Azimuthal asymmetries on proton at COMPASS: $Q^2$- dependence

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Azimuthal asymmetries at COMPASS (proton 2016)

\[
\frac{d^5\sigma}{dx\,dy\,dz\,d\phi_h\,dP_T^2} = \frac{2\pi\alpha^2}{xyQ^2} \frac{y^2}{2(1 - \varepsilon)} \left(1 + \frac{y^2}{2x}\right) \cdot \left( F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1 + \varepsilon)} F_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon F_{UU}^{\cos2\phi_h} \cos2\phi_h + \lambda_1 \sqrt{2\varepsilon(1 - \varepsilon)} F_{LU}^{\sin\phi_h} \sin\phi_h \right)
\]

Exclusive hadrons: discarded (visible part) or subtracted (not visible part, Monte Carlo)

Fit of the amplitude of the modulation in the azimuthal angle of the hadrons
- as a function of \(x\), \(z\) or \(P_T\) (1D)
- with a simultaneous binning (3D)

Azimuthal asymmetries: defined as the following ratios

\[
A_{UU}^{\cos\phi_h} = \frac{F_{UU}^{\cos\phi_h}}{F_{UU}} \quad A_{UU}^{\cos2\phi_h} = \frac{F_{UU}^{\cos2\phi_h}}{F_{UU}} \quad A_{LU}^{\sin\phi_h} = \frac{F_{LU}^{\sin\phi_h}}{F_{UU}}
\]

- **Strong kinematic dependences**
- **Interesting differences** between positive and negative hadrons, as observed in previous measurements by COMPASS on deuteron and by HERMES

The error bars correspond to the statistical uncertainty only. \(\sigma_{syst} \sim \sigma_{stat}\) (1D)
The error bars correspond to the statistical uncertainty only. $\sigma_{\text{stat}} \sim 0.5 \sigma_{\text{stat}} \langle 3D \rangle$.

Clear signal, strong dependence on $P_T$; compatible with zero at high $z$.

In agreement with COMPASS deuteron results.

Expectation from Cahn effect:

$$A_{UU|\text{Cahn}}^\cos \phi_h = \frac{-2zP_T \langle k_T^2 \rangle}{Q \langle P_T^2 \rangle}$$

**Binning in $Q^2$**

- The $A_{UU}^\cos \phi_h$ asymmetry is observed to increase with $Q^2$ \textit{unexpected}!
- The difference between positive and negative hadrons decreases with $Q^2$.
- \textbf{Almost no $Q^2$ dependence for $A_{UU}^{\cos 2 \phi_h}$}

3D azimuthal asymmetries for positive and negative hadrons

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Science at the Luminosity Frontier: Jefferson Lab at 22 GeV
Clear signal, strong dependence on $P_T$; compatible with zero at high $z$.
In agreement with COMPASS deuteron results.

Expectation from Cahn effect:

$$A_{UU}^{\cos \phi_h} |_{\text{Cahn}} = -\frac{2zP_T \langle k_T^2 \rangle}{Q \langle P_T^2 \rangle}$$

**Binning in $Q^2$**

- The $A_{UU}^{\cos \phi_h}$ asymmetry is observed to increase with $Q^2$ unexpected!
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- Almost no $Q^2$ dependence for $A_{UU}^{\cos 2 \phi_h}$
Azimuthal asymmetries

Very interesting observables to access the nucleon structure in unpolarized SIDIS

- **COMPASS** has produced results using a deuteron (published 2014) and proton target (new)

- Intriguing investigations of their properties:
  - rich kinematic dependences, $h^+ h^-$ differences, …

A lot to be understood and/or addressed

- Difference between positive and negative hadrons in azimuthal asymmetries
- Kinematic dependences (sometimes *counterintuitive* for azimuthal asymmetries)
- Role of twist-3 contributions beyond Cahn
- Impact of radiative corrections – not included in the results shown here
  - may give a relevant contribution to the $Q^2$ dependence
- Possible role of vector mesons inclusively produced in SIDIS