Angular correlations measured in pp collisions at the LHC by the ALICE experiment

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Physics goals

Characterize different correlation sources:
- minijets
- femtoscopic correlations
- resonances
- photon conversion
- momentum conservation
- …

Since each correlation source has a unique distribution on $(\Delta \eta, \Delta \phi)$ we would like to quantify their contributions to the overall shape using fitting procedure.

Useful to perform analysis in a more refined way:
- charge dependence
- identified particles
Anatomy of the $\Delta\eta\Delta\phi$ correlation function

- "Away-side" ($\Delta\phi \sim \pi$) jet correlations: Correlation of particles between back-to-back jets
- Bose-Einstein correlations: $(\Delta\phi, \Delta\eta) \sim (0, 0)$
- Momentum conservation: $\sim -\cos(\Delta\phi)$
- "Near-side" ($\Delta\phi \sim 0$) jet peak: Correlation of particles within a single jet
- Photon conversion
- Resonances, string fragmentation
$$\Delta \eta \Delta \phi \text{ Experimental Correlation Function}$$

**Signal distribution**

$$S(\Delta \eta, \Delta \phi) = \frac{d^2 N_{\text{signal}}}{d \Delta \eta d \Delta \phi}$$

**Background distribution**

$$B(\Delta \eta, \Delta \phi) = \frac{d^2 N_{\text{mixed}}}{d \Delta \eta d \Delta \phi}$$

**Same event pairs**

$$\Delta \eta = \eta_1 - \eta_2$$
$$\Delta \phi = \phi_1 - \phi_2$$

**Ratio signal/background**

$$C(\Delta \eta, \Delta \phi) = \frac{N_{\text{mixed}}}{N_{\text{signal}}} \frac{S(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)}$$

**Mixed event pairs**
Charge dependence

Shape of near-side peak differs for like- and unlike-sign.

Femtosopic correlations enhance near-side peak for like-sign pairs.
Multiplicity dependence

Increasing multiplicity

$N_{\text{ch}} < 12$

$17 \leq N_{\text{ch}} \leq 22$

$42 \leq N_{\text{ch}} \leq 51$

Decreasing correlation (per pair) with rising multiplicity

$p_T > 0.12 \text{ GeV/c}$

$|\eta| < 1.0$

Longitudinal ridge structure is visible only for unlike-sign pairs, for low multiplicities.
Results for Pythia

Monte Carlo Simulation

Results for Pythia Monte Carlo Simulation

- **Unlike-sign**
  - Pythia @ 7 TeV, unlike-sign pairs
    - $15 \leq N_{ch} \leq 28$
    - $29 \leq N_{ch} \leq 34$
    - $35 \leq N_{ch} \leq 41$

- **Increasing multiplicity**
  - Pythia @ 7 TeV, positive pairs
    - $15 \leq N_{ch} \leq 28$
    - $29 \leq N_{ch} \leq 34$
    - $35 \leq N_{ch} \leq 41$

- **Like-sign (positive)**
  - Pythia @ 7 TeV, positive pairs
    - $15 \leq N_{ch} \leq 28$
    - $29 \leq N_{ch} \leq 34$
    - $35 \leq N_{ch} \leq 41$
We fit a function of the following form:

\[ C(\Delta \eta, \Delta \phi) = N + M_M \cdot \exp \left( -\frac{(\Delta \phi - \pi)^2}{2 \sigma_{M\phi}^2} \right) e_A = 1 + M_M \cdot \exp \left( -\frac{(\Delta \phi - 2\pi)^2}{2 \sigma_{M\phi}^2} \right) e_A = 1 + M_A \cdot \exp \left( -\frac{(\Delta \phi + \pi)^2}{2 \sigma_{A\phi}^2} \right) e_A = 1 + M_L \cdot \exp \left( -\frac{\Delta \eta^2}{2 \sigma_{L\phi}^2} \right) e_L = 1 + P \cdot \Delta \eta^2 \]

1 parameter

4 parameters

2D Gauss for near-side peak

2 parameters

1D Gauss for away-side ridge

2 parameters

1D Gauss for longitudinal ridge

1 parameter

1D Parabola for wings

= 10 parameters
Fitting results (example)

Correlation function

Fitted function

Subtraction

Longitudinal ridge
(string fragm., resonances)

Near-side peak
(minijets, HBT, resonances)

Away-side ridge
(minijets)

Normalization

Wings
(detector effects)

Function fitted to the histogram obtained from analysis
Near-side

Minijet away-side

Longitudinal ridge

Δφ

σ_{M,Δφ}

σ_{M,Δη}

Δη

σ_{M,Δη}

Δη

Δη

σ_{A,Δφ}

φ_{M}

σ_{A,Δη}

wings

Δη

σ_{A,Δη}

p

Δη

σ_{L,Δη}

normalization

magnitude

magnitude

magnitude

Δφ

Δη

Δη

Δη

Δη

Δη

Δη

m

positive pairs

negative pairs

unlike-sign pairs

12/09/2013, IS2013
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Results for Pythia

- No femtoscopic correlations
- Same width of near-side peak for like- and unlike-sign, magnitude higher for unlike-sign (opposite to the data)
- Away-side comparable (as in data)

Fit to Monte Carlo
Without systematic uncertainties
ΔηΔφ of identified particles

- In addition to the correlation sources mentioned earlier, we expect the **conservation laws** to play a relatively large role for correlations of identified particles.
- Can be a strong constraint on the way quantum numbers are conserved in models.
- For this reason, the study of correlation functions for particles with different quark content, i.e., pions, kaons, protons, is particularly interesting.

<table>
<thead>
<tr>
<th>particles</th>
<th>momentum</th>
<th>charge</th>
<th>strangeness</th>
<th>baryon number</th>
</tr>
</thead>
<tbody>
<tr>
<td>pions</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>kaons</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>protons</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Unlike-sign pairs = particle/antiparticle

The strength of the correlation depends on the energetic price of the alternative solution. The larger the difference in prices between basic and alternative solutions, the stronger the correlation.

- for **pions** the alternative solution is just another opposite-charge particle,
- for **protons** another antibaryon (charged, or neutral plus additional charged particle),
- for **kaons**, which carry the strange quark, the strangeness must be conserved, so the alternative solution would be at least a lambda together with another baryon.
While creating unlike-sign particles the **least energetically expensive** is always to **produce the particle-antiparticle pair**.

Basic solution:

- for **protons**: antiproton
Unlike-sign pairs

• While creating unlike-sign particles the **least energetically expensive** is always to **produce the particle-antiparticle pair**.

\[ \bar{p} \rightarrow p \]

Basic solution:
• for **protons**: antiproton
• then we have only to compensate for the momentum
Unlike-sign pairs

- While creating unlike-sign particles the **least energetically expensive** is always to **produce the particle-antiparticle pair.**

![Diagram of particle interactions]

**Alternative solution:**
- for **protons** another antibaryon (charged, or neutral plus additional charged particle),
- charge, **baryon number** and momentum conserved
Unlike-sign pairs (kaons)

• While creating unlike-sign particles the least energetically expensive is always to produce the particle-antiparticle pair.

Basic solution:
• for **kaons**: kaon of opposite sign
While creating unlike-sign particles the **least energetically expensive** is always to **produce the particle-antiparticle pair.**

**Alternative solution:**
- for **kaons**: another strange particle, at least **lambda**
Unlike-sign pairs

- While creating unlike-sign particles the least energetically expensive is always to produce the particle-antiparticle pair.

Alternative solution:
- for kaons: another strange particle, at least lambda
- since lambda is baryon, we need another baryon to conserve baryon number
- Very expensive solution!
Unlike-sign pairs

- While creating unlike-sign particles the **least energetically expensive** is always to produce the particle-antiparticle pair. Such pairs produce the strong near-side peak in the identified correlations.

- The **strength of the correlation** depends on the energetic **price of the alternative solution**. The larger the difference in prices between basic and alternative solutions, the stronger the correlation.
  - for **pions** the alternative solution is just another opposite-charge particle,
  - for **protons** another antibaryon (charged, or neutral plus additional charged particle),
  - for **kaons**, which carry the strange quark, the strangeness must be conserved, so the alternative solution would be at least a lambda together with another baryon.
Like-sign pairs

- For like-sign particles producing two identical particles is not the cheapest energetically like for particle – antiparticle case

- Masses of the particles play significant role
  - still for kaons and pions we can see the prominent near-side peak in the correlation function (due to the minijets, femtoscopic correlations, resonances)
  - for protons a large dip near the \((\Delta \eta, \Delta \phi) = (0,0)\) is present: by producing two very heavy identical particles going in roughly the same direction we would have to produce also two baryons (two antiprotons), so another two heavy particles. The price of such solution is very high.
$\Delta \eta \Delta \phi$ of identified particles

Raw correlation functions, not corrected for purity and contamination

- **pp $\sqrt{s} = 7$ TeV, protons, unlike-sign pairs**
- **pp $\sqrt{s} = 7$ TeV, kaons, unlike-sign pairs**
- **pp $\sqrt{s} = 7$ TeV, pions, unlike-sign pairs**

pp $\sqrt{s} = 7$ TeV, protons, like-sign pairs

pp $\sqrt{s} = 7$ TeV, kaons, like-sign pairs

pp $\sqrt{s} = 7$ TeV, pions, like-sign pairs
Pythia does not reproduce the shape of the correlation function for identified particles. Suggests that local quantum number conservation processes are not modeled correctly.
Phojet does not reproduce the shape of the correlation function for identified particles. Suggests that local quantum number conservation processes are not modeled correctly.
Summary

- The analysis of pp data at 7 TeV over 5 multiplicity ranges and vs. pair charge combination was performed.
- The results were quantified using fitting procedure.
- The study of the correlation functions was performed for identified particles (pions, kaons, protons)
- Conservation laws seem to play a significant role determining the shape of $\Delta\eta\Delta\varphi$ correlation functions

- Monte Carlo models should be strongly constrained (fragmentation)
  - conservation of all quantum numbers for each fragmentation separately
  - constrain on the way the conservation laws are taken into account

- Particularly interesting in future studies
  - quantitatively describe (fit) features seen in the data for identified particles
Backup
Data samples & analysis

- pp events at 7 TeV registered by ALICE in 2010 were used for the analysis:
  - ~153M minimum bias events.
- Corresponding analysis on Monte Carlo generators (Pythia, Phojet) was performed.
- The analysis was performed on primary particles within the acceptance range of $|\eta|<1.0$ and transverse momentum range $p_T>0.12 \text{ GeV/c}$ which were reconstructed by the ALICE Time Projection Chamber (TPC) and Inner Tracking System (ITS) detectors.
- Electron-positron pairs coming from gamma conversion were removed.
- We observe a combination of undesired physics effects (gamma conversions), true physics correlations (Coulomb interaction) and detector effects (track splitting/merging) in the (0,0) bin. Their systematic study is under way.
- The systematics are not shown in the plots.
p_T-sum dependence cut

Since femtoscopic effects are strongest for small pair transverse momenta, we needed to develop a cut dependent on such observable.

We chose the sum of transverse momenta of both particles:

$$p_{T\text{sum}} = |\vec{p}_{T1}| + |\vec{p}_{T2}|$$

Bins of p_T-sum:

- 0.0 – 0.75 GeV/c
- 0.75 – 1.5 GeV/c
- 1.5 – 2.25 GeV/c
- 2.25 – 100 GeV/c
No Bose-Einstein correlations for unlike-sign pairs

Bose-Einstein correlations decrease with increasing $p_T$

Correlations coming from "minijets" increase with increasing $p_T$

Correlations coming from "minijets" increase with increasing $p_T$ also for like-sign pairs

$0 < p_{T_{sum}} < 0.75$ (GeV/c)

$0.75 < p_{T_{sum}} < 1.5$ (GeV/c)

$1.5 < p_{T_{sum}} < 2.55$ (GeV/c)
Laws conserved globally

Each of the conservation laws must be obeyed in the whole event.

Example: protons

- momentum
- charge  
  \[ q = e + e \]
- strangeness  
  \[ S = 0 \]
- baryon number  
  \[ B = 1 + 1 \]
Laws conserved globally

Each of the conservation laws must be obeyed in the whole event.

Example: protons

- momentum
  \[ q = e + e - e - e = 0 \]
- charge
- strangeness
  \[ S = 0 \]
- baryon number
  \[ B = 1 + 1 - 1 - 1 = 0 \]
Laws conserved locally

Each of the conservation laws must be obeyed for each fragmentation separately:

- For each minijet charge, strangeness and baryon number must be conserved
- Momentum of the minijet has to be balanced with the momenta of the particles going in the opposite direction.

Example:

protons

\[ q = e + e \]
\[ S = 0 \]
\[ B = 1 + 1 \]
Laws conserved locally

Each of the conservation laws must be obeyed for each fragmentation separately:

- For each minijet charge, strangeness and baryon number must be conserved
- Momentum of the minijet has to be balanced with the momenta of the particles going in the opposite direction.

Example: protons

- charge
  \[ q = e + e^- - e - e = 0 \]
- strangeness
  \[ S = 0 \]
- baryon number
  \[ B = 1 + 1 - 1 - 1 = 0 \]
Laws conserved locally

Each of the conservation laws must be obeyed for each fragmentation separately:

- For each minijet charge, strangeness and baryon number must be conserved
- Momentum of the minijet has to be balanced with the momenta of the particles going in the opposite direction.

Example: protons

- charge
  \[ q = e + e^− - e^− - e = 0 \]
- strangeness
  \[ S = 0 \]
- baryon number
  \[ B = 1 + 1 - 1 - 1 = 0 \]
- momentum
Multiplicity dependence

\[
N_{\text{ch}} < 12
\]

\[
17 \leq N_{\text{ch}} \leq 22
\]

\[
42 \leq N_{\text{ch}} \leq 51
\]

Decreasing correlation (per pair) with rising multiplicity

Longitudinal ridge structure is visible only for unlike-sign pairs, for low multiplicities
Multiplicity dependence

**Pythia 7 TeV**

- Increasing multiplicity
- Decreasing correlation (per pair) with rising multiplicity

\[ 17 \leq N_{ch} \leq 22 \]

- No femtoscopic correlations in Pythia!

\[ 42 \leq N_{ch} \leq 51 \]

**Strong production of “minijets”**

- All like-sign (positive)
- Unlike-sign
Near-side peak

- Width of the near-side peak bigger for unlike-sign pairs
- Minijets produce stronger correlation for unlike-sign pairs \( \phi^M \)
  – local charge conservation
- Also other correlation sources play significant role:
  – Resonances more prominent for unlike-sign pairs
  – Femtoscopic correlations exist only for like-sign pairs
- Correlations decrease with multiplicity slower than \( 1/N_{ch} \)
  – do not follow trivial dilution \( 1/N \)
Away-side ridge

- Away-side width and magnitude comparable
- Minijets effect on away-side similar between same-sign and opposite sign
  - Suggests that the differences in the near-side come from other correlation sources: resonances, conservation laws and/or femtoscopy
- Femtoscopic correlations and resonances do not contribute to the away-side
- Correlations of the away-side do not follow trivial scaling 1/N
Longitudinal ridge

- Longitudinal ridge present only for unlike-signs (Positive / Negative / Unlike-sign)
- Prominent for low multiplicities – but follow 1/N scaling
- Visible only at low transverse momenta
- The structure has been explained so far by other experiments by
  - Low-mass resonances
  - Decay of clusters with low $p_T$
  - Local charge conservation in longitudinally fragmenting strings
Unlike-sign pairs

$p_T$-sum and multiplicity dependence

Correlations increase with $p_T$-sum and decrease with multiplicity, consistent with “minijets”
Like-sign pairs (positive)

\[ p_T \text{-sum} \]

& multiplicity dependence

Dependence consistent with combination of correlations coming from “minijets” increasing with \( p_T \)-sum and decreasing with multiplicity plus femtoscopic correlations decreasing with both \( p_T \)-sum and multiplicity.
Like-sign pairs (positive)

\[ p_T^{\text{sum}} \text{-sum} \]

&

Multiplicity dependence

Correlations coming from “minijets” increase with \( p_T^{\text{sum}} \) and decrease with multiplicity.

No femtoscopic correlations for Pythia!
Unlike-sign pairs

$p_T$-sum

&

multiplicity dependence

Correlations coming from “minijets” increase with $p_T$-sum and decrease with multiplicity. Stronger for unlike-sign.

No femtoscopic correlations for Pythia!