Measurement of Two-Particle Correlations and Flow Coefficients in High Multiplicity $e^+e^-$ Collisions Using Archived ALEPH Data at 91-209 GeV

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Advantages of $e^+e^-$ collisions to study QCD

Negligible beam remnant
Controllable initial-state QED radiations

Structureless $e^+/e^-$
- No uncertainties from beam PDF
- No MPI, no pileup

Color-neutral $e^+/e^-$
- No gluonic initial state radiations
- No initial state correlation effects (such as CGC)
The ALEPH detector and sample

- Re-analyze with MIT Open Data format
- ALEPH archived Pythia6 MC: for corrections and the comparison baseline

**Z-resonance dataset**

- $\sqrt{s} = 91.2$ GeV
- Dominant by $e^+e^- \rightarrow \gamma^*/Z \rightarrow ff$
- Suppressed bkg. at the $Z$-pole

**LEP1**

**LEP2**

**High-energy dataset**

- $\sqrt{s} = 130-209$ GeV
- Above $W^+W^-$ threshold (160 GeV), more possible channels
- Radiative-return-to-$Z \Rightarrow$ effective COM energy $\sqrt{s'}$

* There are also $Z$-resonance events in LEP2 sample
Charged multiplicity distributions

**Z-resonance dataset**

- Clean!

**High-energy dataset**

\[ e^+e^- \rightarrow \text{hadrons}, \sqrt{s}=183-209 \text{ GeV} \]

- \( q\bar{q} \)
- \( \gamma\gamma \)
- \( \tau^+\tau^- \)
- \( WW \)
- \( ZZ \)
- Other 4f states

* \( N_{\text{Trk}} \): number of charged particles after selections

**Higher multiplicity reach**
Unfolded thrust distribution — Good quality data

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

Spherical: \( T \) closes to 0.5

Pencil-like: \( T \) closes to 1

Good agreement btw archived data & the published result!
Further comparisons with MC — Anti-$k_T$ jet measurements

Jet energy spectrum

Jet substructure — energy sharing $z_G$

Rising edge sensitive to jet function

Similar trend btw $e^+e^-$ & pp

Room for improvement already in $e^+e^-$!

ALEPH jet

[JHEP 06 (2022) 008]
Cleanest tests for heavy-ion phenomenology & QCD

Two-particle correlations (2PC)

- Soft probe to study Quark-Gluon Plasma (QGP) in HI collisions

- Spatial anisotropy can happen as:
  - Initial density fluctuation
  - Hydrodynamical expansion of perfect-fluid-like QGP

- Ridge-like signals (spatial anisotropy) appears in not only AA, but also pA & pp!

- $e^+e^-$ collisions is clean!

- Onsets of azimuthal anisotropic correlations?

- Useful test with the absence of initial state correlations effect
Analysis method: 2PC observable construction

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

Reference
\[ \eta = -\ln \tan(\theta/2) \]

Track pairs’ angular difference in \( \eta \) (pseudorapidity), \( \phi \) (azimuthal angle)
Analysis method: 2PC observable construction

Signal (raw correlation function) vs. Background (accounting for baseline of random pairing)

Track pairs’ angular difference in $\eta$ (pseudorapidity), $\phi$ (azimuthal angle)

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

$$\frac{1}{N_{\text{trk}}^{\text{corr}}} \frac{d^2 N^{\text{pair}}}{d\Delta\eta d\Delta\phi} = B(0,0) \times \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}$$
LEP1

Long-range \((1.6 \leq |\Delta\eta| \leq 3.2)\) correlations

Data
PYTHIA6 MC

Good data/MC agreement!

LEP1 \(e^+e^-\) 2PC
Results with high-multiplicity events

No significant ridge-like signal enhancement!

High collision energy

Inclusive in multiplicity

ALEPH Archived Data $e^+e^-$, $\sqrt{s} = 183-209$ GeV

Thrust axis
$1.6 < |\Delta y| < 3.2$
$N_{\text{track}} \geq 0$

Fair data/MC agreement

Preliminary!
High collision energy & high multiplicity

Inclusive

High multiplicity ($N_{\text{Trk}} \geq 50$)

Interesting structures in high-multiplicity events
To quantify the excess, Fourier fit on the 1-dim. correlation:

\[ Y(\Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{dN_{\text{pairs}}}{d\Delta \phi} = \frac{N_{\text{assoc}}}{2\pi} \left( 1 + \sum_{n=1}^{n_{\text{max}}} 2V_{n\Delta} \cos(n\Delta \phi) \right) \]

The flow coefficients \( v_n \) correspond to different mode expansions:

\[ v_n \{ 2, 1.6 < |\Delta \eta| < 3.2 \} = \text{sign}(V_{n\Delta})\sqrt{V_{n\Delta}} \]
Flow coefficients ($v_2$)

CMS $pp$ [PLB 765 (2017) 193]

Similar trend btw $e^+e^-$ & $pp$

Preliminary!
Summary

**Z-resonance dataset**

- First 2PC analysis done in $e^+e^-$ collision data
- No hint of the azimuthal anisotropic correlations
- Good agreements btw data & Pythia6 MC

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**High-energy dataset (@ $\sqrt{s} > 180$ GeV)**

- Potential long-range near-side enhancement appears only on data but not MC
- Flow coefficient $v_2$ demonstrates a correspondence with LHC pp data
- On-going. Stay tuned!

Thank you very much!
Backup
High quality archived data

Published results can be reproduced

Big thanks to ALEPH collaboration and MIT open data
LEP 2 data & MC processes

### Year vs. √s vs. int. L

<table>
<thead>
<tr>
<th>Year</th>
<th>Mean energy√s [GeV]</th>
<th>Luminosity [pb⁻¹]</th>
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<td>1995, 1997</td>
<td>130.3</td>
<td>6</td>
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<td>140.2</td>
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<td>1996</td>
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<td>12</td>
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<td>172.1</td>
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<td>1998</td>
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<td>208.0</td>
<td>8</td>
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<td>Total</td>
<td>130 – 209</td>
<td>745</td>
</tr>
</tbody>
</table>

### √s vs. X-section

- **QED processes**
- **two-photon processes**
- **Four fermion processes**
- **Hadronic q̄q production**

Diverse decay channels above

\[ \sqrt{s} = 180 \text{ GeV} \]
Acceptance
Polar angle of sphericity axis: \( 7\pi/36 < \theta_{\text{lab}} < 29\pi/36 \)

Hadronic event selection
\( \geq 5 \) tracks
\( E_{\text{chgd.}} \geq 15 \text{ GeV} \)

Hadronic q\( \bar{q} \) production

Four fermion processes

QED processes

two-photon processes
Acceptance
Polar angle of sphericity axis: $7\pi/36 < \theta_{\text{lab}} < 29\pi/36$

Hadronic event selection
$\geq 5$ tracks
$E_{\text{chgd.}} \geq 15$ GeV

Radiative return to the $Z$
$\sqrt{s} \sim 90$ GeV

Hadronic $q\bar{q}$ production
Four fermion processes
ISR cut

Ref: hep-ex/9904011
Two-particle correlations
Selection

- **Track Selection:**
  - Particle flow candidate 0, 1, 2 (charged hadron / $e^\pm$ / $\mu^\pm$)
  - Number of TPC hits for a charged tracks ($N_{TPC}$) >= 4, $\chi^2$/ndf < 1000
  - $|d0| < 2$ cm
  - $|z0| < 10$ cm
  - $|\cos\theta| < 0.94$
  - $p_T > 0.2$ GeV (transverse momentum with respect to beam axis)

- **Neutral Hadron Selection:**
  - Particle flow candidate 4, 5 (ECAL / HCAL object)
  - $E > 0.4$ GeV
  - $|\cos\theta| < 0.98$

- **Event Selection:**
  - Number of good charged particles >= 5 (including charged hadrons and leptons)
  - Number of good ch+neu. particles >= 13
  - $E_{charged} > 15$ GeV
  - $|\cos(\theta_{sphericity})| < 0.82$
Analysis methods

Selection

Two-particle correlations

Residual MC correction

Signal
(raw correlation function)

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

Track pairs’ angular difference in \( \eta \) (pseudorapidity), \( \phi \) (azimuthal angle)

@ C.M. frame
Analysis methods

Selection

Two-particle correlations

Residual MC correction

Signal (raw correlation function)  |  Background (accounting for baseline of random pairing)

Factoring out the random pairing effect!

Track pairs’ angular difference in $\eta$ (pseudorapidity), $\phi$ (azimuthal angle)

Beam axis (C.M. frame z axis)
Analysis methods

Selection

Two-particle correlations

Residual MC correction

Signal
(raw correlation function)

Background
(accounting for baseline of random pairing)

Track pairs' angular difference in $\eta$ (pseudorapidity), $\phi$ (azimuthal angle)

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

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

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

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

Associated yield vs. $\Delta \phi$

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

Short Range

Middle Range

Long Range

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

Special enhancement?
Corrections

- To calibrate the nonuniform detection efficiency and misconstruction bias
- Reconstructed tracks are weighted by the inverse of the efficiency correction factor:

\[ \varepsilon(p_T, \theta, \phi, N_{trk}) = \left[ \frac{d^3N_{reco}}{dp_T d\theta d\phi} / \frac{d^3N_{gen}}{dp_T d\theta d\phi} \right]_{N_{trk}} \]

- A closure test is performed by comparing the \( p_T, \theta, \phi \) distributions of the generator level and those of the corrected reconstructed level
Corrections

• To deal with remaining possible reconstruction effects

• Bin-by-bin correction: the correction factor is derived from the histogram ratio of MC correlation functions at the reconstruction and generator level as

\[ C(\Delta \phi) = \frac{Y(\Delta \phi)_{\text{gen},i}}{Y(\Delta \phi)_{\text{reco},i}} \]

• Final data correlation results are obtained from the multiplication of the original correlation function with the bin-by-bin correction factor
Perfect-fluid-like QGP expansion

2PC characterizes the medium expansion in the transverse region w.r.t. the reference axis:

- Beam axis analysis: hydrodynamic expansion of possible QGP medium in HI collisions
Hypothetical QGP in $e^+e^-$?

2PC characterizes the medium expansion in the transverse region w.r.t. the reference axis:

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

- **Thrust axis analysis:** soft emissions or QGP in $e^+e^-$ annihilation

Out-going direction of $e^+e^-$ events ≠ beam axis (in general)
If high energy quarks can form some medium, looking from the thrust axis is sensitive to the azimuthal anisotropy of this “imaginary medium.”

Anisotropic correlation around thrust axis in $e^+e^-$?

Thrust axis $\hat{n}$
(used it as z axis)
proxy of dijet axis

$T = \max_{\hat{n}} \frac{\sum_i |\vec{p}_i \cdot \hat{n}|}{\sum_i |\vec{p}_i|}$

Beam pipe

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

$\phi_1$

$\phi_2$

$\bar{e} e^+$

$e^-$

trigger
particle

(quark from $e^+e^-$ annihilation)
Long-range correlations (c.f. MC)

 Beam axis

\[
5 \leq N_{\text{trk}} < 10 \\
10 \leq N_{\text{trk}} < 20 \\
20 \leq N_{\text{trk}} < 30 \\
N_{\text{trk}} \geq 30 \\
\]

Thrust axis

\[
N_{\text{trk}} \geq 35
\]

Good agreement with MC!
2PC — comparisons with the low-energy Belle experiment ($\sqrt{s}=10.52$ GeV)
Results

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

Compared with various fragmentation models

Belle $e^+e^-$ [Phys. Rev. Lett. 128, 142005 (2022)]
Fraction of Total Events

- Data
- EVTGEN

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

\text{Thrust axis}

\text{Correlated syst.} = 0.5\%

\text{Correlated syst.} = 0.7\%

\text{Correlated syst.} = 0.4\%

\text{Correlated syst.} = 1.5\%

\text{Correlated syst.} = 3.9\%

High-multiplicity

Short Range
\(0 \leq |\Delta \eta| < 1\)

Middle Range
\(1 \leq |\Delta \eta| < 1.5\)

Long Range
\(1.5 \leq |\Delta \eta| < 3.0\)
Puzzles we faced along the way…

Low-energy Belle data

- Simulate by Sherpa generator on different $\sqrt{s}$:
- Sharp origin-peak correlation evolved from null to significant intra-jet correlation as $\sqrt{s}$ goes high!

High-energy LEP 2 data

Understood!
Puzzles we faced along the way…

**Difficulties of the analysis:**

- Larger initial-state radiation effects (radiative return to the Z)
- Complicated physics processes above the di-boson production threshold (WW, ZZ)

**Ongoing checks:**

- Scanning of the long-range $|\Delta \eta|$ projection window with MC
  
  *To see if the signals really persist regardless the choice of the configuration*

- Consistency check: look into the year-dependence (collision-energy-dependence)

- Compared with modern MC generators
Anti-$k_T$ jet measurement
**Motivation**

- **$e^+e^-$ system offers cleanest tests of QCD**
  - Unambiguous inputs to pQCD calculation & pheno. models (PYTHIA / HERWIG / SHERPA)
  - Unlike pp & HI, jet energy spectrum at $e^+e^-$ is peaked (not smeared by PDF, gluonic ISR, etc)
  - Sensitive to tunes/params. in fragmentation calculation

**Anti-$k_T$ jet measurement**

- Great opportunity for jet re-analysis @ LEP
  - Modern jet reco. & clustering algo. since the end of LEP
  - Jets are important building blocks!
    - (e.g., BSM searches at LHC, probes of quark-gluon plasma at RHIC)
Analysis method: anti-$k_T$ jet

**Anti-$k_T$ clustering**

$$R = 0.4 \quad (R = \sqrt{\Delta \eta^2 + \Delta \phi^2})$$

Acceptance cut: $0.2\pi < \theta_{jet} < 0.8\pi$

(avoid beam pipe)

**Grooming & substructure**

Soft drop algorithm

$$R_G = \text{opening angle}$$

$$z_G = \text{energy sharing}$$

**Calibration**

Jet resolution

Ex: inclusive jet energy

**Unfold to gen. level**

MC

Data / MC

MC

Data / MC

Gen. Jet E (GeV)

Reco Jet E (GeV)

Underflow bins
Clustering

- Anti-k$_T$ algorithm, $R = 0.4$
  \[ R = \sqrt{\Delta \eta^2 + \Delta \phi^2} \]
- Acceptance:
  (avoid beam pipe)
  $0.2\pi < \theta_{\text{jet}} < 0.8\pi$

- $d_{ij} = \min\left( E_i^{-2}, E_j^{-2} \right) \frac{1 - \cos \theta_{ij}}{1 - \cos R}$
- $d_{iB} = E_i^{-2}$

Anti-k$_T$ clustering (FastJet)
Analysis method: anti-$k_T$ jet

Clustering
- Anti-$k_T$ algorithm, $R = 0.4$

Grooming & substructure

Identify hard structure

Clean up wide-angle soft energy

References:
- JHEP 1405 (2014) 146
- PRL 100 (2008) 242001
Analysis method: anti-$k_T$ jet

**Clustering**
- Anti-$k_T$ algorithm, $R = 0.4$

**Grooming & substructure**
- $R_g =$ opening angle
- $z_g =$ energy sharing
- $M_g =$ invariant mass

Recluster jet constituents with C/A algorithm

Sequentially open up jet until condition is met

$$z \equiv \frac{\min(E_1, E_2)}{E_1 + E_2} > z_{\text{cut}} \left(\frac{\theta_{12}}{R}\right)^\beta$$

$\theta_{12} =$ opening angle btw sub-jet 1&2

$(z_{\text{cut}}, \beta) = (0.1, 0.0)$

JHEP 1405 (2014) 146
PRL 100 (2008) 242001
Analysis method: anti-$k_T$ jet

Clustering
- Anti-$k_T$ algorithm, $R = 0.4$

Grooming & substructure
- $R_g = \text{opening angle}$
- $z_g = \text{energy sharing}$

Calibration

- MC-based calibration

Monitoring on two variables:
- Forward-/backward-side energy difference
- Multi jet mass

Data/MC residual calibration

Response

Raw Corrected

E = 20.0 ~ 25.0 GeV

Calibration

$E = 20.0 ~ 25.0 \text{ GeV}$
Analysis method: anti-$k_T$ jet

**Clustering**
- Anti-$k_T$ algorithm, $R = 0.4$

**Grooming & substructure**
- $R_g =$ opening angle
- $z_g =$ energy sharing

**Calibration**

Jet resolution in simulation

Data/MC ratio vs. GenE

Energy resolution: 10-25%
(Angular resolution: 0.01-0.05)

0-5% difference in energy resolution between data and MC
Analysis method: anti-$k_T$ jet

Clustering
- Anti-$k_T$ algorithm, $R = 0.4$

Grooming & substructure
- $R_g = \text{opening angle}$
- $z_g = \text{energy sharing}$

Calibration

Unfolding to gen. level

Example: inclusive jet energy
## Jet measurement observables

<table>
<thead>
<tr>
<th>Inclusive jets</th>
<th>Leading dijets</th>
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<tbody>
<tr>
<td>Energy spectra</td>
<td>Energy spectra</td>
</tr>
<tr>
<td>Full jet mass</td>
<td>Energy sum</td>
</tr>
<tr>
<td>Groomed jet angle</td>
<td></td>
</tr>
<tr>
<td>Groomed jet mass</td>
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**Soft drop grooming**
- sensitive to the soft radiation
- Leading dijets
- Energy spectra
- Energy sum
- Groomed jet angle
- Energy sharing
- Groomed jet mass

**Jet observables**

**Jet observables**

- Inclusive jets
  - Energy spectra
  - Full jet mass
  - Groomed jet angle
  - Energy sharing
  - Groomed jet mass

- Leading dijets
  - Energy spectra
  - Energy sum

**Notes**
- Soft drop grooming
- Sensitive to the hard part
We want to measure **global** leading dijet

But: out-of-acceptance jets appear lower in energy

→ selection + correction
Rising edge sensitive to jet function

- c.f. analytical calculation
- c.f. fragmentation models

- NLL' resummed generally describes data
- 10-20% disagreement

- @ high E consistent within uncertainties
- @ low E

NLL'

[JHEP 07 (2021) 041]

ALEPH jet

[JHEP 06 (2022) 008]
Jet substructure observables — $R_G$

Opening angle ($R_G$)

@ low E (soft radiation & combinatorial)

higher $R_G$

Worse MC/data agreement

@ high E

more similar to LHC/RHIC

ALEPH jet

[JHEP 06 (2022) 008]
Jet substructure observables — $z_G$

Energy sharing ($z_G$)

Min($\Delta R$, $\Delta \eta$)

Similar trend btw $e^+e^-$ & $pp$!

ALEPH jet

[JHEP 06 (2022) 008]
Energy sharing $z_G$  

High energy  
More similar to the $1/z$ from splitting function