Measurement of Polarized Fragmentation Functions in $e^+e^-$ at

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Presenting work from
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Transverse spin dependent FFs needed as quark polarimeters

- Relativistic Leptonic probe is ‘too fast’ to see transverse spin
- To probe: knock out quark and use effect generated by angular moment conservation
Collins effect in quark fragmentation

\[ \mathbf{k} \quad \text{: quark momentum} \]
\[ \mathbf{s}_q \quad \text{: quark spin} \]
\[ \mathbf{p}_h \quad \text{: hadron momentum} \]
\[ \mathbf{p}_{h\perp} \quad \text{: transverse hadron momentum} \]
\[
\begin{align*}
z_h &= \frac{E_h}{E_q} \\
&= 2 \frac{E_h}{\sqrt{s}} \quad \text{: relative hadron momentum}
\end{align*}
\]

Collins Effect:
Fragmentation with of a quark \( q \) with spin \( s_q \) into a spinless hadron \( h \) carries an azimuthal dependence:
\[
\propto \left( \mathbf{k} \times \mathbf{p}_{h\perp} \right) \cdot \mathbf{s}_q
\]
\[
\propto \sin \phi
\]
Interference FF in Quark Fragmentation

Interference Fragmentation Function:
Fragmentation of a transversely polarized quark \( q \) into two spin-less hadron \( h1, h2 \) carries an azimuthal dependence:
\[
\propto \left( \vec{k} \times \vec{R}_T \right) \cdot \vec{s}_q
\]
\[
\propto \sin \phi
\]

\( \vec{s}_q \): quark spin
\( \vec{k} \): quark momentum
\( \vec{R}_T \): transverse hadron momentum difference
\( z_{pair} \): relative hadron pair momentum
\( m \): hadron pair invariant mass
\( \vec{R} \): momentum difference \( \vec{p}_{h1} - \vec{p}_{h2} \)
Advantages of IFF over Collins route

- Single Hadron asymmetries vanish integrated over transverse momentum: model dependency in global fit
- Di-hadron effect survives after integration over $k_T$: collinear factorization can be used
  - No Sudakov suppression
  - Known evolution
- Less background processes to consider (e.g. from gluon radiation, $t \rightarrow \pi^- \pi^+ \pi^- \nu_{\tau}$)
- SIDIS experiment show that the effect is large

In $p+p$:
No jet reconstruction necessary,
better systematics: “Easier” measurement
Collider allows wide kinematic coverage!
Jet Handedness

\[ \text{Handedness:} \quad \frac{(k_+ \times k_-) \cdot \hat{t}}{|k_+||k_-|} = \sin\Phi > 0 \iff L/R \]

\[ \text{Jet handedness:} \quad \frac{N_R - N_L}{N_R + N_L} \]

Related to \( g_{1T} \), T-odd, not chiral-odd. Effects for sphaleron coupling, or factorized TMD (different) (D. Boer, Pavia DiFF minworkshop 2011)
Measuring spin dependent FFs in $e^+e^-$ Annihilation into Quarks

Spin dependence in $e^+e^-$ quark fragmentation will lead to (azimuthal) asymmetries in correlation measurements!

**Experimental requirements:**
- Small asymmetries $\Rightarrow$ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector

Here for di-hadron correlations:

$$A \propto H_1(z_1, m_1) \overline{H}_1(z_2, m_2) \cos(\phi_1 + \phi_2)$$
Measurement of Fragmentation Functions @ KEKB

- KEKB: $L > 2.11 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$
- Asymmetric collider:
  - $8 \text{ GeV } e^- + 3.5 \text{ GeV } e^+$
  - $\sqrt{s} = 10.58 \text{ GeV } (\Upsilon(4S))$
  - $e^+e^- \Upsilon(4S) \text{ BB}$
- Integrated Luminosity: $> 1000 \text{ fb}^{-1}$
- Continuum production: $10.52 \text{ GeV}$
- $e^+e^- (u, d, s, c)$
- $> 70 \text{ fb}^{-1} \Rightarrow$ continuum
Large acceptance, good tracking and particle identification!
Measuring Light Quark Fragmentation Functions on the $\Upsilon(4S)$ Resonance

- small B contribution (<1%) in high thrust sample
- >75% of X-section continuum under $\Upsilon$ (4S) resonance
- $\sim$100 fb$^{-1} \rightarrow \sim$1000 fb$^{-1}$

\textit{Thrust:} $T = \frac{\sum |p_i \cdot \hat{n}|}{\sum |p_i|}$

\textit{e}^+\textit{e}^- \rightarrow q\bar{q}, q \in uds

\textit{e}^+\textit{e}^- \rightarrow c\bar{c}$

\textit{e}^+\textit{e}^- \rightarrow q\bar{q}, q \in uds

\textit{e}^+\textit{e}^- \rightarrow c\bar{c}$
Collins fragmentation in e^+e^-:
Angles and Cross section cos(\phi_1+\phi_2) method

\begin{align*}
\frac{d\sigma(e^+e^- \to h_1h_2X)}{d\Omega dz_1dz_2d^2q_T} &= \cdots 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
\end{align*}

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

2-hadron inclusive transverse momentum dependent cross section:

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

$\theta_2$-Independent of thrust-axis

$\theta_2$-Convolution integral $I$ over transverse momenta involved

2-hadron inclusive transverse momentum dependent cross section:

$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{d\Omega dz_1 dz_2 d^2 q_T} = \cdots B(\Theta) \cos(2\varphi_0) [2\hat{h}_1 \cdot \hat{h}_2 \cdot p_T - k_T \cdot p_T] \frac{H_1^+ \overline{H}_1^+}{M_1 M_2}$$

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

Net (anti-)alignment of transverse quark spins

[Boer, Jakob, Mulders: NPB504(1997)345]
Spin Projection in **Barrel** and **Endcap**

\[ q \sin^2 q / (1 + \cos^2 q) \]

\[ 1 - \sin^2 \theta / (1 + \cos^2 \theta) \]

\[ \sin^2 \theta / (1 + \cos^2 \theta) \]
Transverse Spin Dependent FFs: Cuts and Binning

• Full off-resonance and on-resonance data
  (7-55): \(~73 \text{ fb}^{-1} + 588 \text{ fb}^{-1}\)
• Visible energy \(>7\text{GeV}\)
• PID: Purities in for pion pairs \(>90\%\)
• Opposite hemisphere between pairs pions
• All hadrons in barrel region: \(-0.6 < \cos (\theta) < 0.9\)
• Thrust axis in central area: cosine of thrust axis around beam \(<0.75\)
• Thrust \(>0.8\) to remove B-events \(\rightarrow <1\%\) B events in sample
• \(Z_{\text{had}1} >0.2\)
Final Collins results

- First direct measurement of the Collins effect: (PRL96: 232002)
- Nonzero asymmetries
- Consistent with BaBar measurement (see talk by David Muller)
- Belle 547 fb\(^{-1}\) data set (PRD78:032011)

Use of double ratios to cancel gluon radiation effects
First global analysis from Collins Hermes, Compass d and Belle data

- First results available, still open questions from evolution of Collins FF and transverse momentum dependence

Projections for Kaon Collins

- Using same PID matrices as recent K/π yield extraction (see Martin Leitgab’s talk)

- Error bars statistical, Charm correction, smearing uncertainties not yet included
Interference Fragmentation – thrust method

- $e^+e^- \rightarrow (\pi^+\pi^-)_{\text{jet1}}(\pi^+\pi^-)_{\text{jet2}}X$
- Find pion pairs in opposite hemispheres
- Observe angles $\varphi_1 + \varphi_2$ between the event-plane (beam, jet-axis) and the two two-pion planes.
- Early work by Collins, Heppelmann, Ladinsky [NPB420(1994)]

Model predictions by:
- Jaffe et al. [PRL 80, (1998)]
- Radici et al. [PRD 65, (2002)]

$$A \propto H_1^< (z_1, m_1) \bar{H}_1^< (z_2, m_2) \cos(\varphi_1 + \varphi_2)$$
Transverse Spin Dependent FFs: Cuts and Binning

- Full off-resonance and on-resonance data (7-55): $\sim 73 \text{ fb}^{-1} + 588 \text{ fb}^{-1}$
- Visible energy $>7\text{GeV}$
- PID: Purities in for di-pion pairs $> 90%$
- Same Hemisphere cut within pair ($\pi^+\pi^-$), opposite hemisphere between pairs
- All 4 hadrons in barrel region: $-0.6 < \cos (\theta) < 0.9$
- Thrust axis in central area: cosine of thrust axis around beam $< 0.75$
- Thrust $> 0.8$ to remove B-events $\rightarrow < 1\%$ B events in sample
- $z_{\text{had}1,\text{had}2} > 0.1$
- $z_1 = z_{\text{had}1} + z_{\text{had}2}$ and $z_2$ binning
- $m_{\pi\pi_1}$ and $m_{\pi\pi_2}$ binning
- Here: Mixed binning
Energy flow with opening cut of 0.8

- A small asymmetry seen due to acceptance effect
- Mostly appearing at boundary of acceptance
- Opening cut in CMS of 0.8 (~37 degrees) reduces acceptance effect to the sub-per-mille level
Asymmetry extraction

- Build normalized yields:
  \[ \frac{N(\phi_1 + \phi_2)}{\langle N \rangle}, \]

- Fit with:
  \[ a_{12} \cos(\phi_1 + \phi_2) + b_{12} \]
  or
  \[ a_{12} \cos(\phi_1 + \phi_2) + b_{12} + c_{12} \cos 2(\phi_1 + \phi_2) + d_{12} \sin(\phi_1 + \phi_2) \]

Amplitude \( a_{12} \) directly measures (IFF) \( x \) (IFF) (no double ratios)
(z_1 x m_1) Binning

arXiv:1104.2425
PRL 107, 072004(2011)
Comparison to theory predictions

- Mass dependence: Magnitude at low masses comparable, high masses significantly larger (some contribution possibly from charm)
- Z dependence: Rising behavior steeper

Red line: theory prediction + uncertainties
Blue points: data
Subprocess contributions (MC)

8x8 $m_1 m_2$ binning

tau contribution (only significant at high z)
charged B (<5%, mostly at higher mass)
Neutral B (<2%)
charm (20-60%, mostly at lower z)
uds (main contribution)
Subprocess contributions (MC)

9x9 $z_1 \ z_2$ binning

tau contribution (only significant at high $z$)
charged B($<5\%$, mostly at higher mass)
Neutral B ($<2\%$)
charm($\sim 20\text{-}60\%$, mostly at lower $z$)
uds (main contribution)
Measurement at Belle leads to first point by point extraction of Transversity

See Marco Radici’s talk
Handedness

\[ \frac{(k_+ \times k_-) \cdot \hat{t}}{|k_+||k_-|} = \sin \Phi > 0 \Rightarrow L/R \]

Jet handedness:
\[ \frac{N_R - N_L}{N_R + N_L} \]

C:
\[ \frac{N_{RL} + N_{LR} - N_{RR} - N_{LL}}{N_{RL} + N_{LR} + N_{RR} + N_{LL}} \]

Expect negative correlation for local p-odd effect
Zero if factorized TMD picture holds
First Look at Handedness Correlation

- Test of TMD picture (C=0)
- Sphaleron interaction would lead to C<0

Work in Progress....

Should be zero. Effect probably due to insufficient separation of hemispheres
Measurements of $G_1 \perp$ will test TMD framework

Together with handedness correlations will give insights into mechanisms behind transverse spin effects

From:
D. Boer,
DiFF Miniworkshop,
Pavia, 2011
KEKB/Belle → SuperKEKB, upgrade (2010–2015)

- Aim: super-high luminosity $\sim 10^{36} \text{cm}^{-2}\text{s}^{-1}$ (~40x KEK/Belle)
- Upgrades of Accelerator (Microbeams + Higher Currents) and Detector (Vtx, PID, higher rates, modern DAQ)
- Significant US contribution

http://belle2.kek.jp
The Belle II Detector

CsI(Tl) EM calorimeter: waveform sampling electronics, pure CsI for end-caps

4 layers DSSD → 2 layers PXD (DEPFET) + 4 layers DSSD

Central Drift Chamber: smaller cell size, long lever arm

RPC $\mu$ & $K_L$ counter: scintillator + Si-PM for end-caps

Time-of-Flight, Aerogel Cherenkov Counter → Time-of-Propagation counter (barrel), proximity focusing Aerogel RICH (forward)

Highlights (for FF measurements) Of Belle II

• Kaon efficiency > 95% over relevant kinematics, fake rate < 5%
• Vertex resolution improved by order of magnitude
• Obviously more statistics
Conclusion and Outlook

• Belle measurements played a crucial role in the first extractions of transversity from single and di-hadron asymmetries

• Current plans include
  – Pi0/eta Collins FF
  – VM Collins FF
  – IFF with $\pi^+/\pi^0$ in final state
  – Handedness and $G_{1\perp}$ correlations

• Belle II will add better vertexing and PID capabilities (and much more statistics)
Backup