Large Q2 Electrodisintegration of the Deuteron

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MENU, May-31, 2010
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NN-interaction as a motivation for deuteron studies

NN-intro:

Phenomenological Fits

$$V^{NN} = V_{\pi}^{NN} + V_{R}^{NN}$$

$$V_{R}^{NN} = V^{c} + V^{t} S_{12} + V^{LS} L \cdot S + V^{l2} L^{2} + V^{ls2} (L \cdot S)^{2}$$

$$V^{i} = V_{int,R}^{i} + V_{core}^{i}, \qquad i = c, t, LS, l2, ls2$$

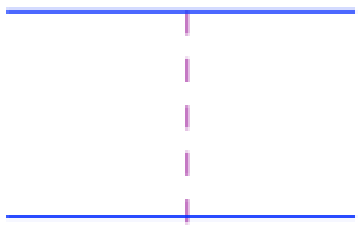
$$V_{core} = \left[1 + e^{\frac{r - r_0}{a}} \right]^{-1}$$

60's

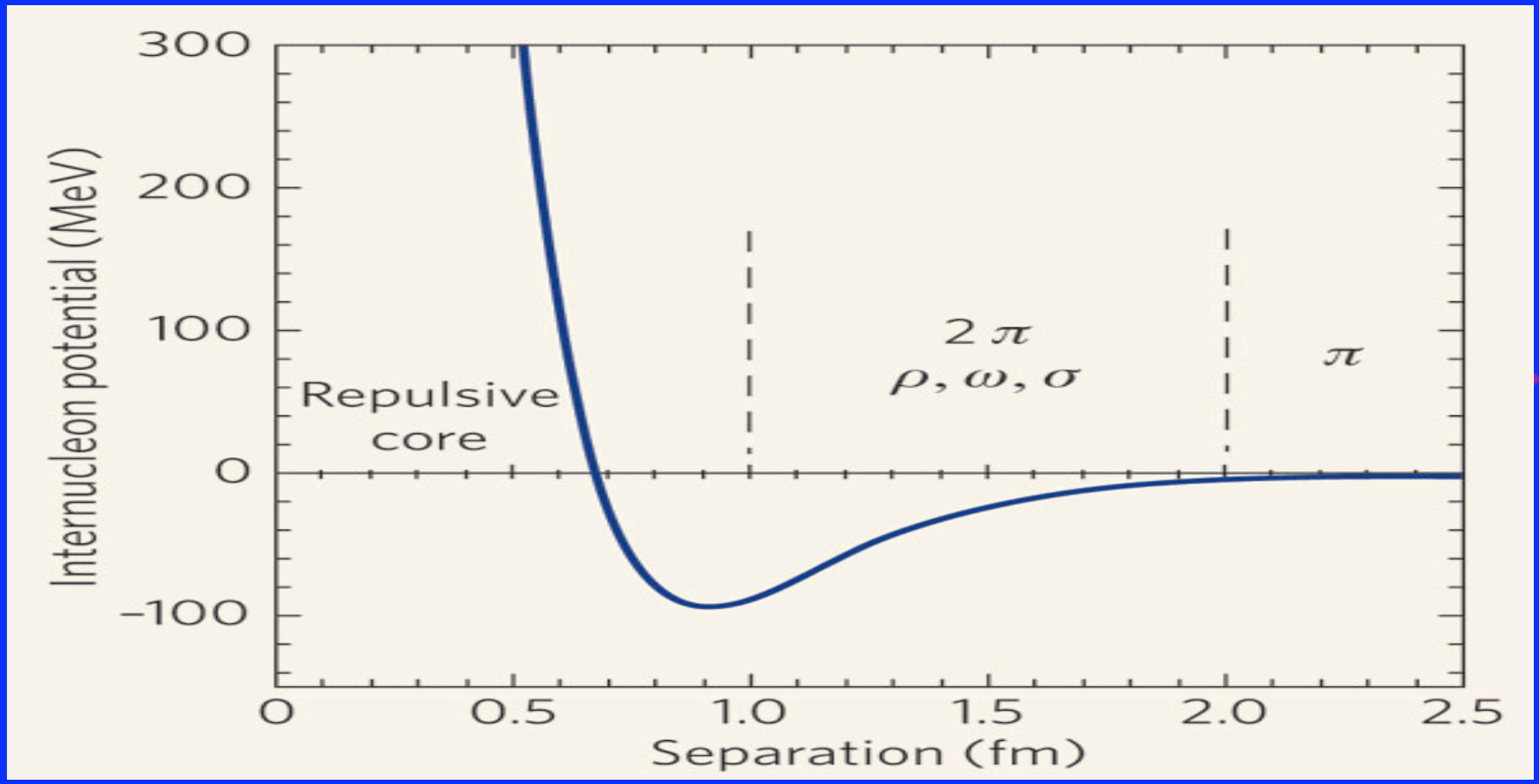
Paris
Argonne

NN-intro: (O)BEP

47's



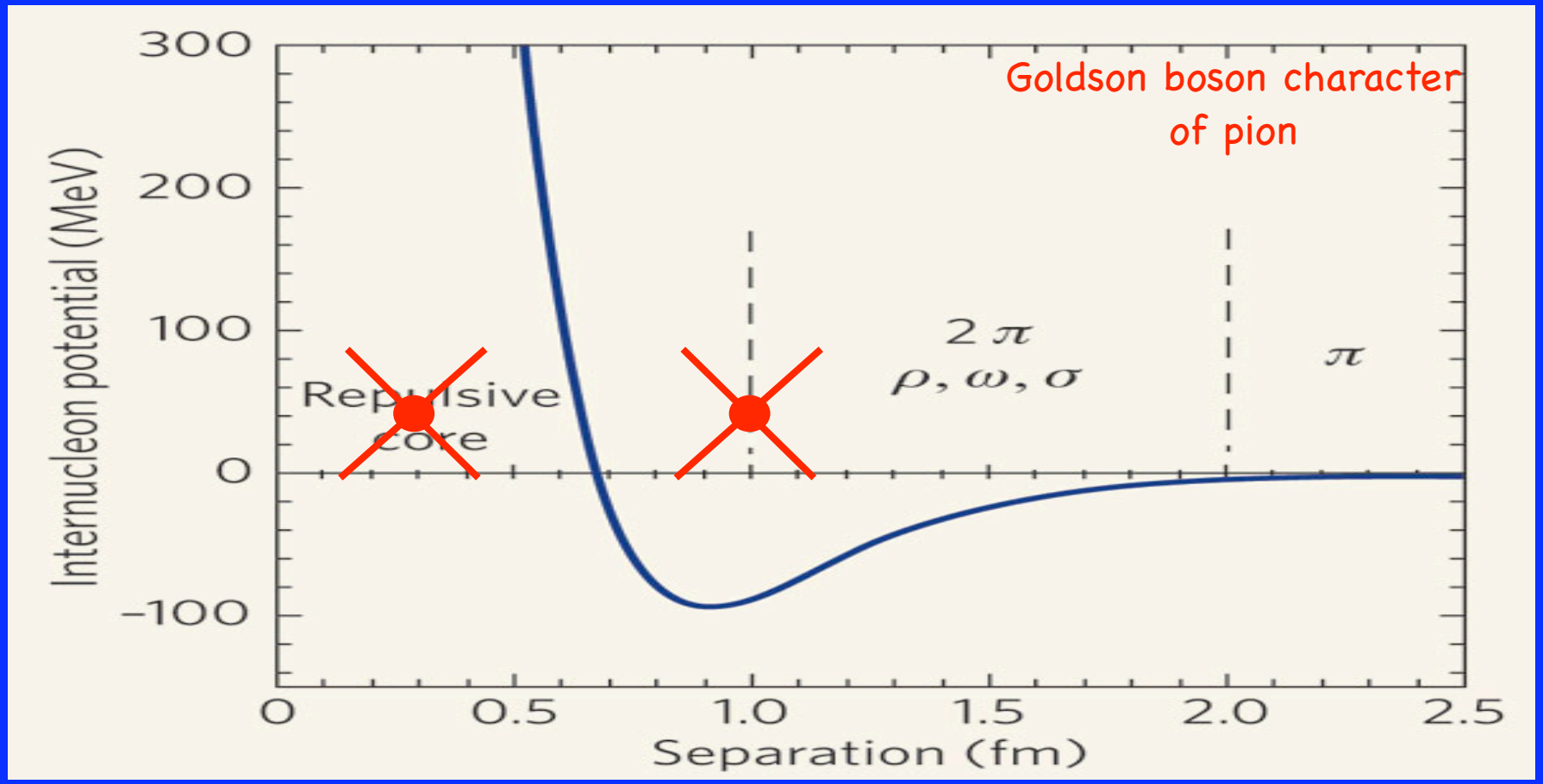
$\sigma, \quad \pi, \quad \rho, \quad \omega, \ldots$



Bonn Potential

NN-intro: Effective Theories

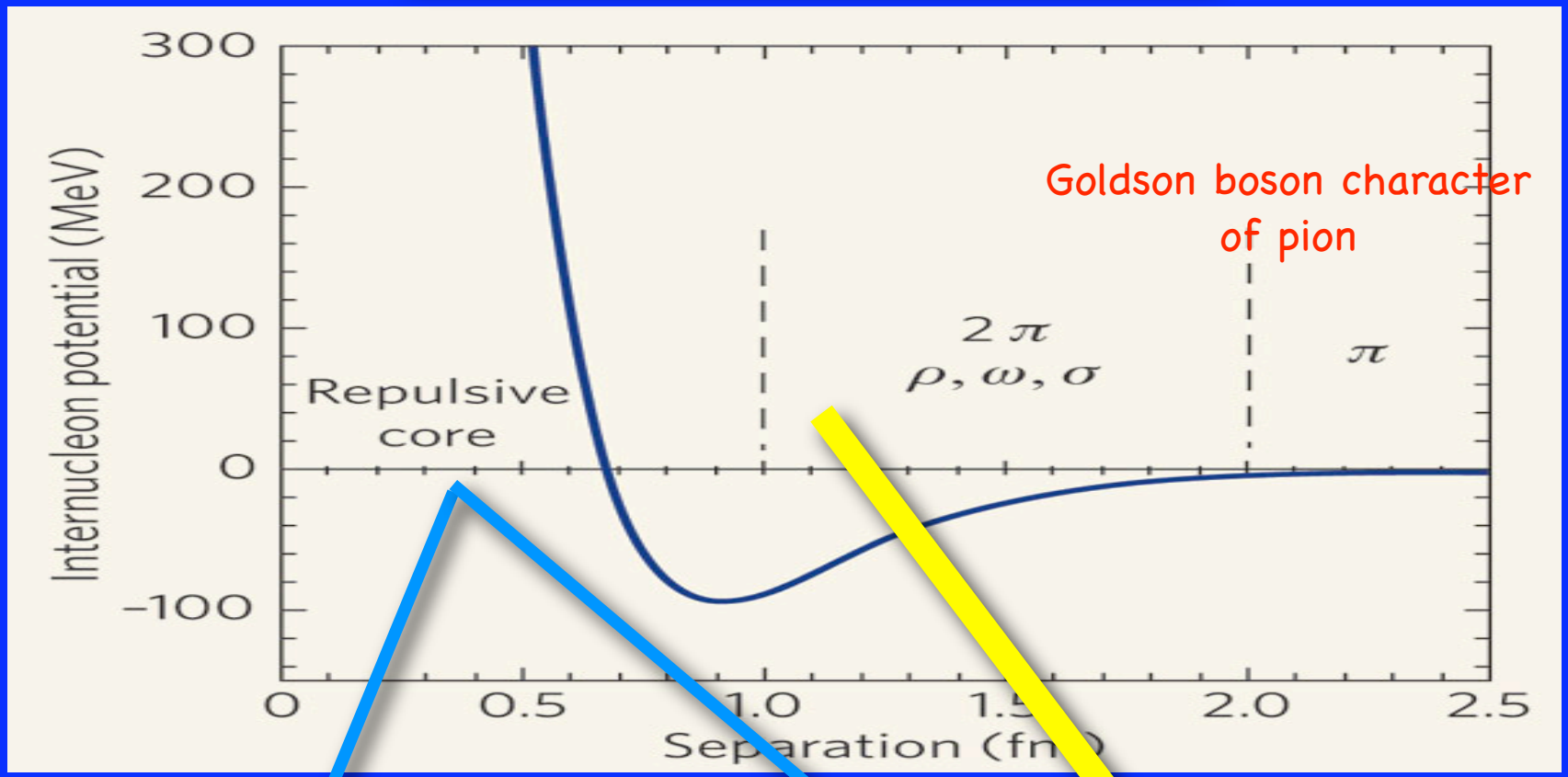
end of 70's

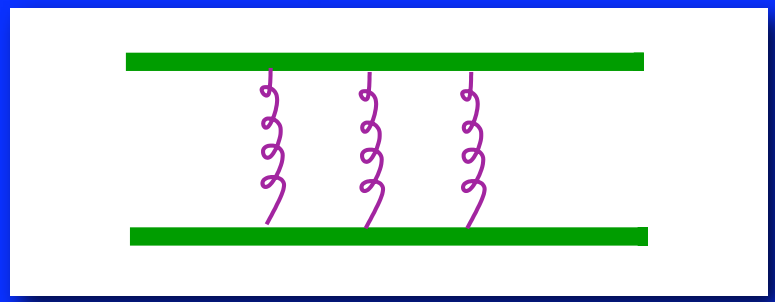


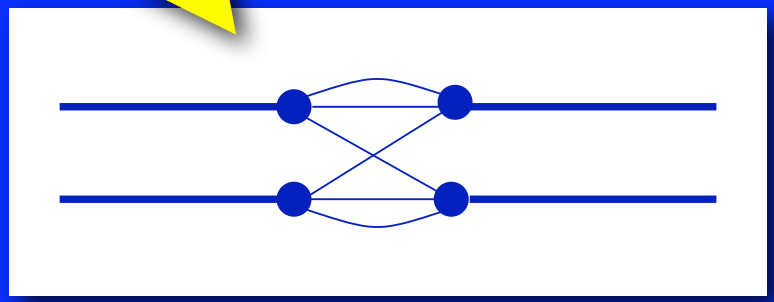
$$\frac{Q}{\Lambda_\chi}, \quad \Lambda_\chi \sim 1GeV \quad Q < 1GeV/c$$

NN-intro: QCD - Quark_Gluon

mid 70's







$Q > 1GeV/c$

NN-intro: Experiments

AGS Last Relevant Experiment, 1994

JPARC pA, pp

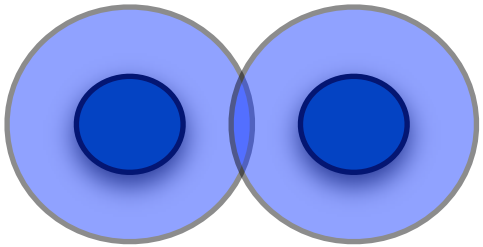
FAIR $\bar{p}$(p)A,

.....

JLAB e+d → e' + p + n

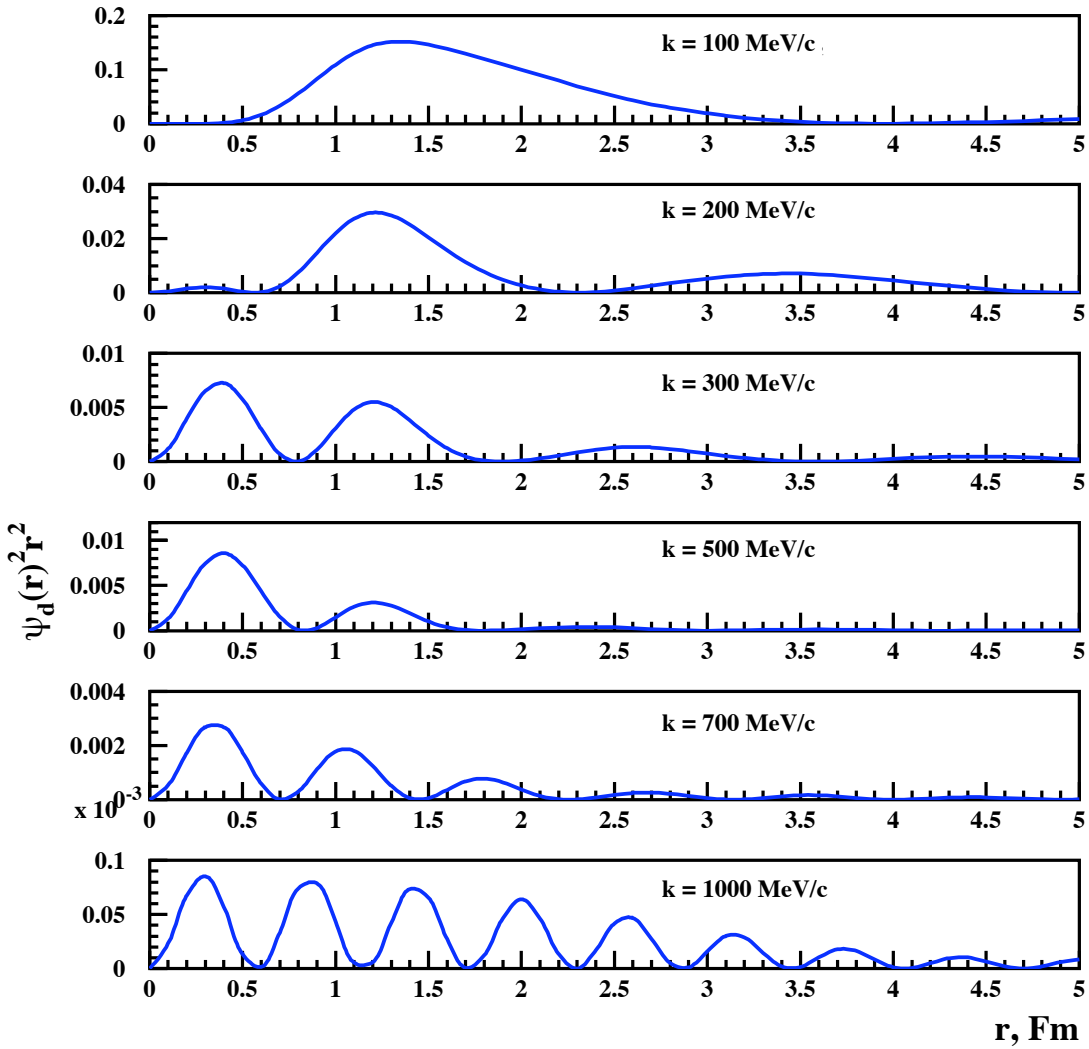
How to get nucleons close together

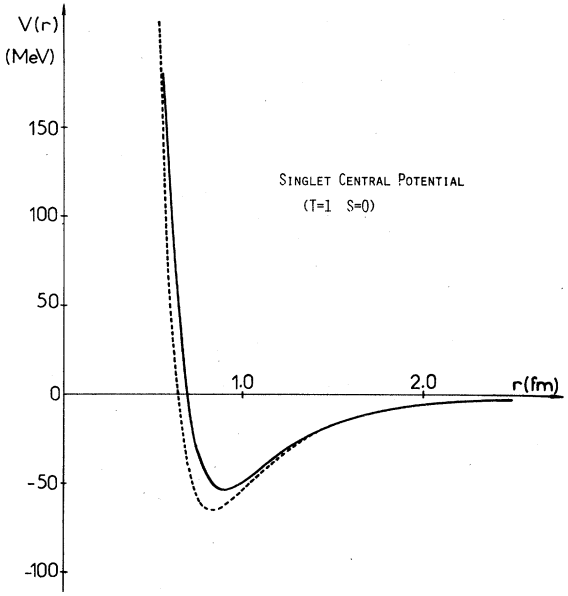
Probing at large relative momenta



$$r \sim \frac{1}{k}$$

$$\psi(r,k) \sim \int \Theta(k-p)\psi(p)e^{-ipr}d^3p$$





We study Deuteron Electrodisintegration

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

$n \longrightarrow$ recoil

$p \longrightarrow$ knock-out

in knock-out kinematics

at

$$(a)\ Q^2 > M_N^2\ \mathrm{GeV}^2$$

$$(b)\ \vec{p}_f \approx \vec{q}$$

$$(c)\ \ p_f \gg p_r \geq 300\ \mathrm{MeV/c}$$

M.Sargsian, arXiv:0910.2016v2,

efforts to cover also the intermediate range

$$(a)\ Q^2 > M_N^2\ \mathrm{GeV}^2$$

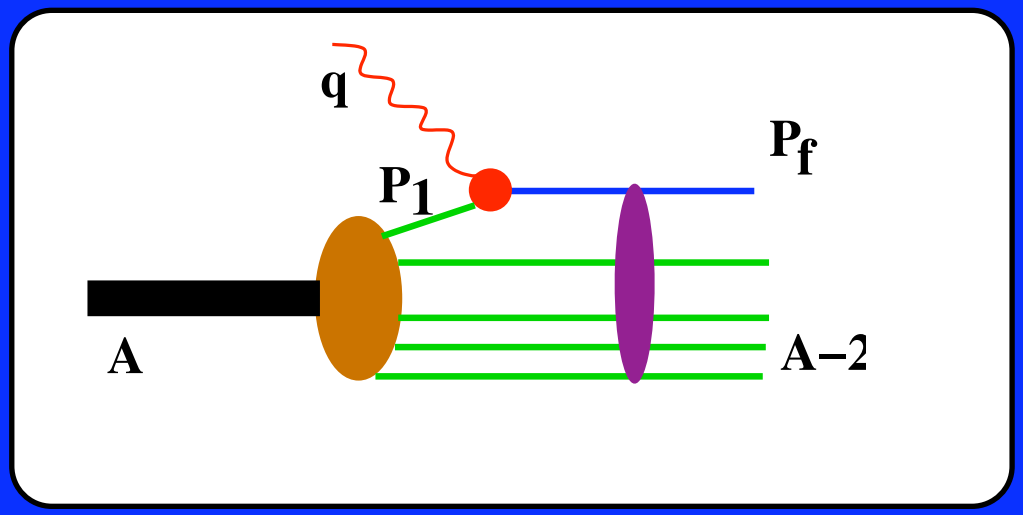
S.Jeschonnek, J.W. Van Orden, 2008,2009

Generalized Eikonal Approximation

Frankfurt, Greenberg, Miller, MS, Strikman, ZPhys 1995 ,

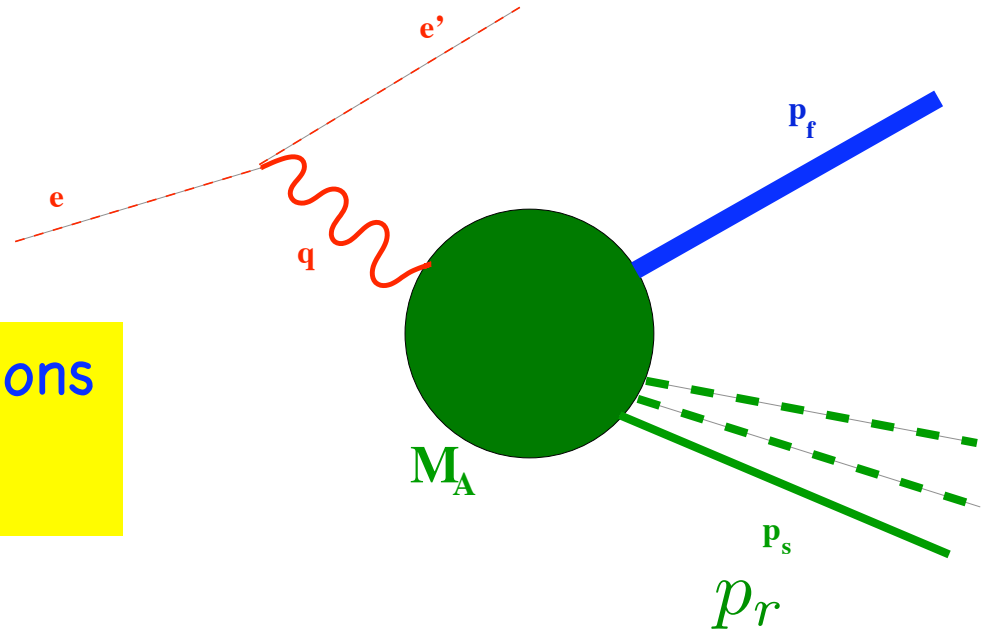
Frankfurt, MS, Strikman, PRC1997 ,

MS, Int. J. Mod. Phys 2001,



High Energy Photo/Electro-Nuclear Reactions

Kinematics

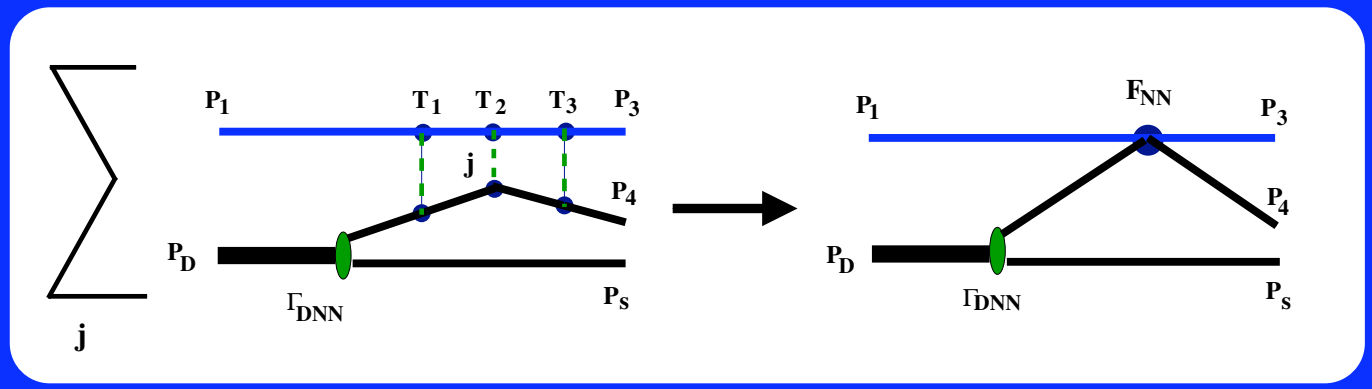


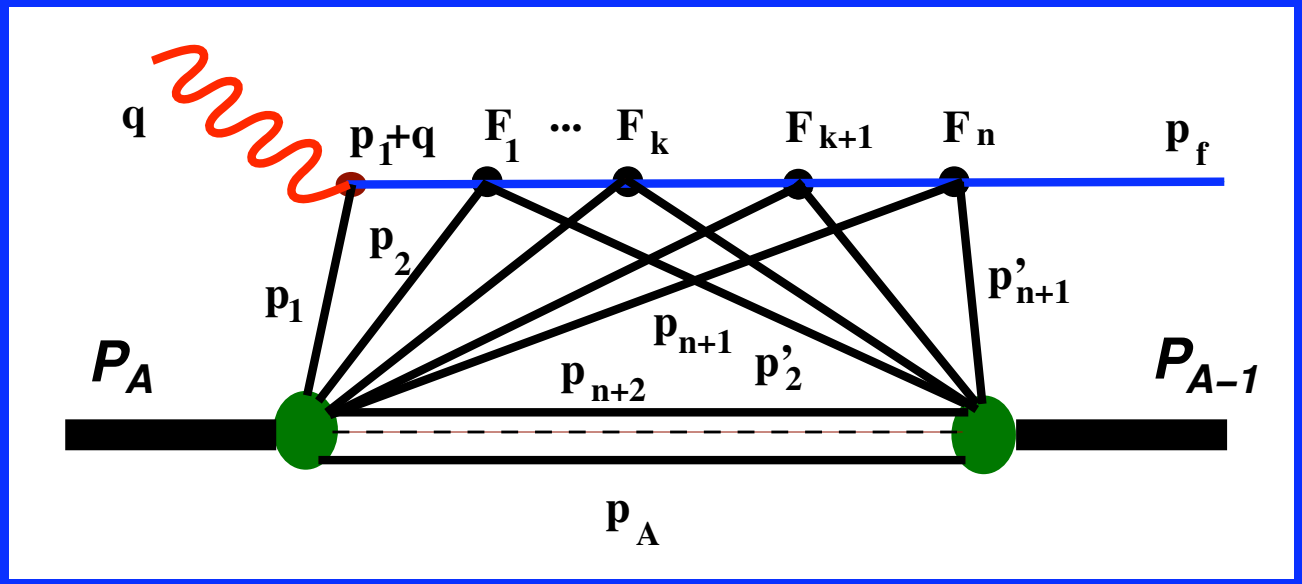
I. Momenta involved in the reactions
$q \approx p_f >$ few GeV/c.

A new small parameter

$$\frac{p_-^f}{p_+^f} \equiv \frac{E^f - p_z^f}{E^f + p_z^f} \approx \frac{m^2}{4p_z^{f,2}} \ll 1$$

$$\frac{x_{Bj} m^2}{Q^2} \ll 1$$

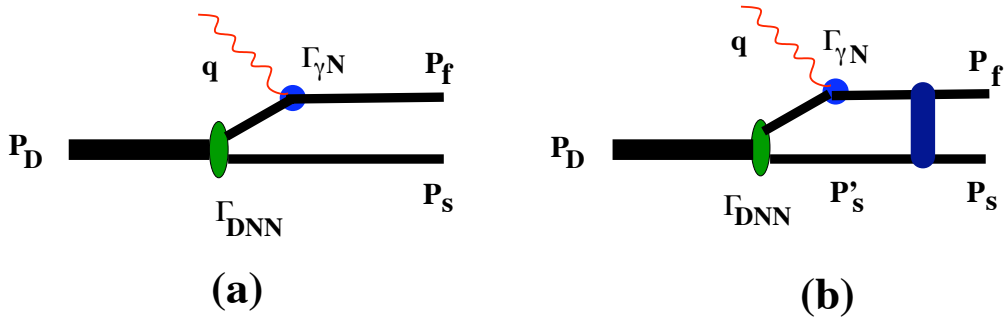




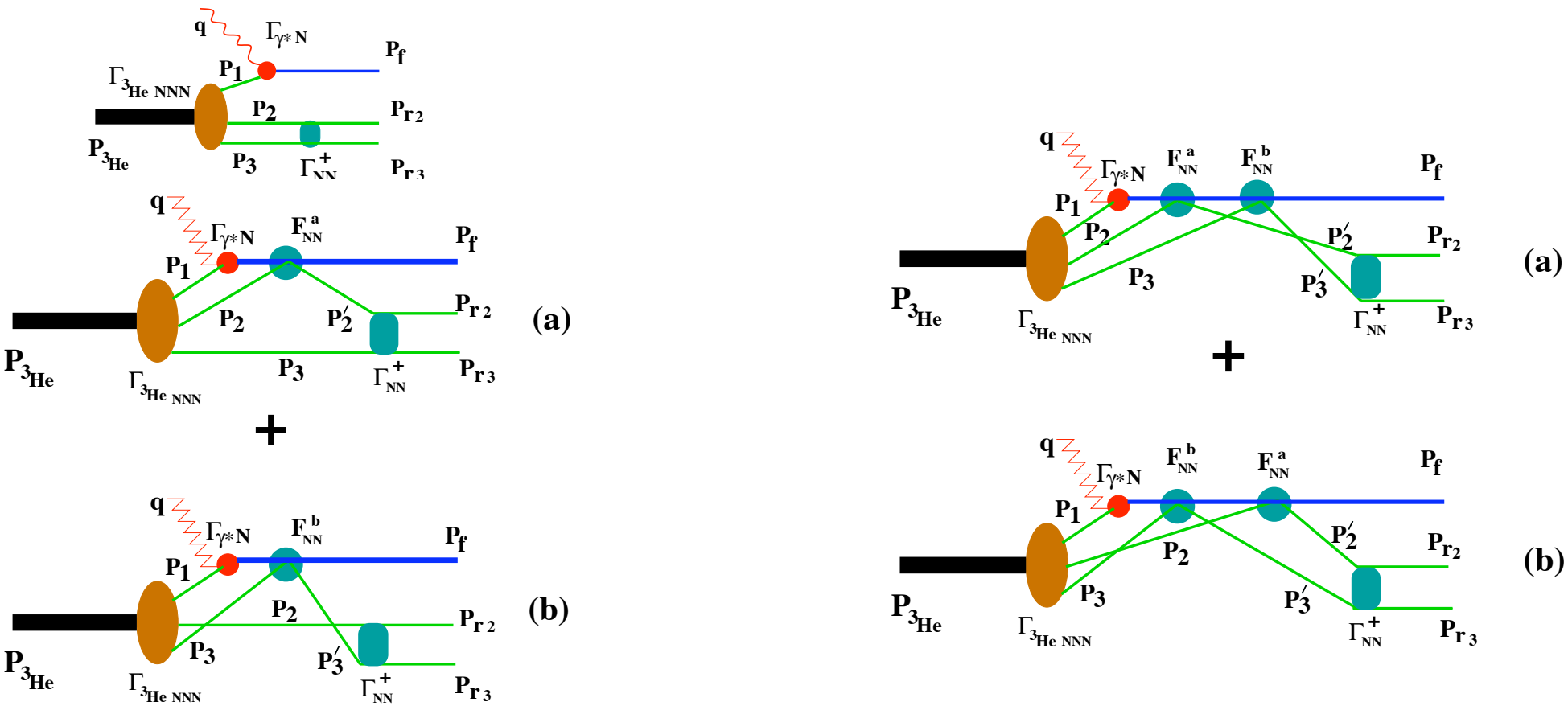
Effective Feynman Diagram Rules

MS, Int. J. Mod. Phys 2001,

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



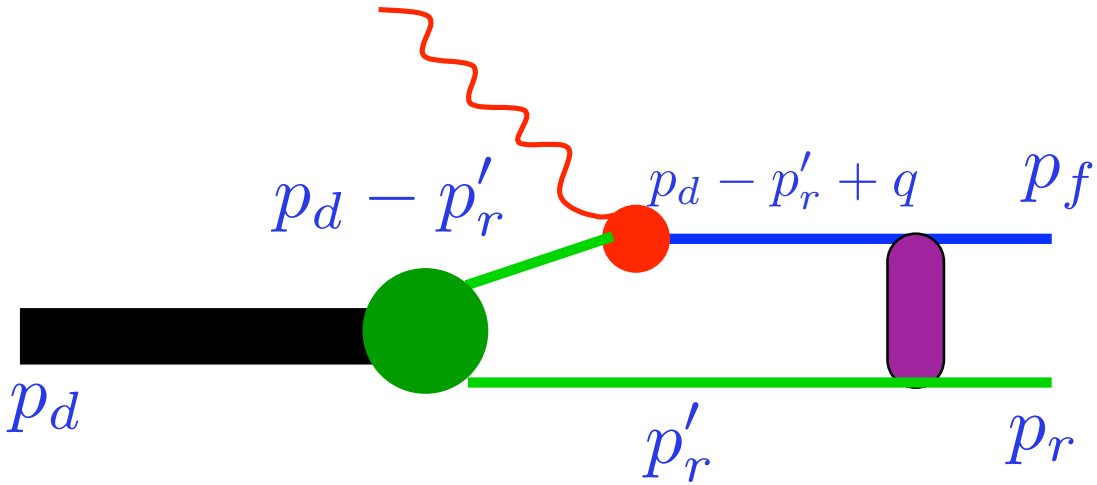
$$e + {}^3He \longrightarrow e' + p + p + n$$



$e + d \to e + p + n$

Frankfurt, Greenberg, Miller, MS, Strikman, ZPhys 1995 ,

Frankfurt, MS, Strikman, PRC1997 ,



Interested only in Final State Interaction

$$A_1^\mu = -\int \frac{d^4 p'_r}{i(2\pi)^4} \frac{\bar{u}(p_f)\bar{u}(p_r) F_{NN} [\not{p}'_r + m][\not{p}_D - \not{p}'_r + \not{q} + m]}{(p_D - p'_r + q)^2 - m^2 + i\epsilon} \frac{\Gamma^\mu_{\gamma^* N}[\not{p}_D - \not{p}'_r + m]\Gamma_{DNN}}{((p_D - p'_r)^2 - m^2 + i\epsilon)(p'^2_r - m^2 + i\epsilon)}.$$

$$\int \frac{d^0 p'_r}{p'^2_r - m^2 + i\epsilon} = -\frac{i(2\pi)}{2E'_r}$$

$$A_1^\mu = -\sqrt{2}(2\pi)^{\frac{3}{2}} \sum_{\lambda_1} \int \frac{d^3p'_r}{(2\pi)^3} \frac{1}{\sqrt{2E'_r}} \frac{\sqrt{s(s-4m^2)} f_{pn}(p_{r\perp} - p'_{r\perp})}{(p_D - p'_r + q)^2 - m^2 + i\epsilon}$$

$$\times J^\mu_{\gamma^* N}(\lambda_f, p_D - p'_r + q; \lambda_1, p_D - p'_r) \cdot \frac{\psi_D(p'_r)}{N(p'_r)}.$$

$$(p_D - p'_r + q)^2 - m^2 + i\epsilon = m_D^2 - 2p_D p'_r + p'^2_r + 2q(p_D - p'_r) - Q^2 - m^2 + i\epsilon.$$

From Energy-Momentum conservation

$$(p_D - p_r + q)^2 = m^2 = m_D^2 - 2p_D p_r + m^2 + 2q(p_D - p_r) - Q^2$$

$$(p_D - p'_r + q)^2 - m^2 + i\epsilon = 2|\mathbf{q}| \left[p'_{rz} - p_{rz} + \frac{q_0}{|\mathbf{q}|}(E_r - E'_r) + \frac{m_D}{|\mathbf{q}|}(E_r - E'_r) \right].$$

$$A_1^\mu = -(2\pi)^{\frac{3}{2}} \sum_{\lambda_1} \int \frac{d^3p'_r}{(2\pi)^3} \frac{1}{2|q|\sqrt{E'_r}} \frac{\sqrt{s(s-4m^2)} f_{pn}(p_{r\perp} - p'_{r\perp})}{p'_{rz} - p_{rz} + \Delta + i\epsilon}$$

$$\times J^\mu_{\gamma^* N}(\lambda_f, p_D - p'_r + q; \lambda_1, p_D - p'_r) \cdot \frac{\psi_D(p'_r)}{N(p'_r)}.$$

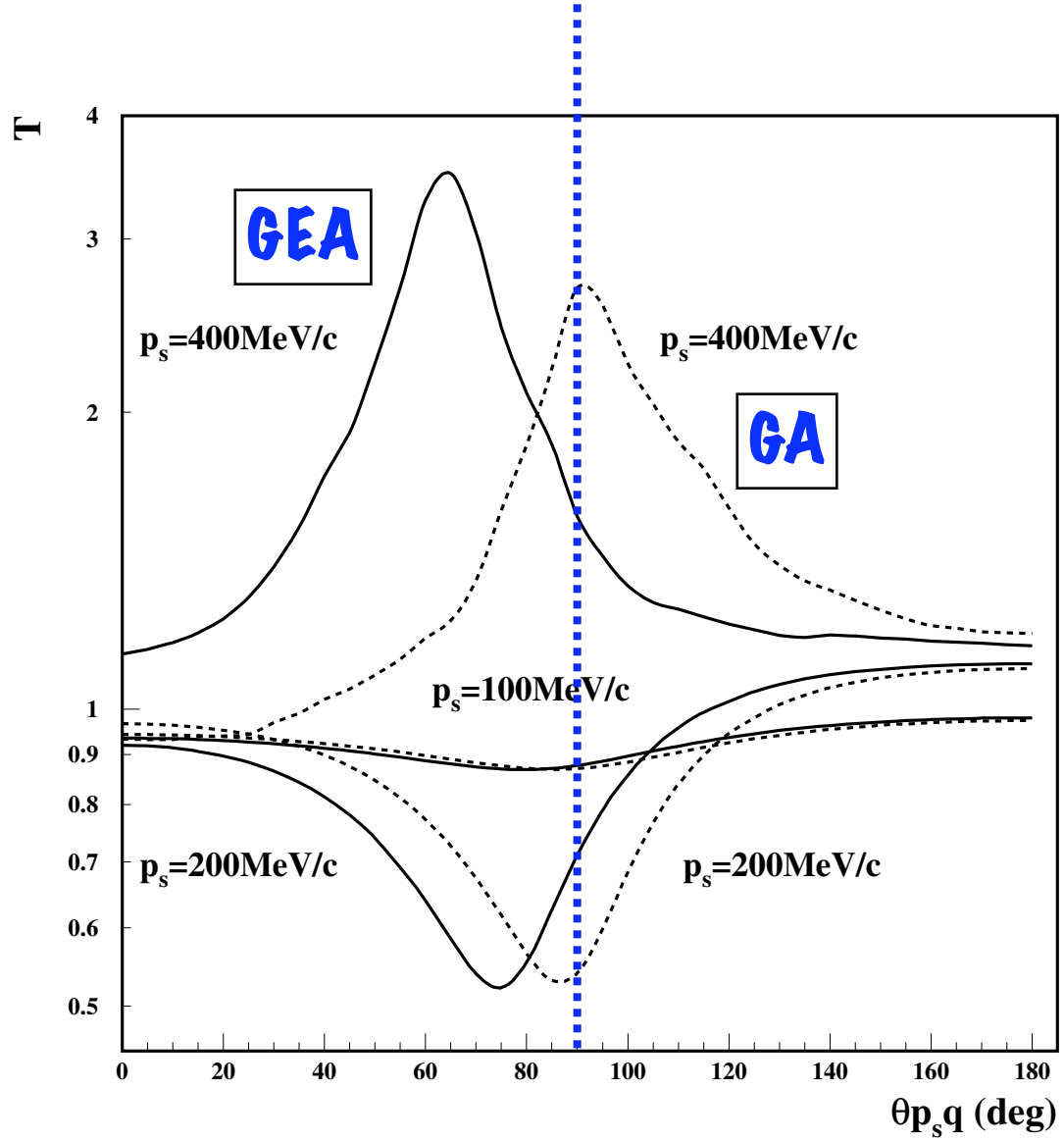
where $\Delta = \frac{q_0}{|q|}(E_r - E'_r) + \frac{M_d}{|q|}(E_r - E'_r)$

$$\int \frac{dp'_{rz}}{(2\pi)} \frac{\Psi_d(p'_r)}{p'_{rz} - (p_{rz} - \Delta) + i\varepsilon} = -\frac{i}{2}\left[\Psi_d(\tilde{p}_r) + i\tilde{\Psi}_d(\tilde{p}_r)\right]$$

where $\tilde{p}_r \equiv (p'_{r\perp}, p_{rz} - \Delta)$

$$A_1^\mu = -\frac{\sqrt{2}(2\pi)^{\frac{3}{2}}}{4i} \sum_{\lambda_1} \int \frac{d^2k_\perp}{(2\pi)^2} \sqrt{2E'_r} \frac{\sqrt{s(s-4m^2)}}{2|q|E'_r}$$

$$\left[f^{on}_{pn}(k_\perp) J^{\mu,on}_{\gamma^* N} \Psi_D(\tilde{p}_r) + i f^{off}_{pn}(k_\perp) J^{\mu,off}_{\gamma^* N} \tilde{\Psi}(\tilde{p}_r)\right] \frac{1}{N(p'_r)}$$



$$T = \frac{\sigma^{PWIA+FSI}}{\sigma^{PWIA}}$$

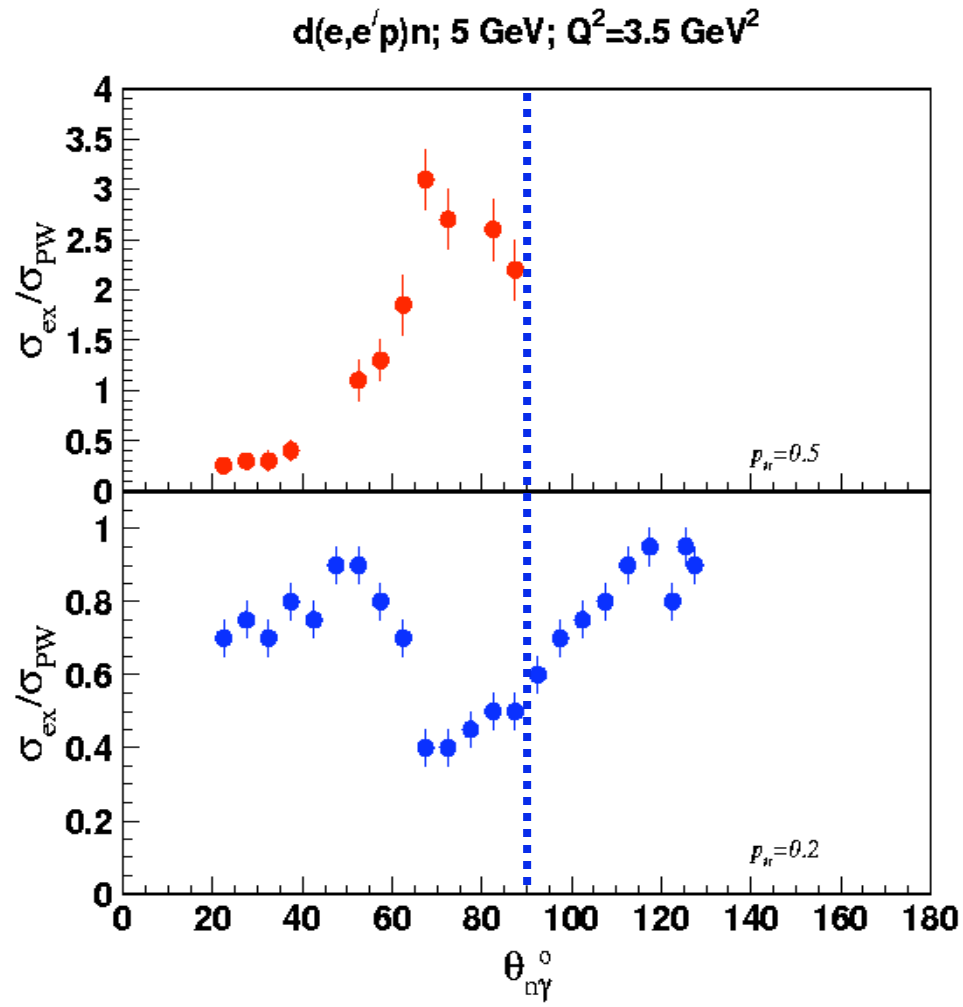
Frankfurt, Greenberg, Miller, MS, Strikman, ZPhys 1995 ,

Frankfurt, MS, Strikman, PRC1997 ,

J.M.Laget CT Workshop 1997

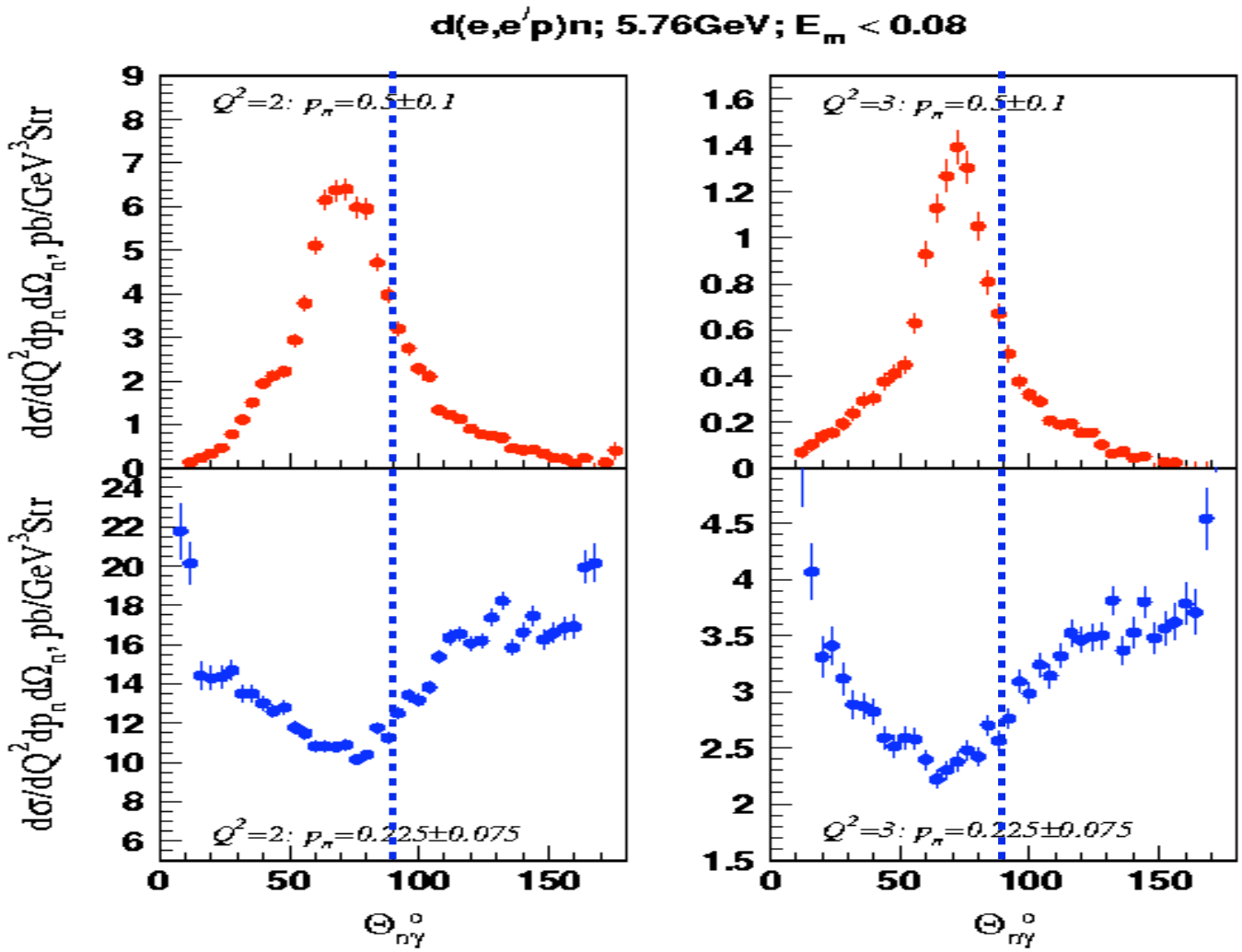
Recoil-Neutron Angular Distributions; Hall A Exp.

Werner Boeglin
Luminita Coman, PhD 2007



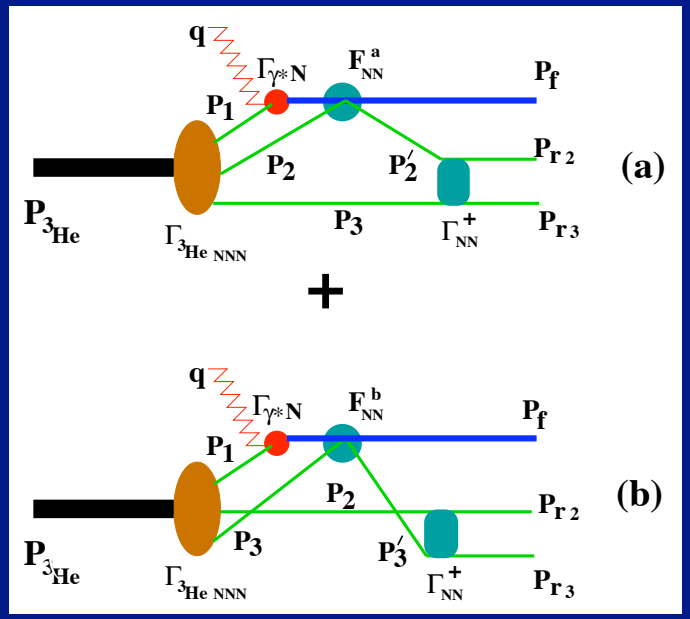
PRELIMINARY

Recoil-Neutron's Angular Distributions - I



K. Egiyan et al, PRL07

Single Rescattering

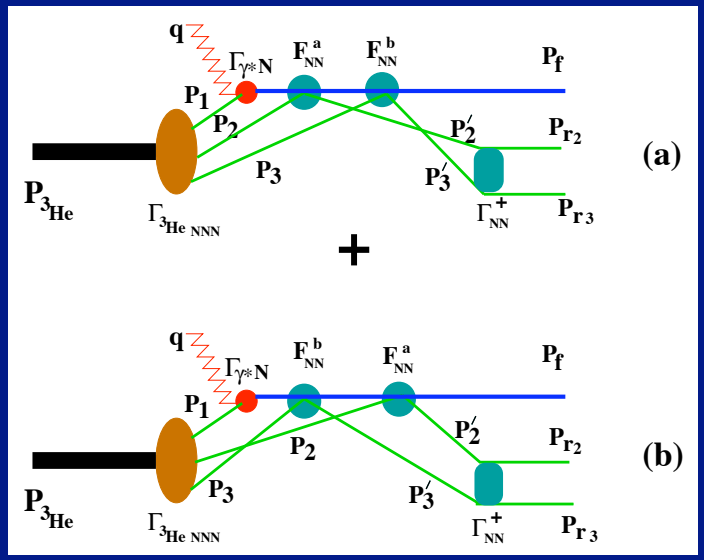


$$
\begin{aligned}
A^{\mu}_{1\mathrm{a}} &= -\int \frac{d^4p_2}{i(2\pi)^4}\frac{d^4p_3}{i(2\pi)^4}\bar{u}(p_{r3})\bar{u}(p_{r2})\bar{u}(p_f)\frac{\Gamma^+_{NN}(p_2',p_3)(\hat{p}_2'+m)}{p_2'^2-m^2+i\varepsilon}\times \\
&\times \frac{F^{\mathrm{a}}_{NN}(p_2'-p_2)(\hat{p}_1+\hat{q}+m)}{(p_1+q)^2-m^2+i\varepsilon}\cdot\Gamma^{\mu}_{\gamma^* N}\cdot\frac{\hat{p}_3+m}{p_3^2-m^2+i\varepsilon}\times \\
&\times \frac{\hat{p}_2+m}{p_2^2-m^2+i\varepsilon}\cdot\frac{\hat{p}_1+m}{p_1^2-m^2+i\varepsilon}\cdot\Gamma_{^3\mathrm{He}NNN}(p_1,p_2,p_3)\,\chi^A.
\end{aligned}
$$

$$
\begin{aligned}
A^{\mu}_{1a} &= -\frac{F}{2}\sum_{s_{1'},s_{2'},s_1,s_2,s_3}\ \sum_{t_1,t_{2'},t_2,t_3}\int\frac{d^3p_2}{(2\pi)^3}d^3p_3\,\Psi^{\dagger p_{r2},s_{r2},t_{r2};p_{r3},s_{r3},t_{r3}}_{NN}(p_2',s_{2'},t_{2'};p_3,s_3,t_3) \\
&\times \frac{\sqrt{s_2^{NN}(s_2^{NN}-4m^2)}}{2qm}\,\frac{f_{NN}(p_2',s_{2'},t_{2'},p_f,s_f,t_f;|p_2,s_2,t_2,p_1+q,s_{1'},t_1)}{p_{mz}+\Delta^0-p_{1z}+i\varepsilon} \\
&\times j^{\mu}_{t_1}(p_1+q,s_{1'};p_1,s_1)\cdot\Psi^{s_A}_A(p_1,s_1,t_1;p_2,s_2,t_2;p_3,s_3,t_3).
\end{aligned}
$$

$$
\Delta^0 = \frac{q_0}{q}\left(T_{r2}+T_{r3}+|\epsilon_A|\right)
$$

Double Rescattering



$$
\begin{aligned}
A^{\mu}_{2a} \;=\; & \frac{F}{4} \sum_{s_1,s_2,s_3} \sum_{t_1,t_2,t_3,t_{1'},t_{2'},t_{3'}} \int \frac{d^3p'_3}{(2\pi)^3} \frac{d^3p_2}{(2\pi)^3} d^3p_3 \Psi^{\dagger p_{r2},s_{r2},t_{r2};p_{r3},s_{r3},t_{r3}}_{NN}(p'_2,s_2,t_{2'};p'_3,s_3,t_{3'}) \times \\
\times \; & \frac{\chi_2(s^{NN}_{b3}) f^{t_{3'},t_f|t_3,t_{1'}}_{NN}(p'_{3\perp}-p_{3\perp})}{\Delta_3 + p'_{3z} - p_{3z} + i\varepsilon} \frac{\chi_1(s^{NN}_{a2}) f^{t_{2'},t_{1'}|t_2,t_1}_{NN}(p'_{2\perp}-p_{2\perp})}{\Delta^0 + p_{mz} - p_{1z} + i\varepsilon} \\
\times \; & j^{\mu}_{t1}(p_1+q,s_f;p_1,s_1) \cdot \Psi^{s_A}_A(p_1,s_1,t_1;p_2,s_2,t_2;p_3,s_3,t_3),
\end{aligned}
$$

$$
\Delta^3 \approx \frac{E_f}{p_{fz}} T_{r3}
$$

e + d ⟶ e' + p + n

extending range of the recoil nucleon momenta

Virtual Nucleon Approximation

Main Assumptions

- we consider only pn component of the deuteron

$$T_N < 2(m_\Delta - m_N) \sim (m_{N^*} - m) \sim 500 \text{ MeV}$$

- neglect the negative energy projection of virtual nucleon

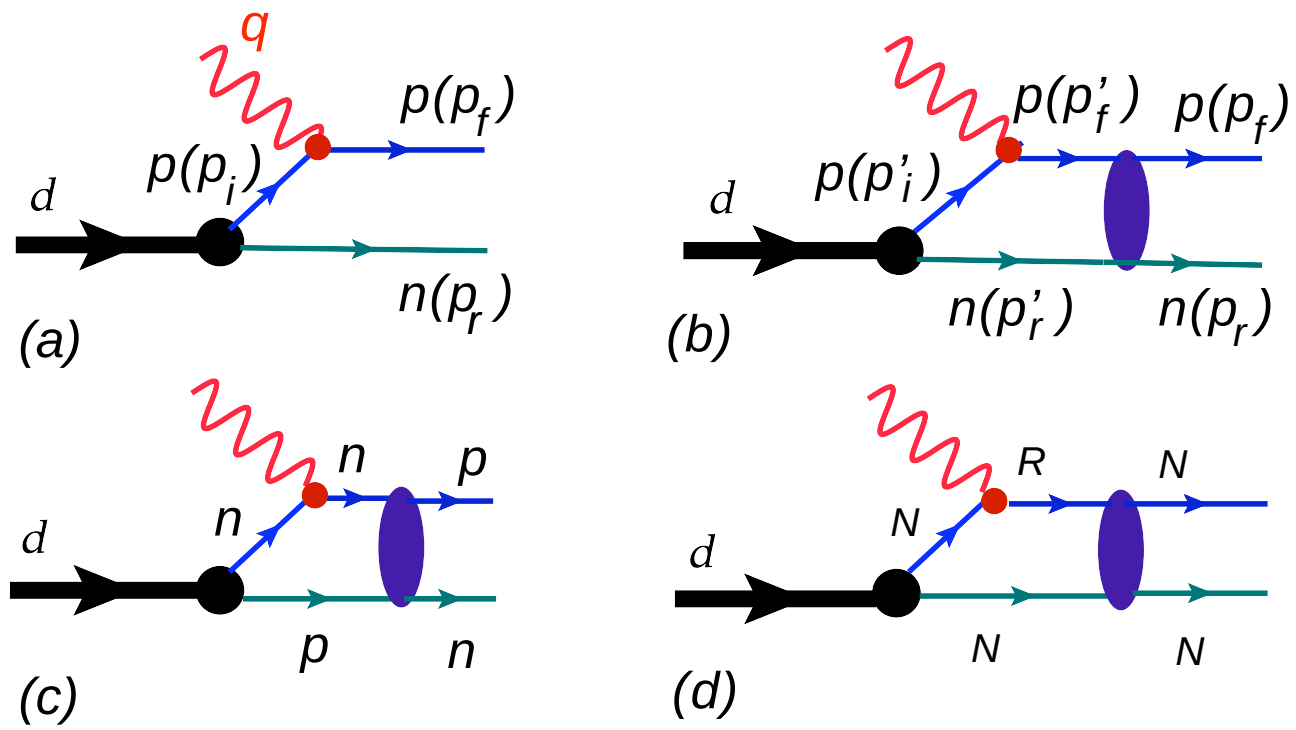
$$M_d - \sqrt{m^2 + p^2} > 0$$

$$p \leq 700 \text{ MeV/c}$$

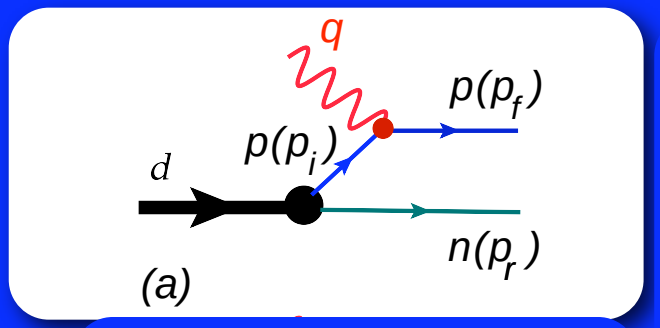
- neglect by meson exchange currents

$$Q^2 \geq 1 \text{ GeV}^2$$

e + d ⟶ e' + p + n



Plane Wave Impulse Approximation Amplitude



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

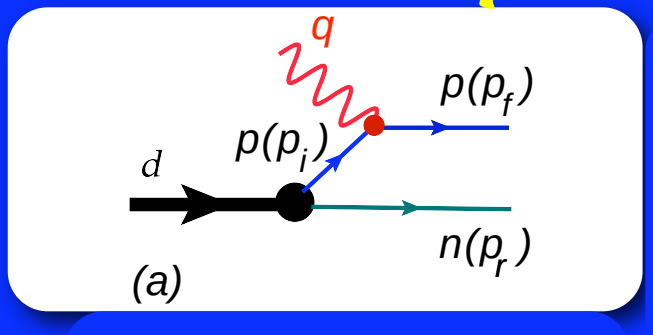
$$p_i = (E_d - E_r, \vec{p}_d - \vec{p}_r) = (M_d - E_r, -\vec{p}_r)\,|_{LaB}\,.$$

$$\not{p}_i + m = \not{p}_i^{on} + m + (E_i^{off} - E_i^{on})\gamma^0, \qquad E_{off} = M_d - \sqrt{m^2 + p^2}, \quad E_{on} = \sqrt{m^2 + p^2}$$

$$\langle s_f, s_r \mid A^\mu_{0,on} \mid s_d \rangle = -\bar{u}(p_r, s_r)\Gamma^\mu_{\gamma^* p}\frac{\not{p}_i^{on} + m}{p_i^2 - m^2} \cdot \bar{u}(p_f, s_f)\Gamma_{DNN}\chi_d^s,$$

$$\langle s_f, s_r \mid A^\mu_{0,off} \mid s_d \rangle = -\bar{u}(p_r, s_r)\Gamma^\mu_{\gamma^* p}\frac{(E_i^{off} - E_i^{on})\gamma^0}{p_i^2 - m^2} \cdot \bar{u}(p_f, s_f)\Gamma_{DNN}\chi_d^s.$$

Plane Wave Impulse Approximation Amplitude



$$\not{p}_i^{on} + m = \sum_{s_i} u(p_i, s_i)\bar{u}(p_i, s_i)$$

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

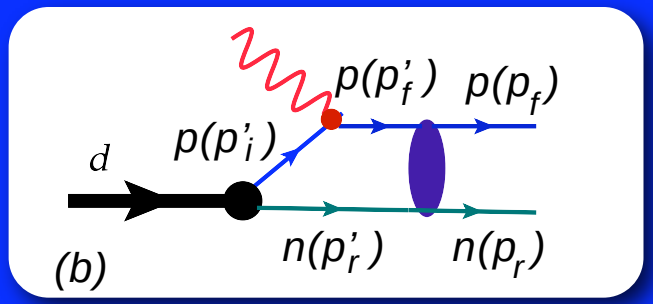
$$\langle s_f, s_r \mid A_0^\mu \mid s_d\rangle = \sqrt{2}\sqrt{(2\pi)^3 2E_r}\sum_{s_i} J_N^\mu(s_f, p_f; s_i, p_i)\Psi_d^{s_d}(s_i, p_i, s_r, p_r)$$

$$J_N^\mu(s_f, p_f; s_i, p_i) = J_{N,on}^\mu(s_f, p_f; s_i, p_i) + J_{N,off}^\mu(s_f, p_f; s_i, p_i).$$

$$J_{N,on}^\mu(s_f, p_f; s_i, p_i) = \bar{u}(p_f, s_f)\Gamma^\mu_{\gamma^* N}u(p_i, s_i).$$

$$J_{N,off}^\mu(s_f, p_f; s_i, p_i) = \bar{u}(p_f, s_f)\Gamma^\mu_{\gamma^* N}\gamma^0 u(p_i, s_i)\frac{E_i^{off}-E_i^{on}}{2m}$$

Forward Elastic Final State Interaction Amplitude



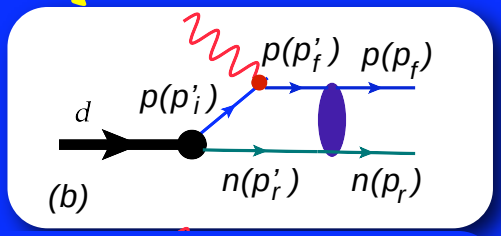
$$\langle s_f, s_r \mid A_1^\mu \mid s_d \rangle = -\int \frac{d^4 p'_r}{i(2\pi)^4} \frac{\bar{u}(p_f, s_f)\bar{u}(p_r, s_r) F_{NN} [\not{p}'_r + m][\not{p}_d - \not{p}'_r + \not{q} + m]}{(p_d - p'_r + q)^2 - m^2 + i\epsilon} \times \frac{\Gamma_{\gamma^* N}[\not{p}_d - \not{p}'_r + m]\Gamma_{DNN}\chi^{s_d}}{((p_d - p'_r)^2 - m^2 + i\epsilon)(p'^2_r - m^2 + i\epsilon)}, \quad (1)$$

$$\int \frac{d^0 p'_r}{p'^2_r - m^2 + i\epsilon} = -i\frac{2\pi}{2E'_r}$$

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

$$\langle p_f, s_f; p_r, s_r \mid f^{NN}(t,s) \mid p'_r, s'_r; p'_f, s'_f \rangle \cdot J_N^\mu(s'_f, p'_f; s_i, p_i) \cdot \Psi_d^{s_d}(s_i, p'_i, s'_r, p'_r). \quad (1)$$

Forward Elastic Final State Interaction Amplitude



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

$$\langle p_f, s_f; p_r, s_r \mid f^{NN}(t,s) \mid p'_r, s'_r; p'_f, s'_f \rangle \cdot J_N^\mu(s'_f, p'_f; s_i, p_i) \cdot \Psi_d^{s_d}(s_i, p'_i, s'_r, p'_r). \quad (1)$$

using condition of quasielastic scattering $(q + p_d - p_r)^2 = p_f^2 = m^2$

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

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

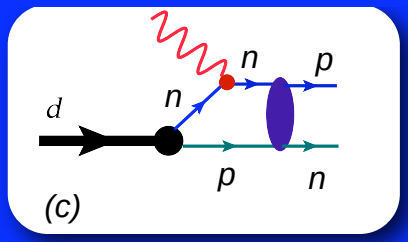
$$\langle s_f, s_r \mid A_1^\mu \mid s_d \rangle = \frac{i\sqrt{2}(2\pi)^{\frac{3}{2}}}{4} \sum_{s'_f, s'_r, s_i} \int \frac{d^2 p'_r}{(2\pi)^2} \frac{\sqrt{2\tilde{E}'_r}\sqrt{s(s-4m^2)}}{2\tilde{E}'_r|q|} \times$$

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

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

$$\frac{\langle p_f, s_f; p_r, s_r \mid f^{NN,off}(t,s) \mid p'_r, s'_r; p'_f, s'_f \rangle}{p'_{r,z} - \tilde{p}'_{r,z}} J_N^\mu(s'_f, p'_f; s_i, p'_i) \cdot \Psi_d^{s_d}(s_i, p'_i, s'_r, p'_r). \quad (1)$$

Charge -Exchange Final State Interaction Amplitude



$$\langle s_f, s_r \mid A^{\mu}_{1,chex} \mid s_d \rangle = \frac{i\sqrt{2}(2\pi)^{\frac{3}{2}}}{4} \sum_{s'_f, s'_r, s_i} \int \frac{d^2 p'_r}{(2\pi)^2} \frac{\sqrt{2\tilde{E}'_r}\sqrt{s(s-4m^2)}}{2\tilde{E}'_r |q|} \times$$

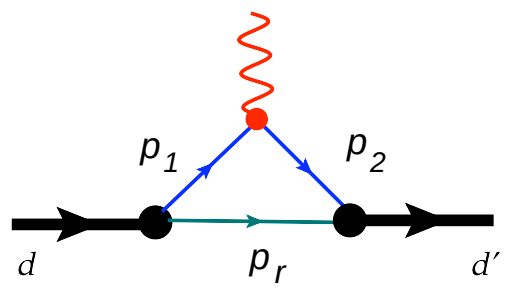
$$\langle p_f, s_f; p_r, s_r \mid f^{chex,on}(t,s) \mid \tilde{p}'_r, s'_r; \tilde{p}'_f, s'_f \rangle \cdot J^{\mu}_n(s'_f, p'_f; s_i, \tilde{p}'_i) \cdot \Psi^{s_d}_d(s_i, \tilde{p}'_i, s'_r, \tilde{p}'_r)$$

$$-\frac{\sqrt{2}(2\pi)^{\frac{3}{2}}}{2} \sum_{s'_f, s'_r, s_1} \mathcal{P} \int \frac{dp'_{r,z}}{2\pi} \int \frac{d^2 p'_r}{(2\pi)^2} \frac{\sqrt{2E'_r}\sqrt{s(s-4m^2)}}{2E'_r |\mathbf{q}|} \times$$

$$\frac{\langle p_f, s_f; p_r, s_r \mid f^{chex,off}(t,s) \mid p'_r, s'_r; p'_f, s'_f \rangle}{p'_{r,z} - \tilde{p}'_{r,z}} J^{\mu}_n(s'_f, p'_f; s_i, p'_i) \cdot \Psi^{s_d}_d(s_i, p'_i, s'_r, p'_r) \quad (1)$$

The Deuteron Wave Function

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

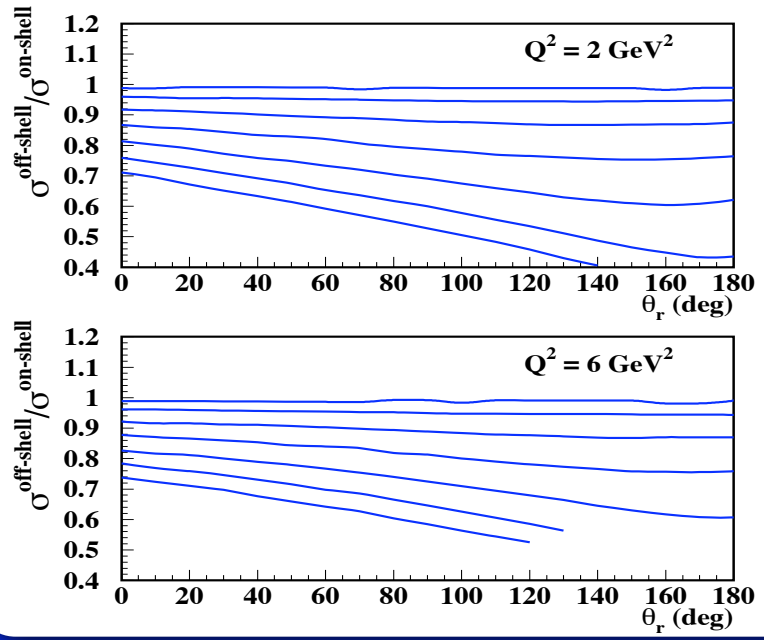


$$\frac{1}{4M_d}\sum_{s'_d=s_d=-1}^{1}\langle p'_d, s'_d \mid A^{\mu=0}(Q^2) \mid p_d, s_d\rangle \mid_{Q^2\to 0} = G_C(0) = 1,$$

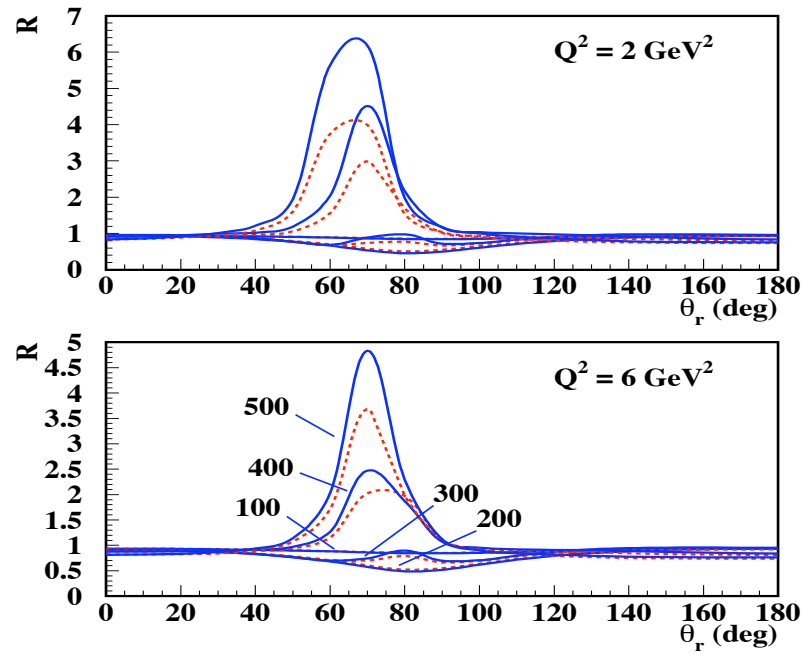
$$\sum_{s_d=-1}^{1}\int \mid \Psi_d^{s_d}(p) \mid^2 \frac{2E_{off}}{M_d} d^3p = 1$$

$$\Psi_d(p) = \Psi_d^{NR}(p)\frac{M_d}{2(M_d-\sqrt{m^2+p^2})}$$

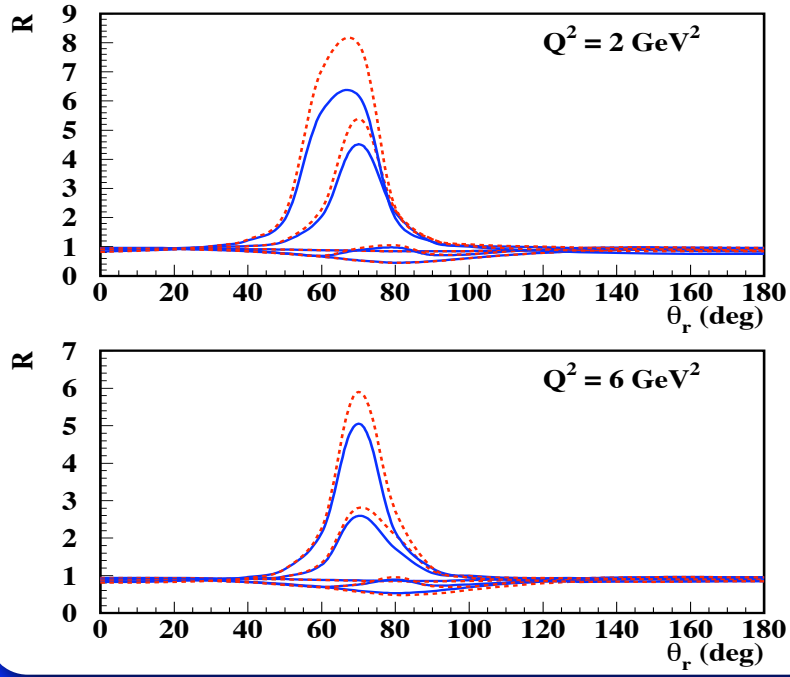
Off-Shell Electromagnetic Current Effects



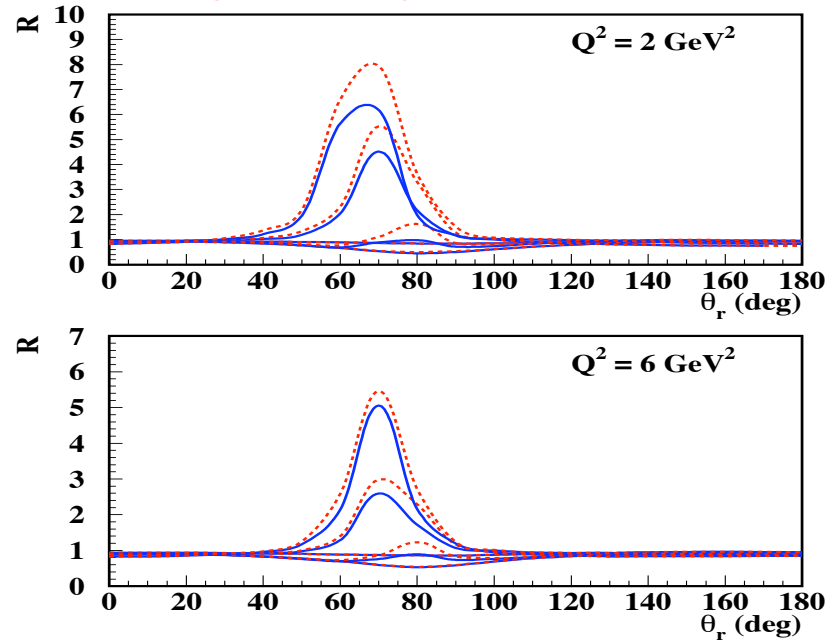
Factorization Approximation



Off-Shell FSI Effects



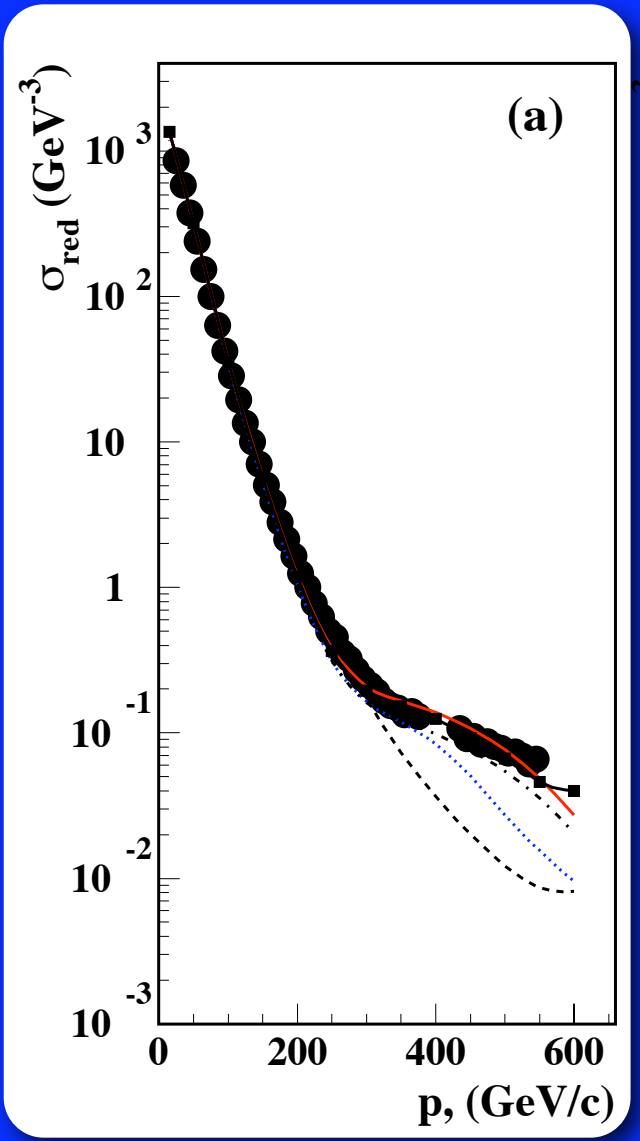
Charge Exchange FSI Effects



Numerical Estimates

JLab Experiment P.E. Ulmer et al. Phys. Rev. Lett. 89, 2002

$$Q^2 = 0.665 GeV^2 \text{ and } x \approx 1$$



$$\sigma_{red} = \frac{d\sigma}{dE'_e, d\Omega_{e'} dp_f d\Omega_f} \cdot \frac{\left| \frac{p_f}{E_f} + \frac{p_f - q cos(\theta_{p_f,q})}{E_r} \right|}{\sigma_{CC1} \cdot p_f^2}$$

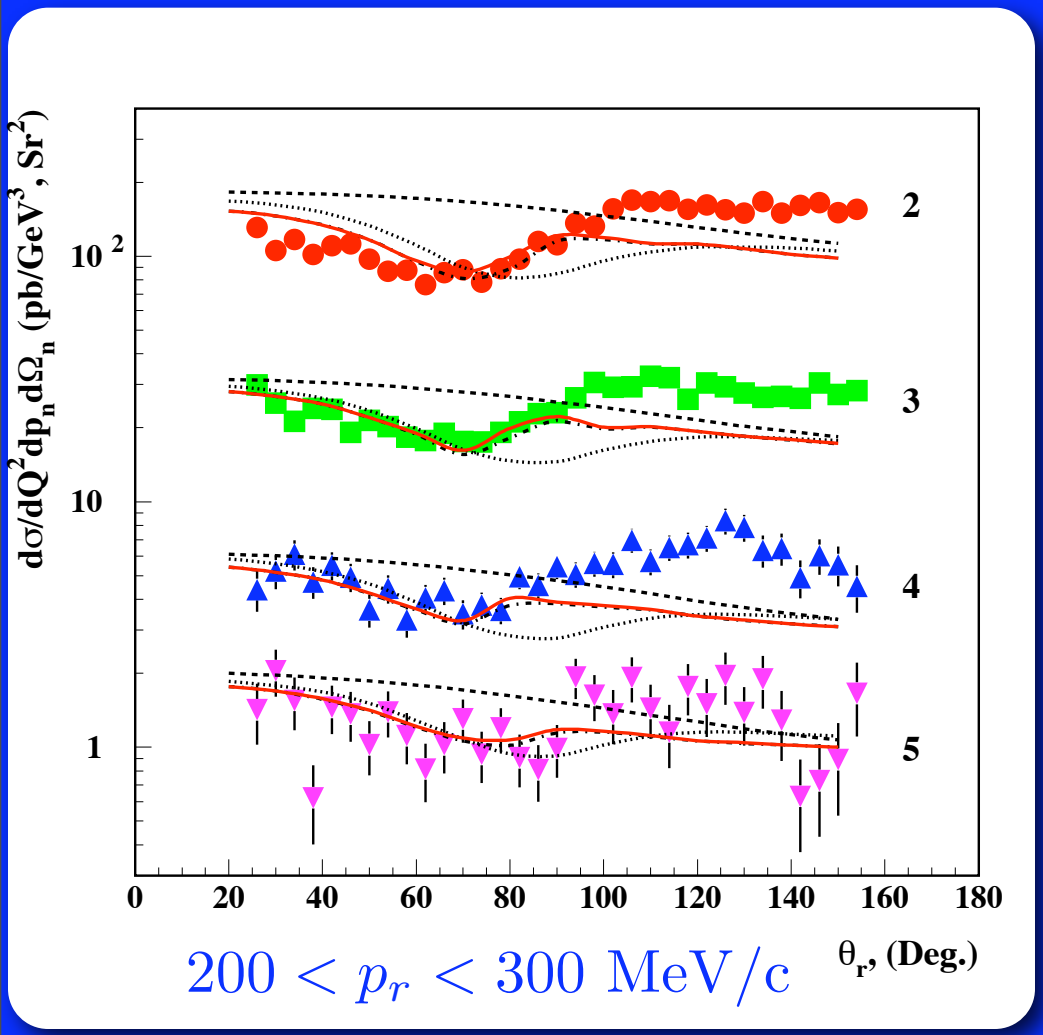
Earlier
S.Jeschonnek and J.W.Van Orden, Phys. Rev. C 78, 2008

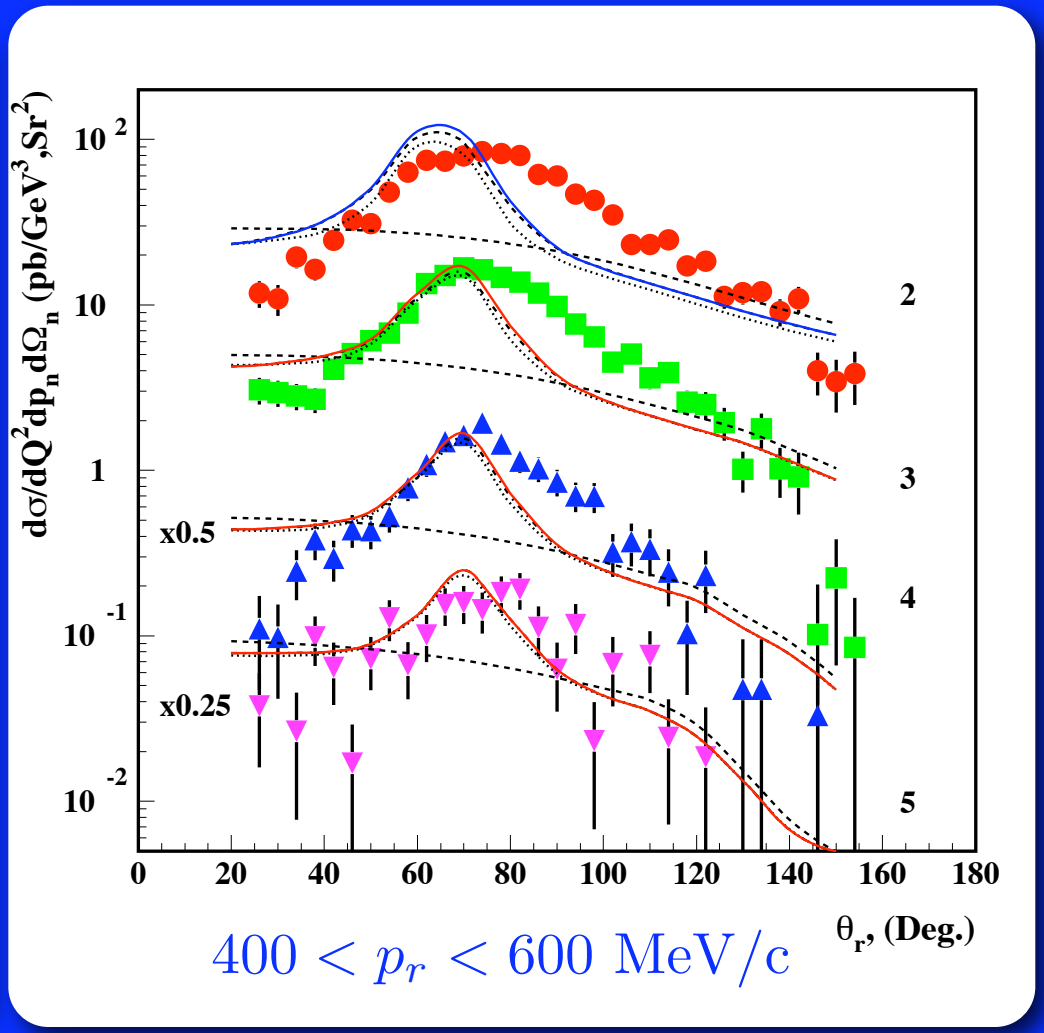
Numerical Estimates

$Q^2 = 2 \pm 0.25; 3 \pm 0.5; 4 \pm 0.5; 5 \pm 0.5 \text{ GeV}^2$

JLab Experiment K.Sh. Egiyan et al. Phys. Rev. Lett. 98 2007

See also J.M.Laget's calculation in the same article



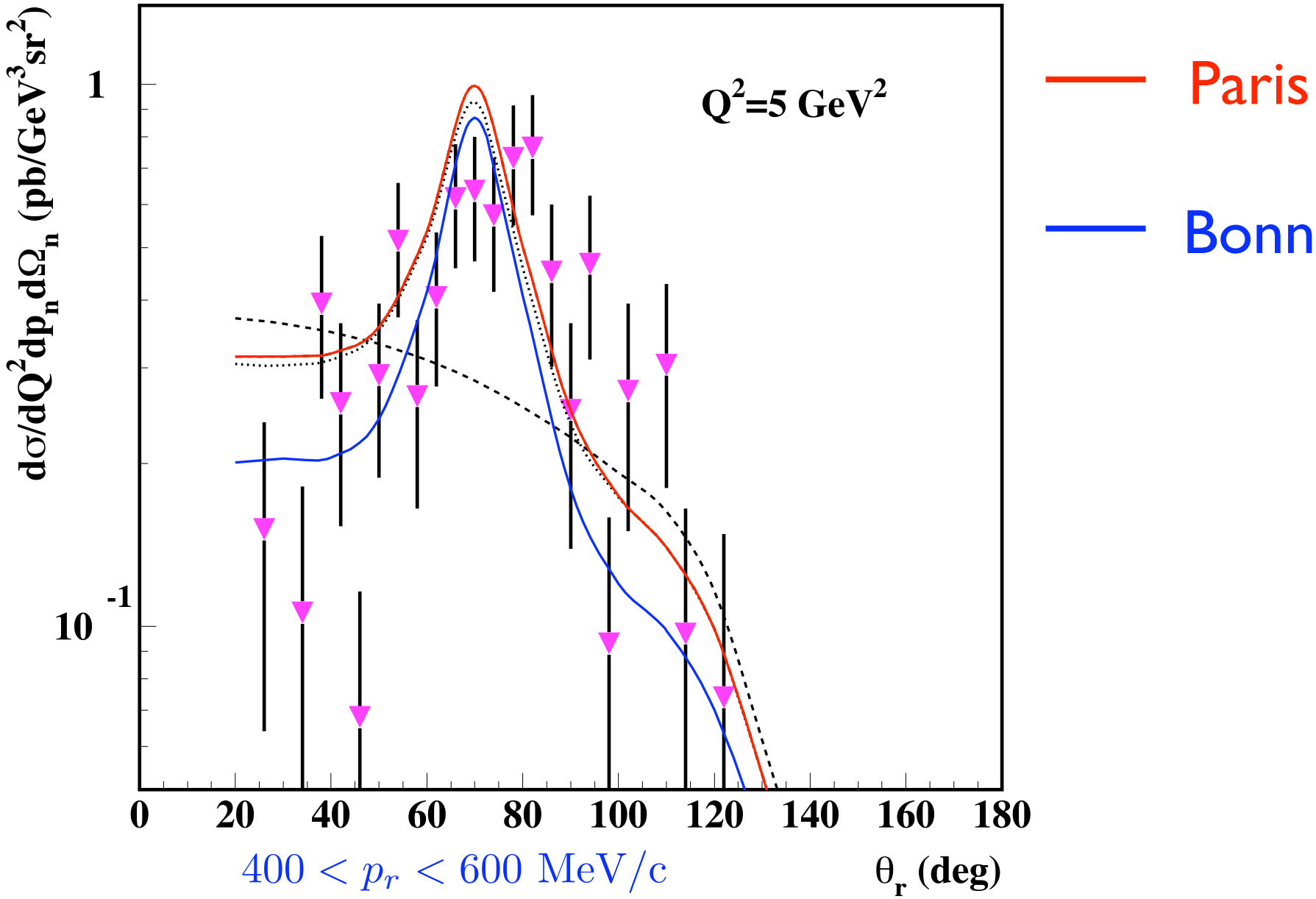


- Starting $Q^2 \geq 4 \text{ GeV}^2$

off-shell effects in the current and FSI are sufficiently well confined

Numerical Estimates

JLab Experiment K.Sh. Egiyan et al. Phys. Rev. Lett. 98 2007



Where we go from here ?

- Isobar Contribution in Virtual Nucleon Approximation

- moving beyond 700 MeV/c Region

- Accounting for vacuum Fluctuations

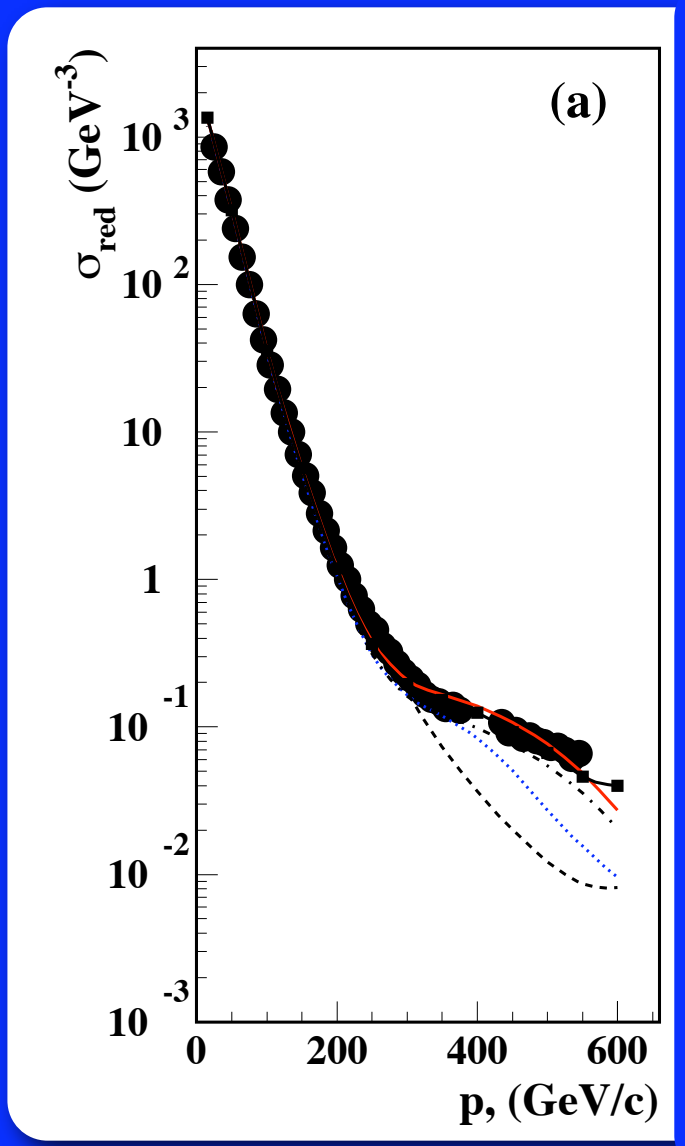
- Wishing for New high Q2 Experimental Data

- One Just Approved by JLAB PAC to measure up to 1500 MeV/c missing momenta

New Phenomenon ?

JLab Experiment P.E. Ulmer et al. Phys. Rev. Lett. 89, 2002

$Q^2 = 0.665 GeV^2$ and $x \approx 1$



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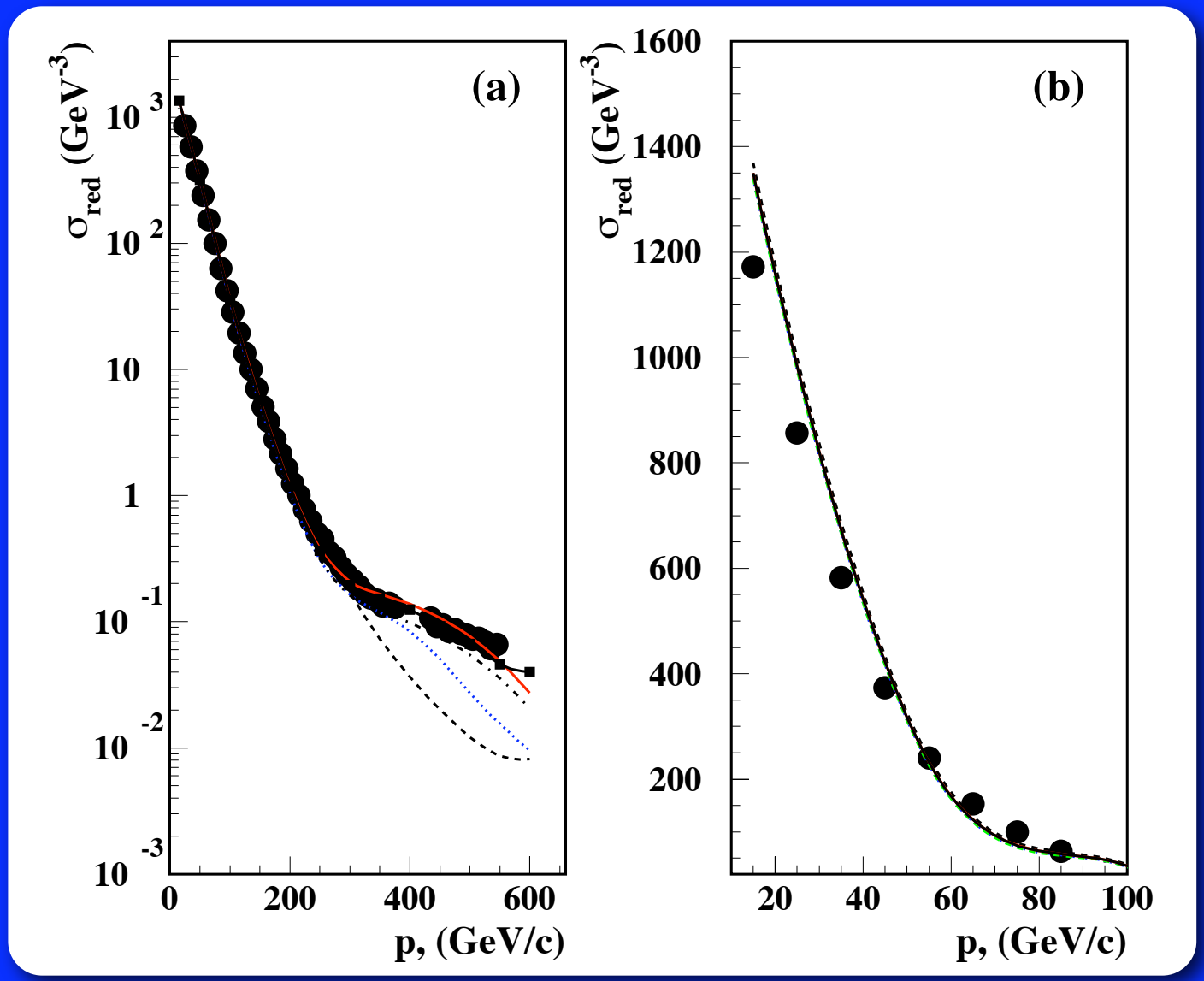

New Phenomenon ?

S.Jeschonnek and J.W.Van Orden, Phys. Rev. C 78, 2008

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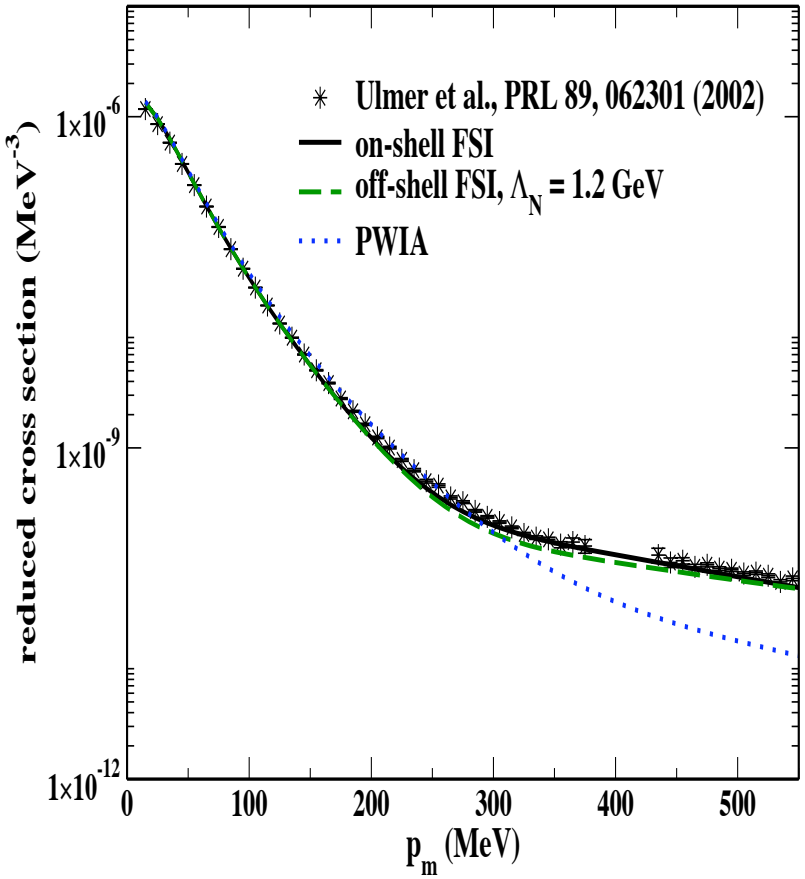

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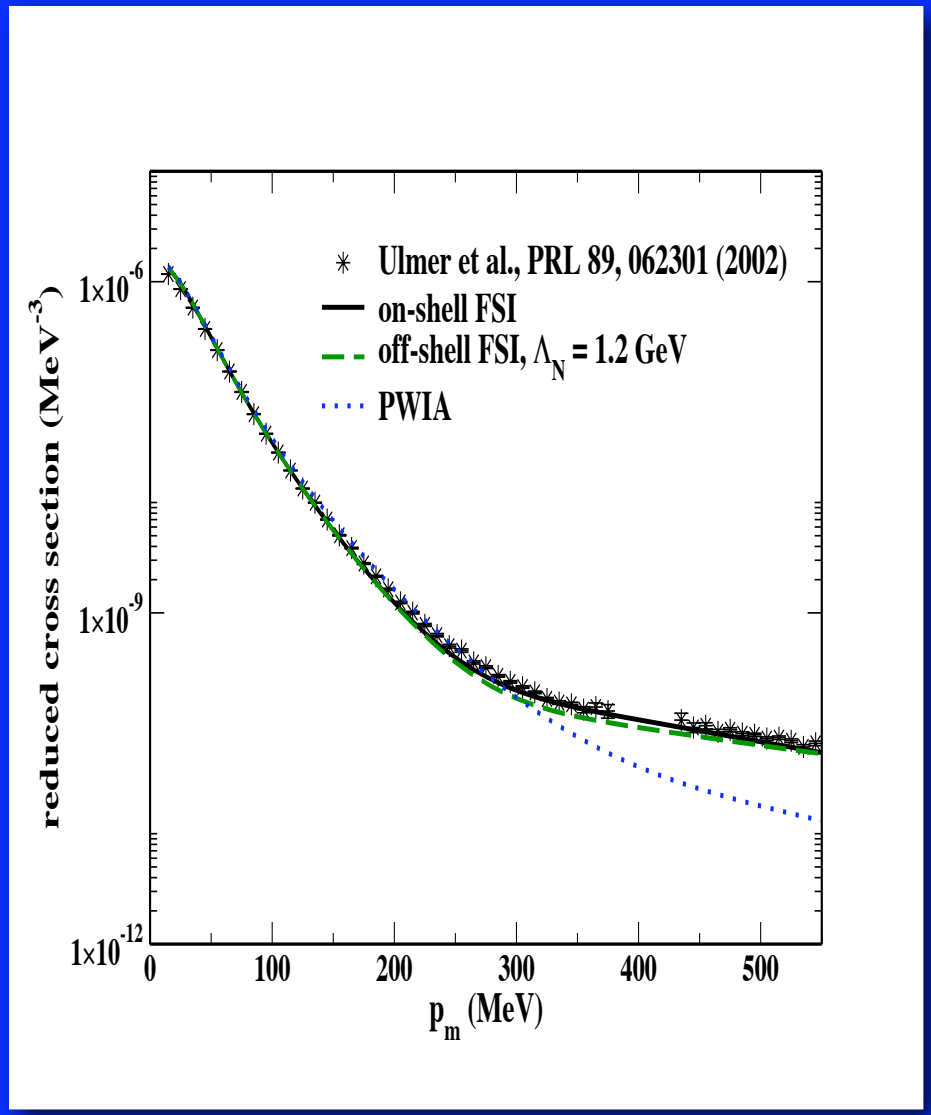

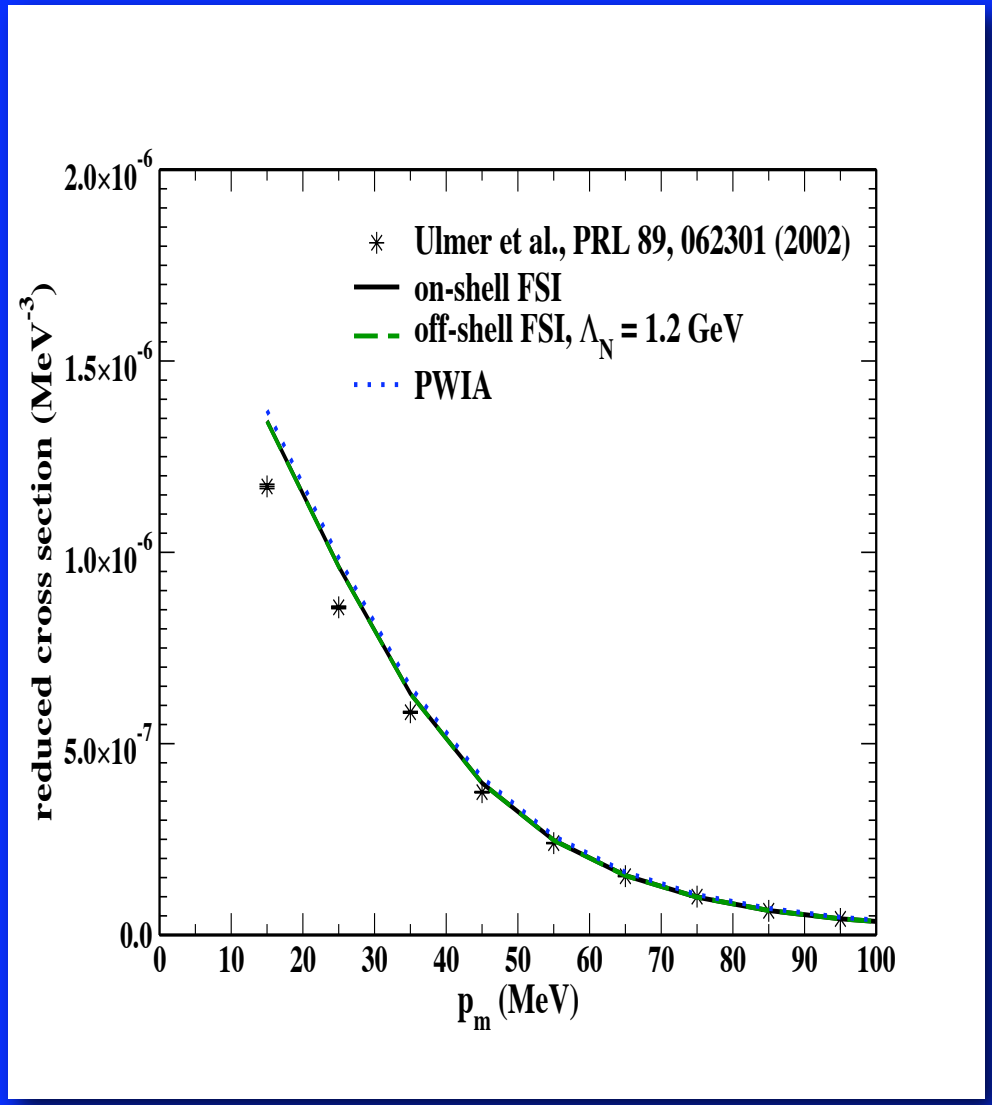

New Phenomenon ?

W. Boeglin et al Phys. Rev. C 78, 2008 (Mainz Data)

$Q^2 = 0.33\ \mathrm{GeV}^2$