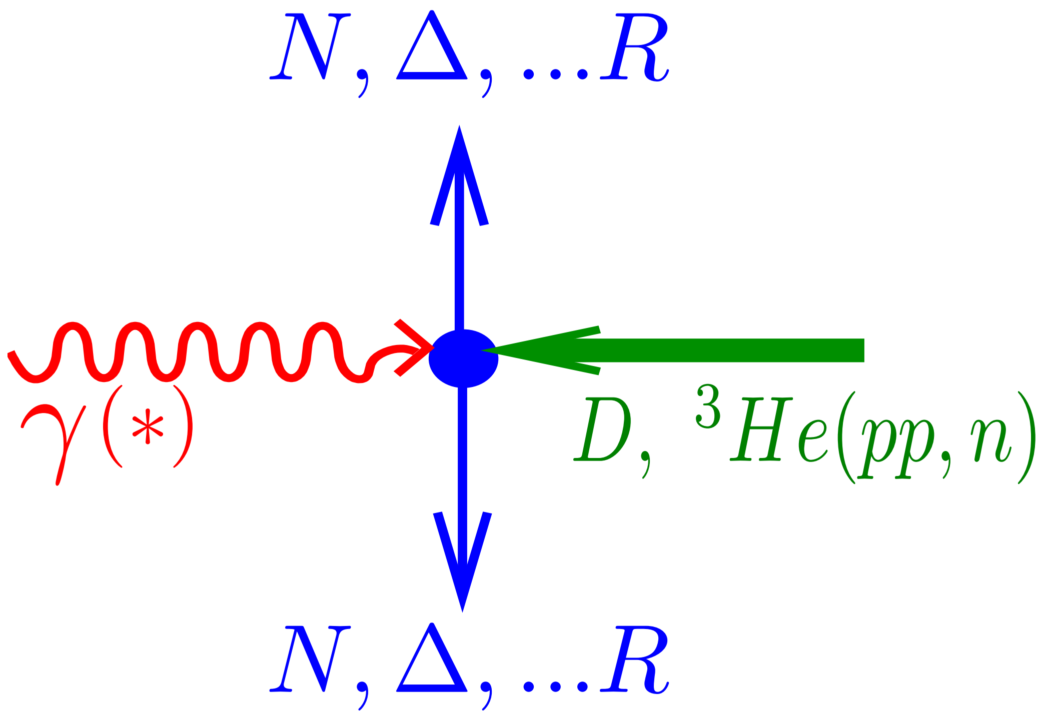
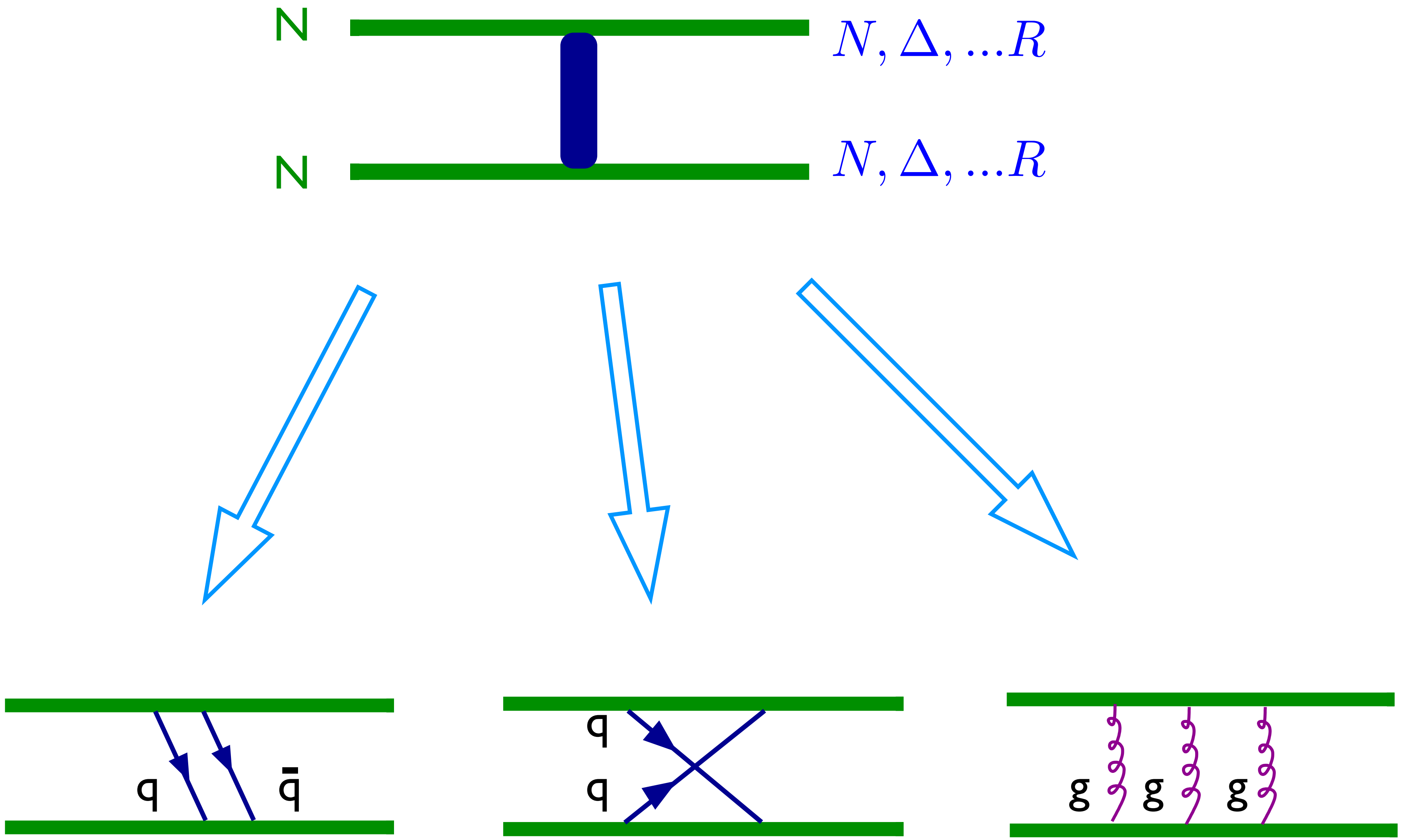
High Energy Deuteron Break-Up

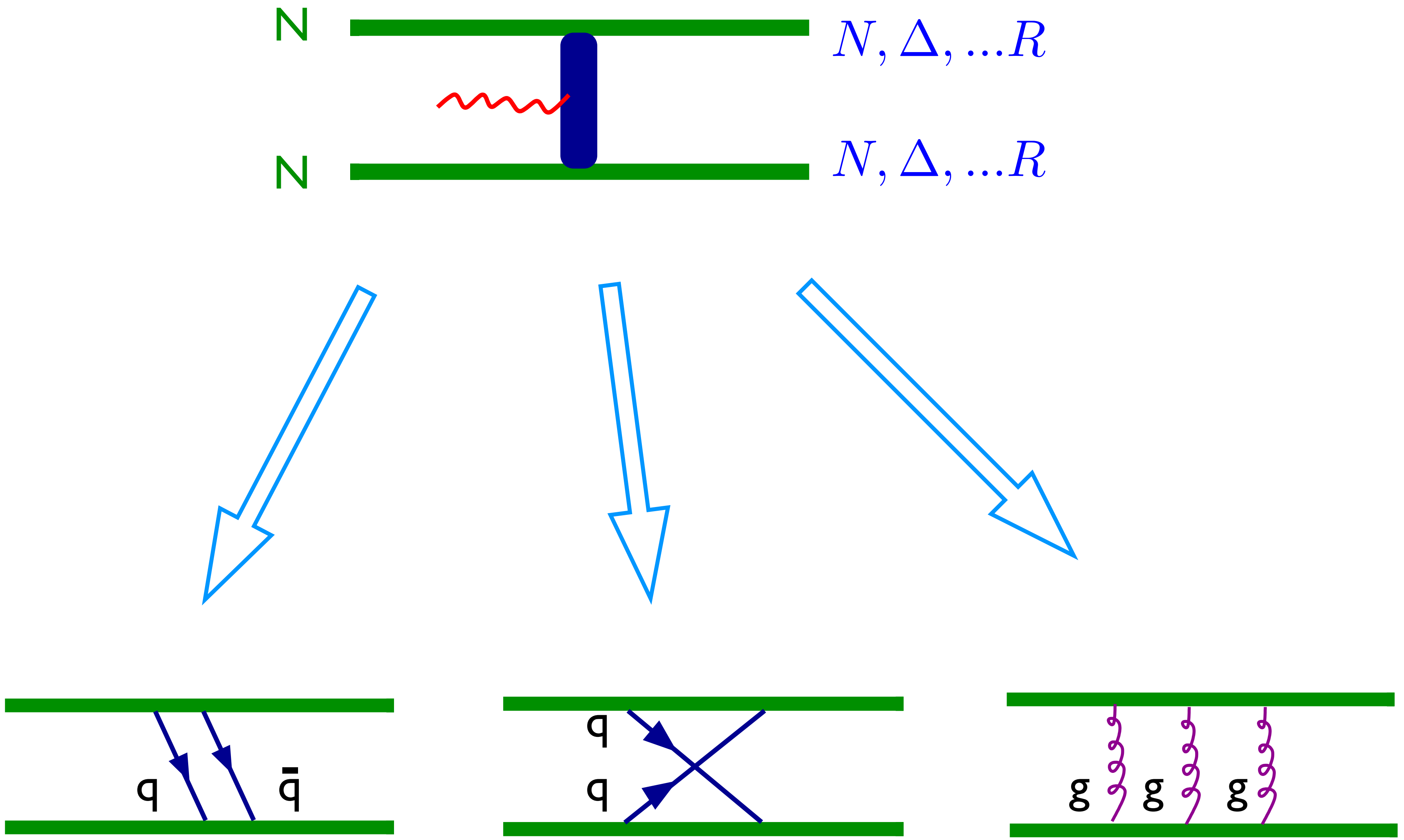
Misak Sargsian
Florida International University

JLab Meeting - March 25-26, 2011

- Large CM angle baryon disintegration from nuclei:




N
N
$N, \Delta, ...R$
$N, \Delta, ...R$
q
q̄
q
q
g
g
g


N
N
$N, \Delta, ...R$
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q
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g
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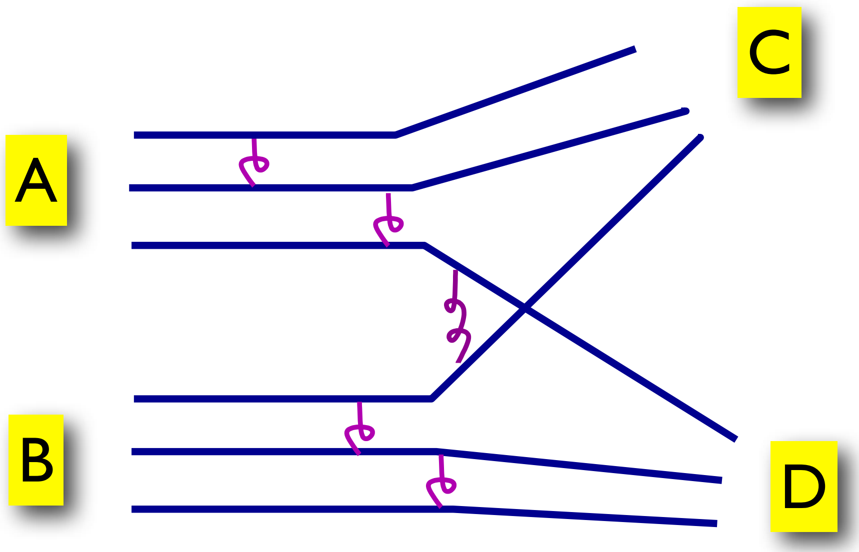
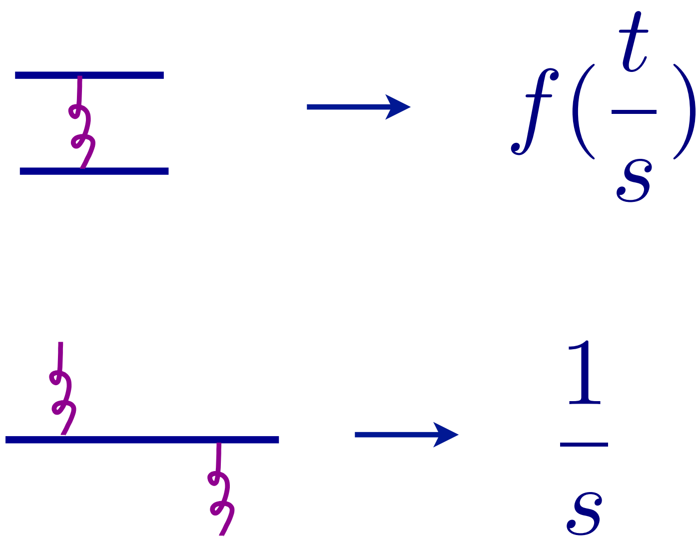
Hard Processes

Consider A+B→C + D





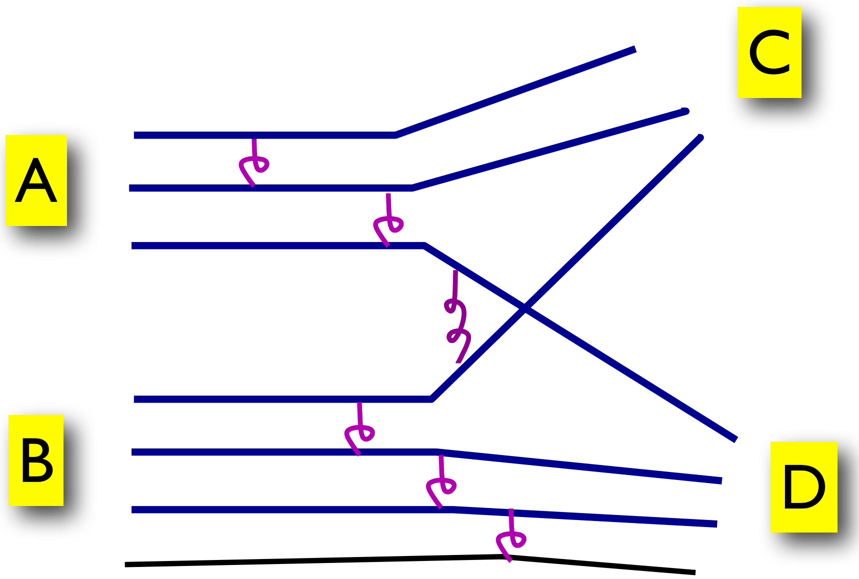
$$A \sim F(\frac{t}{s}) \frac{1}{s^{\frac{n_A+n_B+n_C+n_D}{2}-2}}$$

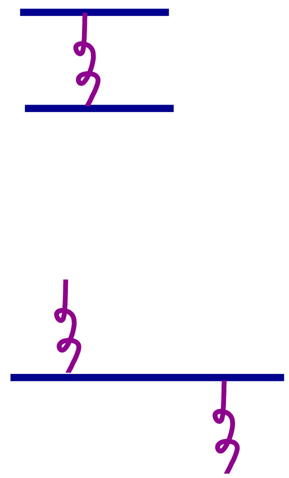
Brodsky, Farrar 1975
Matveev, Muradyan, Takhvelidze, 1975

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

Hard Processes

Consider A+B→C + D





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

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

additional $\frac{1}{s}$

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

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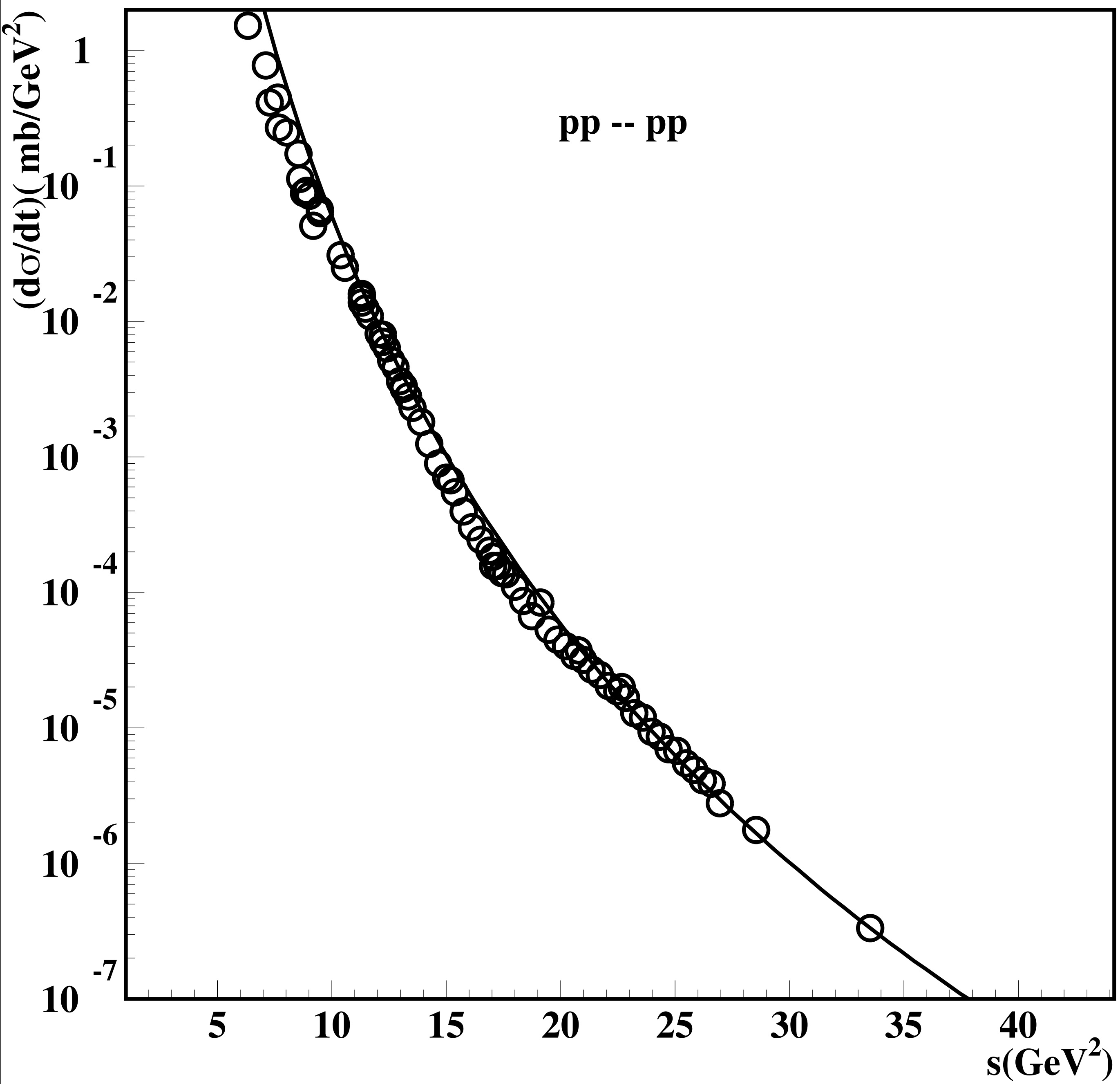
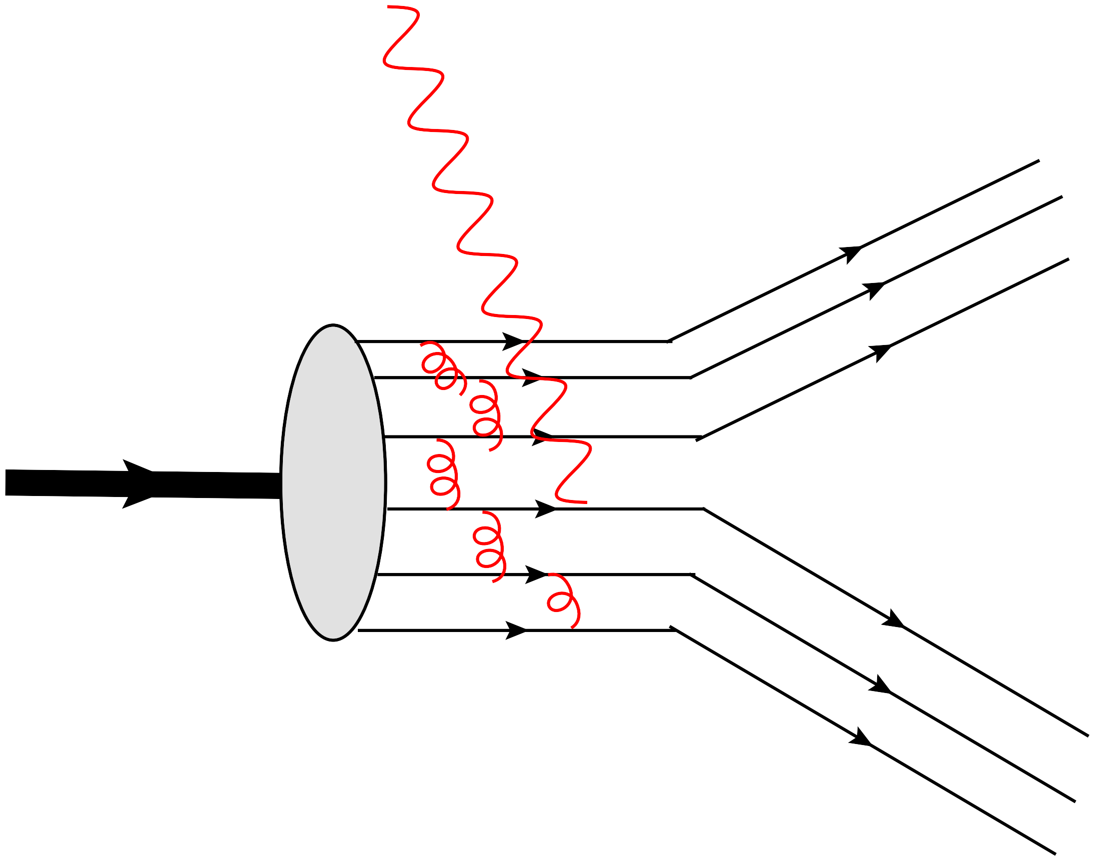

pp -- pp
(dσ/dt)(mb/GeV^2)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
5
10
15
20
25
30
35
40
s(GeV^2)

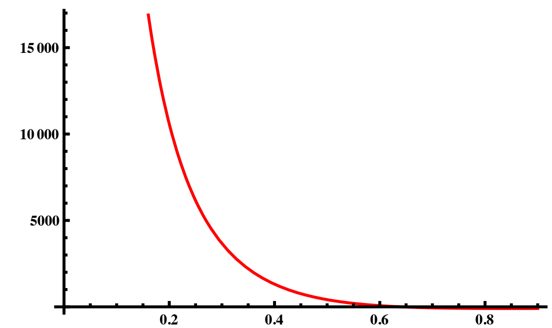
Break up of pn from the deuteron: the original Idea

Brodsky, Chertock, 1976



$$\frac{d\sigma}{dt} \sim s^{-11}$$

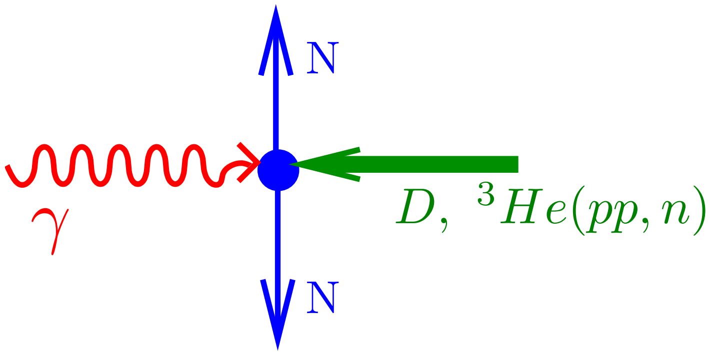
$$\sim \Psi_d\left(\frac{\sqrt{s}}{2}\right)$$

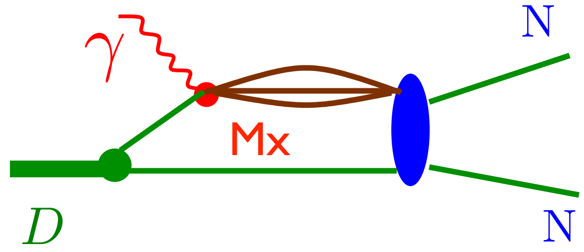


$$\psi^{\mathbf{6q}}_{\mathbf{t=0,s=1}} = \sqrt{\tfrac{1}{9}}\psi_{\mathbf{NN}} + \sqrt{\tfrac{4}{45}}\psi_{\mathbf{\Delta\Delta}} + \sqrt{\tfrac{4}{5}}\psi_{\mathbf{CC}}$$

Brodsky, Lepage, Ji, PRL 1983

- Large CM angle disintegration of nuclei:





Brodsky, Chertock, 1976

Holt, 1990

Gilman, Gross, 2002

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

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

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

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

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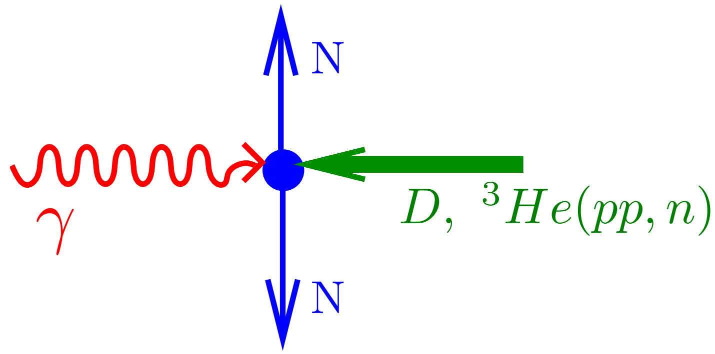

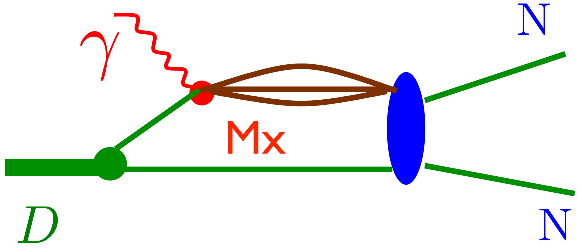

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$\gamma d \rightarrow pn$

scaling

Exclusive large-momentum-transfer scattering

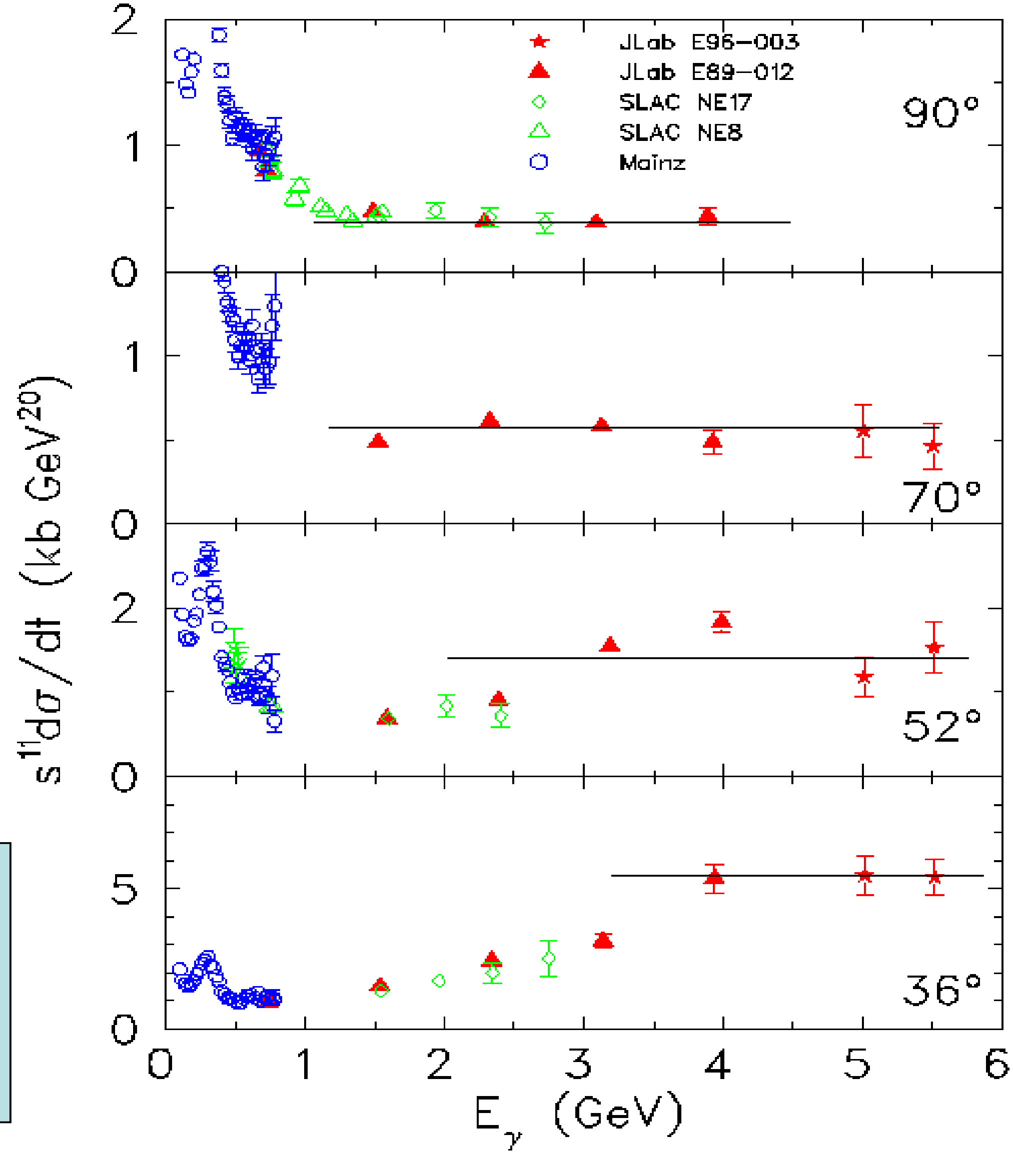
•Dimensional counting rule:

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

For

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

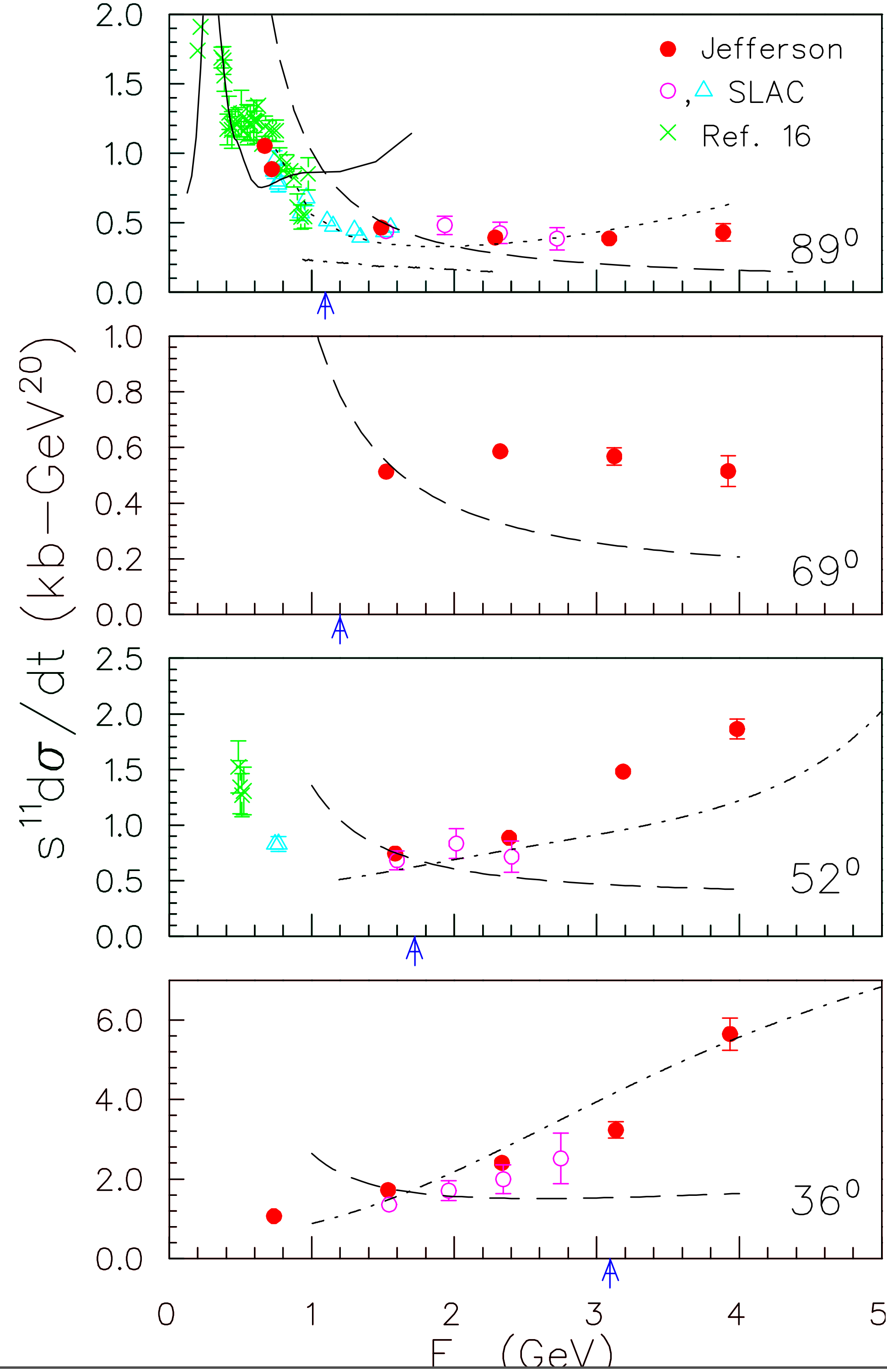
N = 1 + 6 + 3 + 3 – 2 = 11

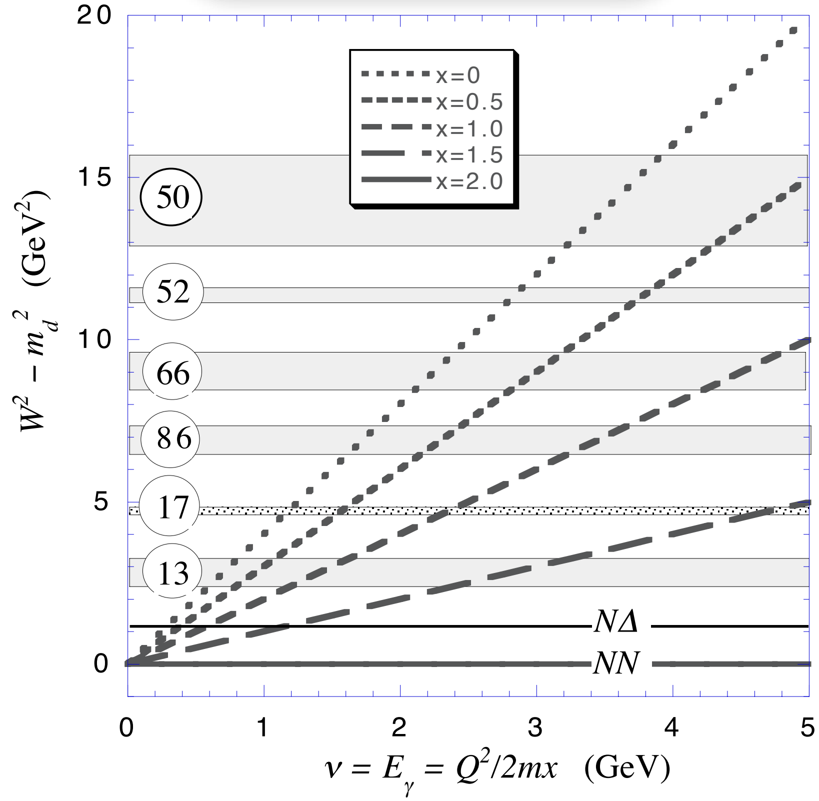


Notice:

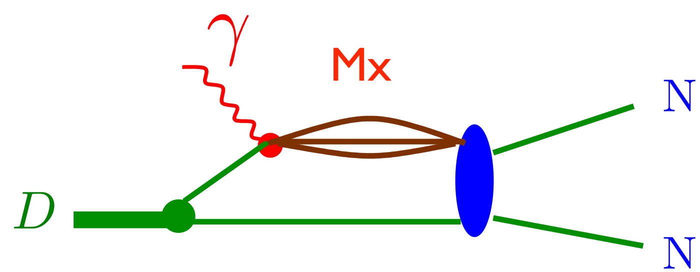
$$\frac{d\sigma}{dt}(E_\gamma = 1\,\text{GeV/c}) \,/\, \frac{d\sigma}{dt}(E_\gamma = 4\,\text{GeV/c}) \approx 10^4$$

$\gamma d \to pn$

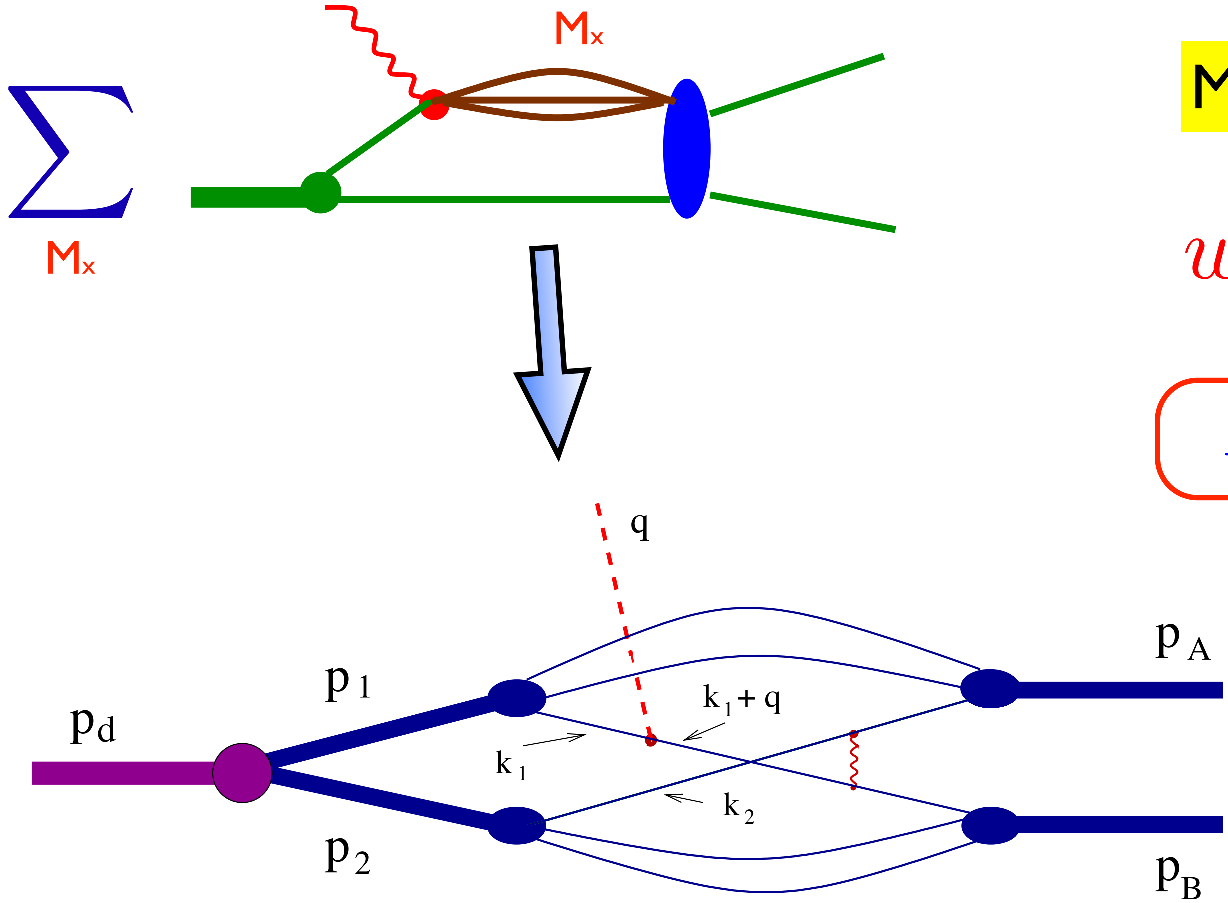




Gilman, Gross, 2002



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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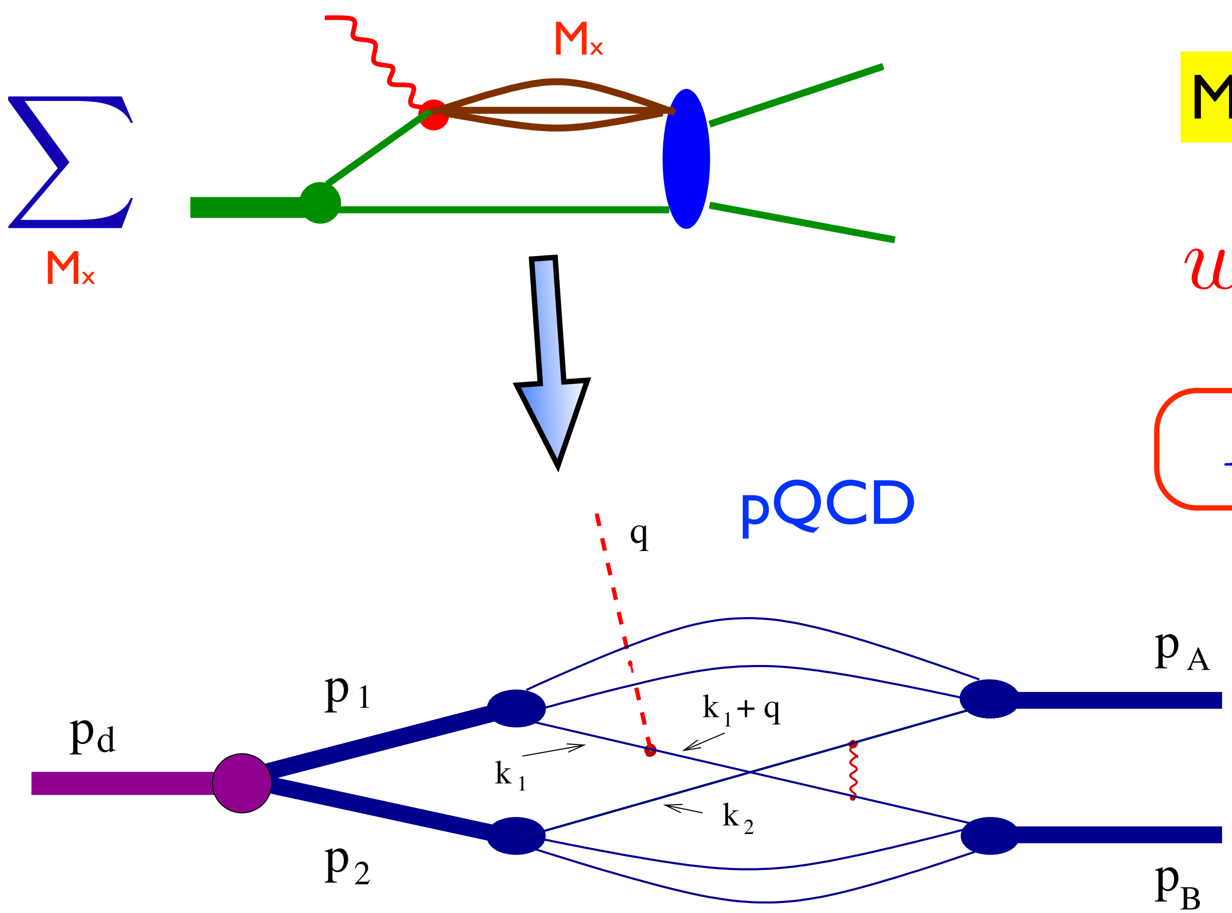

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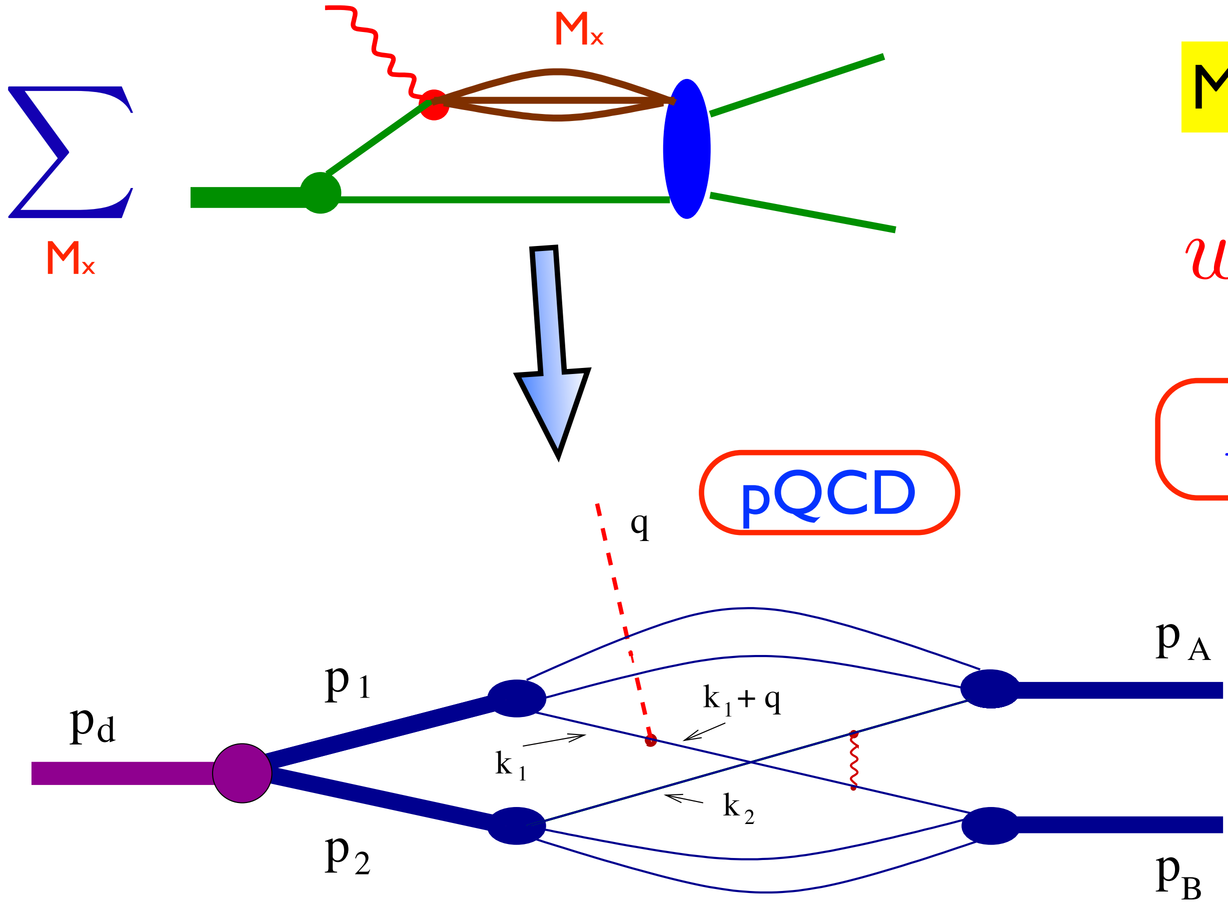

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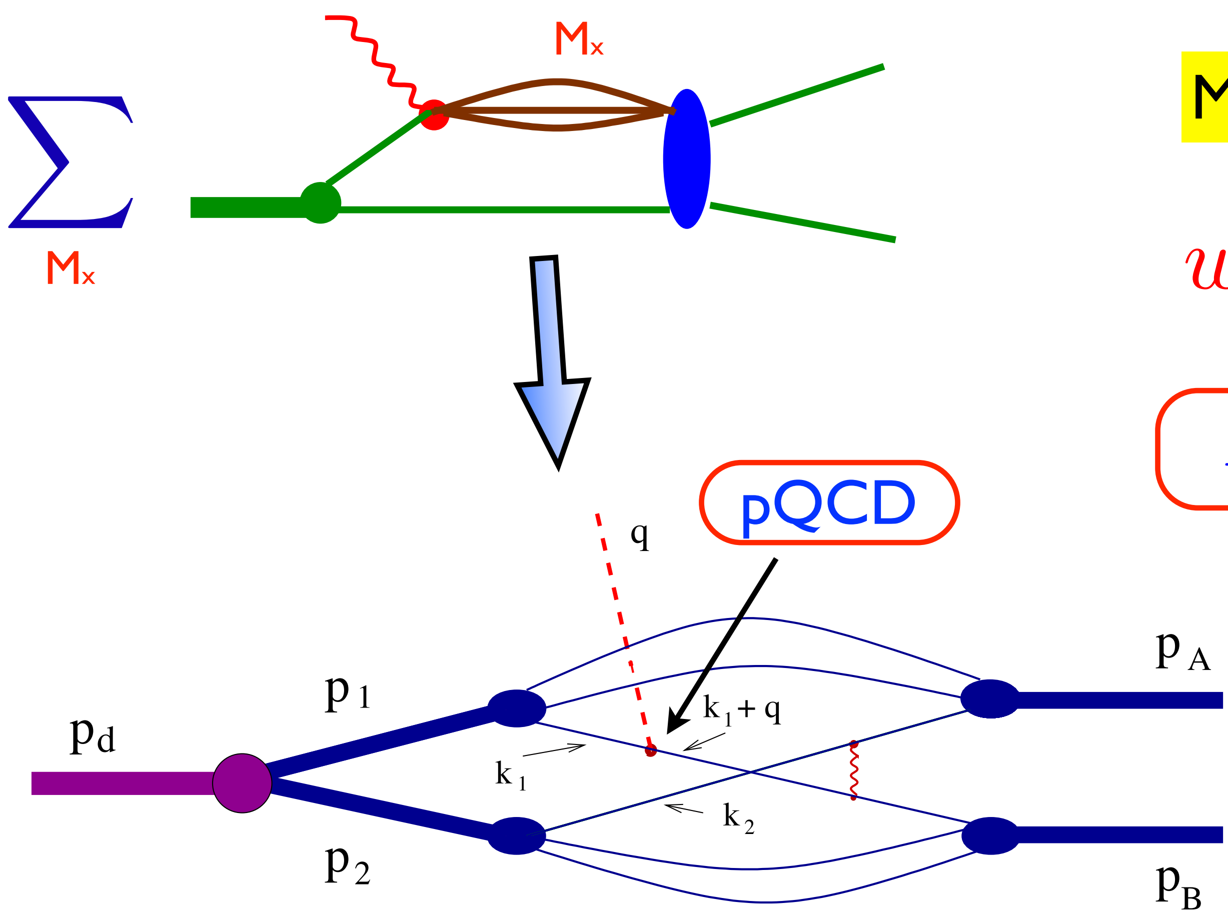

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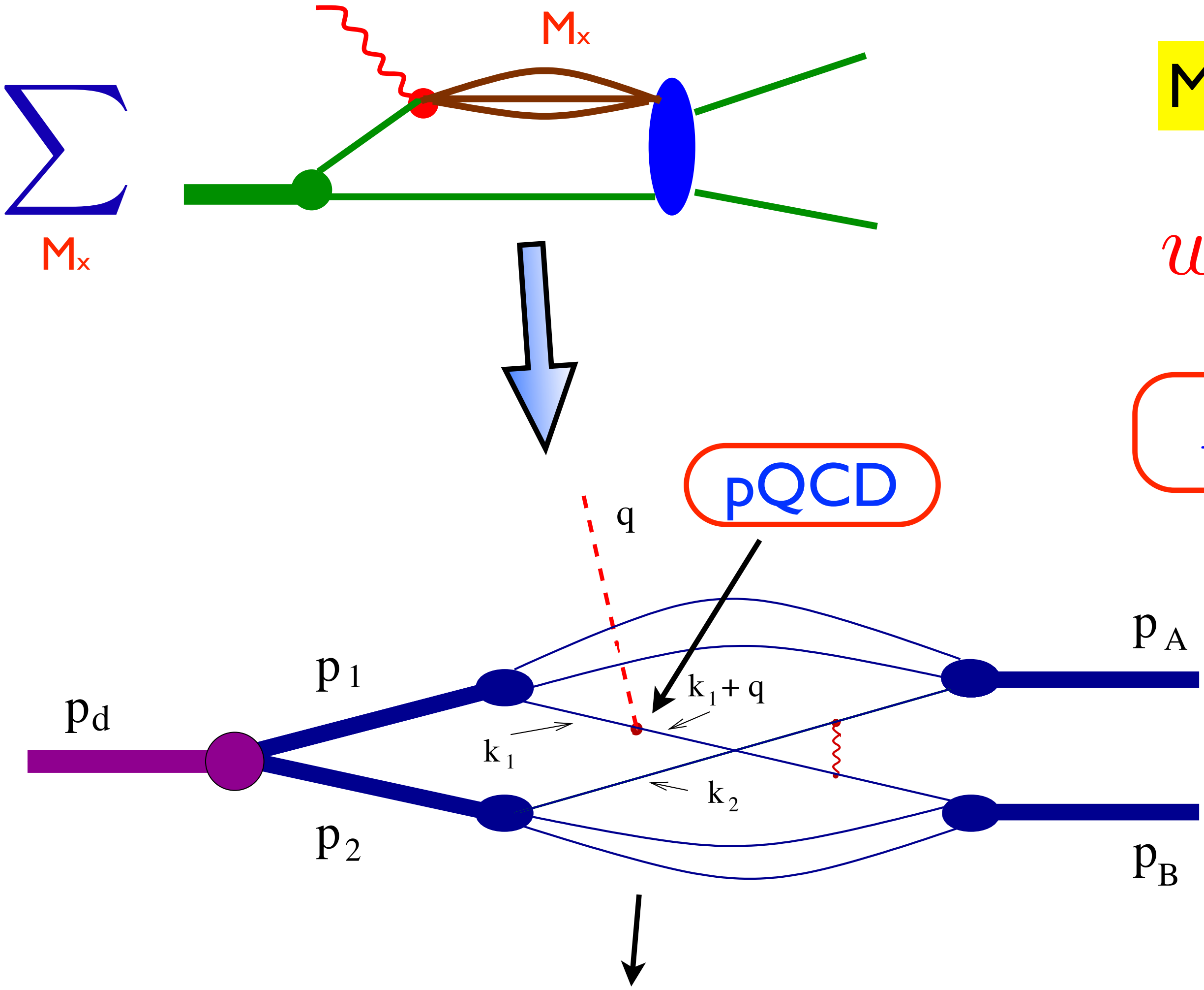

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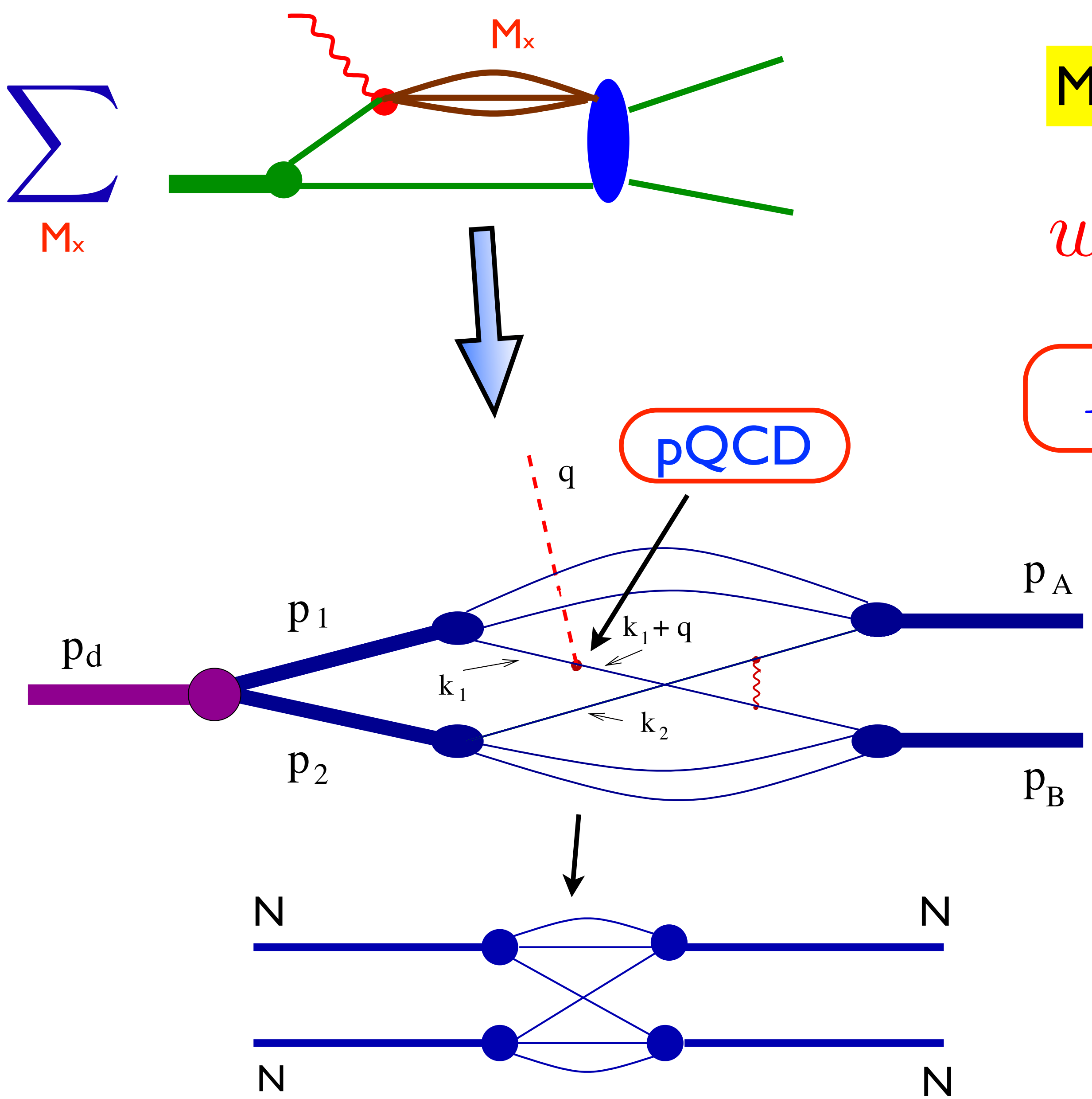

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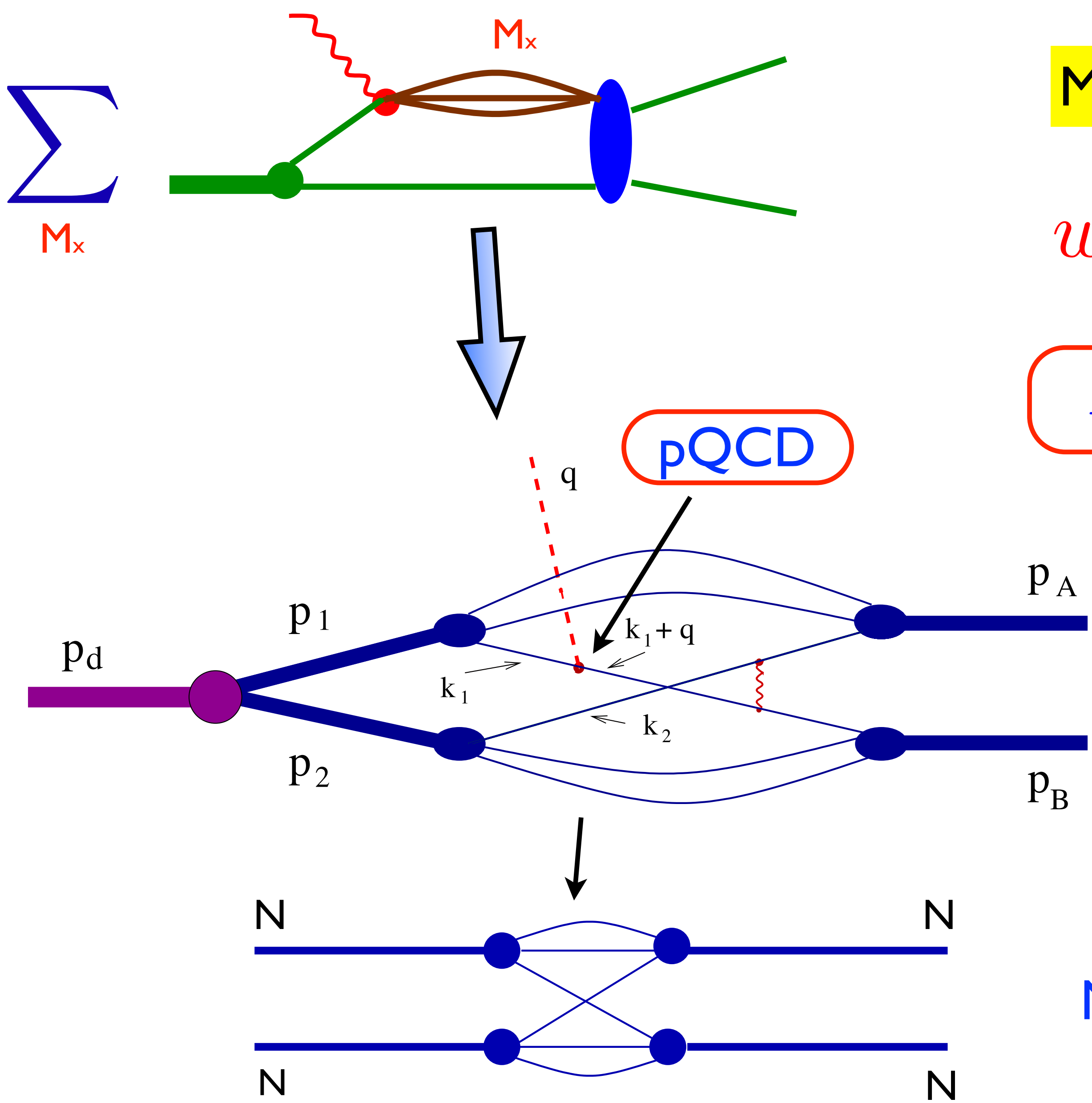

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NN -amplitude

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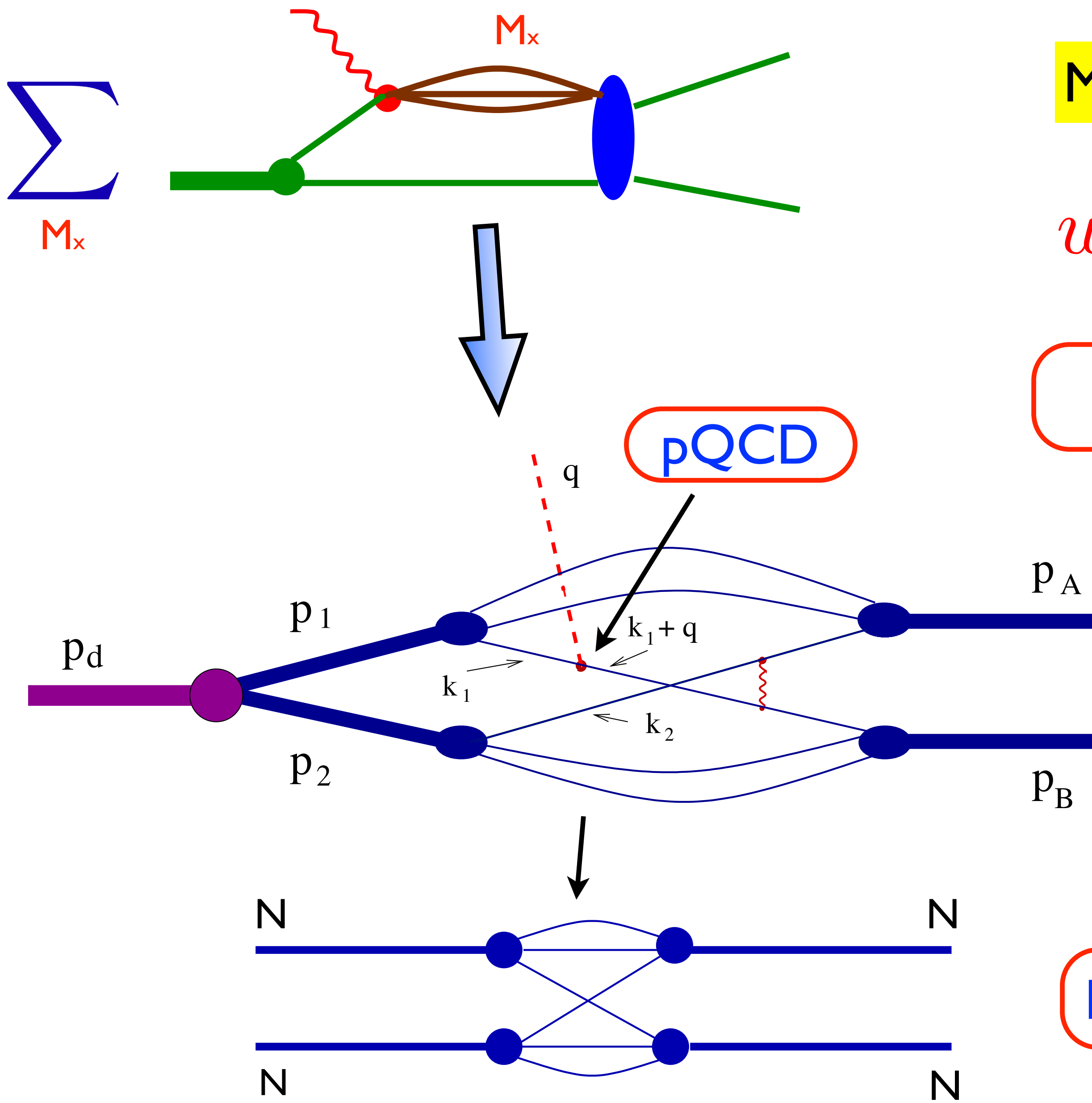

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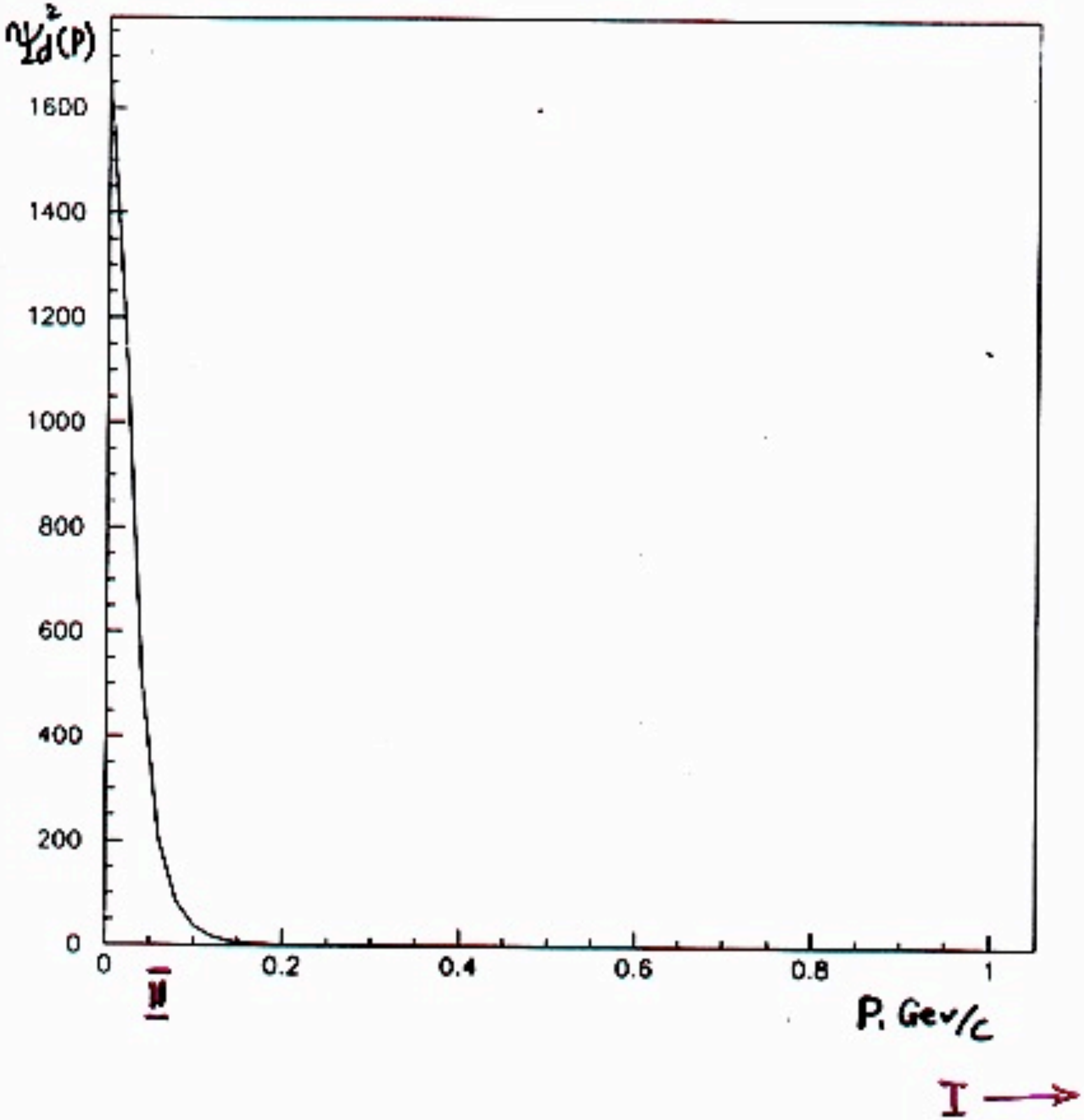
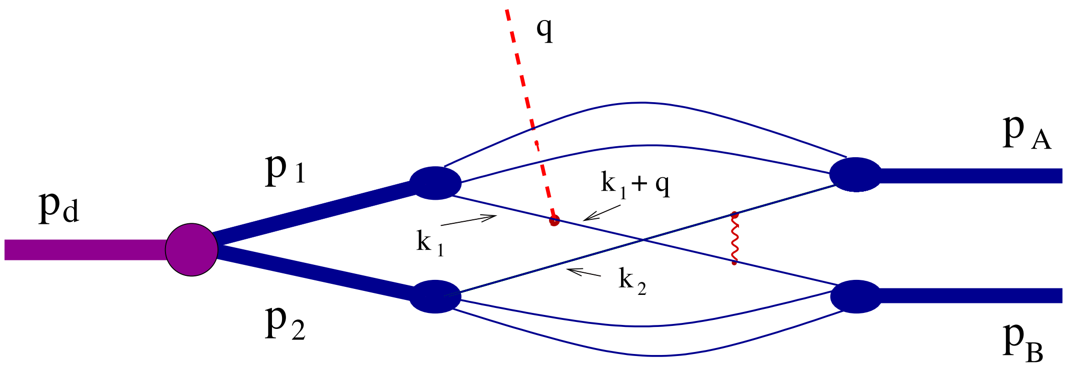
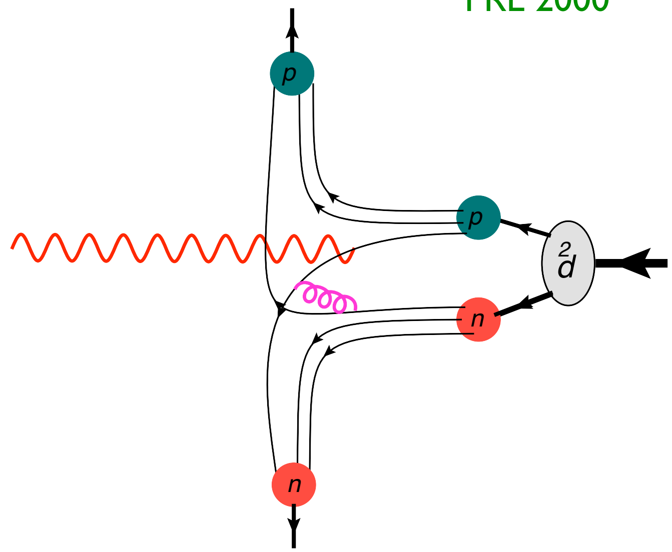


$\Psi_d^2(P)$
1600
1400
1200
1000
800
600
400
200
0
0
0.2
0.4
0.6
0.8
1
P, Gev/c
I →

Frankfurt, Miller, MS, Strikman
PRL 2000





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

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

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

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

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.

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

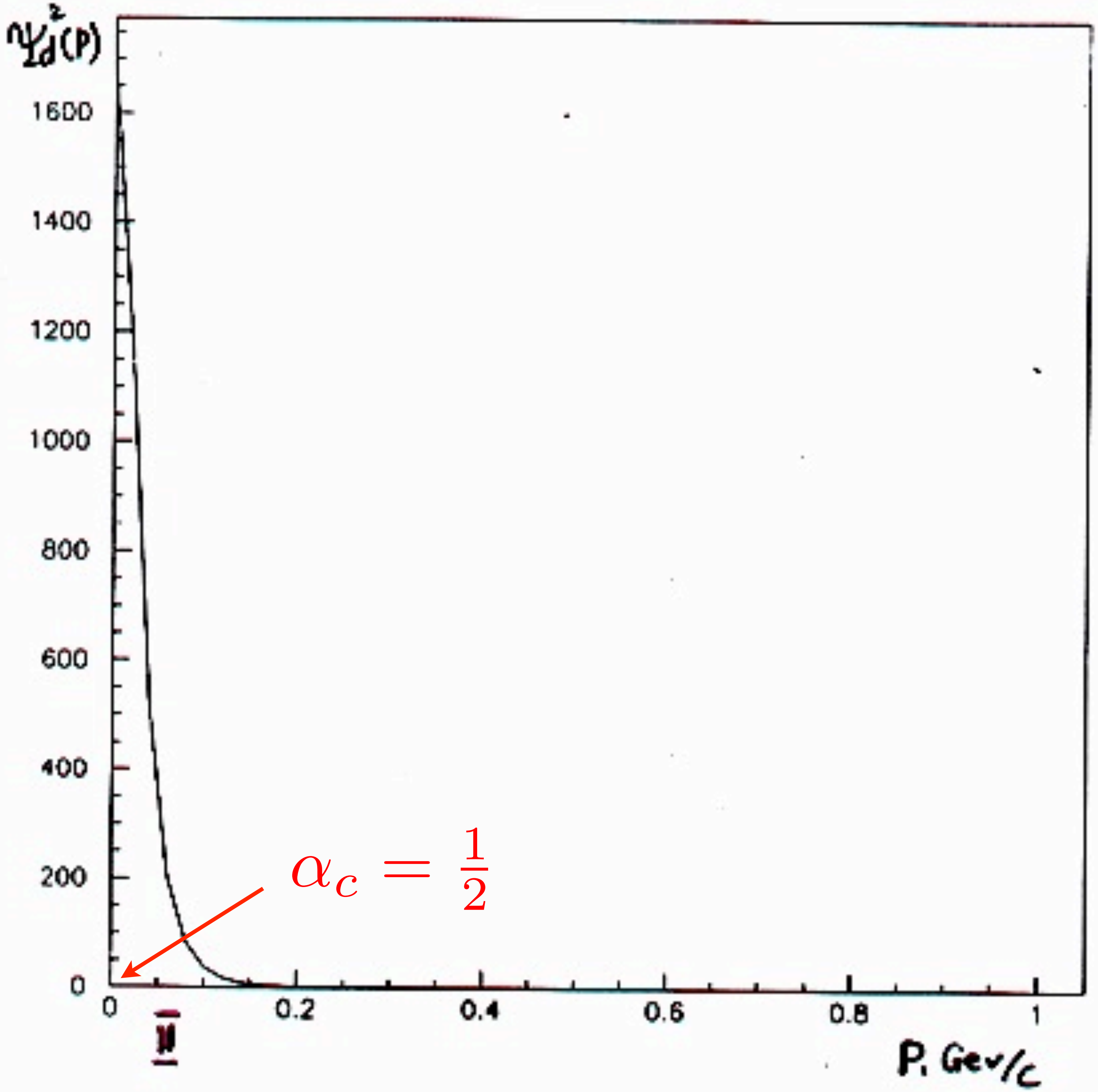
-We are concerned with momenta such that $p_\perp^2 \ll m_N^2 \ll s'$ and $\alpha \sim \frac{1}{2}$ so we neglect terms of order $p_\perp^2, m_N^2/s' \ll 1$ to obtain:

$$(k_1 + q)^2 - m_q^2 + i\epsilon \approx x_1 s'(\alpha - \alpha_c + i\epsilon),$$
$$\alpha_c \equiv \frac{x_1 m_R^2 + k_{1\perp}^2}{(1-x_1)x_1 \tilde{s}}. \quad (2)$$

looking for $\alpha_c \sim \frac{1}{2}$ contribution

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



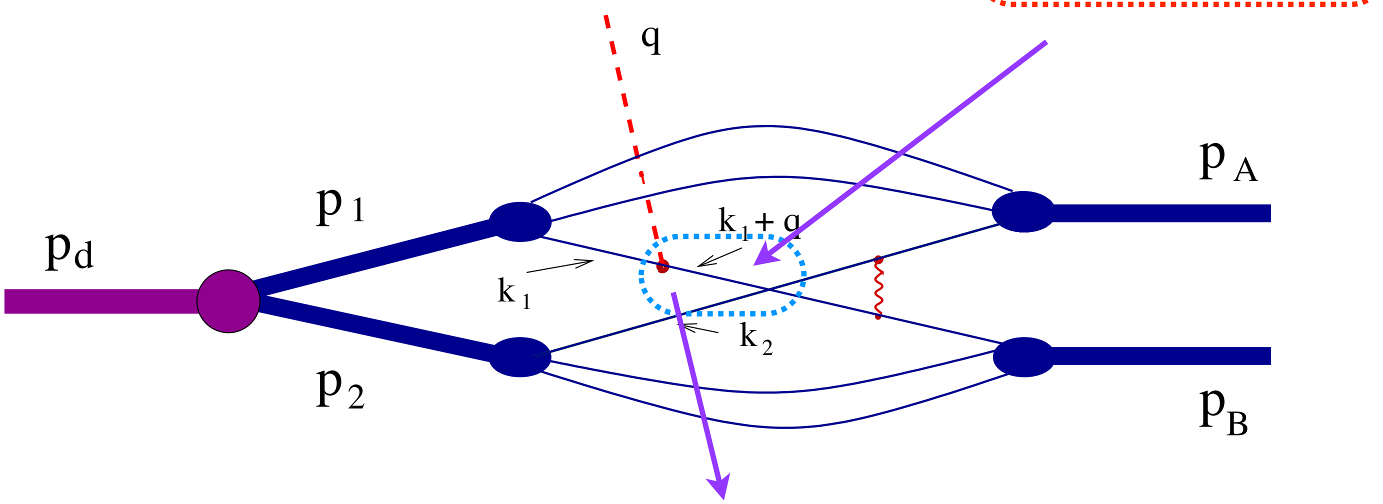
$\psi_d^2(p)$
1600
1400
1200
1000
800
600
400
200
0
0
0.2
0.4
0.6
0.8
1
P, GeV/c
$\alpha_c = \frac{1}{2}$

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

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



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

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

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

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

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

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

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

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

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

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

γnp ⇒ np

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

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

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

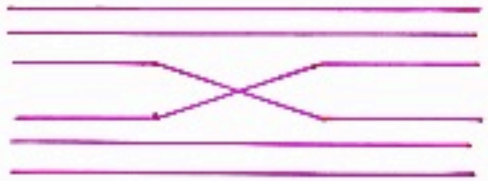
$$\langle p_{\lambda_A}, n_{\lambda_B} \mid A \mid \lambda_\gamma, \lambda_D\rangle = \sum_{\lambda_2} \frac{f(\theta_{cm})}{3\sqrt{2s'}} \times$$
$$\left(\langle p_{\lambda_A}, n_{\lambda_B}|A_{pn}(s,t_n)|p_{\lambda_\gamma}, n_{\lambda_2}\rangle - \langle p_{\lambda_A}, n_{\lambda_B}|A_{pn}(s,u_n)|n_{\lambda_\gamma}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

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

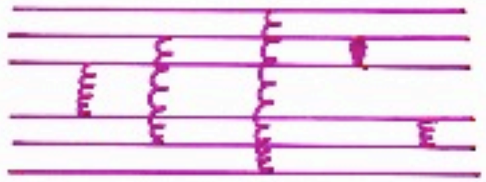
$$\frac{d\sigma^{\gamma d\to pn}}{dt} = \frac{8\alpha}{9}\pi^4 \cdot \frac{1}{s'}C(\frac{\tilde{t}}{s})\frac{d\sigma^{pn\to pn}(s,\tilde{t})}{dt}\left|\int \Psi_d^{NR}(p_z=0,p_\perp)\sqrt{m_N}\frac{d^2p_\perp}{(2\pi)^2}\right|^2,$$

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

QIM



GLUON EXCHANGE



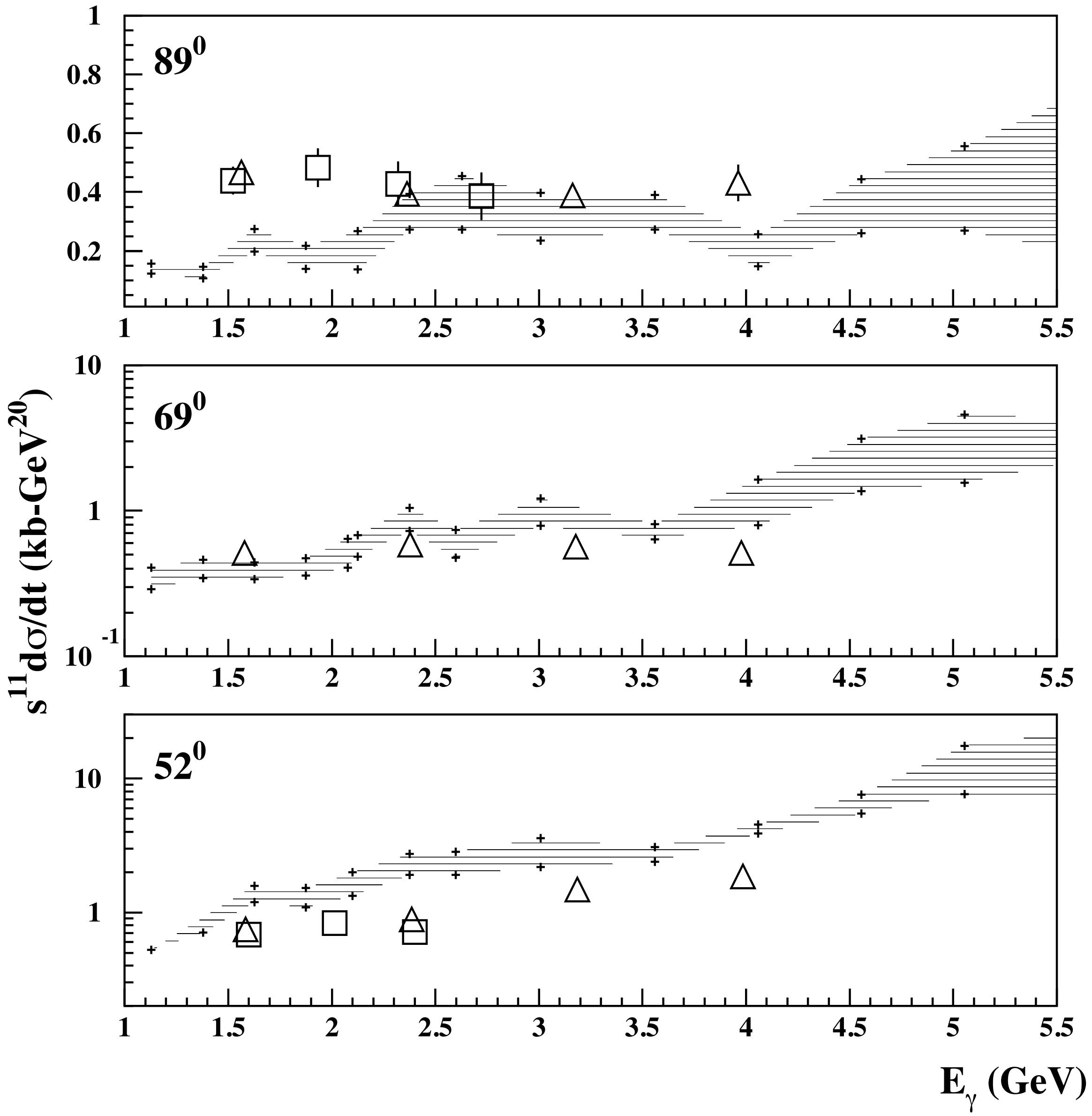
ANIHILLATION

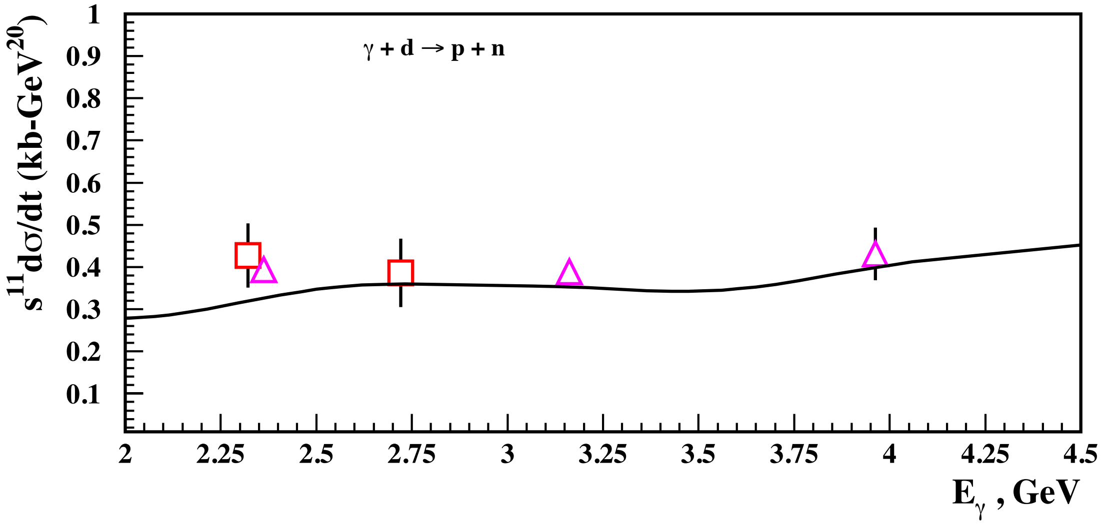
≡ COMPARE $PP \to PP$ AND $P\bar{P} \to P\bar{P}$ CROSS SECTIONS

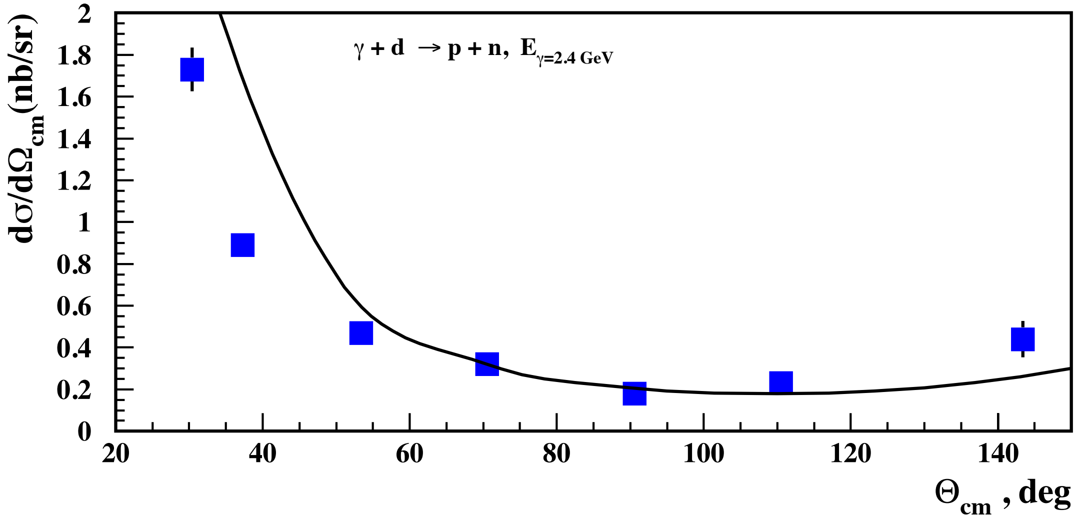
$$\frac{d\sigma^{\bar{P}P}/dt}{d\sigma^{PP}/dt} \quad \begin{array}{l} \sim 1.7 \text{ AT } \theta_{CM} \approx 0^\circ \\ \sim 0.025 \text{ AT } \theta_{CM} = 90^\circ \end{array}$$

Frankfurt, Miller, M.S. Strikman
PRL 2000

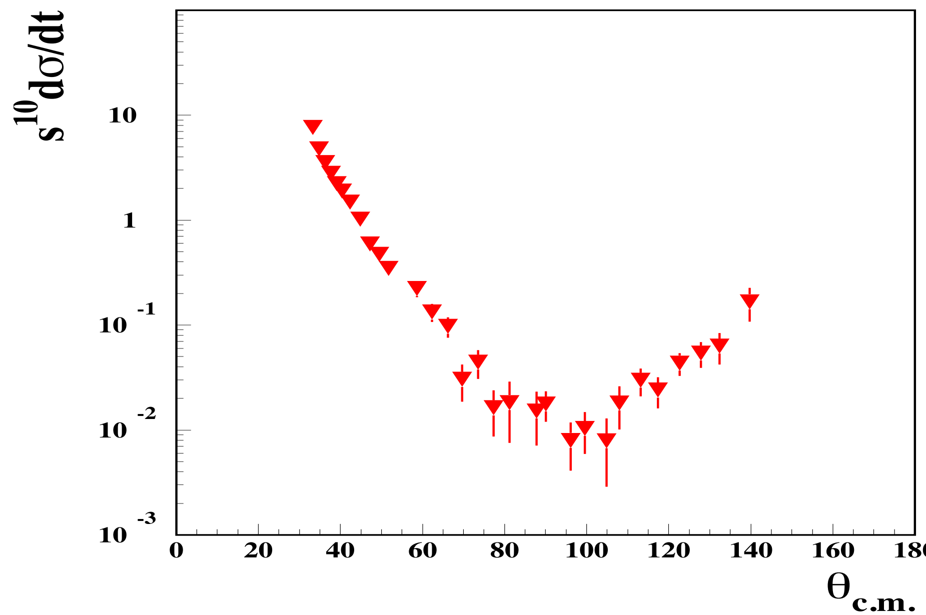
$$\frac{d\sigma^{\gamma d\to pn}}{dt} = \frac{8\alpha}{9}\pi^4 \cdot \frac{1}{s'}C(\frac{\tilde{t}}{s})\frac{d\sigma^{pn\to pn}(s,\tilde{t})}{dt}\left|\int \Psi_d^{NR}(p_z=0,p_\perp)\sqrt{m_N}\frac{d^2p_\perp}{(2\pi)^2}\right|^2,$$

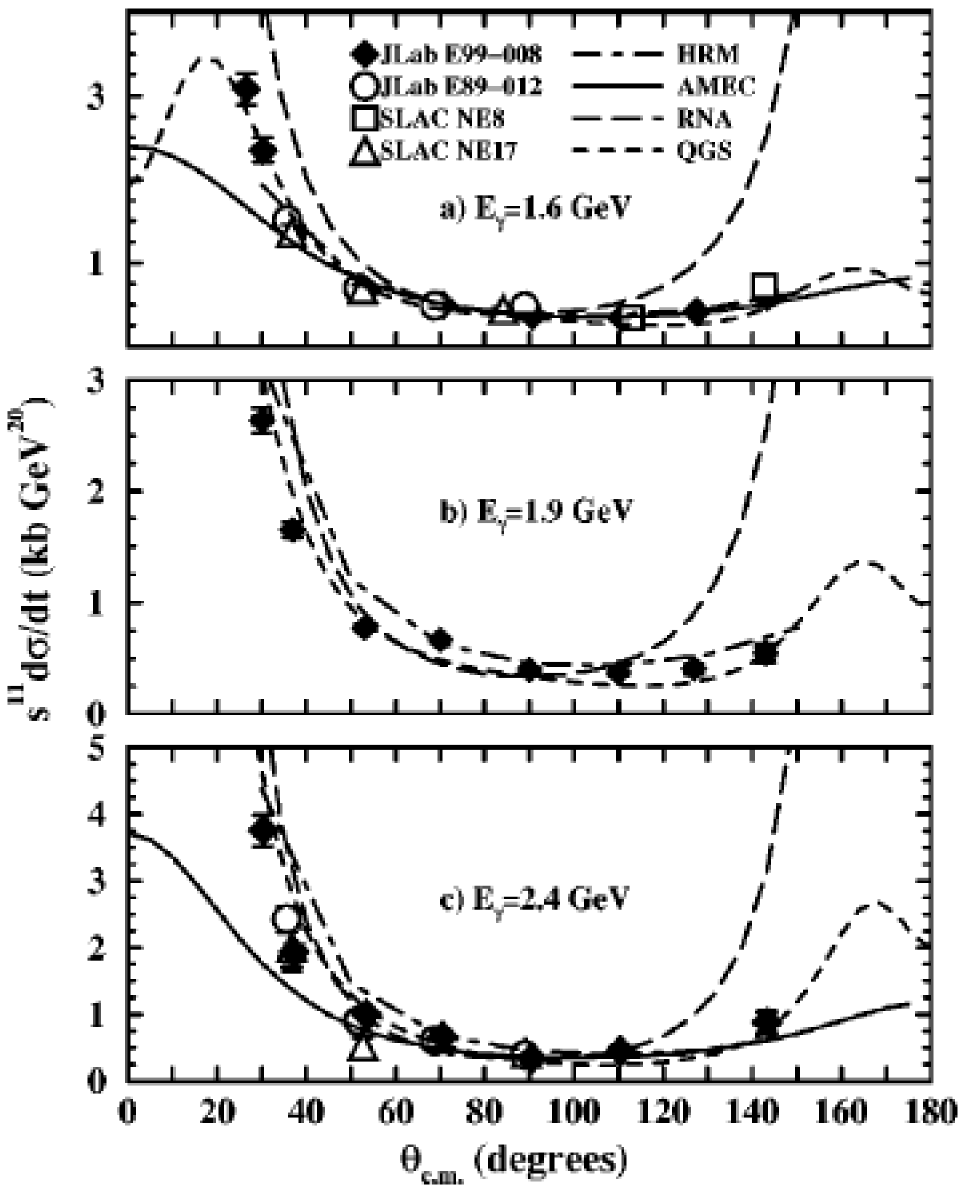



γ + d → p + n
$s^{11}d\sigma/dt$ (kb-GeV^{20})
E_γ , GeV


γ + d → p + n, $E_{\gamma=2.4\ GeV}$
$d\sigma/d\Omega_{cm}$(nb/sr)
Θ_{cm} , deg

$pn \to pn$


$s^{10}d\sigma/dt$
$\Theta_{c.m.}$


JLab E99–008
JLab E89–012
SLAC NE8
SLAC NE17
HRM
AMEC
RNA
QGS
a) Eγ=1.6 GeV
b) Eγ=1.9 GeV
c) Eγ=2.4 GeV
s^11 dσ/dt (kb GeV^20)
θc.m. (degrees)

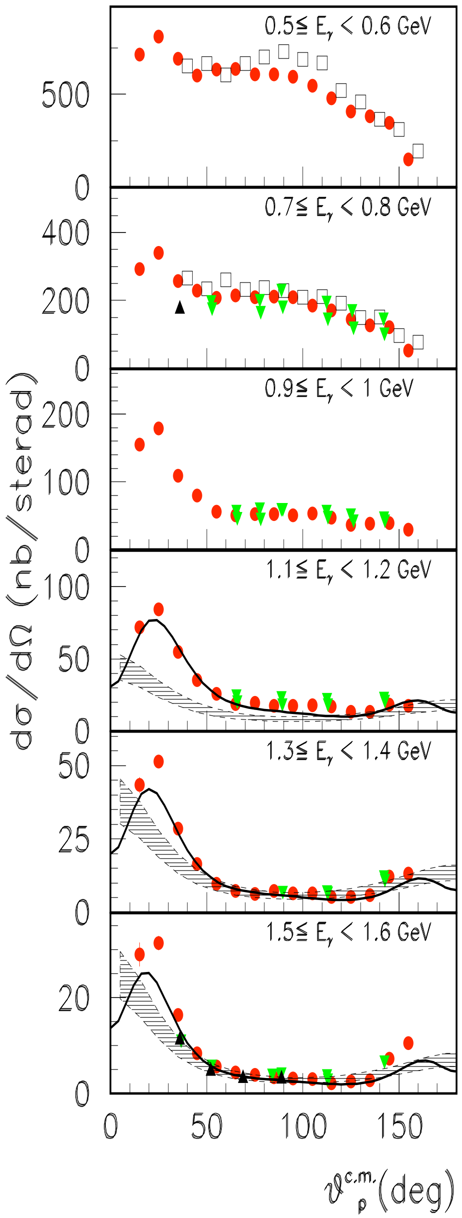


FIG. 7: (Color) Angular distributions of the deuteron photodisintegration cross section measured by the CLAS (full/red circles) in the incident photon energy range $0.50 - 1.70$ GeV. Results from Mainz [26] (open squares, average of the measured values in the given photon energy intervals), SLAC [5,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

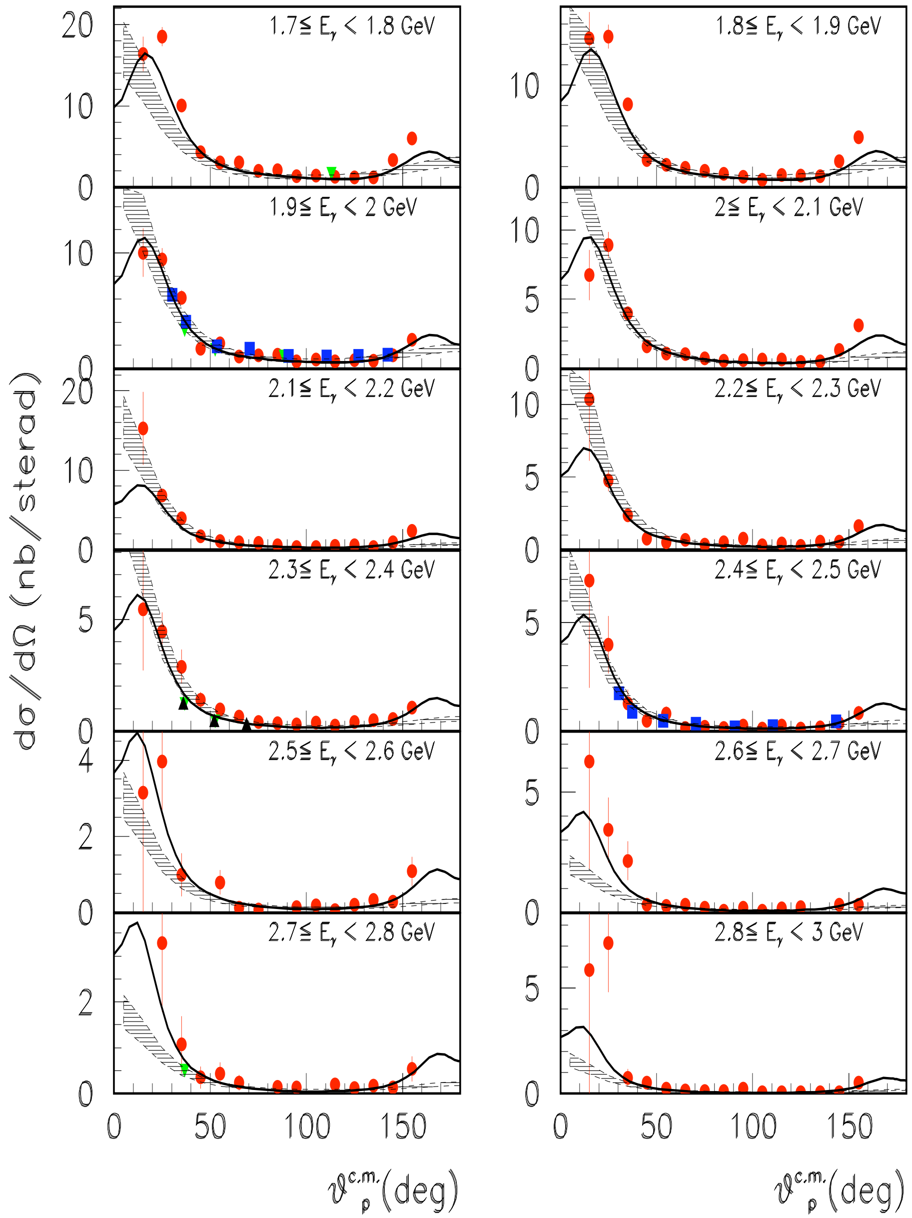


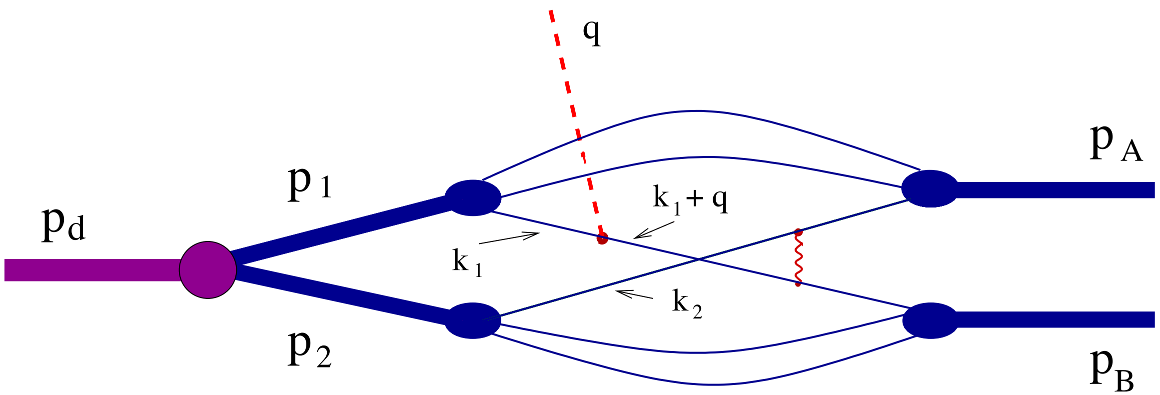
FIG. 8: (Color) Same as Fig. 7 for photon energies $1.7 - 3.0$ GeV.

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.

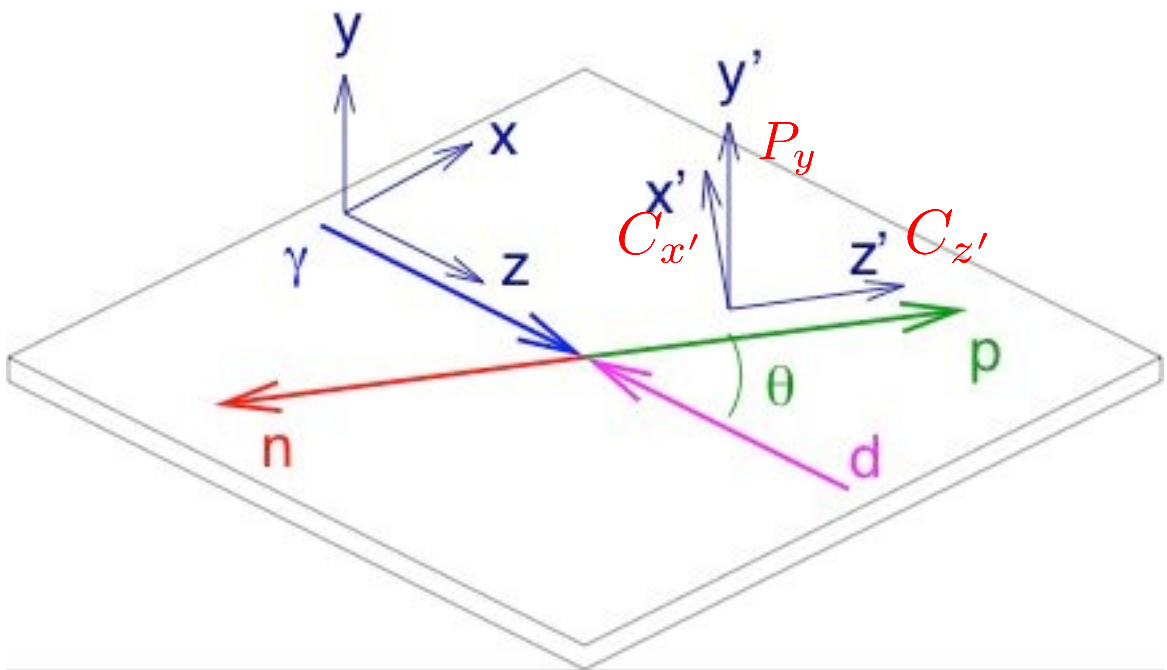


Polarization Observables

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

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

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



Gilman, Gross, 2002

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

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

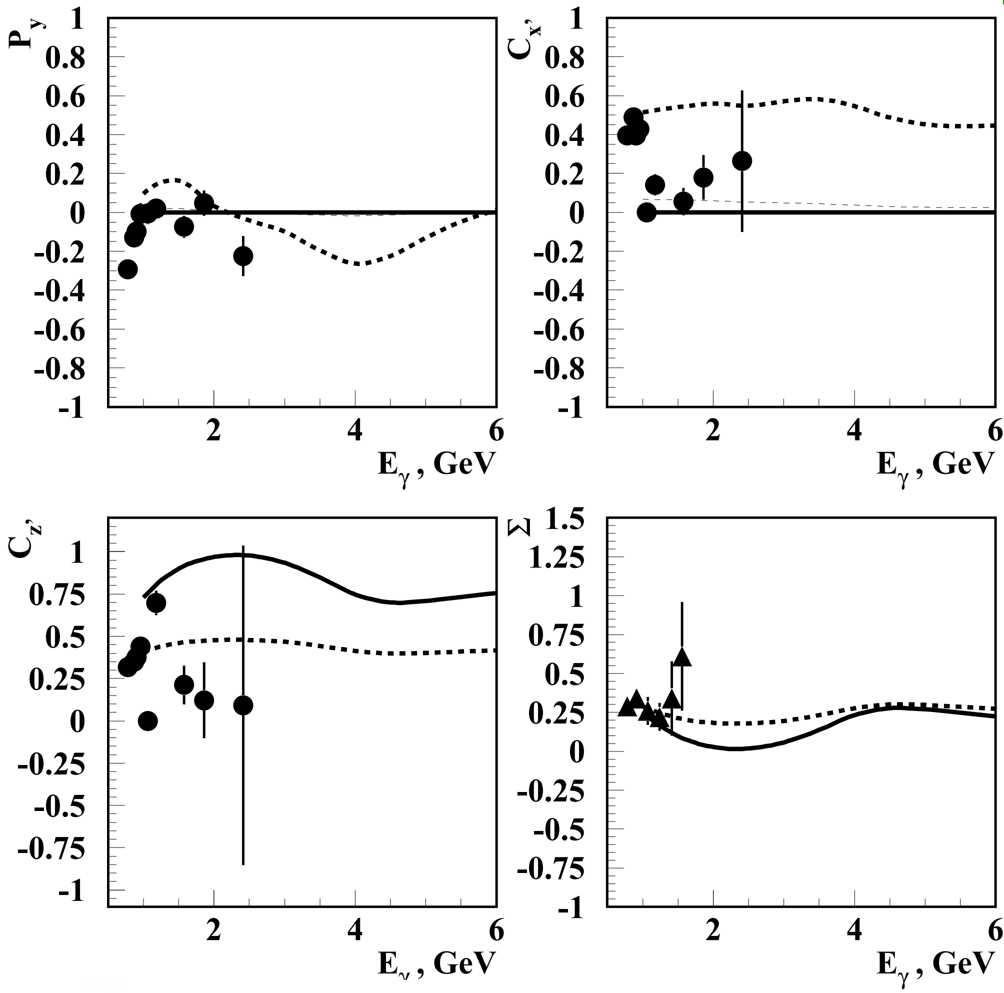
$$C_{z'} = \frac{2|\phi_1|^2-2|\phi_2|^2+|\phi_3|^2-|\phi_4|^2}{2|\phi_1|^2+2|\phi_2|^2+|\phi_3|^2+|\phi_4|^2+6|\phi_5|^2}$$

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

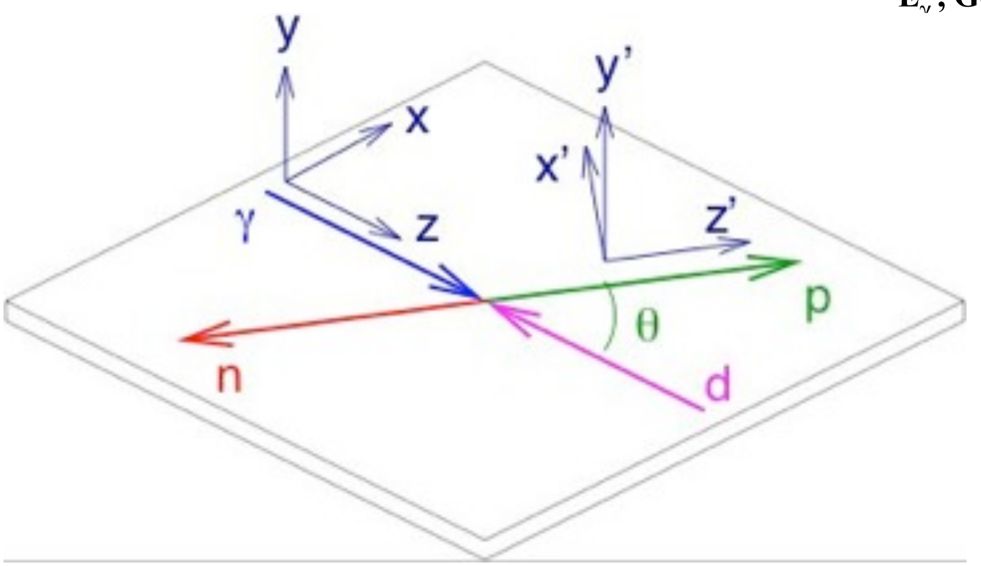
$$\begin{aligned}
\phi_1(s,t_n,u_n) &= \langle +,+ \mid A_{pn} \mid +,+\rangle \\
\phi_2(s,t_n,u_n) &= \langle +,+ \mid A_{pn} \mid -,-\rangle \\
\phi_3(s,t_n,u_n) &= \langle +,- \mid A_{pn} \mid +,-\rangle \\
\phi_4(s,t_n,u_n) &= \langle +,- \mid A_{pn} \mid -,+\rangle \\
\phi_5(s,t_n,u_n) &= \langle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

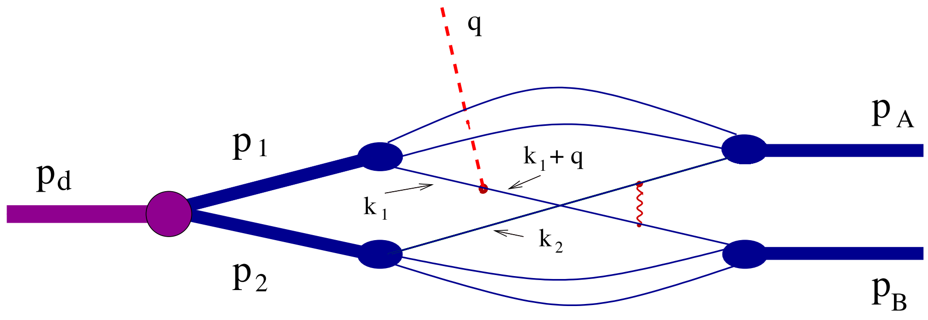
$$|\phi_1| \geq |\phi_3|, |\phi_4| > |\phi_5| > |\phi_2|.$$

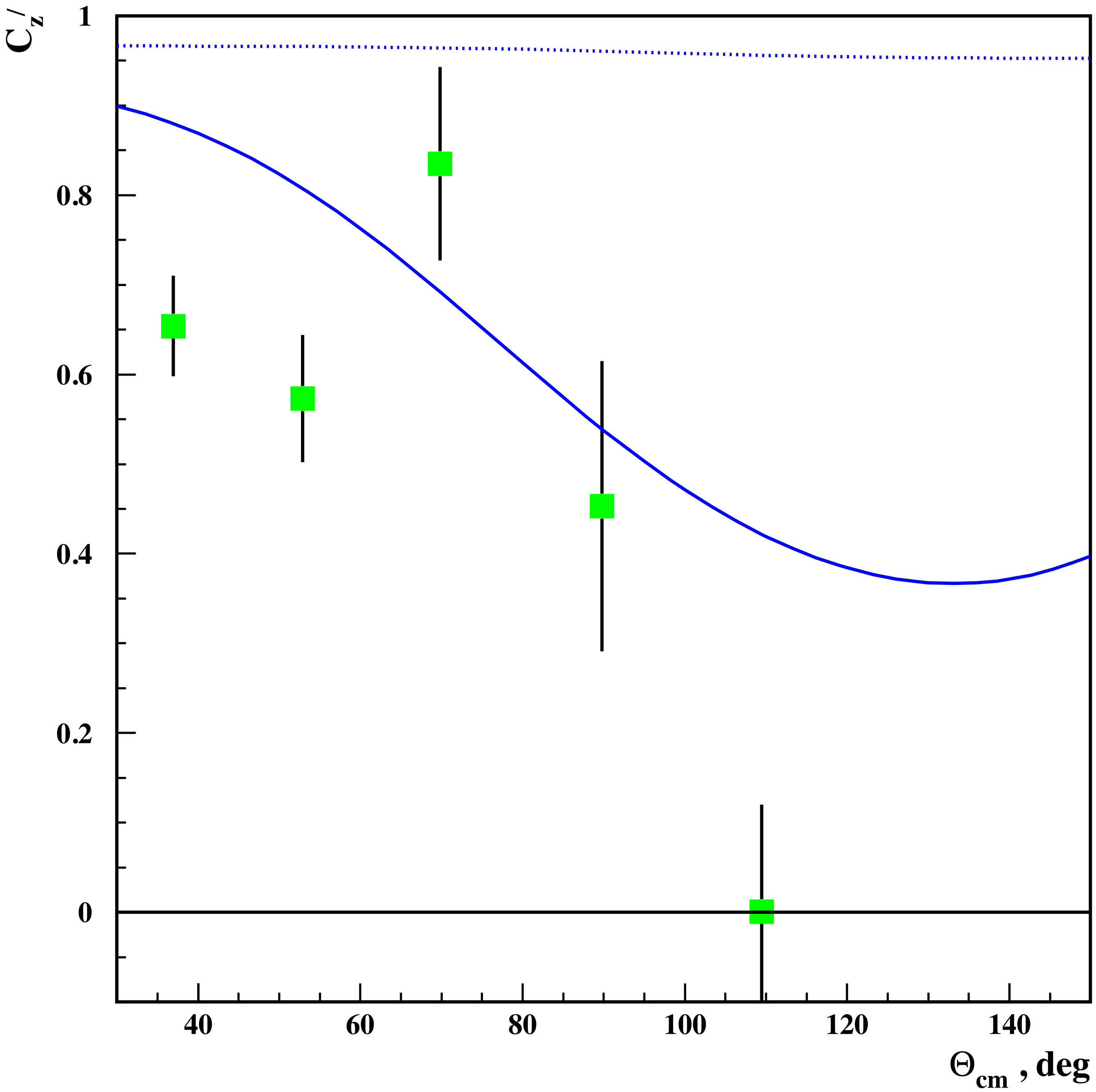
Sargsian, Phys. Lett. B 2004



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





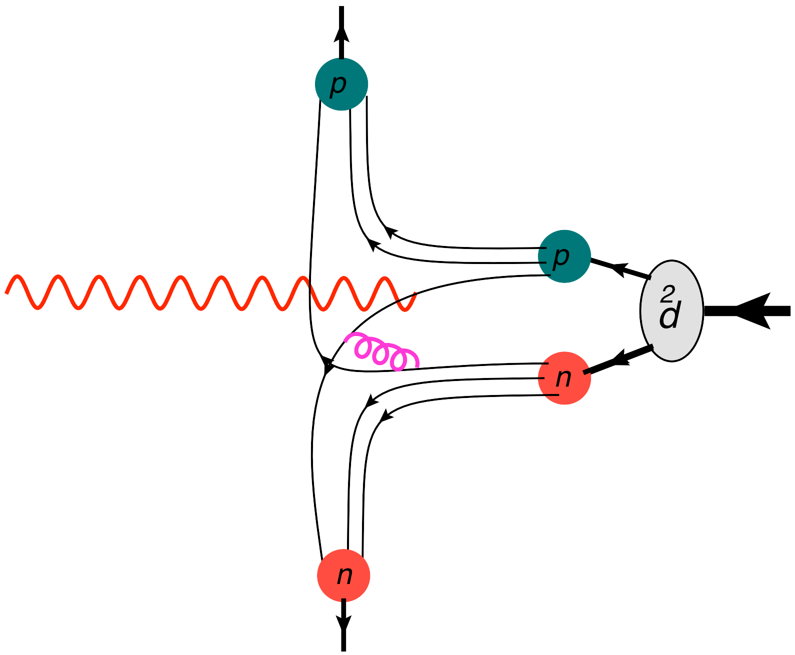


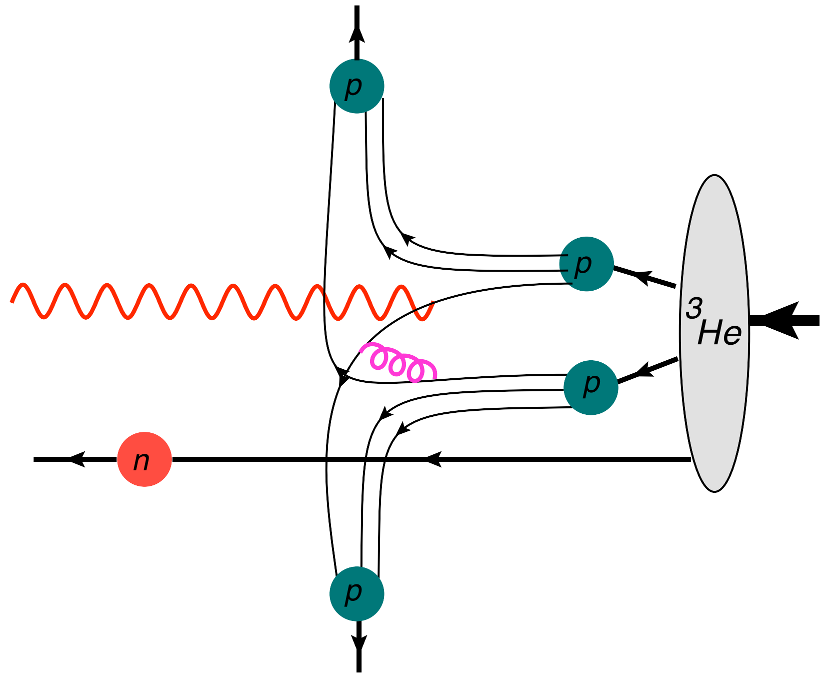
Jiang et al, PRL2007

Break up of pn from the deuteron

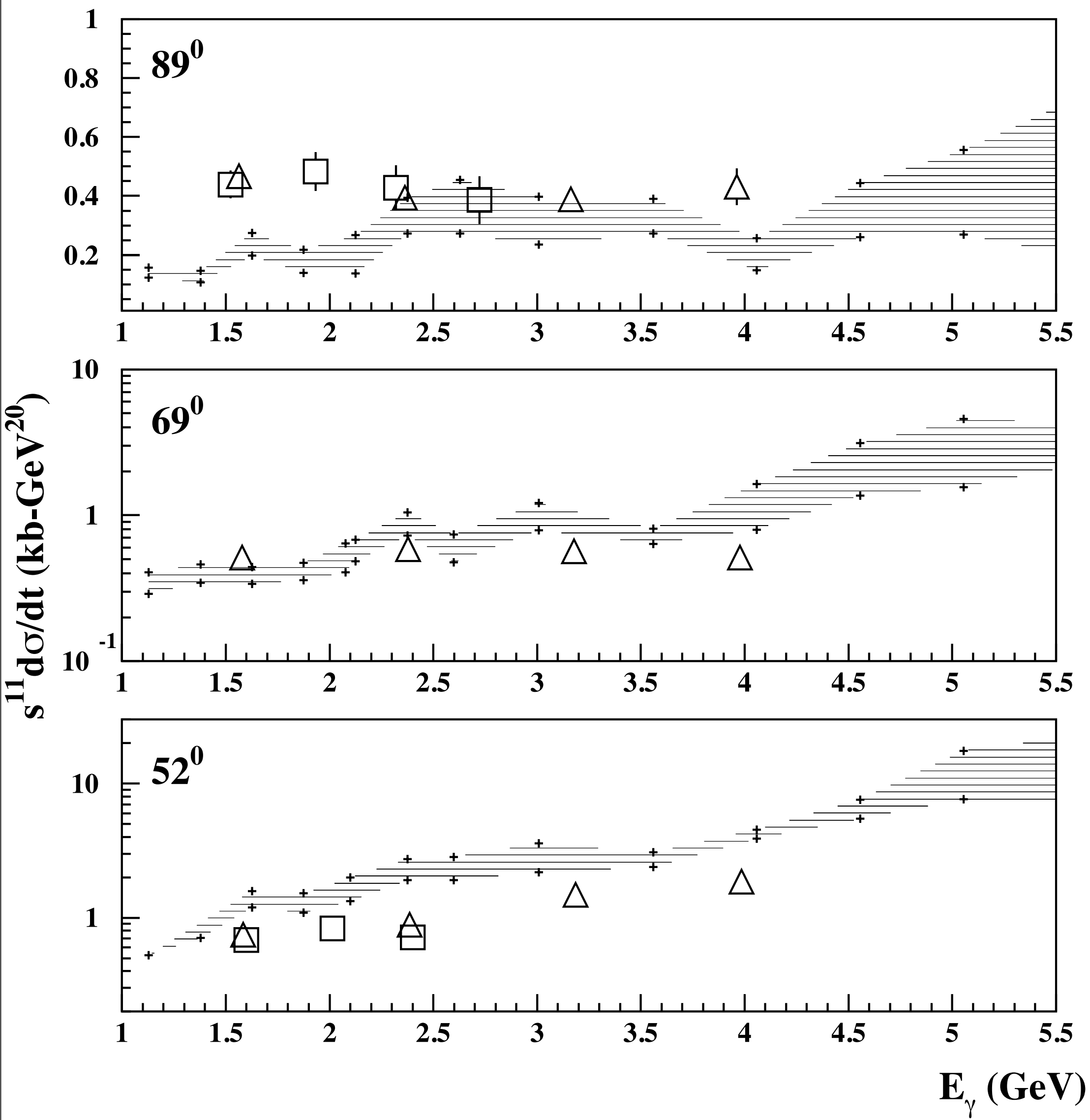
Break up of pp from Helium 3

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

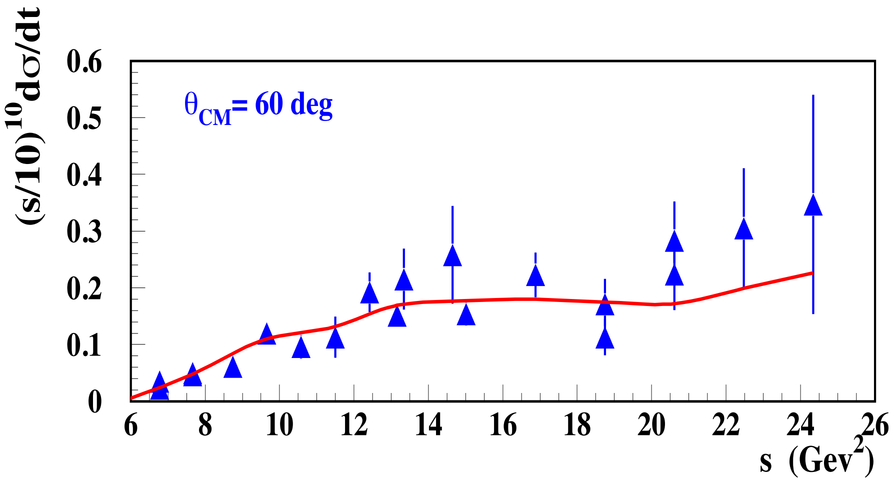


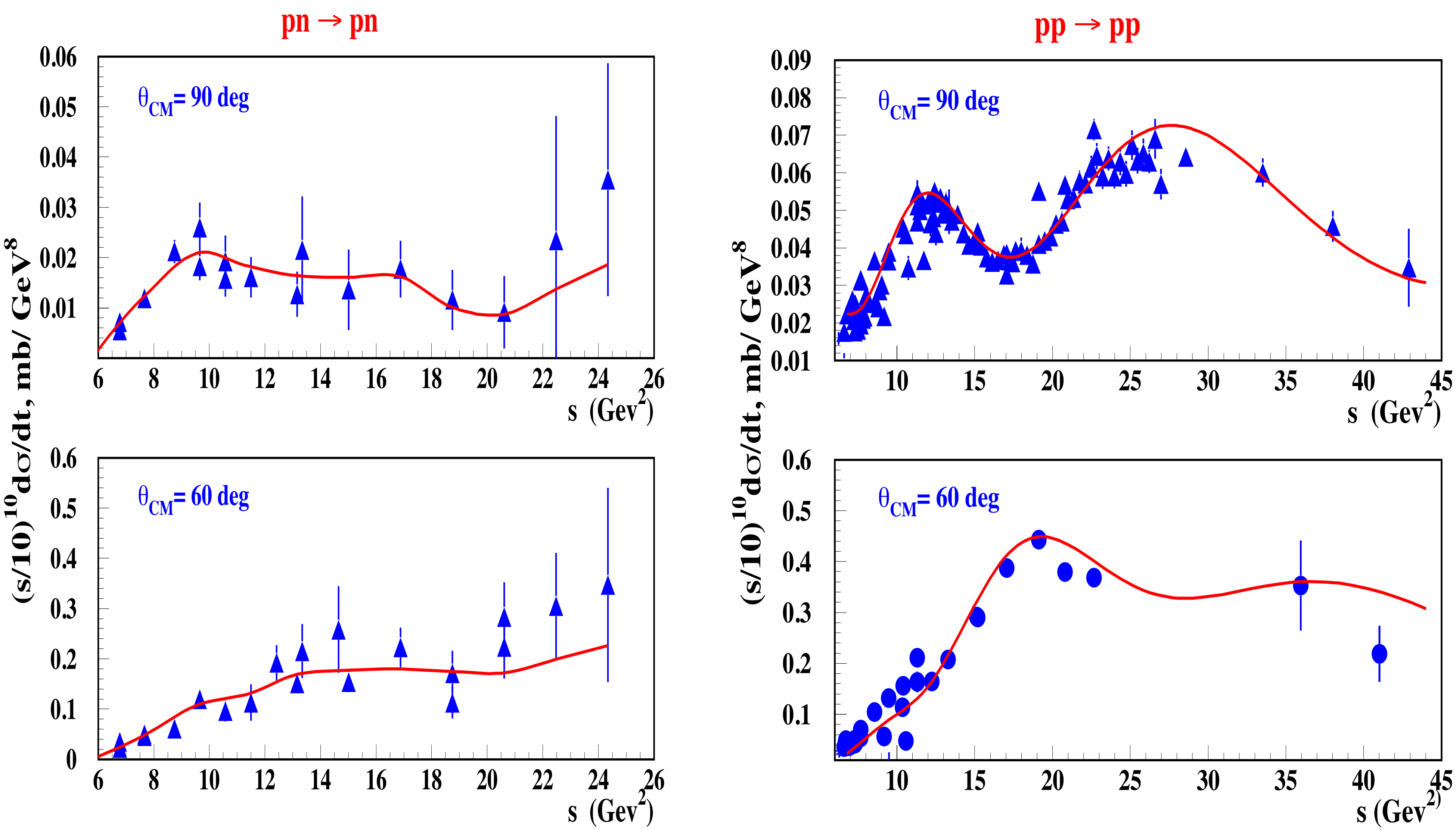


$$\gamma + d \rightarrow p + n$$



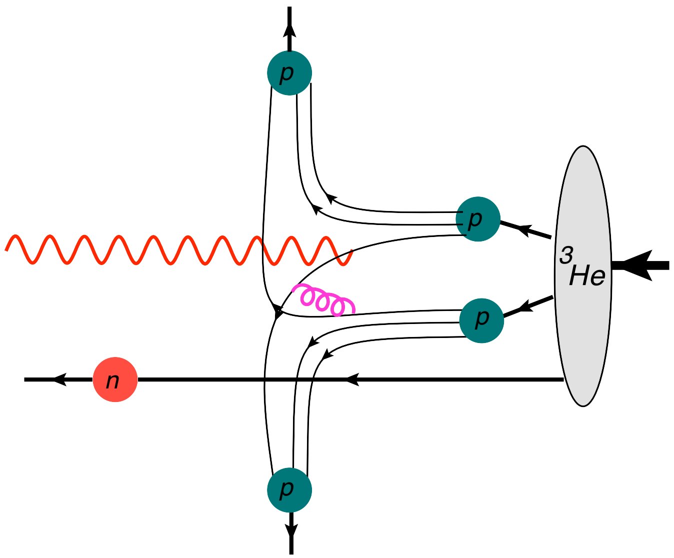
$$p + n \rightarrow p + n$$

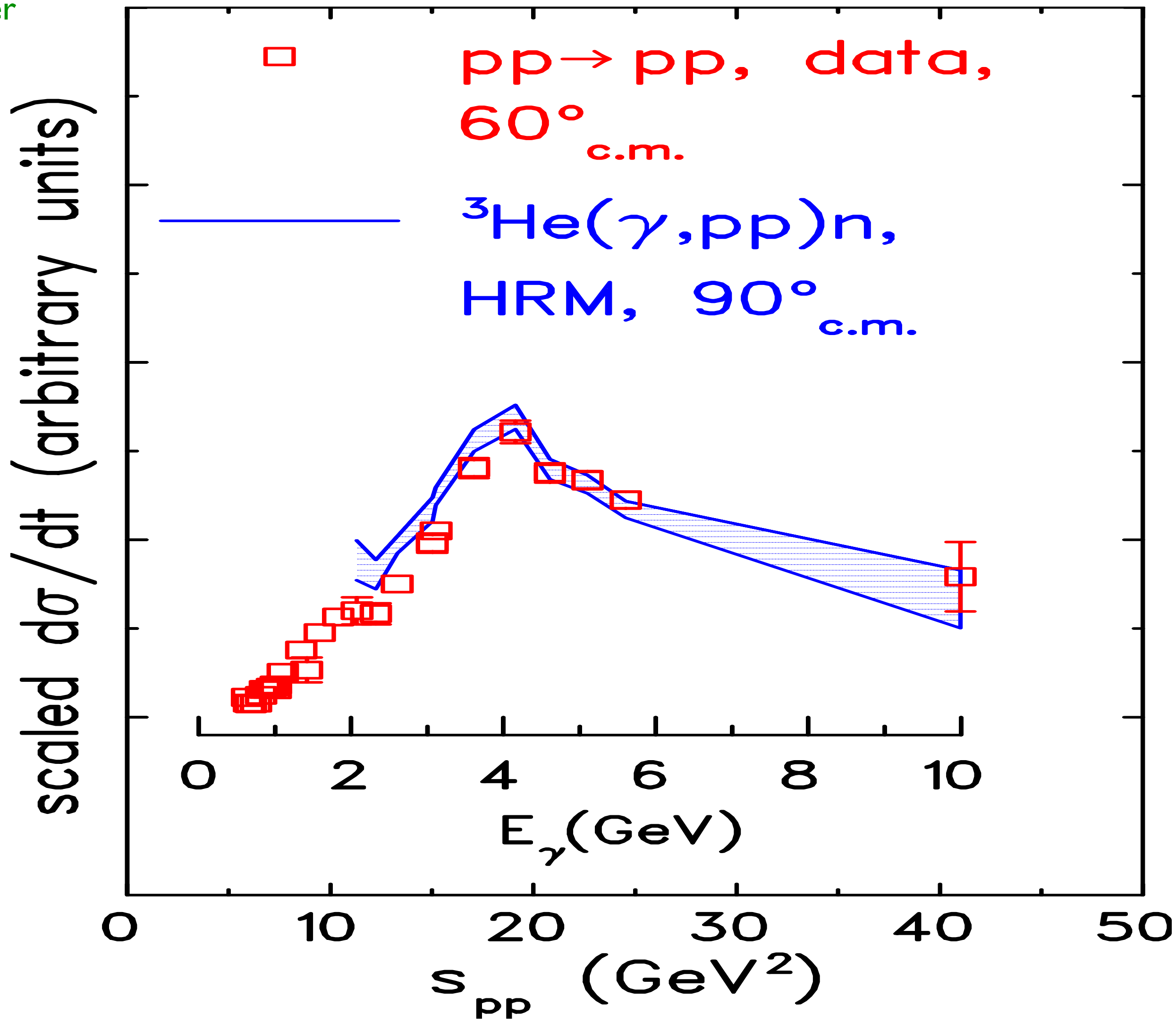



pn → pn
pp → pp
θCM= 90 deg
θCM= 60 deg
(s/10)^10 dσ/dt, mb/ GeV^8
s (Gev^2)
0.06
0.05
0.04
0.03
0.02
0.01
0.09
0.08
0.07
0.6
0.5
0.4
0.3
0.2
0.1
0
6
8
10
12
14
16
18
20
22
24
26
15
25
30
35
40
45

Break up of pp from Helium 3

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

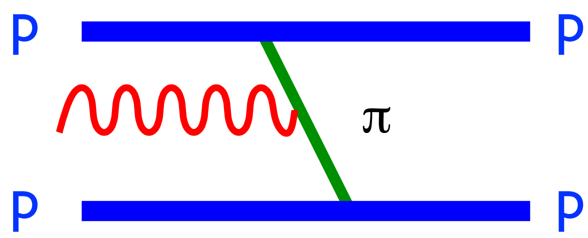




- Hard Photodisintegration of pp pair: $\gamma +^3 He \to pp + n$

What is known?

for $E_\gamma \leq 0.5 GeV$

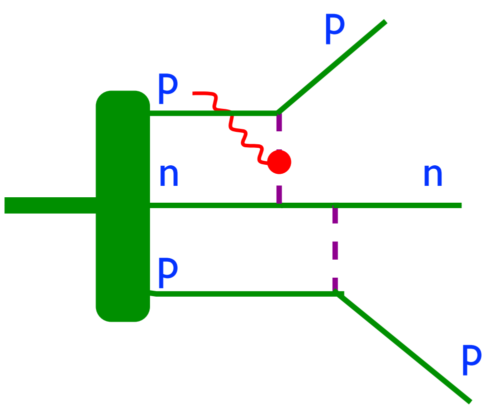


~ 0

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

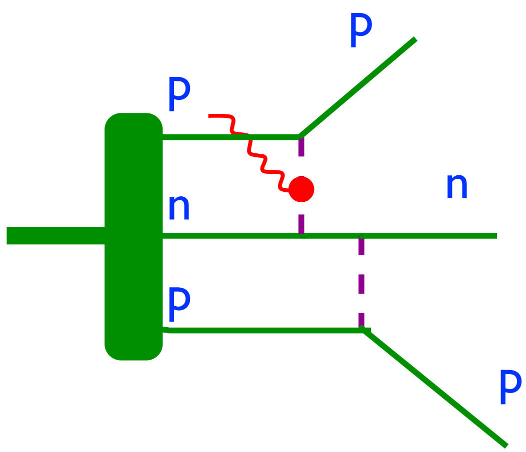
Laget, Nucl.Phys. 1989

- Three Body Processes are Dominant

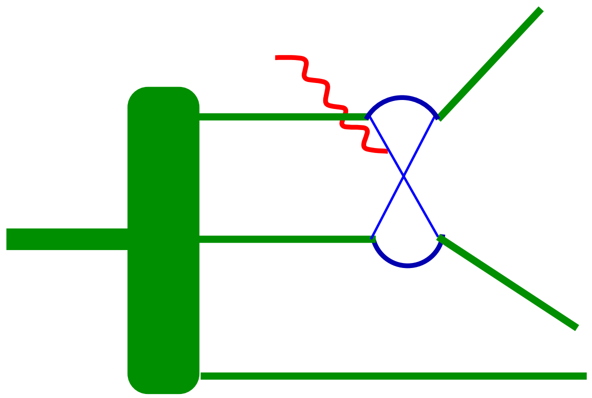


$$\frac{\sigma(\gamma^3 He \to pp)}{\sigma(\gamma^3 He \to pn)} \approx 1\%$$

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



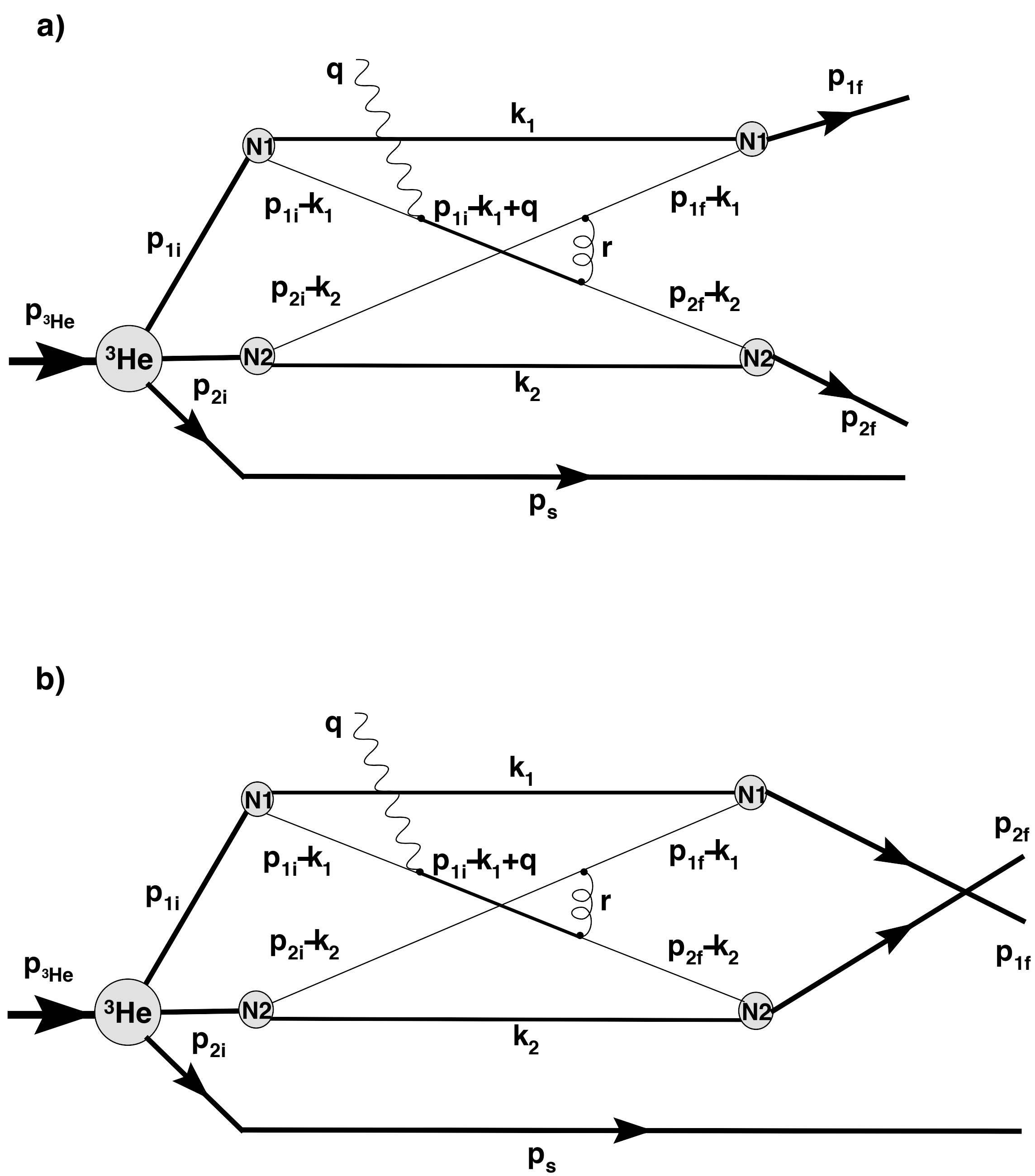
$\sim s^{-13}$



$\sim s^{-11}$

Considering $\gamma + {}^3He \to (NN) + N$

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



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

$$\langle \lambda_{1f}, \lambda_{2f}, \lambda_s \mid A \mid \lambda_\gamma, \lambda_A \rangle = \sum_{(\eta_{1f},\eta_{2f}),(\eta_{1i},\eta_{2i}),(\lambda_{1i},\lambda_{2i})} \int \left\{ \frac{\psi_N^{\dagger \lambda_{2f},\eta_{2f}}(p_{2f}, x_2', k_{2\perp})}{1-x_2'} \bar{u}_{\eta_{2f}}(p_{2f} - k_2) \right.$$

$$\left. [-igT_c^F \gamma^\nu] \frac{i[p_{1i} - k_1 + q + m_q]}{(p_{1i} - k_1 + q)^2 - m_q^2 + i\epsilon} [-\underline{iQ_i} e \epsilon_\perp^{\lambda_\gamma} \gamma^\perp] u_{\eta_{1i}}(p_{1i} - k_1) \frac{\psi_N^{\lambda_{1i},\eta_{1i}}(p_{1i}, x_1, k_{1\perp})}{(1-x_1)} \right\}_1 \times$$

$$\left\{ \frac{\psi_N^{\dagger \lambda_{1f},\eta_{1f}}(p_{1f}, x_1', k_{1\perp})}{1-x_1'} \bar{u}_{\eta_{1f}}(p_{1f} - k_1) [-igT_c^F \gamma^\mu] u_{\eta_{2i}}(p_{2i} - k_2) \frac{\psi_N^{\lambda_{2i},\eta_{2i}}(p_{2i}, x_2, k_{2\perp})}{(1-x_2)} \right\}_2 \times$$

$$G^{\mu,\nu}(r) \frac{dx_1}{x_1} \frac{d^2 k_{1\perp}}{2(2\pi)^3} \frac{dx_2}{x_2} \frac{d^2 k_{2\perp}}{2(2\pi)^3} \frac{\Psi_{^3He}^{\lambda_A,\lambda_{1i},\lambda_{2i},\lambda_s}(\alpha, p_\perp, p_s)}{(1-\alpha)} \frac{d\alpha}{\alpha} \frac{d^2 p_\perp}{2(2\pi)^3} - (p_{1f} \longleftrightarrow p_{2f}), \quad (1)$$

$$\langle \lambda_{1f}, \lambda_{2f}, \lambda_s \mid M \mid \lambda_\gamma, \lambda_A \rangle = \frac{i[\lambda_\gamma] e\sqrt{2}(2\pi)^3}{\sqrt{2S'_{NN}}} \times$$

$$\Bigg\{ \sum_{\lambda_{2i}} \int Q_1 \langle \lambda_{2f}; \lambda_{1f} \mid T^{QIM}_{NN}(s_{NN}, t_N) \mid \lambda_\gamma; \lambda_{2i} \rangle \Psi^{\lambda_A}_{{}^3He,NR}(\vec{p}_1, \lambda_\gamma; \vec{p}_2, \lambda_{2i}; \vec{p}_s, \lambda_s) m_N \frac{d^2 p_\perp}{(2\pi)^2}$$

$$+ \sum_{\lambda_{1i}} \int Q_2 \langle \lambda_{2f}; \lambda_{1f} \mid T^{QIM}_{NN}(s_{NN}, t_N) \mid \lambda_{1i}; \lambda_\gamma \rangle \Psi^{\lambda_A}_{{}^3He,NR}(\vec{p}_1, \lambda_{1i}; \vec{p}_2, \lambda_\gamma; \vec{p}_s, \lambda_s) m_N \frac{d^2 p_\perp}{(2\pi)^2} \Bigg\} \quad (1)$$

$$\alpha = \frac{E_2 + p_{2z}}{M_A - E_s - p_{sz}}; \qquad p_\perp = \frac{p_{1\perp} - p_{2\perp}}{2},$$

$$\alpha_s = \frac{E_s + p_{sz}}{M_A}; \qquad \vec{p}_1 + \vec{p}_2 = -\vec{p}_s.$$

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

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

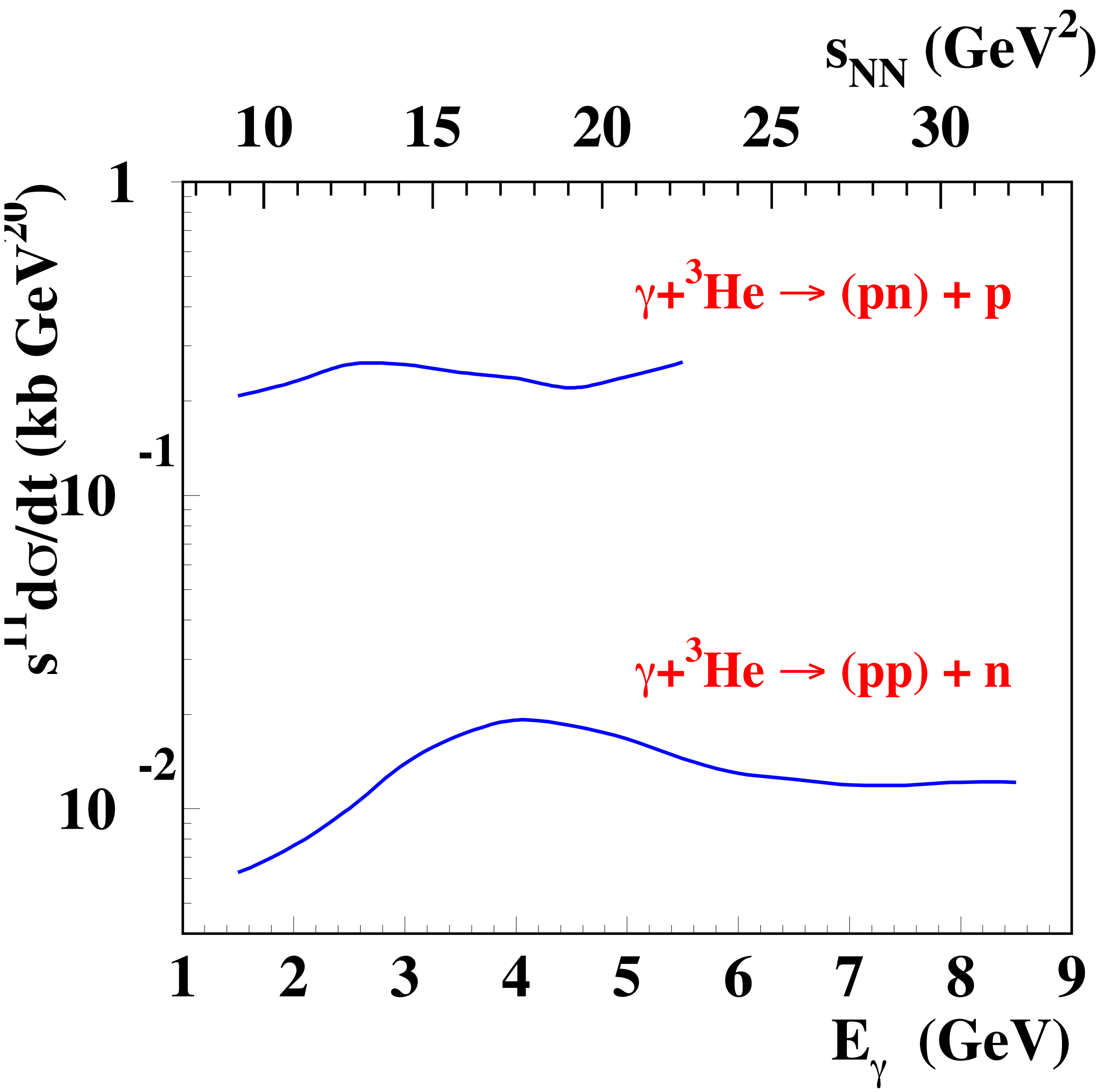
$$
Q_F = Q_1 + Q_2 = \frac{N_{uu}(Q_u + Q_u) + N_{dd}(Q_d + Q_d) + N_{ud}(Q_u + Q_d)}{N_{uu} + N_{dd} + N_{ud}}
$$

$\phi_3 \approx \phi_4$ True only for pn

$\phi_3 \approx -\phi_4$ For pp

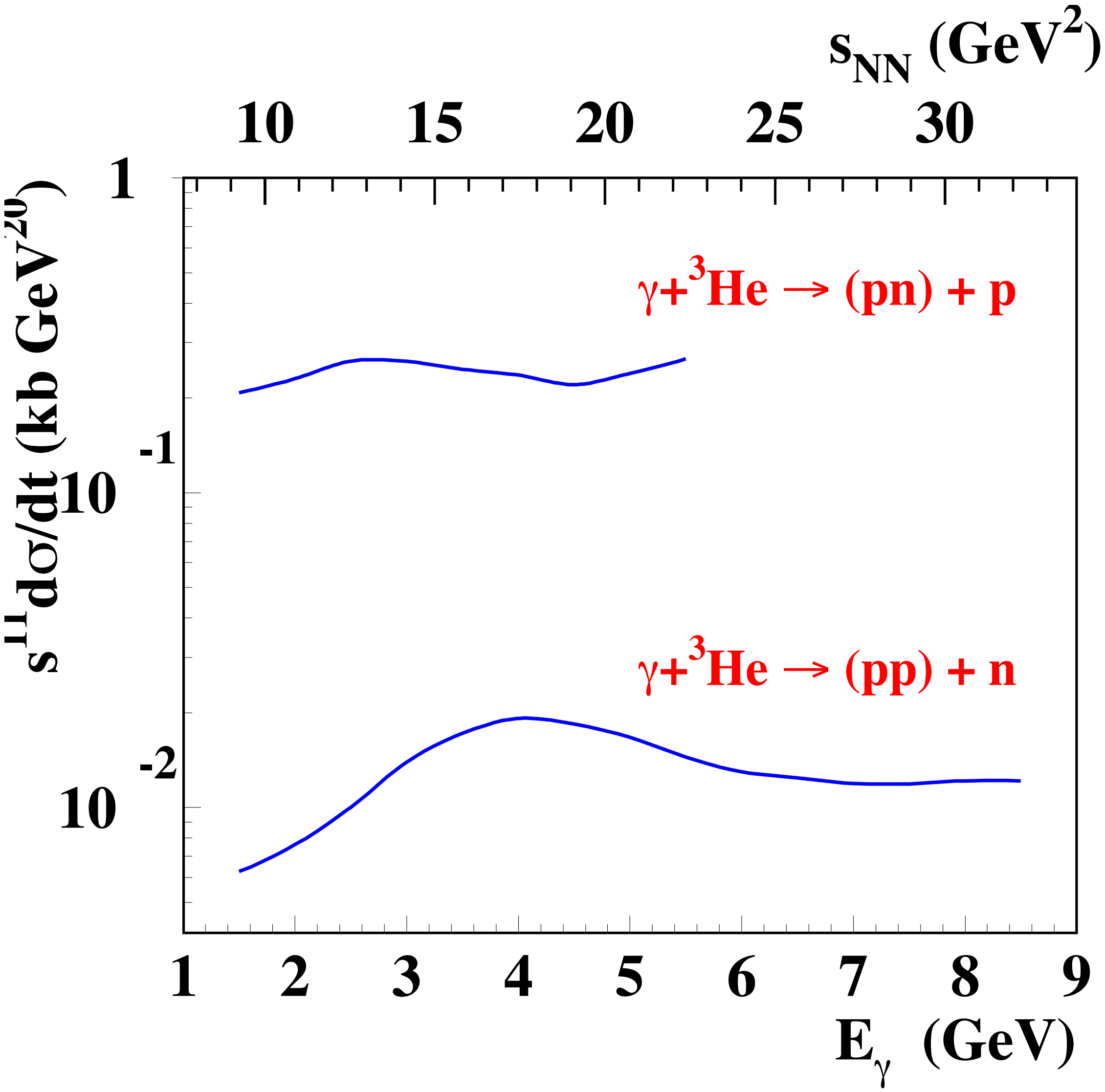
$$\frac{d\sigma}{dt\frac{d^3p_s}{E_s}} = \alpha Q^2_{F,PP} 16\pi^4 S^{pp}_{34}(\alpha=\frac{1}{2},\vec{p}_s)\frac{2C^2\beta^2}{1+2C^2}\frac{s_{NN}(s_{NN}-4m_N^2)}{(s_{NN}-p^2_{NN})^2(s-M^2_{^3He})}\times \frac{d\sigma^{pp\to pp}(s_{NN},t_N)}{dt}, \quad (1)$$

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



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

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

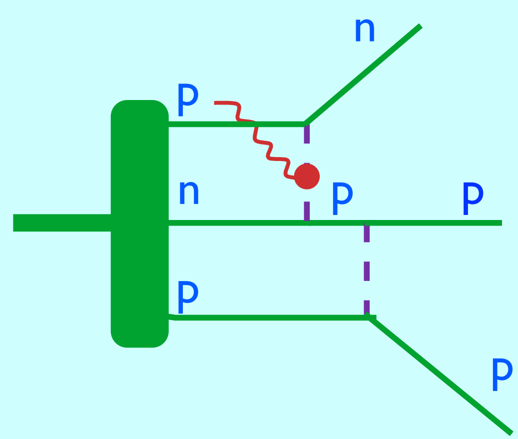


$$\frac{\sigma(\gamma^3He\to pp)}{\sigma(\gamma^3He\to pn)} \approx 0.1 \quad \text{at 4GeV}$$

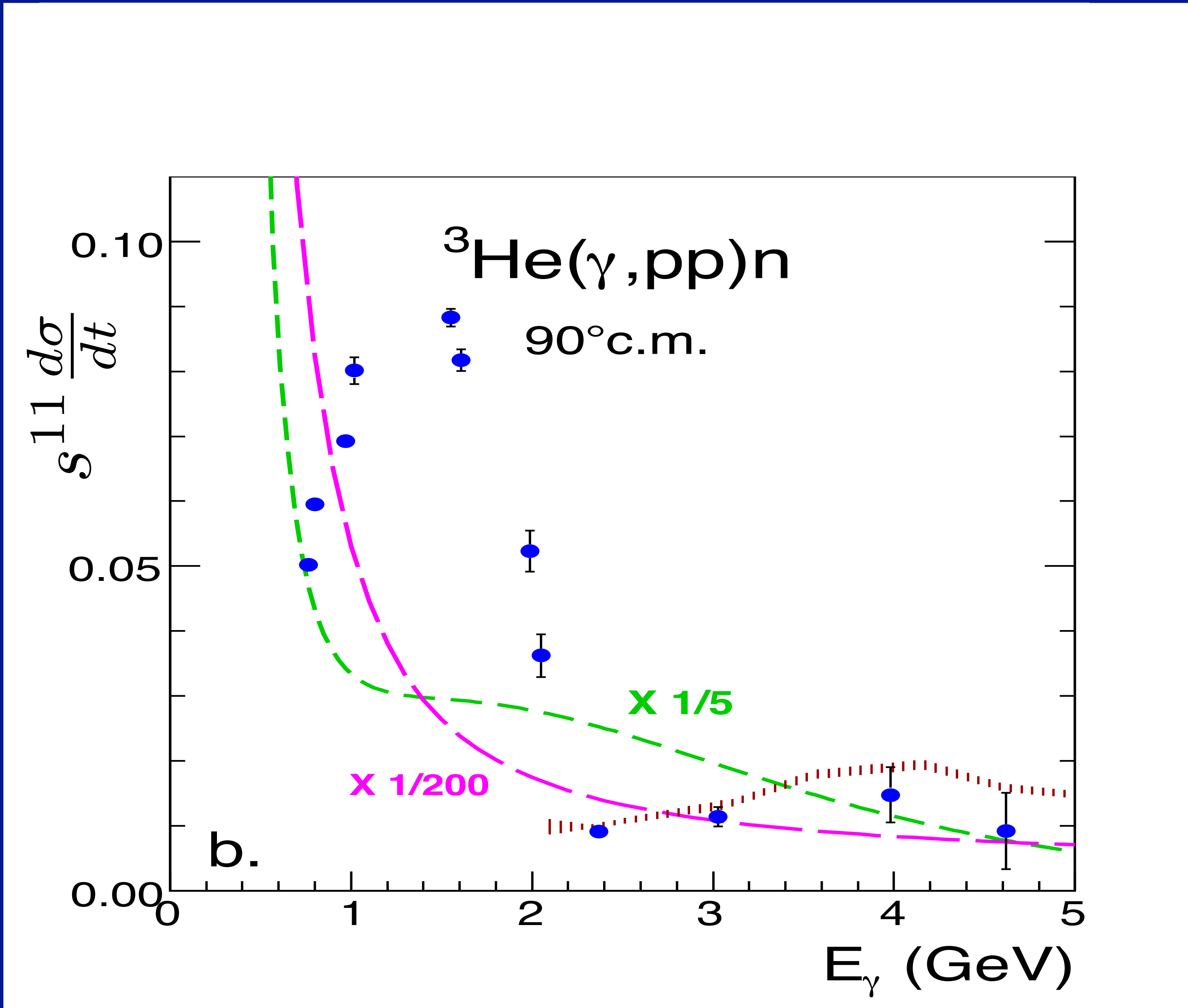
Meson Exchange Picture

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

J-M.Laget, Nucl.Phys. 1989

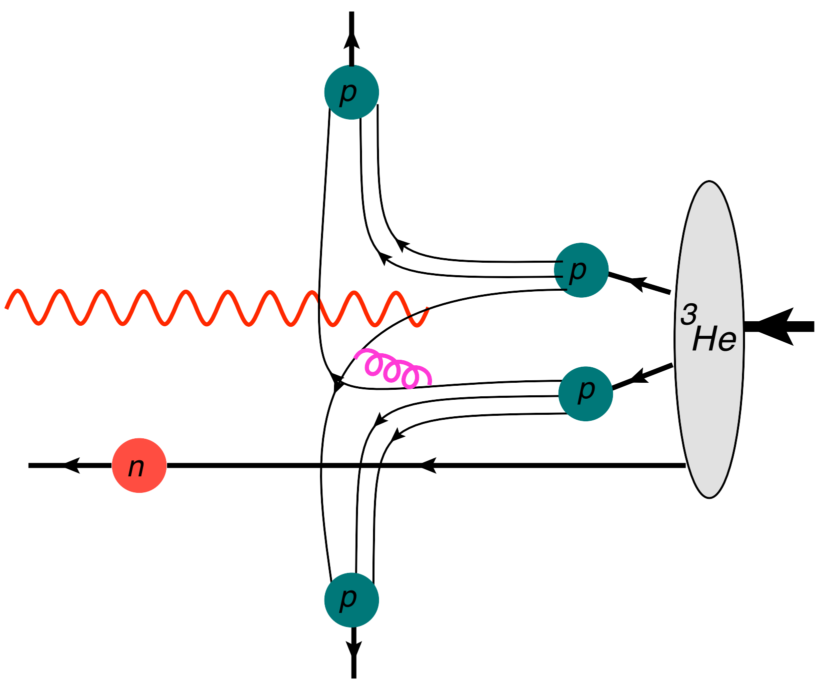


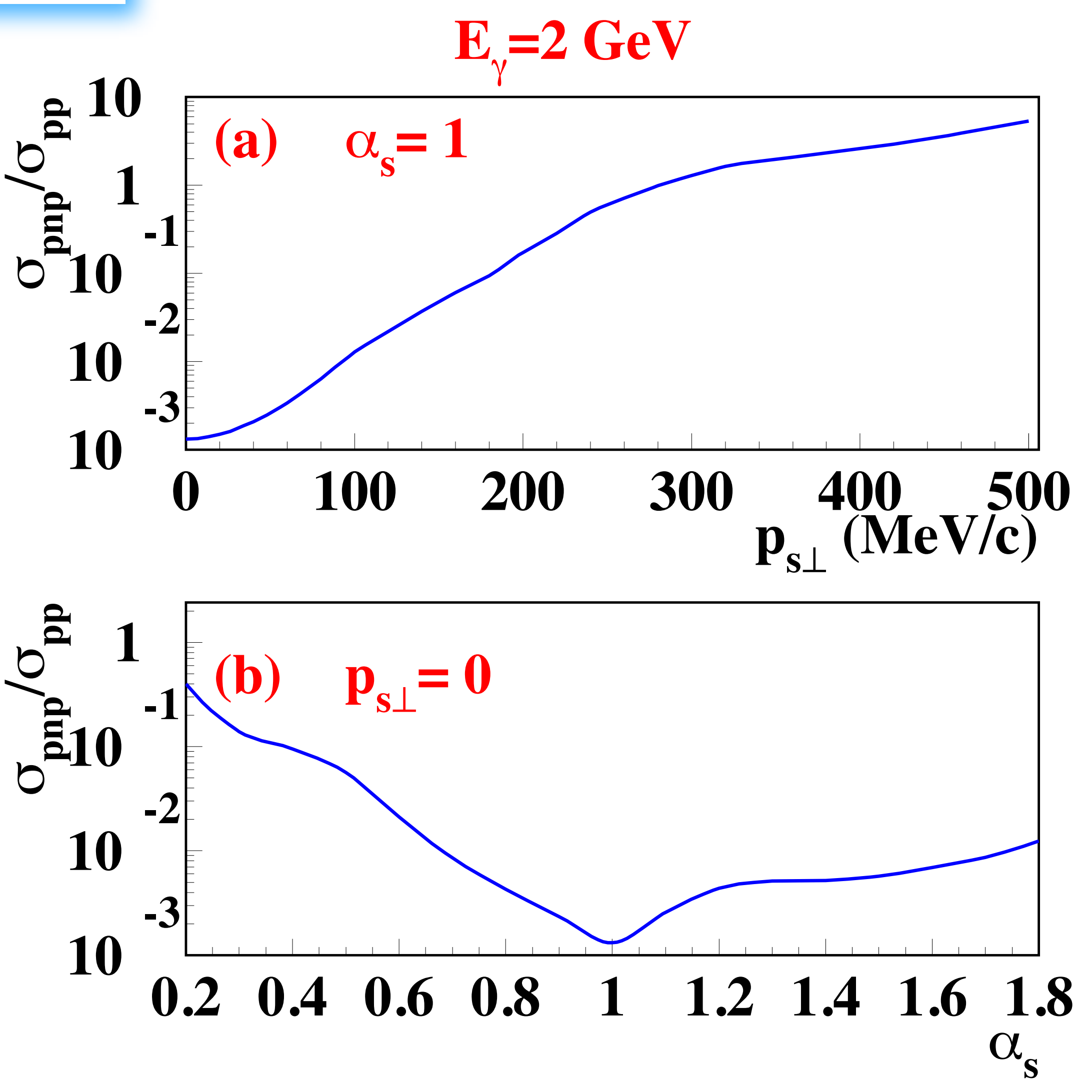
Pomerantz, et al,
Phys. Lett. B 2010



Break up of pp from Helium 3-
role of the third particle

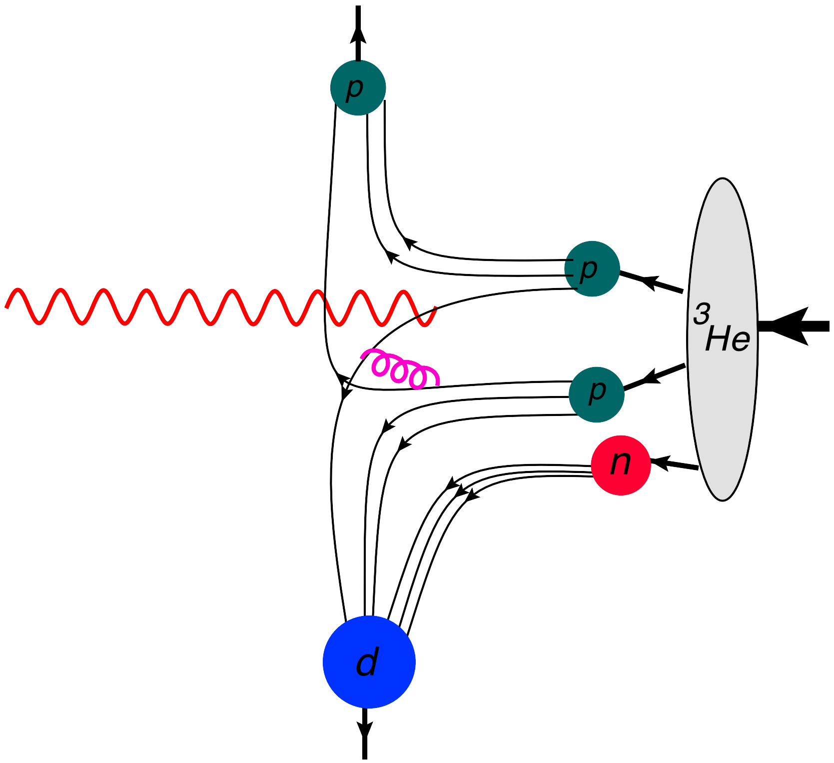
MS, C. Granados Phys. Rev. C, 2009





Break up of pd from Helium 3-
role of the third particle

Pomerantz & CO



$$\sim s^{-17}$$

What's Next:

1. Studying Hard Hadronic Processes

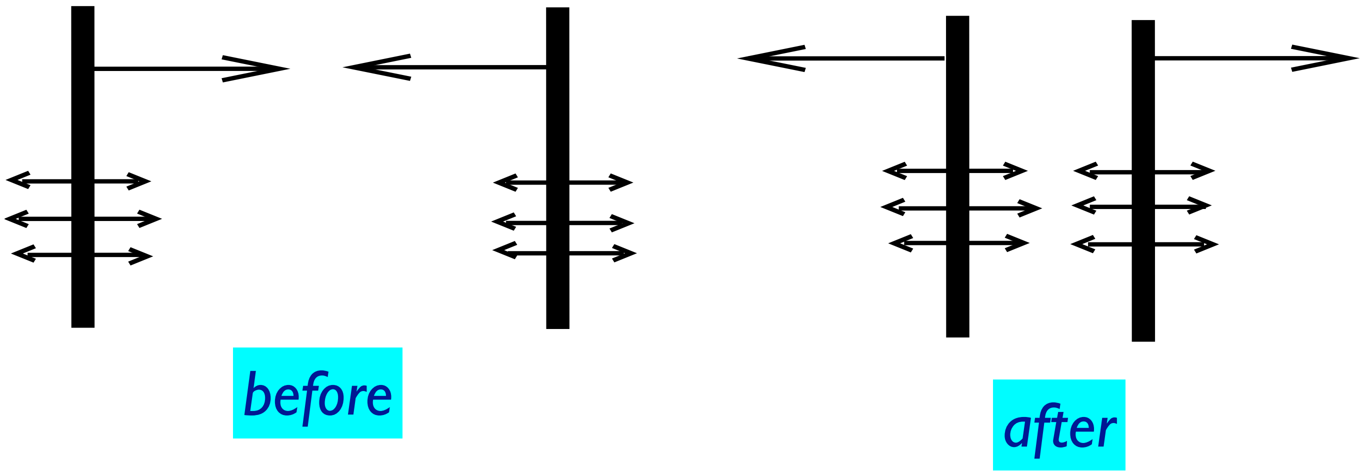
Generalization of break - up reactions to the deuteron break-up
of other 2Baryons

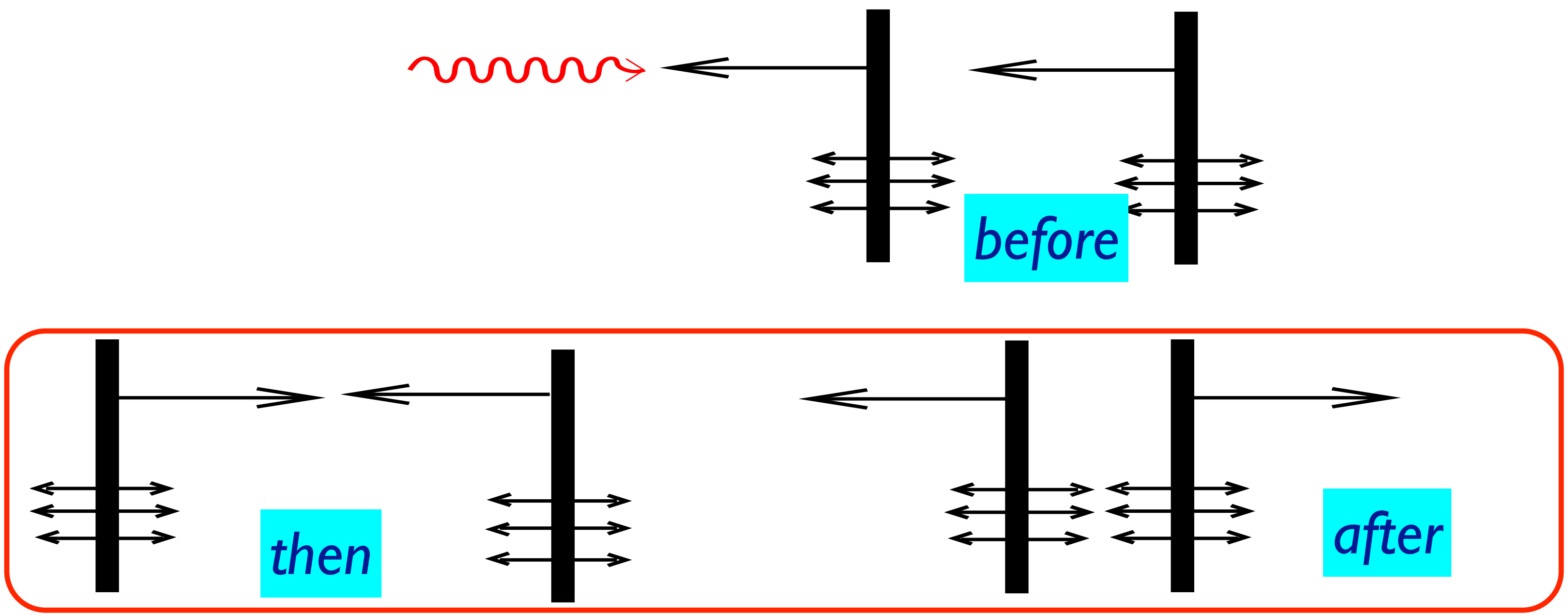
Extraction of hard Baryonic Helicity Amplitudes from
Polarized measurement

2. Probing $(qqq)q\bar{q}$ component of the nucleon

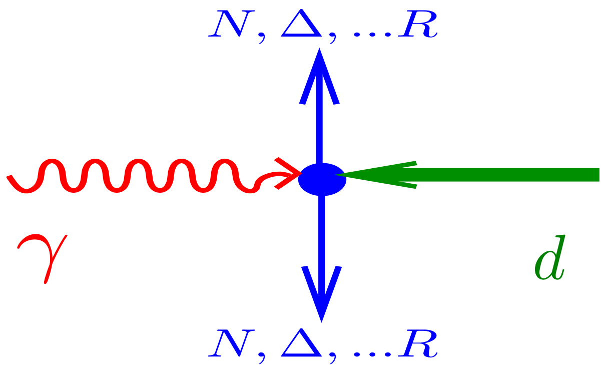
What's Next: Studying Hard Hadronic Processes

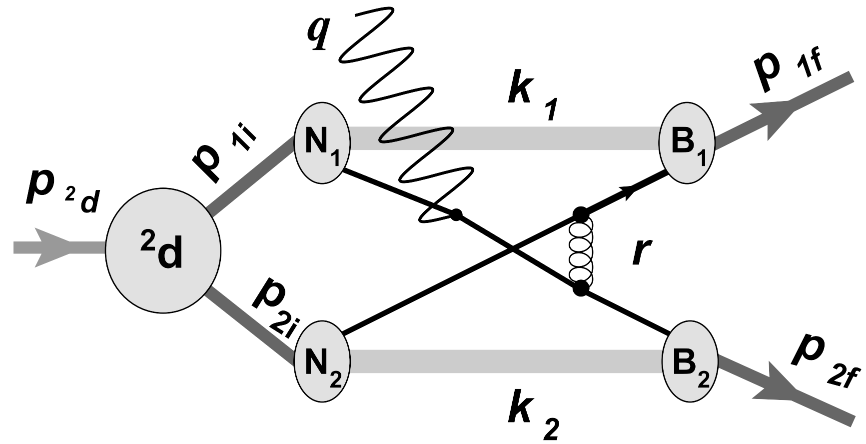
Baryon-Baryon Scattering





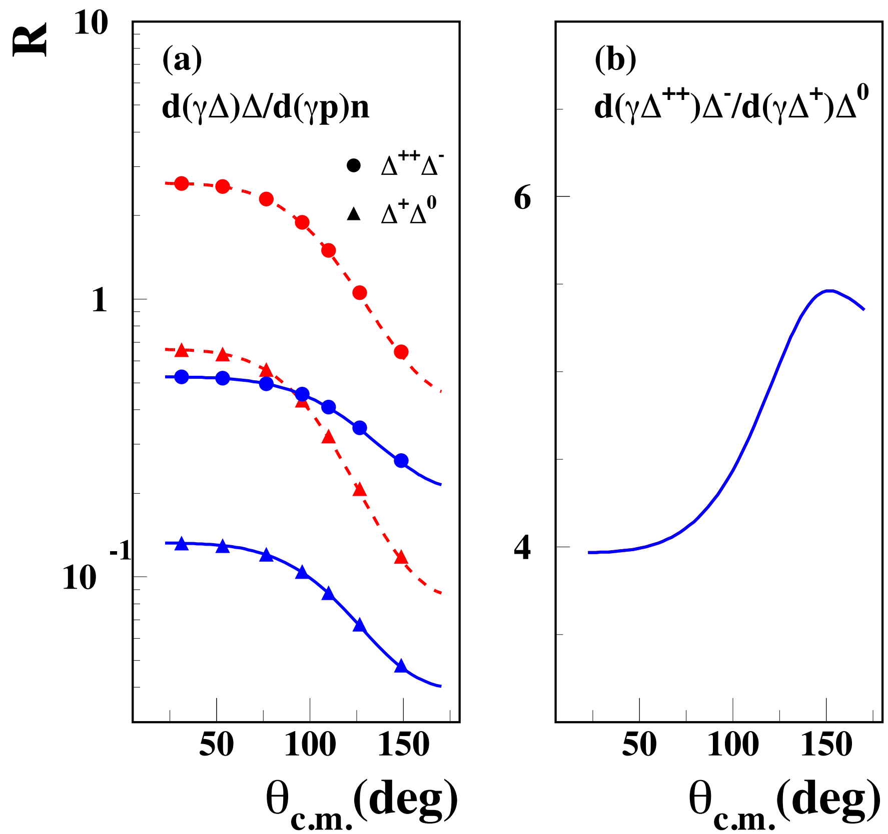
1. Generalization of break – up reactions to the deuteron break-up of other 2Baryons





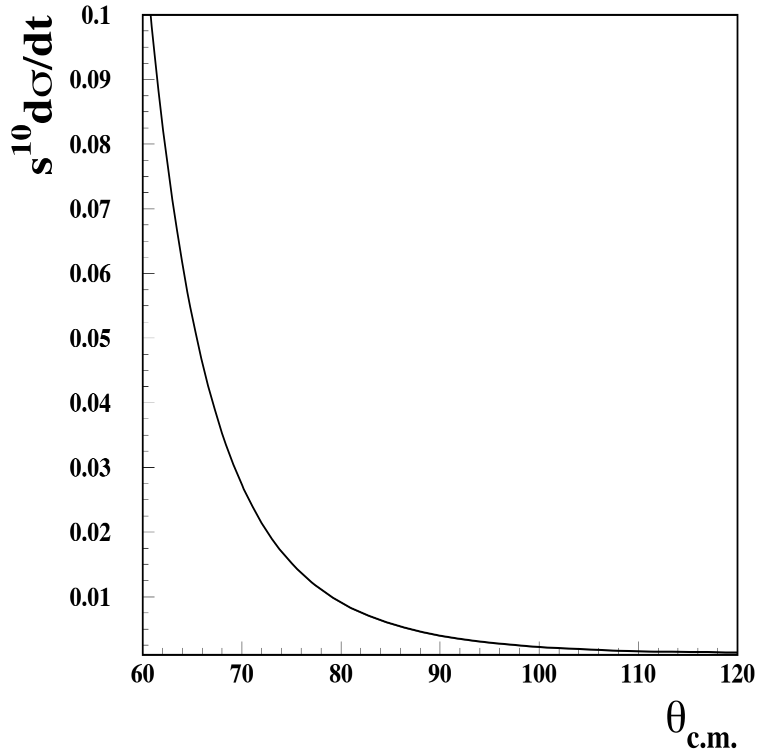
$$\frac{d\sigma^{\gamma d\to\Delta\Delta}(s,\theta_{c.m.})}{dt} = \frac{\alpha Q^2_{F,\Delta\Delta} 8\pi^4}{s'} \frac{d\sigma^{pn\to\Delta\Delta}(s,\theta^N_{c.m.})}{dt} \bar{S}_{0,NR},$$

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

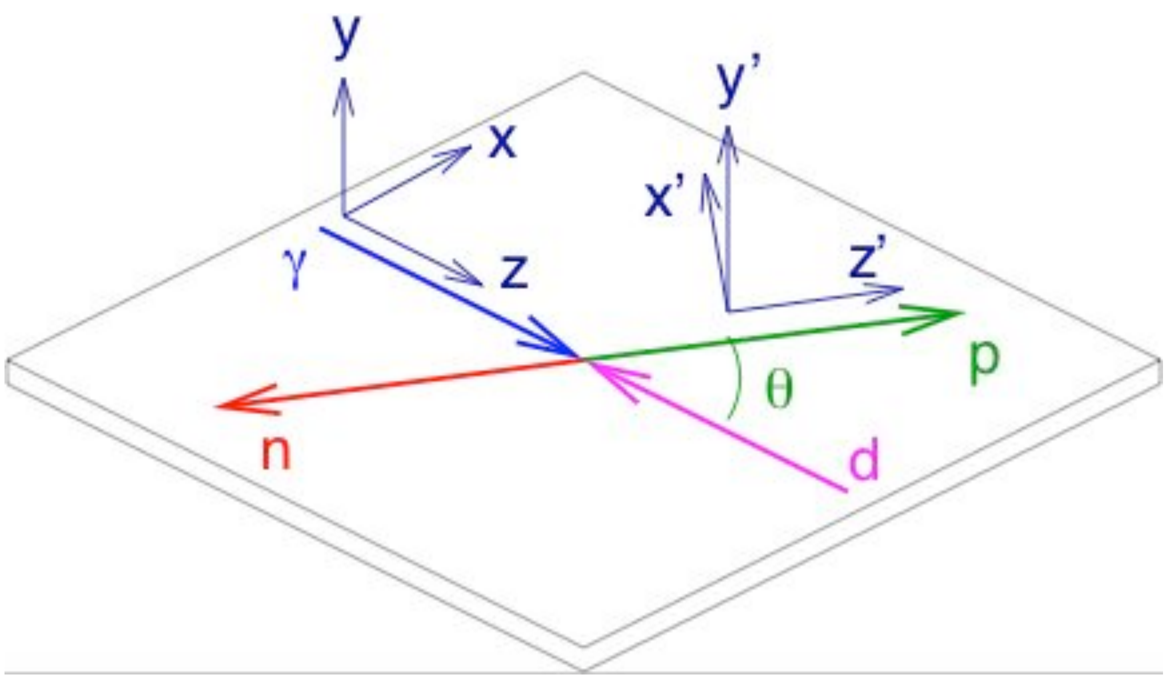
In the world where chiral symmetry is unbroken

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

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

2. Extraction of the hard NN helicity amplitudes for scattering from polarized measurements

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



2. Extraction of the hard NN helicity amplitudes for scattering from polarized measurements

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

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

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

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

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

Speculations on the Subject of Hard Rescattering Mechanism

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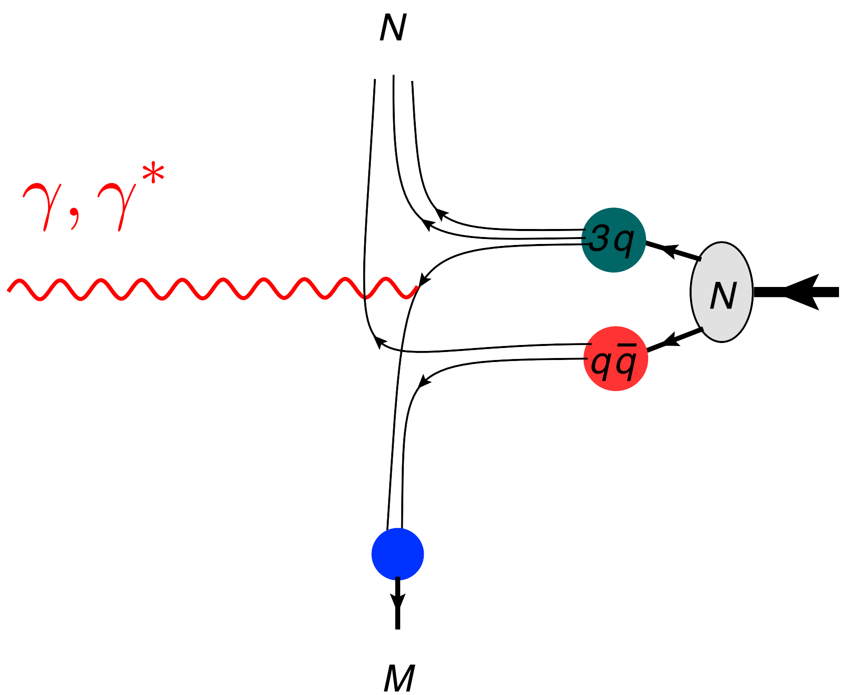
$$\langle p_{\lambda_A}, n_{\lambda_B} \mid A \mid \lambda_\gamma, \lambda_D \rangle = \sum_{\lambda_2} \frac{f(\theta_{cm})}{3\sqrt{2s'}} \times$$

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

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

Studying $q\bar{q}$ component of nucleon

$$s \sim |t|, |u| \gg M^2$$



$$\sim s^{-9}$$

Studying $q\bar{q}$ component of nucleon

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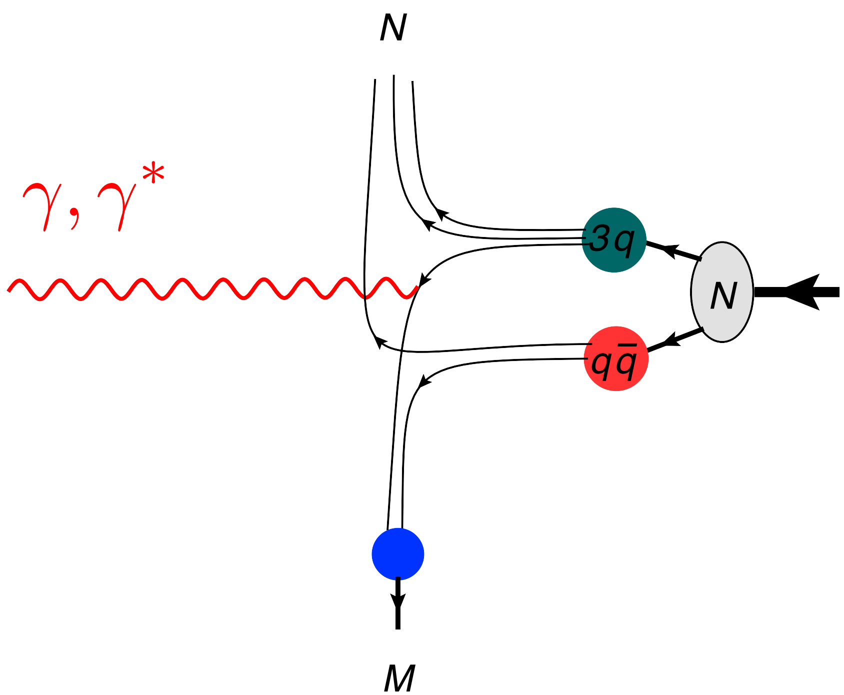

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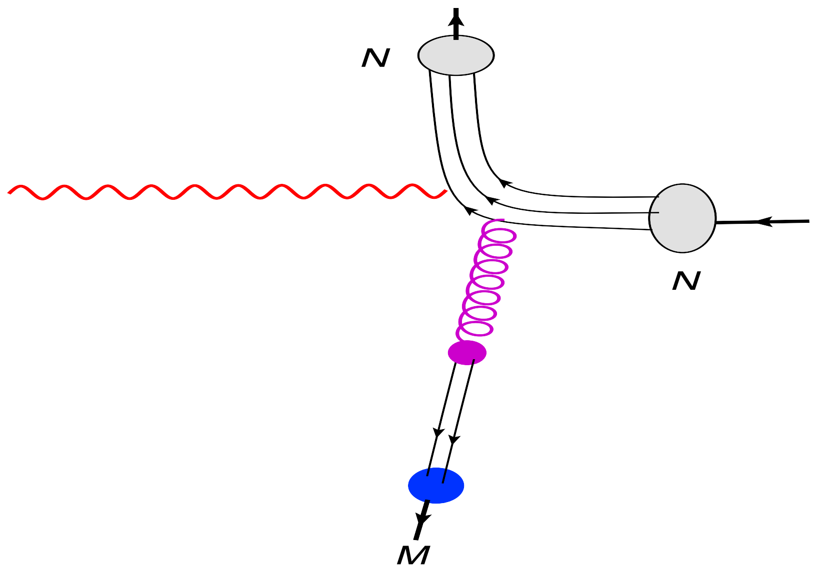

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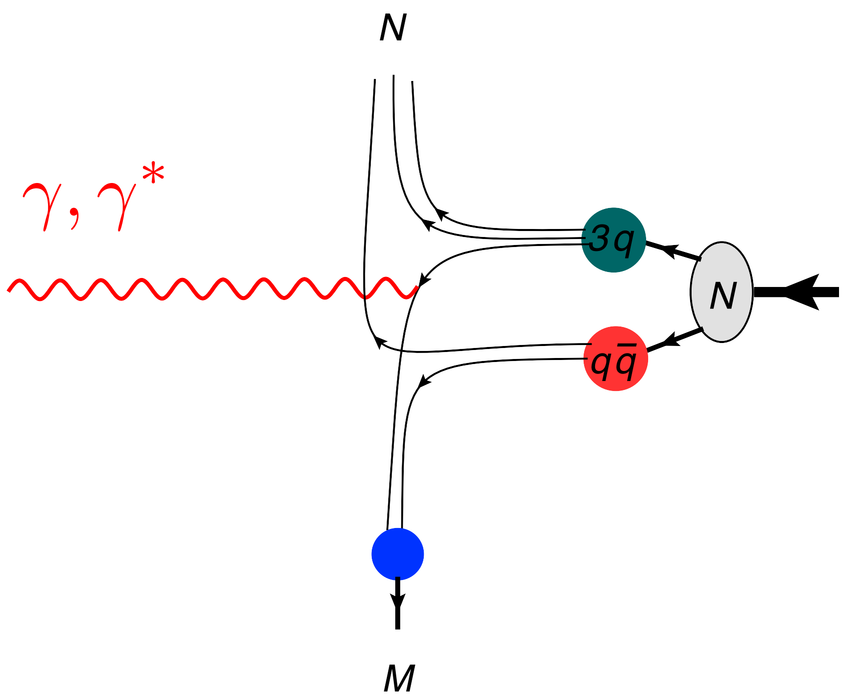
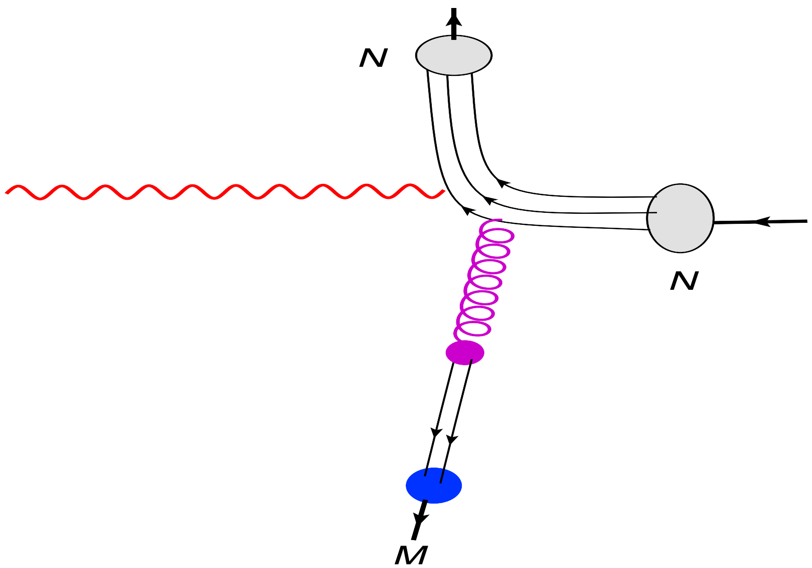


$\sim s^{-9}$



$\sim s^{-7}$

Studying $q\bar{q}$ component of nucleon

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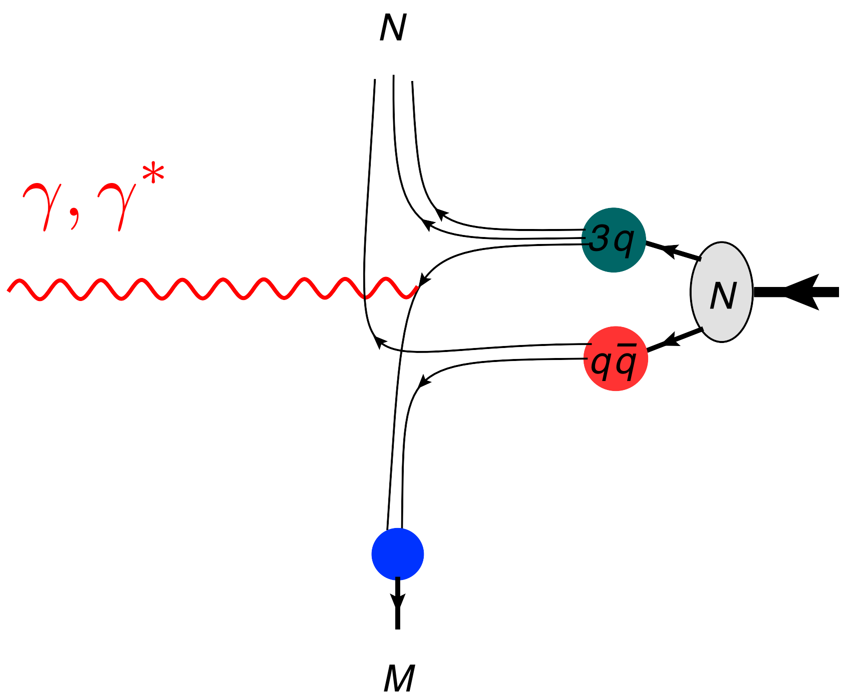

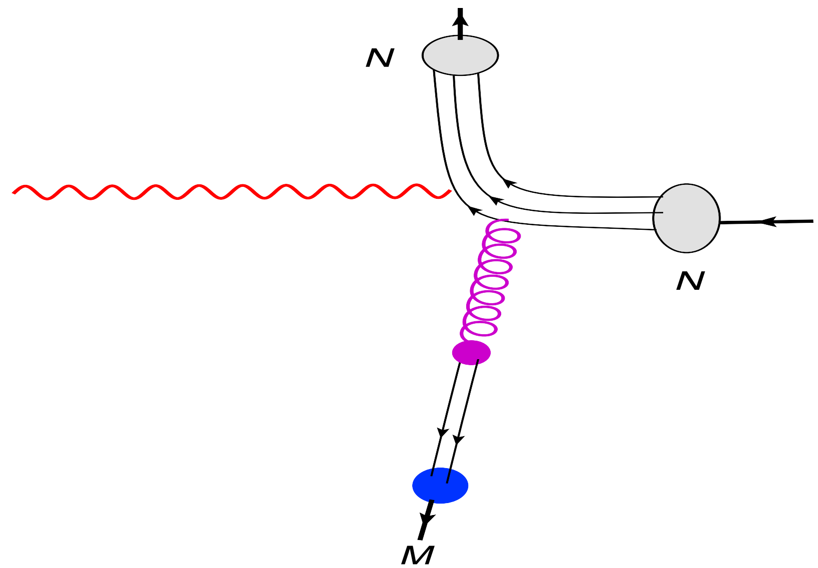

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$$\gamma p \to \pi^+ n$$

Studying $q\bar{q}$ component of nucleon

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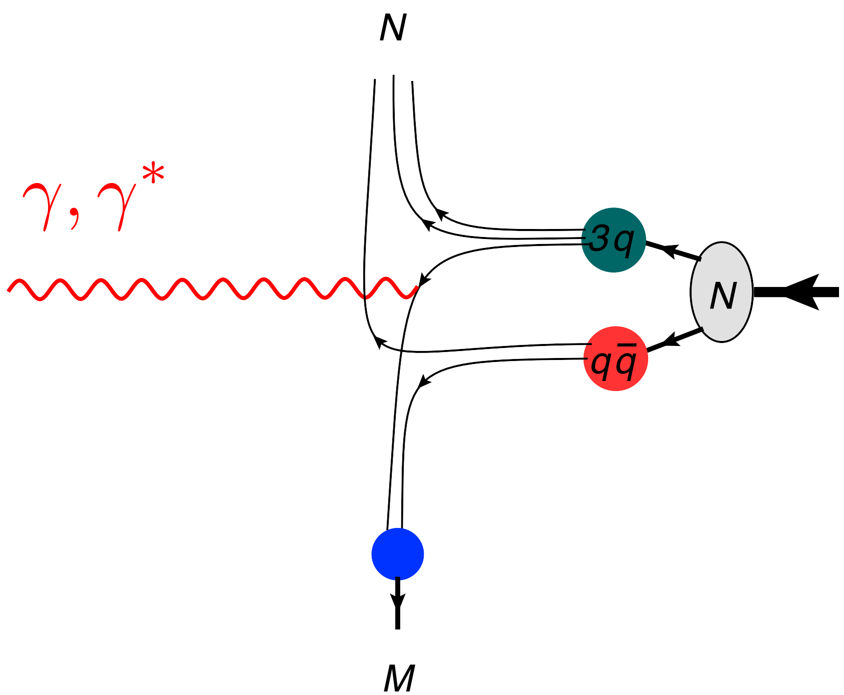

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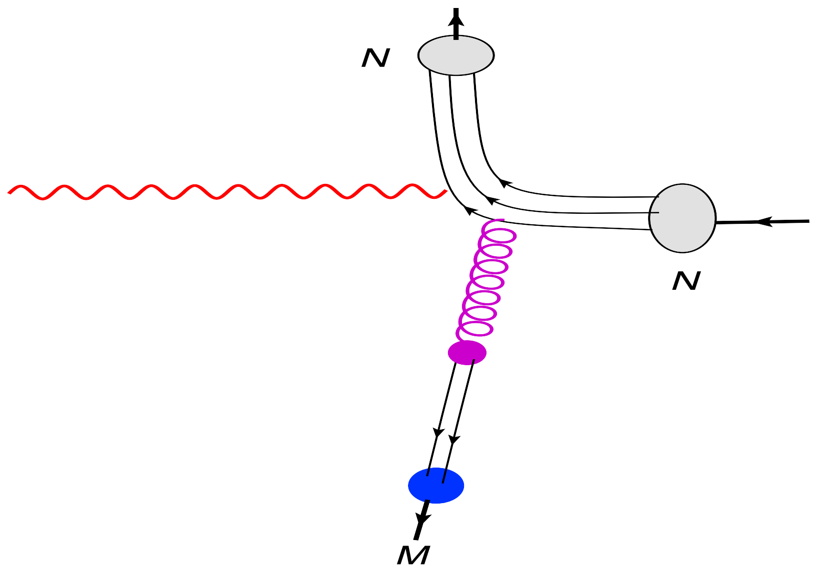

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$$\gamma p \to \pi^+ n$$

$$\gamma p \to K^+ \Lambda$$

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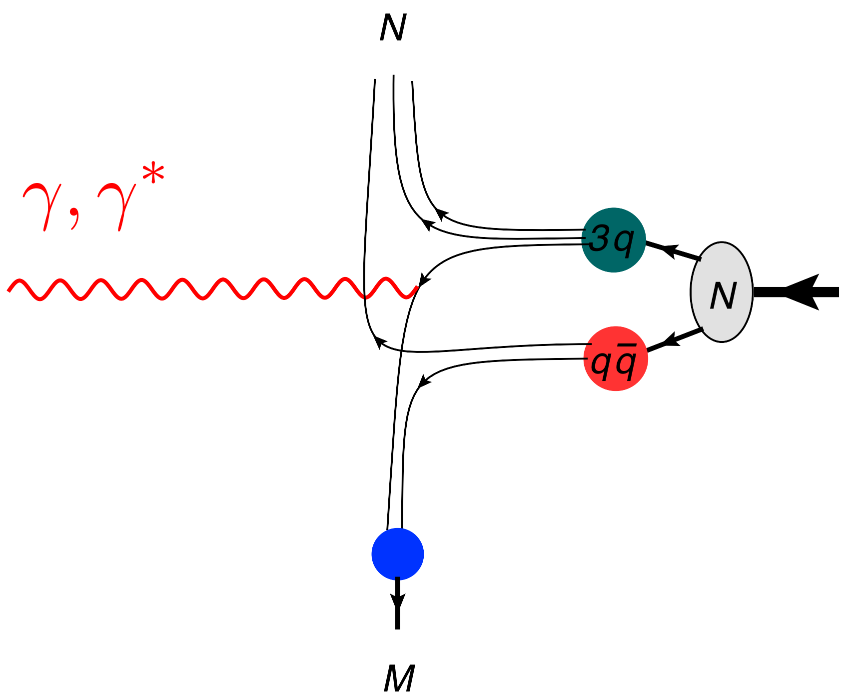
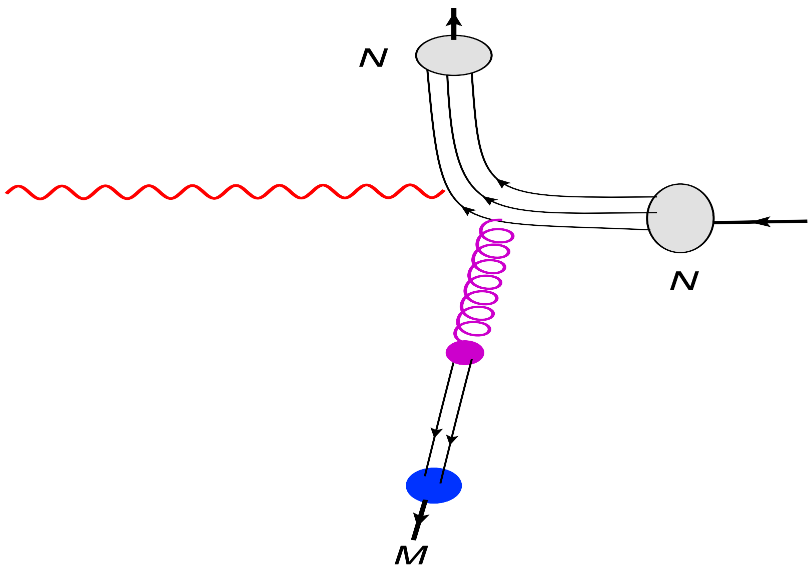


γ, γ^*

$\sim s^{-9}$



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$\gamma p \to \pi^+ n$ H. Gao & CO

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Studying $q\bar{q}$ component of nucleon

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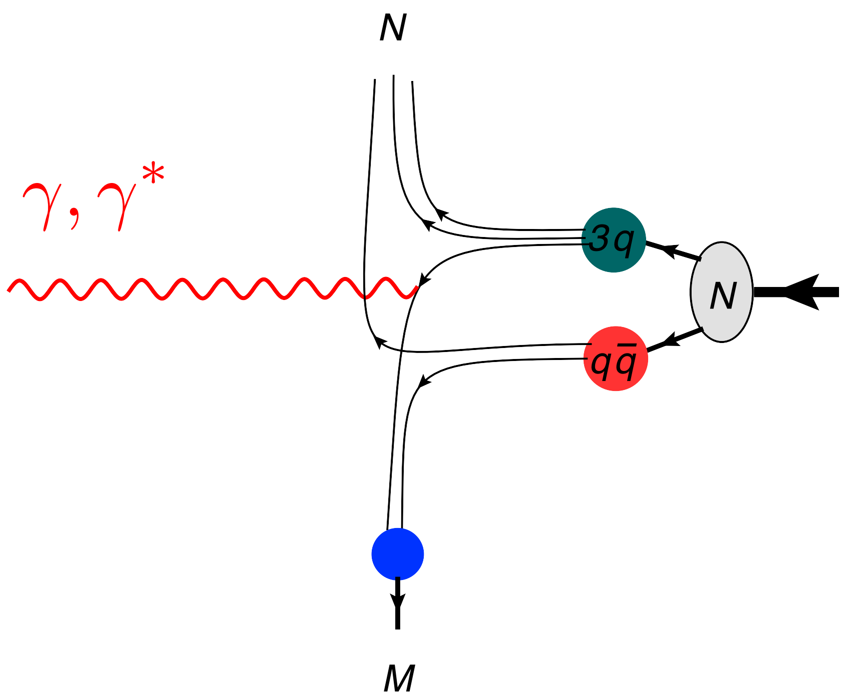

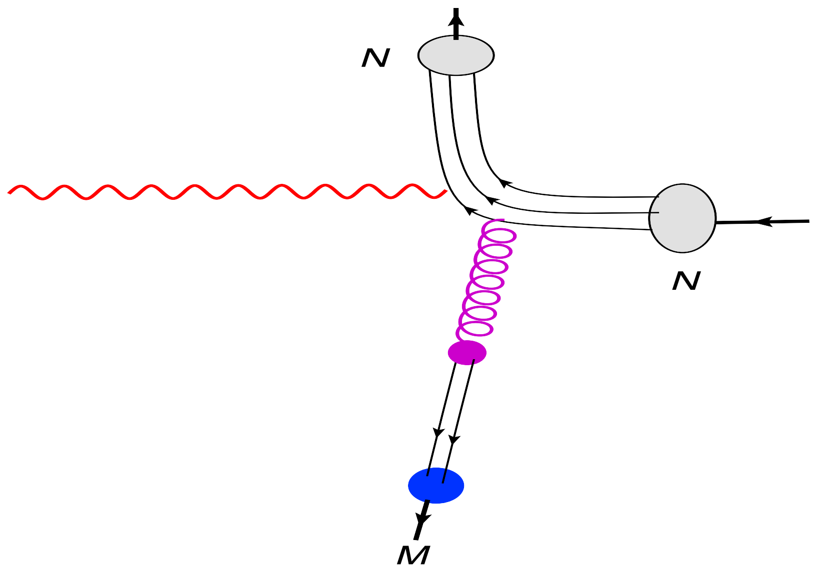

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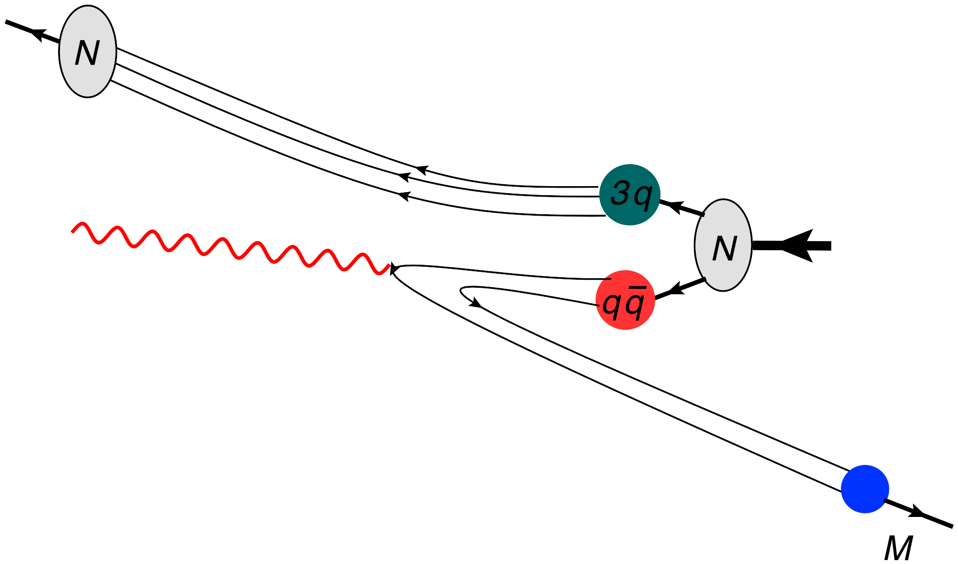
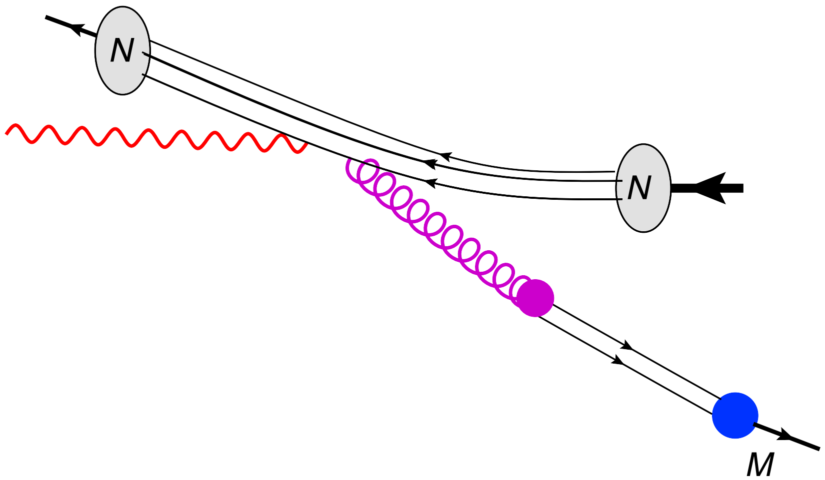
$\gamma p \to \pi^+ n$ H. Gao & CO

$\gamma p \to K^+ \Lambda$ R.Schumacher, MS, 2010

Studying $q\bar{q}$ component of nucleon

$$|t| \ll Q^2$$

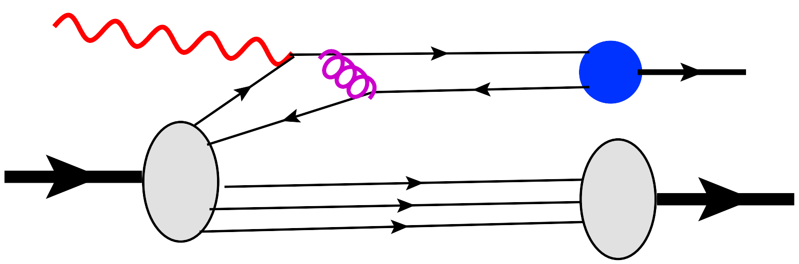


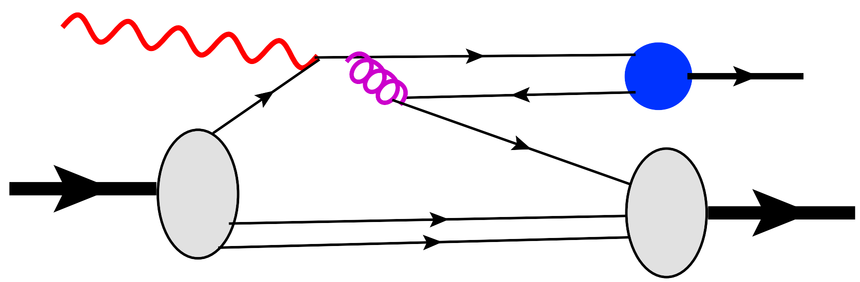


$$M \sim \langle 3q, q\bar{q} \mid \Psi_N \rangle \cdot F_M(Q^2)$$

Studying $q\bar{q}$ component of nucleon

$$|t| \ll Q^2$$





Exotics, Hybrids and Rescattering......