Measurements of Collins asymmetries at BESIII

Workshop on FFs and EECs

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Introduction

Proton spin crisis

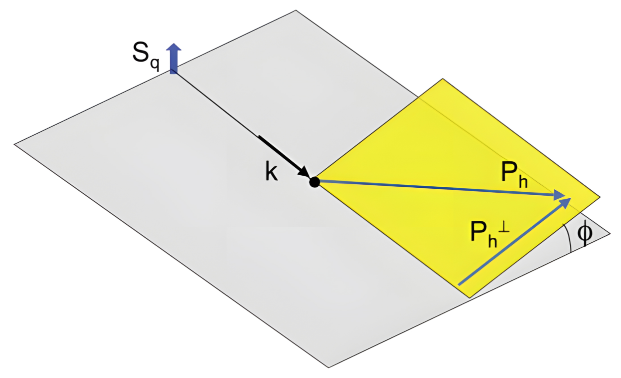
- **EMC (1990s):** Quark spins account for only ∼20–30% of the proton's total spin
- Subseqent measurement by HERMES shown that sea quark and gluon contributions are also small
- The missing spin likely comes from parton orbital angular momentum
- Understanding this requires a 3D picture of the nucleon's internal structure, beyond the collinear parton model

Spin structure: PDFs and Transversity

- Nucleon structure is described by three leading-twist PDFs:
    - $f_1(x)$: Unpolarized parton distribution
    - $g_1(x)$: Helicity (longitudinal polarization)
    - $h_1(x)$: Transversity (transverse polarization, chiral-odd)
- **Transversity** $h_1(x)$ is the least known; it's chiral-odd and hard to access in inclusive DIS
- To extract transversity, one needs to couple it to a chiral-odd partner, such as the Collins fragmentation function

Collins fragmentation function

- The Collins FF ($H_1^\perp$) describes how a transversely polarized quark fragments into a hadron, generating azimuthal asymmetries
- Collins FF is chiral-odd, making it an essential partner for measuring transversity
- Provides direct access to the parton's transverse structure — crucial for resolving the proton spin puzzle

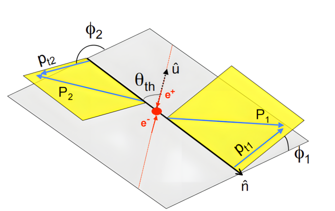


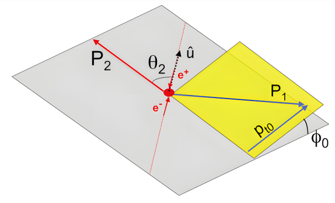
Role of e^+e^- annihilation

- **Semi-inclusive deep inelastic scattering (SIDIS)**
  - Process: $e^- + p^\uparrow \to e^- + h + X$
  - One measures the product: **Transversity** $\otimes$ **Collins FF**
  - Gives access to transversity, but it is entangled with the Collins function
- **Electron-Positron (e^+e^-) annihilation**
  - Process: $e^+e^- \to h_1 + h_2 + X$
  - One measures the product: **Collins FF** $\otimes$ **Collins FF**
  - Provides a clean measurement of Collins FF via azimuthal correlations between hadron pairs

How to measure collins asymmetries?

- In e^+e^- annihilation, the beams are unpolarized:
  - No single-hadron Collins effect can be seen, spin effects cancel on average
  - Product of quark and anti-quark Collins functions leads to a measurable **cosine modulation** in the azimuthal angular distribution of the two hadrons
- Two reference frames are commonly used for the azimuthal angle definition:
  - **Jet frame:** Suitable at high energy, when jet axes are well-defined
  - **Second-Hadron frame:** Used at BESIII, the azimuthal angle ϕ_0 is defined with respect to the second hadron's momentum





Observable: Normalized yields

- **Experimental observable:** Normalized yield distribution as a function of $2\phi_0$:
$$R = \frac{N(2\phi_0)}{\langle N_0 \rangle}$$
$N(2\phi_0)$ is the yield in each $2\phi_0$ bin and $\langle N_0 \rangle$ is the average yield over all bins
- The normalized yield shows a characteristic cosine modulation:
$$R = a\cos(2\phi_0) + b$$
    - a: Amplitude of Collins asymmetry contains detector effects and QCD radiation
    - $b \approx 1$: Normalization constant

Double ratio method

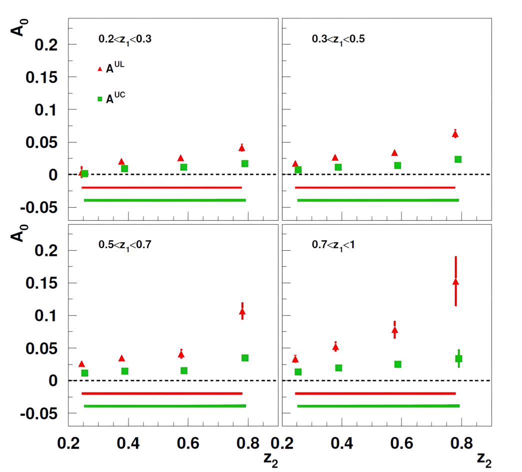
- To reduce systematic uncertainties such as detector acceptance and QCD radiative effects, we construct the double ratio of normalized yields:

$$\frac{R^U}{R^{L(C)}} = \frac{N^U/\langle N^U\rangle}{N^{L(C)}/\langle N^{L(C)}\rangle} = 1 + A^{UL(C)}\cos(2\phi_0).$$

  - Unlike-sign (U): $\pi^+\pi^-$, $K^+\pi^-$
    - Dominated by **favored FF**: $u \to \pi^+$
  - Like-sign (L): $\pi^+\pi^+$, $K^+\pi^+$
    - Dominated by **disfavored FF**: $u \to \pi^-$
  - Charged (C): All $\pi\pi$ combinations
    - Sum of U and L contributions

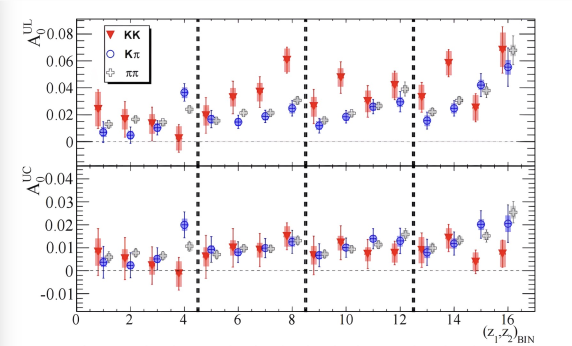
First observation: Belle

- The Collins asymmetry was first observed by **Belle** ($\sqrt{s} = 10.6$ GeV) in $e^+e^- \to \pi\pi X$
- Measurement performed in bins of hadron fractional energy (z)
- Combined with SIDIS: global extraction of transversity



BaBar: Precision and extended channels

- **BaBar** ($\sqrt{s} = 10.6$ GeV) confirmed and extended the Belle measurement
- Performed detailed measurements for $e^+e^- \to \pi\pi X$:
  - Asymmetries vs z, p_t, and $\sin^2\theta/(1+\cos^2\theta)$
  - Also performed a (z, p_t) measurement (limited by statistics)
- Later BaBar measured Collins asymmetries for $e^+e^- \to K\pi X$ and KKX channels (in bins of z)



The Unique position of BESIII

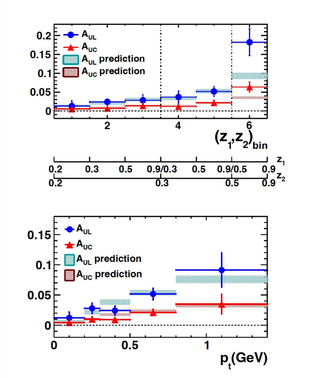
- B **factory (Belle, BaBar):** High Q^2 (≈ 110 GeV^2)
- **SIDIS (HERMES, COMPASS, JLab):** Low Q^2 region ($2 \lesssim Q^2 \lesssim 40$ GeV^2)
- Energy evolution of the Collins FF at different Q^2 is a key factor for extracting transversity
- A measurement in the intermediate region is crucial
- **BESIII** fills this gap, studying e^+e^- annihilation at $10 \lesssim Q^2 \lesssim 20$ GeV^2 directly overlapping with SIDIS

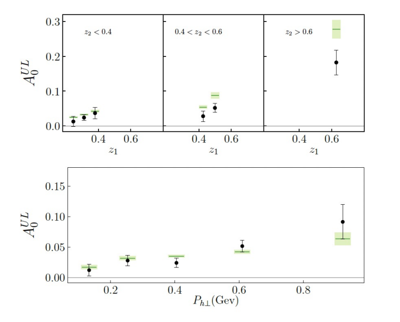
First Measurement at Low Q^2

- BESIII perform the first measurement of Collins asymmetry in $e^+e^- \to \pi\pi X$ at $\sqrt{s} = 3.65$ GeV ($Q^2 \approx 13$ GeV^2)
- Dataset: $\sim$62 pb^{-1} collected in 2011–2012
- Normalized yields analyzed in bins of z, p_t, and $\sin^2\theta/(1+\cos^2\theta)$
- Observed larger asymmetry than B factory
- Provided the first experimental test of Q^2 evolution in the Collins FF at low energy

Tension with theory at high z/p_T

- Overall, the measured asymmetries are consistent with theoretical predictions, but some deviations in high-z and high-p_T bins
- These bins suffer from large statistical uncertainties
- Higher-precision measurements are needed to clarify the observed tension and further test QCD evolution





Precise measurements of Collins asymmetries in inclusive production $e^+e^- \to h_1 h_2 X$

Goals of this analysis

- Provide a **high-precision measurement** of Collins asymmetries at low Q^2 using two large data samples:

$$\sqrt{s} = 3.510\ \text{GeV}\ (\mathcal{L} \approx 446\ \text{pb}^{-1}), \quad \sqrt{s} = 3.650\ \text{GeV}\ (\mathcal{L} \approx 400\ \text{pb}^{-1})$$

- Use a dataset with **14 times more luminosity** than the previous BESIII study
- **Key measurements:**
  - Significantly improve the precision for the $\pi\pi$ channel
  - Perform the **first low-Q^2 measurements** for the $K\pi$ and KK channels at this energy
  - Measure asymmetries in bins of:
    - z
    - p_{t0}
    - $\frac{\sin^2\theta}{1+\cos^2\theta}$
  - For the $\pi\pi$ channel: conduct the **first fully differential 3D measurement** at low Q^2 — simultaneously in (z_1, z_2, p_{t0}) bins

Analysis workflow

1. Event selection and PID criteria
   - Apply all kinematic cuts, multiplicity, thrust, and z range requirements
2. Extraction of raw asymmetries
   - Fit double-ratio distributions with $\cos(2\phi_0)$ modulation
3. MC tuning and misidentification study
   - Tune MC to match data distributions
   - Determine particle misidentification fractions
4. Unfolding to obtain true asymmetries
   - Subtract true asymmetry from measured raw asymmetries
5. Evaluation of systematic uncertainties

Event selection

- General requirements
  - Good charged track requirements
  - PID requirements applied on final state hadrons
- Further selection criteria
  - $N_{good} > 2$
  - $N_{ele} = 0$
  - Opening angel between hadron larger than 120 degree
  - Thrust value $T < 0.99$

$$T = Max[\frac{\sum_{\mathrm{h}} |\mathbf{P_h}^{\mathrm{CMS}} \cdot \hat{\mathrm{n}}|}{\sum_{\mathrm{h}} |\mathrm{P}_{\mathrm{h}}^{\mathrm{CMS}}|}]$$

Asymmetry vs. z_1, z_2

Definition of z binning scheme

- The light-cone fractional energy of a hadron:

$$z = \frac{E_h}{E_{\mathrm{beam}}} \simeq \frac{2E_h}{\sqrt{s}}$$

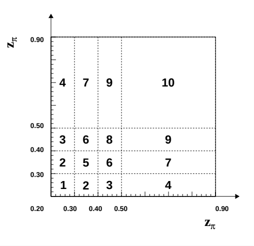
- For **pions**:
  - Require $0.20 < z_\pi < 0.90$
  - Lower bound: suppress pions from resonance decays (ρ, f, etc.)
  - Upper bound: remove two-body decays
  - Four z_π bins for both $\sqrt{s} = 3.510$ and 3.650 GeV:

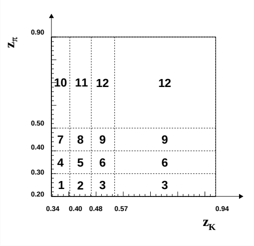
$$[0.20, 0.30],\ (0.30, 0.40],\ (0.40, 0.50],\ (0.50, 0.90]$$

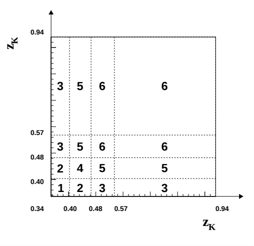
- For **kaons**:
  - Use same **momentum boundaries** as pions, but compute z_K with kaon mass hypothesis
  - 3.510 GeV: $z_K = 0.34$, 0.40, 0.48, 0.57, 0.94
  - 3.650 GeV: $z_K = 0.33$, 0.40, 0.48, 0.56, 0.94

Illustration of binning scheme

- **Symmetric z bins merged:** Identical z_π binning used for both energy points
- **Kaon bins reduced:** Due to limited K statistics, the last two z_K bins are merged:
    - 3.510 GeV: $z_K = 0.34, 0.40, 0.94$
    - 3.650 GeV: $z_K = 0.33, 0.40, 0.94$
- Extract raw asymmetry by fitting the double ratio in each z bin with the function $R = a\cos(2\phi_0) + b$







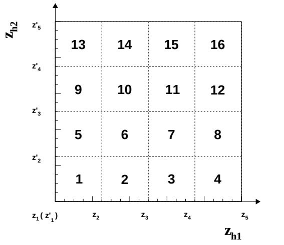
MC tuning for Mis-ID correction

- Misidentification ($\pi \to K$) causes cross-contamination among $\pi\pi X$, $K\pi X$, and KKX samples
- Determine correction weights $w_{\pi\pi}$, $w_{K\pi}$, w_{KK} to make MC yields match data in each channel
- Apply the weights to MC so that the $\pi\pi X$, $K\pi X$, and KKX yields match data in all z bins

$$(1 - f_{\pi\pi}^{\text{other}})N_{\pi\pi}^{\text{data}} = w_{\pi\pi}N_{\pi\pi\to\pi\pi}^{\text{MC}} + w_{K\pi}N_{K\pi\to\pi\pi}^{\text{MC}} + w_{KK}N_{KK\to\pi\pi}^{\text{MC}}$$

$$(1 - f_{K\pi}^{\text{other}})N_{K\pi}^{\text{data}} = w_{\pi\pi}N_{\pi\pi\to K\pi}^{\text{MC}} + w_{K\pi}N_{K\pi\to K\pi}^{\text{MC}} + w_{KK}N_{KK\to K\pi}^{\text{MC}}$$

$$(1 - f_{KK}^{\text{other}})N_{KK}^{\text{data}} = w_{\pi\pi}N_{\pi\pi\to KK}^{\text{MC}} + w_{K\pi}N_{K\pi\to KK}^{\text{MC}} + w_{KK}N_{KK\to KK}^{\text{MC}}.$$



Unfolding the mixed asymmetries

- Due to $K\pi$ mis-ID, the measured raw Collins asymmetry $A^{\mathrm{raw}}_{h_1 h_2}$ is a mixture of $\pi\pi$, $K\pi$, KK components (plus "other", with $A_{\mathrm{other}} = 0$)
- The true asymmetries $A_{\pi\pi}$, $A_{K\pi}$, A_{KK} are obtained by solving :

$$
\begin{aligned}
A^{\mathrm{raw}}_{\pi\pi} &= f^{\pi\pi\to\pi\pi}_{\pi\pi} A_{\pi\pi} + f^{K\pi\to\pi\pi}_{\pi\pi} A_{K\pi} + f^{KK\to\pi\pi}_{\pi\pi} A_{KK},\\
A^{\mathrm{raw}}_{K\pi} &= f^{\pi\pi\to K\pi}_{K\pi} A_{\pi\pi} + f^{K\pi\to K\pi}_{K\pi} A_{K\pi} + f^{KK\to K\pi}_{K\pi} A_{KK},\\
A^{\mathrm{raw}}_{KK} &= f^{\pi\pi\to KK}_{KK} A_{\pi\pi} + f^{K\pi\to KK}_{KK} A_{K\pi} + f^{KK\to KK}_{KK} A_{KK}.
\end{aligned}
$$

- Fractions $f^{h_1' h_2' \to h_1 h_2}_{h_1 h_2}$ are obtained from the MC tuned with mis-ID correction
- Get the true asymmetries by solving in six KKX z-bin subgroups using a χ^2 fit:

$$
\chi = \frac{A^{\mathrm{raw}} - f^{\pi\pi} A_{\pi\pi} - f^{K\pi} A_{K\pi} - f^{KK} A_{KK}}{\Delta A^{\mathrm{raw}}}, \quad \chi^2 = \sum_{i=1}^{N_{\mathrm{bins}}} \chi_i^2
$$

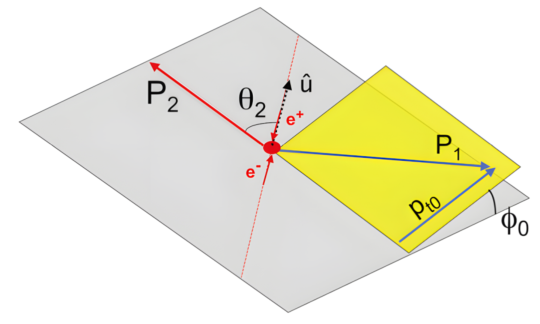
Systematic uncertainties

- Intrinsic asymmetry in MC generation
- Detection effect
- Particle ID and tracking efficiency
- Subtraction method
- Fit function
- Non-zero A_{other}
- Background

Asymmetry vs. P_{t0}

Definiton of P_{t0}

- P_{t0} is defined as the transverse momentum of the first hadron relative to the direction of the second hadron's momentum in the hadron-pair frame
- The ordering of hadron pairs is randomized to avoid bias in P_{t0} definition



Binning scheme in P_{t0}

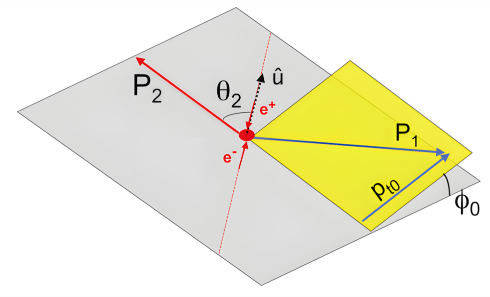
- Binning is optimized separately for each hadron combination:
  - $\pi\pi$: 10 bins
  - $K\pi$: 10 bins
  - KK: 5 wider bins
- The same P_{t0} binning scheme is applied for both $\sqrt{s} = 3.51$ GeV and $\sqrt{s} = 3.65$ GeV datasets
- Analysis procedure follows exactly the same steps as the z-bin analysis:
  - Extract raw asymmetries from data
  - Tune MC to match data and obtain misidentification fractions
  - Use these fractions as input to the unfolding procedure to obtain true asymmetries

$\pi\pi$	0.00	0.16	0.22	0.27	0.31	0.36	0.41	0.46	0.54	0.66	1.36
$K\pi$	0.00	0.16	0.22	0.27	0.31	0.36	0.41	0.46	0.54	0.66	1.36
KK	0.00	0.22		0.31		0.41		0.54		1.36	

Asymmetry vs. $\frac{\sin^2 \theta_2}{1+\cos^2 \theta_2}$

Definition of θ_2

- θ_2 is the polar angle between the momentum direction of the second hadron and the beam axis
- The ordering of hadron pairs is randomized to avoid bias in the θ_2 definition; the second hadron in this order defines θ_2



Binning scheme in $\frac{\sin^2\theta_2}{1+\cos^2\theta_2}$

- Measure asymmetry in bins of $\frac{\sin^2\theta_2}{1+\cos^2\theta_2}$
- Variable choice motivated by the UL (UC) double–ratio expression:

$$\frac{R^U}{R^L(C)} \simeq 1 + < \frac{\sin^2\theta}{1+\cos^2\theta} > \cos(2\phi_0)(G^U - G^L(C))$$

  Predicts asymmetries vanish at $\theta_2 = 0$ and grow with $\frac{\sin^2\theta_2}{1+\cos^2\theta_2}$
- 10 bins for $\pi\pi$ and $K\pi$ channels, 5 bins for KK channel
- Same binning scheme is applied for both $\sqrt{s} = 3.510$ GeV and $\sqrt{s} = 3.650$ GeV datasets
- Analysis procedure follows exactly the same steps as previous variables

<table>
<tr><td>$\pi\pi$</td><td>0.00</td><td>0.15</td><td>0.25</td><td>0.35</td><td>0.45</td><td>0.55</td><td>0.65</td><td>0.75</td><td>0.85</td><td>0.95</td><td>1.00</td></tr>
<tr><td>$K\pi$</td><td>0.00</td><td>0.15</td><td>0.25</td><td>0.35</td><td>0.45</td><td>0.55</td><td>0.65</td><td>0.75</td><td>0.85</td><td>0.95</td><td>1.00</td></tr>
<tr><td>KK</td><td>0.00</td><td colspan="2">0.25</td><td colspan="2">0.45</td><td colspan="2">0.65</td><td colspan="2">0.85</td><td colspan="2">1.00</td></tr>
</table>

Asymmetry vs. (z, P_{t0})

Motivation for the (z, P_{t0}) measurement

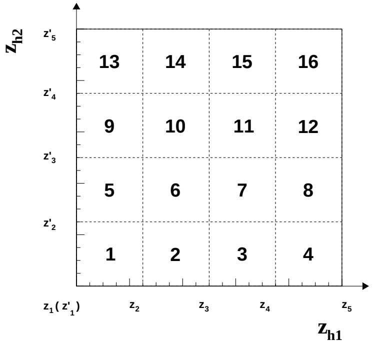
- First fully differential measurement of Collins asymmetry at BESIII in $(z_{\pi 1}, z_{\pi 2}, P_{t0})$ for the $\pi\pi$ channel
- BaBar performed a similar study, but:
    - Measurement done in the jet frame — less convenient for direct use in global fits of Collins fragmentation functions
    - Limited by large statistical uncertainties
- Our analysis:
    - Uses the hadron-pair frame, directly compatible with SIDIS measurements and global fits
    - Based on BESIII large statistic dataset at $\sqrt{s} = 3.51$ GeV and 3.650 GeV

Analysis strategy

- Follows the same framework as the nominal z-bin measurement:
  - Identical event selection criteria
  - Raw asymmetries extracted from $\cos(2\phi_0)$ fits to double ratios
- Key differences in the 3D case:
  - No merging of symmetric z bins, since P_{t0} depends on hadron ordering
  - Each $(z_{\pi 1}, z_{\pi 2})$ bin is analyzed independently
  - No unfolding applied — misidentification effects are treated as systematic uncertainty
- Dedicated MC studies performed to quantify:
  - Possible generator-level asymmetries
  - Detector-induced effects
  - Misidentification rates

Binning scheme for (z, P_{t0})

- 4×4 binning in $(z_{\pi 1}, z_{\pi 2})$:
  - Matches nominal z bin boundaries
- Within each $(z_{\pi 1}, z_{\pi 2})$ bin:
  - Data further divided into 5 bins of P_{t0}
  - Bin edges chosen to yield approximately equal statistics across P_{t0} bins in each z region
- Same $(z_{\pi 1}, z_{\pi 2}, P_{t0})$ binning scheme applied at both energy points



Binning scheme for (z, P_{t0})

z bin	P_{t0} bin 1	P_{t0} bin 2	P_{t0} bin 3	P_{t0} bin 4	P_{t0} bin 5
1	[0.00,0.18]	[0.18,0.25]	[0.25,0.30]	[0.30,0.35]	[0.35,0.46]
2	[0.00,0.25]	[0.25,0.35]	[0.35,0.43]	[0.43,0.49]	[0.49,0.63]
3	[0.00,0.32]	[0.32,0.45]	[0.45,0.55]	[0.55,0.63]	[0.63,0.79]
4	[0.00,0.43]	[0.43,0.60]	[0.60,0.74]	[0.74,0.85]	[0.85,1.41]
5	[0.00,0.18]	[0.18,0.25]	[0.25,0.30]	[0.30,0.35]	[0.35,0.46]
6	[0.00,0.24]	[0.24,0.34]	[0.34,0.42]	[0.42,0.48]	[0.48,0.63]
7	[0.00,0.30]	[0.30,0.43]	[0.43,0.54]	[0.54,0.62]	[0.62,0.78]
8	[0.00,0.39]	[0.39,0.56]	[0.56,0.70]	[0.70,0.83]	[0.83,1.39]
9	[0.00,0.18]	[0.18,0.25]	[0.25,0.30]	[0.30,0.35]	[0.35,0.46]
10	[0.00,0.24]	[0.24,0.34]	[0.34,0.41]	[0.41,0.48]	[0.48,0.63]
11	[0.00,0.28]	[0.28,0.41]	[0.41,0.51]	[0.51,0.61]	[0.61,0.79]
12	[0.00,0.35]	[0.35,0.51]	[0.51,0.66]	[0.66,0.79]	[0.79,1.32]
13	[0.00,0.18]	[0.18,0.25]	[0.25,0.30]	[0.30,0.35]	[0.35,0.46]
14	[0.00,0.23]	[0.23,0.32]	[0.32,0.40]	[0.40,0.47]	[0.47,0.62]
15	[0.00,0.26]	[0.26,0.38]	[0.38,0.48]	[0.48,0.58]	[0.58,0.78]
16	[0.00,0.29]	[0.29,0.43]	[0.43,0.56]	[0.56,0.71]	[0.71,1.27]

Summary

Summary and outlook

- Performed high-precision measurements of Collins asymmetries at low Q^2 ($\sqrt{s} = 3.510$ and 3.650 GeV) with large BESIII datasets
- Measure the Collins asymmetry for $\pi\pi$, $K\pi$ and KK channels in bins of:
  - z
  - P_{t0}
  - $\frac{\sin^2\theta_2}{1+\cos^2\theta_2}$
- First BESIII measurement of (z, P_{t0}) dependence for $\pi\pi$ channel
- We invite collaboration with theorists to:
  - Compare results directly with model predictions
  - Incorporate our measurements into global fits to extract Collins FFs

Thanks!

Backups

Binning scheme for P_{t0}

Table 1: Bin boundaries in P_{t0} (GeV/c) for each hadron combination.

<table>
<tr><td>$\pi\pi$</td><td>0.00</td><td>0.16</td><td>0.22</td><td>0.27</td><td>0.31</td><td>0.36</td><td>0.41</td><td>0.46</td><td>0.54</td><td>0.66</td><td>1.36</td></tr>
<tr><td>$K\pi$</td><td>0.00</td><td>0.16</td><td>0.22</td><td>0.27</td><td>0.31</td><td>0.36</td><td>0.41</td><td>0.46</td><td>0.54</td><td>0.66</td><td>1.36</td></tr>
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</table>

Binning scheme for $\frac{\sin^2\theta_2}{1+\cos^2\theta_2}$

Table 2: Bin boundaries in $\frac{\sin^2\theta_2}{1+\cos^2\theta_2}$ for each hadron combination.

$\pi\pi$	0.00	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95	1.00
$K\pi$	0.00	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95	1.00
KK	0.00	0.25		0.45		0.65		0.85		1.00	