Transverse Target Moments of SIDIS Vector Meson Production at HERMES

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Outline

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- Lund/Artru Model and the Collins Function

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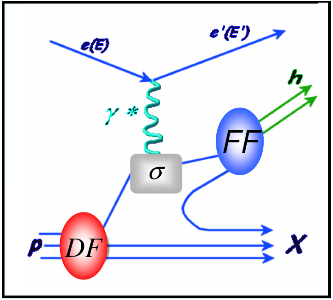
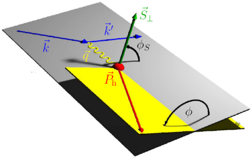
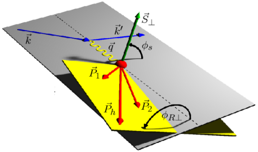
Motivation & Background

SIDIS Meson Production



- SIDIS cross section can be written $\sigma^{ep\rightarrow ehX} = \sum_q DF \otimes \sigma^{eq\rightarrow eq} \otimes FF$
- 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 - $h_{1T}^\perp$ -

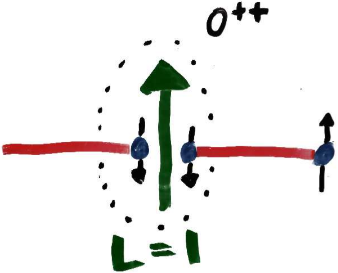
Fragmentation Functions (FF)

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

Why Vector Mesons & Hadron Pairs?

- Many results (and CLAS12 proposals) on pions and kaons
- Vector mesons access all the same distribution functions with different fragmentation functions
- Dihadrons (vector mesons and hadron pairs) provide complimentary measurements for distribution functions
- Flavor mixing slightly different for pseudo-scalar and vector mesons
- ϕ-meson provides unique access to strange quark distribution functions
  - No other final state accesses strange quark distribution functions as cleanly!
  - Strange quark Sivers function yields information on gluon orbital angular momentum.
- Also interesting physics in the fragmentation functions.

Lund/Artru String Fragmentation Model



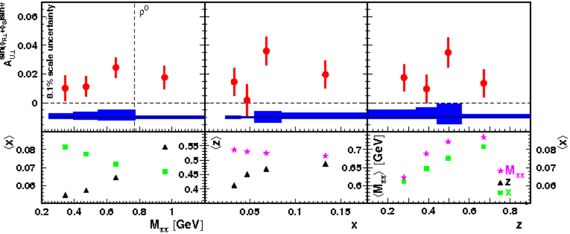
- Consider a gluon flux tube between the struck quark and the remnant.
- Assume the flux tube breaks into a $q\bar{q}$ pair with quantum numbers equal to the vacuum.

- Produced mesons overlapping with $|\frac{1}{2}, \frac{1}{2}\rangle|\frac{1}{2}, -\frac{1}{2}\rangle$ and $|\frac{1}{2}, \frac{1}{2}\rangle|\frac{1}{2}, -\frac{1}{2}\rangle$ states prefer "quark left".
  - $|0, 0\rangle =$ pseudo-scalar mesons.
  - $|1, 0\rangle =$ longitudinally polarized vector mesons.
- Produced mesons overlapping with $|\frac{1}{2}, \frac{1}{2}\rangle|\frac{1}{2}, \frac{1}{2}\rangle$ and $|\frac{1}{2}, -\frac{1}{2}\rangle|\frac{1}{2}, -\frac{1}{2}\rangle$ states prefer "quark right".
  - $|1, \pm 1\rangle =$ transversely polarized vector mesons.
- For each charge, "the Collins function" for π and ρ_L should have opposite sign to "the Collins function" for the two ρ_T.

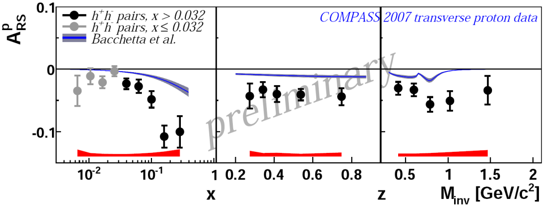
Previous Results & Planned Improvements

Dihadron Results

HERMES



COMPASS



- Measure asymmetry $2\left\langle \sin(\phi_{R\perp} + \phi_S) \sin\theta \right\rangle$ in $\pi^+\pi^-$ pair production
- Collinear access to transversity via IFF $H_{1,UT}^{\sphericalangle sp}$
- 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

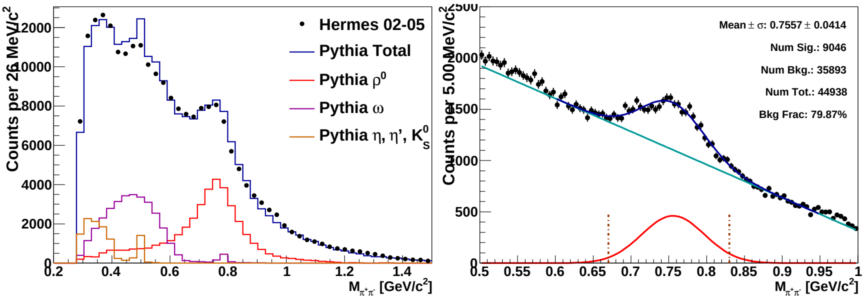
Possible Sources of Discrepancy

- One possible source of discrepancy could be the Q^2 dependence of $\phi_{R\perp}$
  - More natural cross section variable is ϕ_R
  - $(\phi_R - \phi_{R\perp})$ is Q^2 suppressed
  - Effectively reduces resolution, and thus reduces measured moments.
- Another possible source is $\cos\vartheta$ treatment
  - Compass integrates over $\cos\vartheta$
  - Hermes anti-symmetries in $\cos\vartheta$
  - Yet cross section is differential with respect to $\cos\vartheta$
    - The moment of interest should vanish in 4π with integration over $\cos\vartheta$.
    - Integration over $\cos\vartheta$ introduces machine-dependent bias.
- May be other causes as well, but cannot tell until resolve above items.
- Warning for all experiments
  - Momentum acceptance & cuts significantly affect $\cos\vartheta$ distribution.
  - High $|\cos\vartheta|$ implies one high momentum and one low momentum decay particle
  - In order to compare results across experiments, need to not integrate over $\cos\vartheta$ but correct for $\cos\vartheta$ acceptance.
  - Important in both SIDIS and exclusive vector meson analysis

New SIDIS Dihadron Program at HERMES

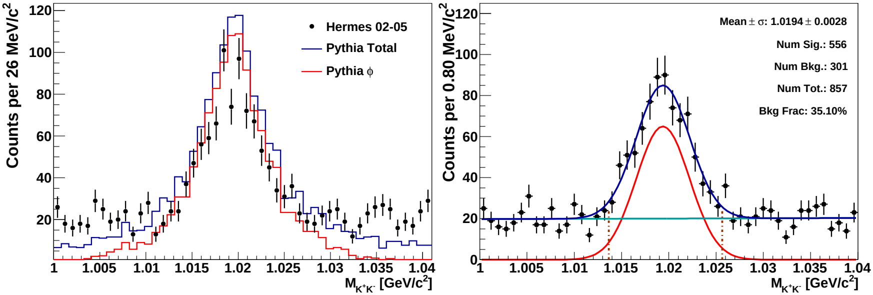
- Use $\cos\vartheta$ dependence and ϕ_R not $\phi_{R\perp}$.
- Apply acceptance correction.
- Transverse momentum dependent (i.e. non-collinear), sub-leading twist analysis
  - Number of unpol. moments: 15 (24 at Tw. 3), compared with pseudo-scalar mesons 2 (3 at Tw. 3).
  - Number of transverse target moments: 27 (54 at Tw. 3), compared with pseudo-scalars 3 (6 at Tw. 3).
  - Must determine which moments are suitable for release.
- Attempt background subtraction to separate vector mesons from hadron pairs.
- Measure at least 4 vector mesons/hadron pairs (ρ-triplet and ϕ).
  - Have data for K^*s (less background than ρ)
  - Theory regarding mixed mass pairs (πK) not as well developed.
    - No model for fragmentation functions.

Mass Distribution: $\rho^0(770)$



- Left panel: comparison with Pythia, highlighting various process decaying into $\pi^+\pi^-$ pair.
- Right panel: Hermes 02-05 data, fit to Breit-Wigner plus linear background.
- High background fraction, but hope only vector mesons in *pp*-wave.
- $\rho^\pm$ distributions effectively the same, but slightly lower statistics.

Mass Distribution: $\phi(1020)$



- Lower signal, but much lower background fraction.
- No other mesons decaying into K^+K^- within mass window.
- Clean access to strange quark distribution and fragmentation functions.

Needed Items, Not Previously Available

- Non-collinear SIDIS Monte Carlo generator at sub-leading twist.
  - Must simulate azimuthal dependence of cross section for systematic studies.
  - Cannot use polynomial fits to the data as was done for pseudo-scalar analysis.

- Generator requires
  - Non-collinear cross section at sub-leading twist.
  - Non-collinear fragmentation models.

- Would also like to understand "Which term in the cross section includes the 'the Collins function' for ρ_L, ρ_T?"
  - Use alternate partial wave expansion
  - Note: some theorists present could have answered this question without new expansion
  - Pursuit of the answer in this manner has led to something not previously computed by any theorist: the sub-leading twist, non-collinear dihadron cross section.

Monte Carlo & Models

New GMC_Trans Generator

- Method
  - Integrates cross section per flavor, yields quark branching ratios
  - Throw a flavor type according to branching ratios
  - Throw kinematic/angular variables by evaluating cross section
    - Can use weights or acceptance rejection
  - Full TMD simulation: each event has specific $|\boldsymbol{p}_T|$, ϕ_p, $|\boldsymbol{k}_T|$, ϕ_k values
  - Includes both pseudo-scalar and dihadron SIDIS cross sections
- Guiding plans
  - Extreme flexibility
    - Models for fragmentation and distribution functions
    - Various final states: pseudo-scalars, vector mesons, hadron pairs, etc.
    - Transverse momentum and flavor dependence
    - Output options & connecting to analysis chains of various experiments
    - Minimize dependencies on other libraries
  - Full flavor and transverse momentum dependence.
- Should prove a useful tool for both experimentalists and theorists to test models and machine response.

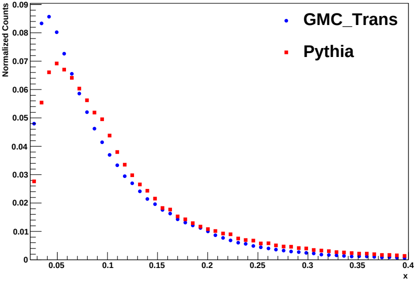
Collinear Spectator Model for Dihadron Fragmentation

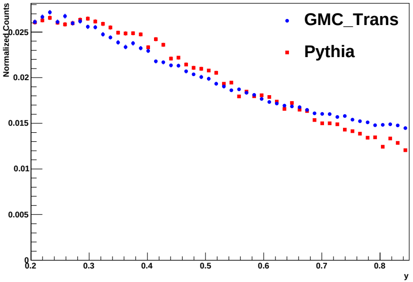
- Model developed by A. Bacchetta & M. Radici, *Phys. Rev.* D74 (2006)
- The SIDIS X is replaced with a single, on-shell, spin-0 particle of mass $M_s \propto M_h$.
- Assume one spectator for hadron pairs and vector mesons.
- The leading twist fragmentation correlation matrix can then be computed from the tree level diagram.
- Integration over transverse momenta is performed before extracting fragmentation functions.
- Includes $\pi^+\pi^-$ pairs, ρ^0, and ω (both two and three pion decays)
- Unfortunately, the model yields nonzero Collins function for only three partial waves—no *pp* waves.

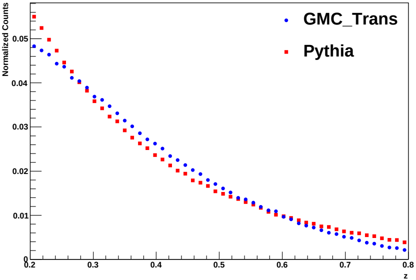
TMD Spectator Model for Dihadron Fragmentation

- Use same $\boldsymbol{k}_T$ dependent fragmentation correlation matrix as collinear case
- Extract fragmentation function without integrating over $\boldsymbol{k}_T$.
  - Requires reworking Dirac matrix algebra
- Generalized to other final states $\pi^\pm\pi^0$, $\rho^\pm$ and K^+K^-, ϕ
  - Slight modifications to p-wave vertex function
  - Must also allow several parameter sets, depending on flavor
- Note: only need up to three flavor parameter sets
  - $\pi^+\pi^-$: $u = -d = -\bar{u} = \bar{d}$, $s = \bar{s}$
  - $\pi^+\pi^0$: $u = \bar{d}$, $d = \bar{u}$, $s = \bar{s}$
  - K^+K^-: $u = \bar{u}$, $d = \bar{d}$, $s = \bar{s}$
- Need to include an extra z dependent $|\boldsymbol{k}_T|$ cutoff.
- Note: mixed mass pairs ($\pi K/K^*$) require more complicated extensions.

ρ^0 Kinematic Distributions, p.1

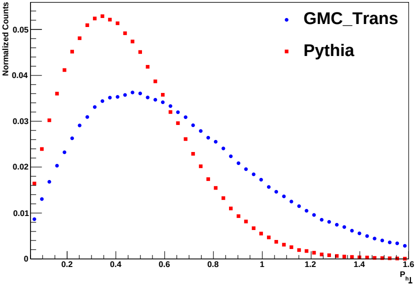


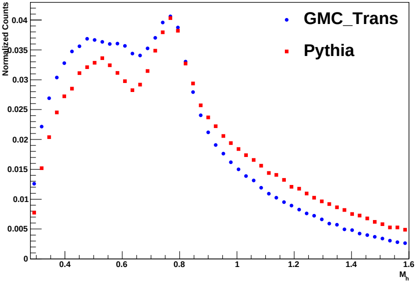




- Close agreement for x, y, z distributions.
- Main discrepancy in x distribution—most likely do to imbalance in the flavor contributions, or a subtle effects of Q^2 scaling.

ρ^0 Kinematic Distributions, p.2



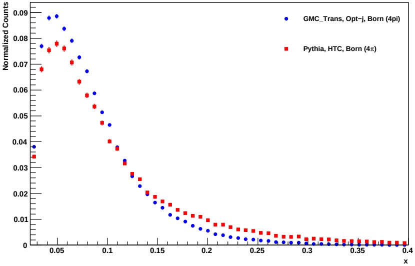


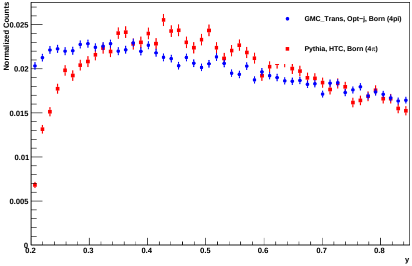
- Difficultly matching both $P_{h\perp}$ and M_h distributions.
- On-shell spectator condition yields

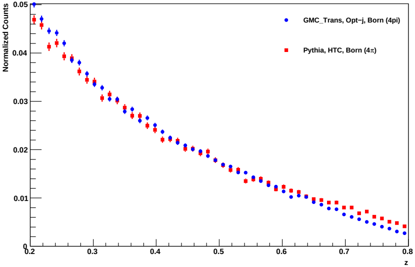
$$k^2 = \frac{z}{1-z}|\boldsymbol{k}_T|^2 + \frac{M_s^2}{1-z} + \frac{M_h^2}{z}.$$

- Exponential cutoff in k^2 cuts off both M_h and $P_{h\perp}$ distributions at high values.
- This motivates the extra $|k_T|^2$ cut off.

ϕ Kinematic Distributions: Scaling Variables



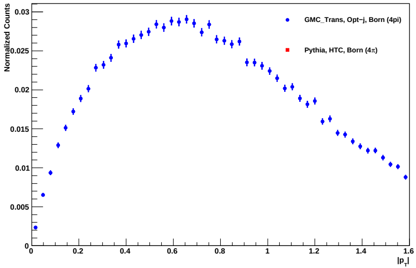




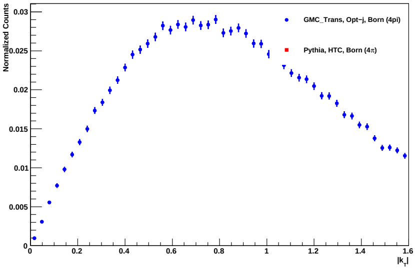
- Close agreement for x, y, z distributions.
- Further optimizing flavor balance can improve x & y distributions.

ϕ Kinematic Distributions, Intrinsic Momentum

Partonic Transverse Momentum $|\boldsymbol{p}_T|$

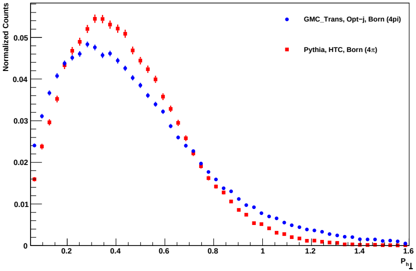


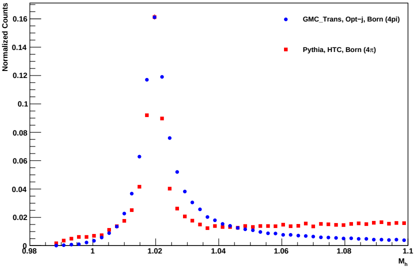
Fragmenting Quark Transverse Momentum $|\boldsymbol{p}_T|$



- Can plot model predictions for intrinsic momentum
  - Unique advantage of this generator.
- Given model requires $p_T \approx k_T$ in order to get narrow $P_{h\perp}$ peak.
- Also, model does not support any flavor dependence to k^2, $|\boldsymbol{k}_T|^2$ cut offs

ϕ Kinematic Distributions, Mass and $P_{h\perp}$

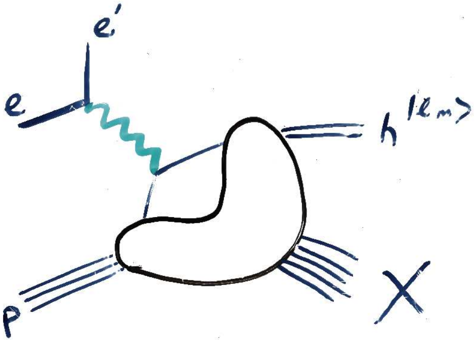




- Parameters optimized for $M_h < 1.05$.
- Includes $|\boldsymbol{k}_T|$ cutoff as well (not present in previous ρ^0 plots).
  - z dependence of both k_T and k^2 cutoffs identical
- Agreement is high and can yet be further optimized.
- The "commissioning" of Monte Carlo generator nearing completion.

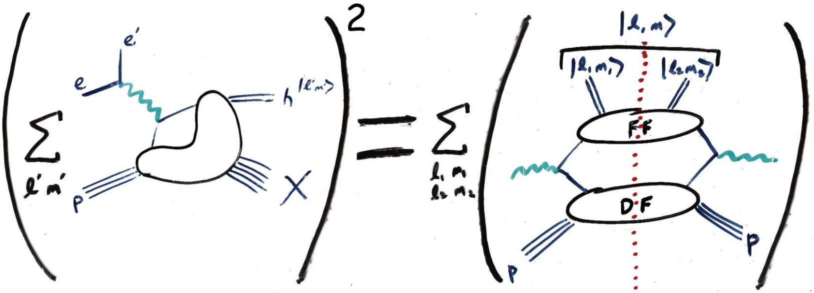
Non-Collinear Cross Section

Amplitude Level Diagram



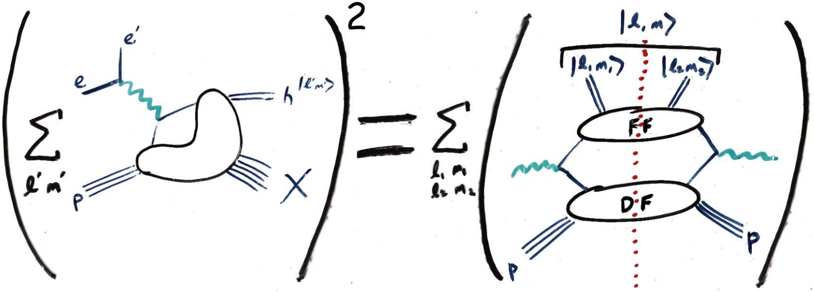
- At the amplitude level, we expect the $|l, m\rangle$ of the produced meson to tell us when the Collins signs match or flip.
- But life is more complicated...

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 $|\frac{1}{2},\frac{1}{2}\rangle|\frac{1}{2},-\frac{1}{2}\rangle$, $|\frac{1}{2},-\frac{1}{2}\rangle|\frac{1}{2},\frac{1}{2}\rangle$.
  - New expansion: in terms of the $|l,m\rangle$ state of the two Dihadron system.

Old Partial Wave Expansion



- Such as in Bacchetta & Radici, *Phys. Rev.* **D** 67(9):094002 (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.

Definitions

- Fragmentation correlation matrix

$$\Delta^{[\Gamma]}(z, M_h, |\boldsymbol{k}_T|, \cos\vartheta, \phi_R - \phi_k) = 4\pi \frac{z|\boldsymbol{R}|}{16 M_h} \int dk^+ \, \mathrm{Tr}\left[\Gamma \Delta(k, P_h, R)\right]\Big|_{k^- = P_h^-/z}.$$

- Define fragmentation functions via trace relations

FF	Pseudo-Scalar	Dihadron, other	Dihadron, Gliske
D_1	$\Delta^{[\gamma^-]}$	$\Delta^{[\gamma^-]}$	$\Delta^{[\gamma^-(1+i\gamma^5)]}$
$G_1^\perp$	$--$	$\propto \Delta^{[\gamma^-\gamma^5]}$	$--$
$H_1^\perp$	$\Delta^{[(\sigma^{1-})\gamma^5]}$	$\Delta^{[(\sigma^{1-})\gamma^5]}$	$\Delta^{[(\sigma^{1-}-i\sigma^{2-})\gamma^5]}$
$\bar{H}_1^{\sphericalangle}$	$--$	$\propto \Delta^{[(\sigma^{2-})\gamma^5]}$	$--$

- Real part of fragmentation function similar
- Gliske's definition of D_1 & $H_1^\perp$
  - Adds "imaginary" part to D_1 & $H_1^\perp$, instead of introducing new functions.
  - Are then complex valued and depends on Q^2, z, $|k_T|$, M_h, $\cos\vartheta$, $(\phi_R - \phi_k)$.
  - Can be denoted the completely unexpanded, unpolarized and Collins functions.

New Partial Wave Expansion

- Dihadron cross section using completely unexpanded fragmentation functions looks identical to pseudo-scalar meson cross section
  - And it should—both are the cross section for producing a single mesonic-system.
  - Further structure about the mesonic system is contained in the fragmentation functions.
- Can now expand D_1, $H_1^{\perp}$ in $|l, m\rangle$ basis of two-dihadron system
  - Simple spherical harmonic expansion $Y_l^m(\cos\vartheta)e^{im(\phi_R-\phi_k)}$.
- After expansion, cross section has identical form to dihadron cross section using previous methods.
- New method uniquely identifies each angular moment with a $|l, m\rangle$ partial wave of the two dihadron system.
- Details in HERMES Internal Note 10-003
  - Publicly available via `http://hermes.desy.de/`.

Unpolarized Cross Section

$$\frac{2\pi xyQ^2}{\alpha^2 M_h P_{h\perp}} \left(1 + \frac{\gamma^2}{2x}\right)^{-1} d^9\sigma_{UU} =$$

$$A(x,y)\left[\sum_{l=0}^{2}\sum_{m=0}^{l} P_l(\vartheta)\cos(m(\phi_h - \phi_R)) F_{UU,T}^{P_l(\vartheta)\cos(m(\phi_h-\phi_R))}\right]$$

$$+ B(x,y)\left[\sum_{l=0}^{2}\sum_{m=-l}^{l} P_l(\vartheta)\cos((2-m)\phi_h + m\phi_R) F_{UU}^{P_l(\vartheta)\cos((2-m)\phi_h+m\phi_R)}\right.$$

$$\left. + C(x,y)\left[\sum_{l=0}^{2}\sum_{m=-l}^{l} P_l(\vartheta)\cos((1-m)\phi_h + m\phi_R) F_{UU}^{P_l(\vartheta)\cos((1-m)\phi_h+m\phi_R)}\right.\right.$$

- At leading twist contains same terms as previously found in the literature.
- Setting $m = 0$ reduces to the terms in the pseudo-scalar cross section.

$$d^6\sigma_{UU} \propto A(x,y) F_{UU,T} + B(x,y)\cos\phi_h F_{UU}^{\cos\phi_h} + C(x,y)\cos\phi_h F_{UU}^{\cos\phi_h}.$$

Transverse Target Terms of the Cross Section

$$\left(\frac{1}{S_T}\right)\frac{2\pi xyQ^2}{\alpha^2 M_h P_{h\perp}}\left(1+\frac{\gamma^2}{2x}\right)^{-1} d^9\sigma_{UT} = \Big[\sum_{l=0}^{2}\sum_{m=-l}^{l}$$

$$A(x,y)P_l(\cos\vartheta)\sin((1-m)\phi_h-\phi_S+m\phi_R)F_{UT,T}^{P_l(\cos\vartheta)\sin((1-m)\phi_h-\phi_S+m\phi_R)}$$

$$+B(x,y)P_l(\cos\vartheta)\sin((1-m)\phi_h+\phi_S+m\phi_R)F_{UT,T}^{P_l(\cos\vartheta)\sin((1-m)\phi_h+\phi_S+m\phi_R)}$$

$$+B(x,y)P_l(\cos\vartheta)\sin((3+m)\phi_h-\phi_S+m\phi_R)F_{UT,T}^{P_l(\cos\vartheta)\sin((3+m)\phi_h-\phi_S+m\phi_R)}$$

$$+V(x,y)P_l(\cos\vartheta)\sin(m\phi_h+\phi_S+m\phi_R)F_{UT,T}^{P_l(\cos\vartheta)\sin(m\phi_h+\phi_S+m\phi_R)}$$

$$+V(x,y)P_l(\cos\vartheta)\sin((2+m)\phi_h-\phi_S+m\phi_R)F_{UT,T}^{P_l(\cos\vartheta)\sin((2+m)\phi_h-\phi_S+m\phi_R)}.$$

- Again, terms in the cross section agree with published results
- Again, setting $m=0$ reduces to the terms in the pseudo-scalar cross section.
- Note: the terms surviving $P_{h\perp}$ integration depend on the moment and on m.

New Partial Wave Expansion: Summary

- Utilizes similarities between pseudo-scalar & dihadron cross sections
  - Can compute dihadron cross section from pseudo-scalar cross section, at any twist
- One symbol for each experimentally accessible fragmentation function.
- No clean access to "The Collins function" for long. vector mesons
  - Is included in $H_1^{|2,0\rangle}$, but mixed with *TT* interference.
    - $|2,0\rangle \in \text{Span}\{|1,0\rangle|1,0\rangle,\ \ |1,1\rangle|1,-1\rangle\} + \text{ h.c.}$
- There does exist "the Collins function" for trans. vector mesons: $H_1^{|2,\pm 2\rangle}$.
  - $|2,\pm 2\rangle = |1,\pm 1\rangle$
  - Requires assuming no tensor mesons
    - Could have *ds* interference also mixed in.
- The previously analyzed $H_{1UT}^{\sphericalangle sp} = H_1^{|1,1\rangle}$ is not pure *sp* interference
  - $|1,1\rangle \in \text{Span}\{|1,1\rangle|0,0\rangle,\ \ |1,1\rangle|1,0\rangle\} + \text{ h.c.}$
  - Includes also *LT pp* interference.
- Process leading to $H_1^{\sphericalangle}$ is understood.
- Collins fragmentation function takes trans. polarized quark and produces any polarized final state.

Conclusion & Outlook

Conclusion & Outlook

- Non-collinear SIDIS Dihadron production provides unique access to
  - Strange quark distribution and fragmentation
  - Testing the Lund/Artru model
- Future analysis need to use ϕ_R rather than $\phi_{R\perp}$ and include $\cos\vartheta$ dependence.
- New partial wave expansion
  - Alternate view greatly simplifies complexity
  - Easier to find "the Collins function" for vector mesons.
  - But is also powerful computational tool.
- All 18 TMD dihadron fragmentation functions are important
  - Hope e^+e^- machines extract all 18, not just 2 of the 5 collinear.
- Cross section for dihadrons can be directly computed from pseudo-scalar cross section, at any twist
- New Monte Carlo Generator is excellent testing ground for flavor and transverse momentum dependent distribution and fragmentation functions.

Backup Slides

Relation with Previous Notation

- Comparing with similar trace definitions, e.g. PRD 67:094002 yields the relations

$$D_1\Big|_{Gliske} = \left[D_1 + i\frac{|\boldsymbol{R}||\boldsymbol{k}_T|}{M_h^2}\sin\vartheta\sin(\phi_R-\phi_k)\,G_1^\perp\right]_{other}, \tag{1}$$

$$H_1^\perp\Big|_{Gliske} = \left[H_1^\perp + \frac{|\boldsymbol{R}|}{|\boldsymbol{k}_T|}\sin\vartheta e^{i(\phi_R-\phi_k)}\,\bar{H}_1^{\sphericalangle}\right]_{other} = \frac{|\boldsymbol{R}|^2}{|\boldsymbol{k}_T|^2}H_1^{\sphericalangle}\Big|_{other}. \tag{2}$$

- Inconsistencies in the literature between definitions of $H_1^{\sphericalangle}, \bar{H}_1^{\sphericalangle}, H_1'^{\sphericalangle}$.

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.