Elliptic Flow of K_S^0 and Λ in O+O Collisions at $\sqrt{s_{NN}} = 200$ GeV

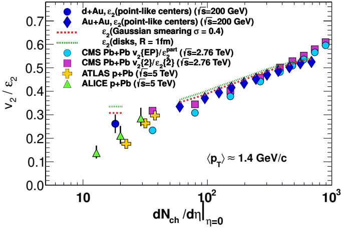
Santanu Prodhan
Supervisor : Dr. Chitrasen Jena
Indian Institute of Science Education and Research (IISER) Tirupati

ALICE-STAR India Collaboration Meeting
November 21-24, 2023
University of Jammu

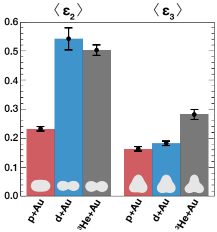
Outline

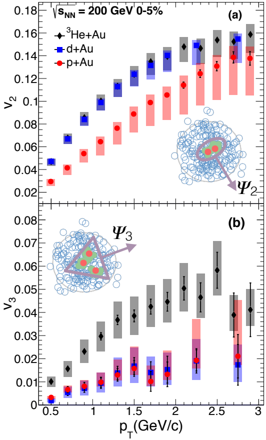
Understanding emergence of collectivity in small systems : p/d/^{3}He+A and A+A (e.g. O+O)

- Small size and short lifetime $\Longrightarrow$ Lack of enough time for thermalization.
- Spatial and momentum anisotropy during initial stages will contribute to collectivity.
    - Initial state models having nucleonic, sub- nucleonic structures and pre-flow needs to be better constrained.



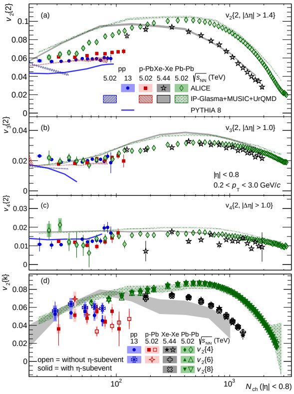
PHENIX, Phys. Rev. Lett. **111**, 212301 (2013)



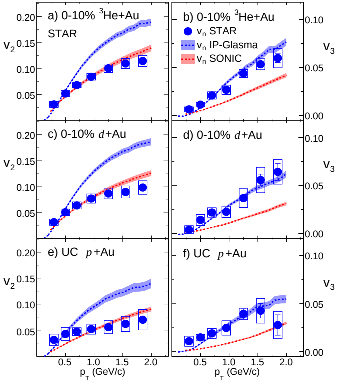


PHENIX, Nature Phys. **15**, 214 (2019)

$$v_n \propto \varepsilon_n \Longrightarrow \begin{cases} v_2^{\text{p+Au}} < v_2^{\text{d+Au}} \approx v_2^{^3\text{He+Au}} \\ v_3^{\text{p+Au}} \approx v_3^{\text{d+Au}} < v_3^{^3\text{He+Au}} \end{cases}$$



ALICE, Phys. Rev. Lett. **123**, 142301 (2019)



STAR, Phys. Rev. Lett. **130**, 242301 (2023)

IP-Glasma includes sub-nucleonic fluctuations whereas SONIC uses nucleon Glauber

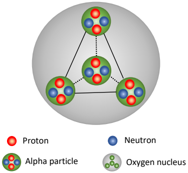
- At LHC energies, IP-Glasma gives only a qualitative description of data for p+Pb.
- At RHIC energies, IP-Glasma (+pre-flow) overestimates v_2 whereas SONIC underestimates v_3.

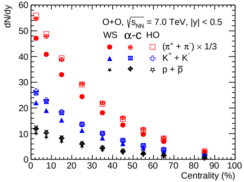
Phenomenological models need to be better constrained to interpret small system collectivity

Introduction

Why O+O ? Systematic variation of system size and collision geometry

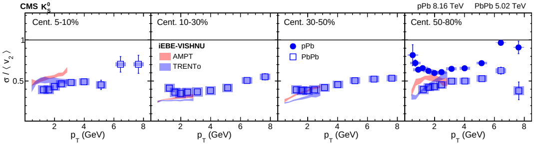
- System size comparable to d+Au at RHIC and p+Pb at LHC but vastly different geometry.
- Comparison with asymmetric small systems and upcoming LHC measurements





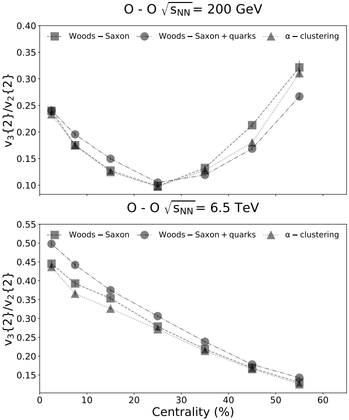
Eur. Phys. J. A **58**, 175 (2022)

AMPT predicts higher yield for α-cluster than Woods-Saxon.



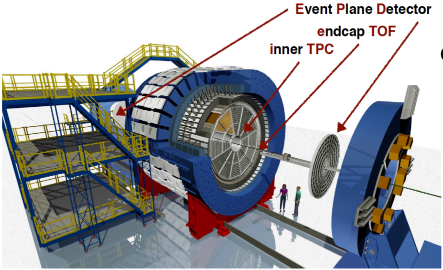
CMS, JHEP **05**, 007 (2023)

(Multi-)Strange hadrons are good probes for initial dynamics



Phys. Rev. C **104**, L041901 (2021)

Hydrodynamics with NLEFT derived initial state predicts suppression of $v_3\{2\}/v_2\{2\}$ in contrast to sub-nucleonic structure



Nucl. Phys. A **956**, 75 (2016)

Current detector setup includes

- inner Time Projection Chamber (iTPC)
  - Larger acceptance : $|\eta| < 1.5$ (was $|\eta| < 1$).
  - Better dE/dx and momentum resolution.
- Event Plane Detector (EPD)
  - Improved capability for event plane (esp. 1^{st} order) reconstruction.

Solenoid Tracker At RHIC (STAR) detector has significant particle identification (PID) capabilities at high energy collisions combining

- Ionization energy loss (dE/dx) of charged particles from Time Projection Chamber (TPC)
- Velocity ($\Delta L/\Delta t$) from Time of Flight (ToF) detector
- Momentum (**p**) measured from curvature of path under strong magnetic field.

System	Production Tag	Trigger ID	Events

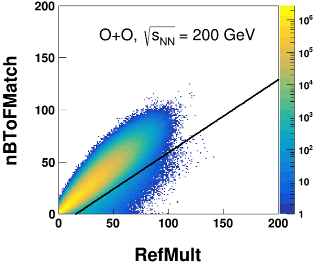
O+O
$\sqrt{s_{\mathrm{NN}}}$ = 200 GeV
	`production_OO_200GeV_2021`
	`production_ps_OO_200GeV_2021`
	`production_FF_OO_200GeV_2021`
		860001, 860011
		860002, 860012
			625M (325M)

$\lvert V_z \rvert$	$\leq$ 30 cm
V_r	$\leq$ 2 cm
$\lvert V_{\mathrm{z,\,VPD}} - V_{\mathrm{z,\,TPC}} \rvert$	$\leq$ 3 cm

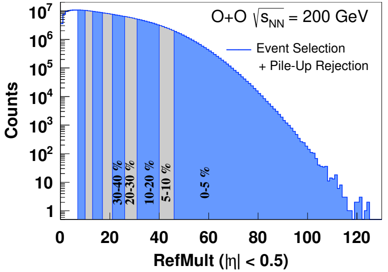
Event Selection

`nHitsFit`	$\geq$ 15
`nHitsdEdx`	$\geq$ 15
`nHitsRatio`	$\geq$ 0.52
$\lvert\eta\rvert$	$\leq$ 1.5

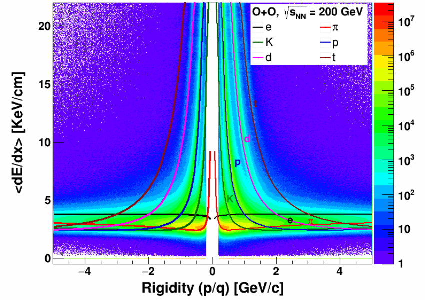
Track Selection

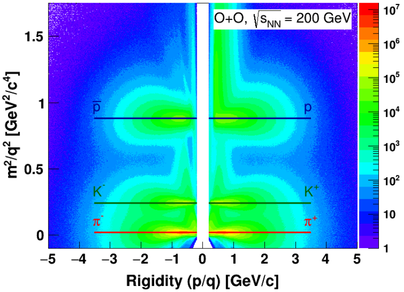


`nBToFMatch` > −11 + 0.7× `RefMult`



Particle Identification





- Particles are identified using $\langle dE/dx \rangle$ information from Time Projection Chamber (TPC)

$$n\sigma_i = \frac{1}{R_i} \ln \frac{\langle dE/dx \rangle^{\text{measured}}}{\langle dE/dx \rangle_i^{\text{Bichsel}}}$$

R_i is the TPC resolution for particle species i. Theoretical curves are from Bichsel function.[1]

- Time of Flight (ToF) information is also used when available

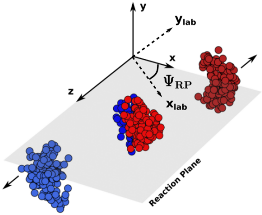
$$m^2 = p^2 \left[\frac{1}{\beta^2} - 1 \right] \quad \text{where} \quad \beta = \frac{1}{c} \left(\frac{\Delta L}{\Delta t_{\text{ToF}}} \right)$$

[1] H. Bichsel, Nucl. Instrum. Meth. A **562**, 154 (2006)

Fourier decomposition of azimuthal distribution of particles

$$\frac{dN}{d\phi} = \frac{1}{2\pi}\left\{1 + \sum_{n\geq 1} v_n \cos\left[n\left(\phi - \Psi_{\mathrm{RP}}\right)\right]\right\}$$

$$v_n = \langle \cos\left[n\left(\phi - \Psi_{\mathrm{RP}}\right)\right]\rangle$$



Event-by-event estimate of Ψ_{RP} from finite multiplicity of each event : Ψ_n

$$\boldsymbol{Q}_{n,\mathrm{raw}} = Q_{n,\mathrm{raw}}\, e^{in\Psi_{n,\mathrm{raw}}} = \sum_{k\,\in\,\mathrm{tracks}} w_k\, e^{in\phi_k} \quad \text{where} \quad w = p_{\mathrm{T}} \times w_\phi$$

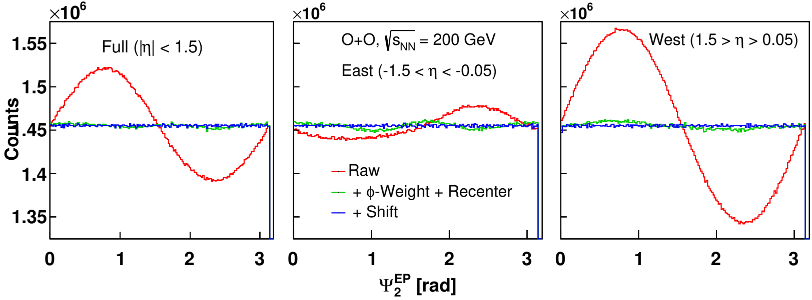
1. **Recentering :** $\boldsymbol{Q}_{n,\mathrm{raw}}$ is re-centered to the origin event-by-event

$$\boldsymbol{Q}_{n,\mathrm{raw}} \longrightarrow \boldsymbol{Q}_{n,\mathrm{rec}} = \boldsymbol{Q}_{n,\mathrm{raw}} - \left\langle \boldsymbol{Q}_{n,\mathrm{raw}} \right\rangle_{\mathrm{event}}$$

2. **Shift :** Event-by-event shifting by means of Fourier expansion

$$\Psi_n = \Psi_{n,\mathrm{rec}} + \Delta\Psi_{n,\mathrm{shift}}$$

$$\Delta\Psi_{n,\mathrm{shift}} = \sum_{k\geq 1}\left(\frac{2}{n\,k}\right)\left[-\left\langle \sin\left(n\,k\,\Psi_{n,\mathrm{rec}}\right)\right\rangle \cos\left(n\,k\,\Psi_{n,\mathrm{rec}}\right) + \left\langle \cos\left(n\,k\,\Psi_{n,\mathrm{rec}}\right)\right\rangle \sin\left(n\,k\,\Psi_{n,\mathrm{rec}}\right)\right]$$



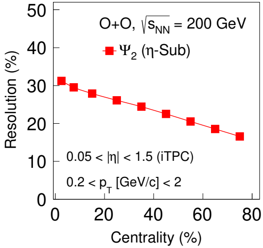
nHitsFit	≥ 15
nHitsdEdx	≥ 15
nHitsRatio	≥ 0.52
DCA	≤ 2 cm
p_T [GeV/c]	[0.2, 2]
$\|\eta\|$	≤ 1.5

Track Selection for Ψ_2^{EP}

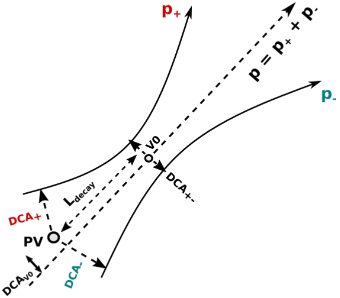
Ψ_n resolution from η-sub events

$$R_n = \sqrt{\cos\left[n\left(\Psi_n^{west} - \Psi_n^{east}\right)\right]}$$

East	$-1.5 < \eta < -0.05$
West	$1.5 > \eta > 0.05$



Signal Extraction



V0 Decay Topology

Yield :

$$\frac{d^3 N}{dM_{\text{inv}}\, dp_{\text{T}}\, d(\phi - \Psi_n)}$$

$$M_{\text{inv}}^2 = (E_+ + E_-)^2 - (\mathbf{p}_+ + \mathbf{p}_-)^2$$

Background :

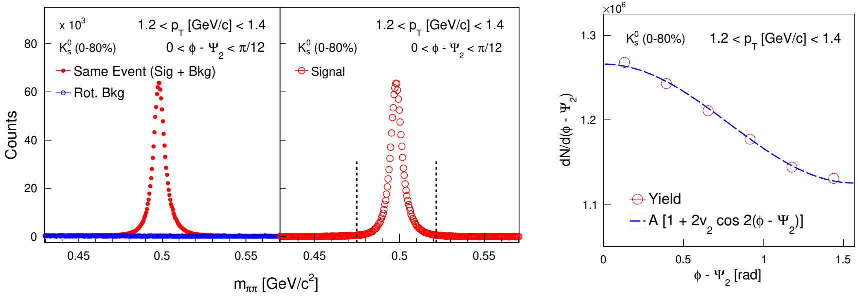
$$(\boldsymbol{p}_{\text{T}},\ p_z) \longrightarrow (-\boldsymbol{p}_{\text{T}},\ p_z)$$

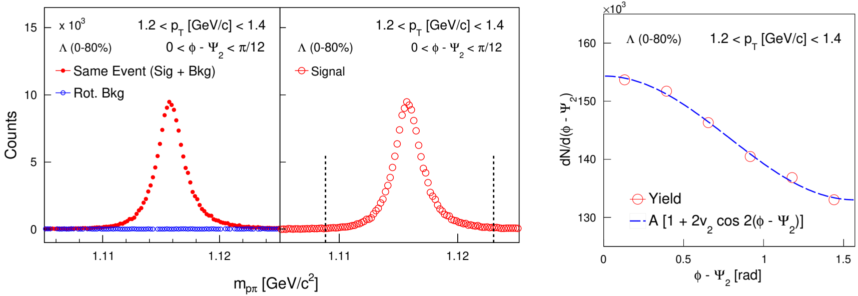
Decay Channel	$K_S^0 \longrightarrow \pi^+ + \pi^-$
Decay Length	> 3 cm
π^+ DCA to PV	> 0.7 cm
π^- DCA to PV	> 0.7 cm
$\pi^+ \pi^-$ DCA	< 1 cm
K_s^0 DCA to PV	< 0.8 cm

Decay Channel	$\Lambda \longrightarrow p + \pi^-$
Decay Length	> 3 cm
p DCA to PV	> 0.6 cm
π^- DCA to PV	> 1.2 cm
$p\,\pi^-$ DCA	< 1 cm
Λ DCA to PV	< 0.7 cm

V0 Topological Cuts

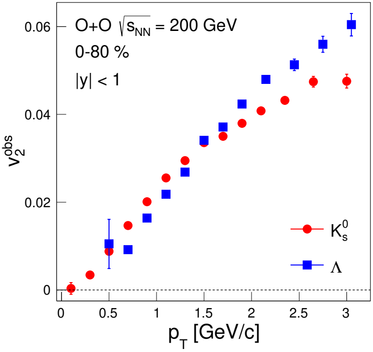
Signal Extraction

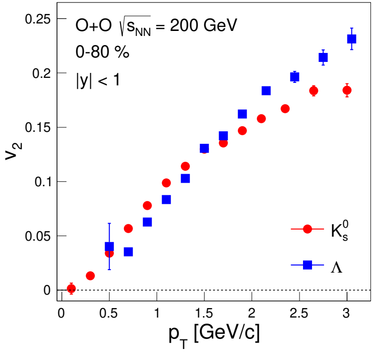




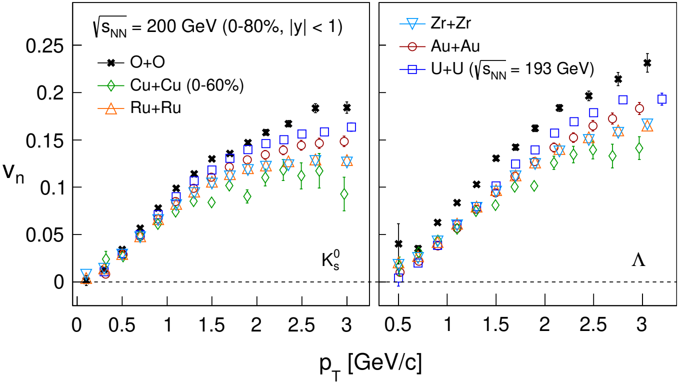
Elliptic Flow

$$v_n = \frac{v_n^{obs}}{\langle R_n \rangle} \quad \text{where } \langle R_n \rangle \text{ is yield-weighted average}$$





- Mass ordering at low p_T ($\lesssim 1.5$ GeV/c) $\Longleftrightarrow$ Hydrodynamic behaviour at low p_T.
- $v_2^{\text{Baryon}} > v_2^{\text{Meson}}$ at intermediate p_T $\Longleftrightarrow$ Collectivity originates at partonic phase.



Non-flow contribution in $v_2(p_T)$ is evident small collisions system e.g. O+O at $\sqrt{s_{NN}}$ = 200 GeV.

- Event plane method for estimating flow is susceptible to other sources of correlations.

Cu+Cu : STAR, Phys. Rev. C **81**, 044902 (2010)

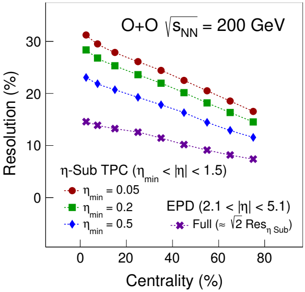
Au+Au : STAR, Phys. Rev. C **103**, 064907 (2021)

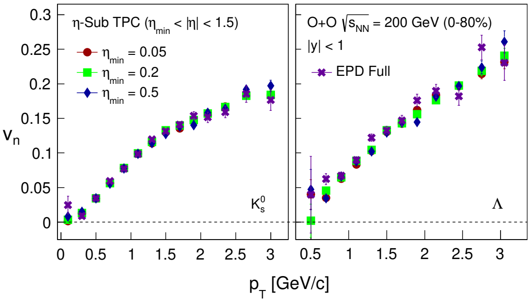
U+U : STAR, Phys. Rev. C **88**, 014902 (2013)

Ru+Ru, Zr+Zr : Priyanshi's Analysis

Further checks for non-flow reduction

- Increasing η-gap between the sub-events : $\Delta\eta = |\eta_{\text{west}} - \eta_{\text{east}}|$
- Using forward detectors for Ψ_n reconstruction : Event Plane Detector (EPD)





Increasing η gap within sub-events is not sufficient to suppress non-flow

- Elliptic flow of K_S^0 and Λ using event plane method were presented for minimum bias O+O collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV.
- Effect of increasing η gap between sub-events and usage of forward detectors in event plane reconstruction were checked for non-flow reduction.

Outlook

- Optimization of different topological cuts.
- Determination of elliptic flow centrality-wise.
- Extend analysis for other strange hadrons and higher harmonics.

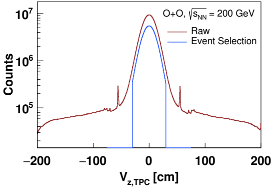
References

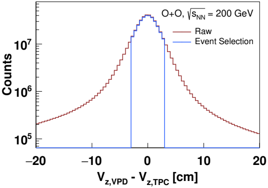
- PHENIX, Phys. Rev. Lett. **111**, 212301 (2013).
- PHENIX, Nature Phys. **15**, 214 (2019).
- ALICE, Phys. Rev. Lett. **123**, 142301 (2019).
- STAR, Phys. Rev. Lett. **130**, 242301 (2023).
- Eur. Phys. J. A **58**, 175 (2022).
- CMS, JHEP **05**, 007 (2023).
- Phys. Rev. C **104**, L041901 (2021).
- Nucl. Phys. A **956**, 75 (2016).
- H. Bichsel, Nucl. Instrum. Meth. A **562**, 154 (2006).
- STAR, Phys. Rev. C **81**, 044902 (2010).
- STAR, Phys. Rev. C **103**, 064907 (2021).
- STAR, Phys. Rev. C **88**, 014902 (2013).

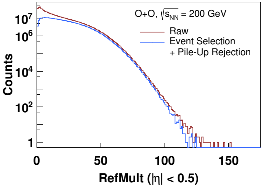
Thank You

Backup

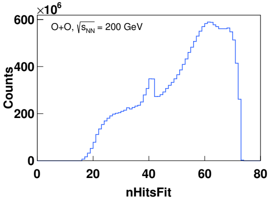
Event QA

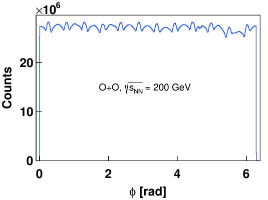


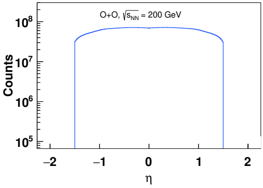




Track QA







After Event + Track selection cuts

Backup

$\Delta\eta$ Check