Insights into the evolution of hadronic collisions with flow observables QCD challenges from pp to AA collisions

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• Overlap between colliding nuclei: ⇒ Initial state, geometry & its fluctuations



Jonah Bernhard, Scott Moreland and Steffen Bass, Nature Phys. 15 (2019) 11, 1113-1117



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v_2 of baryons and mesons in Pb—Pb

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- Intermediate p_T :
 - Crossing point ⇒ radial flow and/or coalescence?





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- Intermediate p_T :
 - Crossing point ⇒ radial flow and/or coalescence?
 - Baryon/meson grouping \Rightarrow coalescence?
- * High p_T : jet quenching [1]





v_2 of baryons and mesons in Pb—Pb comparison to hydro model

• Measurements of v_2 :

⇒ Baryon/meson ordering and crossing

• Hydro + fragmentation:

X Underestimates the data in most cases

✓ Baryon/meson crossing predicted

 \Rightarrow Arises from species-dependent p_T cut,

where fragmentation dominates over hydro



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- Measurements of v_2 :
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- Hydro + fragmentation:
 - X Underestimates the data in most cases
 - ✓ Baryon/meson crossing predicted
 - \Rightarrow Arises from species-dependent p_T cut,
 - where fragmentation dominates over hydro
- Hydro + coalescence + fragmentation: ✓ Significantly better description of data
- But crossing is not unique to coalescence!









v_2 fluctuations of charged hadrons in Pb—Pb collisions

- Emerging p_T dependence from central to peripheral collisions
- Baryon/meson grouping in semi-central collisions \Rightarrow Different from that observed for v_2 \Rightarrow Could point to a different origin of this observation
- Higher moments of the PDF (charged hadrons): \Rightarrow Show evolution with $p_{\rm T}$ in the same range as $F(v_2)$ \Rightarrow Will be interesting to study for identified particles with Run3 data!





Anisotropic flow in p—Pb collisions for identified particles

- p_T -differential measurements of v_2 in p—Pb collisions for identified particles:
 - Inverse mass ordering at low p_T
 - Baryon/meson grouping at intermediate

 p_T with 3σ





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- Comparison to models:

Hydro + fragmentation: largely

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- Comparison to models:

- Hydro + fragmentation: largely underestimates data at intermediate p_T

- Hydro + coalescence + fragmentation: good description of data at intermediate p_T

- ⇒ Presence of partonic collectivity in p-Pb
- \Rightarrow ... but down to which multiplicity?



Anisotropic flow in pp collisions for identified particles

- Inverse mass ordering at low p_{T}
- Clear separation ($> 3\sigma$) between protons and π/K at intermediate p_T !



Hydrodynamics—like trends observed in pp and p-Pb. Are they of the same origin? \Rightarrow Need to study the initial state



Correlation between $[p_T]$ and v_2

- Shape of the fireball: anisotropic flow, $\varepsilon_n \to v_n$
- Size of the fireball: radial flow, $[p_T]$, $1/R \rightarrow [p_T]$
- Initial state: geometry and fluctuations of shape and size
- Final state: correlation between v_n and $[p_T]$
- ⇒ Study with Pearson correlation coefficient:

$$\rho_n\left(v_n^2, \left[p_T\right]\right) = \frac{\operatorname{cov}\left(v_n^2, \left[p_T\right]\right)}{\sqrt{\operatorname{var}\left(v_n^2\right)}\sqrt{\operatorname{var}\left(\left[p_T\right]\right)}}$$



Correlation between $[p_T]$ and v_2 at low multiplicity

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Low multiplicity: geometry \rightarrow initial momentum correlations \Rightarrow Change of slope sign \rightarrow presence of CGC?





Correlation between $[p_T]$ and v_2 in Pb—Pb at low multiplicity

 $\rho(v_2^2, [p_T])$ in Pb–Pb:

- Decreasing + increasing trend at low multiplicity
- Sensitive to p_T interval...

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- and pseudorapidity range...
- and even the multiplicity estimator

Correlation between $[p_T]$ and v_2 comparison to models

- $\rho(v_2^2, [p_T])$ in Pb—Pb:
- IP-glasma+MUSIC+UrQMD:
 - Slope change around 20 charged tracks, significantly lower than in data
- AMPT:
 - Change of slope also observed, although at significantly higher N_{ch}

⇒ Slope change not exclusive to IP-Glasma

$\rho(v_2^2, [p_T])$ in pp:

- Consistent with Pb-Pb at similar N_{ch}
- Underestimated by AMPT, overestimated by PYTHIA

Summary

- p_T -differential v_2 of identified hadrons in pp and p—Pb collisions show remarkable similarities to Pb—Pb collisions \Rightarrow Suggests dynamical evolution similar to that in Pb-Pb
- Relative flow fluctuations: emerging p_T dependence in peripheral collisions • Higher moments of v_2 PDF: evolution with centrality and p_T suggests sensitivity to initial geometry and transport properties of QGP
- Correlations between $[p_T]$ and v_2 :
 - ⇒ Highly sensitive to kinematic cuts and multiplicity estimator
 - Data better described by models with IP-Glasma in initial conditions
 - \Rightarrow Observed decreasing trend at small $N_{\rm ch}$ in Pb—Pb collisions
 - \Rightarrow Change of slope at low N_{ch} not unique to models with IP-Glasma

Backup

v_2 fluctuations: skewness and kurtosis $\frac{1}{2}$ in Pb—Pb collisions

Measure v_2 with multiparticle cumulants:

 \Rightarrow Sensitive to underlying v_2 probability density function (PDF) and thus initial geometry

- Skewness (γ₁) decreasing with centrality, PDF becoming less symmetric
- Kurtosis (γ_2) increasing with centrality, tails become "fatter"

Do γ_1 , γ_2 probe initial geometry exclusively?

Is QGP produced exclusively in heavy-ion collisions?

"Standard" paradigm:

- QGP in heavy-ion collisions
- Cold nuclear matter in proton-ion collisions
- Reference in pp

Pandora's box since 2013:

- Near-side ridge in p-Pb, reminiscent of QGP
- Particle production mechanism in pp and p—Pb similar to that in Pb—Pb
- Non-zero v_2 coefficients

Study it in p_T -differential way

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Flow factorisation ratio $r_n = \frac{\langle v_n^a v_n^t \cos[n(\Psi_n^a - \Psi_n^t)] \rangle}{\sqrt{\langle v_n^{a,2} \rangle \langle v_n^{t,2} \rangle}}$

Flow factorisation ratio $r_n =$ (trigger and associated)

$$\sqrt{\langle v_n^{a,2} \rangle \langle v_n^{t,2} \rangle}$$

Largest fluctuations in central Pb—Pb collisions at high $p_T \Rightarrow$ large event-by-event fluctuations in the initial state

$\frac{\operatorname{vn}^{a} v_{n}^{t} \operatorname{cos}[n \left(\Psi_{n}^{a} - \Psi_{n}^{t}\right)]}{\left(V_{n}^{a} v_{n}^{n} \operatorname{cos}[n \left(\Psi_{n}^{a} - \Psi_{n}^{t}\right)] \right)}$

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Largest fluctuations in central Pb—Pb collisions at high $p_T \Rightarrow$ large event-by-event fluctuations in the initial state

Deviations from $r_n = 1$ can be due to:

• Flow angle fluctuations,

$$\langle \cos\left[n\left(\Psi_n^a - \Psi_n^t\right)\right] \rangle \neq 1$$

- Flow magnitude fluctuations, $\langle v_n^a v_n^t \rangle \neq \mathbf{1}$
- Cannot be measured directly, but upper/lower limits can be estimated

Flow factorisation ratio $r_n = \frac{\langle v_n^a v_n^t \cos[n(\Psi_n^a - \Psi_n^t)] \rangle}{\langle v_n^t \nabla v_n^t \cos[n(\Psi_n^a - \Psi_n^t)] \rangle}$ (trigger and associated)

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- Flow magnitude fluctuations, $\langle v_n^{a,2} \rangle \langle v_n^{t,2} \rangle$ $\langle v_n^a v_n^t \rangle \neq \sqrt{}$
- Cannot be measured directly, but upper/lower limits can be estimated

Flow magnitude fluctuations

- Sensitive to fluctuations in initial state, little sensitivity to n/s
- Strong sensitivity to shear viscosity, but only in the most central collisions

Flow vector fluctuation limits in Pb—Pb $\langle v_n^a v_n^t \cos[n\left(\Psi_n^a - \Psi_n^t\right)] \rangle$

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Largest fluctuations in central Pb—Pb collisions at high $p_T \Rightarrow$ large event-by-event fluctuations in the initial state

- At least 40% of fluctuations in central collisions originate from flow angle fluctuations
- Above 30% centrality, flow magnitude fluctuations are suppressed

First measurement separating flow angle and magnitude fluctuations \Rightarrow Challenges the assumption of a common symmetry plane

Define flow factorisation as $r_n = \frac{V_{n\Delta}(p_{\rm T}^a, p_{\rm T}^t)}{\sqrt{V_{n\Delta}(p_{\rm T}^a, p_{\rm T}^a) \cdot V_{n\Delta}(p_{\rm T}^t, p_{\rm T}^t)}} = \frac{\langle v_n^a v_n^t \cos[n\left(\Psi_n^a - \Psi_n^t\right)] \rangle}{\sqrt{\langle v_n^{a,2} \rangle \langle v_n^{t,2} \rangle}}$

Deviations from $r_n = 1$ can be due to:

• Flow magnitude fluctuations,

 $\langle v_n^a v_n^t \rangle \neq \sqrt{\langle v_n^{a,2} \rangle \langle v_n^{t,2} \rangle}$

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- Cannot measure directly, but *can* measure upper/lower limits!

 Γ_2

Correlation between $[p_T]$ and v_2 and deformation of nuclei

- Shape of the fireball: anisotropic flow, $\varepsilon_n \rightarrow v_n$
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 $\Rightarrow \rho_2$ is significantly smaller in central collisions of deformed Xe nuclei (deformation parameter $\beta_2 \approx 0.16$) compared to spherical Pb ($\beta_2 \approx 0$)

Correlation between $[p_T]$ and v_2 in Pb—Pb and Xe—Xe collisions

- ρ_2 slightly larger in Pb—Pb compared to Xe—Xe
- Comparison to models:
 - Below 20% centrality, all models provide a

decent description

- More peripheral \rightarrow best described by models with IP-Glasma

• Xe-Xe:

 $-\beta_2 = 0.162$ gives better description in most central collisions, similar to $\beta_2 = 0$ in more peripheral

