Two-Particle Correlations in Hadronic $e^+e^-$ Collisions at Belle and Their Implication

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on behalf of the Belle Collaboration

partial results in arXiv:2201.01694 accepted by PRL
new paper in preparation (to be submitted to JHEP)
Collectivity signal
Two-particle correlation: soft probe for Quark-Gluon Plasma (QGP) in heavy ion collisions

Minimal conditions for collectivity behavior [nucl-th:1707.02307]
Smaller collision systems such as ep, e⁺e⁻, yp, γA, to the future EIC!


Thrust-axis two-particle correlation: 
Search for medium expanding transverse to the out-going quark directions

The first measurement at $B$-factory energy:

The advantages:
- **Clean environment** of $e^+e^-$ system: turn-off any possible CGC effect
- **New inputs** to the phenomenological fragmentation models at low collision energy
- Newly-devised “thrust axis analysis” is sensitive to soft emissions
Belle Detector

**Electromagnetic CaLorimeter**
- $\gamma$, $\pi^0$ reconstruction
- $e^\pm$ identification

**Aerogel Cherenkov Counter**
- Particle identification

**Time Of Flight**
- Particle identification

**Silicon Vertex Detector**
- $B$ vertex determination

**Central Drift Chamber**
- Charged track momentum
- Particle identification

**KL / Muon detector**
- $K_L / \mu$ identification

*Boost to the CM frame for the correlation study!*
PYTHIA6-based Belle MC:
- $q\bar{q}$ ($q = u, d, c$ and $s$) fragmentation
- $\Upsilon(4S)$ decays (by EVTGEN)

Also simulated:
- Radiative Bhabha events
- Low multiplicity $e^+e^- \rightarrow l^+l^-$
- Two-photon processes

High statistics sample allows for probing the very stringent high-multiplicity class: $N_{\text{rec}}^{\text{trk}} \geq 14$ (0.02% of all events)
Thrust axis is defined with the consideration of the missing momentum (MET):

\[ T = \max_{\hat{n}} \frac{\sum_i \left| \vec{p}_i \cdot \hat{n} \right|}{\sum_i \left| \vec{p}_i \right|} \]

\[ (i \in \text{charged, neutral particles and MET}) \]

\[ \vec{p}_{\text{MET}} = -\sum_{\text{neu,chg}} \vec{p} \]

**Belle e^+e^−, \sqrt{s} = 10.52 \text{ GeV}**

- **Inclusive \( N_{\text{trk}}^{\text{rec}} \)**
  - Data
  - EVTGEN (PYTHIA6)
- **0 \leq N_{\text{trk}}^{\text{rec}} < 6**
- **6 \leq N_{\text{trk}}^{\text{rec}} < 10**
- **10 \leq N_{\text{trk}}^{\text{rec}} < 12**
- **12 \leq N_{\text{trk}}^{\text{rec}} < 14**
- **\( N_{\text{trk}}^{\text{rec}} \geq 14**

\( T \) closes to 0.5

Spherical

ex: \( B \)-decay

\( T \) closes to 1

Pencil-like

ex: \( q\bar{q} \) fragmentation

**Off-resonance**

(* plot statistics: \( \int \mathcal{L} dt: \) 1.3 fb\(^{-1}\))

on-resonance see backup
Belle has rather spherical events!
Result

Beam-axis two-particle correlations — off-resonance ($\sqrt{s}=10.52$ GeV)

- Reasonable data and MC agreements
- Intriguing discrepancies in high-multiplicity events from short to the middle range

12 ≤ $N_{\text{trk}}^{\text{rec}}$ < 14

High-multiplicity

<table>
<thead>
<tr>
<th>Short Range</th>
<th>Middle Range</th>
<th>Long Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(0 \leq</td>
<td>\Delta \eta</td>
<td>&lt; 1)$</td>
</tr>
</tbody>
</table>

Belle $e^+e^-\rightarrow qar{q}$

| $6 \leq N_{\text{trk}}^{\text{rec}} < 10$ | $1.0 \leq |\Delta \phi| < 1.5$ | $1.5 \leq |\Delta \phi| < 3.0$ |
|--------------------------------|----------------|----------------|
| correlated syst. = 6.3% | correlated syst. = 0.5% | correlated syst. = 0.7% |

arXiv:2201.01694
accepted by PRL

Yu-Chen (Janice) Chen

Quark Matter 2022
Larger discrepancies are observed btw data and PYTHIA6 in the near-side ($\Delta \phi \approx 0$) and away-side ($\Delta \phi \approx \pi$) peak values.

High-multiplicity

$12 \leq N_{\text{trk}}^{\text{rec}} < 14$
New reference z axis: event thrust axis
particles \((p_T, \eta, \phi)\) are re-calculated with respect to thrust axis

Similar to heavy-ion collisions study, the role of beam remnant is replaced by outgoing quarks

If high energy quarks can form some medium, looking from the thrust axis is sensitive to the azimuthal anisotropy of this “imaginary medium.”
The **mid rapidity region** is where a correlation function sensitive to:

- Beam axis analysis: hydrodynamic expansion of possible QGP medium in HI collisions
The **mid rapidity region** is where a correlation function sensitive to:

- **Beam axis analysis:**
  - hydrodynamic expansion of possible QGP medium in HI collisions

- **Thrust axis analysis:**
  - soft emissions or QGP in $e^+e^-$ annihilation
How to understand correlation function in thrust axis coordinate?

- Intra-jet correlation of on-axis jets is diluted!

Collinear leading intra-jet correlation dilutes along $\Delta \phi$
A weakened jet correlation

- Intra-jet correlation of on-axis jets is diluted!
A weakened jet correlation

- Intra-jet correlation of on-axis jets is diluted!
- Back-to-back-jet correlation is excluded at finite $|\Delta \eta|$ region of interest

Working regions for correlation function

Observable

Intra-jet correlation of on-axis jets is diluted!
- Sizable origin-peak is lacking
- Qualitatively good agreement in correlation function shape btw data and MC

Result

Thrust-axis two-particle correlations — off-resonance ($\sqrt{s}$=10.52 GeV)

- $12 \leq N_{\text{trk}}^{\text{rec}} < 14$

High-multiplicity

Belle $e^+e^- \rightarrow q\bar{q}$, $\sqrt{s}$=10.52 GeV

- (preliminary)

Correlated syst. = 1.5% (preliminary)

Data

PYTHIA6

arXiv:2201.01694 accepted by PRL

Yu-Chen (Janice) Chen

Quark Matter 2022
Enhanced long-range near-side correlation, but does NOT resemble to typical ridge structure

Similar enhancement seen in MC

Up to 5% larger discrepancy seen in the correlation magnitude in the long-range region

High-multiplicity

\[ 12 \leq N_{\text{trk}}^{\text{rec}} < 14 \]
Ridge yield upper limits

- Selections are the dominant systematics sources
- Beam axis analysis: $>5\sigma$ exclusion of ridge signal

### Beam axis
- Off $\Upsilon(4S)$ resonance
- On $\Upsilon(4S)$ resonance
- Markers shifted to the right by 0.5

### Thrust axis
- Off $\Upsilon(4S)$ resonance
- On $\Upsilon(4S)$ resonance C.L.
- Central value
- Markers shifted to the right by 0.5

#### Systematics
- Primary particle selection
- Tracking efficiency
- Event selection
- $B(0,0)$ extrapolation
- Thrust mixing reweighting
- MC reweighting
- $\Delta\phi$ bin width

#### Thrust axis analysis:
- Off-resonance: no significant ridge signal, but C.L. in high-multiplicity bins are limited by statistics
- On-resonance: low-scale long-range near-side enhancement
MCs consistent with data in near side
Discrepancies in the away-side magnitude

PYTHIA6 agrees better with data than HERWIG & SHERPA
PYTHIA8 has similar behavior as PYTHIA6
Lack of origin-peak jet correlation

- Sharp origin-peak correlation is recovered as √s goes high
- Thrust-axis analysis: from null to significant intra-jet correlation!

* Demonstrated with 6 ≤ N_{trk} < 10
This phenomenon is seen in all multiplicity ranges

Larger origin peak correlation is found

Quark Matter 2022
Understanding the thrust-axis two-particle correlations

Long-range near-side enhancement in on-resonance sample

- Two $B$-meson decays: special event topology thrust axis alignment
- Toy sample pairing uncorrelated B’s from different events shows similar enhancement!
Conclusion

- First results of two-particle correlations measured in both beam axis and thrust axis coordinates at Belle
- Beam axis analysis, strong exclusion of ridge signals

Thrust axis analysis:
- Off-resonance: no significant ridge signal, origin-peak jet correlation scales with collision energy
- On-resonance: low-scale long-range near-side enhancement due to special decay topology of $\Upsilon(4S) \rightarrow B\bar{B}$ system, observed also on MC
- PYTHIA is in better agreement with data than SHERPA & HERWIG

![Thrust axis graph](image-url)
Backup
### Charged particles

| Primary tracks | • [reconstructed] the distance in the transverse plane of the decay vertex from the primary vertex $< 1$ cm  
  • [MC-truth] decay promptly or from particles with proper lifetime $\tau \leq 1$ cm/c |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance</td>
<td>$17^\circ \leq \theta \leq 150^\circ$</td>
</tr>
<tr>
<td>High quality tracks</td>
<td>$p_T \geq 0.2$ GeV</td>
</tr>
<tr>
<td>Impact parameter</td>
<td>$</td>
</tr>
</tbody>
</table>
| Duplicate track removal | veto the softer track of a low-momentum pair ($p_T < 0.4$ GeV) travelling with a small open angle $\delta$:  
  1. same-sign charges with $\cos \delta > 0.95$  
  2. opposite-sign charges with $\cos \delta < -0.95$ |
| Photon conversion veto | veto track pairs which can form common vertices ($V^0$ objects) with  
  1. $z$ distance between two tracks $< 10$ cm  
  2. reconstructed $V^0$'s mass $< 0.25$ GeV  
  3. decay-vertex radius $> 1.5$ cm |

### Neutral particles (for thrust calculation)

<table>
<thead>
<tr>
<th>Cluster selection</th>
<th>No direct track-matching and tracks matched at cluster edges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance</td>
<td>$17^\circ \leq \theta \leq 150^\circ$</td>
</tr>
</tbody>
</table>
| Energy cut        | **Forward endcap:** $E < 0.10$ GeV  
  **Backward endcap:** $E < 0.15$ GeV  
  **Barrel:** $E < 0.05$ GeV |
On-resonance multiplicity distribution and thrust distribution

*Belle e^+e^-*, $\sqrt{s} = 10.58$ GeV

- Data
- EVTGEN (PYTHIA6)

Fraction of Total Events

On-resonance multiplicity distribution and thrust distribution

**Sample**
Signal
(raw correlation function)

\[ S(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{corr}}^{\text{trk}}} \frac{d^2 N^{\text{same}}}{d \Delta \eta d \Delta \phi} \]

Background
(accounting for baseline of random pairing)

\[ B(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{corr}}^{\text{trk}}} \frac{d^2 N^{\text{mix}}}{d \Delta \eta d \Delta \phi} \]

Two-particle correlation function
(per-trigger-particle associated yield)

\[ \frac{1}{N_{\text{corr}}^{\text{trk}}} \frac{d^2 N^{\text{pair}}}{d \Delta \eta d \Delta \phi} = B(0,0) \times \frac{S(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)} \]
Azimuthal differential associated yield $Y(\Delta \phi)$

Two-particle correlation function (per-trigger-particle associated yield)

$$
\frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{pair}}}{d \eta d \phi}
$$

Associated yield vs. $\Delta \phi$

$$
Y(\Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d N_{\text{pair}}}{d \Delta \phi} = \frac{1}{\Delta \eta_{\text{max}} - \Delta \eta_{\text{min}}} \frac{1}{N_{\text{trig}}} \int_{\Delta \eta_{\text{min}}}^{\Delta \eta_{\text{max}}} \frac{d^2 N_{\text{pair}}}{d \eta d \Delta \phi} d \Delta \eta
$$

- **Short Range** ($0 \leq |\Delta \eta| < 1$)
- **Middle Range** ($1 \leq |\Delta \eta| < 1.5$)
- **Long Range** ($1.5 \leq |\Delta \eta| < 3.0$)

**Ridge Signal** (long-range, near-side ($\Delta \phi \sim 0$))

Illustration, $pPb$

special enhancement?
Origin-peak intra-jet correlations @ near side $(\Delta \eta, \Delta \phi) \sim (0,0)$

Two-particle correlation function (per-trigger-particle associated yield)

\[
\frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{pair}}}{d\Delta \eta d\Delta \phi}
\]

Azimuthal differential associated yield $Y(\Delta \phi)$

$\Delta \eta = \eta_1 - \eta_2 \sim 0$

$\Delta \phi = \phi_1 - \phi_2 \sim 0$
Azimuthal differential associated yield $Y(\Delta \phi)$

Two-particle correlation function (per-trigger-particle associated yield)

\[
\frac{1}{N_{\text{trig}}} \frac{d^2N^{\text{pair}}}{d\Delta \eta d\Delta \phi}
\]

Back-to-back jet correlations @ away side ($\Delta \phi \sim \pi$)

$\Delta \eta = \eta_1 - \eta_2$

$\Delta \phi = \phi_1 - \phi_2 \sim \pi$
Azimuthal differential associated yield $Y(\Delta \phi)$

Ridge correlations
@ long range, near side

Two-particle correlation function
(per-trigger-particle associated yield)

$$\frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{pair}}}{d \Delta \eta d \Delta \phi}$$

$\Delta \eta = \eta_1 - \eta_2$

$\Delta \phi = \phi_1 - \phi_2 \sim 0$

long range
$(1.5 \leq |\Delta \eta| < 3.0)$

ridge enhancement

Belle e$^+$$^-$$^e$; $\sqrt{s} = 10.52$ GeV
6<n$_{LL}$<10
Beam Axis
Off Y(4S) resonance

$Y(\Delta \phi)$

pPb:
**Selections**
1. **Primary particle selection**
   Vary the primary particle definition between the proper lifetime cut $\tau < 1 \text{ cm/c}$ and the vertex cut $V_r < 1 \text{ cm}$
2. **Tracking efficiency**
   Universal 0.35% uncertainty quoted for high $p_T (> 200 \text{ MeV/c})$ tracks
3. **Event selection**
   Vary the energy sum in ECL from $> 0.18 \sqrt{s}$ to $> 0.23 \sqrt{s}$

**Histogramming imperfection**
4. **B(0,0) extrapolation and long-range correlation scaling**
   Corrections of bin-size effect on the B(0,0) scaling factor and the magnitude of the long-range correlations are applied. Uncertainties of the correction factors are considered as sources of systematics
5. **$\Delta \phi$ bin width**

**Reweighting**
- Accessing by reweighting factors with the alternative parametrization
6. **MC reweighting**
7. **Thrust mixing reweighting**
- Selections (primary particle, tracking, and event selections) are the dominant systematics sources
- Others are comparably small: $O(10^{-4})$ up to 0.5%

### Beam axis analysis

<table>
<thead>
<tr>
<th>Source</th>
<th>Off-resonance (%)</th>
<th>On-resonance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary particle selection</td>
<td>$&lt;0.1$-$1.0$</td>
<td>$0.4$-$6.3$</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>$0.35$</td>
<td></td>
</tr>
<tr>
<td>Event selection</td>
<td>$&lt;0.1$-$0.4$</td>
<td>$&lt;0.1$-$0.3$</td>
</tr>
<tr>
<td>B(0,0) extrapolation</td>
<td>$&lt;0.1$-$0.3$</td>
<td>$&lt;0.1$-$0.2$</td>
</tr>
<tr>
<td>&amp; Long-range scaling</td>
<td>$&lt;0.1$-$0.2$</td>
<td>$&lt;0.1$-$0.1$</td>
</tr>
<tr>
<td>MC reweighting</td>
<td>$&lt;0.1$</td>
<td></td>
</tr>
<tr>
<td>$\Delta \phi$ bin width</td>
<td>$&lt;0.1$</td>
<td></td>
</tr>
</tbody>
</table>

### Thrust axis analysis

<table>
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<th>Source</th>
<th>Off-resonance (%)</th>
<th>On-resonance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary particle selection</td>
<td>$&lt;0.1$-$0.5$</td>
<td>$&lt;0.1$-$3.8$</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>$0.35$</td>
<td></td>
</tr>
<tr>
<td>Event selection</td>
<td>$&lt;0.1$-$1.3$</td>
<td>$&lt;0.1$-$1.1$</td>
</tr>
<tr>
<td>B(0,0) extrapolation</td>
<td>$&lt;0.1$-$0.1$</td>
<td>$&lt;0.1$-$0.4$</td>
</tr>
<tr>
<td>Thrust mixing reweighting</td>
<td>$&lt;0.1$-$0.3$</td>
<td>$&lt;0.1$-$0.1$</td>
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<tr>
<td>MC reweighting</td>
<td>$&lt;0.1$-$0.1$</td>
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<td>$\Delta \phi$ bin width</td>
<td>$&lt;0.1$-$0.2$</td>
<td>$&lt;0.1$-$0.1$</td>
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ZYAM method (zero yield at minimum) is applied to calculate “ridge yield”

- No significant ridge signals are observed in both beam, thrust axis coordinates
- Upper limits of ridge yield by the bootstrap method reported

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Upper limits of ridge yield by the bootstrap method reported
Bootstrap method

- Fit the long-range yield distribution $Y(\Delta \phi)$.  
- Vary the functional distribution by statistical and systematic uncertainties to construct a pseudo data.
- Refit the distribution with the same function and get a new ridge yield from this smeared distribution.
- Total 2M pseudo data are constructed.

Ref: [bootstrap]
Belle $e^+e^-$, $\sqrt{s}=10.58$ GeV

(1.5 < $|\eta|$ < 3.0)

Generator study

On-resonance $Y(\Delta\phi)$
Kinematics distribution

For e⁺e⁻ → τ⁺τ⁻ at \( \sqrt{s} = 10.52 \text{ GeV} \):

**Fraction of Total Events**

- **Data**
- Belle MC (reco)
- Belle MC (gen)
- Sherpa
- Herwig

**Ratio**

- **Offline Trk**

**Kinematics distribution**

Generator study