Chiral-odd fragmentation functions at Belle

(see hep-ex/0507063 for details, submitted to PRL)

Compass Seminar

March 20th, CERN

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Collins Effect in Quark Fragmentation


Collins Effect:
Fragmentation of a transversely polarized quark $q$ into spin-less hadron $h$ carries an azimuthal dependence:

$$\propto \left( \vec{k} \times \vec{p}_{h\perp} \right) \cdot \vec{s}_q$$

$$\propto \sin \phi$$

$\vec{k}$ : quark momentum
$\vec{s}_q$ : quark spin
$\vec{p}_h$ : hadron momentum
$\vec{p}_{h\perp}$ : transverse hadron momentum

$$z_h = \frac{E_h}{E_q}$$

$$= 2 \frac{E_h}{\sqrt{s}} : \text{relative hadron momentum}$$
A simple model to illustrate that spin-orbital angular momentum coupling can lead to left right asymmetries in spin-dependent fragmentation:

\[ \pi^+ \] picks up \( L=1 \) to compensate for the pair \( S=1 \) and is emitted to the right.

String breaks and a \( \bar{d}d \)-pair with spin \(-1\) is inserted.
SIDIS experiments (HERMES and COMPASS) measure $\delta q(x)$ together with either Collins Fragmentation function $H^\perp_i(z)$ or Interference Fragmentation function.

RHIC measures the same combinations of quark Distribution (DF) and Fragmentation Functions (FF) plus unpolarized DF $q(x)$.

There are always 2 unknown functions involved which cannot be measured independently.

Universality appears to be proven in LO by Collins and Metz: [PRL93:(2004)252001]

The Spin dependent Fragmentation function analysis yields information on the Collins and the Interference Fragmentation function!
KEKB:  $L > 1.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ !!

- Asymmetric collider
- $8\text{GeV} e^- + 3.5\text{GeV} e^+$
- $\sqrt{s} = 10.58\text{GeV} \ (\Upsilon(4S))$
- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B \bar{B}$
- Off-resonance: 10.52 GeV
- $e^+e^- \rightarrow q \bar{q} \ (u,d,s,c)$
- Integrated Luminosity: $>500 \text{ fb}^{-1}$
- $>45\text{fb}^{-1} \Rightarrow \text{off-resonance}$

Belle detector
Belle Detector

SC solenoid 1.5T
CsI(Tl) 16X₀
TOF counter
8GeV e⁻

3.5GeV e⁺
Aerogel Cherenkov cnt. n=1.015~1.030
Tracking + dE/dx
small cell + He/C₂H₅

Si vtx. det.
3 lyr. DSSD
μ / K₁ detection
14/15 lyr. RPC+Fe

Good tracking and particle identification!
Collins fragmentation in $e^+e^-$: Angles and Cross section $\cos(\phi_1 + \phi_2)$ method

$e^+e^-$ CMS frame:

$$ z = \frac{2E_h}{\sqrt{s}} , \quad \sqrt{s} = 10.52 \text{ GeV} $$

$2$-hadron inclusive transverse momentum dependent cross section:

$$ \frac{d\sigma(e^+e^- \rightarrow h_1h_2X)}{d\Omega dz_1dz_2d^2q_T} = \ldots B(y) \cos(\phi_1 + \phi_2)H_1^{[1]}(z_1)\overline{H_1^{[1]}(z_2)} $$

$$ B(y) = y(1-y) = \frac{1}{4} \sin^2 \Theta $$

Net (anti-)alignment of transverse quark spins

[D.Boer: PhD thesis(1998)]
Collins fragmentation in $e^+e^-$: Angles and Cross section $\cos(2\phi_0)$ method

$\Theta = \Theta \cdot \Theta$, $\phi_0$ 

$2$-hadron inclusive transverse momentum dependent cross section:

$$\frac{d\sigma(e^+e^- \rightarrow h_1 h_2 X)}{d\Omega dz_1 dz_2 d^2p_T} = \cdots B(y) \cos(2\phi_0) I\left[(2\hat{h} \cdot \hat{k} \cdot p_T - k_T \cdot p_T)H_1^+ H_1^- M_1 M_2\right]$$

$B(y) = y(1 - y)^{cm} = \frac{1}{4} \sin^2 \Theta$

• Independent of thrust-axis
• Convolution integral $I$ over transverse momenta involved

[Boer, Jakob, Mulders: NPB504(1997)345]
Applied cuts, binning

• Off-resonance data
  – 60 MeV below $\Upsilon(S)$ resonance
  – 29.1 fb$^{-1}$

• Track selection:
  – $p_T > 0.1$ GeV
  – vertex cut:
    dr<2cm, |dz|<4cm

• Acceptance cut
  – $-0.6 < \cos\theta_i < 0.9$

• Event selection:
  – $N_{\text{track}} \geq 3$
  – Thrust > 0.8
  – $Z_1, Z_2 > 0.2$

• Hemisphere cut
  $$(P_{h2} \cdot \hat{n}) \hat{n} \cdot (P_{h1} \cdot \hat{n}) \hat{n} < 0$$

• $Q_T < 3.5$ GeV

= Diagonal bins
Examples of fits to azimuthal asymmetries

\[ \frac{N(\phi)}{N_0} = \frac{aD_1D_1 + \cos(2\phi)(bH_1H_1 + cD_1D_1)}{aD_1D_1} = P_2 + P_1 \cos(2\phi) \]

\( D_1 \): spin averaged fragmentation function,  
\( H_1 \): Collins fragmentation function

Cosine modulations clearly visible

No change in cosine moments when including sine and higher harmonics (even though double ratios will contain them)
Raw asymmetries vs $Q_T$

- $Q_T$ describes transverse momentum of virtual photon in $\pi\pi$ CMS system.
- Significant nonzero Asymmetries visible in MC (w/o Collins).
- Acceptance, radiative and momentum correlation effects similar for like and unlike sign pairs.

$$\frac{dN}{d\Omega} \propto \sin^2 \theta \cos(2\phi_0) \frac{Q_T^2}{Q^2 + Q_T^2}$$

- uds MC ($\pi\pi$) Unlike sign pairs
- uds MC ($\pi\pi$) Like sign pairs
Methods to eliminate gluon contributions: Double ratios and subtractions

Double ratio method:

\[ R := \frac{N_{Un\text{like}}(\phi)}{N_{Like}(\phi)} \approx 1 + F \left( \frac{H_{1,\text{fav}}(z)}{D_{1}^{\text{fav}}(z)}, \frac{H_{1,\text{unfav}}(z)}{D_{1}^{\text{unfav}}(z)} \right) + \mathcal{O}\left(F(Q_T)^2\right) \]

Pros: Acceptance cancels out
Cons: Works only if effects are small (both gluon radiation and signal)

Subtraction method:

\[ S := \frac{N_{Un\text{like}}(\phi)}{N_{0}^{\text{Un\text{like}}}} - \frac{N_{Like}(\phi)}{N_{0}^{\text{Like}}} = F \left( \frac{H_{1,\text{fav}}(z)}{D_{1}^{\text{fav}}(z)}, \frac{H_{1,\text{unfav}}(z)}{D_{1}^{\text{unfav}}(z)} \right) \]

Pros: Gluon radiation cancels out exactly
Cons: Acceptance effects remain

2 methods give very small difference in the result

\[ F = \frac{\sin^2(\theta)}{1 + \cos^2(\theta)} \left[ \frac{\sum_q e^2(H_{\text{fav}} \cdot \bar{H}_{\text{fav}} + H_{\text{unf}} \cdot \bar{H}_{\text{unf}})}{\sum_q e^2(D_{\text{fav}} \cdot \bar{D}_{\text{fav}} + D_{\text{unf}} \cdot \bar{D}_{\text{unf}})} - \frac{\sum_q e^2(\bar{H}_{\text{fav}} \cdot H_{\text{unf}} + H_{\text{unf}} \cdot \bar{H}_{\text{fav}})}{\sum_q e^2(\bar{D}_{\text{fav}} \cdot D_{\text{unf}} + D_{\text{unf}} \cdot \bar{D}_{\text{fav}})} \right] \]
Testing the double ratios with MC

- Asymmetries do cancel out for MC
- Double ratios of $\pi^+\pi^+/\pi^-\pi^-$ compatible with zero
- Mixed events also show zero result
- Asymmetry reconstruction works well for $\tau$ MC (weak decays)
- Single hemisphere analysis yields zero

$\Rightarrow$ Double ratios are safe to use

<table>
<thead>
<tr>
<th></th>
<th>$\pi\pi$ uds</th>
<th>$\pi\pi$ charm</th>
<th>$\pi\pi$ mixed</th>
<th>$K\bar{K}$ mixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>constant</td>
<td>0.26%±0.19%</td>
<td>-0.45%±0.33%</td>
<td>0.06%±0.09%</td>
<td>0.01%±0.16%</td>
</tr>
<tr>
<td>reduced $\chi^2$</td>
<td>1.17</td>
<td>1.35</td>
<td>1.14</td>
<td>1.2</td>
</tr>
</tbody>
</table>

- uds MC ($\pi\pi$–pairs)
- charm MC ($\pi\pi$–pairs)
- Data ($\pi^+\pi^+/$ $\pi^-\pi^-$)
Small double ratios in low thrust data sample

- Low thrust contains radiative effects
- Collins effect vanishes
  ➔ Strong experimental indication that double ratio method works
Results for $e^+ e^- \rightarrow \pi \pi X$ for 29 fb$^{-1}$

- Significant non-zero asymmetries
- Rising behavior vs. $z$
- $\cos(\phi_1+\phi_2)$ double ratios only marginally larger
- First direct measurement of the Collins function
- Integrated results:
  - $\cos(2\phi_0)$ method
    $(3.06\pm0.65\pm0.55)\%$
  - $\cos(2\phi_1+\phi_2)$ method
    $(4.26\pm0.78\pm0.68)\%$

Systematic error
Contributions to systematic errors

Other uncertainties:
• smearing (reweighted MC)
• PID (variation of PID cuts)
• charm contribution (corrected by $D^{*}$ data sample)
• $\tau$ content (evaluated in $e^{+}e^{-} \rightarrow \tau^{+}\tau^{-}$ enhanced sample)
• Statistical correlations
• Thrust axis reconstruction
• Beam polarization tested

Systematic errors

MC double ratio
Charge sign ratio
Higher moments
Double ratio method
An experimentalist’s interpretation: fitting parameterizations of the Collins function(s)

- Take unpolarized parameterizations (Kretzer at $Q^2=2.5\text{GeV}^2$)
- Assume $H_1^{\perp,fav} = a \ z^b \ (1 - z)^c$
  (PDF-like behavior)
- Assume $H_1^{\perp,unfav}/H_1^{\perp,fav} = -0.1$
- Little sensitivity to to favored/disfavored Collins ratio
Favored/Disfavored contribution $\rightarrow$ Sensitivity

$$F = \frac{\sin^2(\theta)}{1 + \cos^2(\theta)} \left[ \frac{\sum_q e^2 (H_{Fav} \cdot H_{Fav}^\dagger + H_{Unf} \cdot H_{Unf}^\dagger)}{\sum_q e^2 (D_{Fav} \cdot D_{Fav}^\dagger + D_{Unf} \cdot D_{Unf}^\dagger)} - \frac{\sum_q e^2 (H_{Fav} \cdot H_{Unf}^\dagger + H_{Unf} \cdot H_{Fav}^\dagger)}{\sum_q e^2 (D_{Fav} \cdot D_{Unf}^\dagger + D_{Unf} \cdot D_{Fav}^\dagger)} \right]$$

Take simple parameterization to test sensitivity on favored to disfavored Ratio

$$H_{1,Fav} = b z D_{1,Fav}$$

$$H_{1,Unf} = c \cdot b z D_{1,Unf}$$
Other Favored/Unfavored Combinations $\rightarrow \pi^0$

Problem: current double ratios not very sensitive to favored to disfavored Collins function ratio ➔ Examine other combinations:

- **Unlike-sign pion pairs:**
  
  \[(\text{favored} \times \text{favored}) + \text{unfavored} \times \text{unfavored}\]

- **Like-sign pion pairs:**
  
  \[(\text{favored} \times \text{unfavored}) + \text{unfavored} \times \text{favored}\]

- **$\pi^\pm\pi^0$ pairs**
  
  \[(\text{favored} + \text{unfavored}) \times (\text{favored} + \text{unfavored})\]

- P. Schweitzer([hep-ph/0603054]): charged $\pi\pi$ pairs are similar (and are easier to handle):
  
  \[(\text{favored} + \text{unfavored}) \times (\text{favored} + \text{unfavored})\]

➔ Build new double ratios

- **Favored** = $u \rightarrow \pi^+, d \rightarrow \pi^-, cc.$
- **Unfavored** = $d \rightarrow \pi^+, u \rightarrow \pi^+, cc.$
Why is it possible to include on_resonance data?

Different Thrust distributions

\[
\text{thrust} = \frac{\sum_i |p_i \cdot \hat{n}|}{\sum_i |p_i|}
\]

- \(e^+ e^- \rightarrow q \bar{q}\) (q in uds) MC
- \(Y(4S) \rightarrow B^+ B^-\) MC
- \(Y(4S) \rightarrow B^0 \bar{B}^0\) MC
Interference Fragmentation – thrust method

- $e^+e^- \rightarrow (\pi^+\pi^-)_{\text{jet}1}(\pi^-\pi^+)_{\text{jet}2}X$
- Stay in the mass region around $\rho$-mass
- Find pion pairs in opposite hemispheres
- Observe angles $\phi_1 + \phi_2$
  between the event-plane (beam, jet-axis) and the two two-pion planes.
- Transverse momentum is integrated
  (universal function, evolution easy
  $\rightarrow$ directly applicable to semi-inclusive DIS
  and pp)
- Theoretical guidance by papers of Boer,Jakob,Radici and Artru,Collins

$$A \propto H_1^\leq(z_1, m_1) \overline{H}_1^\leq(z_2, m_2) \cos(\phi_1 + \phi_2)$$
Interference Fragmentation – "φ₀" method

- Similar to previous method
- Observe angles $\phi_{1R} + \phi_{2R}$ between the event-plane (beam, two-pion-axis) and the two pion planes.
- Theoretical guidance by Boer, Jakob, Radici

$$A \propto H_1^\zeta(z_1, m_1)\overline{H}_1^\zeta(z_2, m_2) \cos(\phi_{1R} + \phi_{2R})$$
Different model predictions for IFF

• Jaffe at al. [Phys. Rev. Lett. 80 (1998)]: inv. mass behavior out of $\pi\pi$-phaseshift analysis $\Rightarrow$ sign change at $\rho$-mass
  - originally no predictions on actual magnitudes
  - Tang included some for RHIC-Spin
Different model predictions for IFF

- Radici et al. [Phys. Rev. D65 (2002)]:
  Spectator model in the s-p channel
  no sign change observed (updated model has Breit-Wigner like asymmetry)

![Graph showing model predictions](image)

PRELIMINARY

- $f_1, h_1$ from spectator model
- $f_1, h_1 = g_1$ from GRV98 & GRSV96
What would we see?

Simply modeled the shapes of these predictions in an equidistant Mass1 x Mass2 binning.

“Jaffe”

“Radici”
What do we see? I: events

- Animation of an event
- **lepton tracks**, thrust axis and all particle momenta in the CMS frame
  - $P_{h1} = P_1 + P_2$
  - $P_{h2} = P_3 + P_4$
- Plane defined by leptons and thrust
- Planes defined by hadron pairs
Summary:

- Double ratios:
  - double ratios from data
  - most systematic errors cancel
- Analysis procedure passes all null tests
- Main systematic uncertainties understood
- Significant nonzero asymmetry with double ratios are observed
- Naive LO analysis shows significant Collins effect
- Data can be used for more sophisticated analysis
- Paper (hep-ex/0507063) is submitted

Outlook:

- On resonance $\rightarrow 10 \times$ statistics
- Include $\pi^0$ and all charged $\pi\pi$ pairs into analysis:
  - Better distinction between favored and disfavored Collins function
- Interference fragmentation function analysis started
  - First look promising
- Include Vector Mesons into analysis:
  - Possibility to test string fragmentation models used to describe Collins effect
- Timelike DVCS at Belle?
Outline

• Motivation
  – Study transverse spin effects in fragmentation
  – Global transversity analysis
  – Feasibility → LEP analysis
    [hep-ph/9901216]
• The BELLE detector
• Collins analysis
  – Angular definitions and cross sections
  – Double Ratios to eliminate radiative/momentum correlation effects
  – An experimentalist’s interpretation
• Summary
Offline+Online Luminosity (pb⁻¹) (day)

Belle log total: 457234 pb⁻¹

Date

Off-resonance, on-resonance, energy scan

Integrated Luminosity (pb⁻¹)

0 2000 4000 6000 8000 10000 12000 14000

Belle total: 457234 pb⁻¹

Date

Off-resonance, on-resonance, energy scan

Integrated Luminosity (pb⁻¹)

0 2000 4000 6000 8000 10000 12000 14000

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Off-resonance, on-resonance, energy scan

Integrated Luminosity (pb⁻¹)

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Belle total: 457234 pb⁻¹

Date
Typical hadronic events at Belle

\[ \text{thrust} = \frac{\sum |p_i \cdot \hat{n}|}{\sum |p_i|} \]
Belle is well suited for FF measurements:

- Good detector performance (acceptance, momentum resolution, pid)
- Jet production from light quarks
  → off-resonance (60 MeV below resonance)
    (~10% of all data)
- Intermediate Energy
  → Sufficiently high scale \( Q^2 \sim 110 \text{ GeV}^2 \)
    - can apply pQCD
  → Not too high energy \( Q^2 << M_Z^2 \)
    - avoids additional complication from Z interference
- Sensitivity = \( A^2 \sqrt{N} \sim x19 \ (60) \) compared to LEP
  \[ \frac{A_{\text{Belle}}}{A_{\text{LEP}}} \sim x2 \ (A \text{ scales as ln } Q^2) \]
  \[ \frac{L_{\text{Belle}}}{L_{\text{LEP}}} \sim x23 \ (230) \]
Event Structure at Belle

Near-side Hemisphere:
\[ h_i, \ i=1,N_n \text{ with } z_i \]

Far-side:
\[ h_j, \ j=1,N_f \text{ with } z_j \]

Jet axis: Thrust

Spin averaged cross section:
\[
\frac{d\sigma(e^+e^- \to h_1h_2X)}{d\Omega dz_1dz_2} = \frac{3\alpha^2}{Q^2} A(y) \sum_{a,\bar{a}} e_a^2 D_1(z_1) \bar{D}_1(z_2)
\]

\[
A(y) = \left( \frac{1}{2} - y + y^2 \right)^{(cm)} = \frac{1}{4} \left( 1 + \cos^2 \Theta \right)
\]

\[ z = \frac{2E_h}{\sqrt{s}}, \quad \sqrt{s} = 10.52 \text{ GeV} \]

\[ <N_{h^+,\bar{h}^-}> = 6.4 \]
What is the transverse momentum $Q_T$ of the virtual photon?

- In the lepton CMS frame $e^- = -e^+$ and the virtual photon is only time-like:
  $$q^\mu = (e^- + p^+) = (Q, 0, 0, 0)$$
- Radiative (=significant BG) effects are theoretically best described in the hadron CMS frame where $P_{h1} + P_{h2} = 0$\[\Rightarrow q'^\mu = (q'_0, q')\]
- Inclusive Cross section for radiative events (acc. to D.Boer):

$$\frac{dN}{d\Omega} \propto \sin^2 \theta \cos(2\phi_0) \frac{Q_T^2}{Q^2 + Q_T^2}$$
Experimental issues

• Cos2\(\phi\) moments have two contributions:
  – Collins
  – Radiative effects
  ➔ Can be isolated either by subtraction or double ratio method
  ➔ Cancels exactly in subtraction method, and in LO of double ratios

• Beam Polarization zero?
  ➔ Cos(2\(\phi_{\text{Lab}}\)) asymmetries for jets or \(\gamma\gamma\)
  ➔ Study effect in \(\tau\) decays, constrain through D tagging

• False asymmetries from weak decays
  ➔ \(Q_T\) or polar angle cut

• False asymmetries from misidentified hemispheres

• False asymmetries from acceptance
  ➔ Cancels in double ratios, can be estimated in charge ratios, fiducial cuts

• Decaying particles
  ➔ lower \(z\) cut
Double Ratio vs Subtraction Method:

The difference was assigned as a systematic error.

$R - S < 0.002$
Systematics: charm contribution?

- Weak (parity violating) decays could also create asymmetries
  (seen in $\tau \rightarrow \pi \pi \nu \bar{\nu}$, overall $\tau$ dilution 5%)
- Especially low dilution in combined $z$-bins with large pion asymmetry
- Double ratios from charm MC compatible to zero

$\Rightarrow$ Charm decays cannot explain large double ratios seen in the data

$\Rightarrow$ Charm enhanced $D^*$ Data sample used to calculate and correct the charm contribution to the double ratios (see hep-ex/0507063 for details)
Different charge combinations

- Unlike sign pairs contain either only favored or only unfavored fragmentation functions on quark and antiquark side:

  \[ D_1^{f_{av}}(z_1)D_1^{f_{av}}(z_2) + D_1^{u_{fav}}(z_1)D_1^{u_{fav}}(z_2) \]

- Like sign pairs contain one favored and one unfavored fragmentation function each:

  \[ D_1^{f_{av}}(z_1)D_1^{u_{fav}}(z_2) + D_1^{u_{fav}}(z_1)D_1^{f_{av}}(z_2) \]

Favored = \( u \rightarrow \pi^+, d \rightarrow \pi^-, \text{cc.} \)

Unfavored = \( d \rightarrow \pi^+, u \rightarrow \pi^+, \text{cc.} \)

\[
\frac{N(\phi)}{N_0} = \frac{aD_1\overline{D_1} + \cos(2\phi) \left( bH_1\overline{H_1} + cD_1\overline{D_1} \right)}{aD_1\overline{D_1}}
\]

\[
\frac{N(\phi)}{N_0} = 1 + \cos(2\phi) \left( \frac{bH_1\overline{H_1}}{aD_1\overline{D_1}} + \frac{c}{a} \right)
\]
Example: Left-Right Asymmetry in Pion Rates

Collins Effect

\[ A_T = \frac{N_L - N_R}{N_L + N_R} \neq 0 ! \]

\( N_L \) : pions to the left

\( N_R \) : pions to the right
Number density for finding
a spin-less hadron $h$ from a
transversely polarized quark, $q$:

\[ D_{q \uparrow}^h(z, \vec{p}_{h\perp}) = D_{1q}^{h,q}(z) + H_{1q}^{h,q}(z, p_{h\perp}^2) \left( \frac{\hat{k} \times \vec{p}_{h\perp}}{zM_h} \right) \cdot \vec{s}_q \]

unpolarized FF  Collins FF
Raw asymmetries vs transverse photon momentum $Q_T$

- Already MC contains large asymmetries
- Strong dependence against transverse photon Momentum $Q_T$
- Expected to be due to radiative effects
- Difference of DATA and MC is signal

- DATA ($\pi\pi$) fiducial cut
- DATA (KK) fiducial cut
- UDS-MC fiducial cut
- CHARM-MC fiducial cut