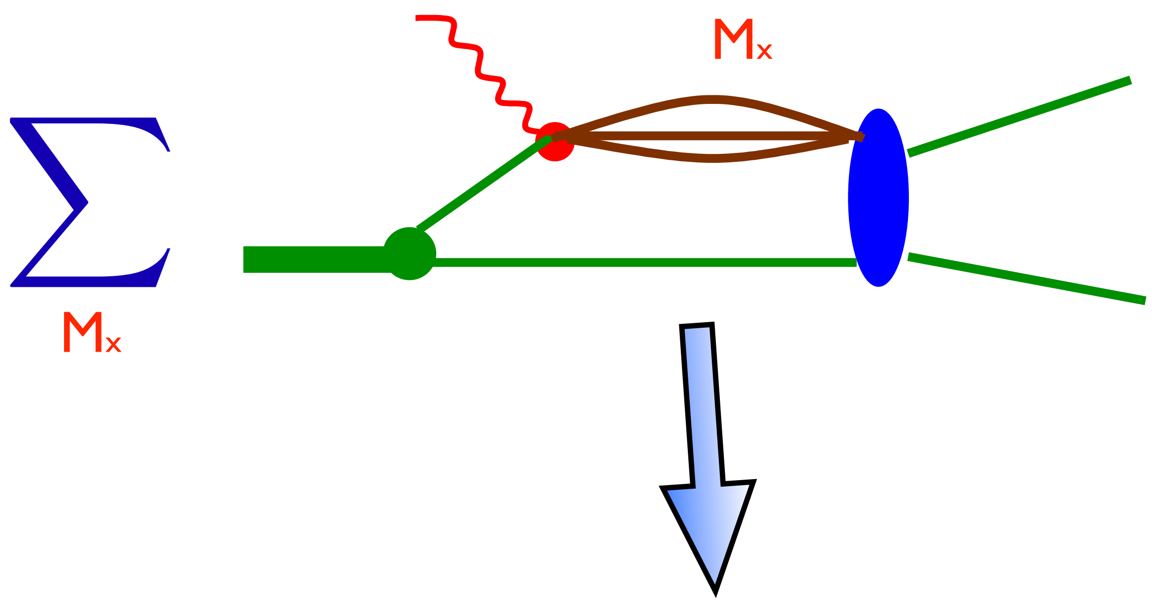




Gilman, Gross, 2002



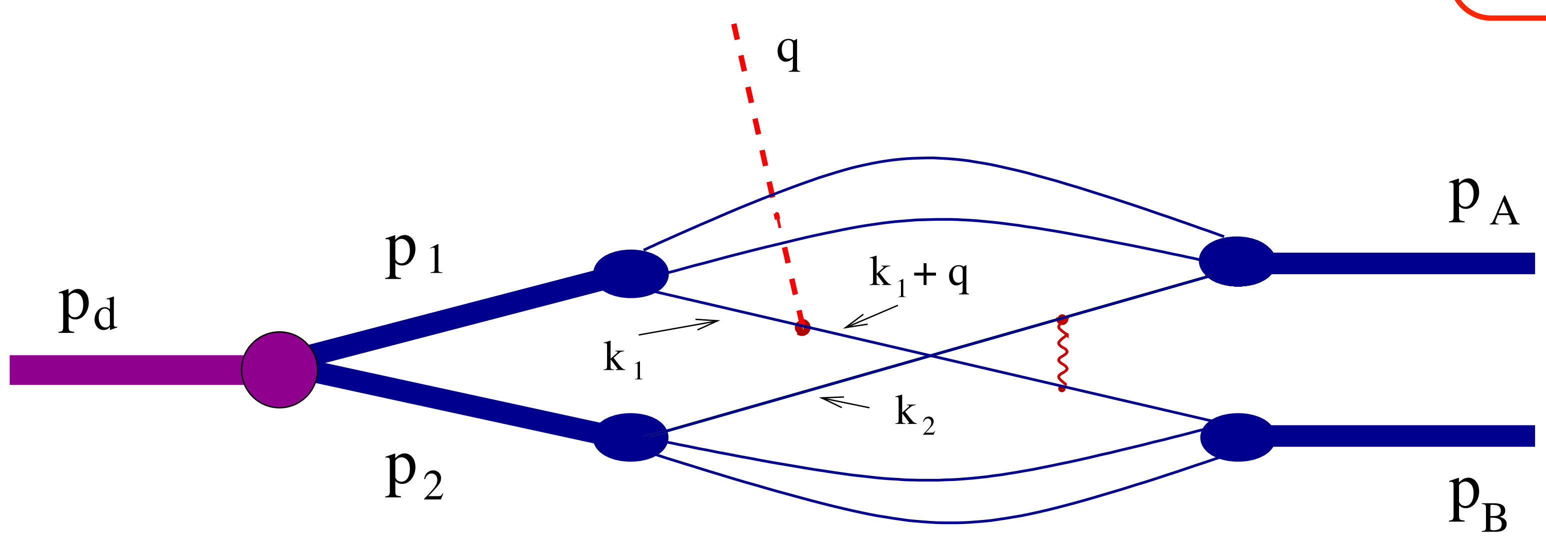
Hard Rescattering Mechanism



Mmax=w > 2 GeV

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

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



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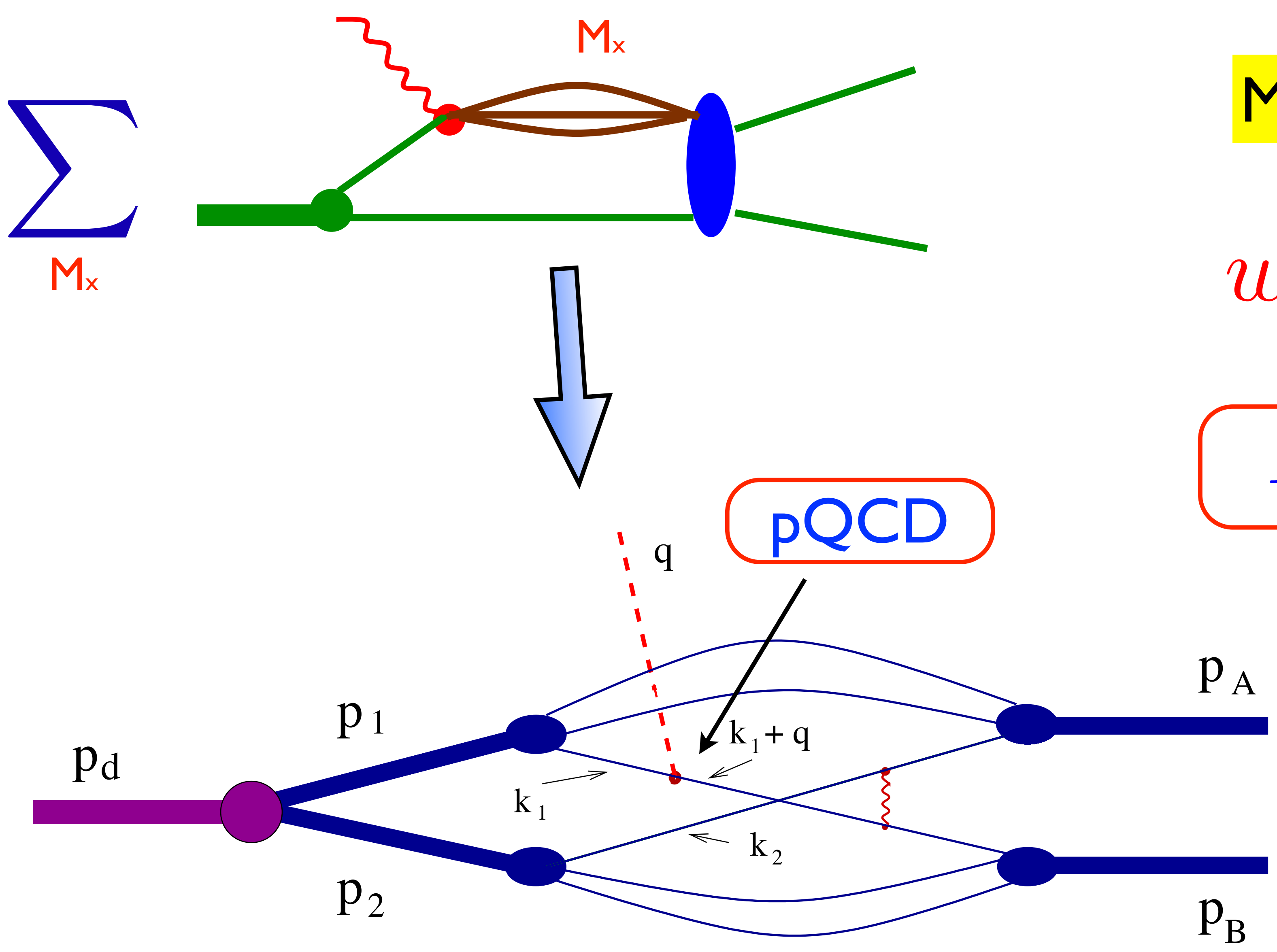

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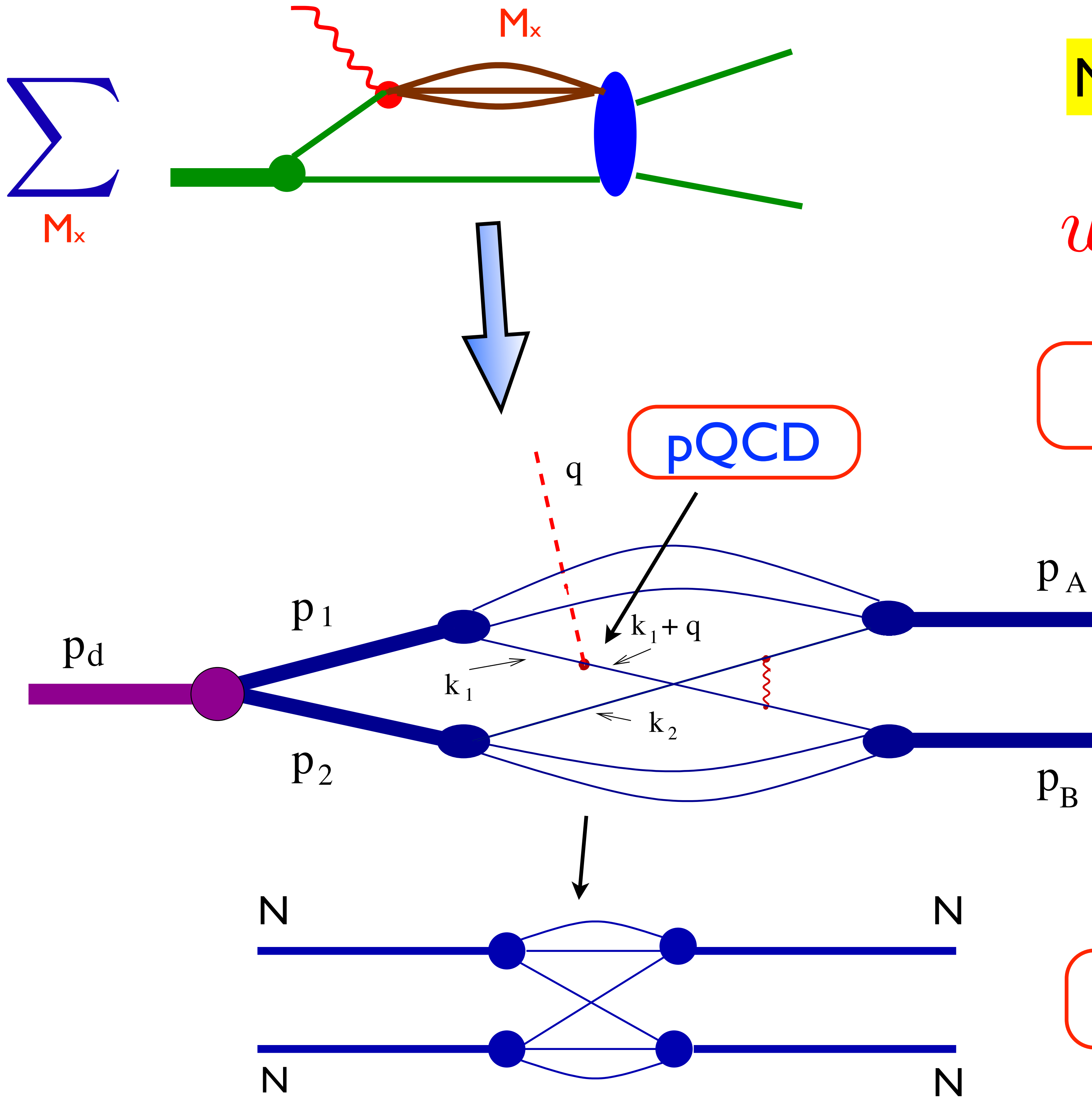

Mmax=w > 2 GeV

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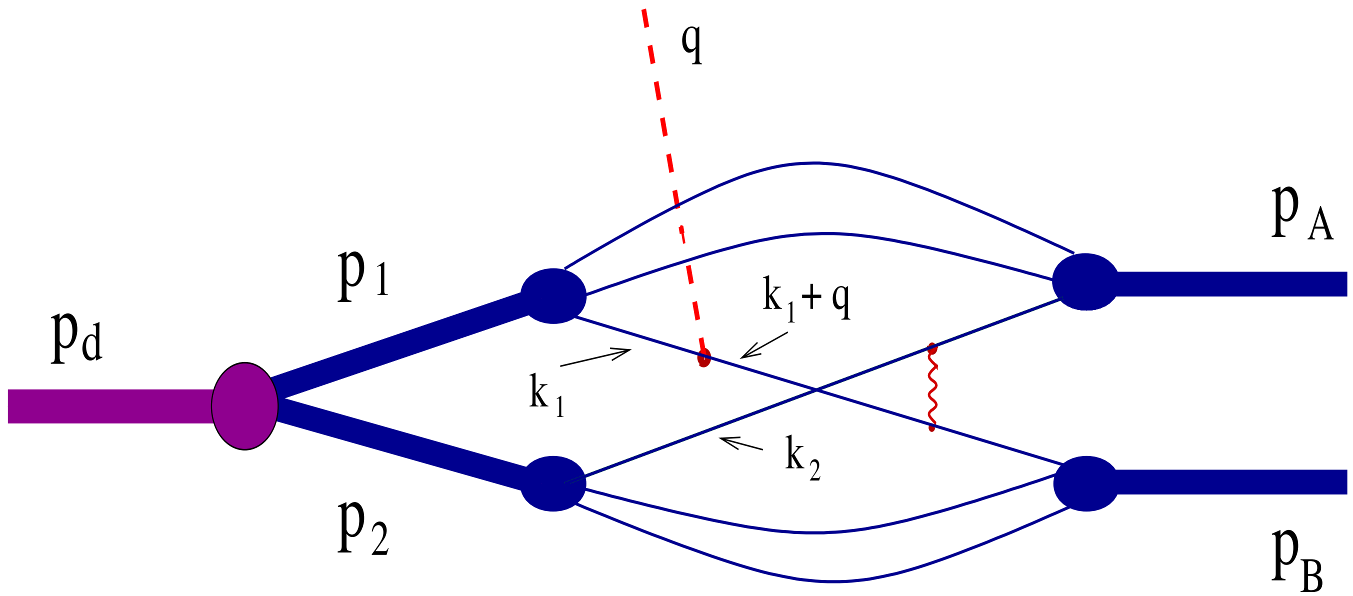
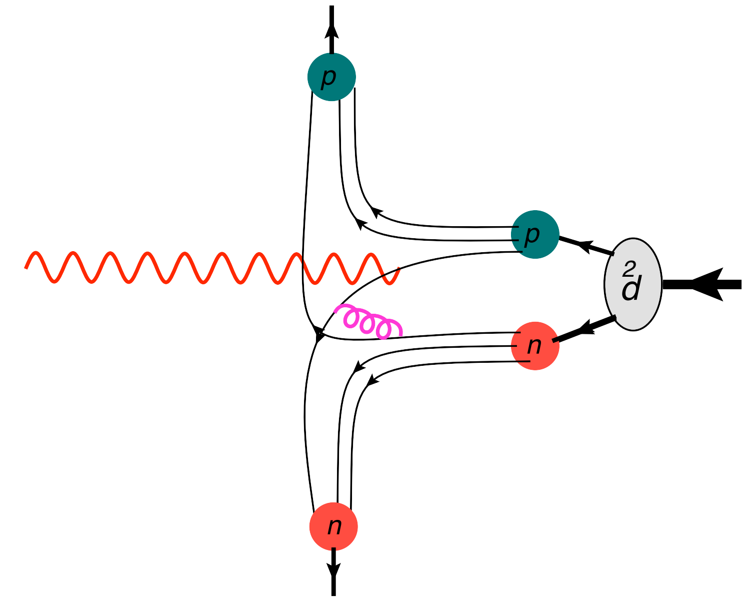
NN -amplitude



Frankfurt, Miller, MS, Strikman
PRL 2000



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

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

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

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

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:

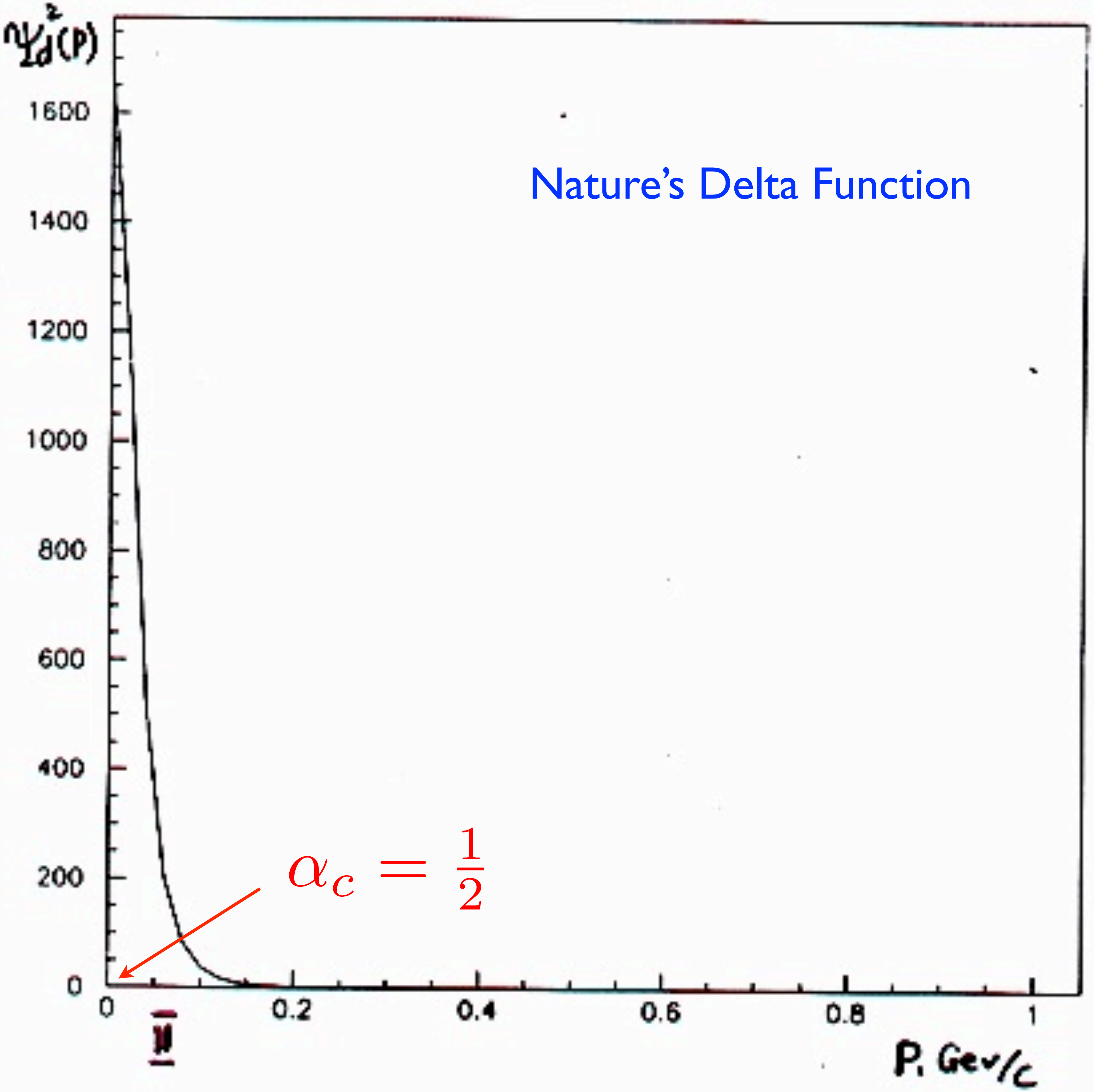
$$(k_1+q)^2 - m_q^2 + i\epsilon \approx x_1 s'(\alpha - \alpha_c + i\epsilon),$$

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

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 $\alpha_c = \frac{1}{2}$.

Nature's Delta Function



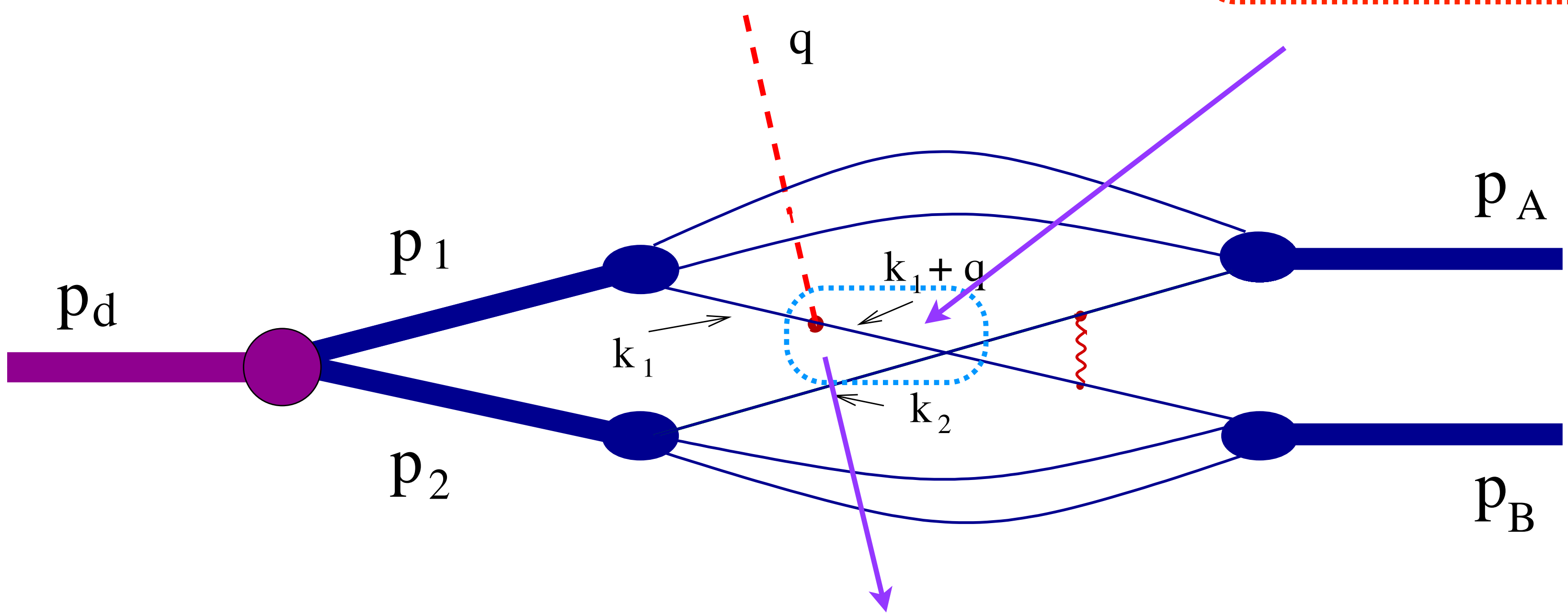
$\alpha_c = \frac{1}{2}$

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

- 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: $(\alpha - \alpha_c + \epsilon)^{-1} \equiv \mathcal{P}(\alpha - \alpha_c)^{-1} - i\pi\delta(\alpha - \alpha_c)$:



$$\bar{u}^\beta(k_1 + q)\,[-ie\epsilon^\mu(\lambda_\gamma)\gamma_\mu]\,u^\alpha(k_1) = ie_q 2\sqrt{2E_2 E1}(-\lambda_\gamma)\delta^{\beta,\alpha}\delta^{\lambda_\gamma,\alpha}$$

$$\langle \lambda_A, \lambda_B \mid A \mid \lambda_\gamma, \lambda_D \rangle = \sum_{(\eta_1,\eta_2),(\xi_2),(\lambda_1,\lambda_2)} \int \frac{e_q\sqrt{2}}{x_1\sqrt{s'}} \sqrt{[1-(1-\alpha_c)x_1](1-\alpha_c)x_1}$$

$$\left\{ \frac{\psi_N^{\dagger\lambda_B,\eta_2}(p_B, x_2', k_{2\perp})}{x_2'} \bar{u}_{\eta_2}(p_B - k_2)[-igT_c^F\gamma^\nu] \cdot u_{\lambda_\gamma}(p_1 - k_1 + q) \frac{\psi_N^{\lambda_1,\lambda_\gamma}(p_1, x_1, k_{1\perp})}{x_1} \times \right.$$

$$\left. \frac{\psi_N^{\dagger\lambda_A,\eta_1}(p_B, x_1', k_{1\perp})}{x_1'} \bar{u}_{\eta_1}(p_A - k_1)[-igT_c^F\gamma^\mu] u_{\xi_2}(p_2 - k_2) \frac{\psi_N^{\lambda_2,\xi_2}(p_2, x_2, k_2)}{x_2} G^{\mu,\nu}(r) \frac{dx_1}{1-x_1} \frac{d^2k_{1\perp}}{2(2\pi)^3} \frac{dx_2}{1-x_2} \frac{d^2k_{2\perp}}{2(2\pi)^3} \right\}$$

$$\frac{\Psi^{\lambda_D,\lambda_1,\lambda_2}(\alpha, p_\perp)}{(1-\alpha)\alpha} \frac{d^2p_\perp}{4(2\pi)^2}. \quad (1)$$

$$A_{pn}^{QIM} = \int \frac{\psi_N^\dagger(x_2', p_{B\perp}, k_{2\perp})}{x_2'} \bar{u}(p_B - p_2 + k_2) \left[-igT_c^F\gamma^\nu\right] u(k_1 + q) \frac{\psi_N(x_1, p_{1\perp}, k_{1\perp})}{x_1}$$

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

$$\times \frac{dx_1}{1-x_1} \frac{d^2k_{1\perp}}{2(2\pi)^3} \frac{dx_2}{1-x_2} \frac{d^2k_{2\perp}}{2(2\pi)^3} \quad (1)$$

Frankfurt, 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

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

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

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

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

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

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

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

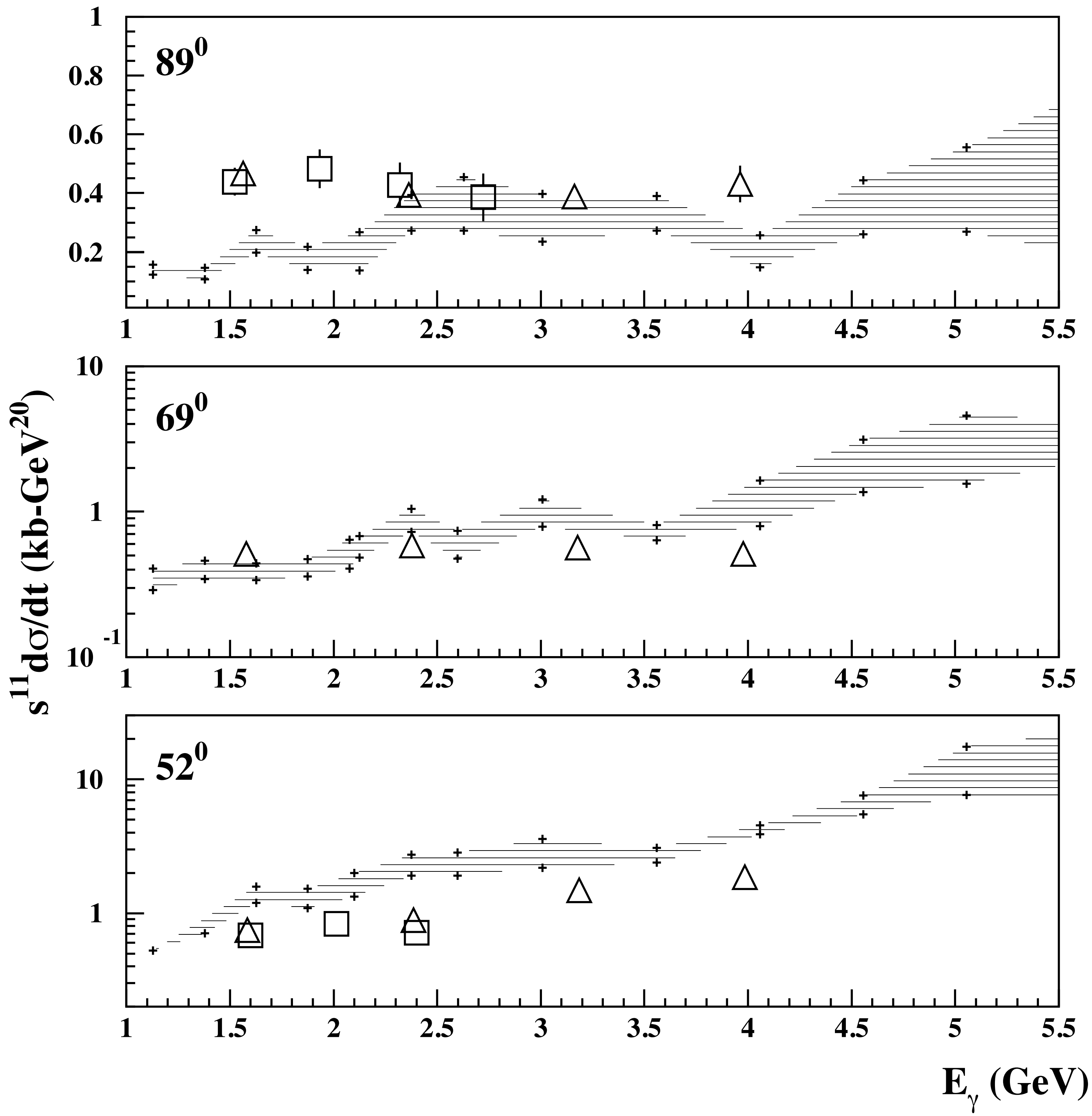
$$s = (k_\gamma + p_d)^2 = (p_p + p_n)^2$$
$$t = (k_\gamma - p_p)^2 = (p_d - p_n)^2$$
$$\tilde{t} = (k_\gamma + \frac{p_d}{2} - p_p)^2 = (\frac{p_d}{2} - p_n)^2$$

$\theta_{cm} = 90^0$

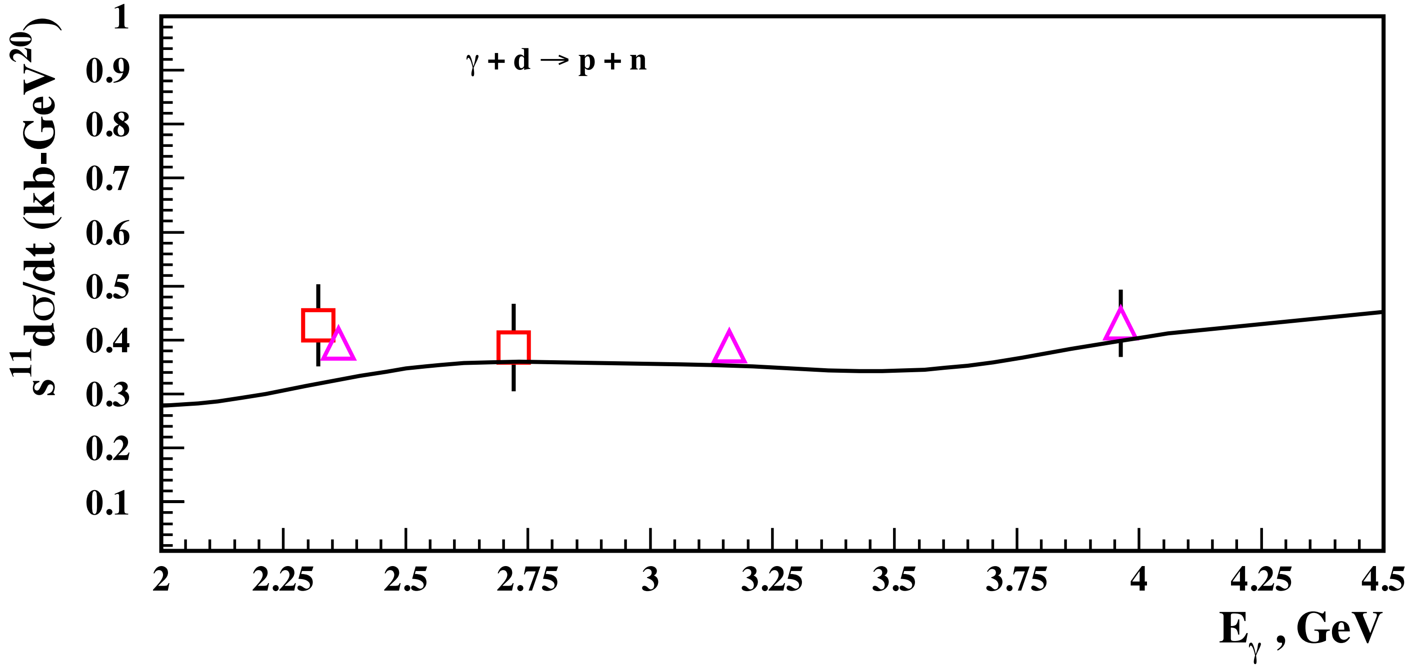
$\tilde{\theta}^{pn}_{cm} \approx 60^0$

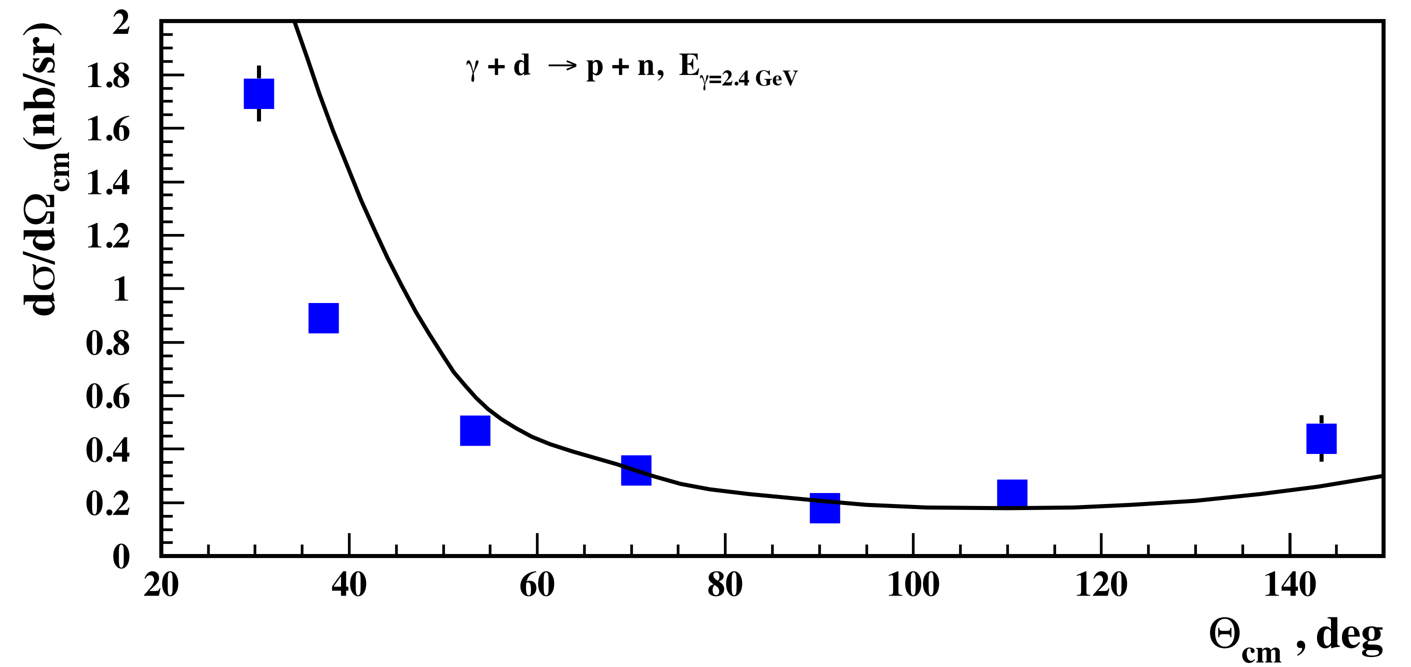
Frankfurt, Miller, M.S. Strikman
PRL 2000

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



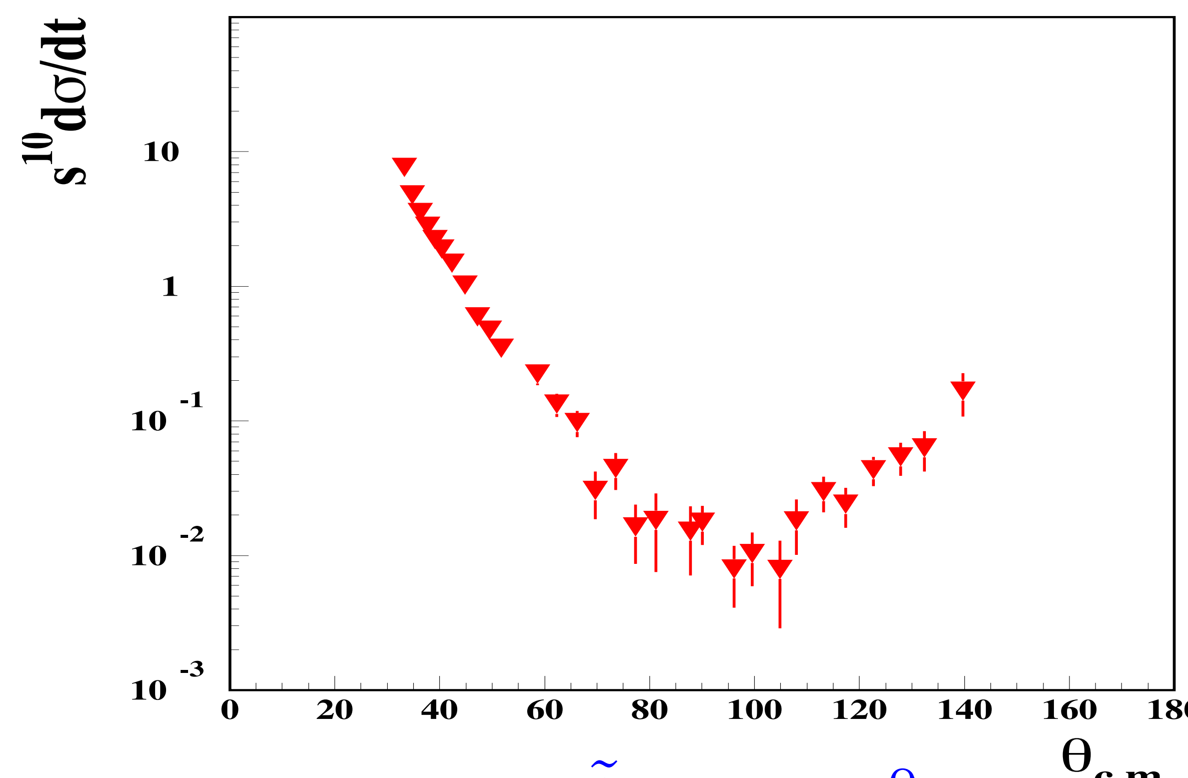
$\gamma + d \to p + n$



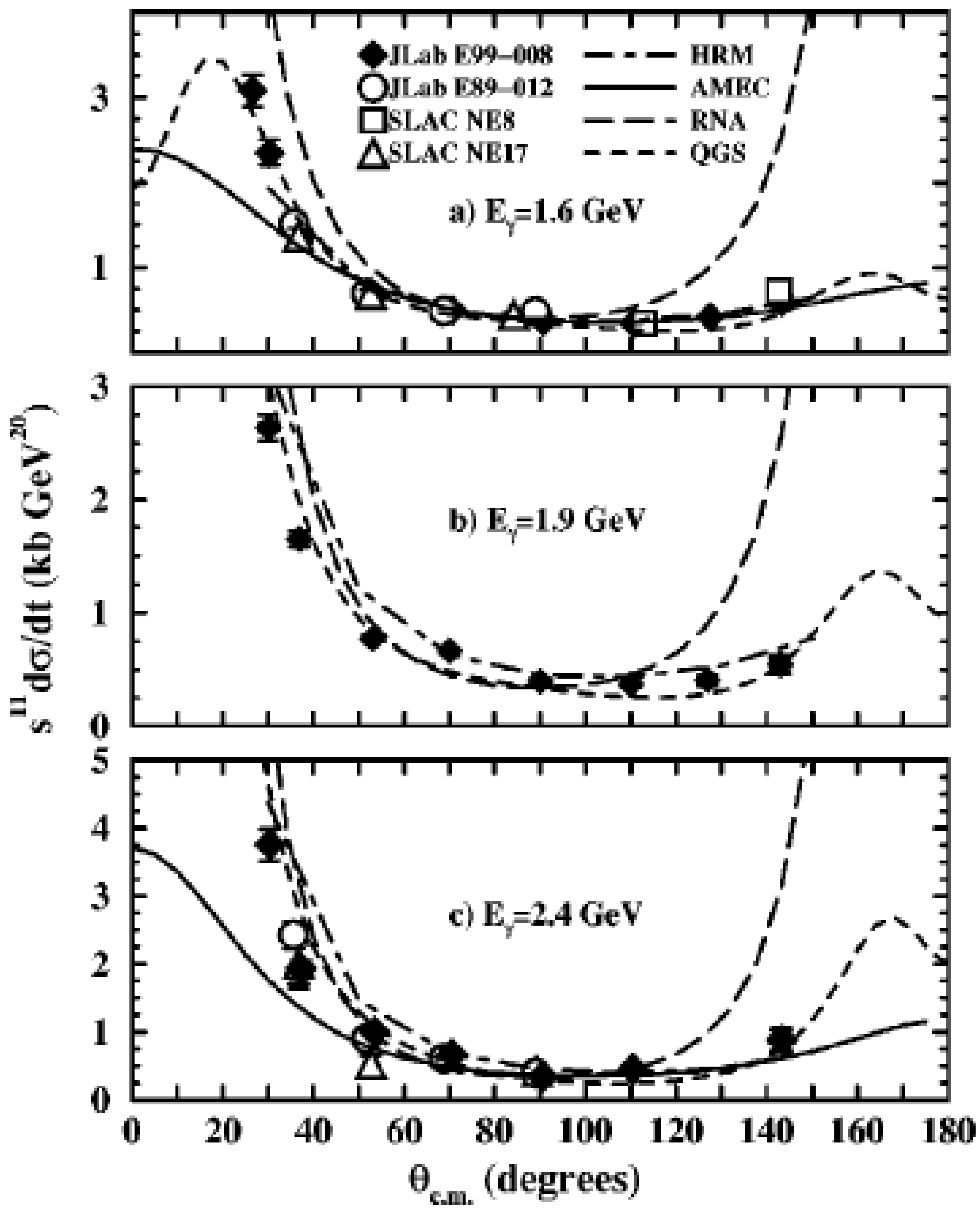


$\theta_{cm} = 90^0$

$pn \to pn$



$\tilde{\theta}^{pn}_{cm} \approx 60^0$


JLab E99–008
JLab E89–012
SLAC NE8
SLAC NE17
HRM
AMEC
RNA
QGS
a) E_γ=1.6 GeV
b) E_γ=1.9 GeV
c) E_γ=2.4 GeV
$s^{11}d\sigma/dt$ (kb GeV^{20})
$\theta_{c.m.}$ (degrees)

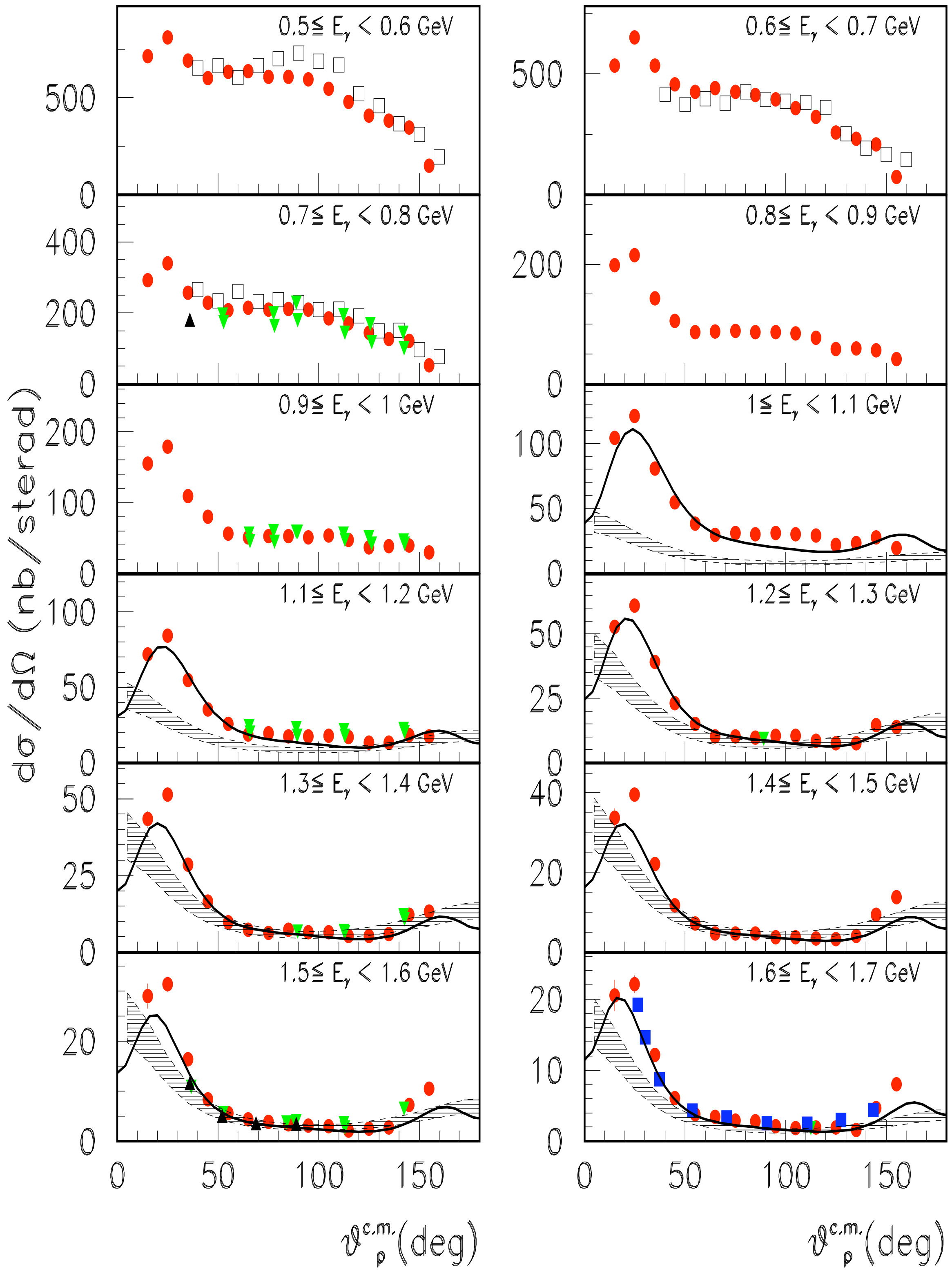


FIG. 7: (Color) Angular distributions of the deuteron photodisintegration cross section measured by the CLAS (full/red circles) in the incident photon energy range 0.50 − 1.70 GeV. Results from Mainz [26] (open squares, average of the measured values in the given photon energy intervals), SLAC [5, 6, 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.

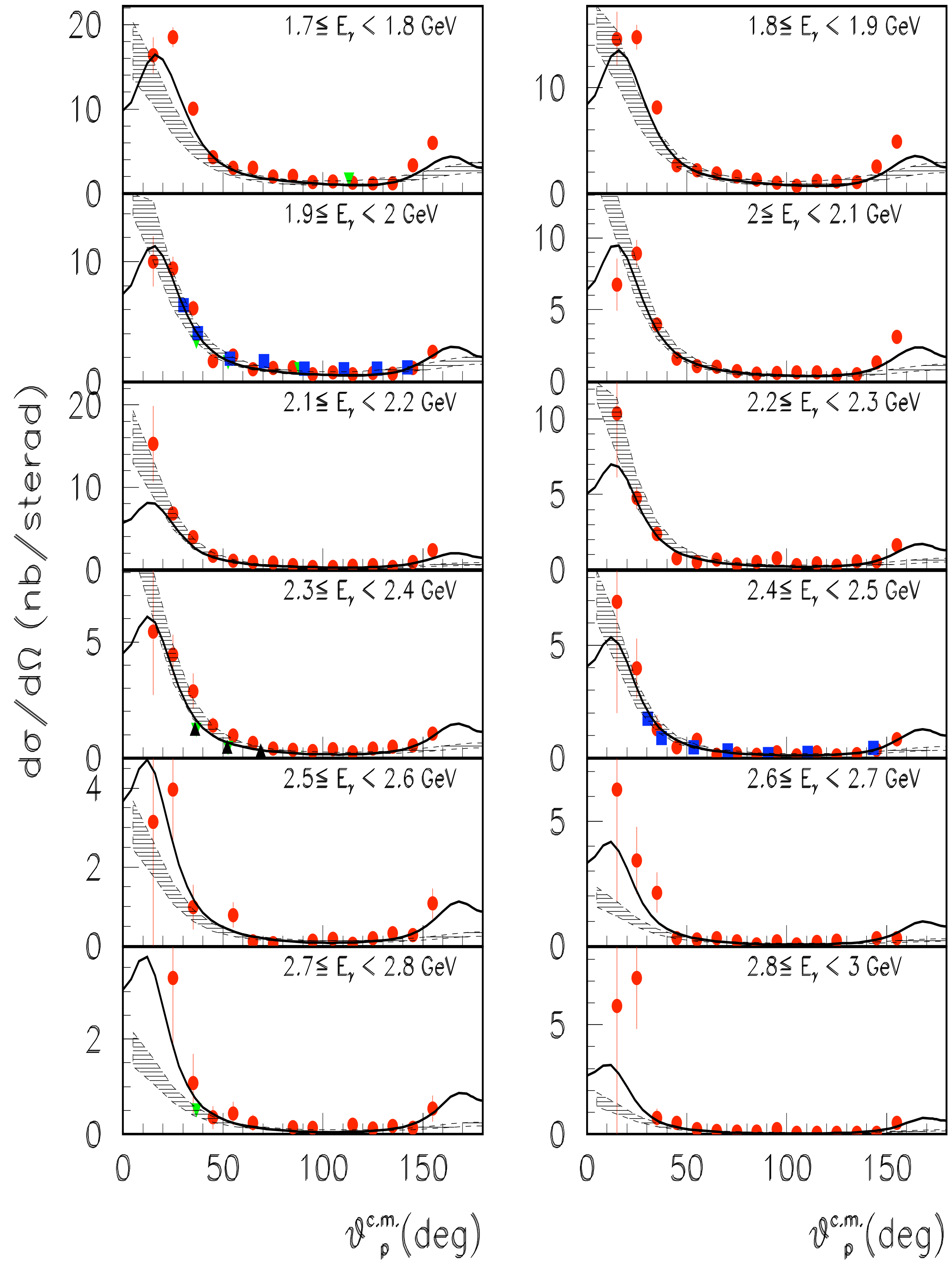
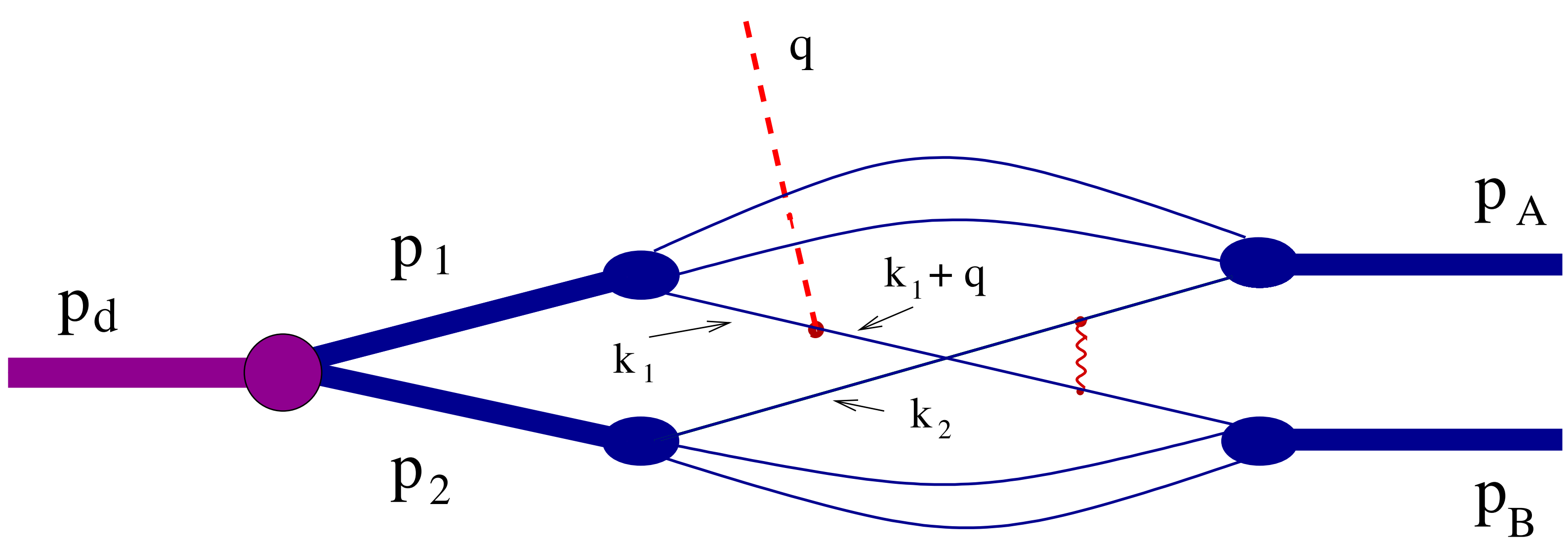


FIG. 8: (Color) Same as Fig. 7 for photon energies 1.7 − 3.0 GeV.

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.

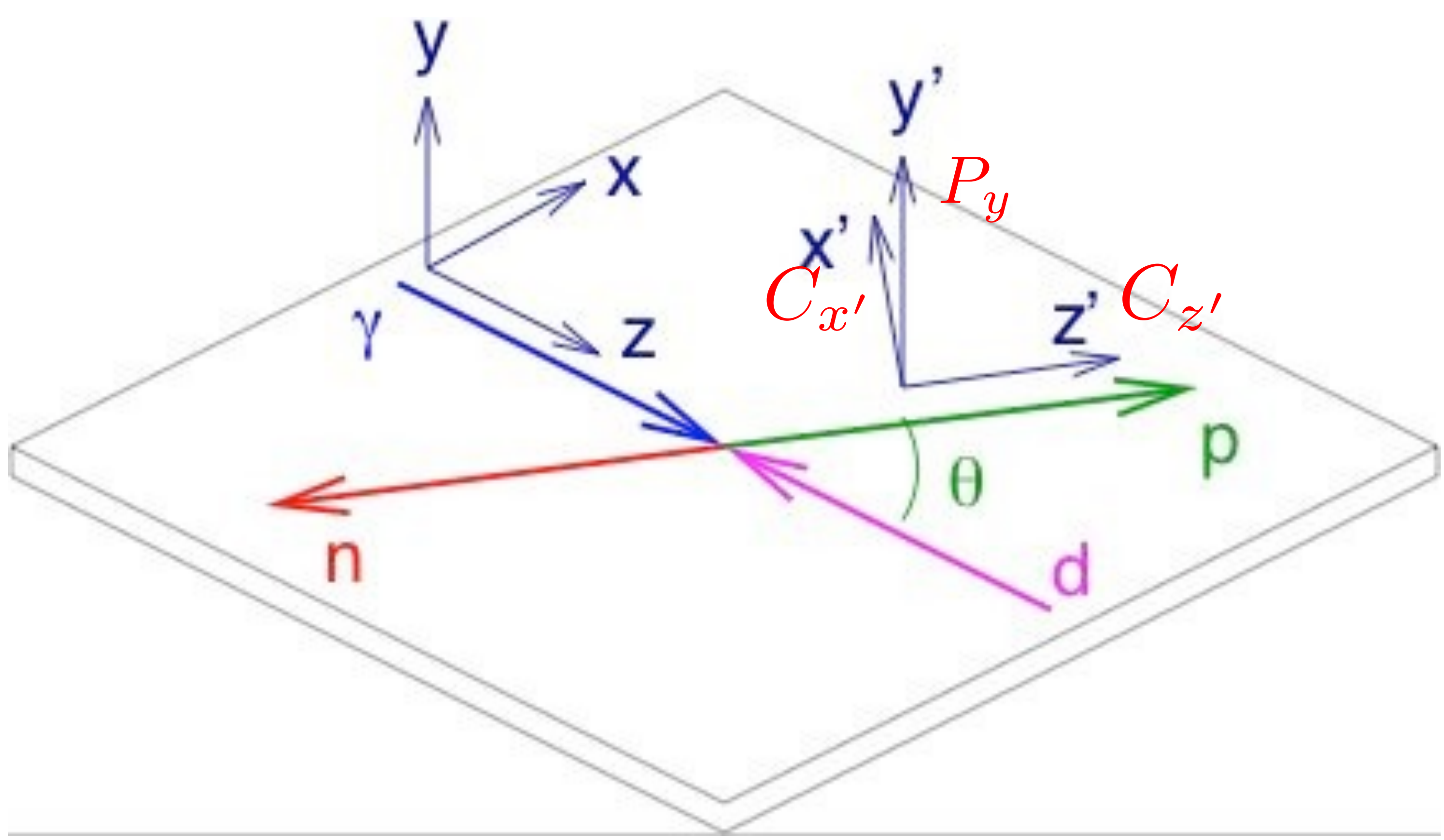


Polarization Observables

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

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

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



Gilman, Gross, 2002

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

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

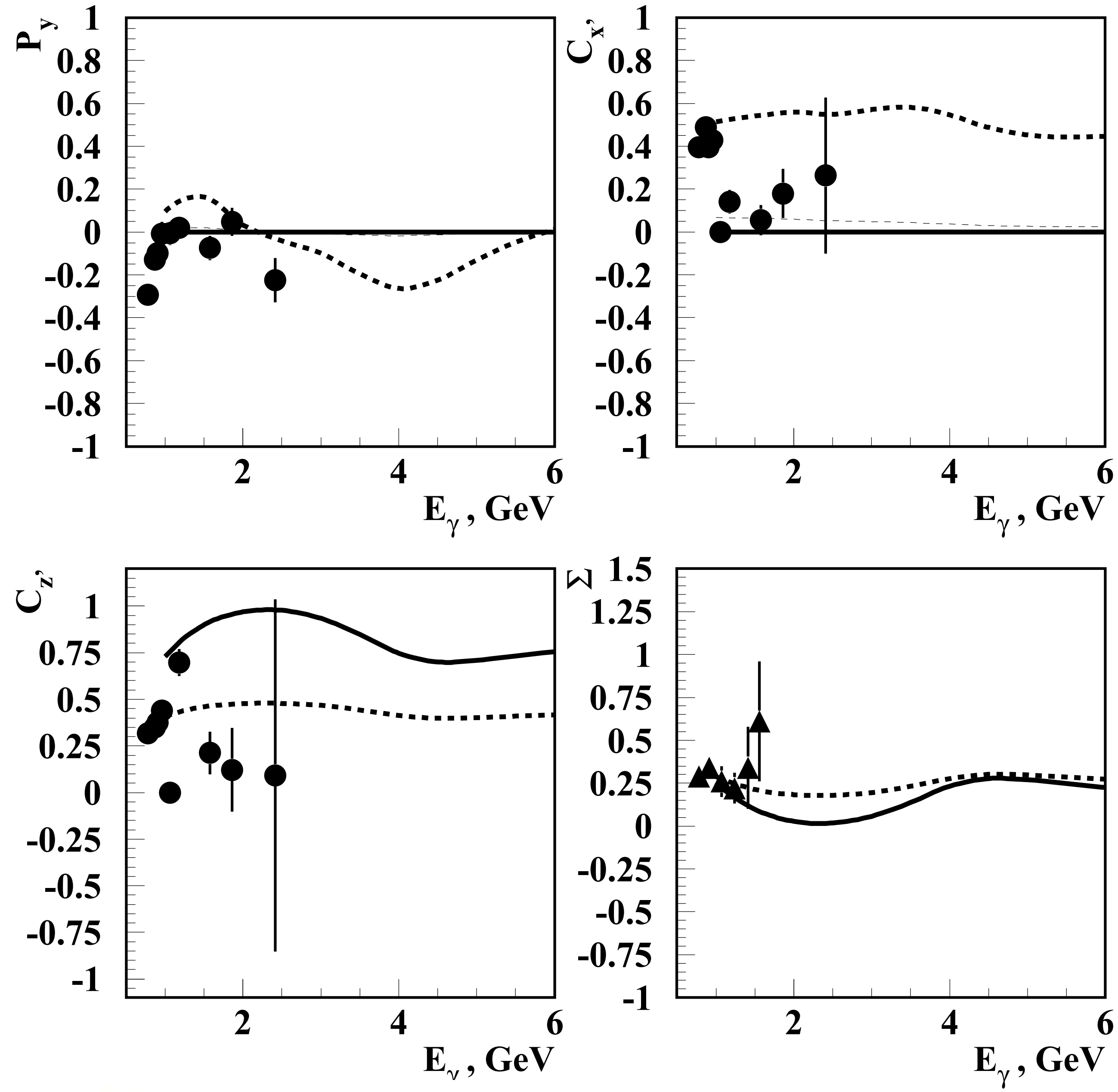
$$C_{z'} = \frac{2|\phi_1|^2-2|\phi_2|^2+|\phi_3|^2-|\phi_4|^2}{2|\phi_1|^2+2|\phi_2|^2+|\phi_3|^2+|\phi_4|^2+6|\phi_5|^2}$$

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

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

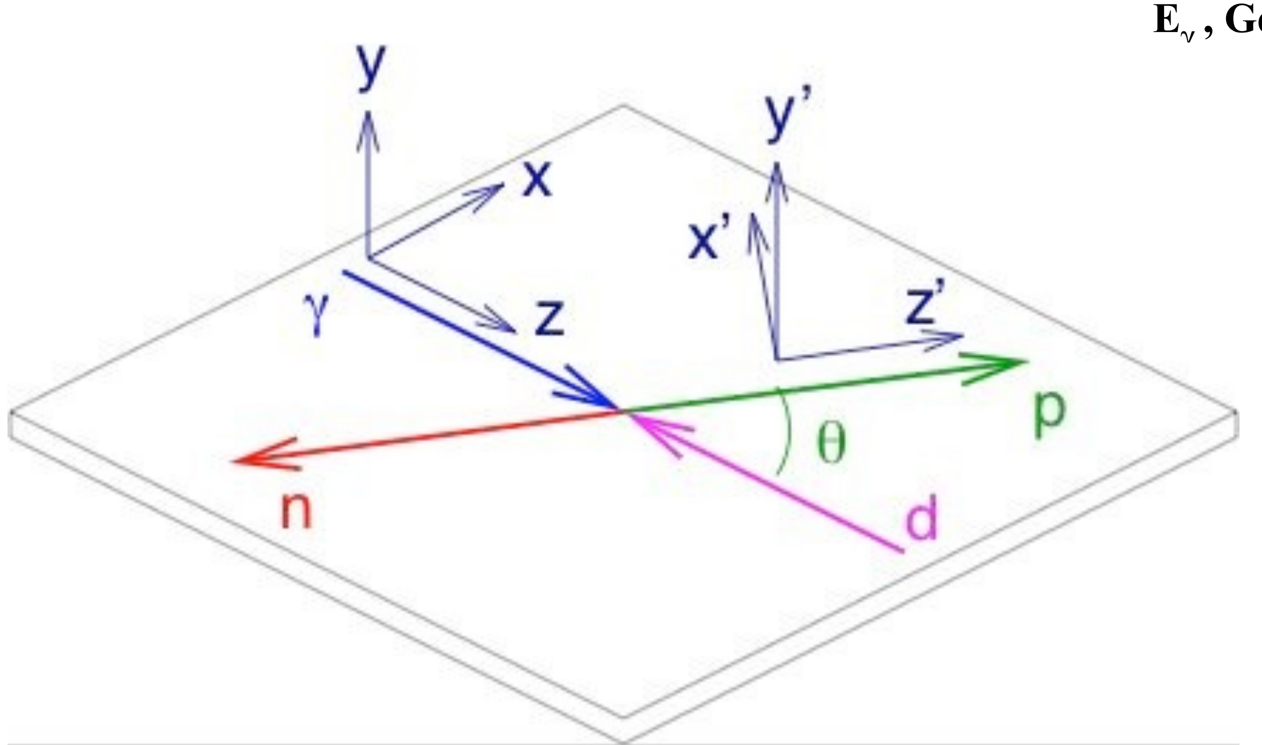
$$|\phi_1| \geq |\phi_3|, |\phi_4| > |\phi_5| > |\phi_2|.$$

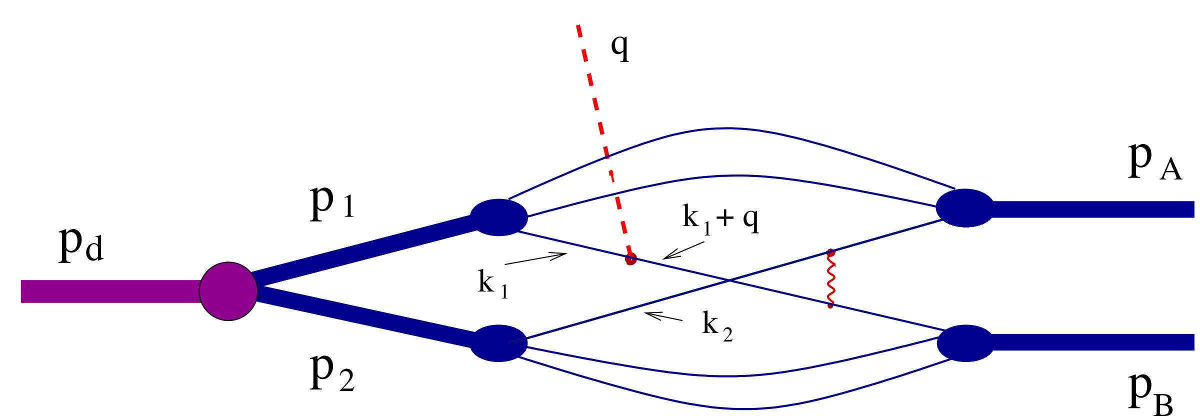
Sargsian, Phys. Lett. B 2004

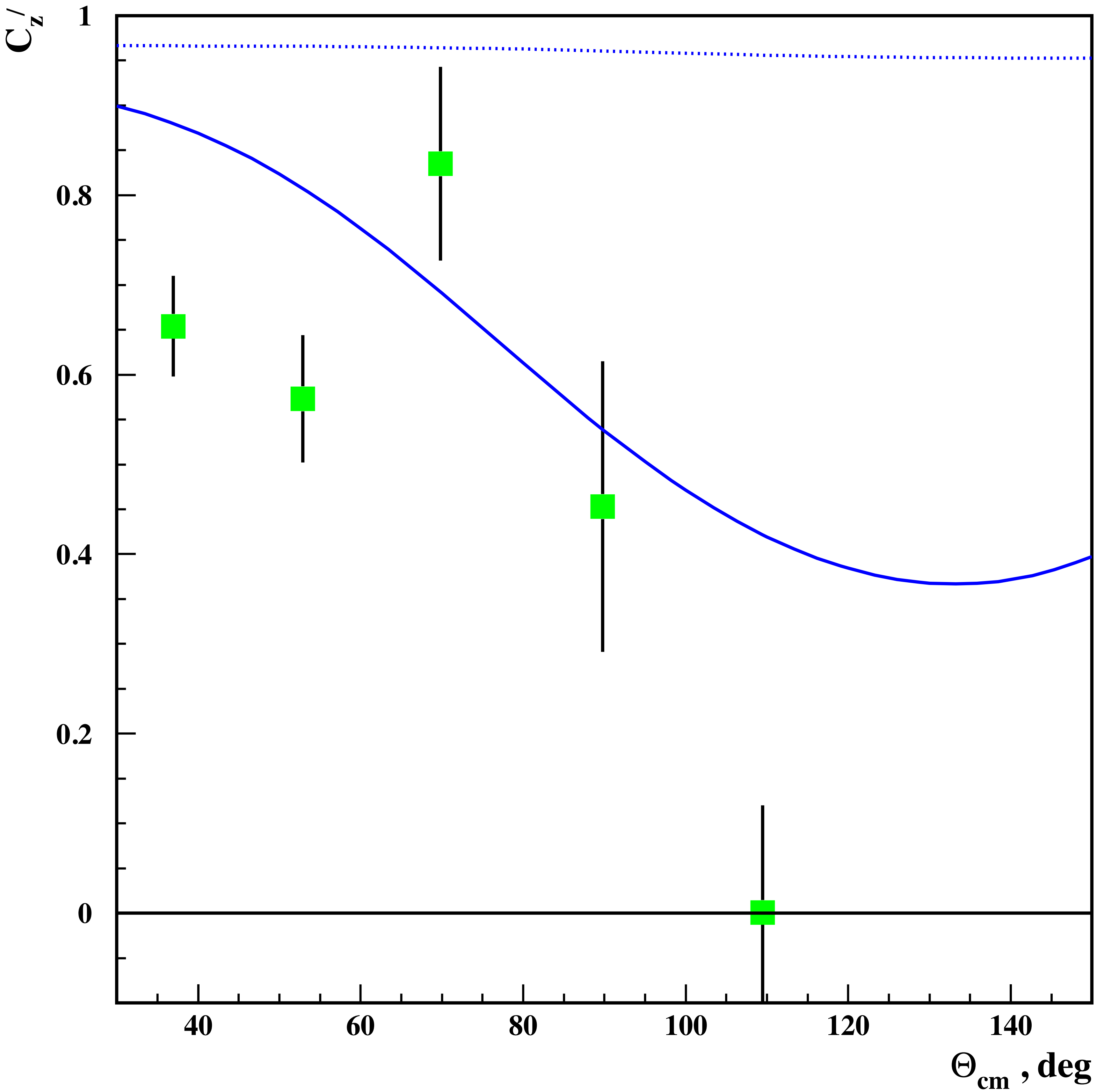


$$C_{z'} = 0.5 \div 1.0$$

Data, JLab 2002



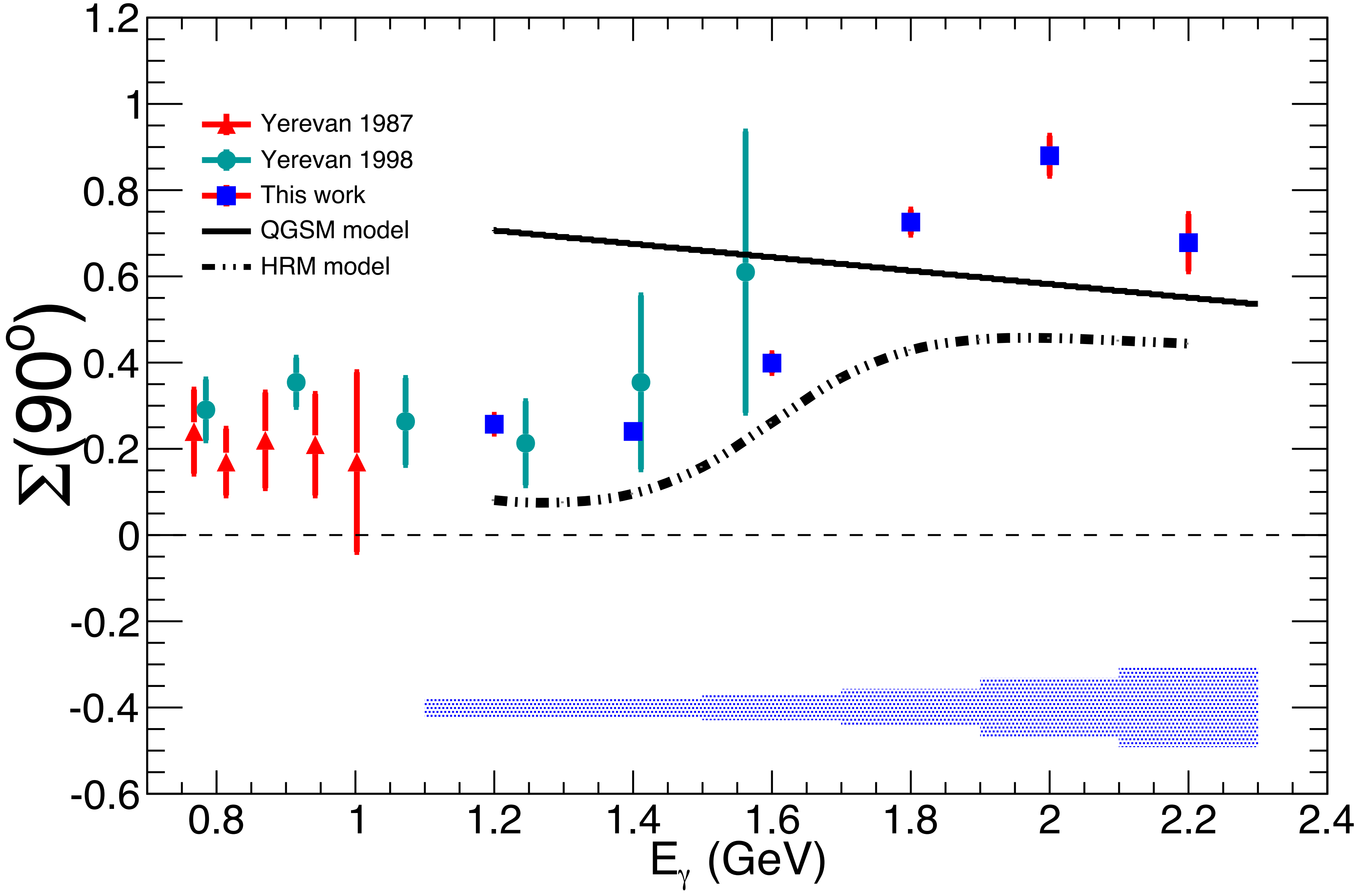


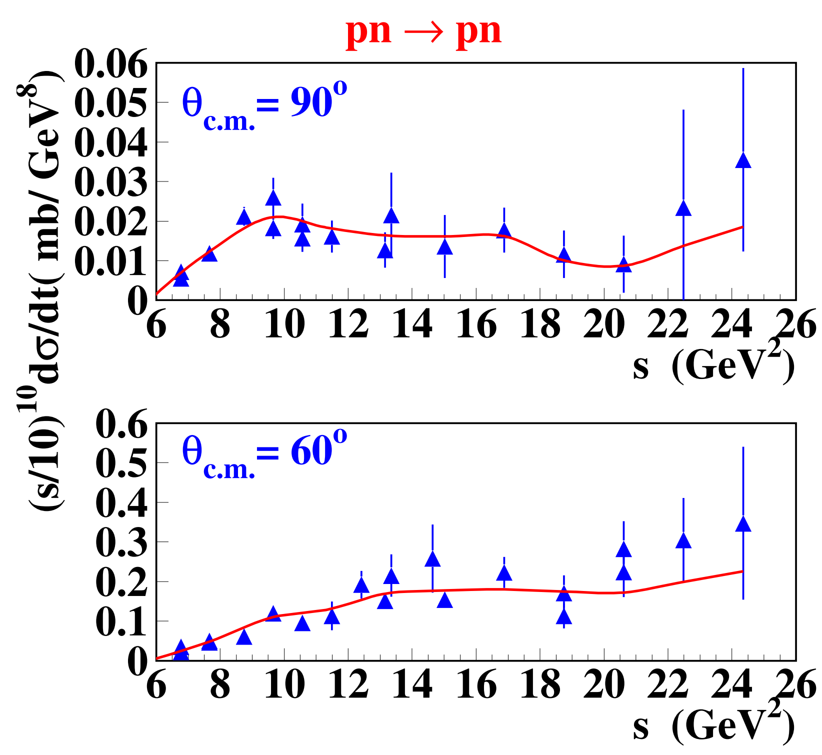


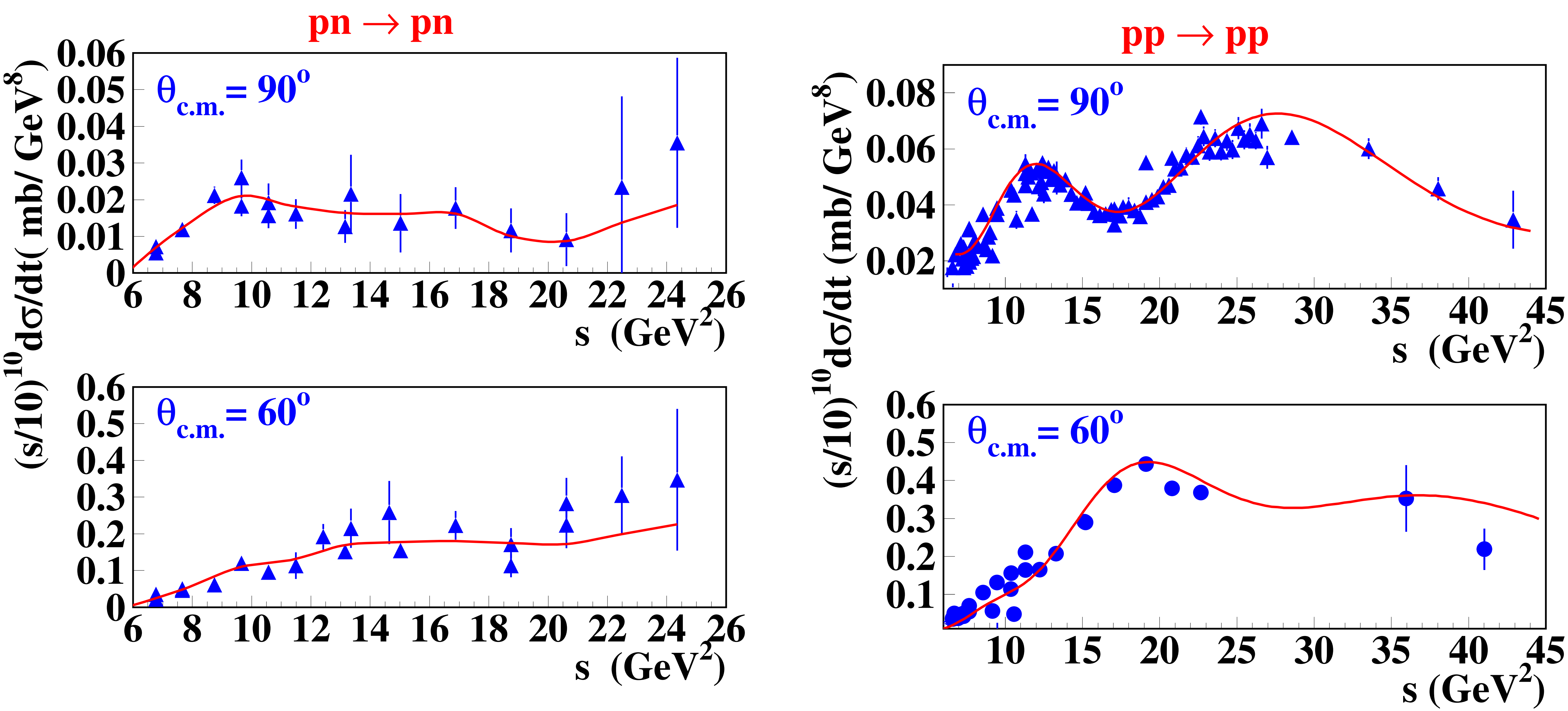
Jiang et al, PRL2007

N. Zachariou et al, PRC 2015

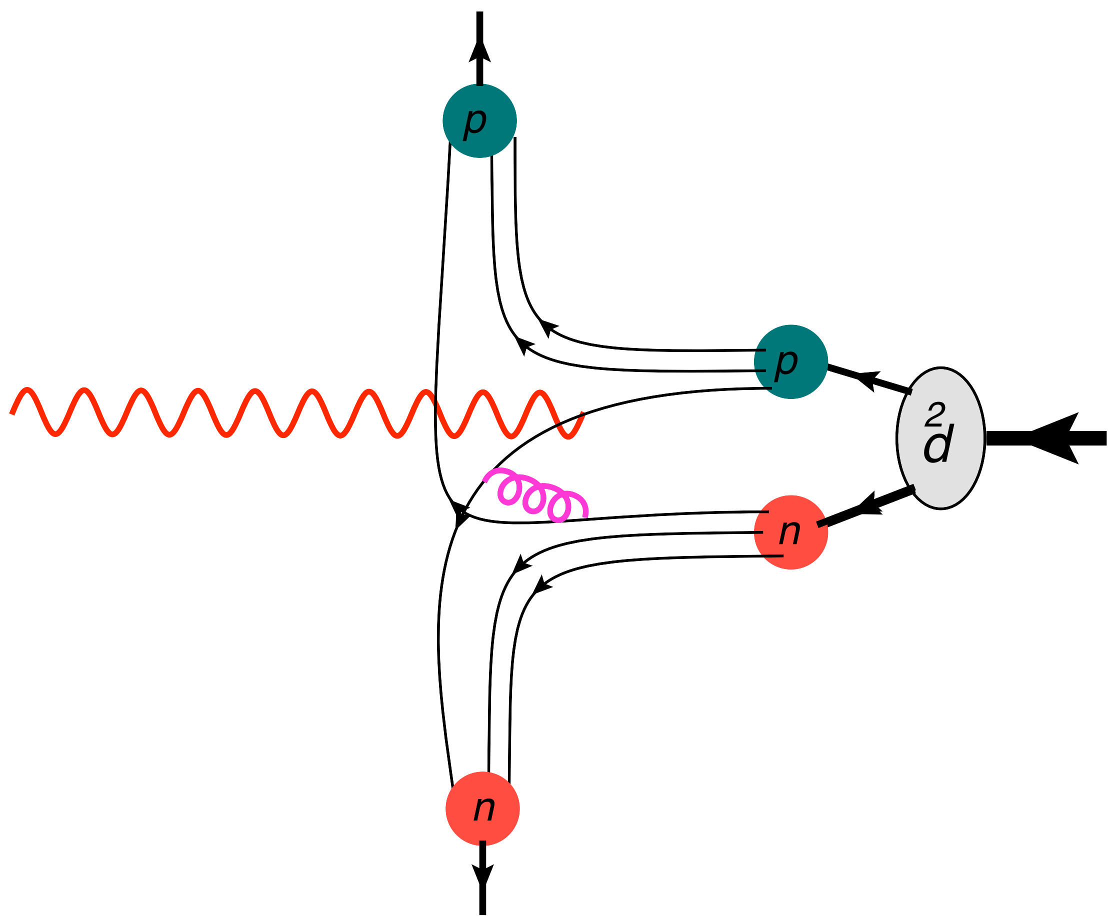
Y. Ilieava talk





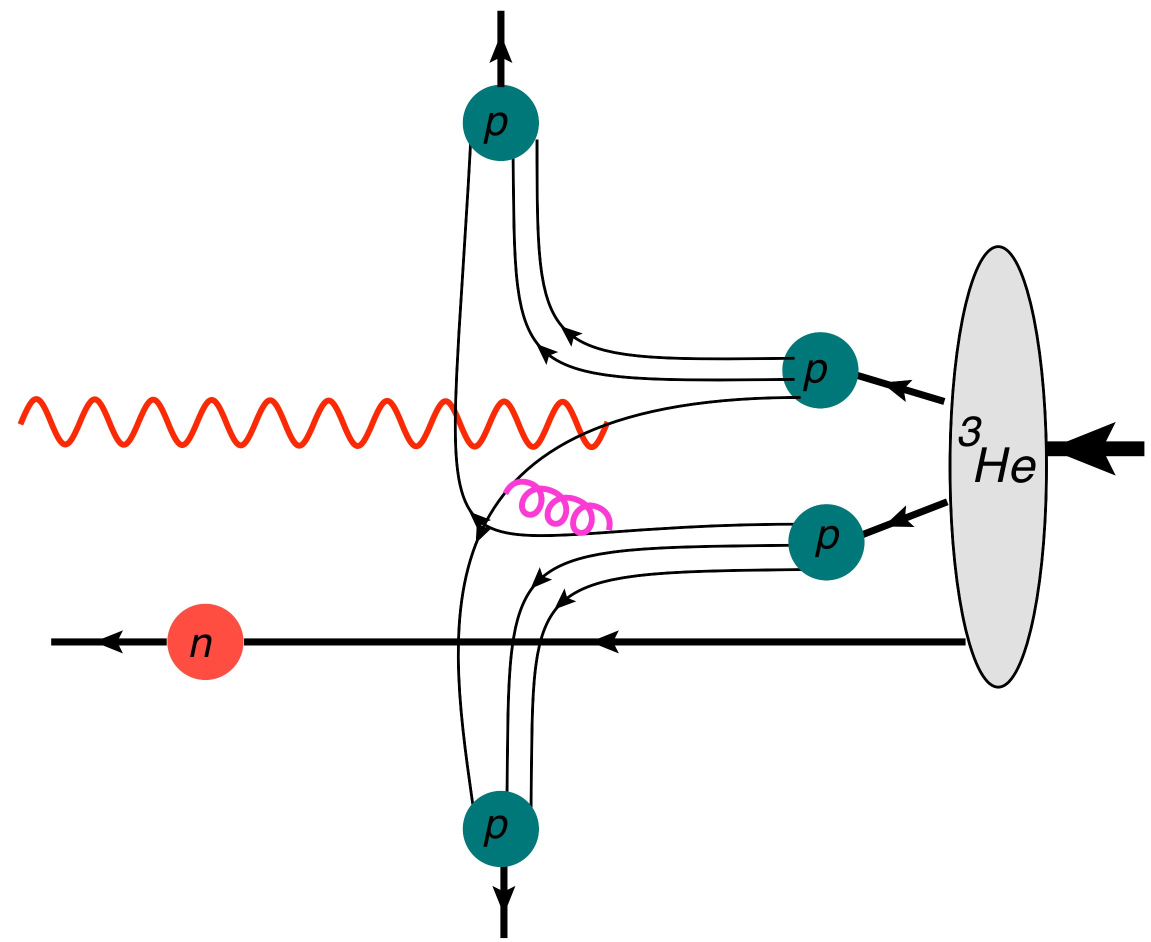

pn → pn
pp → pp
θc.m.= 90°
θc.m.= 60°
(s/10)^10 dσ/dt(mb/ GeV^8)
(s/10)^10 dσ/dt (mb/ GeV^8)
s (GeV^2)

Break up of pn from the deuteron



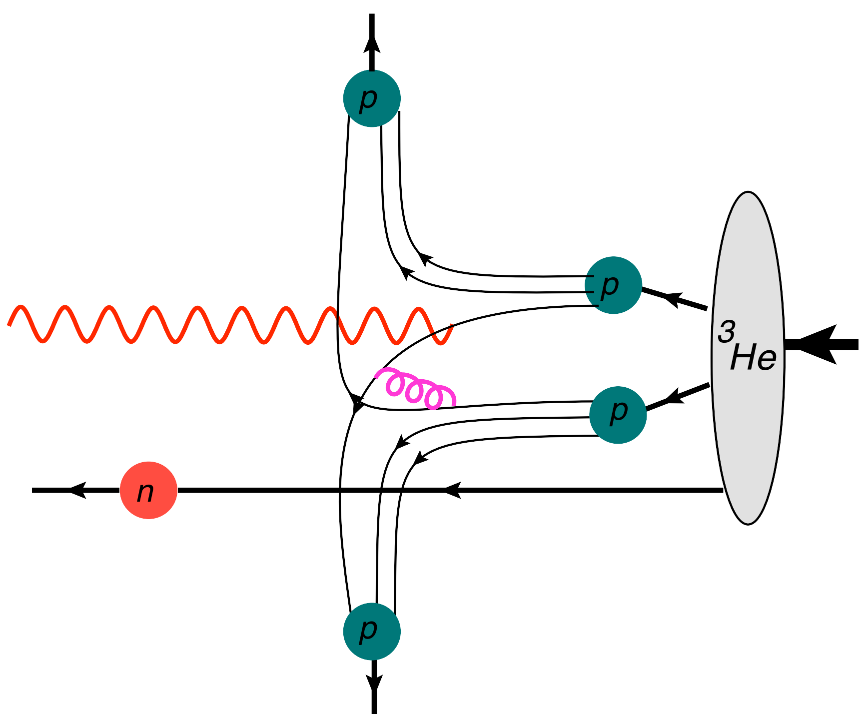
Break up of pp from Helium 3

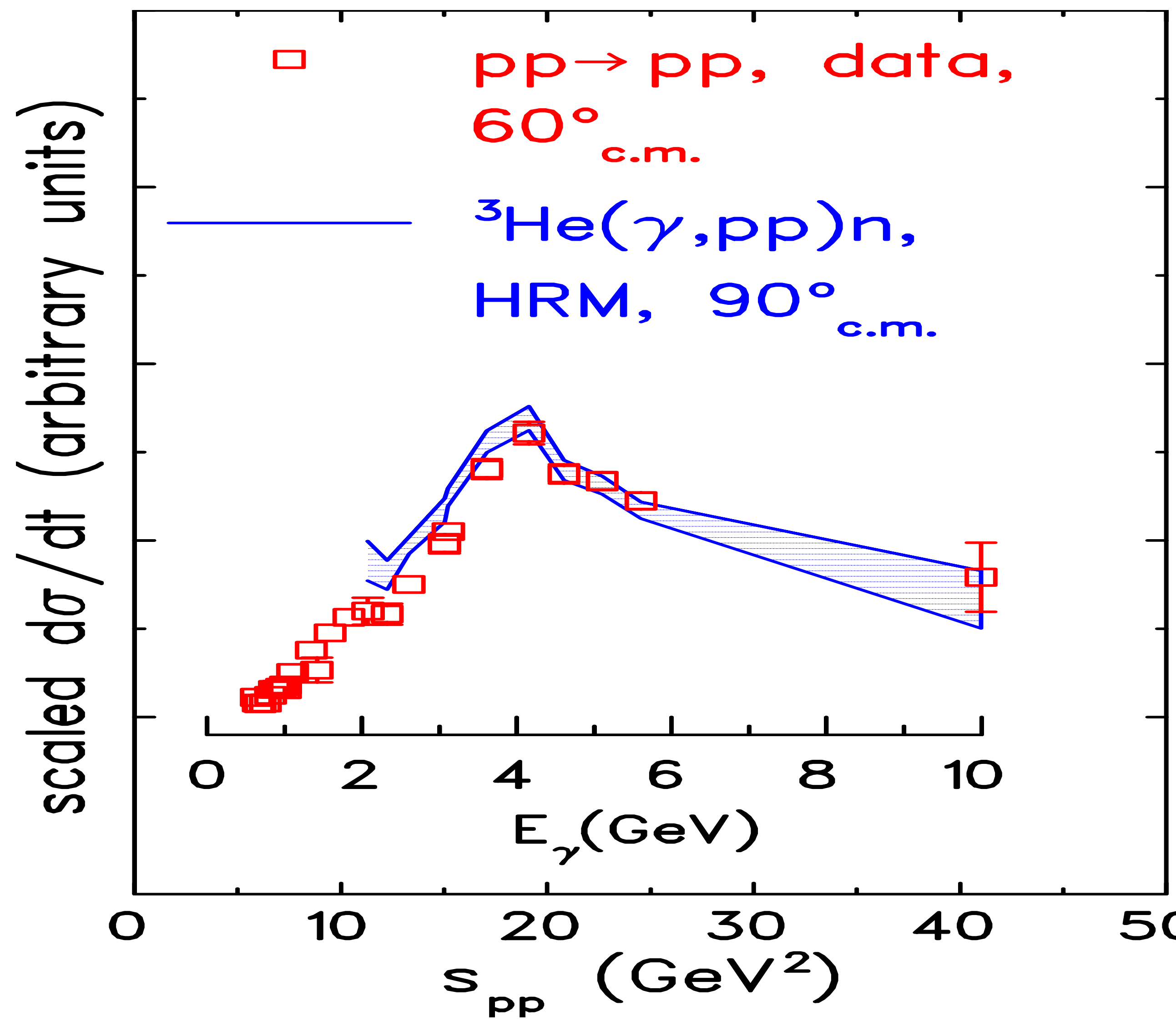
Brodsky, Frankfurt, Gilman, Hiller, Miller
Piasetzky, M.S., Strikman
Phys. Lett. B 2004



Break up of pp from Helium 3

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





Friday, April 29, 16

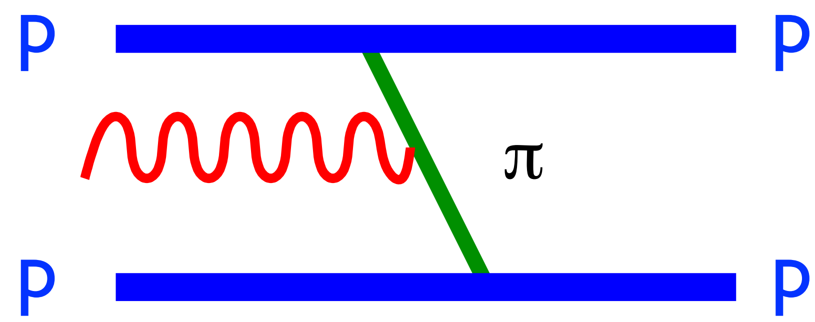
Info from Lower Energies

- Hard Photodisintegration of pp pair: $\gamma + ^3He \rightarrow pp + n$

What is known?

for $E_\gamma \leq 0.5 GeV$

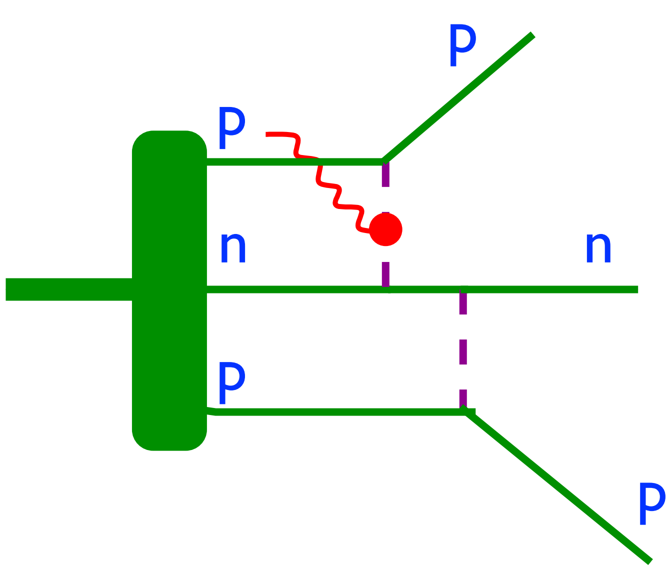
$$\sigma_{\gamma pp} \ll \sigma_{\gamma pn}$$



~ 0

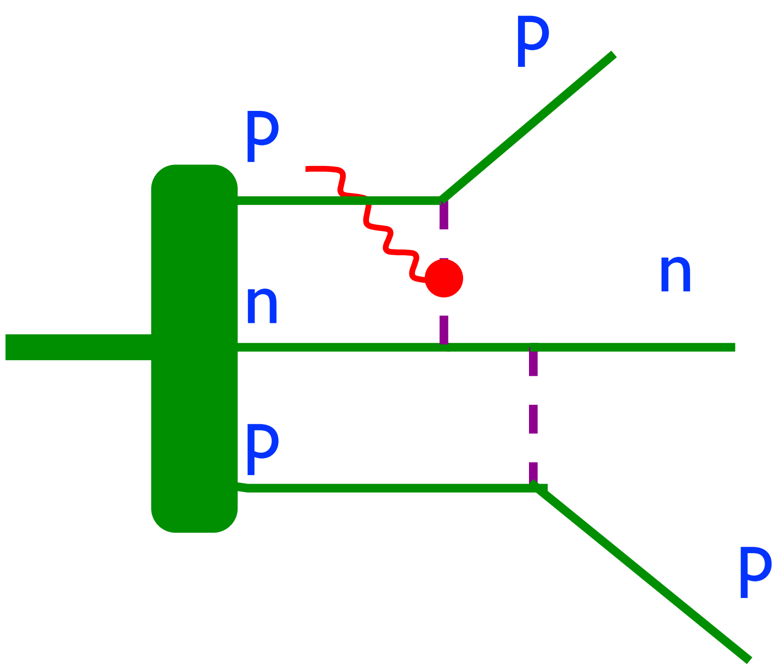
Laget, Nucl.Phys. 1989

- Three Body Processes are Dominant

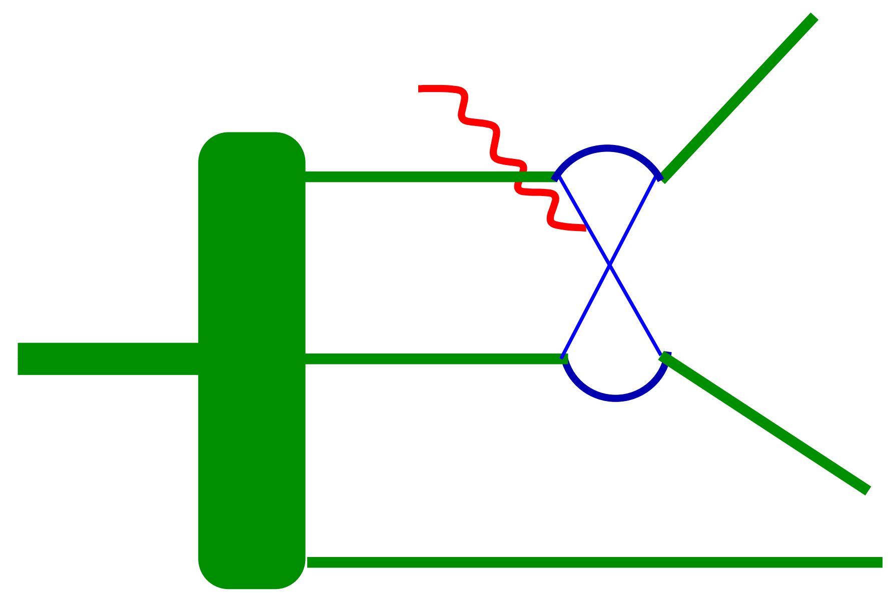


$$\frac{\sigma(\gamma^3He \rightarrow pp)}{\sigma(\gamma^3He \rightarrow pn)} \approx 1\%$$

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



$\sim s^{-13}$

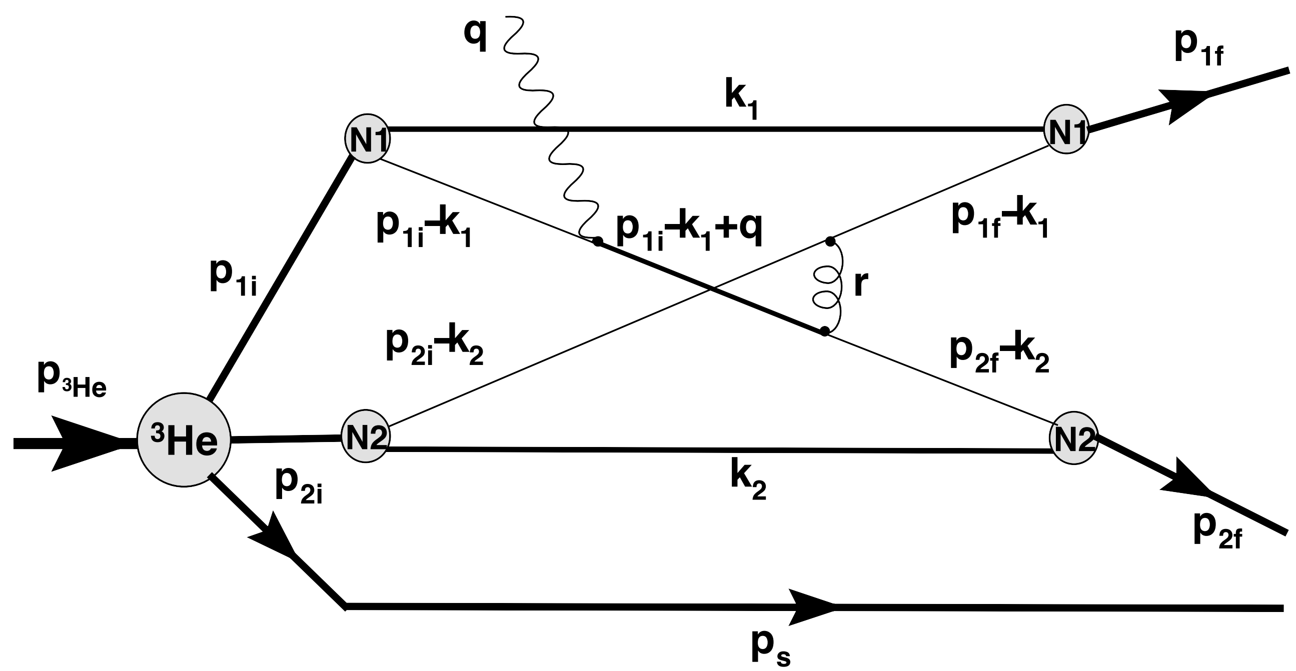


$\sim s^{-11}$

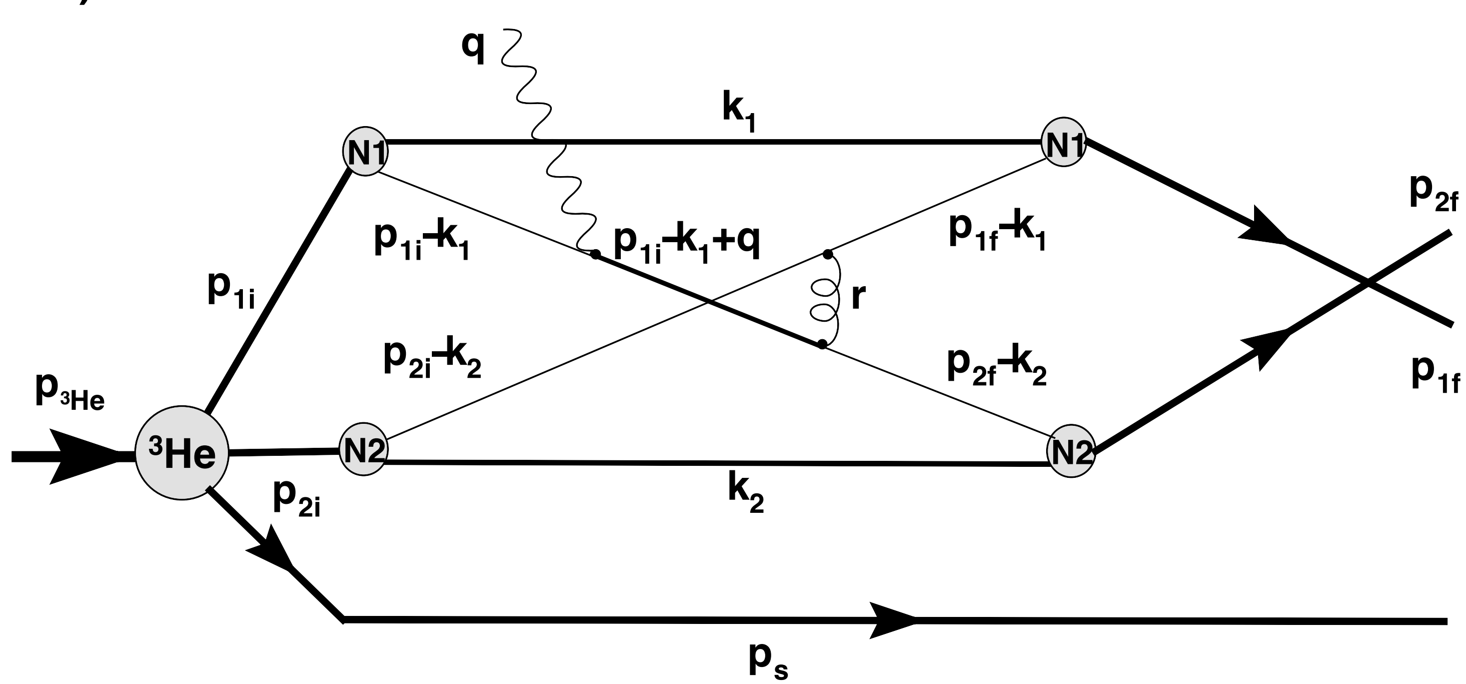
Considering $\gamma + ^3He \rightarrow (NN) + N$

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

a)



b)



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

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

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

$\phi_3 \approx -\phi_4$ For pp

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

$$S_{12}(t_1, t_2, \alpha, \vec{p}_s) = N_{NN}\sum_{\lambda_1=\lambda_2=-\frac{1}{2}}^{\frac{1}{2}}\sum_{\lambda_3=-\frac{1}{2}}^{\frac{1}{2}}\left|\int \Psi^{\frac{1}{2}}_{{}^3\text{He,NR}}(\vec{p}_1, \lambda_1, t_1; \vec{p}_2, \lambda_2, t_2; \vec{p}_s, \lambda_3) m_N \frac{d^2p_\perp}{(2\pi)^2}\right|^2,$$

$$S_{34}(t_1, t_2, \alpha, \vec{p}_s) = N_{NN}\sum_{\lambda_1=-\lambda_2=-\frac{1}{2}}^{\frac{1}{2}}\sum_{\lambda_3=-\frac{1}{2}}^{\frac{1}{2}}\left|\int \Psi^{\frac{1}{2}}_{{}^3\text{He,NR}}(\vec{p}_1, \lambda_1, t_1; \vec{p}_2, \lambda_2, t_2; \vec{p}_s, \lambda_3) m_N \frac{d^2p_\perp}{(2\pi)^2}\right|^2$$

and

$$S_0 = S_{12} + S_{34}.$$

$\phi_3 \approx -\phi_4$ For pp

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

$$\beta = \frac{2(|\phi_3| - |\phi_4|)}{|\phi_1|}$$

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

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

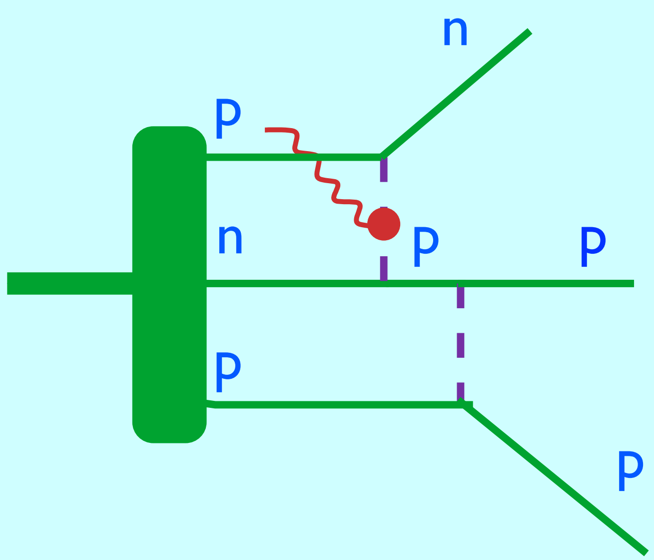
$$\beta = \frac{2(|\phi_3| - |\phi_4|)}{|\phi_1|}$$

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

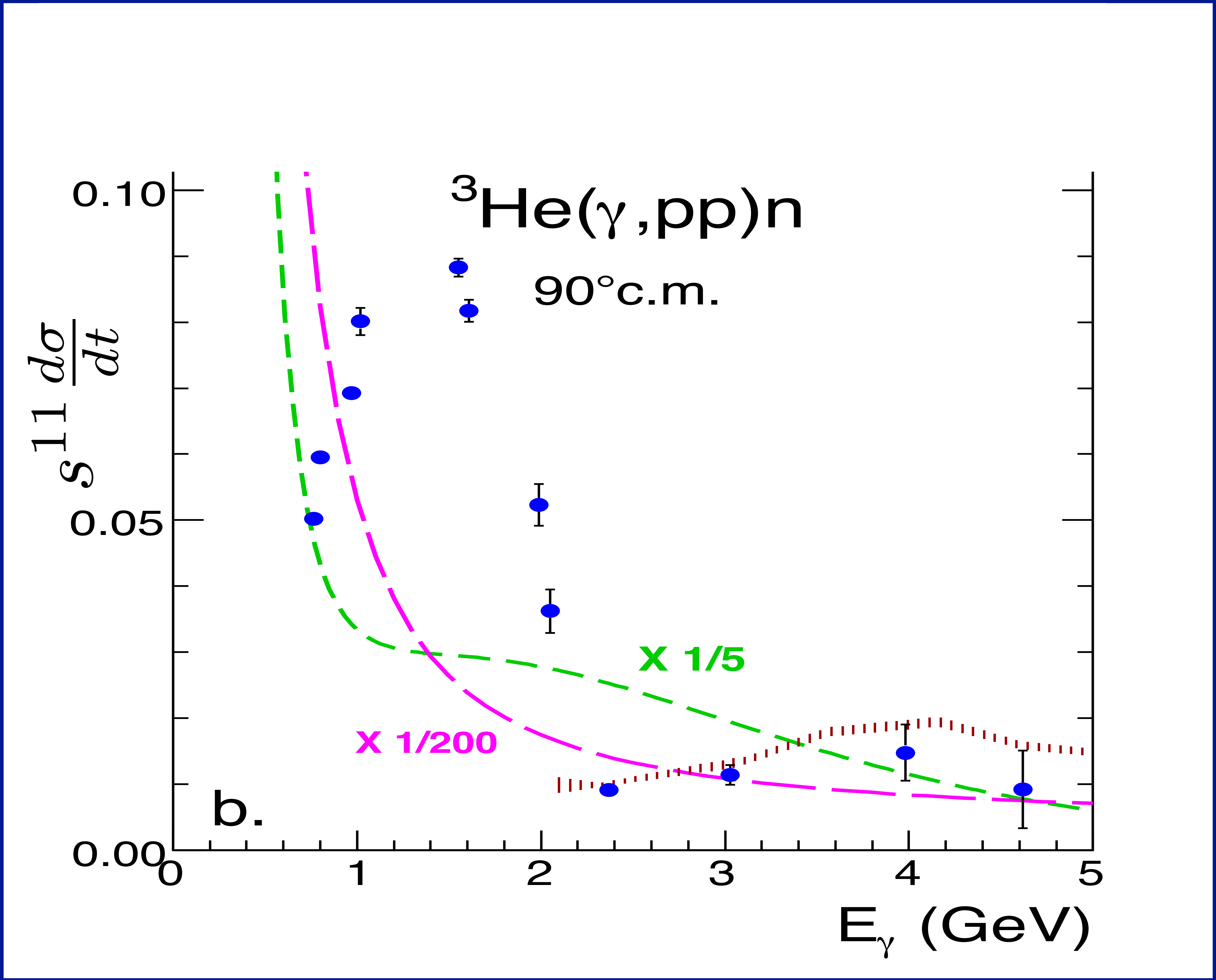
Meson Exchange Picture

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

J-M.Laget, Nucl.Phys. 1989



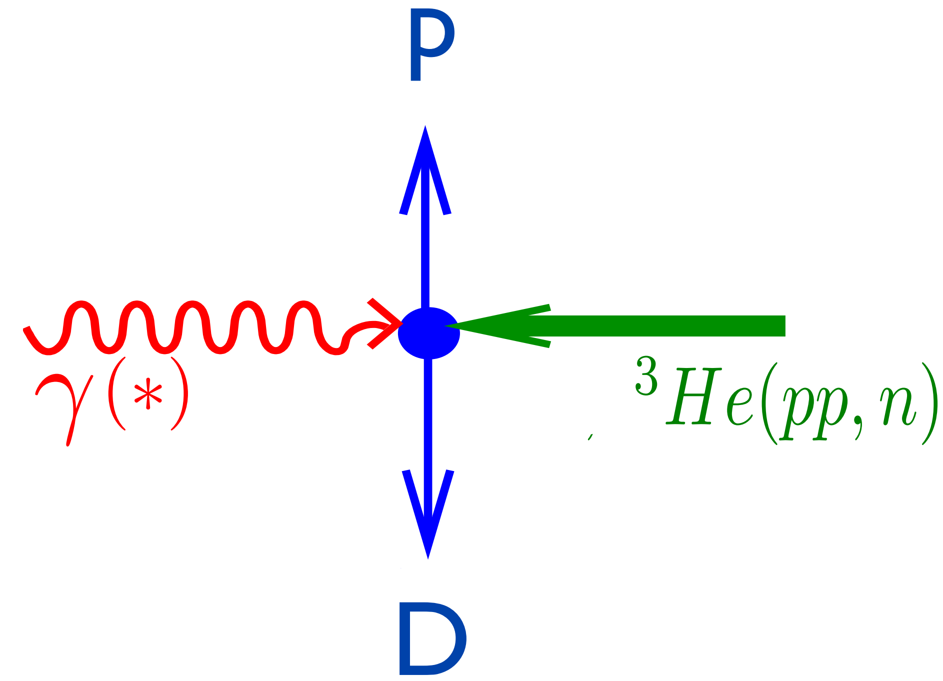
Pomerantz, et al,
Phys. Lett. B 2010

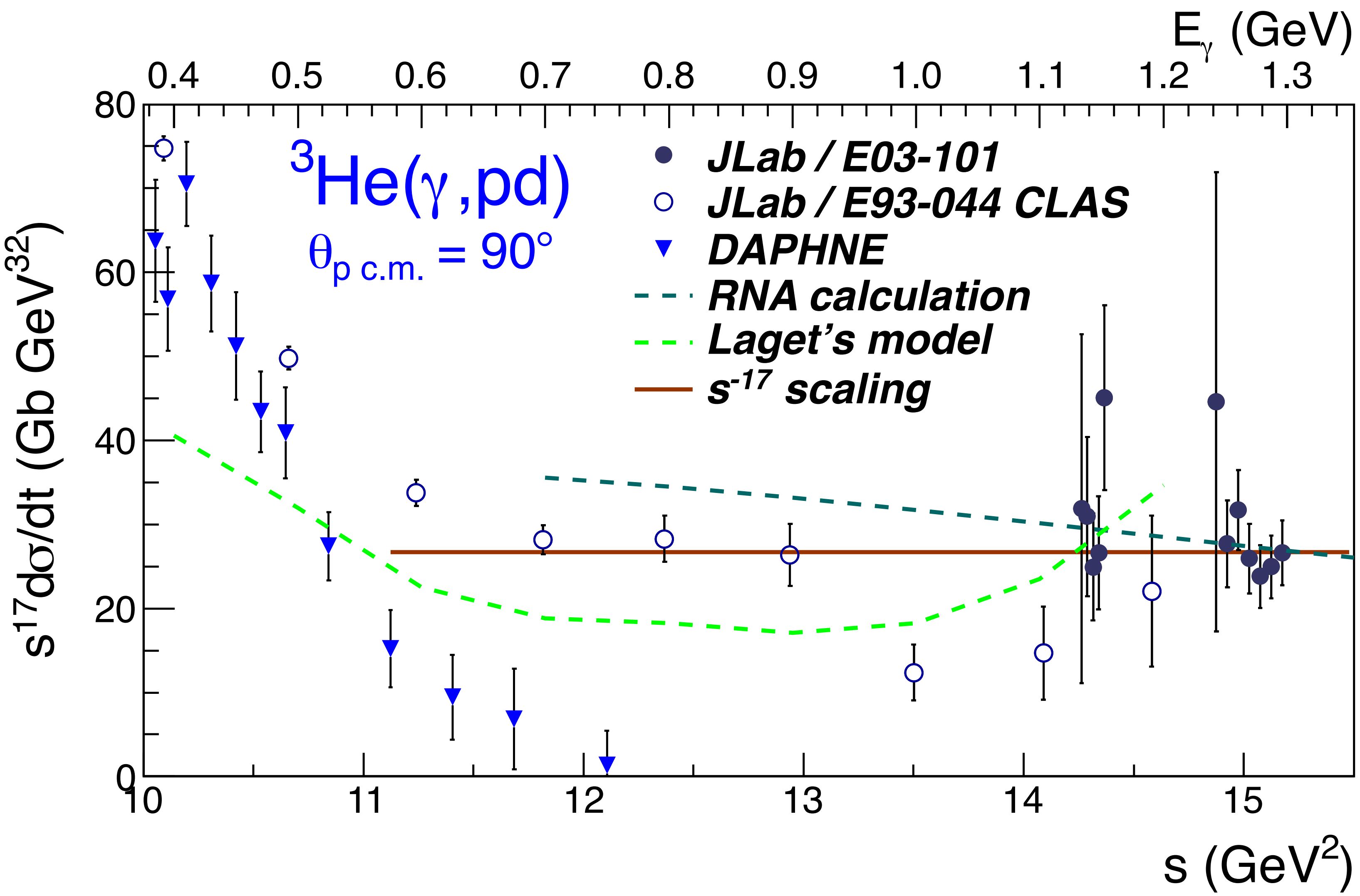


M. S., C.Granados
Phys. Rev. C 2009

What's Now:

p-d break-up 3He and scaling of $s^{17}\frac{d\sigma}{dt}$!

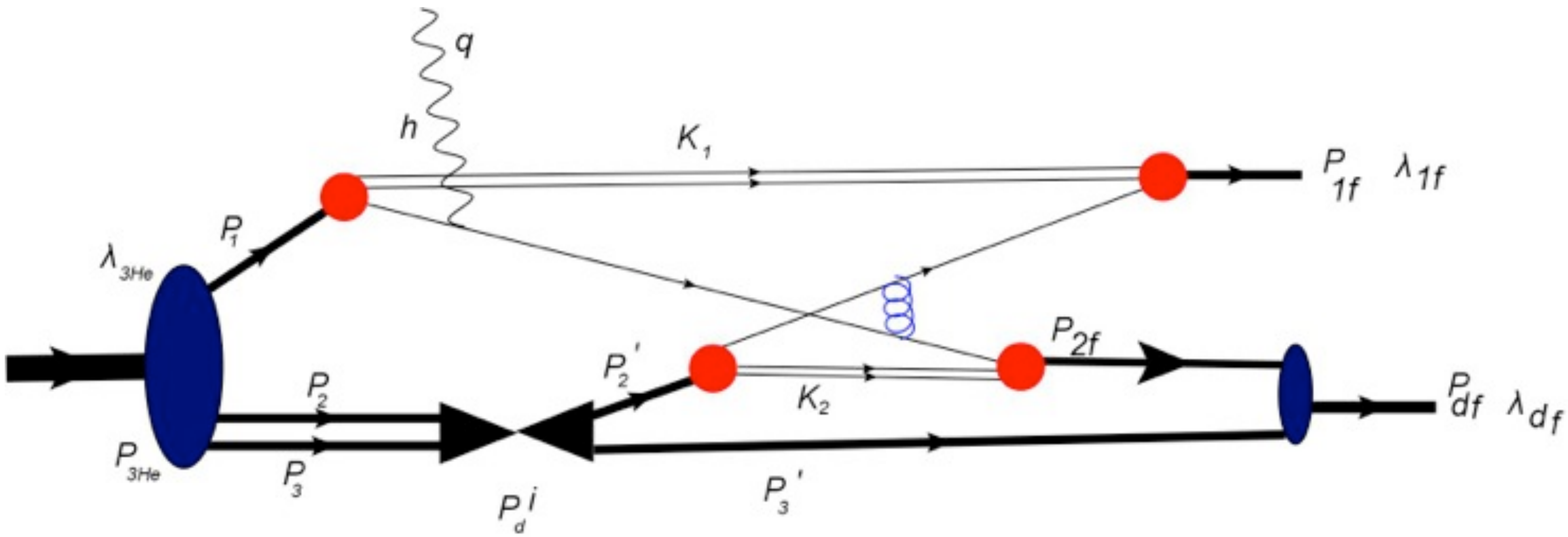


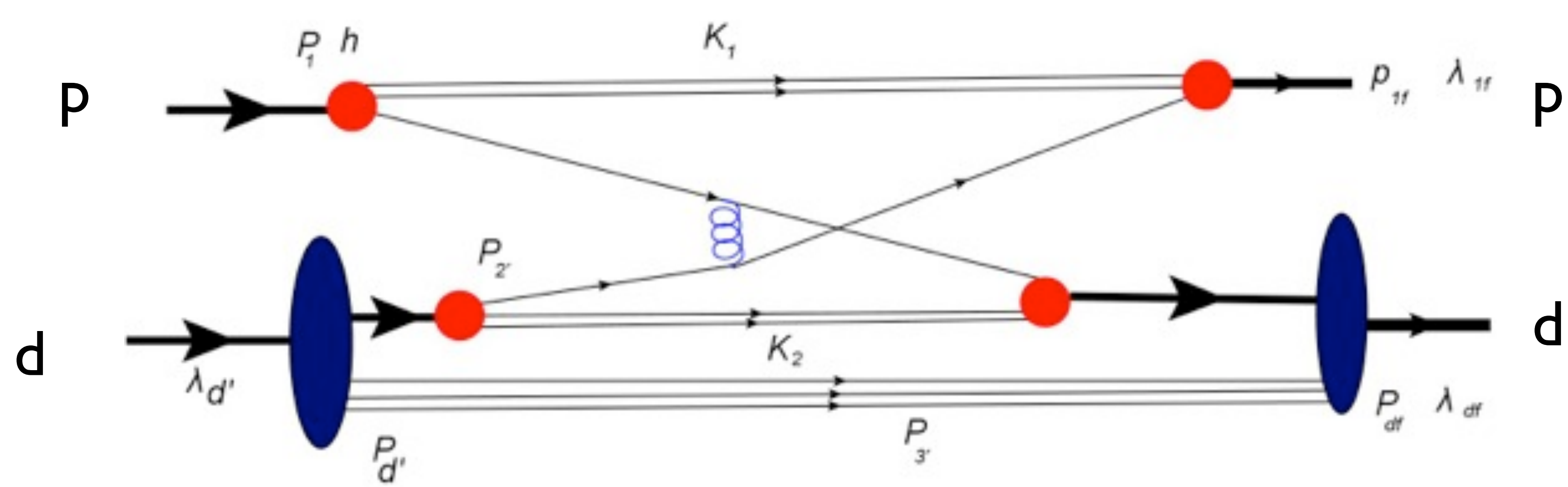


$\sim 0.3nb/GeV^2$

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

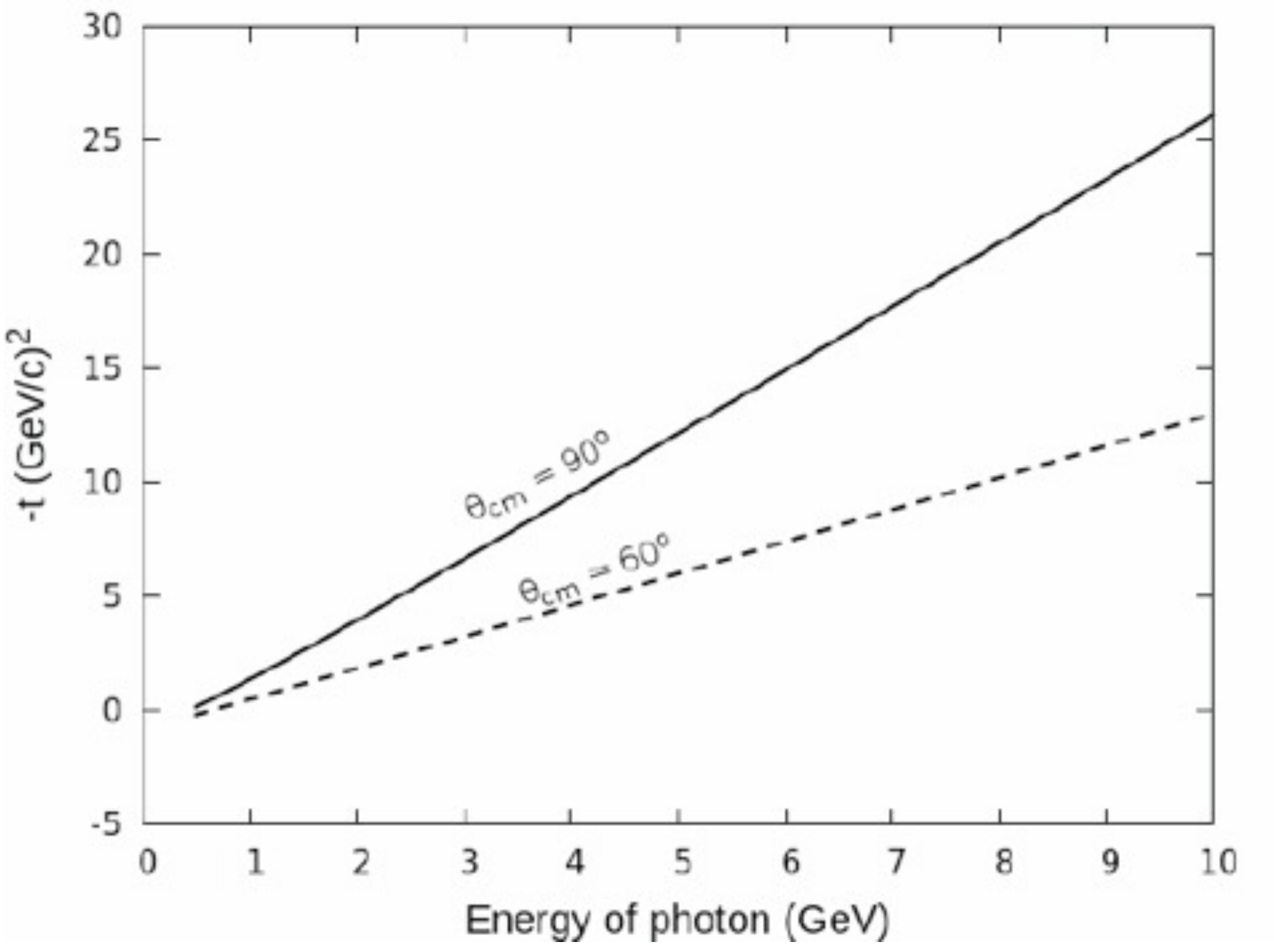
D. Maheswari, M.S., 2016

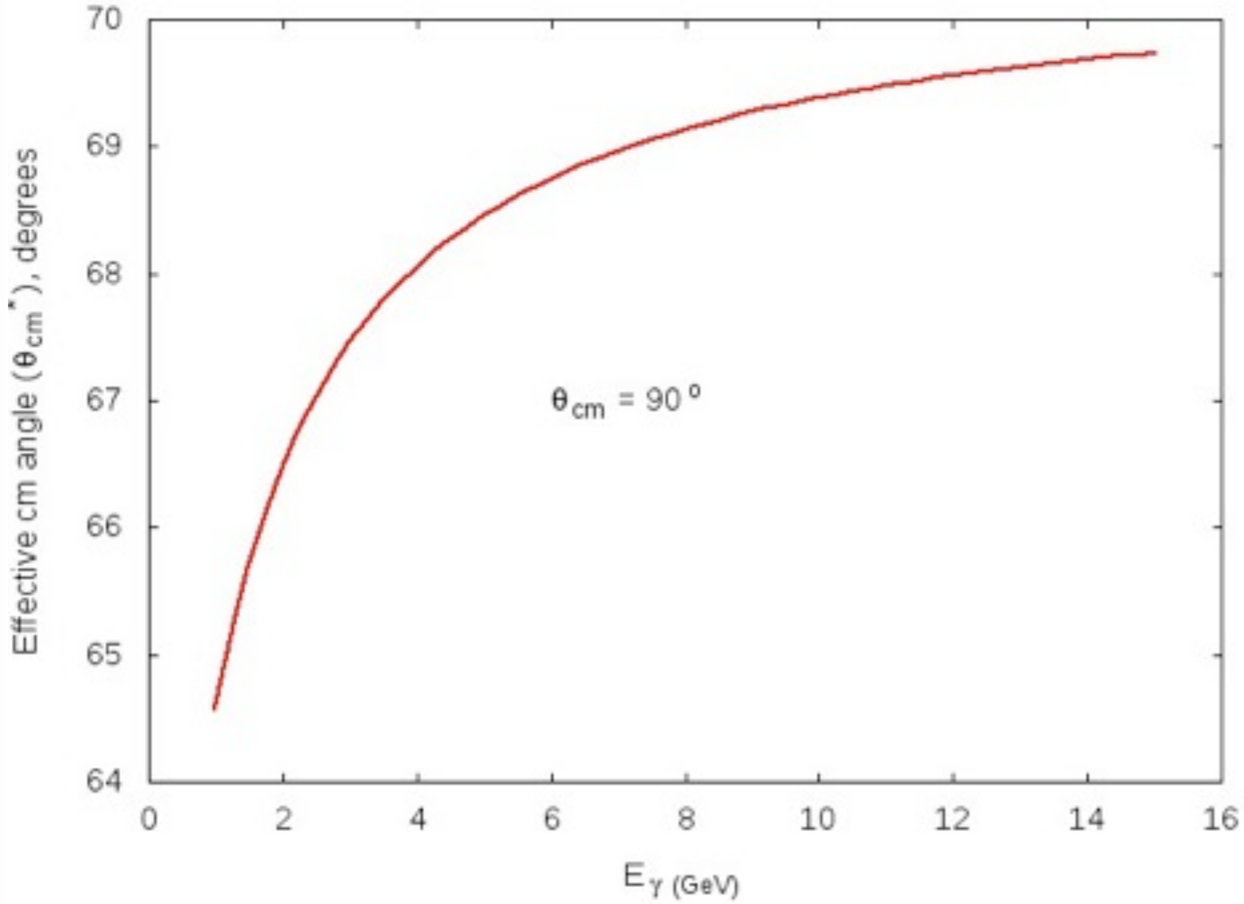




$\gamma + ^3He \rightarrow p + d$

D. Maheswari, M.S., 2016





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

D. Maheswari, M.S., 2016

$$\mathcal{M}^{\lambda_{df},\lambda_{1f};\lambda_{3He},h} = \sum_{\substack{(\lambda_{2f})(\lambda_{2'},\lambda_{3'})(\lambda_d)\\(\lambda_1,\lambda_2,\lambda_3)\\(\eta_1,\eta_{q1})(\eta_{1f},\eta_{2f})(\eta_{2'})}} \int \frac{\Psi_d^{\dagger\lambda_{df}}(\alpha_{2f}/\gamma_d, p_{2\perp}, \alpha_3/\gamma_d, p_{3'\perp})}{1-\alpha_3/\gamma_d} \left\{ \frac{\Psi_{n2f}^{\dagger\lambda_{2f};\eta_{2f}}(x_{s2}, p_{2f\perp}, k_{2\perp})}{1-x_{s2}} \right.$$

$$\bar{u}_q(P_{2f}, K_2, \eta_{2f})[-igT_c^\alpha \gamma_\nu]\left[\frac{u_q(P_1+q-K_1,\eta_{q1})\bar{u}_q(P_1+q-K_1,\eta_{q1})}{s'(1-x_1)(\beta_1-\beta_s+i\epsilon)}\right]\times$$

$$\left. [-ie\epsilon^\mu\gamma_\mu]u_q(P_1-K_1,\eta_1)\frac{\Psi_{n1}^{\lambda_1;\eta_1}(x_1,K_{1\perp},p_{1\perp})}{1-x_1}\right\}_1 \left\{\frac{\Psi_{n1f}^{\dagger\lambda_{1f};\eta_{1f}}(x_{s1},K_{1\perp},p_{1f\perp})}{1-x_{s1}}\right.$$

$$\left. \bar{u}_q(P_{1f}-K_1,\eta_{1f})[-igT_c^\beta\gamma_\mu]u_q(P_{2'}-K_2,\eta_{2'})\frac{\Psi_{n2'}^{\lambda_{2'};\eta_{2'}}(x_{2'},p_{2'\perp},k_{2\perp})}{1-x_{2'}}\right\}_2 G^{\mu\nu}(r)$$

$$\frac{\Psi_d^{\lambda_d}(\alpha_3,p_{d\perp},p'_{3\perp})}{1-\alpha_3}\frac{\Psi_d^{\dagger\lambda_d}(\alpha_3,p_{3\perp},p_{d\perp})}{1-\alpha_3}\frac{\Psi_{^3He}^{\lambda_{3He}}(\beta_1,\lambda_1,p_{1\perp},\beta_2,p_{2\perp}\lambda_2,\lambda_3)}{\beta_1}\frac{d\beta_d}{\beta_d}\frac{d^2p_{d\perp}}{2(2\pi)^3}$$

$$\frac{d\beta_3}{\beta_3}\frac{d^2p_{3\perp}}{2(2\pi)^3}\frac{d\alpha_{3'}}{\alpha_{3'}}\frac{d^2p_{3'\perp}}{2(2\pi)^3}\frac{dx_1}{x_1}\frac{d^2k_{1\perp}}{2(2\pi)^3}\frac{dx_{2'}}{x_{2'}}\frac{d^2k_{2\perp}}{2(2\pi)^3}. \qquad (10)$$

$$\mathcal{M}^{\lambda_{df},\lambda_{1f};\lambda_{3He},h} = \frac{3}{4}\frac{1}{\sqrt{s'}}\sum_i eQ_i(h)\sum_{\substack{\lambda_d\\\lambda_2,\lambda_3}}\int \mathcal{M}_{pd}^{\lambda_{df},\lambda_{1f};\lambda_d,h}(s,t_N)\frac{\Psi_d^{\dagger\lambda_d:\lambda_2,\lambda_3}(\alpha_3,p_{3\perp},\beta_d,p_{d\perp})}{1-\alpha_3}\times$$

$$\Psi_{^3He}^{\lambda_{3He}:h,\lambda_2,\lambda_3}(\beta_1=1/3,p_{1\perp},\beta_2,p_{2\perp})\frac{d^2p_{d\perp}}{(2\pi)^2}\frac{d\beta_3}{\beta_3}\frac{d^2p_{3\perp}}{2(2\pi)^3}. \qquad (14)$$

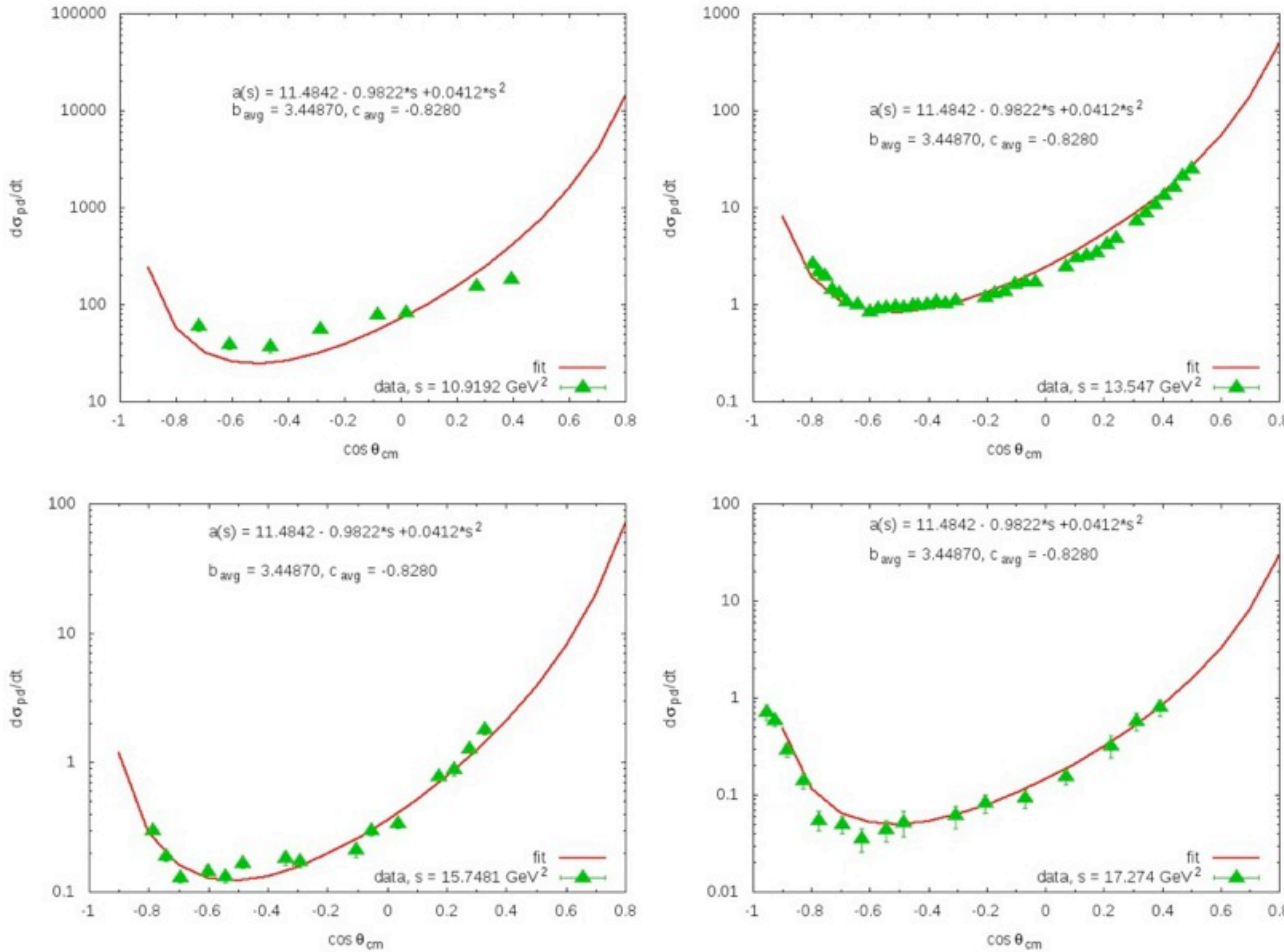
$$\gamma + {}^3He \to p + d$$

$$\frac{d\sigma}{dt} = \frac{3\pi^4 \alpha Q^2_{eff}}{s'_{^3He}} \left(\frac{s'_N}{s'_{^3He}}\right) \frac{d\sigma_{pd}}{dt}(s, t_{pd}) \cdot m_N S^{NR}_{^3He/d}(P_{1z} = 0)$$

$$S^{NR}_{^3He/d}(P_{1z}) = \frac{1}{2} \sum_{\lambda_{^3He};\lambda_1,\lambda_d} \left| \int \Psi^{\lambda_{^3He}:\lambda_1,\lambda_d}_{^3He/d,NR}(P_{1z}, P_{1\perp}) \frac{d^2 P_{1\perp}}{(2\pi)^2} \right|^2 = 4.1 \times 10^{-4} \mathrm{GeV}$$

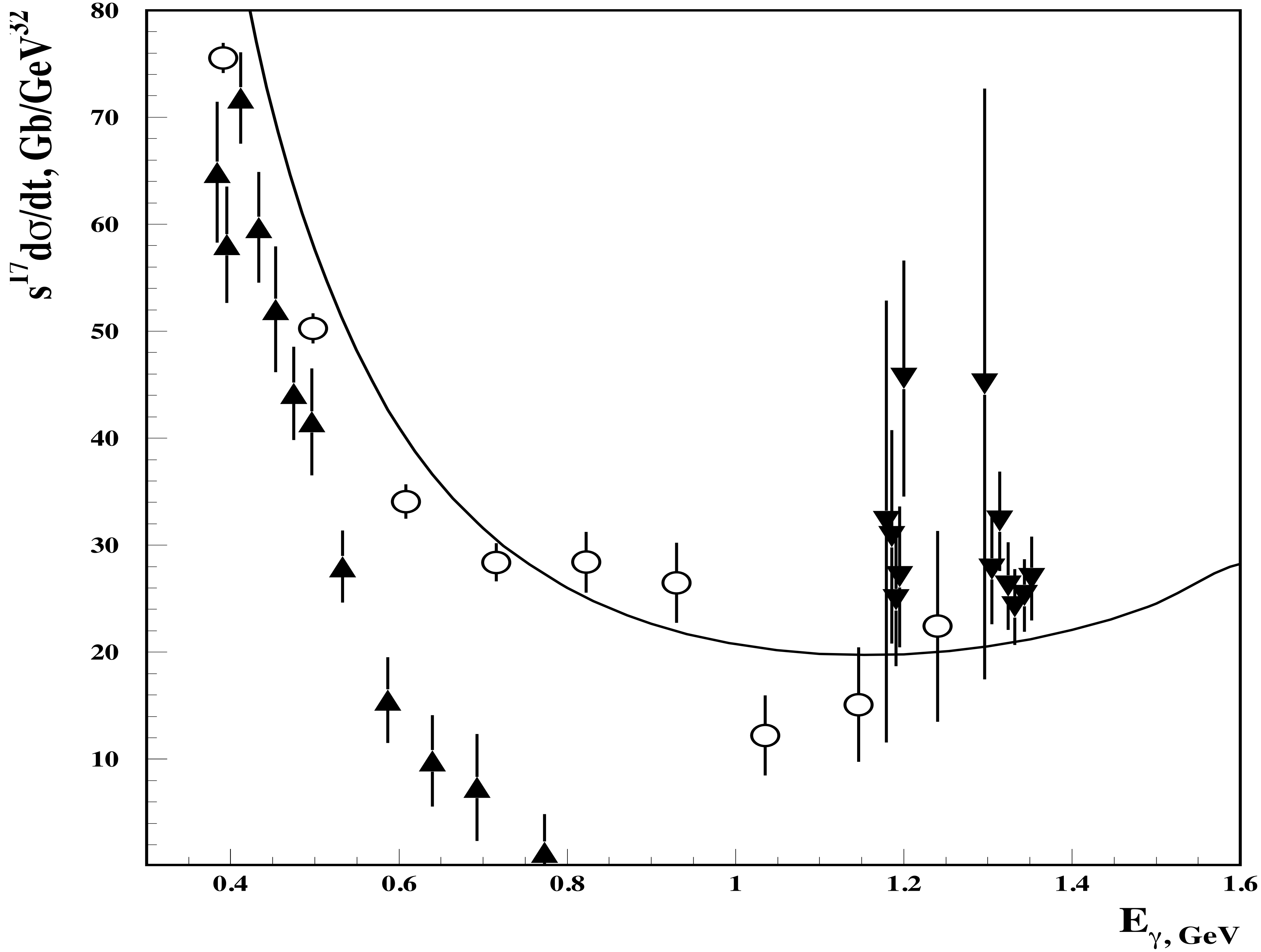
$$\frac{d\sigma^{pd\to pd}}{dt}(s, \tilde{t}) \sim \mu bn/GeV^2$$

$$\frac{d\sigma^{pd\to pd}}{dt}(s,\tilde{t})$$



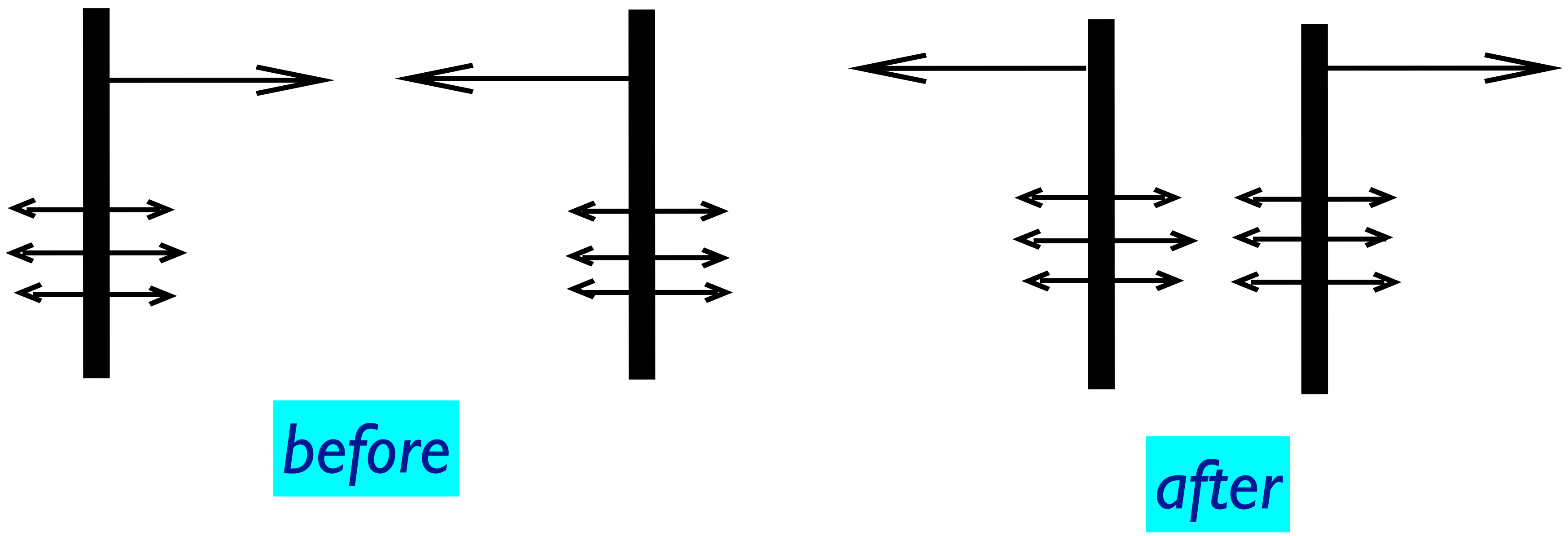
$\gamma + ^3He \to p + d$

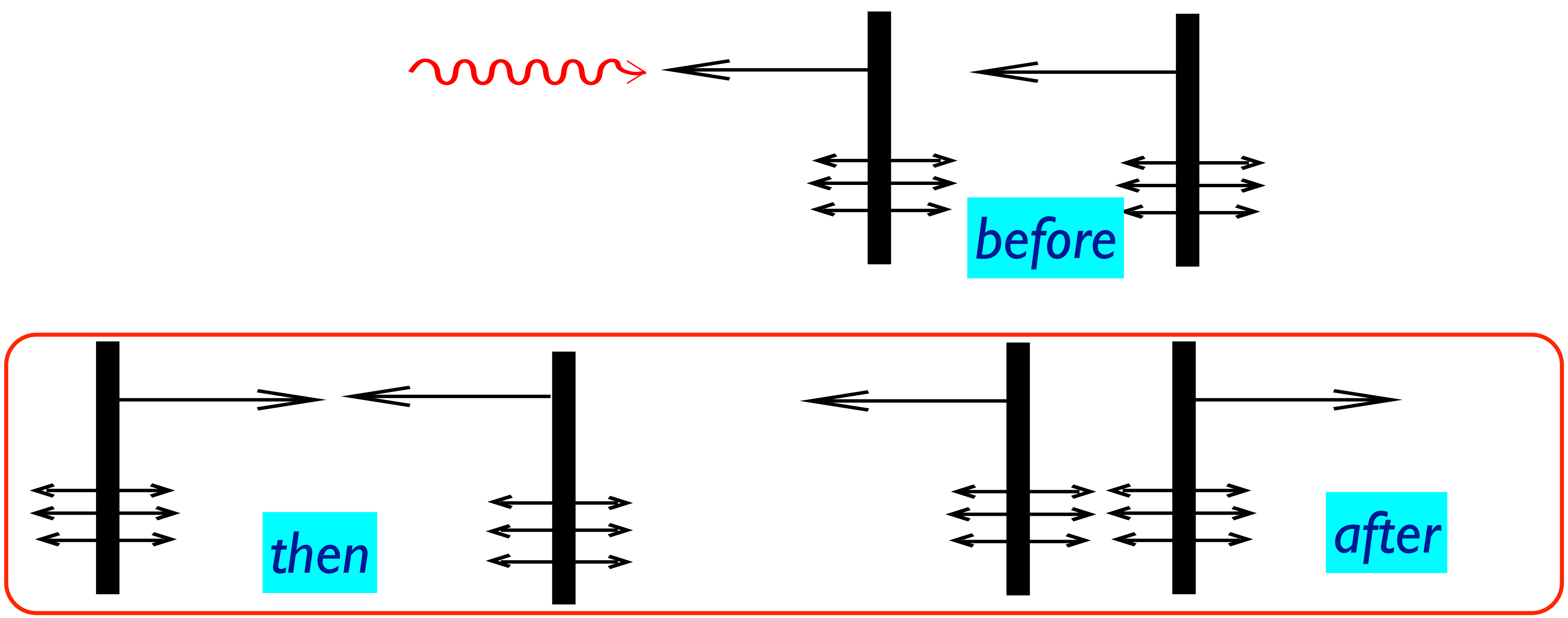
D. Maheswari, M.S., 2016



Generalizing to the Baryon-Baryon hard scattering

Baryon-Baryon Scattering



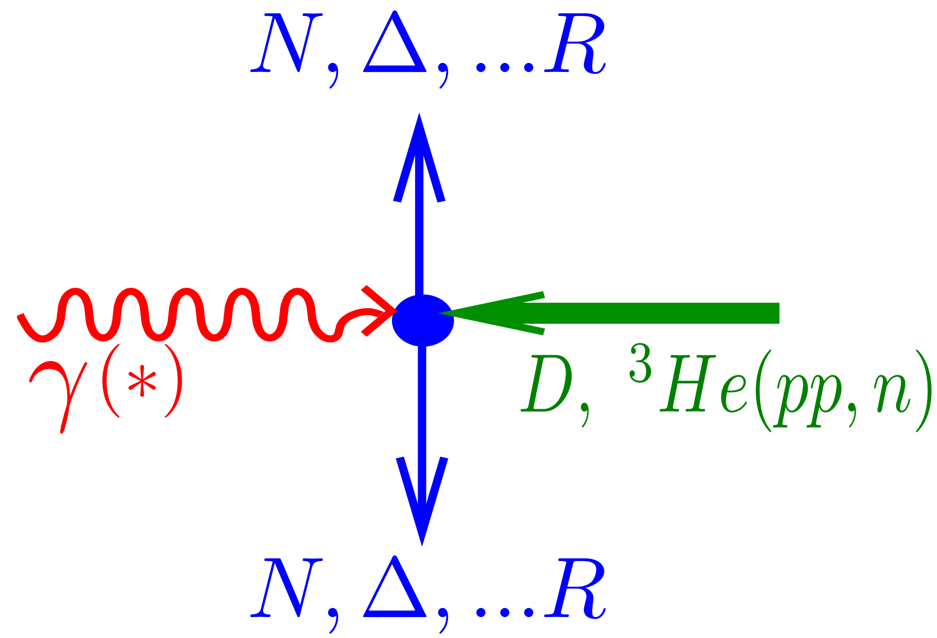


What Next?

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



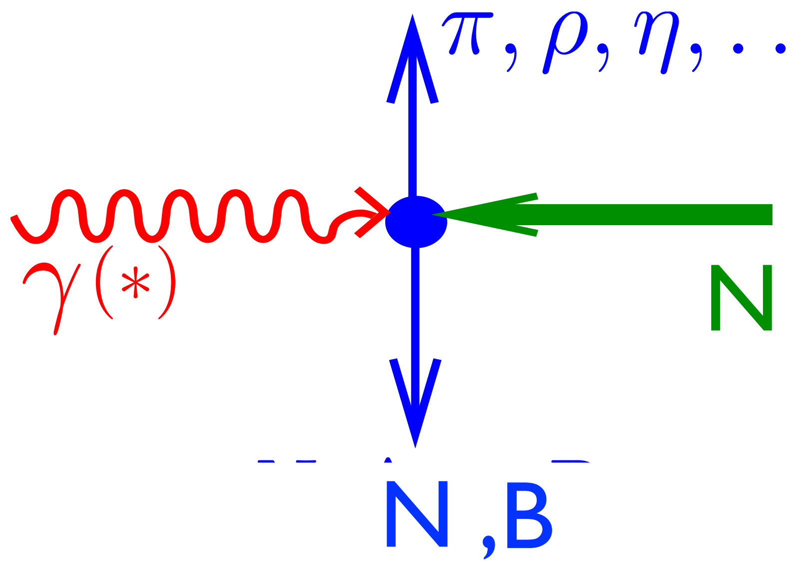
$$\langle \lambda_{1f}, \lambda_{2f} \mid \mathcal{M} \mid \lambda_\gamma, \lambda_d \rangle = ie[\lambda_\gamma] \times$$
$$\left\{ \sum_{i \in N_1} \sum_{\lambda_{2i}} \int \frac{Q_i^{N_1}}{\sqrt{2s'}} \langle \lambda_{2f}; \lambda_{1f} \mid T^{QI}_{(pn \to B_1 B_2),i}(s, t_N) \mid \lambda_\gamma; \lambda_{2i} \rangle \Psi_{\rm d}^{\lambda_d}(p_{1i}, \lambda_\gamma; p_{2i}, \lambda_{2i}) \frac{d^2 p_\perp}{(2\pi)^2} \right.$$
$$\left. + \sum_{i \in N_2} \sum_{\lambda_{1i}} \int \frac{Q_i^{N_2}}{\sqrt{2s'}} \langle \lambda_{2f}; \lambda_{1f} \mid T^{QI}_{(pn \to B_1 B_2),i}(s, t_N) \mid \lambda_{1i}; \lambda_\gamma \rangle \Psi_{\rm d}^{\lambda_d}(p_{1i}, \lambda_{1i}; p_{2i}, \lambda_\gamma) \frac{d^2 p_\perp}{(2\pi)^2} \right\}$$

Extraction of hard Baryonic Helicity Amplitudes from Polarized measurement

What Else ?

Hard Break-up of proton to nucleon-meson pair

$$\gamma + N \to N + meson$$



$$\mathcal{M}^{\gamma N \to NM} \sim \frac{Q}{\sqrt{s}} M^{\lambda_{N_f}, \lambda_M; \lambda_{N_i} \lambda_\gamma}_{MN \to MN}(s, \tilde{t}) \int \psi_{MN}(\alpha_N = 1, p_t) \frac{d^2 p_t}{(2\pi)^2}$$

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

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

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

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

Extraction of hard Baryon-Meson Helicity Amplitudes from Polarized measurement

Outlook

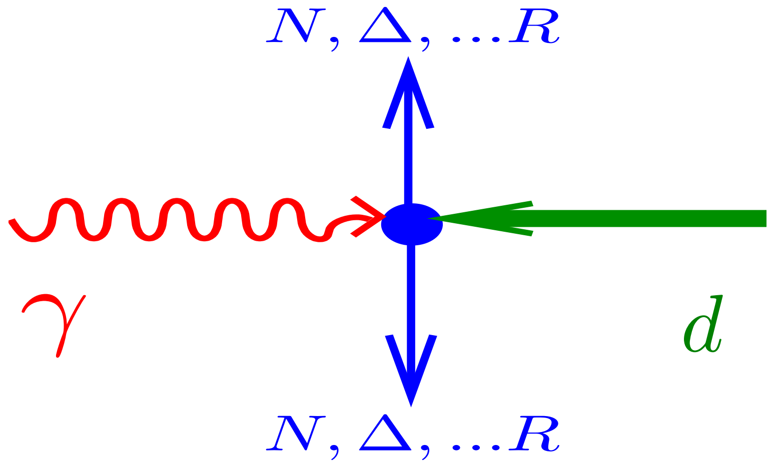
- Hard Rescattering Mechanism consistent with major observations of the break-up reactions including deuteron and 3He targets

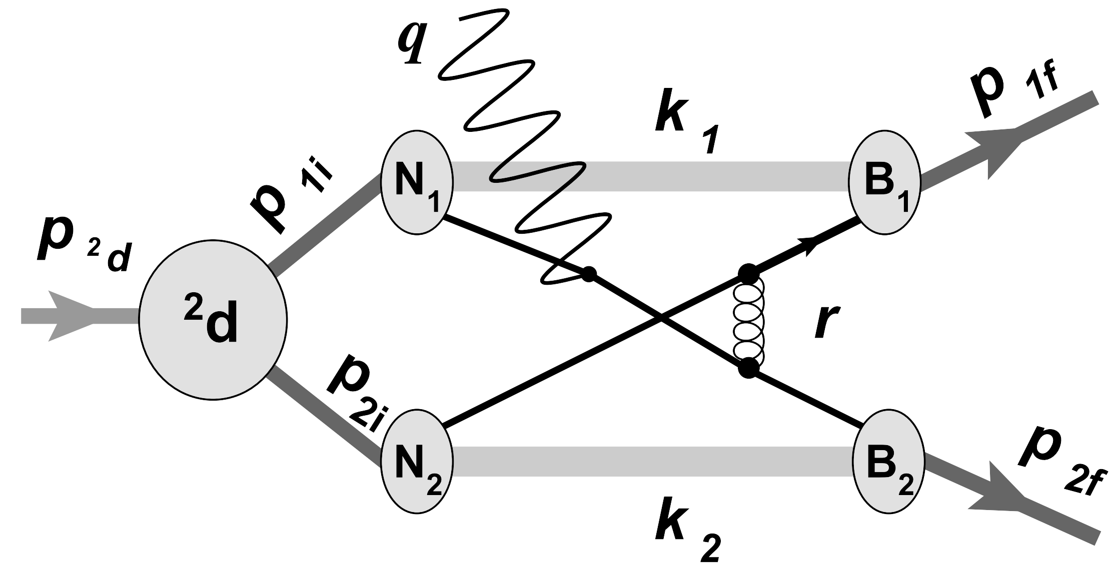
- Within this framework one can try to extract helicity amplitudes of NN-> BB hard scattering

- This approach can be extended to proton break-up reactions probing helicity amplitudes of meson-nucleon elastic amplitudes

- We didn't see yet the proton decay, but we can break it...

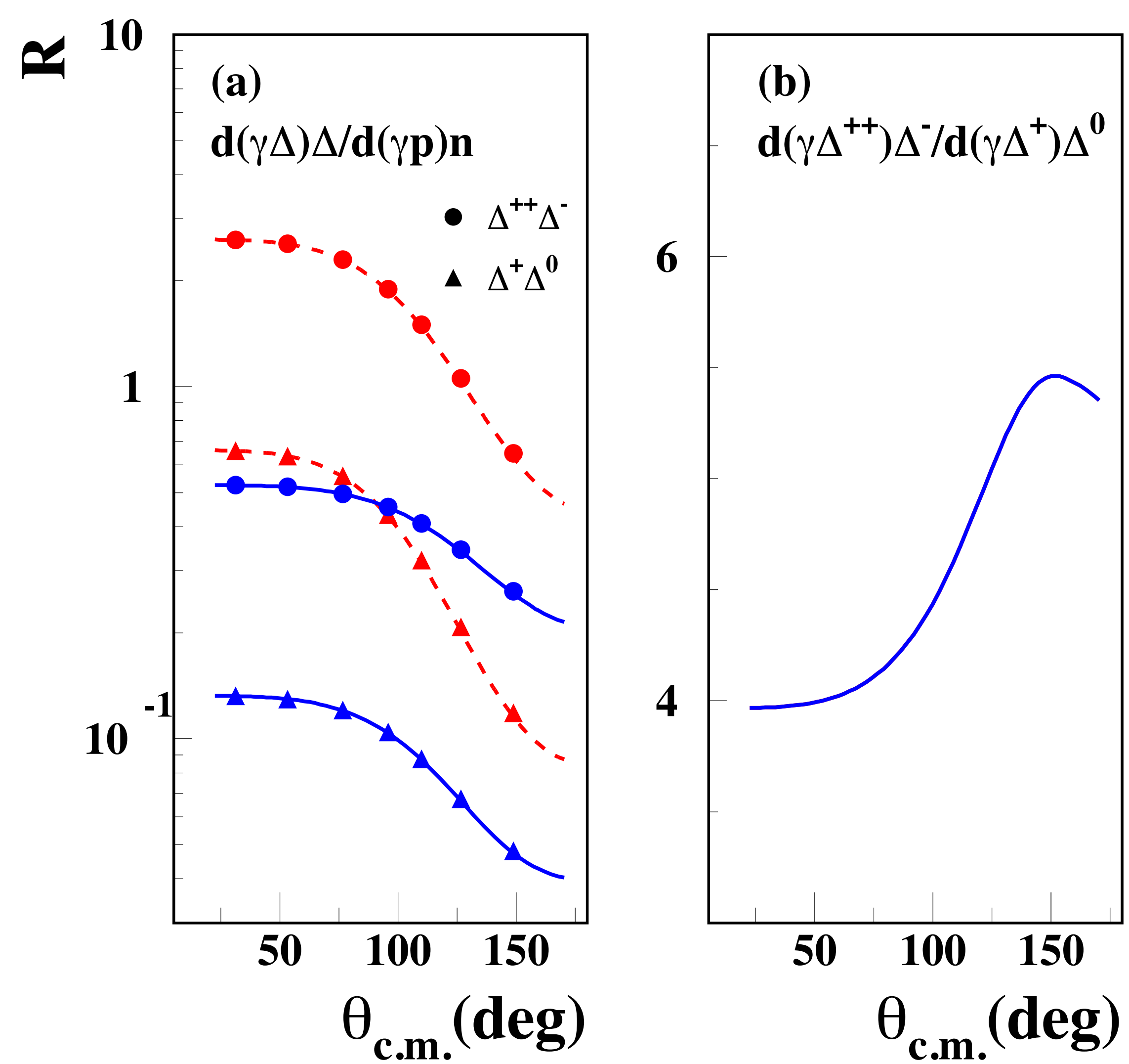
1. Generalization of break – up reactions to the deuteron break-up of other 2Baryons





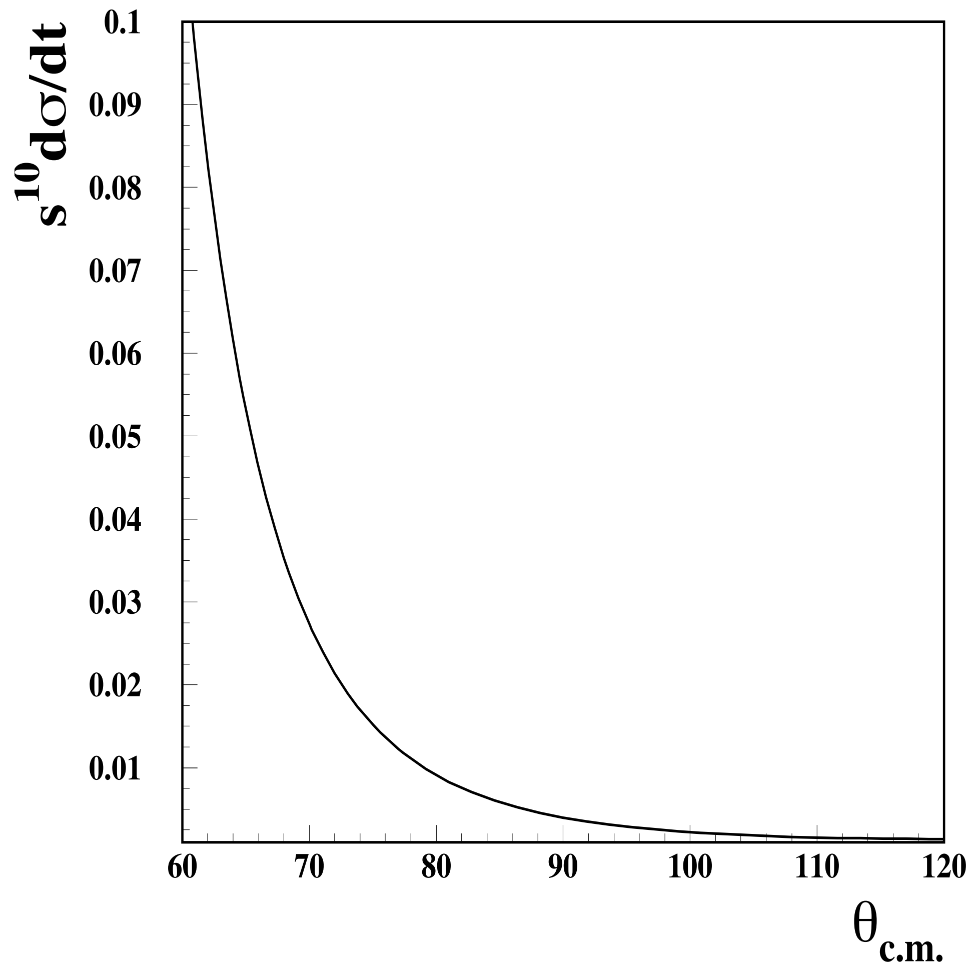
$$\frac{d\sigma^{\gamma d\to\Delta\Delta}(s,\theta_{c.m.})}{dt} = \frac{\alpha Q^2_{F,\Delta\Delta} 8\pi^4}{s'} \frac{d\sigma^{pn\to\Delta\Delta}(s,\theta^N_{c.m.})}{dt} \bar{S}_{0,NR},$$

M. S. C.Granados
ArXiv 2010



Δ-isobar production in QIM

$p+n \longrightarrow p+\Delta^0$ $p+n \longrightarrow n+\Delta^+$	$c_t = c_u$
$p+n \longrightarrow \Delta^+\Delta^0$	$c_t \neq c_u$
$p+n \longrightarrow \Delta^{++}\Delta^-$	$c_u = 0$



$p+n \longrightarrow \Delta^{++}+\Delta^-$

- $\frac{d\sigma}{dt}$ proportional to $F(\theta_{c.m.})^2$
- Backward supression will test QIM.
- Same angular distribution is expected in corresponding photodisintegration process, $\gamma + d \longrightarrow \Delta^{++} + \Delta^-$.
- At large angle $0.1 < \frac{\sigma^{\gamma d \longrightarrow \Delta^{++}\Delta^-}}{\sigma^{\gamma d \longrightarrow pn}} < 0.5$

Compared With

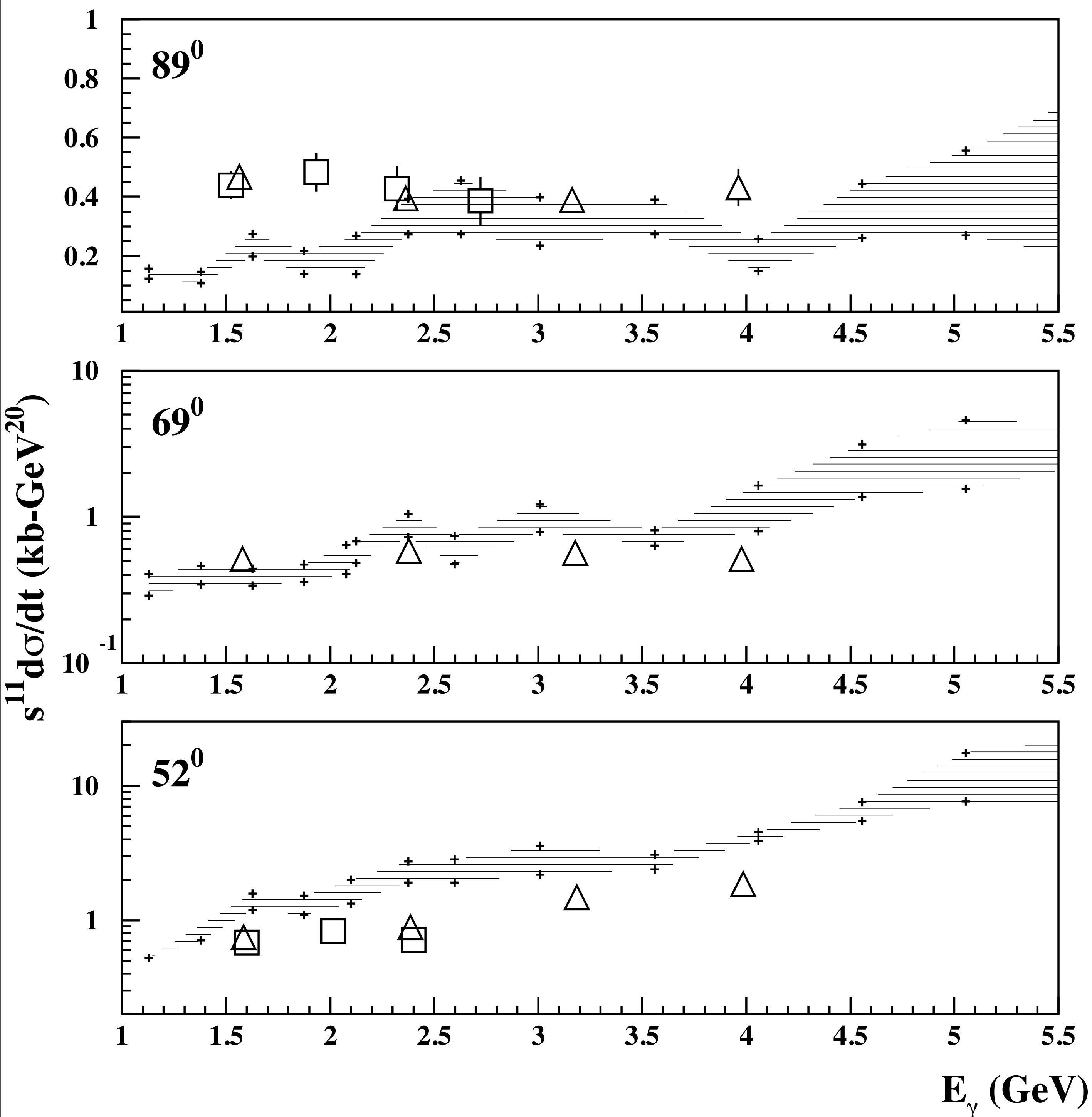
In the world where chiral symmetry is unbroken

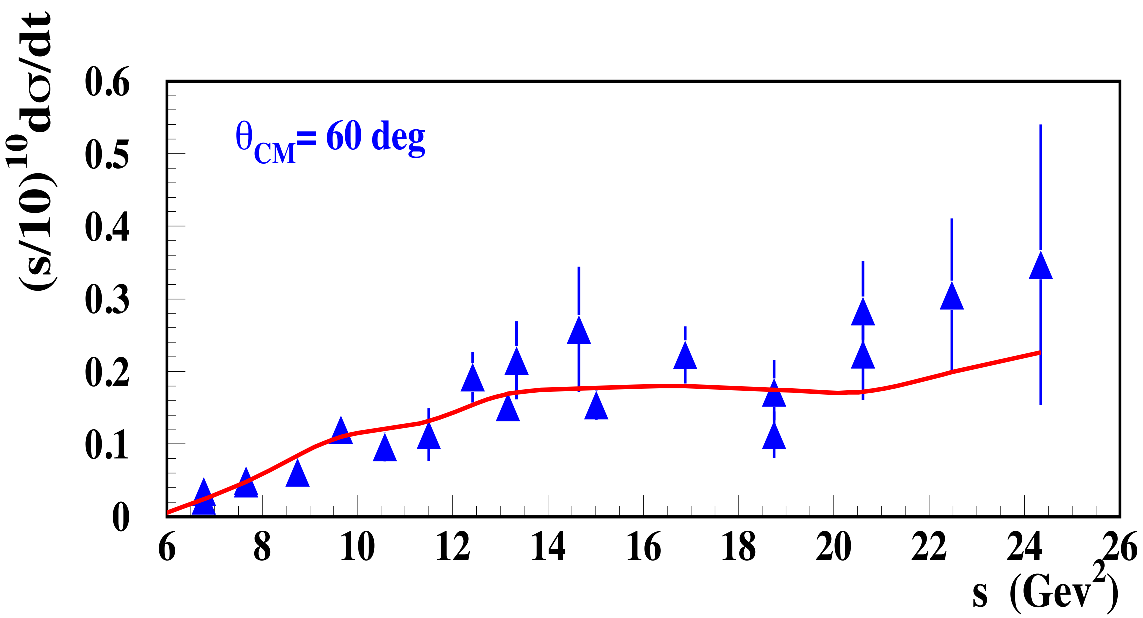
$$\psi^{\mathbf{6q}}_{\mathbf{t=0,s=1}} = \sqrt{\frac{\mathbf{1}}{\mathbf{9}}}\psi_{\mathbf{NN}} + \sqrt{\frac{\mathbf{4}}{\mathbf{45}}}\psi_{\mathbf{\Delta\Delta}} + \sqrt{\frac{\mathbf{4}}{\mathbf{5}}}\psi_{\mathbf{CC}}$$

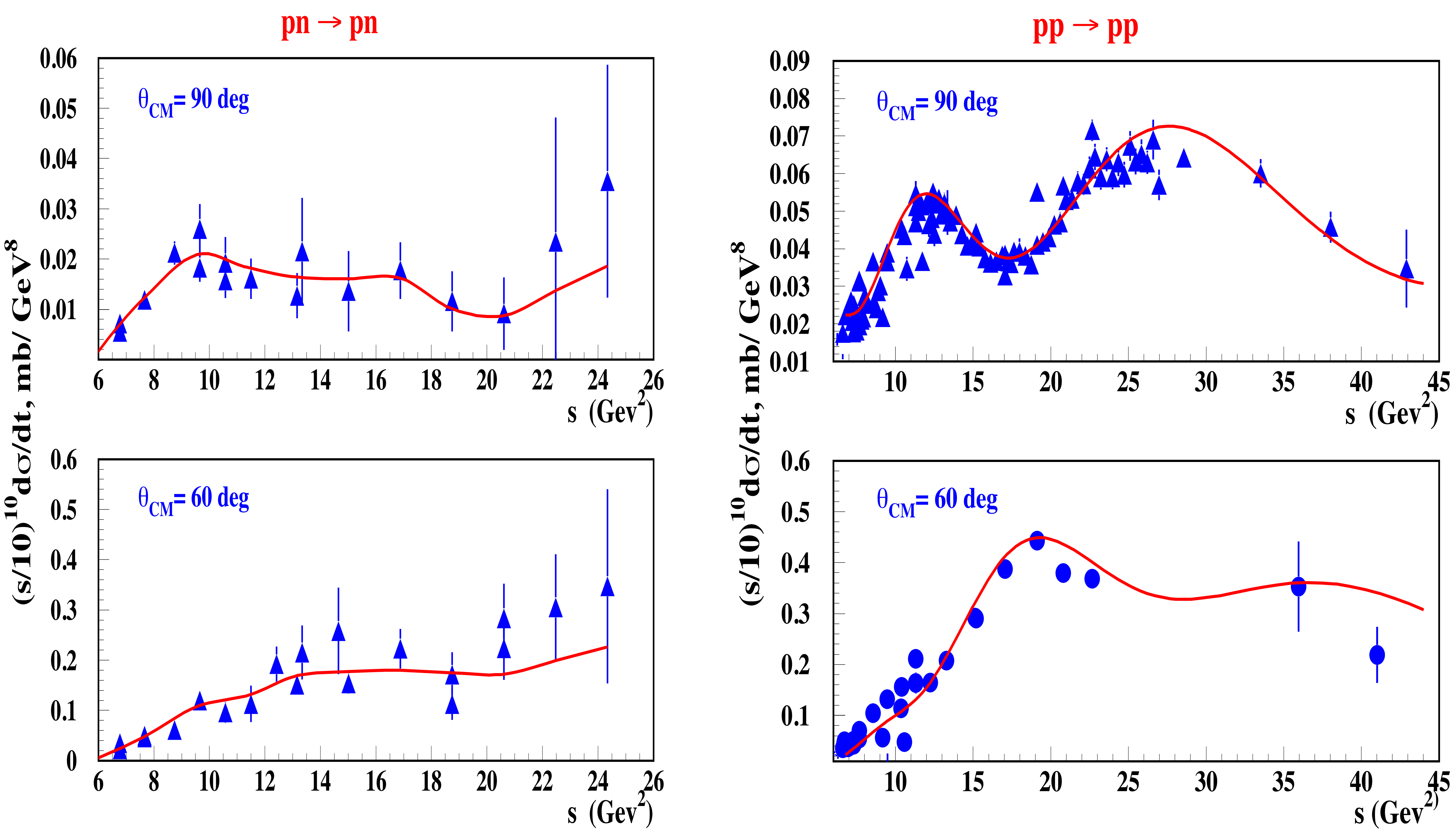
$$\frac{\sigma(\gamma d \rightarrow \Delta\Delta)}{\sigma(\gamma d \rightarrow pn)} \approx 1$$

$\gamma + d \rightarrow p + n$

$p + n \rightarrow p + n$







pn → pn
pp → pp
θCM= 90 deg
θCM= 60 deg
(s/10)10dσ/dt, mb/ GeV8
s (Gev2)