Color Transparency & Hadronization Studies with the Deuteron

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Future of Color Transparency and Hadronization Studies at Jlab & Beyond
Online June 7-8, 2021

Two components of Color Transparency

(1) Formation of small size color neutral configurations (PLC)

- *Feynman Mechanism*
- *Q2 are not large enough for PLC formation*

(2) Evolution (Expansion) of PLCs to Normal Hadrons

- *Rate of expansion*
  how fast, instantaneous ?

CT Observables

- Diminished Interaction of PLC in the Nuclear Environment

- *(current) Diminished absorption of PLC in the nuclear medium*

- *(new) Diminished cross section dominated by PLC-Nucleon Rescattering*

- Reaction Processes Studied so Far Focused on Observing Diminished Absorption with Increase of Q2(current)

- *A(e,e′p)X,* $A(e,e'\pi)X,\ A(e,e'\rho)X$

- *Problem is in dealing with nuclei A>4*

- Suggestion is to study Diminished Cross Section (new)

- *In d(e,e′p)n reaction dominated by Final State Interaction*

- *Advantage is in dealing with deuteron*

Frankfurt, Greenberg, Miller, MS, Strikman
PLB1996, Z.Phys A 1995

CT Subprocesses

Quasi-Elastic Exclusive Processes

- (current) ep->ep, eN-> eρN, ep-> eπN

- (new) Deep Inelastic eN-> eX

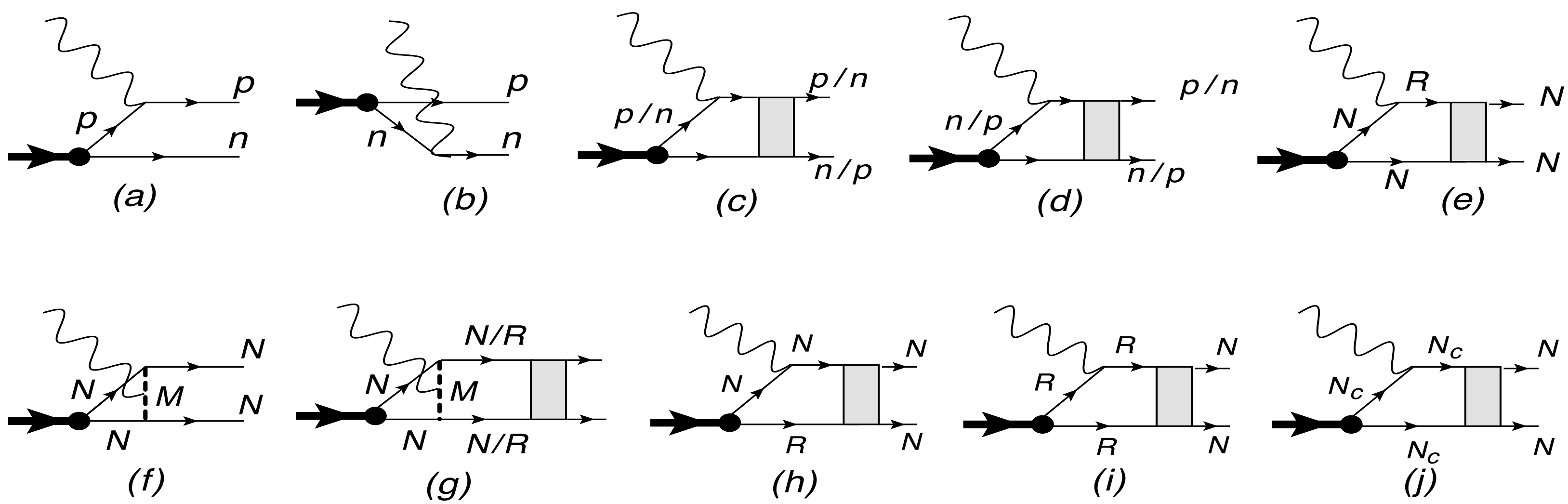
W. Cosyn, & MS
IJMPE 2017 & Phys. Rev. C 2011

- (new) Deep Inelastic eN-> e, meson,X,.. hadronization

Theory of Deuteron Electro-disintegration at large Q2

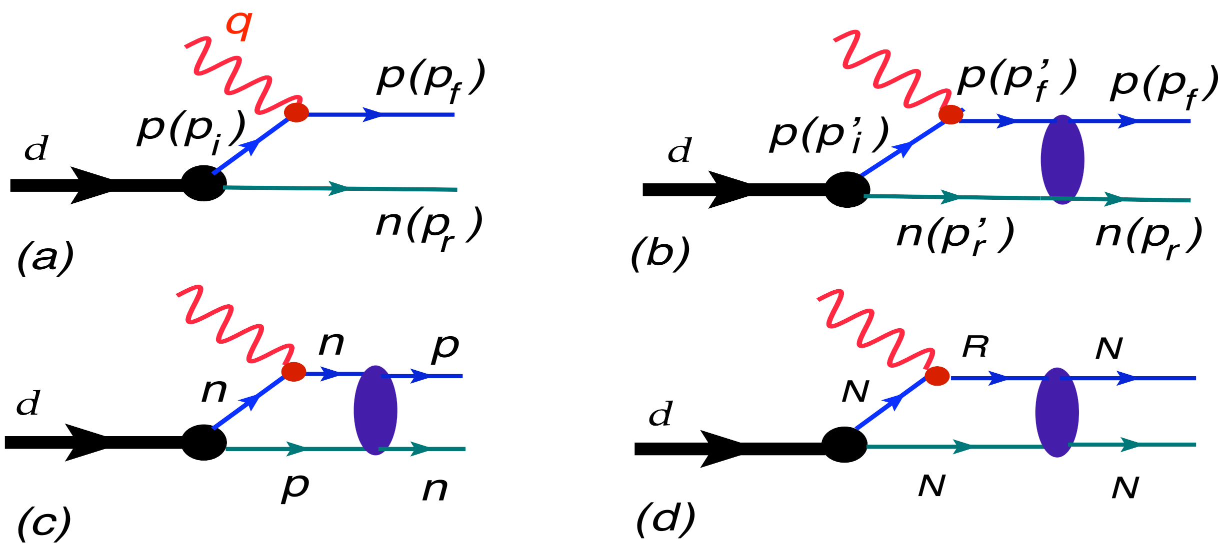
Considering a reaction $e + d \rightarrow e' + p + n$

In knock-out kinematics: One of the nucleon (p) takes almost all the transferred momentum and the other is recoil



“Modern Studies of the Deuteron”
W. Boeglin, & MS IJMPE 2015

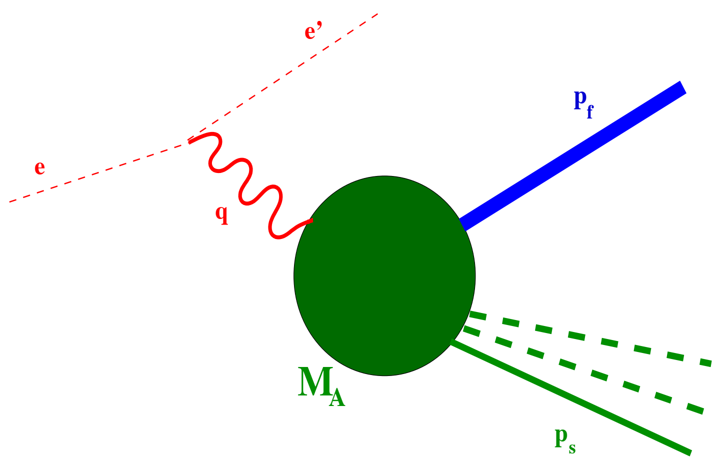
In high momentum transfer limit: $Q^2 > 1\text{-}2\ GeV^2$



MS, Phys. Rev C 2010

Generalized Eikonal Approximation at large Q2, 1997-2010

Theory of High Energy eA Scattering:



High Energy Approximations:

$$|\vec{q}| = q_3 \sim p_{f3} \gg p \sim M_N$$

$$Q^2 \geq few \quad \mathrm{GeV}^2$$

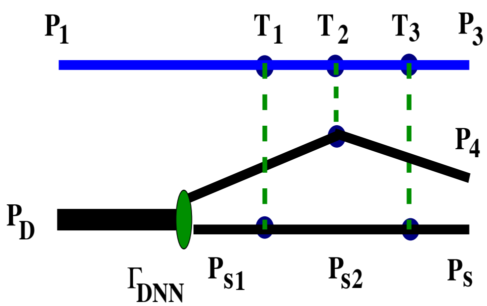
Both for QE/DIS

- Emergence of the small parameter

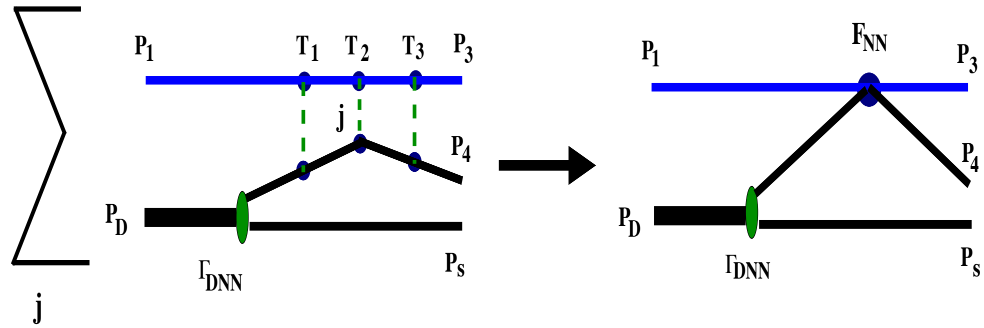
$$\frac{q_-}{q_+} = \frac{q_0 - q_3}{q_0 + q_3} \ll 1 \qquad \mathcal{O}(\frac{q_-}{q_+})$$

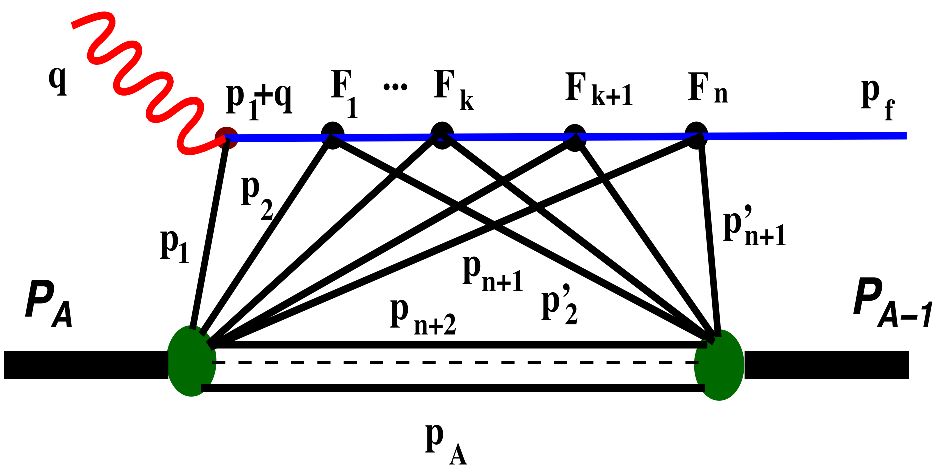
$$\frac{p_{f-}}{p_{f+}} = \frac{E_f - p_{f3}}{E_f + p_{f3}} \ll 1 \qquad \mathcal{O}(\frac{p_{f-}}{p_{f+}})$$

Emergence of "effective" theory



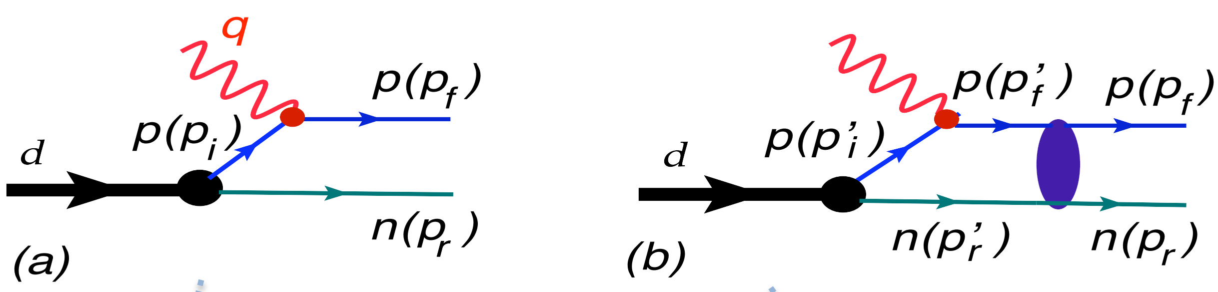
$\mathcal{O}\left(\frac{p_{1-}}{p_{1+}}\right)$





Effective Feynman
Diagrammatic Rules

M.S. IJMS 2001

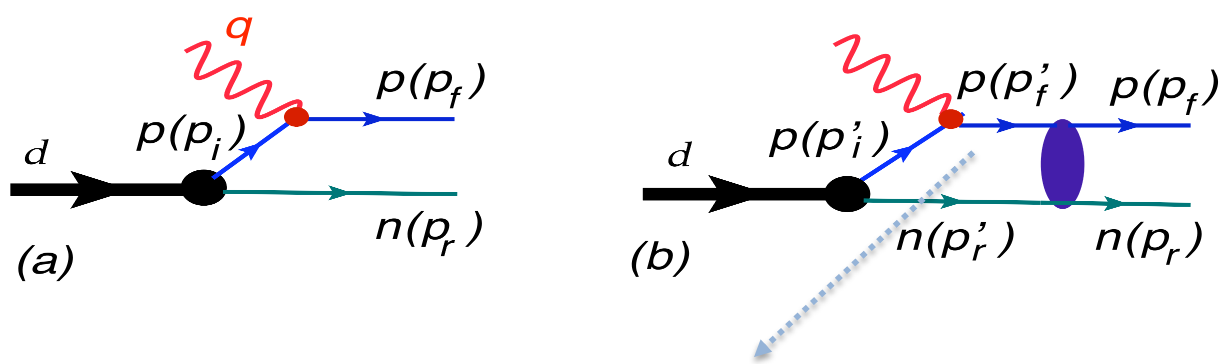


$$\langle s_f, s_r \mid A_0^\mu \mid s_d\rangle = -\bar{u}(p_r, s_r)\Gamma^\mu_{\gamma^* p}\frac{\not{p}_i + m}{p_i^2 - m^2}\cdot \bar{u}(p_f, s_f)\Gamma_{DNN}\cdot \chi^{s_d}$$

$$\langle s_f, s_r \mid A_1^\mu \mid s_d\rangle \quad = \quad -\int \frac{d^4 p'_r}{i(2\pi)^4}\frac{\bar{u}(p_f, s_f)\bar{u}(p_r, s_r)F_{NN}[\not{p}'_r + m][\not{p}_d - \not{p}'_r + \not{q} + m]}{(p_d - p'_r + q)^2 - m^2 + i\epsilon}$$
$$\times \frac{\Gamma_{\gamma^* N}[\not{p}_d - \not{p}'_r + m]\Gamma_{DNN}\chi^{s_d}}{((p_d - p'_r)^2 - m^2 + i\epsilon)(p'^2_r - m^2 + i\epsilon)}$$

$$\Psi_d^{s_d}(s_1, p_1, s_2, p_2) = -\frac{\bar{u}(p_1, s_1)\bar{u}(p_2, s_2)\Gamma^{s_d}_{DNN}\chi_{s_d}}{(p_1^2 - m^2)\sqrt{2}\sqrt{(2\pi)^3(p_2^2 + m^2)^{\frac{1}{2}}}}$$

In high momentum transfer limit: **$Q^2 > 1\text{-}2\ \mathrm{GeV}^2$**



MS, Phys. Rev C 2010

$$(q + p_d - p_r)^2 = p_f^2 = m^2$$

$$(p_d - p'_r + q)^2 - m^2 + i\epsilon = 2|\mathbf{q}|(p'_{r,z} - p_{r,z} + \Delta + i\epsilon),$$

$$\Delta = \frac{q_0}{|\mathbf{q}|}(E_r - E'_r) + \frac{M_d}{|\mathbf{q}|}(E_r - E'_r) + \frac{p'^2_r - m^2}{2|\mathbf{q}|}.$$

$$\frac{1}{(p'_{r,z} - p_{r,z} + \Delta + i\epsilon} = -i\pi\delta(p'_{r,z} - (p_{r,z} - \Delta)) + \mathcal{P}\int \frac{1}{p'_{r,z} - (p_{r,z} - \Delta)}$$

$$\langle s_f, s_r \mid A_0^\mu \mid s_d \rangle = \sqrt{2}\sqrt{(2\pi)^3 2E_r} \sum_{s_i} J_N^\mu(s_f, p_f; s_i, p_i) \Psi_d^{s_d}(s_i, p_i, s_r, p_r)$$

$$\langle s_f, s_r \mid A_1^\mu \mid s_d \rangle = \frac{i\sqrt{2}(2\pi)^{\frac{3}{2}}}{4} \sum_{s'_f, s'_r, s_i} \int \frac{d^2 p'_r}{(2\pi)^2} \frac{\sqrt{2\tilde{E}'_r}\sqrt{s(s-4m^2)}}{2\tilde{E}'_r |q|} \times$$

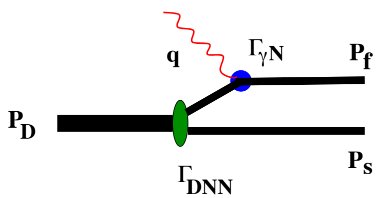
$$\langle p_f, s_f; p_r, s_r \mid f^{NN,on}(t,s) \mid \tilde{p}'_r, s'_r; \tilde{p}'_f, s'_f \rangle \cdot J_N^\mu(s'_f, p'_f; s_i, \tilde{p}'_i) \cdot \Psi_d^{s_d}(s_i, \tilde{p}'_i, s'_r, \tilde{p}'_r)$$

$$-\frac{\sqrt{2}(2\pi)^{\frac{3}{2}}}{2} \sum_{s'_f, s'_r, s_i} \mathcal{P} \int \frac{dp'_{r,z}}{2\pi} \int \frac{d^2 p'_r}{(2\pi)^2} \frac{\sqrt{2E'_r}\sqrt{s(s-4m^2)}}{2E'_r |\mathbf{q}|} \times$$

$$\frac{\langle p_f, s_f; p_r, s_r \mid f^{NN,off}(t,s) \mid p'_r, s'_r; p'_f, s'_f \rangle}{p'_{r,z} - \tilde{p}'_{r,z}} J_N^\mu(s'_f, p'_f; s_i, p'_i) \cdot \Psi_d^{s_d}(s_i, p'_i, s'_r, p'_r)$$

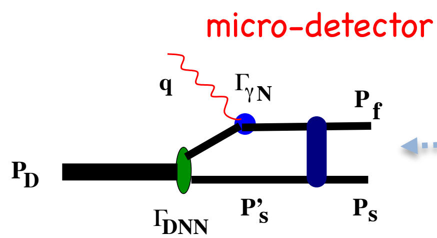
Some Results: $e + d \to e' + p + n$

Frankfurt, M.S., Strikman, PRC 1997



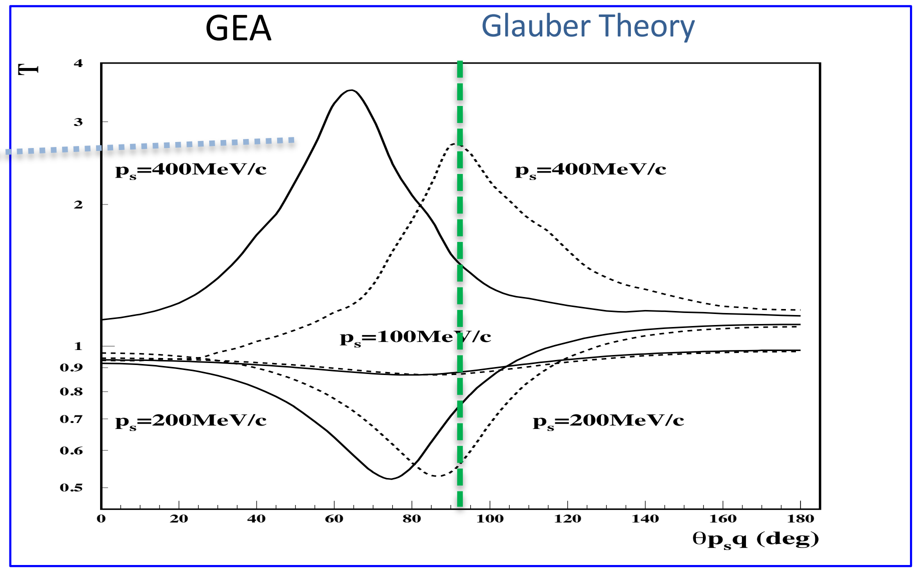
(a)

A_0^μ



(b)

A_1^μ

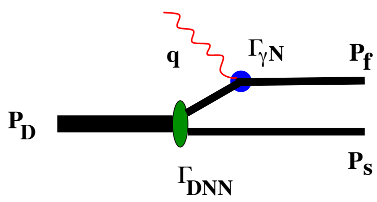


$$A^\mu = A_0^\mu + A_1^\mu$$

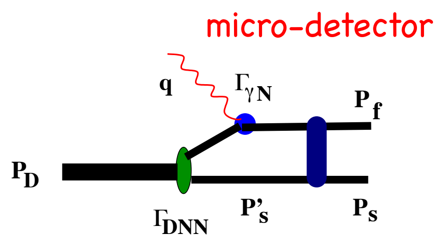
$$A^{\nu\dagger} A^\mu = A_0^{\nu\dagger} A_0^\mu - A_0^{\mu\dagger} Im A_1^\mu - Im A_1^{\mu\dagger} A_0^\mu + A_1^{\nu\dagger} A_1^\mu$$

Some Results: $e + d \rightarrow e' + p + n$

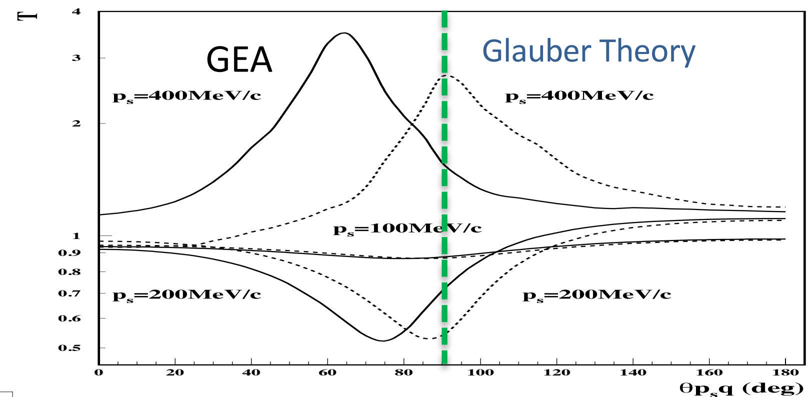
Frankfurt, M.S., Strikman, PRC 1997



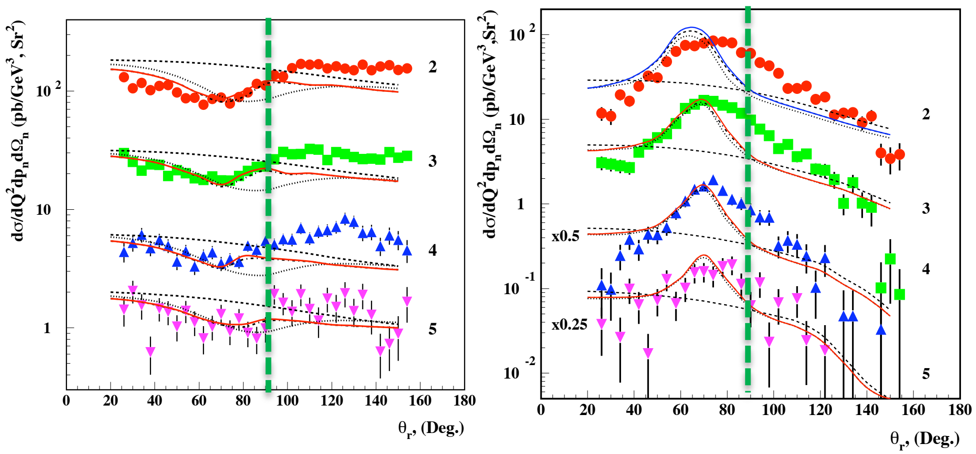
(a)



(b)

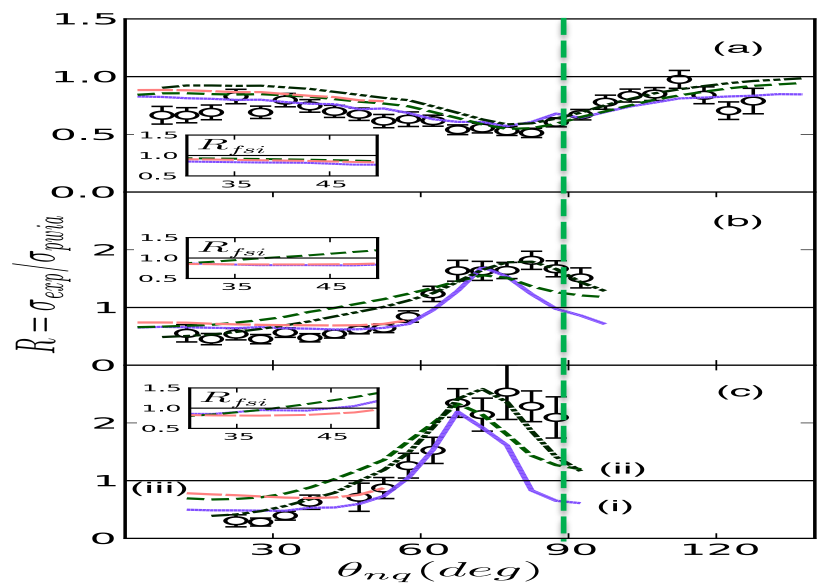


K. Egiyan et al PRL 2008



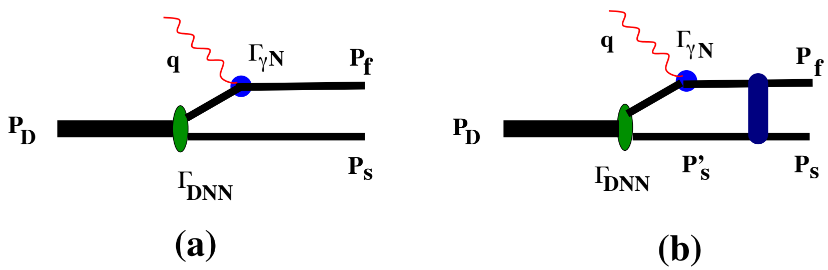
M.Sargsian, PRC 2010

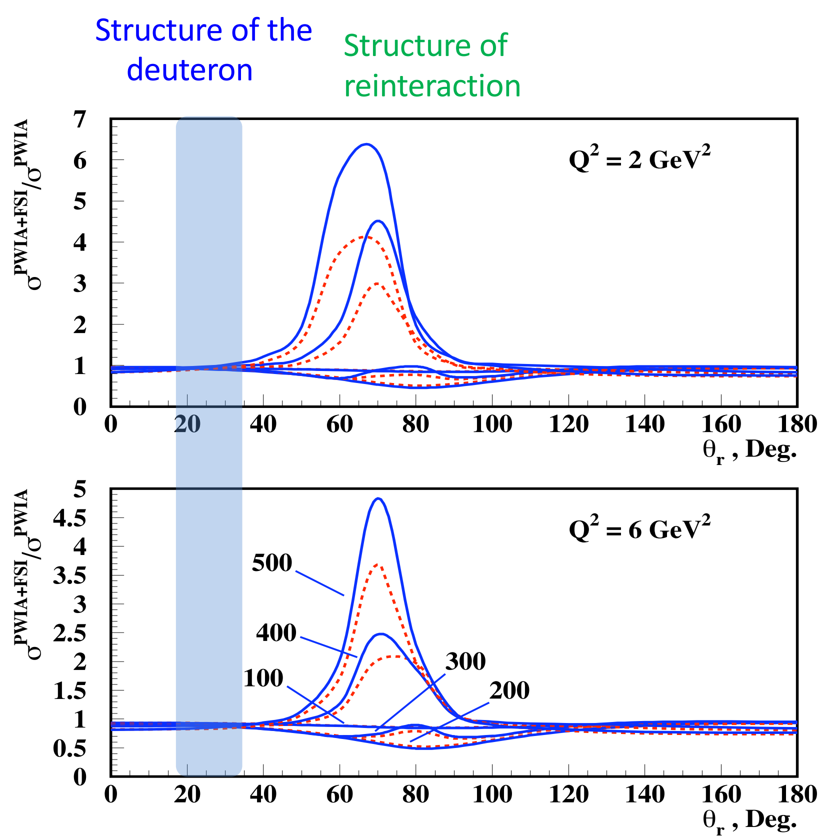
W. Boeglin et al PRL 2011



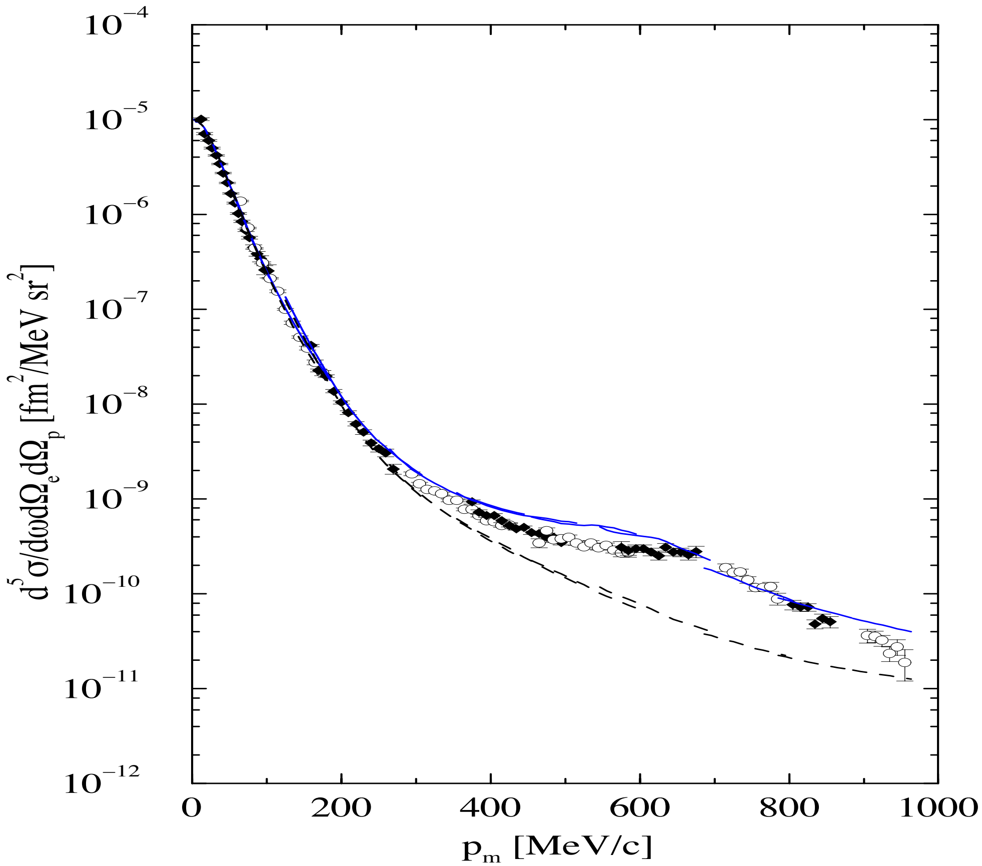
Some Results: $e + d \to e' + p + n$

Probing Short Distance Structure of the Deuteron

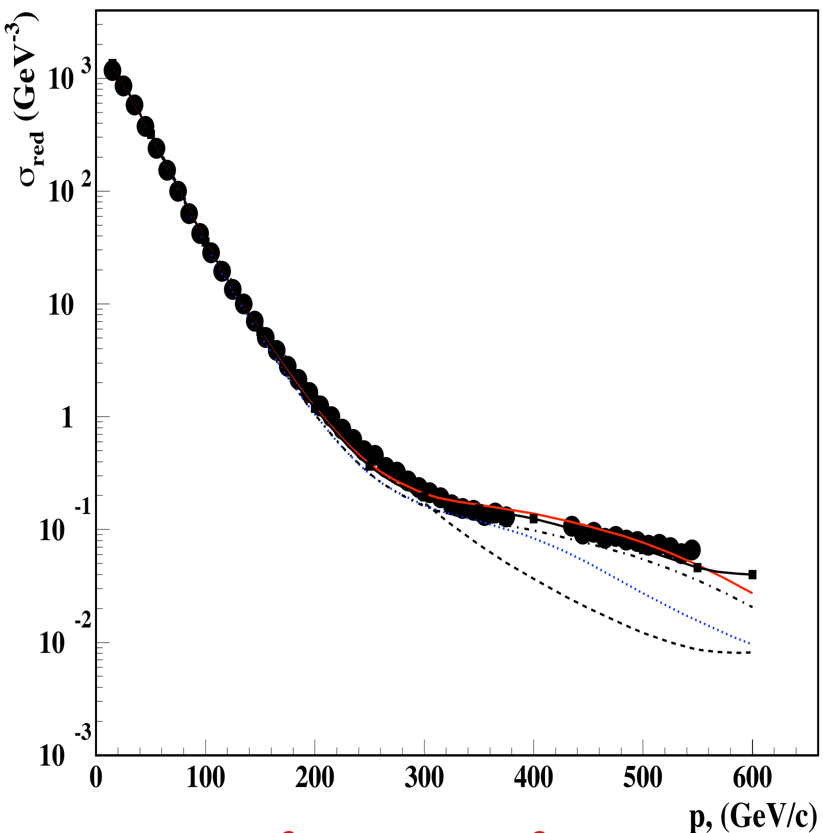




Impossibility to Probe Deuteron at Small Distances at low Q^2

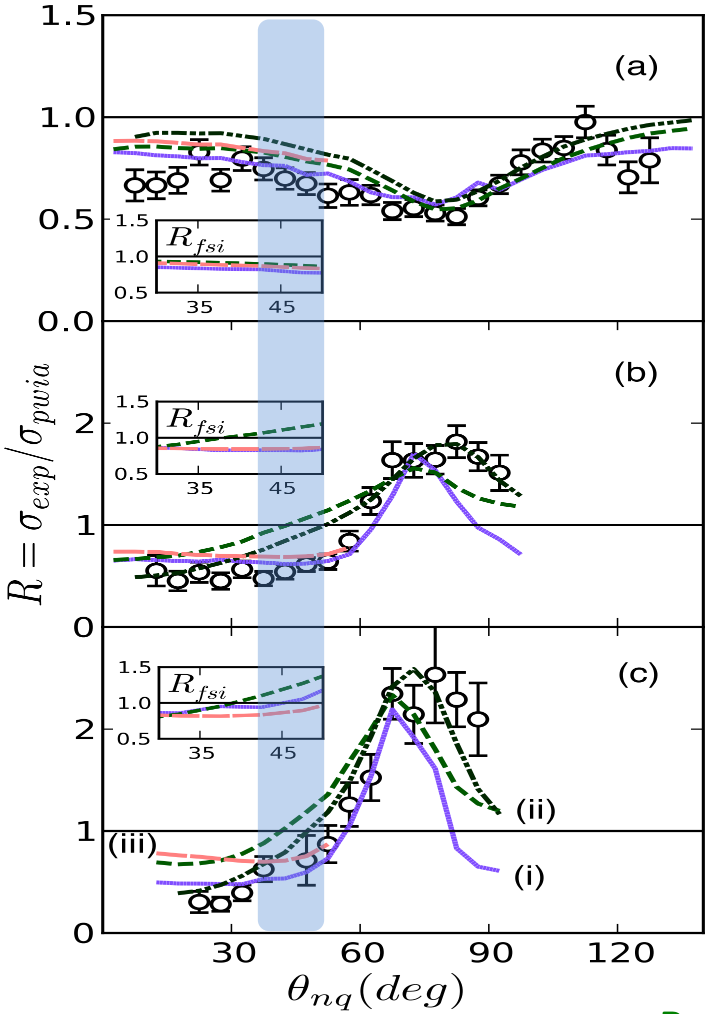


Mainz, $Q^2 = 0.33$ GeV^2



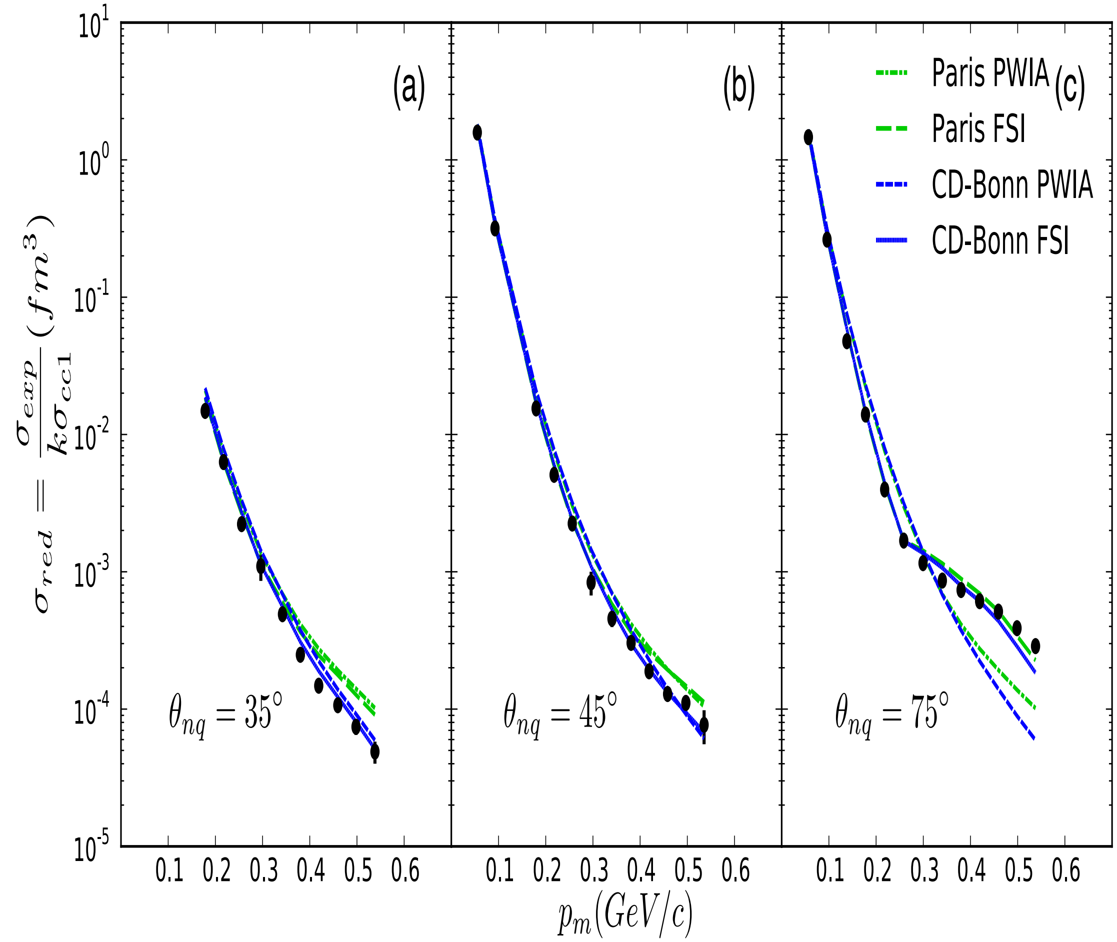
JLab, $Q^2 = 0.66$ GeV^2

Probing Deuteron at Small Distances at large Q^2



JLab, $Q^2 = 3.5\ GeV^2$

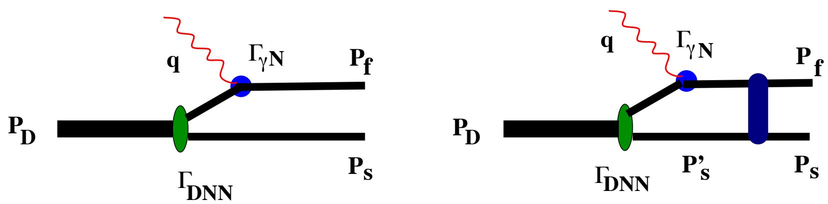
M.Sargsian, PRC 2010



Boeglin et al PRL 2011, deuteron probed at up to 550MeV/c

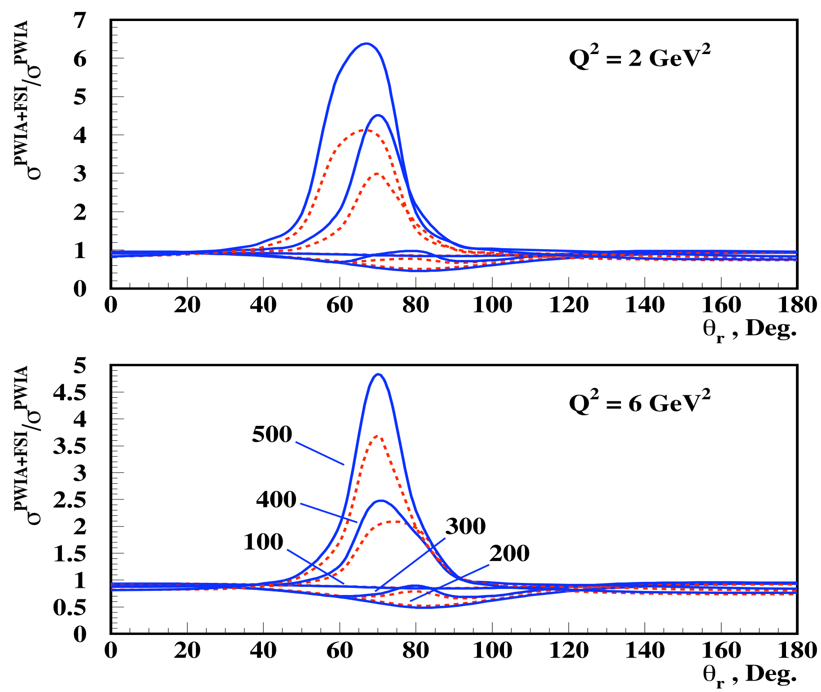
Some Results: $e + d \to e' + p + n$

Probing Rescattering:
Double Scattering as a tool to study
Color Transparency



(a) (b)

(1) *Larger momentum of spectator nucleon chooses shorter distances between production and rescattering vertices*

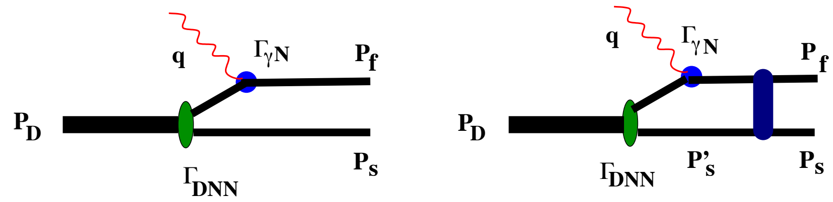


Observable

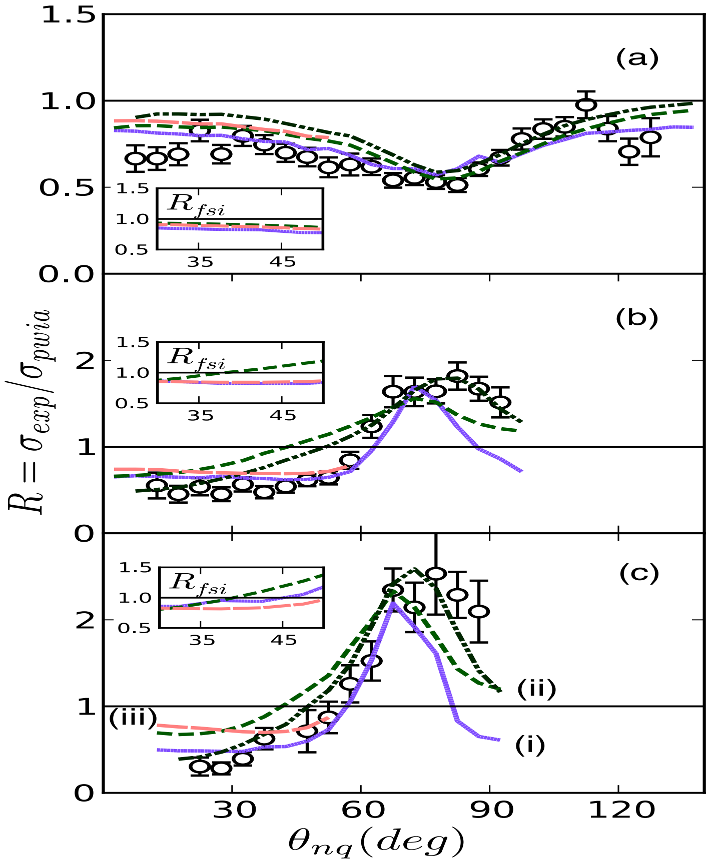
(2) $$\downarrow R = \frac{\sigma(p_r = 400 MeV/c)\downarrow}{\sigma(p_r = 200 MeV/c)\uparrow}$$

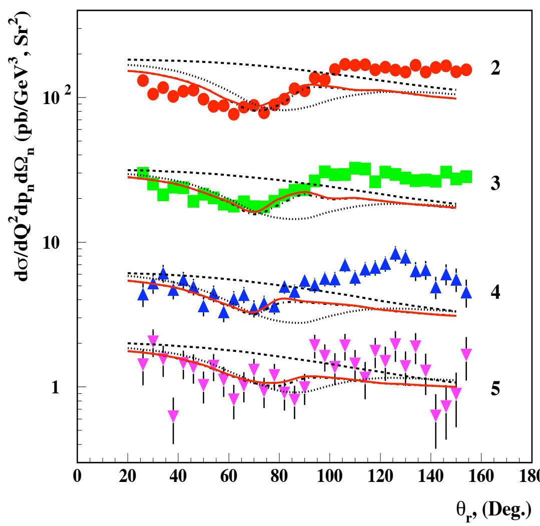
Greenberg, Frankfurt, Miller, MS, Strikman, Z.Phys A 1995

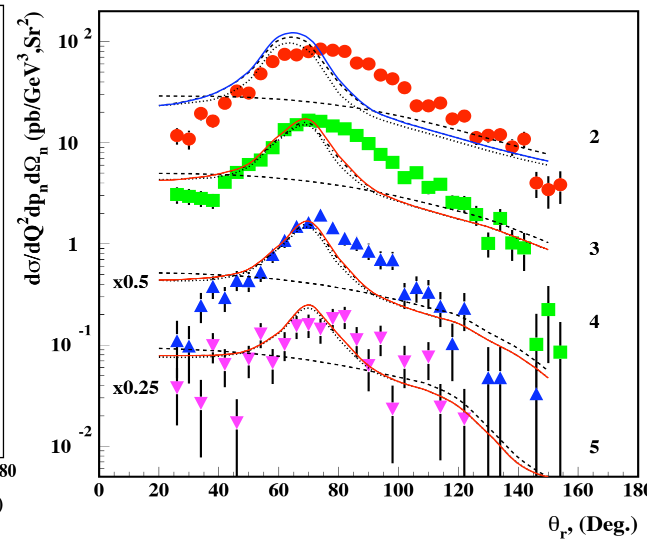
$e + d \to e' + p + n$ CT in Double Scattering



(a) (b)

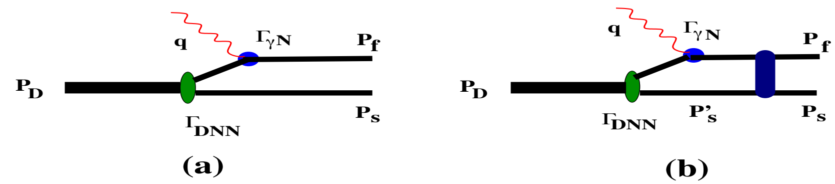






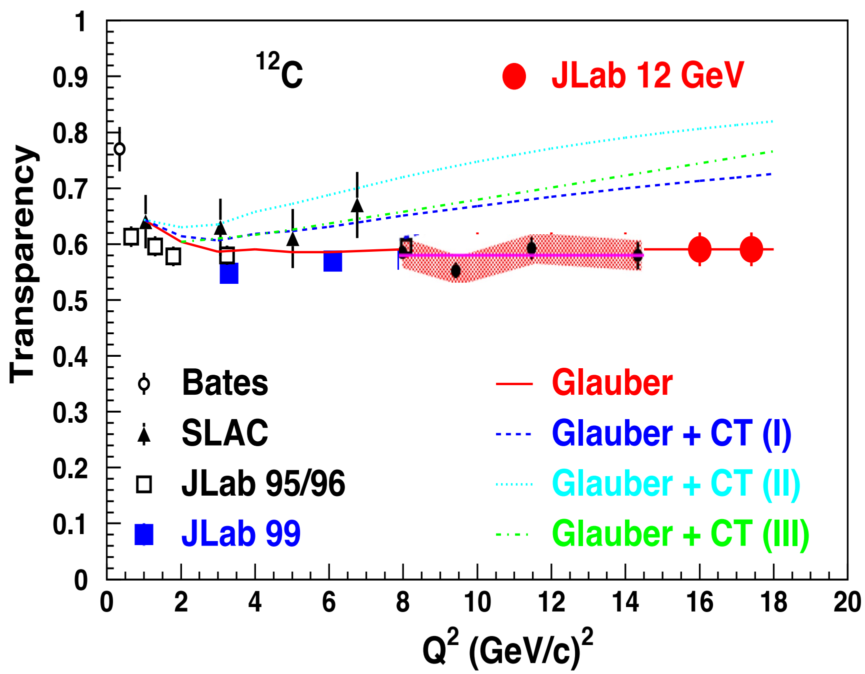
$$\downarrow R = \frac{\sigma(p_r{=}400MeV/c)\downarrow}{\sigma(p_r{=}200MeV/c)\uparrow}$$

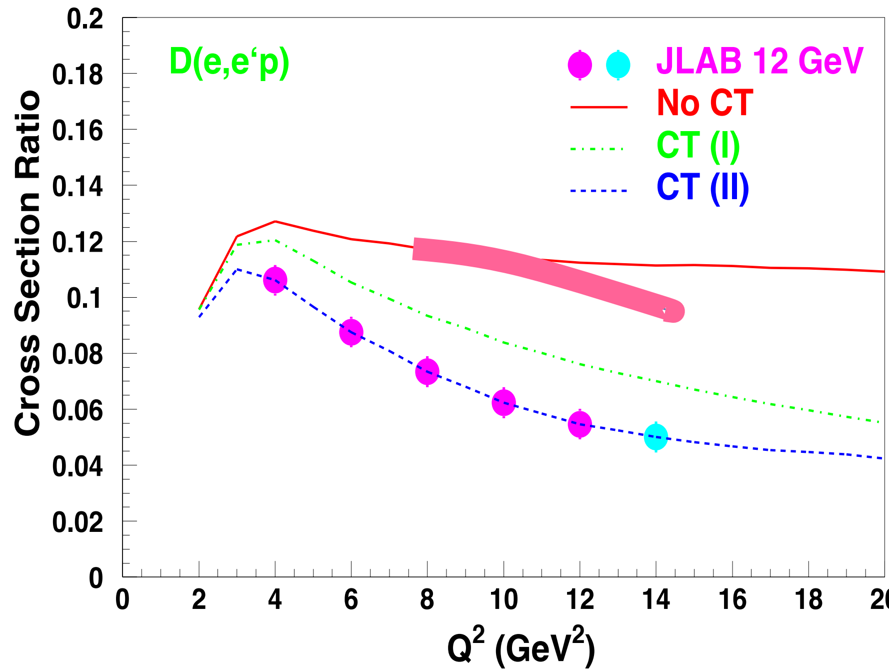
$e + d \rightarrow e' + p + n$ CT in Double Scattering



MS et al, Hadrons in the Nuclear Medium, J.Phys. G 2003

$$R = \frac{\sigma(p_r = 400 MeV/c)}{\sigma(p_r = 200 MeV/c)}$$





$$\sigma_{tot}(l, Q^2) = \sigma_{tot} \left\{ \left[\left(\frac{l}{l_h} \right)^n + \frac{\langle r_t(Q^2)^2 \rangle}{\langle r_t^2 \rangle} \left(1 - \left(\frac{l}{l_h} \right)^n \right) \right] \Theta(l_h - l) + \Theta(l - l_h) \right\},$$

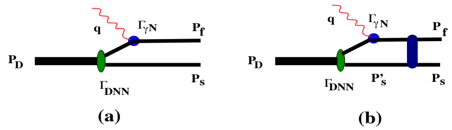
$$l_h = 2p_f / \Delta M^2 \qquad \Delta M^2 = 1.1\ GeV^2$$

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

Experimental Status of Double Scattering

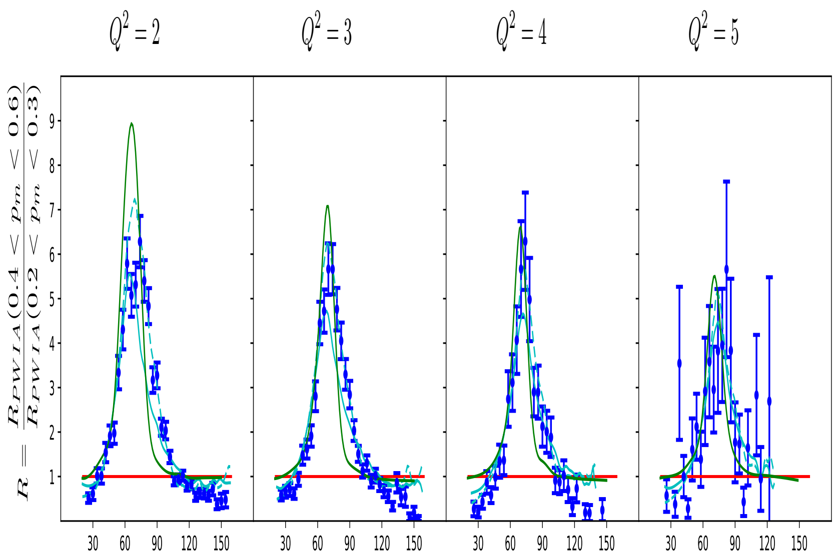
Werner Boeglin (FIU)

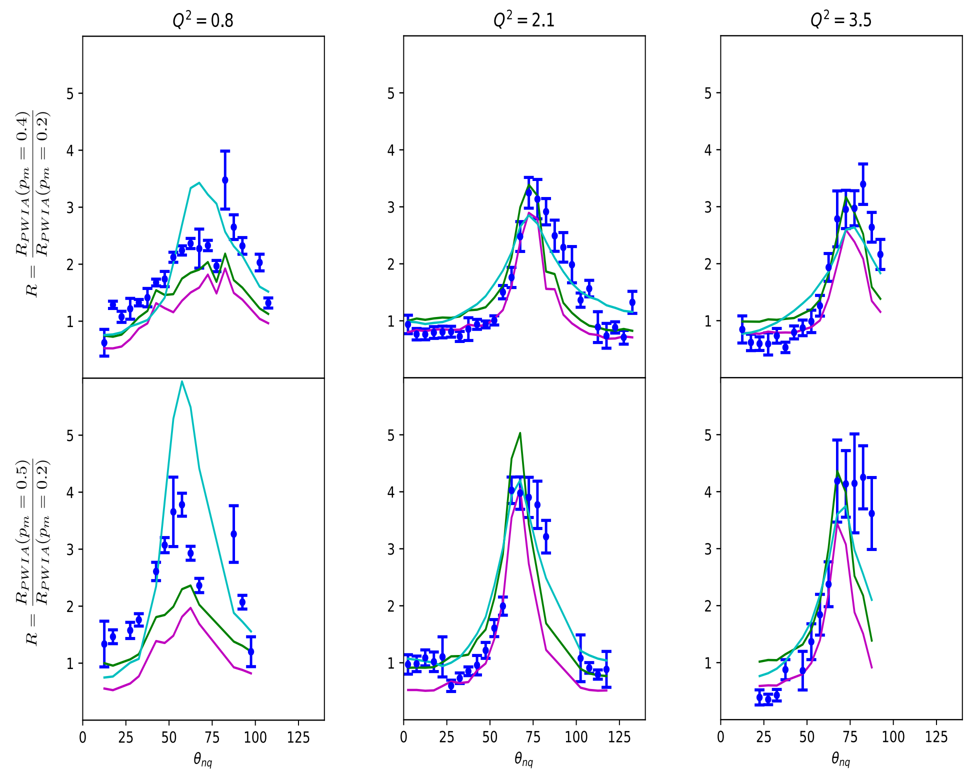
$e + d \rightarrow e' + p + n$



W. Boeglin et al PRL 2011

K. Egiyan et al PRL 2008





JN.Laget, PLB 2005

M.Sargsian, PRC 2010

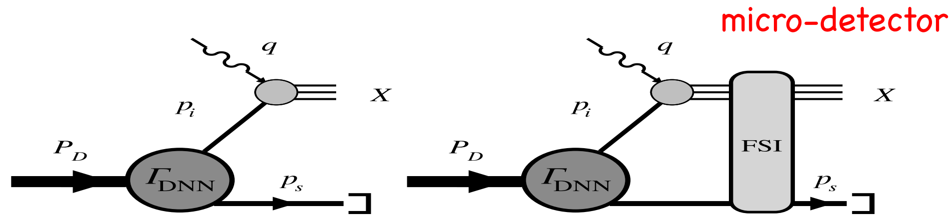
Rate Estimates

- Electrons: SHMS
- Protons: HMS
- Target: 10cm liquid D
- Beam current: 50μA
- Rates estimated with SIMC using PWIA including radiation
- Standard acceptance cuts
- Electrons: $\theta_{tar} \leq \pm 50 \;\; \phi_{tar} \leq \pm 0.25 \;\; -8 \leq \delta \leq 4.$
- Protons: $\theta_{tar} \leq \pm 60 \;\; \phi_{tar} \leq \pm 0.25 \; -10 \leq \delta \leq 10.$

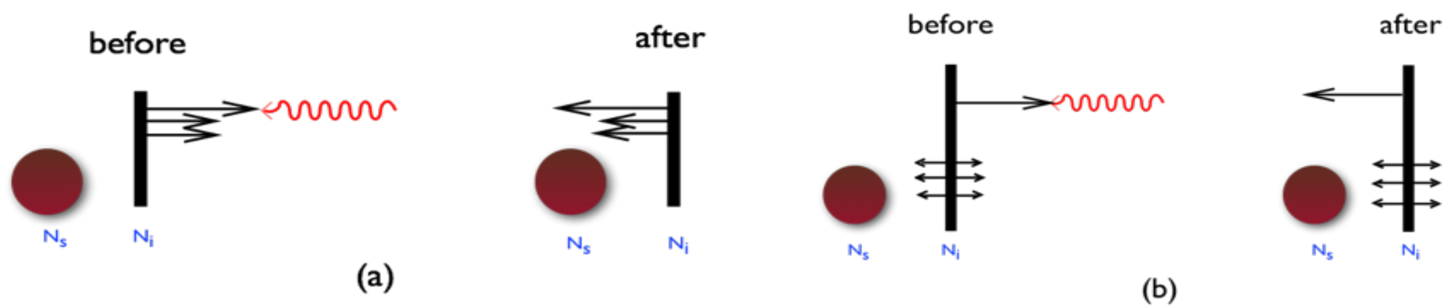
Q^2 min	Q^2 max	P_m min	P_m max	θ_{nq} min	θ_{nq} max	Events/Hour	Precision (%)	Number of Events	Beam Time (h)
3.75	4.25	0.15	0.25	55	85	2571.9	5	400	0.2
3.75	4.25	0.35	0.45	55	85	73.8	5	400	5.4
4.75	5.25	0.15	0.25	55	85	997.0	5	400	0.4
4.75	5.25	0.35	0.45	55	85	25.6	5	400	15.6
5.75	6.25	0.15	0.25	55	85	389.8	5	400	1.0
5.75	6.25	0.35	0.45	55	85	9.5	5	400	42.0
6.75	7.25	0.15	0.25	55	85	152.0	5	400	2.6
6.75	7.25	0.35	0.45	55	85	3.7	6	278	75.0
7.75	8.25	0.15	0.25	55	85	61.9	6	278	4.5
7.75	8.25	0.35	0.45	55	85	1.6	7	204	129.4
8.75	9.25	0.15	0.25	55	85	27.2	7	204	7.5
8.75	9.25	0.35	0.45	55	85	0.7	7	204	291.3
9.5	10.5	0.15	0.25	55	85	23.1	10	100	4.3
9.5	10.5	0.35	0.45	55	85	0.6	10	100	156.6
Total (hours)									735.8
Total (days)									30.7

Extension to DIS:

Christian Weise, Talk
Wim Cosyn, Talk



Distinguish Between PLC and Feynman mechanisms



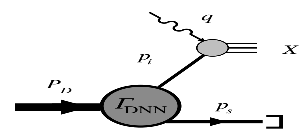
PLC

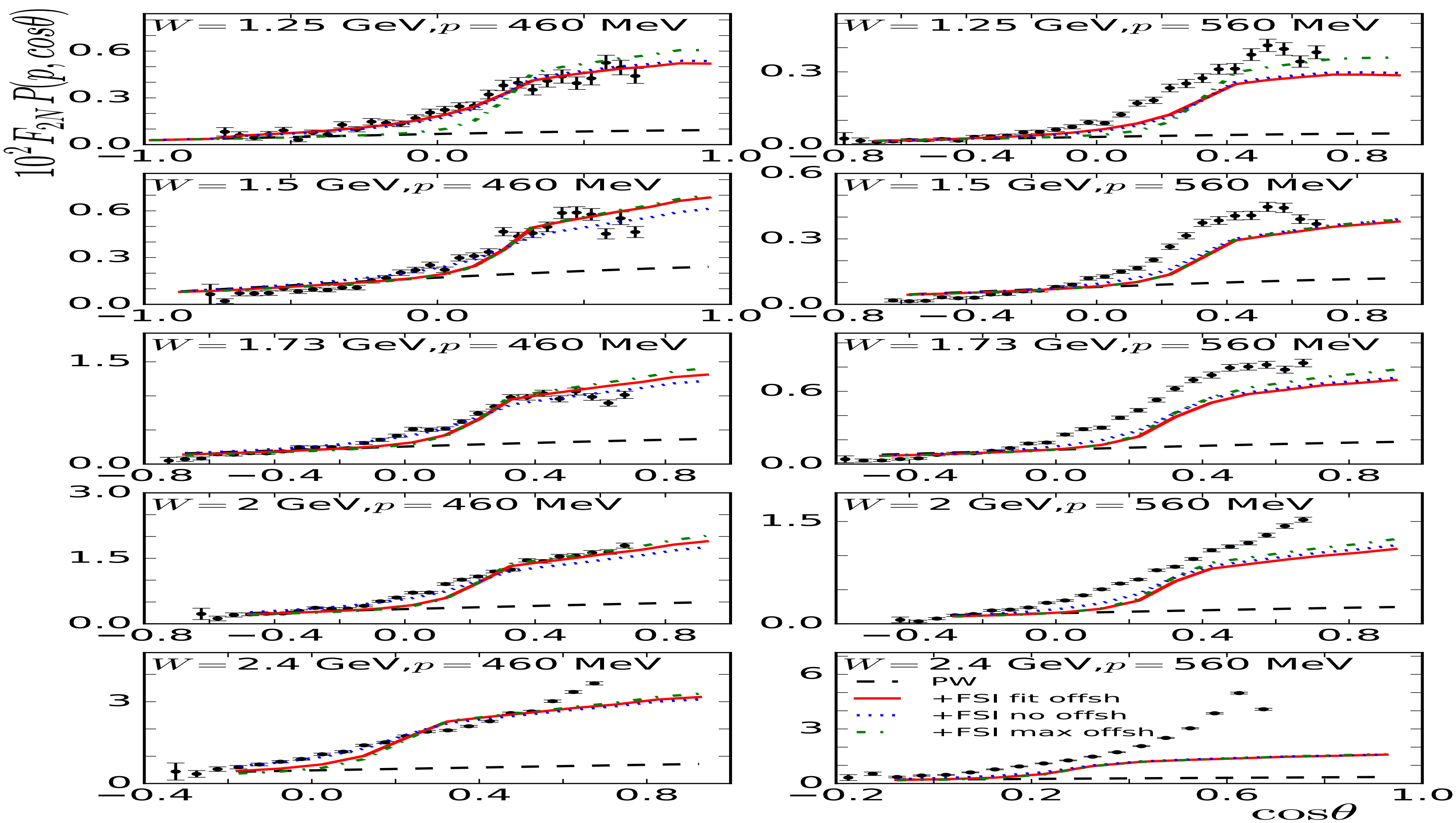
Feynman

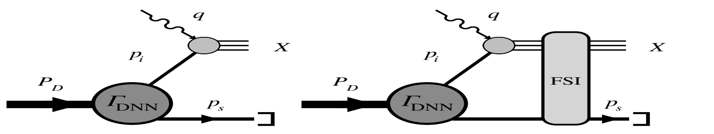
Extension to DIS:

$$e + d \rightarrow e' + p_s + X$$

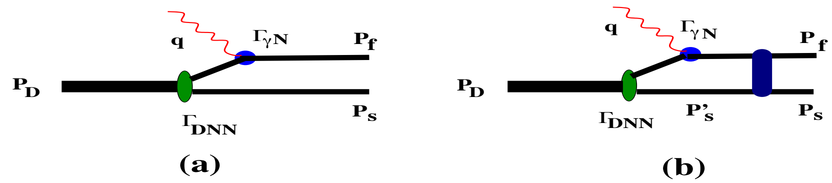
W.Cosyn & M.Sargsian, PRC 2011







$f_{NX} = \sigma_{tot}(Q^2)(i + \alpha(Q^2))e^{\beta(Q^2)t}$

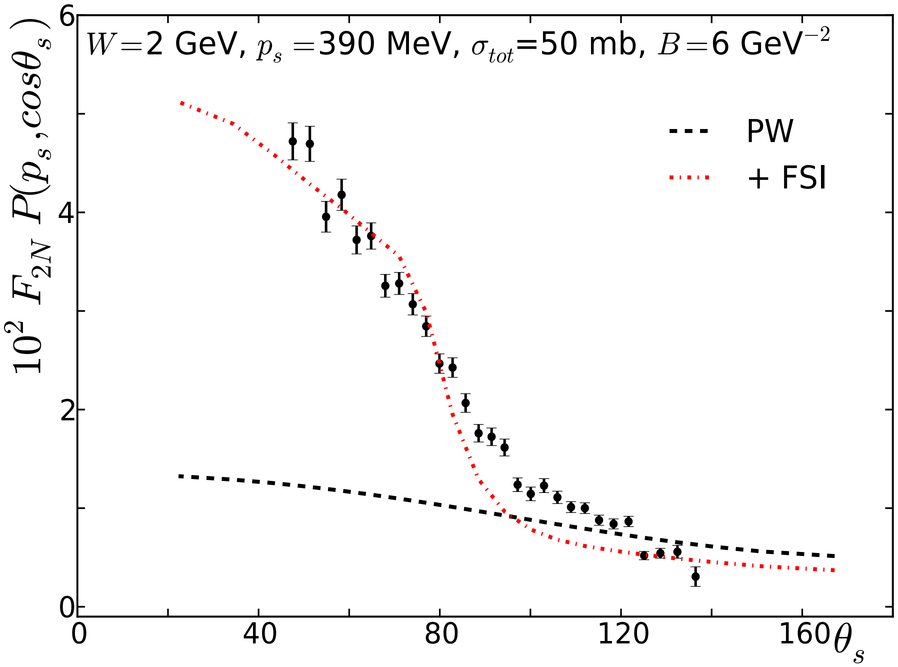


M.Sargsian, PRC 2010

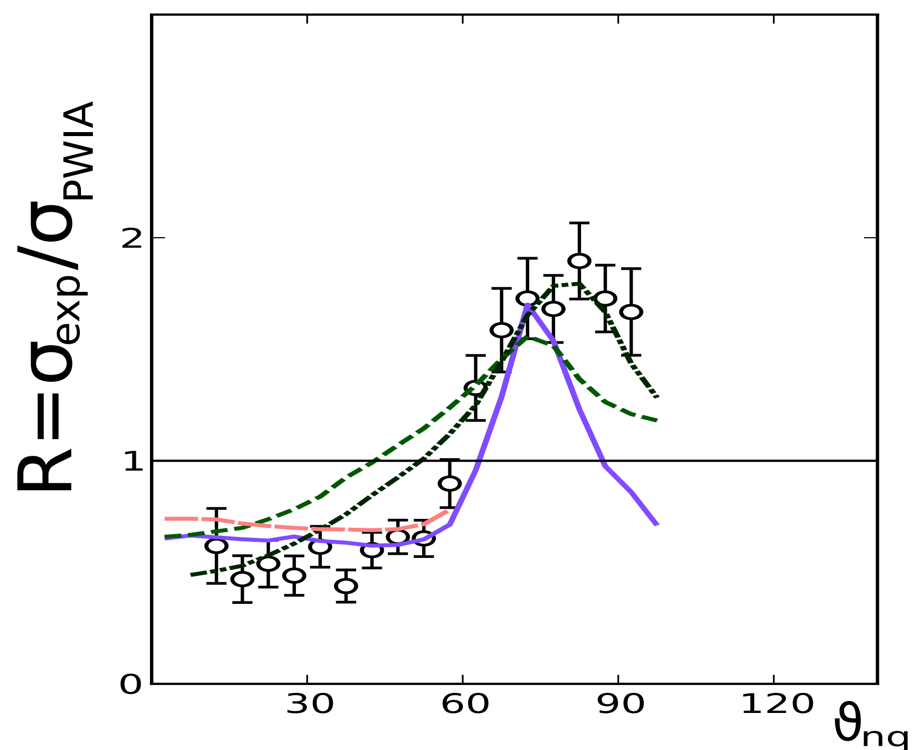
W.Cosyn & M.Sargsian, PRC 2011

$$e + d \rightarrow e' + X + p_r$$

$$e + d \rightarrow e' + p + n_r$$



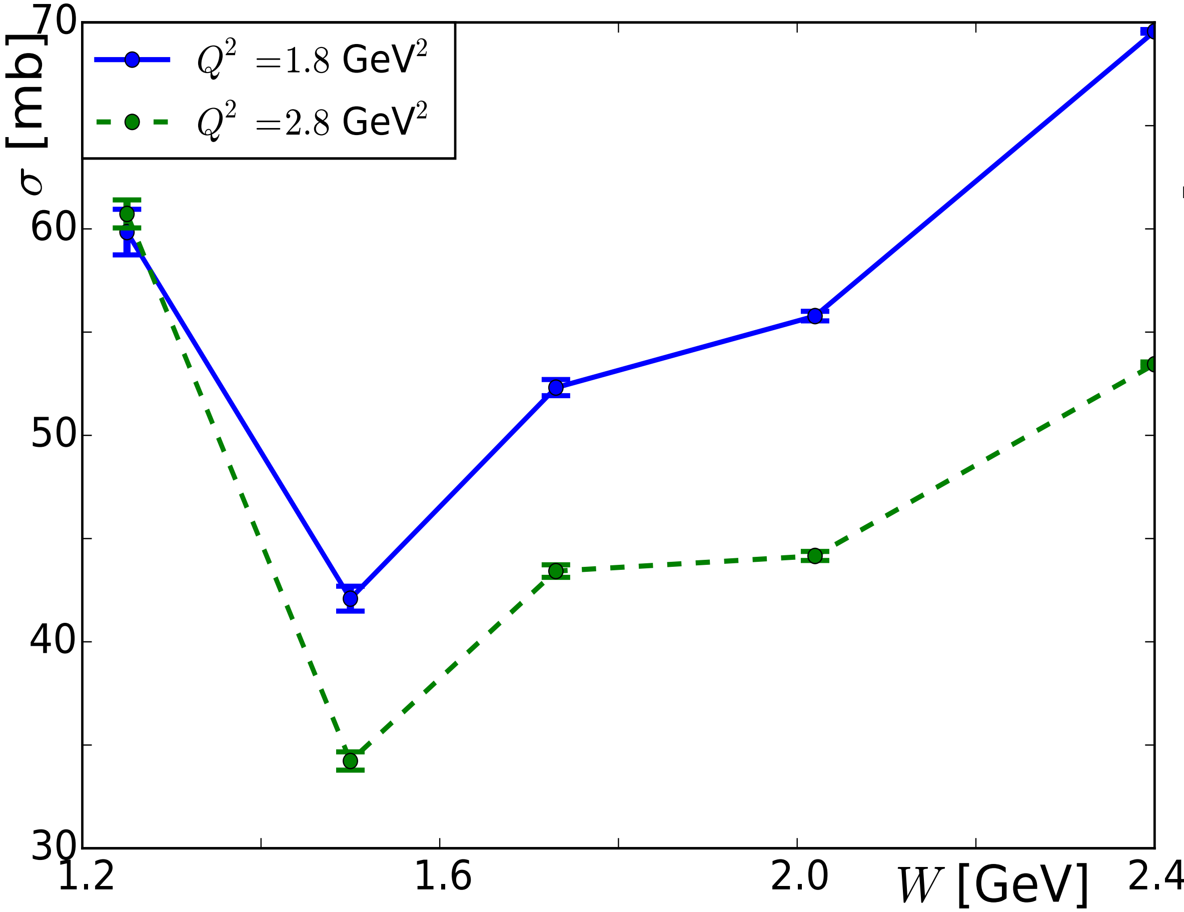
A.V. Klimenko et al PRC 2006

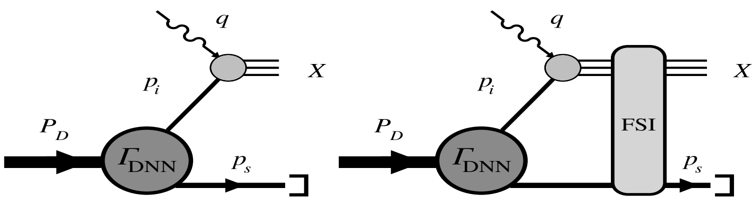


W. Boeglin et al PRL 2011

Hadronization Studies in $e + d \to e' + X + p_r$ DIS:

$$f_{NX} = \sigma_{tot}(Q^2)(i + \alpha(Q^2))e^{\beta(Q^2)t}$$





W.Cosyn & M.Sargsian, PRC 2011

W.Cosyn & M.Sargsian, IJMP 2017

Some Outlook

- Deuteron can present as a micro-detector for probing structure of produced baryons through the rescattering off the spectator nucleon

- By selecting larger momentum of spectator one can control distances at which PLC evolves (if it is produced)

- Tagged processes with the Deuteron, may potentially present a new venue for CT and Hadronization processes.

- In addition to $e + d \to e' + X + p_r$ one can also consider $e + d \to e' + X + meson + N_r$ to probe the hadronization of meson through meson-N_r rescattering