Deuteron Break-up Theory (role of FSI)

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2nd Workshop on Quantitative Challenges in SRC and EMC Research
MIT March 20-23, 2019

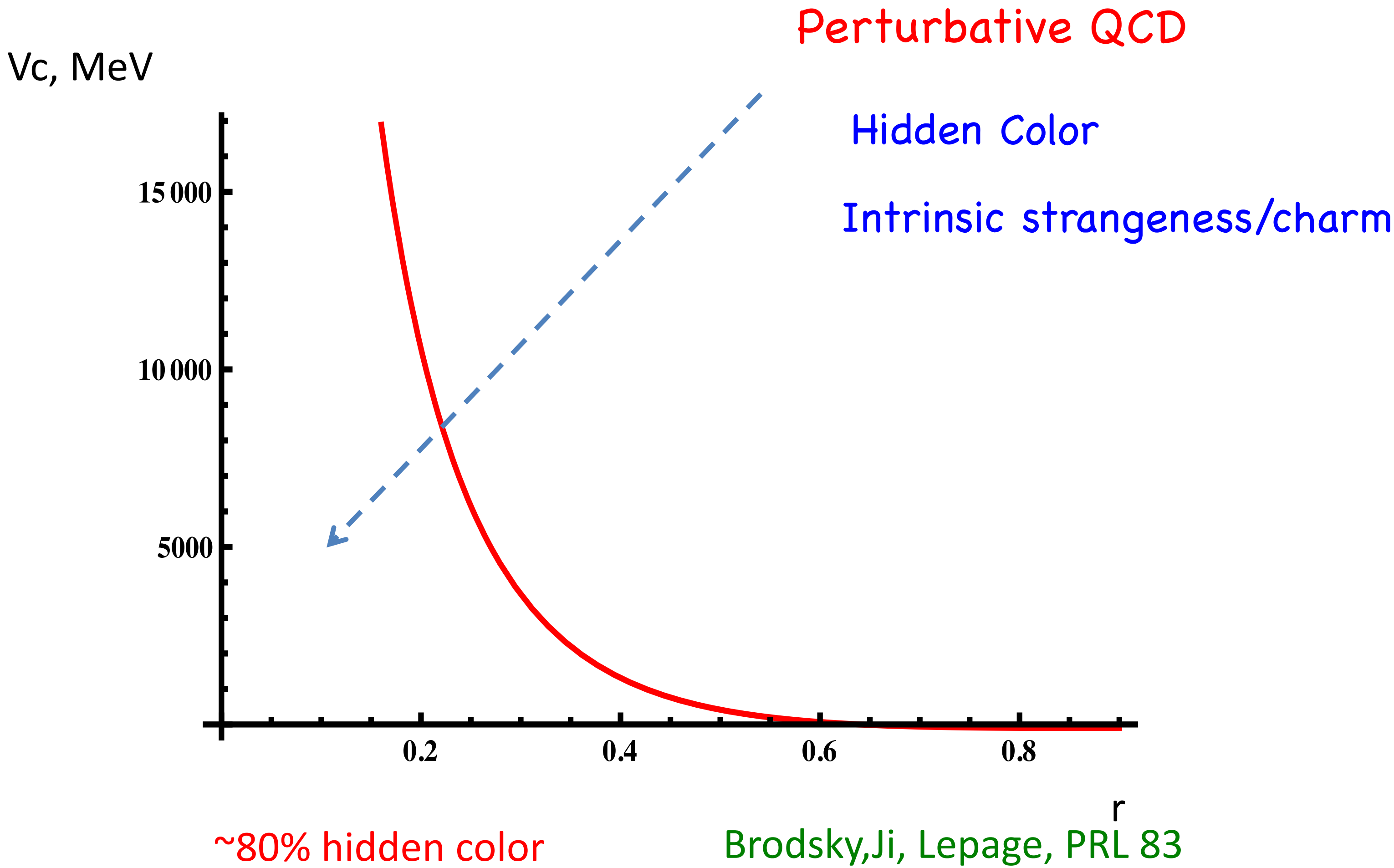
Motivation for Deuteron Studies

Probing NN Repulsive Core & Hadron-Quark Transition

- *strength of the core;*
- *non-nucleonic components, hidden color, gluons*
- *hadronization in the deuteron*

Processes to Study

- *probing superfast quarks (x>1) in inclusive d(ee')X processes*
- *break-up processes in d(e,eN)N reactions*
- *DIS tagged processes*



Perturbative QCD
Vc, MeV
Hidden Color
Intrinsic strangeness/charm
15 000
10 000
5000
0.2
0.4
0.6
0.8
r
~80% hidden color
Brodsky,Ji, Lepage, PRL 83

Probing the Deuteron at Short Distances

$$\Psi_d = \Psi_{pn} + \Psi_{\Delta\Delta} + \Psi_{NN^*} + \Psi_{hc} \cdots$$

$$\Psi_{hc} = \Psi_{N_c,N_c}$$

The NN core can be due to the orthogonality of

$$\langle \Psi_{N_c,N_c} \mid \Psi_{N,N} \rangle = 0$$

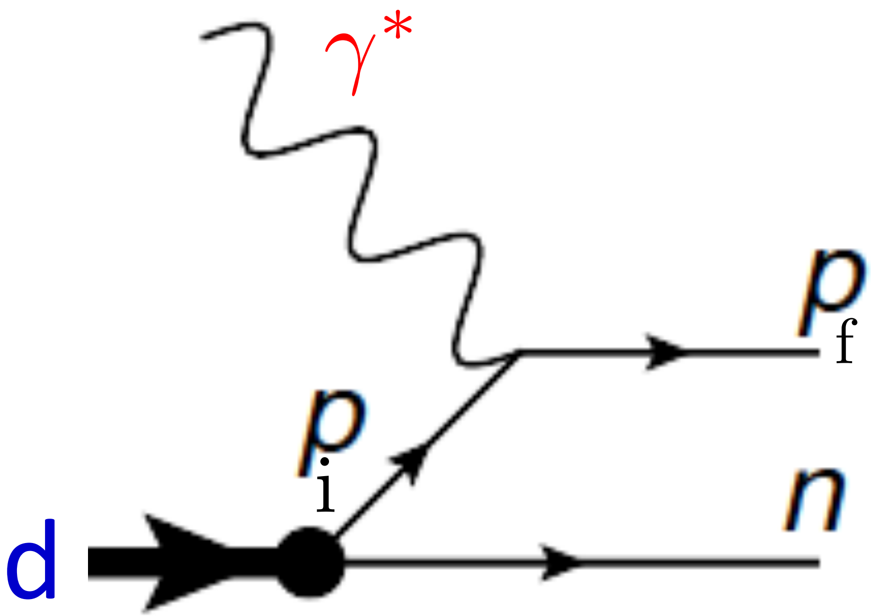
Conceptually: How to probe nuclei at short nucleon separations

- Probe bound nucleons at large internal momenta

- Need high energy probes to resolve such nucleons in nuclei

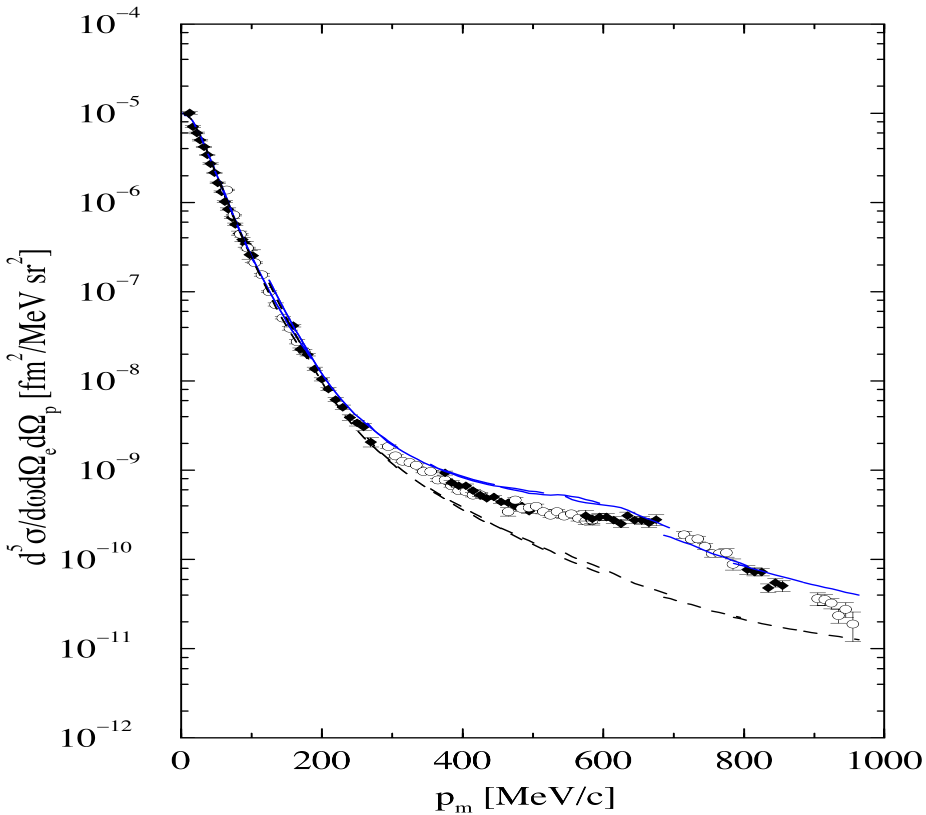
Probing the Deuteron at Short Distances

Considering reaction: $e + d \rightarrow e' + p_f + n$

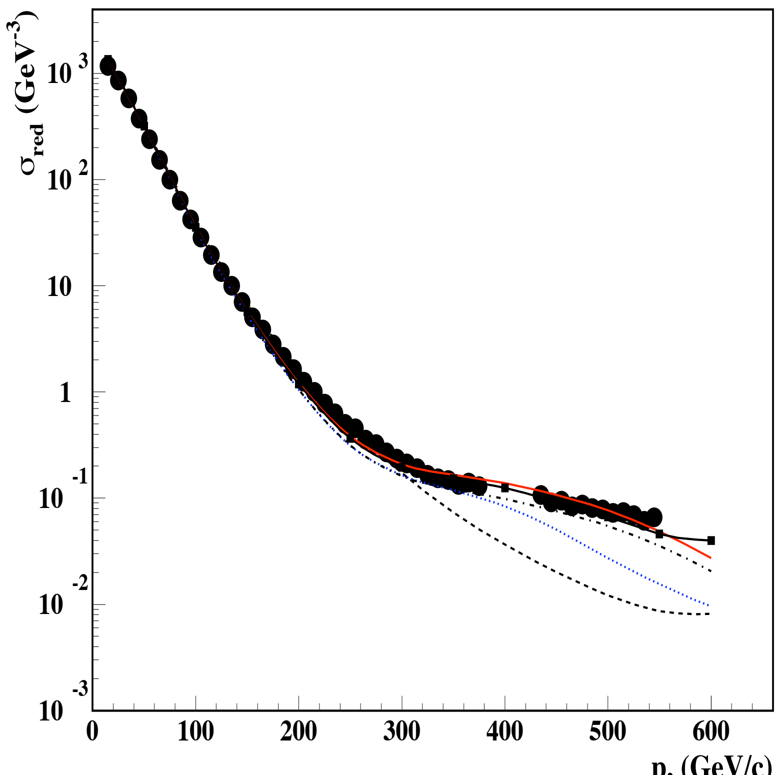


$$|p_i| = |p_f - q| > 300 \text{ MeV/c}$$

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

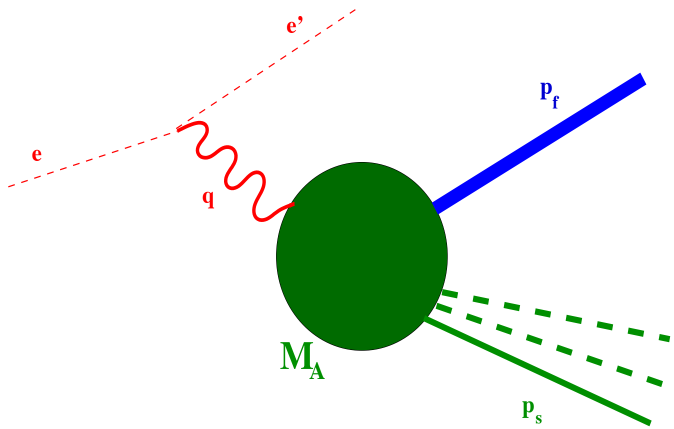


Mainz, $Q^2 = 0.33$ GeV^2



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

#Theory of High Energy eA Scattering:



High Energy Approximations:

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

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

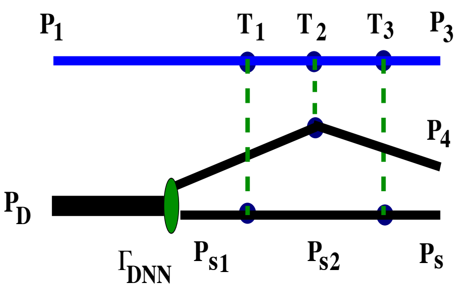
Both for QE/DIS

- Emergence of the small parameter

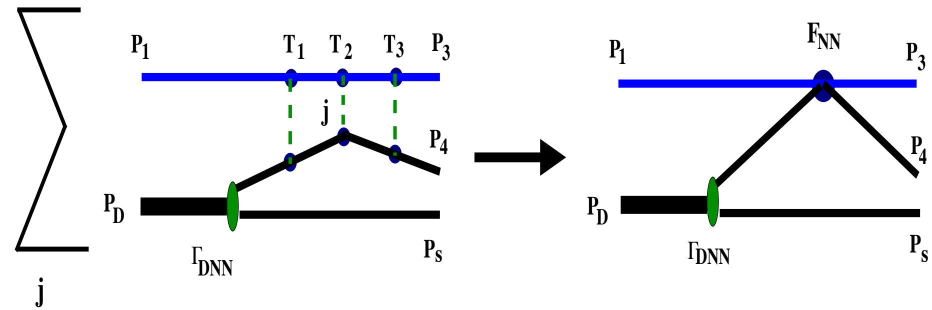
$$\frac{q_-}{q_+} = \frac{q_0 - q_3}{q_0 + q_3} \ll 1 \qquad \mathcal{O}(\frac{q_-}{q_+})$$

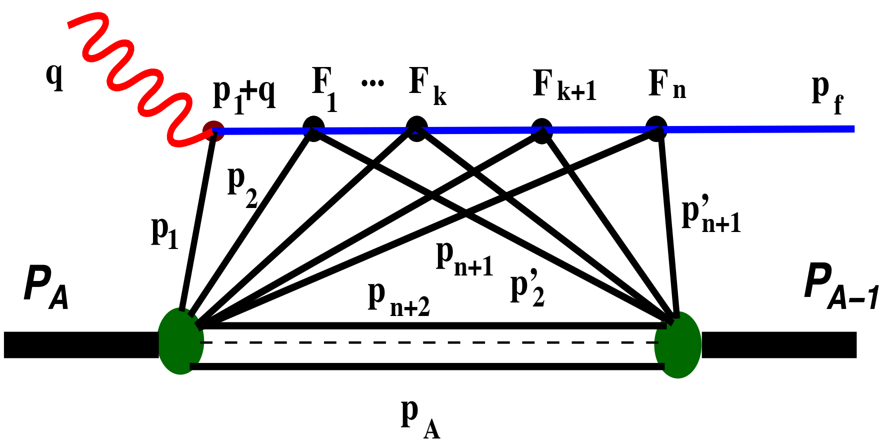
$$\frac{p_{f-}}{p_{f+}} = \frac{E_f - p_{f3}}{E_f + p_{f3}} \ll 1 \qquad \mathcal{O}(\frac{p_{f-}}{p_{f+}})$$

Emergence of "effective" theory



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





Effective Feynman Diagrammatic Rules

M.S. IJMS 2001

Wave function?

From Schroedinger Equation -> Feynman Diagrams-> Light-Front Wave Function

Schroedinger eq. → **Lipmann-Schwinger Eq.**

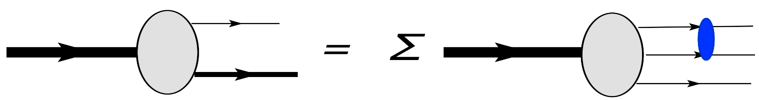
$$\left[-\sum_i \frac{\nabla_i^2}{2m} + \frac{1}{2}\sum_{i,j} V(x_i - x_j)\right]\psi(x_1,\cdots,x_A) = E\psi(x_1,\cdots,x_A)$$

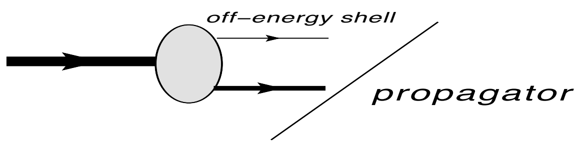
$$\left(\sum_i \frac{k_i^2}{2m} - E_b\right)\Phi(k_1,\cdots,k_A) = -\frac{1}{2}\sum_{i,j}\int U(q)\,\Phi(k_1,\cdots,k_i-q,\cdots k_j+q,\cdots,k_A)d^3q$$

Lipmann-Schwinger Eq → **t- ordered diagrammatic method**

$$\left(\sum_i \frac{k_i^2}{2m} - E_b\right)\Phi(k_1,\cdots,k_A) = -\frac{1}{2}\sum_{i,j}\int U(q)\,\Phi(k_1,\cdots,k_i-q,\cdots k_j+q,\cdots,k_A)d^3q$$

$$\Phi(k_1,\cdots k_A) = \frac{1}{\sum \frac{k_i^2}{2m} - E_b}\Gamma_{A\to N,A-1}$$

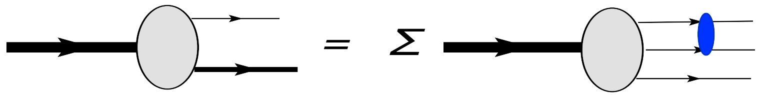


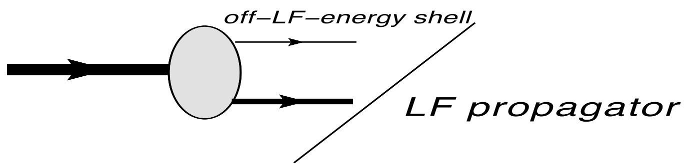


Weinberg Eq → **τ - ordered diagrammatic method**

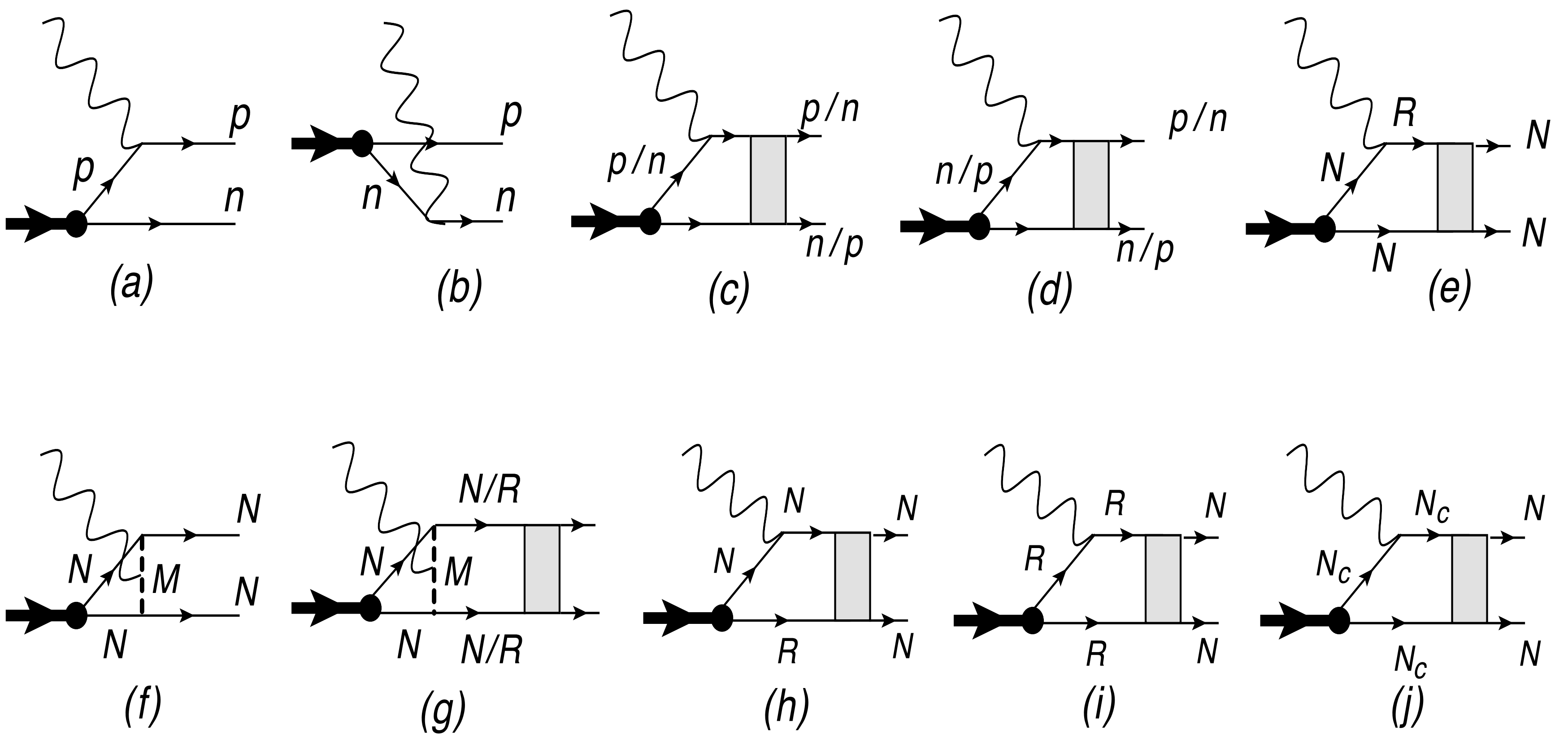
$$\left(\sum \frac{k_{i\perp}^2+m^2}{\alpha_i} - M_A^2\right)\Phi_{LF}(k_1,\cdots k_A) = \frac{1}{2}\sum_{i,j}\int U_{LF}(q)\Phi_{LF}(k_1,\cdots k_A)\prod \frac{d\alpha_i}{\alpha_i}d^2k_{i\perp}$$

$$\Phi_{LF}(k_1,\cdots k_A) = \frac{1}{\sum \frac{k_{i\perp}^2+m^2}{\alpha_i} - M_A^2}\Gamma_{A\to N,A-1}$$

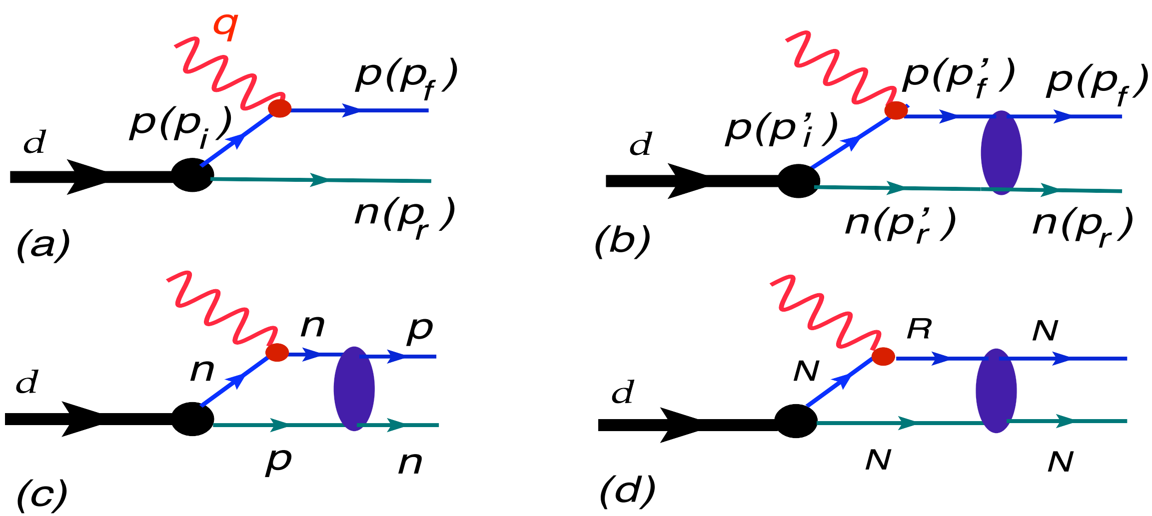




Impossibility to Probe Deuteron at Small Distances at low Q^2



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



Generalized Eikonal Approximation at large Q2, 1997-2010

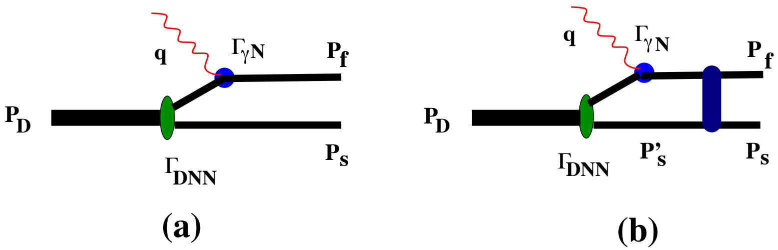
$$\langle s_f, s_r \mid A_0^\mu \mid s_d \rangle = -\bar{u}(p_r, s_r)\Gamma^\mu_{\gamma^* p} \frac{\not{p}_i + m}{p_i^2 - m^2} \cdot \bar{u}(p_f, s_f)\Gamma_{DNN} \cdot \chi^{s_d}$$

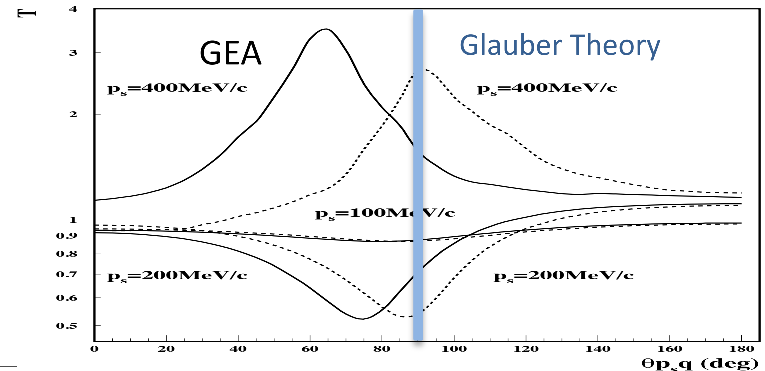
$$\langle s_f, s_r \mid A_1^\mu \mid s_d \rangle = -\int \frac{d^4 p'_r}{i(2\pi)^4} \frac{\bar{u}(p_f, s_f)\bar{u}(p_r, s_r) F_{NN}[\not{p}'_r + m][\not{p}_d - \not{p}'_r + \not{q} + m]}{(p_d - p'_r + q)^2 - m^2 + i\epsilon} \times \frac{\Gamma_{\gamma^* N}[\not{p}_d - \not{p}'_r + m]\Gamma_{DNN}\chi^{s_d}}{((p_d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

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

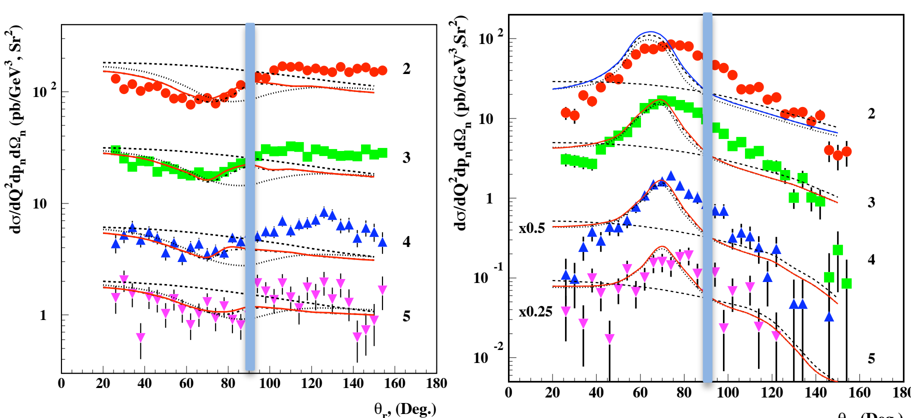
Some Results: $e + d \rightarrow e' + p + n$

Frankfurt, M.S., Strikman, PRC 1997



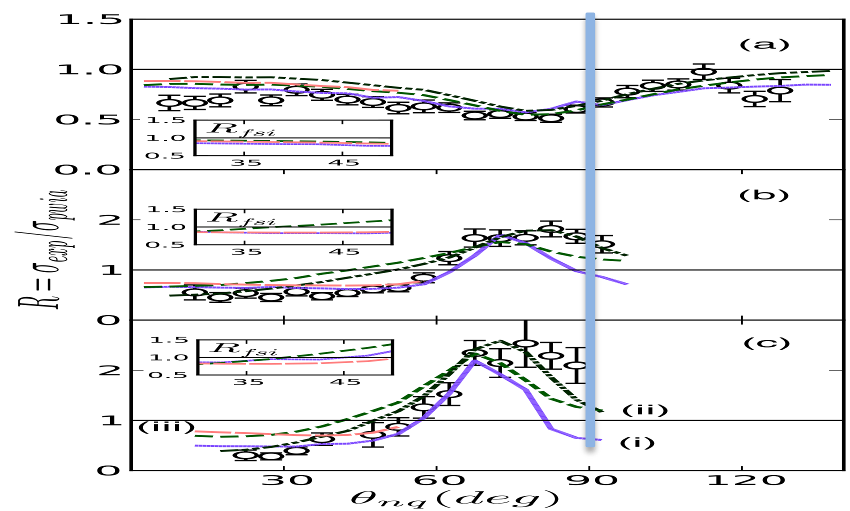


K. Egiyan et al PRL 2008



M.Sargsian, PRC 2010

W. Boeglin et al PRL 2011



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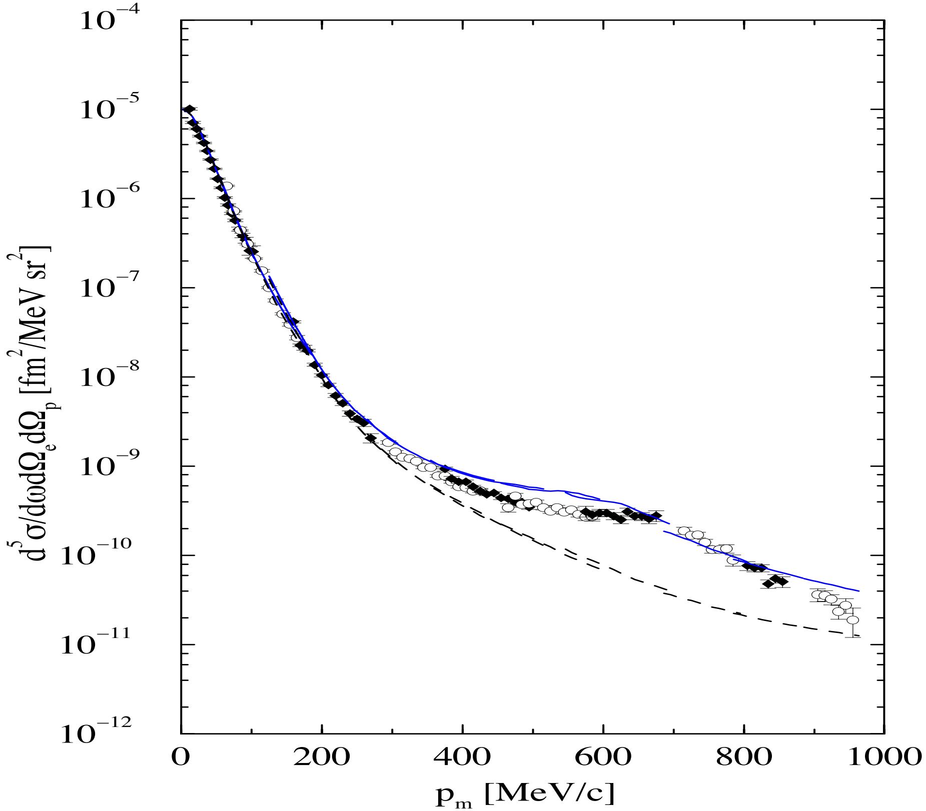
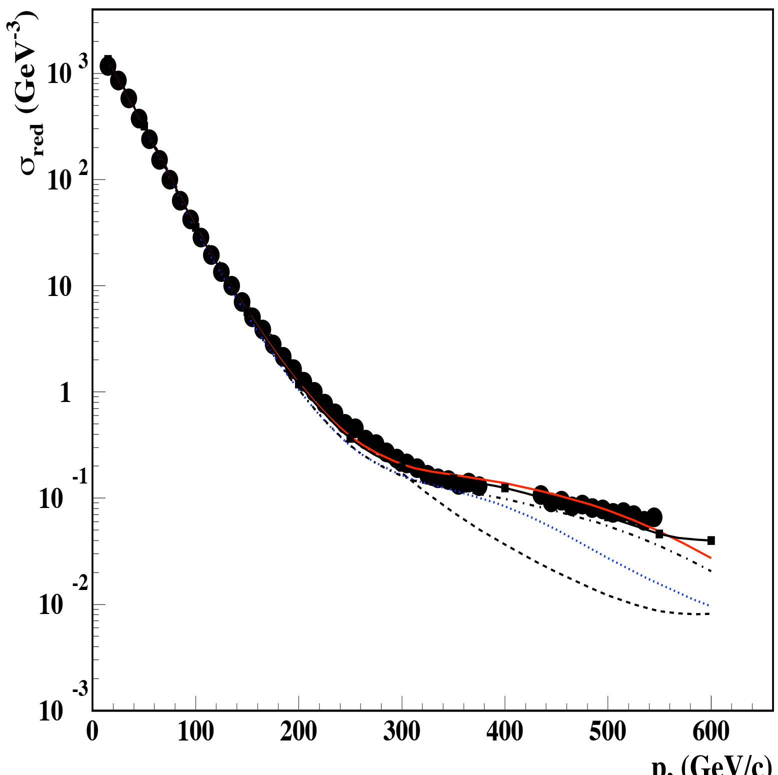
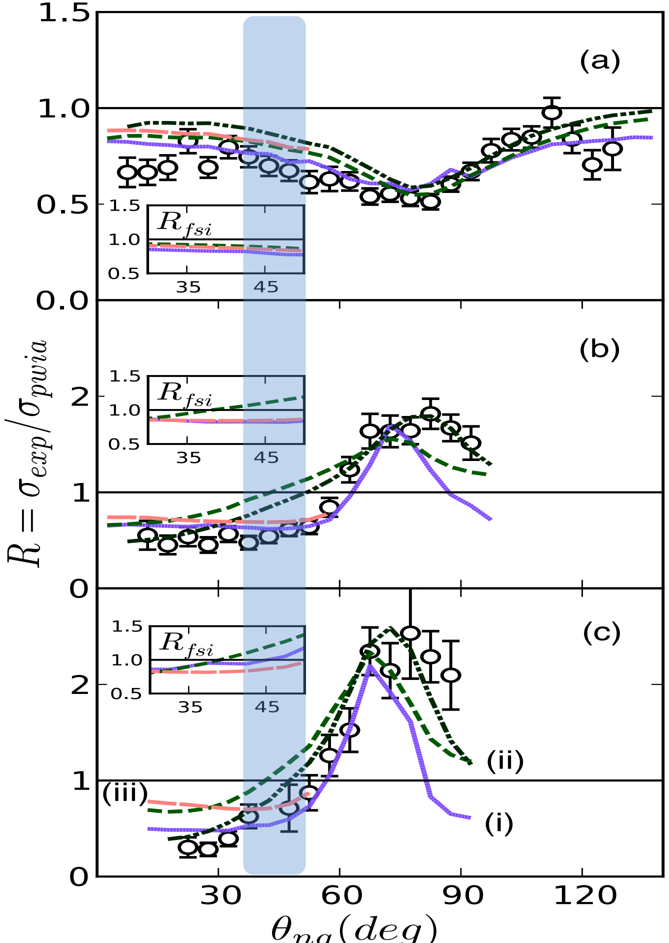


Mainz, $Q^2 = 0.33$ GeV^2



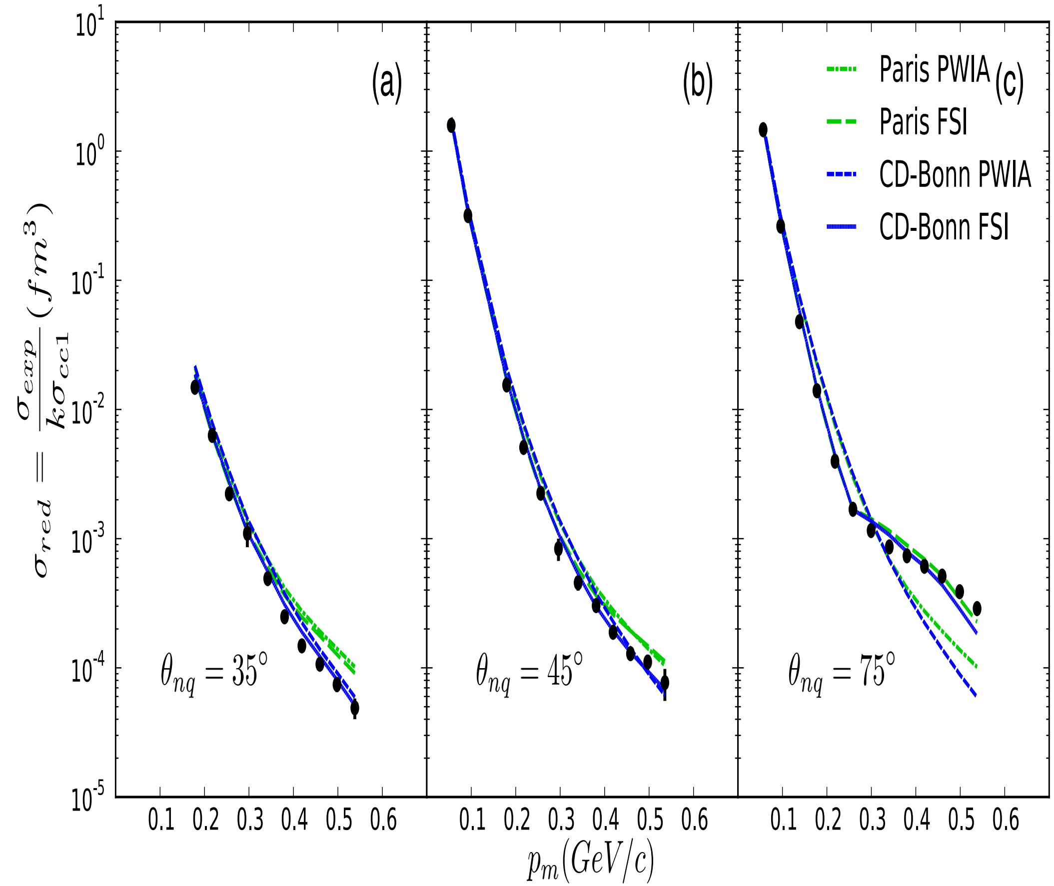
JLab, $Q^2 = 0.66$ GeV^2

Probing Deuteron at Small Distances at large Q^2



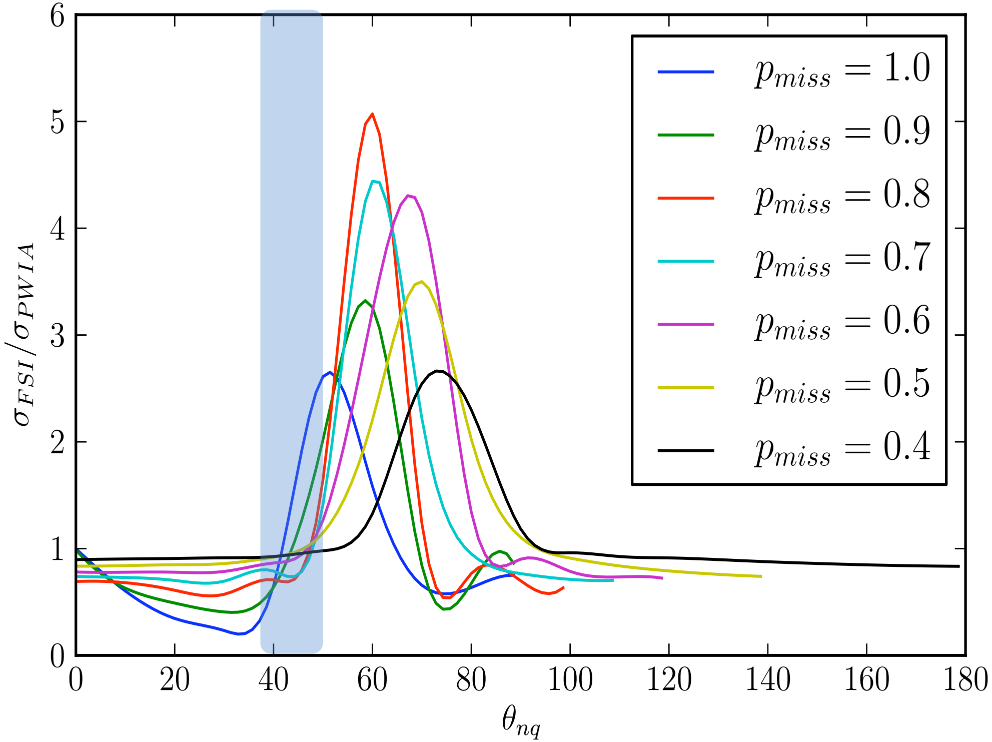
JLab, $Q^2 = 3.5$ GeV^2

M.Sargsian, PRC 2010

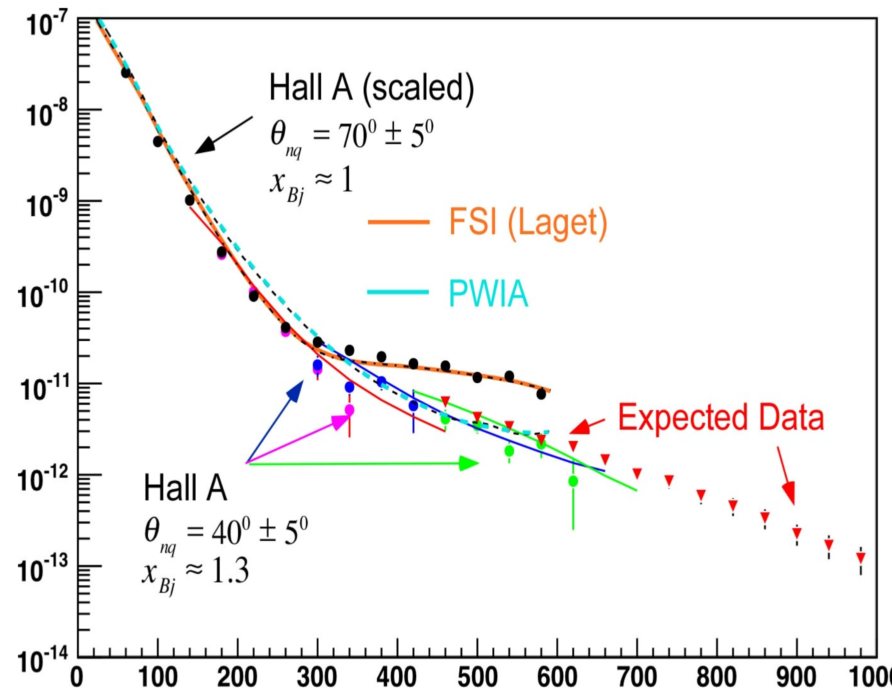


Boeglin et al PRL 2011, deuteron probed at up to 550MeV/c

Probing Deuteron at Core Distances at large Q^2



JLab proposal $Q^2 = 4\ GeV^2$



Carlos' talk

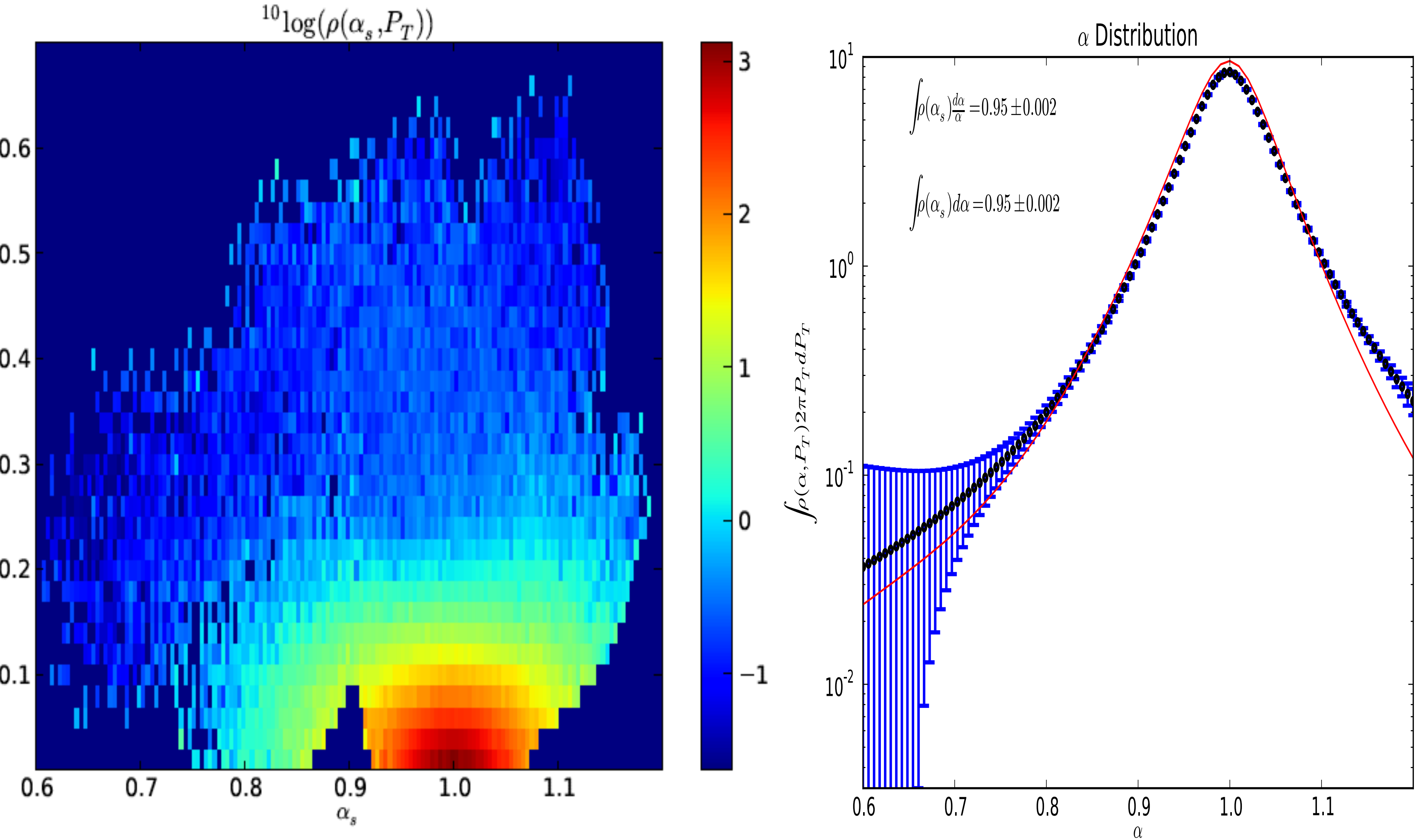
Extraction of Deuteron Light-Cone Momentum Distribution $\rho(\alpha, p_T)$

$$F_{2d}(x_{Bj}, Q^2) = \int_{x_{Bj}}^{2} F_{2p}^{bound}(\frac{x_{Bj}}{\alpha}, Q^2)\rho_d(\alpha)\frac{d\alpha}{\alpha} + \int_{x_{Bj}}^{2} F_{2n}^{bound}(\frac{x_{Bj}}{\alpha}, Q^2)\rho_d(\alpha)\frac{d\alpha}{\alpha}$$

$$\rho_d(\alpha) = \int \rho(\alpha, p_T)d^2p_T$$

For d(e,e'p)n reaction:

$$\frac{d\sigma}{dEe'd\Omega_e d\Omega_s} = K\sigma_{eN}^{LC}(\alpha, p_t)\rho(\alpha, p_t),$$

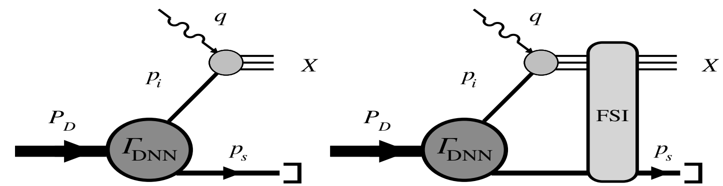


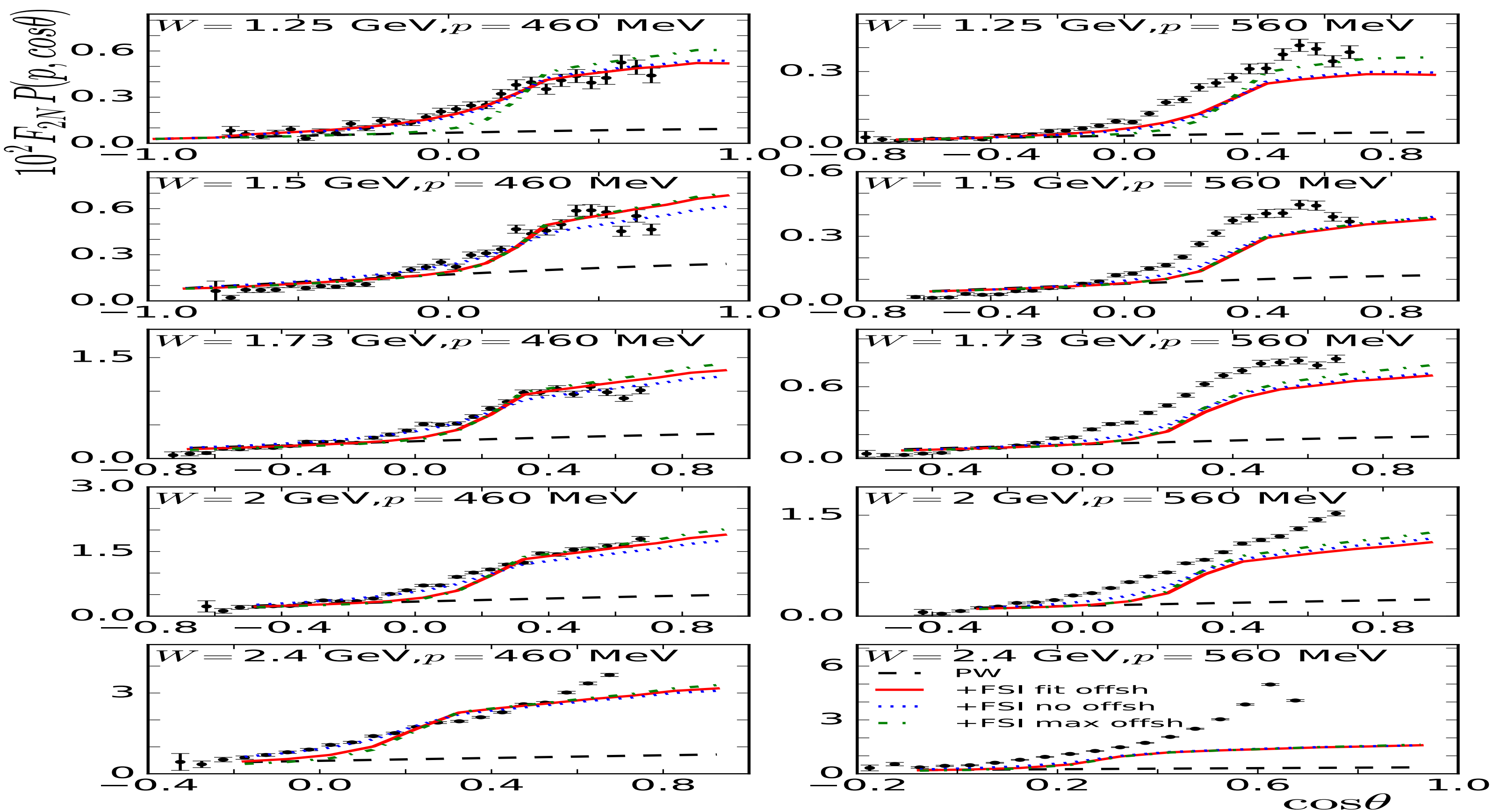
$^{10}\log(\rho(\alpha_s, P_T))$
0.6
0.5
0.4
0.3
0.2
0.1
0.6 0.7 0.8 0.9 1.0 1.1
α_s
3
2
1
0
−1
α Distribution
10^1
10^0
10^{-1}
10^{-2}
$\int \rho(\alpha_s)\frac{d\alpha}{\alpha} = 0.95 \pm 0.002$
$\int \rho(\alpha_s)d\alpha = 0.95 \pm 0.002$
$\int \rho(\alpha, P_T)2\pi P_T dP_T$
0.6 0.7 0.8 0.9 1.0 1.1
α

Extension to DIS:

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

W.Cosyn & M.Sargsian, PRC 2011



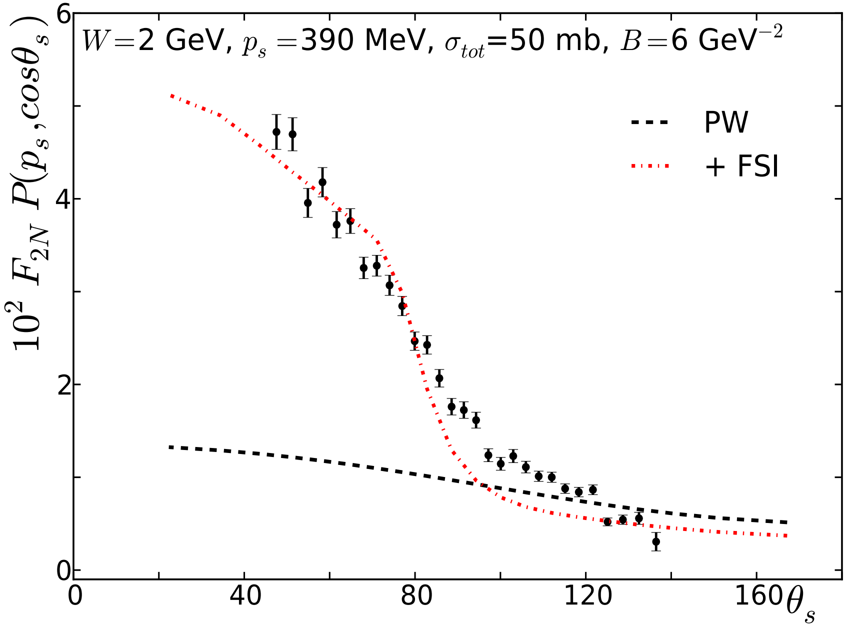


W.Cosyn & M.Sargsian, PRC 2011

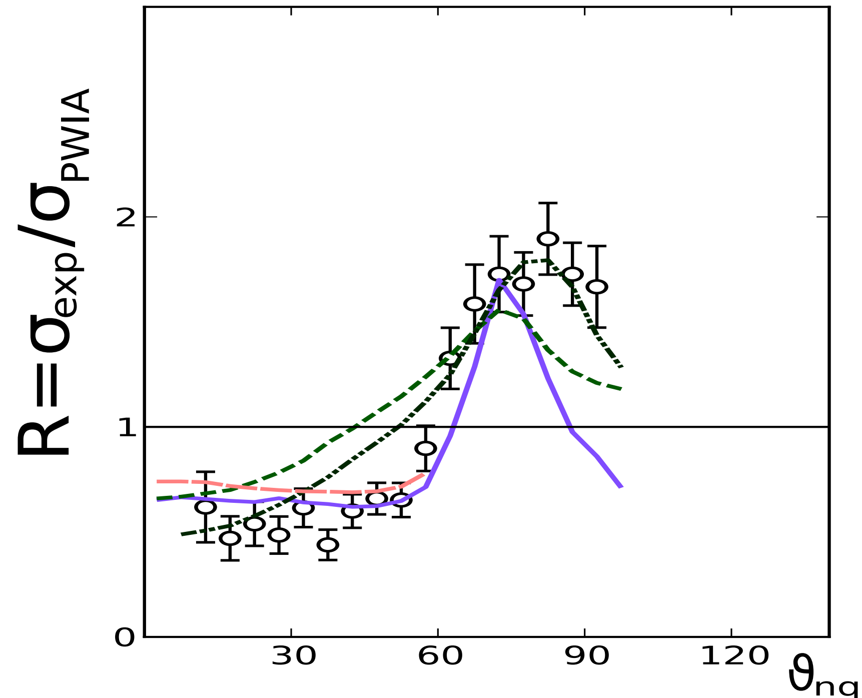
M.Sargsian, PRC 2010

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

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

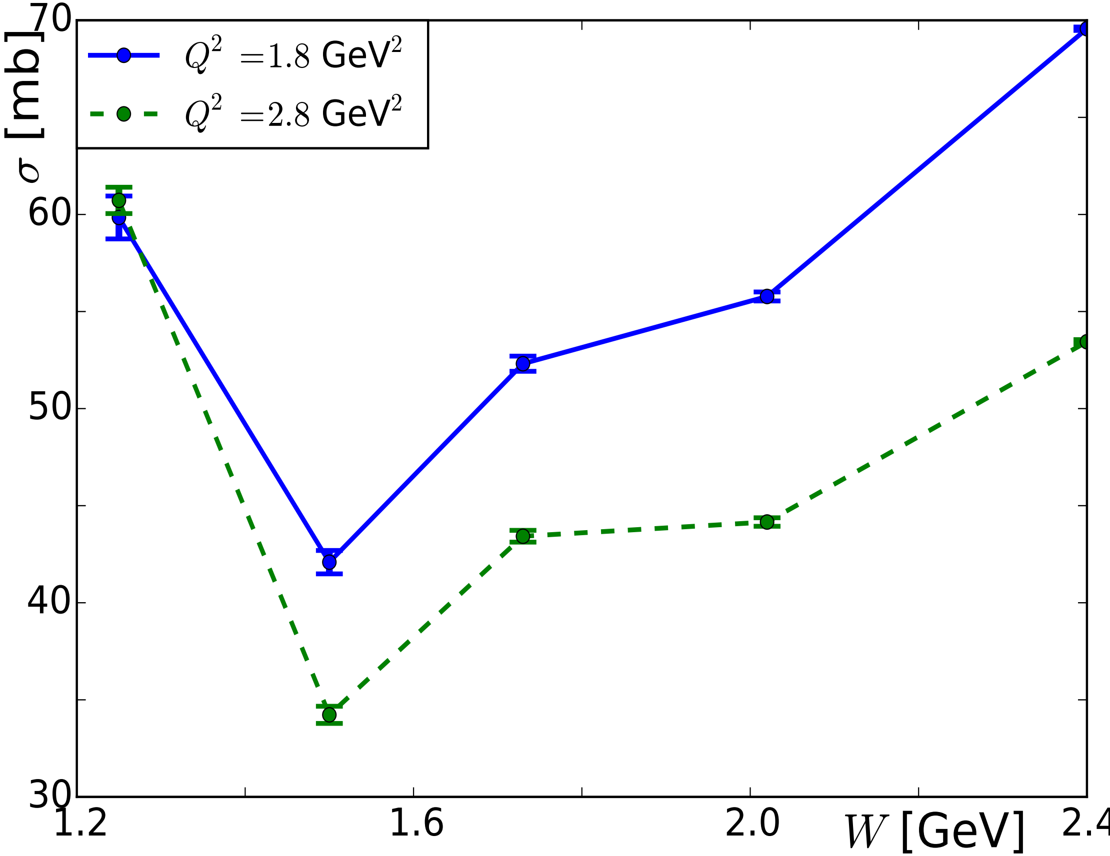


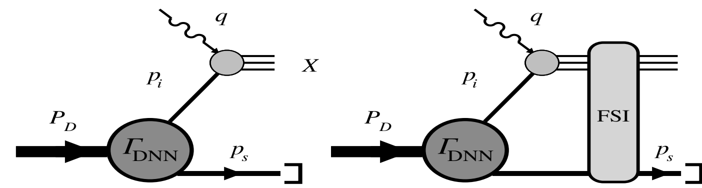
A.V. Klimenko et al PRC 2006



W. Boeglin et al PRL 2011

Hadronization Studies in $e + d \rightarrow e' + p_s + X$ DIS:





W.Cosyn & M.Sargsian, PRC 2011

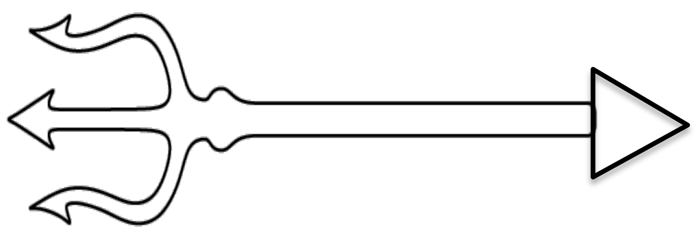
W.Cosyn & M.Sargsian, IJMP 2017

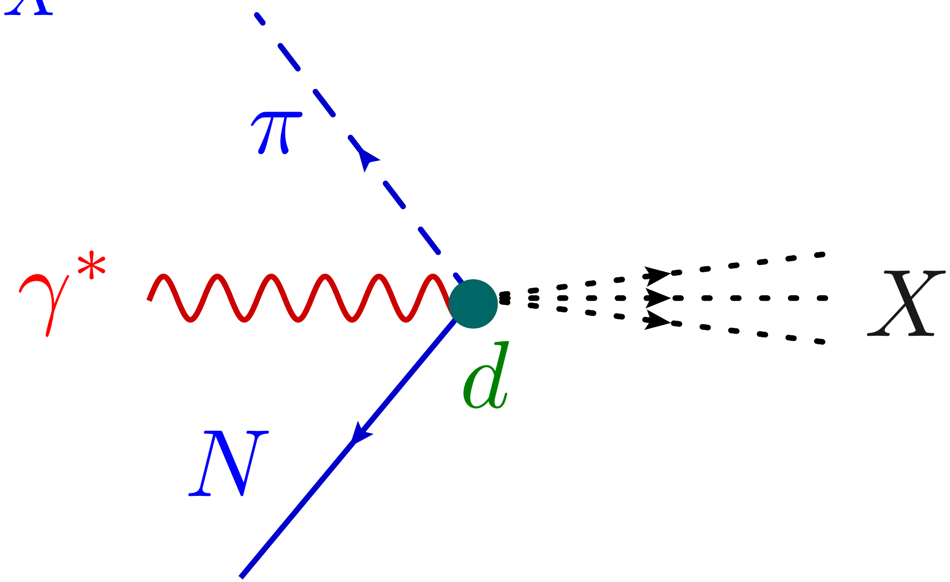
Probing Deuteron at Core Distances at large Q²

$$\Psi_d = \Psi_{pn} + \Psi_{\Delta\Delta} + \Psi_{NN^*} + \Psi_{hc} \cdots$$

$$e + d \rightarrow e' + \Delta_{backward} + X$$

$$e + d \rightarrow e' + N^*_{backward} + X$$





LOI 2019
Boeglin, et al...

Some Outlook

- Deuteron deserves a special status for studies of the almost all issues relevant to contemporary high energy nuclear physics

- Inclusive Deuteron at x>1, unpolorized polorized

- Quasielastic Deuteron Break-Up at large pmiss

- Tagged processes with the Deuteron

- Fast backward production of B+M in DIS with the deuteron