Impact of elliptic flow on higher order flow coefficients in heavy-ion collisions at the LHC

Based On:

S. Prasad, N. Mallick, S. Tripathy, R. Sahoo, Phys. Rev. D **107** (2023) 074011.

S. Prasad, A. Menon K. R., R. Sahoo, N. Mallick, Phys. Lett. B **868** (2025) 139753.

Presented By:

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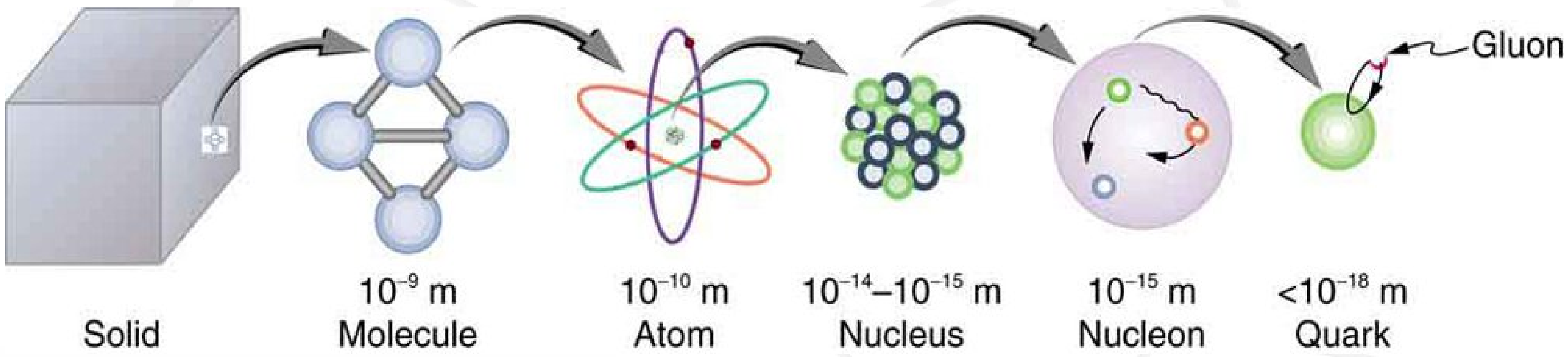
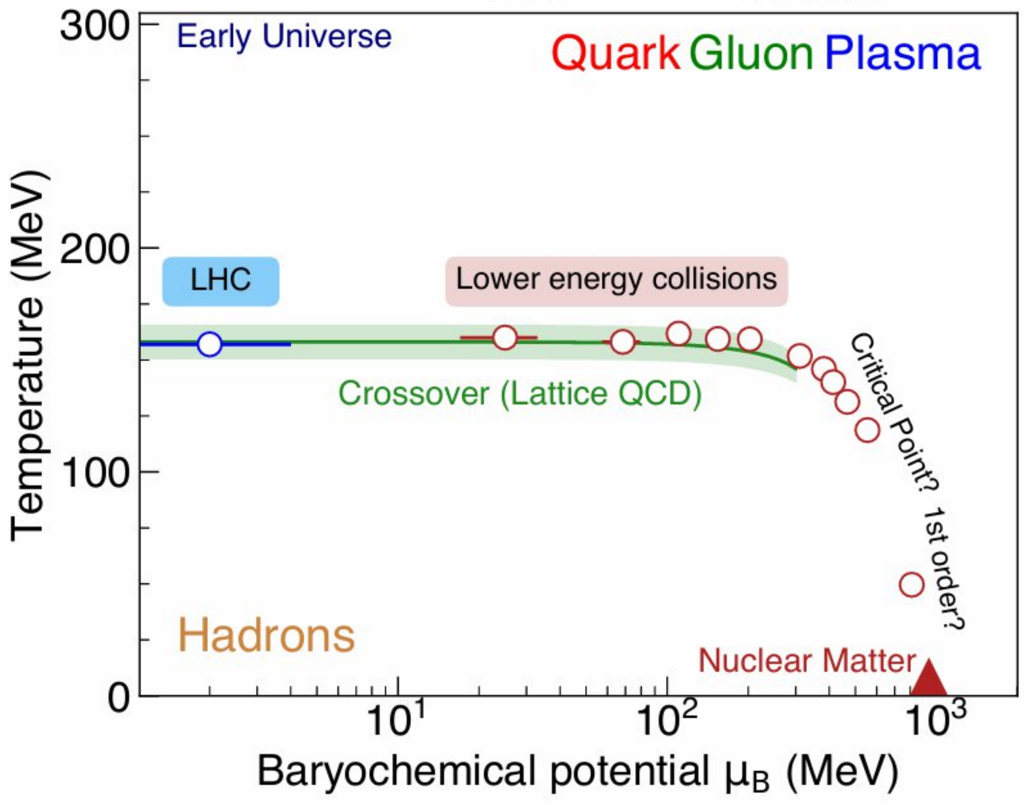
08 August 2025

QCD Phase diagram

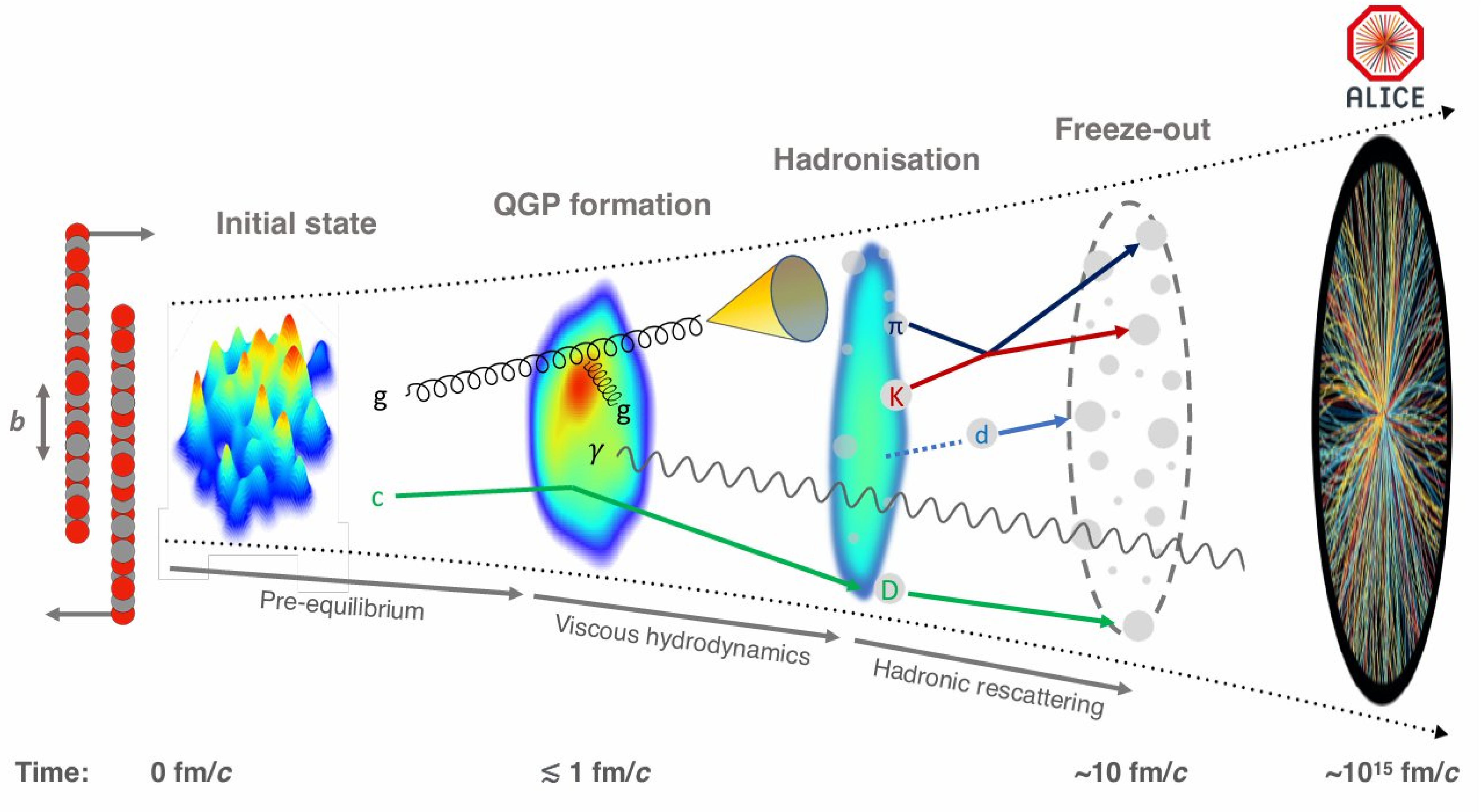


S. Acharya et al. (ALICE), Eur. Phys. J. C 84, 813 (2024)

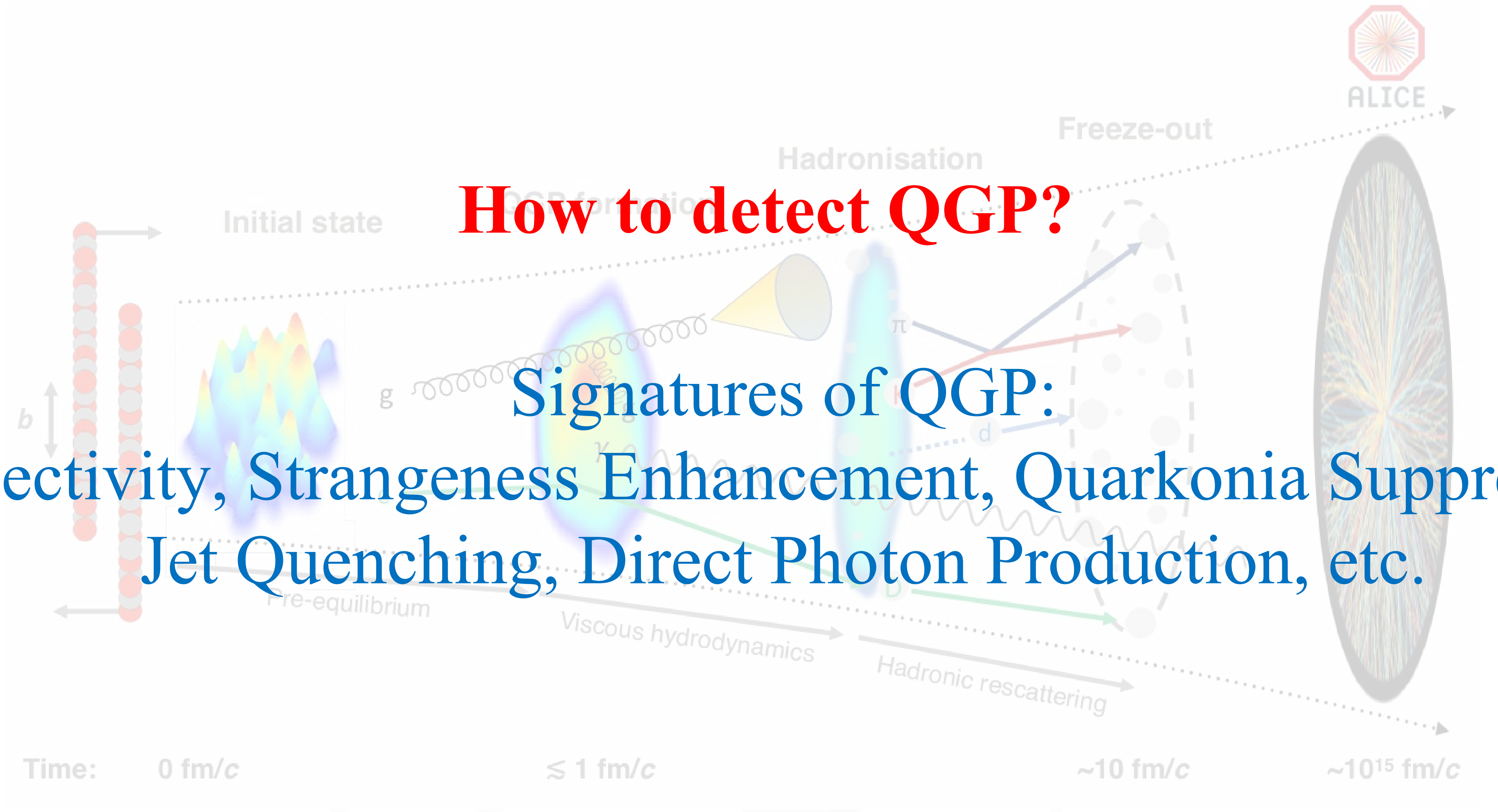


- The quarks are bound through gluons inside hadrons, such as , protons and neutrons. No isolated parton can be observed —> Color Confinement
- If the matter is heated up to incredible temperatures ($\sim 10^5$ times the temperature in core of the Sun) a "soup" of partons can be formed where quarks and gluons can move freely
- A similar state can be achieved by increasing the baryochemical potential

Heavy-Ion Collisions and Quark Gluon Plasma



S. Acharya et al. (ALICE), Eur. Phys. J. C 84, 813 (2024)

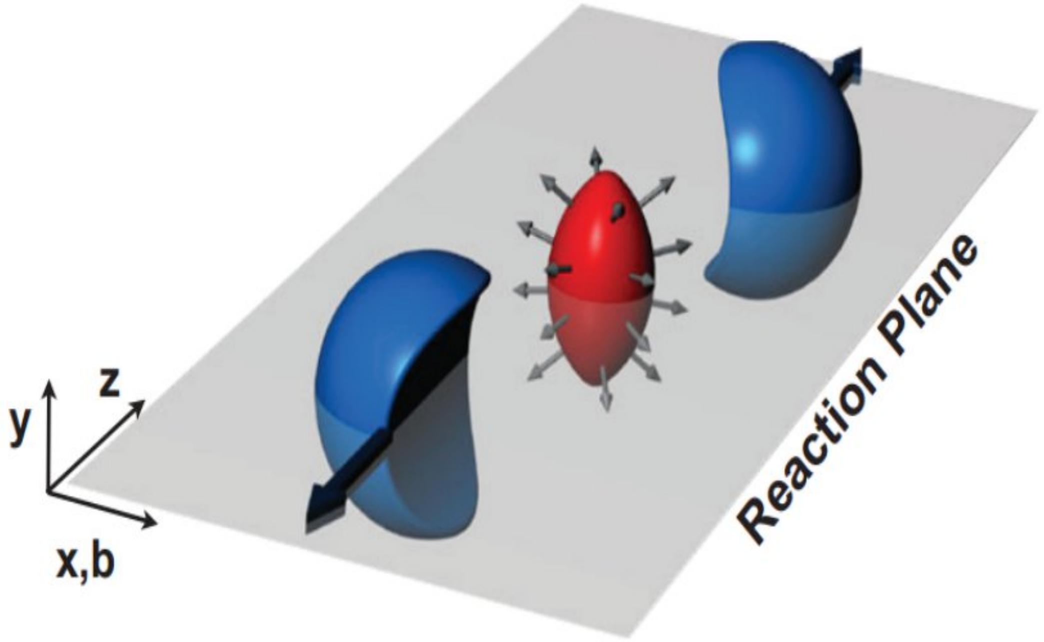


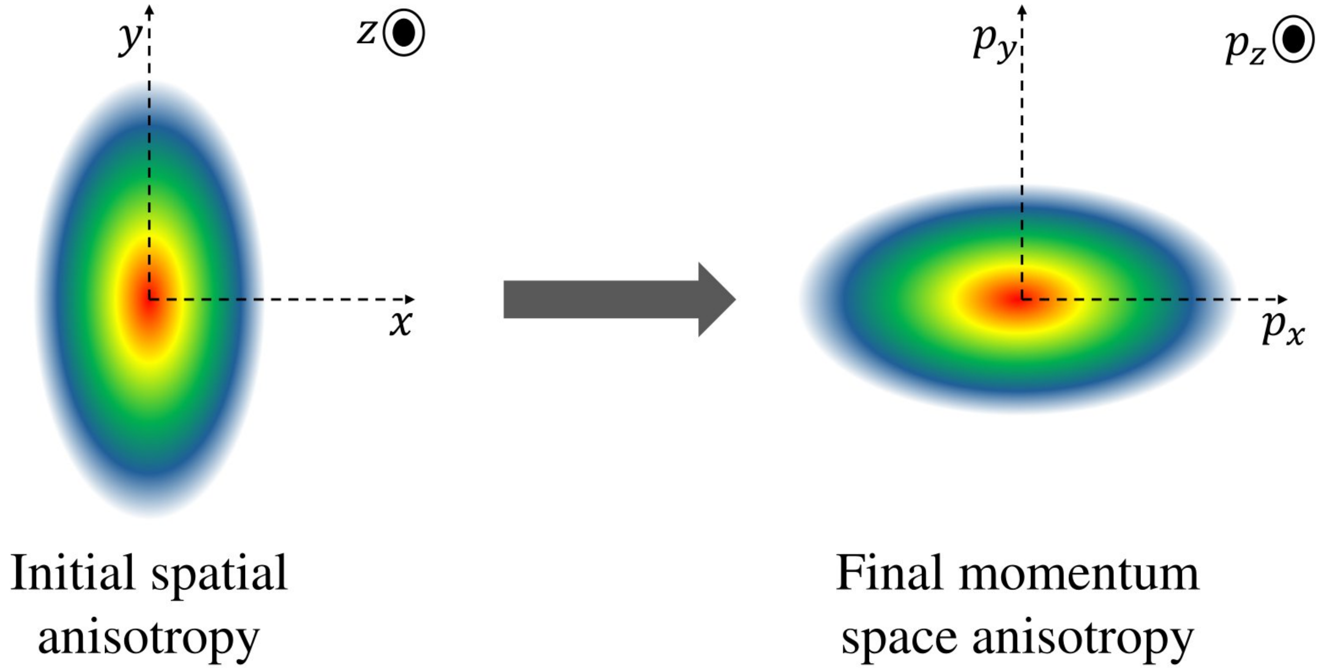
How to detect QGP?

Signatures of QGP:
Collectivity, Strangeness Enhancement, Quarkonia Suppression, Jet Quenching, Direct Photon Production, etc.

S. Acharya et al. (ALICE), Eur. Phys. J. C 84, 813 (2024)

Anisotropic Flow



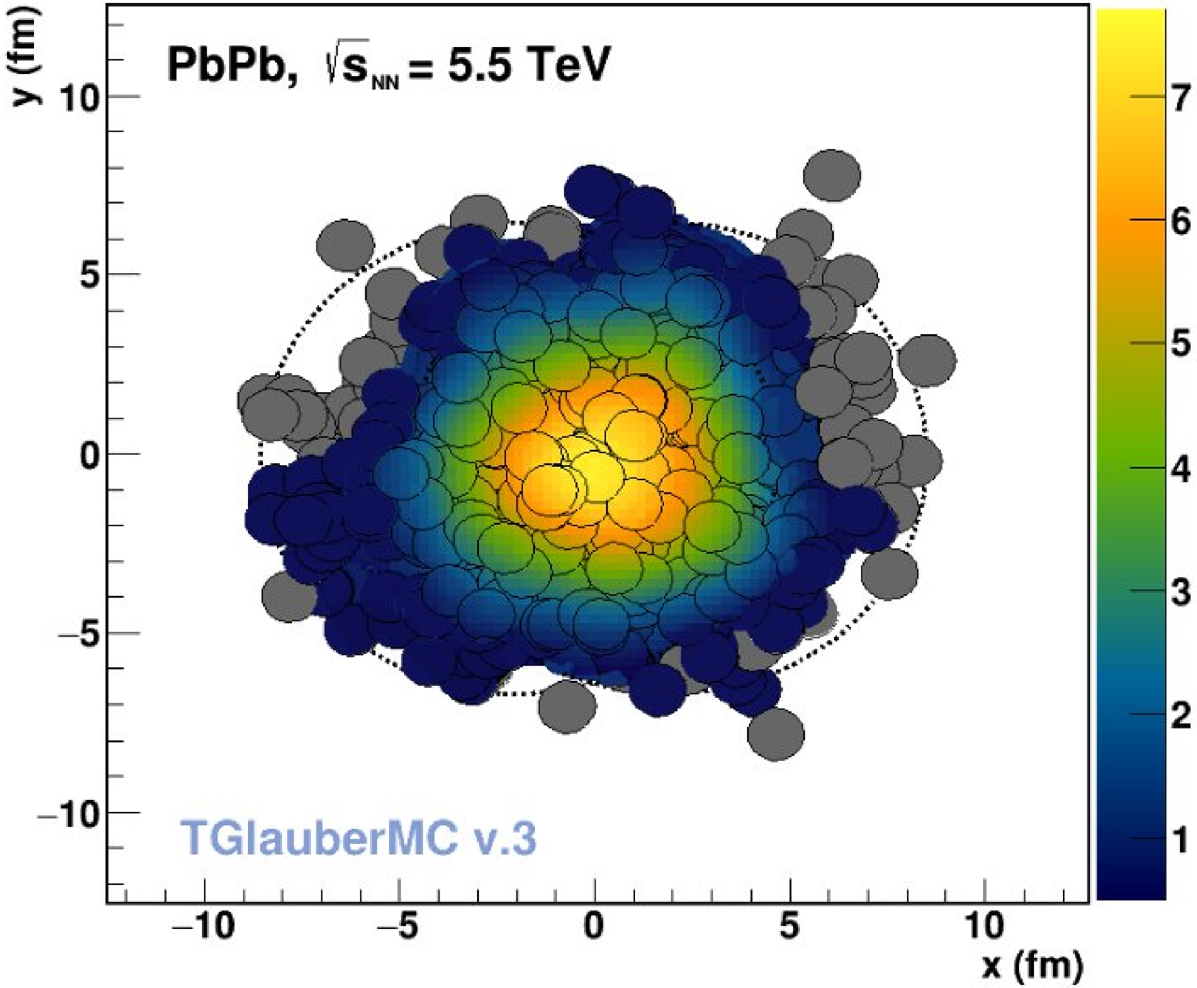


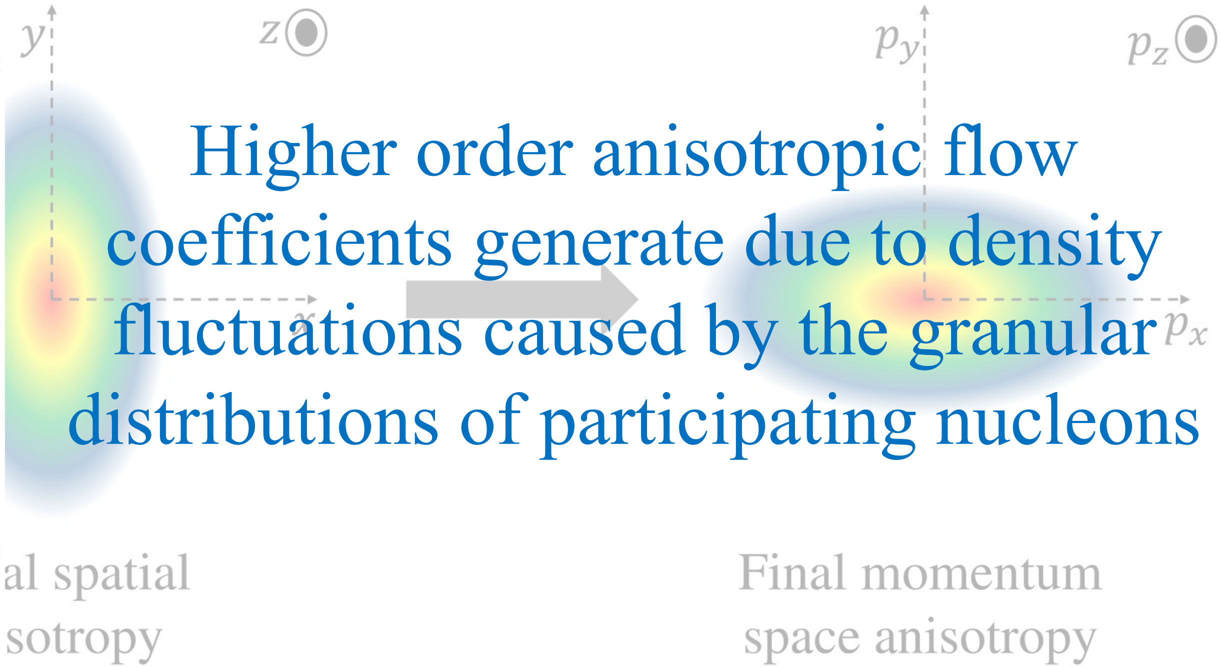
- Anisotropic flow: hydrodynamic response to spatial deformation of the initial participant distribution

Annual Review of Nuclear and Particle Science 71:315-44 (2021)

N. Mallick, R. Sahoo, S. Tripathy, and A. Ortiz, J. Phys. G 48, 045104 (2021)
ALICE Collaboration, JHEP 1506, 190 (2015)

Anisotropic Flow





Higher order anisotropic flow coefficients generate due to density fluctuations caused by the granular distributions of participating nucleons

- Anisotropic flow: hydrodynamic response to spatial deformation of the initial participant distribution

Annual Review of Nuclear and Particle Science 71:315-44 (2021)

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ALICE Collaboration, JHEP 1506, 190 (2015)

Anisotropic Flow

$$E\frac{d^3N}{dp^3} = \frac{d^2N}{2\pi p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n)]\right) = \frac{d^2N}{2\pi p_T dp_T dy}\left(1 + 2v_1\cos(\phi-\psi_1) + 2v_2\cos[2(\phi-\psi_2)] + 2v_3\cos[3(\phi-\psi_3) + \ldots]\right)$$

Directed flow (v_1), Elliptic flow (v_2), Triangular flow (v_3)

- Anisotropic flow coefficients are excellent probes for transport properties of the medium
- Higher order coefficients are more sensitive to system response/transport properties of the medium

Elliptic and triangular flow interfere with measurements of higher order harmonics

$$v_4 e^{i4\Phi_4} = a_0\epsilon_4 e^{i4\psi_4} + a_1(\epsilon_2 e^{i2\psi_2})^2 + \ldots$$
$$= c_0 e^{i4\psi_4} + c_1(v_2 e^{i2\Phi_2})^2 + \ldots,$$

$$v_5 e^{i5\Phi_5} = a_0\epsilon_5 e^{i5\psi_5} + a_1\epsilon_2 e^{i2\psi_2}\epsilon_3 e^{i3\psi_3} + \ldots$$
$$= c_0 e^{i5\psi_5} + c_1 v_2 v_3 e^{i(2\Phi_2+3\Phi_3)} + \ldots,$$

Large fluctuations of flow tend to interfere with physical interpretation of observed phenomena

→ **Event Shape Analysis**

N. Mallick, R. Sahoo, S. Tripathy, and A. Ortiz, J. Phys. G 48, 045104 (2021)
ALICE Collaboration, JHEP 1506, 190 (2015)

Multiparticle Q-cumulant method

Event plane and average method

$$v_n = \langle \cos[n(\phi - \psi_n)] \rangle$$

(Affected by non-flow and requires ψ_n)

Multiparticle Q-cummulant method

– Flow vector $$Q_n = \sum_{j=1}^{M} e^{in\phi_j}$$

– The 2- and 4-particle cummulants are:

$$\langle 2 \rangle = \frac{|Q_n|^2 - M}{M(M-1)},$$

$$\langle 4 \rangle = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2 \cdot \mathrm{Re}[Q_{2n} Q_n^* Q_n^*]}{M(M-1)(M-2)(M-3)} - 2\frac{2(M-2) \cdot |Q_n|^2 - M(M-3)}{M(M-1)(M-2)},$$

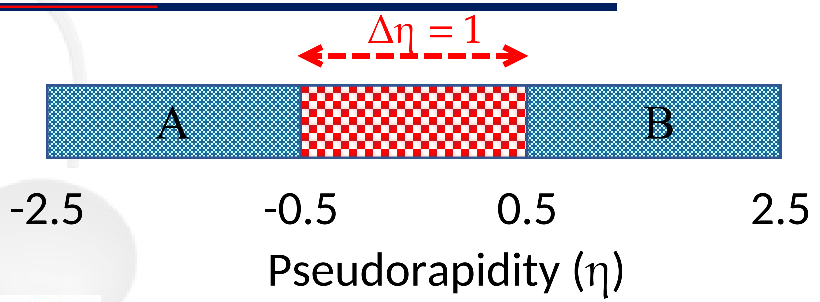
→

$$c_n\{2\} = \langle\langle 2 \rangle\rangle,$$
$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 \cdot \langle\langle 2 \rangle\rangle^2$$

→

$$v_n\{2\} = \sqrt{c_n\{2\}},$$
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

Suppressing the non-flow contribution:



- Kinematical cut: 2 sub-events, A&B are intoduced, with a rapidity gap:

$$\langle 2 \rangle_{\Delta\eta} = \frac{Q_n^A \cdot Q_n^{B*}}{M_A \cdot M_B} \quad \longrightarrow \quad v_n\{2,|\Delta\eta|\}(p_{\mathrm{T}}) = \frac{d_n\{2,|\Delta\eta|\}}{\sqrt{c_n\{2,|\Delta\eta|\}}}$$

- Differential flow cummulants:

$$d_n\{2\} = \langle\langle 2' \rangle\rangle,$$
$$d_n\{4\} = \langle\langle 4' \rangle\rangle - 2\langle\langle 2' \rangle\rangle\langle\langle 2 \rangle\rangle$$

$$\longrightarrow \quad d_n\{2,|\Delta\eta|\} = \langle\langle 2' \rangle\rangle_{\Delta\eta}$$

- Mean and the fluctuations of the flow & ratio:

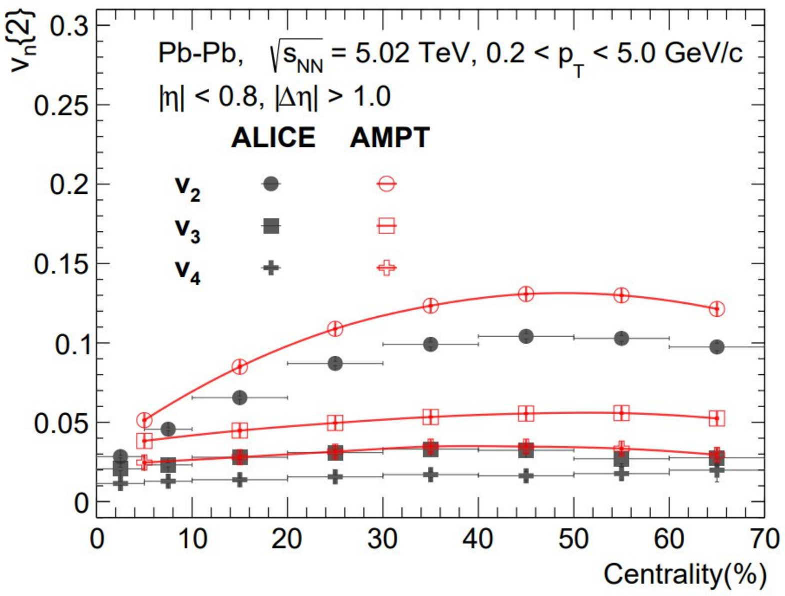
$$\langle v_n \rangle = \sqrt{\frac{v_n^2\{2,|\Delta\eta|\} + v_n^2\{4\}}{2}}$$

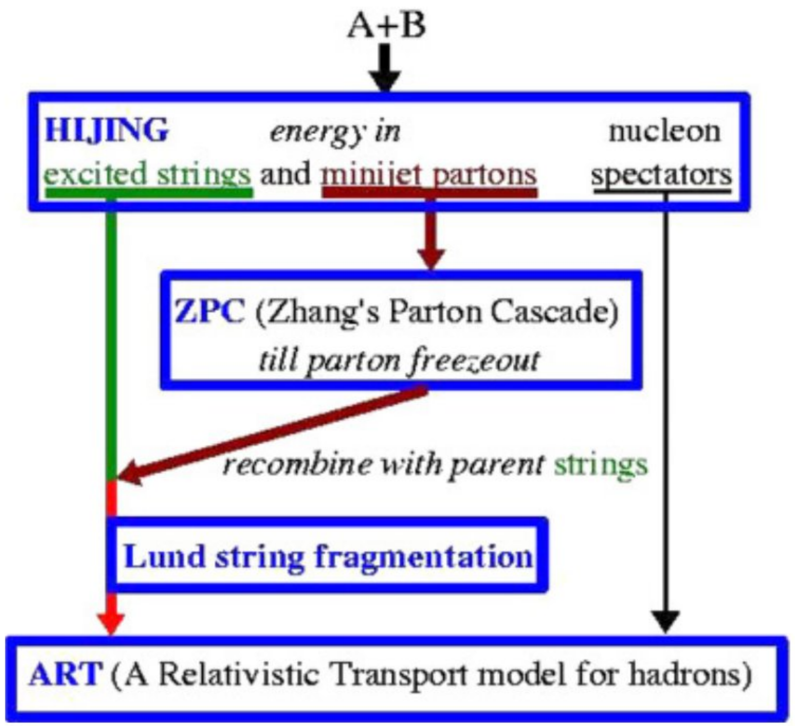
$$\sigma_{v_n} = \sqrt{\frac{v_n^2\{2,|\Delta\eta|\} - v_n^2\{4\}}{2}}$$

$$\longrightarrow \quad F(v_n) = \frac{\sigma_{v_n}}{\langle v_n \rangle}$$

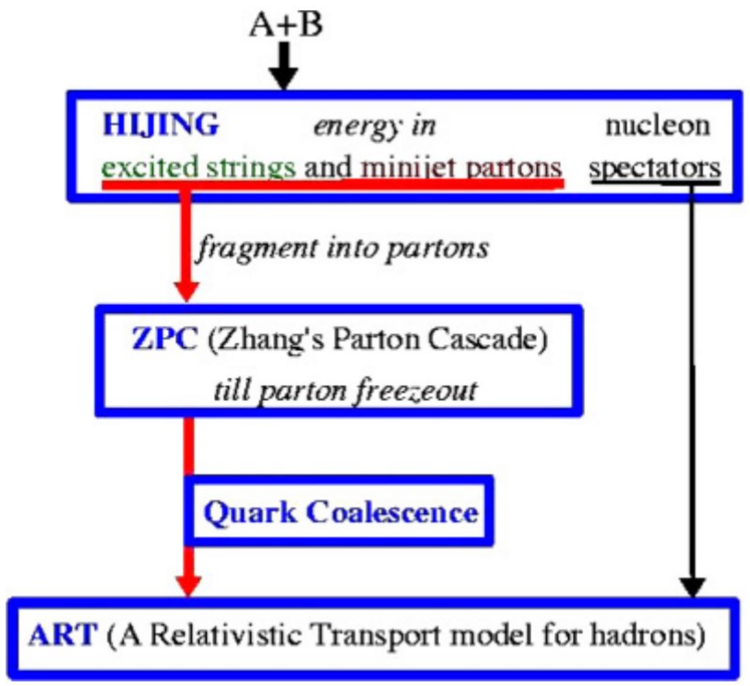
A Multi-Phase Transport Model (AMPT)

- Initialisation of collisions (HIJING)
- Parton Transport (ZPC)
- Hadronisation (Lund string fragmentation / Quark coalescence)
- Hadron Transport (ART)





Default Version



String Melting Version

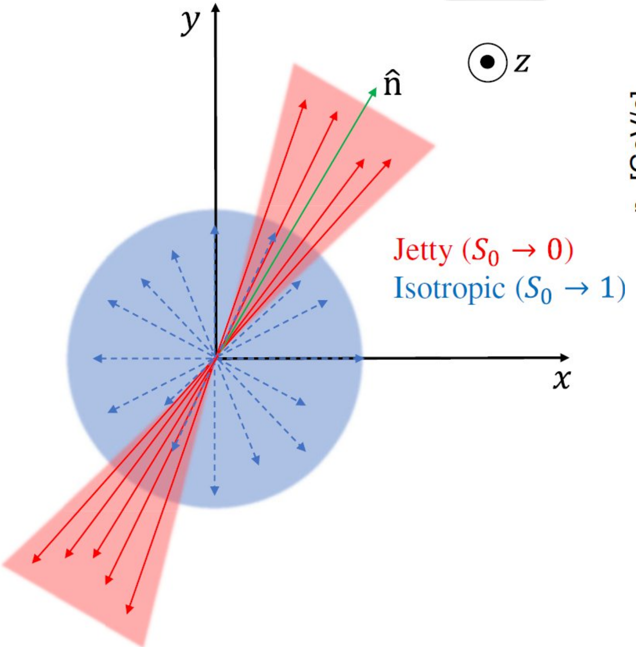
S. Prasad, A. Menon K. R., R. Sahoo, N. Mallick, Phys. Lett. B 868 (2025) 139753
Zi-Wei Lin, Che Ming Ko, Bao-An Li, Bin Zhang, and Subrata Pal, Phys. Rev. C 72, 064901 (2005)

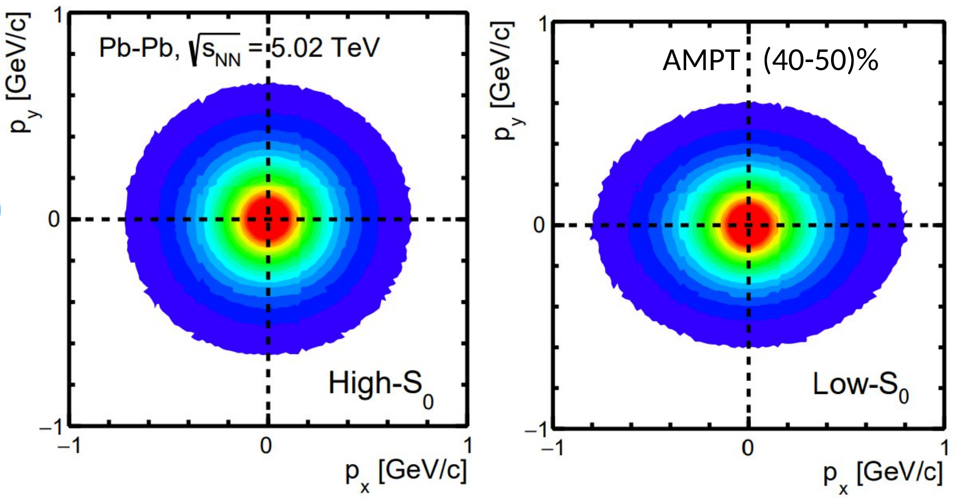
Transverse Spherocity

- Event shape observable: separates events based on geometrical shapes

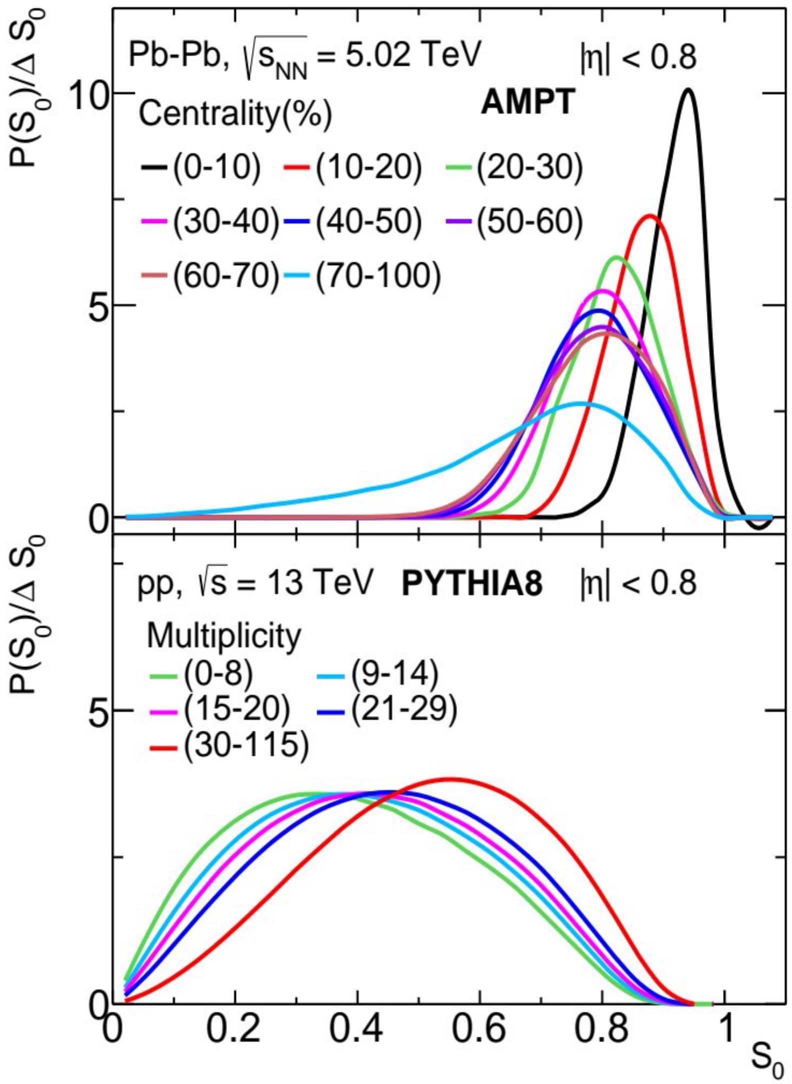
$$S_0 = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\sum_i \left| \vec{p}_{T_i} \times \hat{n} \right|}{\sum_i \left| \vec{p}_{T_i} \right|} \right)^2$$

- "Isotropic" limit (Soft-QCD processes)
- "Pencil-like" or "jetty" limit (Hard-QCD processes)

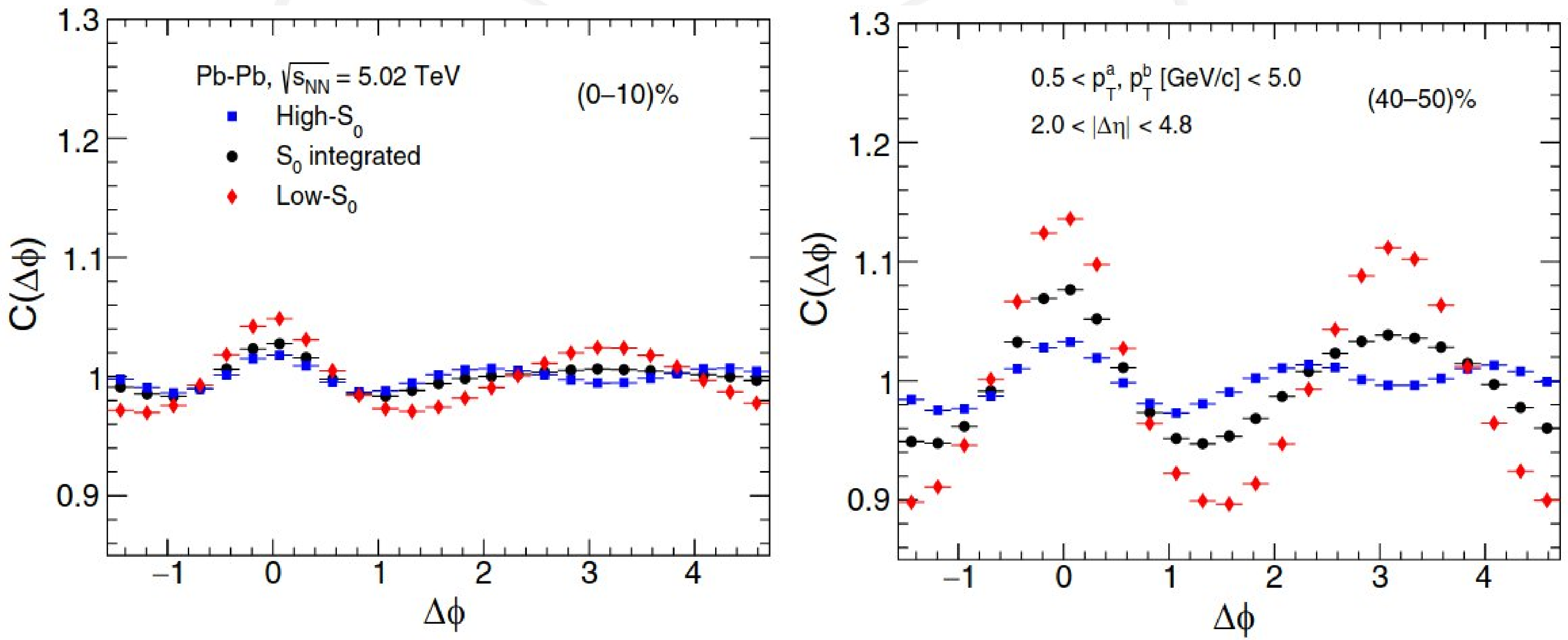




N. Mallick, R. Sahoo, S. Tripathy, A. Ortiz, J. Phys. G 48, 045104 (2021)



S. Prasad, N. Mallick, S. Tripathy, and R. Sahoo, Phys. Rev. D 107, 074011 (2023)
S. Prasad, N. Mallick, D. Behera, R. Sahoo and S. Tripathy, Sci. Rep. 12, 3917 (2022)



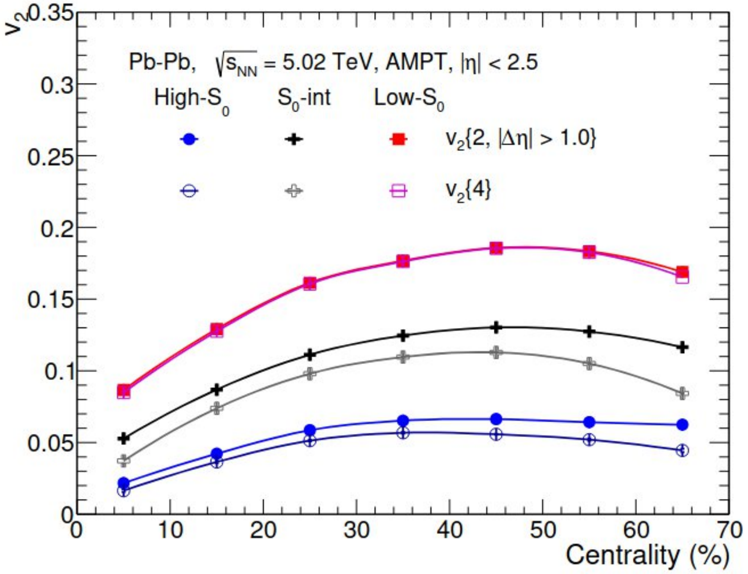
S. Prasad, N. Mallick, S. Tripathy, and R. Sahoo, Phys. Rev. D 107, 074011 (2023)

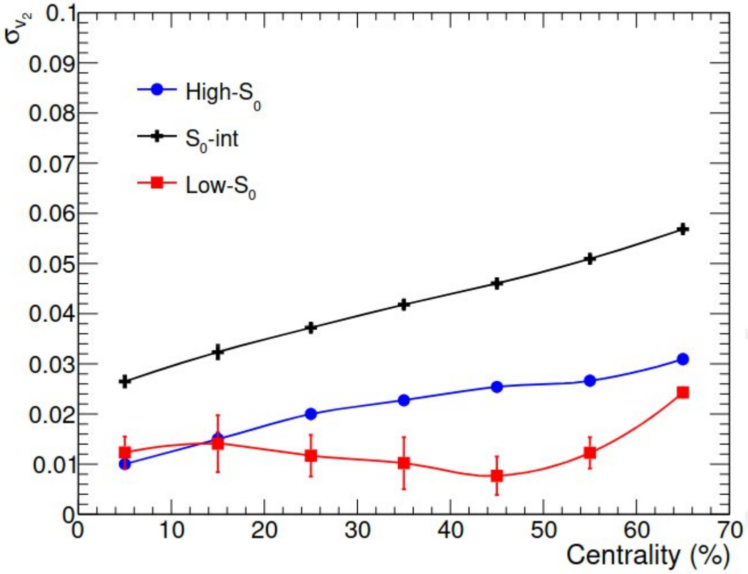
$$C(\Delta\phi) = \frac{dN_{\text{pairs}}}{d\Delta\phi} \propto \left[1 + 2\sum_{n=1}^{\infty} v_{n,n}(p_{\text{T}}^{a}, p_{\text{T}}^{b}) \cos n\Delta\phi\right]$$

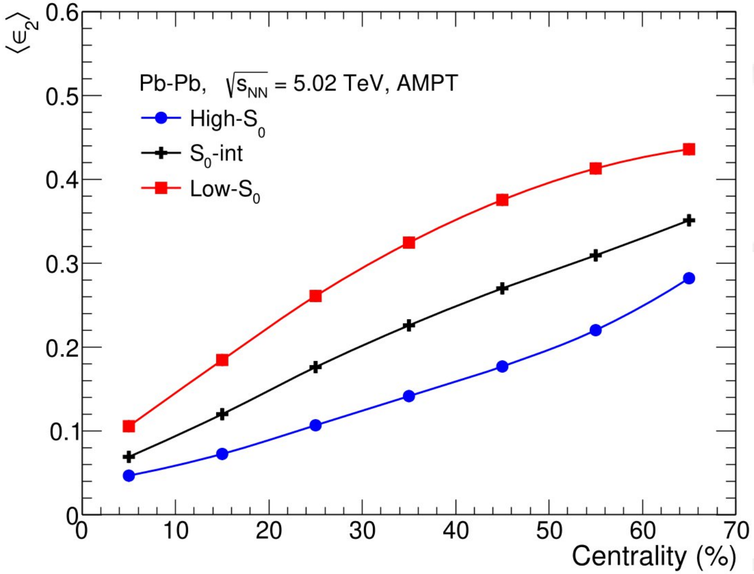
$$C(\Delta\phi) = \frac{dN_{\text{pairs}}}{d\Delta\phi} = A \times \frac{S(\Delta\phi)}{B(\Delta\phi)} = A \times \frac{\int S(\Delta\eta, \Delta\phi) d\Delta\eta}{\int B(\Delta\eta, \Delta\phi) d\Delta\eta}$$

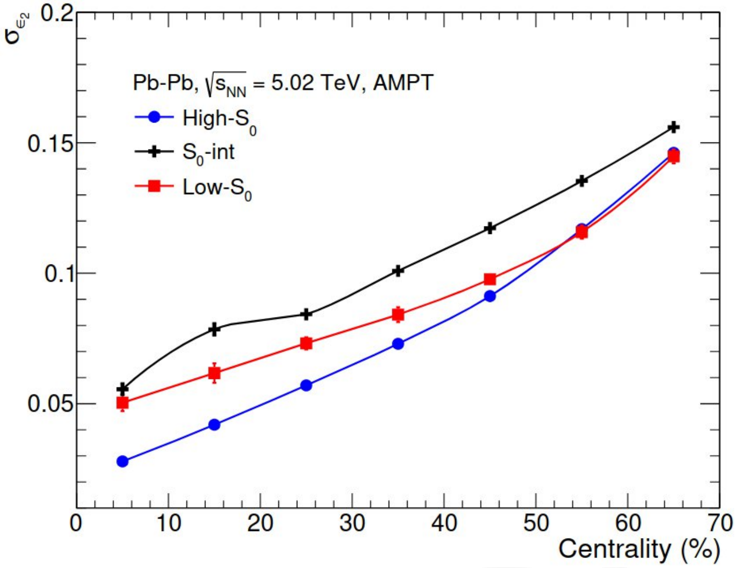
- Correlation function is stronger for (40-50)% centrality than (0-10)% centrality —> More flow in midcentral collisions
- Clear transverse spherocity dependence; 3 peak structure in high-S_0 events —> Large triangular flow
- Low-S_0 events show larger two peak structure —> Large elliptic flow

Eccentricity, Elliptic Flow and Their Fluctuations









$$\epsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi_{\text{part}})\rangle^2 + \langle r^n \sin(n\phi_{\text{part}})\rangle^2}}{\langle r^n \rangle}$$

- Flow estimated using multi-particle Q-cumulant method
- Rise of v_2 from central to mid-central collisions followed by a decrease towards peripheral collisions —> Contribution from initial stage
- Clear v_2 dependence on S_0 —> Low S_0 events have large v_2 and vice versa
- σ_{v_2} is large for S_0-int events and peripheral collisions
- σ_{v_2} is smallest for low-S_0 events
- σ_{ϵ_2} shows a different S_0 dependence

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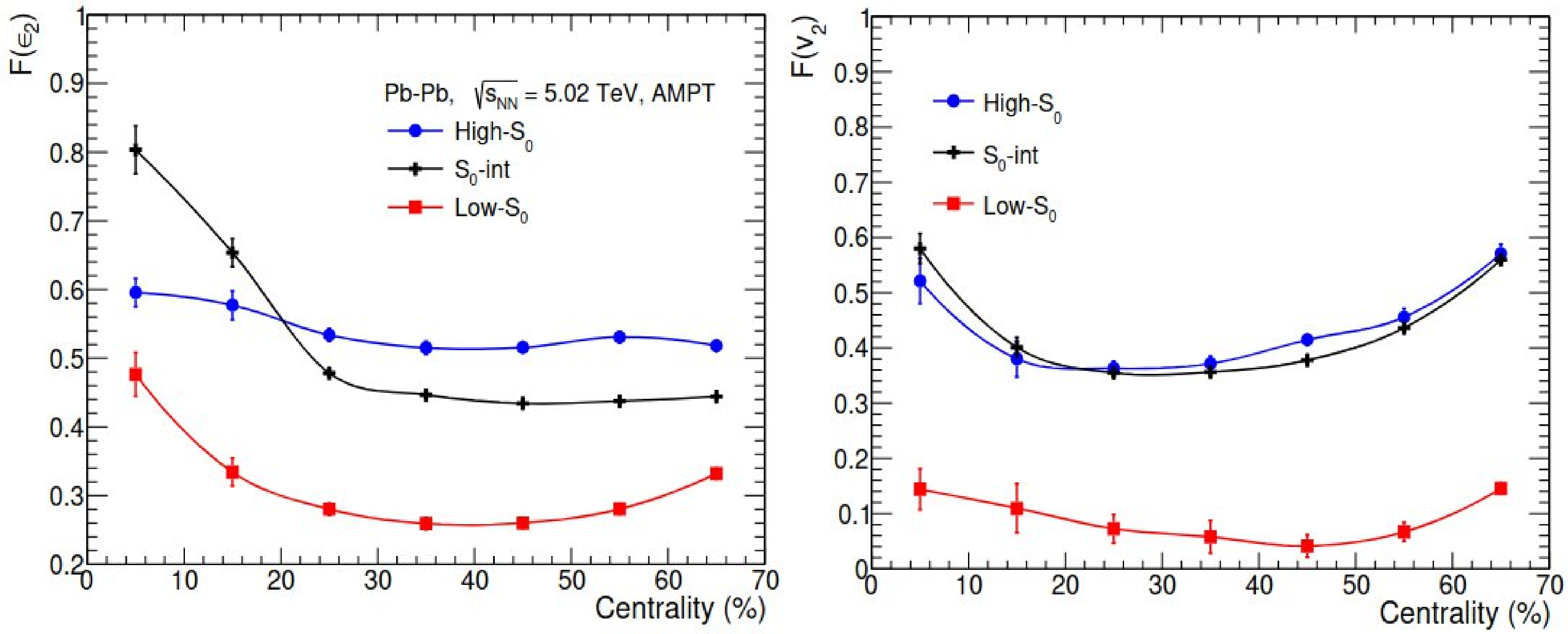

$$\langle v_n \rangle = \sqrt{\frac{v_n^2\{2,|\Delta\eta|\} + v_n^2\{4\}}{2}}$$

$$\sigma_{v_n} = \sqrt{\frac{v_n^2\{2,|\Delta\eta|\} - v_n^2\{4\}}{2}}$$

$$F(\mathrm{v}_2) = \frac{\sigma_{\mathrm{v}_2}}{\langle \mathrm{v}_2 \rangle}$$

$$\sigma_{\epsilon_2} = \sqrt{\langle \epsilon_2^2 \rangle - \langle \epsilon_2 \rangle^2}$$

$$F(\epsilon_2) = \frac{\sigma_{\epsilon_2}}{\langle \epsilon_2 \rangle}$$

- Central collisions have large $F(\mathrm{v}_2)$ —> Decreases towards mid-central followed by a rise towards peripheral collisions
- In central collisions, S_0-int events have largest $F(\mathrm{v}_2)$ and $F(\epsilon_2)$
- Low-S_0 events have smallest $F(\mathrm{v}_2)$ and $F(\epsilon_2)$

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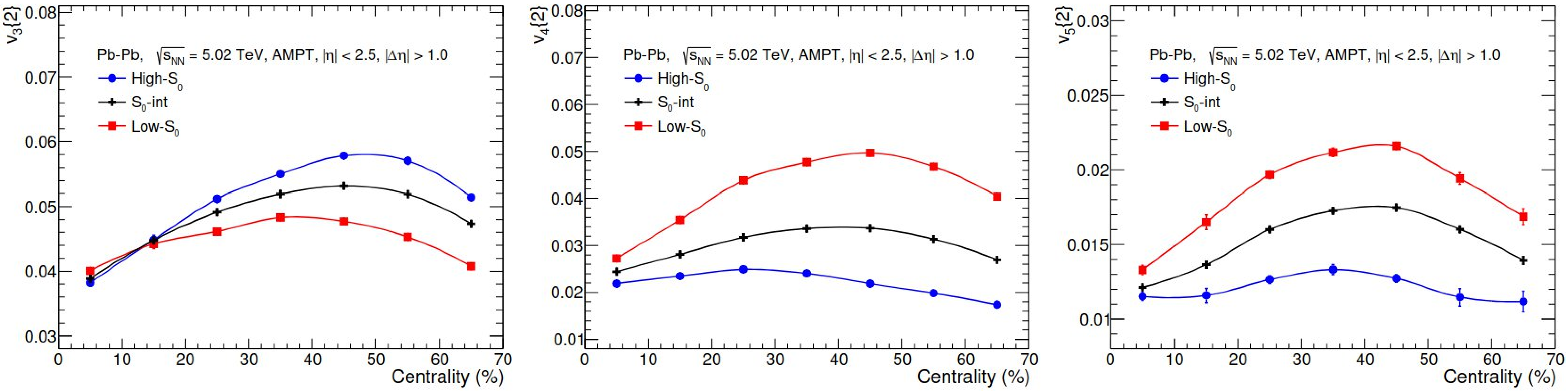
Higher Order Flow Coefficients



- Centrality dependence weakens for v_n when going from n=3 to n=5 —> Stronger damping effects for v_5 than v_4 than v_3
- v_3 shows an anti-correlation with S_0 selection —> Attributed to anti-correlation between v_2 and v_3
- v_4 and v_5 has non-linear contributions from v_2 —> Reflected in their anti-correlation with S_0 selection
- High-S_0 events have lowest contribution from v_2 and Low-S_0 events have highest contribution from v_2

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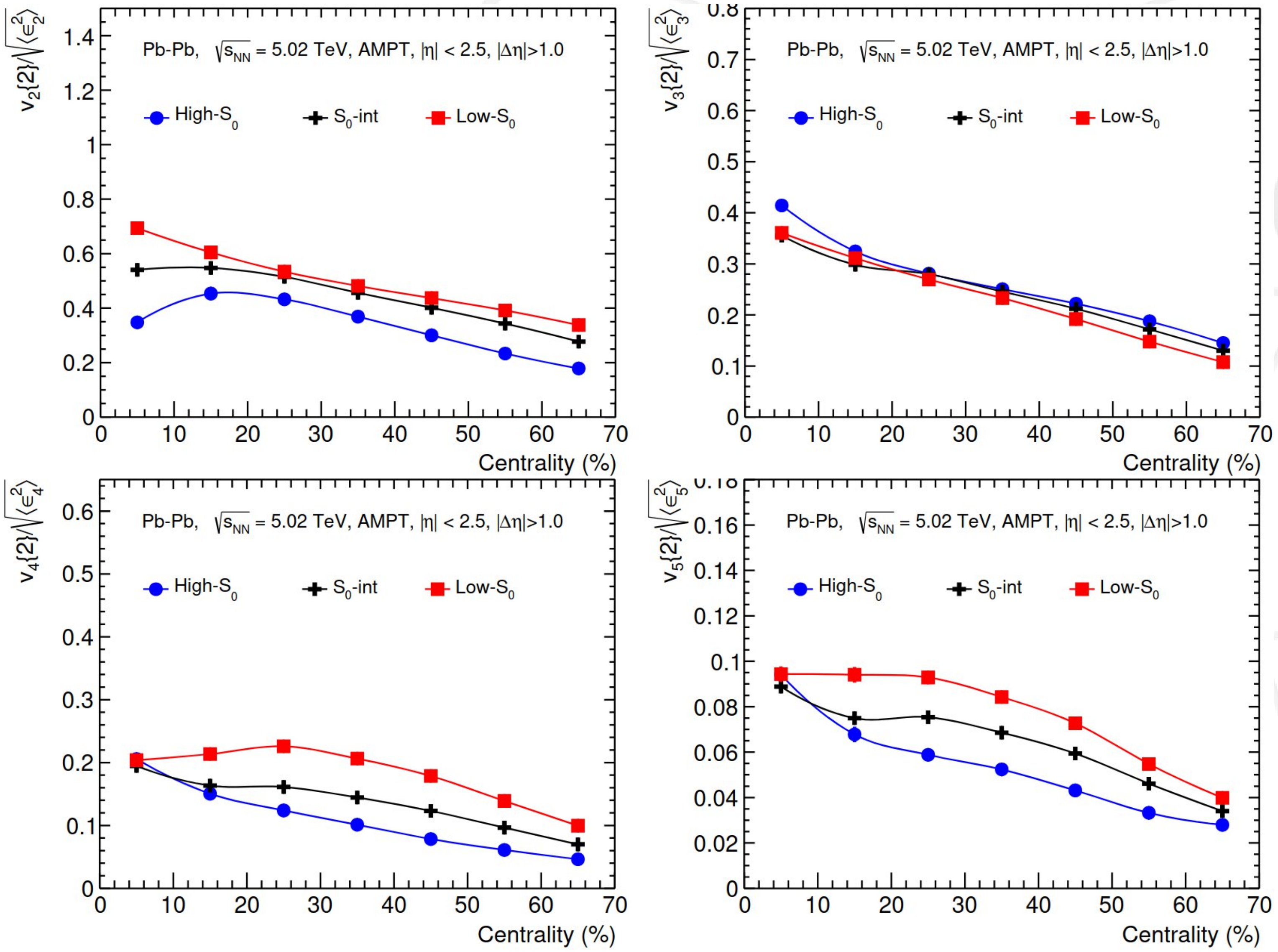
Spherocity Dependence of $v_n\{2\}/\sqrt{\langle\epsilon_n^2\rangle}$



- System response to geometrical anisotropy is different from that arising due to fluctuations
- Isotropisation adversely affects the transformation of ϵ_2 to v_2
- High-S_0 events show stronger damping effects for n=4 and n=5
- Low-S_0 events for n=4 shows a small rise near (20-30)% centrality
- Low-S_0 events show saturation behaviour near central collisions for n=5

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Summary

- S_0 based event selection are capable of selecting events with larger or smaller v_2 than in comparison to q_2
- S_0 based event selection is better than q2 event in low-multiplicity environments —> Useful for O-O, Ne-Ne and pO collisions
- v_2 is anti-correlated to event selection based on S_0, v_3 has positive correlation
- v_2 fluctuations are large for high-S_0 events, smaller for low-S_0 events
- System response to geometrical anisotropy is different from that arising due to fluctuations
- Isotropisation adversely affects the transformation of ϵ_2 to v_2
- High-S_0 events show stronger damping effects
- With S_0, one can select events with smaller values of v_2 —> useful to study higher order harmonics

S. Prasad, A. Menon K. R., R. Sahoo, N. Mallick, Phys. Lett. B 868 (2025) 139753

S. Prasad, N. Mallick, S. Tripathy, and R. Sahoo, Phys. Rev. D 107, 074011 (2023)

Thank You

for Your Attention

Backup Slides

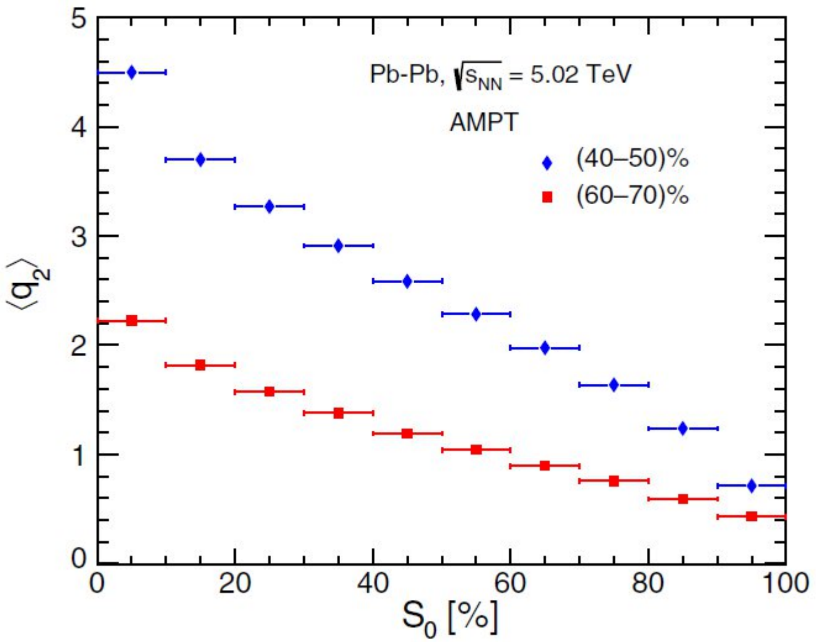
S_0 versus q_n

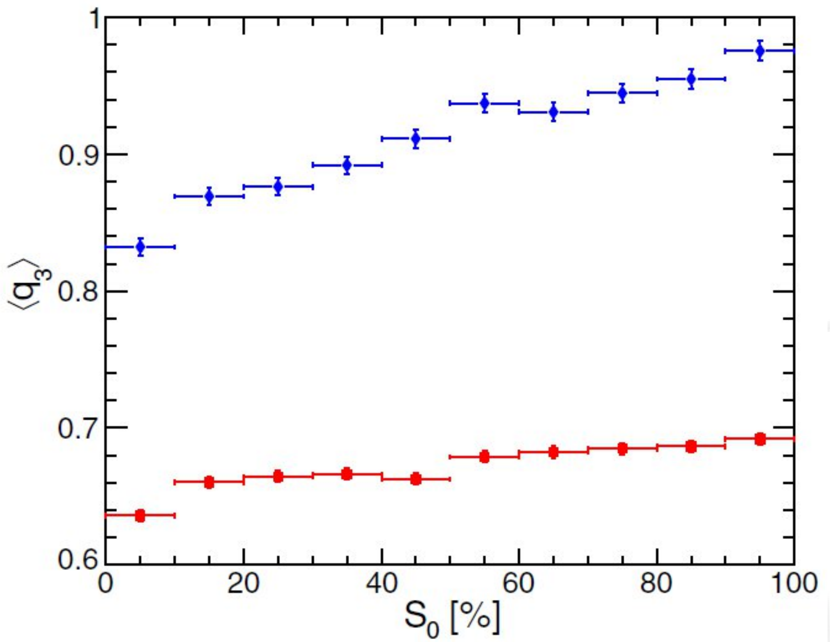
Event classifier; generally used in heavy-ion collisions, defined as:

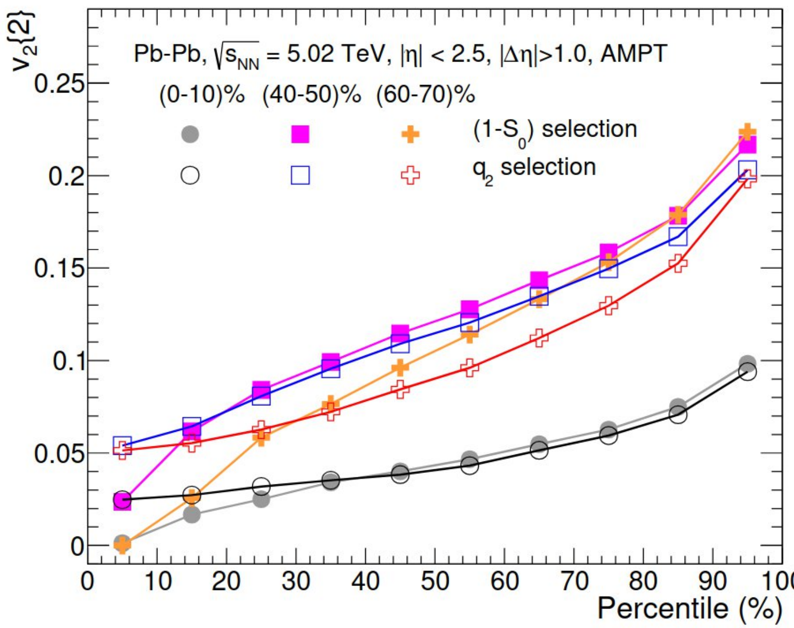
$$q_n = \frac{|Q_n|}{\sqrt{M}};\ Q_n = \sum_{j=1}^{M} e^{ni\phi_j}$$

M= multiplicity, ϕ_j= azimuthal angle of j^{th} particle

- q_2 is strongly anti-correlated with transverse spherocity
- q_3 is weakly positively correlated with transverse spherocity







G. Aad *et al.* (ATLAS Collaboration), Phys. Rev. C **92**, 034903 (2015).
S. Prasad, N. Mallick, S. Tripathy, and R. Sahoo, Phys. Rev. D 107, 074011 (2023)

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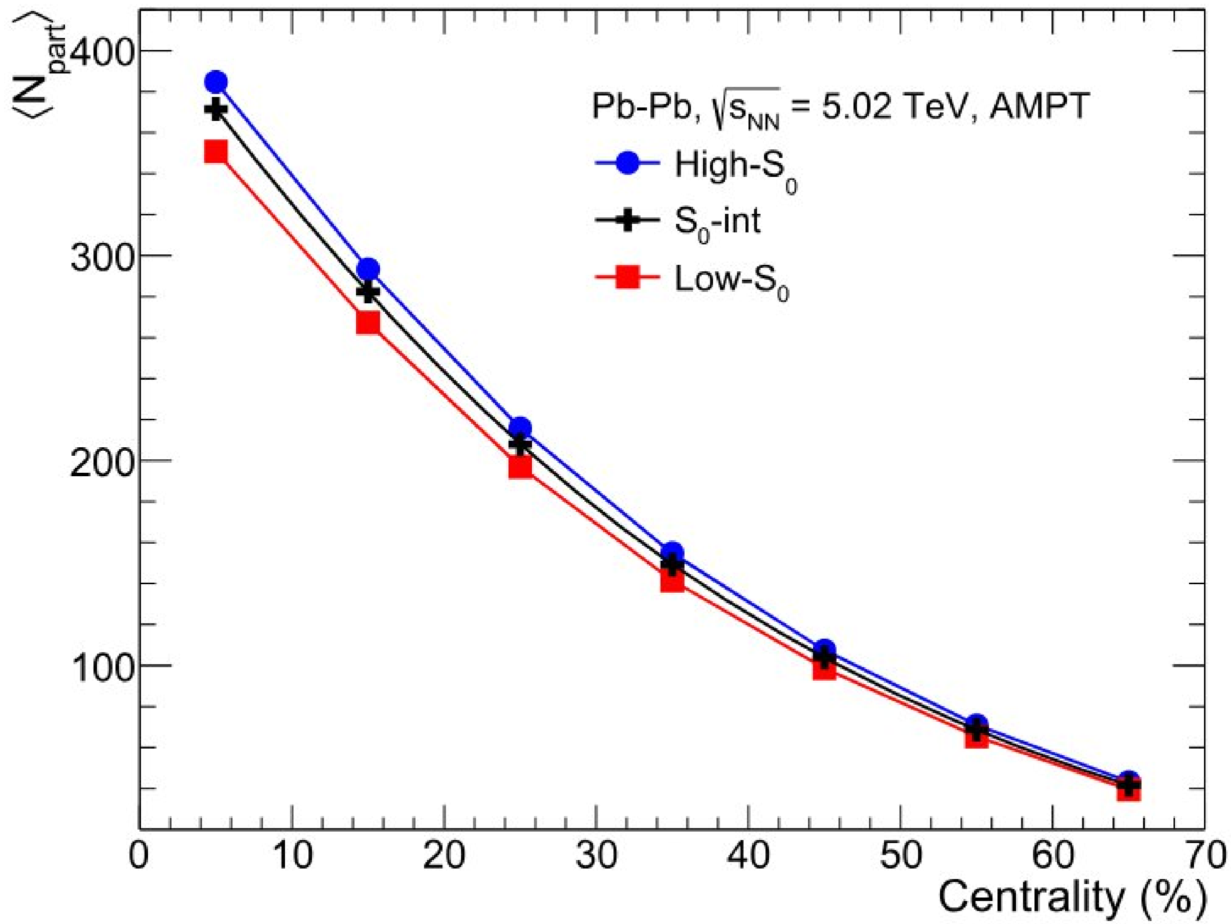
S_0 versus N_{part}



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