Some recent results

Klaus Rith

COMPASS Meeting, June 2018
Some (not really) recent *hermes* results
(still awaiting publication)

Klaus Rith

COMPASS Meeting, June 2018
So far:
80 papers (~8600 citations)

HEDT

- $A_{LL}^h$
- $A_{U(L)T}^h$ ('all' TMDs)
- $A_{UT}^{2h}$
- $A_{LU}^h$
- $\Lambda$ Polarization
- Kaons from nuclei
Semi-inclusive Deep-Inelastic Scattering

Factorisation

$$\sigma^{eN \rightarrow ehX} = \sum_q \sigma^{eq \rightarrow eq} \otimes DF^{N \rightarrow q} \otimes FF^{q \rightarrow h}$$

DF($x, Q^2$): Parton Distribution Function - $f_1(x, Q^2), g_{1L}(x, Q^2), h_1(x, Q^2), ...$

FF($z, Q^2$): Fragmentation Function - $D_1^{q \rightarrow h}(z, Q^2), H_{1 \perp q \rightarrow h}(z, Q^2), ...$

$$Q^2 = - q^2 = -(k-k')^2$$

$$\nu = Pq/M$$

$$x = Q^2/(2Pq)$$

$$z = E_h/\nu$$
Azimuthal modulations of SIDIS cross section

\[
\frac{d\sigma}{dx\ dy\ dz\ d\phi\ d\phi_s\ dP_{h\perp}^2} = \frac{d^6\sigma}{dx\ dy\ dz\ d\phi\ d\phi_s\ dP_{h\perp}^2}
\]

\[
d\sigma = d\sigma_{UU}^0 + \cos 2\phi \ d\sigma_{UU}^1 + \frac{1}{Q} \cos \phi \ d\sigma_{UU}^2 + \lambda_e \frac{1}{Q} \sin \phi \ d\sigma_{LU}^3 \\
+ S_T \left\{ \sin(\phi - \phi_S) \ d\sigma_{UT}^8 + \sin(\phi + \phi_S) \ d\sigma_{UT}^9 + \sin(3\phi - \phi_S) \ d\sigma_{UT}^{10} \\
+ \frac{1}{Q} \sin(2\phi - \phi_S) \ d\sigma_{UT}^{11} + \frac{1}{Q} \sin \phi_s d\sigma_{UT}^{12} \\
+ \lambda_e \left[ \cos(\phi - \phi_S) \ d\sigma_{LT}^{13} + \frac{1}{Q} \cos \phi_s d\sigma_{LT}^{14} + \frac{1}{Q} \cos(2\phi - \phi_S) d\sigma_{LT}^{15} \right] \right\} \\
+ S_L \left\{ \sin 2\phi \ d\sigma_{UL}^4 + \frac{1}{Q} \sin \phi \ d\sigma_{UL}^5 + \lambda_e \left[ d\sigma_{LL}^6 + \frac{1}{Q} \cos \phi \ d\sigma_{LL}^7 \right] \right\}
\]
Azimuthal modulations of SIDIS cross section

\[ d\sigma = d\sigma_{UU}^0 + \cos 2\phi \left( d\sigma_{UU}^1 \right) + \frac{1}{Q} \cos\phi \left( d\sigma_{UU}^2 \right) + \lambda_e \frac{1}{Q} \sin\phi \left( d\sigma_{LU}^3 \right) \]

\[ + S_T \left\{ \sin(\phi - \phi_S) \left( d\sigma_{UT}^8 \right) + \sin(\phi + \phi_S) \left( d\sigma_{UT}^9 \right) + \sin(3\phi - \phi_S) \left( d\sigma_{UT}^{10} \right) \right\} \]

\[ + \frac{1}{Q} \sin(2\phi - \phi_S) \left( d\sigma_{UT}^{11} \right) + \frac{1}{Q} \sin\phi_S \left( d\sigma_{UT}^{12} \right) \]

\[ + \lambda_e \left[ \cos(\phi - \phi_S) \left( d\sigma_{LT}^{13} \right) + \frac{1}{Q} \cos\phi_S \left( d\sigma_{LT}^{14} \right) + \frac{1}{Q} \cos(2\phi - \phi_S) \left( d\sigma_{LT}^{15} \right) \right] \}

\[ + S_L \left\{ \sin 2\phi \left( d\sigma_{UL}^4 \right) + \frac{1}{Q} \sin\phi \left( d\sigma_{UL}^5 \right) + \lambda_e \left[ d\sigma_{LL}^6 + \frac{1}{Q} \cos\phi \left( d\sigma_{LL}^7 \right) \right] \right\} \]
The others are subleading, i.e., suppressed by $1/Q$
Azimuthal modulations of SIDIS cross section

\[
d\sigma = d\sigma_{UU}^0 + \cos 2\phi \left( d\sigma_{UU}^1 + \frac{1}{Q} \cos \phi \right) d\sigma_{UU}^2 + \frac{1}{Q} \sin \phi \left( d\sigma_{LU}^3 + \lambda_e \right)
\]

\[
+ S_T \left\{ \sin(\phi - \phi_S) d\sigma_{UT}^8 + \sin(\phi + \phi_S) d\sigma_{UT}^9 + \sin(3\phi - \phi_S) d\sigma_{UT}^{10} \right. \\
+ \left. \frac{1}{Q} \sin(2\phi - \phi_S) d\sigma_{UT}^{11} + \frac{1}{Q} \sin \phi_S d\sigma_{UT}^{12} \right\}
\]

\[
+ \lambda_e \left[ \cos(\phi - \phi_S) d\sigma_{LT}^{13} + \frac{1}{Q} \cos \phi_S d\sigma_{LT}^{14} + \frac{1}{Q} \cos(2\phi - \phi_S) d\sigma_{LT}^{15} \right]
\]

\[
+ S_L \left\{ \sin 2\phi d\sigma_{UL}^4 + \frac{1}{Q} \sin \phi d\sigma_{UL}^5 + \lambda_e \left[ d\sigma_{LL}^6 + \frac{1}{Q} \cos \phi d\sigma_{LL}^7 \right] \right\}
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Azimuthal modulations of SIDIS cross section

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d\sigma = d\sigma_{UU}^0 + \cos 2\phi \left( d\sigma_{UU}^1 \right) + \frac{1}{Q^{\phi}} d\sigma_{UU}^2 + \lambda_e \frac{1}{Q^{\phi}} \sin \phi \ d\sigma_{LU}^3
\]

\[
+ S_T \left\{ \sin (\phi - \phi_S) \ d\sigma_{UT}^8 + \sin (\phi + \phi_S) \ d\sigma_{UT}^9 + \sin (3\phi - \phi_S) \ d\sigma_{UT}^{10} \right. \\
\left. + \frac{1}{Q^{\phi}} \sin (2\phi - \phi_S) \ d\sigma_{UT}^{11} + \frac{1}{Q^{\phi}} \sin \phi_S \ d\sigma_{UT}^{12} \right. \\
\left. + \lambda_e \ \left[ \cos (\phi - \phi_S) \ d\sigma_{LT}^{13} + \frac{1}{Q^{\phi}} \cos \phi_S \ d\sigma_{LT}^{14} + \frac{1}{Q^{\phi}} \cos (2\phi - \phi_S) \ d\sigma_{LT}^{15} \right] \right\}
\]

\[
+ S_L \left\{ \sin 2\phi \ d\sigma_{UL}^{4} + \frac{1}{Q^{\phi}} \sin \phi \ d\sigma_{UL}^{5} + \lambda_e \ left[ d\sigma_{LL}^{6} + \frac{1}{Q^{\phi}} \cos \phi \ d\sigma_{LL}^{7} \right] \right\}
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The others are subleading, i.e., suppressed by \( 1/Q \).
Azimuthal modulations of SIDIS cross section

\[ d\sigma = d\sigma_{UU}^0 + \cos 2\phi \, d\sigma_{UU}^1 + \frac{1}{Q} \cos \phi \, d\sigma_{UU}^2 + \frac{1}{Q} \sin \phi \, d\sigma_{LU}^3 \]

\[ + S_T \left\{ \sin(\phi - \phi_S) \, d\sigma_{UT}^8 + \sin(\phi + \phi_S) \, d\sigma_{UT}^9 + \sin(3\phi - \phi_S) \, d\sigma_{UT}^{10} \right\} \]

\[ + \frac{1}{Q} \sin(2\phi - \phi_S) \, d\sigma_{UT}^{11} + \frac{1}{Q} \sin \phi_S \, d\sigma_{UT}^{12} \]

\[ + \lambda_{e} \left[ \cos(\phi - \phi_S) \, d\sigma_{LT}^{13} + \frac{1}{Q} \cos \phi_S \, d\sigma_{LT}^{14} + \frac{1}{Q} \cos(2\phi - \phi_S) \, d\sigma_{LT}^{15} \right] \}

\[ + S_L \left\{ \sin 2\phi \, d\sigma_{UL}^4 + \frac{1}{Q} \sin \phi \, d\sigma_{UL}^5 + \lambda_{e} \left[ d\sigma_{LL}^6 + \frac{1}{Q} \cos \phi \, d\sigma_{LL}^7 \right] \right\} \]

The others are subleading, i.e., suppressed by \(1/Q\).
Leading Twist TMDs

\[
d^6\sigma = \frac{dx\,dy\,dz\,d\phi\,d\phi_s\,dP^2_{h\perp}}{d\phi}
\]

**Nucleon**

- **f\_1 number density**
  - unpol.
  - trans. pol.

- **g\_1L**
  - helicity
  - T-odd

- **f\_1T\perp**
  - Sivers
  - T-odd

- **g\_1T\perp**
  - worm-gear 1

- **h\_1\perp**
  - Boer-Mulders
  - T-odd

- **h\_1T\perp**
  - pretzelosity

- **h\_1T\perp**
  - transversity

**Expressions**

- Unpol. (U)
- Long. pol. (L)
- Trans. pol. (T)

- \( \sin(\phi - \phi_s) \)
- \( \cos(\phi - \phi_s) \)
- \( \sin(3\phi - \phi_s) \)
- \( \sin(\phi + \phi_s) \)
- \( \cos 2\phi \)

K.R.
Topic 1: $A_{LL}^h$
Consistent with zero

No significant kinematic dependence observed

Compatible result for proton and deuteron

**publication coming soon**
Cosφ moment of asymmetry $A_{LL}$

Consistent with zero

No significant kinematic dependence observed

Compatible result for proton and deuteron

Presented at Praha, July 2012 !!!

Publication coming soon
**Subleading twist**

**cosφ moment of asymmetry $A_{LL}$**

\[ C[g_{1L}^q(x, p_T^2) \otimes D_1^q(z, k_T^2)] \]

<table>
<thead>
<tr>
<th>Process</th>
<th>$A_{LL}^{cos\phi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ep \rightarrow e^+hX$</td>
<td><img src="image1" alt="Graph" /></td>
</tr>
<tr>
<td>$ep \rightarrow e^0X$</td>
<td><img src="image2" alt="Graph" /></td>
</tr>
<tr>
<td>$ed \rightarrow e^+hX$</td>
<td><img src="image3" alt="Graph" /></td>
</tr>
<tr>
<td>$ed \rightarrow e^0X$</td>
<td><img src="image4" alt="Graph" /></td>
</tr>
</tbody>
</table>

**HERMES preliminary**

- **Proton Target**
  - $0.2 < z < 0.4$
  - $0.4 < z < 0.8$

- **Deuteron Target**
  - $0.2 < z < 0.4$
  - $0.4 < z < 0.6$

- **Consistent with zero**
- **No significant kinematic dependence observed**
- **Compatible result for proton and deuteron**

**Presented at Praha, July 2012 !!!**

**Publication coming soon**
Topic 2: $A_{U(L)T}^h$ (‘all’ TMDs)
Data taken in 2002-2005
5 PhD theses in 2004-2010
3 publications (Sivers and Collins for pions and charged kaons)
(So far ~1140 citations)
Since then - include protons and antiprotons
  - extend analysis to 3D in (x, z, P_{h\perp}) for all but antiprotons
    (important for global fits)
  - detailed study of systematics
Simultaneous fit of the Fourier amplitudes for
\sin(\phi-\phi_s), \sin(\phi+\phi_s), \sin(3\phi-\phi_s), \sin(\phi_s), \sin(2\phi-\phi_s), \sin(2\phi+\phi_s) \quad (UT)
\cos(\phi-\phi_s), \cos(\phi_s), \cos(2\phi-\phi_s) \quad (LT)
>200 plots

K.R.
Transversity and Collins FF

\[ C[h_1^q(x) \otimes H_{1\perp}^q(z)] \]

Airapetian et al., PLB 693(2010) 11

- Transversity DF and Collins FF non-zero, lead to large effects
- Opposite in sign for charged pions
- Disfavored Collins FF large and opposite in sign to favored one
Positive Collins SSA for positive Kaons

Consistent with zero for negative Kaons
Transversity and Collins FF

\[ C[h_1^q(x) \otimes H_1^{\perp q}(z)] \]

Positive Collins SSA for positive Kaons
Consistent with zero for negative Kaons and (anti-)protons
Vanishing sea-quark transversity and baryon Collins effect?
Transversity and Collins FF

\[ C[h_1(x) \times H_1^{\perp,q}(z)] \]

Z. Kang et al., PRD 93 (2016) 014009

M. Anselmino et al., PRD 87 (2013) 094019
(M. Radici et al., JHEP 1505 (2015) 123)

HERMES (PRL 1003 (2009) 152002)
JLAB - Hall A (PRL 107 (2011) 072003)
e+e- data from
BELLE (PRD 78 (2008) 032011)
BABAR (PRD 90 (2014) 052003)
Transversity and Collins FF

\[ C[h_1^q(x) \otimes H_{1^\perp q}(z)] \]

\[ P_{h^\perp} \quad Z \]

- \( \pi^- \) amplitudes increasing with \( x \) at large \( P_{h^\perp} \), increasing with \( z \)

- Other hadrons: no such clear kinematic dependencies

- No 3D for antiprotons

K.R.
Positive Sivers amplitude for positive pions and kaons

Experimental evidence for orbital angular momentum $L_q$ of quarks

Positive Sivers amplitude for (anti-)protons, Similar magnitude as for $\pi^+$

Sivers amplitudes

<table>
<thead>
<tr>
<th>N/q</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>f_1</td>
<td>$h_1^+$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>g_1</td>
<td>$h_{1T}^+$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_{1T}$</td>
<td>$h_1$</td>
<td>$h_{1T}$</td>
<td></td>
</tr>
</tbody>
</table>
Sivers amplitudes

\[ C[f_{1T}^q(x) \otimes D_1^q(z)] \]

A. Airapetian et al., PRL 103 (2009) 152002

Largest at large \( x \) and \( z \), region of purest "u-quark probe"

3D for pions, kaons, protons

K.R.
**Sivers amplitudes**

\[ C[f_{1T}^q(x) \otimes D_1^q(z)] \]

<table>
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<tbody>
<tr>
<td>U</td>
<td>( f_i )</td>
<td>( h_i )</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>( g_i )</td>
<td>( h_i )</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>( f_{1T} )</td>
<td>( g_{1T} )</td>
<td>( h_1 )</td>
</tr>
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A. Airapetian et al., PRL 103 (2009) 152002

Large \( K^+ \) Sivers amplitude
**Sivers amplitudes**

\[ C[f_{1T}^q(x) \otimes D_{1T}(z)] \]

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</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>( f_1 )</td>
<td>( h_{1T} )</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>( g_1 )</td>
<td>( h_{1L} )</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>( f_{1T} )</td>
<td>( g_{1T} )</td>
<td>( h_1 )</td>
</tr>
</tbody>
</table>

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A. Airapetian et al., PRL 103 (2009) 152002

**Large \( K^+ \) Sivers amplitude**

**Largest at large \( x \) and \( z \), Region of purest „u-quark probe“**
Sivers amplitudes

\[ C[f_{LT}^q(x) \otimes D_1^q(z)] \]

A. Airapetian et al., PRL 103 (2009) 152002

Large \( K^+ \) Sivers amplitude

A. Martin et al., PRD 95 (2017) 094024

Largest at large \( x \) and \( z \), Region of purest "u-quark probe"

COMPASS data only
Pretzelosity DF $h_{1T}^\perp$

<table>
<thead>
<tr>
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<th>L</th>
<th>T</th>
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<tbody>
<tr>
<td>U</td>
<td>$f_1$</td>
<td></td>
<td>$h_{1T}^\perp$</td>
</tr>
<tr>
<td>L</td>
<td>$g_1$</td>
<td>$h_{1T}^\perp$</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>$f_{1T}$</td>
<td>$g_{1T}$</td>
<td>$h_1$ (h_{1T}^\perp)</td>
</tr>
</tbody>
</table>

Sideways transversely polarised quarks in transversely polarised nucleon

\[
F_{UT}^{\sin(3\phi_h-\phi_S)} = \frac{2 (\hat{h} \cdot p_T) (p_T \cdot k_T) + p_T^2 (\hat{h} \cdot k_T) - 4 (\hat{h} \cdot p_T)^2 (\hat{h} \cdot k_T)}{2M^2M_h} \left[ h_{1T}^\perp H_{1T}^\perp \right]
\]

- leading-twist
- Related to parton orbital motion: requires interference between wave functions with OAM difference by 2 units
- Expected to scale with $(p_T)^2k_T$
- Suppressed w.r.t - Collins and Sivers (these scale with $k_T$, $p_T$)
  - Cahn, Boer-Mulders ($\langle \cos \phi \rangle$ scales with $k_T$, $p_T$)
  - Boer-Mulders ($\langle \cos 2\phi \rangle$ scales with $k_Tp_T$)

K.R.
Pretzelosity DF $h_{1T}^\perp$

$C[h_{1}^\perp, q(x) \otimes H_{1}^\perp q(z)]$

Compatible with zero within uncertainties

$h_{1T}^\perp$ might be non-zero, look at higher $p_T$

3D for pions, kaons, protons

K.R.
Pretzelosity DF $h_{1T}^\perp$

$C[h_{1T}^\perp, q(x) \otimes H_{1T}^\perp q(z)]$

Compatible with zero within uncertainties

$h_{1T}^\perp$ might be non-zero, look at higher $p_T$


Data from COMPASS, HERMES, JLAB

for pions, kaons, protons
Worm-gear DF $g_{1T}^{\perp, q}$

longitudinally polarised quarks in transversely polarised nucleon

$C[g_{1T}^{\perp, q}(x) \otimes D_1^q(z)]$

- Related to parton orbital motion: requires interference between wave functions with OAM difference by 1 unit

- $g_{1T}^{\perp, q} = - h_{1L}^{\perp, q}$ (supported by many models)

- \[ g_{1T}^{\perp, q} \approx x \int \frac{dy}{y} \ g_1^q(y) \] (Wandzura-Wilczek type approximation)

- Slightly non-zero

- for pions, kaons, protons
Twist-3 $\langle \sin(\phi_S) \rangle_{UT}$

\[ \propto C \left[ f_T^q \right] \times D_1^q, h_{1T}^q \times [\tilde{H}^q, h_T^q] \times H_1^{1,q}, g_{1T}^q \times [\tilde{G}^q, h_T^1] \times H_1^{1,q}, f_1^q \times \tilde{D}^q \]

\[ \int \ldots \, dP_{h_{\perp}}^2 \]

\[ \langle \sin(\phi_S) \rangle_{UT} = -x \frac{2M_h}{Q} \sum_q e_q^2 h_{1T}^q \frac{\tilde{H}^q}{z} \]

Significant non-zero amplitude for $\pi^-$ increasing with $x, z$
Twist-3 $\langle \sin(\phi_S) \rangle_{UT}$

$$\propto C \left[ f_T^q \times D_1^q, h_{1T}^q \times \tilde{H}_1^q, h_T^q \times H_1^q, g_{1T}^q \times \tilde{G}_1^q, h_{1T}^q \times H_1^q, f_{1T}^q \times \tilde{D}_1^q \right]$$
Topic 4: $A_{LU}^h$
Twist-3 $\langle \sin(\phi) \rangle_{LU}$

$\propto C[h_1^{\perp q} \otimes \tilde{q}, x e^{\perp q} H_1^{\perp}; x g^{\perp q} \otimes D_1^{q}, f_1^{q} \otimes G^{\perp q}]$

Chiral-odd T-even

Chiral-even T-odd

H, D data from 1996-2007

Virtual-photon asymmetries

Agreement between H and D data

Positive asymmetries for pions

K.R.
Twist-3 $\langle \sin(\phi) \rangle_{LU}$

$\propto C[h_1^q \otimes \tilde{E}_q \times e^q \otimes H_1^q ; x g^q \otimes D_1^q, f_1^q \otimes \tilde{G}^q]$}

H, D data from 1996-2007

Chiral-odd T-even

Chiral-even T-odd

No clear kinematic dependencies in

K.R.
D data from 1999-2007

\[ \propto C[h_{1q} \otimes \bar{E}_{q} \times e_{q} \otimes H_{1q} ; x \ g_{1q} \otimes D_{1q}, f_{1q} \otimes \tilde{G}_{1q}] \]

Chiral-odd
T-even

Chiral-even
T-odd

Data at high z not used for other projections

Consistent behavior for charged pions/hadrons at HERMES/COMPASS for isoscalar targets
Twist-3 $\langle \sin(\phi) \rangle_{LU}$

$\propto C[h_{1,q} \otimes \tilde{E}_q \times e^q \otimes H_{1,q} ; \times g_{-q} \otimes D_{1}, f_{1,q} \otimes \tilde{G}_{-q}]$

- Chiral-odd
- T-even
- Chiral-even
- T-odd

H data from 1996-2007

Opposite behavior for $\pi^{-}$ $z$ projection
CLAS probes higher $x$ region; more sensitive to $x e^q \otimes H_{1,q}$.

W. Gohn et al., PRD 89 (2014) 072011
Twist-3 $\langle \sin(\phi) \rangle_{LU}$

$$\propto C[h_{1,q} \otimes \tilde{E}_q \times e^q \otimes H_{1,q}^{-q} ; \times g_{-q} \otimes D_1^q, f_{1,q} \otimes \tilde{G}_{-q}^{-q}]$$

- Chiral-odd T-even
- Chiral-even T-odd

H data from 1996-2007

Opposite behavior for $\pi^{-}z$ projection
CLAS probes higher $x$ region; more sensitive to $x e^q \otimes H_{1,q}^{-q}$?

W. Gohn et al., PRD 89 (2014) 072011

Draft in 1st circulation
Topic 5: Λ Polarization
Beam-helicity induced $\Lambda$ and $\bar{\Lambda}$ polarization

$\bar{\Lambda}$ polarization $\vec{P}^{\Lambda}$ from proton angular distribution in $\Lambda$ rest frame

$$\propto \left(1 + \alpha \vec{P}^{\Lambda} \cdot \hat{p}\right) = \left(1 + \alpha \sum_i P_i^{\Lambda} \cos \theta_i\right)$$  \hspace{1cm} (i = X, Y, Z)

$P_Z^{\Lambda} = P_B \sqrt{1-\varepsilon^2} \ D_{LZ}(x,z)$  \hspace{1cm} $P_B = \left|P_B\right| \lambda_e$ longitudinal beam polarization

$P_X^{\Lambda} = P_B \ 2\sqrt{2\varepsilon(1-\varepsilon)} \ D_{LX}(x,z)$

$P_Y^{\Lambda} = 2\sqrt{2\varepsilon(1+\varepsilon)} \ D_{LY}(x,z)$ beam-helicity independent transverse $\Lambda$ pol.

$D_{LX}(x,z), D_{LY}(x,z), D_{LZ}(x,z)$: "spin-transfer coefficients"

Asymmetry for helicity balanced data set: $P_Y^{\Lambda}$ drops out
Beam-helicity induced $\Lambda$ and $\bar{\Lambda}$ polarization

Relations between spin-transfer coefficients and TMDs:

$$D_{LZ}(x,z) = \frac{\sum_q e_q^2 x f_1^q(x) G_{1q}^{\Lambda}(z)}{\sum_q e_q^2 x f_1^q(x) D_{1q}^{\Lambda}(z)}$$

Production of longitudinally polarized $\Lambda$s from originally unpolarized quarks and longitudinally polarized virtual photons
Beam-helicity induced Λ and \( \bar{\Lambda} \) polarization

Relations between spin-transfer coefficients and TMDs:

\[ D_{LZ}(x,z) = \frac{\sum_q e_q^2 x f_1^q(x) G_{1 \rightarrow \Lambda}^q(z)}{\sum_q e_q^2 x f_1^q(x) D_{1 \rightarrow \Lambda}^q(z)} \]

Production of longitudinally polarized Λs from originally unpolarized quarks and longitudinally polarized virtual photons

\[ D_{LX}(x,z) = -\frac{M}{Q} \left\{ \sum_q e_q^2 x^2 e_q(x) H_{1 \rightarrow \Lambda}^q(z) + \frac{M}{M} \sum_q e_q^2 x f_1^q(x) \tilde{G}_{\perp \rightarrow \Lambda}^q(z)/z \right\} \]

\[ \sum_q e_q^2 x f_1^q(x) D_{1 \rightarrow \Lambda}^q(z) \]
Beam-helicity induced $\Lambda$ and $\bar{\Lambda}$ polarization

Relations between spin-transfer coefficients and TMDs:

$$D_{LZ}(x,z) = \frac{\sum_q e_q^2 x f_1^q(x) G_1^{q \rightarrow \Lambda}(z)}{\sum_q e_q^2 x f_1^q(x) D_1^{q \rightarrow \Lambda}(z)}$$

Production of longitudinally polarized $\Lambda$s from originally unpolarized quarks and longitudinally polarized virtual photons

$$D_{LX}(x,z) = \frac{-\frac{M}{Q} \{ \sum_q e_q^2 x^2 e^q(x) H_{1^\perp,q}^{q \rightarrow \Lambda}(z) + \frac{M^\perp}{M} \sum_q e_q^2 x f_1^q(x) \tilde{G}_{1^\perp,q}^{q \rightarrow \Lambda}(z)/z \}}{\sum_q e_q^2 x f_1^q(x) D_1^{q \rightarrow \Lambda}(z)}$$

Same combinations of PDFs and FF as in Twist-3 $\langle \sin(\phi) \rangle_{LU}$

$$\propto C[h_{1^\perp,q} \otimes \tilde{E}^q, x e^q \otimes H_{1^\perp,q}; x g_{1^\perp,q} \otimes D_1^q, f_{1^\perp,q} \otimes \tilde{G}_{1^\perp,q}]$$
Beam-helicity induced $\Lambda$ and $\bar{\Lambda}$ polarization

Cross check in progress
Beam-helicity induced $\Lambda$ and $\bar{\Lambda}$ polarization

Cross
Topic 6: Kaons from nuclei
typical hadronisation length $\propto (1-z) v$

is of order of nucleus size (1-10 fm)

time development of hadronisation can be studied with nuclei of increasing size

struck quark or qq-pair propagate through 'cold' nuclear matter

interaction signature: reduction of the number of hadrons per DIS event and per nucleon

Useful for understanding the fundamental aspects of hadronisation

Input for calculations of nuclear PDFs and FF

$$R_A^h(\nu, Q^2, z, p_t^2) = \frac{\left( \frac{N^h(\nu, Q^2, z, p_t^2)}{N_e(\nu, Q^2)} \right)_A}{\left( \frac{N^h(\nu, Q^2, z, p_t^2)}{N_e(\nu, Q^2)} \right)_D}$$

Multi-dimensional study
Fragmentation in nuclear matter

Example: $\nu$-dependence

- less pronounced trends in Ne compared to Kr and Xe
- $\pi^+$, $\pi^-$, $K^-$: increase of $R_A$ with $\nu$
- $K^+$: increase of $R_A$ with $\nu$ for lowest $z$-slice, flatter behaviour for higher $z$
- $p$: weak $\nu$-dependence
- $p$: $R_A$ exceeding unity at high $\nu$ and low $z$ (apart from hadronisation other production mechanisms contribute)
**Charged Kaon production in nuclear matter**

N.B. Chang et al., PRC 89 (2014) 034911

**Prediction:** enhanced medium modified FF for $K^-$ and enhanced $K^-/K^+$ production ratio at large $x$ and $z$
**Charged Kaon production in nuclear matter**

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**Prediction:** enhanced medium modified FF for $K^-$ and enhanced $K^-/K^+$ production ratio at large $x$ and $z$

**Analysis completed. Results to be released in a few weeks**