Fragmentation Function measurements at Belle

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Outline

- Single hadron fragmentation
  - Hyperon and charmed Baryon fragmentation
  - $\Lambda$ polarizing fragmentation
- Di-hadron fragmentation
  - Unpolarized mass, $z$ dependence
- Other ongoing measurements (kt dependence)
Access to FFs

**SIDIS:**
\[ \sigma^h(x, z, Q^2, P_{h\perp}) \propto \sum_q e_q^2 q(x, p_t, Q^2) D^h_{1,q}(z, k_t, Q^2) \]
- Relies on unpol PDFs
- Parton momentum known at LO
- Flavor structure directly accessible
- Transverse momenta convoluted between FF and PDF

**pp:**
\[ \sigma^h(P_T) \propto \int x_1 x_2 dz \sum_{a, a'} f_a(x_1) \otimes f_{a'}(x_2) \otimes \sigma_{aa'} \otimes D^h_{1,q}(z) \]
- Relies on unpol PDFs
- Leading access to gluon FF
- Parton momenta not directly known

**e+e-:**
\[ \sigma^h(z, Q^2, k_t) \propto \sum_q e_q^2 \left( D^h_{1,q}(z, k_t, Q^2) + D^h_{1,q}(z, k_t, Q^2) \right) \]
- No PDFs necessary
- Clean initial state, parton momentum known at LO
- Flavor structure not directly accessible
**Belle Detector and KEKB**

- Asymmetric collider
- $8\text{GeV} \, \text{e}^- + 3.5\text{GeV} \, \text{e}^+$
- $\sqrt{s} = 10.58\text{GeV}$ ($Y(4S)$)
- $e^+e^- \rightarrow Y(4S) \rightarrow B \bar{B}$
- Continuum production: $10.52\,\text{GeV}$
- $e^+e^- \rightarrow q \, \bar{q}$ (u,d,s,c)
- Integrated Luminosity: $>1000\,\text{fb}^{-1}$
- $>70\text{fb}^{-1} \Rightarrow$ continuum
Single hadron fragmentation

\[ D_{1,q}^h (z, Q^2) \]

\[ D_{1,q}^h (z, k_T, Q^2) \]

\[ H_{1,q}^h (z, k_T, Q^2) \]

\[ D_{1,q}^\perp h (z, k_T, Q^2) \]

\[ H_{1,q}^h (z, Q^2) \]

\[ G_q^h (z, z_h, \omega_J R, \mathbf{j}_\perp, Q^2) \]

In $e^+e^-$ annihilation:

\[ Q = \sqrt{s} \]

\[ z = \frac{2E_h}{Q} \approx \frac{E_h}{E_q} \]
Hyperons similar to light hadron fragmentation \( \rightarrow \) peaking at low \( z \) (\( x_p \))

Baryon production not too well described by Pythia 6 default settings
Charmed baryons carry large fraction of parton momentum, similar to charmed mesons.

Charmed fragmentation reasonably described in Pythia for main states.
Baryon production rates

- First feed-down corrected production rates extracted
- No $\Lambda(1520)$ enhancement seen
- Strangeness suppression seen for hyperons:
  \[ \frac{\sigma(S = -1)}{(2J + 1)} > \frac{\sigma(S = -2, -3)}{(2J + 1)} \]
- Difference in slopes for $\Lambda_c$ and $\Sigma_c$ in support of diquark production picture (spin 1 diquarks suppressed)
Single $\Lambda$ polarization measurements

- Related to open question about $\Lambda$ polarization in hadron collisions from 40 years ago!
- Fragmentation counterpart to the Sivers Function:
  - unpolarized parton fragments into transversely polarized baryon with transverse momentum wrt to parton direction
- Reconstruct $\Lambda$, its transverse momentum and polarization

YingHui Guan (Indiana/KEK): arXiv:1611.06648

$$D_{1,q}^{h}(z, k_{T}, Q^{2})$$

\[ z_{\Lambda} \text{ binning [0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9]} \]

- anti-$\Lambda$
- $\Lambda$ anti-anti-$\Lambda$ data ratio

Belle preliminary
Interesting $z_\pi$ and $z_\Lambda$ dependence:

- At low $z_\Lambda$ light quark fragmentation dominant, some charm in $\pi^-$ \rightarrow different signs
- At high $z_\Lambda$ strange + charm fragmentation more relevant $\rightarrow$ same signs
Di-hadron fragmentation functions

\[ D_{1,q}^{h_1 h_2} (z, m, Q^2) \]

\[ H_{1,q}^{h_1 h_2} (z, Q^2, M_h) \]

\[ D_{1,q}^h (z_1, Q^2) D_{1,q}^h (z_2, Q^2) \]
Di-hadrons

• Single inclusive hadron multiplicities (e+e−→hX) sum over all available flavors and quarks and antiquarks:

\[ d\sigma(e^+e^- \rightarrow hX)/dz \propto \sum_q e_q^2(D^h_{1,q}(z, Q^2) + D^h_{1,q}(\bar{z}, Q^2)) \]

• Especially distinction between favored (ie u→π+) and disfavored (\bar{u} → π+) fragmentation would be important

• Idea: Use di-hadron fragmentation, preferably from opposite hemispheres and access favored and disfavored combinations:

\[
\begin{align*}
\bar{u}u &\rightarrow \pi^+\pi^- X \propto D^+_{u, fav}(z_1, Q^2) \cdot D^-_{u, fav}(z_2, Q^2) + D^+_{u, dis}(z_1, Q^2) \cdot D^-_{u, dis}(z_2, Q^2) \\
\bar{u}u &\rightarrow \pi^+\pi^+ X \propto D^+_{u, fav}(z_1, Q^2) \cdot D^+_{u, dis}(z_2, Q^2) + D^+_{u, dis}(z_1, Q^2) \cdot D^+_{u, fav}(z_2, Q^2)
\end{align*}
\]

• Also: unpol baseline for interference fragmentation
Ratios to opposite charge pion pairs

\[ R \approx \frac{D_{\text{dis}}(z_1)D_{\text{fav}}(z_2) + D_{\text{fav}}(z_1)D_{\text{dis}}(z_2)}{D_{\text{fav}}(z_1)D_{\text{fav}}(z_2) + D_{\text{dis}}(z_1)D_{\text{dis}}(z_2)} \]

\( \pi^+\pi^+ \) comparable to \( \pi^+\pi^- \) at low z, decreasing towards high z:

→ Favored and disfavored fragmentation similar at low z

→ Disfavored much smaller at high z
Hemisphere composition

Same hemisphere contribution drops rapidly: Consistent with LO assumption of
Same hemisphere: single quark → di-hadron FF: \((z_1 + z_2 < 1)\)
Opposite hemisphere: single quark → single hadron FF

Diagonal
\(z_1, z_2\) bins

Belle: RS et al., PRD92 (2015) 092007
Systematic uncertainties not displayed
Explicit di-hadron mass dependence

- Global fits currently missing unpolarized di-hadron FF baseline

⇒ Belle to the rescue
- Use same hemisphere di-hadrons for this analysis
- 16 z bins between 0.2 – 1
- 100 mass bins between 0.3 – 2.3 GeV
- Data analysis and correction steps same as previous di-hadron analysis, except for ISR treatment
Di-hadron mass dependence

Similar analysis in same hemisphere and mass – combined z binning. Important input for IFF based transversity global analysis

Belle: RS et.al. PRD96 (2017), 032005
Mass dependence comparisons to Pythia tunes

Magnitude and z dependence reasonable in Pythia 6.4 default, Intermediate mass structure better described by LEP tunes (higher spin mesons)
Di-pion individual contributions

Contributions from various resonances and direct fragmentation

Belle: RS et.al. PRD96 (2017), 032005

\[ \frac{d^2 \sigma}{dz dm_{\pi\pi}} \]
Summary and outlook

- Hyperon and charmed baryon fragmentation measurements just published, support for diquark picture in charm FF
- Nonzero Lambda polarization measured, interesting flavor dependence
- Di-hadron fragmentation functions measured, important input for di-hadron related Transversity/Tensor charge extractions
- Transverse momentum dependent fragmentation analysis ongoing
- Other results being finalized as well ($\eta, \pi^0$ Collins)