TMDs and Fragmentation Functions in $e^+e^-$ and relation to EIC

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EIC without B factory input?

**Very unlikely**

- Very limited helicity analysis possible (based on Kretzer or KKP)
- Only model dependent Tensor charge extraction
- Sivers and all TMDs just with naïve Gaussian dependence (no x or z dependence)
Outline

- Single hadron fragmentation
  - Light hadron, Hyperon and charmed Baryon fragmentation (not TMDs)
  - Collins measurements
  - A polarizing fragmentation

- Di-hadron fragmentation
  - IFF measurements
  - Unpolarized mass, z dependence (for IFF)

- Other ongoing measurements (kt dependence)
- Other possibilities

Anselms talk
Access to FFs

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

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

- **e+e-:**
  \[ \sigma^h(z, Q^2, k_t) \propto \sum_q e_q^2 (D_{1,q}^h(z, k_t, Q^2) + D_{1,q}^h(z, k_t, Q^2)) \]
  - No PDFs necessary
  - Clean initial state, parton momentum known at LO
  - Flavor structure not directly accessible
B Factories: KEKB and PEP-II

- Asymmetric colliders
  - 8GeV + 3.5GeV (Belle)
  - 9GeV + 3.1 GeV (BABAR)
- $\sqrt{s} = 10.58$GeV ($Y(4S))$
- $e^+e^- \rightarrow Y(4S) \rightarrow B\bar{B}$
- Continuum production: 10.52 GeV
- $e^+e^- \rightarrow q\bar{q}$ (u,d,s,c) (75% of on resonance xsec)
- Integrated Luminosity: >1000 fb$^{-1}$ (Belle) + 500 fb$^{-1}$ (BABAR) on resonance
- >70fb$^{-1}$ => continuum
- + various other energies

- Also BESIII as charm factory at various energies with fragmentation function input
B factory data (Q~10GeV)

- High precision pion and kaon data from both B factory experiments
- Precision up to very high z
- Lever arm to much higher energy (Q~20 − 200GeV) data allows for determination of gluon fragmentation over evolution
New addition: single protons

PRD92 (2015) 092007

- Default Pythia and current Belle in good agreement with pions and kaons
- Protons not well described by any tune
Hyperon Fragmentation

Hyperons similar to light hadron fragmentation → peaking at low $z$ ($x_p$).

Baryon production not too well described by Pythia 6 default settings.

Belle: Niiyama et. al. PRD 97 (2018), 072005

\[ x_p = \frac{P^h}{P^h_{max}} \]
Charmed baryon Fragmentation

Belle: Niiyama et. al. PRD 97 (2018), 072005

- Charmed baryons carry large fraction of parton momentum, similar to charmed mesons
- Charmed fragmentation reasonably described in Pythia for main states
Charmed Fragmentation

- Heavier particles generally plotted vs normalized momentum \( x_p = \frac{P^h}{P^h_{max}} \)
- Unlike light hadrons, charmed hadrons contain large fraction of charm quark momentum

PRL.95, 142003 (2005) (Babar)
PRD73, 032002 (2006) (Belle)
PRD75, 012003 (2007) (Babar)
PRL 99, 062001 (2007) (Babar)
Collins fragmentation function


\[ D^h_{q \uparrow}(z, P_{h\perp}) = D^{h}_{1,q}(z, P_{h\perp}^2) + H^{\perp h}_{1,q}(z, P_{h\perp}^2) \frac{(\hat{k} \times \mathbf{P}_{h\perp}) \cdot \mathbf{S}_q}{z M_h} \]

- Spin of quark correlates with hadron transverse momentum
- Translates into azimuthal anisotropy of final state hadrons
Belle Collins asymmetries

- **Red points**: \( \cos(\phi_1 + \phi_2) \) moment of Unlike sign pion pairs over like sign pion pair ratio: \( A_{UL} \)
- **Green points**: \( \cos(\phi_1 + \phi_2) \) moment of Unlike sign pion pairs over any charged pion pair ratio: \( A_{UC} \)
- Collins fragmentation is large effect
- Consistent with SIDIS indication of sign change between favored and disfavored Collins FF

RS et al (Belle), PRL96: 232002
PRD 78:032011, D86:039905
Explicit transverse momentum dependence

- First explicit transverse momentum dependent extraction for Collins asymmetries (relative to thrust axis* or second hadron)
- Global Transversity and Collins fit (PRD 93 (2016) 014009) able to reproduce the dependence
Quark transversity via Collins: Kaons

Addition of kaon Collins fragmentation strongly needed for flavor decomposition of quark transversity

Large amount of potentially participating FFs well described by light and “heavy” favored and disfavored FFs

Allows inclusion of HERMES and COMPASS kaon asymmetries (+eventually EIC) in fits

Also: pion Collins at lower scale (BESIII) consistent with TMD evolution

Soon also $\pi^0$ and $\eta$ results

Belle update from with kaons and $k_t$ dependence (multi-dimensional) planned
Di-hadron fragmentation functions

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

\[ H^{h_1, h_2, \triangleleft}_{1,q}(z, Q^2, M_h) \]
Interference Fragmentation (IFF) in $e^+e^-$

- $e^+e^- \rightarrow (\pi^+\pi^-)_{\text{jet}_1}(\pi^+\pi^-)_{\text{jet}_2}X$
- Early work by Collins, Heppelmann, Ladinsky [NPB 420 (1994)]

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

$$A \propto H_1(z_1, m_1)\overline{H_1}(z_2, m_2)\cos(\varphi_1 + \varphi_2)$$
Belle IFF asymmetries: \((z_1 x m_1)\) Binning

2 d distributions of one hemisphere

PRL107:072004(2011)
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

\[ \frac{d^2\sigma}{dz dm_{\pi\pi}} \]
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)

\[
\frac{d^2\sigma}{dz dm_{\pi\pi}}
\]
Transverse momentum dependence

Aka un-integrated PDFs and FFs

\[ D_{1,q}^h(z, Q^2, k_t) \]
**K_T Dependence of FFs in e+e-**

- Gain also sensitivity into transverse momentum generated in fragmentation
- Two ways to obtain transverse momentum dependence
  - Traditional 2-hadron FF
    - Use transverse momentum between two hadrons (in opposite hemispheres)
    - Usual convolution of two transverse momenta
  - Single-hadron FF wrt to Thrust or jet axis
    - No convolution
    - Need correction for q\bar{q} axis
MC sample for various hadrons

6 thrust bins [0.5, 0.7, 0.8, 0.85, 0.9, 0.95, 1.0] x 18 z bins x 20 $k_T$ bins

$\frac{d^2\sigma}{dzdk_T}$

$\pi^+$  $K^+$  $p^+$
MC examples vs $k_T^2$

Fit exponential to smaller transverse momenta for Gaussian $k_T$ dependence and power low at higher $k_T$.
MC Gaussian widths

Once available for data this will be the first direct (no convolutions) measurement of z dependence of Gaussian widths.
K_T analysis status

- Single hadron analysis:
  - Analysis finished, Last stages of Belle internal review, paper draft written
  - Will include fits of Gaussian widths as a function of x and thrust for each particle
- Two-hadron k_T-analysis:
  - Finalizing analysis and cross checks
New possibilities:
From Correcting ISR to using it as a tool

• During di-hadron analysis and kt analysis successfully checked actual boost of qqbar pair in ISR events

• General Idea: Use photons reconstructed in Belle(2) to tune the reduced sqrt(s) and scale of the fragmenting qqbar system

• Belle(2) acceptance covers a larger range with EM Calorimetry than for tracking→ good at catching not too soft photons

• First test: use all photons that cannot be combined with another photon to be close to the π⁰ (0.1-0.17) or η (0.5-0.6) mass range
CMS energy of the $q\bar{q}$ system

- Remove detected photon(s), $E > 0.5\text{GeV}$ from system
- Correlation to true CMS energy seen

Possible improvements:
- Correlation with angle to the thrust axis
- Small angles to the beam directions
- Mostly from the higher energy beam
- Total reconstructed energy
New possibilities: jet-substructure+fragmentation

- Could jet-substructure work from HEP be used at EIC (and e+e-/pp/pA)?
  - Possibility to use jet charge and mass to distinguish quark and gluon jets might be very useful
  - Even better flavor separation
  - Gluon background removal for chiral-odd measurements?
- Up-down separation also possible? Sufficient discriminators available in e+e- or ep?

Plan to study this in the next years (if JSPS has mercy)
New possibilities:
other final state FFs needed?

- Extension of di-hadron analysis to any resonant hadron possible:
  - $K_s$, $K^*$, $\phi$, $\rho$, etc
- $\pi K$ and $K K$ IFF measurements
- Other Collins measurements?
EIC input

- Tensor charge: Flavor separation ($\pi,K$ Collins, IFF), reduced model dependence ($k_T$ dependence, unpol di-hadron FFs)
- Sivers, Boer-Mulders, etc: Flavor separation (unpol FFs), reduced model dependence ($k_T$ dependence)
- Helicity global analysis (unpol FFs)
- Heavy flavor access (clean charm FFs)
- Explicit TMD evolution input? (explicit ISR)
- Quark and gluon separated jet input? (jet-shape + FF)