Collins fragmentation functions at BABAR and BESIII

I. Garzia - INFN Sezione di Ferrara
on behalf of BESIII and BaBar Collaborations

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Outline

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- **BaBar preliminary results: Collins asymmetries for KK and $K\pi$ hadron pairs**

- **Summary and conclusions**
Introduction: the Collins effect

Our understanding of the hadronic physics depends strongly on what we know about the parton distributions functions (PDFs) and \textbf{fragmentation functions} (FFs)
• Universal
• Non-perturbative objects

\textbf{Transverse Momentum Dependent (TMD)} FFs ⇒ to study the spin-dependent observables

• when only spinless hadrons (π, K) are considered, we have:

\[ D_{1}^{q}(z, P_{\perp}; s_{q}) = D_{1}^{q}(z, P_{\perp}) + \frac{P_{\perp}}{zM_{h}}H_{1}^{q}(z, P_{\perp})s_{q} \cdot (k_{q} \times P_{\perp}) \]

\textbf{Unpolarized FF} \hspace{1cm} \textbf{Collins FF} \ [\text{NPB 396, 161 (1993)}]: chiral-odd function, related to the probability that a transversely polarized quark (q↑) fragments into a spinless hadron

\textbf{Physics motivation:}
• e^+e^- annihilation experiments are the most clean environment to study fragmentation processes
• evolution of TMD objects
• Global analysis (PRD 78,032011 (2007); PRD 87,094019 (2013), PRD 91,014034 (2015)):
  • combines Semi Inclusive Deep Inelastic Scattering (SIDIS) and e^+e^- data
  • extraction of H_{1}^{⊥} and transversity parton distributions h_{1} for the “u” and “d” quarks
Collins effect in $e^+e^-$ annihilation

In $e^+e^- \rightarrow q\bar{q}$, spins unknown, but $s_q \parallel s_{\bar{q}}$ with transverse spin component $\sim \sin^2\theta$

- exploit this correlation by using hadrons in opposite jets
- define favored ($u \rightarrow \pi^+, d \rightarrow \pi^-$) and disfavored ($d \rightarrow \pi^+, u \rightarrow \pi^-, s(\bar{s}) \rightarrow \pi^\pm$) FFs

$$e^+e^- \rightarrow q\bar{q} \rightarrow h_1 h_2 X \ (q=u,d,s) \Rightarrow \sigma \propto \cos(\phi_1+\phi_2)H_{1\perp}(h_1) \times H_{1\perp}(h_2)$$

Azimuthal modulation wrt the quark spin direction:
Collins effect (or Collins asymmetry)

Example: Unlike $\pi \pi$ pairs (U)

Collins asymmetry for $\pi \pi$

Example: Unlike KK pairs (U)

Collins asymmetry for KK:
Favored contribution to the fragmentation of the strange quark

Collins asymmetries for KK pairs not yet available: only BaBar preliminary results
The BaBar and BESIII detectors

- **PEP-II storage ring**
  - **asymmetric** $e^+e^-$ collider operating at the $\Upsilon(4S)$ resonance ($\sqrt{s}=10.58$ GeV)
  - High Energy Ring (HER): 9.0 GeV $e^-$
  - Low Energy Ring (LER): 3.1 GeV $e^+$
  - c.m.-lab boost, $\beta\gamma\approx 0.56$
- High luminosity: $\mathcal{L} \sim 468$ fb\(^{-1}\) used here

  NIM **A479**, 1 (2002),
  update: NIM **A729**, 615 (2013)

- **Beijing Electron Positron Collider II (BEPCII)**
  - **Symmetric** $e^+e^-$ collider
  - Beam energy: 1-2.3 GeV
  - 2008: test run
  - 2009-today: BESIII physics runs
  - Luminosity: $\mathcal{L} \sim 62$ pb\(^{-1}\) @ 3.65 GeV used here (below open charm threshold)

  NIM **A614**, 345 (2010)
Reference frames

\[ \frac{d\sigma(e^+e^- \rightarrow h_1 h_2 X)}{d\Omega dz_1 dz_2 d\phi_1 d\phi_2} = \sum_{q, \bar{q}} \frac{3\alpha^2 e_q^2}{Q^2} \frac{z_1^2 z_2^2}{4} \left[ (1 + \cos^2 \theta) D_1^{q,(0)}(z_1) \bar{D}_1^{\bar{q},(0)}(z_2) + \sin^2(\theta) \cos(\phi_1 + \phi_2) \bar{H}_1^{q,(1),q}(z_1) \bar{H}_1^{\bar{q},(1),\bar{q}}(z_2) \right] \]

All quantities in e+e- center of mass

\[ \theta: \text{ angle between the } e^+e^- \text{ axis and the thrust axis;} \]
\[ \phi_{1,2}: \text{ azimuthal angles between } P_{h1(h2)} \text{ and the scattering plane} \]

\[ \theta_2: \text{ angle between the } e^+e^- \text{ axis and } P_{h2}; \]
\[ \phi_0: \text{ angle between the plane spanned by } P_{h2} \text{ and the } e^+e^- \text{ axis, and the direction of } P_{h1} \text{ perpendicular to } P_{h2}. \]

All quantities in e+e- center of mass

\[ \frac{d\sigma(e^+e^- \rightarrow h_1 h_2 X)}{d\Omega dz_1 dz_2 d^2 \vec{q}_T} = \frac{3\alpha^2}{Q^2} \frac{z_1^2 z_2^2}{4} \left\{ A(y) \mathcal{F}[D_1 \bar{D}_2] + \left[ B(y) \cos(2\phi_0) \mathcal{F} \left( (2\hat{h} \cdot \vec{k}_T \hat{h} \cdot p_T - \vec{k}_T \cdot p_T) \frac{H_1^{\perp} \bar{H}_2^{\perp}}{M_1 M_2} \right) \right] \right\} \]
The only frame used in BESIII
- low center of mass energy: more spherical events
- Jet-like topology ensured by requiring $\theta_{h1h2} > 120^\circ$

Jet-like events
- B factories (BaBar and Belle)
- No useful in BESIII
Analysis Strategy

- Event and track selection
- Construction of spinless hadron pairs
  - KK, K\(\pi\), \(\pi\pi\) for BaBar
  - \(\pi\pi\) for BESIII
- Measure of the azimuthal angles \(\phi_1\) and \(\phi_2\) in RF12 (BaBar), and \(\phi_0\) in RF0 (BaBar and BESIII)
- Construction of the normalized raw distributions for like (L), Unlike (U) and Charged (C=U+L) hadron pairs: \(R_i=N_i(\phi)/<N>\)
- Calculation of the ratios of normalized distributions: U/L and U/C
  - fit to these distributions with the function \(b+a\cdot\cos(x)\)
- Evaluation of background contributions and extraction of the Collins asymmetries

BaBar RESULTS (PRD90,052003):
- RF12 and RF0
- \(A^UL\) and \(A^UC\)
- \((z_1,z_2)\) bins, where \(z_{1,2}=2E_h/\sqrt{s}\), \((p_{t1},p_{t2})\) and \(p_0\) bins, \(\sin^2\theta/(1+\cos^2\theta)\), and 2D analysis: \((z_1,z_2)\) vs. \((p_{t1},p_{t2})\)
- NEW PRELIMINARY (arXiv:1506.05864)
  - KK and K\(\pi\) asymmetries vs. \((z_1,z_2)\)

BESIII PRELIMINARY RESULTS:
- arXiv:1507.06824
- RF0
- \(A^UL\) and \(A^UC\)
- \((z_1,z_2)\) bins, where \(z_{1,2}=2E_h/\sqrt{s}\), \((p_{t1},p_{t2})\) and \(p_0\) bins, \(\sin^2\theta/(1+\cos^2\theta)\)
Management of Collins effect

- Normalized azimuthal distribution for hadron pair with same charge (L), opposite charge (U), and the sum of the two samples (C)
- Collins effect is not simulated in uds-MC $\rightarrow$ strong azimuthal MC modulation principally due to the detector acceptance
- Nonzero Collins effect in data sample $\rightarrow$ different combinations of fav and dis FF for L, U, and C

**Double ratio of U/L and U/C normalized distributions:**
Collins effect measured by fitting the double ratio distributions with the function $B + A \cdot \cos(\phi_i)$
BaBar results for $\pi\pi$ pairs

- Collins asymmetry measured as function of
  - $6\times6$ bins of pion fractional energy (similar behavior in RF0, for both UL and UC)
  - $4\times4$ bins of $(p_{t1}, p_{t2})$ in RF12
  - 9 bins of $p_{t0}$ in RF0
  - asymmetry vs. $\sin^2\theta_{th}/(1+\cos^2\theta_{th})$ and $\sin^2\theta_2/(1+\cos^2\theta_2)$
BESIII preliminary results

Collins asymmetry measured as function of
- 6 symmetric \((z_1,z_2)\) bins
- 5 bins of \(p_t\)
- asymmetry vs. \(\sin^2\theta_2/(1+\cos^2\theta_2)\)
- comparison with prediction reported in arXiv: 1505.05589

Submitted on PRL arXiv:1507.06824

RF0 only
Asymmetries comparison in RF0

Comparison between different results obtained at different $Q^2$:
- **BaBar and Belle @ $Q^2 \sim 110 \text{ GeV}^2$**
- **BESIII @ $Q^2 \sim 13 \text{ GeV}^2$**
  - BaBar and Belle results that fall in the larger BESIII $z$-bins are averaged taking into account the statistical and systematic uncertainties
  - Good agreement between different data set for low $z$
  - BESIII larger asymmetries in the last $z$-bins: consistent with the prediction reported in arXiv:1505.05589
New BaBar Preliminary Result: Collins asymmetries for KK and $K\pi$ hadron pairs
Event and track selection

More stringent cuts optimized in order to reduce biases on the KK pairs

**EVENT SELECTION**

- Number of charged tracks > 2
- Selection of two jets topology: thrust > 0.8
- $|\cos(\theta_{\text{thrust}})| < 0.6$
- Visible energy $E_{\text{vis}} > 11$ GeV
- Most energetic photon $E_\gamma < 2$ GeV

**TRACK SELECTION**

- Electrons and muons veto
- K and $\pi$ in the DIRC acceptance region
- K/$\pi$ fractional energy $z$: $0.15 < z < 0.9$
- Opening angle $\theta_{h-\text{thrust}}$ of hadron with respect to the thrust axis < 45°
- $Q_t < 3.5$ GeV, where $Q_t$ is the transverse momentum of the virtual photon in the two hadrons center-of-mass energy

Thrust axis: charged tracks + neutral candidates; thrust axis direction chosen random
GOAL: simultaneous extraction of the asymmetries corrected for backgrounds and K/π misidentification for each interval of fractional energy

- 3 samples: KK, Kπ, ππ
- we fit independently the double ratio distributions of the three samples

\[
A_{KK}^{meas} = F_{uds}^{KK} \cdot (\xi_{KK}^{(KK)} A_{KK} + \xi_{K\pi}^{(KK)} A_{K\pi} + \xi_{\pi\pi}^{(KK)} A_{\pi\pi}) + \\
F_{c\bar{c}}^{KK} \cdot (\xi_{KK}^{(KK)c\bar{c}} A_{c\bar{c}KK} + \xi_{K\pi}^{(KK)c\bar{c}} A_{c\bar{c}K\pi} + \xi_{\pi\pi}^{(KK)c\bar{c}} A_{c\bar{c}\pi\pi}) + \\
F_{uds}^{D^*} \cdot (\xi_{KK}^{(KK)D^*} A_{KK}^{D^*} + \xi_{K\pi}^{(KK)D^*} A_{K\pi}^{D^*} + \xi_{\pi\pi}^{(KK)D^*} A_{\pi\pi}^{D^*}) + \\
F_{c\bar{c}}^{D^*} \cdot (\xi_{KK}^{(KK)c\bar{c}D^*} A_{c\bar{c}KK}^{D^*} + \xi_{K\pi}^{(KK)c\bar{c}D^*} A_{c\bar{c}K\pi}^{D^*} + \xi_{\pi\pi}^{(KK)c\bar{c}D^*} A_{c\bar{c}\pi\pi}^{D^*})
\]

1. Background sources:
   - mainly from $e^+e^- \rightarrow c\bar{c}$ events (more than 30%); smaller contribution from $B\bar{B}$, $\tau^+\tau^-$ ($A_{bb} \sim A_{\tau \tau} \sim 0$)
     - we construct a $D^*$-enhanced MC and data control samples
     - we calculate from MC the fraction ($F(f)_{\text{sig/bkg}}^{hh}$) of hadron pairs coming from signal (uds) and background events ($c\bar{c}$, $B\bar{B}$, $\tau^+\tau^-$)

2. K/π misidentification:
   - we evaluate from MC the fraction ($\xi_{hh}^{(hh)}$) that a given hadron pair is reconstructed as KK, Kπ, or ππ pair
   - fractions evaluated in all samples used in the analysis: uds ($\xi_{hh}^{(hh)}$), $D^*$-uds ($\xi_{hh}^{(hh)D^*}$), $c\bar{c}$ ($\xi_{hh}^{(hh)c\bar{c}}$), $c\bar{c}-D^*$ ($\xi_{hh}^{(hh)c\bar{c}D^*}$)
Simultaneous extraction of asymmetry

Three samples (KK, Kπ, ππ) + background + K/π misidentification ⇒ system of six equations and six unknown parameters

\[ A_{KK}^{\text{meas}} = F_{uds}^{KK} \cdot (\xi_{KK}^{KK} A_{KK} + \xi_{K\pi}^{KK} A_{K\pi} + \xi_{\pi\pi}^{KK} A_{\pi\pi} + \xi_{KK}^{K\pi} A_{K\pi} + \xi_{K\pi}^{K\pi} A_{K\pi} + \xi_{\pi\pi}^{K\pi} A_{\pi\pi}) + F_{c\bar{c}}^{KK} \cdot (\xi_{KK}^{K\pi} A_{K\pi} + \xi_{K\pi}^{K\pi} A_{K\pi} + \xi_{\pi\pi}^{K\pi} A_{\pi\pi}) + \]

\[ A_{K\pi}^{\text{meas}} = F_{uds}^{K\pi} \cdot (\xi_{KK}^{K\pi} A_{KK} + \xi_{K\pi}^{K\pi} A_{K\pi} + \xi_{\pi\pi}^{K\pi} A_{\pi\pi}) + F_{c\bar{c}}^{K\pi} \cdot (\xi_{KK}^{K\pi} A_{K\pi} + \xi_{K\pi}^{K\pi} A_{K\pi} + \xi_{\pi\pi}^{K\pi} A_{\pi\pi}) + \]

\[ A_{\pi\pi}^{\text{meas}} = F_{uds}^{\pi\pi} \cdot (\xi_{KK}^{\pi\pi} A_{KK} + \xi_{K\pi}^{\pi\pi} A_{K\pi} + \xi_{\pi\pi}^{\pi\pi} A_{\pi\pi}) + F_{c\bar{c}}^{\pi\pi} \cdot (\xi_{KK}^{\pi\pi} A_{K\pi} + \xi_{K\pi}^{\pi\pi} A_{K\pi} + \xi_{\pi\pi}^{\pi\pi} A_{\pi\pi}) + \]

\[ A_{KK}^{D^*} = f_{uds}^{KK} \cdot (\xi_{KK}^{KK} A_{KK} + \xi_{K\pi}^{KK} A_{K\pi} + \xi_{\pi\pi}^{KK} A_{\pi\pi}) + f_{c\bar{c}}^{KK} \cdot (\xi_{KK}^{K\pi} A_{K\pi} + \xi_{K\pi}^{K\pi} A_{K\pi} + \xi_{\pi\pi}^{K\pi} A_{\pi\pi}) \]

\[ A_{K\pi}^{D^*} = f_{uds}^{K\pi} \cdot (\xi_{KK}^{K\pi} A_{KK} + \xi_{K\pi}^{K\pi} A_{K\pi} + \xi_{\pi\pi}^{K\pi} A_{\pi\pi}) + f_{c\bar{c}}^{K\pi} \cdot (\xi_{KK}^{K\pi} A_{K\pi} + \xi_{K\pi}^{K\pi} A_{K\pi} + \chi_{K\pi}^{K\pi} A_{\pi\pi}) \]

\[ A_{\pi\pi}^{D^*} = f_{uds}^{\pi\pi} \cdot (\xi_{KK}^{\pi\pi} A_{KK} + \xi_{K\pi}^{\pi\pi} A_{K\pi} + \xi_{\pi\pi}^{\pi\pi} A_{\pi\pi}) + f_{c\bar{c}}^{\pi\pi} \cdot (\xi_{KK}^{\pi\pi} A_{K\pi} + \xi_{K\pi}^{\pi\pi} A_{K\pi} + \chi_{\pi\pi}^{\pi\pi} A_{\pi\pi}) \]

= Collins asymmetries for light hadrons
Simultaneous measurement of KK, K\pi and \pi\pi Collins asymmetries
• all corrections are applied

• Rising of the asymmetry as a function of z (more pronounced for U/L)
• A_{UL} KK asymmetry slightly higher than pion asymmetry for high z
• KK asymmetry consistent with zero at lower z

Note that A_{UL} and A_{UC} asymmetries are obtained using the same data sample, and are strongly correlated
Conclusions

• Collins asymmetries for $\pi\pi$ pairs was deeply investigated:
  • BaBar and Belle @ $Q^2\sim110$ GeV$^2$ (PRD90,052003, PRD86,039905)
  • BESIII preliminary results @ $Q^2\sim13$ GeV$^2$ allow to study the evolution of TMD objects
  • Collins effect studied as a function of several kinematic variables

• BaBar preliminary results: simultaneous extraction of $A_{KK}$, $A_{K\pi}$, and $A_{\pi\pi}$ Collins asymmetries
  • 16 ($z_1,z_2$)-bins
  • Good agreement with previous BaBar results (PRD 90,052003 (2014))

• Agreement with theoretical prediction !? [PL B659, 234 (2008); PRD 86, 034025 (2012)]
  • $A^{UL}$ asymmetry for KK are slightly larger than $\pi\pi$
  • $A^{UC}$ asymmetry for KK are slightly lower than $\pi\pi$
Backup slides