Interference Fragmentation in e^+e^- and pp Collisions

AGS & RHIC User Meeting

BNL June 7th - June 11th 2010

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presenting Belle & PHENIX results
Outline

- Motivation and Present Knowledge of Transversity QDFs and the Tensor Charge
- Limitations and Alternate Access: Interference Fragmentation (IFF)
- IFF Asymmetries in e+e- in Belle
- IFF Asymmetries in pp in PHENIX
- Future Possibilities at RHIC
Why are Measurements of Spin Dependent Fragmentation Functions Interesting?

- Very basic QCD process: Fundamental test case for any approach to solve QCD at soft scales.
- Tests schemes of universality and factorization between $e^+e^-$, DIS and p-p collisions.
- Symmetry properties.
- Test evolution as fundamental QCD prediction.
- 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, RHIC and in the future EIC.
Global Analysis: Extract Transversity Distributions

SIDIS
\[ \sim \delta q(x) \times CFF(z) \]
\[ \sim \delta q(x) \times IFF(z) \]

Transversity, \( \delta q(x) \)
Tensor Charge

Lattice QCD: Tensor Charge = \( \sum_{q=u,d} \int_0^1 \delta q(x) dx \)

\begin{align*}
\text{e}^+\text{e}^- & \sim CFF(z_1) \times CFF(z_2) \\
& \sim IFF(z_1) \times IFF(z_2)
\end{align*}

\begin{align*}
\text{pp} & \rightarrow \text{jets} \\
& \sim G(x_1)x\delta q(x_2) \times CFF(z) \\
\text{pp} & \rightarrow h^+ + h^- + X \\
& \sim G(x_1)x\delta q(x_2) \times IFF(z) \\
\text{pp} & \rightarrow l^+ + l^- + X \\
& \sim \delta q(x_1) \times \delta q(x_2)
\end{align*}
Determination of Quark Transversity Distributions and Collins Fragmentation Functions

**Program:**

QCD analysis of Collins asymmetries in SIDIS (HERMES & COMPASS) + Collins asymmetries in e+e- (Belle)

⇒ extract quark transversity distributions and Collins fragmentation functions

\[ \sqrt{s}=10 \text{ GeV} \ e^+ + e^- \rightarrow \pi^+ + \pi^- + X \]

\[ \sqrt{s}=27.5 \text{ GeV} \ e+p \rightarrow \pi + X \]

\[ \sqrt{s}=160 \text{ GeV} \ \mu+d \rightarrow \pi + X \]
SIDIS $A_{UT}$ is sensitive to the Product of
[Transversity, $\delta q(x)$] $\times$ [Collins FF, $CFF(z)$]

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

Collins Asymmetries in semi-inclusive deep inelastic scattering

$e+p \rightarrow e + \pi + X$

$\sim \text{Transversity}(x) \times \text{Collins}(z)$

cannot unfold $\delta q(x)$ without additional information!

$A_{UT} \sin(\phi + \phi_S)$

HERMES data cover $x < 0.3$
e^+e^- Annihilation into Quarks is sensitive to \([Collins~FF, CFF(z_1)] \times [Collins~FF, CFF(z_2)]\)

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

\[ e^+e^- \rightarrow \pi^+ + \pi^- + X \]

\[ N_{\pi_1^+\pi_2^-}(\phi_1+\phi_2) \sim a_{12}\cos(\phi_1+\phi_2) \]

\[ a_{12} \sim Collins(z_1) \times Collins(z_2) \]
e^+e^- Annihilation into Quarks is sensitive to
[Collins FF, $CFF(z_1)$] x [Collins FF, $CFF(z_2)$]

Collins Asymmetries in e^+e^- annihilation into hadrons

$$e^+ + e^- \rightarrow \pi^+ + \pi^- + \chi$$

\[ A_{12} \approx \text{Collins}(z_1) \times \text{Collins}(z_2) \]

Extraction of Quark Transversity Distributions and Collins Fragmentation Functions \( \text{SIDIS} + e^+e^- \)

Belle: Collins Asymmetries

+ HERMES, & COMPASS data ➔ first extraction of \( \delta q(x) \)

Anselmino, Prokudin et al. 

Extraction of Transversity & Collins FF including errors!
Comparison of HERMES + Belle Based Prediction for COMPASS to Data

Preliminary COMPASS Collins Asymmetries for Proton Target vs predictions from Anselmino, Prokudin et al.

COMPASS at DIS 2009, Madrid

Good agreement of COMPASS proton data with predictions from fit to HERMES, COMPASS-d +Belle. Important cross check as COMPASS is at higher $Q^2$!

no data at $x > 0.4 \ldots$

$\delta q(x)$ not bound at large $x$

uncertainty in tensor charge
Interference Fragmentation in e+e− and pp Collisions

Prokudin et al. at Ferrara

\[ \int \delta u(x) \, dx = +0.59^{+0.14}_{-0.13} \]
\[ \int \delta d(x) \, dx = -0.20^{+0.05}_{-0.07} \] at \( Q^2 = 0.8 \text{ GeV}^2 \)


\[ \int \delta u(x) \, dx = +0.86 +/- 0.02 \]
\[ \int \delta d(x) \, dx = -0.22 +/- 0.05 \] at \( Q^2 = 0.8 \text{ GeV}^2 \)

Can nucleon structure be described ab initio QCD with the help of Lattice QCD?

Possible, future RHIC Contribution:
Constrain tensor charge by measuring transversity at medium and high x!
(likely requires forward upgrades)
Collins Extraction of Transversity: Model Dependence from Transverse Momentum Dependences!

\[
A_{UT}^{Collins} = \sum_q e_q^2 \int d\phi_s d\phi_h d^2 p_{\perp} q(x, k_{\perp}) \frac{d(\Delta\sigma)}{dy} H_{1,q}^{\perp}(z, p_{\perp}) \sin(\phi_s + \phi + \phi_h) \sin(\phi_s + \phi_h)
\]

\[
\sum_q e_q^2 \int d\phi_s d\phi_h d^2 p_{\perp} q(x, k_{\perp}) \frac{d(\Delta\sigma)}{dy} D_h^q(z, p_{\perp})
\]

- \(k_{\perp}\): transverse quark momentum in nucleon
- \(p_{\perp}\): transverse hadron momentum in fragmentation

The transverse momentum dependencies are unknown and difficult to obtain experimentally!

IFF will provide alternative route of access independent of knowledge of transverse momentum dependencies.

Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin, Turk
Alternative Approach:
Spin-Dependent di-Hadron Fragmentation:
Interference Fragmentation $\Rightarrow$ transverse
single spin asymmetries “survive” $k_T$ integration

Measured asymmetry $A$ is a convolution of
transversity $\Delta_T q(x)$ and
Two-Hadron-Interference-FF $H_1^{<}$:

$$A_{RS} = \frac{A}{f P_T D_{nn}} = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot H_1^{<}(z, M^2_{h^+h^-})}{\sum_q e_q^2 \cdot q(x) \cdot D_1(z, M^2_{h^+h^-})}$$
Interference Fragmentation in Polarized Proton-Proton Collisions

\[ \sigma_{ij}(x_1, x_2) = \int \frac{d^3 \sigma(q_1, q_2 \rightarrow q_3, q_4)}{dx_1 dx_2 dt} \times \int \delta q(x_1) \cdot q(x_2) \, dx_1 \, dx_2 \, dt \]

Interference Fragmentation (IFF)

Extracted from e^+e^- data

PQCD

Jian Tang, Thesis MIT, June 1999
**IFF in Polarized Proton-Proton Collisions**

Interference Fragmentation in $e^+e^-$ and $pp$ Collisions

$\phi$ = 1

$\eta = 0, m_{\rho,\sigma} = 0.83 \text{ GeV}, \cos \phi = 1$

$\delta q^2 = 4\delta q_0\delta q_1 / 3, \ 2|\delta q| \leq q + \Delta q$

$N^\to : \text{Pion Pair Yield}$

$\sin \delta_i : \text{Two Pion Phase Shifts}$

$\delta q(x) : \text{Transversity quark DFs}$

$\delta q(z) : \text{Pol. Fragmentation Func.}$

\[
A_\perp = \frac{1}{P_{\text{beam}}} \left( \frac{N^\to - N^\leftarrow}{N^\to + N^\leftarrow} \right) = -\frac{\sqrt{6}\pi}{4} \sin \delta_0 \sin \delta_1 \sin(\delta_0 - \delta_1) \cdot \cos(\phi) \cdot
\]

\[
\left[ \delta q(x_1) \cdot G(x_2) \cdot \delta q_1(z) \right] \delta \hat{q}_{gg} + \ldots
\]

\[
\left[ G(x_1) \cdot G(x_2) \right] \delta \hat{q}_{gg} + \ldots \cdot \left[ \sin^2 \delta_0 \hat{q}_0(z) + \sin^2 \delta_1 \hat{q}_1(z) \right]
\]
$A_{UT}$ compatible $\sim 0$

dilution from gg processes!

Future:

$\rightarrow$ more statistics!

$\rightarrow$ move forward to enhance qg fraction and move to higher $x$ (tensor charge!)

New Experiment at IP-2 that takes data with transverse spin in parallel to W-program would be not luminosity limited!
Measurement of IFF Asymmetries

Results released at the Spin Workshop in Dubna, 2009
see Anselm Vossen’s talk

For theoretical aspects of the measurement:
Interference Fragmentation in Correlation of di-Hadron Pairs in e^+e^- Annihilation into Quarks!

IFF in e^+e^- quark fragmentation leads to azimuthal asymmetries in the correlation of two hadron pairs:

\[ N_{\text{pair}_1,\text{pair}_2}(\phi_{\text{pair}_1} + \phi_{\text{pair}_2}) \sim a_{12} \cos(\phi_{\text{pair}_1} + \phi_{\text{pair}_2}) \]

**Experimental requirements:**

- Small asymmetries \( \Rightarrow \) very large data sample!
- Good particle ID to high momenta.
- Hermetic detector
- Events with back-to-back jets
Interference Fragmentation in e+e− and pp Collisions

KEKB: \( L > 2.1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \) !!

- Asymmetric collider
- 8 GeV e− + 3.5 GeV e+
- \( \sqrt{s} = 10.58 \text{ GeV}, \ e^+e^- \rightarrow \Upsilon(4S) \rightarrow B \bar{B} \)
- Off-resonance: 10.52 GeV
  \( e^+e^- \rightarrow q \bar{q} \) (u,d,s,c)
- Integrated Luminosity:
  588 fb\(^{-1}\) (on resonance)
  73 fb\(^{-1}\) (off-resonance)

Average Trigger rates:
- \( \Upsilon(4S) \rightarrow BB \) 11.5 Hz
- \( q \bar{q} \) 28 Hz
- \( \mu\mu + \tau\tau \) 16 Hz
- Bhabha 4.4 Hz
- 2γ 35 Hz

KEKB B-Factory

1.5 x 10^9 hadronic events in analysis ~ 430 x DELPHI …
Large acceptance, good tracking and particle identification!
Hadronic Events observed with Belle

$1.5 \times 10^9$ hadronic events in analysis

\[ \text{Thrust} \approx 1 \]

\[ \text{thrust} = \frac{\sum \vec{p}_i \cdot \hat{n}}{\sum_i |\vec{p}_i|} \]

\[ \approx 0.5 \]
Interference Fragmentation in e+e- and pp Collisions

**Thrust Method (e+e- CMS frame)**

- $e^+e^- \rightarrow \pi^+\pi^-)_{jet1}(\pi^-\pi^+)_{jet2}X$
- Find pion pairs in opposite hemispheres
- Measure azimuthal correlations of

$$N(\varphi_1 + \varphi_2) \propto H^\perp_1(z_1, m_1) \overline{H^\perp_1}(z_2, m_2) \cos(\varphi_1 + \varphi_2)$$

Amplitude of modulation directly measures IFF! (squared)

Here: $z_1, z_2$ relative momenta of first and second pair
Asymmetry Extraction

- Form normalized yields:
  \[ R(\phi_1 + \phi_2) = \frac{N_{12}(\phi_1 + \phi_2)}{\langle N_{12} \rangle} , \]

- Fit with:
  \[ R_{12} (\phi_1 + \phi_2) = a_{12} \cos(\phi_1 + \phi_2) + b_{12} \]

or

\[ R_{12} (\phi_1 + \phi_2) = a_{12} \cos(\phi_1 + \phi_2) + b_{12} + c_{12} \cos 2(\phi_1 + \phi_2) + d_{12} \sin(\phi_1 + \phi_2) \]

Amplitude \( a_{12} \) directly measures IFF squared!
Zero Tests:
(I) IFF not Included in MC!

- Small false asymmetry due to acceptance effect!
- Appearing at boundary of acceptance.
- Jet opening cut in CMS of 0.8 (~37 degrees) reduces acceptance effect to less than 0.001.
- Cut $\sin^2 \theta/(1 + \cos^2 \theta) > 0.5$
Zero Tests (II) : False
Asymmetries ~ 0 in Mixed Events

Thrust Axis from Event n or n-1
Impact of Smearing in Thrust Axis: Weighted MC Studies

- Inject asymmetries in Monte Carlo
- Reconstruction smears thrust axis,
- ~94% of input asymmetry is reconstructed
- Effect is understood, can be reproduced in Toy MC
- Asymmetries corrected
IFF- $a_{12}$ vs Invariant Mass

$8 \times 8 m_1 m_2$ binning

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

Interference Fragmentation in $e^+e^-$ and pp Collisions
Interference Fragmentation in $e^+e^-$ and pp Collisions

IFF- $a_{12}$ vs Pair Momentum Fraction $z_i$
Mass dependence: magnitude at low masses comparable, high masses significantly larger (some contribution possibly from charm)

Z dependence: Rising behavior steeper in data
Interference Fragmentation in e+e- and pp Collisions

- $a_{12}$ asymmetries directly measure IFF squared.
- IFF asymmetries provide analyzing power for quark spin without transverse momentum dependence.
- Double ratio approach to cancel contributions from radiative effects from Collins analysis not needed!
Summary

• First extraction of transversity from Collins data in e^+e^- and SIDIS has been carried out.

• Collins based, $\delta q(x)$ extraction is model dependent and SIDIS data only constrain $\delta q(x)$ for $x < 0.4$.

• IFF offers an alternative approach to resolve the model dependence and possibly to access higher $x$.

• First e^+e^- results for the IFF are available.

• Measurements at RHIC require more luminosity at mid-rapidity.

• Forward measurements at RHIC would offer better sensitivity + access to high $x$ but likely require upgrades.
Measurements of Quark Transversity
(from Ruizhe Yang)

1991

p+p
- E704, 1991
  Large forward SSA

SIDIS
- HERMES 2005,
  COMPASS 2006
  $A_{UT}$

$e^+e^-$
- BELLE 2006
  Collins FF

2005

Underway
- STAR, PHENIX,
  BRAHMS,
  2004~2005
  Inclusive $A_N$
- RHIC
  IFF asym.
- COMPASS
  p target
- BELLE
  IFF

Future
- RHIC
  Collins asym.
- JParc, RHIC, FAIR
  Drell-Yan
- JLab
  $^3$He and 12 GeV
- BELLE
  $k_T$ dep. Pol. & upol
  FF, pol. Lambda FF
Cuts and Binning

• Similar to Collins analysis, full off-resonance and on-resonance data: ~73 fb\(^{-1}\) (off) + 588 fb\(^{-1}\) (on).
• Visible energy >7GeV.
• PID: purities in pion/pion sample > 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: \(|T_z| < 0.75\)
• Thrust > 0.8
• \(z_{\pi^-}, z_{\pi^+} > 0.1\)
• \(z_1 = z_{\pi^+} + z_{\pi^+}^2\) and \(z_2\) in 9x9 bins
• \(m_{\pi\pi_1}\) and \(m_{\pi\pi_2}\) in 8x8 bins: \([0.25 - 2.0]\) GeV
Systematic Studies

- Mc asymmetries
- Reweighted asymmetries
  - Constant, linear weights
- Mixed events
- Single hemispheres
- Higher harmonics
- Binning
- Inverse thrust
- Relative process contributions
- Correlation studies
- Combining data from diff exp
- Kinematics correlations & center values
- Pid systematics
- Cross checks
- Asymmetries as polar angles
- Decay angle dependent asymmetries
- Mixed binning asymmetries
Systematic Errors

• Dominant:
  – MC asymmetries + its statistical error ( ~% level)

• Smaller contributions:
  – Mixed event asymmetries: ~ 0.001
  – Higher moments: < 0.001
  – Axis smearing
  – Tau contribution
  – Charm contributions

• Possible effects from gluon radiation not included in systematic error.
Subprocess Contributions: uds, charm, tau, Bs

9x9 $z_1$ $z_2$ binning

tau contribution (only significant at high $z$)
charged $B$ (<5%, mostly at higher mass)
Neutral $B$ (<2%)
charmed (20-60%, mostly at lower $z$)
uds

Data not corrected for Charm contributions
Subprocess Contributions:
uds, charm, tau, Bs

Data not corrected for Charm contributions

charged B (<5%, mostly at higher mass)
Neutral B (<2%)
charm (20-60%, mostly at highest masses)
uds
Projections for $(\pi^+\pi^0)(\pi^+\pi^0)$ for 580 fb$^{-1}$
Projections for $(\pi^+K^-)(K^+\pi^-)$ for 580 fb$^{-1}$
Luminosity vs Time for 24 hours at KEKB
Continuous Injection $\rightarrow$ Constant Collision Rate

\[ \int L dt = 1 \text{fb}^{-1}/\text{day} \]
Measuring Light Quark Fragmentation Functions on the $\Upsilon(4S)$ Resonance

\[ \sum_i p_i \cdot \hat{n} = \text{thrust} \]

- small B contribution (<2%) in high thrust sample.
- keep >75% of cross-section continuum under $\Upsilon$ (4S) resonance
  \[ \Rightarrow \] 73 fb\(^{-1}\) off-resonance data in analysis
  & 588 fb\(^{-1}\) on-resonance data for IFF and slightly less for Collins analysis.
- charm contribution sizeable!
Motivation $\Delta G$ from QCD Analysis of $A_{LL}$ for inclusive hadrons: $\pi^0,+,\pm, \eta, K^+,\pm$

PHENIX $\pi^0$ cross section $a |\eta|<0.35$


Deviation connected to uncertainties in FFs $\Rightarrow$ gluon FF!

Idea: QCD analysis of LEP and Belle data will fix uncertainty in knowledge of FFs (gluon FF, flavor separation)

$A_{LL} \equiv \frac{d \Delta \sigma}{d \sigma} = \frac{d \sigma^{++} - d \sigma^{+-}}{d \sigma^{++} + d \sigma^{+-}}$

Data-QCD/QCD

$p_T$ (GeV/c)
Impact on the Knowledge of FFs

Belle: Charged $h^{\pm}$, pions, kaons, protons

$z = \frac{E^h}{\sqrt{s} / 2}$

$\frac{1}{\sigma_{\text{tot}}} \frac{d\sigma}{dz} \times \alpha(s)$

<1% of data sample

→ work in progress

precision at high z!

Input also for precision measurements of quark helicity distributions in SIDIS, in particular at a possible future electron-polarized proton collider.
Collins Fragmentation: Angles and Cross Section \( \cos(2\varphi_0) \) Method (CMS Frame)

Observable: yield, \( N_0(2\varphi_0) \) of \( \pi^+\pi^- \) pairs

Independent of thrust-axis
Convolution integral \( I \) over transverse momenta
[Boer, Jakob, Mulders: NPB504(1997)345]

2-hadron inclusive transverse momentum dependent cross section:

\[
\frac{d\sigma(e^+e^- \rightarrow h_1h_2X)}{d\Omega dz_1dz_2d^2q_T} = \ldots B(y) \cos(2\varphi_0) I \left[ \left( 2\hat{h} \cdot k_T \hat{h} \cdot p_T - k_T \cdot p_T \right) \frac{H_1^\perp \overline{H}_1^\perp}{M_1 M_2} \right]
\]

\[
B(y) = y(1 - y) \left( \frac{cm}{4} \right) \sin^2 \Theta
\]

Net anti-alignment of transverse quark spins
Final Charm Corrected Results for $e^+ e^- \rightarrow \pi \pi X$ (29fb$^{-1}$, off-resonance Data)

- Significant non-zero asymmetries
- Rising behavior vs. $z$
- UL/C asymmetries about 40-50% of UL/L asymmetries
- First direct measurements of the Collins function
- UL/L data published

\[
\begin{align*}
A_0(UL/L) &= (3.06 \pm 0.57 \pm 0.55)\% \\
A_{12}(UL/L) &= (4.26 \pm 0.68 \pm 0.68)\% \\
A_0(UL/C) &= (1.27 \pm 0.49 \pm 0.35)\% \\
A_{12}(UL/C) &= (1.75 \pm 0.59 \pm 0.41)\%
\end{align*}
\]
Preliminary Charm Corrected Results for
$e^+ e^- \rightarrow \pi \pi X$ (547 fb$^{-1}$, on-resonance)

- Significance largely increased
- Behavior unchanged
- Reduced systematics
- Precise measurements of the Collins function

**Integrated results:**

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<tbody>
<tr>
<td>$A_0(UL/L)$</td>
<td>$(2.67 \pm 0.10 \pm 0.26)$%</td>
</tr>
<tr>
<td>$A_{12}(UL/L)$</td>
<td>$(3.55 \pm 0.08 \pm 0.15)$%</td>
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<tr>
<td>$A_0(UL/C)$</td>
<td>$(1.11 \pm 0.11 \pm 0.22)$%</td>
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<tr>
<td>$A_{12}(UL/C)$</td>
<td>$(1.46 \pm 0.09 \pm 0.13)$%</td>
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