pt and phi* studies from 12-GeV era Hall C SIDIS experiments

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Analysis from three Hall C experiments in 2018-2019

• Pt-SIDIS wide range of Pt for six \((x,Q^2)\) settings with detection of SIDIS \(\pi^+\) and \(\pi^-\) from proton, deuteron, and aluminum, for \(0.3 < z < 0.9\). No graduate student at present. Mostly being analyzed by myself.

• CSV-SIDIS: 26 more settings in \((x,Q^2)\) for \(\pi^+\) and \(p\) and \(\pi^-\) from deuteron (and some proton) but limited Pt coverage, again \(0.3 < z < 0.9\). Graduate students Hem Bhatt and Shuo Jia. (see previous talk).

• Kaon-LT: inelastic \(\pi^+\) and \(K^+\) on proton target useful for measuring SIDIS at high \(z\), including the ratio \(R = \sigma_L/\sigma_T\)
Semi-Inclusive Deep Inelastic Scattering (SIDIS)

Few kinematic quantities:

\[ x = \frac{Q^2}{2M_p\nu} \]  
Fraction of proton’s momentum carried by the quark (Bjorken x)

\[ M_p = \text{mass of proton} \]

\[ \nu = \text{energy Transfer in lab frame (E - E')} \]

\[ Q^2 = 4 \text{momentum transfer squared} = 4EE' \sin^2(\Theta/2) \]

\[ z = \text{fraction of energy transfer carried by outgoing hadron (pion)} = \frac{E_h}{\nu} = \frac{\sqrt{m^2_\pi + p^2_\pi}}{\nu} \]

Assumptions:

=> Factorization

=> Hadronization

\[ u \Rightarrow \pi^+ \]
\[ d \Rightarrow \pi^- \]
Experiments overview

• HMS spectrometer detects electrons at scattering angles from 13 to 49 degrees, momenta from 1 to 6 GeV. Twenty-eight distinct settings: each divided into two \((x,Q^2)\) bins. Solid angle 4 msr.

• SHMS detects particles on opposite side of the beam line. At angles from 6 to 30 degrees, momenta from 2 to 7 GeV.

• Beam energy mostly 10.6 GeV, beam currents 2 to 70 \(\mu\)A

• Targets are 10 cm liquid hydrogen and deuterium, and “dummy’ to measure aluminum endcap contributions.

• Trigger was time coincidence between two spectrometers. Typical rate about 3000 Hz.

• Only one hadron per event (unlike open detectors such as CLAS)
Kinematic coverage in \((x,Q^2)\)

Solid circles are from pt-SIDIS, open circles CSV SIDIS

CLAS coverage extends to lower \(x\) and lower \(Q^2\)

each circle has 10,000 to 1,000,000 events

Dominated by valance quark distributions

![Graph showing kinematic coverage in \((x,Q^2)\)]
Kinematic coverage in $P_t$ and $\phi$

Typica $pt$-SIDIS setting at $z=0.5$

Typica CSV-SIDIS setting at $z=0.5$
Data Analysis Tasks Completed (more or less)

- Determination of beam energy and position
- Calibration of beam current monitors and target boiling corr.
- Computer and electronic dead time correction
- Debugging and improvements to tracking code
- Corrections for multiple trigger signals
- Calibration of spectrometer optics for $-18<d<38\%$ in SHMS
- Modifications to SIMC for better matching of data and simulation (shms_hut.f and hms_hut.f in particular)
- Calibration of all spectrometer detectors, including “hole” in heavy gas detector.
- Determination of pair-symmetric background ($<1\%$)
- Optimization of PID for pions, kaons, and protons
- Improved models of exclusive pion and $\pi\Delta$ for rad. Corr.
- New model of diffractive rho contributions to cross sections.
Binning
For each of 56 \((x, Q^2)\) settings
With separate files for \(\pi, K\)

- 6 target/polity bins (p+, d+, Al+, p-, d-, Al-)
- 20 bins in \(z\) from 0.1 to 1 (bin 1 for excl. bin 2 for Delta)
- 15 bins in phi from 0 to 360 degrees
- 16 bins in \(P_t\) from 0 to 1 GeV

For each bin:
- Pions, kaons, and protons
- Monte Carlo predicted rate for 4 processes

Typically 500 bins with >50 counts for pt-SIDIS, 100 for CSV-SIDIS, kLT
Bins used individually in global fitting
Study of exclusive pion missing mass distributions versus dp/p in SHMS. Conclusion, can use -16<dp/p<36% because peak position is stable and a factor of two larger width is not acceptable.
Status of pion SIDIS results

- Table with 21,000 cross section and multiplicity results for pion SIDIS pretty much finalized.
- The table includes both the subtractive and multiplicative radiative corrections used.
- The table includes one estimate of diffractive rho (DVM) contributions, which can be applied to the results by the user if desired.
- The results ideally will be incorporated into large global analyses by groups such as JAM, updated with new results from CLAS12, COMASS, R_SIDIS as they become available.
- Meanwhile, have begun interpretation using our data only.
Formalism from Anselmino et al.

\[
\frac{d^5 \sigma_{p \rightarrow hX}}{dx_B dQ^2 dz_h d^2P_T} \approx \sum_q \frac{2\pi \alpha^2 e_q^2}{Q^4} f_q(x_B) D^h_q(z_h) \left[ 1 + (1 - y)^2 \right]
- 4 \frac{(2 - y)\sqrt{1 - y} \langle k_\perp^2 \rangle z_h P_T}{\langle P_T^2 \rangle Q} \cos \phi_h \left[ \frac{1}{\pi \langle P_T^2 \rangle} e^{-P_T^2/\langle P_T^2 \rangle} \right],
\]

where \( \langle P_T^2 \rangle = \langle p_\perp^2 \rangle + z_h^2 \langle k_\perp^2 \rangle \). The term proportional to \( \cos \phi_h \) describes the Cahn effect [1].

By fitting the data [10] on unpolarized SIDIS we obtain the following values of the parameters: \( \langle k_\perp^2 \rangle = 0.25 \text{ (GeV/c)}^2 \), \( \langle p_\perp^2 \rangle = 0.20 \text{ (GeV/c)}^2 \). The results are shown in Fig. 1.

- Cahn effect predicts \( \cos(\phi) \) term proportional to \( \langle k_t \rangle \) of quarks
- Gaussian width has constant term from fragmentation plus quadric term in \( \langle k_t \rangle \)
Typical examples of $\cos(\phi)$ term

- Solid line is from Anselmino paper. With about 500 MeV quark width. Our results instead consistent with very small quark $k_t$ width (<100 MeV).
- Confirms small $\cos(\phi)$ seen at HERMES and CLAS, but with order of magnitude smaller error bars.
- COMPASS found that diffractive rho contribution has huge impact: effect on results under study use HEPGEN code.
Gaussian widths versus transverse momentum

- From simultaneous fit of cos(\(\phi\)) term linear in \(P_T\) and cos(2\(\phi\)) term quadratic in \(P_T\), and \(P_T\)-slope to cross section.
- Solid lines are from Anselmino fit to EMC/Fermilab data
- Our results are somewhat similar, but don’t clearly show predicted constant plus quadratic \(z\)-dependence.
- Not much difference between \(p\), \(d\) targets, \(\pi^+\) or \(\pi^-\).
- Diffractive rho contributions (not considered in above figures) improve agreement with Anselmino fit, and furthermore \(\langle P_T \rangle\) for favored and unfavored fragmentation consistent with being the same.
To-do list

• Figure out why inclusive DIS fits F1F2IN09 and F1F2IN21 differ by about 5% in most of our kinematic range for deuteron.
• Compare DVM correction from Dave Gaskell with newer model from COMPASS as implemented in HEPGEN generator.
• Figure out why cross sections for HMS yptar<0 and yptar>0 differ by about 4%.
• Improve the radiative corrections for the kaon and proton SIDIS results by iterating on global fits to results.
• because pt-SIDIS and CSV have low statistical accuracy.
• Finalize extraction of R at high z from KLT data for pi+ and K+.