

# Tagged spectator DIS off a polarized spin-1 target

Wim Cosyn

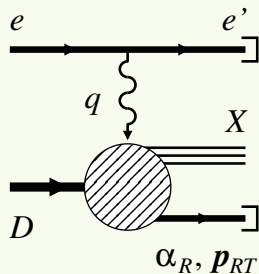
Ghent University, Belgium

DIS 2016  
DESY Hamburg

in collaboration with  
Ch. Weiss (JLab) & M. Sargsian (FIU)



# Tagged spectator DIS process with deuteron



- DIS off a nuclear target with a slow (relative to nucleus c.m.) nucleon detected in the final state
- Control nuclear configuration
- Advantages for the deuteron
  - ▶ simple  $NN$  system, non-nucleonic ( $\Delta\Delta$ ) dof suppressed
  - ▶ active nucleon identified
  - ▶ recoil momentum selects nuclear configuration (medium modifications)
  - ▶ limited possibilities for nuclear FSI, calculable
- Wealth of possibilities to study (nuclear) QCD dynamics
- Will be possible in a wide kinematic range @ EIC (**polarized** for JLEIC)
  - ▶ dedicated talk Wed. in WG7

# What is needed?

- General expression of SIDIS for a polarized spin 1 target
  - ▶ Tagged spectator DIS is SIDIS in the target fragmentation region

$$\vec{e} + \vec{T} \rightarrow e' + X + h$$

- Dynamical model to express structure functions of the reaction
  - ▶ First step: impulse approximation (IA) model
- Light-front structure of the deuteron
  - ▶ Natural for high-energy reactions as **off-shellness of nucleons** in LF quantization remains **finite**

# Polarized spin 1 particle

- Spin state described by a 3\*3 density matrix in a basis of spin 1 states polarized along the collinear virtual photon-target axis

$$W_D^{\mu\nu} = \text{Tr}[\rho_{\lambda\lambda'} W^{\mu\nu}(\lambda'\lambda)]$$

- Characterized by **3 vector** and **5 tensor** parameters

$$S^\mu = \langle \hat{W}^\mu \rangle, \quad T^{\mu\nu} = \frac{1}{2} \sqrt{\frac{2}{3}} \langle \hat{W}^\mu \hat{W}^\nu + \hat{W}^\nu \hat{W}^\mu + \frac{4}{3} \left( g^{\mu\nu} - \frac{\hat{P}^\mu \hat{P}^\nu}{M^2} \right) \rangle$$

- Split in longitudinal and orthogonal components

$$\rho_{\lambda\lambda'} = \frac{1}{3} \begin{bmatrix} 1 - \frac{3}{2} S_L + \sqrt{\frac{3}{2}} T_{LL} & \frac{3}{2\sqrt{2}} S_\perp e^{+i(\phi_h - \phi_s)} + \sqrt{3} T_{L\perp} e^{+i(\phi_h - \phi_{T_L})} & \sqrt{\frac{3}{2}} T_{\perp\perp} e^{+i(2\phi_h - 2\phi_{T_L})} \\ \frac{3}{2\sqrt{2}} S_\perp e^{-i(\phi_h - \phi_s)} + \sqrt{3} T_{L\perp} e^{-i(\phi_h - \phi_{T_L})} & 1 - \sqrt{6} T_{LL} & \frac{3}{2\sqrt{2}} S_\perp e^{i(\phi_h - \phi_s)} - \sqrt{3} T_{L\perp} e^{i(\phi_h - \phi_{T_L})} \\ \sqrt{\frac{3}{2}} T_{\perp\perp} e^{-i(2\phi_h - 2\phi_{T_L})} & \frac{3}{2\sqrt{2}} S_\perp e^{-i(\phi_h - \phi_s)} - \sqrt{3} T_{L\perp} e^{-i(\phi_h - \phi_{T_L})} & 1 + \frac{3}{2} S_L + \sqrt{\frac{3}{2}} T_{LL} \end{bmatrix}$$

# Spin 1 SIDIS: General structure of cross section

- To obtain structure functions, enumerate all possible tensor structures that obey hermiticity and QED Ward identity
- Cross section has 41 structure functions,

$$\frac{d\sigma}{dx dQ^2 d\phi'} = \frac{y^2 \alpha^2}{Q^4 (1 - \epsilon)} (F_U + F_S + F_T) d\Gamma_{P_h},$$

- ▶ U + S part identical to spin 1/2 case [Bacchetta et al. JHEP ('07)]

$$F_U = F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \epsilon \cos 2\phi_h F_{UU}^{\cos 2\phi_h} + h \sqrt{2\epsilon(1-\epsilon)} \sin \phi_h F_{LU}^{\sin \phi_h}$$

$$\begin{aligned} F_S = & \mathbf{S}_L \left[ \sqrt{2\epsilon(1+\epsilon)} \sin \phi_h F_{US_L}^{\sin \phi_h} + \epsilon \sin 2\phi_h F_{US_L}^{\sin 2\phi_h} \right] \\ & + \mathbf{S}_L h \left[ \sqrt{1-\epsilon^2} F_{LS_L} + \sqrt{2\epsilon(1-\epsilon)} \cos \phi_h F_{LS_L}^{\cos \phi_h} \right] \\ & + \mathbf{S}_\perp \left[ \sin(\phi_h - \phi_S) \left( F_{US_T,T}^{\sin(\phi_h - \phi_S)} + \epsilon F_{US_T,L}^{\sin(\phi_h - \phi_S)} \right) + \epsilon \sin(\phi_h + \phi_S) F_{US_T}^{\sin(\phi_h + \phi_S)} \right] \\ & + \epsilon \sin(3\phi_h - \phi_S) F_{US_T}^{\sin(3\phi_h - \phi_S)} + \sqrt{2\epsilon(1+\epsilon)} \left( \sin \phi_S F_{US_T}^{\sin \phi_S} + \sin(2\phi_h - \phi_S) F_{US_T}^{\sin(2\phi_h - \phi_S)} \right) \\ & + \mathbf{S}_\perp h \left[ \sqrt{1-\epsilon^2} \cos(\phi_h - \phi_S) F_{LS_T}^{\cos(\phi_h - \phi_S)} + \right. \\ & \left. \sqrt{2\epsilon(1-\epsilon)} \left( \cos \phi_S F_{LS_T}^{\cos \phi_S} + \cos(2\phi_h - \phi_S) F_{LS_T}^{\cos(2\phi_h - \phi_S)} \right) \right], \end{aligned}$$

# Spin 1 SIDIS: General structure of cross section

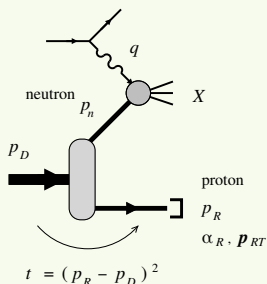
- To obtain structure functions, enumerate all possible tensor structures that obey hermiticity and QED Ward identity
- Cross section has 41 structure functions,

$$\frac{d\sigma}{dx dQ^2 d\phi_{l'}} = \frac{y^2 \alpha^2}{Q^4 (1 - \epsilon)} (F_U + F_S + F_T) d\Gamma_{P_h},$$

- ▶ 23 SF unique to the spin 1 case (tensor pol.)

$$\begin{aligned}
 F_T = & T_{LL} \left[ F_{UT_{LL},T} + \epsilon F_{UT_{LL},L} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_h F_{UT_{LL}}^{\cos \phi_h} + \epsilon \cos 2\phi_h F_{UT_{LL}}^{\cos 2\phi_h} \right] \\
 & + T_{LL} h \sqrt{2\epsilon(1-\epsilon)} \sin \phi_h F_{LT_{LL}}^{\sin \phi_h} \\
 & + T_{L\perp} [\dots] + T_{L\perp} h [\dots] \\
 & + T_{\perp\perp} \left[ \cos(2\phi_h - 2\phi_{T\perp}) \left( F_{UT_{TT},T}^{\cos(2\phi_h - 2\phi_{T\perp})} + \epsilon F_{UT_{TT},L}^{\cos(2\phi_h - 2\phi_{T\perp})} \right) \right. \\
 & + \epsilon \cos 2\phi_{T\perp} F_{UT_{TT}}^{\cos 2\phi_{T\perp}} + \epsilon \cos(4\phi_h - 2\phi_{T\perp}) F_{UT_{TT}}^{\cos(4\phi_h - 2\phi_{T\perp})} \\
 & \left. + \sqrt{2\epsilon(1+\epsilon)} \left( \cos(\phi_h - 2\phi_{T\perp}) F_{UT_{TT}}^{\cos(\phi_h - 2\phi_{T\perp})} + \cos(3\phi_h - 2\phi_{T\perp}) F_{UT_{TT}}^{\cos(3\phi_h - 2\phi_{T\perp})} \right) \right] \\
 & + T_{\perp\perp} h [\dots]
 \end{aligned}$$

# Tagged DIS with deuteron: model for the IA



- Hadronic tensor can be written as a product of nucleon hadronic tensor with deuteron light-front densities

$$W_D^{\mu\nu}(\lambda', \lambda) = 4(2\pi)^3 \frac{\alpha_R}{2 - \alpha_R} \sum_{i=U,z,x,y} W_{N,i}^{\mu\nu} \rho_D^i(\lambda', \lambda),$$

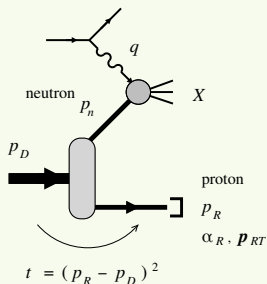
- Nucleon hadr tensor has standard (un)polarized contributions

- ▶ Effective Bjorken  $\tilde{x}$  depends on recoil momentum ( $\alpha_R, \mathbf{p}_{R\perp}$ )

$$W_{N,U}^{\mu\nu} = -F_{1N}(\mathbf{g}^{\mu\nu} + e_q^\mu e_q^\nu) + F_{2N} \frac{L_n^\mu L_n^\nu}{(p_n q)} \quad W_{N,i}^{\mu\nu} = -i\epsilon^{\mu\nu\rho\sigma} \frac{m_N q_\rho}{(p_i q)} \left[ s_{i,\sigma}(\mathbf{g}_{1N} + \mathbf{g}_{2N}) - \frac{(q s_i)}{(p_n q)} p_{n,\sigma} \mathbf{g}_{2N} \right]$$

- $\rho_D^U(\lambda', \lambda)$  related distribution of **unpolarized** nucleons in the deuteron
- $\rho_D^Z(\lambda', \lambda)$  to **longitudinally** pol. nucleon distribution (deut. "helicity")
- $\rho_D^{X,Y}(\lambda', \lambda)$  to **transversally** pol. nucleon distr. (deut. "transversity")

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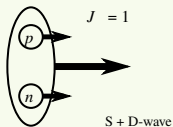
Allows us to write all of the 41 conditional structure functions as a product of a factor dep. on nucleon SF and a D spectral function dep. on the polarization state. One example:

$$F_{UU}^{\cos 2\phi_h} = \frac{|\mathbf{p}_{R\perp}|}{(p_n q)} F_{2N}(x, \alpha_R, \mathbf{p}_{R\perp}) \times [U(k)^2 + W(k)^2] \frac{(2\pi)^3 E_k}{\pi(2 - \alpha_R)^2}.$$

- In the IA the following structure functions are **zero**
  - ▶ lepton pol. SSA [ $F_{LU}^{\sin \phi_h}$ ]
  - ▶ target vector pol. SSA [8 SFs]
  - ▶ target tensor pol. DSA [7 SFs]



# Deuteron light-front wave function

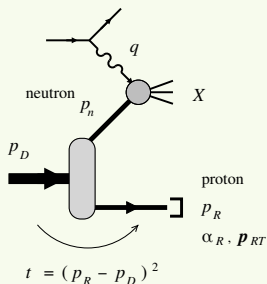


- Up to momenta of a few 100 MeV dominated by  $NN$  component
- Can be evaluated in LFQM [Coester,Keister,Polyzou et al.] or covariant Feynman diagrammatic way [Frankfurt,Sargsian,Strikman]
- One obtains a Schrödinger (non-rel) like eq. for the wave function components
- Light-front WF obeys baryon and momentum sum rule

$$\Psi_{\lambda}^D(\mathbf{k}_f, \lambda_1, \lambda_2) = \sqrt{E_{k_f}} \sum_{\lambda'_1 \lambda'_2} \mathcal{D}_{\lambda_1 \lambda'_1}^{\frac{1}{2}} [R_{f_c}(k_{1_f}^{\mu} / m_N)] \mathcal{D}_{\lambda_2 \lambda'_2}^{\frac{1}{2}} [R_{f_c}(k_{2_f}^{\mu} / m_N)] \Phi_{\lambda}^D(\mathbf{k}_f, \lambda'_1, \lambda'_2)$$

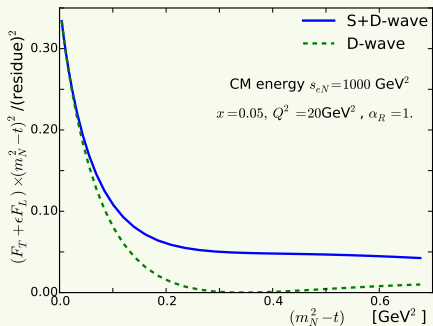
- Differences with non-rel wave function:
  - ▶ appearance of the **Melosh rotations** to account for light-front quantized nucleon states
  - ▶ 3-momentum  $\mathbf{k}_f$  is the relative momentum of the nucleons in the light-front boosted rest-frame of the free 2-nucleon state (so not a “true” kinematical variable)

# Pole extrapolation for on-shell nucleon structure



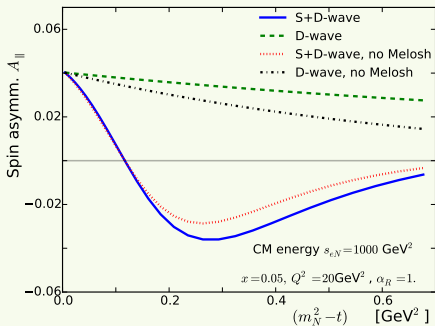
- Allows to extract free neutron structure
  - ▶ Recoil momentum  $p_R$  controls off-shellness of neutron  $t - m_N^2$
  - ▶ Free neutron at pole  $t - m_N^2 \rightarrow 0$ : “on-shell extrapolation”
  - ▶ Small deuteron binding energy results in small extrapolation length
  - ▶ Eliminates nuclear binding and FSI effects [Sargsian, Strikman PLB '05]
- D-wave suppressed at on-shell point  $\rightarrow$  neutron  $\sim 100\%$  polarized
- Precise measurements of neutron structure at an EIC

# Unpolarized structure function



- Extrapolation for  $(m_N^2 - t) \rightarrow 0$  corresponds to on-shell neutron  $F_{2N}(x, Q^2)$
- Clear effect of deuteron D-wave, largest in the region dominated by the tensor part of the  $NN$ -interaction
- D-wave drops out at the on-shell point

# Polarized structure function



- Spin asymmetry  $A_{\parallel} = \frac{\sigma(++)-\sigma(-+)}{\sigma(++)+\sigma(-+)} = \frac{F_{LSL}}{F_T + \epsilon F_L} \propto \frac{g_{1n}}{F_{1n}}$
- Again clear contribution from D-wave at finite recoil momenta
- Relativistic nuclear effects through Melosh rotations, grow with recoil momenta
- Both effects drop out near the on-shell extrapolation point

- Study of tensor polarized observables
- Final-state interactions, shadowing corrections
- Medium modifications at higher nucleon momenta
- More exclusive final-states (SIDIS in neutron current fragmentation region)

# Conclusion

- General form of SIDIS with a spin 1 target, 23 tensor polarized structure functions unique to spin 1
- Results for the impulse approximation using deuteron light-front structure
- Important contributions from deuteron  $D$ -wave, Melosh rotations at larger spectator momenta. Become small if one does pole extrapolation of observables.
- Range of applications at an EIC (with polarized deuterons)