Transverse Target Moments of SIDIS Vector Meson Production at HERMES

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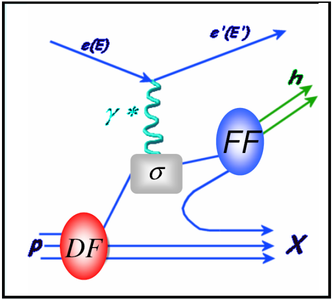
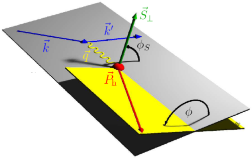
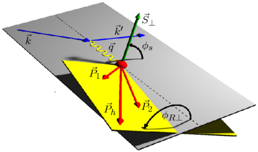
Motivation & Background

SIDIS Meson Production



- SIDIS cross section can be written $\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$
- Access integrals of DFs and FFs through azimuthal asymmetries in ϕ_h, ϕ_S, ϕ_R





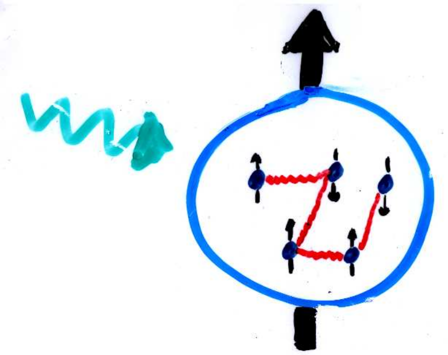
Distribution Functions (DF)

		quark		
		U	L	T
nucleon	U	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

Fragmentation Functions (FF)

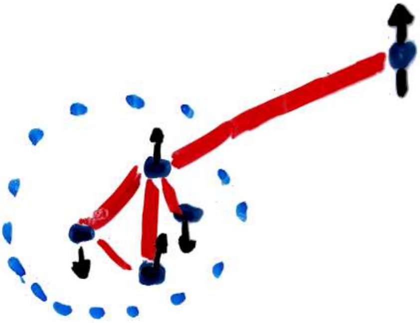
quark		
U	L	T
D_1	$G_1^\perp$	$H_1^\perp$

Lund/Artru String Fragmentation Model
Step 1:



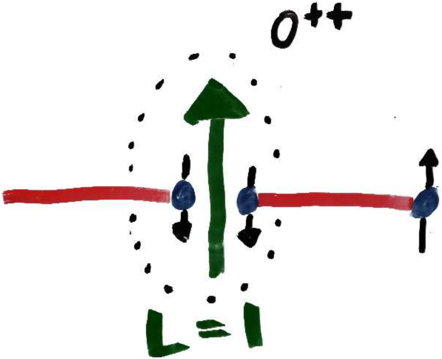
Virtual photon about to strike transversely polarized quark within the nucleus.

Lund/Artru String Fragmentation Model
Step 2:



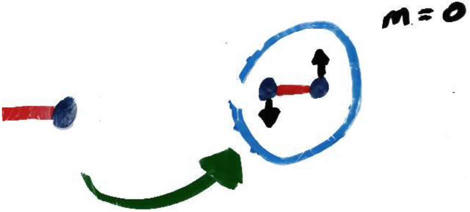
Struck quark separates from remnant
but is still connected via gluon flux tube (string).

Lund/Artru String Fragmentation Model
Step 3:



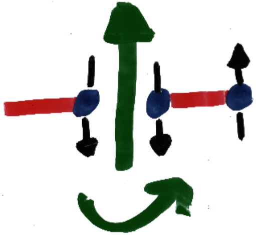
Eventually flux tube breaks, such that produced $q\bar{q}$ system has the quantum numbers of the vacuum.

Lund/Artru String Fragmentation Model
Step 4:

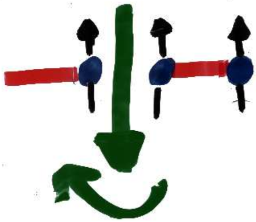


Angular momentum causes the produced meson to prefer moving into the page (i.e. to the left with respect to the quark polarization).

Lund/Artru Model and Spin States



Pseudo-scalar $|0,0\rangle$ and vector mesons w/ $|1,0\rangle$ both prefer "quark left"



Vector mesons w/ $|1,\pm 1\rangle$ prefer "quark right"

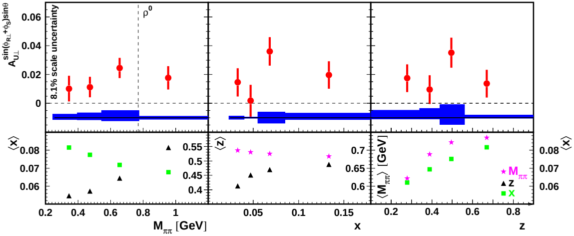
Collins function changes sign!

Published Results

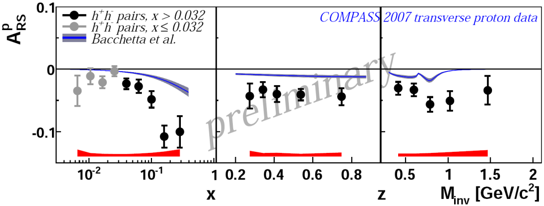
- Single Hadrons
  - Sivers Moments, e.g. *Phys. Rev. Lett.* 103 (2009)
  - Collins Moments, e.g. *Phys. Lett.* B 693 (2010)
  - Other A_{UT} Moments
    - See tomorrow's talk by Markus Diefenthaler.
  - Unpolarized Moments
    - See tomorrow's talk by Francesca Giordano.
  - Many more publications, presentations, regarding other polarization combinations as well as results from other experiments.
    - Many of which will also be presented at this conference.
- Vector Mesons & Hadron Pairs (Dihadrons)
  - One collinear A_{UT} Moment
    - Measured at HERMES and also at COMPASS

Di-hadron Results

HERMES



COMPASS



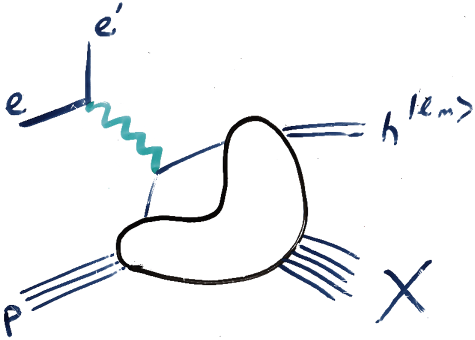
- Measure asymmetry $2\,\langle \sin(\phi_{R\perp} + \phi_S)\sin\theta\rangle$ in π^+, π^- pair production
- Related to *sp* interference FF $H_{1,UT}^{\sphericalangle sp}$ and transversity
- Model based on HERMES results by Bacchetta, *et al.* (PRD 74:114007, 2006)
- Prediction for COMPASS results yields too small of an asymmetry (arXiv:0907.0961v1)
- Both experiments indicate non-zero $H_{1,UT}^{\sphericalangle sp}$ and non-zero transversity function

SIDIS Dihadron Program at HERMES

- Improvements, Goals, and Hopes
  - Sub-leading twist analysis (though not all moments are suitable for release).
  - Use ϕ_R not $\phi_{R\perp}$.
  - Apply acceptance correction.
  - Attempt background subtraction to separate vector mesons from hadron pairs.
  - Preform transverse momentum dependent (TMD), i.e. non-collinear, analysis
    - 15 leading twist (24 sub-leading) transverse target moments rather than 3.
    - 27 leading twist (54 sub-leading) transverse target moments rather than 2.
  - Measure 8 vector mesons/hadron pairs, rather than just $\pi^+\pi^-$
- Needed items, not previously available
  - Non-collinear cross section at sub-leading twist.
  - Non-collinear SIDIS Monte Carlo generator.
  - Non-collinear fragmentation models.

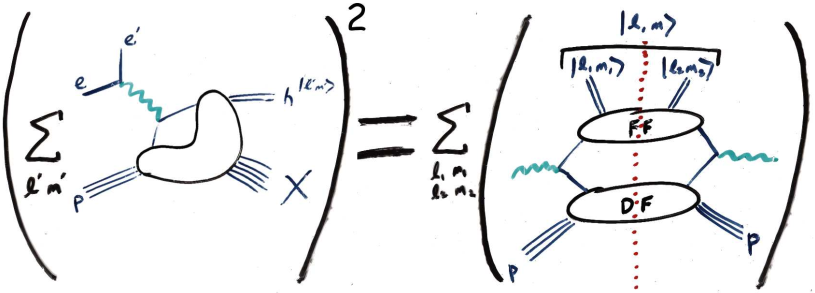
Non-Collinear Cross Section

Amplitude Level Diagram



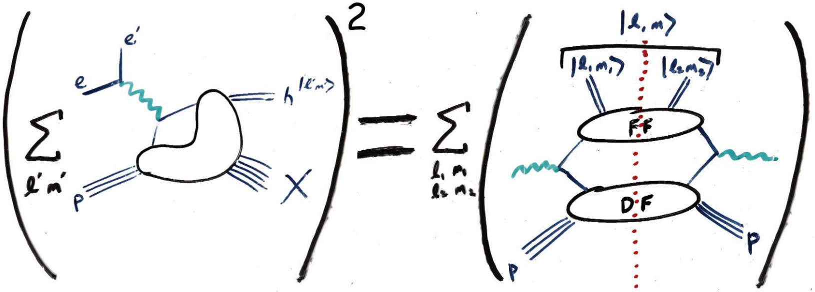
- At the amplitude level, we expect the $|l, m\rangle$ of the produced meson to tell us when the Collins signs match or flip.
- But life is more complicated…

Optical Theorem



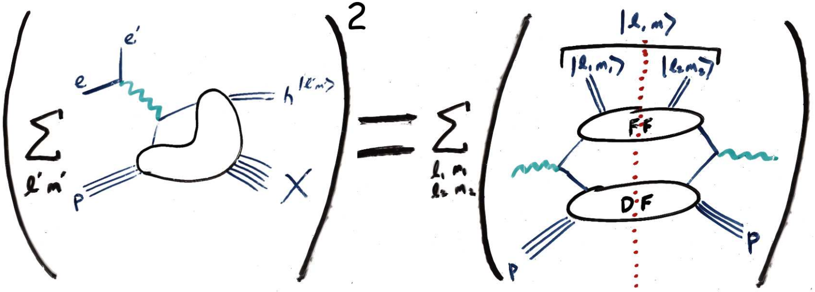
- Amplitudes of different $|l', m'\rangle$ are summed before amplitude is squared.
- Analog two-dihadron amplitude includes sum the states of both dihadrons.
- Note: cross sections and physical quantities usually prefer direct-sum over direct-product bases.
  - E.g., physical meson states are basis elements $|0,0\rangle$ and $|1,0\rangle$, not basis elements $|\frac{1}{2},\frac{1}{2}\rangle|\frac{1}{2},-\frac{1}{2}\rangle$, $|\frac{1}{2},-\frac{1}{2}\rangle|\frac{1}{2},\frac{1}{2}\rangle$.

Old Partial Wave Expansion



- Such as in *Phys. Rev.* D 67:9 (2003)
- Initially expand $\cos\vartheta$ dependence of fragmentation functions in Legendre Polynomials
- Write out cross section
- Write partial wave expansion in $|l_1, m_1\rangle|l_2, m_2\rangle$ basis via traces of products of 8×8 and 16×16 matrices.

New Partial Wave Expansion



- Initially have no expansion of fragmentation functions
  - Each fragmentation function depends on Q^2, z, $|k_T|$, M_h, $\cos\vartheta$, $(\phi_R - \phi_k)$.
  - Cross section for dihadron production has identical form to single hadron production, since both are the cross sections for producing a single system.
- Expand in $|l, m\rangle$ basis via spherical harmonics $Y_l^m(\cos\vartheta)e^{im(\phi_R - \phi_k)}$.
- Details in HERMES Internal Note 10-003
  - Publically available via `http://hermes.desy.de/`.

Comparison of Expansions

- Note: only the interpretation of the cross section terms changed—identical Fourier/Legendre moments in both cases.
- New expansion motivates the Legendre polynomial expansion of the older method.
- The quantities $H_{1,UT}^{\sphericalangle sp}$, $H_{1,TT}^{\sphericalangle pp}$ are understood as just additional partial waves of the same Collins function.
- Each term in the cross section can be directly interpreted as a specific partial wave—no need for complicated traces of matrices.
- Relation between basis expansions related to Clebsch-Gordan coefficients.
- Since before the expansion dihadron and single hadron cross sections are the same, any single hadron cross section computation has direct (and obvious) analog for dihadrons:
- Specifically, the twist-3, non-collinear, dihadron cross section can be directly computed from the single hadron cross section!

Unpolarized Cross Section at Twist 3

- Can write in terms of structure functions

$$
\begin{aligned}
&\frac{2\pi x y Q^2}{\alpha^2 M_h P_{h\perp}} \left(1 + \frac{\gamma^2}{2x}\right)^{-1} d^9\sigma_{UU} = \\
&\quad A(x,y)\Big[F_{UU,T} + \cos\vartheta F_{UU,T}^{\cos\vartheta} + P_2(\vartheta) F_{UU,T}^{P_2(\vartheta)} + \sin\vartheta\cos(\phi_h - \phi_R) F_{UU,T}^{\sin\vartheta\cos(\phi_h-\phi_R)} \\
&\qquad + \sin 2\vartheta \cos(\phi_h - \phi_R) F_{UU,T}^{\sin 2\vartheta\cos(\phi_h-\phi_R)} + \sin^2\vartheta\cos(2\phi_h - 2\phi_R) F_{UU,T}^{\sin^2\vartheta\cos(2\phi_h-2\phi_R)}\Big] \\
&\quad + B(x,y)\Big[\cos 2\phi_h F_{UU}^{\cos 2\phi_h} + \cos\vartheta\cos 2\phi_h F_{UU}^{\cos\vartheta\cos 2\phi_h} + P_2(\vartheta)\cos 2\phi_h F_{UU}^{P_2(\vartheta)\cos 2\phi_h} \\
&\qquad + \sin\vartheta\cos(\phi_h + \phi_R) F_{UU}^{\sin\vartheta\cos(\phi_h+\phi_R)} + \sin 2\vartheta\cos(\phi_h + \phi_R) F_{UU}^{\sin 2\vartheta\cos(\phi_h+\phi_R)} \\
&\qquad + \sin^2\vartheta\cos 2\phi_R F_{UU}^{\sin^2\vartheta\cos 2\phi_R} + \sin\vartheta\cos(3\phi_h - \phi_R) F_{UU}^{\sin\vartheta\cos(3\phi_h-\phi_R)} \\
&\qquad + \sin 2\vartheta\cos(3\phi_h - \phi_R) F_{UU}^{\sin 2\vartheta\cos(3\phi_h-\phi_R)} + \sin^2\vartheta\cos(4\phi_h - 2\phi_R) F_{UU}^{\sin^2\vartheta\cos(4\phi_h-2\phi_R)}\Big], \\
&\quad + V(x,y)\Big[\cos\phi_h F_{UU}^{\cos\phi_h} + \cos\vartheta\cos\phi_h F_{UU}^{\cos\vartheta\cos\phi_h} + P_2(\vartheta)\cos\phi_h F_{UU}^{P_2(\vartheta)\cos\phi_h} \\
&\qquad + \sin\vartheta\cos(2\phi_h - \phi_R) F_{UU}^{\sin\vartheta\cos(2\phi_h-\phi_R)} + \sin 2\vartheta\cos(2\phi_h - \phi_R) F_{UU}^{\sin 2\vartheta\cos(2\phi_h-\phi_R)} \\
&\qquad + \sin^2\vartheta\cos(3\phi_h - 2\phi_R) F_{UU}^{\sin^2\vartheta\cos(3\phi_h-2\phi_R)} + \sin\vartheta\cos\phi_R F_{UU}^{\sin\vartheta\cos\phi_R} \\
&\qquad + \sin 2\vartheta\cos\phi_R F_{UU}^{\sin 2\vartheta\cos\phi_R} + \sin^2\vartheta\cos(\phi_h - 2\phi_R) F_{UU}^{\sin^2\vartheta\cos(\phi_h-2\phi_R)}\Big].
\end{aligned} \tag{1}
$$

Transverse Target Moments at Twist 2

$$
\begin{aligned}
\left(\frac{1}{S_T}\right)\frac{2\pi xyQ^2}{\alpha^2 M_h P_{h\perp}}\left(1+\frac{\gamma^2}{2x}\right)^{-1} d^9\sigma_{UT} = A(x,y)\Big[&\sin(\phi_h-\phi_S)F_{UT,T}^{\sin(\phi_h-\phi_S)} + \sin\vartheta\,\sin(2\phi_h-\phi_R-\phi_S)F_{UT,T}^{\sin\vartheta\,\sin(2\phi_h-\phi_R-\phi_S)} \\
&+\cos\vartheta\,\sin(\phi_h-\phi_S)F_{UT,T}^{\cos\vartheta\,\sin(\phi_h-\phi_S)} + \sin\vartheta\,\sin(\phi_R-\phi_S)F_{UT,T}^{\sin\vartheta\,\sin(\phi_R-\phi_S)} \\
&+\sin^2\vartheta\,\sin(3\phi_h-2\phi_R-\phi_S)F_{UT,T}^{\sin^2\vartheta\,\sin(3\phi_h-2\phi_R-\phi_S)} + \sin 2\vartheta\,\sin(2\phi_h-\phi_R-\phi_S)F_{UT,T}^{\sin 2\vartheta\,\sin(2\phi_h-\phi_R-\phi_S)} \\
&+P_{2,0}(\vartheta)\,\sin(\phi_h-\phi_S)F_{UT,T}^{P_{2,0}(\vartheta)\,\sin(\phi_h-\phi_S)} + \sin 2\vartheta\,\sin(\phi_R-\phi_S)F_{UT,T}^{\sin 2\vartheta\,\sin(\phi_R-\phi_S)} \\
&+\sin^2\vartheta\,\sin(\phi_h-2\phi_R+\phi_S)F_{UT,T}^{\sin^2\vartheta\,\sin(\phi_h-2\phi_R+\phi_S)}\Big] \\
+B(x,y)\Big[&\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)} + \sin\vartheta\,\sin(2\phi_h-\phi_R+\phi_S)F_{UT}^{\sin\vartheta\,\sin(2\phi_h-\phi_R+\phi_S)} \\
&+\cos\vartheta\,\sin(\phi_h+\phi_S)F_{UT}^{\cos\vartheta\,\sin(\phi_h+\phi_S)} + \sin\vartheta\,\sin(\phi_R+\phi_S)F_{UT}^{\sin\vartheta\,\sin(\phi_R+\phi_S)} \\
&+\sin^2\vartheta\,\sin(3\phi_h-2\phi_R+\phi_S)F_{UT}^{\sin^2\vartheta\,\sin(3\phi_h-2\phi_R+\phi_S)} + \sin 2\vartheta\,\sin(2\phi_h-\phi_R+\phi_S)F_{UT}^{\sin 2\vartheta\,\sin(2\phi_h-\phi_R+\phi_S)} \\
&+P_{2,0}(\vartheta)\,\sin(\phi_h+\phi_S)F_{UT}^{P_{2,0}(\vartheta)\,\sin(\phi_h+\phi_S)} + \sin 2\vartheta\,\sin(\phi_R+\phi_S)F_{UT}^{\sin 2\vartheta\,\sin(\phi_R+\phi_S)} \\
&+\sin^2\vartheta\,\sin(\phi_h-2\phi_R+\phi_S)F_{UT}^{\sin^2\vartheta\,\sin(\phi_h-2\phi_R+\phi_S)} + \sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&+\sin(4\phi_h-\phi_R-\phi_S)F_{UT}^{\sin(4\phi_h-\phi_R-\phi_S)} + \sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&+\sin(2\phi_h+\phi_R-\phi_S)F_{UT}^{\sin(2\phi_h+\phi_R-\phi_S)} + \sin(5\phi_h-2\phi_R-\phi_S)F_{UT}^{\sin(5\phi_h-2\phi_R-\phi_S)} \\
&+\sin(4\phi_h-\phi_R-\phi_S)F_{UT}^{\sin(4\phi_h-\phi_R-\phi_S)} + \sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&+\sin(2\phi_h+\phi_R-\phi_S)F_{UT}^{\sin(2\phi_h+\phi_R-\phi_S)} + \sin(\phi_h-2\phi_R-\phi_S)F_{UT}^{\sin(\phi_h-2\phi_R-\phi_S)}\Big]. \qquad (2)
\end{aligned}
$$

Interpretation of Collins Structure Functions

$$F_{UT}^{\sin(\phi_h+\phi_S)} = -\mathcal{I}\left[\frac{|\boldsymbol{p}_T|}{M}\cos(\phi_h-\phi_k)h_1 H_1^{\perp\,|0,0\rangle}\right], \quad (3)$$

$$F_{UT}^{\sin\vartheta\,\sin(2\phi_h-\phi_R+\phi_S)} = -\mathcal{I}\left[\frac{|\boldsymbol{p}_T|}{M}\cos(2\phi_h-2\phi_k)h_1 H_1^{\perp\,|1,-1\rangle}\right], \quad (4)$$

$$F_{UT}^{\cos\vartheta\,\sin(\phi_h+\phi_S)} = -\mathcal{I}\left[\frac{|\boldsymbol{p}_T|}{M}\cos(\phi_h-\phi_k)h_1 H_1^{\perp\,|1,0\rangle}\right], \quad (5)$$

$$F_{UT}^{\sin\vartheta\,\sin(\phi_R+\phi_S)} = -\mathcal{I}\left[\frac{|\boldsymbol{p}_T|}{2M}h_1 H_1^{\perp\,|1,1\rangle}\right], \quad (6)$$

$$F_{UT}^{\sin^2\vartheta\,\sin(3\phi_h-2\phi_R+\phi_S)} = -\mathcal{I}\left[3\frac{|\boldsymbol{p}_T|}{M}\cos(3\phi_h-3\phi_k)h_1 H_1^{\perp\,|2,-2\rangle}\right], \quad (7)$$

$$F_{UT}^{\sin 2\vartheta\,\sin(2\phi_h-\phi_R+\phi_S)} = -\mathcal{I}\left[\frac{3}{2}\frac{|\boldsymbol{p}_T|}{M}\cos(2\phi_h-2\phi_k)h_1 H_1^{\perp\,|2,-1\rangle}\right], \quad (8)$$

$$F_{UT}^{P_{2,0}(\vartheta)\,\sin(\phi_h+\phi_S)} = -\mathcal{I}\left[\frac{|\boldsymbol{p}_T|}{M}\cos(\phi_h-\phi_p)h_1 H_1^{\perp\,|2,0\rangle}\right], \quad (9)$$

$$F_{UT}^{\sin 2\vartheta\,\sin(\phi_R+\phi_S)} = -\mathcal{I}\left[\frac{3}{2}\frac{|\boldsymbol{p}_T|}{2M}h_1 H_1^{\perp\,|2,1\rangle}\right], \quad (10)$$

$$F_{UT}^{\sin^2\vartheta\,\sin(\phi_h-2\phi_R-\phi_S)} = \mathcal{I}\left[3\frac{|\boldsymbol{p}_T|}{M}\cos(\phi_h-\phi_k)h_1 H_1^{\perp\,|2,2\rangle}\right]. \quad (11)$$

- All structure functions have azimuthal dependence of the form

$$\sin((1-m)\phi_h + m\phi_R + \phi_S).$$

- Those which survive in collinear case $\left(H_1^{\sphericalangle}\right)$ are those with $m=1$.

Monte Carlo & Models

New GMC_Trans Generator

- Generates events according to SIDIS cross section.
  - Both single hadrons and dihadrons
- Each event has specific $|\boldsymbol{p}_T|$, ϕ_p, $|\boldsymbol{k}_T|$, ϕ_k values
  - I.e. it is a full transverse momentum dependent generator.
- Designed to allow great flexibility in selecting the models for distribution and fragmentation functions.
- Inheritance structure and object oriented design allows for future growth:
  - Additional particles
  - Additional models for distribution & fragmentation functions.
  - Higher twist and/or other polarization combinations.
  - Output to additional database structures for IO, for use with other experiments.
- Code is independent of HERMES software structure
- Program is in final debugging stage.

Non-Collinear Spectator Model

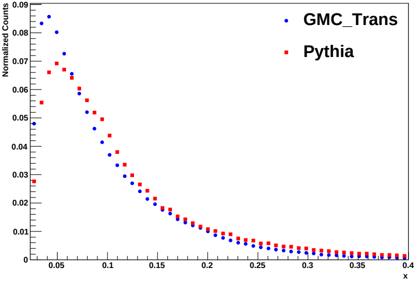
- Based on Bacchetta/Radici spectator model for collinear dihadron production *Phys. Rev.* D74 (2006)
  - The SIDIS X is replaced with a single, on-shell, spin-0 particle of mass $M_s \propto M_h$.
  - Assume one spectator for hadron pairs and vector mesons.
  - The leading twist fragmentation correlation matrix can then be computed from the tree level diagram.
  - Integration over transverse momenta is preformed before extracting fragmentation functions.
- One can use the same correlator to extract non-collinear fragmentation functions
  - One just needs to not integrate and follow the Dirac-matrix algebra and partial wave expansion.
- Model intended for $\pi^+\pi^-$ pairs, but generalizes to $\pi^+\pi^0$, $\pi^-\pi^0$ pairs.
- Slight change to vertex function allows generalization to K^+K^- pairs.
- Mixed mass pairs (πK) require non-trivial extensions.
- Unfortunately, the model only includes partial waves of the Collins function for $l < 2$.

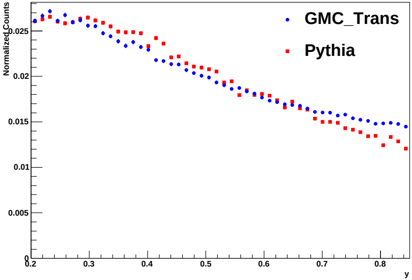
Parameter Settings

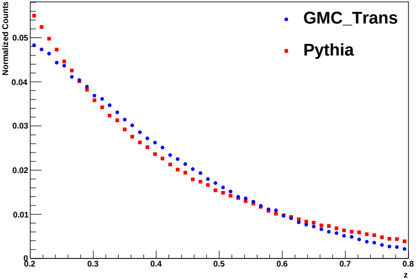
- For f_1: Use CTEQ 6 for f_1, multiplied by an exponential cutoff in $|\boldsymbol{p}_T|^2$, (i.e. Gaussian ansatz)
- For D_1: Use the non-collinear spectator model described on last slide
- Consider just $\pi^+\pi^-$, ρ^0, ω production
- Alternate parameter settings are used for non-collinear case
  - Otherwise $P_{h\perp}$ distribution is unreasonable.
- Consider the domain

$$\begin{aligned} &Q^2 > 1, && 0.2 < z < 0.8, \\ &W^2 > 4, && 0.05 < P_{h\perp} < 1.6, \\ &0.023 < x < 0.4, && M_h < 1.6. \\ &0.2 < y < 0.85, && \end{aligned}$$

Kinematic Distributions, p.1

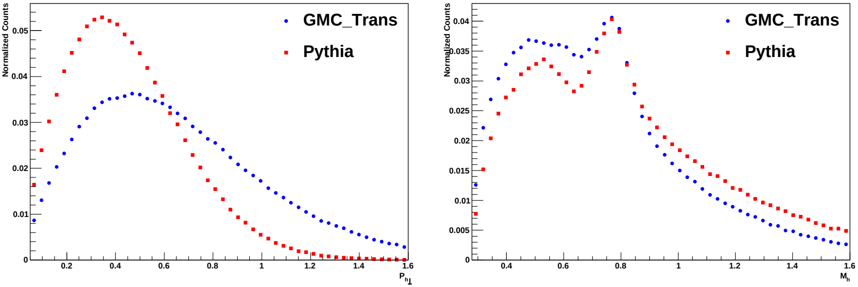






- Close agreement for x, y, z distributions.
- Main discrepancy in x distribution—due to either the f_1 distribution model, or a subtle effect of improper Q^2 scaling.

Kinematic Distributions, p.2



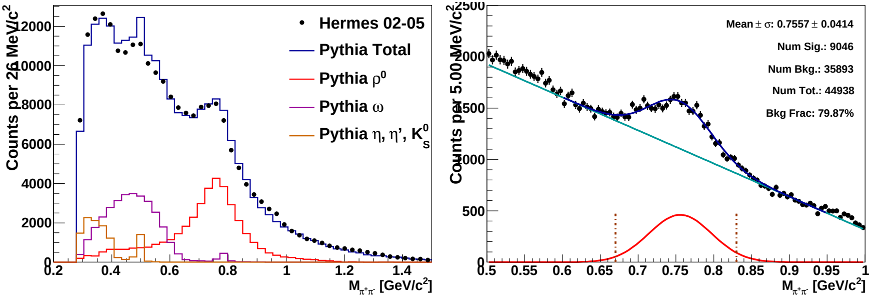
- Difficultly matching both $P_{h\perp}$ and M_h distributions.
- On-shell spectator condition yields

$$k^2 = \frac{z}{1-z}|\boldsymbol{k}_T|^2 + \frac{M_s^2}{1-z} + \frac{M_h^2}{z}.$$

- Exponential cutoff in k^2 cuts off both M_h and $P_{h\perp}$ distributions at high values.

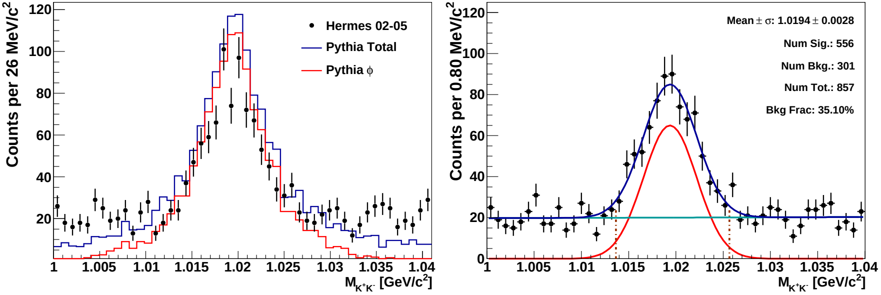
HERMES Analysis

Mass Distribution: ρ^0



- Left panel: comparison with Pythia, highlighting various process decaying into $\pi^+\pi^-$ pair.
- Right panel: Hermes 02-04 data, fit to Breit-Wigner plus linear background to estimate background fraction.
- High background fraction, but hope only VMs in *pp*-wave.

Mass Distribution: ϕ



- Lower signal, but much lower background fraction.
- No other mesons decaying into K^+K^- within mass window.
- Interest in Sivers function $f_{1T}^{\perp}$ for ϕ-meson, as related to angular momentum of gluons.

Extraction Method & Systematics

- Use maximum likelihood estimation to preform fit within each kinematic bin.
- Exact number of unpolarized and polarized terms to be included is not yet determined.
- Acceptance correction:
  - Use `GMC_Trans` to generate kinematic distribution, but flat in angles
  - Run `GMC_Trans` "no angular dependence" data through acceptance
  - Make Kernel Density Estimation (KDE) over angles within each kinematic bin
    - This is now an estimate of the effective acceptance function integrated over the bin.
  - Weight each data point by 1/KDE.
- Smearing effects and effectiveness of acceptance correction to be tested via "PEPSI Challenge"
  - Generate data using Pythia with RadGen & place through acceptance
  - Weight using angular portion of cross section via `GMC_Trans` or KDE of data.
  - Compare weighting 4π vs. acceptance + smearing.
- Linear extrapolate moments in mass sidebands to estimate background under VM peak, then perform background subtraction.

Conclusion & Outlook

Conclusion & Outlook

- Non-collinear SIDIS Dihadron production is a complex, yet fruitful area.
- Major background items to the analysis have been completed
  - Non-collinear cross section at twist 3 has been computed using new partial wave expansion.
  - New TMD SIDIS Generator (`GMC_Trans`) has been developed.
  - Model calculation of non-collinear fragmentation functions has been computed.
- Systematic studies are in progress for transverse target moments, starting with ρ^0, $\rho^\pm$, and ϕ-mesons.
- Expect preliminary results to be released this winter.