9th APCTP - BLTP JINR Joint Workshop at Kazakhstan

Modern problems of nuclear and elementary particle physics

June 27 - July 4, 2015, Almaty, Kazakhstan

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(BLTh, Dubna)

SIDIS off polarized 3He: tagging the transversal nucleon structure, the EMC effect and the hadronization mechanism

with

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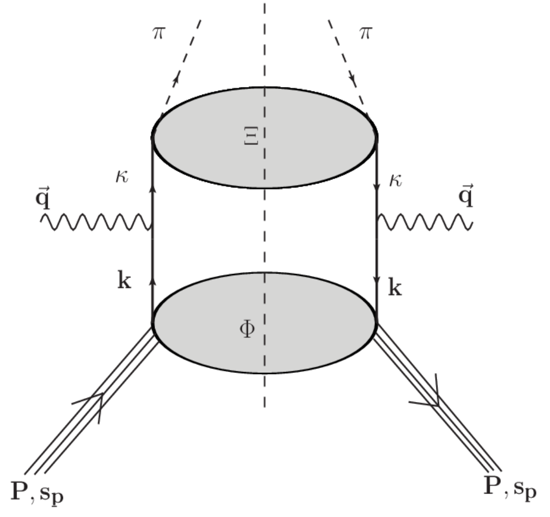
1. Introduction: "Standard" SIDIS

$$\vec{l} + \vec{p} = l' + h + X$$



$$W^{\mu\nu(S)} = \frac{1}{2}\sum_a e_a^2 \int \frac{\mathrm{d}k^-\,\mathrm{d}^2\boldsymbol{k}_T}{(2\pi)^4} \int \frac{\mathrm{d}\kappa^+\,\mathrm{d}^2\boldsymbol{\kappa}_T}{(2\pi)^4} \times \delta^2(\boldsymbol{k}_T + \boldsymbol{q}_T - \boldsymbol{\kappa}_T)\ \mathrm{Tr}\left[\Phi\,\gamma^{\{\mu}\,\Xi\,\gamma^{\nu\}}\right]_{k^+=xP^+,\,\kappa^-=P_h^-/z}$$

$$\begin{aligned}\mathbf{Tr}\left[\boldsymbol{\Phi}\,\gamma^{\{\mu}\,\boldsymbol{\Xi}\,\gamma^{\nu\}}\right] = \frac{1}{2}\Big\{ & \mathbf{Tr}\left[\boldsymbol{\Phi}\right]\mathbf{Tr}\left[\boldsymbol{\Xi}\right] + \mathbf{Tr}\left[\mathbf{i}\,\boldsymbol{\Phi}\,\gamma_5\right]\mathbf{Tr}\left[\mathbf{i}\,\boldsymbol{\Xi}\,\gamma_5\right] \\ & - \mathbf{Tr}\left[\boldsymbol{\Phi}\,\gamma^\alpha\right]\mathbf{Tr}\left[\boldsymbol{\Xi}\,\gamma_\alpha\right] - \mathbf{Tr}\left[\boldsymbol{\Phi}\,\gamma^\alpha\,\gamma_5\right]\mathbf{Tr}\left[\boldsymbol{\Xi}\,\gamma_\alpha\,\gamma_5\right] \\ & + \frac{1}{2}\mathbf{Tr}\left[\mathbf{i}\,\boldsymbol{\Phi}\,\sigma^{\alpha\beta}\,\gamma_5\right]\mathbf{Tr}\left[\mathbf{i}\,\boldsymbol{\Xi}\,\sigma_{\alpha\beta}\,\gamma_5\right]\Big\}\, g^{\mu\nu} \\ & + \frac{1}{2}\mathbf{Tr}\left[\boldsymbol{\Phi}\,\gamma^{\{\mu}\right]\mathbf{Tr}\left[\boldsymbol{\Xi}\,\gamma^{\nu\}}\right] + \frac{1}{2}\mathbf{Tr}\left[\boldsymbol{\Phi}\,\gamma^{\{\mu}\,\gamma_5\right]\mathbf{Tr}\left[\boldsymbol{\Xi}\,\gamma^{\nu\}}\,\gamma_5\right] \\ & + \frac{1}{2}\mathbf{Tr}\left[\mathbf{i}\,\boldsymbol{\Phi}\,\sigma^{\alpha\{\mu}\,\gamma_5\right]\mathbf{Tr}\left[\mathbf{i}\,\boldsymbol{\Xi}\,\sigma_\alpha^{\nu\}}\,\gamma_5\right].\end{aligned}$$

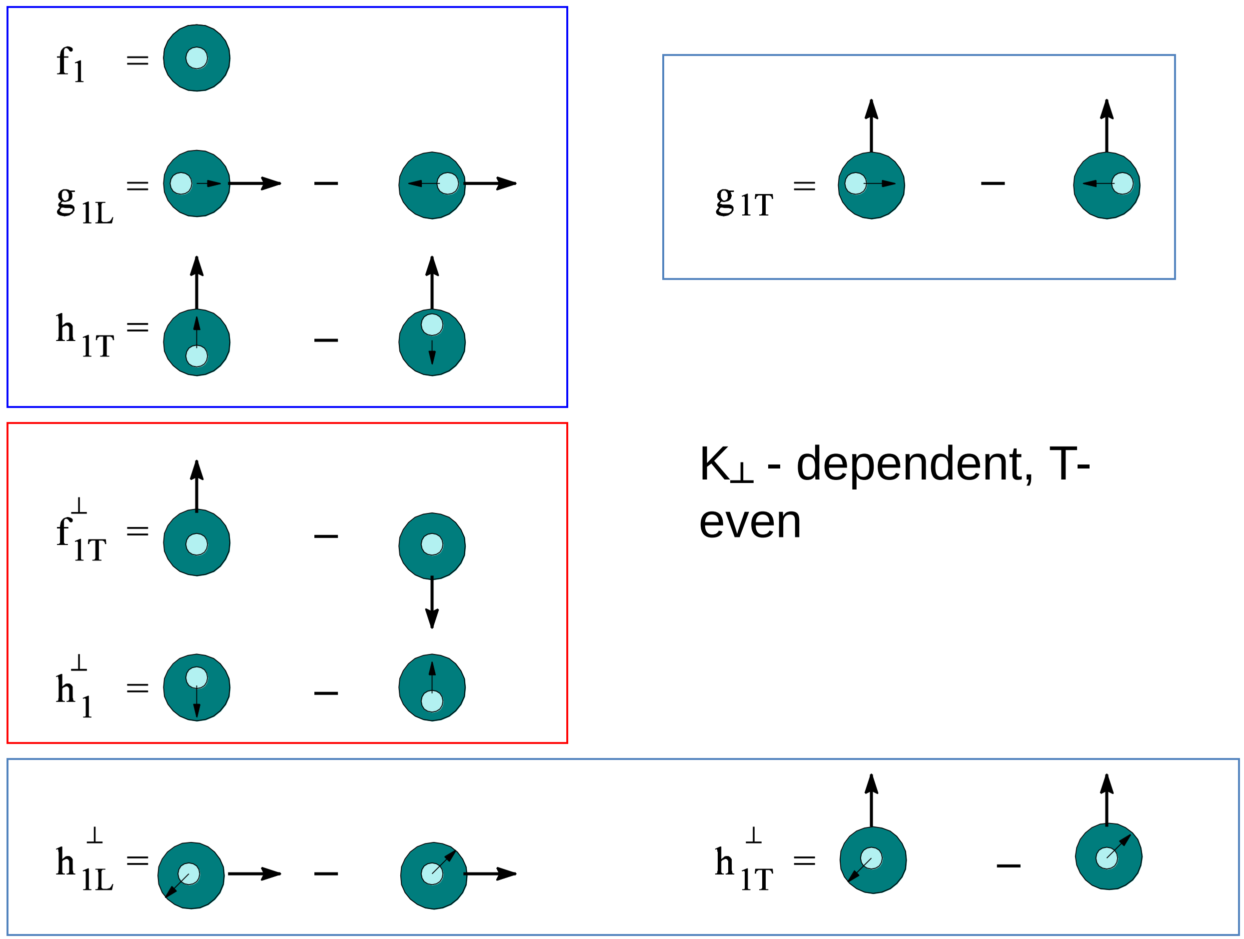
Leading-Twist Quark Distributions

(A total of eight distributions)

No $K_\perp$ dependence

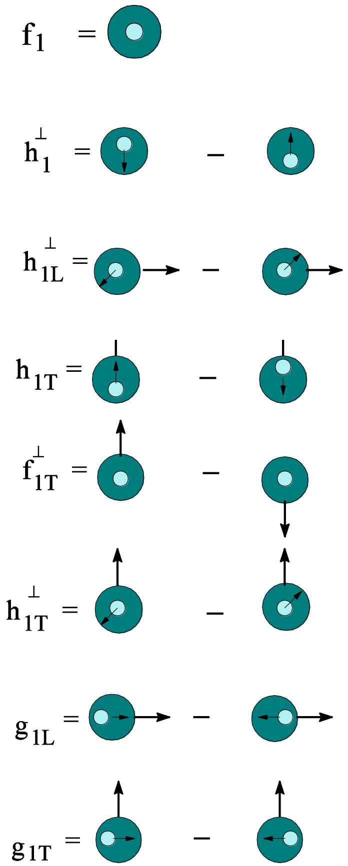
$K_\perp$ - dependent, T-odd

$K_\perp$ - dependent, T-even



Eight Quark Distributions Probed in SIDIS

$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4}\times$$



Transversity (h_{1T})

Sivers ($f_{1T}^\perp$)

Unpolarized

$$\{[1+(1-y)^2]\sum_{q,\bar q} e_q^2 f_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar q} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarized target

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar q} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar q} e_q^2 h_1^q(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar q} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar q} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarzied beam and target

$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar q} e_q^2 g_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar q} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z,P_{h\perp}^2)\}$$

S_L and S_T: Target Polarizations; λe: Beam Polarization

Single Spin Asymetry

$$A_{UT}(\phi_h,\phi_S) \equiv \frac{d\sigma(\phi_h,\phi_S) - d\sigma(\phi_h,\phi_S+\pi)}{d\sigma(\phi_h,\phi_S) + d\sigma(\phi_h,\phi_S+\pi)} \Longrightarrow A_{UT}^{Coll.(Siv.)} = \frac{\int d\phi_S d\phi_h \sin(\phi_h \pm \phi_s) d\sigma_{UT}}{\int d\phi_S d\phi_h d\sigma_{UU}};$$

$$A_{UT}^{Collins} \sim |\mathbf{S_T}| \times \frac{\sum_q e_q^2 \int d^2\kappa_\mathbf{T} d^2\mathbf{k_T} \delta^2(\mathbf{k_T}+\mathbf{q_T}-\kappa_\mathbf{T}) \frac{\hat{\mathbf{h}}\cdot\kappa_\mathbf{T}}{\mathbf{M_h}} h_1^q(x,\mathbf{k_T}^2) H_1^{\perp q,h}(z,(z\kappa_\mathbf{T})^2)}{\sum_q e_q^2 \int d^2\kappa_\mathbf{T} d^2\mathbf{k_T} \delta^2(\mathbf{k_T}+\mathbf{q_T}-\kappa_\mathbf{T}) f_1^q(x,\mathbf{k_T^2}) D_1^{q,h}(z,(z\kappa_\mathbf{T})^2)}$$

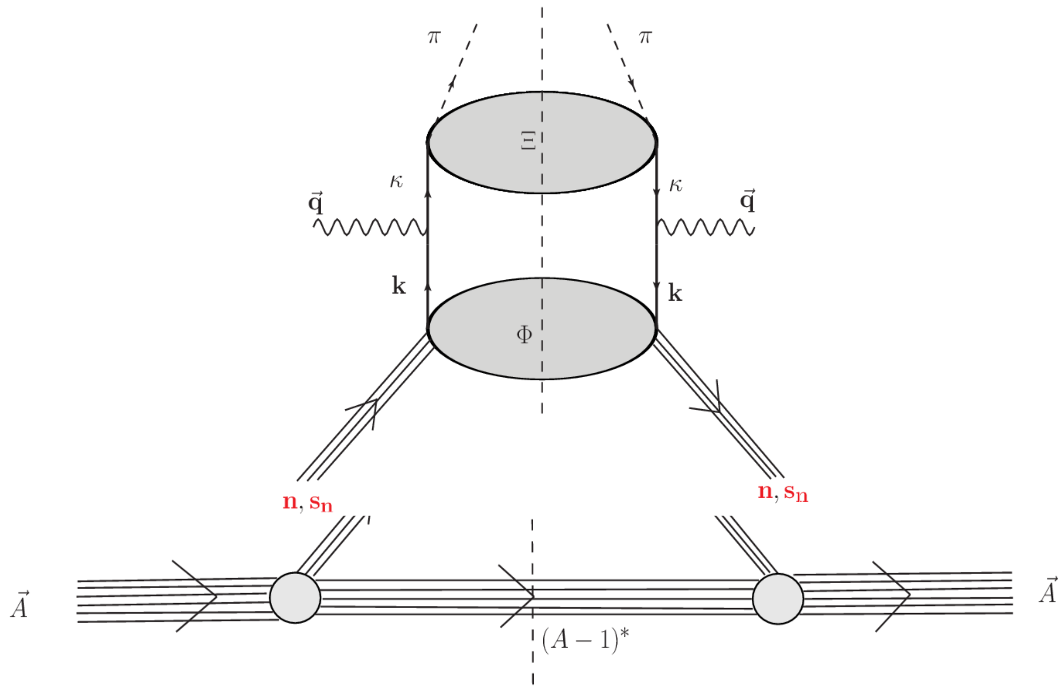
$$A_{UT}^{Sivers} = |\mathbf{S_T}| \frac{\sum_q e_q^2 \int d^2\kappa_\mathbf{T} d^2\mathbf{k_T} \delta^2(\mathbf{k_T}+\mathbf{q_T}-\kappa_\mathbf{T}) \frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{\mathbf{M}} f_{1T}^{\perp q}(x,\mathbf{k_T}^2) D_1^{q,h}(z,(z\kappa_\mathbf{T})^2)}{\sum_q e_q^2 \int d^2\kappa_\mathbf{T} d^2\mathbf{k_T} \delta^2(\mathbf{k_T}+\mathbf{q_T}-\kappa_\mathbf{T}) f_1^q(x,\mathbf{k_T^2}) D_1^{q,h}(z,(z\kappa_\mathbf{T})^2)}$$

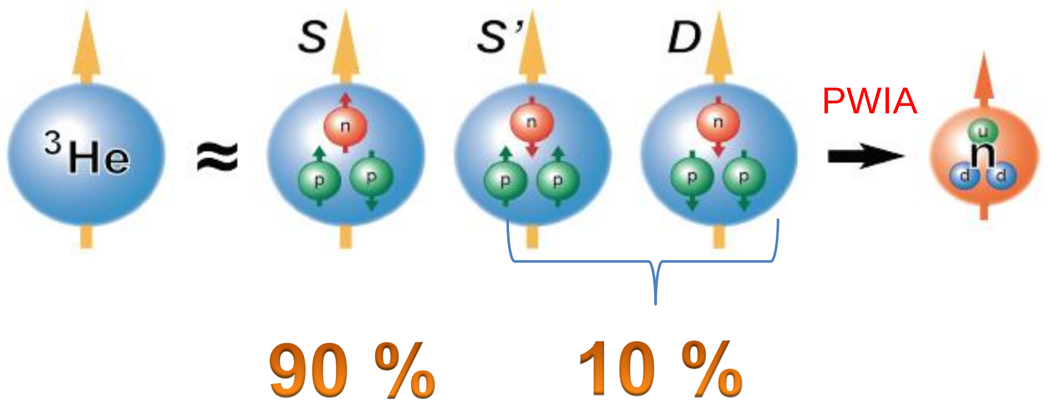
$H_1^{\perp q,h}(z,(z\kappa_\mathbf{T})^2)$, the (a T-odd) Collins fragmentation function $\equiv$ number density of scalar hadrons originating from the fragmentation of a transversely polarized quark

$f_{1T}^{\perp q}(x,\mathbf{k_T}^2)$ **the Sivers distribution function (T-odd) $\equiv$ number density of unpolarized quarks in a transversely polarized target**

HERMES, COMPASS, JLAB $\qquad \vec{l} + \vec{p} = l' + h + X$

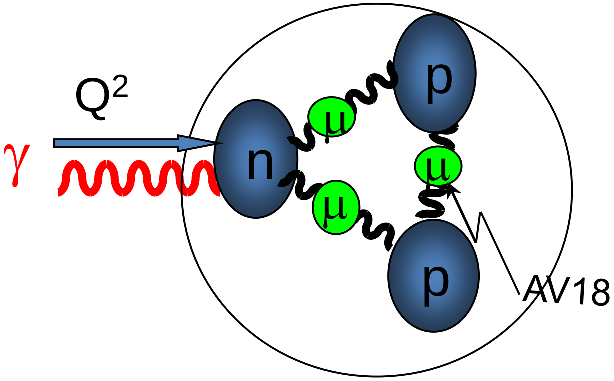
Polarized neutron?

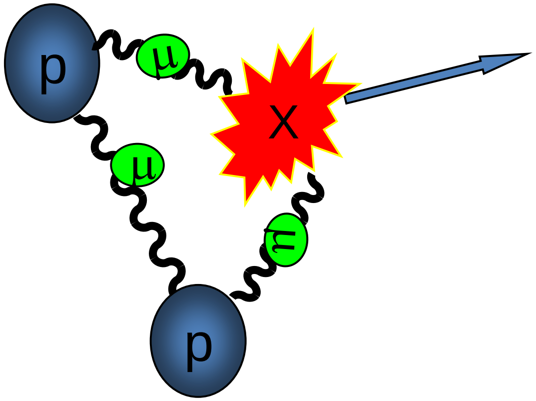


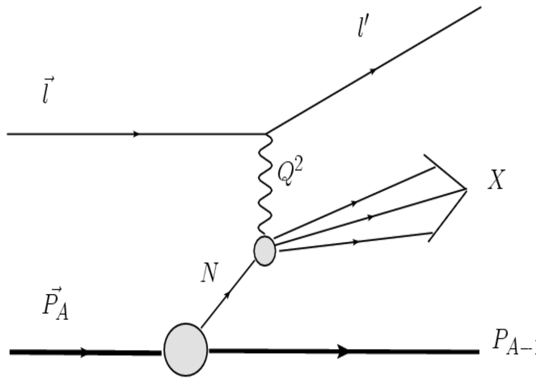


Single Target-Spin Asymmetry in Semi-Inclusive π Electroproduction on a Transversely Polarized ^{3}He Target (JLAB, E03-004(010,011), EPJ Plus, 126 (2011) 2)

What's PWIA?







Exact factorization & the nuclear spectral function

CdA & LPK **Phys.Rev. C66 (2002) 044004**

$$d\sigma(eA) = K\ d\sigma(eN) P(k_1, E_{rem})$$

$$\mathbf{P}(\mathbf{k}, \mathbf{E_{rem}}) = \sum_{\mathbf{f}} |\langle (\mathbf{A}-\mathbf{1})_{\mathbf{f}} \, |\mathbf{a}(\mathbf{k})| \, \mathbf{A}\rangle|^{\mathbf{2}} \, \delta \left(\mathbf{E_{rem}} - \sqrt{\mathbf{P^2_{A-1}}} - \mathbf{m_N} + \mathbf{M_A} \right)$$

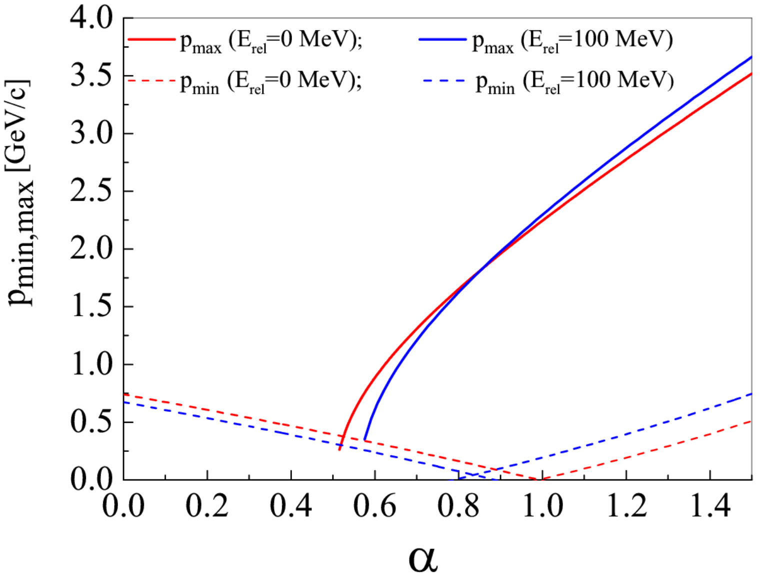
many-body problem

$$\mathcal{F}^A\left(x_{Bj},Q^2\ldots\}\right)=\sum_N\int_{x_{Bj}}^{A}\mathcal{F}^N\left(x_{Bj}/\alpha,Q^2\ldots,\}\right)f_N^A(\alpha,Q^2\ldots)d\alpha;$$

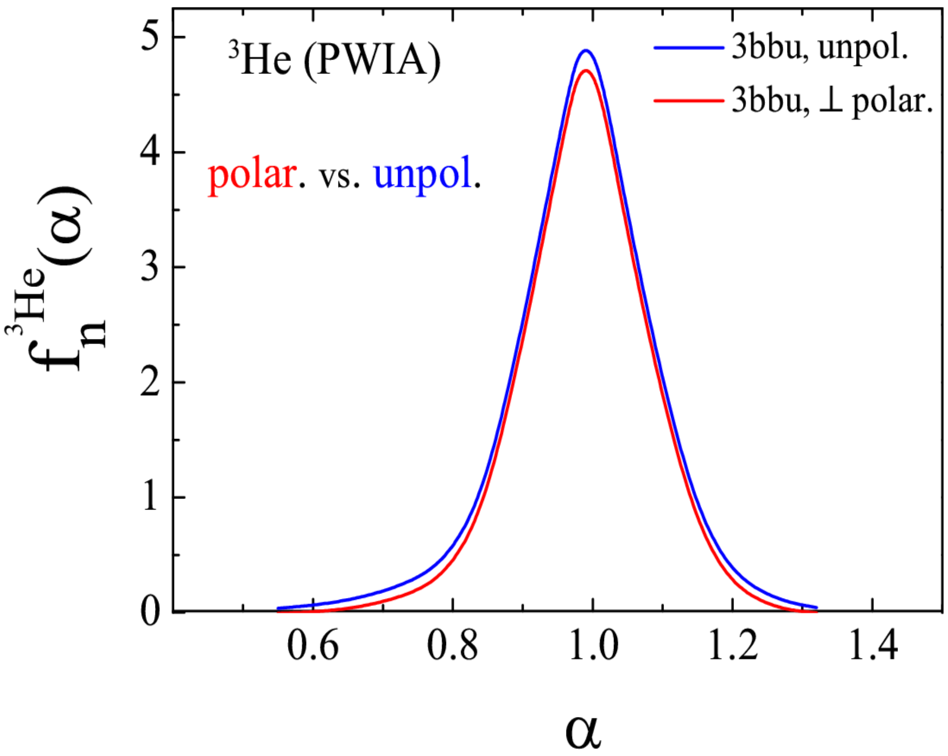
$$f_N^A(\alpha,Q^2\ldots)=\int dE\int_{p_{min}(\alpha,Q^2\ldots)}^{p_{max}(\alpha,Q^2\ldots)}P_N^A(\mathbf{p},E)\delta\left(\alpha-\frac{pq}{m\nu}\right)\theta\left(W_x^2-(M_N+M_\pi)^2\right)d^3\mathbf{p}$$

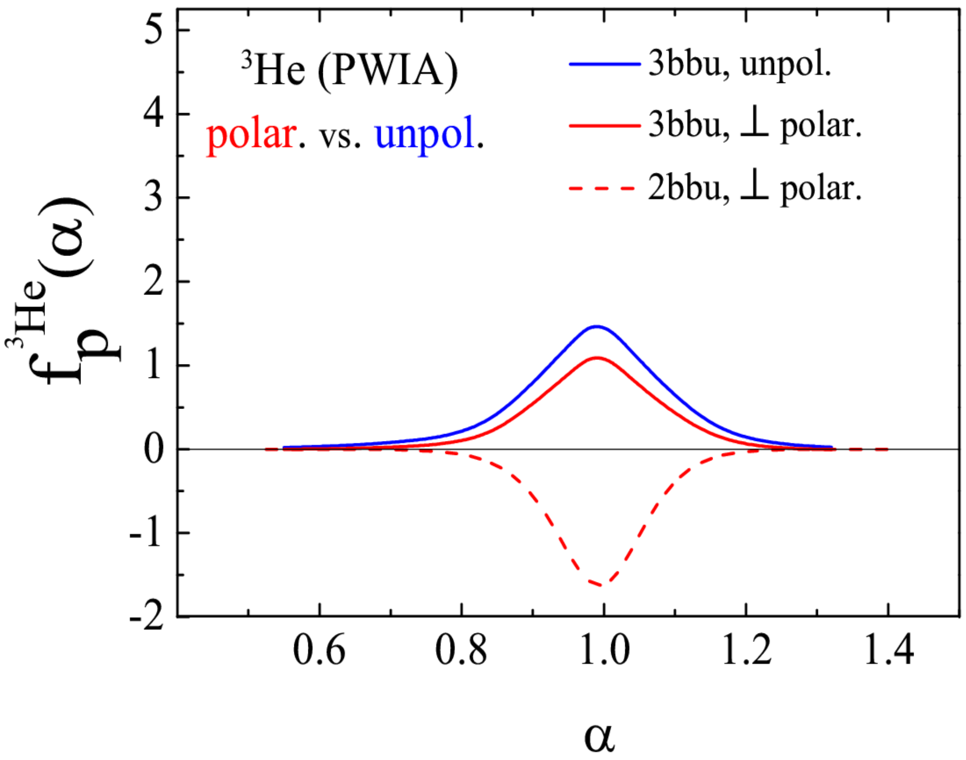
- **Bjorken Limit:** $|\mathbf{q}|\to\infty,\ \nu\to\infty$, $\mathbf{p}_{min;max}$ **depend only on** α **and, consequently,** $f_N^A(\alpha)$ **is independent on** Q^2 **and** $x_{Bj}\equiv\dfrac{Q^2}{2M_N\nu 2}$ **and** $0\le\ \alpha\le A$

- **JLAB kinematics,** $|\mathbf{q}|=\nu\sqrt{\mathbf{1}+\frac{\mathbf{4M_N^2x_{Bj}^2}}{\mathbf{Q^2}}}$
  $E_0=8.80\ GeV;\quad E'=2.44\ GeV;\quad \theta_{scatt.}=30^o$
  $\alpha_{min}\ \neq\ 0$ →



L. P.K., A. Del Dotto, E. Pace, G. Salm`e, S.Scopetta., PRC 89 (2014) 035206


^{3}He (PWIA)
polar. vs. unpol.
3bbu, unpol.
3bbu, ⊥ polar.
$f_n^{^3He}(\alpha)$
α
0
1
2
3
4
5
0.6
0.8
1.0
1.2
1.4


^{3}He (PWIA)
polar. vs. unpol.
3bbu, unpol.
3bbu, ⊥ polar.
2bbu, ⊥ polar.
$f_p^{^3He}(\alpha)$
α
-2
-1
0
1
2
3
4
5
0.6
0.8
1.0
1.2
1.4

Unfold the convolutoin formula by taking advantage of the fact that $\alpha \sim 1$, the distribution function $f_N^A(\alpha, Q^2) \sim \delta(\alpha - 1)$. Then the extraction procedure is based on two main conjectures:
i) The calculated cross section within the PWIA describes the experimental data, i.e.

$$d\sigma_3^{exp.} \simeq d\sigma_3^{PWIA}$$

ii) The binding effects in ^3He are small and the intrinsic neutron can be treated as quasi-free. Then the experimentally measures asymmetry A_3 (Collins or/and Sivers) can be written as

$$A_3^{exp} = \frac{\Delta\vec{\sigma}_3^{exp.}}{\sigma_{unpol.}^{exp.}} \simeq \frac{\Delta\vec{\sigma}(ntr)\cdot\int dE\; d^3\mathbf{p}\vec{P}_n(E,\mathbf{p}) + 2\Delta\vec{\sigma}(prt)\cdot\int dE\; d^3\mathbf{p}\vec{P}_p(E,\mathbf{p})}{\sigma_{unpol.}(ntr)\int dE\; d^3\mathbf{p}P_n^{unpol}(E,\mathbf{p}) + 2\sigma_{unpol.}(prt)\int dE\; d^3\mathbf{p}P_p^{unpol}(E,\mathbf{p})},$$

Introduce the so-called "dilution" functions as

$$A_3^{exp} = \langle p_n\rangle \underbrace{\frac{\Delta\vec{\sigma}(ntr)}{\sigma_{unpol.}(ntr)}}_{A_n} \underbrace{\frac{\sigma_{unpol.}(ntr)}{\langle N_n\rangle\sigma_{unpol.}(ntr) + 2\langle N_p\rangle\sigma_{unpol.}(prt)}}_{d_n} +$$

$$+2\langle p_p\rangle \underbrace{\frac{\Delta\vec{\sigma}(prt)}{\sigma_{unpol.}(prt)}}_{A_p} \underbrace{\frac{\sigma_{unpol.}(prt)}{\langle N_n\rangle\sigma_{unpol.}(ntr) + 2\langle N_p\rangle\sigma_{unpol.}(prt)}}_{d_p} \equiv \langle p_n\rangle d_n A_n + 2\langle p_p\rangle d_p A_p,$$

$$\mathbf{A_n = \frac{1}{\langle p_n\rangle d_n}\left[A_3^{exp.} - 2\langle p_p\rangle d_p A_p^{exp.}\right]}.$$

C. Ciofi degli Atti, S. Scopetta, E.Pace, G. Salme, PR.C 48 (1993) 968.

PWIA and Sivers and Collins Asymetries

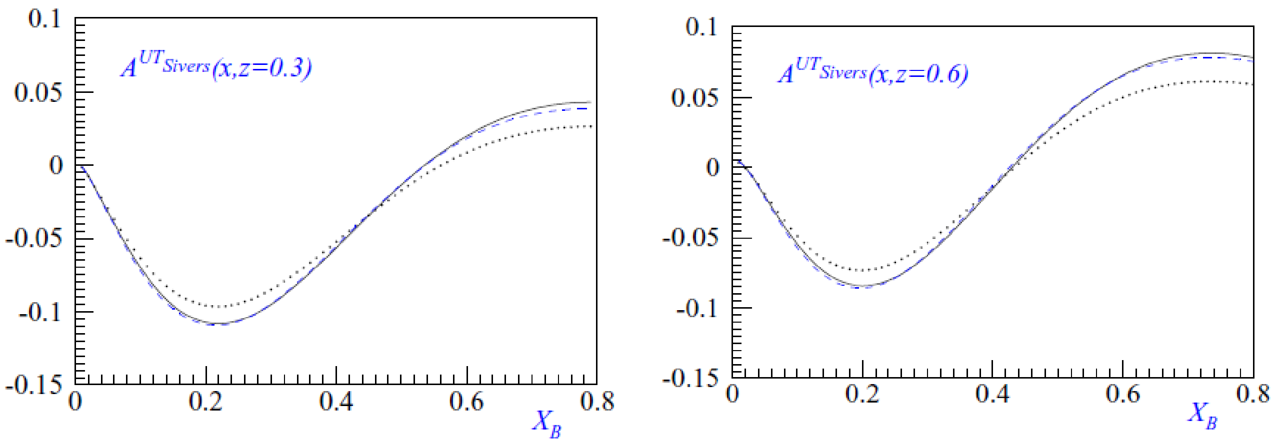
- A realistic spin-dependent spectral function of 3He within the AV18 interaction and w.f. by the Pisa group (A. Kievsky et al., NPA 577, 511 (1994).)

- Parameterizations of data for pdfs and fragmentation functions whenever available $(f_1^q(x,k_\perp)$ GRV 1998, $f_{1T}^{\perp q}(x,k_\perp)$ Anselmino et al.,2005, $D_1^{qh}(z,z^2\kappa_T^2)$ Kretzer, 2000)

- Models for the unknown pdfs and fragmentation functions.

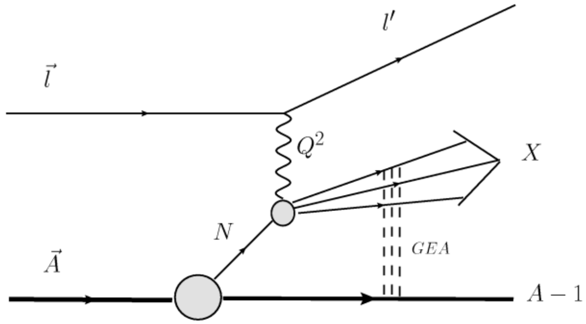
($h_1^q(x,k_\perp)$ GRVW, 2001, $H_1^{\perp hq}(z,z^2\kappa_T^2)$ Amrath et al, 2005)

S. Scopetta, Phys.Rev. D75 (2007) 054005



full – "free" neutron (input)
dot - extracted without prt
dash – extracted with dilution factors

In PWIA (!) nuclear effects in the extarction of the neutron information from polarized ^3He are found to be under control



PWIA + FSI (Generalized Eikonal Approximation)

$$d\sigma(eA) \sim l^{\mu\nu} \cdot W^A_{\mu\nu}(S_A)$$

1
$$W^A_{\mu\nu} \sim \overline{\sum_{\alpha_A}} \sum_{\alpha_{A-1},\alpha_N} \langle \alpha_A \mathbf{P} | \hat{\mathbf{J}}^A_\mu(0) | \alpha_\mathbf{N} \mathbf{p_1}, \alpha_\mathbf{A-1} \mathbf{P_{A-1}} \mathbf{E^f_{A-1}} \rangle \langle \mathbf{E^f_{A-1}} \mathbf{P_{A-1}} \alpha_\mathbf{A-1}, \mathbf{p_1} \alpha_\mathbf{N} | \hat{\mathbf{J}}^A_\nu(0) | \alpha_\mathbf{A} \mathbf{P_A} \rangle \ ,$$

2
$$\Phi_{^3\mathrm{He}}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) = \mathcal{A} e^{i\mathbf{P}\mathbf{R_c}} \Psi_3(\boldsymbol{\rho}, \mathbf{r}); \qquad \Phi^*_\mathbf{f}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) = \mathcal{A} \mathbf{G}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) e^{-i\mathbf{p}'\mathbf{r_1}} e^{-i\mathbf{P_{23}}\mathbf{R_{23}}} \Psi^*_{23}(\mathbf{r})$$

3
$$\mathbf{G}(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) = \prod_{\mathbf{j=2}}^{\mathbf{3}} \left[\mathbf{1} - \theta\left(\mathbf{r_{j\|}} - \mathbf{r_{1\|}}\right) \boldsymbol{\Gamma}\left(\mathbf{r_{j\perp}} - \mathbf{r_{1\perp}}\right)\right], \qquad \boldsymbol{\Gamma}(\mathbf{r_\perp}) = \boldsymbol{\Gamma}(\mathbf{r_\perp}, \sigma^{\mathbf{NX}}_{\mathbf{eff}})$$

4
$$J_\mu = \int d\mathbf{r}_1 d\mathbf{r}_2 d\mathbf{r}_3 \Psi^{*f}_{23}(\mathbf{r}_2, \mathbf{r}_3) e^{-\mathbf{p}_X \mathbf{r}_1} \chi^+_{\lambda_X} \phi^*(\xi_x) \cdot \mathcal{G}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3) \hat{j}_\mu(\mathbf{r}_1, X) \vec{\Psi}^M_3(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3)$$

5
$$\left[\mathcal{G}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3, \sigma^{NX}_{eff}), \hat{j}_\mu(\mathbf{r}_1, X)\right] = 0!!!(?) \longrightarrow$$ **FACTORIZATION**

etc

M. Alvioli, CdA & LPK PRC 81 (Rapid Comm.) (2010) 02100;
CdA &LPK Phys.Rev.Lett. 100 (2008) 122301;

CdA & LPK, *PRL* **95**, 052502 (2005), L. Frankfurt, M. Sargsian, M. Strikman Int. J.Mod. Phys. **A23** **(2008)** 2291

SIDIS AND FSI-EFFECTS

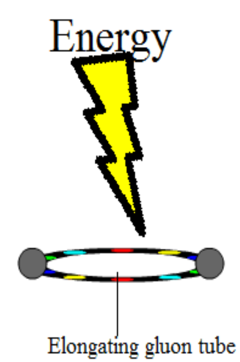
$$\mathcal{O}_{\lambda\lambda'}^{MM'(FSI)}(p_N,E)=\int\left\langle \mathcal{G}(1,2,3,\sigma_{eff}^{NX})\left\{\Psi_{23}^{\mathbf{t}},\lambda,\mathbf{p}_N\right\}|\Psi_{^3He}^{M}\right\rangle\left\langle\Psi_{^3He}^{M'}|\mathcal{G}(1,2,3,\sigma_{eff}^{NX})\left\{\Psi_{23}^{\mathbf{t}},\lambda',\mathbf{p}_N\right\}\right\rangle\delta\left(E-\frac{t^2}{M_N}\right)\frac{d^3\mathbf{t}}{(2\pi)^3}$$

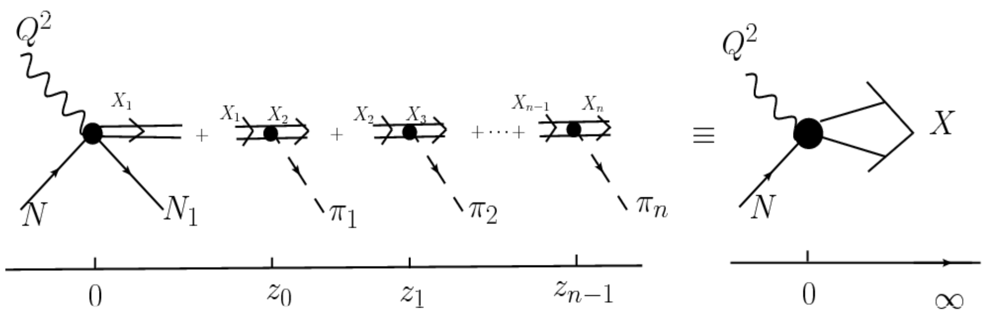
$$\mathcal{F}^A\left(x_{Bj},Q^2\dots\}\right)=\sum_N\int_{x_{Bj}}^{A}\mathcal{F}^N\left(x_{Bj}/\alpha,Q^2\dots,\}\right)f_N^A(\alpha,Q^2\dots)d\alpha;$$

$$f_N^A(\alpha,Q^2\dots)=\int dE\int_{p_{min}}^{p_{max}}P_N^{FSI}(\mathbf{p},E,\sigma_{eff}^{NX})\delta\left(\alpha-\frac{pq}{m\nu}\right)\theta\left(W_x^2-(M_N+M_\pi)^2\right)d^3\mathbf{p}$$

$$\boldsymbol{\sigma}_{eff.}^{XN}=?$$

Color string model + gluon radiation





$$\sigma_{eff}(z)=\sigma_{tot}^{NN}+\sigma_{tot}^{\pi N}\left[n_M(z)+n_G(z)\right]$$

C. CdA, L.P.K,et al. PRC 80 (2009) 054610; ibidPRC C81(2010)
C. CdA, L.P.K, C.B. Mezzetti, Fizica 20, (2012).

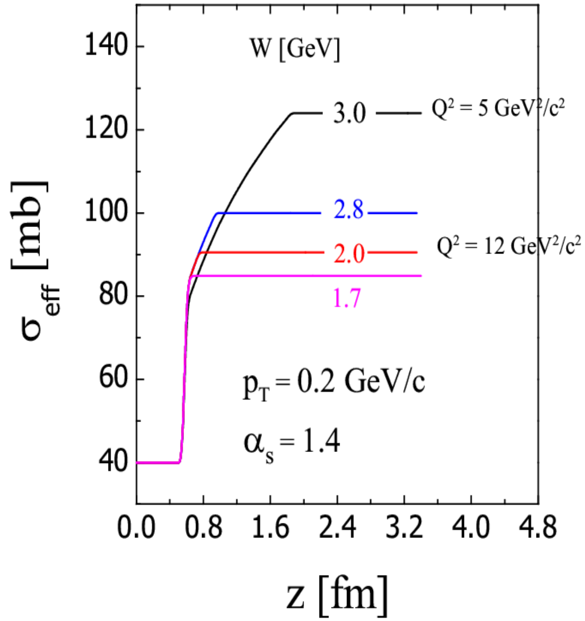
$$\mathbf{n_M(t)} = \frac{\ln(\mathbf{1} + \mathbf{t}/\boldsymbol{\Delta}\mathbf{t})}{\ln \mathbf{2}}$$

$t < t_0$

$$\mathbf{n_G}(\mathbf{t}) = \frac{\mathbf{16}}{\mathbf{27}} \left\{ \ln\left(\frac{\mathbf{Q}}{\boldsymbol{\lambda}}\right) + \ln\left(\frac{\mathbf{t}\,\boldsymbol{\Lambda}_{\mathbf{QCD}}}{\mathbf{2}}\right) \ln\left[\frac{\ln(\mathbf{Q}/\boldsymbol{\Lambda}_{\mathbf{QCD}})}{\ln(\boldsymbol{\lambda}/\boldsymbol{\Lambda}_{\mathbf{QCD}}}\right]\right\}$$

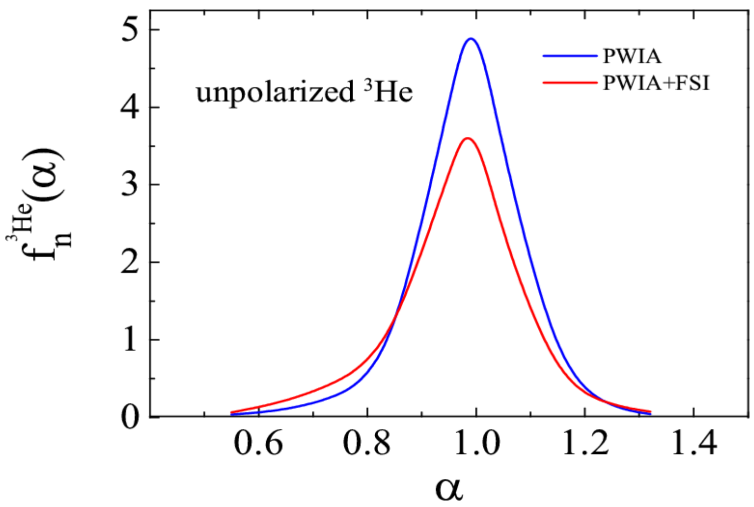
$t > t_0$

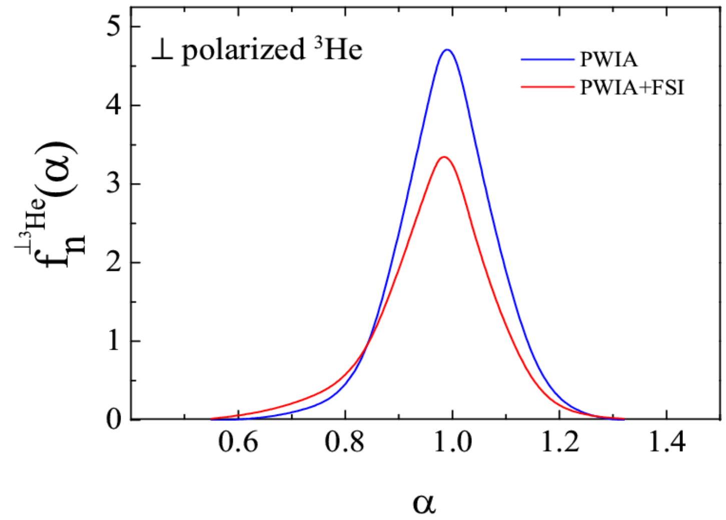
$$\mathbf{n_G}(\mathbf{t}) = \frac{16}{27} \left\{ \ln\left(\frac{Q}{\boldsymbol{\lambda}}\frac{t_0}{t}\right) + \ln\left(\frac{t\,\boldsymbol{\Lambda}_{QCD}}{2}\right) \ln\left[\frac{\ln(Q/\boldsymbol{\Lambda}_{QCD}\sqrt{t_0/t})}{\ln(\boldsymbol{\lambda}/\boldsymbol{\Lambda}_{QCD})}\right] + \ln\left(\frac{Q^2\,t_0}{2\,\boldsymbol{\Lambda}_{QCD}}\right) \ln\left[\frac{\ln(Q/\boldsymbol{\Lambda}_{QCD})}{\ln(Q/\boldsymbol{\Lambda}_{QCD}\,\sqrt{t_0/t})}\right]\right\}$$



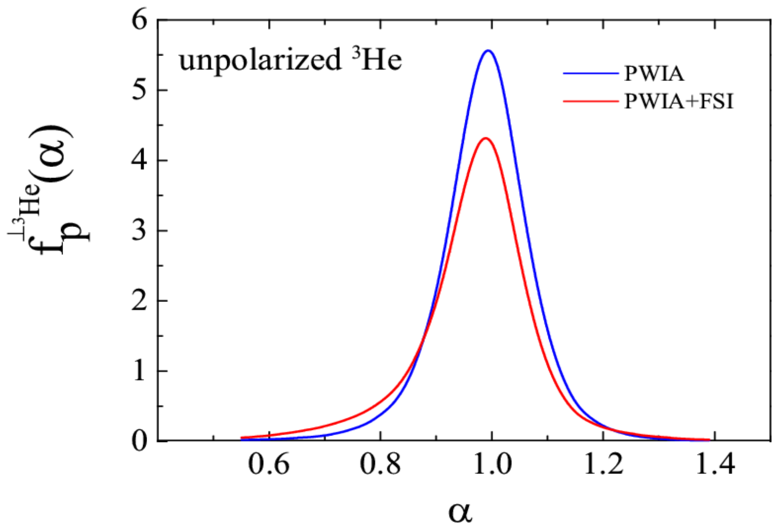
C. CdA, L.P.K, B.Z. Kopeliovich, E.P.J. **A19** (2004) 133; ibid p. 145
V. Palli, C. CdA, L.P.K, C.B. Mezzetti, M. Alvioli, PRC **80** (2009) 054610; ibidPRC **C81**(2010)

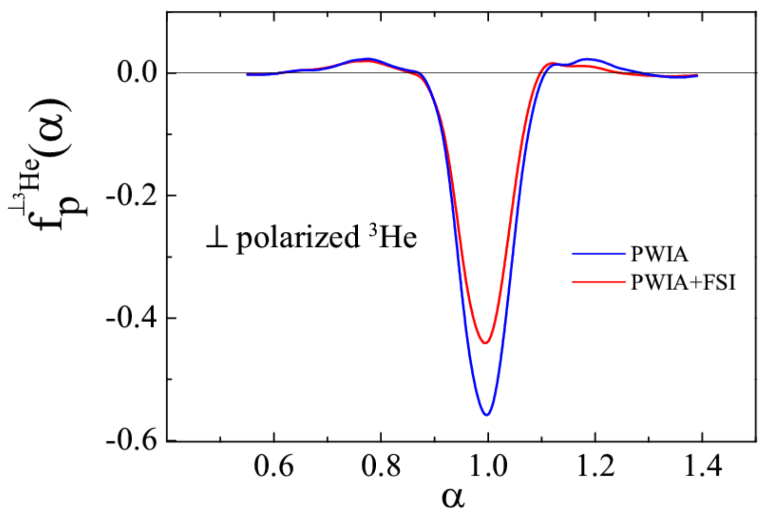
NEUTRON





PROTON





DILUTION FACTORS

$$A_3^{exp} \simeq \frac{\Delta\vec{\sigma}_3^{exp.}}{\sigma_{unpol.}^{exp.}} \Longrightarrow \frac{\langle \vec{s}_n \rangle \Delta\vec{\sigma}(n) + 2\langle \vec{s}_p \rangle \Delta\vec{\sigma}(p)}{\langle N_n \rangle \sigma_{unpol.}(n) + 2\langle N_p \rangle \sigma_{unpol.}(p)} = \langle \vec{s}_n \rangle d_n A_n + 2\langle \vec{s}_p \rangle d_p A_p$$

PWIA:

$$\langle \vec{s}_{n(p)} \rangle = \int dE \int d^3p P_{||}(E, \mathbf{p}) = \mathbf{p}_{n(p)};$$
$$\langle N \rangle = \int dE \int d^3p P_{unpol.}(E, \mathbf{p}) = 1.$$

$$\Longrightarrow \quad d_{n,(p)}(x,z) = \frac{\sum_q e_q^2 f_1^{q,n(p)}(x) D_1^{q,h}(z)}{\sum_N \sum_q e_q^2 f_1^{q,N}(x) D_1^{q,h}(z)}$$

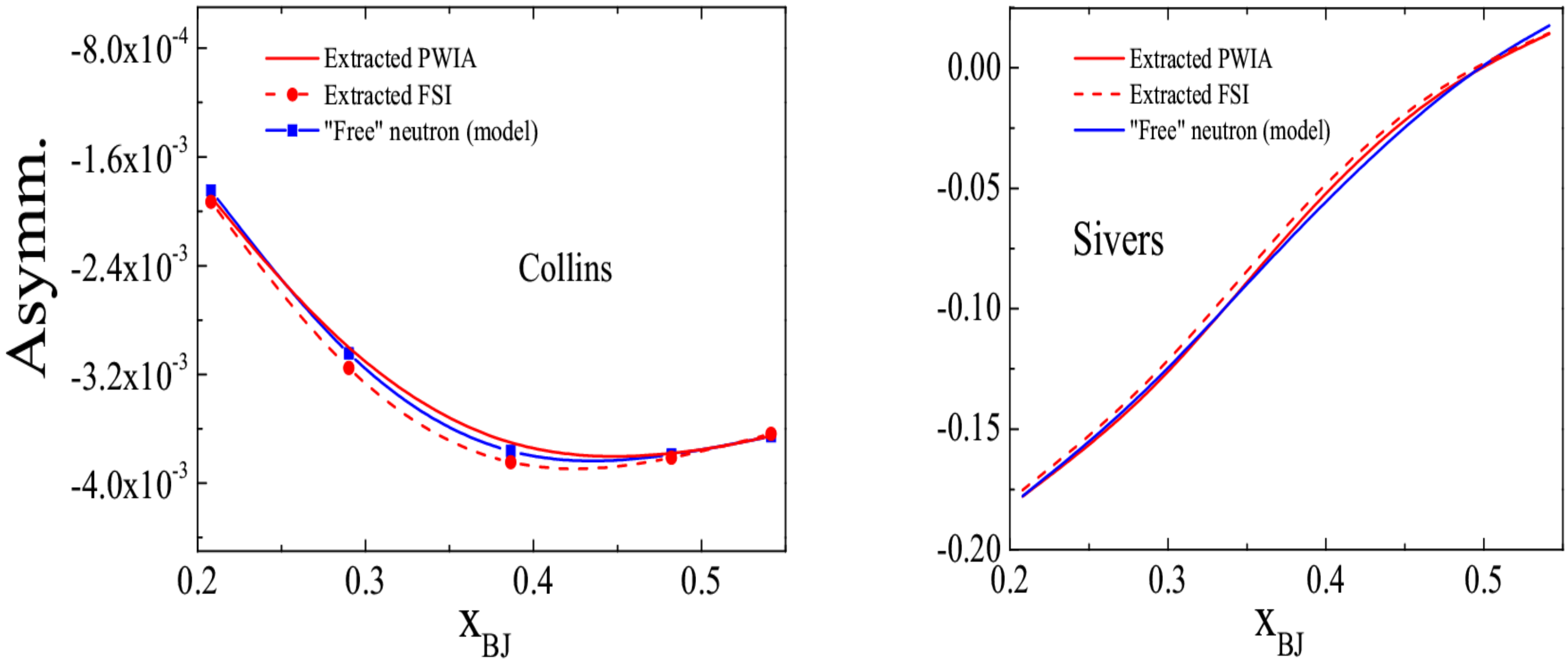
FSI:

$$\langle \vec{s}_{n(p)} \rangle = \int dE \int d^3p P_{||}^{FSI}(E, \mathbf{p}) = \mathbf{p}_{n(p)}^{FSI};$$
$$\langle N \rangle = \int dE \int d^3p P_{unpol.}^{FSI}(E, \mathbf{p}) < 1.$$

$$\Longrightarrow \quad d_{n,(p)}^{FSI}(x,z) = \frac{\sum_q e_q^2 f_1^{q,n(p)}(x) D_1^{q,h}(z)}{\sum_N \langle N \rangle \sum_q e_q^2 f_1^{q,N}(x) D_1^{q,h}(z)}$$

$$A_n \simeq \frac{1}{p_n^{FSI}\ d_n^{FSI}} \left(A_3^{exp} - 2p_p^{FSI} d_p^{FSI} A_p^{exp} \right) \simeq \frac{1}{p_n\ d_n} \left(A_3^{exp} - 2p_p d_p A_p^{exp} \right)$$

Extracted Asymmetries



INTERMEDIATE conclusions

- **PWIA describes data fairly well at low and moderate intrinsic momenta (up to 250-300 MeV/c)**
- **PWIA + GEA describes data in the whole kinematical region in q.e. ($\sigma = \sigma_{NN}$) high energy e.m. processes off ^{3}He**
- **PWIA + GEA with factorization adequately describes unpolarized spectator SIDIS ($\sigma = \sigma_{eff}(t,Q^2,x_{Bj})$) at intrinsic momenta up to 400-500 MeV/c**
- **Since in the "standard" SIDIS processes one integrates over undetected removal energy and momenta (from 0 to infinity) the PWIA + GEA ($\sigma = \sigma_{eff}(t,Q^2,x_{Bj})$) with factorization can be applied to extarct free Information information also from polarized SIDIS processes**

Tagging the Nucleon Structure in the "Spectator" SIDIS

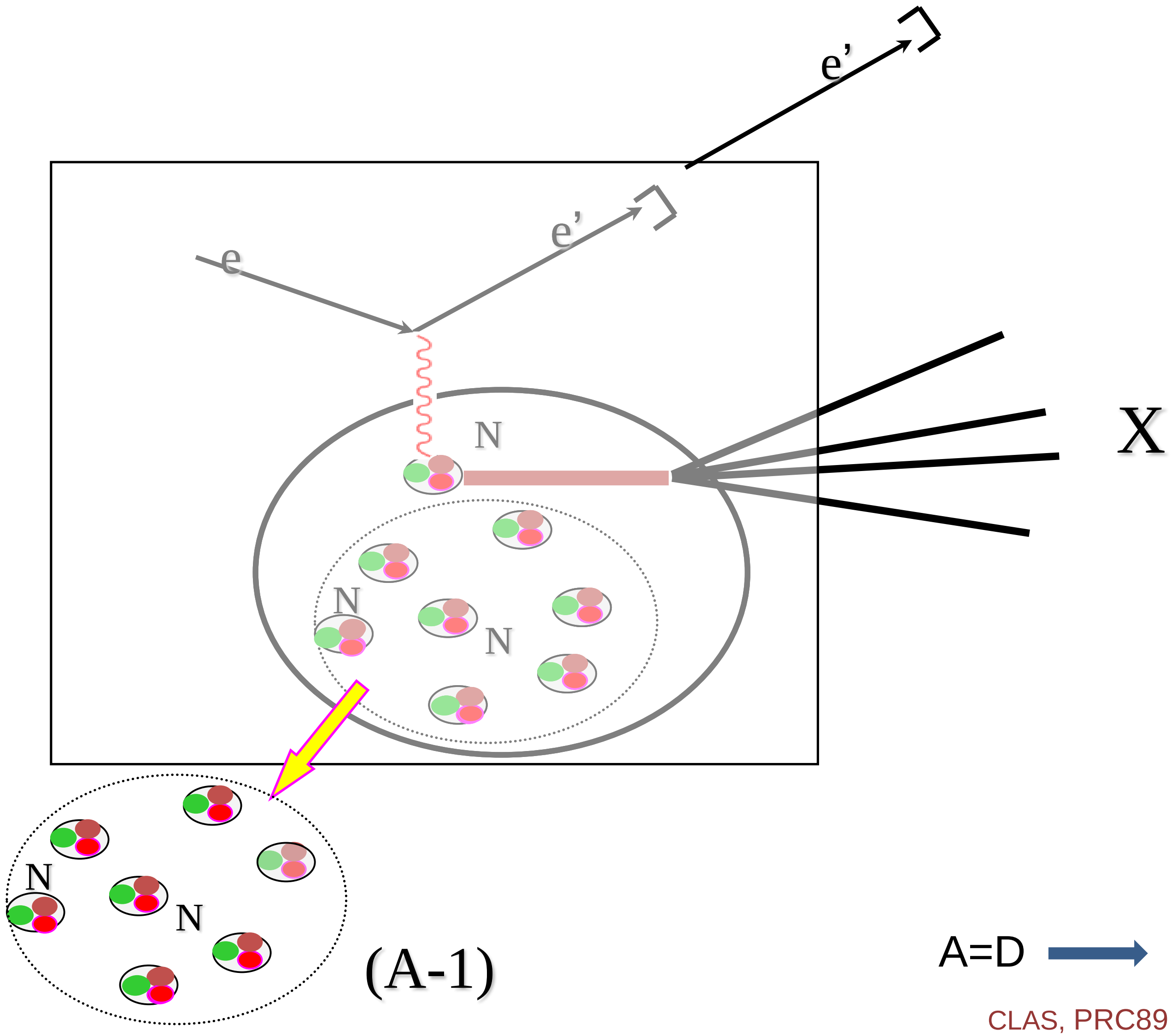
In spite of many experimental and theoretical efforts, the origin of the nuclear EMC effect exhibited by INCLUSIVE DIS of leptons off nuclei, has not yet been fully clarified, and the problem as to whether and to what extent the quark distributions of nucleons undergo deformations due to the nuclear medium remains open. We argue that in SPECTATOR SIDIS off a complex nucleus A, the detection, in coincidence with the scattered electron, of a nucleus $(A-1)$ in the ground or excited state may provide unique information on:

$i)$ **the medium induced modifications of the nucleon structure function and the origin of the EMC effect, and**

$ii)$ **the mechanism of quark hadronization in the nuclear medium.**

C. Ciofi degli Atti, L. P.K., S. Scopetta, EPJA 5 (1999) 191; PRC 83 (2011) 044602,;
C. Ciofi degli Atti, L.P.K. , B. Kopeliovich, EPJ A19, (2004), 133 C. Ciofi degli Atti, L. P.K., and
C. Mezzeti Fizika B20 (2011) 161
CLAS, Phys.Rev. C89 (2014) 4, 045206, Phys.Rev. C90 (2014) 5, 059901
L. P.K., A. Del Dotto, E. Pace, G. Salm`e, S.Scopetta., PRC 89 (2014) 035206

Tagging the Nucleon Structure in the "Spectator" SIDIS



A=D ⟶ Deeps(BONUS)

CLAS, PRC89 (2014) 4, 045206,
PRC90 (2014) 5, 059901

Tagging the Nucleon Structure in the "Spectator" SIDIS

$$\frac{d\vec{\sigma}^{A,FSI}}{dx_{Bj}dQ^2dEd\mathbf{P_{A-1}}} = K^A\left(x_{Bj}, Q^2, y_A, z_1^{(A)}\right)\left(\frac{y}{y_A}\right)^2 z_1^{(A)}\mathcal{F}^{N/A}(x_A, Q^2, k_1^2)\,\vec{P}^A\,(E, \mathbf{P_{A-1}})\,,$$

$$K^A(x_{Bj}, Q^2, y_A, z_1^{(A)}) = \frac{4\alpha_{em}^2}{Q^4}\frac{\pi}{x_{Bj}}\cdot\left[\frac{y_A^2}{2} + (1-y_A) - \frac{k_1^2 x_{Bj}^2 y_A^2}{z_1^{(A)2}Q^2}\right] \, .$$

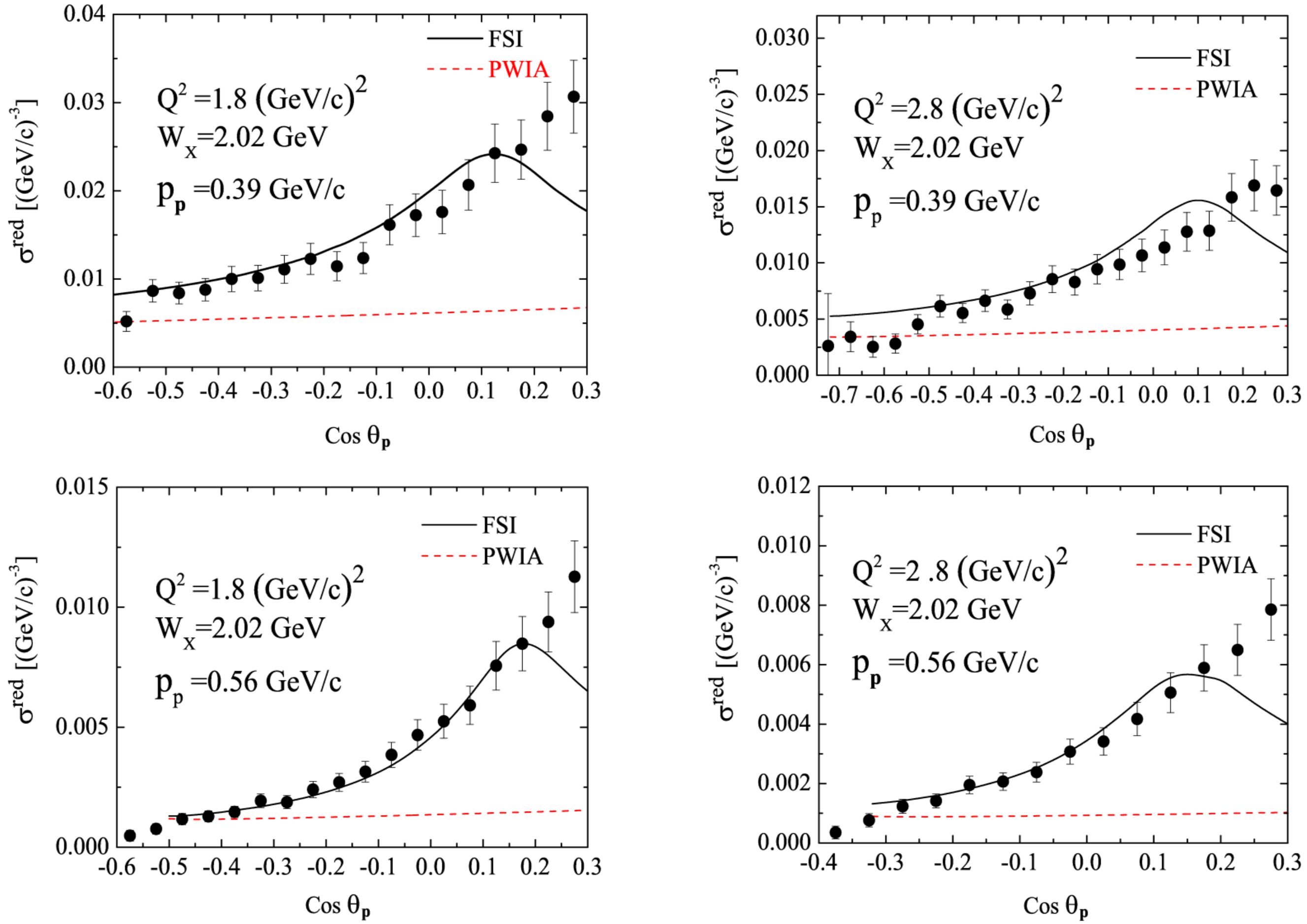
$$y_A = \frac{k_1\cdot q}{k_1\cdot k_e}\,, \quad x_A = \frac{x_{Bj}}{z_1^{(A)}}, \quad z_1^{(A)} = \frac{k_1\cdot q}{m_N\nu}\,,\,, \quad k_1 = P_A - P_{A-1}.$$

$$\vec{\sigma}^{red}(x_{Bj}, Q^2, \mathbf{p}_p) = \frac{1}{K^A(x_{Bj}, y_A, Q^2)}\left(\frac{y_A}{y}\right)^2\frac{1}{z_1^{(A)}}\frac{d\vec{\sigma}^{A,exp}}{dx_{Bj}dQ^2dEd\mathbf{p}_{A-1}}$$

$$\vec{\sigma}^{red}(x_{Bj}, Q^2, \mathbf{p}_p) = \mathcal{F}^{N/D}(x_A, Q^2, k_1^2)\,\vec{P}^A(E, \mathbf{p}_p)$$

Tagging the Hadronization Mechanism

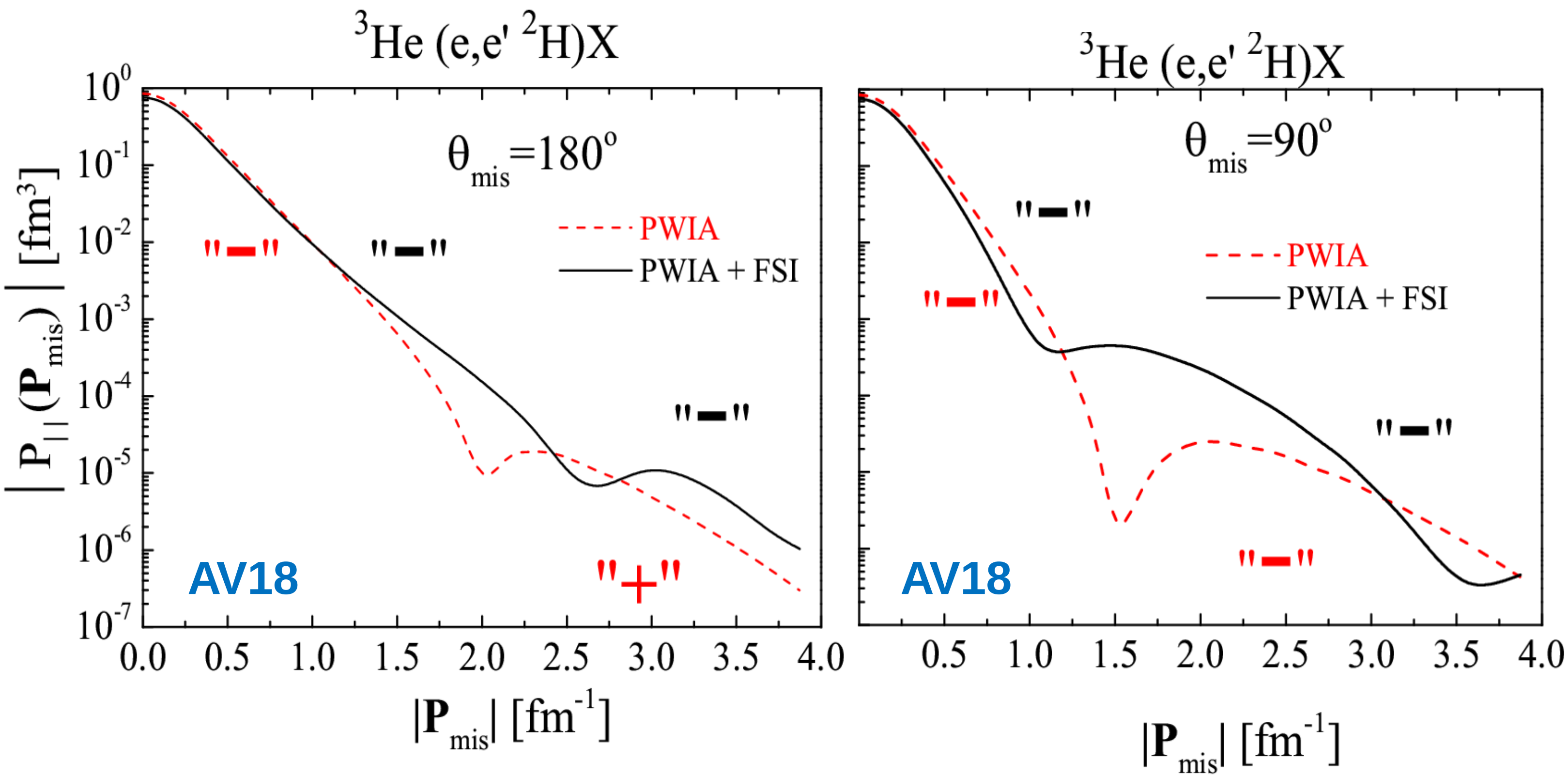
$D(e, e'p)X$ (Recent Jlab experiment)



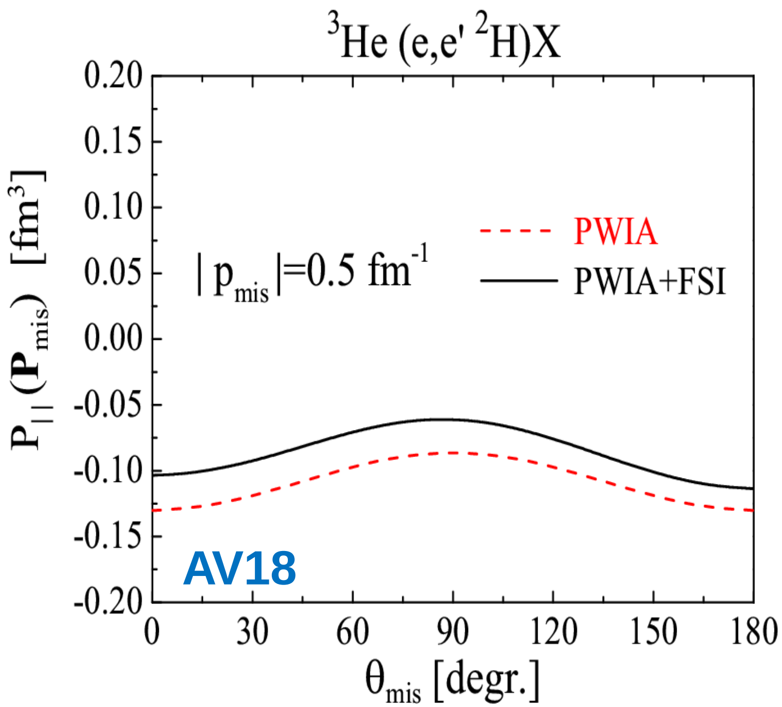
C. CdA, L.P.K, B.Z. Kopeliovich, E.P.J. **A19** (2004) 133; ibid p. 145
V. Palli, C. CdA, L.P.K, C.B. Mezzetti, M. Alvioli, PRC **80** (2009) 054610; ibidPRC **C81**(2010)
C. CdA, L.P.K, C.B. Mezzetti, Fizica **20**, (2012); W. Cosyn, M. Sargsian PRC **84** (2011) 014601

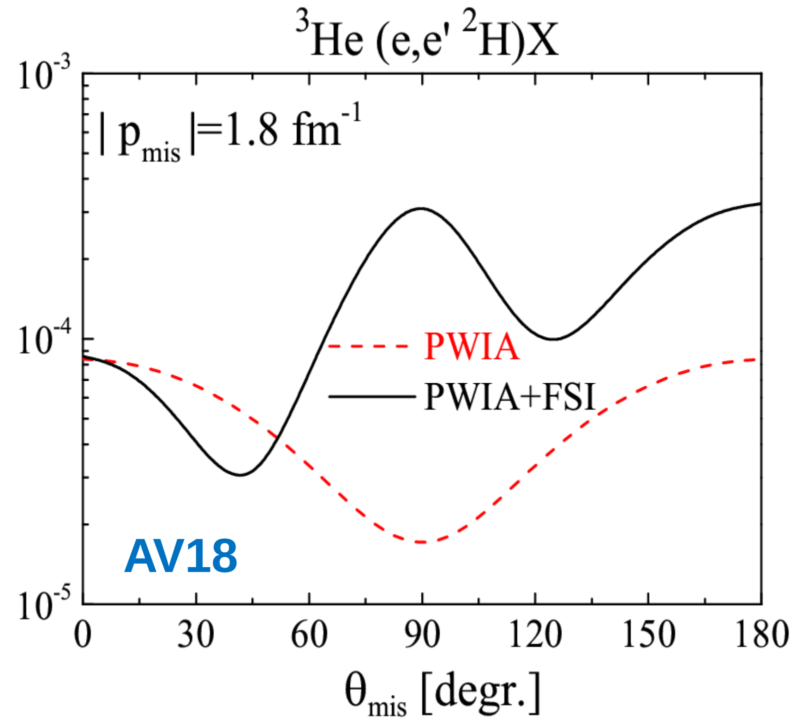
Tagging the Spin Dependent Spectral Function

L. P.K., A. Del Dotto, E. Pace, G. Salm`e, S.Scopetta., PRC 89 (2014) 035206



The Parallel (along the target polarization) Spin Dependent Spectral Function P|| (p_{mis},θ_{mis})

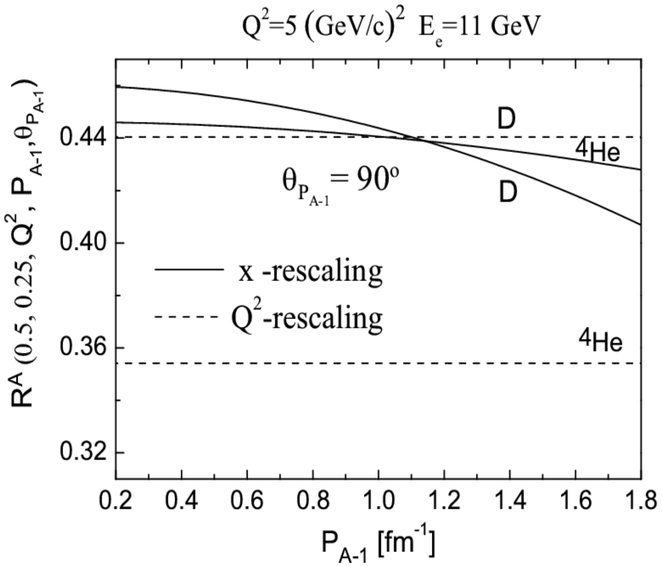


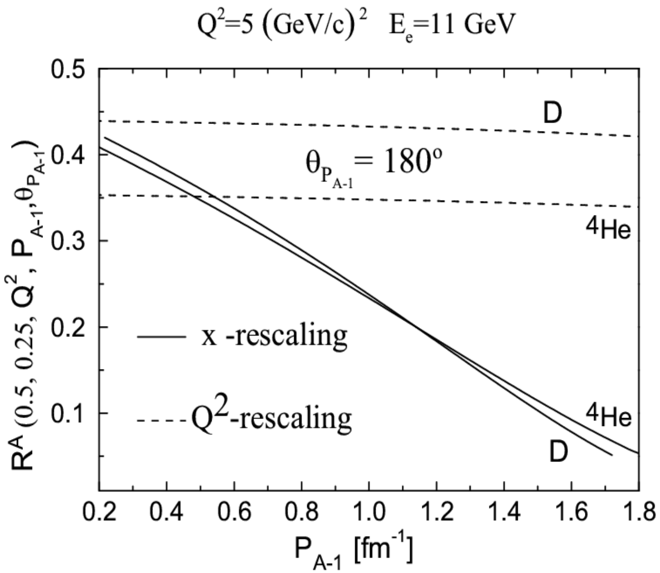


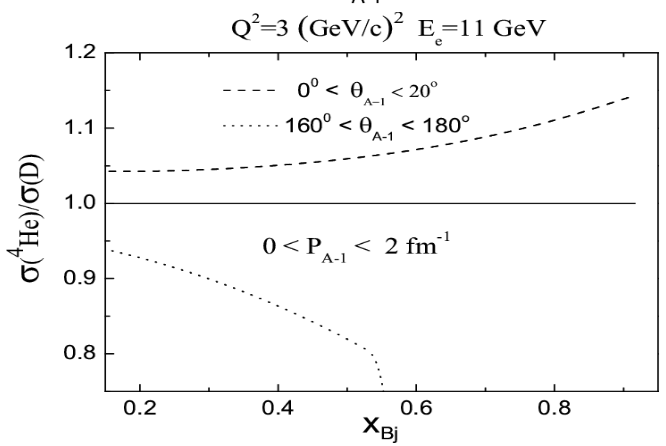
L.P. Kaptari

Tagging the EMC-effect

$$R(x_{Bj}, x'_{Bj}, Q^2, |\mathbf{P}_{A-1}|, z_1^{(A)}, y_A) = \frac{\sigma^{A,exp}(x_{Bj}, Q^2, |\mathbf{P}_{A-1}|, z_1^{(A)}, y_A)}{\sigma^{A,exp}(x'_{Bj}, Q^2, |\mathbf{P}_{A-1}|, z_1^{(A)}, y_A)} \to \frac{F_2^{N/A}(x_A, Q^2, k_1^2)}{F_2^{N/A}(x'_A, Q^2, k_1^2)}$$







C. Ciofi degli Atti, L. P.K., S. Scopetta, EPJA 5 (1999) 191; CdA, LPK, PRC 83 (2011) 044602,;

SUMMARY

- **Plane Wave Impulse Approximation (PWIA) seems to describe rather well the Semi-Inlusive Processes $^3He(e,e'p(pn)X$, $^3He(e,e'h)X$, $^2H(e,e'p)X$, etc. This, at first glance, justifies the use of the simple formula $\mathbf{A_n \simeq \frac{1}{p_n\ f_n}\left(A_3^{exp} - 2p_pf_pA_p^{exp}\right)}$ to extract the Sivers and Collins asymmetries from data on polarized ^3He.**

- **PWIA holds only in a restricted kinematical range of intrinsic momenta and removal energies. Beyond this region the Final State Interaction (FSI) plays an important role. It leads to a partial depolarization of nucleons and hinders the use of the simple extraction procedure. However, by a proper redefinition of polarizations $\mathbf{p_{n(p)}}$ and dfunctions $\mathbf{f_{n(p)}}$ one can derive a similar formula for the asymmetries wich takes properly into account FSI effects.**

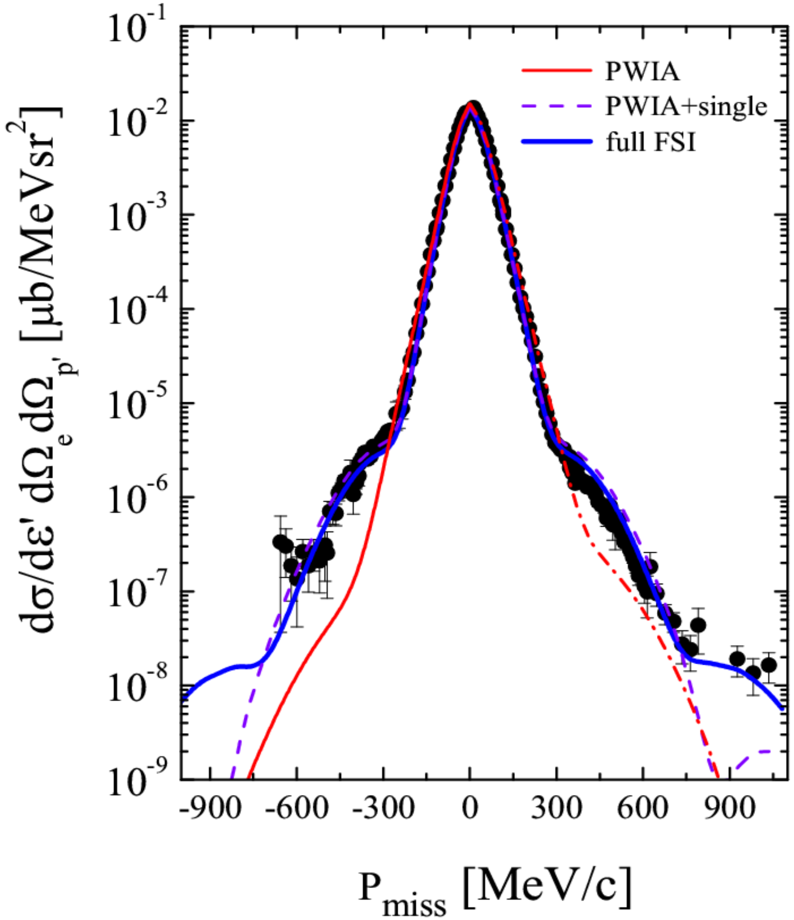
- **The extraction procedures within the PWIA and with FSI taken into account provide (with most deviation $< 4\%$) basically the same results and, consequently, the PWIA procedure can be safely applied even in the presence of FSI effects.**

- **An unambiguous, model independent, extraction of the T-odd asymmetries would be possible in a "double" SIDIS process, when the $(A-1)$ nucleus is also detected.**

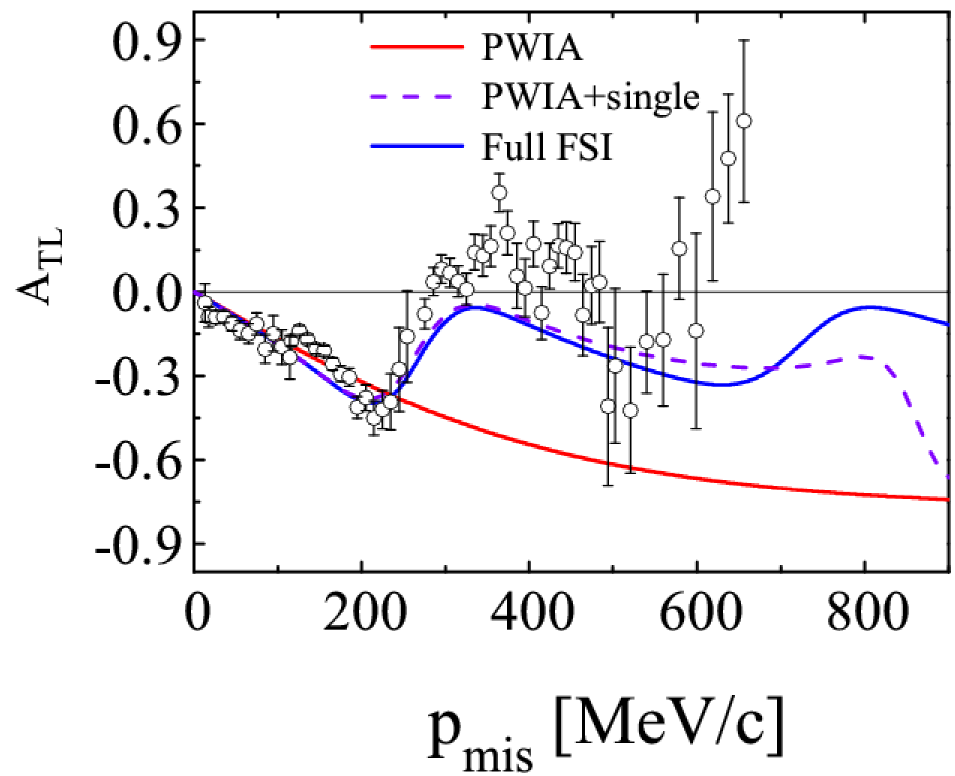
- **Moreover, it is arugued that such a "spectator" SIDIS can serve as a powerful tool to also provide unique information on: $i)$ the in-medium induced modifications of the nucleon parton distributions and the origin of the EMC effect, and $ii)$ the mechanism of quark hadronization in the nuclear medium**

Check of the GEA: unfactorized calcs. of q.e $^3He(e,e,p)D$.

M. Alvioli, CdA & LPK PRC 81 (Rapid Comm.) (2010) 02100, R. Schiavilla et al, PRC. 72 064003 (2005),



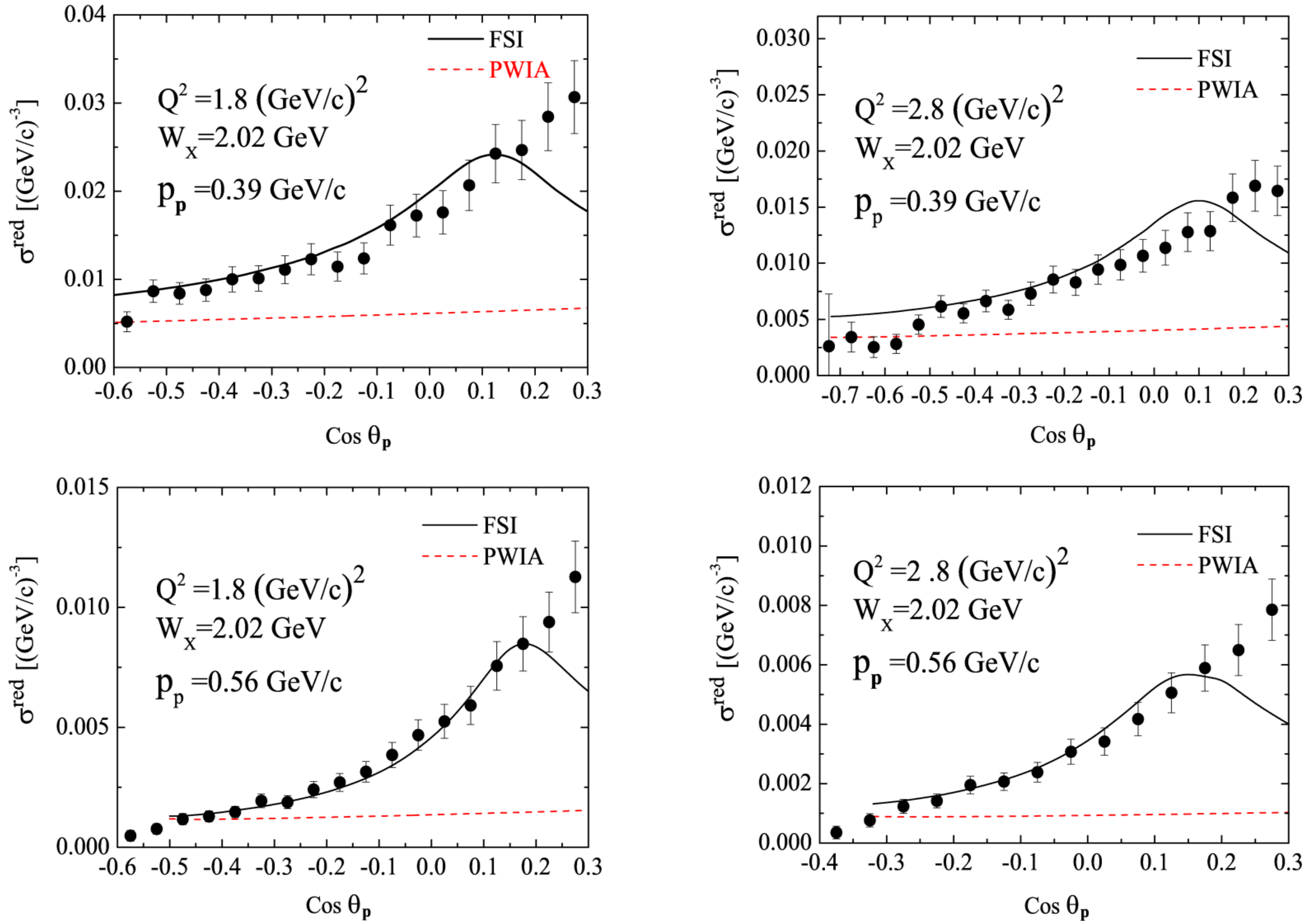
$$A_{TL} = \frac{d\sigma(\phi=0^o)-d\sigma(\phi=180^o)}{d\sigma(\phi=0^o)+d\sigma(\phi=180^o)}.$$



Check of the factorization of GEA in DIS: $D(e,e'p)X$

C. CdA, L.P.K, B.Z. Kopeliovich, E.P.J. **A19** (2004) 133; ibid p. 145
V. Palli, C. CdA, L.P.K, C.B. Mezzetti, M. Alvioli, PRC **80** (2009) 054610; ibidPRC **C81**(2010)
C. CdA, L.P.K, C.B. Mezzetti, Fizica **20**, (2012); W. Cosyn, M. Sargsian PRC **84** (2011) 014601

$D(e,e'p)X$ (Recent Jlab experiment)

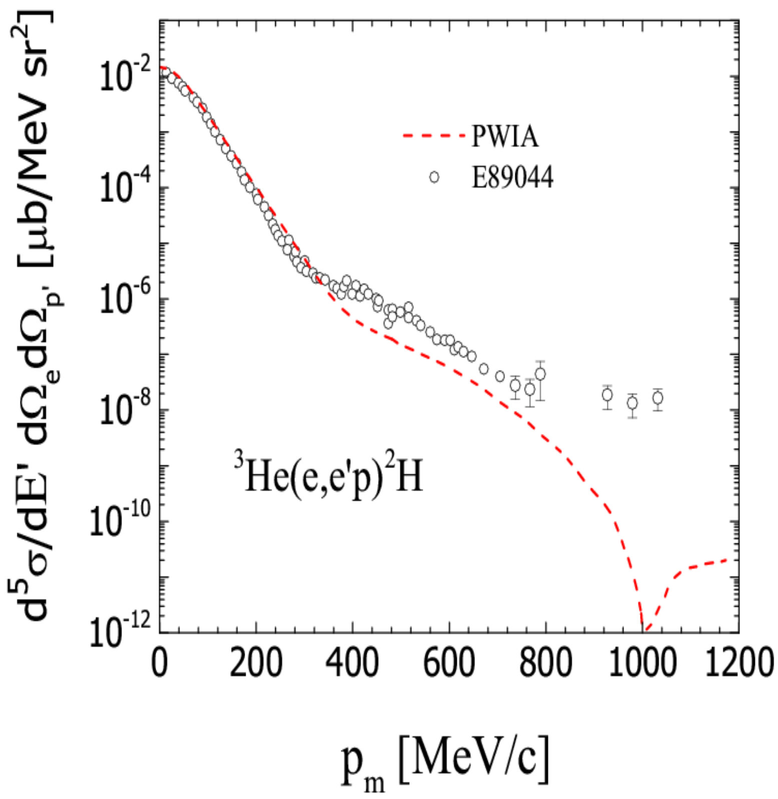


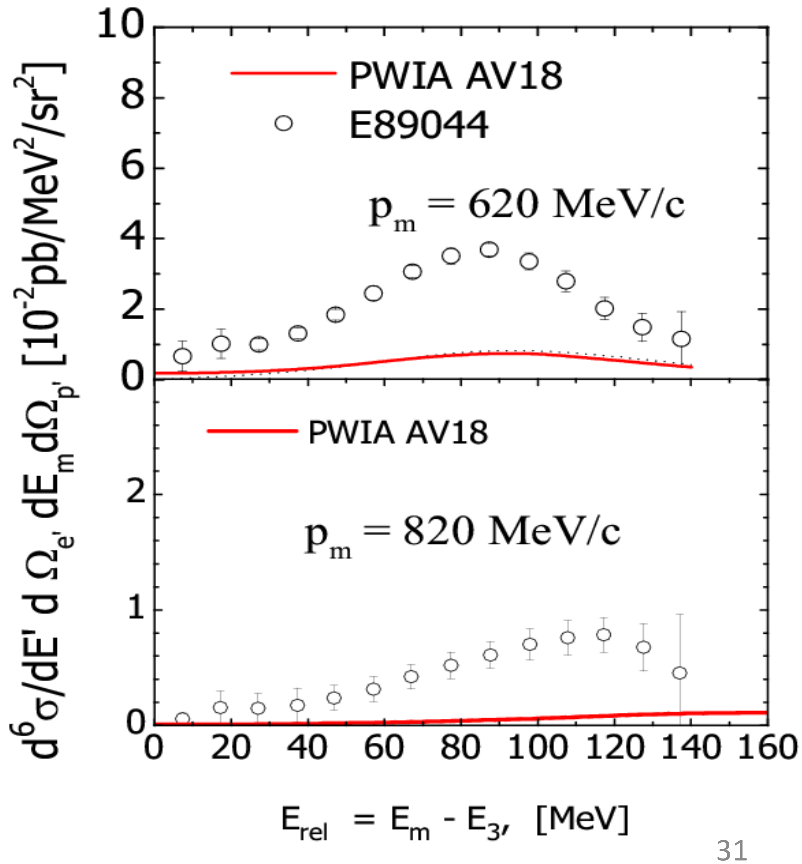
How "good" is the PWIA approximation?

Results from q.e. $^3He(e,e')pD$, $^3He(e,e')ppn$

CdA & LPK, *PRL* **95**, 052502 (2005), R. Schiavilla et al, PRC. 72 064003 (2005), L. Frankfurt, M. Sargsian, M. Strikman Int. J.Mod. Phys. **A23** **(2008)** 2291

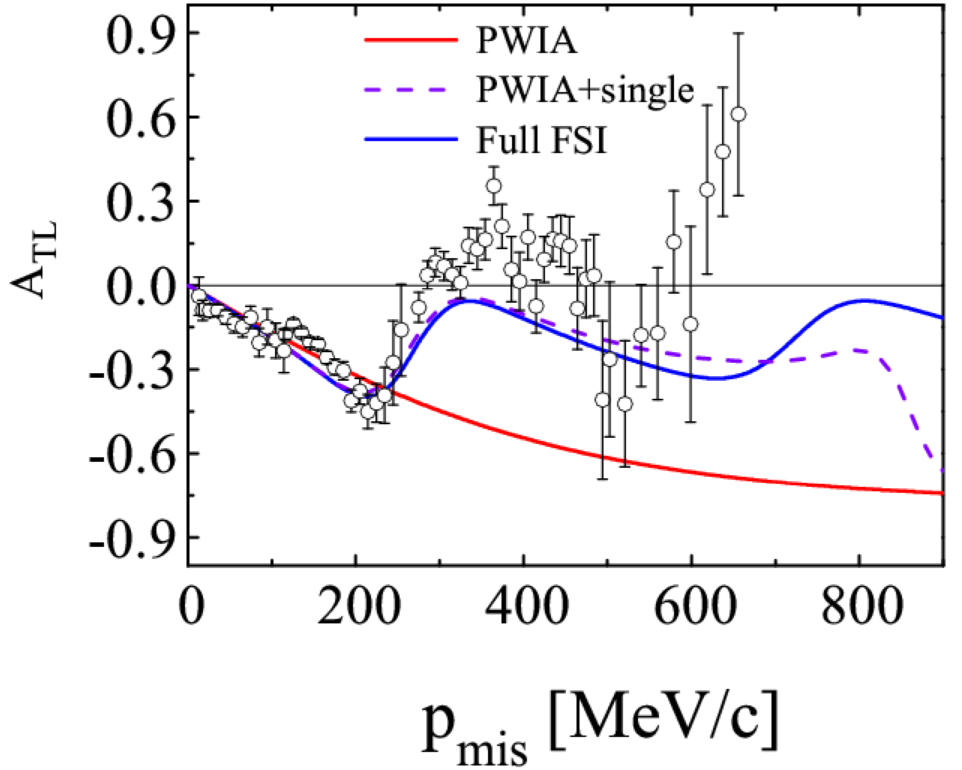
M.M. Rvachev et al., *PRL* **94**(2005) 192302





$$A_{TL} = \frac{d\sigma(\phi=0^o) - d\sigma(\phi=180^o)}{d\sigma(\phi=0^o) + d\sigma(\phi=180^o)}.$$

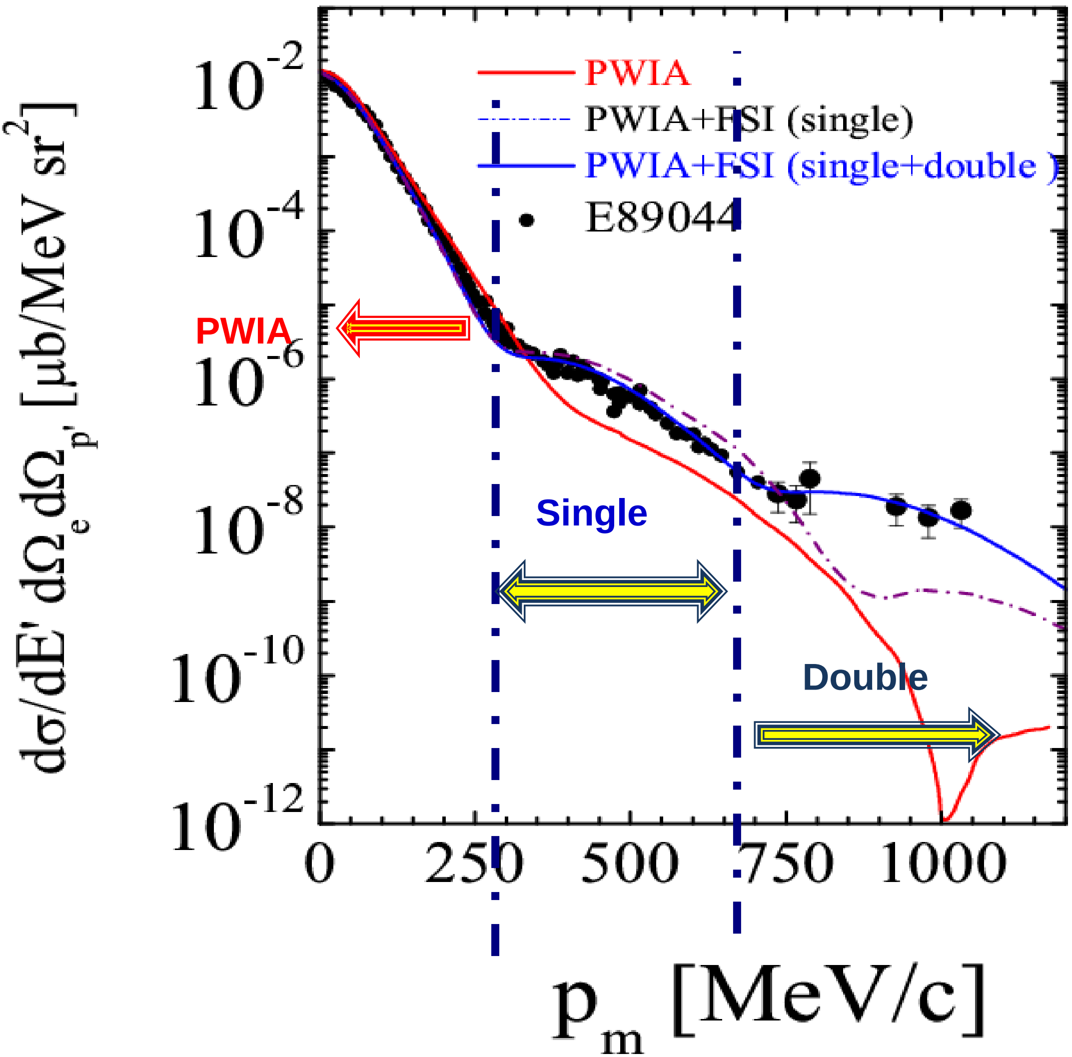
q.e. $^3He(e,e')pD$



PWIA works for nucleon momenta $0 < p < 250 \div 300$ **meV/c**

Multiple Scattering Contributions

CdA & LPK, *PRL* **95**, 052502 (2005), R. Schiavilla et al, PRC. 72 064003 (2005)



$d\sigma(p_m)$ has different (three) slopes

different Multiple Scattering Components

1) **PWIA:** $\langle p_n \rangle$= **0.876**, $\langle p_p \rangle$= **-0.0237**, $\theta_e = 30^o$, $\theta_\pi = 14^o$

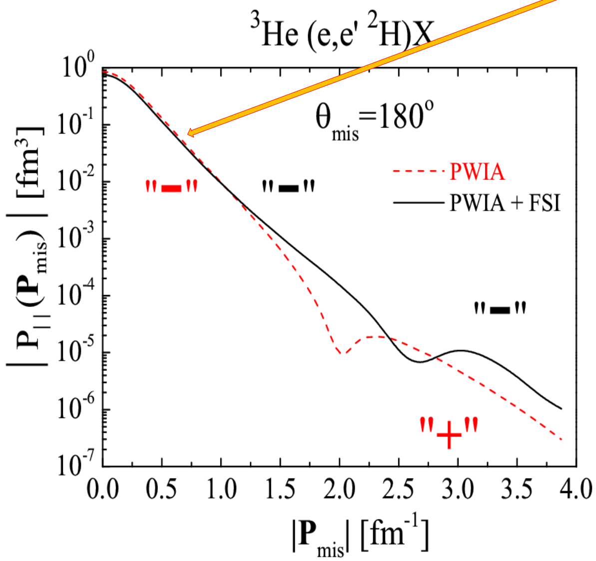
E_{beam}, GeV	x_{Bj}	ν GeV	p_π GeV/c	$f_n(x,z)$	$\langle p_n \rangle f_n$	$f_p(x,z)$	$\langle p_p \rangle f_p$
8.8	**0.21**	**7.55**	**3.40**	**0.304**	**0.266**	**0.348**	-8.410^{-3}
8.8	**0.29**	**7.15**	**3.19**	**0.286**	**0.251**	**0.357**	-8.510^{-3}
8.8	**0.48**	**6.36**	**2.77**	**0.257**	**0.225**	**0.372**	-8.910^{-3}
11	**0.21**	**9.68**	**4.29**	**0.302**	**0.265**	**0.349**	-8.310^{-3}
11	**0.29**	**9.28**	**4.11**	**0.285**	**0.25**	**0.357**	-8.510^{-3}

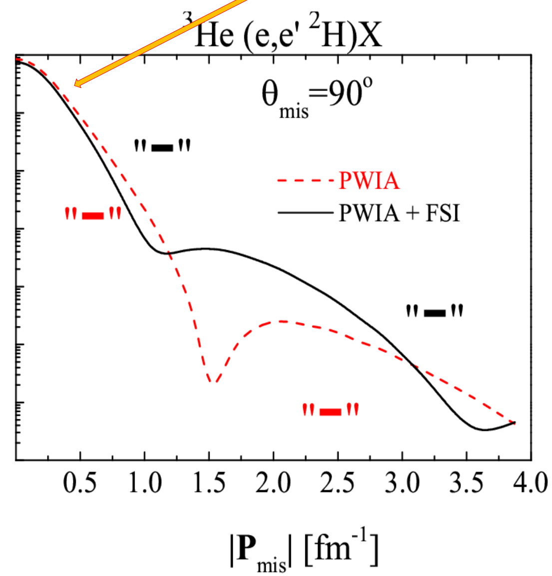
1) **FSI:** $\langle p_n \rangle$= **0.756**, $\langle p_p \rangle$= **-0.0265**,$\langle N_n \rangle = 0.85$,$\langle N_p \rangle = 0.87$, $\langle \sigma_{eff.} \rangle = 71\ mb$

E_{beam}, GeV	x_{Bj}	ν GeV	p_π GeV/c	$f_n(x,z)$	$\langle p_n \rangle f_n$	$f_p(x,z)$	$\langle p_p \rangle f_p$
8.8	**0.21**	**7.55**	**3.40**	**0.353**	**0.267**	**0.405**	-1.110^{-2}
8.8	**0.29**	**7.15**	**3.19**	**0.332**	**0.251**	**0.415**	-1.110^{-2}
8.8	**0.48**	**6.36**	**2.77**	**0.298**	**0.225**	**0.432**	-1.210^{-2}
11	**0.21**	**9.68**	**4.29**	**0.351**	**0.266**	**0.405**	-1.10^{-2}
11	**0.29**	**9.28**	**4.11**	**0.331**	**0.250**	**0.415**	-1.110^{-2}

$$\mathcal{F}^A(x,\{\alpha\}) \simeq \int_x^A \mathcal{F}^N(\xi/x,\{\alpha\}) f^A(\xi) d\xi; \quad f^A(\xi) = \int dE \int_{\mathbf{p_{min}}}^{p_{max}} P^A(\mathbf{p},E)\,\delta\left(\xi - \frac{pq}{m\nu}\right) d^3\mathbf{p}$$

$$\mathbf{p} = \mathbf{p_{min}} \rightarrow |\cos\theta_{\mathbf{p}}| = \mathbf{1}$$ (**FSI minimized, Spectral Function maximized !!!**)





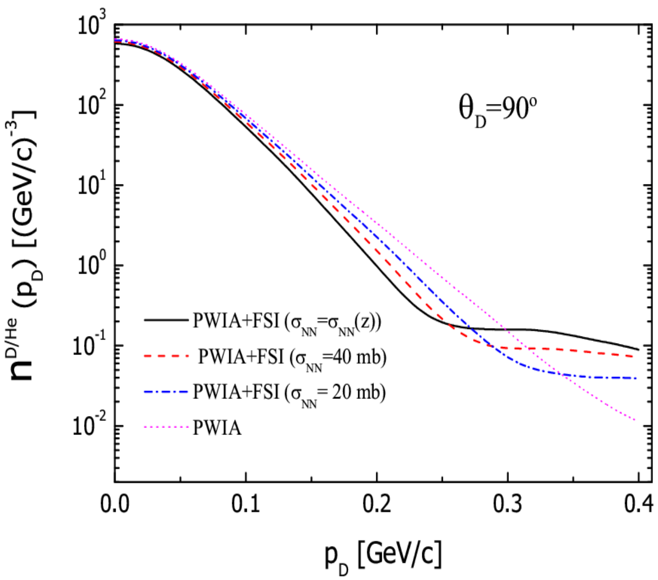
$$\mathbf{A_n} \simeq \frac{\mathbf{1}}{\mathbf{p_n^{FSI}\ f_n}}\left(\mathbf{A_3^{exp}} - \mathbf{2p_p^{FSI} f_p A_p^{exp}}\right)$$

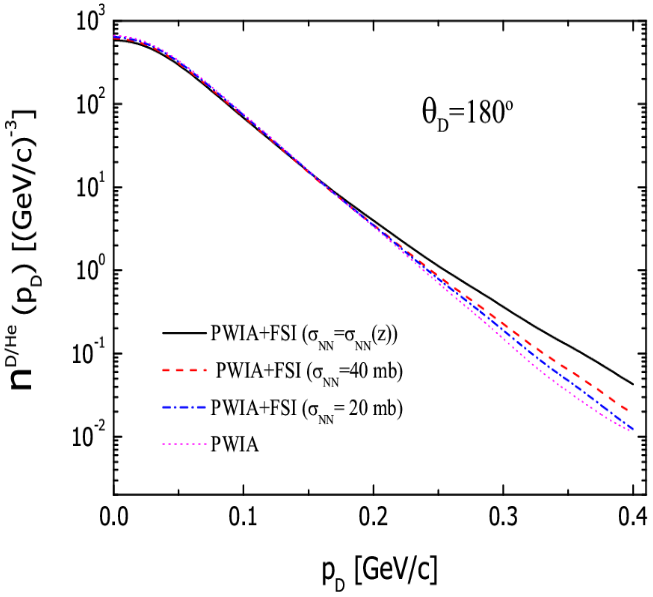
$$\mathbf{p_N^{FSI}} = \int \mathbf{P}_{\|}^N(\vec{p}_{mis},E)\,dE\,d^3\mathrm{p}_{mis} = \mathbf{p_N^{PWIA}} - \delta\mathbf{p_N^{FSI}}(\mathbf{Q^2},\mathbf{x_{Bj}})$$

Preliminary $\delta \mathrm{p_N^{FSI}}(\mathrm{Q^2}, \mathrm{x_{Bj}}) \sim 10 - 15\ \%$

$^3He(e,e'D)X$

C. CdA, L.P.K, B.Z. Kopeliovich, EIC white book, arXiv:1108.1713,INT-PUB-11-034,BNL-96164-2011,JLAB-THY-11-1373. Aug 2011. 547 pp., e-Print: arXiv:1108.1713 [nucl-th]





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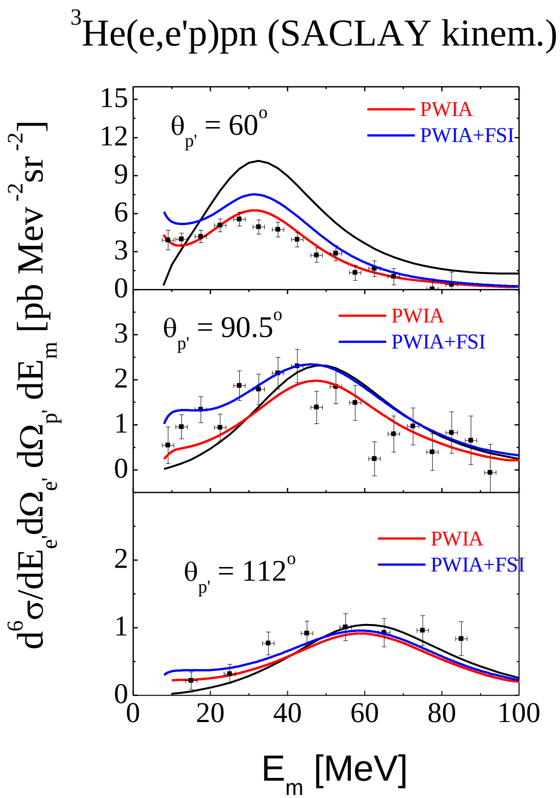
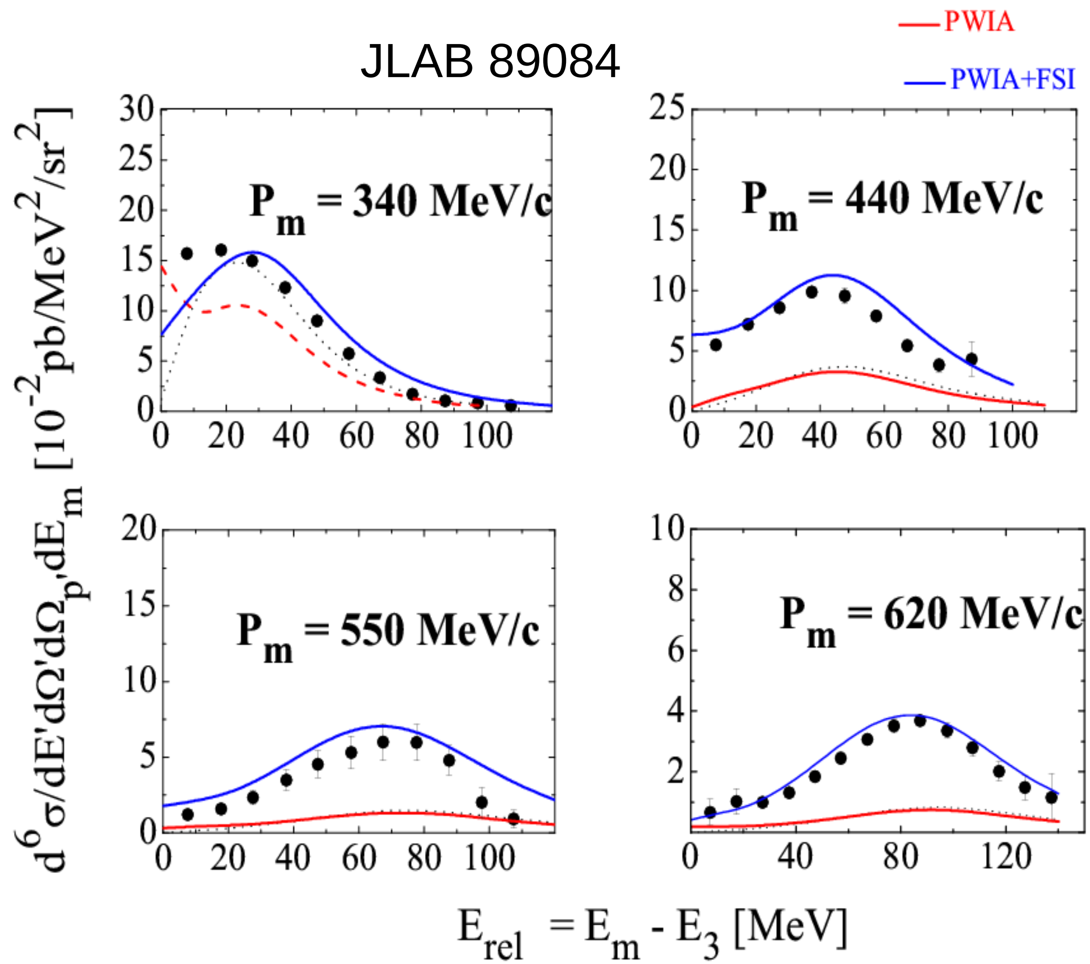




CdA & LPK, *PRL* **95**, 052502 (2005), L. Frankfurt, M. Sargsian, M. Strikman Int. J.Mod. Phys. **A23** **(2008)** 2291

$$d\sigma(eA) \sim l^{\mu\nu} \cdot \; W^A_{\mu\nu}(S_A)$$

where

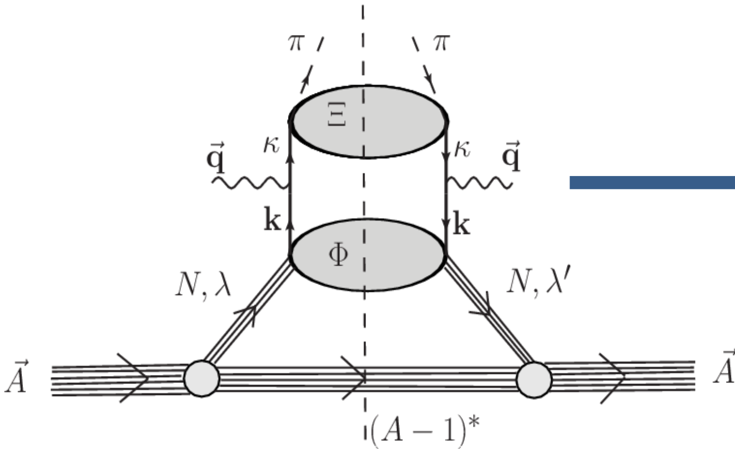
$$W^A_{\mu\nu} = \sum_f \langle\, \mathbf{P}_A, S_A | \hat{J}_\nu | \mathbf{P}_f \,\rangle \langle\, \mathbf{P}_f | \hat{J}_\mu | \mathbf{P}_A, S_A \,\rangle \delta^{(4)}\left(q + P_A - P_f\right) d\tau_X$$

$$W^{MM'}_{\mu\nu} = \sum_{\lambda,\lambda'} \langle\, \lambda' | \hat{w}^N_{\mu\nu} | \lambda \,\rangle \; \mathcal{O}^{MM'}_{\lambda\lambda'}(\mathbf{t}_f, \mathbf{P}_{mis})$$

$$\mathcal{O}^{MM'}_{\lambda\lambda'}(\mathbf{t}_f, \mathbf{P}_{mis}) = \langle\, \lambda, \phi^{*\mathbf{t}_f}(\mathbf{r}) e^{i\mathbf{P}_{mis}\boldsymbol{\rho}} | \vec{\Psi}^M_3(\mathbf{r}, \boldsymbol{\rho}) \,\rangle \langle\, \vec{\Psi}^{M'}_3(\mathbf{r}', \boldsymbol{\rho}') | \lambda', \phi^{\mathbf{t}_f}(\mathbf{r}') e^{-i\mathbf{P}_{mis}\boldsymbol{\rho}} \,\rangle$$

$$P^{MM'}_{\lambda\lambda'}(E, \mathbf{P}_{mis}) = \int \frac{d\mathbf{t}_f}{(2\pi)^3} \delta\left(E - \frac{t_f^2}{m_N}\right) \mathcal{O}^{MM'}_{\lambda\lambda'}(\mathbf{t}_f, \mathbf{P}_{mis})$$

The Spin Dependent Spectral Function



$$W^{s.i.}_{\mu\nu}(S^A, Q^2) \sim \sum_{\lambda\lambda'} \langle \lambda' | \hat{w}^N_{\mu\nu}(Q^2, p_N) | \lambda \rangle \mathcal{O}^{S_A}_{\lambda\lambda'}(p_N)$$

$$\mathcal{O}^{MM'(FSI)}_{\lambda\lambda'}(p_N, E) = \int \left\langle \mathcal{G}(1,2,3,\sigma^{NX}_{eff}) \left\{ \Psi^{\mathbf{t}}_{23}, \lambda, \mathbf{p}_N \right\} | \Psi^M_{^3He} \right\rangle \left\langle \Psi^{M'}_{^3He} | \mathcal{G}(1,2,3,\sigma^{NX}_{eff}) \left\{ \Psi^{\mathbf{t}}_{23}, \lambda', \mathbf{p}_N \right\} \right\rangle \delta\left(E - \frac{t^2}{M_N} \right) \frac{d^3\mathbf{t}}{(2\pi)^3}$$

$$\vec{P}^{S_A}(E, \mathbf{p}_N) = P^{S_A}_{||}\ \mathbf{e}_0 + P^{S_A}_{1\perp}\ \mathbf{e}_+ + P^{S_A}_{2\perp}\ \mathbf{e}_-$$

$$P^{S_A}_{||} = \mathcal{O}^{S_A}_{\frac{1}{2}\frac{1}{2}} - \mathcal{O}^{S_A}_{-\frac{1}{2}-\frac{1}{2}}; \quad P^{S_A}_{+} = -\sqrt{2}\mathcal{O}^{S_A}_{\frac{1}{2}-\frac{1}{2}}; \quad P^{S_A}_{-} = \sqrt{2}\mathcal{O}^{S_A}_{-\frac{1}{2}\frac{1}{2}}$$

“II” means along S_A