Measurements of multi-particle correlations and collective flow with the ATLAS detector

Tomasz Bold, AGH UST Kraków, Poland on behalf of the ATLAS Collaboration

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Correlation measurements in ATLAS experiment

• Detailed measurements of correlations in the Pb-Pb system

• Measurement to answer fundamental question of correlations origin in small system

• In this talk only highlights from recent Pb-Pb results and new results for small systems

• All results can be found in: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavylionsPublicResults
Flow harmonics at Pb-Pb $\sqrt{s_{\text{NN}}} = 5.02$ TeV

- Measurement of the $v_n$ in Pb-Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV allowed to reach high $p_T$ of 25 GeV, study very central collisions and measure harmonics up to $n=7$ [ATLAS-CONF-2016-105]

- Similar $p_T$ dep. in all harmonics up to 10 GeV,
  - Above only $v_2\{\text{SP}\}$ is non-0 (slow fall), rise in 2PC measurement
  - Weak $\eta$ dependence
  - The SP and EP method differ for $v_2$ only (~3%),
  - The $v_n$ at $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV energies are similar
Pb-Pb $v_n$ decorrelation

- Majority of flow studies assume boost invariance in longitudinal direction
- The role/importance of the $\eta$ dependent fluctuations
- ATLAS measured new observables „correlation between $v_n$ in bins of $\eta$“ in Pb-Pb at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV [ATLAS-CONF-2017-003]

- $r_{n|n;k}$ expected 1 if longitudinal flow fluctuations not present, $k=1,2,3$
- $R_{n,n|n,n}$ sensitive to the event-plane twist

$R_{n,n|n,n}(\eta) = \frac{\langle q_n(-\eta)q^*_n(\eta_{\text{ref}}) \rangle}{\langle q_n^2(\eta) \rangle}$


Both variables robust against detector effects (ratios),
Observed no dependence on $\eta_{\text{ref}}$ reference
**Pb-Pb $v_n$ decorrelation**

- Factorisation of two particle $v_{nn}$ into single particle $v_n$ broken as function of $\eta$
- Effects slightly stronger for $\sqrt{s_{NN}}=2.76\text{TeV}$
- Centrality dependence for $r_{2|2;1}$ unlike higher $n$
- Event plane twist effect comparable to magnitude change
- Higher order indicate: $v_2 v_3$ long. fluct. independent, $v_4 \propto c v_2^2$, $v_5 \propto v_2 v_3$

$\ell$ The $v_2(\eta)$ decorrelates with centrality while $v_3(\eta)$ - and higher does not

Event plane twist has sizeable contribution - the $v_2$ decorrelation changing with centrality not caused by twist of event-plane.
Small systems measurements

• The observation of the ridge structure in 2PC in p-p opened discussion on the small systems:


• Robust method required for long-range correlation measurements in small systems

  • 2PC method require elaborate non-flow subtraction [arXiv:1609.0621


• „Orthogonal“ measurement: azimuthal HBT analysis
By correlating particles from rapidity separated sub-events the self-correlation (mostly di-jets) is mostly suppressed

\[ v_n\{2\}_n = \sqrt{c_n\{2\}} \quad \text{and} \quad v_n\{4\}_n = \frac{4}{4} \!-\! c_n\{4\} \]

Negative \( C_2\{4\} \) indicates collectivity

arXiv: 1701:03830
C₂{4} from sub-event cumulants

Standard cumulant meth. indicates no v₂{4} unless for very specific reference particles choice and event multiplicity.

Signs of improvement in 2 sub-event cumulant. Weakly dependent on the choice of reference particles.

The 3 sub-event cumulant: Consistently below 0. Independent on the choice of reference particles. Negative C₂{4} at low mult.

All methods consistent in p-Pb. Tests on MC indicate suppression of the non-flow v₂=0.

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Sub-event cumulant results

The $v_2\{4\}$ obtained in p-p (wide multiplicity range) and p-Pb.
Nearly independent of ev. multiplicity in three systems, very little $\sqrt{s_{NN}}$ dep. in p-p

The $v_2$ with reduced non-flow contributions lower than measured previously

The $v_3$ consistent with 0

$v_2\{4\}/v_2\{2\}$ estimate number of sources (model dependent: [Phys. Rev. Lett. 112, 082301 (2014)])

Same multiplicity = same number of sources irrespectively of the collision system!

Consistent with F-B multiplicity correlation results [PRC 95 (2017) 064914]
Muon-hadron correlations

• Heavy flavour long range correlations studied through muon-hadron correlation

• ATLAS measured the azimuthal muon-hadron correlations in Pb-Pb collisions at 2.76 TeV [ATLAS-CONF-2015-053]
  • observed $v_2$ in range of $4<p_T<12$ GeV from 6 to ~0%

• Now also measured in p-Pb at $\sqrt{s_{NN}}=8.16$ TeV
  • high-multiplicity + muon trigger to collect the sample
  • 2PC method with template fits to subtract non-flow contribution [ATLAS-CONF-2017-006]
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**Results: muon-hadron correlation**

A significant $h$-$\mu v_2$ observed (about 60% lower than $h$-$h$ - mind $p_T$ range difference)

Independent of event multiplicity

The $p_T$ dependence resembles $h$-$h v_2$ at high $p_T$ (mind that muons are from HF decays - additional kinematics to take into account before comparison)

Significant azimuthal anisotropy of HF particles observed in p-Pb
Summary

In correlation measurements ATLAS concentrates on:

- **Detailed understanding of correlations properties in Pb-Pb collisions**
  
  - High precision thanks to large statistics available
  
  - New observables: short & long range component in FB multiplicity correlations, $v_n$ decorrelations

- **Advanced methods to answer the question on the origin of correlations in small systems**
  
  - Advancing non-flow components removal, novel sub-event cumulant provides robust results

  - Performed muon-hadron correlation analysis

  (in backup: observation of azimuthal modulation of source size)
Backup
Azimuthal HBT results

- Modulation of source radii in small system favours evolution scenario

- **Now performed azimuthal HBT analysis** [ATLAS-CONF-2017-008] (inclusive [arXiv:1704.01621])
  - Data set enhanced by high-multiplicity events, Event Plane (EP) established in „forward” calorimeter region, results corrected for EP resolution
  - Measured are relative radii change as function of distance from the EP and its scaling with overall azimuthal asymmetry (magnitude of the elliptic flow vector $|q_2|$)

- Measurements of multi-particle correlations and collective flow with the ATLAS detector