Polarized Fragmentation Function Measurements at BABAR

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Outline

INTRODUCTION
• Theoretical framework
  • Collins effect in di-hadron correlations
  • Reference frames
• PEP-II and the BaBar detector at SLAC

ANALYSIS OVERVIEW
• Analysis method
• Extraction of the asymmetry for light quarks
• Asymmetry corrections and studies of systematic uncertainty

RESULTS
• Asymmetries vs. fractional energies, hadron transverse momentum, and analysis axis polar angle

CONCLUSIONS
Results reported in PRD90, 052003 (2014) and ArXiv:1506.05864 (Submitted to Phys. Rev. Lett.)
Collins Fragmentation Function

Fragmentation Functions (FFs)
- dimensionless and universal functions
- non-perturbative information
- describe the final state particles in hard processes
- dependence on $z = 2E_h / \sqrt{s}$, $P_\perp$, and $s_q$

Unpolarized FF

$$D_{q}^{1\uparrow}(z, P_{\perp}; s_q) = D_{1}^{q}(z, P_{\perp}) + \frac{P_{\perp}}{zM_h} H_{1}^{\perp q}(z, P_{\perp}) s_q \cdot (k_q \times P_{\perp})$$
Collins Fragmentation Function

**Fragmentation Functions (FFs)**

- Dimensionless and universal functions
- Non-perturbative information
- Describe the final state particles in hard processes
- Dependence on $z = 2E_h / \sqrt{s}$, $P_\perp$, and $s_q$

Mathematical expression:

$$D_1^{q\uparrow}(z, P_\perp; s_q) = D_1^{q}(z, P_\perp) + \frac{P_\perp}{zM_h} H_1^{\perp q}(z, P_\perp) s_q \cdot (k_q \times P_\perp)$$

- Could arise from a spin-orbit coupling
- Leads to asymmetry in the angular distribution of final state particles (Collins Effect)

- $H_1^{\perp}$ is the *polarized* fragmentation function or Collins FF, describing the fragmentation of a transversely polarized quark into a spinless (or unpolarized) hadron $h$
- **Chiral-odd** function, ideal to access the chiral-odd parton distribution functions in Semi-Inclusive Deep Inelastic Scattering (SIDIS)
Collins Effect

**SIDIS**
- Unpolarized lepton beam ($l$) off transversely polarized target ($N$) $lN \rightarrow l'\pi X$
- non-zero Collins effects
- spin direction known ($S$)
- $\sigma \propto \sin(\phi_h + \phi_s) h_1(x_B) \otimes H_1^\perp(z_1)$
- two chiral-odd functions
- azimuthal Single Spin Asymmetry

**e^+e^- annihilation**
- $\gamma^*$ (spin-1) goes to spin-1/2 $q$ and $\bar{q}$
  - in a given event, the spin directions are unknown, but they must be parallel
  - they have a polarization component transverse to the $q$ direction
- exploit this correlation by using hadrons in opposite jets
  
  $e^+e^- \rightarrow q\bar{q} \rightarrow h_1h_2X \quad (q = u,d,s)$

  $\sigma \propto \cos(\phi_i) H_1^\perp(z_1) \otimes H_1^\perp(z_2)$

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Polarized FF at BABAR – Brown, DPF15
Extracting Collins FF from data

Perform a **Global Analysis**, simultaneously determining $H_1^\perp$ and the transversity parton distribution function.

Anselmino et al., PRD 75, 054032, NP Proc.Suppl. 191, 98

**BABAR** study offers:
- Large number of energy intervals
- Asymmetry as a function of hadron transverse momentum

$A \propto H_1^\perp(z_1) \otimes H_1^\perp(z_2)$
Collins Effect in $e^+e^-$ Annihilation

$$e^+e^- \rightarrow q\bar{q} \rightarrow h_1^+h_2^\pm X \quad (q = u,d,s \ h = \pi,K)$$

- Experimentally, we see Like (L) or Unlike (U) sign pairs of charged hadrons
  - Can’t unambiguously assign hadron to specific quark
- Introduce notion of favored and disfavored fragmentation functions
  - **Favored**: the parent quark matches a valence quark in the hadron
  - **Disfavored**: no such match $u \rightarrow \pi^-, d \rightarrow \pi^+, s \rightarrow \pi^\pm$, etc

**Unlike-sign pion pair = U:**
$$\pi^+\pi^\pm: (\text{fav x fav}) + (\text{dis x dis})$$

**Like-sign pion pair = L:**
$$\pi^\pm\pi^\pm: (\text{fav x dis}) + (\text{dis x fav})$$

**Charged pion pair = C (U+L):**
$$\pi\pi: (\text{fav + dis}) \times (\text{fav + dis})$$

Graphics: thanks I. Garzia
Collins Effect with Kaons

• Collins effect not previously measured with Kaons
  – Provides direct access to the favored contribution to the Collins Fragmentation Function for the strange quark
Analysis Reference Frame (RF)

[See NPB 806, 23 (2009)]

**RF12 or Thrust RF**
- **Thrust axis** to estimate the q̅q direction
- \( \phi_{1,2} \) defined using thrust-beam plane
- Modulation diluted by gluon radiation, detector acceptance,…

\[
\sigma \sim 1 + \frac{\sin^2 \theta_{th}}{1 + \cos^2 \theta_{th}} \cos(\phi_1 + \phi_2) \frac{H_1^\perp (z_1) H_1^\perp (z_2)}{D_1(z_1) D_1(z_2)}
\]

**RF0 or Second hadron momentum RF**
- Alternatively, just use **one track** in a pair
- Very clean experimentally (no thrust axis), less theoretically
- Gives quark direction for higher pion momentum

\[
\sigma \sim 1 + \frac{\sin^2 \theta_2}{1 + \cos^2 \theta_2} \cos(2\phi_0) \mathcal{F} \left[ \frac{H_1^\perp (z_1) H_1^\perp (z_2)}{D_1(z_1) D_1(z_2)} \right]
\]
The **BABAR** Experiment at SLAC

- Asymmetric-energy beams for boost
- Modern/state of the art detector
- 5 cylindrical subdetectors with a 40-layer drift chamber
- Excellent electromagnetic calorimetry
- Multiple measurements for particle identification
- Excellent momentum resolution

- Primarily designed for study of $CP$-violation in $B$ meson decays
- Quality and general-purpose design make it suitable for a large variety of studies

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The **BABAR** Running Era

7 Runs over the course of 9 years

- First collisions with BaBar May 26, 1999
- Final data taken 12:43 p.m., April 7, 2008

This analysis uses 468 fb⁻¹ of data

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### BaBar

**Run 1-7**

- PEP II Delivered Luminosity: 553.34/fb
- BaBar Recorded Luminosity: 531.32/fb
- BaBar Recorded Y(4s): 432.89/fb
- BaBar Recorded Y(3s): 30.23/fb
- BaBar Recorded Y(2s): 14.45/fb
- Off Peak Luminosity: 53.74/fb

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**Graph Details**

- **Y(2S)**
- **Y(3S)**
- **Delivered Luminosity**
- **Recorded Luminosity**
- **Recorded Luminosity Y(4S)**
- **Recorded Luminosity Y(3S)**
- **Recorded Luminosity Y(2S)**
- **Off Peak**

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**As of 2008/04/07 00:00**

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**Notes**

- Polarized FF at BABAR – Brown, DPF15
- 2015 Aug 6
Analysis Strategy

- **Goal:** simultaneous measurement of KK, K\(\pi\), and \(\pi\pi\) pairs
  - Event and track selection
  - we identify the three sample of hadron pairs (KK, K\(\pi\), \(\pi\pi\)), and we divide the two hadrons in opposite jets using the thrust axis
  - we measure the azimuthal angles \(\phi_1\) and \(\phi_2\) in RF12, and \(\phi_0\) in RF0
  - we construct the normalized raw distributions for like (L), Unlike (U) and Charged (C=U+L) hadron pairs: \(R^i=N^i(\phi)/\langle N\rangle\)
  - we calculate the ratios of normalized distributions: U/L and U/C and we fit these distributions
  - we extract the Collins asymmetries and we correct for the K/\(\pi\) misidentification, background contributions,…
  - we study systematic effects

**RESULTS:** \(4x4\ (z_1,z_2)\) bins, where \(z_{1,2}=2E_h/\sqrt{s}\) is the hadron fractional energy

- \(z_{1,2} = (0.15-0.2), (0.2-0.3), (0.3-0.5), (0.5-0.9)\)
- RF12 and RF0
- \(A^{UL}\) and \(A^{UC}\)

Thanks to I. Garzia
Event Selection

• Select Hadronic Events:
  – Number of charged tracks > 2
  – Visible energy ($E_{\text{vis}}$) > 11 GeV
  – Veto events with $\mu^\pm$ or $e^\pm$
  – Remove events in the $\tau^+\tau^-$ region

• Refine Event Selection
  – Select two-jet events by requiring thrust > 0.8
  – Hadrons close to thrust axis: $|\cos \theta_{\text{thrust}}| < 0.6$
  – Most energetic photon in event has $E_\gamma < 2$ GeV

DATA: $E_{\text{vis}}$ vs thrust

Bhabha and mu-pair events

$\tau^+\tau^-$ region
Particle Selection

• Select hadrons
  – Charged tracks well-identified via combined ionization and Cerenkov radiation measurements
  – Charged tracks in region of highest detector acceptance: $0.41 < \theta_{lab} < 2.54$ rad
  – hadron fractional energies: $0.15 < z = 2E_h / \sqrt{s} < 0.9$

Use particle ID tuned for high hadron efficiency across all lab momenta (typically 95+%)
With minimimal misidentification of electrons (< 2%) and muons (<4%)
Raw Asymmetries

- **Collins asymmetry**
  - consider all the U and L pion pairs
  - make histograms of $\phi_\alpha = \phi_1 + \phi_2$ or $2\phi_0$ ($\alpha=12,0$)
  - normalize by the average:

  $R_\alpha = \frac{N(\phi_\alpha)}{<N_\alpha>} = a + b \cdot \cos(\phi_\alpha)$

  Proportional to the product (convolution) of the two Collins functions

- **The MC generator (JETSET) does not include the Collins effect, but it shows a strong cosine modulation**
  - due to acceptance of the detector
  - depends strongly on the thrust axis polar angle
  - but similar distribution for U and L pairs

- **Data shows a large difference between U and L distributions**, that can be ascribed to the Collins effect
Double Ratios

\[ \frac{R^U_{\alpha}}{R^L(C)} = \frac{N^U(\phi_\alpha)/ <N^U(\phi_\alpha)>}{N^L(C)(\phi_\alpha)/ <N^L(C)(\phi_\alpha)>} \rightarrow B^{UL}_{\alpha}(UC) + A^{UL}_{\alpha}(UC) \cdot \cos(\phi_\alpha) \]


\[
\begin{align*}
\text{MC: consistent with a flat distribution} \\
\text{DATA: cosine modulation clearly visible} \\
A: \text{contains only the Collins effect and higher order radiative effects}
\end{align*}
\]

Acceptance effects can be reduced by performing the ratio of Unlike/Like sign pion pairs (or Unlike/Charged)
- small deviation from zero still present (\(\ll\) asymmetry measured in data sample)
Raw and Ratio Data for KK

See the same trends in data for KK as for ππ (both current and previous analyses)
Asymmetry dilution – thrust axis

Thrust axis reconstruction is not perfectly aligned with $q\bar{q}$ axis. Introduces dilution of asymmetry in RF12. Correct through MC study.
Extracting uds asymmetry

- In each bin, the data sample includes pairs from
  - signal uds events
  - BB events (small, mostly at low z)
  - cc events (important at low/medium z)
  - \(\tau^+\tau^-\) events (important at high z)

- We measure:

\[
A_{\alpha}^{meas} = (1 - \sum_i F_i) \cdot A_{\alpha} + \sum_i F_i \cdot A_{\alpha}^i
\]

Fraction of pion pairs due to the \(i^{th}\) background process

- We must calculate these quantities:
  - \(F_i\) using MC sample; we assign MC-data difference in each bin as systematic error
  - \(A^{BB}\) must be zero; we set \(A^{BB} = 0\)
  - \(A^\tau\) small in simulation; checked in data; we set \(A^\tau = 0\)
Extracting uds Asymmetry 2

- Charm background contribution is about 30% on average
  - Both fragmentation processes and weak decays can introduce azimuthal asymmetries
  - We used a D^{*±}-enhanced control sample to estimate its effect on a bin-by-bin basis
  - 4 complementary decay modes D^{*±} \rightarrow D^0\pi^±, with D^0 \rightarrow K\pi, K3\pi, K\pi\pi^0, K_s\pi\pi
  - mostly c\bar{c} events, some B\bar{B}

- Again, f_i from MC, data-MC difference as systematic error

\[
A^{\text{meas}}_\alpha = (1 - F_c - F_B - F_\tau) \cdot A_\alpha + F_c \cdot A^{\text{ch}}_\alpha
\]

\[
A^D_{\alpha} = f_c \cdot A^{\text{ch}}_\alpha + (1 - f_c - f_B) \cdot A_\alpha
\]

- the A^{\text{ch}} are very small (slightly negative?)
Results: $A_{12}$ vs $(z_1,z_2)$

- **Very significant nonzero $A^{UL}$ and $A^{UC}$**
  - $\Rightarrow$ strong dependence on $(z_1,z_2)$,
  - $A^{UC} < A^{UL}$ as expected; complementary information about the favored and disfavored fragmentation processes (PRD 73, 094025 (2006))
  - $\Rightarrow$ consistent with $z_1 \Leftrightarrow z_2$ symmetry
Results: $A_0$ vs $(z_1, z_2)$

- Very significant nonzero $A_{UL}$ and $A_{UC}$
  - $\Rightarrow$ strong dependence on $(z_1, z_2)$,
  - $\Rightarrow$ smaller than $A_{12}$;
  - $\Rightarrow A_{UC} < A_{UL}$; complementary information on $H_{\perp, \text{fav}}$ and $H_{\perp, \text{dis}}$
  - $\Rightarrow$ consistent with $z_1 \leftrightarrow z_2$ symmetry

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Summary & Conclusions

• *BABAR* continues producing interesting and competitive results.
  
• *BABAR* has measured Collins asymmetries for charged hadron pairs in two-jet events. Measurements are made in two different reference frames.
  
  • Asymmetries increase with increasing fractional energy for $\pi\pi$ and $K\pi$ but the same cannot be concluded for $KK$
  
  • Improves our understanding of quark fragmentation.
  
  • New results for $\pi\pi$ in study including $K$'s consistent with previous study using only pions
  
  • Results consistent with theoretical predictions (PLB659, 234 (2009); PRD86, 034025 (2012))

Results reported in PRD90, 052003 (2014) and ArXiv:1506.05864 (Submitted to Phys. Rev. Lett.)

Thank You!
Back Up Slides
Asymmetry binning and corrections

- The Collins effect is expected to depend on \( z_1, z_2, p_{t1}, p_{t2} \) (or \( p_{t0} \)), as well as \( \cos\theta_{th} \) (or \( \cos\theta_2 \))
  \[ \Rightarrow \text{analyze in bins of these quantities:} \]

  \[ \text{6x6 bins in } (z_1, z_2) \]

  \[ \text{4x4 bins in } (p_{t1}, p_{t2}) \ (9 \text{ in } p_{t0}) \]

After reconstruction, simulated data shows small asymmetry due to detector acceptance effects. Correct for this on a bin-by-bin basis

Systematic effect on MC value evaluated by varying track/event selections
Asymmetries vs. transverse momenta

- **nonzero $A_{UL}$ and $A_{UC}$**
  - only modest dependence on $(p_{t1}, p_{t2})$; disagreement with the expectation
  - $A_{UC} < A_{UL}$; complementary information on $H_{1\perp, fav}$ and $H_{1\perp, dis}$
  - $A_0 < A_{12}$, but interesting structure in $p_t$

**FIRST MEASUREMENT** of Collins asymmetries vs. $p_t$ in $e^+e^-$ annihilation at $Q^2 \sim 110$ (GeV/c)$^2$ (time-like region)
Results: Angular comparison

**RF12: thrust polar angle \( \theta_{th} \)**

\[ A_{12} \propto \frac{\sin^2 \theta_{th}}{1 + \cos^2 \theta_{th}} \cos(\phi_1 + \phi_2) \frac{H_1^+(z_1) \bar{H}_1^+(z_2)}{D_1(z_1)D_1(z_2)} \]

\[ \Rightarrow \text{Intercept consistent with zero, as expected (consistent with Belle results)} \]

**BABAR preliminary**

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**RF0: second-hadron polar angle \( \theta_2 \)**

\[ A_0 \propto \frac{\sin^2 \theta_2}{1 + \cos^2 \theta_2} \cos(2\phi_0) \mathcal{F} \left[ \frac{H_1^+(z_1) \bar{H}_1^+(z_2)}{D_1(z_1)D_1(z_2)} \right] \]

\[ \Rightarrow \text{The linear fit gives a non-zero constant parameter \( \rightarrow \) the second hadron momentum provides a worse estimation of the } q\bar{q} \text{ direction (consistent with Belle results)} \]