Transverse spherocity dependent correlation studies of initial spatial anisotropy and final azimuthal anisotropy in heavy-ion collisions at the LHC

Based On:

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, [arXiv:2207.12133 [hep-ph]]

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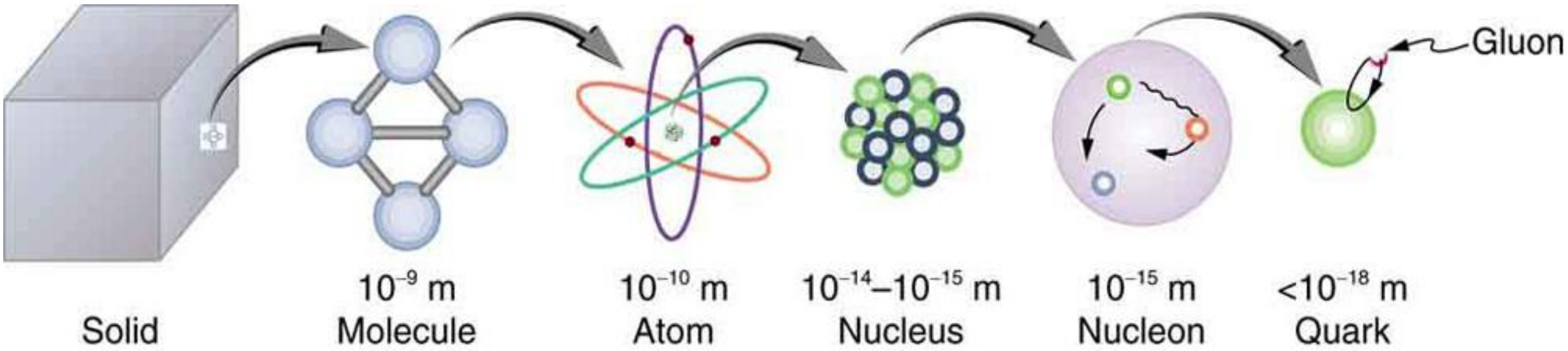
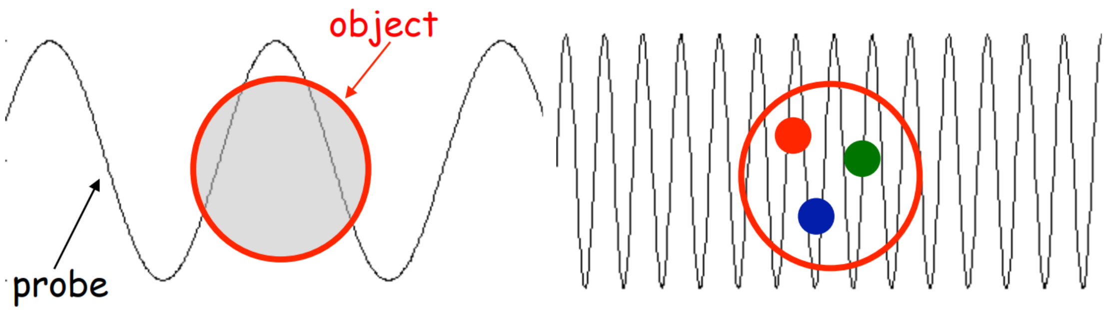
Constituents of matter



- Energy is related to wavelength by de Broglie's formula: $p = h/\lambda$
- To probe inside smaller objects we need higher energy

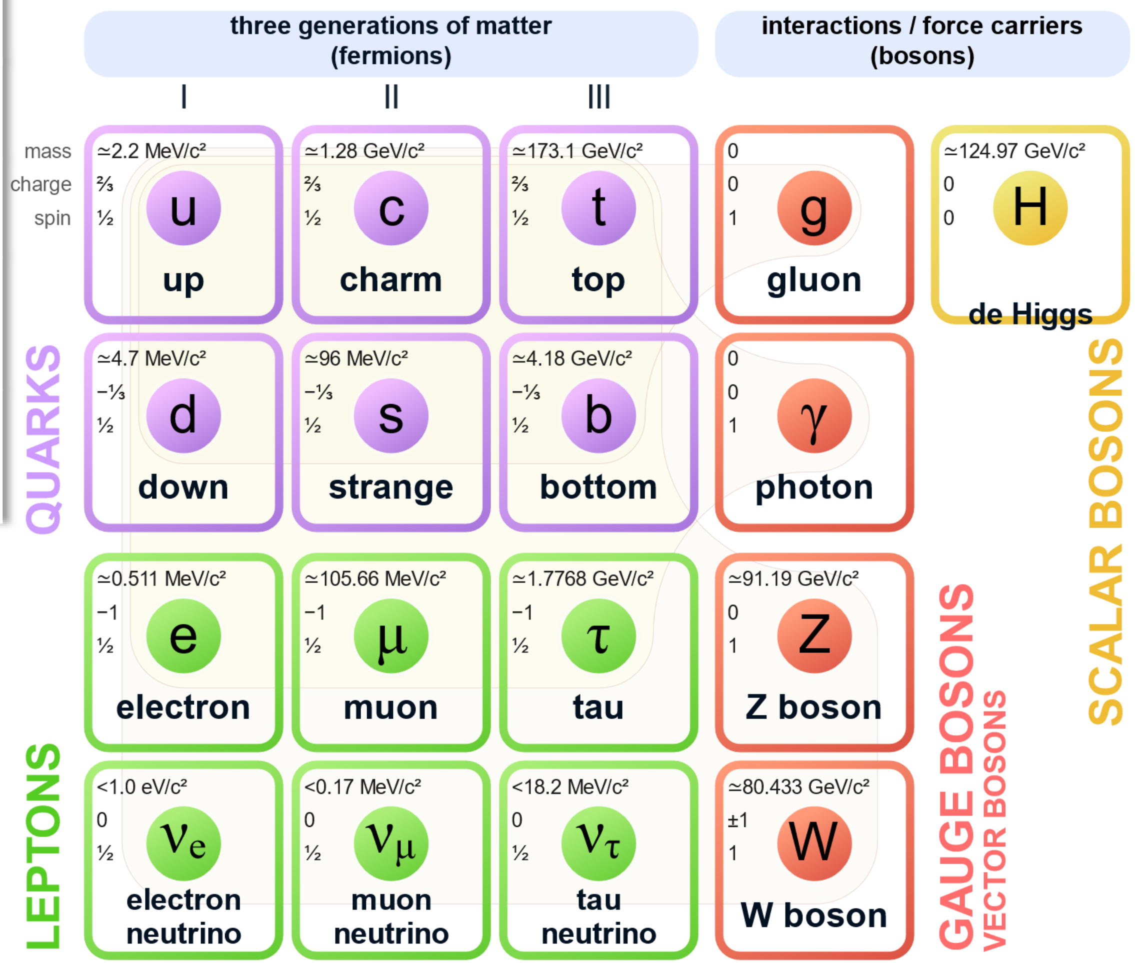


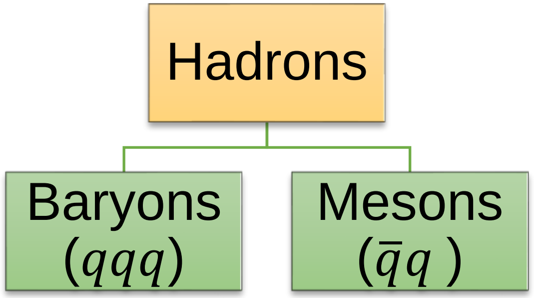
[1] R. Sahoo, "Relativistic Kinematics", [arXiv:1604.02651 [nucl-ex]]

Fundamental interactions

	Gravitational	Weak	Electromagnetic	Strong
Acts on	Mass-Energy	Flavour	Electric Charge	Color Charge
Strength	$\approx 10^{-36}$	$\approx 10^{-7}$	1	≈ 100
Particles mediating	graviton	$W^{\pm}, Z^{0}$	γ	Gluons
Particle experiencing	All	Leptons, quarks	Electrically charged	Quarks, gluons

Standard Model of Elementary Particles





Hadrons

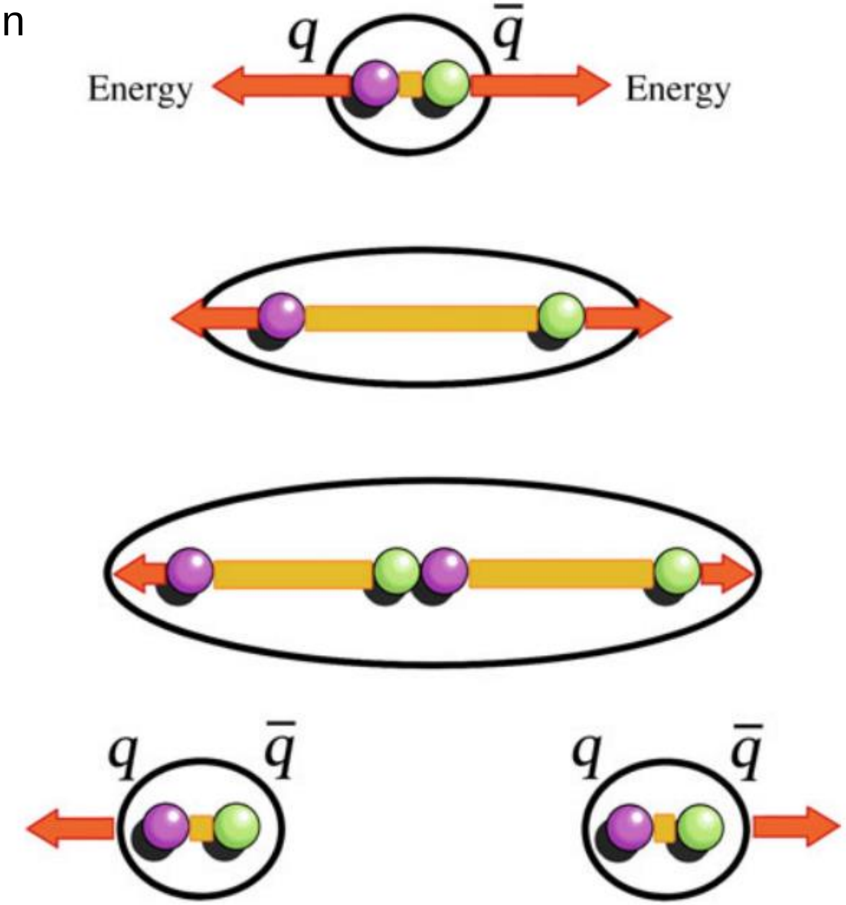
Baryons (qqq)

Mesons $(\bar{q}q\ )$

- QED: Quantum Electrodynamics: Theory of electromagnetic interaction
- QCD: Quantum Chromodynamics: Theory of Strong interaction

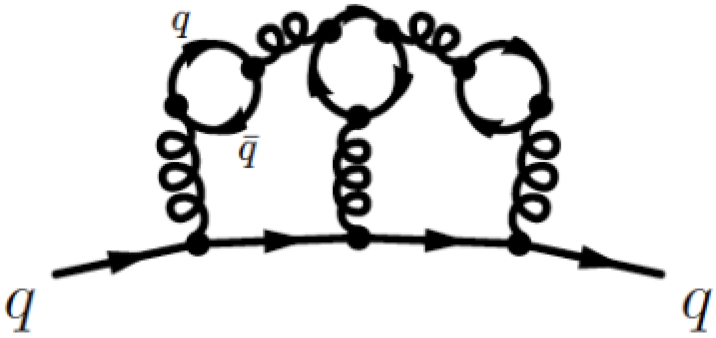
Perkins, D. (2000). *Introduction to High Energy Physics* (4th ed.). Cambridge: Cambridge University Press. doi:10.1017/CBO9780511809040

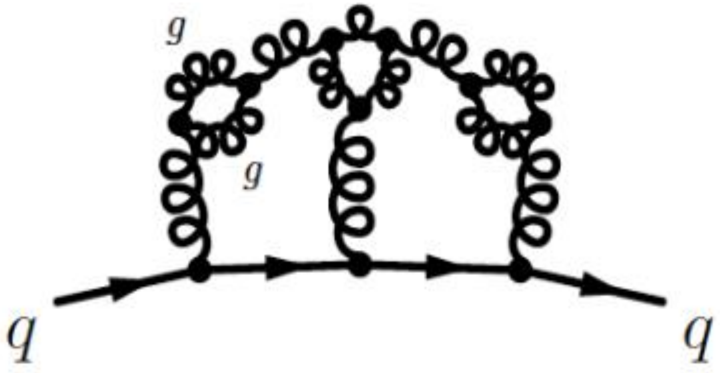
Strong Interaction



- Unlike QED, in QCD gluons have color charge which permits gluon-gluon interaction
- Color charges can’t freely exist : Color confinement

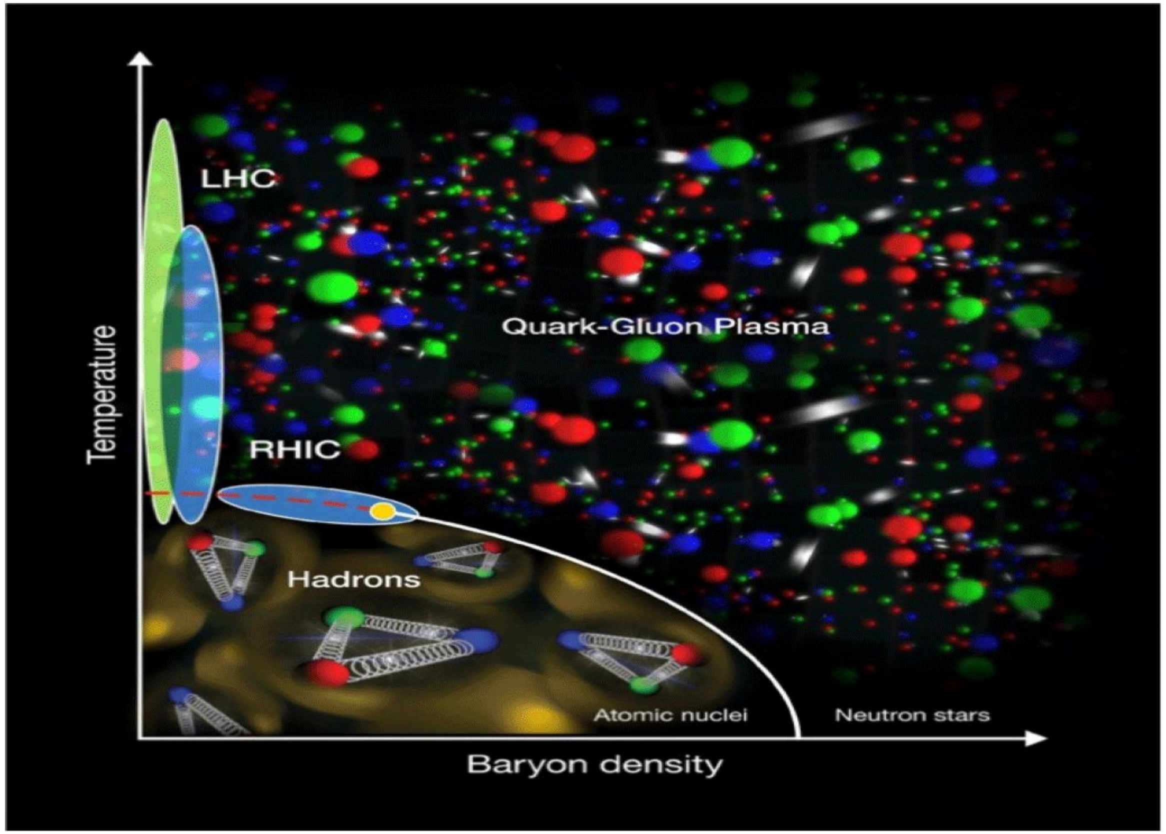
- At high energies, α_s becomes smaller : Asymptotic freedom

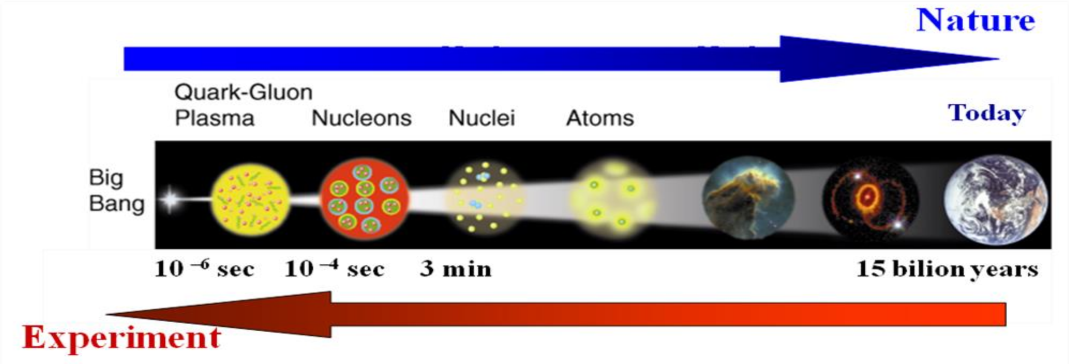


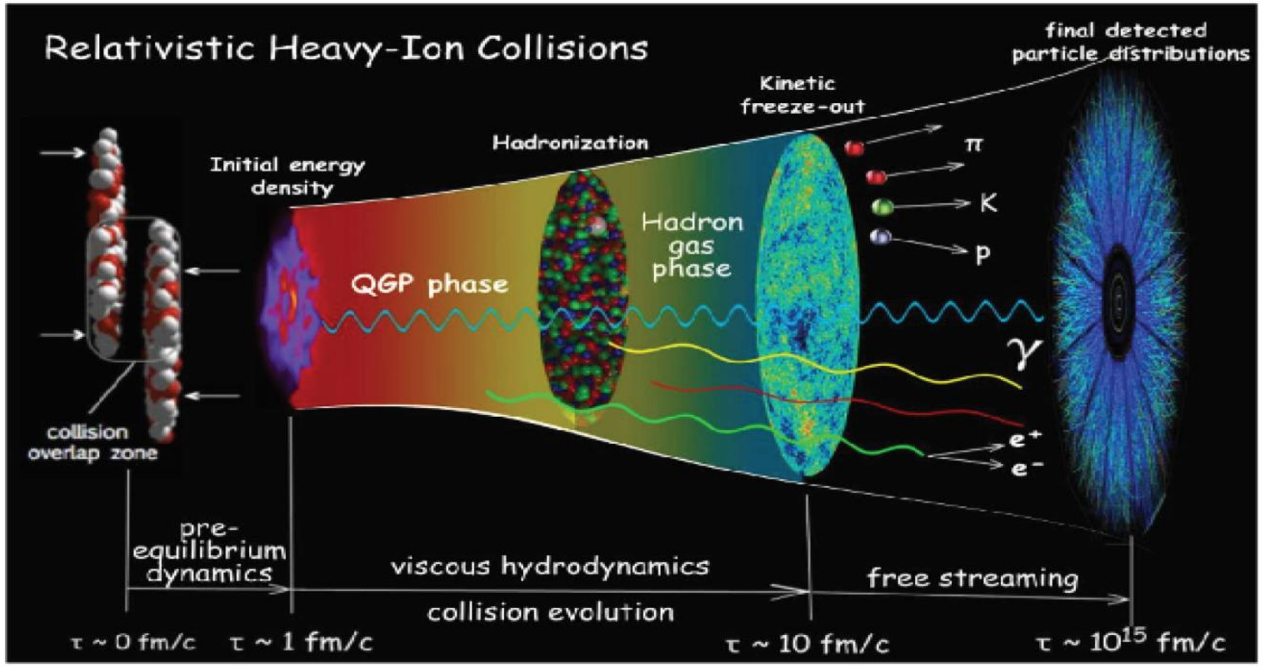


Obertelli, A., Sagawa, H. (2021). Nuclear Physics and Standard Model of Elementary Particles. In: Modern Nuclear Physics. UNITEXT for Physics. Springer, Singapore

Heavy-ion collisions (HIC) and Quark gluon plasma (QGP)

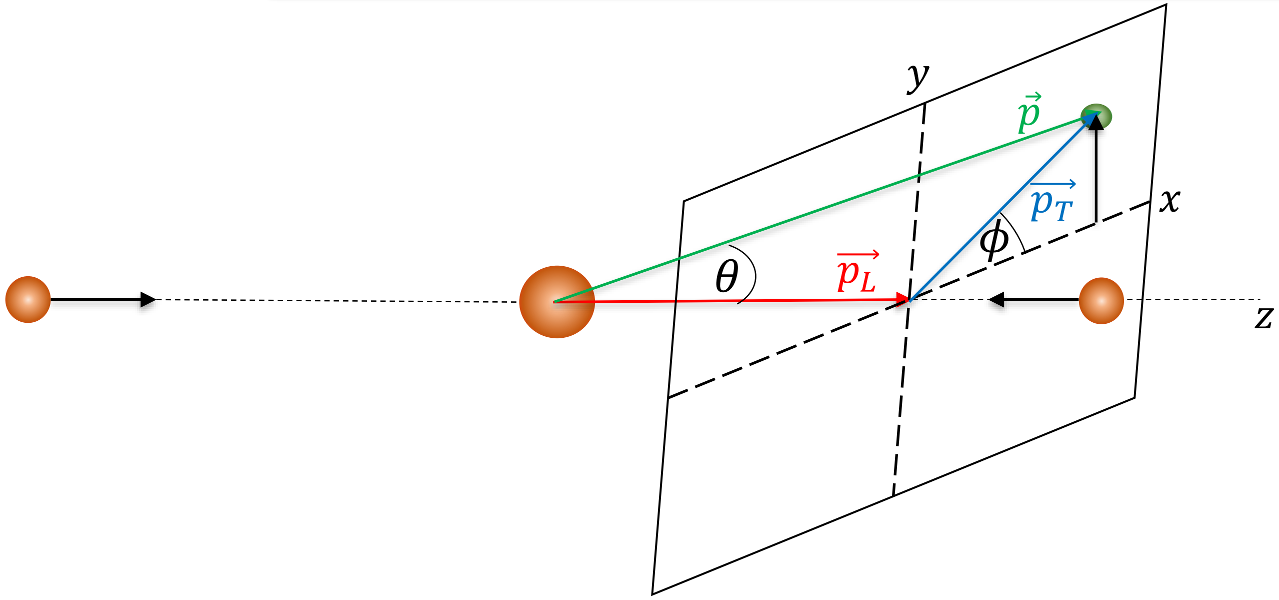


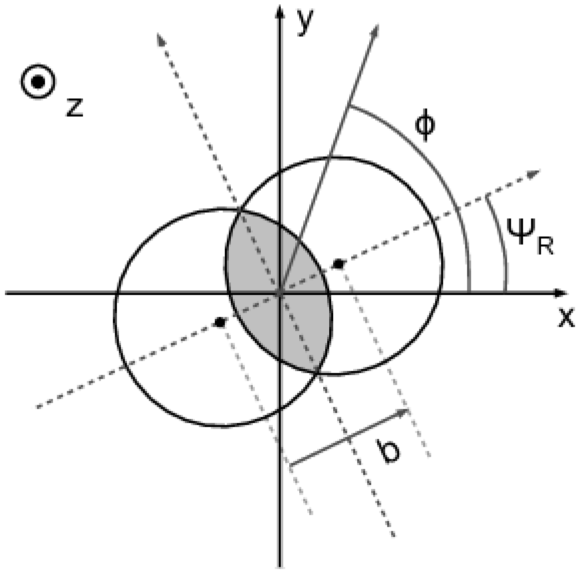




[1] R. Sahoo, AAPPS Bull. 29, 16 (2019).
[2] U. Heinz, Int. J. Mod. Phys. A 30, 1530011 (2015).
[3] R. Sahoo, and T. K. Nayak, Curr. Sci. 121, 1403 (2021).

Kinematic Observable in HIC

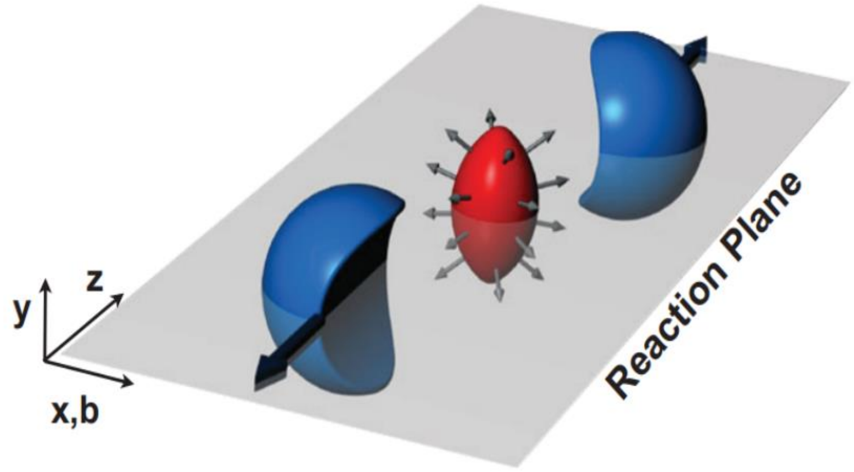


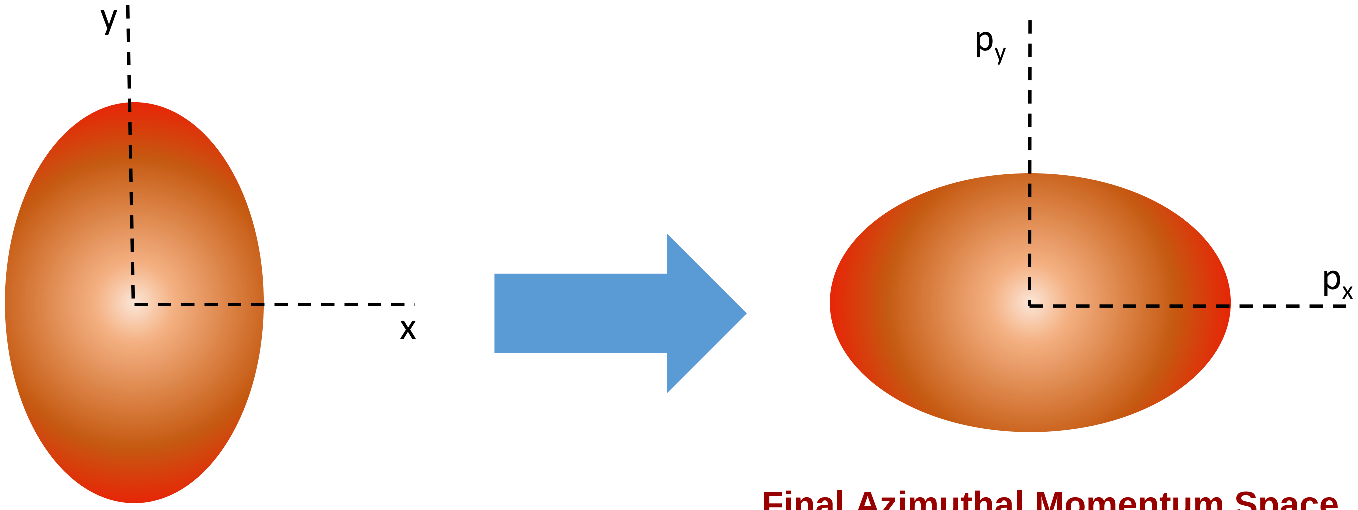


- Transverse Momentum, $p_T = \sqrt{p_x^2 + p_y^2}$
- Azimuthal Angle, $\phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$
- Polar angle, $\theta = \tan^{-1}\left(\frac{p_T}{p_z}\right)$
- Rapidity, $y = \frac{1}{2}\ln\left(\frac{E+p_Z}{E-p_Z}\right)$
- Pseudo-rapidity, $\eta = -\ln\left(\tan\frac{\theta}{2}\right)$
- Reaction plane angle, ψ_R: Angle made by impact parameter (b) with x-axis

[1] R. Sahoo, "Relativistic Kinematics", [arXiv:1604.02651 [nucl-ex]]

Anisotropic flow coefficients (v_n)





Initial Spatial Anisotropy

Final Azimuthal Momentum Space Anisotropy

- ❑ Anisotropic flow: hydrodynamic response to spatial deformation of the initial density profile.

$$E\frac{d^3N}{dp^3} = \frac{d^2N}{2\pi p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi-\psi_n)]\right) = \frac{d^2N}{2\pi p_T dp_T dy}\left(1 + \underset{\substack{\Downarrow\\ \text{Directed flow}}}{2v_1\cos(\phi-\psi_1)} + \underset{\substack{\Downarrow\\ \text{Elliptic flow}}}{2v_2\cos[2(\phi-\psi_2)]} + \underset{\substack{\Downarrow\\ \text{Triangular flow}}}{2v_3\cos[3(\phi-\psi_3)} + ...]\right)$$

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

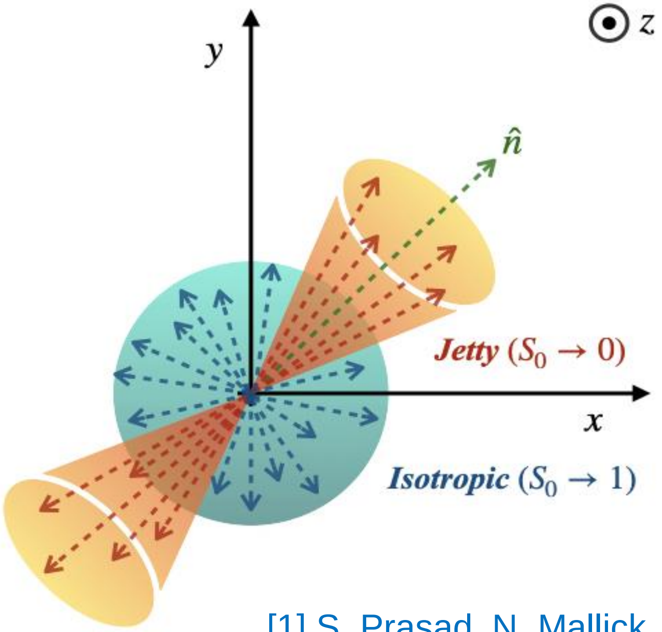
N. Mallick, R. Sahoo and S. Tripathy, and A. Ortiz, J. Phys. G 48, 045104 (2021)
B. B. Abelev et al. [ALICE Collaboration], JHEP 1506, 190 (2015)

Transverse Spherocity (S_0)

- Event shape observable: separates events based on geometrical shapes

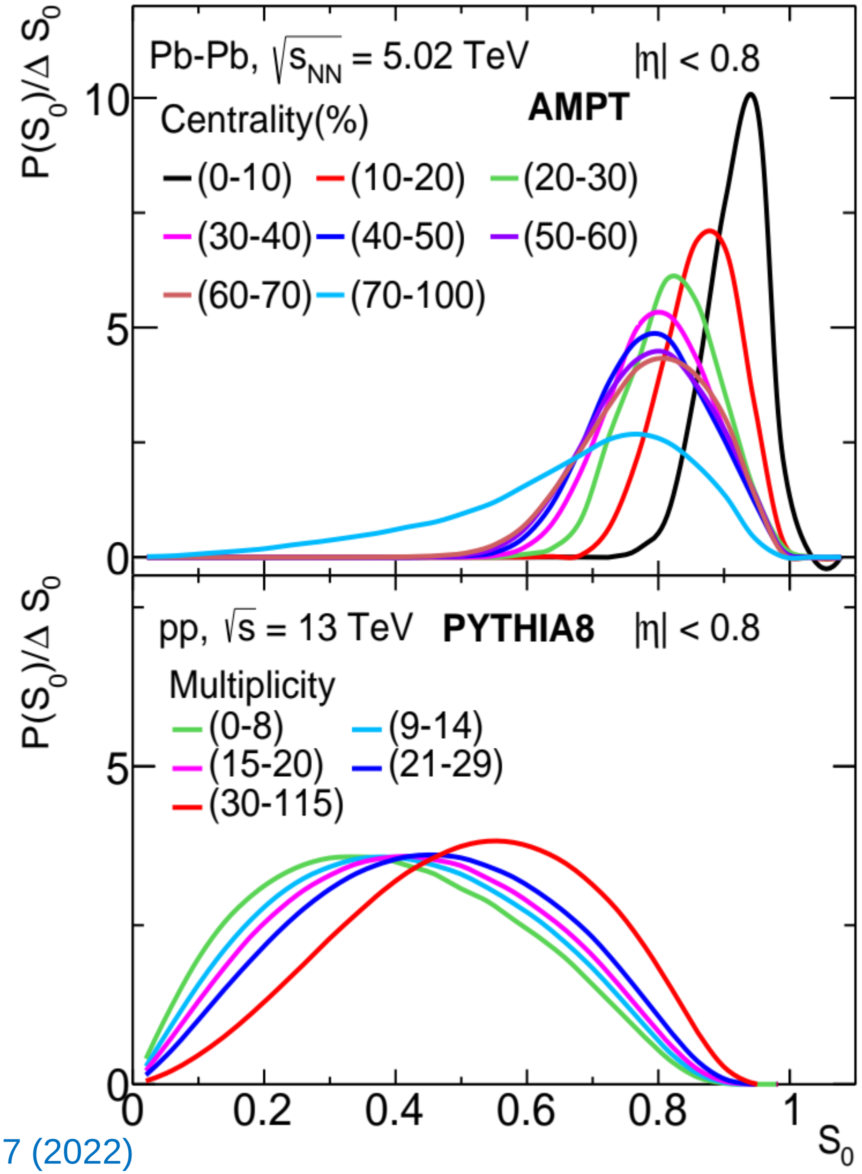
$$\boxed{S_0 = \frac{\pi^2}{4} \times \min_{\hat{n}=(n_T,0)} \left(\frac{\sum_i |\overrightarrow{p_{T_i}} \times \hat{n}|}{\sum_i p_{T_i}} \right)^2}$$

- “Isotropic” limit (Soft-QCD processes)
- “pencil-like” or “jetty” limit (Hard-QCD Processes)



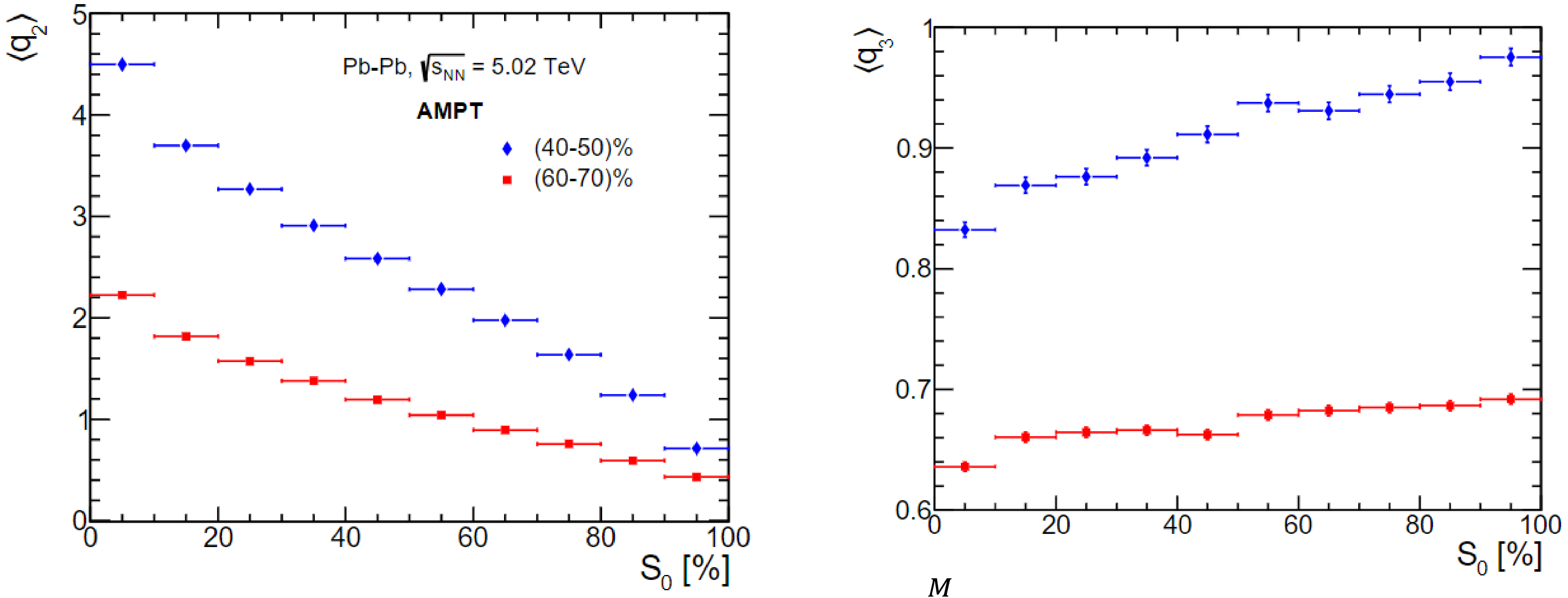
- Peak shifts towards jetty limit while going from central to peripheral collisions

- Central collisions are dominated more with isotropic events than the peripheral collisions



[1] S. Prasad, N. Mallick, D. Behera, R. Sahoo and S. Tripathy, Sci. Rep. 12, 3917 (2022)

Reduced flow vector (q_n) vs S_0



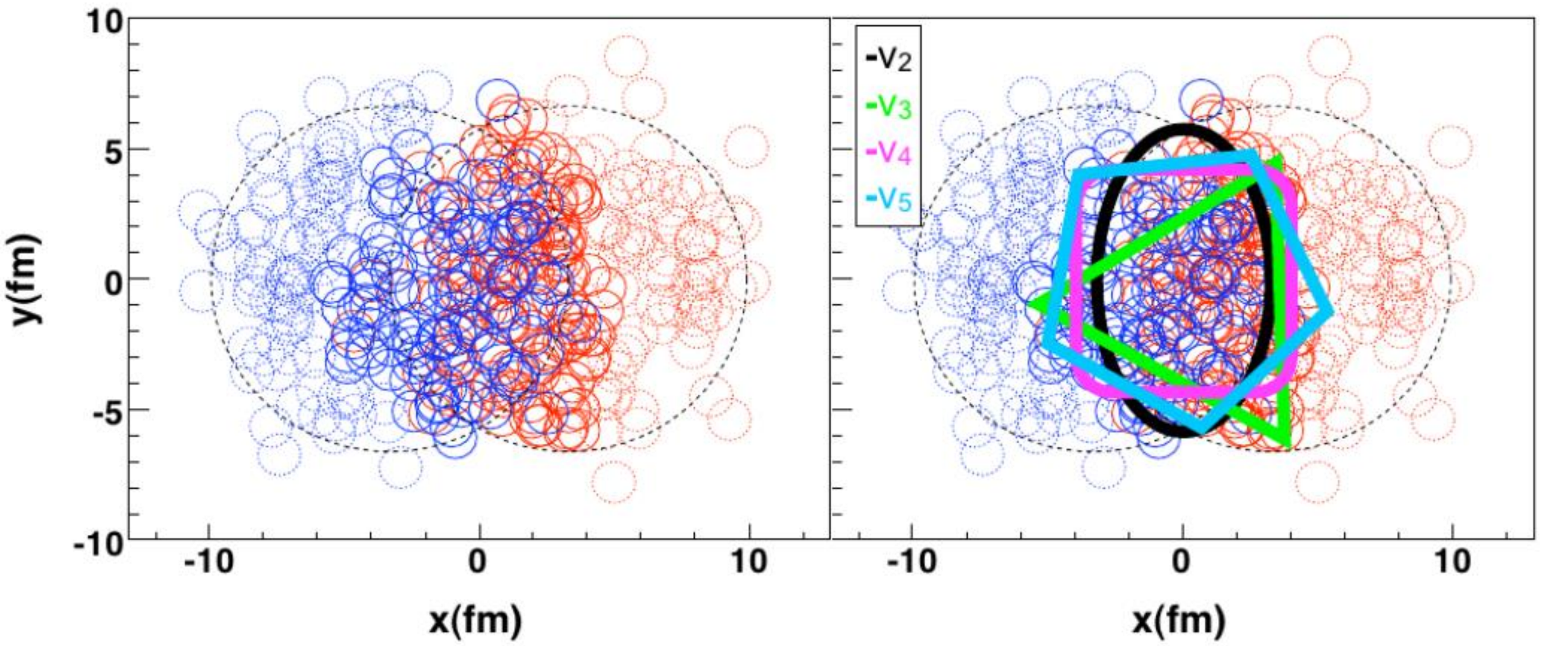
$$q_n = \frac{|Q_n|}{\sqrt{M}};\ Q_n = \sum_{j=1}^{M} e^{ni\phi_j}$$

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

- $\langle q_2 \rangle$ is found to be anti-correlated with transverse spherocity, where as $\langle q_3 \rangle$ is positively correlated

S. Prasad, N. Mallick, S. Tripathy and R. Sahoo, [arXiv:2207.12133 [hep-ph]]

Results: (eccentricity (ε_2) and triangularity (ε_3) vs centrality)

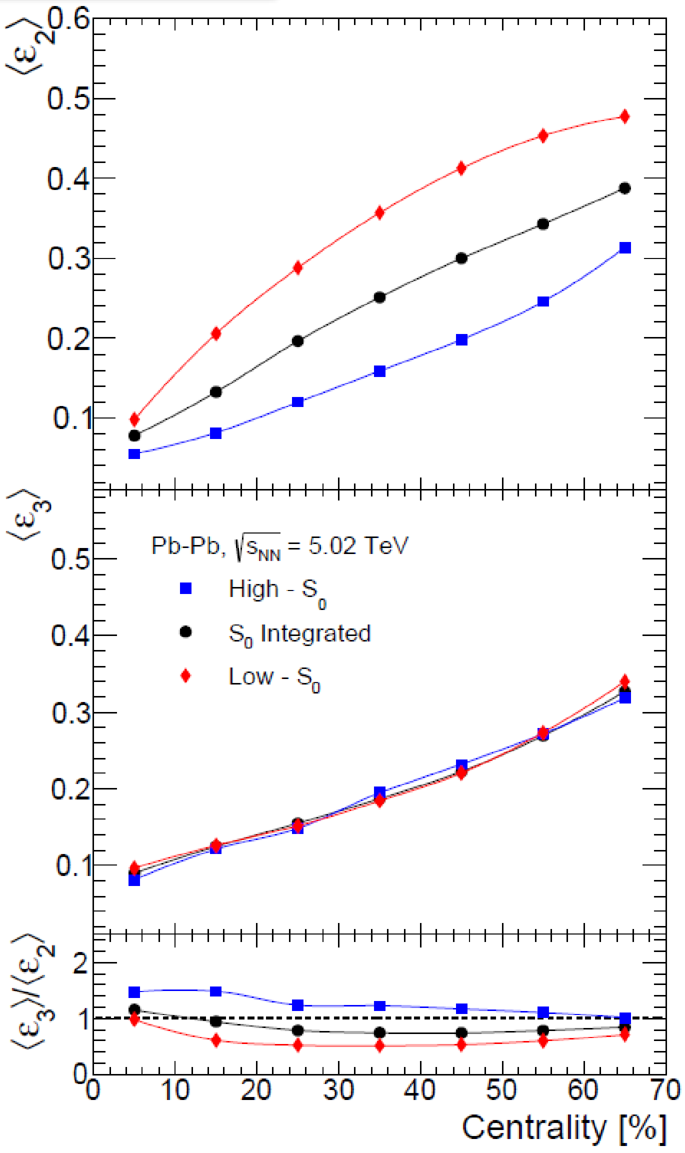


$$\varepsilon_n = \frac{\sqrt{< r^n cos(n\phi_{part}) >^2 + < r^n sin(n\phi_{part}) >^2}}{< r^n >}$$

where, r and ϕ_{part} are the polar coordinates of participating nucleons.

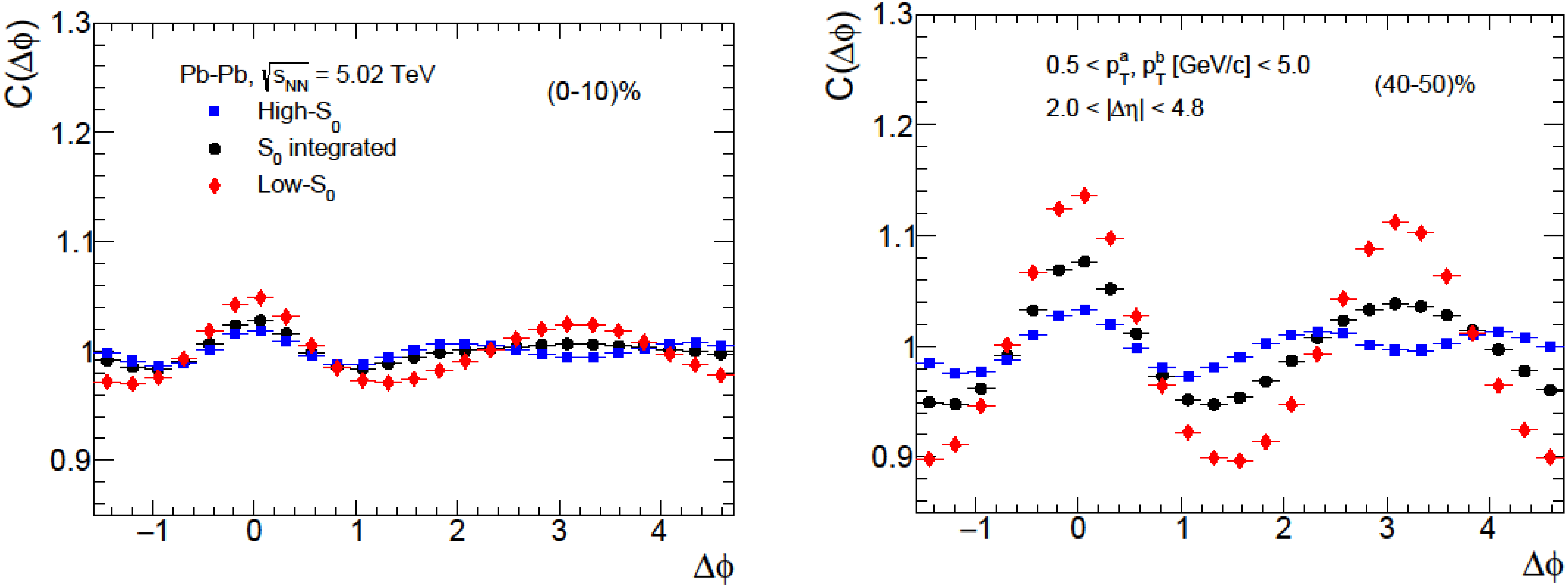
- ε_2 has significant centrality and spherocity dependence
- ε_3 is found to not have dependence with transverse spherocity, and have comparably less centrality dependence

C. Loizides, J. Nagle, P. Steinberg, SoftwareX 1–2, 13 (2015)



S. Prasad, N. Mallick, S. Tripathy and R. Sahoo, [arXiv:2207.12133 [hep-ph]]

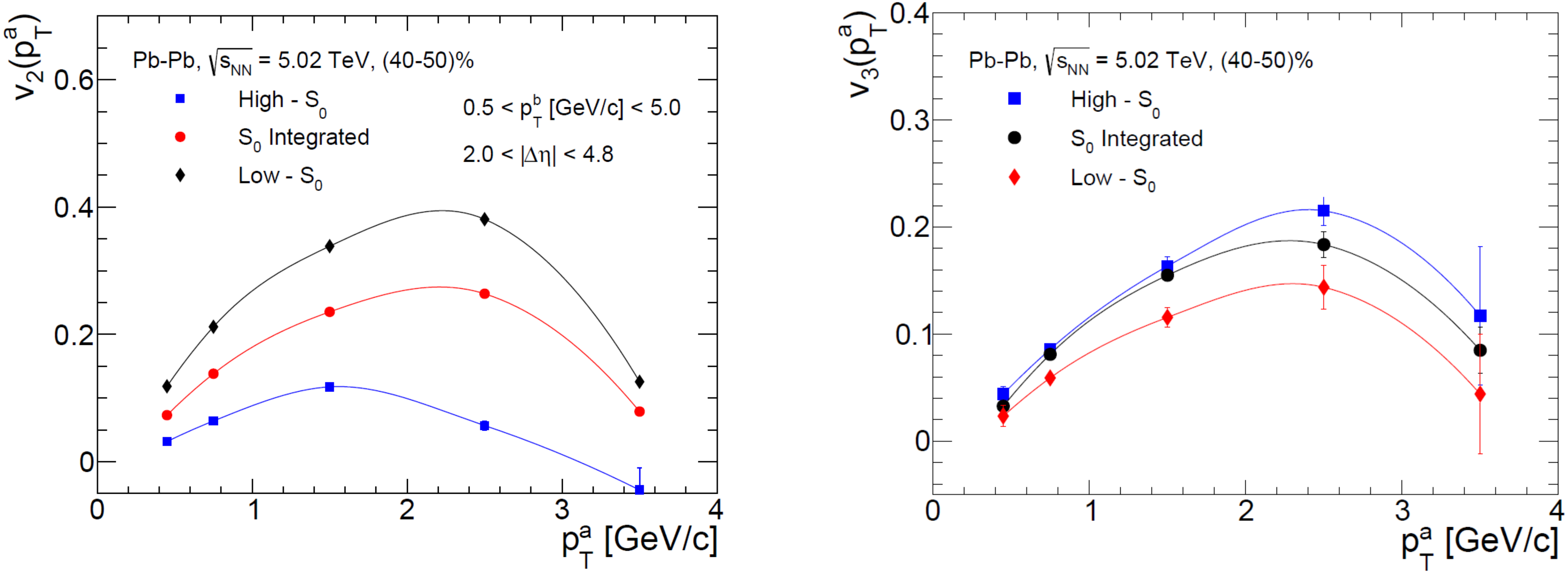
Results: (Correlation function)



- Centrality and transverse spherocity selection strongly affects the azimuthal correlation function

S. Prasad, N. Mallick, S. Tripathy and R. Sahoo, [arXiv:2207.12133 [hep-ph]]

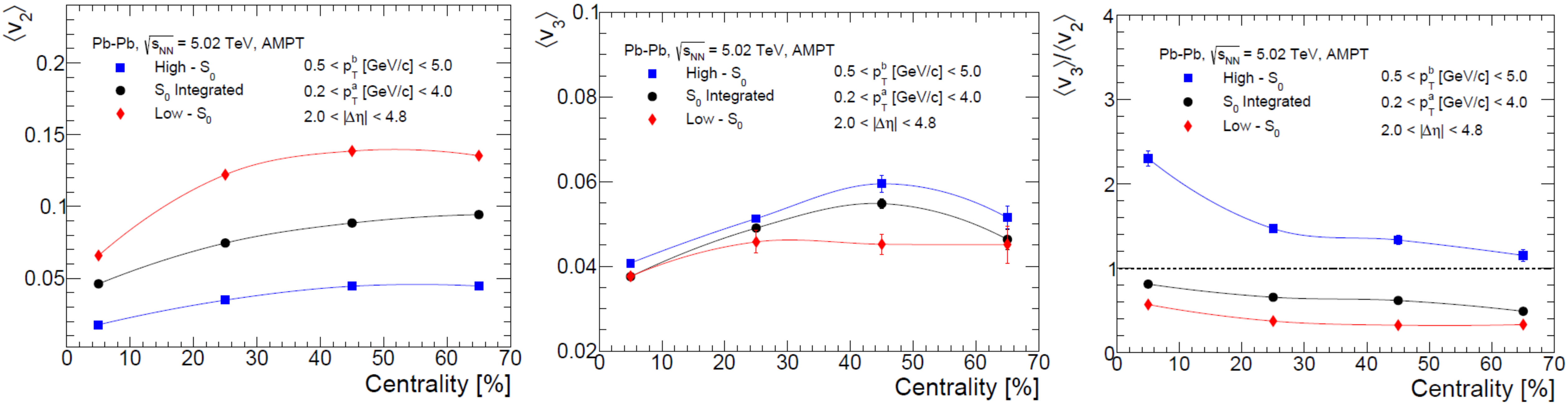
Results: $(v_n$ vs $p_T)$



- v_2 is strongly anti-correlated with transverse spherocity selection
- v_3 is found to have +ve correlation with transverse spherocity

S. Prasad, N. Mallick, S. Tripathy and R. Sahoo, [arXiv:2207.12133 [hep-ph]]

Results: (v_n vs Centrality)

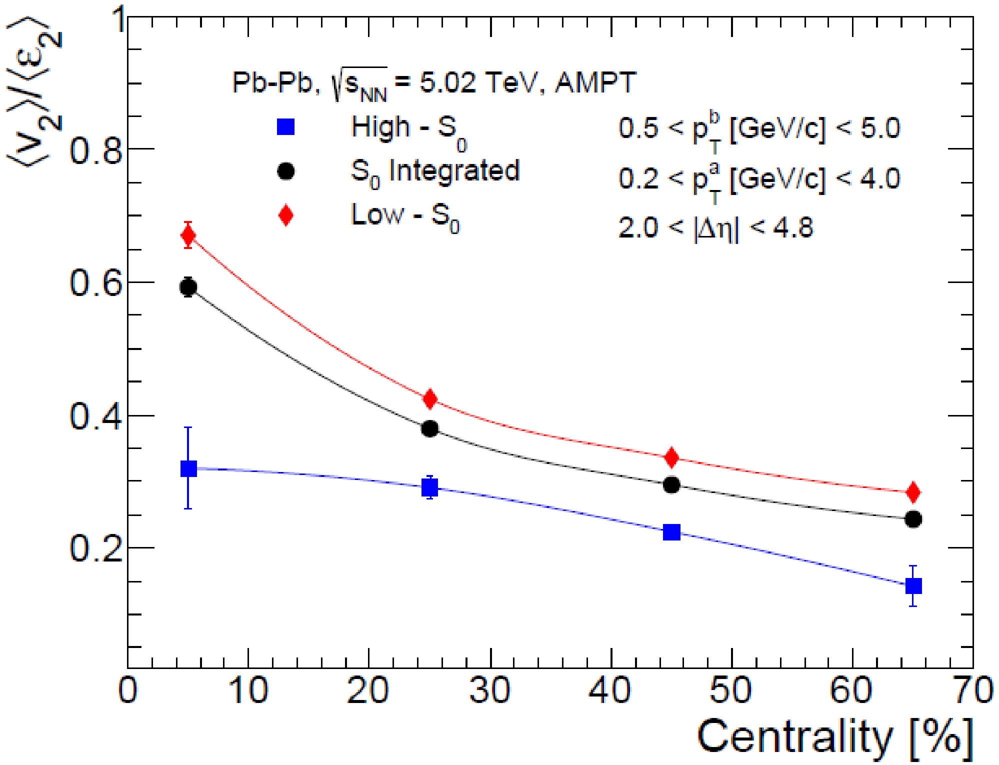


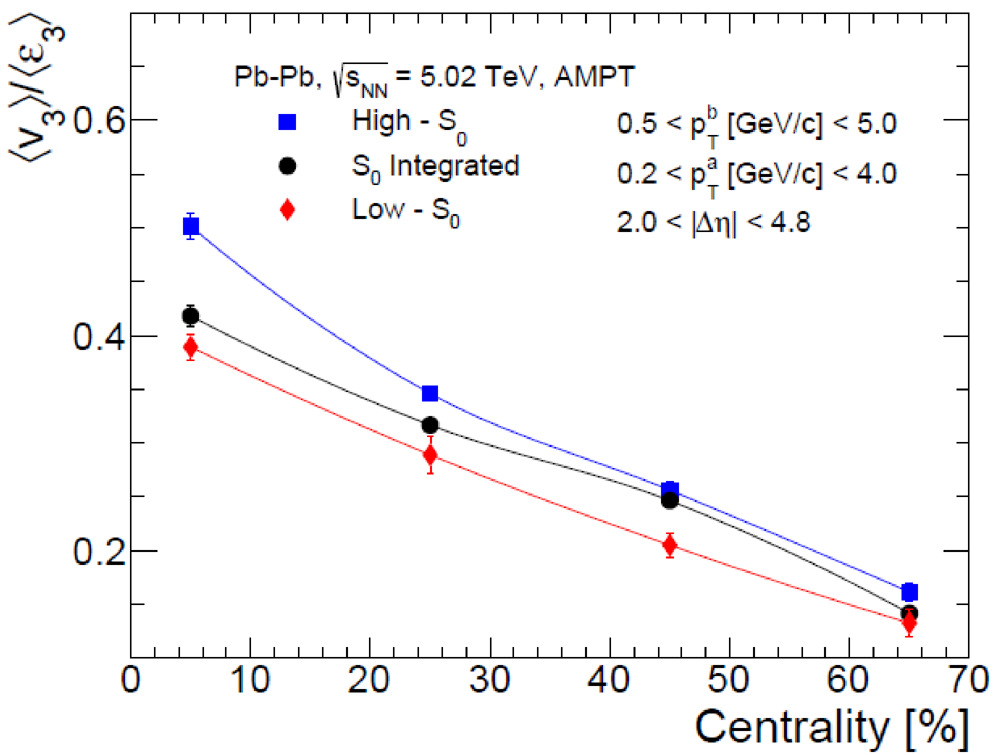
- v_2 is strongly anti-correlated with transverse spherocity selection

- v_3 is found to have +ve correlation with transverse spherocity and have less centrality dependence as compared to v_2

S. Prasad, N. Mallick, S. Tripathy and R. Sahoo, [arXiv:2207.12133 [hep-ph]]

Results: (v_n/ε_n vs Centrality)

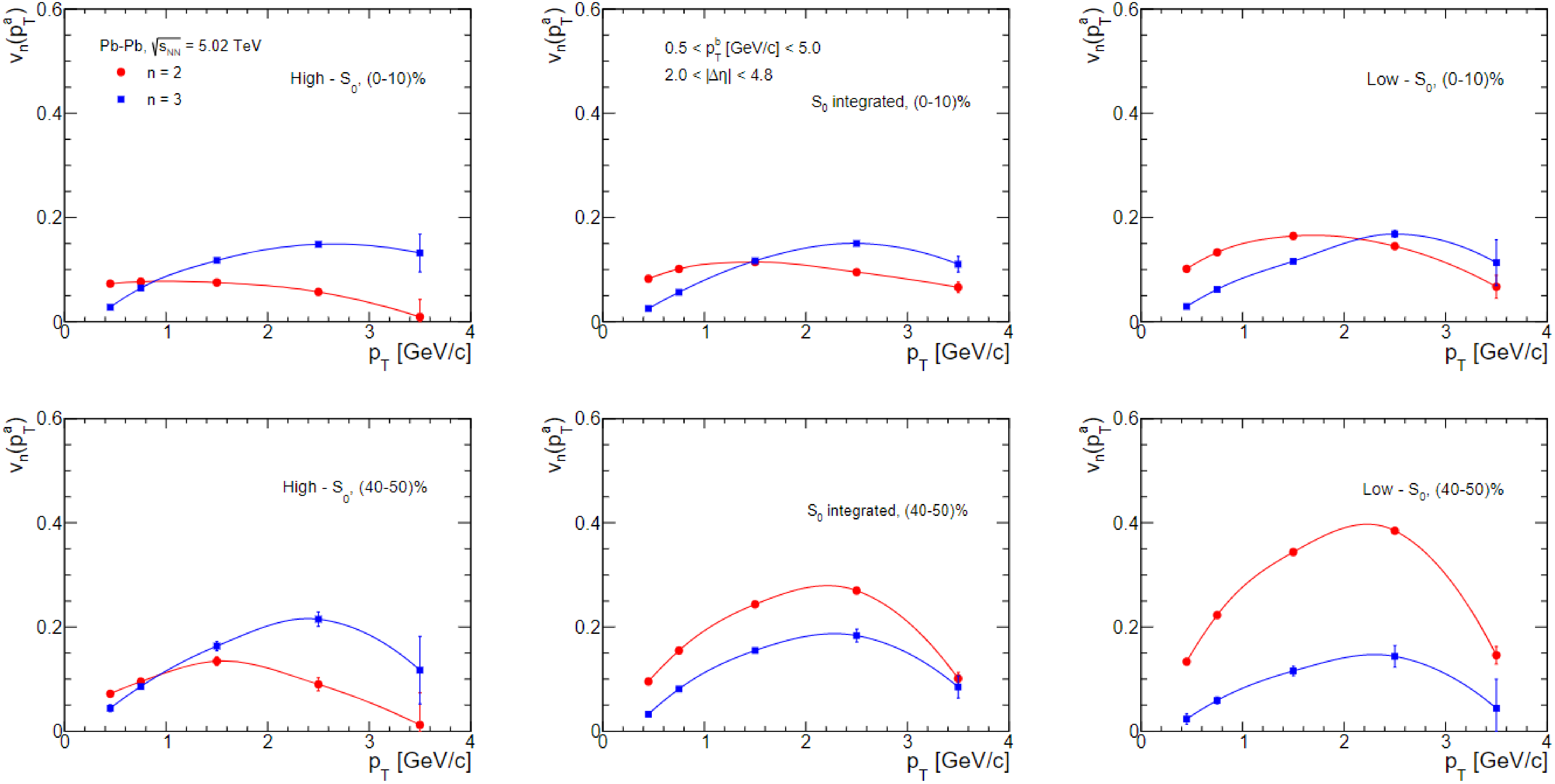




- Non-linear correlation among initial spatial anisotropy and momentum space azimuthal anisotropy
- Indicates different flow coefficients are affected differently by the medium effects

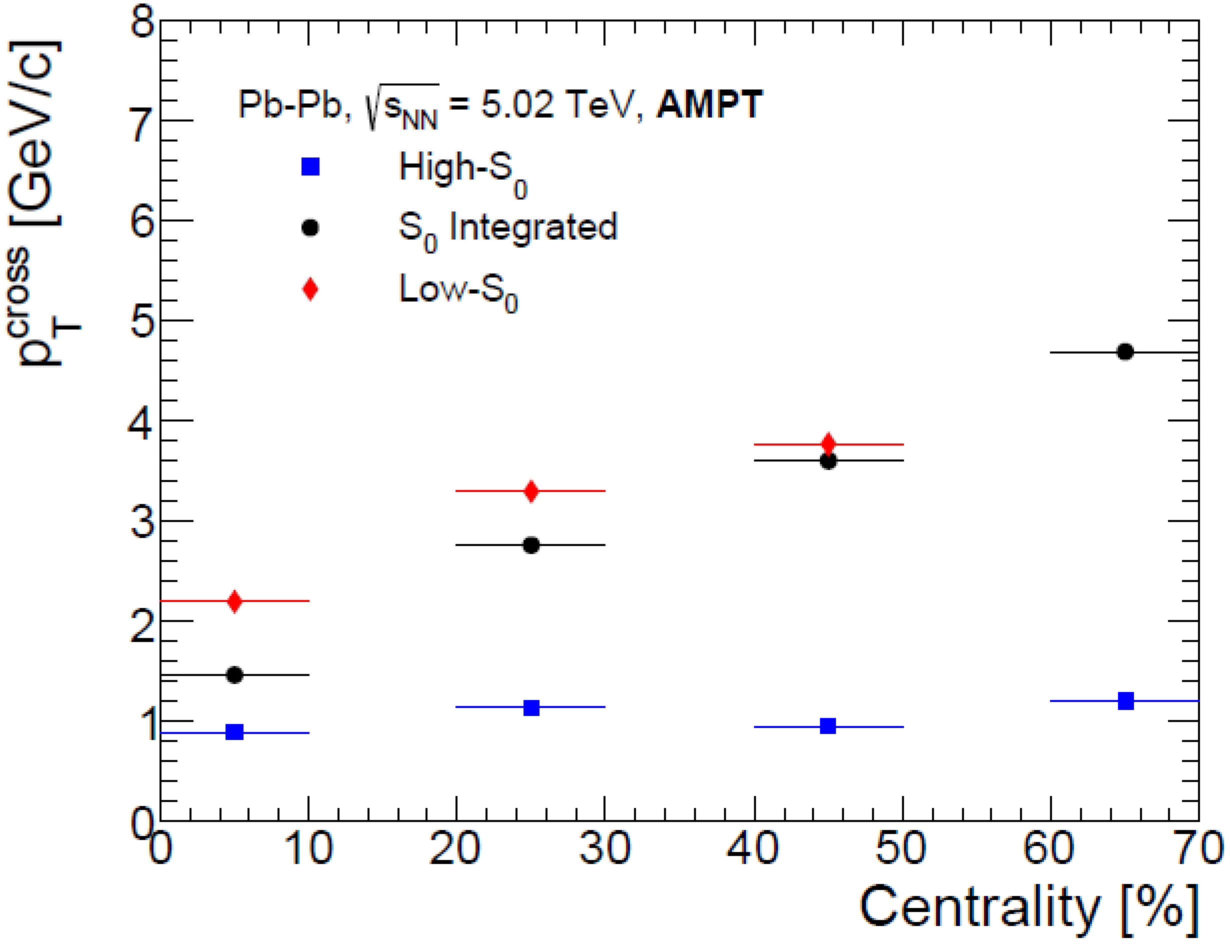
S. Prasad, N. Mallick, S. Tripathy and R. Sahoo, [arXiv:2207.12133 [hep-ph]]

Results ($v_2 - v_3$ crossing)



S. Prasad, N. Mallick, S. Tripathy and R. Sahoo, [arXiv:2207.12133 [hep-ph]]

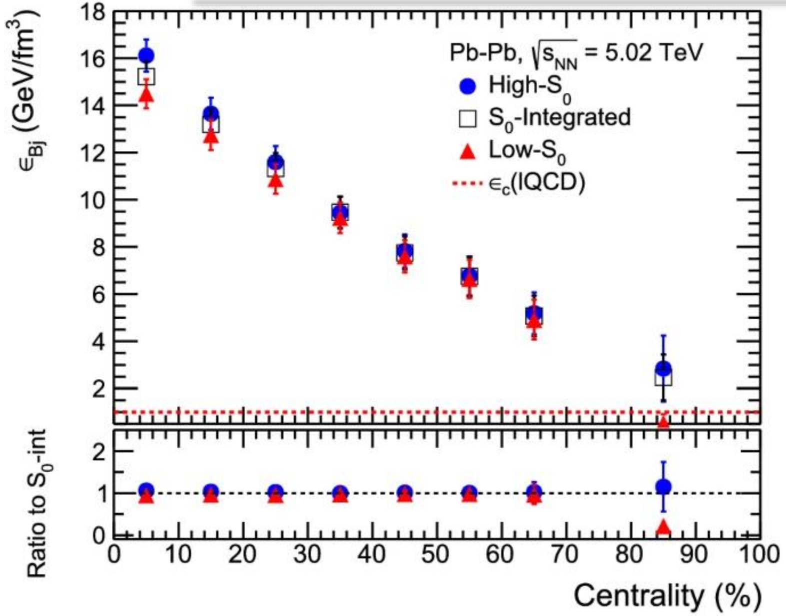
Results ($v_2 - v_3$ crossing)

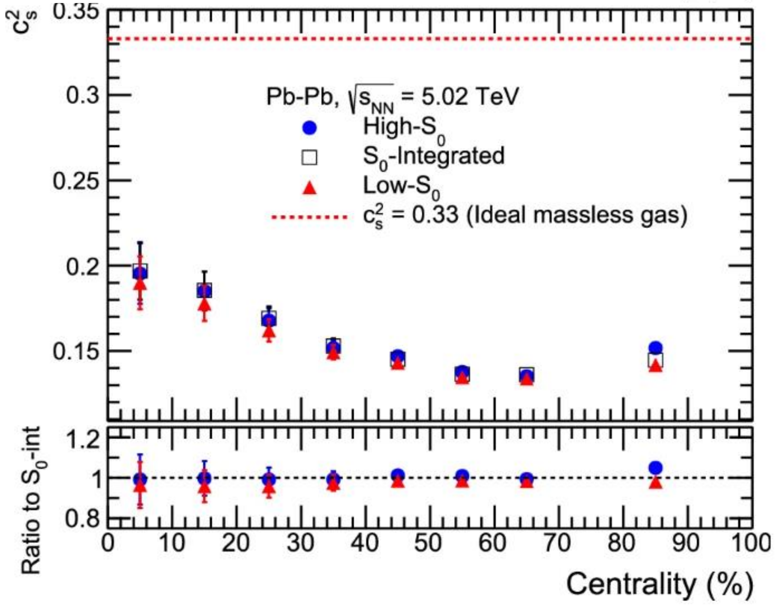


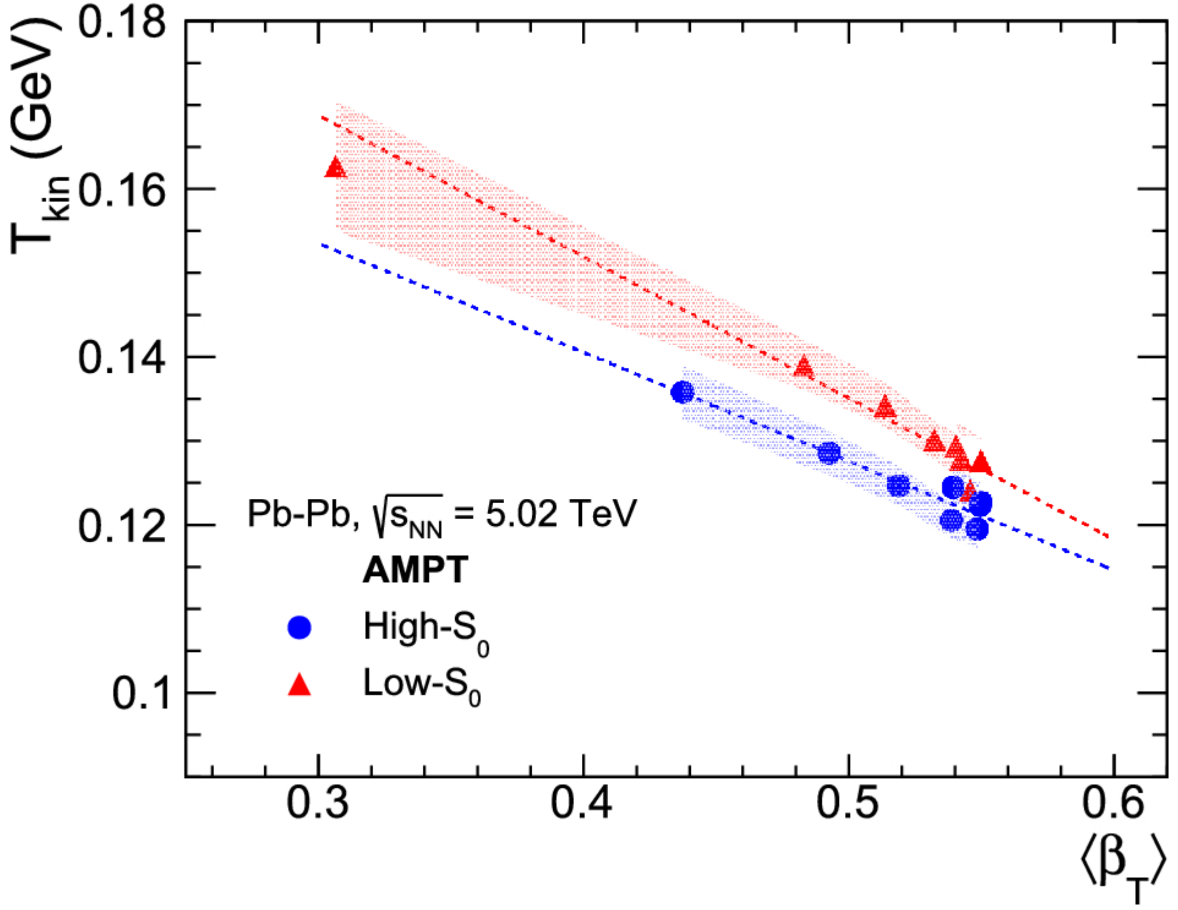
- p_T^{cross} is centrality and transverse spherocity dependent
- p_T^{cross} increases when going from central to peripheral collisions, as v_2 dominates over v_3
- p_T^{cross} is found to be increasing for jetty like events, than isotropic events
- p_T^{cross} is lower and almost flat for high-S_0 events, indicating the dominance of density fluctuations over geometry during the evolution of the anisotropic flow

S. Prasad, N. Mallick, S. Tripathy and R. Sahoo, [arXiv:2207.12133 [hep-ph]]

Results (Global Observables)







S. Prasad, N. Mallick, D. Behera, R. Sahoo and S. Tripathy, Sci. Rep. 12, 3917 (2022)

Summary

- Transverse spherocity can successfully be used to study event topology-based particle production dynamics both in small systems and in heavy-ion collisions

- S_0 is found to have non-zero correlation with reduced flow vectors
- Significant dependance of spherocity on eccentricity is observed, (less in triangularity)
- Study of elliptic flow as a function of spherocity suggests that low S_0 events have more contribution on elliptic flow and high S_0 events have least contribution
- Unlike elliptic flow, most of the contribution in triangular flow is from high S_0 events, and low S_0 events contribute least

- p_T –dependent crossover is observed between v_2 and v_3. The crossover p_T-value decreases towards central and isotropic events: more v_3 than v_2 at high-p_T

- Non-linear relationship between elliptic flow and eccentricity, triangular flow and triangularity
- Kinetic freeze-out temperature and mean transverse radial flow velocity are found to be strongly dependent on transverse spherocity

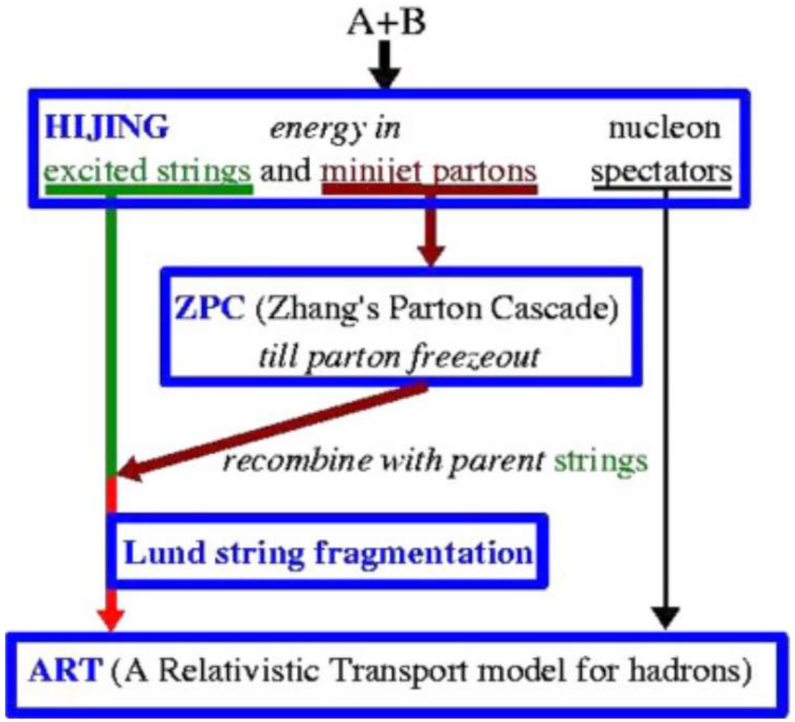
S. Prasad, N. Mallick, D. Behera, R. Sahoo and S. Tripathy, Sci. Rep. 12, 3917 (2022)
S. Prasad, N. Mallick, S. Tripathy and R. Sahoo, [arXiv:2207.12133 [hep-ph]]

Thank you

for the attention

A Multi-phase Transport Model (AMPT)

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



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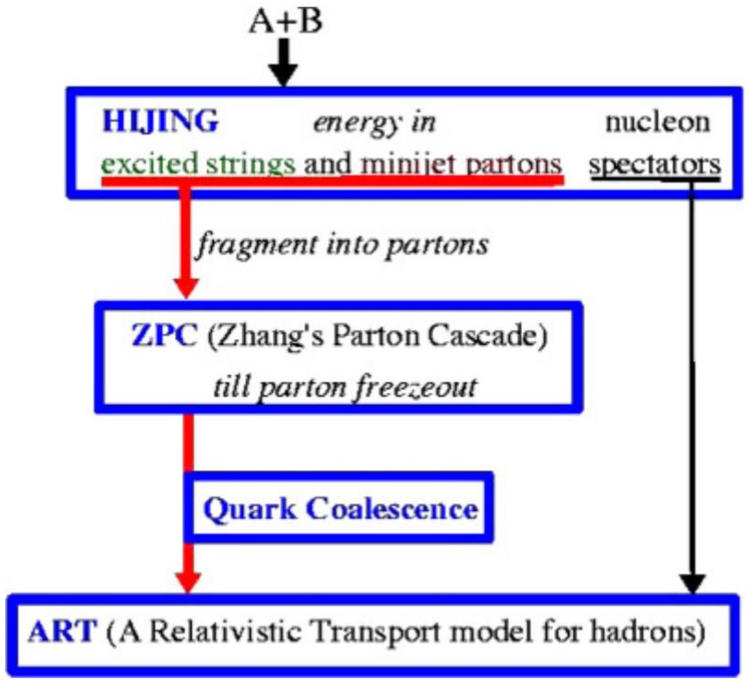

SM Version

Zi-Wei Lin, Che Ming Ko, Bao-An Li, Bin Zhang, and Subrata Pal, Phys. Rev. C 72, 064901 (2005)

Two Particle Correlation

- We construct two groups of charged particles based on p_T cuts.
  a : trigger group (small p_T bins) i.e. (0.5-1) GeV/c , (1-2) GeV/c, ... , (4-5)GeV/c
  b : associated group (whole p_T range) i.e. (0.5-5) GeV/c
- Particle pairs are made by choosing each particle from 'a' paired with all particles from 'b'.
- Same event pairs ($S(\Delta\eta, \Delta\phi)$) and mixed event pairs ($B(\Delta\eta, \Delta\phi)$) are calculated. ($\Delta\eta = \eta_a - \eta_b$, and $\Delta\phi = \phi_a - \phi_b$)
  $S(\Delta\eta, \Delta\phi)$: 'a' and 'b' belong to same event
  $B(\Delta\eta, \Delta\phi)$: 'a' and 'b' belong to different event
- $|\eta| < 2.5$ has been applied to above calculations. We further apply $2.0 < |\Delta\eta| < 4.8$ to remove non flow contributions in the calculations.
- We calculate two particle correlation function, $C(\Delta\phi) = \frac{S(\Delta\phi)}{B(\Delta\phi)}$
- 1D two particle correlation function can be expanded in terms of fourier series as:
  $C(\Delta\phi) \propto [1 + 2\sum_{n=1}^{\infty} v_{n,n}(p_T^a, p_T^b)\, cos(n\Delta\phi)]\,;$
  $v_{n,n}(p_T^a, p_T^b)$= two particle nth flow coefficient $=< cos(n\Delta\phi) >$
- One particle flow coefficient, $v_n(p_T^a) = \frac{v_{n,n}(p_T^a,p_T^b)}{\sqrt{v_{n,n}(p_T^b,p_T^b)}}$

G. Aad et al. (ATLAS Collaboration) 2015 Phys. Rev. C 92, 034903