Study of Transverse Spherocity dependence of particle production and Application of Machine Learning in Heavy-ion collisions at the LHC

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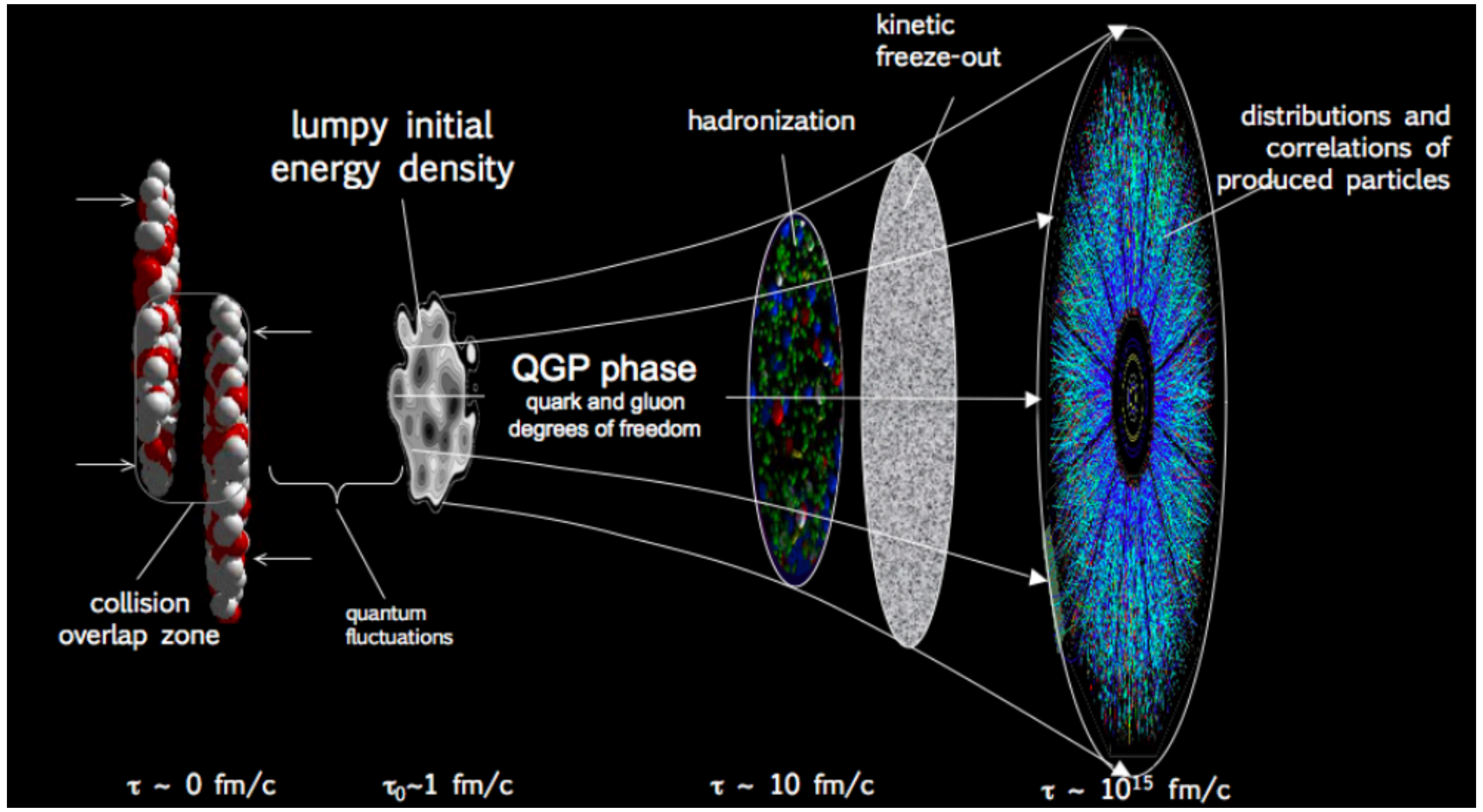
Based on:

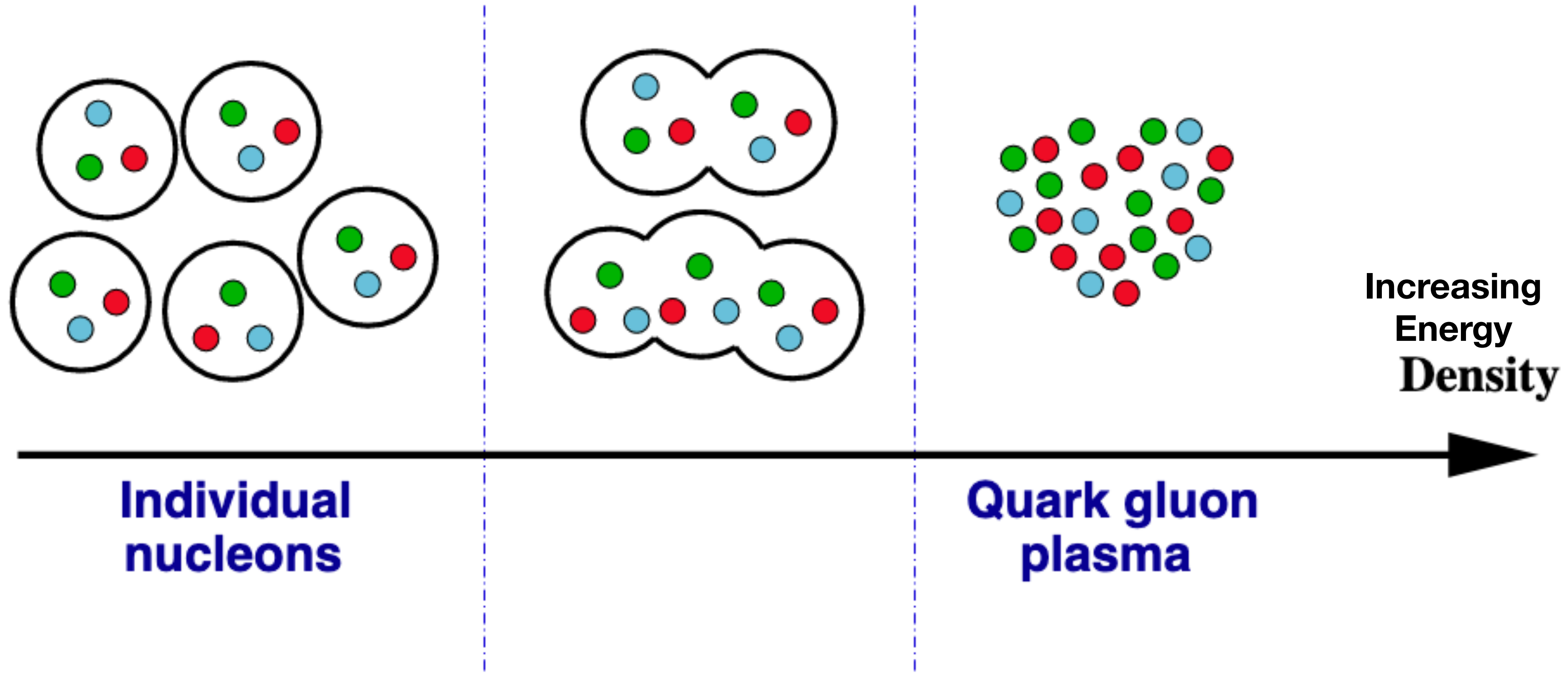
- N. Mallick, S. Tripathy, R. Sahoo, and A. Ortiz, arXiv:2001.06849 [hep-ph]
- N. Mallick, R. Sahoo, S. Tripathy, and A. Ortiz, arXiv:2008.13616 [hep-ph] [JPG (In Press)]
- N. Mallick, S. Tripathy, A. N. Mishra, S. Deb, and R.Sahoo, arXiv:2103.01736 [hep-ph]

Outline

- Heavy-ion collisions: “A Little Bang”
- Signature of QGP: Elliptic flow (v_2)
- Physics Motivation
- Event Shape observable: Transverse Spherocity (S_0)
- Spherocity dependence of azimuthal anisotropy
- Estimation of Spherocity using Machine Learning
- Results
- Summary and outlook

Heavy-ion collisions

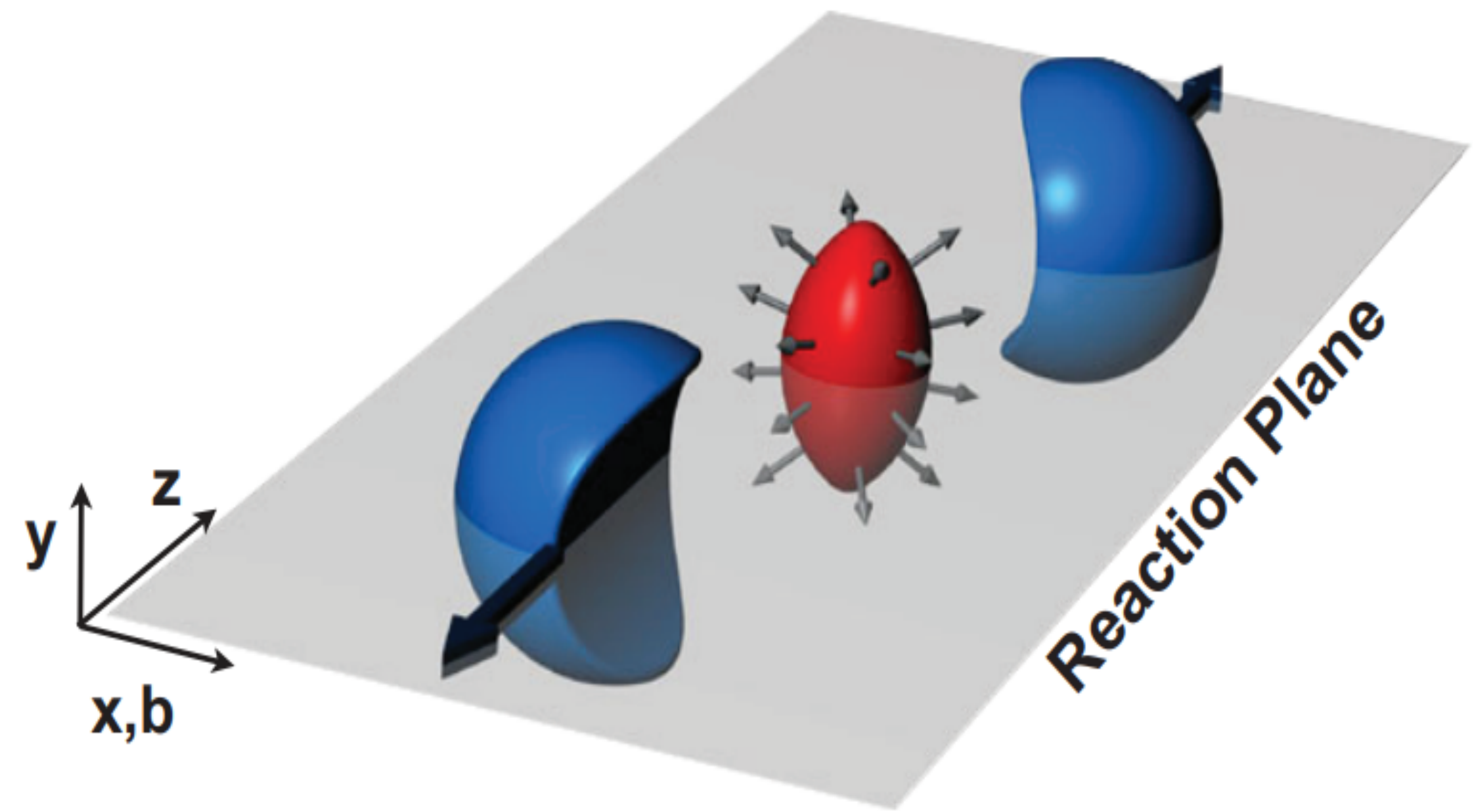


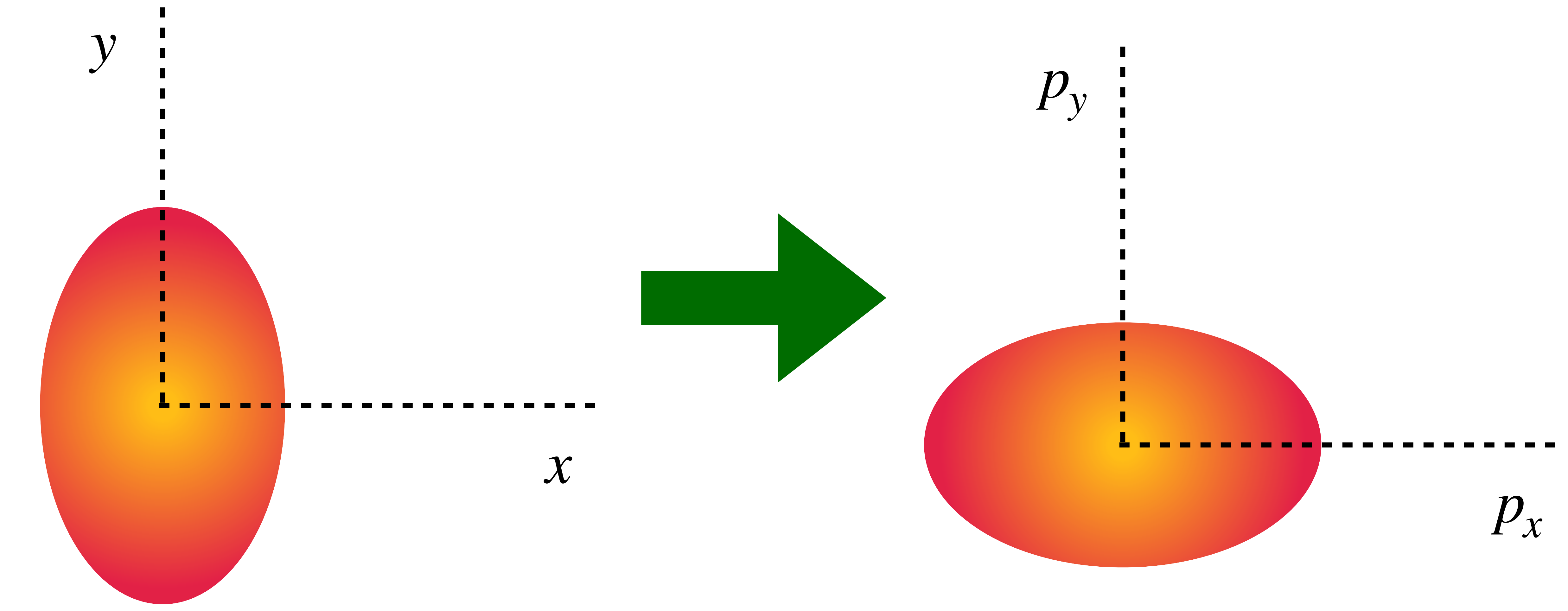


- For low temperature / density: quarks and gluons confined to hadrons
- For high temperature / density: deconfined quarks and gluons
- In between no sharp phase transition but continuous crossover

- Quarks: Fundamental bits of matter,
  Gluons: Carriers of strong force
- Quark confinement: free quarks can not exist under regular conditions —> confined inside hadrons *i.e.* mesons ($q\bar{q}$) and baryons (qqq)
- Asymptotic freedom: the interaction of fundamental fields becomes weaker as the energy density increases —> Strong coupling constant decreases with increase in energy
- Quark gluon plasma is a thermally equilibrated hot and dense state of matter in which partons are very weakly bound and are almost free to move
- Very high temperature (T) and/or high net baryon density (μ_B)
- Heavy-ion collisions recreate the early universe kind of conditions in a miniature level inside the labs

The Elliptic Flow (v_2)



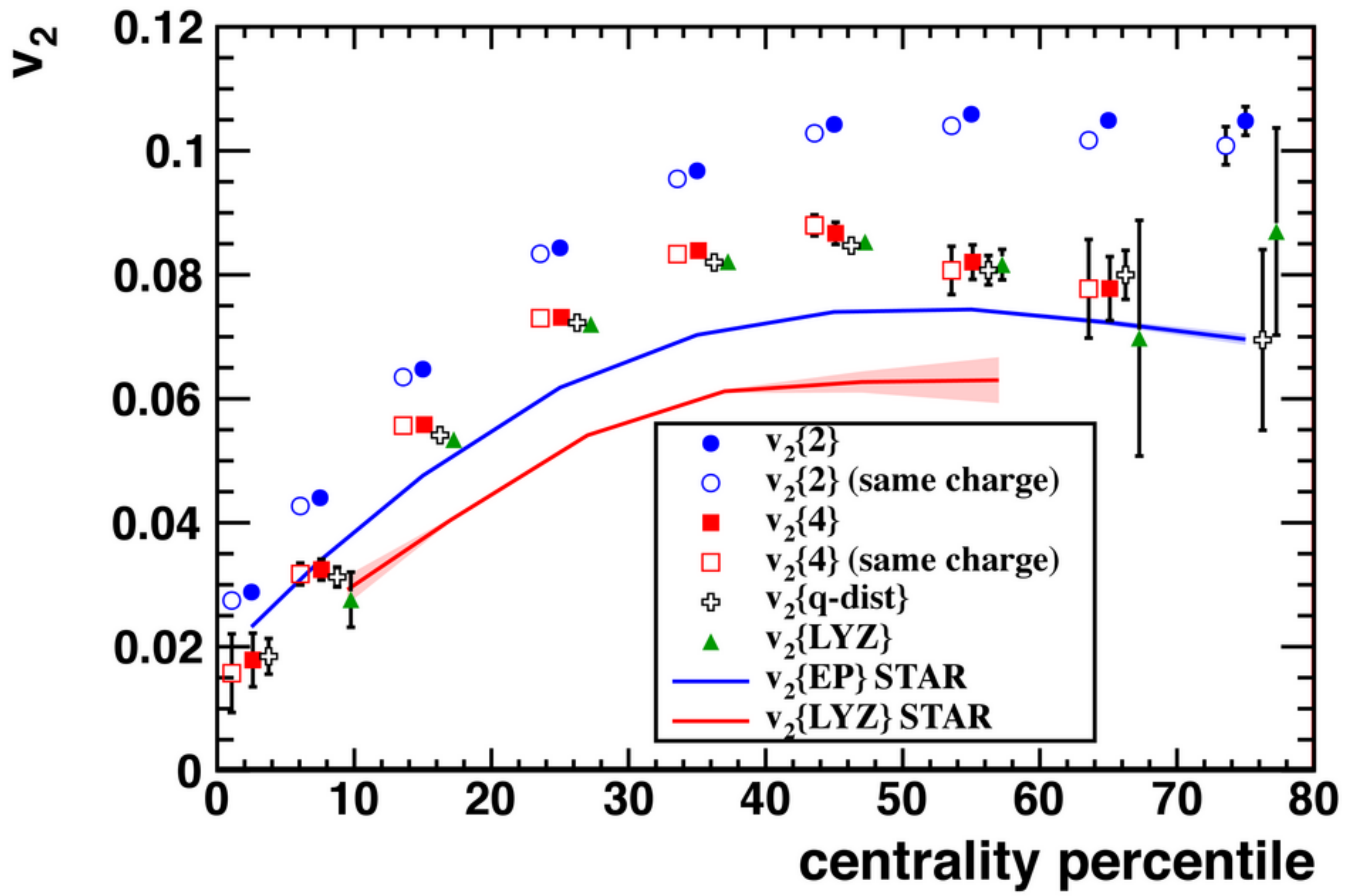


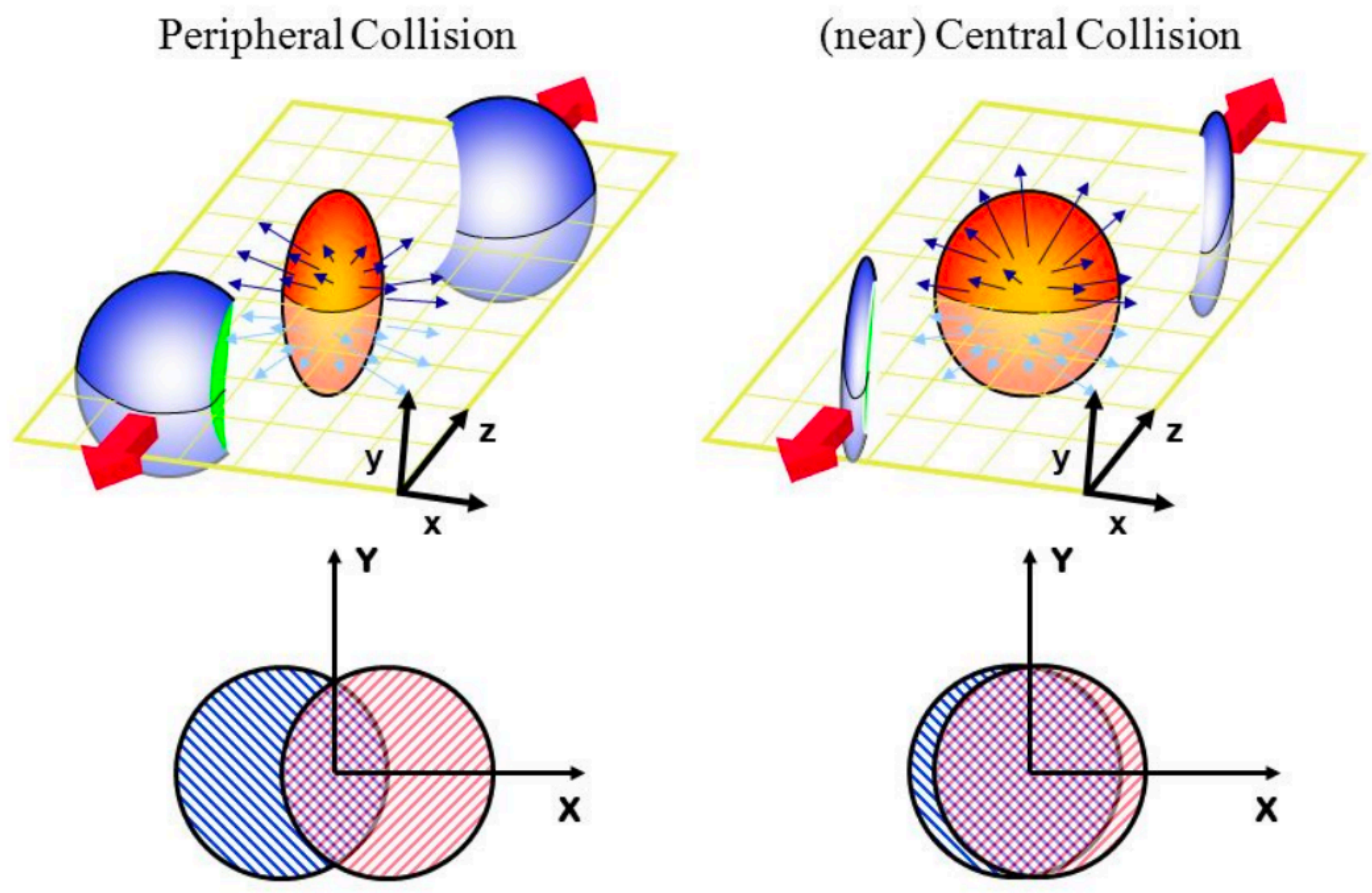
- Elliptic flow describes the azimuthal momentum space anisotropy of particle emission for a non-central heavy-ion collision
- It is defined as the 2nd harmonic coefficient of the Fourier expansion of azimuthal momentum distribution ($dN/d\phi$)
- Fundamental observable that directly reflects the initial spatial anisotropy of the nuclear overlap region in the transverse plane

$$E\frac{d^3N}{d^3p} = \frac{d^3N}{p_\mathrm{T}dp_\mathrm{T}dyd\phi} = \frac{d^2N}{p_\mathrm{T}dp_\mathrm{T}dy}\frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n)]\right)$$

$$v_2(p_\mathrm{T}, y) = \langle \cos(2(\phi - \psi_2)) \rangle$$
$$\phi = \tan^{-1}(p_y/p_x)$$

Physics Motivation





$0 \le b \le 2R$

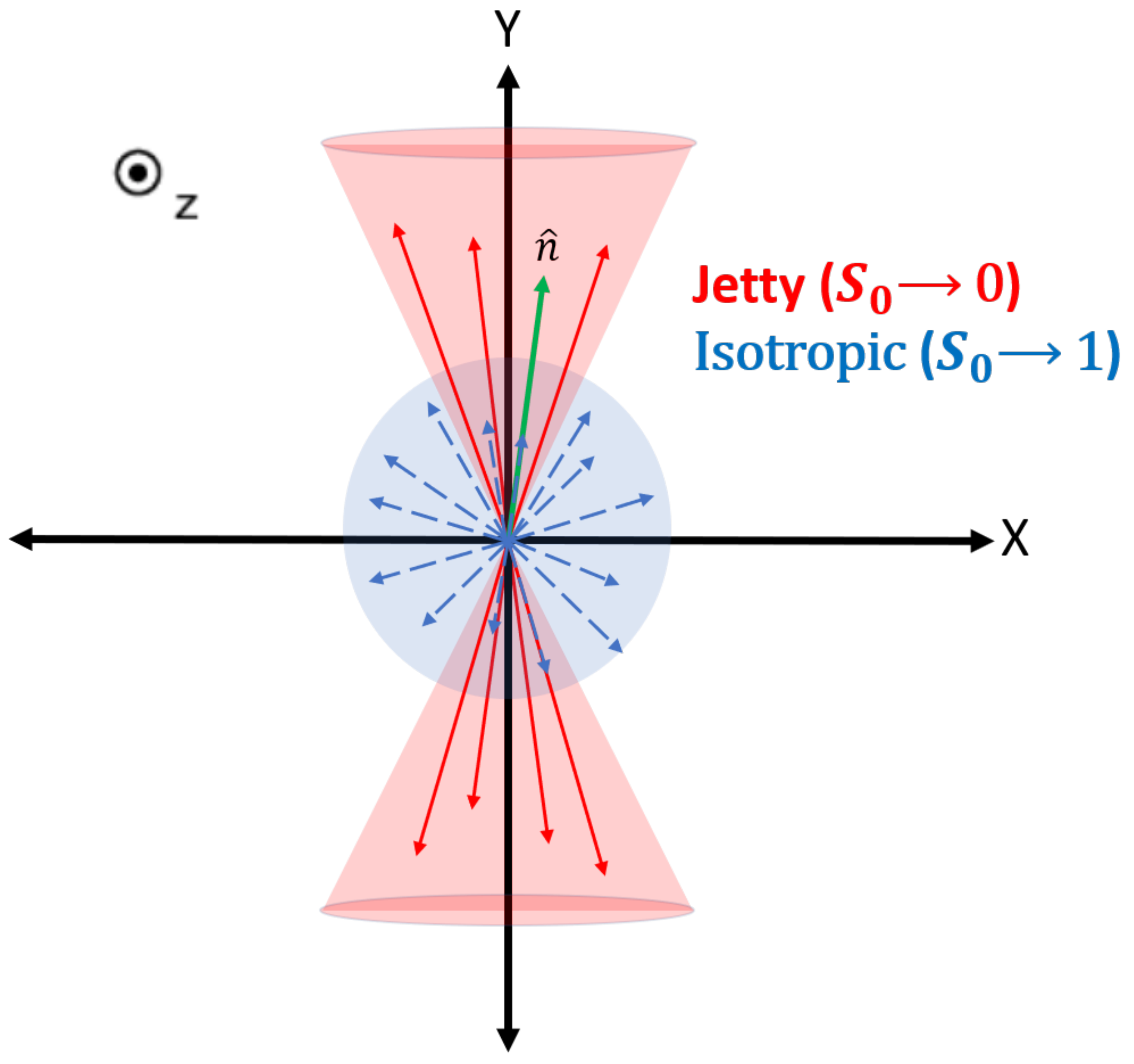
- Experiments observe significant elliptic flow for heavy-ion collisions indicating finite azimuthal anisotropy in the system
- As expected, the elliptic flow is higher for non-central collisions compared to central collisions (v_2 has strongest centrality dependence)

ALICE, Phys. Rev. Lett. 105 (2010) 252302

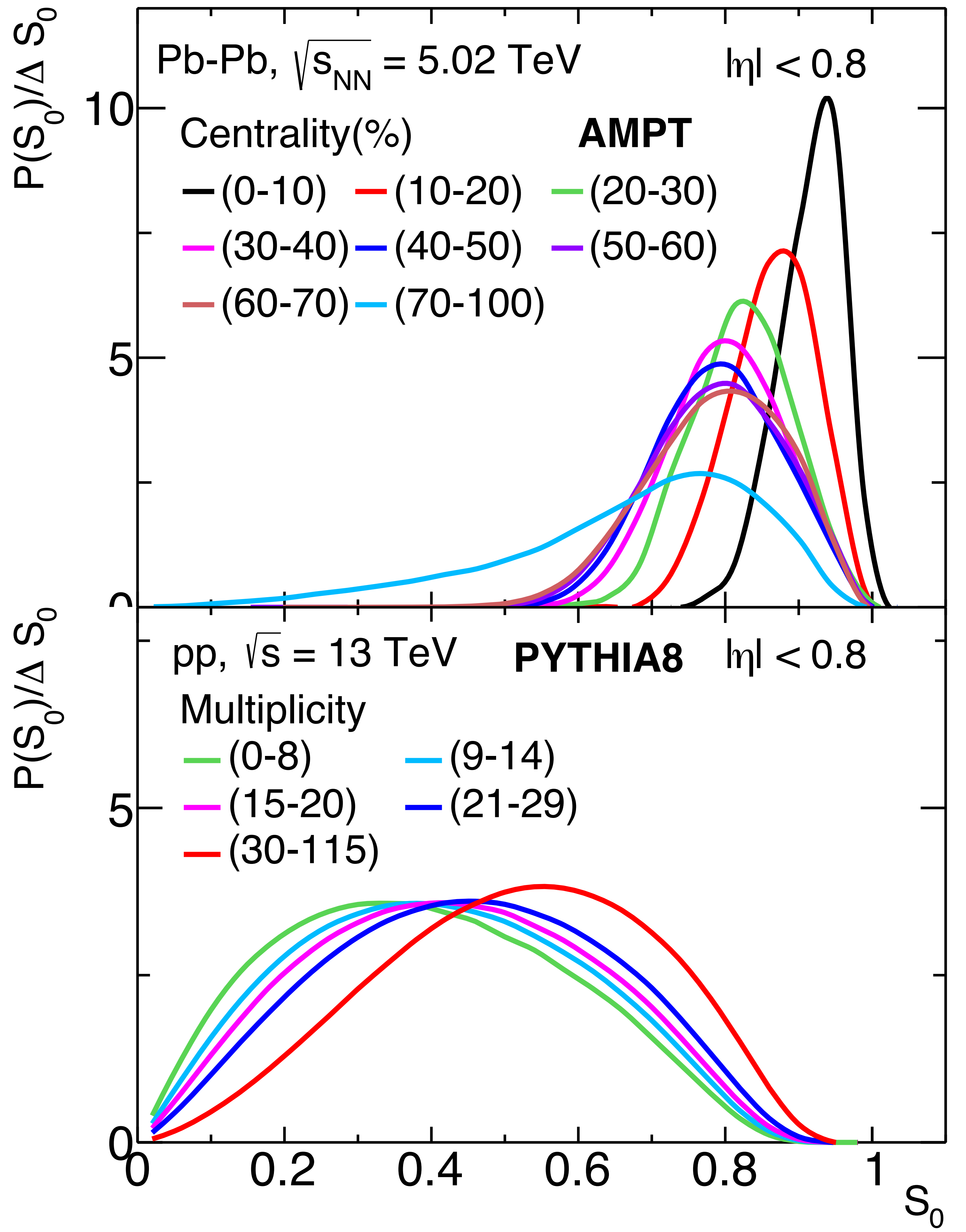
Transverse Spherocity (S_0)

- Transverse Spherocity distinguishes hard and soft processes
- In pp collisions,
  1. **Jetty**: Back-to-back structure, indication of hard-QCD
  2. **Isotropic**: soft-QCD process
- Dominance of isotropic events in high multiplicity pp collisions
- $\langle p_T \rangle$ is higher for jetty events
- S_0 has multiplicity and centrality dependence

$$S_0 = \frac{\pi^2}{4} \times \min_{\hat{n}=(n_x,n_y,0)} \left(\frac{\Sigma_i \, |\vec{p}_{T_i} \times \hat{n}|}{\Sigma_i \, \vec{p}_{T_i}} \right)^2$$



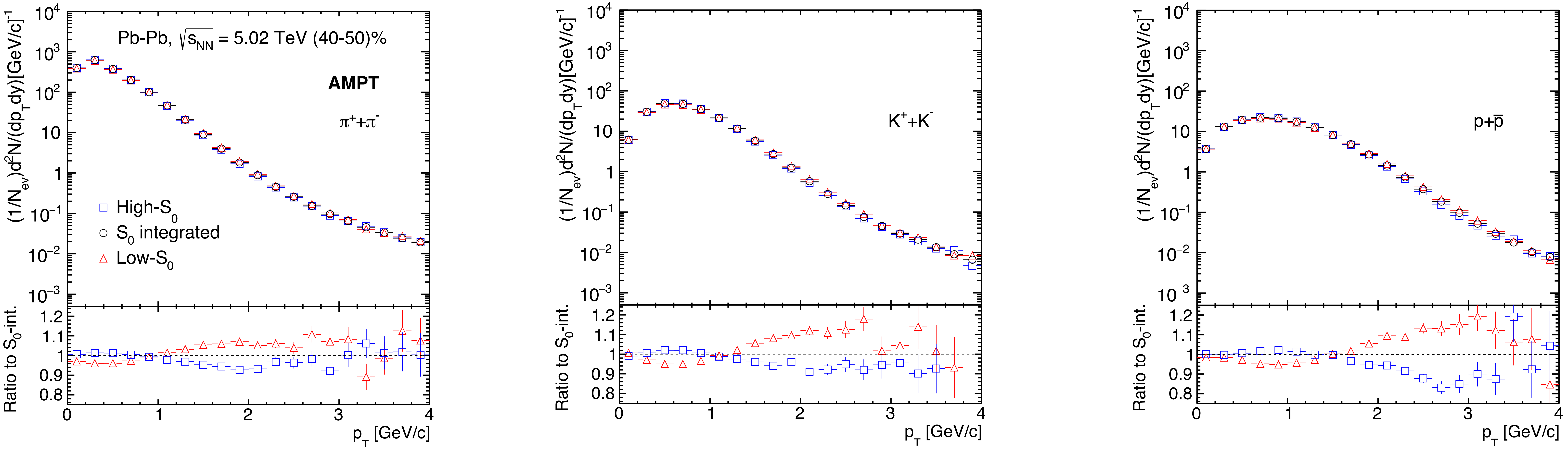
Schematic picture showing possible **jetty** and **isotropic** event formations in the transverse plane



A. Khuntia et al., J.Phys.G 48 (2021) 3, 035102

N. Mallick, R. Sahoo, S. Tripathy, and A. Ortiz, arXiv:2008.13616 [hep-ph] [JPG (In Press)]

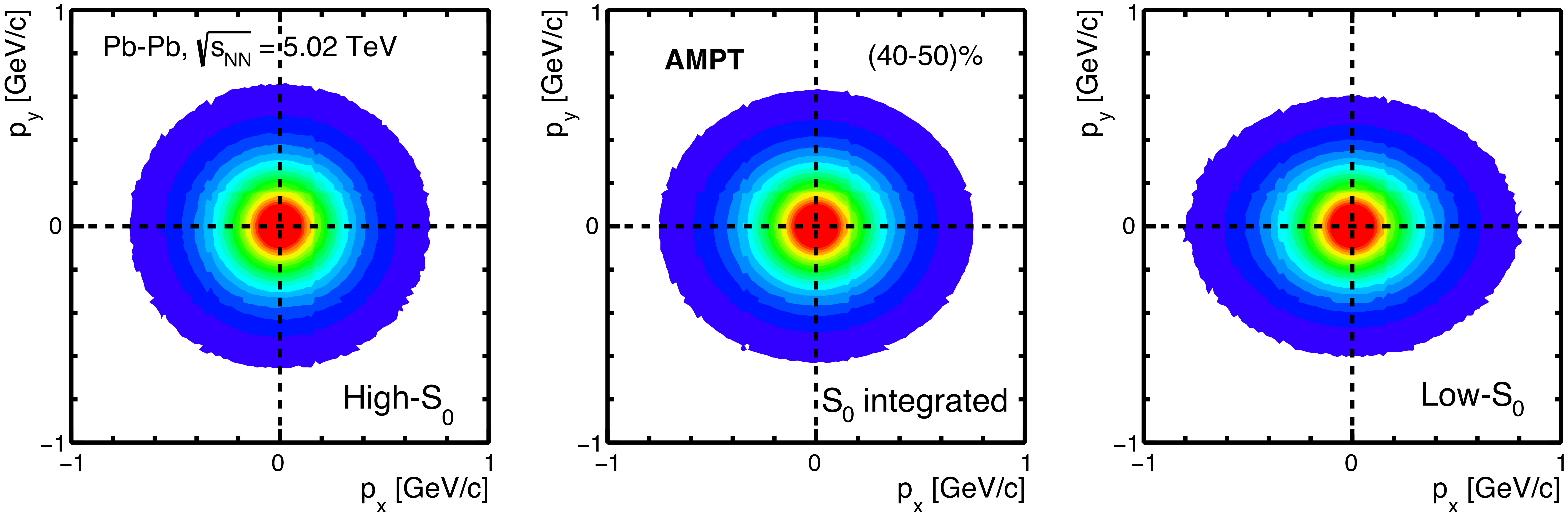
Transverse momentum (p_T) Spectra



- In low-p_T region, particle production is dominated by **high-S_0** events, after the crossing point particle production gets dominated by **low-S_0** events
- **The crossing point is mass dependent —> gets shifted towards higher p_T as the mass increases**
- This behaviour is an indication of possible collectivity in heavy-ion collisions

N. Mallick, S. Tripathy, R. Sahoo, and A. Ortiz, arXiv:2001.06849 [hep-ph]

Spherocity dependence of azimuthal anisotropy



- Elliptic flow should be an indication of initial state spatial anisotropy
- If jets are produced in an event, then it would contribute to elliptic flow which we call as non-flow effect
- Non-flow effect is due to bias introduced by jets and is not related to initial state spatial anisotropy produced due to the medium
- As we are studying events based on spherocity, the jetty events would be dominated by jets and thus non-flow effect would be very significant in those events

N. Mallick, R. Sahoo, S. Tripathy, and A. Ortiz, arXiv:2008.13616 [hep-ph] [JPG (In Press)]

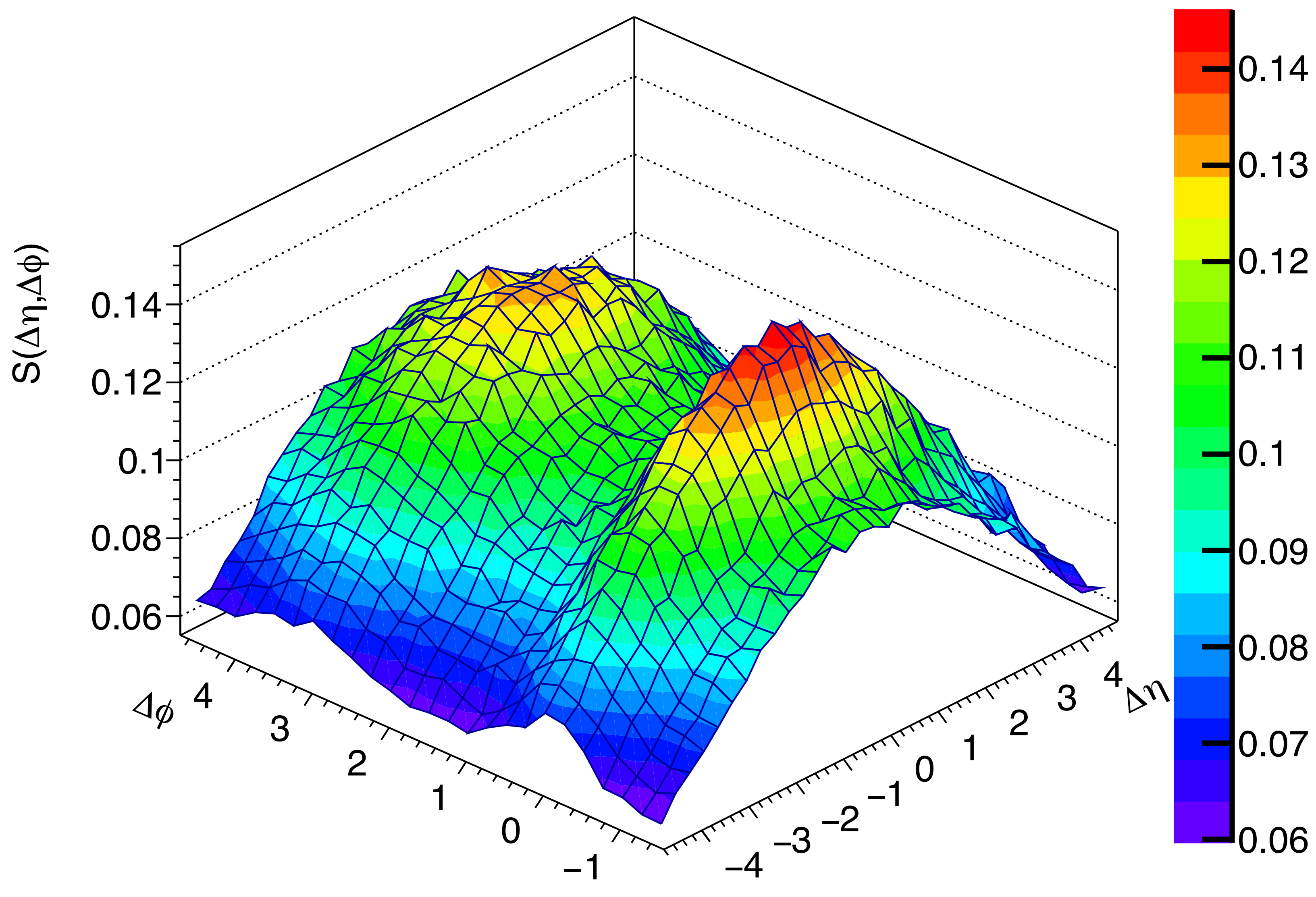
Two-particle correlation

- Two groups of charged particles based on certain p_{T}-cuts:
  a: trigger group
  b: associated group
- Particle pairs are made by choosing each particle from a and pairing with all particles from b
- In same event, a and b groups belong to the same event.
  In background event, a and b belong to two different (cross) events (also called mixed-event pairs).
- We have used five such randomly chosen events to construct background pairs.
- We find $\Delta\eta = \eta_a - \eta_b$ and $\Delta\phi = \phi_a - \phi_b$ for such pairs of particles in $|\eta| < 2.5$
- $C(\Delta\phi) = \dfrac{S(\Delta\phi)}{B(\Delta\phi)}$ is constructed by accepting particle pairs within $2.0 < |\Delta\eta| < 4.8$
- Mathematically, this 1D correlation function $C(\Delta\phi)$ can be expressed as a Fourier series :
  $C(\Delta\phi) = G \times [1 + \sum_n 2v_{n,n} cos(n\Delta\phi)]$, where $v_{n,n}$ is called the two-particle flow coefficient.
- From which, $v_{n,n}$ could be found as simply taking the average: $v_{n,n} = \langle cos(n\Delta\phi)\rangle$ and
  $v_n(p_T^a) = \dfrac{v_{n,n}(p_T^a, p_T^b)}{\sqrt{v_{n,n}(p_T^b, p_T^b)}}$, for $n = 2$, it gives the elliptic flow coefficient.

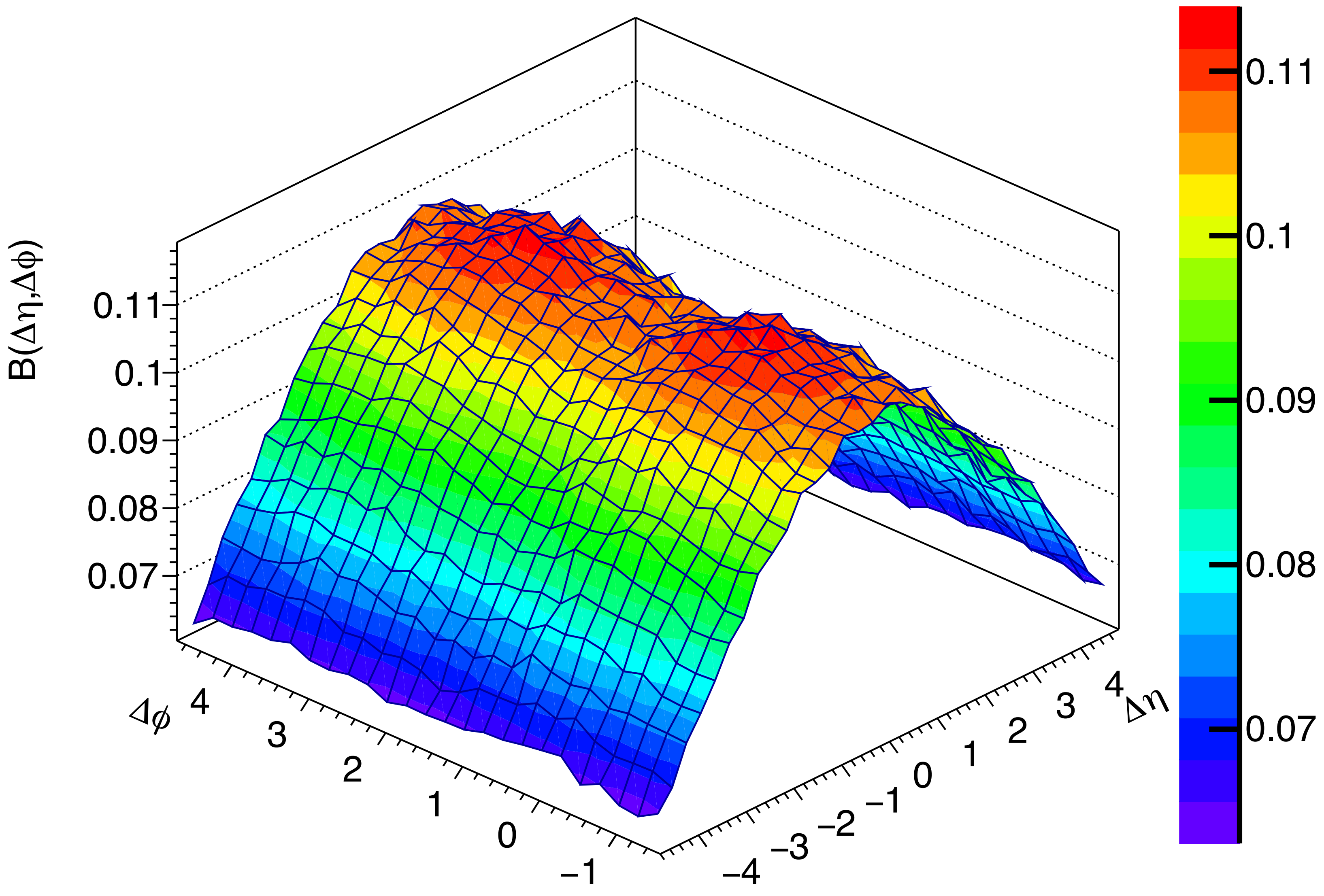
ATLAS, *Phys.Rev.C* 86 (2012), 014907

Two-particle correlation (Contd.)

Same



Background



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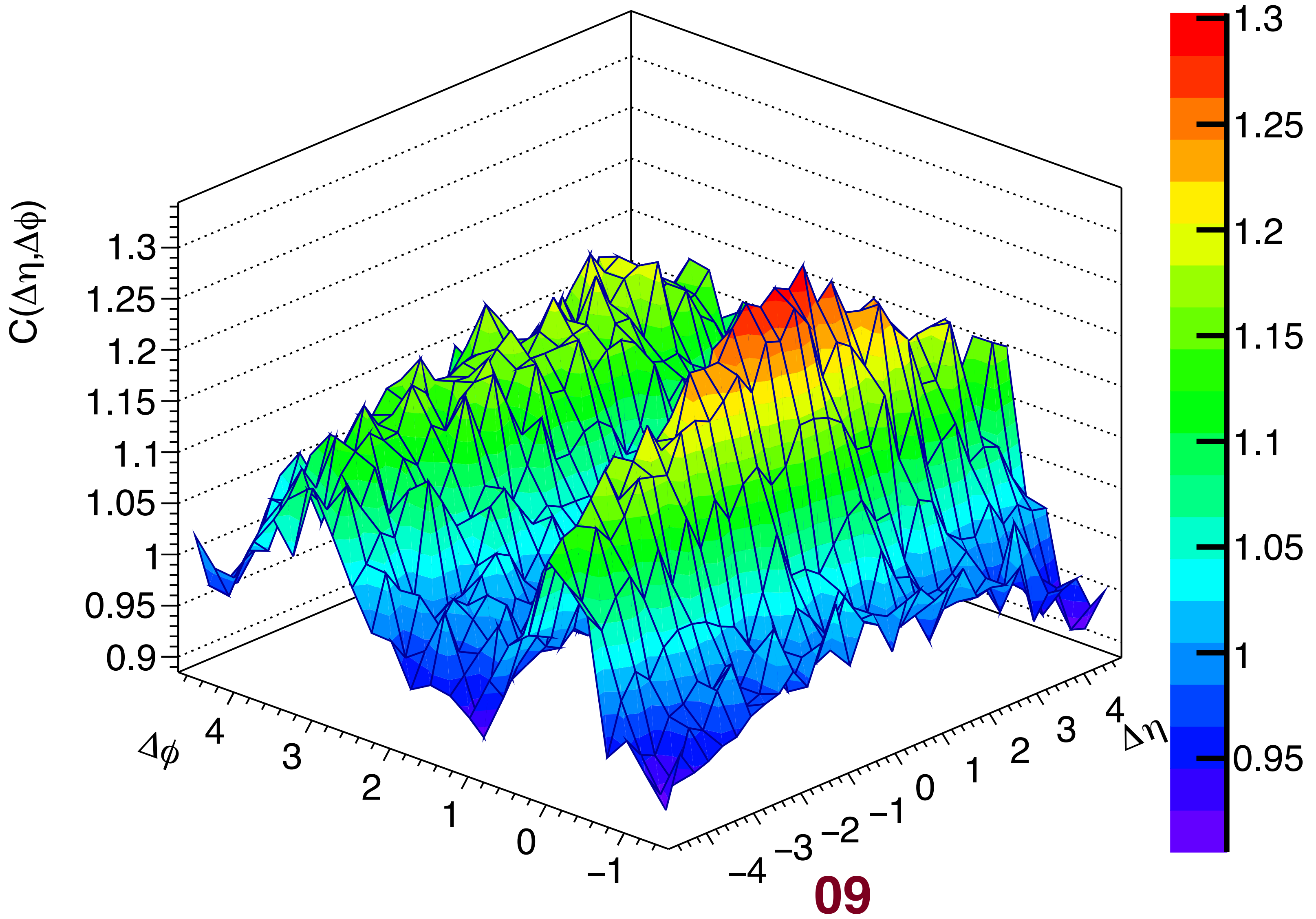
Signal

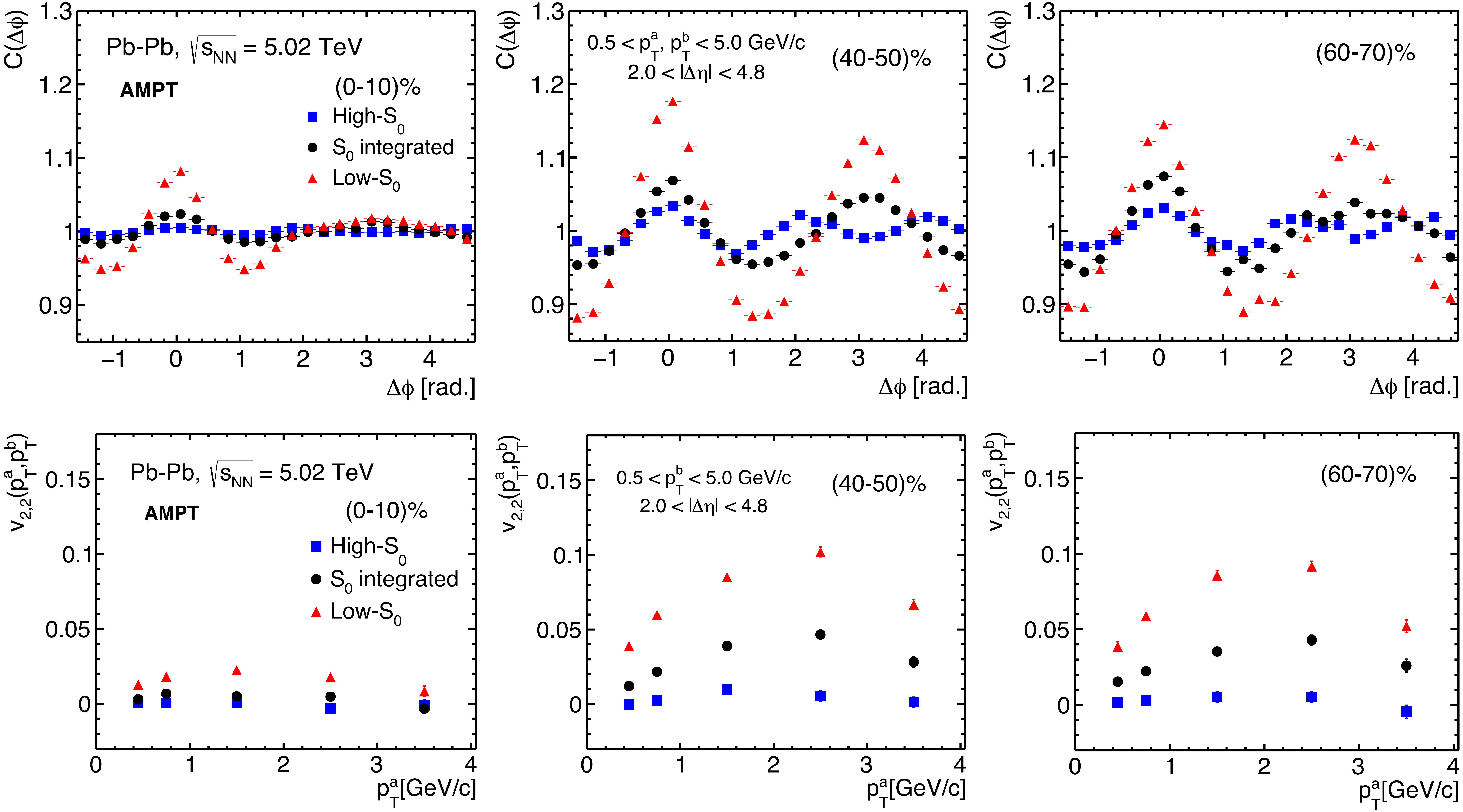
$$C(\Delta\eta, \Delta\phi) = B(0,0) \times \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}$$



Jet peak is clearly seen in $-2 < \Delta\eta < 2$

- Ratio to background ensures: No non-uniformity and improves pair acceptance
- Contains no physical correlations (cross-events are randomly chosen)

Results



$$C(\Delta\phi) = \frac{S(\Delta\phi)}{B(\Delta\phi)}$$

$$v_{n,n} = \langle cos(n\Delta\phi) \rangle$$

$$v_{n,n} = \frac{\sum_{m=1}^{N} cos(n\Delta\phi_m) \times C(\Delta\phi_m)}{\sum_{m=1}^{N} C(\Delta\phi_m)}$$

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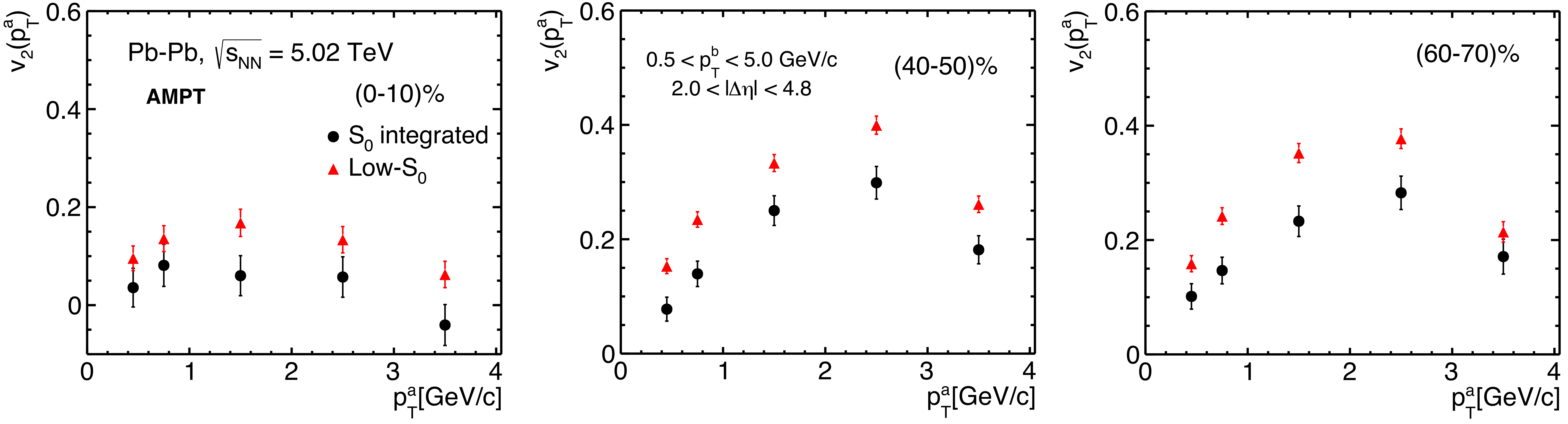
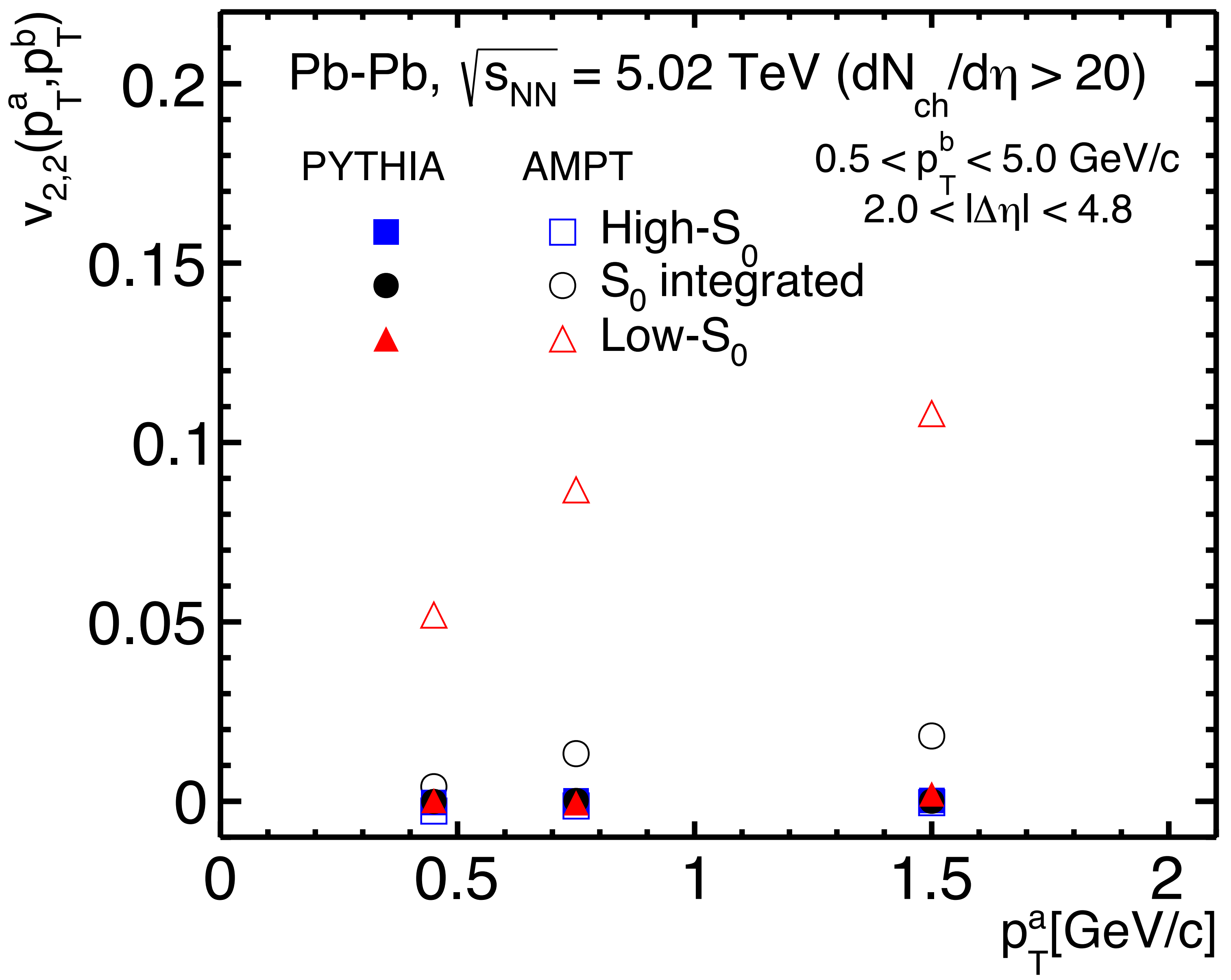
Results



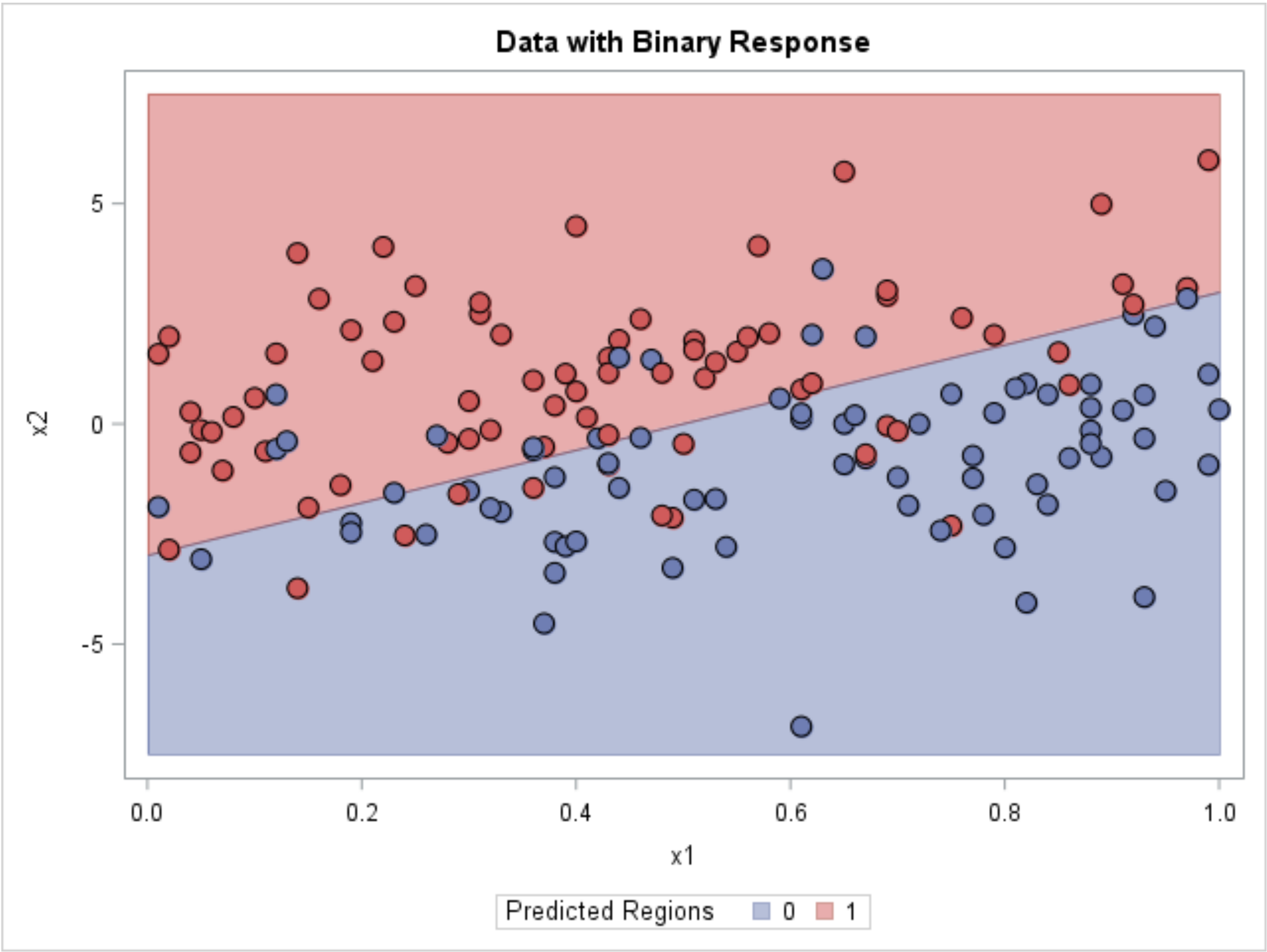


$$v_{n,n} = \langle cos(n\Delta\phi) \rangle$$

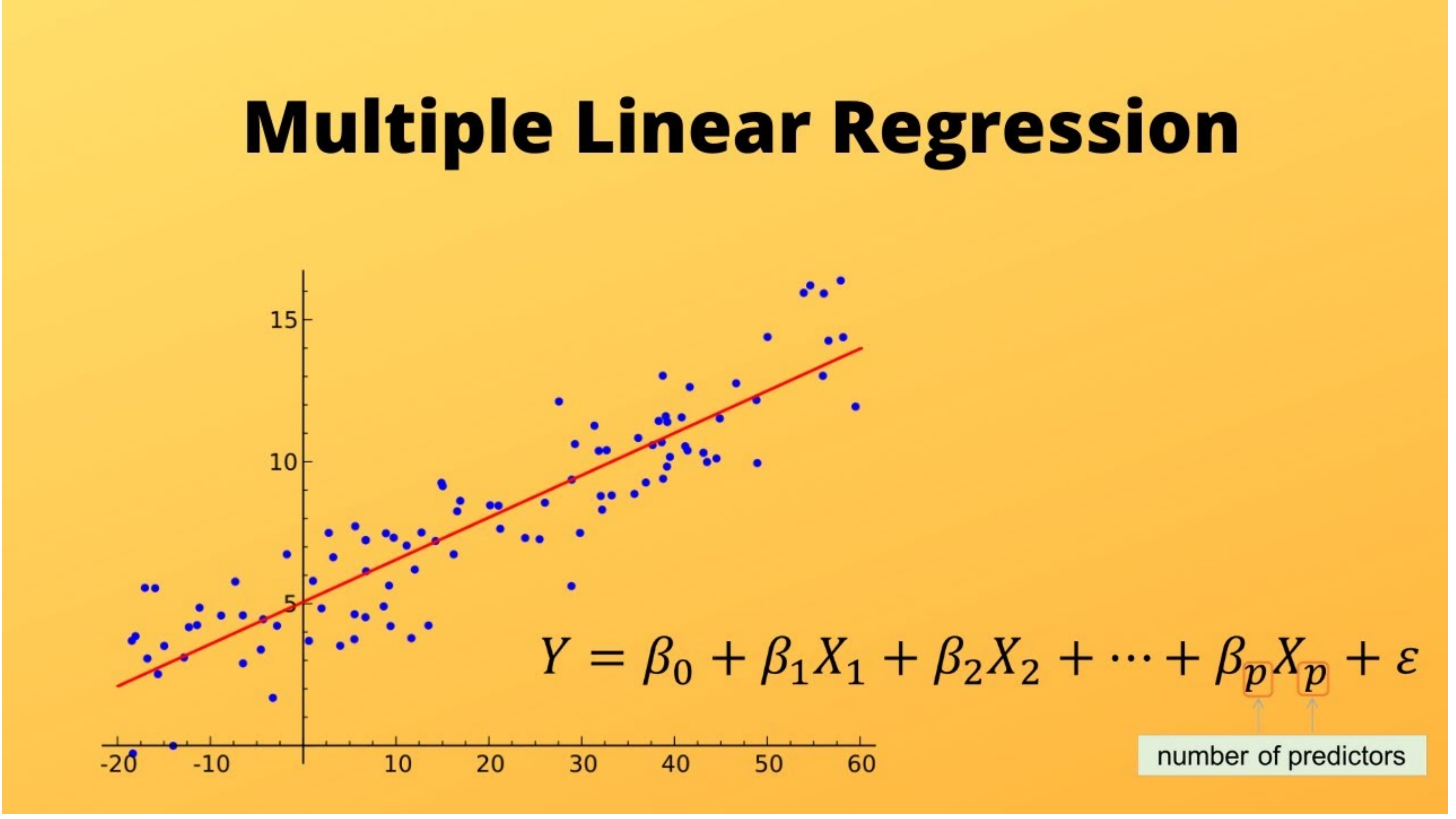
$$v_n(p_T^a) = \frac{v_{n,n}(p_T^a, p_T^b)}{\sqrt{v_{n,n}(p_T^b, p_T^b)}}$$

N. Mallick, R. Sahoo, S. Tripathy, and A. Ortiz, arXiv:2008.13616 [hep-ph] [JPG (In Press)]

Machine Learning



Classification

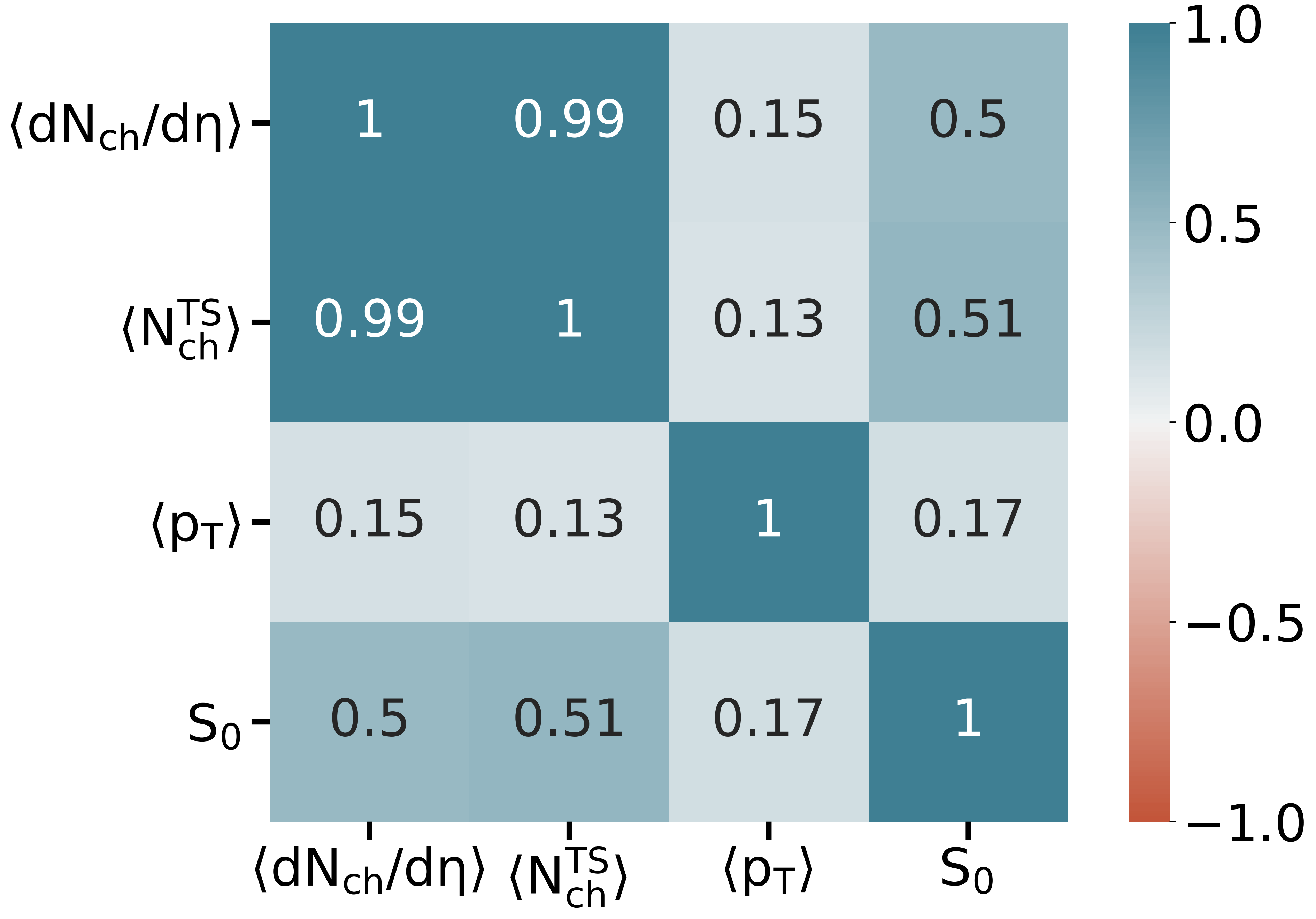


Regression

- We have implemented ML-based regression technique to estimate the transverse spherocity distributions for Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ and 5.02 TeV by using simulated data from A Multi-Phase Transport (AMPT) model.
- The ML-model is trained with 5.02 TeV minimum bias simulated data and used to predict centrality wise distributions.
- Also, the same model is used to estimate the min. bias spherocity distribution for 2.76 TeV.

Estimation of Spherocity (S_0)

- Input Variables: $\langle dN_{ch}/d\eta \rangle$, $\langle N_{ch}^{TS} \rangle$ and $\langle p_T \rangle$
  Output variable: S_0
- Machine Learning model: Boosted Decision Tree (BDT)
  Boosting method: Gradient Boosting (GBDT)

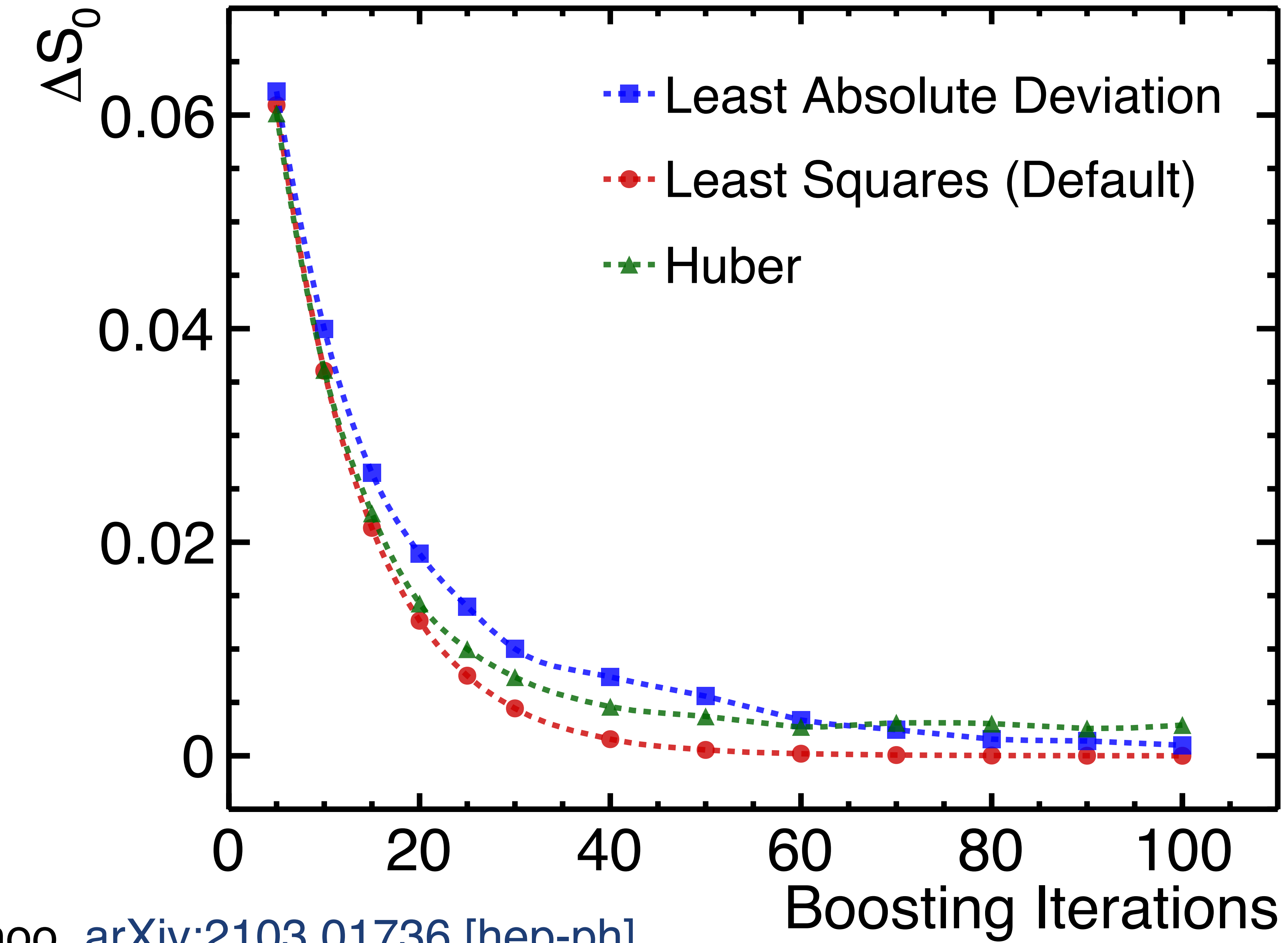


$$\rho = \frac{\text{cov}(x, y)}{\sigma_x \sigma_y}$$

Parameters in the GDBT-ML Model

- Loss Function: Least Square Loss
- Learning rate is kept small = 0.1
- No. of trees = 100
- Maximum Depth: 40
- Training Size: 60,000 events (min. bias)

$$\Delta S_0 = \frac{1}{N_{\text{events}}} \sum_{n=1}^{N_{\text{events}}} | S_{0_n}^{true} - S_{0_n}^{pred.} |$$



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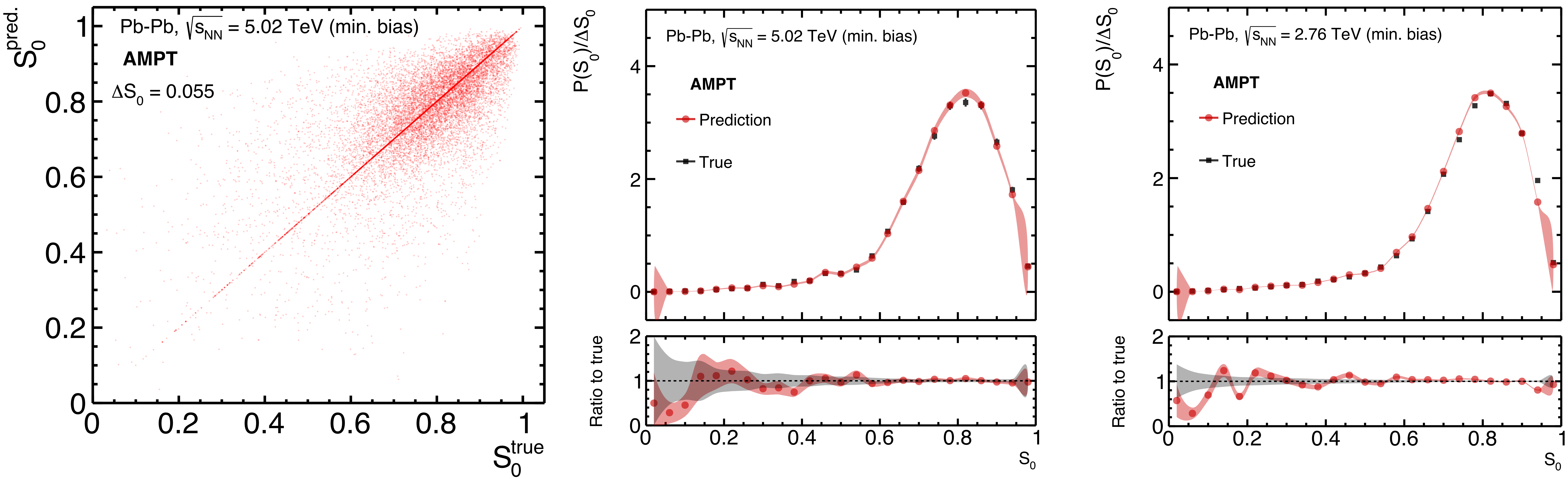
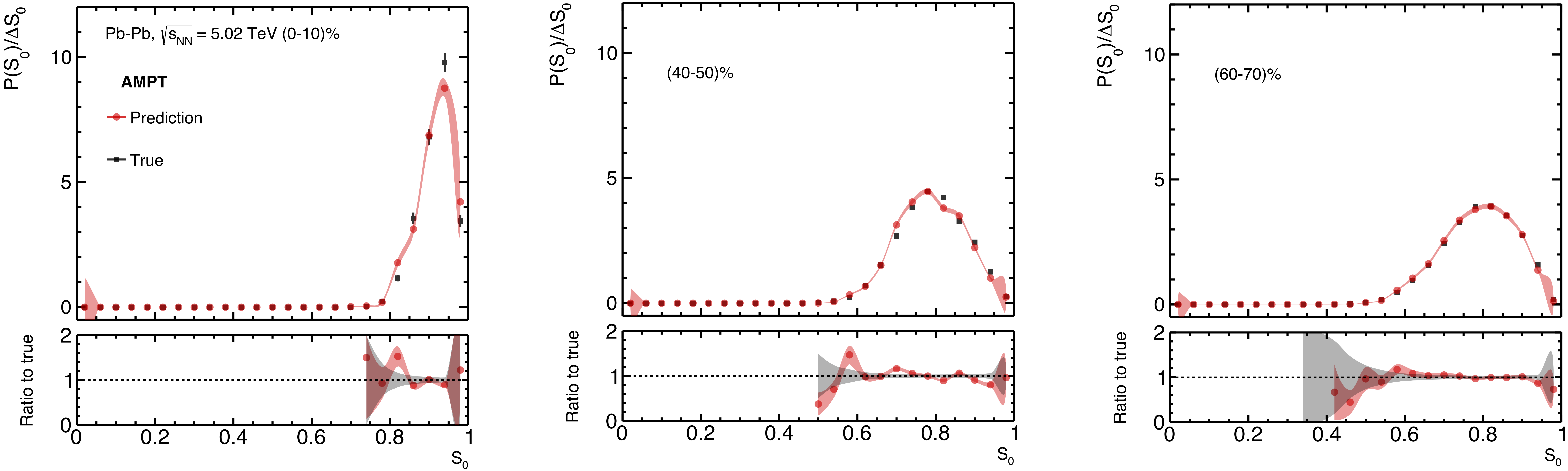


- Most of the points populate the straight line inclined at an angle 45 degrees with the x-axis
- The ML-model is trained with 5.02 TeV minimum bias simulated data.
- The predictions for spherocity distributions are in good agreement with the simulated data

N. Mallick, S. Tripathy, A. N. Mishra, S. Deb, and R. Sahoo, arXiv:2103.01736 [hep-ph]

Results



- The ML-model is also quite successful in predicting the centrality wise spherocity distributions
- Training is done using minimum bias simulated data

N. Mallick, S. Tripathy, A. N. Mishra, S. Deb, and R. Sahoo, arXiv:2103.01736 [hep-ph]

Summary and outlook

- We report the first implementation of transverse spherocity analysis for heavy-ion collisions at the Large Hadron Collider energies using A Multi-Phase Transport Model (AMPT).

- The results show that transverse spherocity successfully differentiates the heavy-ion collisions event topology based on their geometrical shape *i.e.* high-S_0 and low-S_0.

- The indication of collectivity in heavy-ion collisions can be clearly seen while comparing the transverse momentum spectra from high-S_0 and low-S_0 events.

- The elliptic flow as a function of transverse spherocity shows that the high-S_0 events have nearly zero elliptic flow and low-S_0 events have major contribution towards the elliptic flow.

- We propose a ML-based regression method for the estimation of transverse spherocity in heavy-ion collisions at the LHC.

- ML-model trained with minimum bias data at one energy successfully estimates centrality wise distributions and minimum bias distribution at lower energy.