Deuteron Electrodisintegration for Large *W*

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Motivation for *d(e,e'p)*

- Degrees of Freedom
  - Quarks vs. Hadrons
  - High Momentum Components
  - "Exotic" Contributions
  - Color Transparency
- Deuteron as a Neutron Target
  - Neutron Form Factor

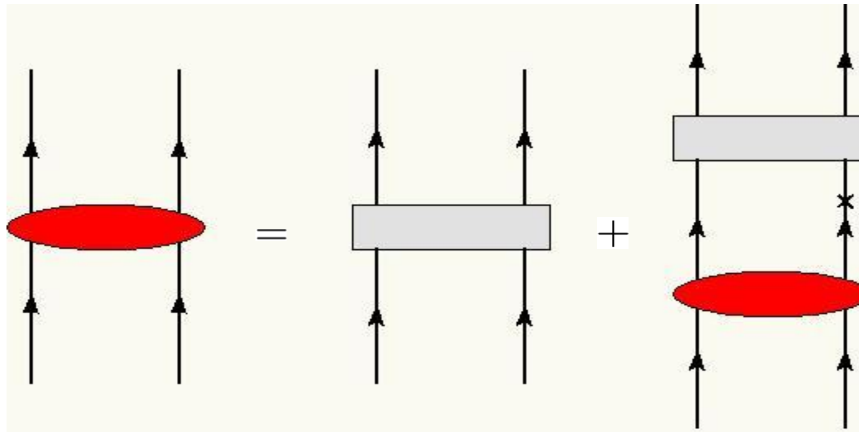
Hadronic Models of *d(e,e'p)*

- Potential Models

- Field Theory Inspired Models
  e.g. Bethe-Salpeter-like models with meson-exchange kernels

Spectator or Gross Equation

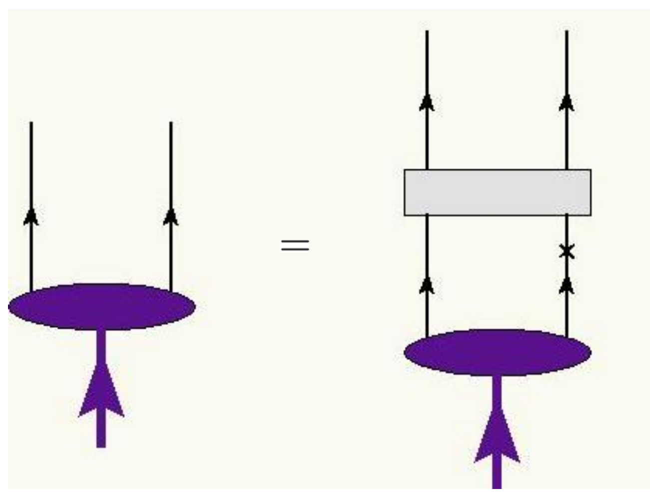
t matrix



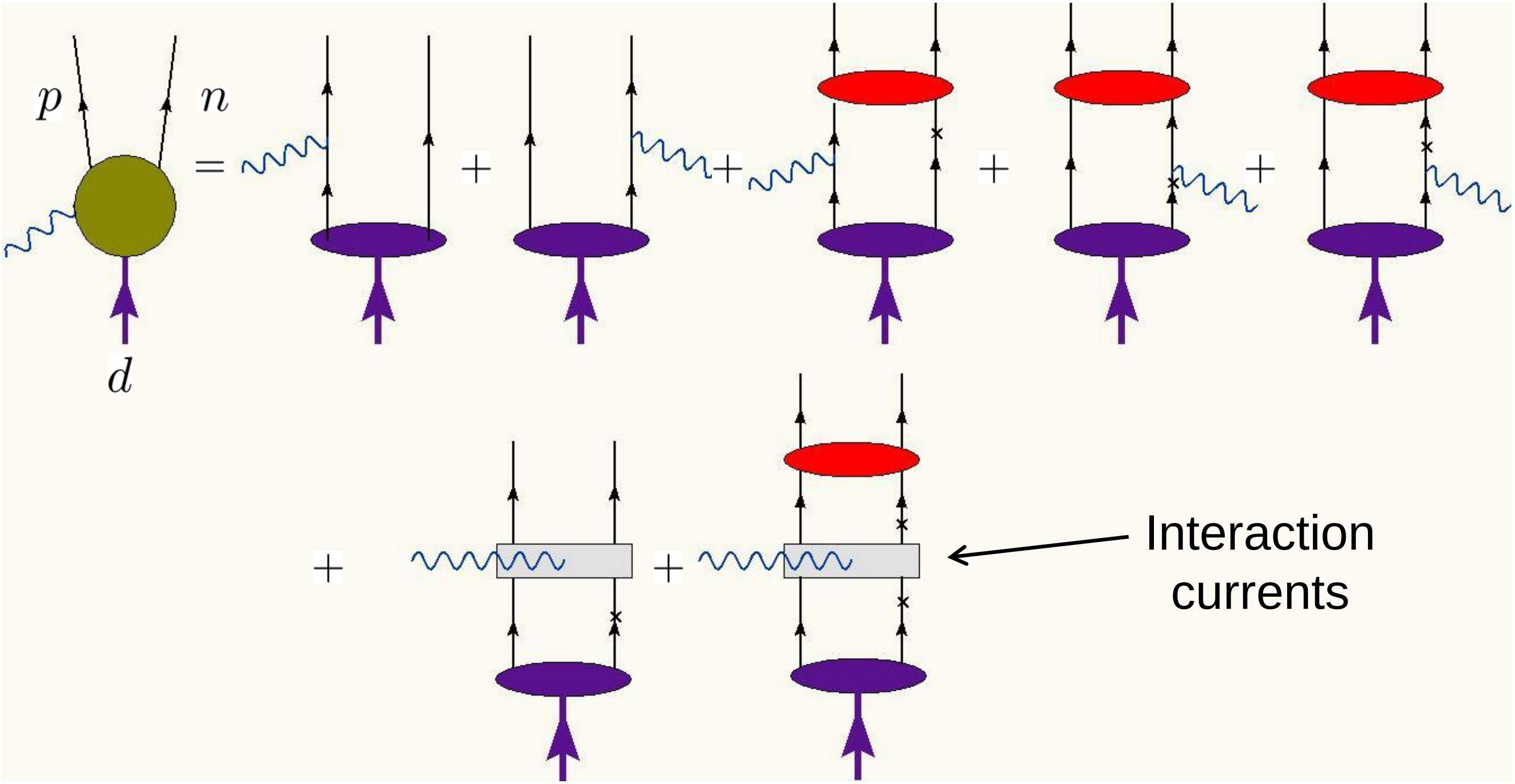
Irreducible
kernel

Positive-energy
on shell

Deuteron vertex
function



Deuteron Electrodisintegration



- This approach is covariant and conserves current.

- It becomes increasingly difficult to construct kernels as W increases above $W=2m_N+m_\pi$.
- Partial-wave expansions converge slowly for large W.
- Most calculations for these kinematics use eikonal or Glauber approximations.
- The final state scattering is usually represented by a simple parameterization containing no spin-flip contributions.

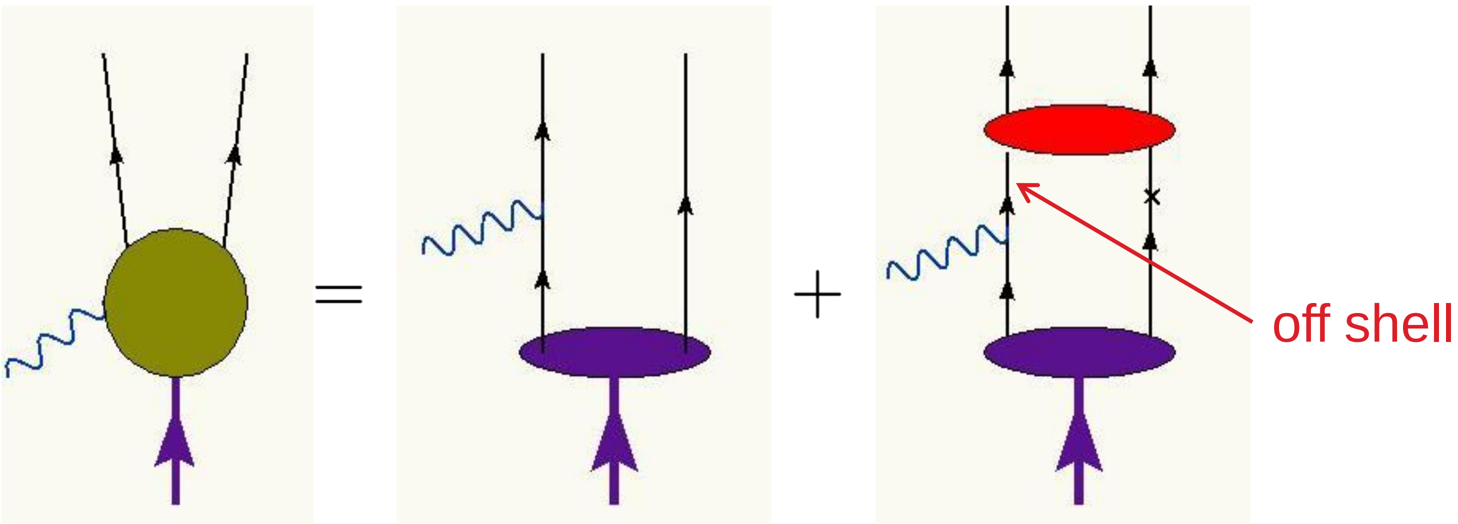
$$T \sim 2\pi(i+\alpha)e^{\frac{B}{2}t}\delta_{s'_1 s_1}\delta_{s'_2 s_2}$$

A New Calculation

- Uses helicity amplitudes from SAID for the final state interaction.
- Contains all spin-flip contributions.
- Makes no forward scattering approximation.

S. Jeschonnek & JWVO,
Phys. Rev. C **78**, 014007 (2008);
Phys. Rev. C **80**, 054001 (2009);
Phys. Rev. C **81**, 014008 (2010).

Relativistic Impulse Equation



Final State Interaction (FSI)

The on-shell *np* scattering amplitudes can be obtain from the Fermi-invariant representation of the four-point vertex function

$$M_{ab;cd} = \mathcal{F}_S(s,t)\delta_{ac}\delta_{bd} + \mathcal{F}_V(s,t)\gamma_{ac}\cdot\gamma_{bd} + \mathcal{F}_T(s,t)\sigma^{\mu\nu}_{ac}(\sigma_{\mu\nu})_{bd}$$
$$+\mathcal{F}_P(s,t)\gamma^5_{ac}\gamma^5_{bd} + \mathcal{F}_A(s,t)(\gamma^5\gamma)_{ac}\cdot(\gamma^5\gamma)_{bd}$$

where *a*, *b*, *c* and *d* are Dirac indices.

We use the five independent helicity amplitudes provided by the SAID analysis to the five functions $\mathcal{F}_i(s,t)$

Latest SAID analysis for pn scattering up to 1.3GeV, see Arndt, Briscoe, Strakovsky, Workman, Phys.Rev.C76:025209,2007

In order to estimate the size of off-shell contributions, we ignore any additional new terms and calculate the c.m. angle as

$$\cos\theta = \frac{t-u}{\sqrt{s-4m^2}\sqrt{\frac{(4m^2-t-u)^2}{s}-4m^2}}$$

and replace the Fermi-invariant functions with

$$\mathcal{F}_i(s,t) \rightarrow \mathcal{F}_i(s,t,u)F_N(s+t+u-3m^2)$$

where

$$F_N(p^2) = \frac{(\Lambda_N^2-m^2)^2}{(p^2-m^2)^2+(\Lambda_N^2-m^2)^2}$$

is a from factor that limits the virtuality of the off-shell proton.

A two-component form of the scattering matrix is often written in the Saclay representation as

$$\widetilde{M} = \frac{1}{2}\left[(a_s+b_s)+(a_s-b_s)\boldsymbol{\sigma}_1\cdot\hat{\boldsymbol{n}}\boldsymbol{\sigma}_2\cdot\hat{\boldsymbol{n}}+(c_s+d_s)\boldsymbol{\sigma}_1\cdot\hat{\boldsymbol{m}}\boldsymbol{\sigma}_2\cdot\hat{\boldsymbol{m}} \right.$$
$$\left. +(c_s-d_s)\boldsymbol{\sigma}_1\cdot\hat{\boldsymbol{l}}\boldsymbol{\sigma}_2\cdot\hat{\boldsymbol{l}}+e_s(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot\hat{\boldsymbol{n}}\right]$$

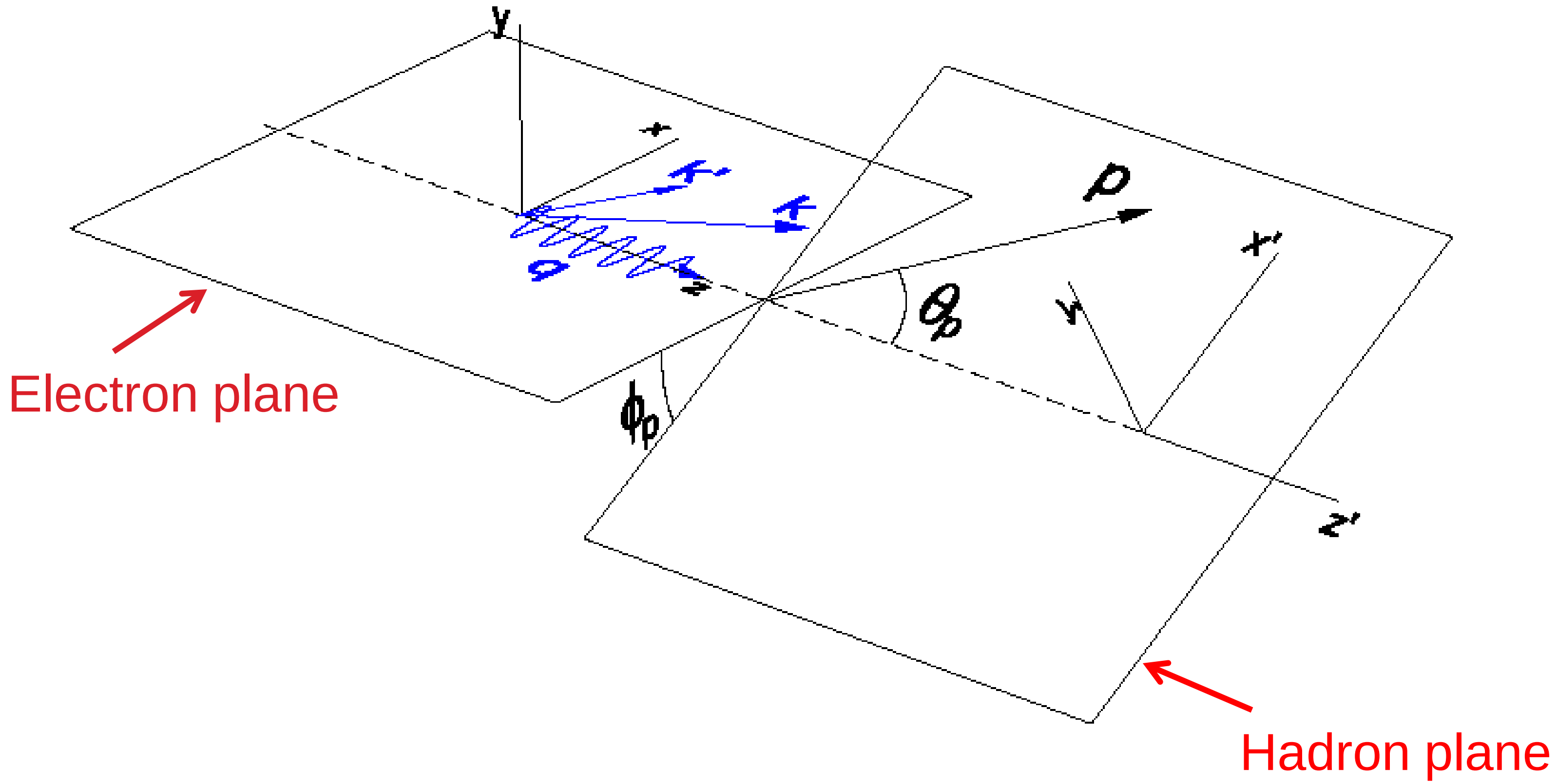
where

$$\hat{\boldsymbol{l}} = \frac{\boldsymbol{p}'+\boldsymbol{p}}{|\boldsymbol{p}'+\boldsymbol{p}|}, \quad \hat{\boldsymbol{m}} = \frac{\boldsymbol{p}'-\boldsymbol{p}}{|\boldsymbol{p}'-\boldsymbol{p}|}, \quad \hat{\boldsymbol{n}} = \frac{\boldsymbol{p}\times\boldsymbol{p}'}{|\boldsymbol{p}\times\boldsymbol{p}'|}$$

The Fermi invariants can be written in terms of a_s, b_s, c_s, d_s and e_s.

This allows the importance of single and double spin-flip terms to be studied.

d(e,e'p) Kinematics



General Form of the Differential Cross Section

Quantized in hadron plane

$$\left(\frac{d\sigma^5}{d\epsilon' d\Omega_e d\Omega_p}\right)_h = \frac{m_p\, m_n\, p_p}{16\pi^3\, M_d}\,\sigma_{Mott}\, f_{rec}^{-1}\Big[v_L\ \overline{R}_L^{(I)} + v_T \overline{R}_T^{(I)}$$
$$+v_{TT}\left(\overline{R}_{TT}^{(I)}\cos 2\phi_p + \overline{R}_{TT}^{(II)}\sin 2\phi_p\right)$$
$$+v_{LT}\left(\overline{R}_{LT}^{(I)}\cos\phi_p + \overline{R}_{LT}^{(II)}\sin\phi_p\right)$$
$$+h\, v_{LT'}\left(\overline{R}_{LT'}^{(I)}\sin\phi_p + \overline{R}_{LT'}^{(II)}\cos\phi_p\right)$$
$$+h\, v_{T'}\overline{R}_{T'}^{(II)}\Big]$$

Kinematic factors

$$v_L = \frac{Q^4}{q^4} \qquad v_{LT} = -\frac{Q^2}{\sqrt{2}q^2}\sqrt{\frac{Q^2}{q^2}+\tan^2\frac{\theta_e}{2}}$$

$$v_T = \frac{Q^2}{2q^2}+\tan^2\frac{\theta_e}{2} \qquad v_{LT'} = -\frac{Q^2}{\sqrt{2}q^2}\tan\frac{\theta_e}{2}$$

$$v_{TT} = -\frac{Q^2}{2q^2} \qquad v_{T'} = \tan\frac{\theta_e}{2}\sqrt{\frac{Q^2}{q^2}+\tan^2\frac{\theta_e}{2}}$$

The response tensor in the helicity basis is

$$\overline{w}_{\lambda'_\gamma,\lambda_\gamma}(\overline{\hat{\mathcal{S}}},\overline{D}) = 2\sum_{s_1,s'_1 s_2}\sum_{\lambda'_d,\lambda_d}\overline{\langle \boldsymbol{p}_1 s'_1;\boldsymbol{p}_2 s_2;(-)|\,J_{\lambda'_\gamma}\,|\boldsymbol{P}\lambda'_d\rangle}^{\,*}\rho_{\lambda'_d,\lambda_d}(\overline{D})$$
$$\times\overline{\langle \boldsymbol{p}_1 s_1;\boldsymbol{p}_2 s_2;(-)|\,J_{\lambda_\gamma}\,|\boldsymbol{P}\lambda_d\rangle}\mathcal{P}_{s'_1 s_1}(\overline{\hat{\mathcal{S}}})$$

where the proton spin projection operator is

$$\mathcal{P}_{s'_1 s_1}(\overline{\hat{\mathcal{S}}}) = \frac{1}{2}\left(\mathbf{1}+\boldsymbol{\sigma}\cdot\overline{\hat{\mathcal{S}}}\right)_{s'_1 s_1}$$

and the deuteron density matrix is

$$\boldsymbol{\rho}(\overline{D}) = \frac{1}{3}\begin{pmatrix} 1+\sqrt{\frac{3}{2}}\,\overline{T}_{10}+\frac{1}{\sqrt{2}}\overline{T}_{20} & -\sqrt{\frac{3}{2}}(\overline{T}^*_{11}+\overline{T}^*_{21}) & \sqrt{3}\,\overline{T}^*_{22} \\ -\sqrt{\frac{3}{2}}(\overline{T}_{11}+\overline{T}_{21}) & 1-\sqrt{2}\,\overline{T}_{20} & -\sqrt{\frac{3}{2}}(\overline{T}^*_{11}-\overline{T}^*_{21}) \\ \sqrt{3}\,\overline{T}^*_{22} & -\sqrt{\frac{3}{2}}(\overline{T}_{11}-\overline{T}_{21}) & 1-\sqrt{\frac{3}{2}}\,\overline{T}_{10}+\frac{1}{\sqrt{2}}\overline{T}_{20} \end{pmatrix}$$

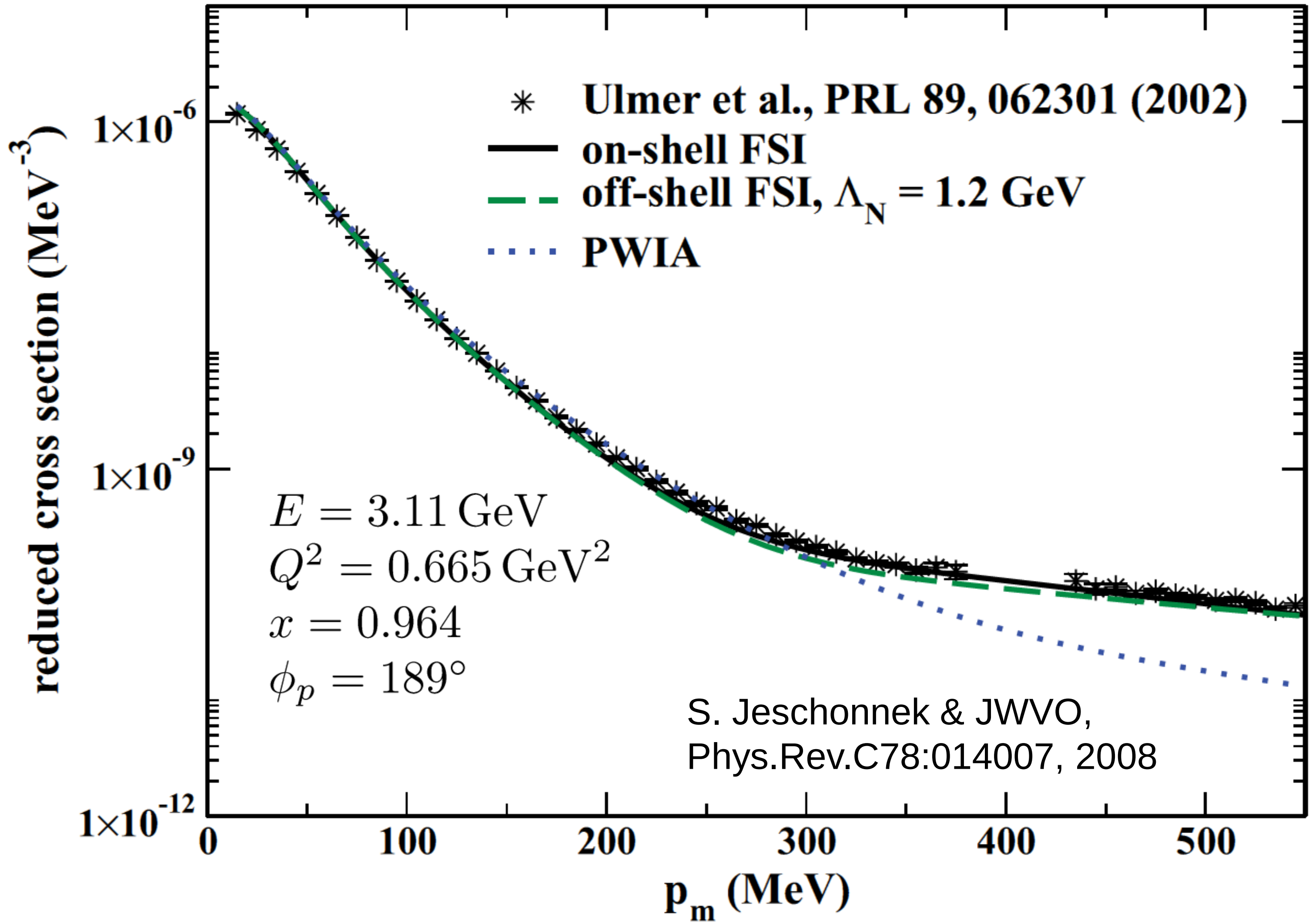
The response functions are given by

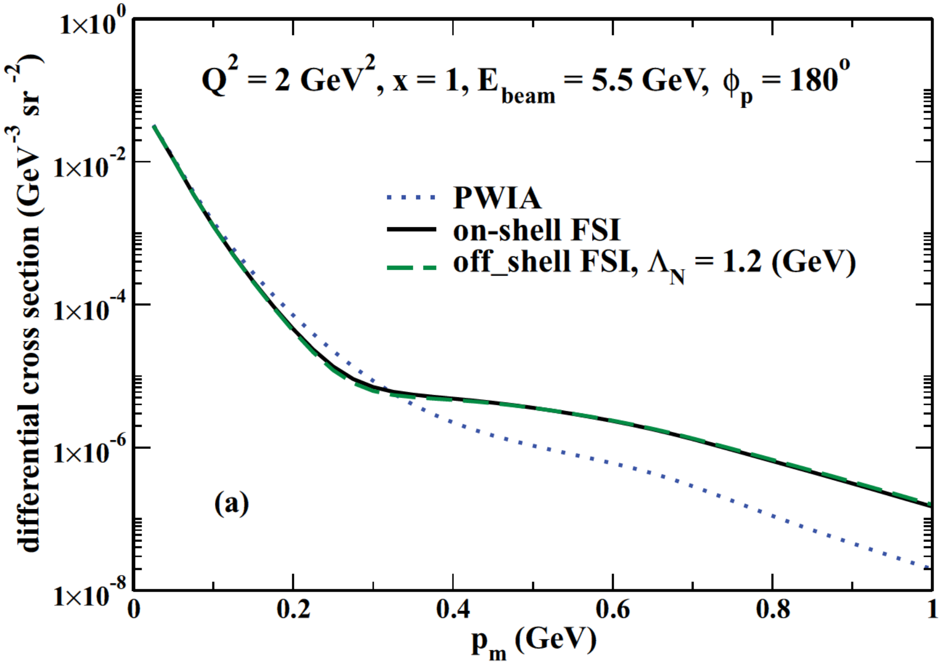
$$
\begin{aligned}
\overline{R}_L^{(I)} &= \overline{w}_{00} \\
\overline{R}_T^{(I)} &= \overline{w}_{1,1} + \overline{w}_{-1,-1} \\
\overline{R}_{TT}^{(I)} &= 2\mathrm{Re}(\overline{w}_{1,-1}) \\
\overline{R}_{TT}^{(II)} &= 2\mathrm{Im}(\overline{w}_{1,-1}) \\
\overline{R}_{LT}^{(I)} &= -2\mathrm{Re}(\overline{w}_{01} - \overline{w}_{0-1}) \\
\overline{R}_{LT}^{(II)} &= 2\mathrm{Im}(\overline{w}_{01} + \overline{w}_{0-1}) \\
\overline{R}_{LT'}^{(I)} &= 2\mathrm{Im}(\overline{w}_{01} - \overline{w}_{0-1}) \\
R_{LT'}^{(II)} &= -2\mathrm{Re}(\overline{w}_{01} + \overline{w}_{0-1}) \\
\overline{R}_{T'}^{(II)} &= \overline{w}_{1,1} - \overline{w}_{-1,-1}
\end{aligned}
$$

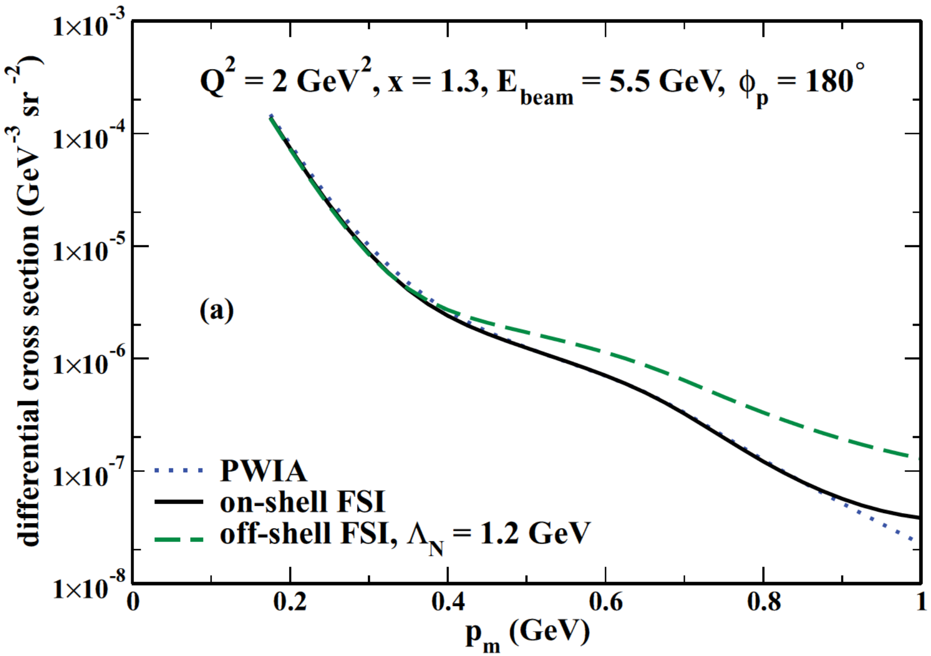
Results

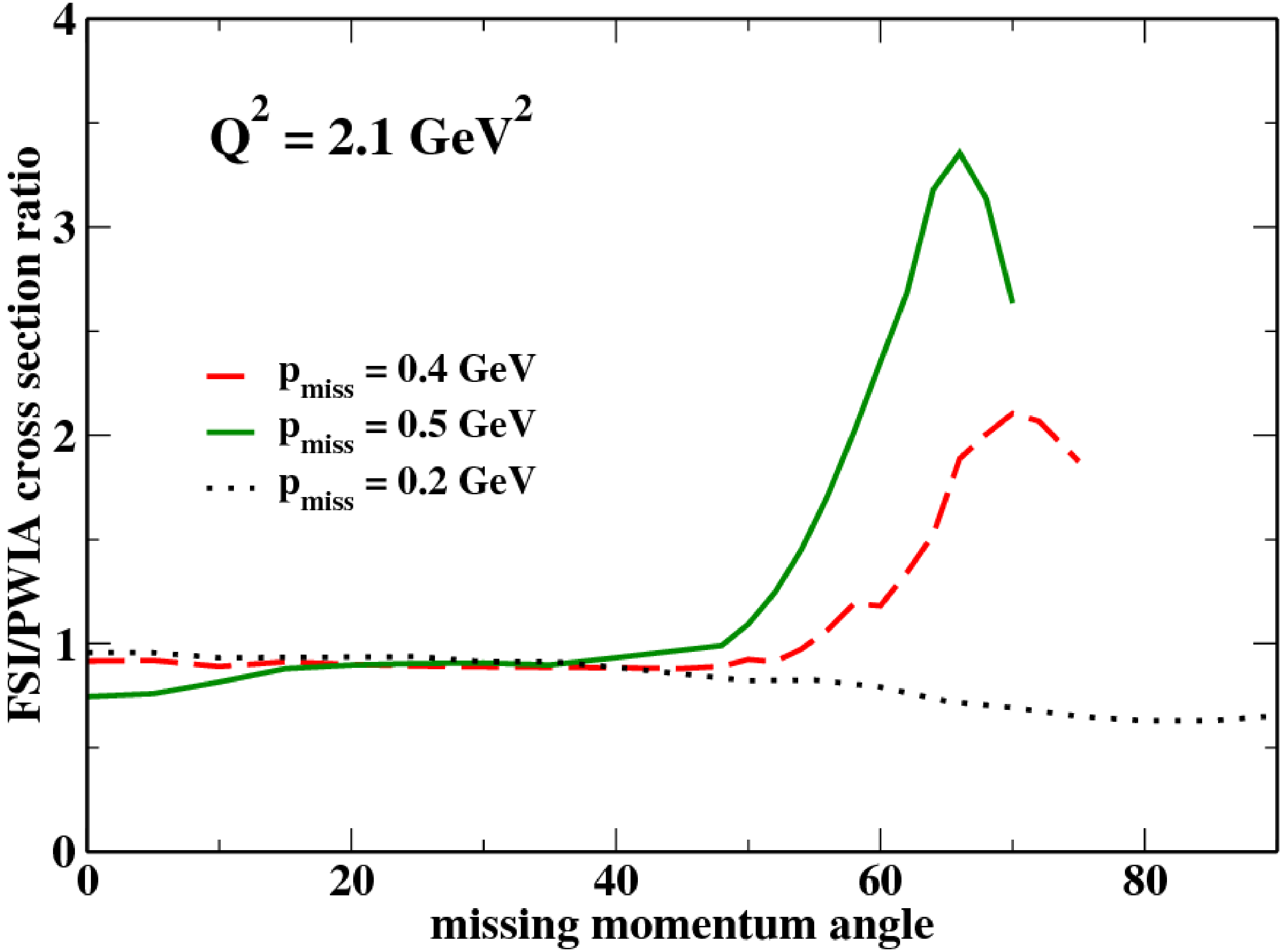
Unpolarized Protons and Deuterons

Differential Cross Section




Q^2 = 2 GeV^2, x = 1, E_{beam} = 5.5 GeV, ϕ_p = 180^o
PWIA
on-shell FSI
off_shell FSI, Λ_N = 1.2 (GeV)
(a)
differential cross section (GeV^{-3} sr^{-2})
p_m (GeV)

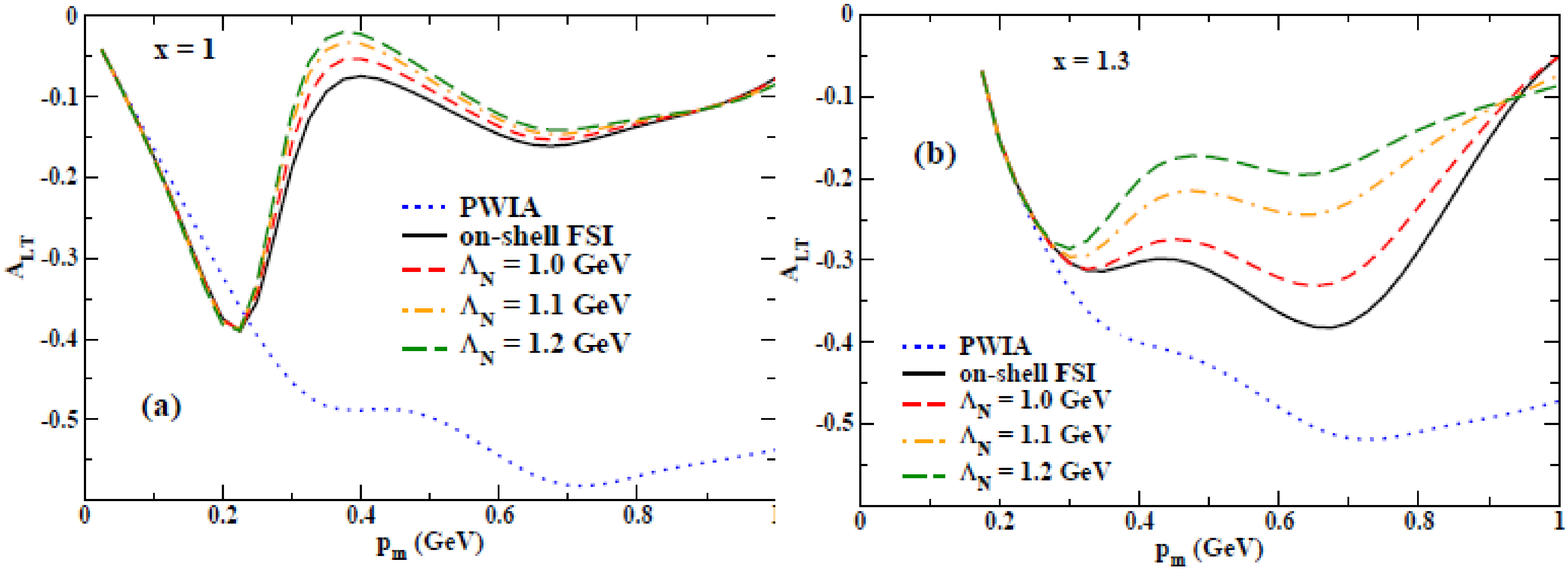

Q^2 = 2 GeV^2, x = 1.3, E_{beam} = 5.5 GeV, ϕ_p = 180°
(a)
PWIA
on-shell FSI
off-shell FSI, Λ_N = 1.2 GeV
differential cross section (GeV^{-3} sr^{-2})
p_m (GeV)



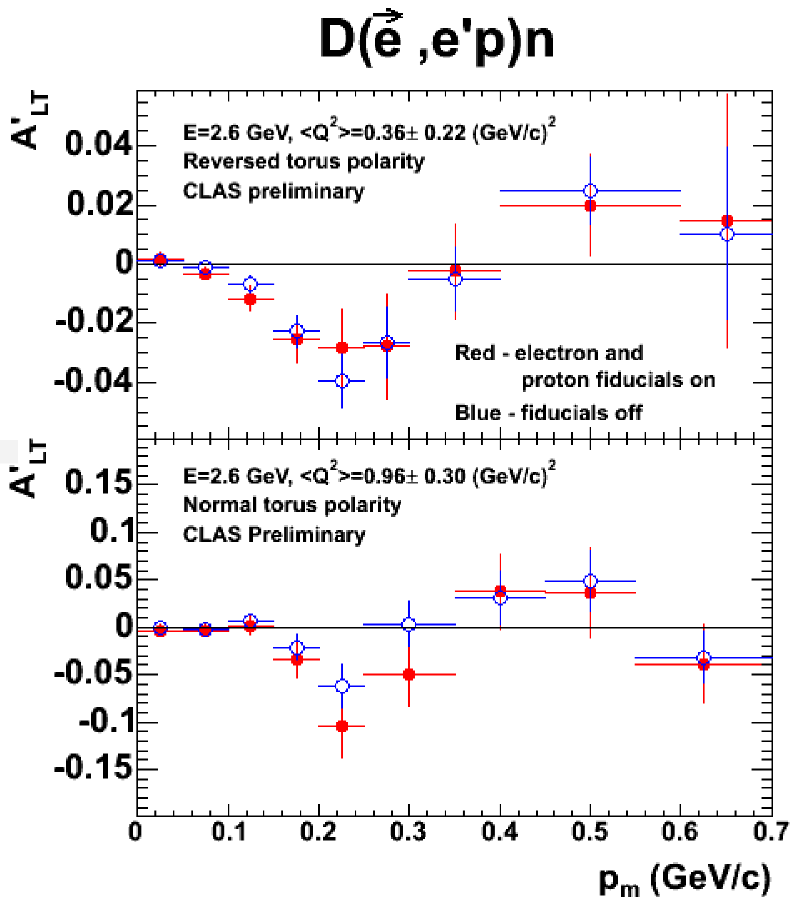
Q^2 = 2.1 GeV^2
p_miss = 0.4 GeV
p_miss = 0.5 GeV
p_miss = 0.2 GeV
FSI/PWIA cross section ratio
missing momentum angle
0
1
2
3
4
0
20
40
60
80

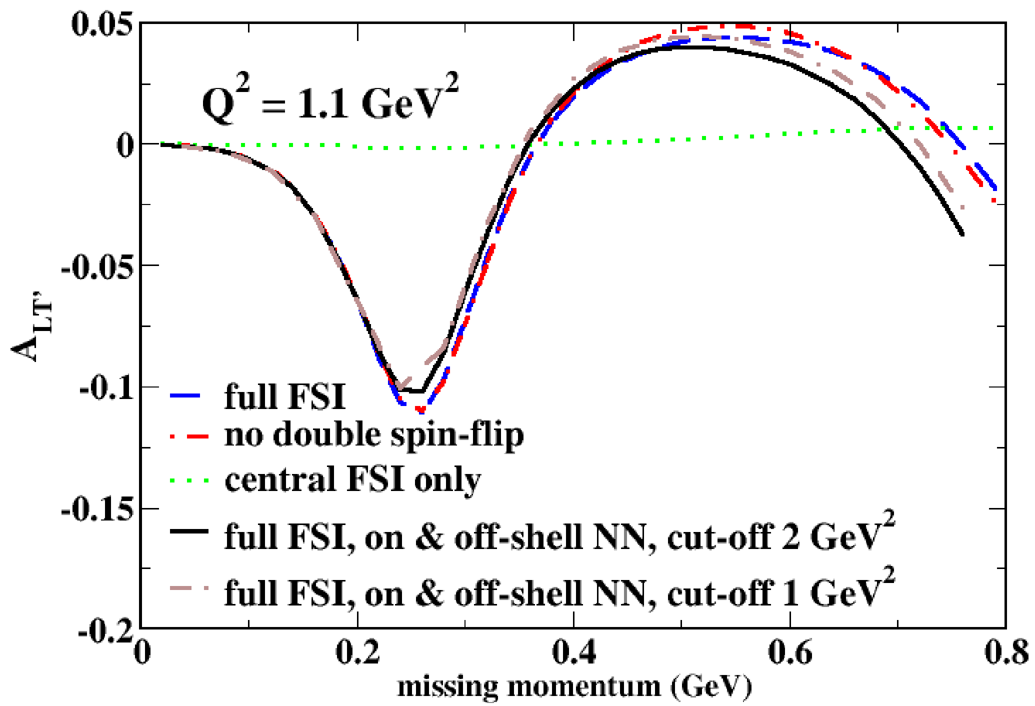
E01-020

$$A_{LT} = \frac{v_{LT} R_{LT}}{v_L R_L + v_T R_T + v_{TT} R_{TT}}$$



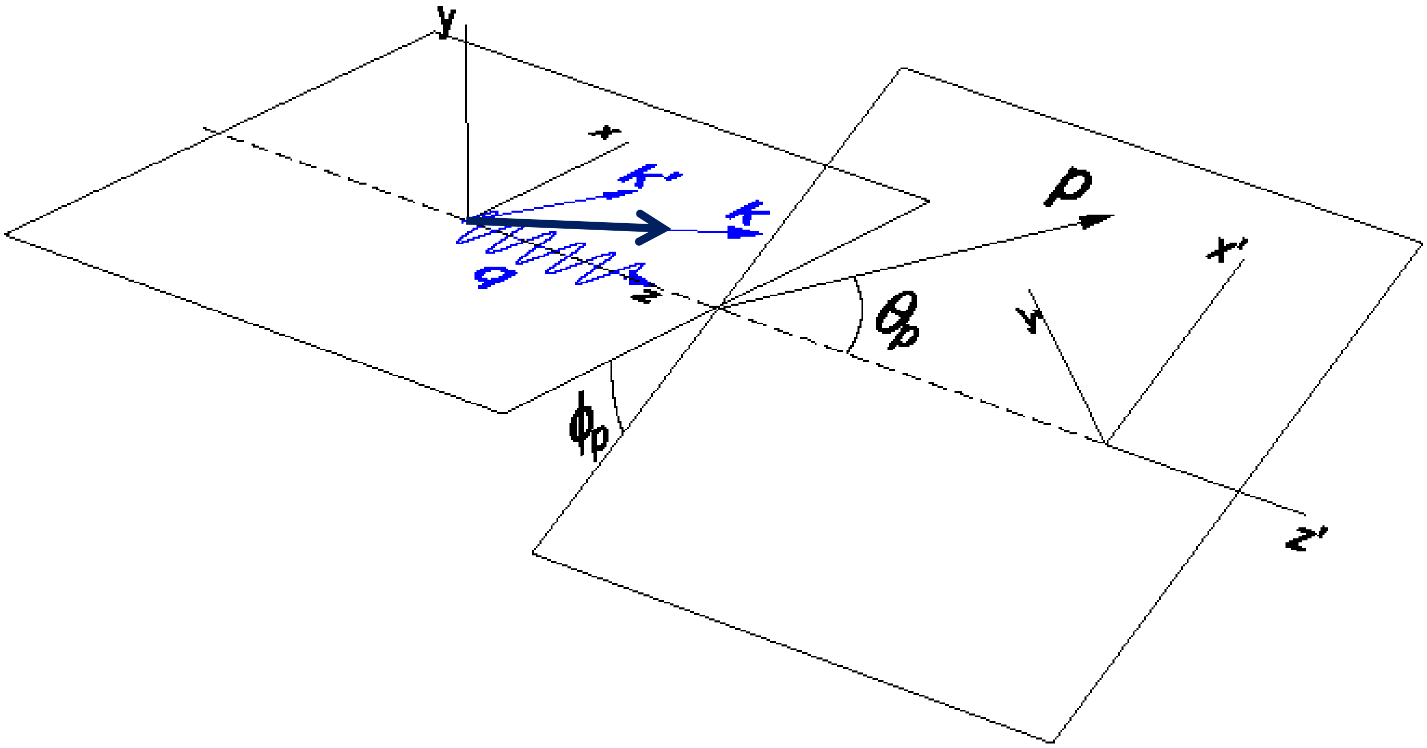
$$A_{LT'} = \frac{v_{LT'} R_{LT'}}{v_L R_L + v_T R_T - v_{TT} R_{TT}}$$





Jefferson Lab, **CLAS Preliminary Data,** Jerry Gilfoyle

Target Polarization



Observables

$$A_d^V = \frac{v_L R_L(\widetilde{T}_{10}) + v_T R_T(\widetilde{T}_{10}) + v_{TT} R_{TT}(\widetilde{T}_{10}) + v_{LT} R_{LT}(\widetilde{T}_{10})}{\widetilde{T}_{10}\Sigma}$$

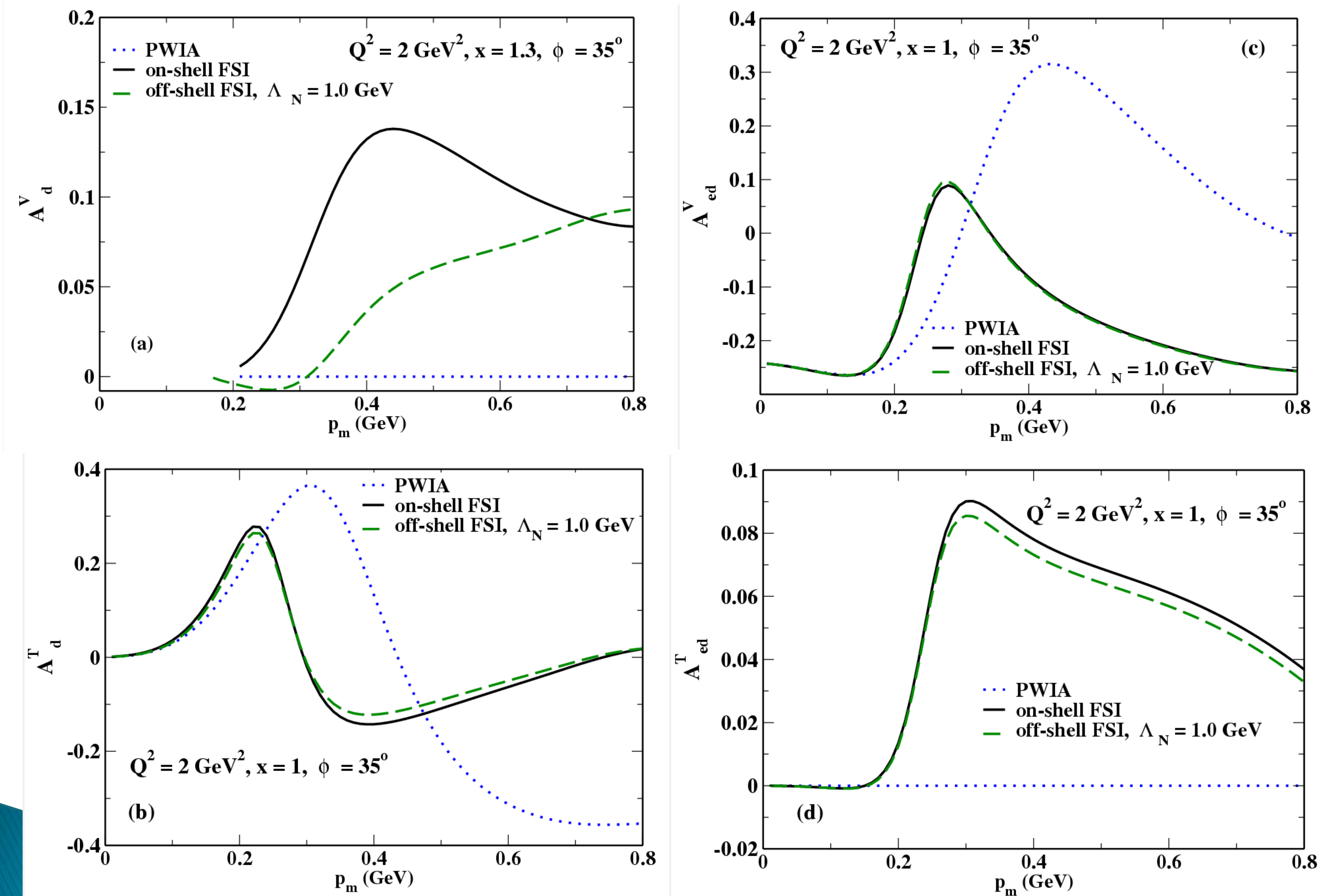
$$A_d^T = \frac{v_L R_L(\widetilde{T}_{20}) + v_T R_T(\widetilde{T}_{20}) + v_{TT} R_{TT}(\widetilde{T}_{20}) + v_{LT} R_{LT}(\widetilde{T}_{20})}{\widetilde{T}_{20}\Sigma}$$

$$A_{ed}^V = \frac{v_{LT'} R_{LT'}(\widetilde{T}_{10}) + v_{T'} R_{T'}(\widetilde{T}_{10})}{\widetilde{T}_{10}\Sigma}$$

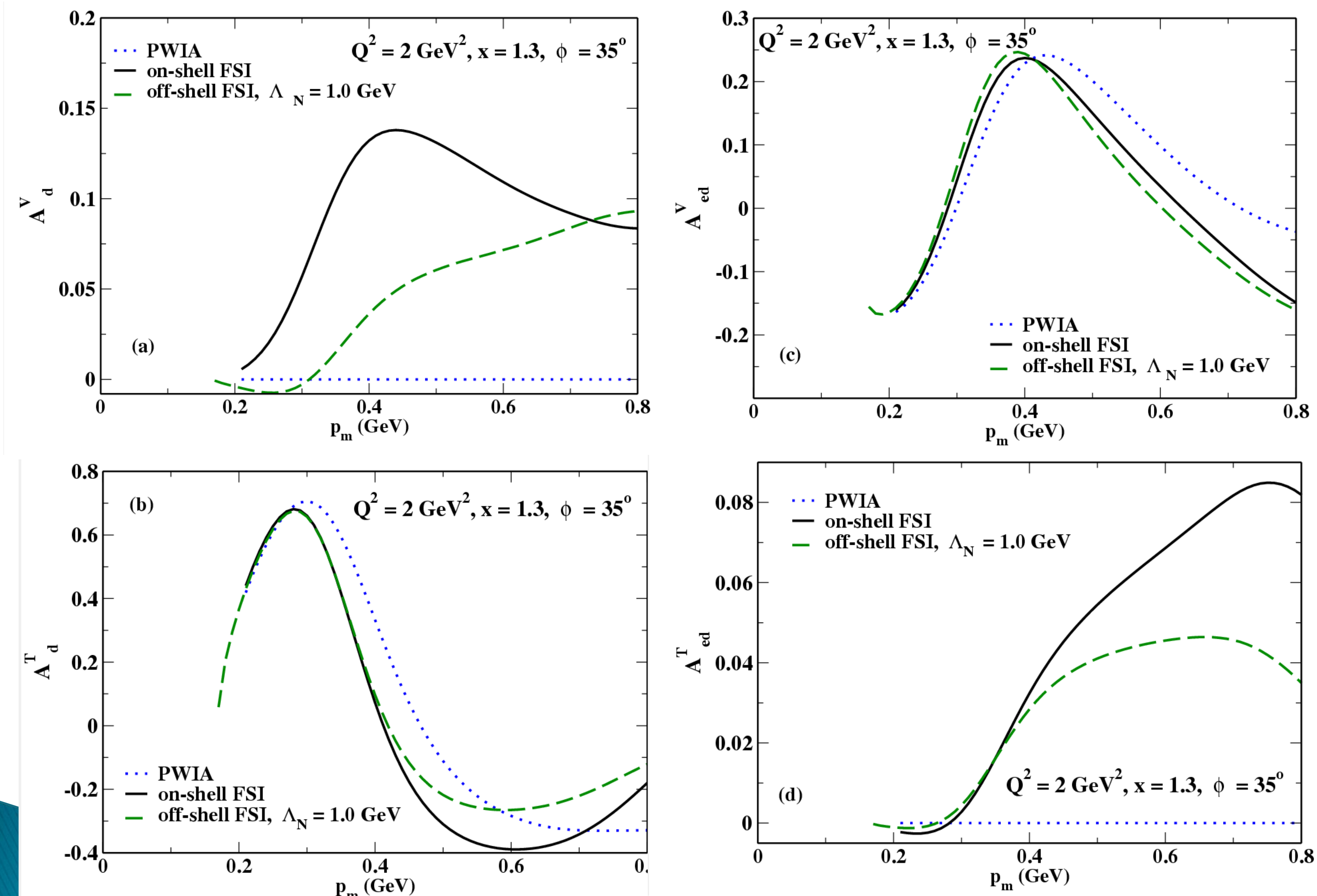
$$A_{ed}^T = \frac{v_{LT'} R_{LT'}(\widetilde{T}_{20}) + v_{T'} R_{T'}(\widetilde{T}_{20})}{\widetilde{T}_{20}\Sigma}$$

$$\Sigma = v_L R_L(U) + v_T R_T(U) + v_{TT} R_{TT}(U) + v_{LT} R_{LT}(U)\,.$$

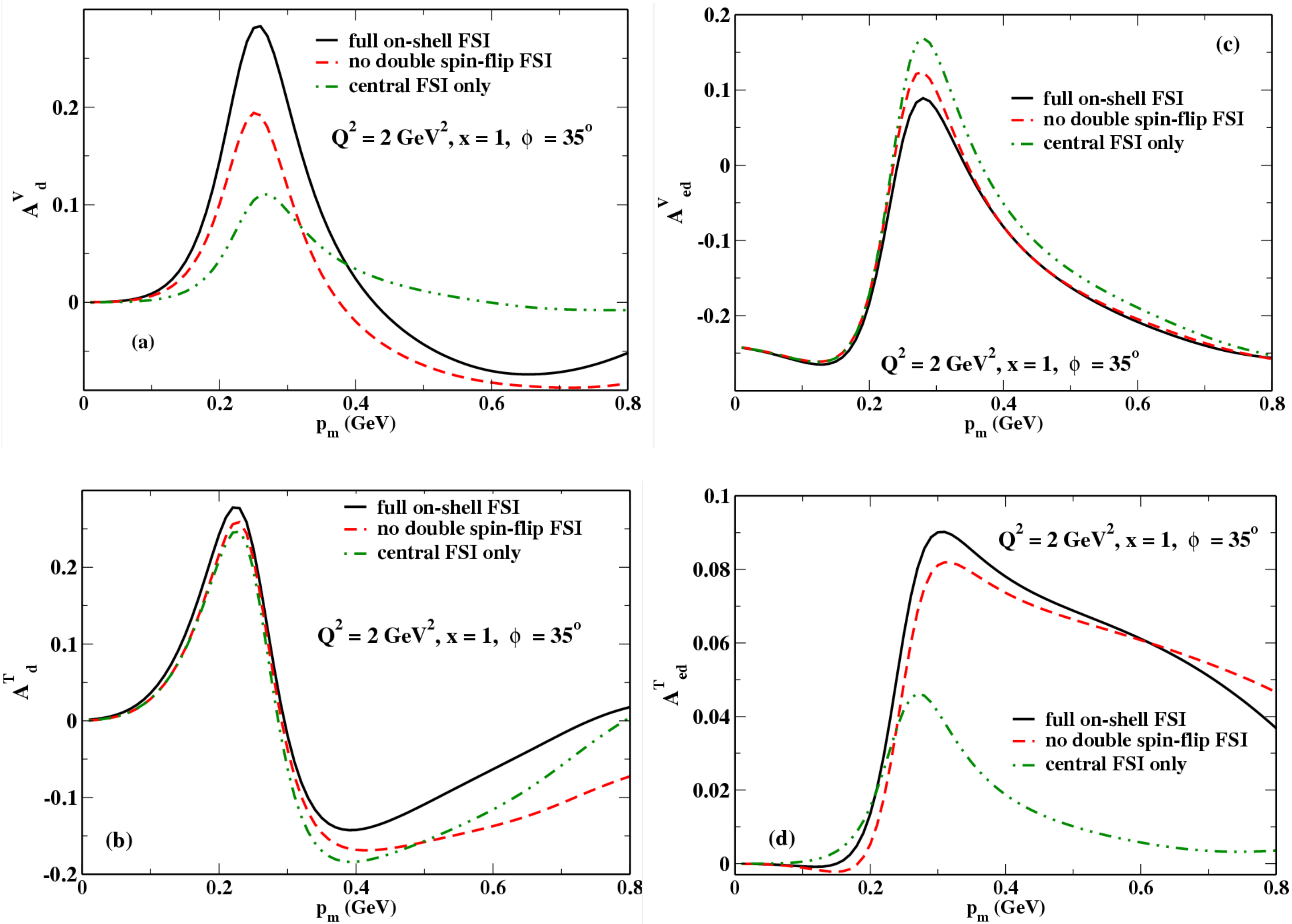
$x = 1,\ Q^2 = 2\,\mathrm{GeV}^2$



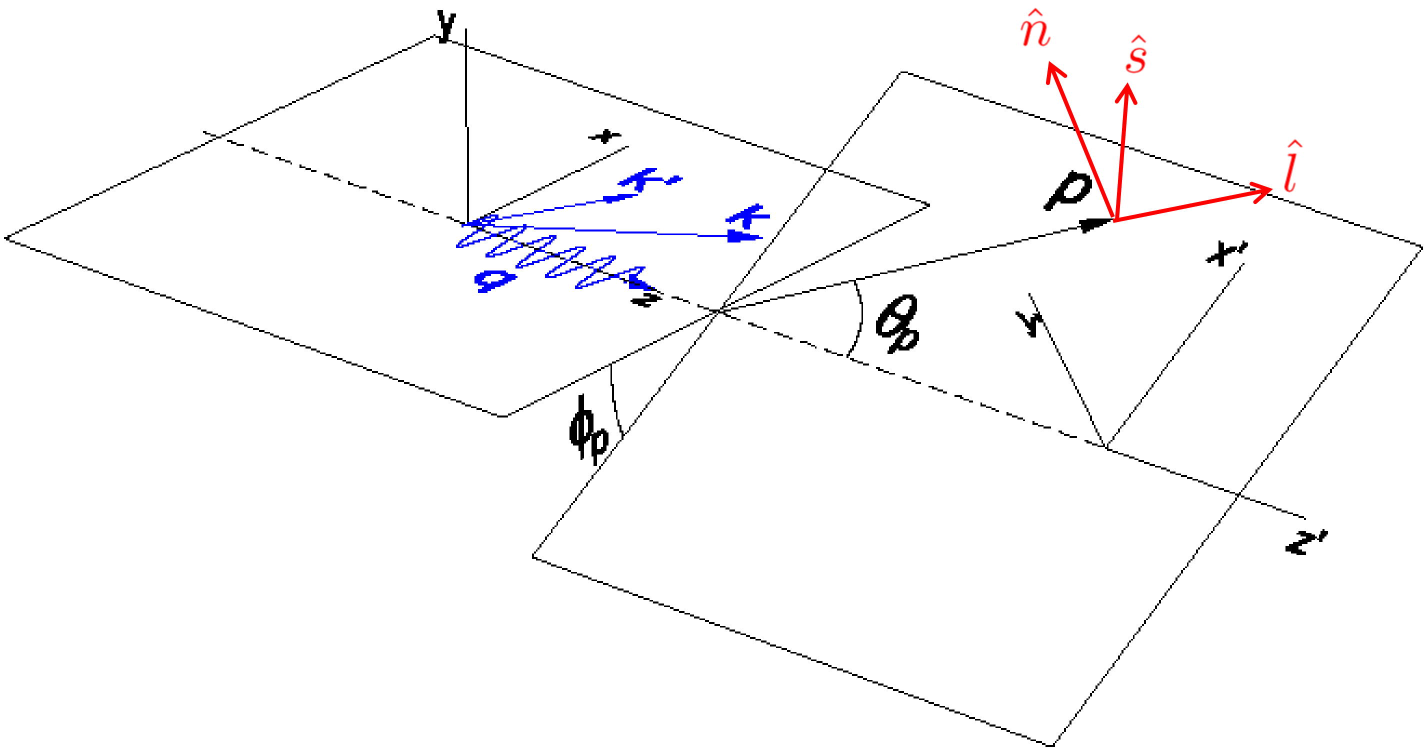
$$x = 1.3,\ Q^2 = 2\,\mathrm{GeV}^2$$



Role of Spin-Dependent FSIs: Single Spin Flip and Double Spin Flip



Polarized Protons

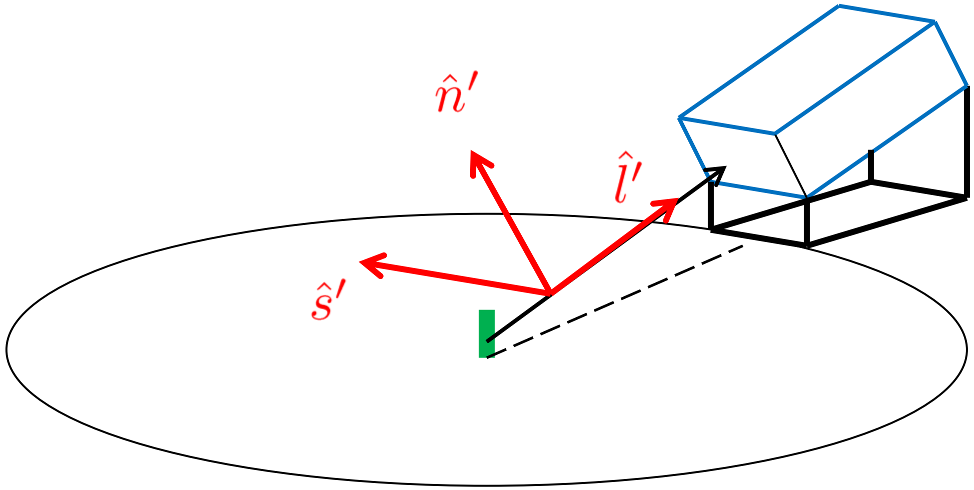


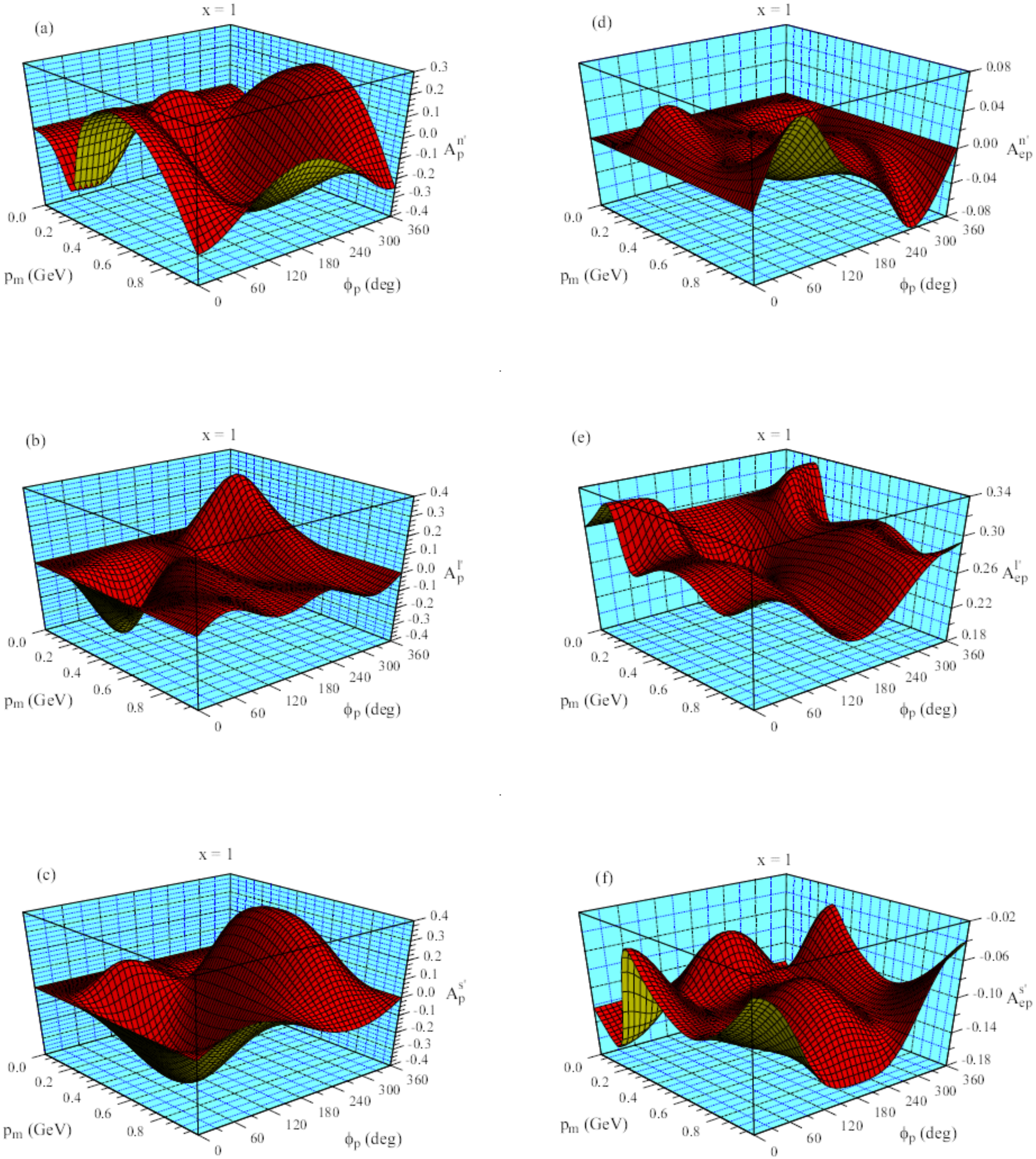
Asymmetries

Care must be taken in defining asymmetries so that they are well defined at forward and backward angles

This can be done by defining a new set of unit vectors

$$
\begin{aligned}
\hat{l}' &= \hat{l} \\
\hat{s}' &= \frac{\hat{y} \times \hat{l}}{|\hat{y} \times \hat{l}|} \\
\hat{n}' &= \hat{l}' \times \hat{s}'
\end{aligned}
$$





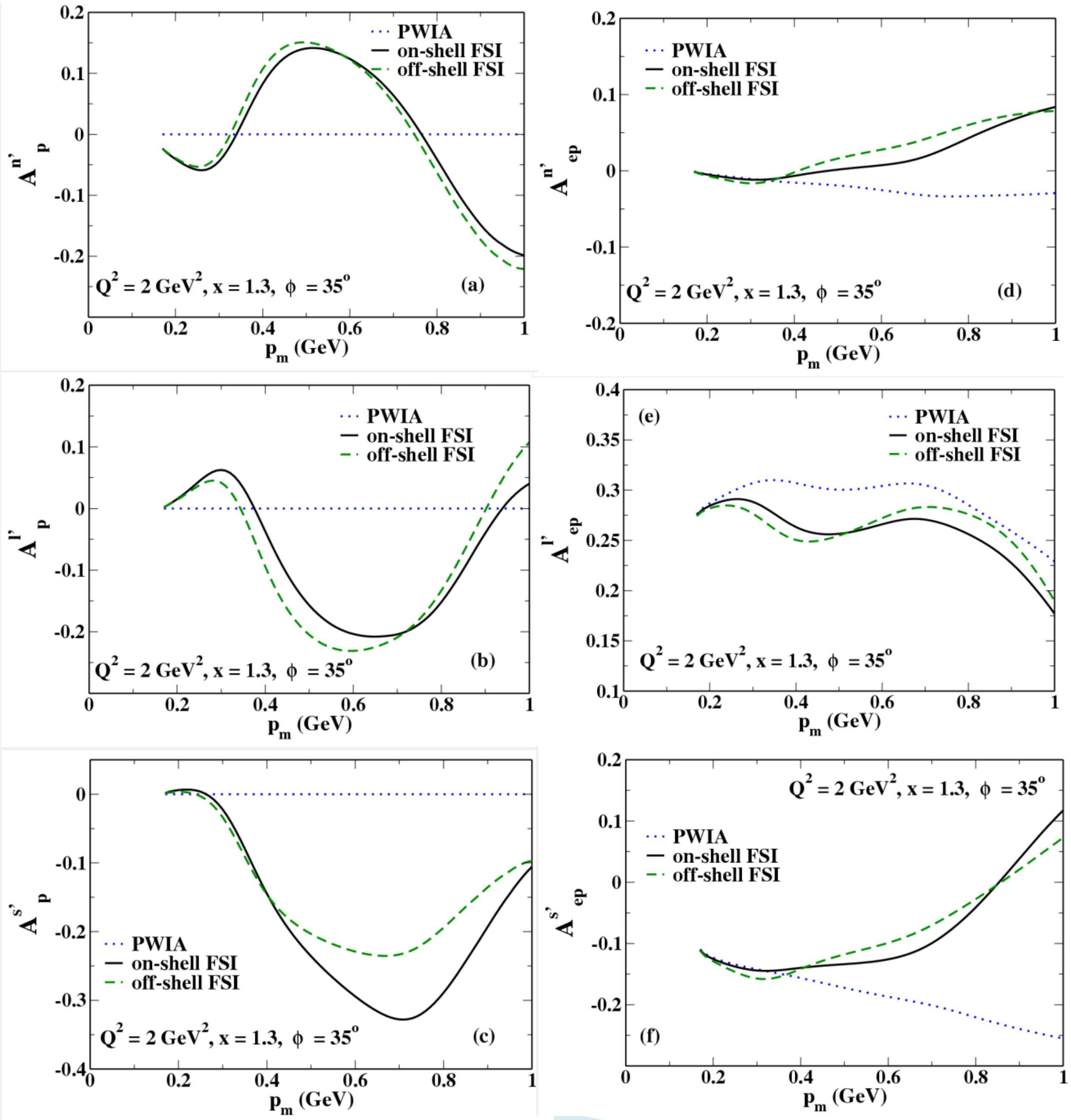
left column: unpolarized beam

right column: polarized beam

top row: **normal** (induced polarization)

middle row: **longitudinal**

bottom row: **sideways**

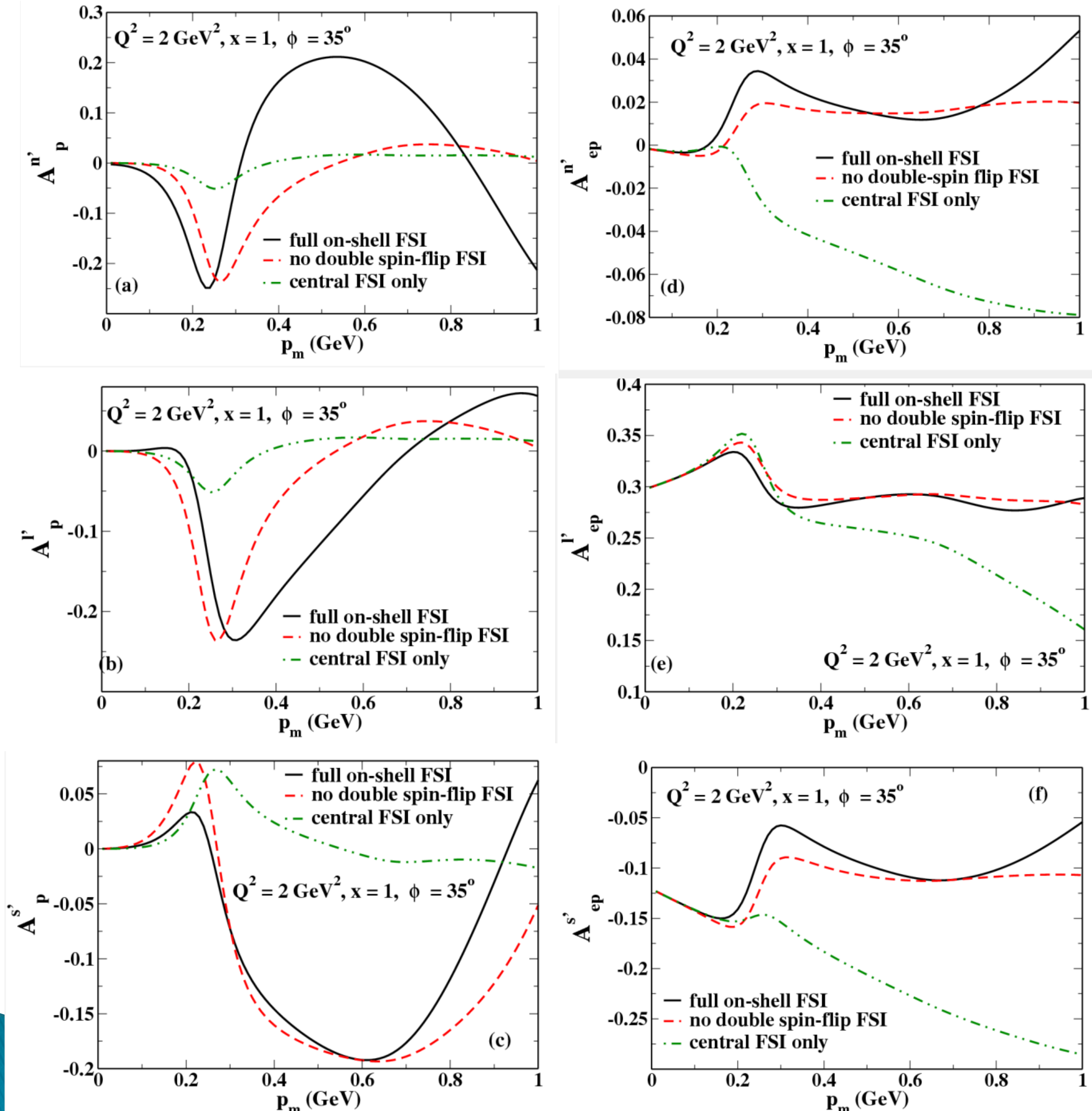


PWIA

on-shell FSI

off-shell FSI

$$x = 1.3$$
$$Q^2 = 2\,\mathrm{GeV}^2$$
$$\phi_p = 35^\circ$$



full on-shell FSI

central &

spin-orbit FSI

central FSI only

$$x = 1$$

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

$$\phi_p = 35^\circ$$

Summary

- This approach works well in comparison to available data.
- Off-shell contributions are potentially large away from x=1 and at large missing momenta.
- The spin-flip contributions can be large.

Outlook

- We are constructing a model to extrapolate from existing helicity amplitude "data" to higher *W.*

- Exchange currents

- Complete Spectator Equation calculation for use below pion threshold.