Polarized fragmentation functions from \textit{Belle}

8\textsuperscript{th} Circum Pan Pacific Symposium on High Energy Spin Physics
Cairns, June 21, 2011

\textbf{Ralf Seidl (RIKEN)}

for the Belle Collaboration
Transverse quark polarization

Unpolarized distribution function \( q(x) \)

Helicity distribution function \( \Delta q(x) \)

Transversity distribution function \( \delta q(x) \)

Sum of quarks with parallel and antiparallel polarization relative to proton spin (well known from Collider DIS experiments)

Difference of quarks with parallel and antiparallel polarization relative to longitudinally polarized proton (known from fixed target (SI)DIS experiments)

Difference of quarks with parallel and antiparallel polarization relative to transversely polarized proton (first results from HERMES and COMPASS – with the help of Belle)
Transversity properties

- Helicity flip amplitude
- Chiral odd
- Since all interactions conserve chirality one needs another chiral odd object
- Does not couple to gluons $\Rightarrow$ different QCD evolution than $\Delta q(x)$
- Valence dominated $\Rightarrow$
  Comparable to Lattice calculations, especially tensor charge

$$q(x) = q_+(x) + q_-(x) \sim Im(A_{++,+} + A_{-,-,+})$$
$$\Delta q(x) = q_+(x) - q_-(x) \sim Im(A_{++,++} - A_{+-,+-})$$
$$\delta q(x) = q_\uparrow(x) - q_\downarrow(x) \sim ImA_{+-,+-}$$

Positivity bound:
$$|\delta q(x)| \leq q(x)$$

Soffer bound:
$$|\delta q(x)| \leq \frac{1}{2} (q(x) + \Delta q(x))$$
How to access Transversity: another chiral-odd function

Drell Yan:
- Combine two Transversity distributions with each other

SIDIS/pp:
- Combine Transversity distributions with chiral-odd fragmentation function (FF)
- Total process is chiral-even: OK
- Possible Partners:
  - Collins FF
  - Interference FF
  - Transverse L FF
- Most require single spin asymmetries in the fragmentation

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Towards a global transversity analysis: Chiral –odd Fragmentation functions

RHIC and SIDIS experiments measure:

Transversity $\delta q(x) \times$

Collins Fragmentation function $H^\perp_i(z)$

or Interference Fragmentation function (IFF)

Belle measures:

Collins X Collins - finished for charged pion pairs

or IFF X IFF – charged pions about to be published

2 Unknown Functions measured together

Transversity

• Universality understood
• Evolution?
KEKB: $L > 2.1 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ !!

- Asymmetric collider
- 8GeV $e^- + 3.5$GeV $e^+$
- $\sqrt{s} = 10.58$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)
- Integrated Luminosity: >1000 fb$^{-1}$
- >70fb$^{-1}$ => continuum

Main research at Belle:
CP violation and determination of Cabibbo Kobayashi Maskawa (CKM) matrix
Belle Detector

SC solenoid
1.5T

CsI(Tl)
16X₀

TOF counter

Aerogel Cherenkov cnt.
n=1.015~1.030

Central Drift Chamber
small cell +He/C₂H₆

μ / K_L detection
14/15 lyr. RPC+Fe

Si vtx. det.
3/4 lyr. DSSD

3.5 GeV e^+

8 GeV e^-

Good tracking and particle identification!
ε(K)~85%,
ε(π→K)<10%

ε(K)~85%,
Fragmentation functions in $e^+e^-$ annihilation

Process: $e^+ e^- \rightarrow hX$

At leading order sum of unpolarized fragmentation functions from quark and anti-quark side

\[
F^h(z, s) = \frac{\sum_q e_q^2 [D^h_q(z) + D^h_{\bar{q}}(z)]}{\sum_q e_q^2}
\]

LO

\[
F^h(z, s) = \sum_i \int_0^1 \frac{dz'}{z'} C_i(s; z' \alpha_s) D^h_q(z)
\]

NLO

$z = \frac{2E_h}{\sqrt{s}}$, $\sqrt{s} = 10.52 \text{GeV}$
Collins fragmentation in $e^+e^-$:

Angles and Cross section $\cos(\phi_1+\phi_2)$ method

$e^+e^-$ CMS frame:

$$z = \frac{2E_h}{\sqrt{s}}, \quad \sqrt{s} = 10.52 \text{ GeV}$$

2-hadron inclusive transverse momentum dependent cross section:

$$\frac{d\sigma(e^+e^- \rightarrow h_1h_2X)}{d\Omega dz_1dz_2d^2q_T} = \cdots B(y) \cos(\phi_1 + \phi_2)H_1^{[1]}(z_1)\overline{H_1^{[1]}}(z_2)$$

$$B(y) = y(1-y)^{cm} = \frac{1}{4} \sin^2 \Theta$$

Net (anti-)alignment of transverse quark spins

[D. Boer: PhD thesis (1998)]
Final Collins results

- First direct measurement of the Collins effect:
  (PRL96: 232002)
- 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: $A^{UC}$
- Nonzero asymmetries seen
- Factor 19 increase in statistics in second, long paper: 547 fb\(^{-1}\) data set (PRD78:032011)
Transverse single spin asymmetries in SIDIS

- Measure azimuthal asymmetries for (at least) two angular modulations simultaneously

\[ A_{UT}^{\sin(\phi+\phi_S)} \propto S_\perp \frac{\sum_{q,\bar{q}} e_q^2 \delta q(x) \, H_1^\perp(z)}{\sum_{q,\bar{q}} e_q^2 q(x) \, D_1(z)} \]

\[ A_{UT}^{\sin(\phi-\phi_S)} \propto S_\perp \frac{\sum_{q,\bar{q}} e_q^2 f_{1T}^\perp q(x) \cdot D_1(z)}{\sum_{q,\bar{q}} e_q^2 q(x) \, D_1(z)} \]

U: unpolarized beam
T: transversely polarized target

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Collins amplitudes I

- Large, nonzero asymmetries seen
- Transversity and Collins effect nonzero
- Large $\pi^-$ asymmetries require disfavored Collins function of opposite sign

M. Diefenthaler @ DIS07, hep-ex 0707.0222 and HERMES, PRL. 94 (2005) 012002

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COMPASS amplitudes II

COMPASS, hep-ex/0802.2160

Asymmetries nonzero, consistent with HERMES

- Compatible with zero due to cancellation

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SIDIS: Most recent Collins moments

Not completely used in fit, yet

Proton

Deuteron
First global analysis from Collins Hermes, Compass d and Belle data

- First results available, still open questions from evolution of Collins FF and transverse momentum dependence
- More data available now
- Cross check using interference fragmentation functions needed

Interference Fragmentation — thrust method

- $e^+e^- \rightarrow (\pi^+\pi^-)_{\text{jet}_1}(\pi^+\pi^-)_{\text{jet}_2}X$
- Look in the mass region around $\rho$-mass (largest interference expected)
- Find pion pairs in opposite hemispheres
- Observe angles $\phi_1+\phi_2$ between the event-plane (beam, jet-axis) and the two two-pion planes.
- Transverse momentum is integrated (universal function, evolution known $\rightarrow$ directly applicable to semi-inclusive DIS and pp)
- Early work by Collins, Heppelmann, Ladinsky [NPB420(1994)]

$$A \propto H_1^\perp (z_1, m_1)\overline{H}_1^\perp (z_2, m_2) \cos(\phi_1 + \phi_2)$$

Model predictions by:

- Jaffe et al. [PRL 80, (1998)]
- Radici et al. [PRD 65, (2002)]
Asymmetry extraction

- Build normalized yields:
  \[ \frac{N(\phi_1 + \phi_2)}{\langle N \rangle} \]

- Fit with:
  \[ a_{12} \cos(\phi_1 + \phi_2) + b_{12} \]
  or
  \[ a_{12} \cos(\phi_1 + \phi_2) + b_{12} + c_{12} \cos 2(\phi_1 + \phi_2) + d_{12} \sin(\phi_1 + \phi_2) \]

Amplitude \( a_{12} \) directly measures (IFF) \( x \) (−IFF) (no double ratios)
Zero tests: Mixed Events

(Red/blue points: Thrust axis last or current event)
Inject asymmetries in Monte Carlo
Reconstruction smears thrust axis,
~94% of input asymmetry is reconstructed
(Integrated over thrust axis: 98%)
Effect is understood, can be reproduced in Toy MC
Asymmetries corrected

Smearing in azimuthal Angle of thrust Axis in CMS

Black: injected
Purple reconstructed

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Systematic Errors

- Dominant:
  - MC asymmetry + its statistical error (up to % level)

- Smaller contributions:
  - PID: per mille level
  - higher moments: sub per mille level
  - Uncertainty on axis smearing correction
  - mixed asymmetries: per mille level
  - Tau asymmetries

- Note: asymmetries contain events from u,d,s and c events

arXiv:1104.2425
Submitted to PRL
Results incl. sys. errors: \((z_1 \times z_2)\) Binning

Magnitude increasing with \(z\)

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$m_1 \times m_2$ binning

Magnitude increasing with mass, then leveling off

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(z_1 x m_1) Binning

2 d distributions of one hemisphere

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(m_1 \times z_1) Binning

Binning

Polarized fragmentation functions from Belle
First transversity extraction from HERMES and Belle IFF data

Alessandro Bacchetta at RHIC DY workshop May 2011:

First glimpses at transversity

- Early studies indicate little effect of evolution in Collins function, both results comparable
- Preliminary data by Compass and PHENIX not used

Not in disagreement with Anselmino et al.

Bacchetta, Radici, Courtoy, arXiv:1104.3855
Unpolarized Fragmentation functions

- Process:
  \( e^+ e^- \rightarrow hX \)

- At leading order sum of unpolarized fragmentation functions from quark and anti-quark side

\[
\begin{align*}
    z &= \frac{2E_h}{\sqrt{s}}, \quad \sqrt{s} = 10.52 \text{ GeV} \\

    \text{LO} \quad F^h(z, s) &= \frac{\sum_q e_q^2 [D^h_q(z) + D^\bar{h}_q(z)]}{\sum_q e_q^2} \\
    \text{NLO} \quad F^h(z, s) &= \sum_i \int_{\alpha_z}^1 \frac{dz'}{z'} C_i(s; z', \alpha_z) D^h_q(z)
\end{align*}
\]
World data and motivation for precise FFs

- Most data obtained at LEP energies,
- At lower CMS energies very little data available
- 3-jet fragmentation to access gluon FF theoretically difficult
  ➔ Gluon fragmentation from evolution not yet well constrained
  ➔ Higher z FFs (>0.7) hardly available
Current knowledge on fragmentation functions – DSS, HKNS, AKK


Differences between different global fits still large for high-z gluon contributions, kaons and disfavored fragmentation


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Systematic studies: Particle identification

- **Particle identification**: create PID efficiency matrix for K, π, p, e, μ
- **PID responses from MC not reliable**, use well identified decays from data:
  - Use $D^* \rightarrow \pi_{\text{slow}}$ for K, π identification
  - Use $\Lambda \rightarrow \pi p$ for p, π identification
  - $J/\psi \rightarrow \mu^+ \mu^-$, $e^+ e^-$ for leptons
    (if needed also Y(1S))
  - **Unfolding**

\[
\begin{pmatrix}
N_{e_{\text{likelihood-cut}}} \\
N_{\mu_{\text{likelihood-cut}}} \\
N_{\pi_{\text{likelihood-cut}}} \\
N_{K_{\text{likelihood-cut}}} \\
N_{p_{\text{likelihood-cut}}}
\end{pmatrix} = 
\begin{pmatrix}
\epsilon_e - \epsilon_e & \epsilon_e - \mu & \epsilon_e - \pi & \epsilon_e - K & \epsilon_e - p \\
\epsilon_\mu - \epsilon_e & \epsilon_\mu - \mu & \epsilon_\mu - \pi & \epsilon_\mu - K & \epsilon_\mu - p \\
\epsilon_\pi - \epsilon_e & \epsilon_\pi - \mu & \epsilon_\pi - \pi & \epsilon_\pi - K & \epsilon_\pi - p \\
\epsilon_K - \epsilon_e & \epsilon_K - \mu & \epsilon_K - \pi & \epsilon_K - K & \epsilon_K - p \\
\epsilon_p - \epsilon_e & \epsilon_p - \mu & \epsilon_p - \pi & \epsilon_p - K & \epsilon_p - p
\end{pmatrix} 
\begin{pmatrix}
N_{e_{\text{real}}} \\
N_{\mu_{\text{real}}} \\
N_{\pi_{\text{real}}} \\
N_{K_{\text{real}}} \\
N_{p_{\text{real}}}
\end{pmatrix}
\]
2. Unpolarized Fragmentation Functions
New precision measurement at $Q^2 = 100$ GeV$^2$ in progress at Belle

Extensive PID studies PID probabilities extracted from real data over wide kinematic range:

```
e.g. $D^* \rightarrow 
\pi_{\text{slow}} \ (D^0 \rightarrow \pi_{\text{fast}} \ K)$
```

Further corrections for momentum smearing, acceptance effects

---

Martin Leitgab’s Spin 2010 talk
**D* Extraction**

final extraction: large acceptance region covered

**Status of FF analysis:**
- PID study finished
- Smearing correction finished
- Acceptance correction + nonQCD contribution removal ongoing
- Plan: have results soon
Event Structure for hadron pairs in $e^+e^-$ annihilation

**Spin averaged cross section:**

$$\frac{d\sigma(e^+e^- \to h_1h_2X)}{d\Omega dz_1dz_2} = \frac{3\alpha^2}{Q^2} A(y) \sum_{a,\bar{a}} e_a^2 D_1(z_1)\overline{D}_1(z_2)$$

$$A(y) = \left(\frac{1}{2} - y + y^2\right)^{(cm)} = \frac{1}{4} \left(1 + \cos^2 \Theta\right)$$

Jet axis: Thrust

**e^+e^- CMS frame:**

$$z = \frac{2E_h}{\sqrt{s}}, \quad \sqrt{s} = 10.52 \text{ GeV}$$

$$\langle N_{h^+,\gamma} \rangle = 6.4$$
Unpolarized 2-hadron fragmentation

- Detect two hadrons simultaneously:
  \( e^+e^- \rightarrow hhX \)
- If two hadrons in opposite hemispheres one obtains sensitivity to favored/disfavored fragmentation:
- Difficulty: contribution from one quark fragmentation \( q \rightarrow hhX \) 
  \( \rightarrow \) measure all three:
  - \((hh)_{\text{jet1}} X\)
  - \((h)_{\text{jet1}}(h)_{\text{jet2}} X\)
  - \(hhX,\)
  ( ) requires thrust cut

- Unlike-sign pion pairs (U):
  \((\text{favored} \times \text{favored} + \text{unfavored} \times \text{unfavored})\)
- Like-sign pion pairs (L):
  \((\text{favored} \times \text{unfavored} + \text{unfavored} \times \text{favored})\)
- any charge hadron pairs (C):
  \((\text{favored} + \text{unfavored}) \times (\text{favored} + \text{unfavored})\)

\[ \text{Favored} = u \rightarrow \pi^+, d \rightarrow \pi^-, \text{cc.} \]
\[ \text{Unfavored} = d \rightarrow \pi^+, u \rightarrow \pi^-, \text{cc.} \]
Sample MC (udsc) distributions

- $\pi\pi$

- 45 fb$^{-1}$ sampled (~50% of off resonance data)
- PID corrected using Martin’s Matrices
- Smearing not yet corrected (but small)
- Acceptance not yet corrected

⇒ Statistic reasonable out to high $z$

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Sample MC (udsc): \( \pi^+\pi^+/\pi^+\pi^- \) ratio

- Yield ratios will be almost directly sensitive to disfavored/favored FF ratio
- Acceptance effects cancel

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polarized fragmentation functions from Belle
## Summary and outlook

- **First direct measurement of the interference fragmentation function**
  - Large asymmetries seen, rising with $z$ and invariant mass
  - No sign change at $\rho$ mass
  - No double ratios make interpretation simple
  - Submitted to PRL
- **Significant, nonzero Collins asymmetries**, Data used already in Global analysis
- **Measure precise unpolarized fragmentation functions of many final states**
  - Important input for general QCD physics and helicity structure measurements
  - Analysis progressing:
    - PID studies finished
    - smearing correction finished
    - Acceptance correction ongoing

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<th>New di-hadron fragmentation function analysis started</th>
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<td>- Information of favored/disfavored FF</td>
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<td>- Vector meson FFs</td>
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<td><strong>VM Collins analysis started</strong></td>
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<td>- Artru Model test</td>
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<td><strong>Continue to measure precise spin dependent fragmentation functions at Belle</strong></td>
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<td>- $kT$ dependence of Collins function,</td>
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<td>- $\pi^0, \eta, K$ Collins,</td>
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<td>- $pK, KK$ IFF</td>
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<td><strong>Measure other interesting QCD-related quantities at Belle:</strong></td>
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<td>- Chiral-odd $\Lambda$-fragmentation function</td>
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<td>- $\Lambda$ single spin asymmetry</td>
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<td>Belle Fragmentation activity</td>
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<th>RIKEN/RBRC</th>
<th>Illinois</th>
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</table>
| Unpol FFs $e^+e^- \rightarrow hX:$ | $e^+e^- \rightarrow hhX, (h)(h)X,$ hhX: | **Neutral hadrons:** $(\pi^0, \eta^0)$  
**John Koster**  
**Charged di-hadrons:** Ralf Seidl | **Charged hadrons ($\pi,K,P$):**  
Martin Leitgab | **Black:** about to start  
**Green:** ongoing  
**Grey:** finished |
| **Unpol $k_T$ dependence:** | | | Martin Leitgab | |
| Collins FFs $e^+e^- \rightarrow (h)(h)X$: | $\pi\pi^0 : \text{John Koster}$  
$\pi\rho^0 : \text{Ralf Seidl}$  
$\pi\pi : \text{Ralf Seidl}$  
$\pi\pi^0 : \text{John Koster}$ | $\pi K, KK: \text{Francesca Giordano}$  
Francesca Giordano | | |
| **$k_T$ dependence:** | | | | |
| Interference FF: $e^+e^- \rightarrow (hh)(hh)X$ | Charged $\pi\pi : \text{Ralf Seidl}$ | Charged $\pi\pi : \text{Anselm Vossen}$  
$\pi\pi^0 : \text{Anselm Vossen}$ | Charged $\pi K$,  
KK: Nori-aki Kobayashi | |
| Local $P: \Lambda(polFF, SSA)$ : Jet-jet asy. | | | | |

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Backup Slides
A simple model to illustrate that spin-orbital angular momentum coupling can lead to left right asymmetries in spin-dependent fragmentation:

\[ u \rightarrow \pi^+ \] picks up \( L=1 \) to compensate for the pair \( S=1 \) and is emitted to the right.

String breaks and a \( d\bar{d} \)-pair with spin -1 is inserted.

In Artru Model: favored (ie \( u \rightarrow \pi^+ \)) and disfavored (ie \( u \rightarrow \pi^- \)) Collins function naturally of opposite sign.
Collins fragmentation in $e^+e^-$: Angles and Cross section $\cos(2\phi_0)$ method

$e^+e^-$ CMS frame:

\[ \Theta_2 \]

\[ \varphi_0 \]

2-hadron inclusive transverse momentum dependent cross section:

\[
\frac{d\sigma(e^+ e^- \rightarrow h_1 h_2 X)}{d\Omega dz_1 dz_2 d^2q_T} = \cdots B(\Theta) \cos(2\phi_0) I \left[ \left( \hat{h}_1 \cdot \hat{h} \cdot p_T - k_T \cdot p_T \right) \frac{H_1^+ H_1^-}{M_1 M_2} \right]
\]

\[
B(\Theta) = \frac{1}{4} \sin^2 \Theta
\]

Net (anti-)alignment of transverse quark spins

- Independent of thrust-axis
- Convolution integral $I$ over transverse momenta involved

[Boer, Jakob, Mulders: NPB504(1997)345]
Interference Fragmentation – “$\phi_0$” method

- Similar to previous method
- Observe angles $\phi_{1R} + \phi_{2R}$ between the event-plane (beam, two-pion-axis) and the two two-pion planes.
- Theoretical guidance by Boer, Jakob, Radici

$$A \propto H_1^L(z_1, m_1)H_1^L(z_2, m_2)\cos(\phi_{1R} + \phi_{2R})$$
tau contribution (only significant at high z)
charged B(<5%, mostly at higher mass)
Neutral B (<2%)
charm(20-60%, mostly at lower z)
uds (main contribution)
Subprocess contributions (MC)

tau contribution (only significant at high z)
charged B(<5%, mostly at higher mass)
Neutral B (<2%)
charm (20-60%, mostly at lower z)
uds (main contribution)
Zero tests: MC

- A small asymmetry seen due to acceptance effect
- Mostly appearing at boundary of acceptance
- Opening cut in CMS of 0.8 (~37 degrees) reduces acceptance effect to the sub-per-mille level

\[ \frac{P_h \cdot \hat{n}}{|P_h|} = \cos(P, n) \]
Heavy flavor fragmentation

Rolf Seuster:
Phys.Rev.D73:032002, 2006, 103 fb⁻¹

- Charmed hadron fragmentation much harder than light hadron fragmentation
- heavy quark more likely to stay in heavy hadron
Sample MC (udsc) distributions - $\pi\pi$

- opposite hemispheres
- Yields very similar
  $\Rightarrow$ Naturally dominating at higher $z$

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Sample MC (udsc) distributions

- $\pi\pi$

- same hemisphere:
  - Distributions falling off rapidly
  - Naturally as $z_1 + z_2 < 1$

- For same hemisphere also interesting:
  - $z^{\text{Pair}}, m^{\text{Pair}}$ distribution
  - Corresponding resonances’ FF ($\rho$, $K^*$, $\Phi$)

- Also unpol Baseline for IFF

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Higher statistics available at high $z$

- B decays almost at rest $\rightarrow$ no hadrons above 0.5
- Instead of about 90 pb$^{-1}$ almost 1000 fb$^{-1}$ available
- Useful at high $z$, where statistics is low

Polarized fragmentation functions from Belle
Rho Collins – similar plans for $\pi^0, \eta$

- Measure Collins effect for $e^+e^- \rightarrow \pi^\pm \rho^0 X$
- According to Artru model sign change expected wrt. pion Collins:
  
  $$\text{sgn} \ a_{12}(\pi^\pm \rho^0) = - \text{sgn} \ a_{12}(\pi^\pm \pi^\pm)$$

- Instead of double ratios to eliminate acceptance/radiative effects use combinatoric BG

Normally:

$$A_{\text{Real}} = \frac{N_{\text{All}}}{N_{\text{Signal}}} A_{\text{Signal}} - \frac{N_{\text{BG}}}{N_{\text{Signal}}} A_{BG}$$
MC (uds) Rho Collins example

- Acceptance effect visible in all three mass ranges
- Magnitude similar, but need more statistics to confirm method