Fragmentation Functions at $e^+e^-$ machines

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Outline

☆ Introduction
☆ Unpolarized Fragmentation Function
☆ Available data sets
☆ Present data about FF (DSS)
☆ Preliminary BaBar results

☆ Collins Fragmentation Function (Collins FF)
☆ Collins FF Results
☆ Interference Fragmentation Function (IFF)
☆ IFF results
☆ Summary and conclusion
Introduction: Unpolarized Fragmentation Function

Definition ($e^+e^-\rightarrow\gamma/Z^0\rightarrow h+X$)

Fragmentation: hadron production from quark, antiquark or gluon. The Fragmentation Function (FF) $D_i^h(x,s)$ is defined as the momentum distribution of hadron $h$ inside a jet of flavour $i$ and hardness $Q$.

- $x=2E_h/\sqrt{s}$ with $Q$ the momentum of the intermediate $\gamma$ or $Z$ boson.

Coefficient function; calculated in perturbative QCD

Parton Fragmentation Functions; Non perturbative and universal; determined from experiments.

Interpretation:

FF $D_i^h(z,\mu^2)$ can be seen as the probability that a parton $i$ fragments into a hadron $h$ carrying away a fraction $z$ of the parton’s momentum (analogus to Parton Distribution Functions).
Present data about FF

The electron-positron fragmentation functions for all charged particles for different $\sqrt{s}$ versus $x$

Perturbative QCD corrections lead to logarithmic scaling violations via the evolution equations (DGLAP):

$$\frac{\delta}{\delta \ln \mu^2} D_i(x, \mu^2) = \sum_j \int_x^1 \frac{dz}{z} P_{ji}(z, \alpha_s(\mu^2)) D_j\left(\frac{x}{z}, \mu^2\right)$$

- Most of data are obtained at LEP energies;
- At lower CMS energies and higher $x$, very little data are available;
- No information on how to disentangle quark from antiquark fragmentation;
- The information on how the individual $q$ flavour fragment into $h$ depends on the “tagging techniques”;
- 3-jet fragmentation to access gluon FF difficult (not yet well constrained).
Data sets

First measurements done in $e^+e^-$ collision:

- @CERN (LEP): ALEPH, DELPHI, L3, OPAL;
- @DESY (PETRA, DORISII): PLUTO, TASSO, ARGUS
- @SLAC (SLC): SLD.

Most recent data sets:

- B-factories $e^+e^-$: BABAR (@SLAC), BELLE (@KEK).

Data from ep and pp:

- Deep Inelastic Scattering: H1, HERMES, COMPASS, ZEUS;
- Hadronic Collision (RHIC): BRAHMS, PHENIX, STAR;
Many attempts to extract FF from $e^+e^-$ data: KKP, AKK, HKNS, Kretzer …

Uncertainty ranges of determined FF where not estimated;

Large difference between different fits.


Global analysis: DeFlorian, Sassot, Stratmann (DSS)

$e^+e^-$: Clean processes, high statistic, sensitivity to heavy quarks;
No gluons, no flavour/charge separation

$e^-p$: Flavour/charge separation, comparison with $e^+e^-$ frame (Breit frame)

$h^+h^-$: charge separation, sensitive to gluons, large z behavior
Large theoretical uncertainties, not sensitive to heavy quarks.
New sets of pion and kaon fragmentation functions obtained in next-to-leading order combined analysis of single-inclusive hadron production in $e^+e^-$ annihilation, pp collisions and SIDIS.

<table>
<thead>
<tr>
<th>Data used in NLO global analysis for <strong>pion FF</strong></th>
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<tbody>
<tr>
<td>TPC ($\sqrt{s}=29$GeV)</td>
<td>Inclusive, &quot;uds,c,b&quot; tag</td>
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<tr>
<td>TASSO ($\sqrt{s}=34/44$GeV)</td>
<td>Inclusive</td>
</tr>
<tr>
<td>SLD ($Z^0$)</td>
<td>Inclusive, &quot;uds,c,b&quot; tag</td>
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<tr>
<td>ALEPH</td>
<td>Inclusive</td>
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<tr>
<td>DELPHI ($Z^0$)</td>
<td>Inclusive, &quot;uds,c,b&quot; tag</td>
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<tr>
<td>OPAL</td>
<td>Inclusive, &quot;u,d,s,c,b&quot; tag</td>
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<tr>
<td>HERMES</td>
<td>$\pi^+$, $\pi^-$</td>
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<td>PHENIX (RHIC)</td>
<td>$\pi^0$</td>
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<td>STAR (RHIC)</td>
<td>$\pi^0$</td>
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<td>BRAHMS (RHIC)</td>
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<th>Data used in NLO global analysis for <strong>kaon FF</strong></th>
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<td>Inclusive</td>
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<tr>
<td>HERMES</td>
<td>$k^+$, $k^-$</td>
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<tr>
<td>STAR (RHIC)</td>
<td>$k^0_s$</td>
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<tr>
<td>BRAHMS (RHIC)</td>
<td>$k^+$, $k^-$</td>
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**DSS fit results**

**HERMES data:** constrain the separation between favored and unfavored distribution; 
**RHIC data:** stringent constraints on the gluon FF and on the large $z$ behavior; 

AKK, KRE NLO sets based only on SIA data

Hadron production in **BABAR/BELLE** would open up the possibility for studies of scaling violations with unprecedented precision and allow to reduce the present uncertainties.
BaBar Inclusive Hadronic Particle Spectra

BaBar measurement based on:
- **0.9 fb⁻¹ @10.54GeV** (below \(\Upsilon(4S)\));
  (10.58GeV ⇒ \(\Upsilon(4S)\) peak).

Plot scaled momentum distribution compared to ARGUS, TASSO and SLD data

Good consistency between BaBar and ARGUS data (ARGUS extends to lower values; BaBar covers the high side of the spectrum until the end with good precision, limited only by systematic effects).
Hadronization should be scaled invariant except for “small” effects of hadron masses, running $\alpha_s$, …

Scaling violation at low $x_p$, due to masses, are well know and modelled adequately (here JETSET is shown for comparison)

Expect substantial scaling violation at high $x_p$:  
• seen clearly in $\pi$ and $k$ data;  
• NOT seen in $p/\bar{p}$ data! Wrong model predictions.
Spin Dependent Fragmentation Function

- Tests of universality and factorization between $e^+e^-$, DIS and p-p collisions;
- Connection between microscopic (quark spin) and macroscopic observables (azimuthal hadron distribution);
- Provides final state spin analyzer for the study of quark transversity distributions from data taken by HERMES, COMPASS, JLab and RHIC experiments.

Outline
- Introduction;
- Collins Fragmentation Function;
- Interference Fragmentation Function;
- Results;
Motivation: transversity quark distribution from Collins FF and Interference FF

After averaging over the quark transverse momentum, three parton distribution functions are needed at leading twist for a complete description of the momentum and spin distribution of the quarks inside the nucleon (red in figure).

Transversity distribution function: describes the distribution of the quark’s transverse spin in a transversely polarized nucleon → it remains the less known fundamental quark distribution function.

### Table: Unpolarized quark distribution function

<table>
<thead>
<tr>
<th>QUARK</th>
<th>U</th>
<th>L</th>
<th>T</th>
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<tbody>
<tr>
<td>U</td>
<td>$f_1$</td>
<td></td>
<td>$h_1$</td>
</tr>
<tr>
<td>L</td>
<td>$g_1$</td>
<td></td>
<td>$h_{1L}$</td>
</tr>
<tr>
<td>T</td>
<td>$f_{1T}$</td>
<td>$g_{1T}$</td>
<td>$h_{1T}$</td>
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Transverse Momentum Dependent (TDM) distribution function arise when the transverse momentum of the quark is not integrated over, blue in the figure (non collinear phenomena).
Motivation: transversity quark distribution from Collins FF and Interference FF

SIDIS: Semi Inclusive Deep Inelastic Scattering

Factorization theorem:

$$\sigma^{ep\rightarrow e^+e^-X} = \sum_q DF \times \sigma(eq \rightarrow eq) \times FF$$

$$A_T \propto h_1(x) \times CFF(z)$$
$$A_T \propto h_1(x) \times IFF(z)$$

Global analysis to extract Transversity ($h_1$)

Collins and IFF asymmetries in $e^+e^-$ annihilation are:

$$\propto CFF(z_1) \times CFF(z_2)$$
$$\propto IFF(z_1) \times IFF(z_2)$$

Collins Asymmetries from HERMES, eg.
Luciano Pappalardo, DIS 2009, Madrid
Collins FF

Number density for finding an hadron h produced from a transversely polarized quark q:

\[ D_{hq}^{\uparrow} = D_1^q(z, P_{h\perp}^2) + H_1^{\perp q}(z, P_{h\perp}^2) \frac{\hat{k} \times \hat{P}_{h\perp} \cdot \vec{S}_q}{z M_h} \]

- Quark spin direction unknown: measurement of Collins function in one hemisphere is not possible (the \( \sin(\phi) \) modulation will average out)
- Correlation between two hemispheres results in \( \cos(\phi_1 + \phi_2) \) (or \( \cos(2\phi_0) \)) modulation of the observed di-hadron yield.

Measurement of azimuthal correlations for pion pairs (CFF) or pairs of pion pairs (IFF) around the jet axis in events with back-to-back jets!
Collins Effect: Fragmentation of a quark $q$ with Spin $S_q$ into a spinless hadron $h$ carries an azimuthal dependence

$$\propto (k \times p_{h,\perp}) S_q$$

Collins effect in $e^+e^-$ quark fragmentation will lead to azimuthal asymmetries in di-hadron correlation measurements:

$$N_{h_1h_2}(\phi_1+\phi_2) \sim a_{12}\cos(\phi_1+\phi_2)$$

Experimental requirements:

- small asymmetries need large data sample;
- the essential experimental requirements for FF measurements is the ability to identify hadron pair and to precisely measure the momenta and charge sign⇒good Particle Identification
- Large acceptance;
- Good tracking.
Analysis Reference Frame

\( \theta_1 \): angle between the lepton axis and the thrust axis;
\( \phi_{1,2} \): azimuthal angles of the two hadrons between the scattering plane and the transverse hadrons momenta \( P_{hiT} \).

\[ \frac{d\sigma(e^+e^- \rightarrow h_1h_2X)}{d\Omega dz_1dz_2d\phi_1d\phi_2} = \sum_{q,q'} \frac{3\alpha^2 e_q^2}{4Q^2} z_1^2 z_2^2 \left[ (1 + \cos^2 \theta) D_1^{q,0}(z_1) \bar{D}_1^{q,0}(z_2) + \sin^2(\theta) \cos(\phi_1 + \phi_2) H^{\perp,q,1}(z_1) \bar{H}_1^{\perp,q,1}(z_2) \right] \]

\( \theta_2 \): angle between the lepton axis and the second hadron momenta \( P_{h2} \);
\( \phi_0 \): angle between the plane spanned by one hadron momentum and the lepton momenta and the transverse momentum of the second hadron respect to the first hadron momentum.
Asymmetries extraction

Accessing the Collins Asymmetries: measurement of cosine modulation of hadron pair \((N(\phi_1 + \phi_2), \ N(2\phi_0))\) on the top of flat distribution due to unpolarized part of fragmentation function \(<N>\).

\[
R_\alpha = \frac{N(\phi_\alpha)}{<N_\alpha>} = a + b \cdot \cos(\phi_\alpha)
\]

- \(N(\phi_\alpha)\) contains Collins + radiative effects + acceptance effects

Method to eliminate the acceptance and radiative effects: Double Ratio of Raw Asymmetries:

\[
R = \frac{R^{UnLike}}{R^{Like}} = \frac{N^{UL}(\phi_\alpha)}{N^{L}(\phi_\alpha)} / \frac{<N>} {<N>} \propto 1 + \cos(\phi_\alpha)A^{UL/L}(z_1, z_2)
\]

\[
A^{UL/L}(z_1, z_2) \propto \frac{H_1^{fav} H_2^{fav} + H_1^{dis} H_2^{dis}}{D_1^{fav} D_2^{fav} + D_1^{dis} D_2^{dis}} - \frac{H_1^{fav} H_2^{dis} + H_1^{dis} H_2^{fav}}{D_1^{fav} D_2^{dis} + D_1^{dis} D_2^{dis}}
\]

- Asymmetries generated by QCD radiative events and acceptance effects are charge independent and cancel;
- Different combination of favored and disfavored FF

\(A^{UL/L}\) contains only Collins Asymmetries and higher order radiative effects.
Final Collins results \((e^+ e^- \rightarrow \pi \pi X)\)

4x4 \(z_1\) vs \(z_2\) binned analysis
\((z=\text{fractional energy of the pion})\)

- First results obtained by Belle Collaboration with pions.
  \(\text{}\)\(\text{PRL96,232002}\) 29fb\(^{-1}\) @10.52 GeV and 
  \(\text{}\)\(\text{PRD78,032011}\) 55fb\(^{-1}\) @10.52 GeV, 
  \(\text{}\)492fb\(^{-1}\) @10.58GeV \)

- Non zero asymmetries

- \textbf{BaBar analysis ongoing}
Global analysis results

Favoured and unfavoured Collins FF
- HERMES $A_{UT}$ p data
- COMPASS $A_{UT}$ d data
- Belle $e^+ e^-$ Collins data


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Global analysis results

First extraction of transversity
- HERMES $A_{UT}$ p data
- COMPASS $A_{UT}$ d data
- Belle $e^+ e^-$ Collins data
IFF in correlation of hadron pairs

Independent way to extract transversity, involving collinear FF: we consider the semi-inclusive production of two hadrons inside the same current jet: the fragmentation \( q \rightarrow (\pi^+ \pi^-)X \) is described by an (extended) Dihadron FF (or IFF).

**DiFF (IFF):** represents the probability that at some hard scale a parton hadronizes in two hadrons with fractional energies \( z_1 \) and \( z_2 \).

**IFF in \( e^+e^- \) quark fragmentation leads to azimuthal asymmetries in the correlation of two hadron pairs:**
\[
N_{\text{pair1,pair2}}(\phi_{\text{pair1}}+\phi_{\text{pair2}}) \sim a_{12}\cos(\phi_{\text{pair1}}+\phi_{\text{pair2}})
\]

\[
a_{12} \propto \frac{\sin^2(\theta)}{1 + \cos^2(\theta)} H_1(z_{\text{pair1}}, M_{h\text{pair1}}^2)H_1(z_{\text{pair2}}, M_{h\text{pair2}}^2)
\]
Interference Fragmentation Function

\[ R = P_{h1} - P_{h2} \]

\( e^+e^- \rightarrow (\pi^+\pi^-)_{\text{jet}1} (\pi^+\pi^-)_{\text{jet}2} X; \)
\( \Rightarrow \) detection pion pairs in opposite hemispheres;
\( \Rightarrow \) Observe azimuthal angle between the event plane the two two-pion-pairs;
\( \Rightarrow \) Transverse momentum is integrated (not TMD): universal, easy evolution, directly applicable to SIDIS and proton data;
\( \Rightarrow \) Analysis in z-bin and \( M_h \)-bin

Theoretical paper:
A.Bianconi, S.Boffi, R.Jakob, M.Radici, Phys.Rev. D62, 034008(2002);
(model prediction for \( e^+e^- \))
IFF-a_{12} vs Invariant Mass

8x8 m_1 m_2 binning

Systematic errors shown. a_{12} increases with m_1 and m_2 reaches \(|a_{12}| \sim 0.1\) at large m_i.
Unpolarized FF

⇒ We have precise data such from LEP and SLD at $Q=M_Z$, so that accurate small $Q^2$ data are needed for probing the $Q^2$ evolution ⇒ BaBar and Belle data contribution expected;

⇒ Many attempts to extract FF from $e^+e^-$ data: KKP, AKK, HKNS, Kretzer... with large difference between different fits;

⇒ First Global analysis extraction of FF for pions and kaons (DSS):
   ★ good global description of all $e^+e^-$, ep and pp data;
   ★ pions FF well determined; kaons less.
Summary II

Collins FF

- Significant non-zero Collins asymmetries found by Belle Collaboration (long paper published);
- BaBar Collins Asymmetries analysis ongoing;
- First global analysis done.

Interference FF

- Preliminary measurement of the Interference FF by Belle Collaboration
- Large asymmetries seen, rising with z and invariant mass (in agreement to theoretical prediction).

Future plans:

Carry out CFF asymmetries for the kaons system and the IFF asymmetries for other species: $(\pi^0, \pi^{\pm})$, $(K^+, K^-)$, $(\pi^+, K^-)$, …

Thanks to M. Grosse Perdekamp and R. Seidl for their helpfulness and suggestions
Backup slides
Raw asymmetries and Double Ratio

Collins asymmetries not included in Monte Carlo simulation

Fit function:
\[ a + b \cos(\phi) \]

Raw Asymmetries in the RF0

\[ b_0 \sim 1; \]
\[ a_0: \text{raw asymmetry parameter} \]
\[ \text{(include the acceptance effects and radiative effects)} \]

Double Ratio in the RF0

\[ B_0 \sim 1; \]
\[ A_0: \text{contains only the Collins Asymmetries and higher order radiative effects.} \]

PRL96.232002 29fb^{-1} @10.52 GeV
The B-factories, PEP-II and KEK, consist of asymmetric electron-positron beams. The center of mass energy is selected to be on the peak on the $\Upsilon(4S)$ meson (10.58 GeV/c$^2$), which decay more than 96% into BB meson pairs.

- $9 \text{ GeV } e^- - 3.1 \text{ GeV } e^+$;
- $\sqrt{s}=10.58 \text{ GeV } (\Upsilon(4S))$;
- continuum production: 10.54 GeV;
- Excellent PID and vertex production;
- $L \sim 500 \text{ fb}^{-1}$

- $8 \text{ GeV } e^- - 3.5 \text{ GeV } e^+$;
- $\sqrt{s}=10.58 \text{ GeV } (\Upsilon(4S))$;
- continuum production: 10.52 GeV;
- much available data;
- $L > 1000 \text{ fb}^{-1}$
The B-factories, PEPII and KEK, consist of asymmetric electron-positron beams. The center of mass energy is selected to be on the peak on the $\Upsilon(4S)$ meson ($10.58\text{ GeV}/c^2$), which decay more than 96% into $\BB$ meson pairs.

Physics program:
- The principal physics goal of the B-factories is to test the Kobayashi-Maskawa picture of CP violation by measuring the angle of the unitary triangle;
- precision measurements of decays of bottom and charm mesons of the $\tau$ lepton;
- search for rare processes;
- the very clean environment make BaBar suitable also for inclusive studies of hadron production:

**Study of the azimuthal asymmetries in the inclusive production of two back-to-back hadron in the reaction:** $e^+e^-\rightarrow h_1h_2X$
BaBar detector

**1.5T Solenoid**

**Electromagnetic Calorimeter**
6580 CsI(Tl) crystals

**Silicon Vertex Tracker**
5 layers of double sided silicon strips

**Instrumented Flux Return**
- 19 RPCs layers (Run1-Run3)
- 12 LSTs layers (Run4-Run7)

**DIRC**
144 quartz bars

**Drift CHamber**
40 stereo layers

**e⁻ (9GeV)**

**e⁺ (3.1GeV)**