Recent results on jets and collective phenomena in ALICE experiment

Marek Bombara on behalf of the ALICE Collaboration

(Pavol Jozef Šafárik University, Košice, Slovakia)

52nd International Symposium on Multiparticle Dynamics
Gyöngyös, Hungary
21-26 August 2023
• dedicated to study the hot and dense nuclear matter in heavy-ion collisions
• crucial part of the physics programme is to study pp and p–Pb collisions
• excellent at particle identification and track reconstruction in high track density environment (central Pb–Pb) up to very low $p_T$ (100 MeV/c in Run 2)
Long-range correlations in heavy-ion collisions

- long-range, near-side correlations (large $\Delta \eta$ and small $\Delta \phi$) in Pb–Pb connected to hydrodynamic expansion of the quark-gluon plasma

Two-particle angular correlation method

$\Delta \phi = \phi_{\text{trigger}} - \phi_{\text{associated}}$

$\Delta \eta = \eta_{\text{trigger}} - \eta_{\text{associated}}$

Depending on $p_T$ intervals ($p_{T,\text{trig}}$ and $p_{T,\text{assoc}}$) the method can be used to study flow (lower $p_T$) or jets (higher $p_T$).
Azimuthal anisotropy in heavy-ion collisions

- initial spatial asymmetry of partonic matter leads to azimuthal momentum space anisotropy in hadron distribution due to different pressure gradients

- anisotropy can be quantified by second Fourier coefficient of the particle distribution (i.e. $v_2$ a.k.a. elliptic flow)

- “lumpiness” of the fireball (due to fluctuations of the initial energy density profile of the colliding nucleons) can give rise to higher harmonics ($v_n$, $n=3,4,\ldots$)

$$E \frac{d^3N}{d^3p} = \frac{1}{2\pi p_T dp_T dy} \left( 1 + 2 \sum_{n=1}^{\infty} v_n(p_T, y) \cos[n(\phi - \Psi_R)] \right)$$

$$v_n(p_T, y) = \langle \cos[n(\phi - \Psi_R)] \rangle$$

$\Psi_R$ - reaction plane angle
Long-range correlations in small systems

- structures from two-particle correlations previously connected to collectivity in Pb–Pb collisions visible also in p–Pb and pp
Long range correlations in small systems - is there a limit?

- long-range two-particle correlations measured by ALICE up to the smallest multiplicities with very high precision
- non-zero ridge yield even for events with low multiplicities
Long-range correlations in small systems - comparison to $e^+e^-$ collisions

- the cleanest environment ($e^+e^-$) does not show any significant ridge structure at $\Delta \phi = 0$

- ridge yields in $pp$ higher than yields (upper limits) in ($e^+e^-$) at the same multiplicities (10, 15)
Flow in \( \text{Pb–Pb, Xe–Xe, p–Pb} \) \ and pp \ collisions

- similar multiplicity dependence of \( v_n \) in pp and p–Pb collisions to that observed in large systems
  - anisotropic flow is created as a response to initial geometry via final state interactions of produced matter

- non-zero flow coefficients using multiparticle correlations in pp and p–Pb collisions, compatible with those in large systems
  - presence of long-range and multiparticle correlations \( \rightarrow \) collectivity

- data cannot be described by purely non-flow based models

- hydrodynamic calculations show qualitative agreement with Pb–Pb, Xe–Xe and p–Pb collisions, while they fail for pp collisions

\[ \text{ALICE, PRL 123 (2019) 142301} \]
Strangeness enhancement


- experimental variable based on comparison of strange hadron production in nucleus-nucleus collision with nucleon-nucleon (or nucleon-nucleus) collision - strangeness enhancement confirmed
Strangeness enhancement

- $N_{\text{part}}$-scaling does not hold at LHC energies - a different experimental variable is used: ratio to pion production as a function of multiplicity.

- remarkable overlap of $p$–Pb and peripheral Pb–Pb with Cu–Cu and Au–Au - even for 25 times smaller energy (RHIC) the strangeness production is similar!

- a smooth transition from pp to central Pb–Pb - seems the only parameter needed to estimate strangeness production is multiplicity.
Strangeness enhancement

- $N_{\text{part}}$-scaling does not hold at LHC energies - a different experimental variable is used: ratio to pion production as a function of multiplicity.

- Remarkable overlap of $p$–Pb and peripheral Pb–Pb with Cu–Cu and Au–Au - even for 25 times smaller energy (RHIC) the strangeness production is similar!

- A smooth transition from pp to central Pb–Pb - seems the only parameter needed to estimate strangeness production is multiplicity.

- Hierarchy of the enhancement determined by the hadron strangeness!

What are the roles of jet/underlying event in strangeness production in high-multiplicity pp or p–Pb collisions?
Strangeness enhancement in small systems

- trigger particle (jet axis proxy) - charged hadron with highest $p_T$ in event & $p_T > 3$ GeV/c
- associated particles: identified strange hadrons
Strangeness enhancement in small systems

- toward-leading spectra of strange hadrons harder than transverse-to-leading spectra or full spectra
- same behaviour also for different multiplicity classes and different collision energy (13 TeV)
Strangeness enhancement in small systems

- strange hadron yields from transverse-to-leading and full samples increase with multiplicity and they are consistent with each other - the increase is driven by soft processes

- no difference in trends for different collision energies

- toward-leading yields do not depend on multiplicity (or depend very mildly)
Strangeness enhancement in small systems

- transverse-to-leading and full yield ratios show an enhancement as a function of multiplicity (resembling the enhancement of the inclusive strangeness production w.r.t. pions) - can be attributed to the strangeness difference: $\Xi^−$ vs. $K^0_S (|\Delta S|=1)$
- toward-leading contributes less to the enhancement
- transverse-to-leading and toward-leading trends are compatible
Deuteron production

- if proton and neutron are close in phase space and match the spin state, they can form the deuteron [S. T. Butler et al., Phys. Rev. 129 (1963) 836]
- the parameter $B_2$ quantifies the probability of the coalescence
- small collision systems ideal for studying coalescence - the phase space smaller than in heavy-ion collisions - the coalescence should be more probable

$$B_2 = \left( \frac{1}{2\pi p_T^d} \frac{d^2 N_d}{dy dp_T^d} \right) / \left( \frac{1}{2\pi p_T^p} \frac{d^2 N_p}{dy dp_T^p} \right)^2$$

$B_2^{(pp)} > B_2^{(p-Pb)} > B_2^{(Pb-Pb)}$
Deuteron production in jets

- phase-space distance between nucleons in jet smaller than in underlying event (UE) - naively the coalescence probability in jets should be enhanced w.r.t. underlying event

leading particle with $p_T > 5$ GeV/c

ALICE, arXiv:2301.10120
Deuteron production in jets

- **in-jet** = Toward - Transverse
- **underlying event** = Transverse
- **$B_2$ for jets larger than for UE** as predicted by coalescence model
- **underlying event**: $B_2$ for p–Pb smaller than for pp - source size is bigger in p-Pb
- **in-jet**: $B_2$ for p–Pb larger(!) than for pp - assuming same source size for the nucleons in jet, the nucleons are closer in phase-space in p–Pb jets than in pp jets
- could be the difference related to particle composition in jets (p–Pb vs. pp)?
Deuteron production in jets

- $d/p$ ratio for jets in $p$–$Pb$ bigger than for the $pp$ - different particle composition in the two collision systems?

**Graph:**

- ALICE Preliminary
- $p$–$Pb$, $\sqrt{s_{NN}} = 5.02$ TeV
- $p^\text{lead}_T > 5$ GeV/$c$

**Legend:**

- Red squares: in-jet
- Blue squares: underlying event

**Data:**

- $pp$, $\sqrt{s} = 13$ TeV
- $p^\text{lead}_T > 5$ GeV/$c$
ALICE 2.0 in Run 3

- new Inner Tracking System - 7 pixel layers, first layer at 20 mm
- new Forward Muon Tracker - forward vertexing and tracking for muons
- new readout chambers of the TPC (Time Projection Chamber) based on GEM (Gas Electron Multipliers) technology
- new FIT (Fast Interaction Trigger) - interaction trigger, multiplicity estimator
- from < 1 kHz single events in Run 2 to 50 kHz of continuous readout data in Run 3
- building new reconstruction and analysis framework O² (Online/Offline) from scratch
- expected 50-100 times more statistics for selected rare probes than in Run1+Run2

From < 1 kHz single events...

...to 50 kHz of continuous readout data.
Summary

- **long-range correlations** (connected to the flow in Pb–Pb):
  - observed also in small systems
  - ridge yields in pp collisions bigger than the yields in e⁺e⁻ (events with comparable multiplicity)

- **strangeness enhancement in small systems**:
  - out-of-jet processes give dominant contribution to strangeness enhancement in small systems
  - non-negligible contribution also from in-jet processes

- **deuteron production in jet and in underlying event**:
  - higher coalescence probability \( B_2 \) in jets than in underlying event
  - higher coalescence probability \( B_2 \) in jets in p–Pb than in jets in pp collisions

- stay tuned for the new Run 3 results