Aram's no-nonsense TMDs

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FOM

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Memories over 25 out of 70 years

Aram’s no-nonsense TMDs

My first encounter with Aram’s work

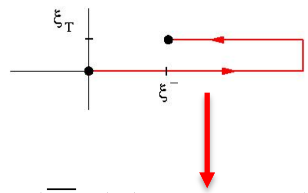
Our work

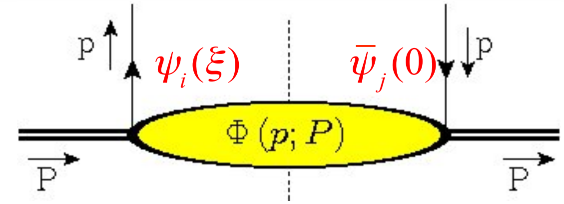
Ideas and discussions

First of all: I clearly admire Aram

TMDs (with gauge links)

- quark-quark TMD correlator





$$u_i(k)\overline{u}_j(k) \Longrightarrow$$

$$\Phi_{ij}^{[U]}(x,p_T;n) = \int \frac{d\,\xi{\cdot}P\,d^2\xi_T}{(2\pi)^3}\,e^{ip\cdot\xi}\langle P,S|\overline{\psi}_j(0)\,U_{[0,\xi]}\psi_i(\xi)|P,S\rangle\,\big|_{\xi\cdot n=0}$$

- Parametrization

$$\Phi^{[U]}(x,k_T) = \left\{f_1^{[U]}(x,k_T^2) + i\,h_1^{\perp\,[U]}(x,k_T^2)\,\frac{\not k_T}{M}\right\}\frac{\not P}{2} \qquad \Phi(x) = f_1(x)\,\frac{\not P}{2}$$

$$\Phi_L^{[U]}(x,k_T) = \left\{S_L g_1^{[U]}(x,k_T^2)\gamma_5 + S_L h_{1L}^{\perp\,[U]}(x,k_T^2)\frac{\gamma_5\not k_T}{M}\right\}\frac{\not P}{2} \qquad \Phi_L(x) = S_L\,g_1(x)\,\gamma_5\,\frac{\not P}{2}$$

$$\Phi_T^{[U]}(x,k_T) = \left\{g_{1T}^{[U]}(x,k_T^2)\,\frac{k_T{\cdot}S_T}{M}\gamma_5 + f_{1T}^{\perp[U]}(x,k_T^2)\,\frac{k_T\times S_T}{M}\right.$$

$$\left. + \,h_1^{[U]}(x,k_T^2)\gamma_5\not S_T + h_{1T}^{\perp\,[U]}(x,k_T^2)\,\frac{k_T^{\alpha\beta}S_{T\alpha}\gamma_\beta\gamma_5}{M^2}\right\}\frac{\not P}{2} \qquad \Phi_T(x) = h_1(x)\,\gamma_5\,\not S_T\,\frac{\not P}{2}$$

- Surviving in collinear correlators Φ(x) and including flavor index

$$f_1^q(x) \equiv q(x) \quad g_1^q(x) = \Delta q(x) \quad h_1^q(x) = \delta q(x)$$

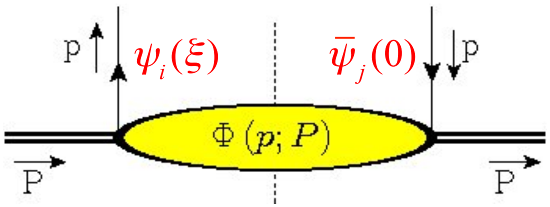
- Including twist three part (only collinear)

$$\Phi(x) = \left\{f_1(x) + S_L\,g_1(x)\,\gamma_5 + h_1(x)\,\not S_T\right\}\frac{\not P}{2} + \left\{e(x) + g_T(x)\not S_T\,\gamma_5 + S_L\,h_L(x)\,\gamma_5\right\}\frac{M}{2}$$

- quark-quark correlator for free quark ensemble

$$u_i(k)\overline{u}_j(k) \Longrightarrow$$

$$u^{(s)}(k)\mathcal{P}_{ss'}(k)u^{(s')}(k) = \mathcal{P}(k)(\not{k}+m)\left(\frac{1+\gamma_5\,\not{s}(k)}{2}\right)$$



$$k = x\,P + k_T + \ldots$$

$$s(k) = s_L(k)\,\frac{k}{m} + s_T(k) + \ldots$$

- no-nonsense result (Kotzinian and Mulders-Tangerman)

$$P(x,k_T^2) = f_1(x,k_T^2)$$

$$P(x,k_T^2)\,s_L(x,k_T^2) = g_{1L}(x,k_T^2)\,S_L + g_{1T}(x,k_T^2)\,\frac{k_T\!\cdot\!S_T}{M}$$

$$P(x,k_T^2)\,s_T(x,k_T^2) = h_{1T}(x,k_T^2)\,S_T + \frac{k_T}{M}\left[h_{1L}^{\perp}(x,k_T^2)\,S_L + h_{1T}^{\perp}(x,k_T^2)\,\frac{k_T\!\cdot\!S_T}{M}\right]$$

LIGHT FRONT language
GOOD
CHIRAL
CHIRAL ODD

- and relations like

$$e = \frac{m}{Mx}\,f_1$$

$$g_T = \frac{g_{1T}^{(1)}}{x} + \frac{m}{Mx}h_1$$

$$h_L = -\frac{2\,h_{1L}^{\perp(1)}}{x} + \frac{m}{Mx}g_1$$

		PARTON SPIN	
QUARKS	γ^+	$\gamma^+\gamma_5$	$\gamma^+\gamma^\alpha\gamma_5$
TARGET SPIN U	f_1		$h_1^\perp$
TARGET SPIN L		g_1	$h_{1L}^\perp$
TARGET SPIN T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Competitors in 1994/1995

- J.P. Ralston and D.E. Soper, NPB 152 (1979) 109
  - transverse momenta in Drell-Yan at nonzero Q_T
- R.L. Jaffe and X.D. Ji, PRL 67 (1991) 552
  - collinear functions, polarization, leading and subleading twist, notation f, g, h
  - early work in my group with e.g. Joachim Levelt, …
- R.D. Tangerman and P.J. Mulders, hep-ph/9403227, PRD 51 (1995) 3357
  - TMD functions, polarization, leading, notation g_{1T}, h_{1L}, … , used in Drell-Yan
  - hep-ph/9408305 for subleading functions g_T and h_L
  - Includes the omitted term in Ralston-Soper (first: Levelt-Tangerman → Pretzelocity)
- A. Kotzinian, hep-ph/9412283, NPB 441 (1995) 234
  - no-nonsense TMD's, used in leptoproduction
- R.D. Tangerman and P.J. Mulders, hep-ph/9501202, PLB 352 (1995) 129

First 'encounter' …

hep-ph/9412283

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Nuclear Physics B 441 (1995) 234–256

NUCLEAR PHYSICS B

New quark distributions and semi-inclusive electroproduction on polarized nucleons

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Received 23 December 1994; revised 9 February 1995; accepted 23 February 1995

Abstract

The quark-parton model calculation including the effects of intrinsic transverse momentum and of all six twist-two distribution functions of quarks in polarized nucleons is performed. It is demonstrated that new twist-two quark distribution functions and polarized quark fragmentation functions can be investigated in semi-inclusive DIS at leading order in Q^2. The general expression for the cross-section of semi-inclusive DIS of polarized leptons on polarized nucleons in terms of structure functions is also discussed.

[1] Now a visitor at CERN, PPE-Division, CH-1211, Geneva 23, Switzerland.

hep-ph/9403227

General consideration of the quark DF in a polarized nucleon in the case of nonvanishing k_T has been done by Ralston and Soper [1] and recently by Tangerman and Mulders [18]. They have found that at the leading twist one needs six independent DFs depending on x and k_T^2: f_1,g_{1L}, g_{1T}, h_{1T}, $h_{1L}^{\perp}$, and $h_{1T}^{\perp}$. The distributions $s_L^{(\mathrm{in})}(x, \boldsymbol{k}_T)$ and $\boldsymbol{s}_T^{(\mathrm{in})}(x, \boldsymbol{k}_T)$ are given by [18]

$$\mathcal{P}_N^q(x, k_T^2) = f_1(x, k_T^2),$$

$$\mathcal{P}_N^q(x, k_T^2)\, s_L^{(\mathrm{in})}(x, \boldsymbol{k}_T) = g_{1L}(x, k_T^2)\, S_L + g_{1T}(x, k_T^2)\, \frac{\boldsymbol{k}_T \cdot \boldsymbol{S}_T}{m_D},$$

$$\mathcal{P}_N^q(x, k_T^2)\, \boldsymbol{s}_T^{(\mathrm{in})}(x, \boldsymbol{k}_T) = h_{1T}(x, k_T^2)\, \boldsymbol{S}_T + \left[h_{1L}^{\perp}(x, k_T^2) S_L + h_{1T}^{\perp}(x, k_T^2) \frac{\boldsymbol{k}_T \cdot \boldsymbol{S}_T}{m_D}\right] \frac{\boldsymbol{k}_T}{m_D}, \qquad (27)$$

where m_D is an unknown mass parameter, S_L and $\boldsymbol{S}_T$ are the nucleon longitudinal and transverse polarization with respect to its momentum. The "new" DFs have clear physical interpretation: for example, g_{1T} describes the quark longitudinal polarization in a transversely-polarized nucleon. It is important to notice that due to this DF even the initial quark longitudinal spin distribution in a polarized nucleon exhibits an azimuthal asymmetry.

Christmas – New Year's eve 1994

hep-ph/9501202

8 June 1995

ELSEVIER

PHYSICS LETTERS B

Physics Letters B 352 (1995) 129–133

Probing transverse quark polarization in deep-inelastic leptoproduction

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Editor: P.V. Landshoff

Abstract

The azimuthal dependence of hadrons produced in lepton scattering off a polarized hadron probes the quark transverse-spin distributions. In the calculation of the asymmetries, transverse momenta of quarks in the distribution and fragmentation functions must be incorporated. In addition to the $\sin(\phi + \phi_S)$ asymmetry for transversely polarized hadrons, known as the Collins effect, we find a $\sin(3\phi - \phi_S)$ asymmetry. Furthermore, we find a $\sin 2\phi$ angular dependence for longitudinally polarized hadrons.

Competitors in 1994/1995

- J.P. Ralston and D.E. Soper, NPB 152 (1979) 109
  - transverse momenta in Drell-Yan at nonzero Q_T
- R.L. Jaffe and X.D. Ji, PRL 67 (1991) 552
  - collinear functions, polarization, leading and subleading twist, notation f, g, h
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  - TMD functions, polarization, leading, notation g_{1T}, h_{1L}, … , used in Drell-Yan
  - hep-ph/9408305 for subleading functions g_T and h_L
- A. Kotzinian, hep-ph/9412283, NPB 441 (1995) 234
  - no-nonsense TMD’s, used in leptoproduction
- R.D. Tangerman and P.J. Mulders, hep-ph/9501202, PLB 352 (1995) 129

- Followed up with ’complete analysis’ (Rik Tangerman), phenomenology (Aram Kotzinian) and study of T-odd functions (Daniel Boer)

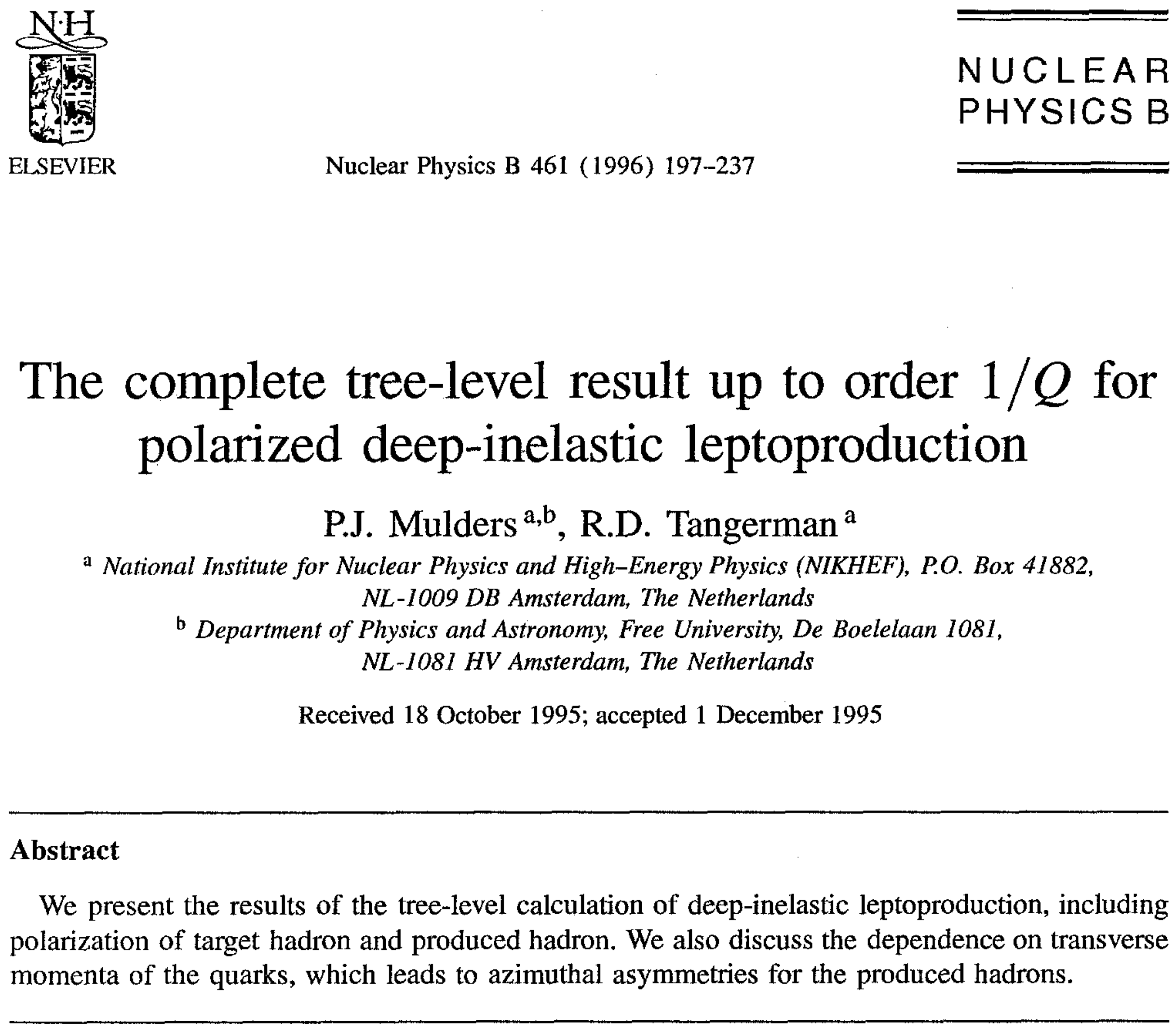
working hard in 1995

Includes subleading 1/Q

Discusses 'staple' links

Use of $g_{1T}^{(1)}$, etc.

No T-odd stuff
(came in 1997)



collaborators in 1996

PHYSICAL REVIEW D VOLUME 54, NUMBER 1 1 JULY 1996

Longitudinal quark polarization in transversely polarized nucleons

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(Received 27 November 1995)

Accounting for transverse momenta of the quarks, a longitudinal quark spin asymmetry exists in a transversely polarized nucleon target. The relevant leading quark distribution $g_{1T}(x,k_T^2)$ can be measured in semi-inclusive deep-inelastic scattering. The average k_T^2 weighted distribution function $g_{1T}^{(1)}$ can be obtained directly from the inclusive measurement of g_2. [S0556-2821(96)03813-1]

Based on EOM relations

$$g_T = \frac{g_{1T}^{(1)}}{x} + \frac{m}{M}\frac{h_1}{x} + \tilde{g}_T = g_1 + \frac{d}{dx}\, g_{1T}^{(1)}$$

WW

$$g_2(x) = -\left[g_1(x) - \int_x^1 dy\, \frac{g_1(y)}{y}\right]$$

$$h_L = \frac{m}{M}\frac{g_1}{x} - 2\,\frac{h_{1L}^{\perp(1)}}{x} + \tilde{h}_L = h_1 - \frac{d}{dx}\, h_{1L}^{\perp(1)}$$

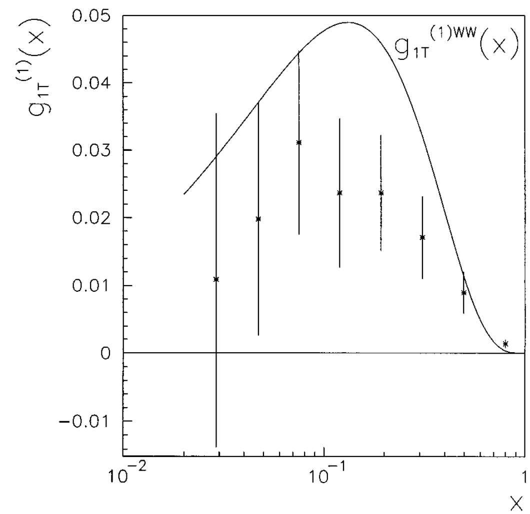

FIG. 2. The function $g_{1T}^{(1)}(x)$ as obtained from E143 data using Eq. (22) or from the BBS parametrizations for g_1 using Eq. (25).

Many follow-up developments

- T-odd functions (Dennis Sivers, John Collins, Daniel Boer, …)
- Phenomenology (Aram Kotzinian, Elena Boglione, Rainer Jakob, …)
- Extensions including higher spin (Alessandro Bacchetta), gluons (Joao Rodrigues, Andreas Metz, …)

PARTON SPIN / TARGET SPIN

QUARKS	γ^+	$\gamma^+\gamma_5$	$\gamma^+\gamma^\alpha\gamma_5$
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$
LL	f_{1LL}		$h_{1LL}^\perp$
LT	f_{1LT}	g_{1LT}	h_{1LT} $h_{1LT}^\perp$
TT	f_{1TT}	g_{1TT}	h_{1TT} $h_{1TT}^\perp$

PARTON SPIN / TARGET SPIN

GLUONS	$-g_T^{\alpha\beta}$	$\varepsilon_T^{\alpha\beta}$	$p_T^{\alpha\beta}, \ldots$
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_1^g $h_{1T}^{\perp g}$
LL	f_{1LL}^g		$h_{1LL}^{\perp g}$
LT	f_{1LT}^g	g_{1LT}^g	h_{1LT}^g $h_{1LT}^{\perp g}$
TT	f_{1TT}^g	g_{1TT}^g	h_{1TT}^g $h_{1TT}^{\perp g}$ $h_{1TT}^{\perp\perp g}$

- Links to off-forward GPD's, …
- Operator structure including gauge links and gluonic poles, factorization breaking
  - Ted Rogers, John Collins, …
  - Fetze Pijlman, Cedran Bomhof, Maarten Buffing, …
- Analytic structure, bounds and spectator models, low x, …
  - Leonard Gamberg, Asmita Mukherjee, Sabrina Cotogno, Tom van Daal, Elena Petreska, …

Since then we met at many meetings, Aram always modest

… but he certainly deserves to be in the center like here!

and today

Congratulations!

Happy birthday