Photon/Electron Induced Hard Nuclear Break-Up

Misak Sargsian
Florida International University

Rutgers EIC Meeting - March 14-15, 2010

High Density Nuclear Physics

- Nuclear Potential

Nuclear Hamiltonian

$$H = -\sum_i \frac{\nabla_i^2}{2m} + \sum_{i<j} V_{ij}^{2N} + \sum_{i<j<k} V_{i,j,k}^{3N} + \ldots$$

$$H\Psi_A(r_1, ..., r_A) = E\Psi_A(r_1, ..., r_A)$$

$$V^{2N} = V_{EM}^{2N} + V_{\pi}^{2N} + V_R^{2N}$$

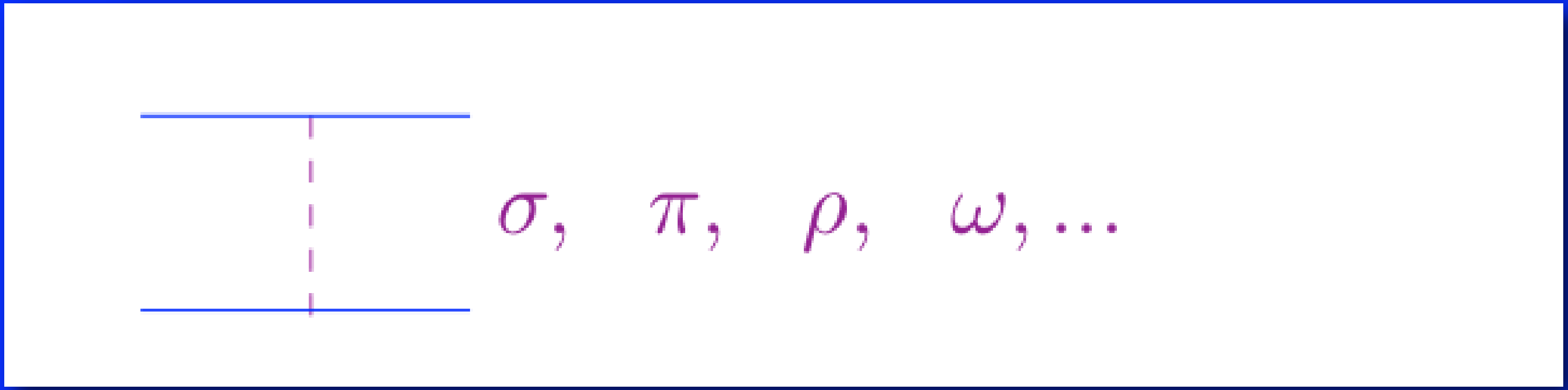
$$V_R^{2N} = V^c + V^{l2}L^2 + V^t S_{12} + V^{ls} L \cdot S + v^{ls2}(L \cdot S)^2$$

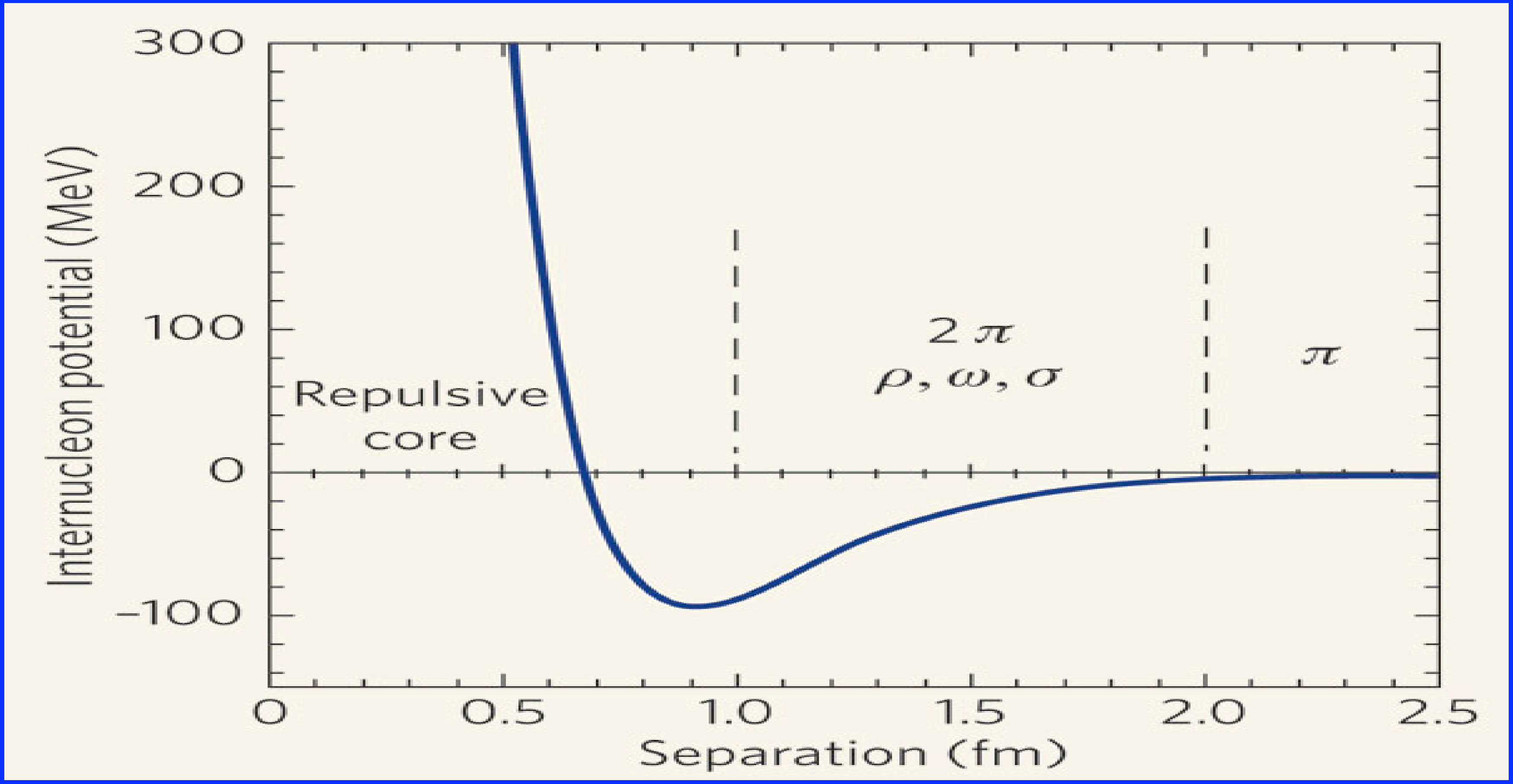
$$V^i = V_{int,R} + V_{core}$$

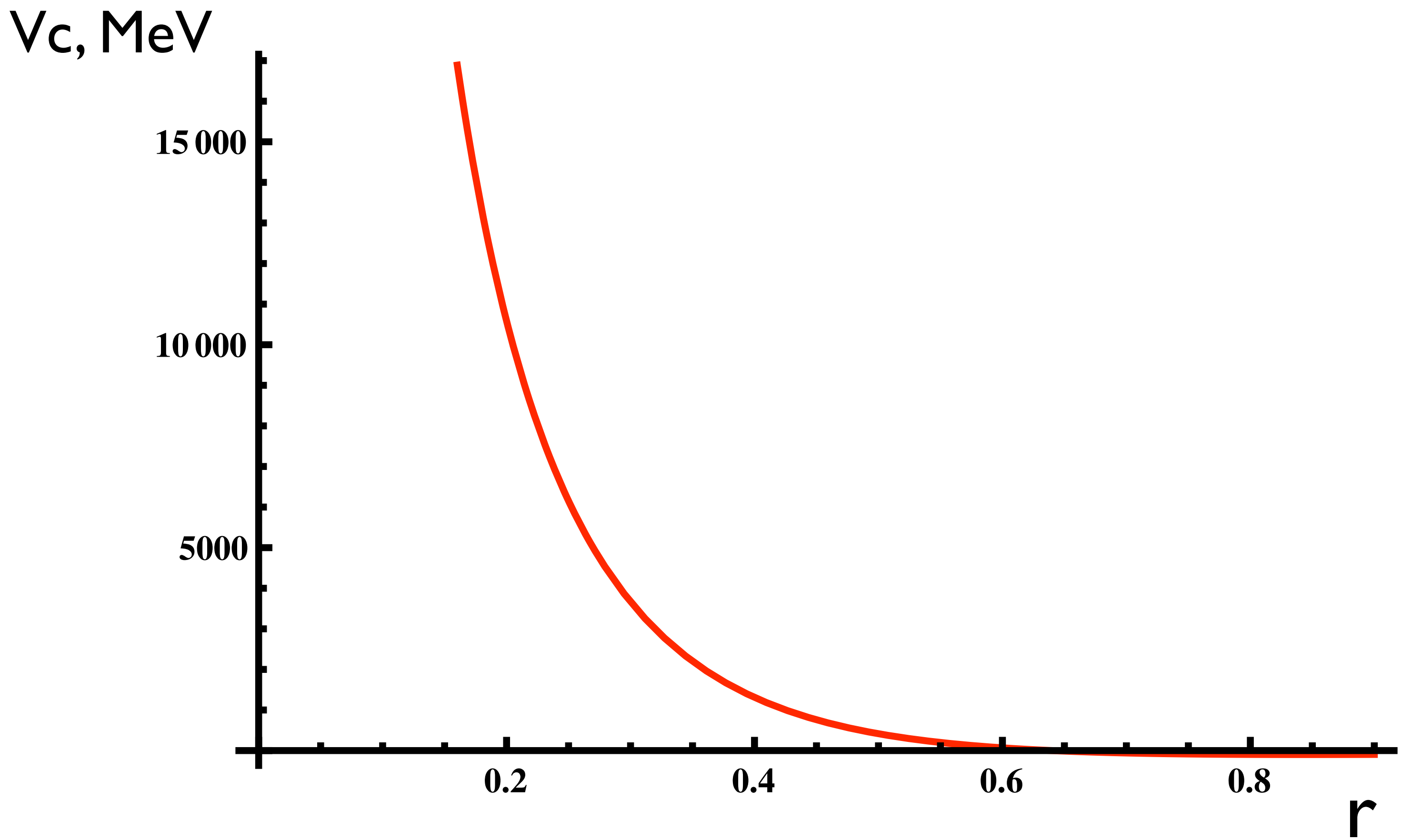
$$V_{core} = \left[1 + e^{\frac{r-r_0}{a}}\right]^{-1}$$

60's

-Phenomenological OBE models 1947-







Vc, MeV
15 000
10 000
5000
0.2
0.4
0.6
0.8
r


High Energy Nuclear Physics and QCD
FIU, Miami, February 3-6, 2010
- About the Meeting
- Participants
- Program
- Photos
- Registration
- Accommodation
- Contact
High Energy Nuclear Physics and QCD
February 3-6, 2010
Florida International University, Miami
Main Topics
FIU
Jefferson Lab
Florida International University
Miami
1965
JSA Jefferson Science Associates, LLC
Jefferson Lab

Nuclear EIC (Endeavors in Color)

Hierarchy: Processes/ Physics

1. Inclusive

1.1 Physics: Superfast Quarks

Kinematics: Large Q^2 and x \sim 1.
Probe the superfast quarks in nuclei. It will allow the investigation of quark-clusters and quark-correlations in nuclei.
((Q^2 dependence at very large x is sensitive to higher twist, breakdown of DGLAP evolution at high x. Q^2 dependence in D/p ratio at large x yields information on integral of pdf at larger x values))

Key issues: kinematic coverage, accounting for low cross section at large x. This will also require high luminosity, sufficient resolution and acceptance for small scattering angles.

1.2 Physics: Nuclear Modification - EMC effect

Kinematics: x = 0.1-0.9 for antishadowing/EMC regions, smaller for shadowing
- Measure the Q^2 evolution in the nuclear medium: Measurement of the EMC effect in the extended Q^2 range will allow study of the evolution of parton distribution in the nuclear medium
- Isospin Dependence of the nuclear medium modification (EMC & antishadowing region)
- Gluon shadowing through F_L
- Physics of antishadowing

Key issue: kinematic coverage, accounting for low cross section at large x. Large radiative corrections at low x values; is explicit detection of radiated photons required? A reliable way to provide precise, relative normalization for different nuclei will be extremely important. May need variable energies to make good measurements of Q^2 dependence over wide x range.

2. Semi-Inclusive

2.1 Probing Higher-order Nucleonic Correlations in Nuclei

Considering e + A --> e' + NF + NB1 + NB2 + X:

Measuring two fast backward nucleons and momentum fraction larger than one for A>3 nuclei.

Advantage of EIC is that one can simultaneously measure target and current fragmentations

2.2 Probing Hidden-Color Component of Nuclei:

Considering e+ A --> e' + FF+ FB + X:

Measuring the yield of fast backward resonances such as \Delta on can probe
the hidden color component in 6q configurations

Measuring resonances with strangeness or charm as a function of internal momentum of the nucleus will allow us to probe the effects of chiral-simmetry
restoration and strangeness/charm content of nucleon wave function.

2.3 Nuclear Medium Modification

- Considering e + A --> e' + pi/K + N + X will allow us to measure the flavor dependence of nuclear modification effects. Measuring extra nucleon in specially chosen kinematics will allow control of the initial state.
- The same reaction at x\approx 0.1 will allow the study of the origin of nuclear enhancement.
- Considering e + A --> e' + J/Psi + N + X

For nuclear modification of gluonic field controlling the local density from where the J/Psi is produced.
- Spectator tagging: e + D --> e’ + N_s + X

Examine nucleon structure as function of nucleon virtuality. Spectator proton tagging for ‘effective free neutron’ target, spectator neutron tagging for ‘effective free proton’ measurement to verify that the low momentum spectator reproduces free nucleon, high momentum spectators to study nucleons at high virtuality.
- Nuclear incoherent DVCS: medium modifications of quark GPDs

2.4 Color Transparency

- Considering e + A --> e' + B + X

Most challenging to observe the color transparency for baryons.
In addition to \bar q q case, QCD allows also color neutrality.
Interesting to observe A dependence for B=nucleon, strange, charmed baryons.

- Considering e + A --> e' + M + X

where M is a meson and X=A(coherent), noncoherent.

- coherent productions of two pions with a pion (2q) in the t-channel
  first establish CT, then interpret in terms of target GPD's

- considering reaction \gamma + N --> pi + B + pi (baryon color transparency)
  (Strikman Kumano)

3. Exclusive

3.1 Hard Photodisintegration

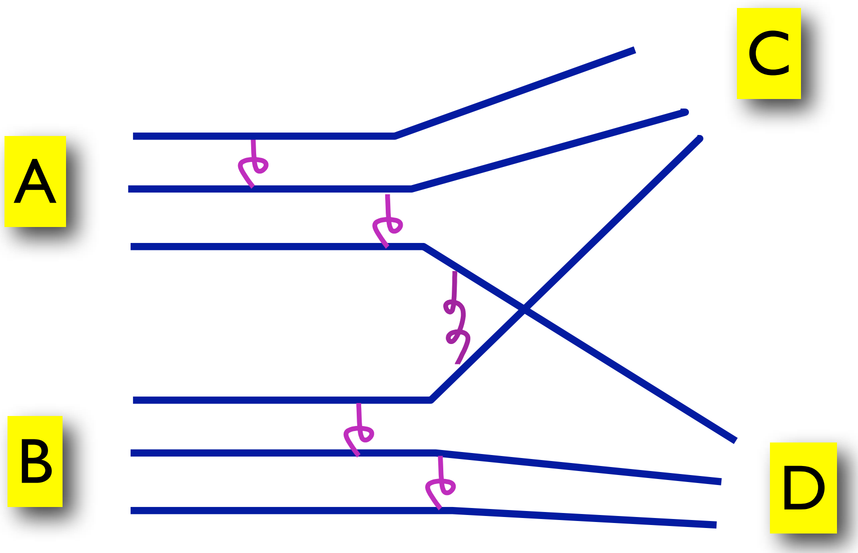
- Considering reactions e/gamma + A --> e' + B1 + B2 + (A-2)'

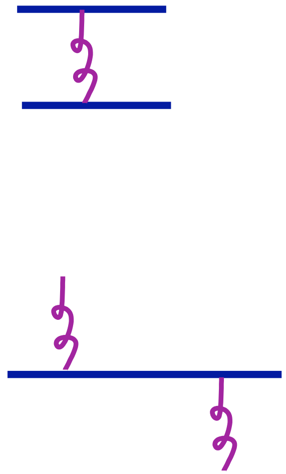
where B = N, Strange, Charmed baryons produced at large center of mass angles of B1 B2 system.

These studies will allow not only to probe the mechanism of hard break-up but also the dynamics of hard NN scattering such as the role of the charm threshold predicted to be important in hard NN scattering.

Hard Processes

Consider A+B→C + D





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

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

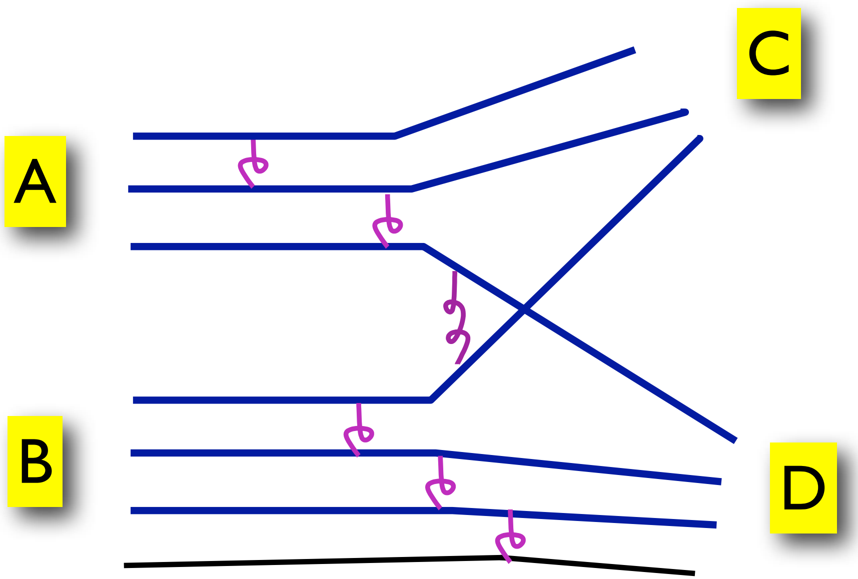
$$A \sim F\left(\frac{t}{s}\right)\frac{1}{s^{\frac{n_A+n_B+n_C+n_D}{2}-2}}$$

Brodsky, Farrar 1975
Matveev, Muradyan, Takhvelidze, 1975

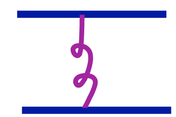
$$\frac{d\sigma}{dt} \approx \frac{|A|^2}{s^2} = F^2\left(\frac{t}{s}\right)\frac{1}{s^{n_A+n_B+n_C+n_D-2}}$$

Hard Processes

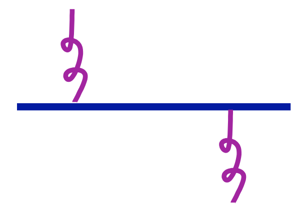
Consider A+B→C + D



additional $\frac{1}{s}$



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

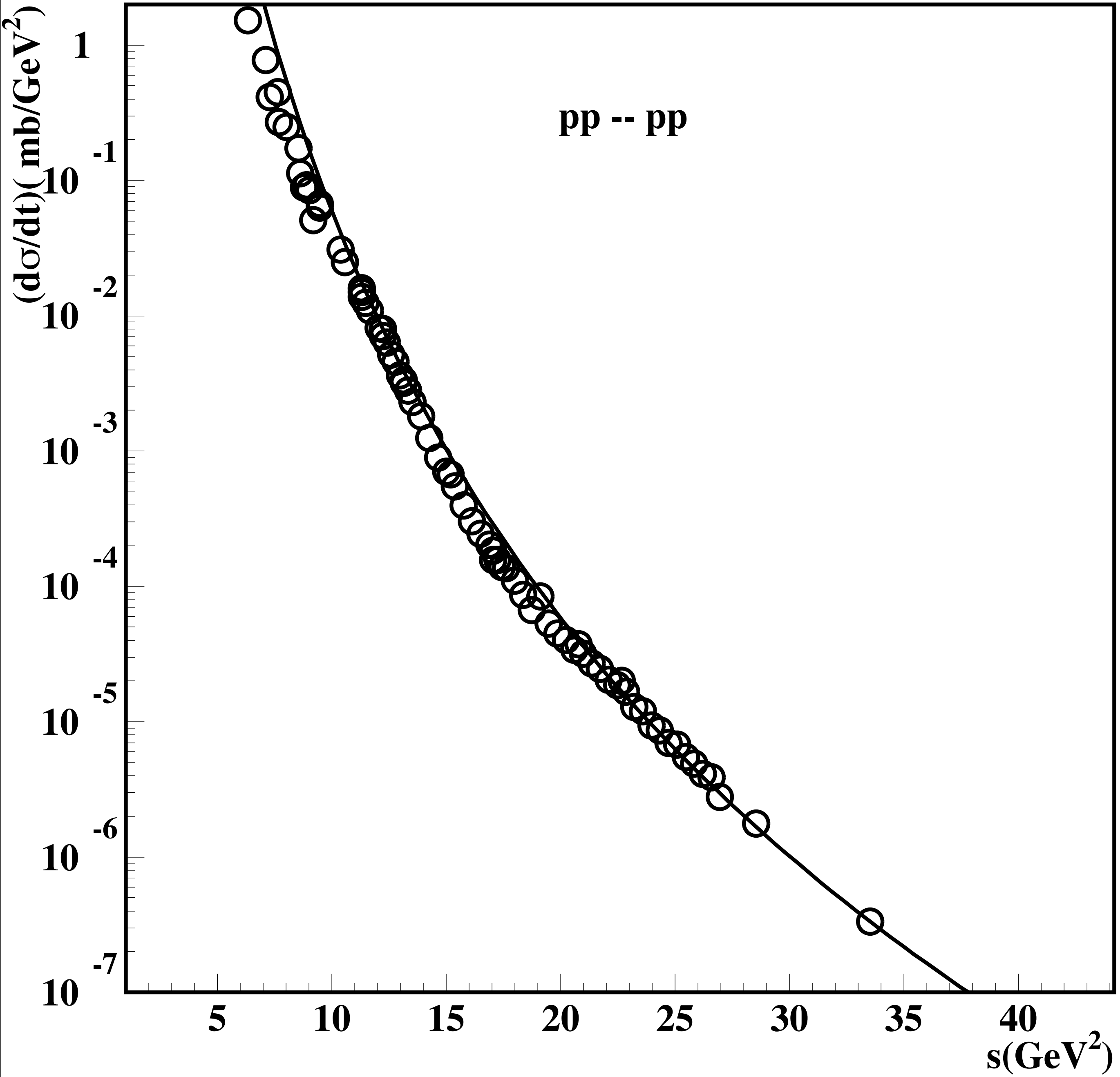


$$\longrightarrow \frac{1}{s}$$

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

Brodsky, Farrar 1975
Matveev, Muradyan, Takhvelidze, 1975

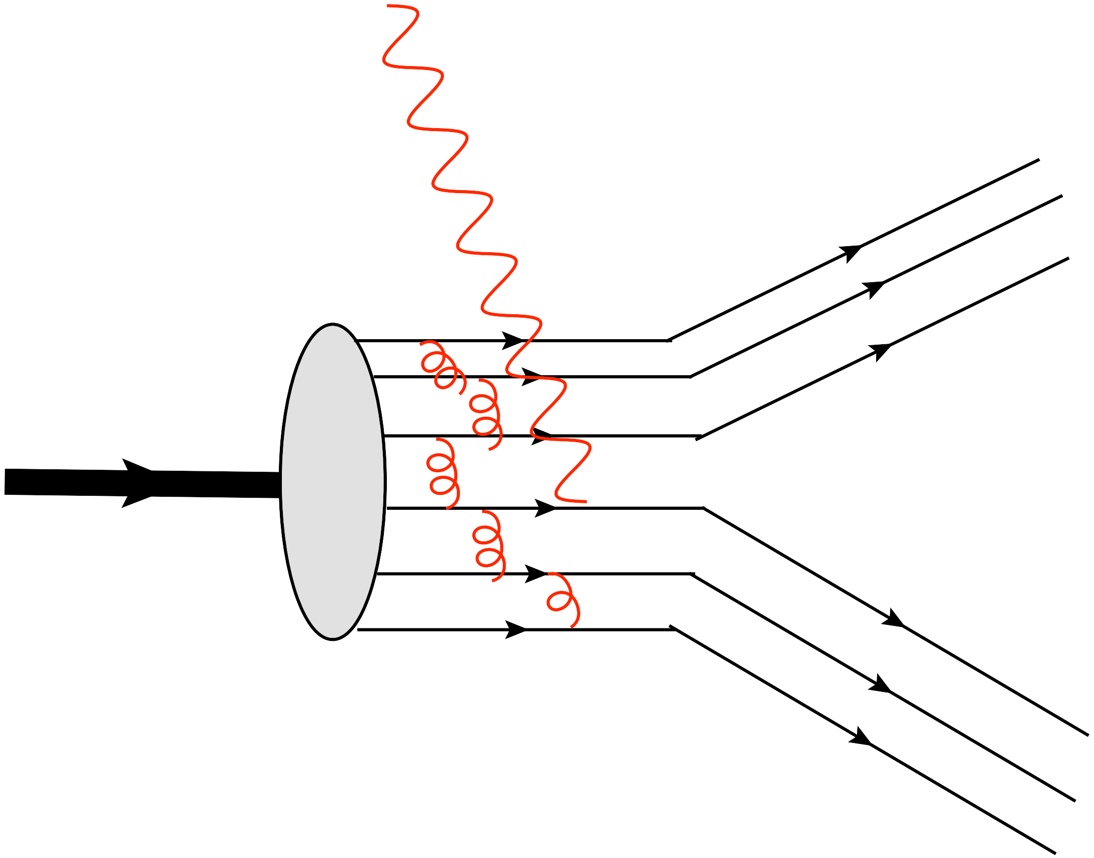
$$\frac{d\sigma}{dt} \approx \frac{|A|^2}{s^2} = F^2(\frac{t}{s}) \frac{1}{s^{n_A+n_B+n_C+n_D-2}}$$



pp -- pp
(dσ/dt)(mb/GeV²)
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
5
10
15
20
25
30
35
40
s(GeV²)

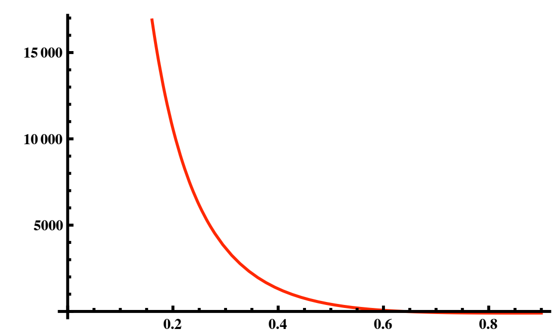
Break up of pn from the deuteron: the original Idea

Brodsky, Chertock, 1976



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

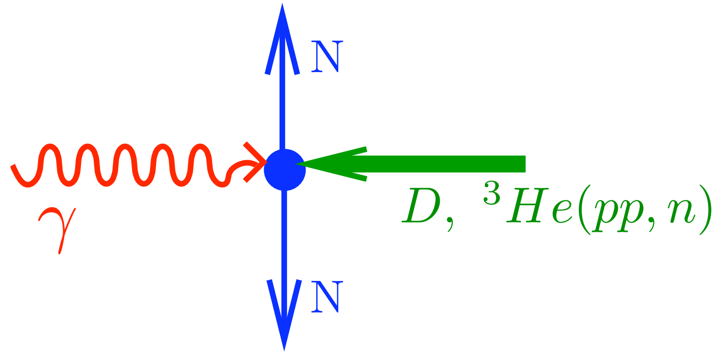
$$\sim \Psi_d\left(\frac{\sqrt{s}}{2}\right)$$

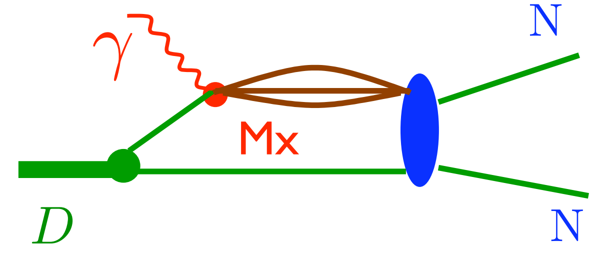


$$\psi^{\mathbf{6q}}_{\mathbf{t=0,s=1}} = \sqrt{\frac{1}{9}}\psi_{\mathbf{NN}} + \sqrt{\frac{4}{45}}\psi_{\mathbf{\Delta\Delta}} + \sqrt{\frac{4}{5}}\psi_{\mathbf{CC}}$$

Brodsky, Lepage, Ji, PRL 1983

- Large CM angle disintegration of nuclei:





Brodsky, Chertock, 1976

Holt, 1990

Gilman, Gross, 2002

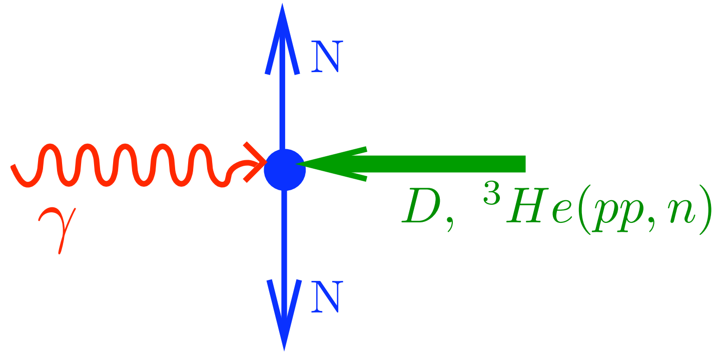
$$s = (k_\gamma + p_d)^2 = 2M_d E_\gamma + M_d^2$$

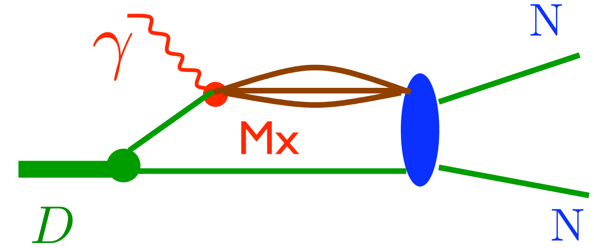
$$t = (k_\gamma - p_N)^2 = [cos\theta_{cm} - 1]\frac{s - M_d^2}{2}$$

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

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

- Large CM angle disintegration of nuclei:





Brodsky, Chertock, 1976

Holt, 1990

Gilman, Gross, 2002

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

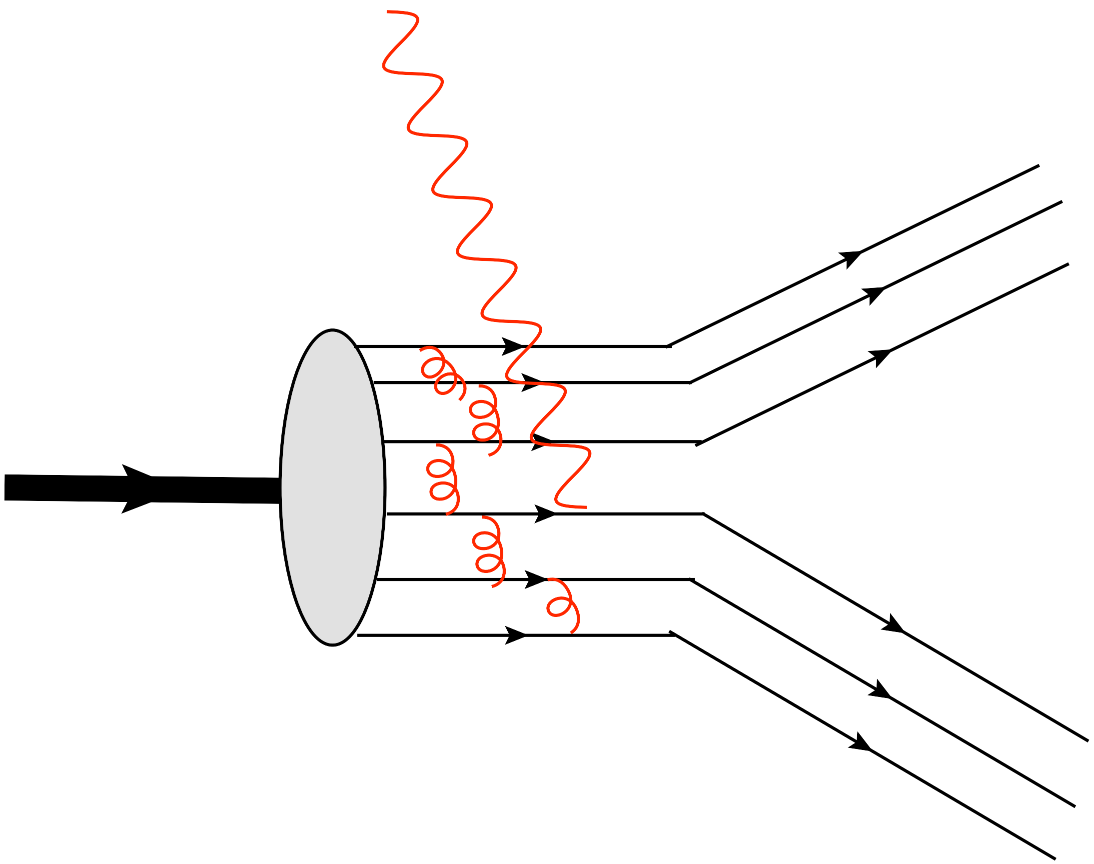
$$t = (k_\gamma - p_N)^2 = [cos\theta_{cm} - 1]\frac{s - M_d^2}{2}$$

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

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

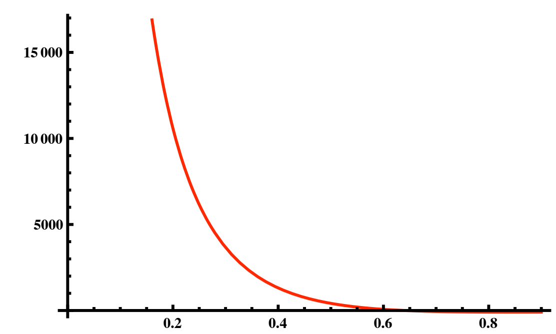
Break up of pn from the deuteron: original Idea

Brodsky, Chertock, 1976



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

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



$\gamma d \to pn$

Exclusive large-momentum-transfer scattering

•Dimensional counting rule:

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

For

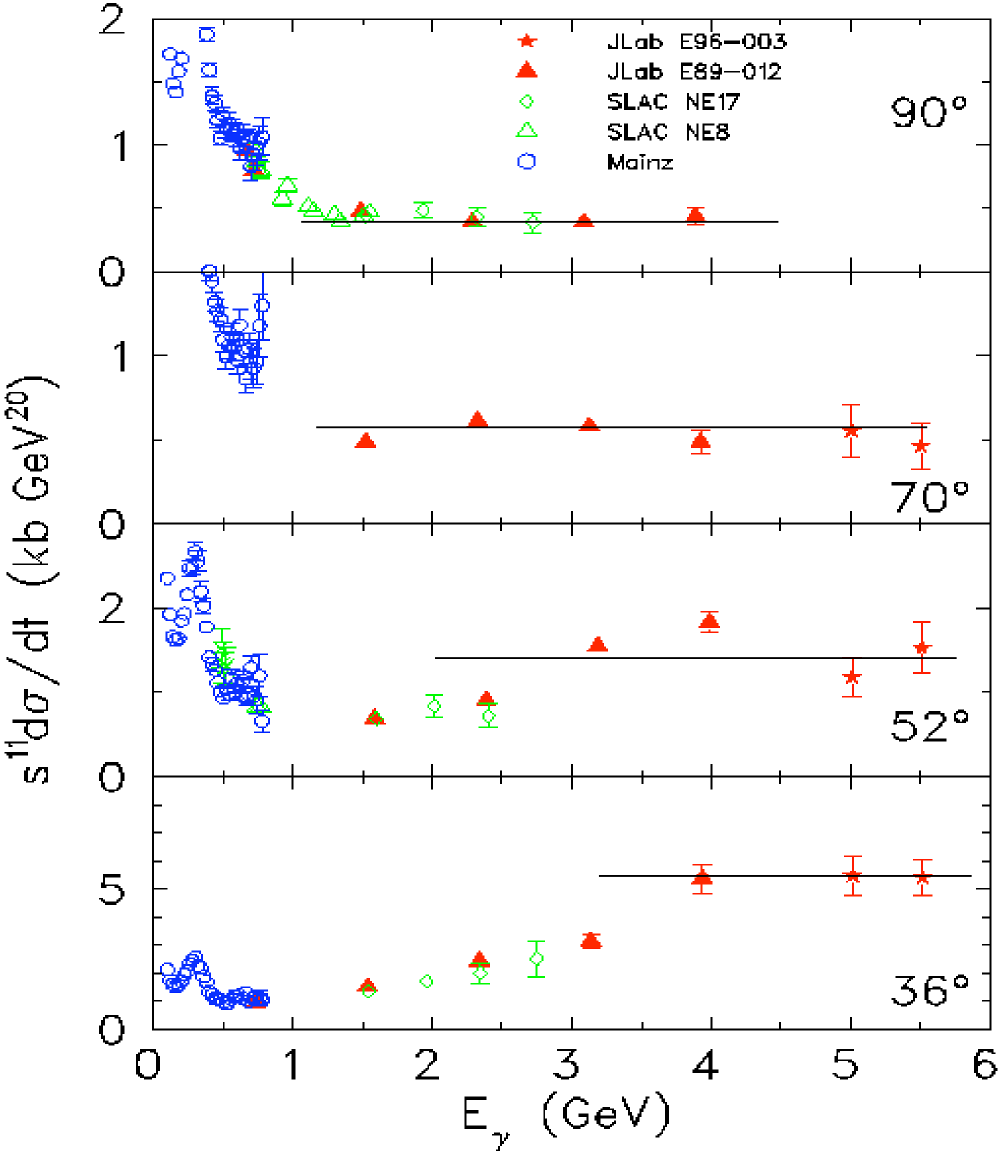
$$\gamma\ d \to p\,(high\ p_t) + n\,(high\ p_t)$$

N = 1 + 6 + 3 + 3 – 2 = 11

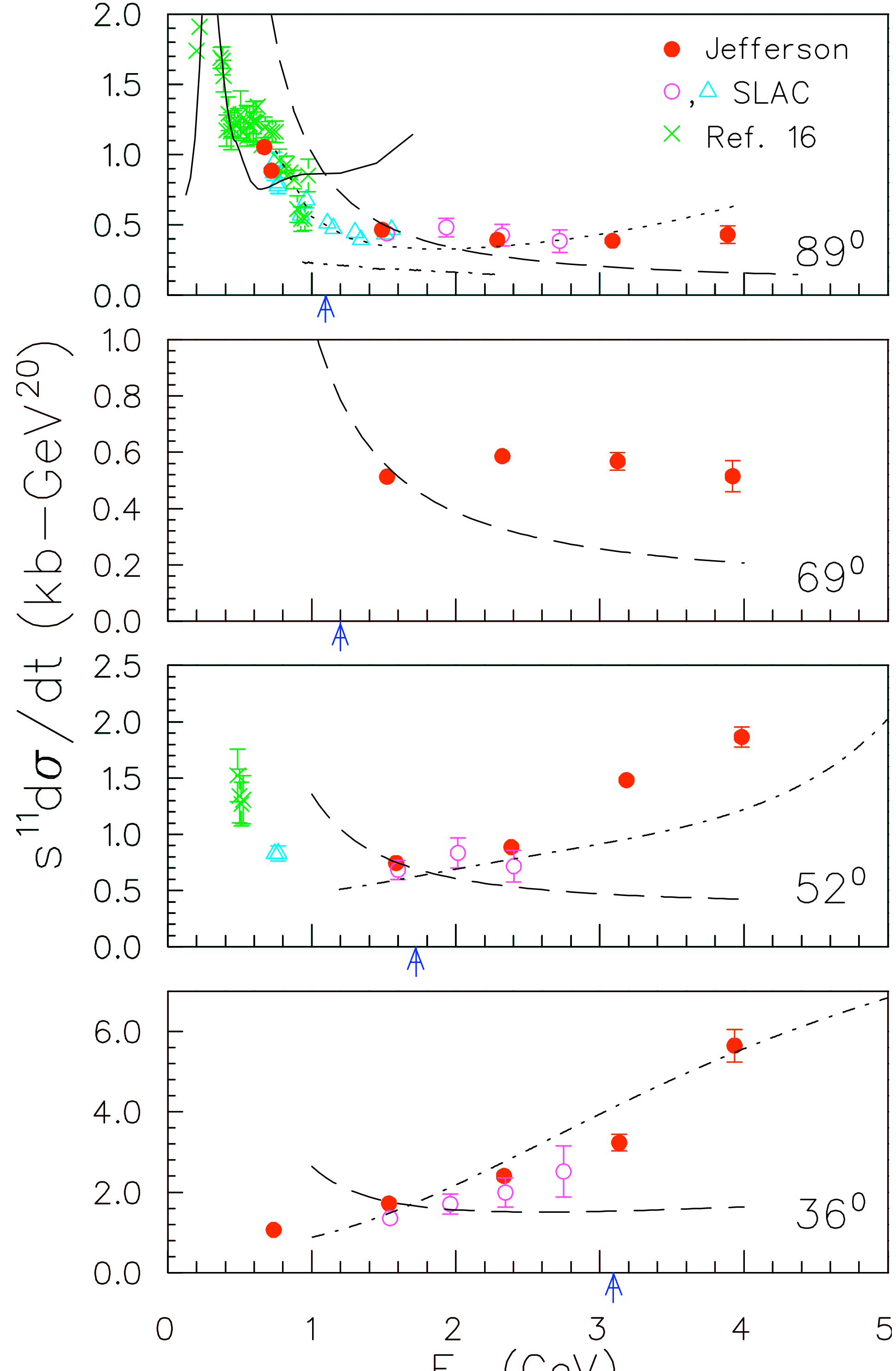
Notice:

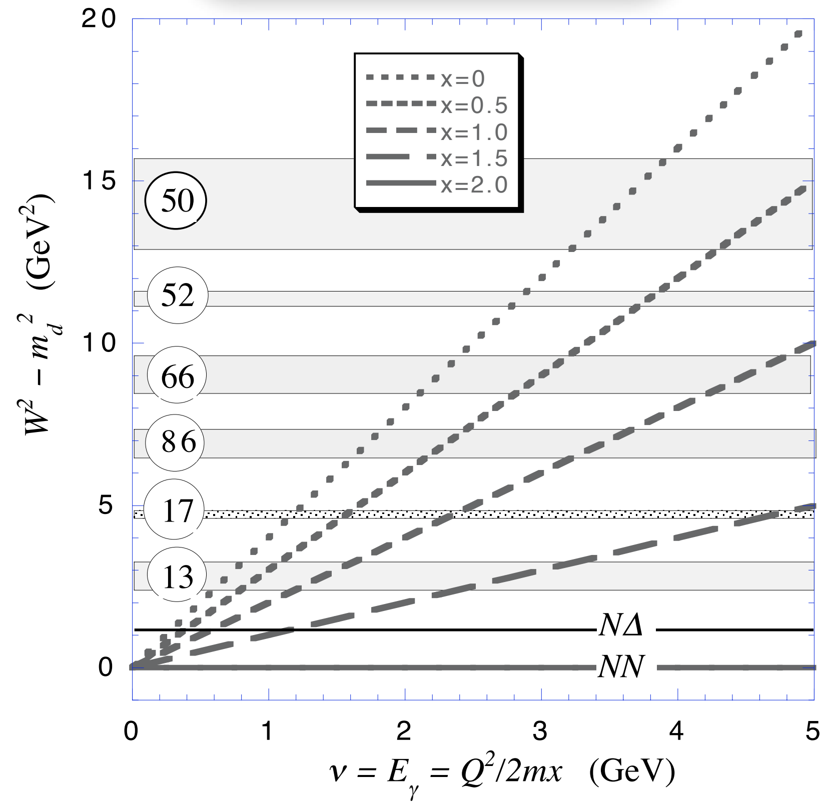
$$\frac{d\sigma}{dt}(E_\gamma = 1\,\mathrm{GeV/c}) / \frac{d\sigma}{dt}(E_\gamma = 4\,\mathrm{GeV/c}) \approx 10^4$$

scaling

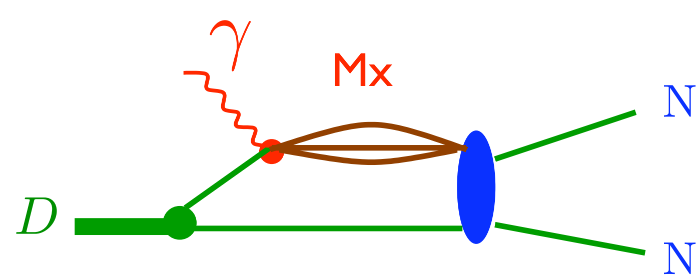


$\gamma d \to pn$

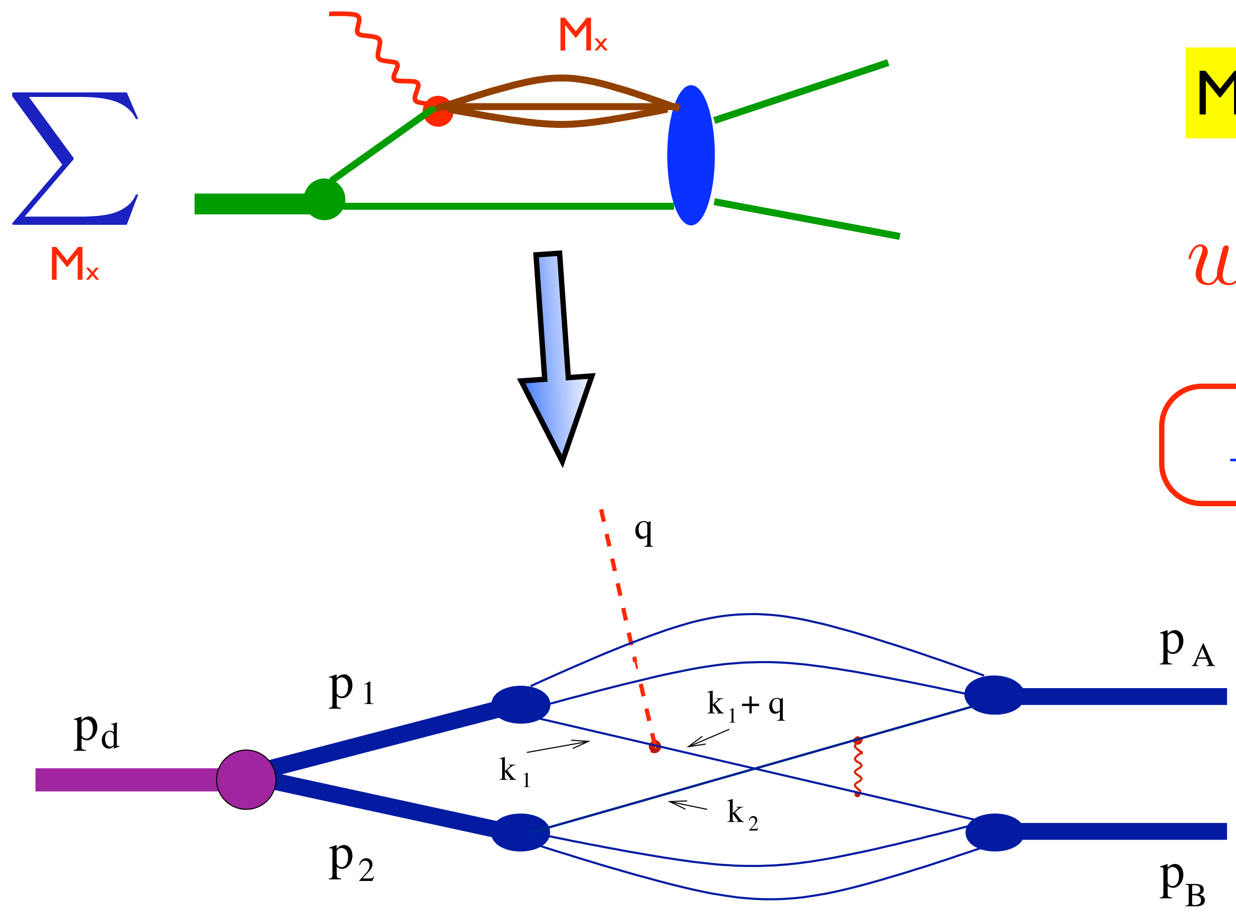




Gilman, Gross, 2002



Hard Rescattering Mechanism

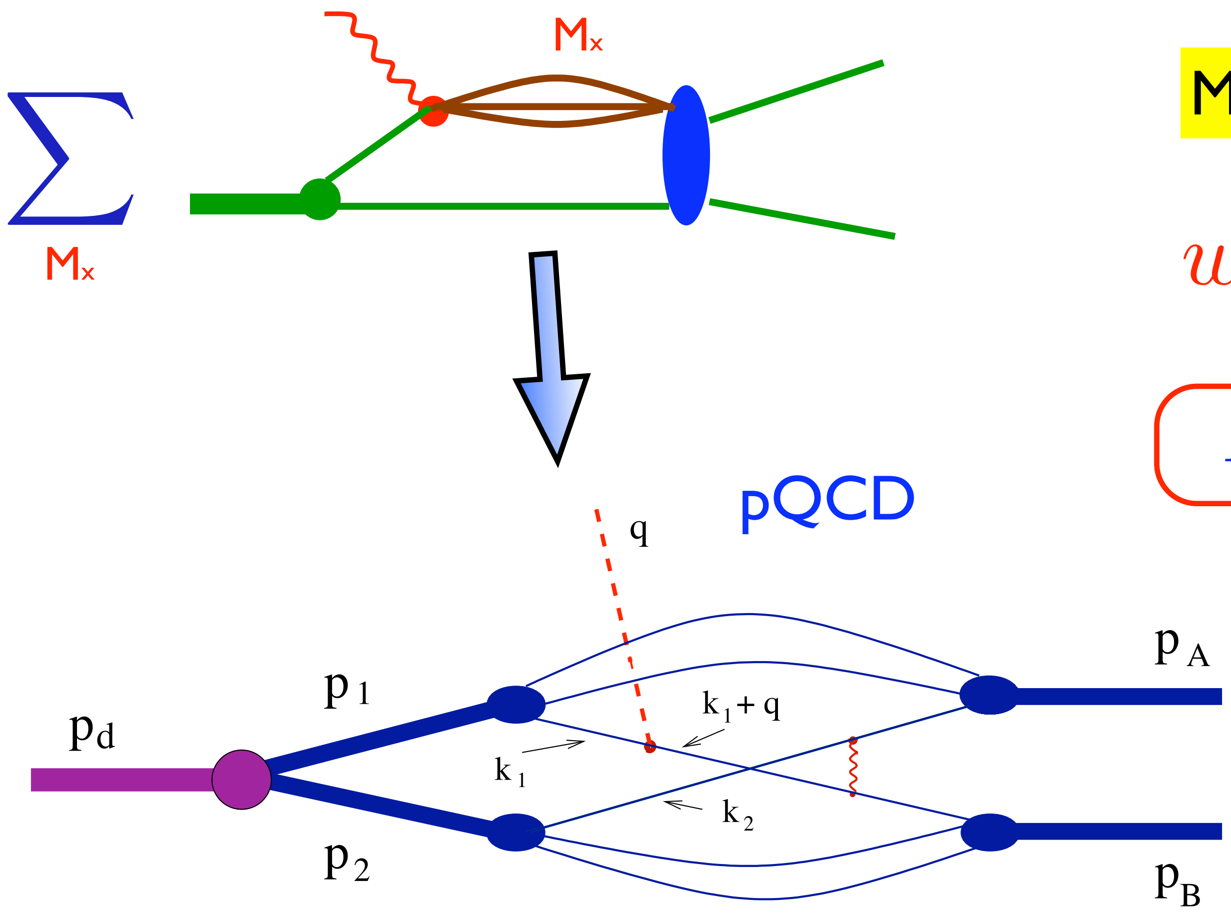


Mmax=w > 2 GeV

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

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

Hard Rescattering Mechanism

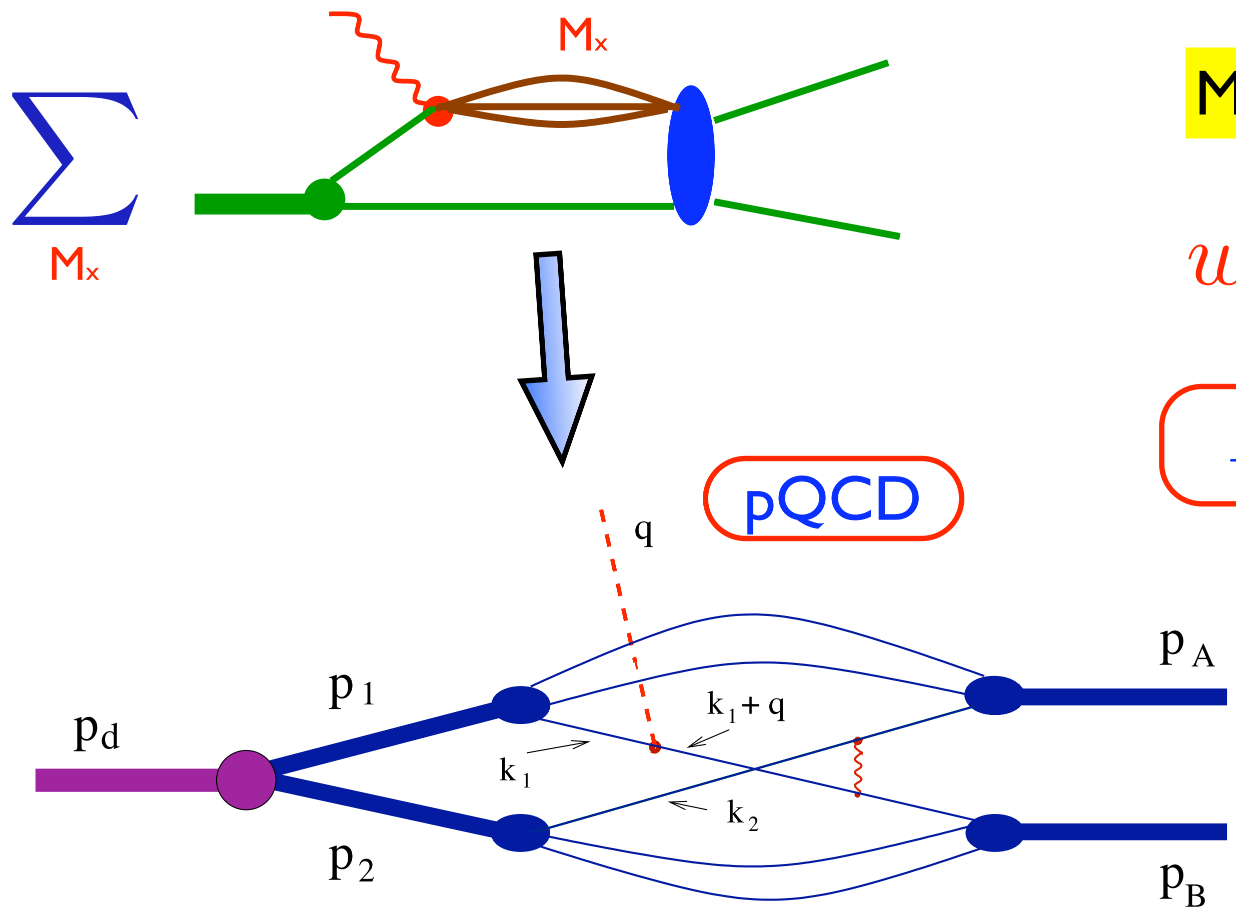


Mmax=w > 2 GeV

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

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

Hard Rescattering Mechanism

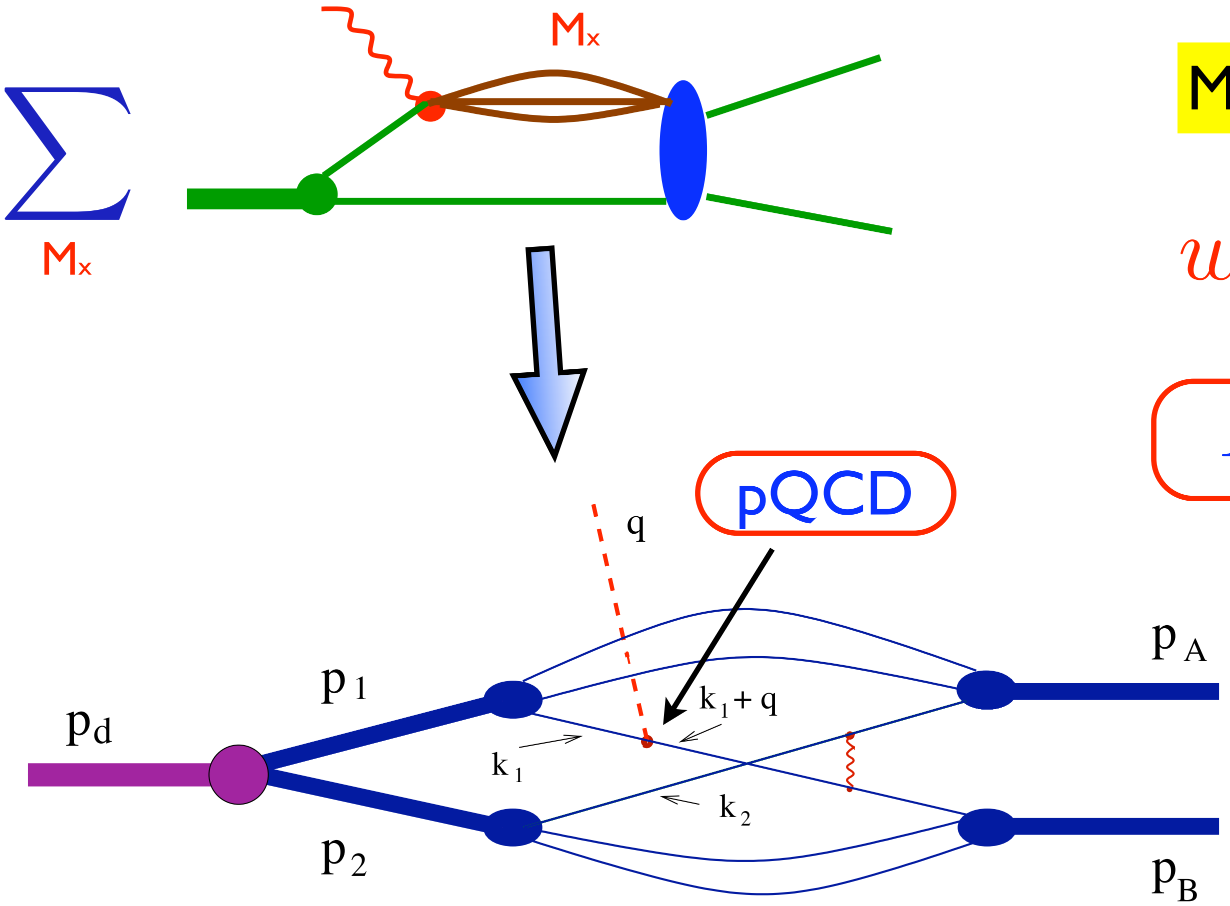


Mmax=w > 2 GeV

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

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

Hard Rescattering Mechanism

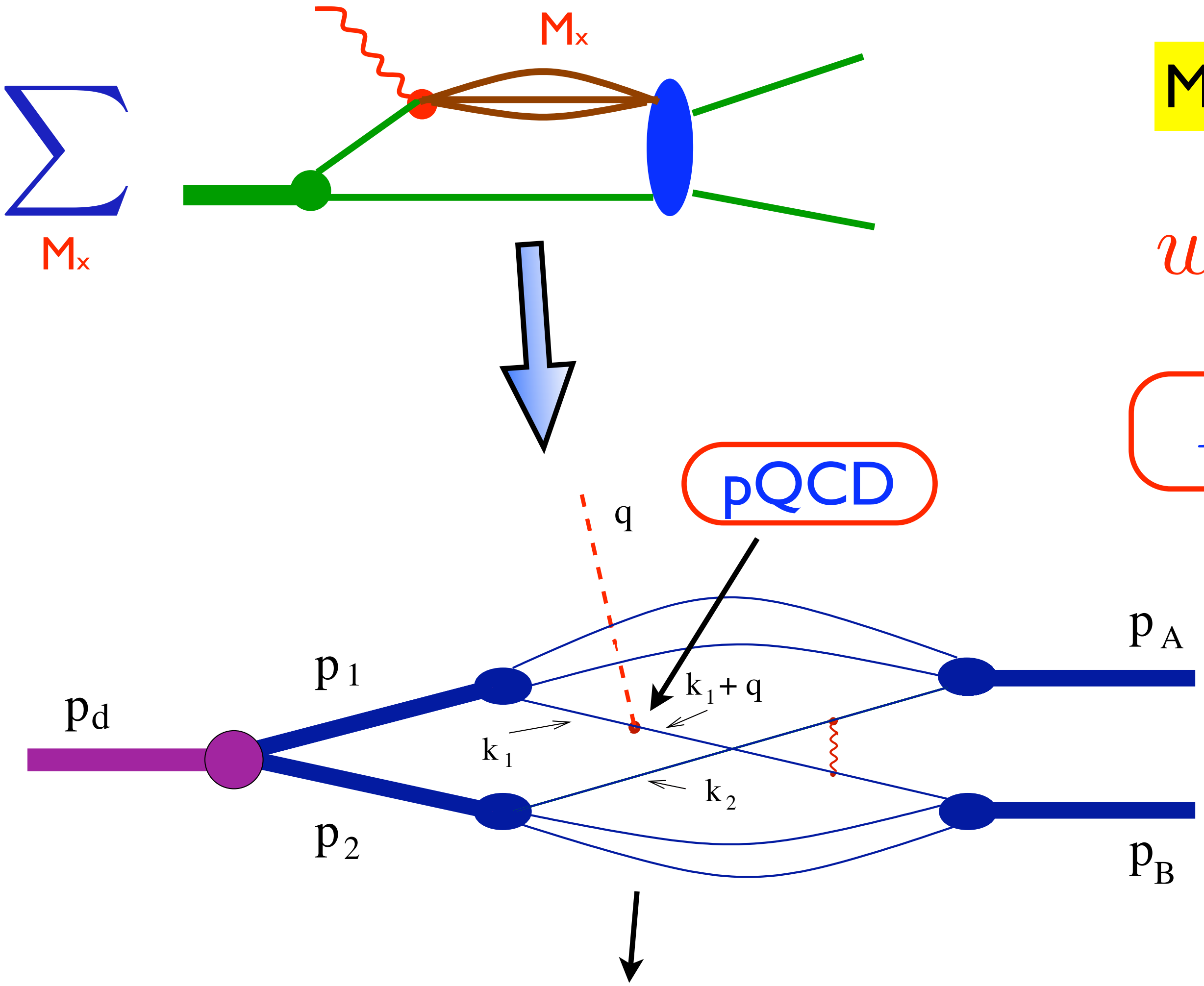


Mmax=w > 2 GeV

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

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

Hard Rescattering Mechanism

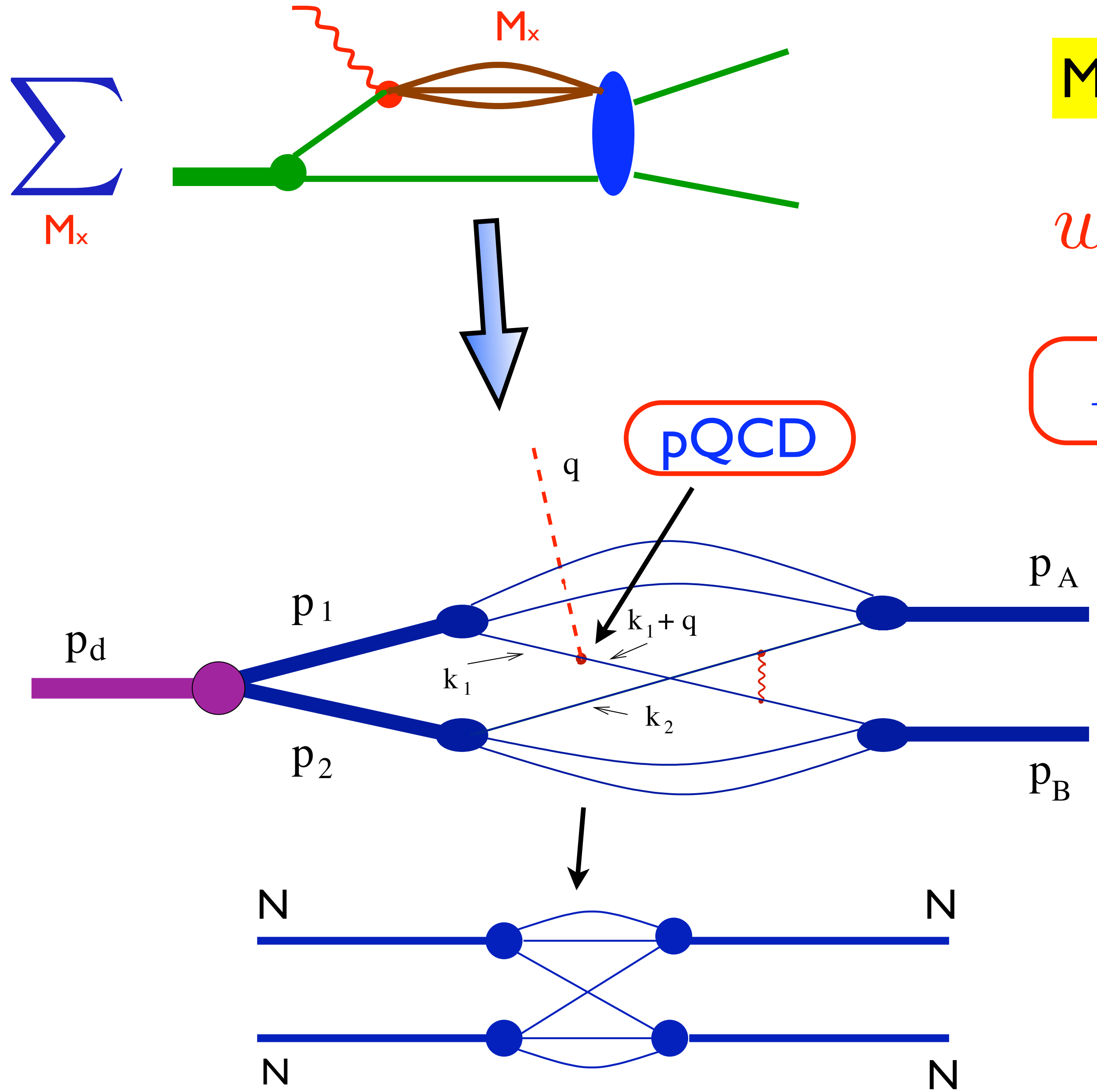


Mmax=w > 2 GeV

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

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

Hard Rescattering Mechanism

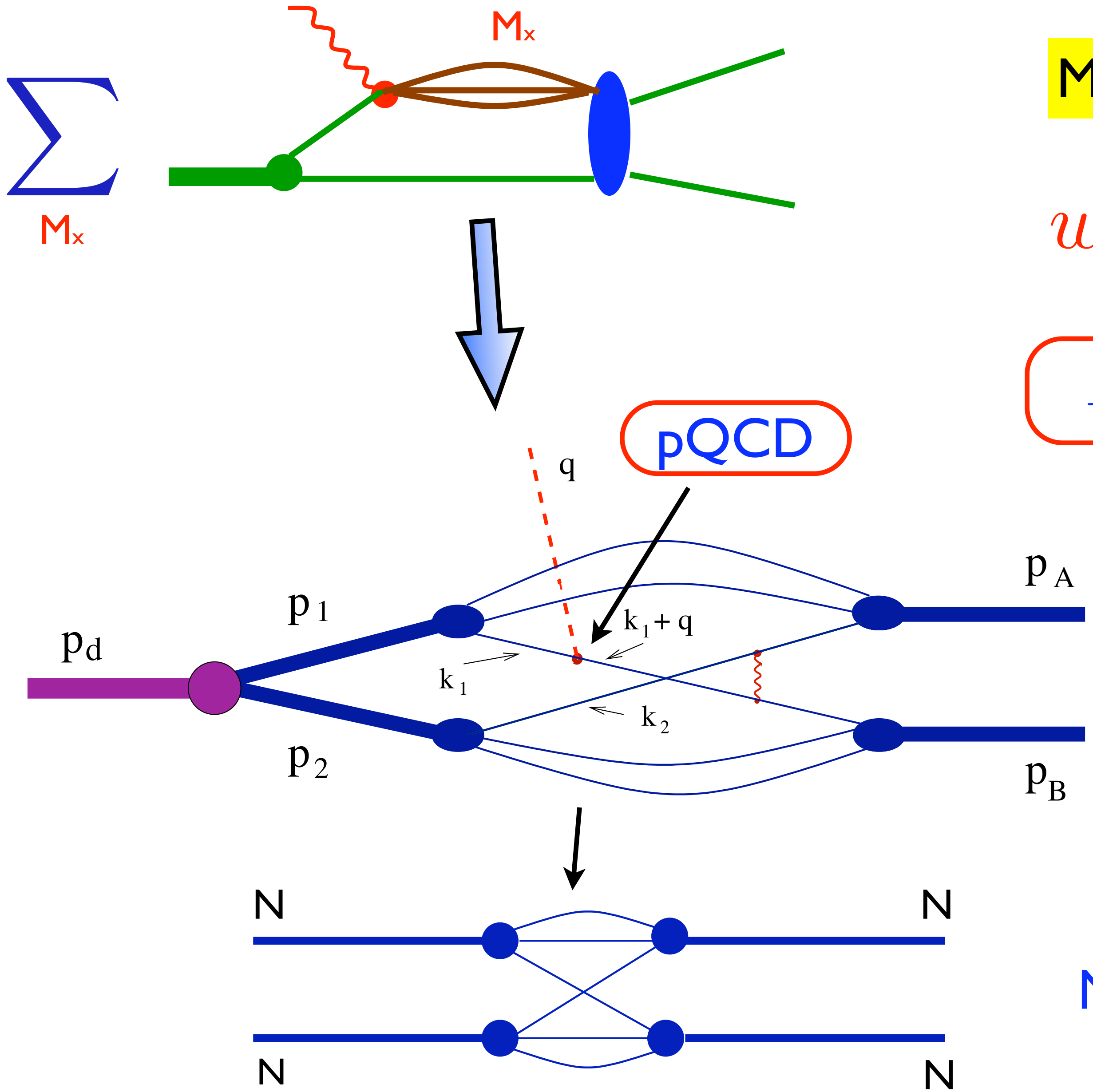


Mmax=w > 2 GeV

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

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

Hard Rescattering Mechanism



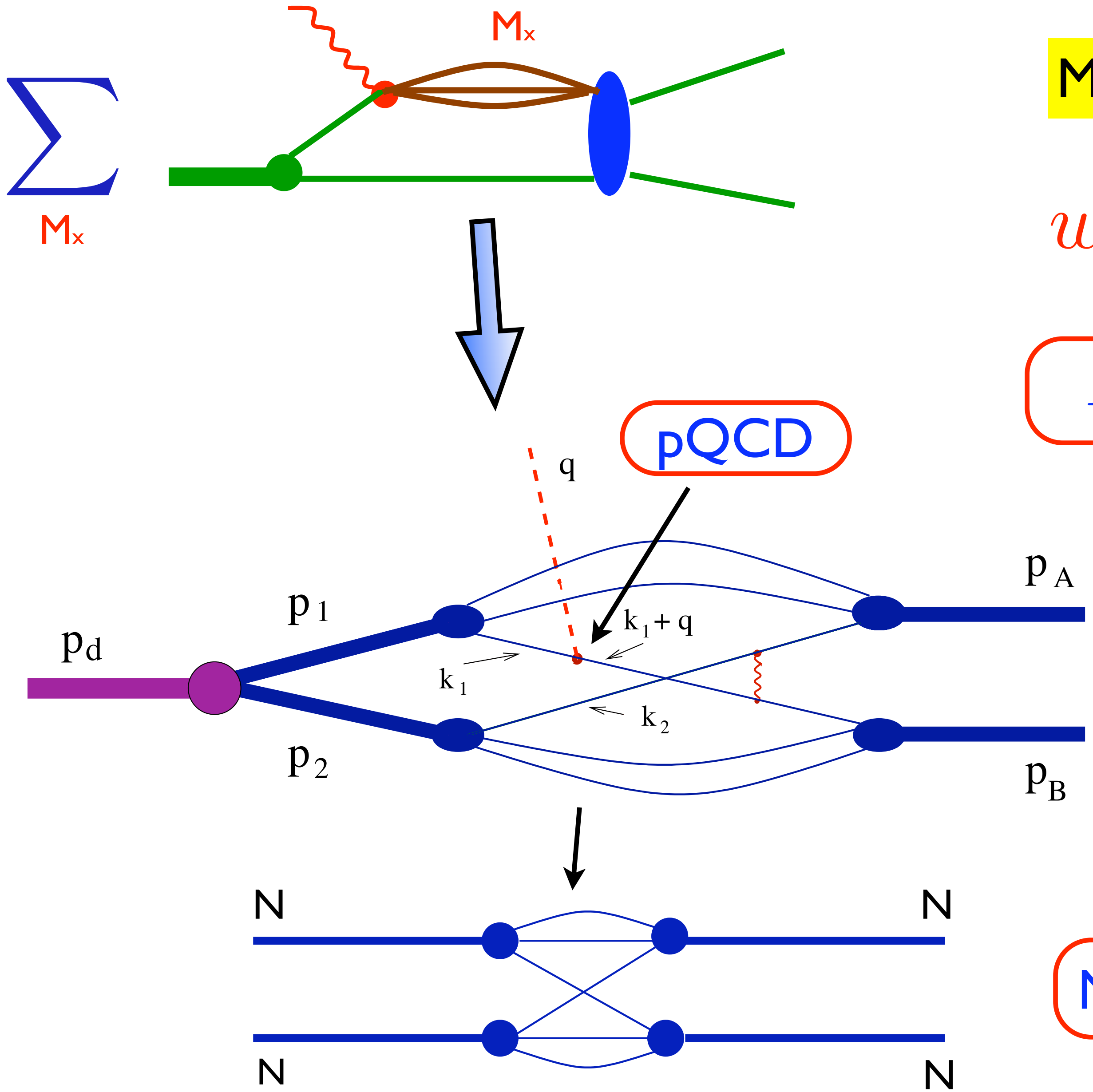
Mmax=w > 2 GeV

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

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

NN -amplitude

Hard Rescattering Mechanism

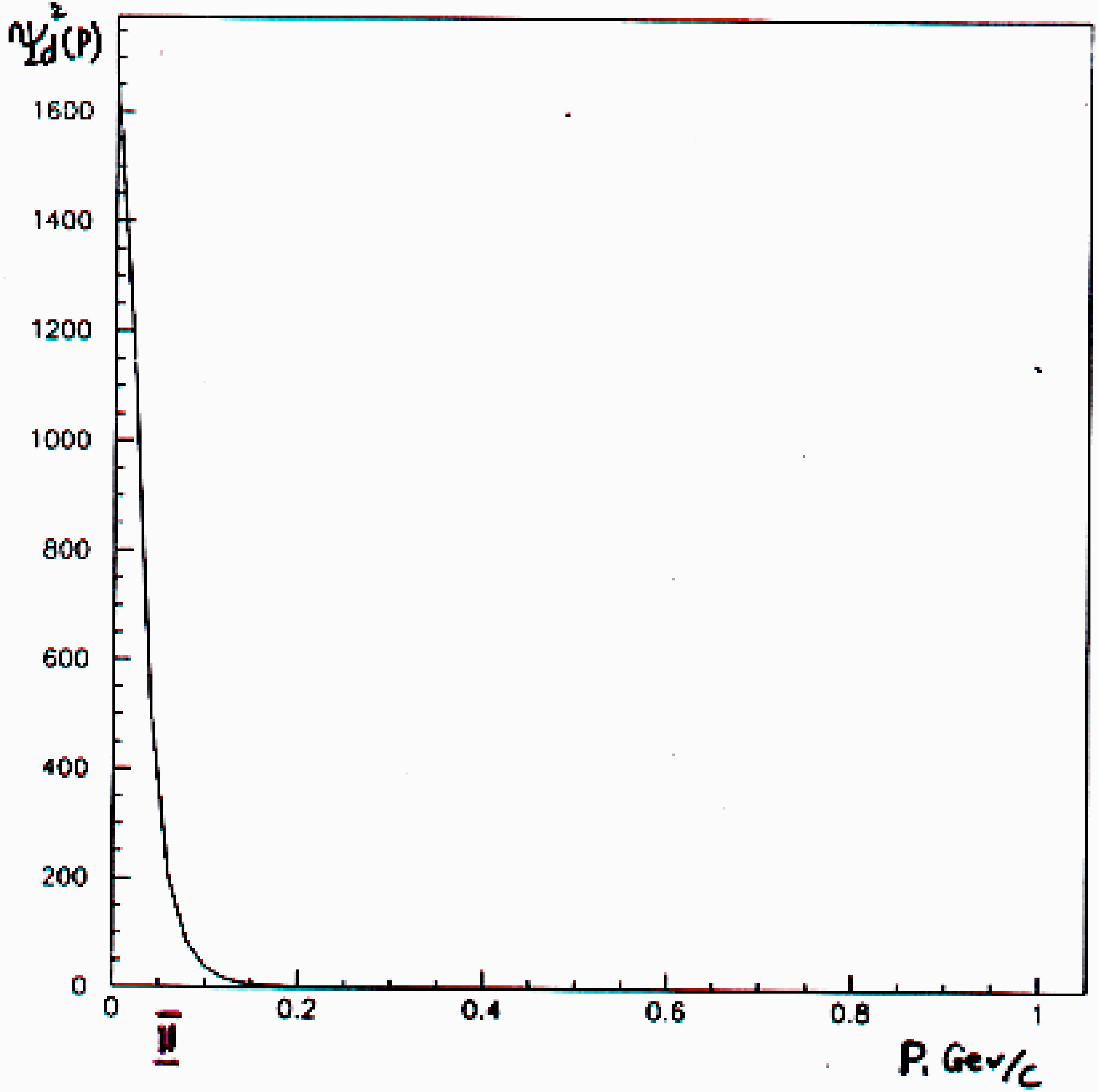


Mmax=w > 2 GeV

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

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

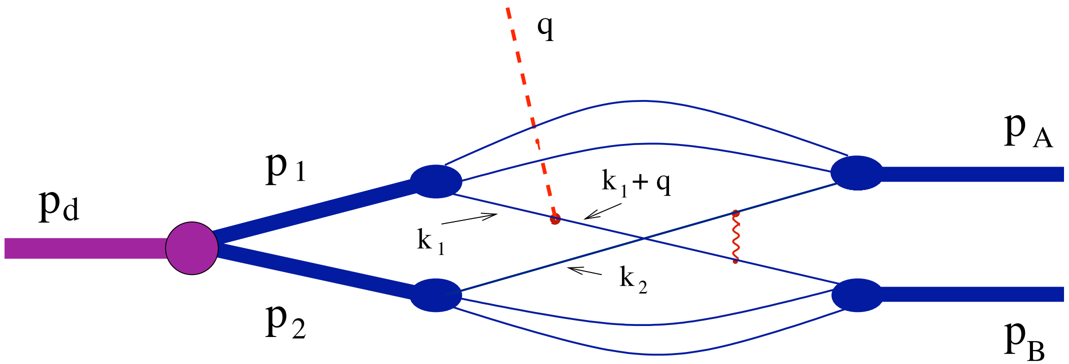
NN -amplitude

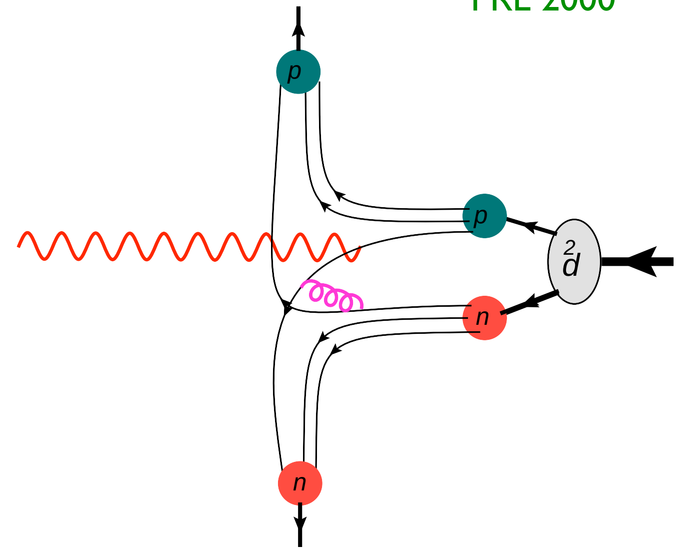


$\Psi_d^2(P)$
1600
1400
1200
1000
800
600
400
200
0
0
0.2
0.4
0.6
0.8
1
P, GeV/c

I →

Frankfurt, Miller, MS, Strikman
PRL 2000





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

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

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

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

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:

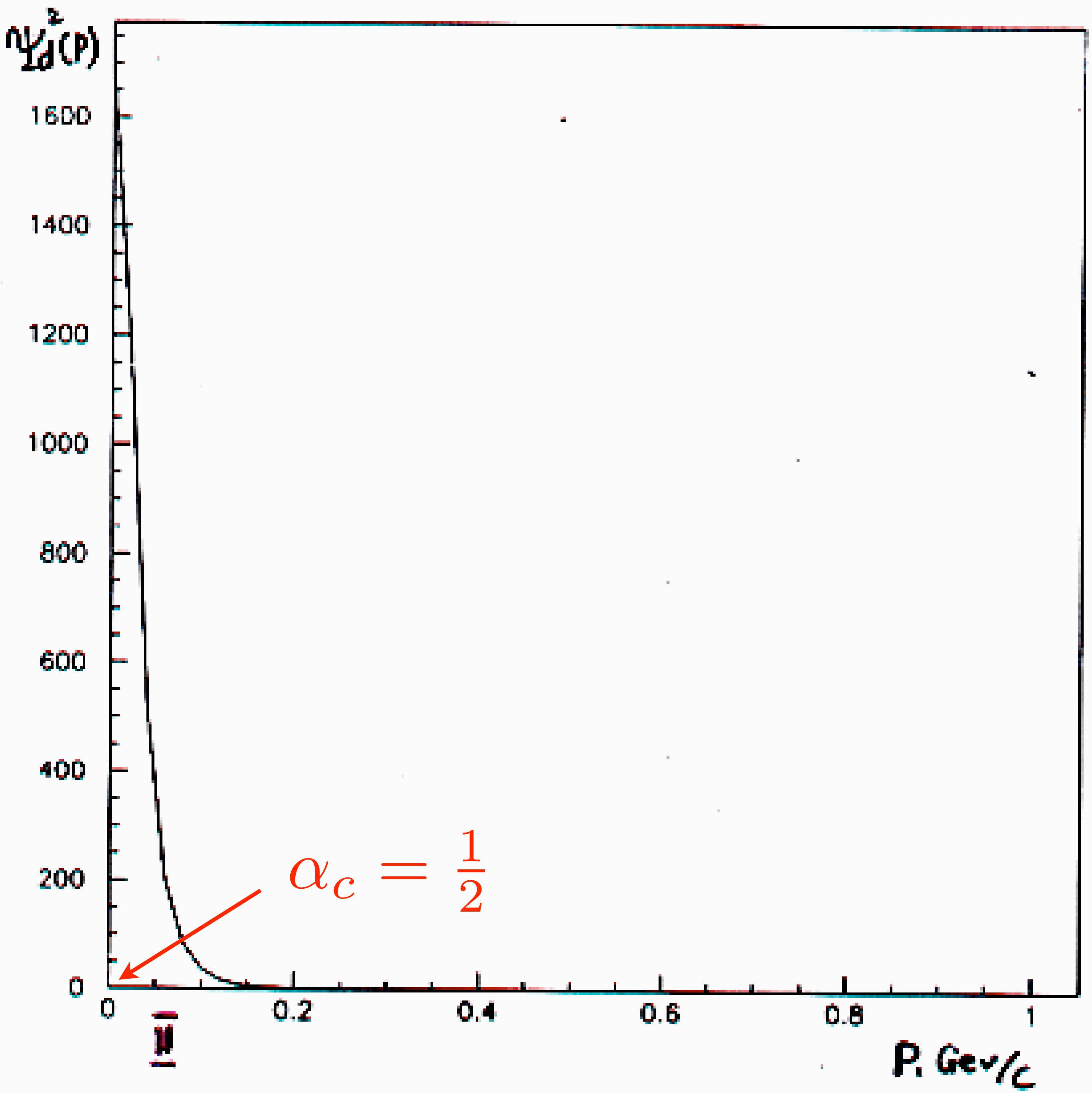
$$(k_1 + q)^2 - m_q^2 + i\epsilon \approx x_1 s'(\alpha - \alpha_c + i\epsilon),$$

$$\alpha_c \equiv \frac{x_1 m_R^2 + k_{1\perp}^2}{(1-x_1)x_1 \tilde{s}}. \quad (2)$$

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

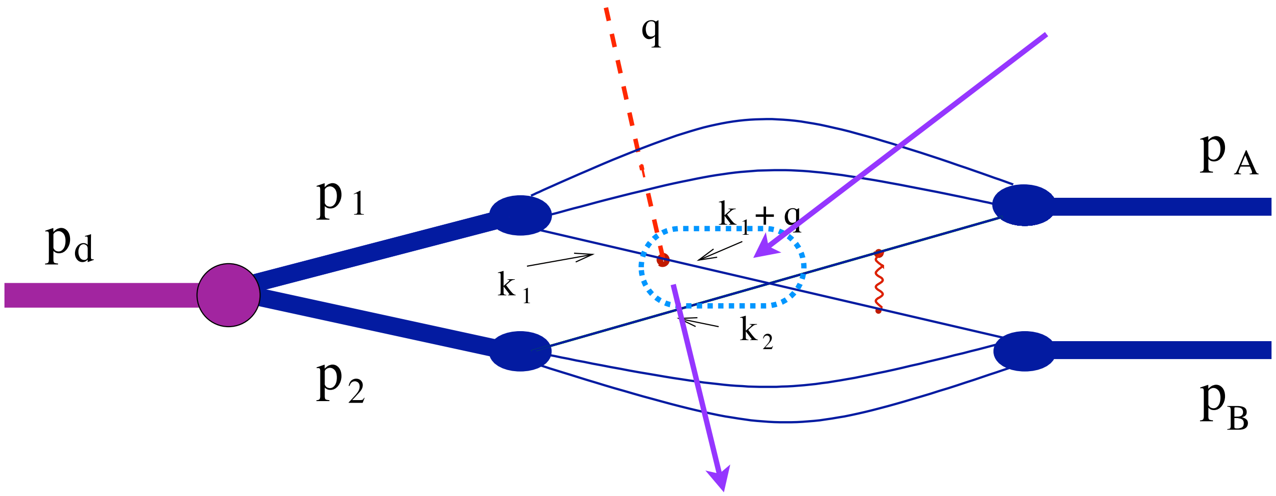

1600
1400
1200
1000
800
600
400
200
0
0
0.2
0.4
0.6
0.8
1
P, Gev/c
$\alpha_c = \frac{1}{2}$

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

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



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

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

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

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

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

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

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

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

Frankfurt, 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

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

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

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

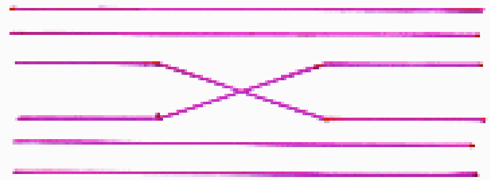
$$\langle p_{\lambda_A}, n_{\lambda_B} \mid A \mid \lambda_\gamma, \lambda_D \rangle = \sum_{\lambda_2} \frac{f(\theta_{cm})}{3\sqrt{2s'}} \times$$
$$\Big(\langle p_{\lambda_A}, n_{\lambda_B} | A_{pn}(s,t_n) | p_{\lambda_\gamma}, n_{\lambda_2} \rangle - \langle p_{\lambda_A}, n_{\lambda_B} | A_{pn}(s,u_n)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

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

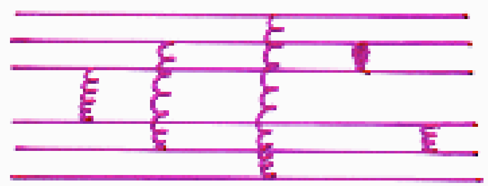
$$\frac{d\sigma^{\gamma d \to pn}}{dt} = \frac{8\alpha}{9}\pi^4 \cdot \frac{1}{s'} C\left(\frac{\tilde{t}}{s}\right) \frac{d\sigma^{pn\to pn}(s,\tilde{t})}{dt} \left| \int \Psi_d^{NR}(p_z = 0, p_\perp) \sqrt{m_N} \frac{d^2 p_\perp}{(2\pi)^2} \right|^2,$$

$$C\left(\frac{\tilde{t}}{s}\right) \Big|_{\theta_{cm}=90} = 1$$

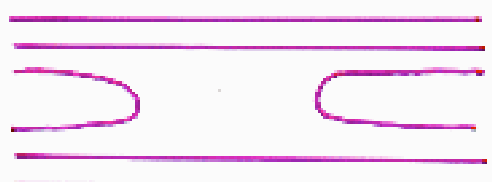
QIM



GLUON EXCHANGE



ANIHILLATION

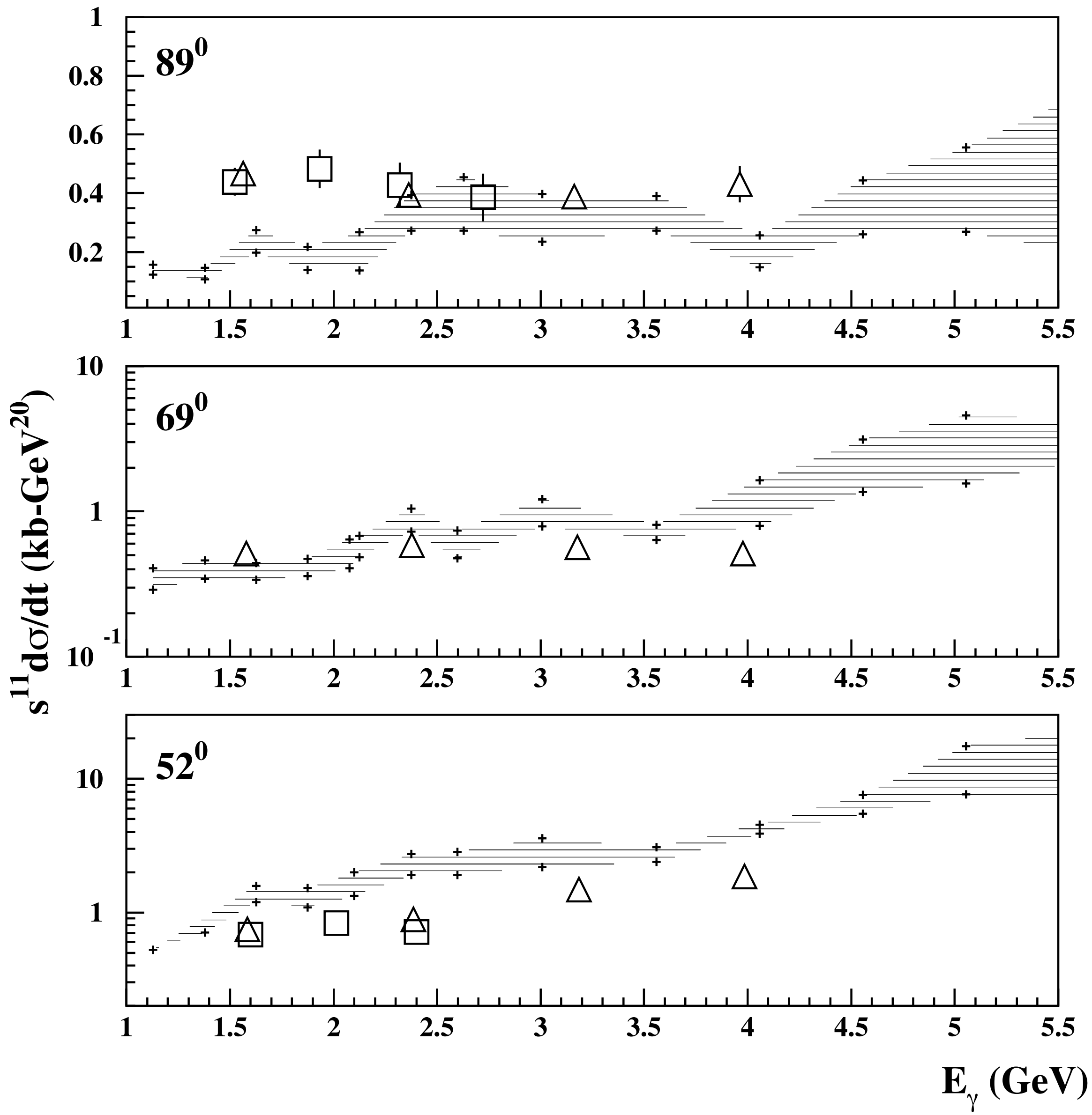


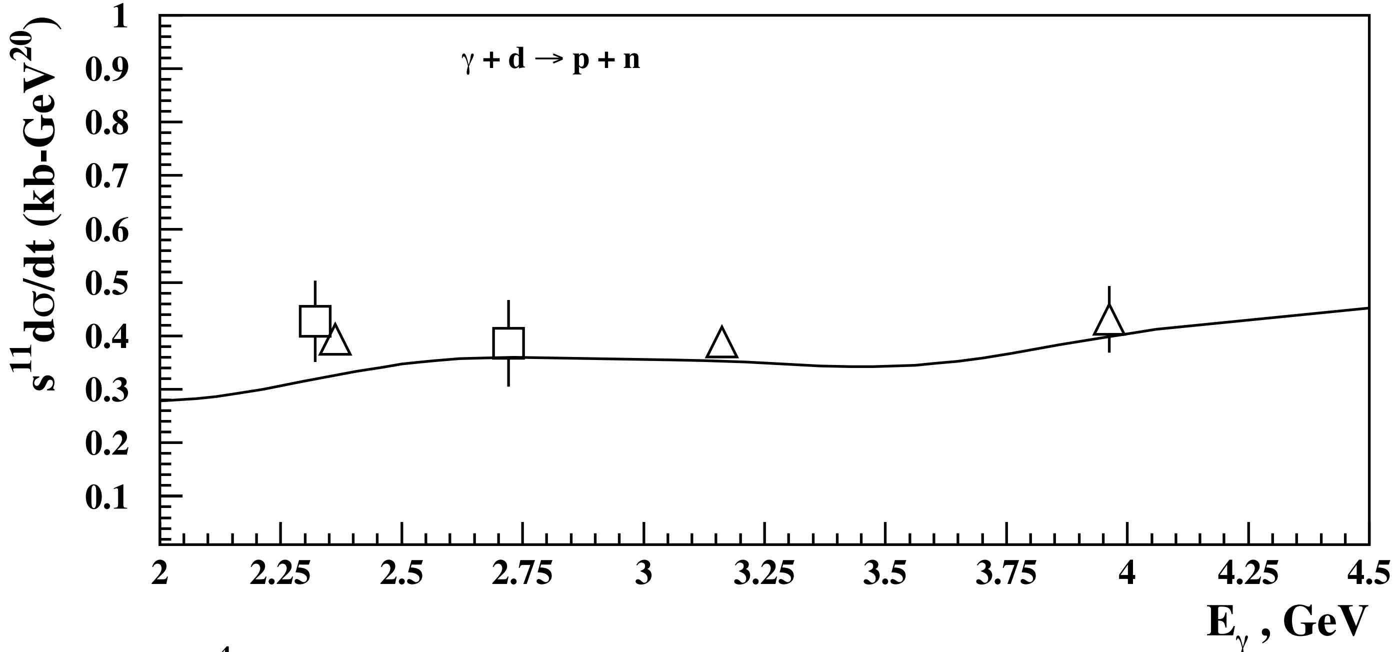
≡ COMPARE $PP \to PP$ AND $P\bar{P} \to P\bar{P}$ CROSS SECTIONS

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

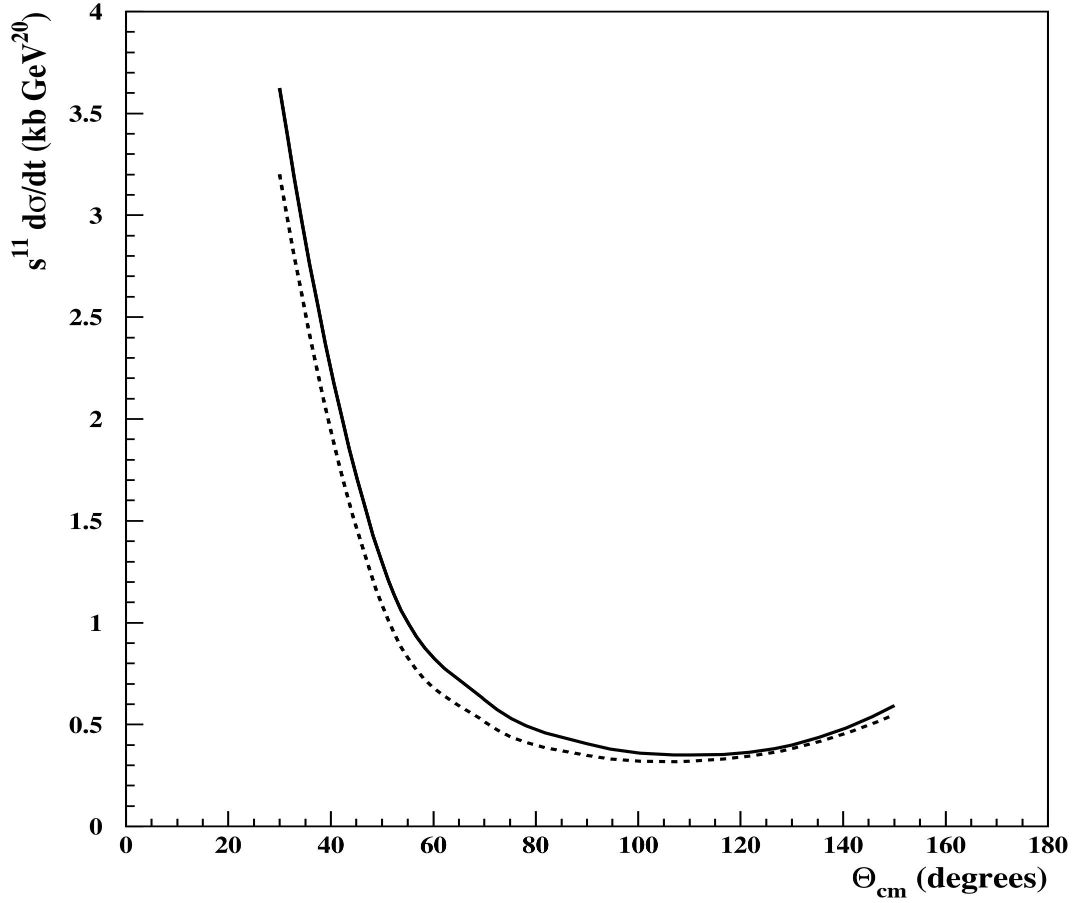
Frankfurt, Miller, M.S. Strikman
PRL 2000

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

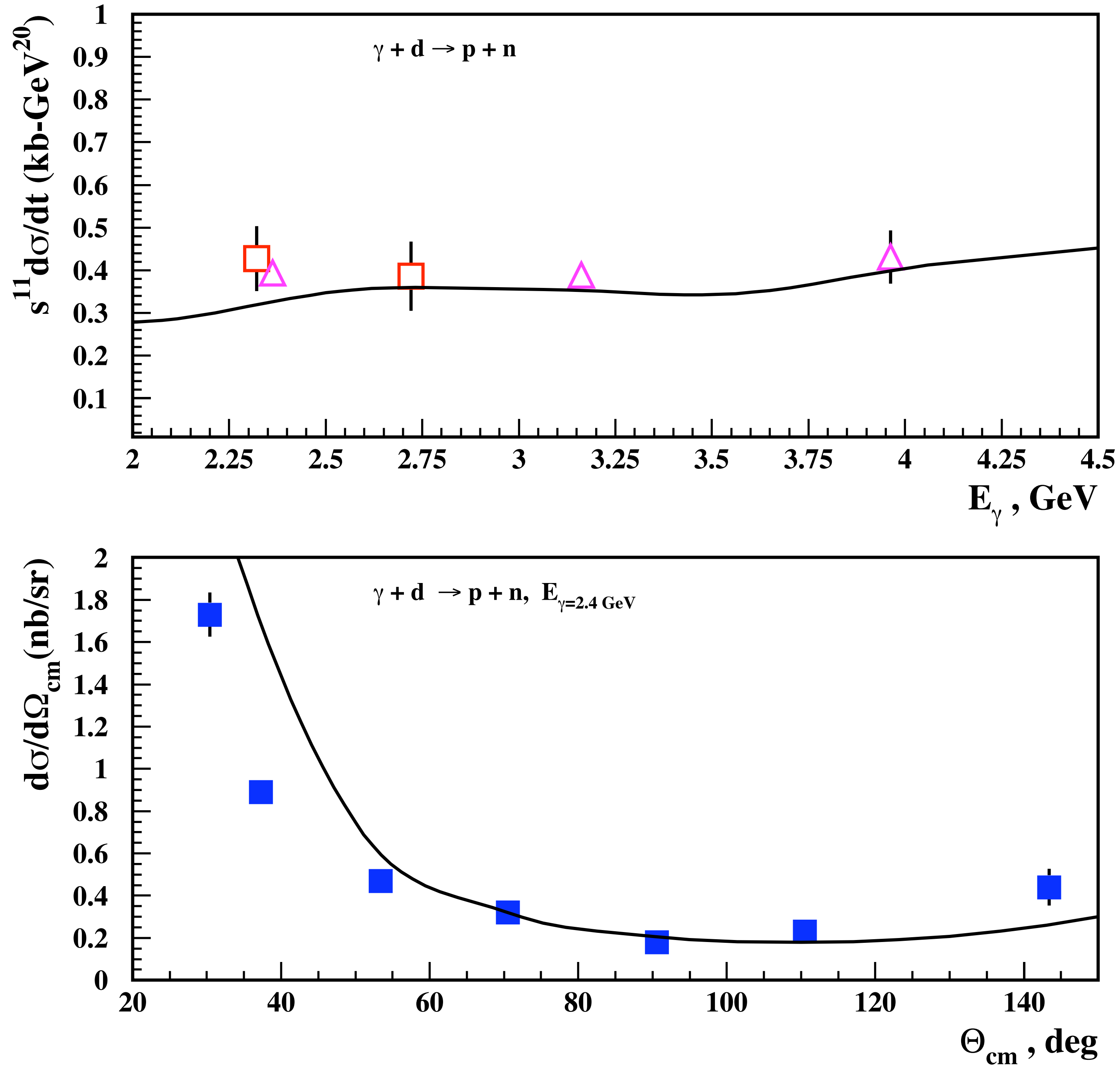




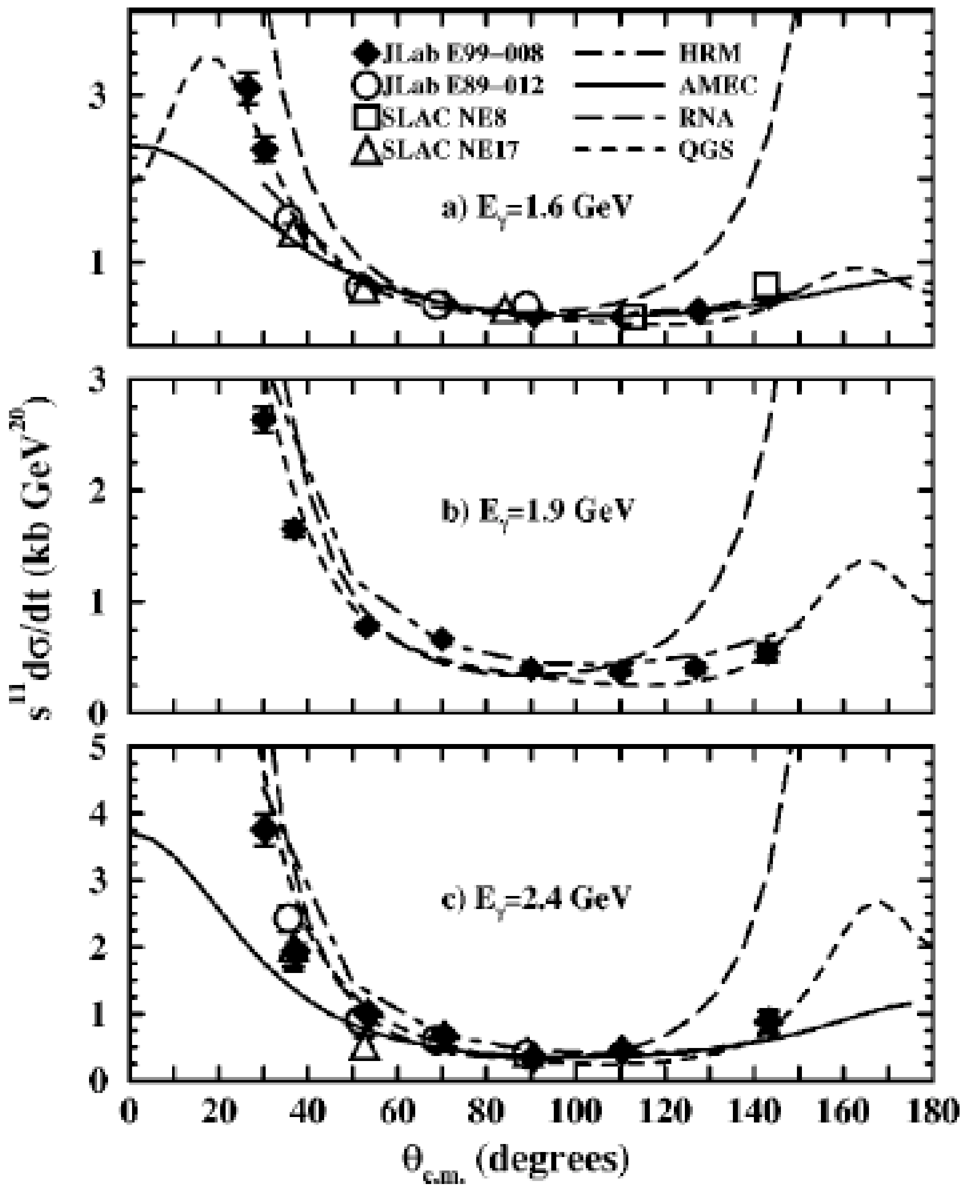
γ + d → p + n
$s^{11}d\sigma/dt$ (kb-GeV^{20})
E_γ , GeV



$s^{11}d\sigma/dt$ (kb GeV^{20})
Θ_{cm} (degrees)



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



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)

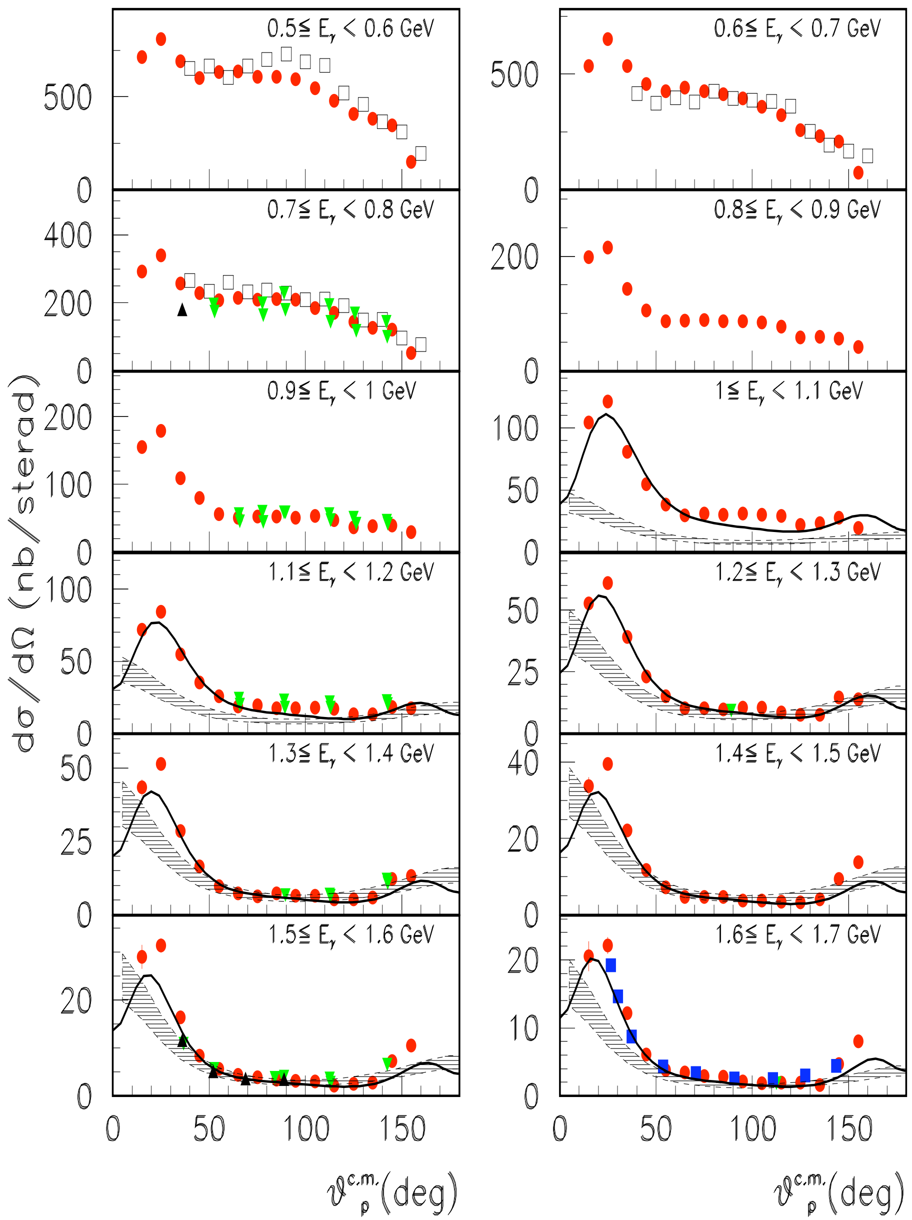


FIG. 7: (Color) Angular distributions of the deuteron photodisintegration cross section measured by the CLAS (full/red circles) in the incident photon energy range 0.50 – 1.70 GeV. Results from Mainz [26] (open squares, average of the measured values in the given photon energy intervals), SLAC [5, 6,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

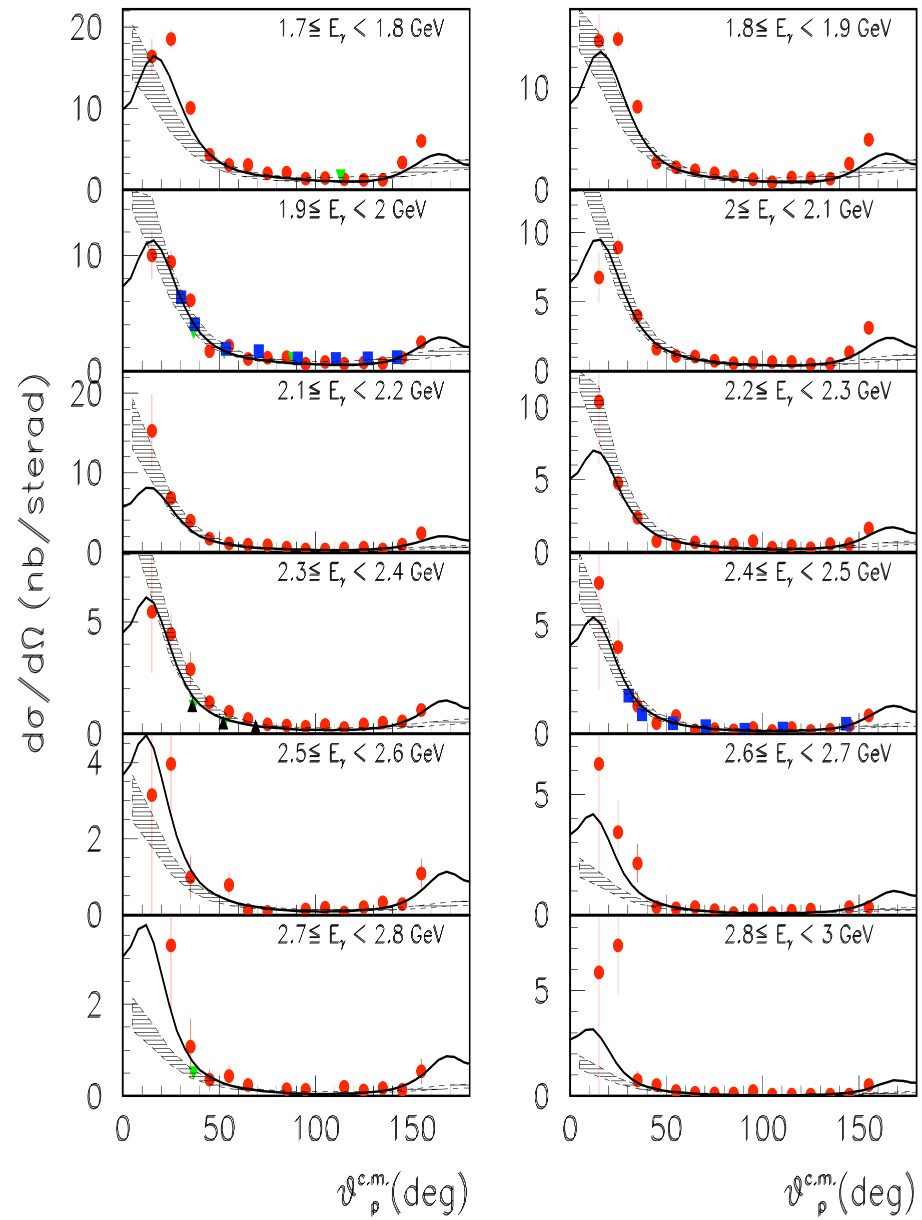
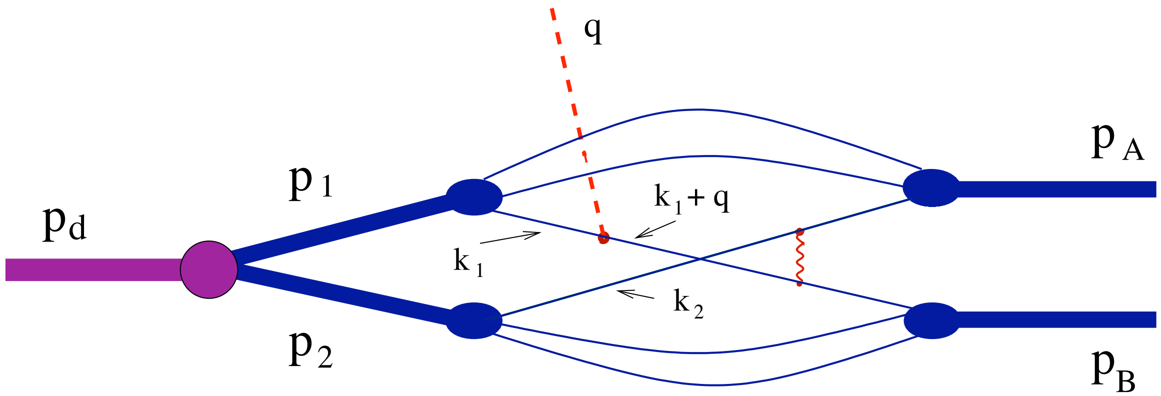


FIG. 8: (Color) Same as Fig. 7 for photon energies 1.7 – 3.0 GeV.

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.

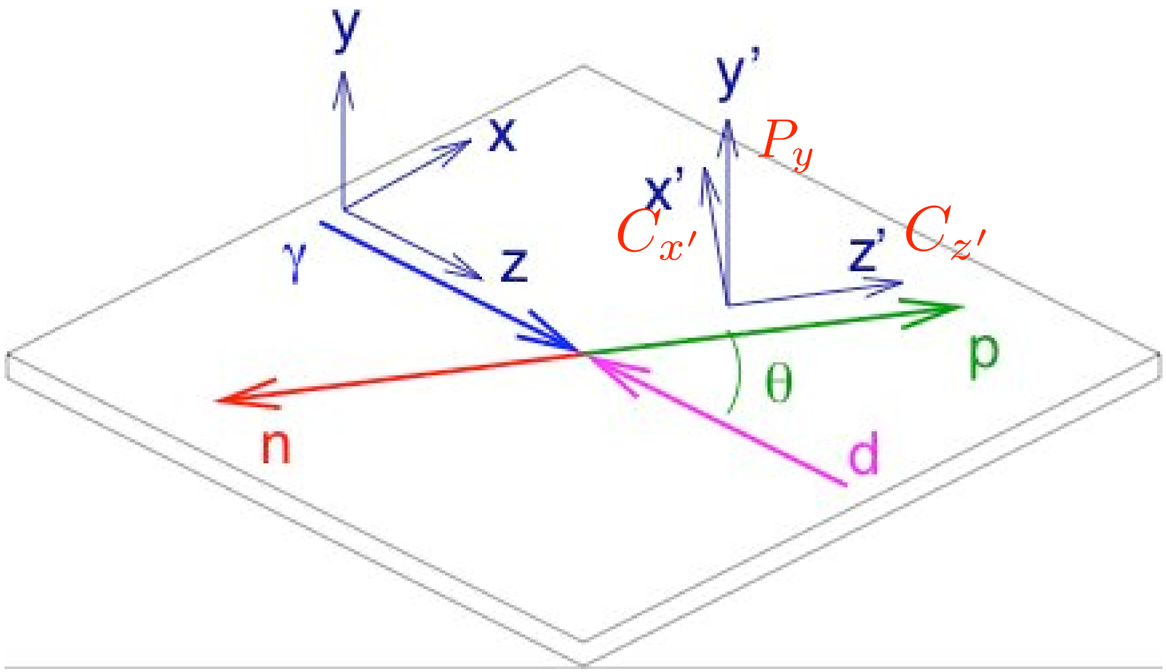


Polarization Observables

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

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

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



Gilman, Gross, 2002

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

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

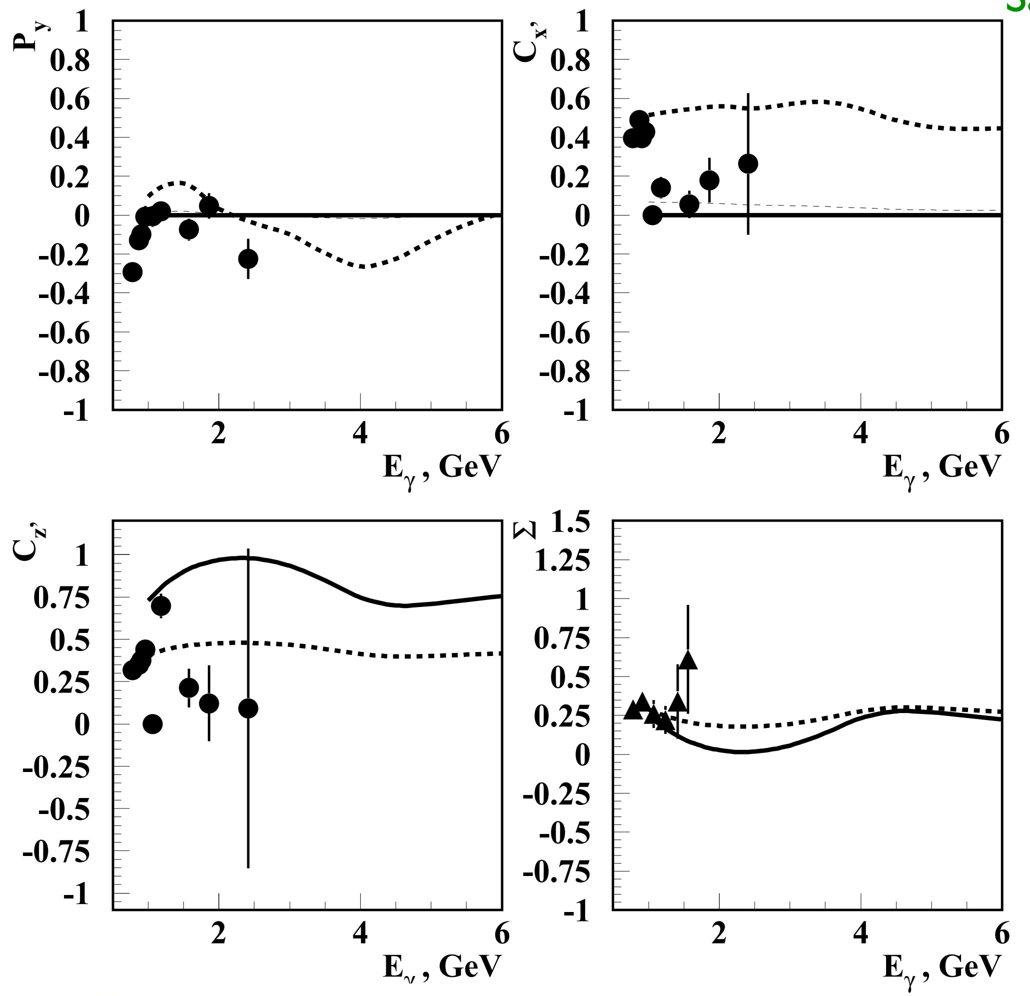
$$C_{z'} = \frac{2|\phi_1|^2-2|\phi_2|^2+|\phi_3|^2-|\phi_4|^2}{2|\phi_1|^2+2|\phi_2|^2+|\phi_3|^2+|\phi_4|^2+6|\phi_5|^2}$$

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

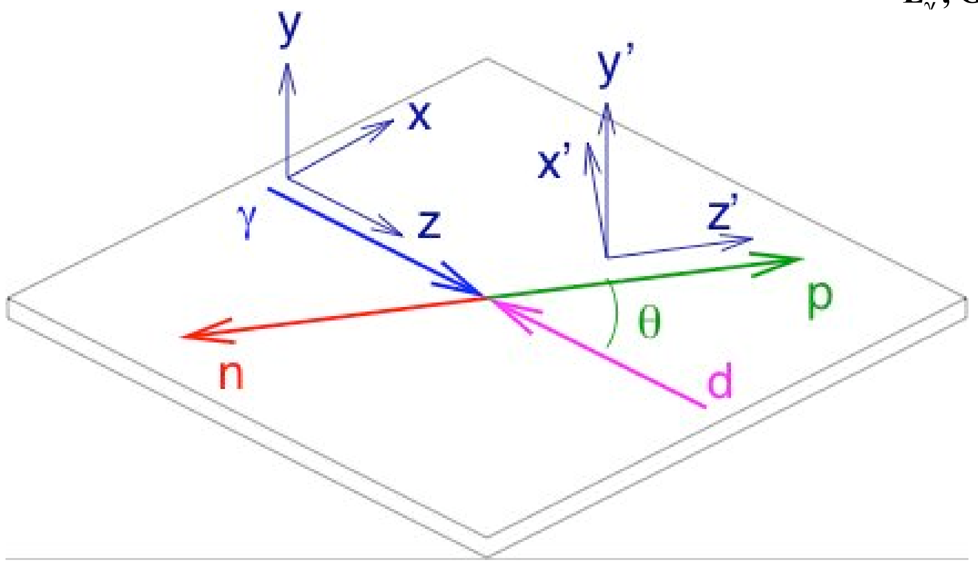
$$\begin{aligned}
\phi_1(s,t_n,u_n) &= \langle +,+ \mid A_{pn} \mid +,+\rangle \\
\phi_2(s,t_n,u_n) &= \langle +,+ \mid A_{pn} \mid -,-\rangle \\
\phi_3(s,t_n,u_n) &= \langle +,- \mid A_{pn} \mid +,-\rangle \\
\phi_4(s,t_n,u_n) &= \langle +,- \mid A_{pn} \mid -,+\rangle \\
\phi_5(s,t_n,u_n) &= \langle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

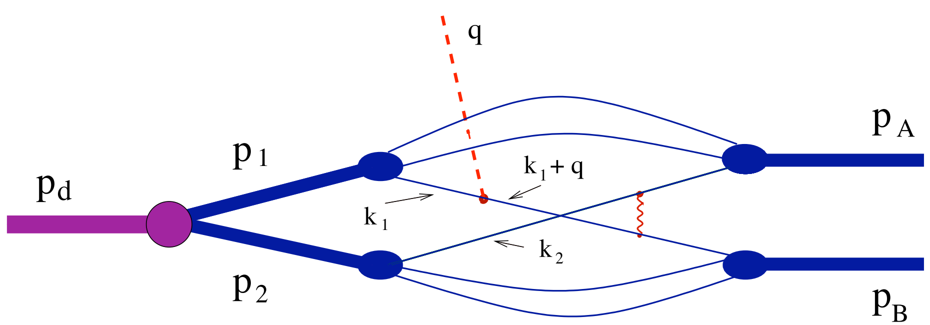
$$|\phi_1| \geq |\phi_3|, |\phi_4| > |\phi_5| > |\phi_2|.$$

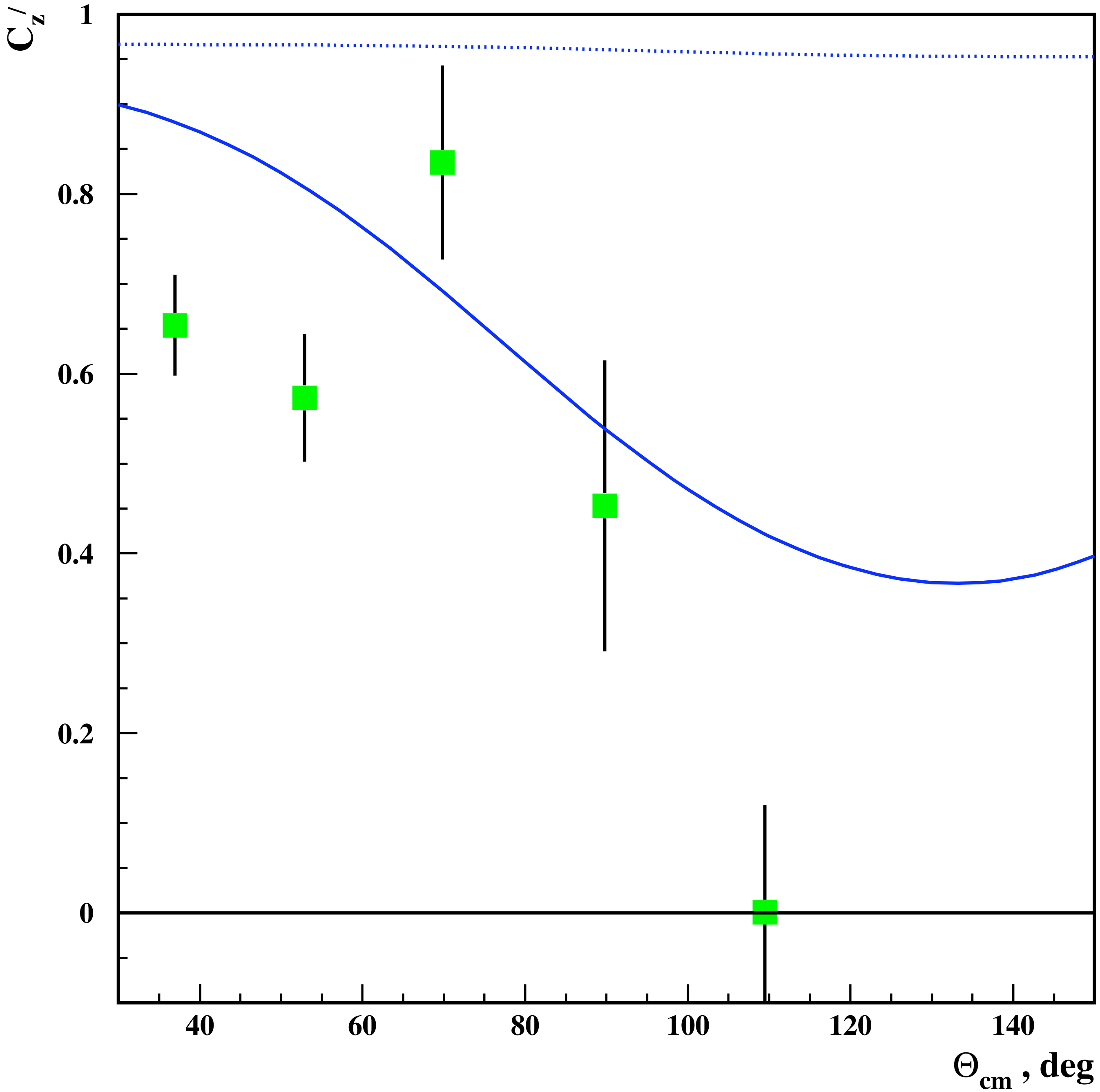
Sargsian, Phys. Lett. B 2004



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





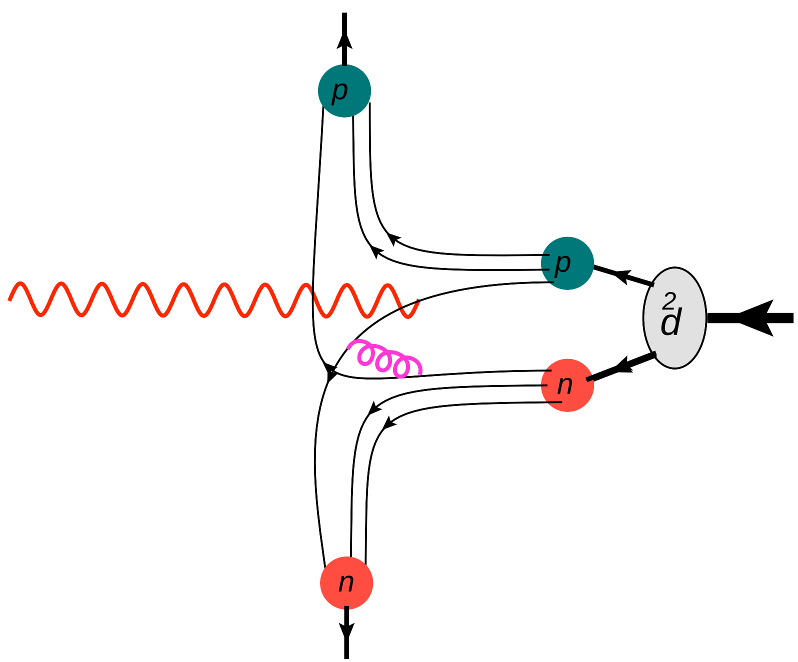


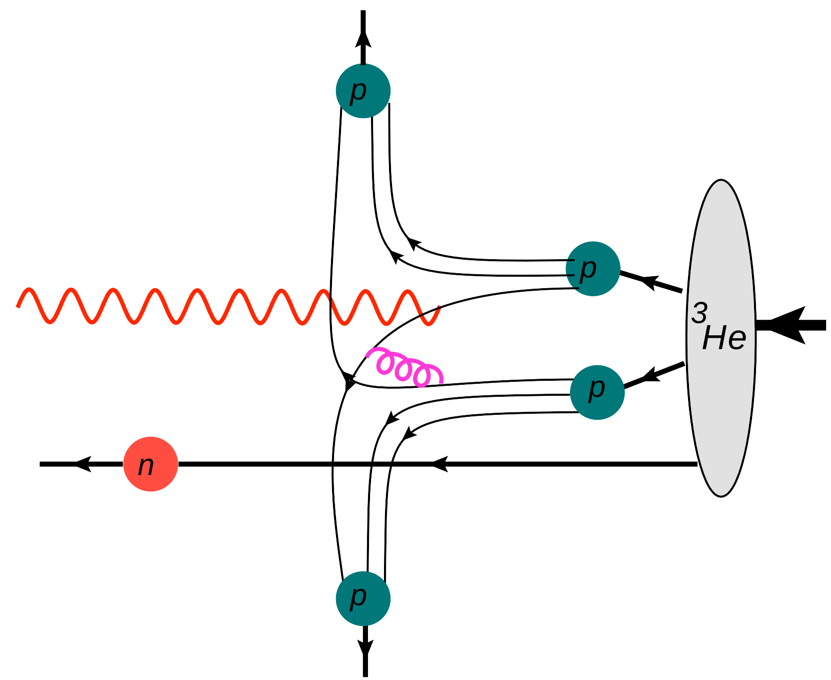
Jiang et al, PRL2007

Break up of pn from the deuteron

Break up of pp from Helium 3

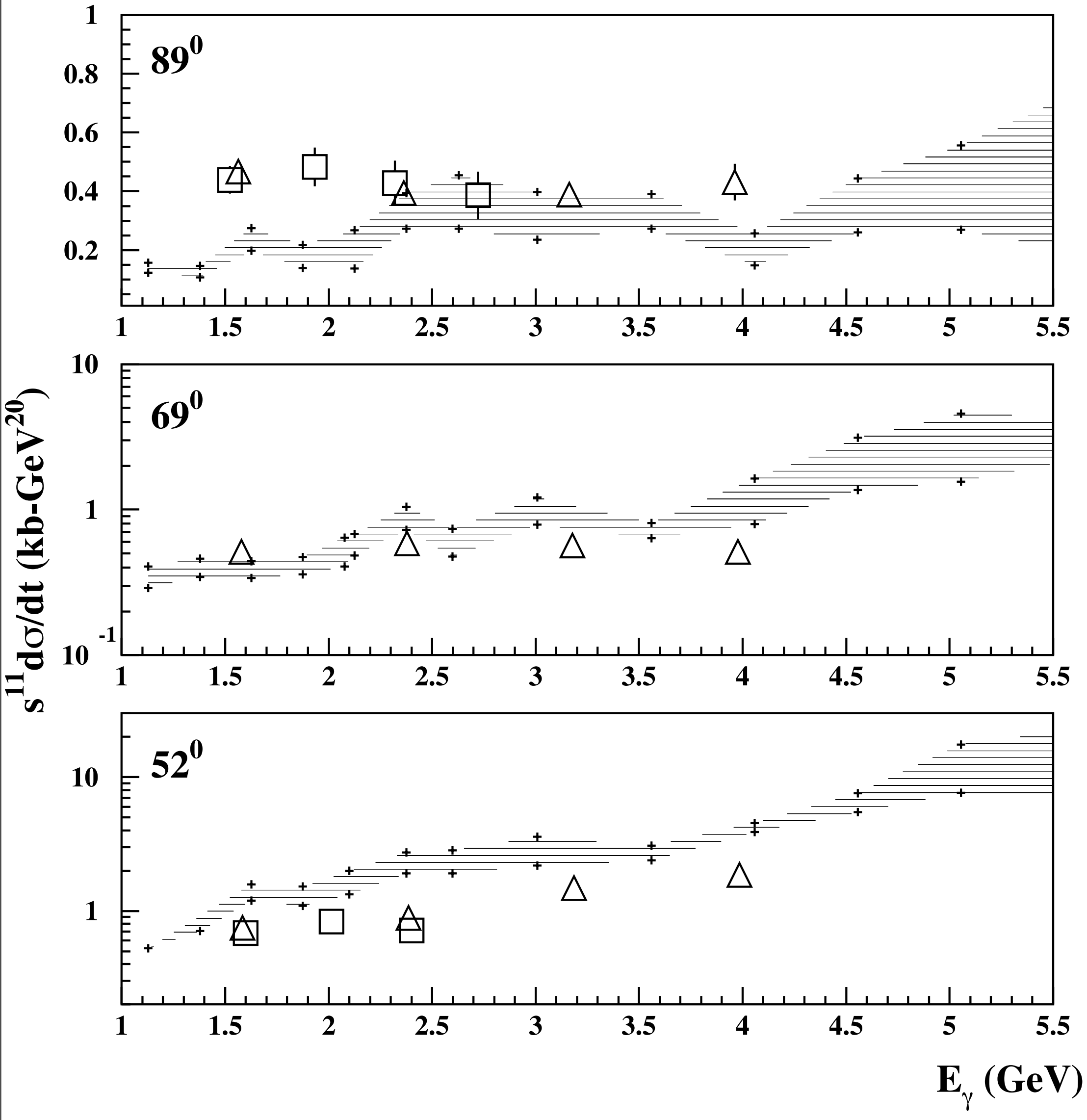
Brodsky, Frankfurt, Gilman, Hiller, Miller
Piasetzky, M.S., Strikman
Phys. Lett. B 2004

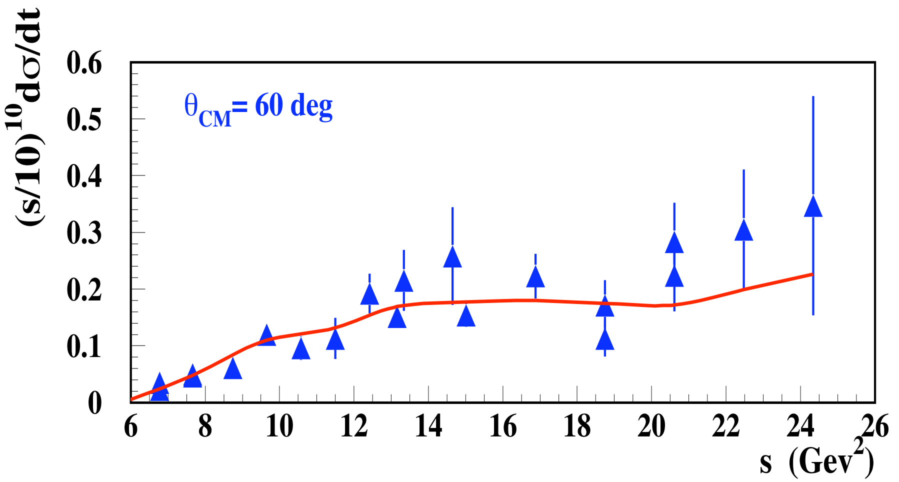


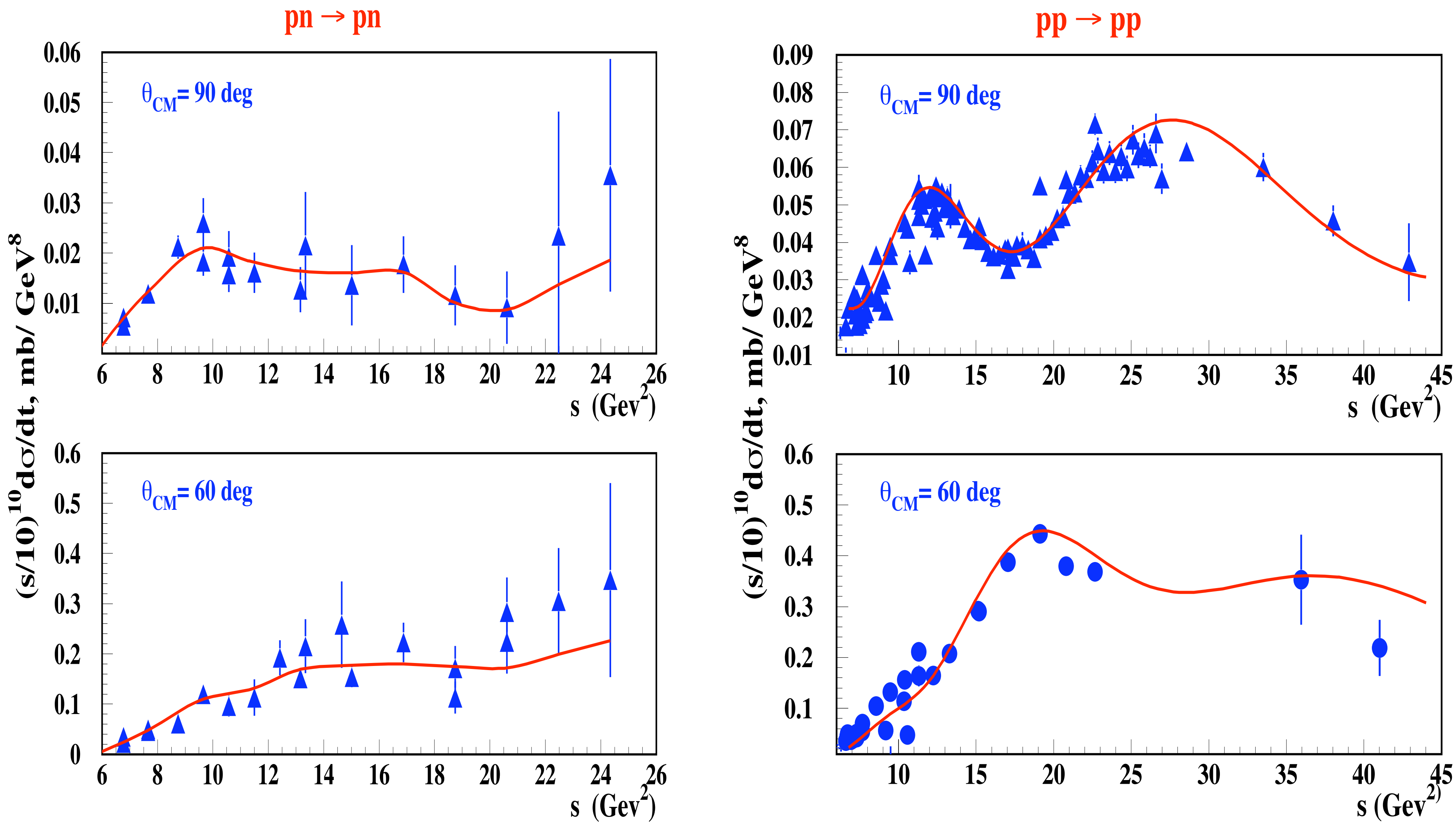


$$\gamma + d \rightarrow p + n$$

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



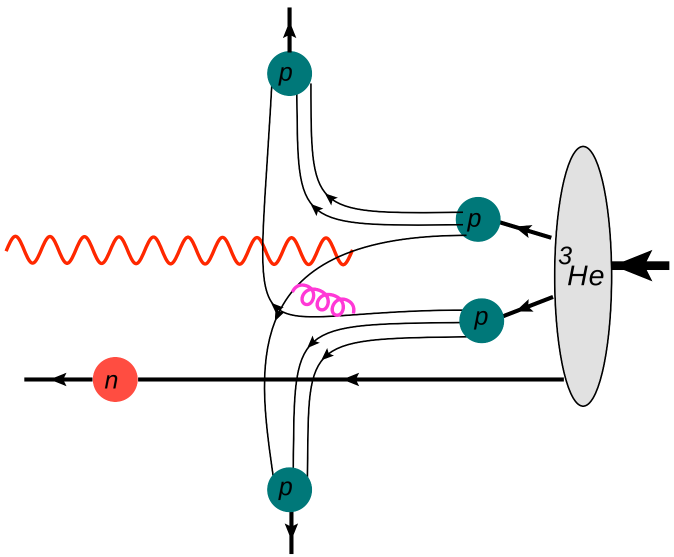


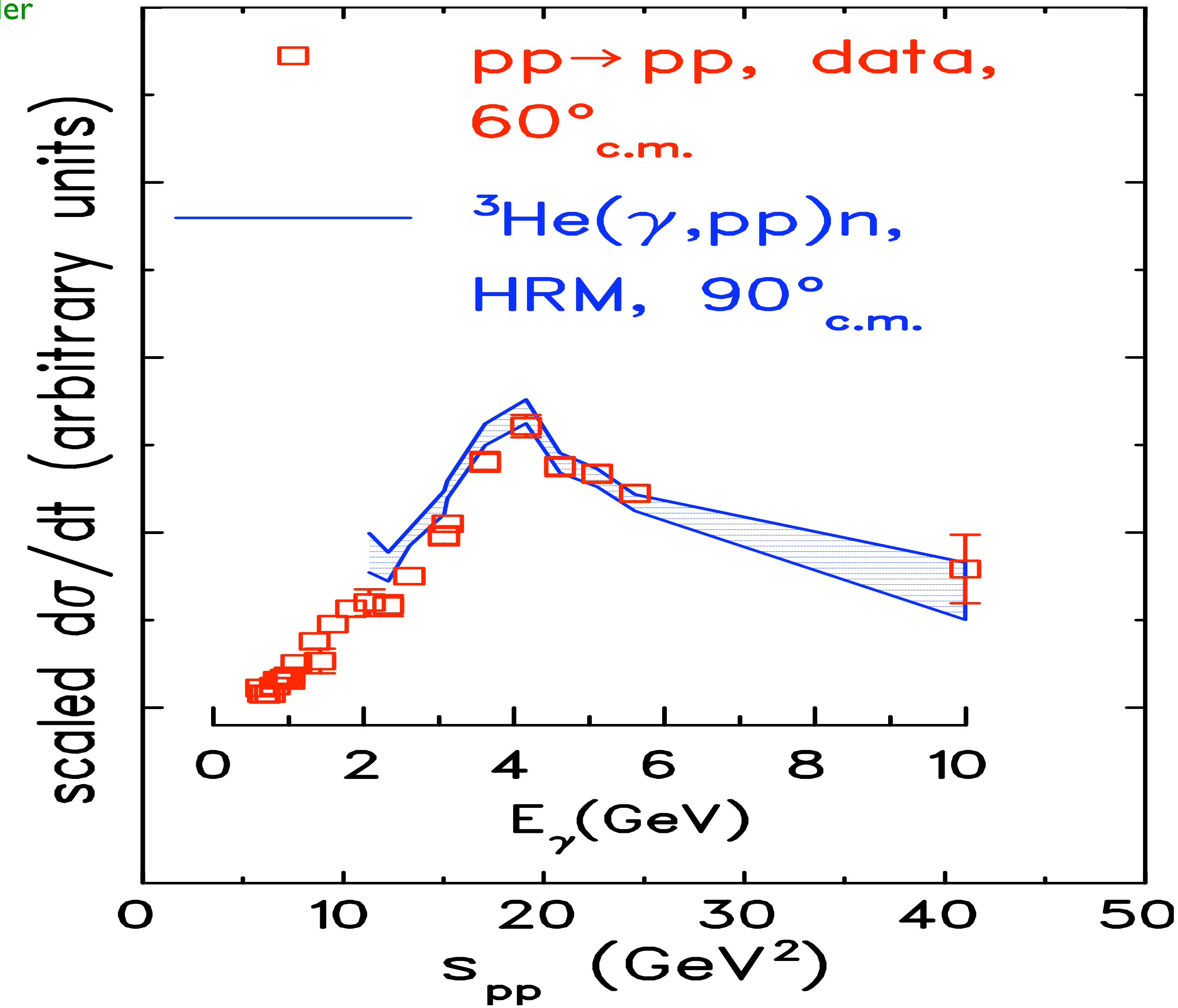


pn → pn
pp → pp
θCM= 90 deg
θCM= 60 deg
(s/10)^10 dσ/dt, mb/ GeV^8
s (Gev^2)

Break up of pp from Helium 3

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

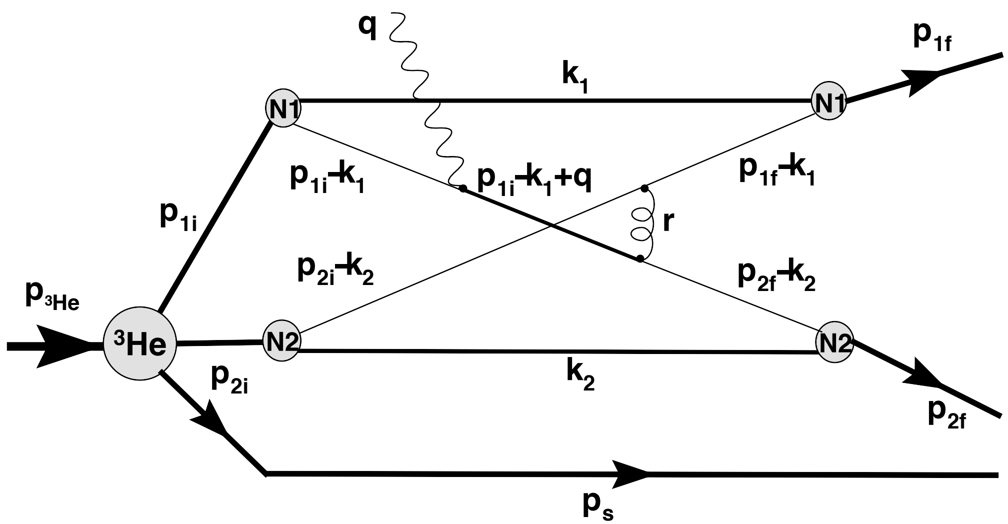




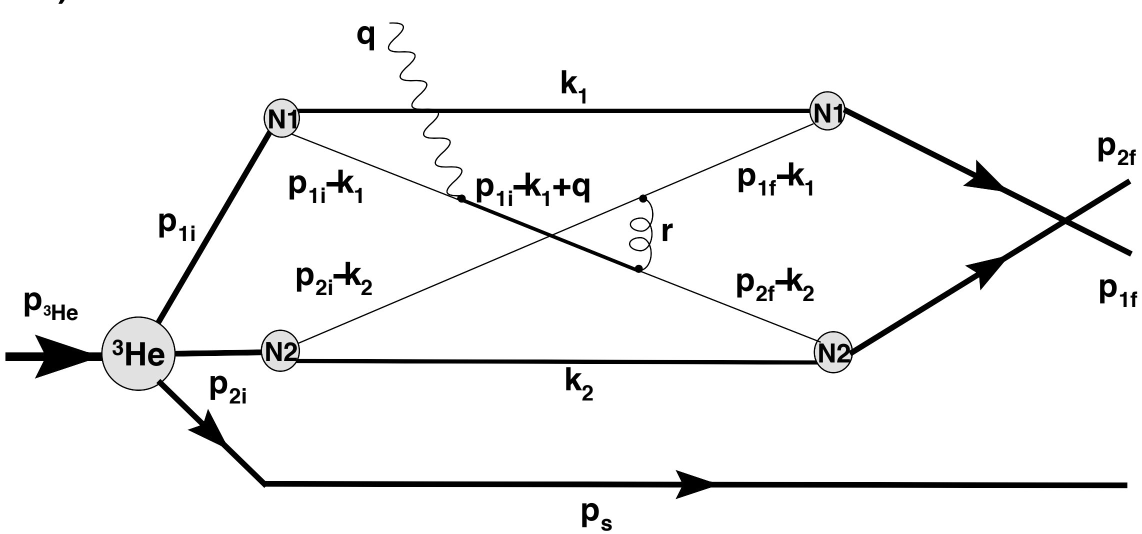
Considering $\gamma +^3 He \rightarrow (NN) + N$

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

a)



b)



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

$$
\langle \lambda_{1f}, \lambda_{2f}, \lambda_s \mid A \mid \lambda_\gamma, \lambda_A \rangle = \sum_{(\eta_{1f},\eta_{2f}),(\eta_{1i},\eta_{2i}),(\lambda_{1i},\lambda_{2i})} \int \Bigg\{ \frac{\psi_N^{\dagger \lambda_{2f},\eta_{2f}}(p_{2f}, x'_2, k_{2\perp})}{1-x'_2} \bar{u}_{\eta_{2f}}(p_{2f}-k_2)
$$

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

$$
\Bigg\{ \frac{\psi_N^{\dagger \lambda_{1f},\eta_{1f}}(p_{1f}, x'_1, k_{1\perp})}{1-x'_1} \bar{u}_{\eta_{1f}}(p_{1f}-k_1)[-igT_c^F\gamma^\mu] u_{\eta_{2i}}(p_{2i}-k_2) \frac{\psi_N^{\lambda_{2i},\eta_{2i}}(p_{2i}, x_2, k_{2\perp})}{(1-x_2)} \Bigg\}_2 \times
$$

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

$$\langle \lambda_{1f}, \lambda_{2f}, \lambda_s \mid M \mid \lambda_\gamma, \lambda_A \rangle = \frac{i[\lambda_\gamma] e \sqrt{2} (2\pi)^3}{\sqrt{2S'_{NN}}} \times$$
$$\Bigg\{ \sum_{\lambda_{2i}} \int Q_1 \langle \lambda_{2f}; \lambda_{1f} \mid T^{QIM}_{NN}(s_{NN}, t_N) \mid \lambda_\gamma; \lambda_{2i} \rangle \Psi^{\lambda_A}_{^3He,NR}(\vec{p}_1, \lambda_\gamma; \vec{p}_2, \lambda_{2i}; \vec{p}_s, \lambda_s) m_N \frac{d^2 p_\perp}{(2\pi)^2}$$
$$+ \sum_{\lambda_{1i}} \int Q_2 \langle \lambda_{2f}; \lambda_{1f} \mid T^{QIM}_{NN}(s_{NN}, t_N) \mid \lambda_{1i}; \lambda_\gamma \rangle \Psi^{\lambda_A}_{^3He,NR}(\vec{p}_1, \lambda_{1i}; \vec{p}_2, \lambda_\gamma; \vec{p}_s, \lambda_s) m_N \frac{d^2 p_\perp}{(2\pi)^2} \Bigg\} \quad (1)$$

$$\alpha = \frac{E_2 + p_{2z}}{M_A - E_s - p_{sz}}; \qquad p_\perp = \frac{p_{1\perp} - p_{2\perp}}{2},$$
$$\alpha_s = \frac{E_s + p_{sz}}{M_A}; \qquad \vec{p}_1 + \vec{p}_2 = -\vec{p}_s.$$

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

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

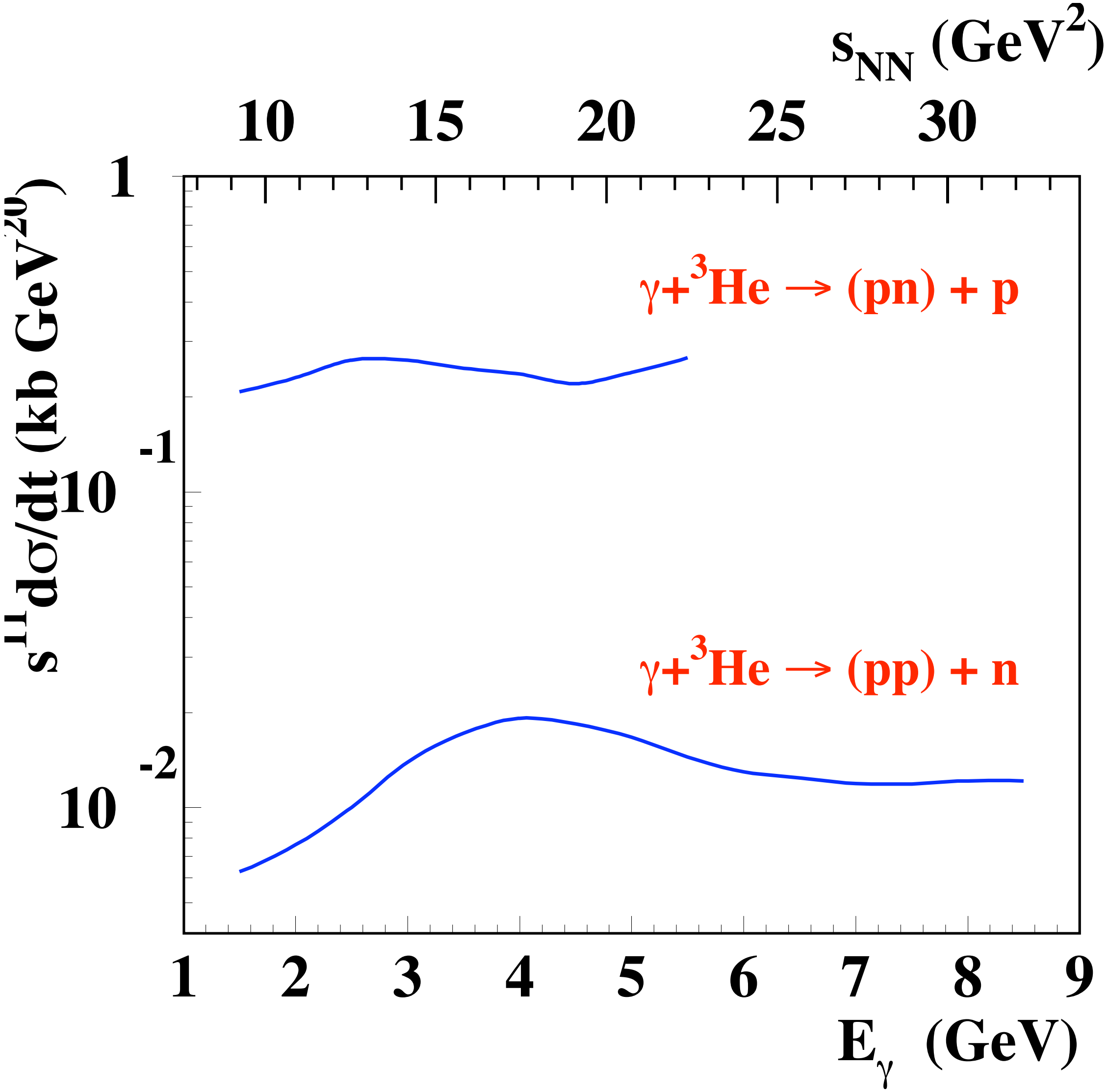
$$
Q_F = Q_1 + Q_2 = \frac{N_{uu}(Q_u + Q_u) + N_{dd}(Q_d + Q_d) + N_{ud}(Q_u + Q_d)}{N_{uu} + N_{dd} + N_{ud}}
$$

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

$\phi_3 \approx -\phi_4$ For pp

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

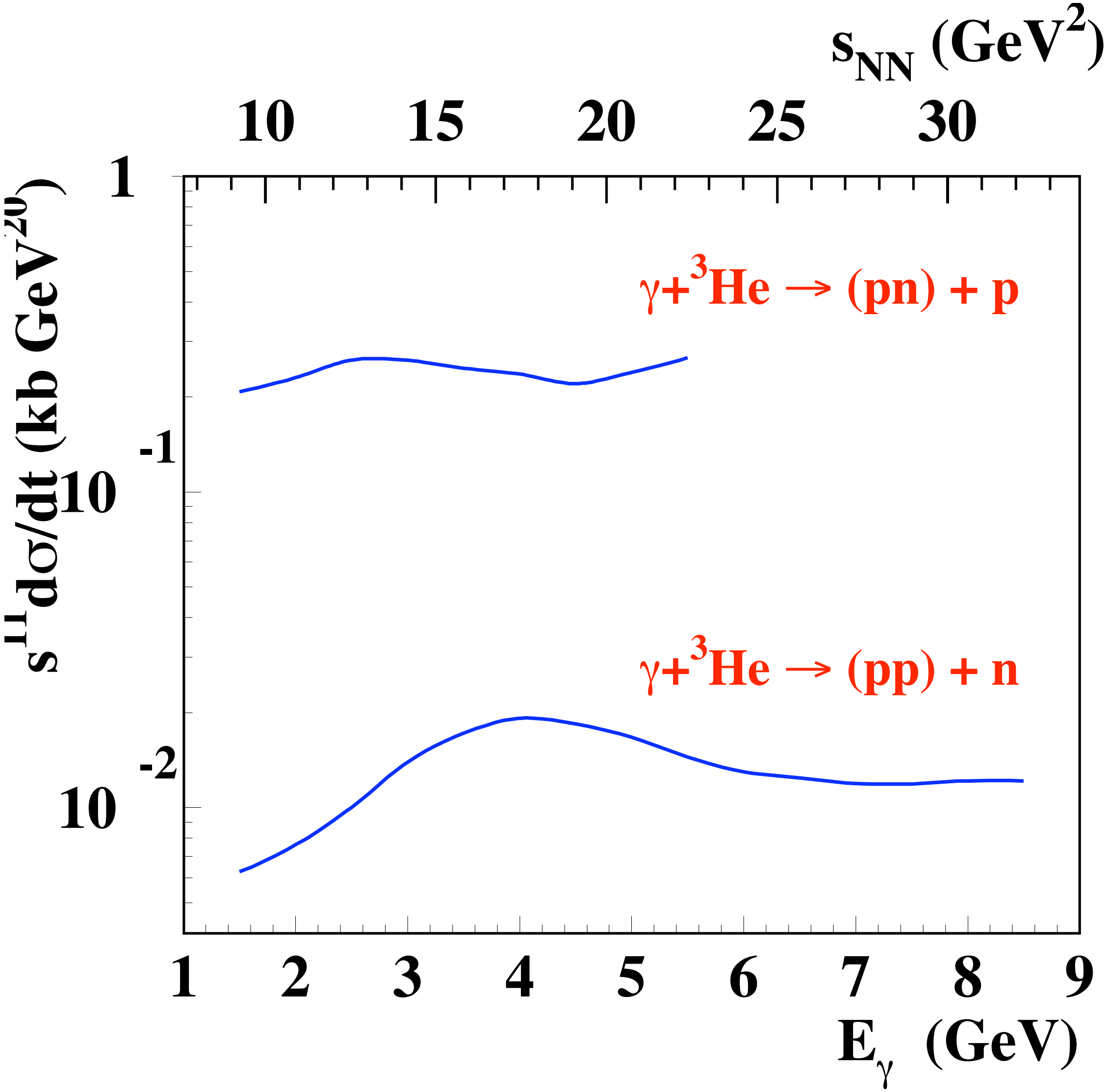
$$\beta = \frac{2(|\phi_3|-|\phi_4|)}{|\phi_1|}$$



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

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

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

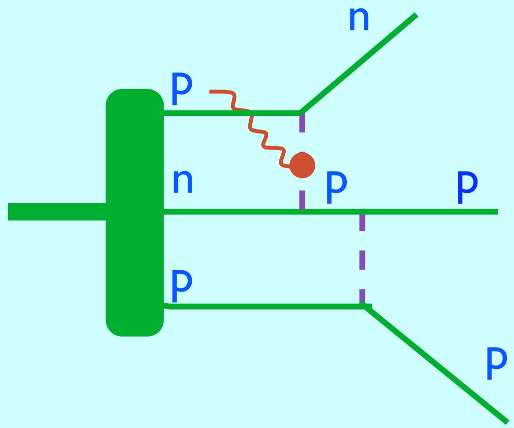


$$\frac{\sigma(\gamma^3He\to pp)}{\sigma(\gamma^3He\to pn)} \approx 0.1$$ at 4GeV

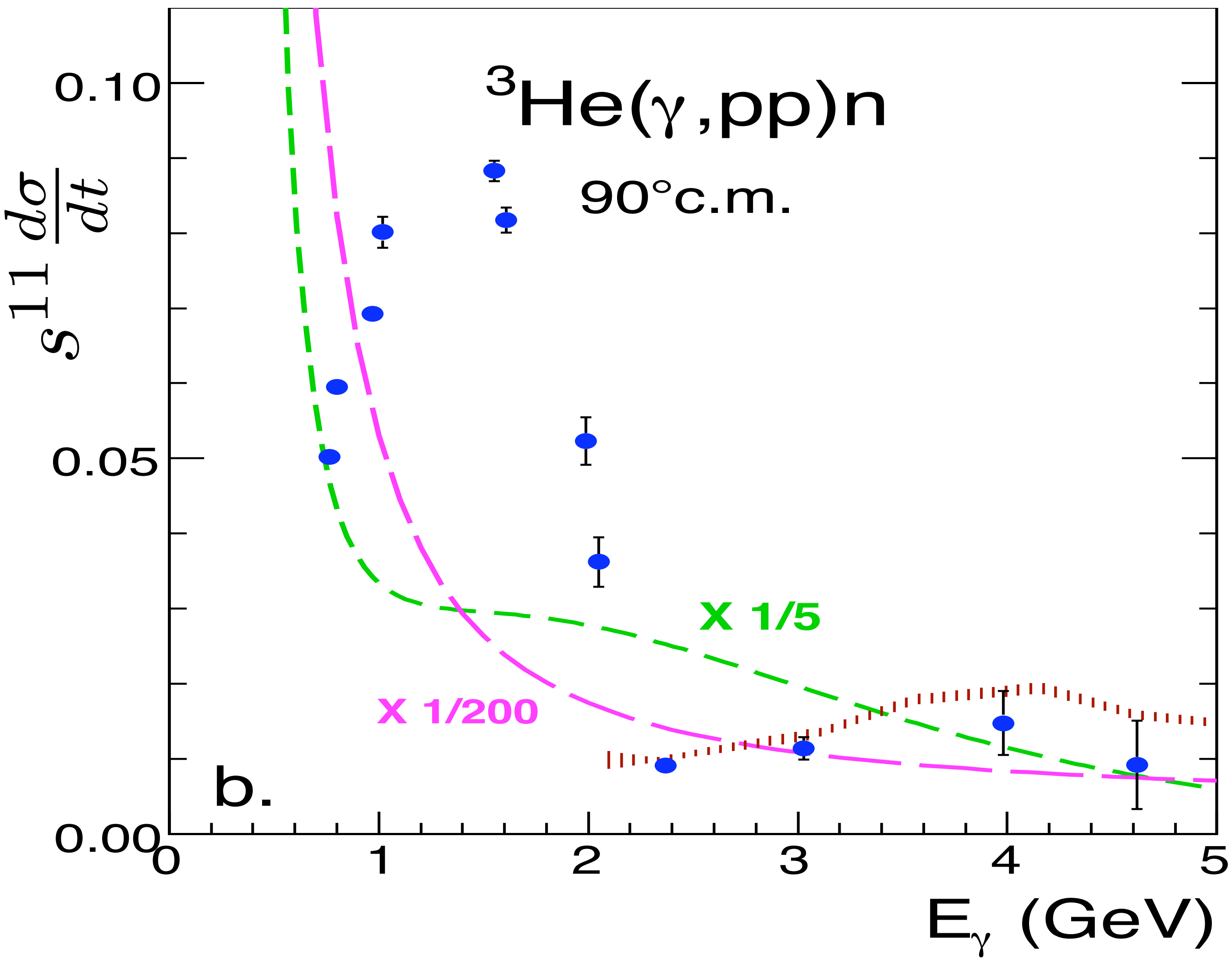
Meson Exchange Picture

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

J-M.Laget, Nucl.Phys. 1989

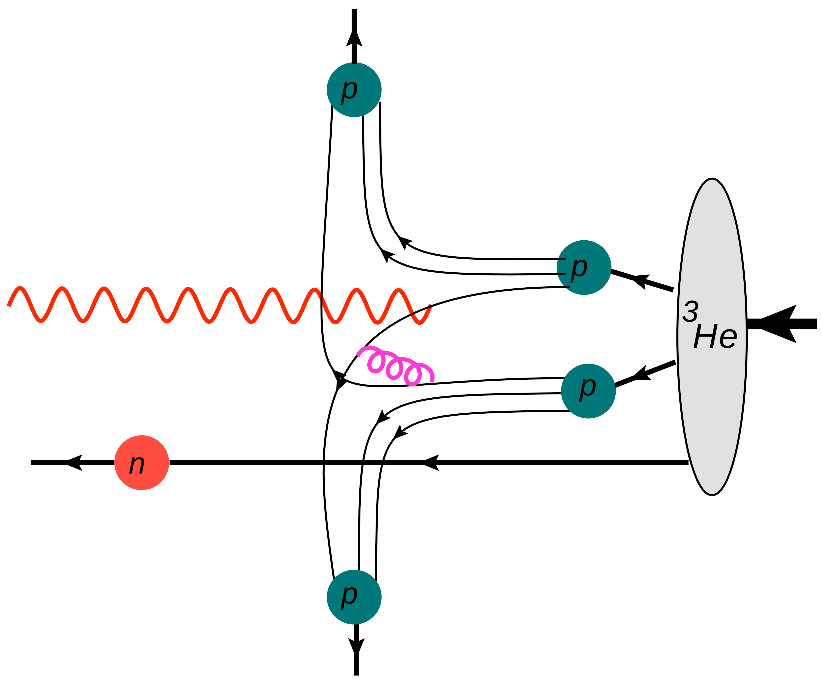


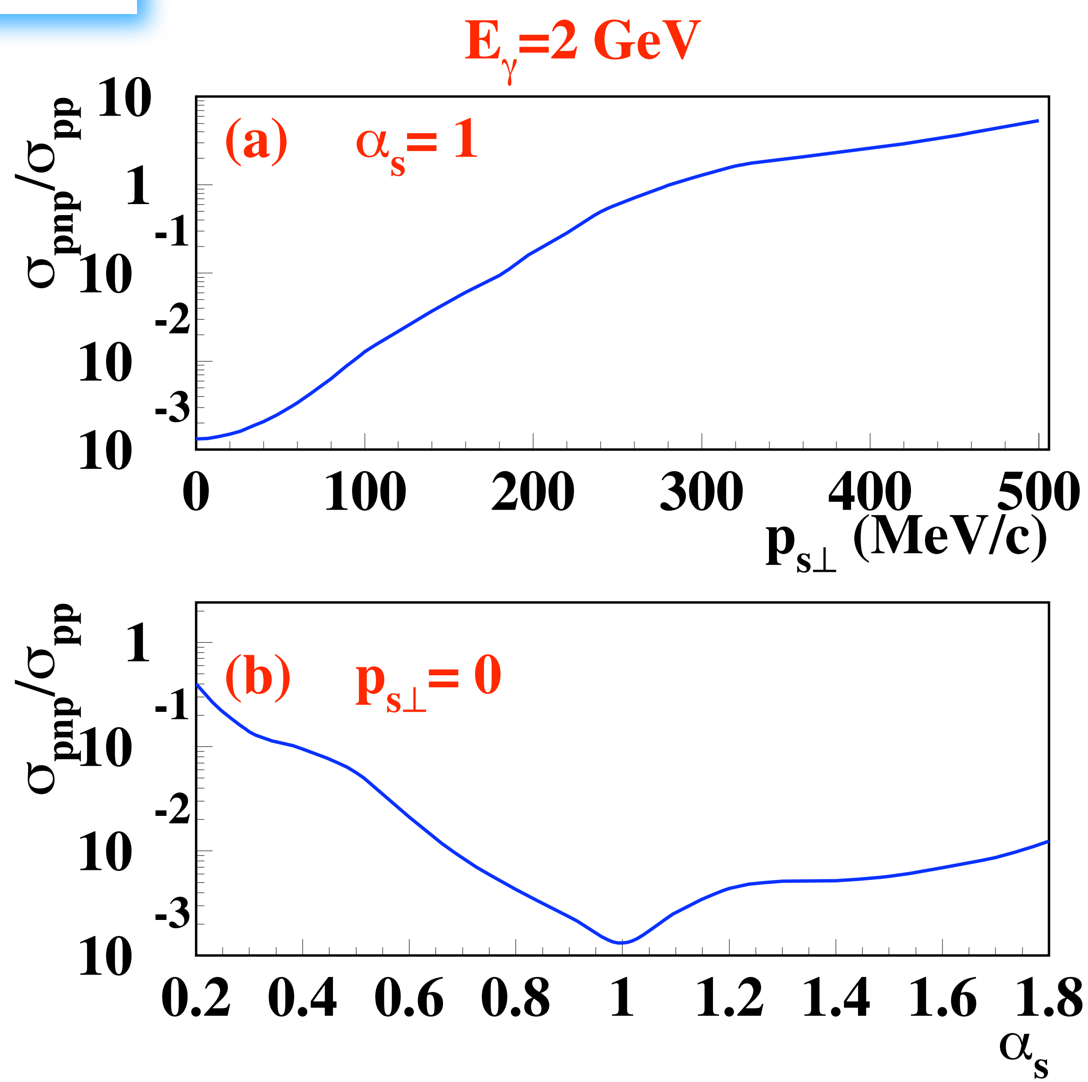
Pomerantz, et al,
Phys. Lett. B 2010



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

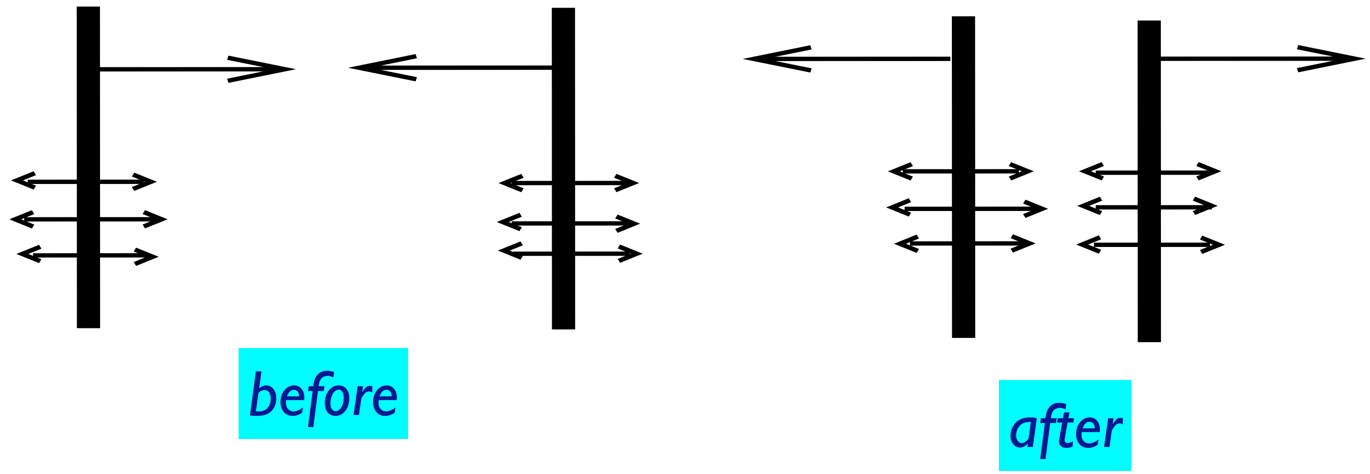
MS, C. Granados Phys. Rev. C, 2009

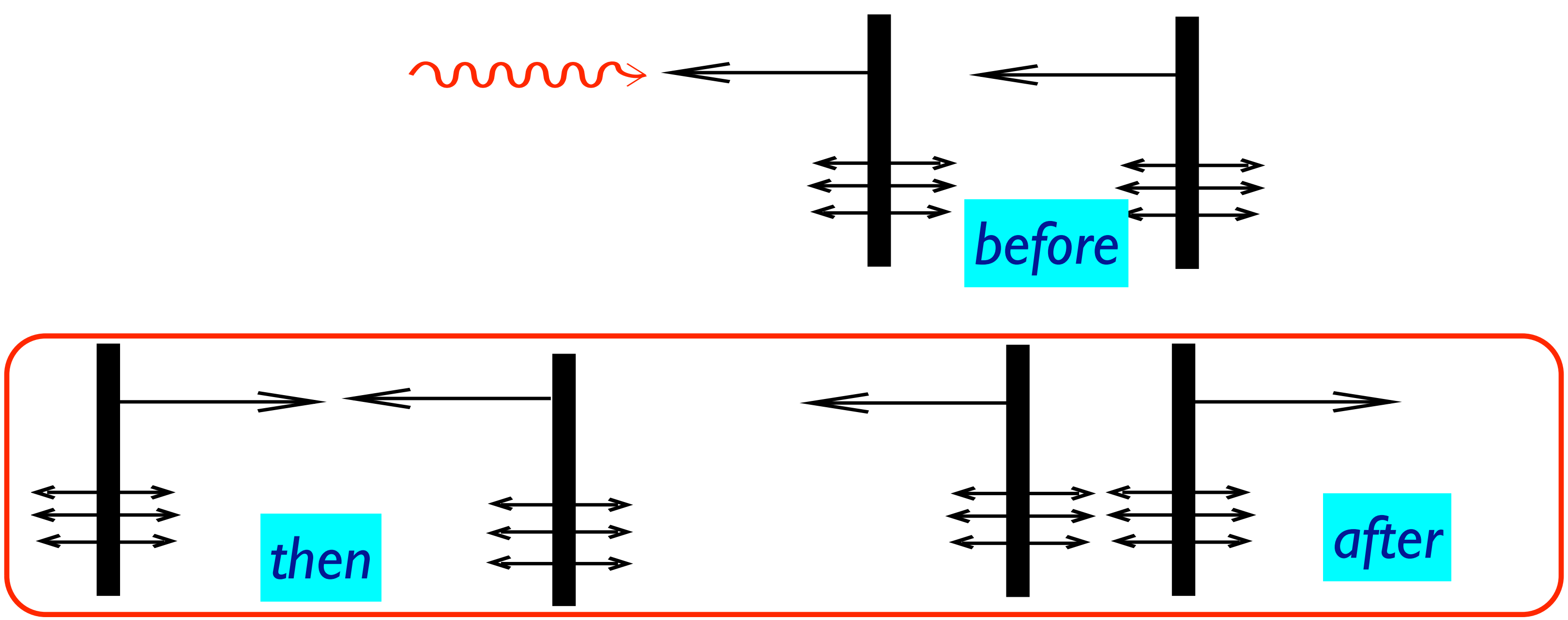




What's Next: Studying Hard Hadronic Processes

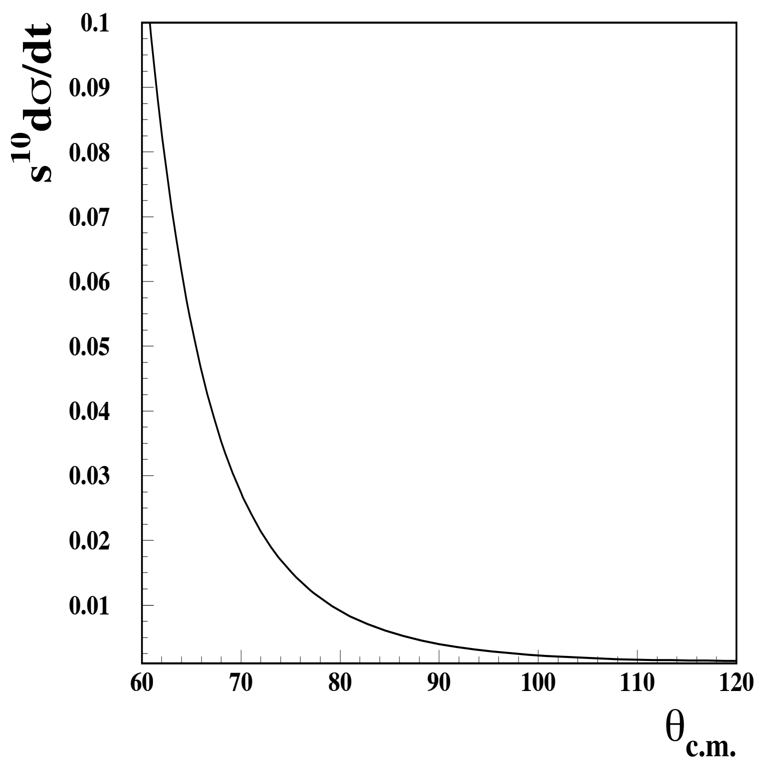
Baryon-Baryon Scattering





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

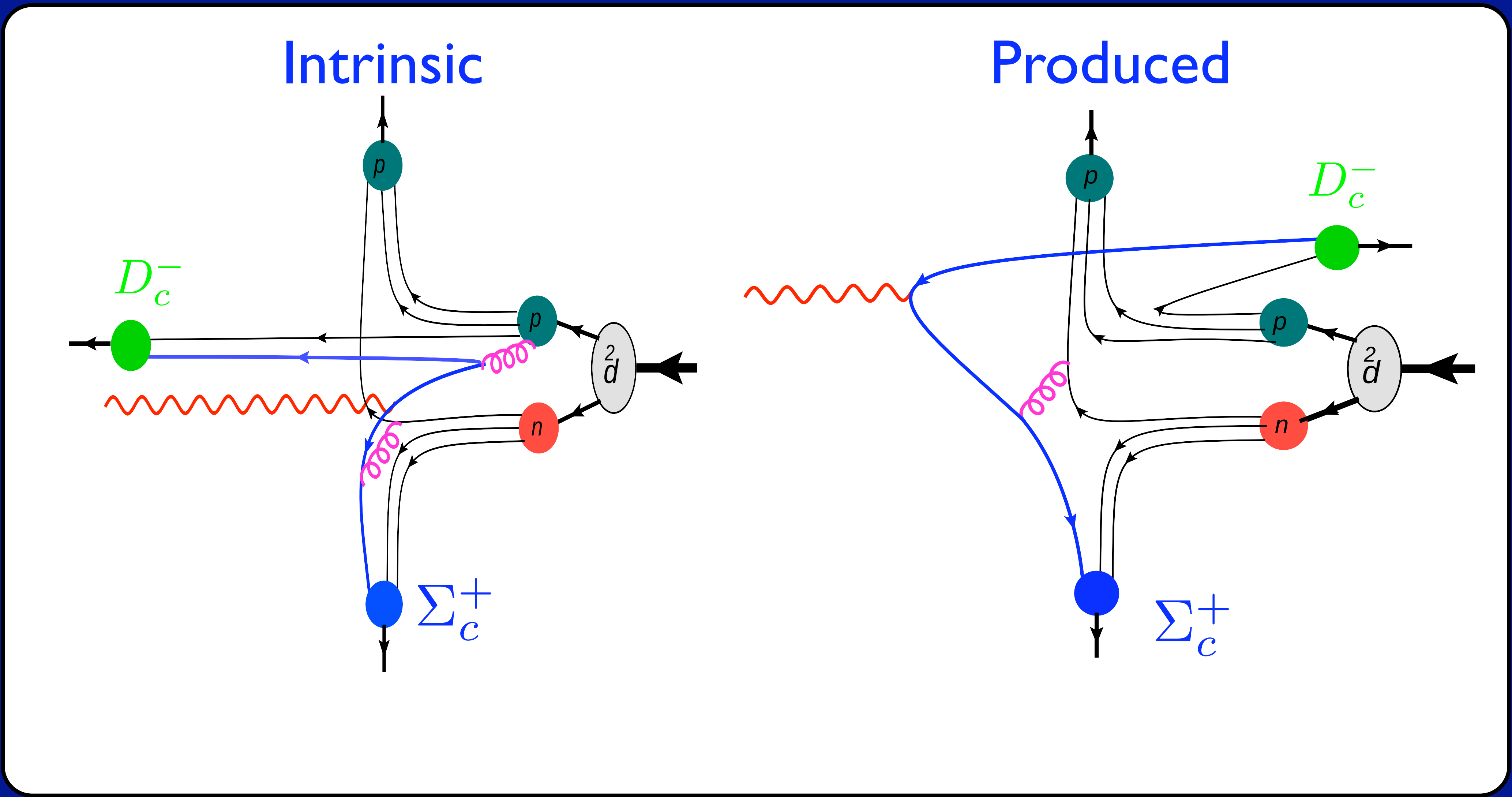
In the world where chiral symmetry is unbroken

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

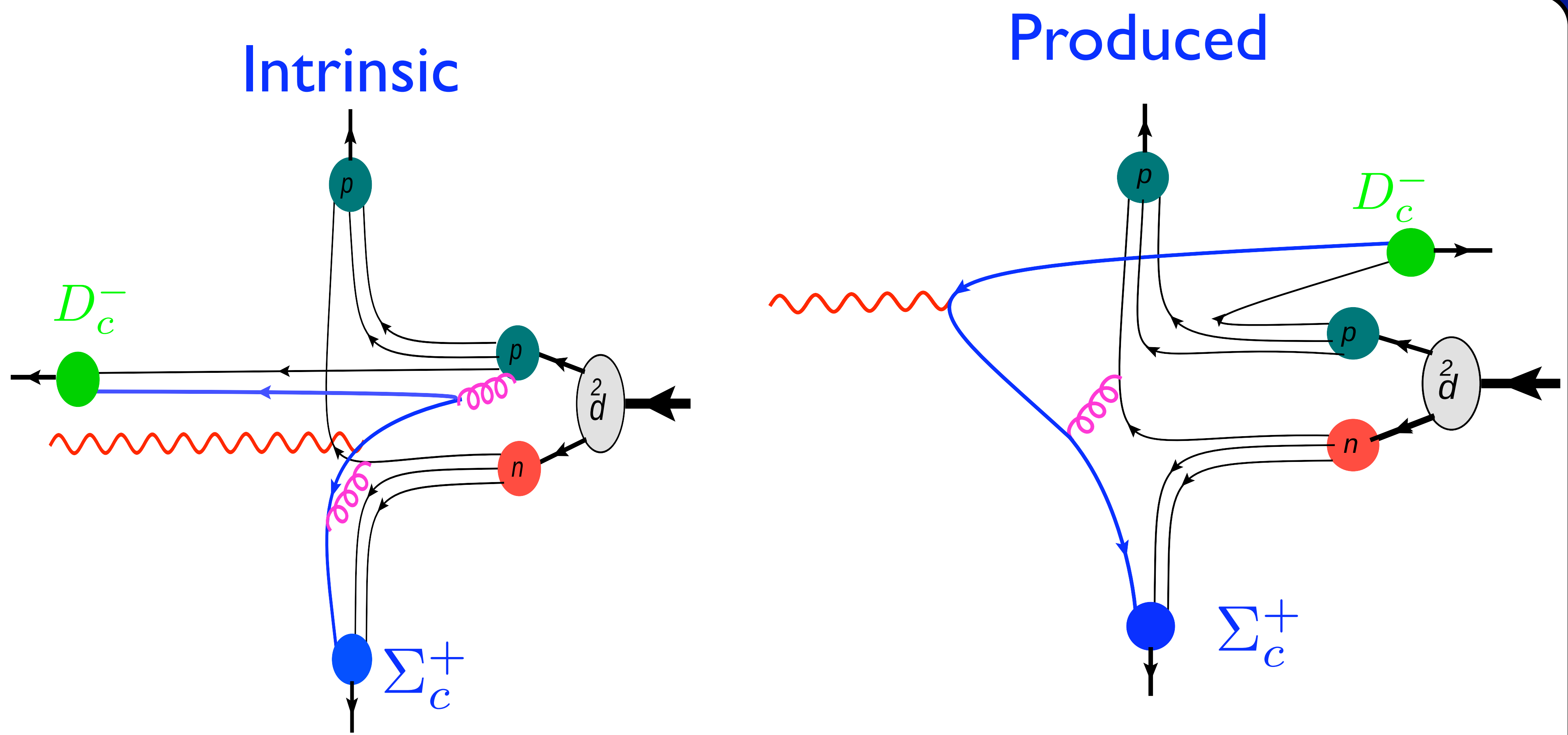
$$\frac{\sigma(\gamma d \rightarrow \Delta\Delta)}{\sigma(\gamma d \rightarrow pn)} \approx 1$$

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

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



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



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

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

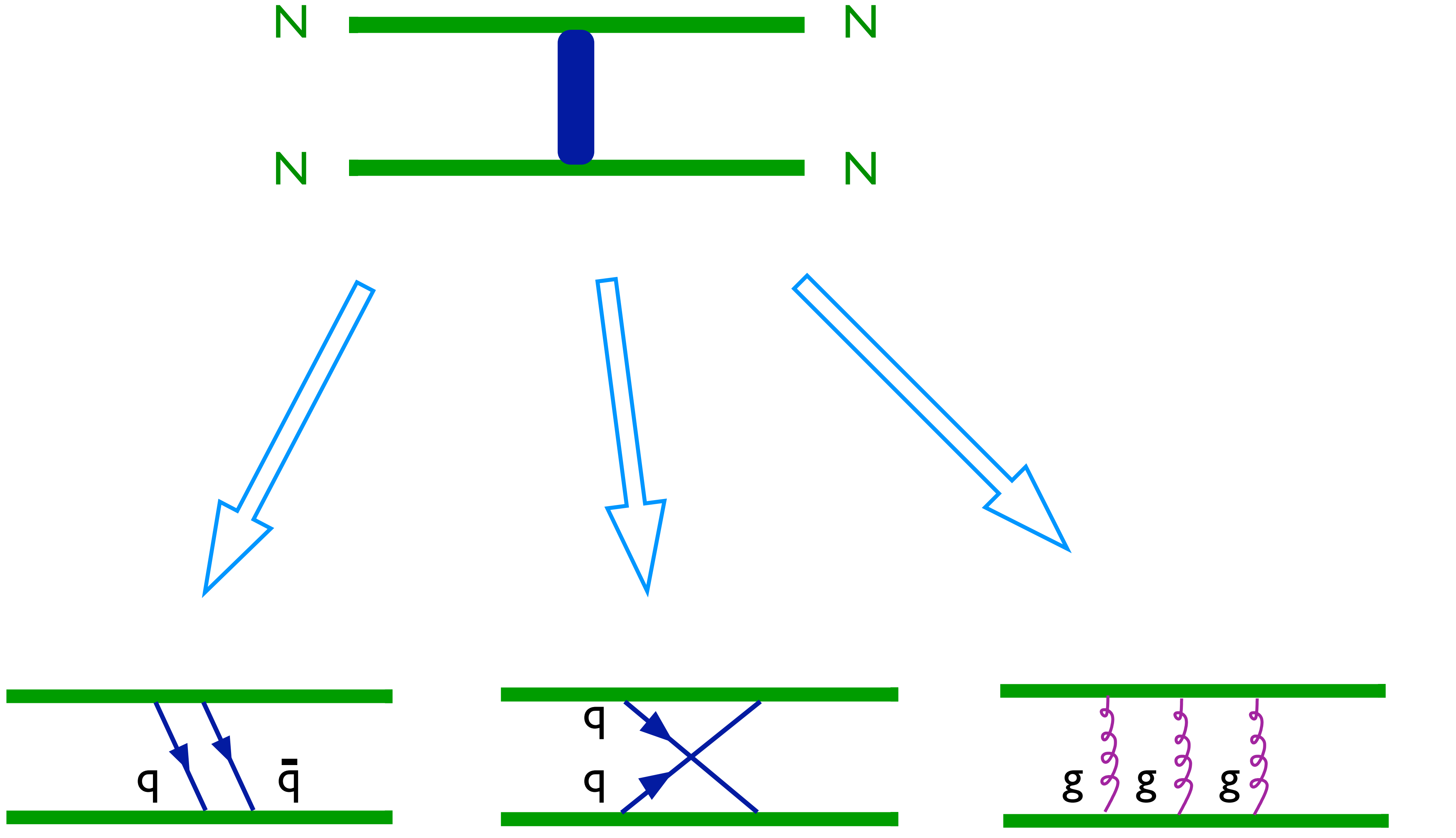
Outlook

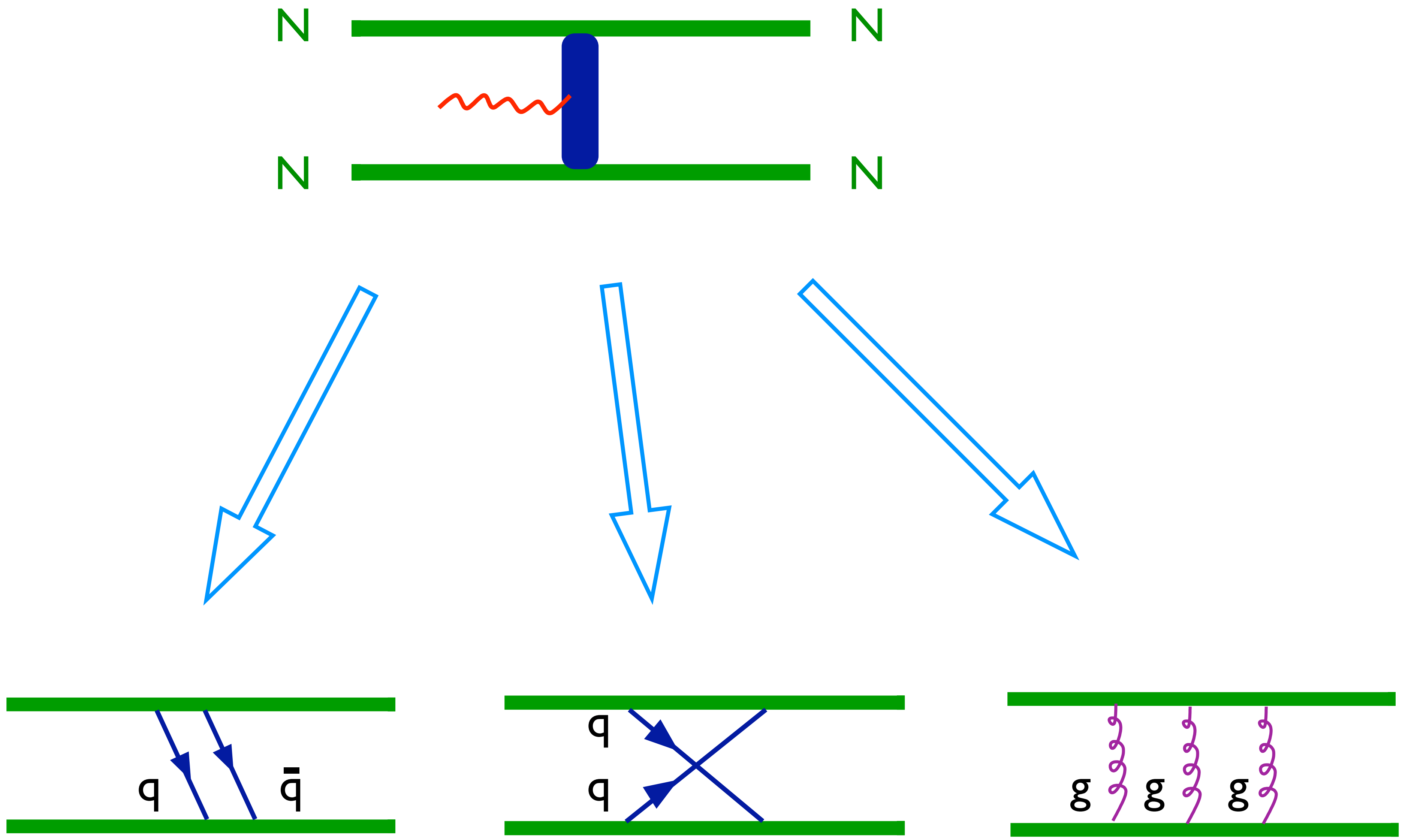
- (JLAB 4-6 GeV era) : Experimentally established adequacy of QCD degrees of freedom in hard break-up of light nuclei

- (JLAB 4-6 GeV era) : Hard Rescattering Mechanism consistent with major observations of the break-up reaction

- (JLAB 12 GeV era) : Studying Hard Rescattering Mechanism of break up of light nuclei into baryonic resonances (including strangeness production)

- (EIC era) : Using/Studying Hard Rescattering Mechanism for probing quark/gluon content of NN syste


N
N
N
N
q
q̄
q
q
g
g
g


N
N
N
N
q
q̄
q
q
g
g
g