Charge correlation using balance function of identified particles in heavy-ion collisions at LHC energy

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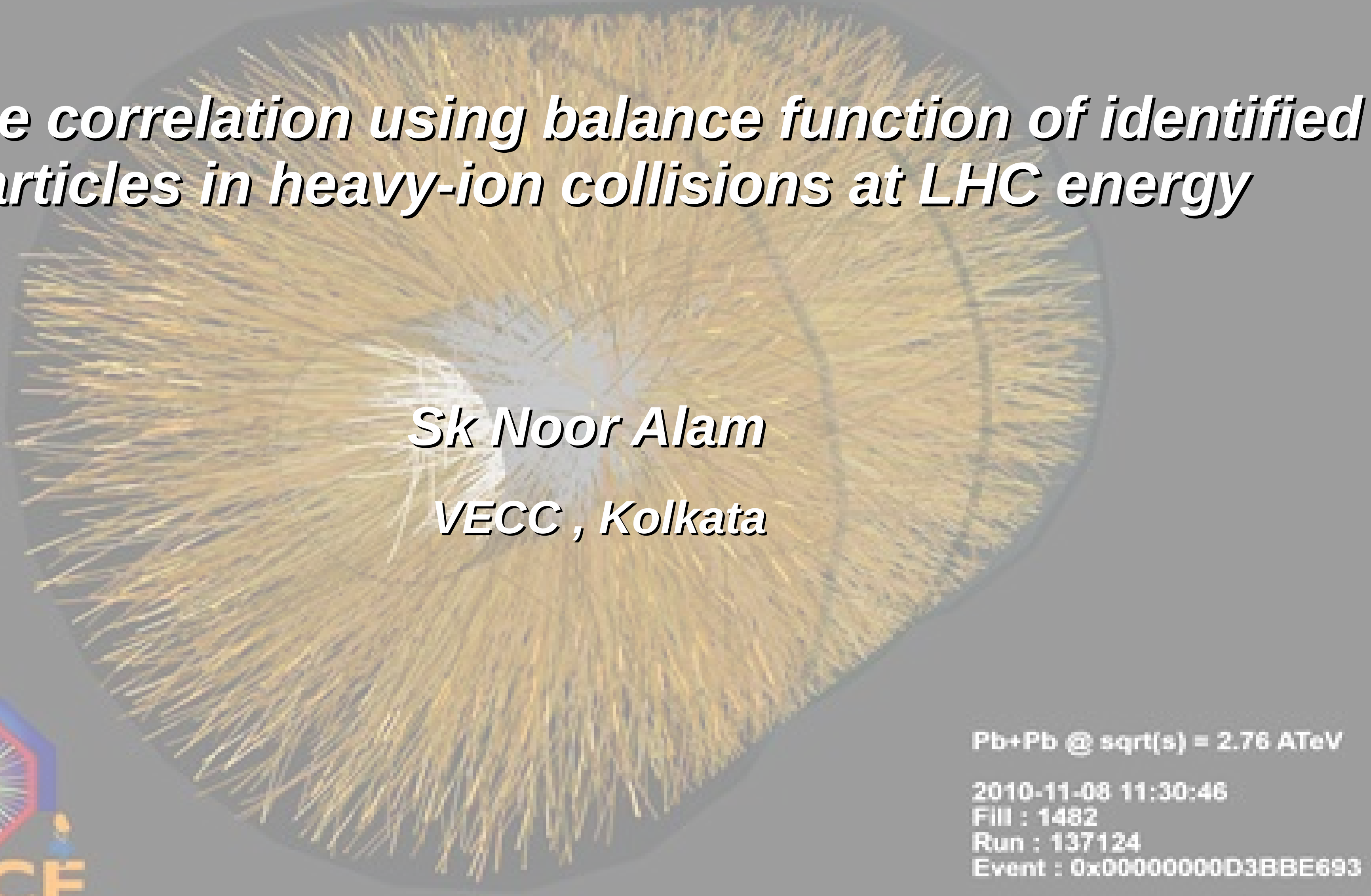
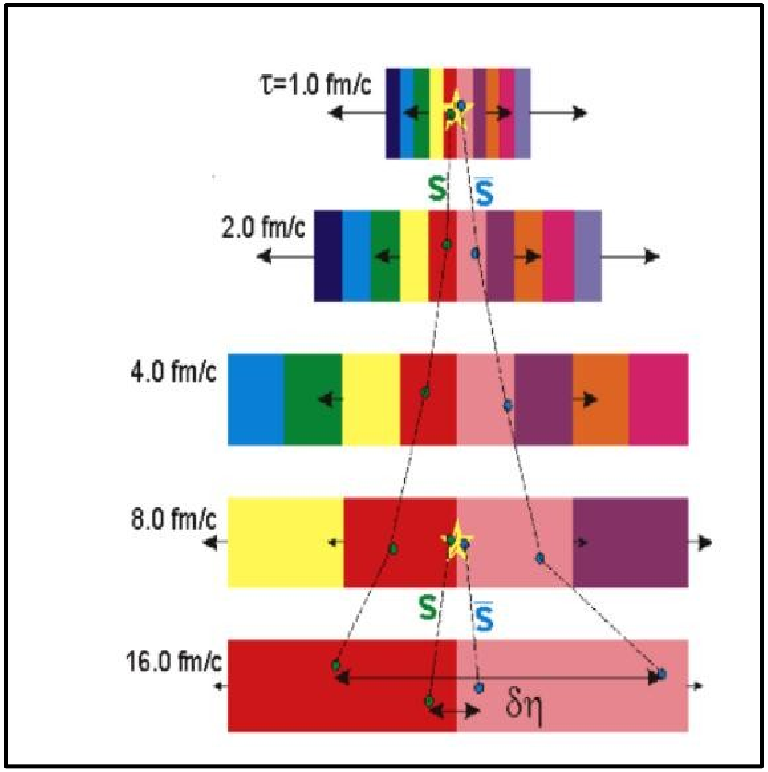


Balance function

- The correlations between the emitted particles can be used as a probe to gain insight into the charge creation mechanisms.
- Correlations between charges and their associated anti-charges are evaluated with the use of balance functions (BF) where charges and anti-charges are produced at same space-time point.
- BF is used to address fundamental questions concerning hadronization in heavy-ion collisions. Balance function has a sense of probing production time of quarks.
- Balancing charge pairs are strongly correlated in rapidity/pseudo-rapidity and azimuthal angle due to collective flow of produced system. So BF is very sensitive to the charge separation between positively and negatively charged particles.
- By studying balance functions of several hadronic species, one can gain insight into the chemical evolution of the Quark Gluon Plasma and radial flow.



- Pairs produced latter ---- > pairs are more correlated in rapidity-azimuthal plane. It makes balance functions distribution narrower.
- Pairs produced early ---- > Separate further in rapidity-azimuthal plane. It makes balance functions wider.
- Rescattering and annihilation --- > affect balance functions distribution.

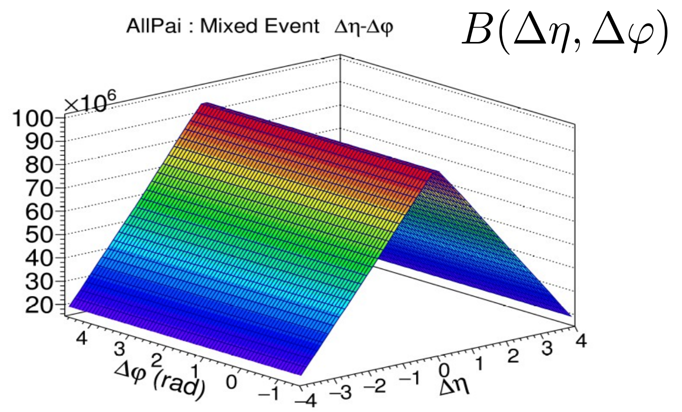
$$\frac{\partial f(\tau,\eta)}{\partial \tau} = -\frac{\beta}{\tau}\frac{\partial^2 f(\tau,\eta)}{\partial \eta^2}$$

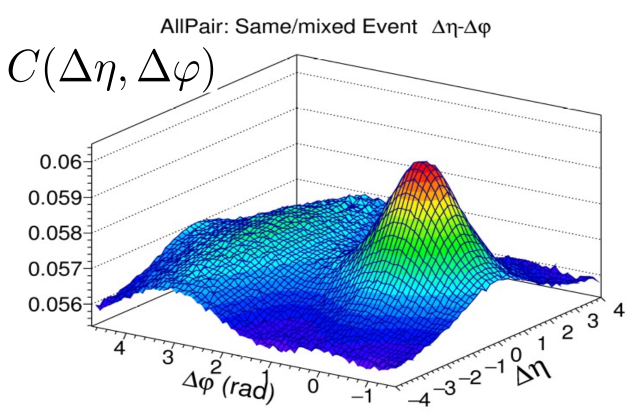
Variance = $2\beta \log(\frac{\tau}{\tau_0})$

- In the limit of zero mean free path, the diffusion constant tends to zero.

Phys. Rev. Lett. 85, (2000) 2689.

Definition of two particles correlation and balance function





$$C(\Delta\eta, \Delta\varphi) = \frac{\frac{1}{N^{signal}_{pairs}} S(\Delta\eta, \Delta\varphi)}{\frac{1}{N^{mixed}_{pairs}} B(\Delta\eta, \Delta\varphi)}$$

- The balance function is defined as a conditional distribution

$$B(p_2|p_1) = \frac{1}{2}\left\{\rho(b, p_2|a, p_1) - \rho(b, p_2|b, p_1) + \rho(a, p_2|b, p_1) - \rho(a, p_2|a, p_1)\right\}$$

$$\rho(b, p_2|a, p_1) = \frac{N(b, p_2|a, p_1)}{N(a, p_1)} = C_{a,b}(p_2, p_1)$$

- It is the distribution of pair of two particles called trigger particle (a) & associated particle (b)
- p_2 refers to relative rapidity/pseudo-rapidity ($\eta_a - \eta_b$) or azimuthal angle ($\varphi_a - \varphi_b$).

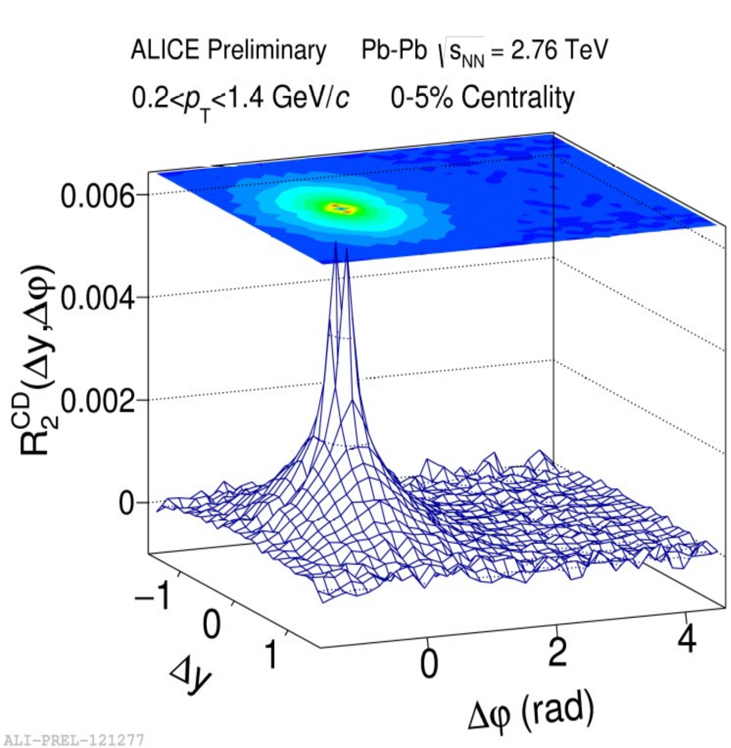
$$B(\Delta\eta, \Delta\varphi) = \frac{1}{2}\left[C_{+,-}(\Delta\eta, \Delta\varphi) - C_{-,-}(\Delta\eta, \Delta\varphi) + C_{-,+}(\Delta\eta, \Delta\varphi) - C_{+,+}(\Delta\eta, \Delta\varphi)\right]$$

$$\sum_{p_2} B(p_2|p_1) = 1$$

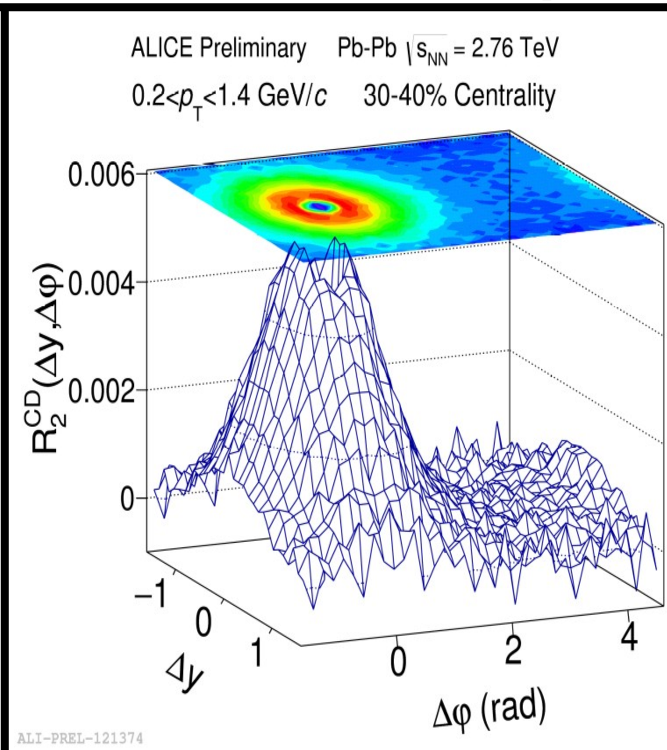
- If every charge has an opposite balancing charge, balance function would integrate to 1.

DOI: https://doi.org/10.22323/1.314.0151

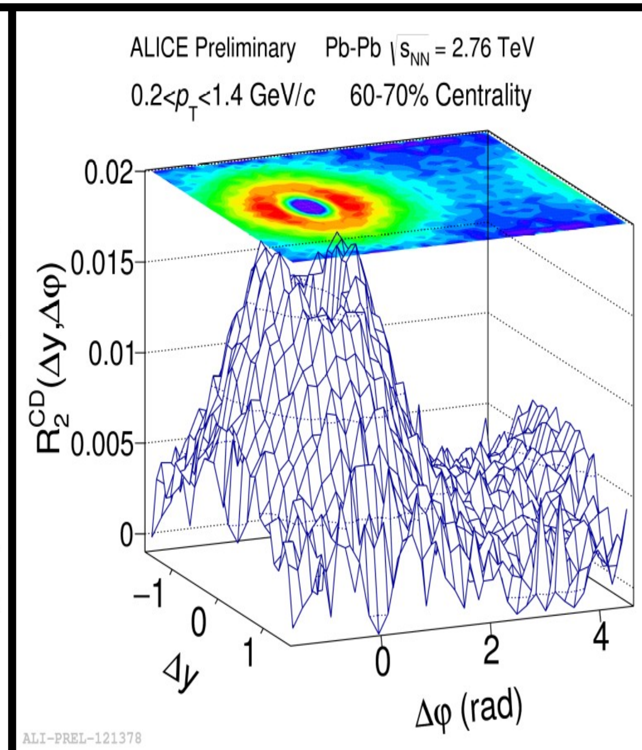
Balance function of pion



2D Plot : 0-5 %



2D Plot : 30-40 %



2D Plot : 60-70 %

- The bulk of the pion correlation is at the near side of $\Delta\varphi$ region i.e $-\pi/2 < \Delta\varphi < \pi/2$.
- Balance function gets narrower in the near side region when centrality of event goes from peripheral to most central
- There is a depletion around point at $(\Delta y, \Delta\varphi) = (0, 0)$ for all centrality classes. There is a centrality dependence of this depletion. The depletion is more prominent at the most peripheral collisions.
- It is observed that there is larger magnitude of balance function at $\pi/2 < \Delta\varphi < 3\pi/2$ for peripheral collisions compared to central collisions.

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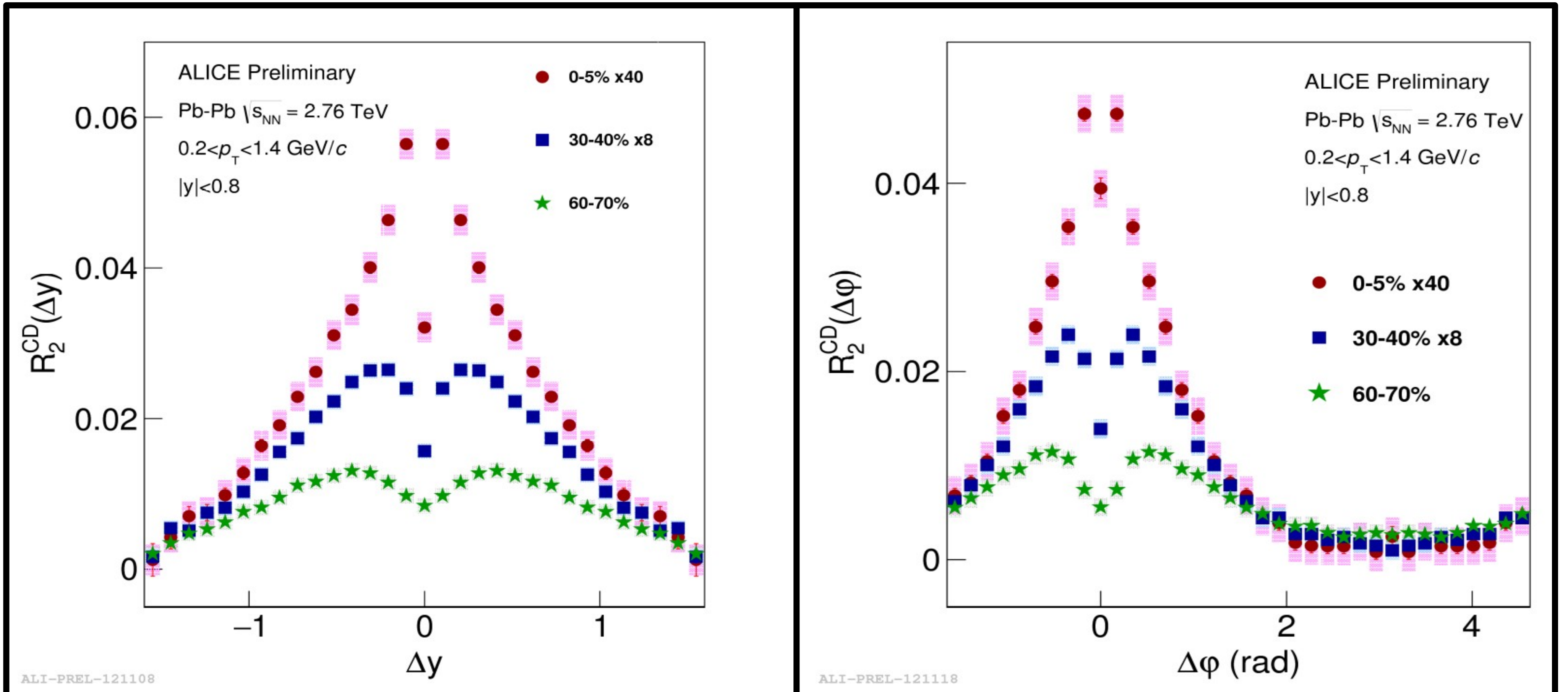

Pion balance function in Δy **Pion balance function in Δφ**

- Shape of distributions in both Δy and Δφ change with centrality.
- The correlation functions have a dip near Δy=0 and Δφ=0.
- The broadening of the balance functions for less central collisions is a result of a larger separation of balancing charges ==> consistent with the delayed hadronization picture but also with increasing radial flow for more central events.

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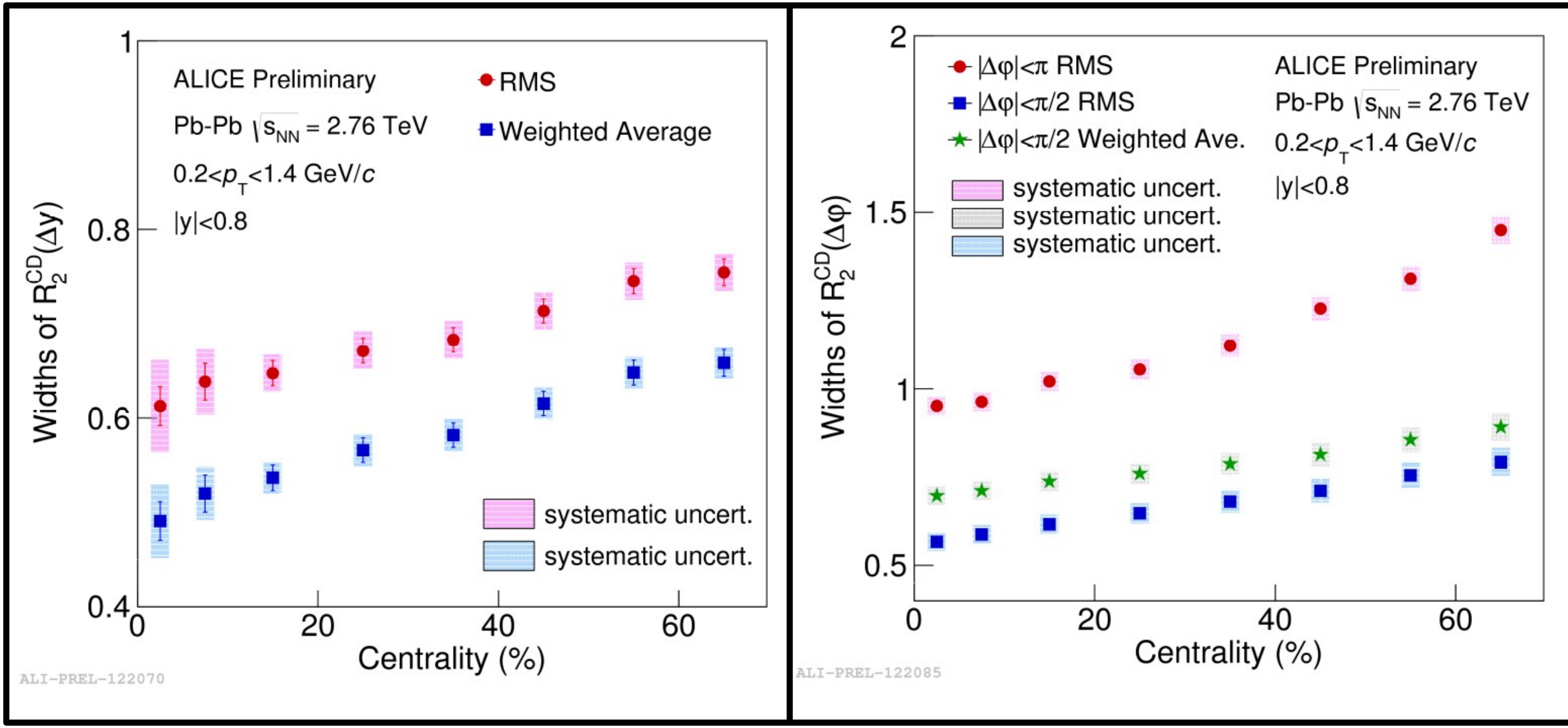
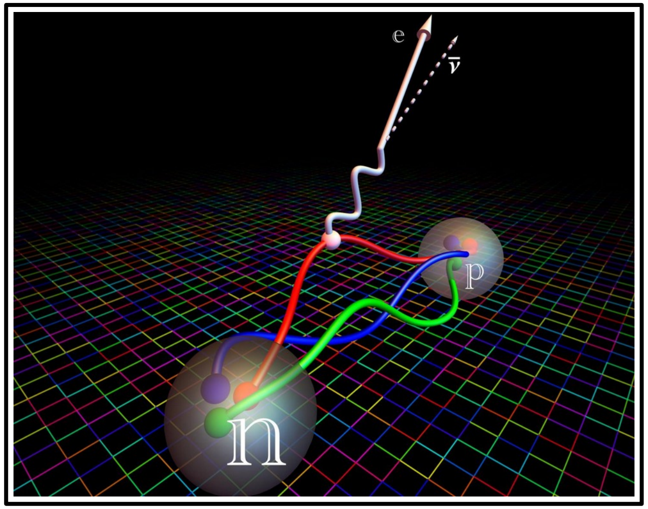
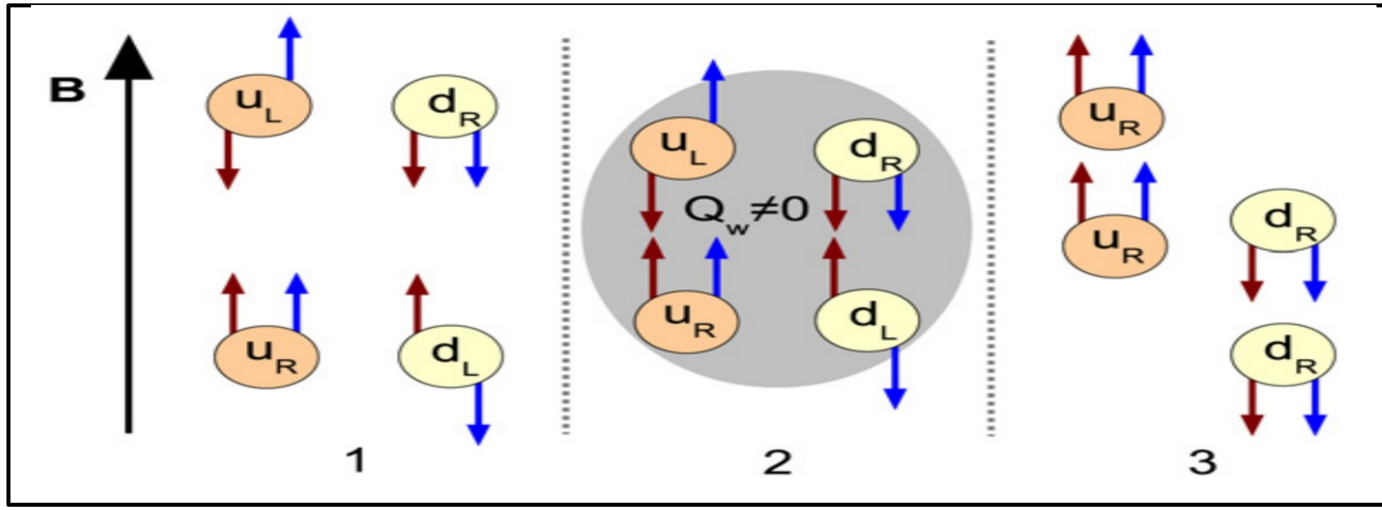


- Centrality dependence of the width of the pion balance function distributions in Pb+Pb collisions at $\sqrt{S_{NN}}$ = 2.76 TeV for both Δy and Δφ.
- Two different ranges of Δφ (|Δφ| < π/2, |Δφ| < π) are used for width in Δφ.
- Width of the balance function distributions changes as function of centrality. It is decreasing with increasing centrality. It is also observed that width of balance function in Δφ space is larger when |Δφ| < π is used.
- The broadening of the balance functions for less central collisions is a result of a larger separation between the balancing charges and higher kinetic freeze-out temperature. It is consistent with picture of delayed hadronisation in more central collisions.

Parity violation in strong interaction and Chiral Magnetic Effect (CME)



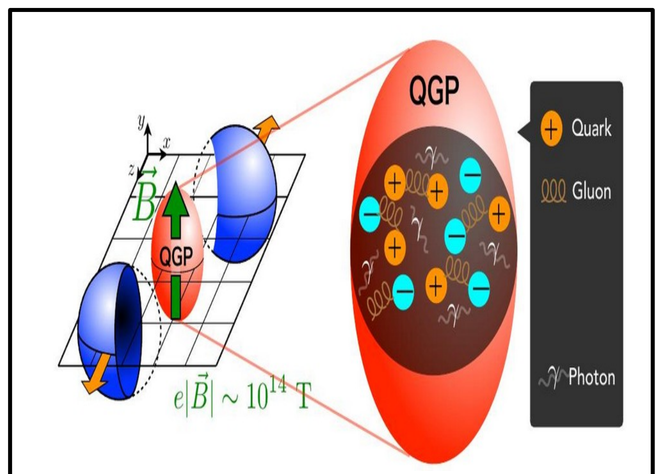
- Parity is violated in weak interaction.
- Wu experiment : asymmetry in the electron distribution between θ and 180 – θ (Phys. Rev.105, 1413 (1957))
- Partiy conserve in strong interaction ?



- Metastable domains of gluonic field configuration are generated carrying an imbalance between left and right-handed quark.

$$Q_W = \frac{g^2}{32\pi^2} \int d^4x F^{\alpha}_{\mu\nu} \tilde{F}^{\mu\nu}_{\alpha}$$

$$\frac{d(N_R - N_L)}{dt} = \frac{-g^2 N_f}{16\pi^2} \int d^3x F^{\alpha}_{\mu\nu} \tilde{F}^{\mu\nu}_{\alpha}$$



- Non zero Q_W can separate charge in the presence of the magnetic field.
- Flipping the momentum direction of the left handed quarks to opposite direction.
- Spin direction is same.

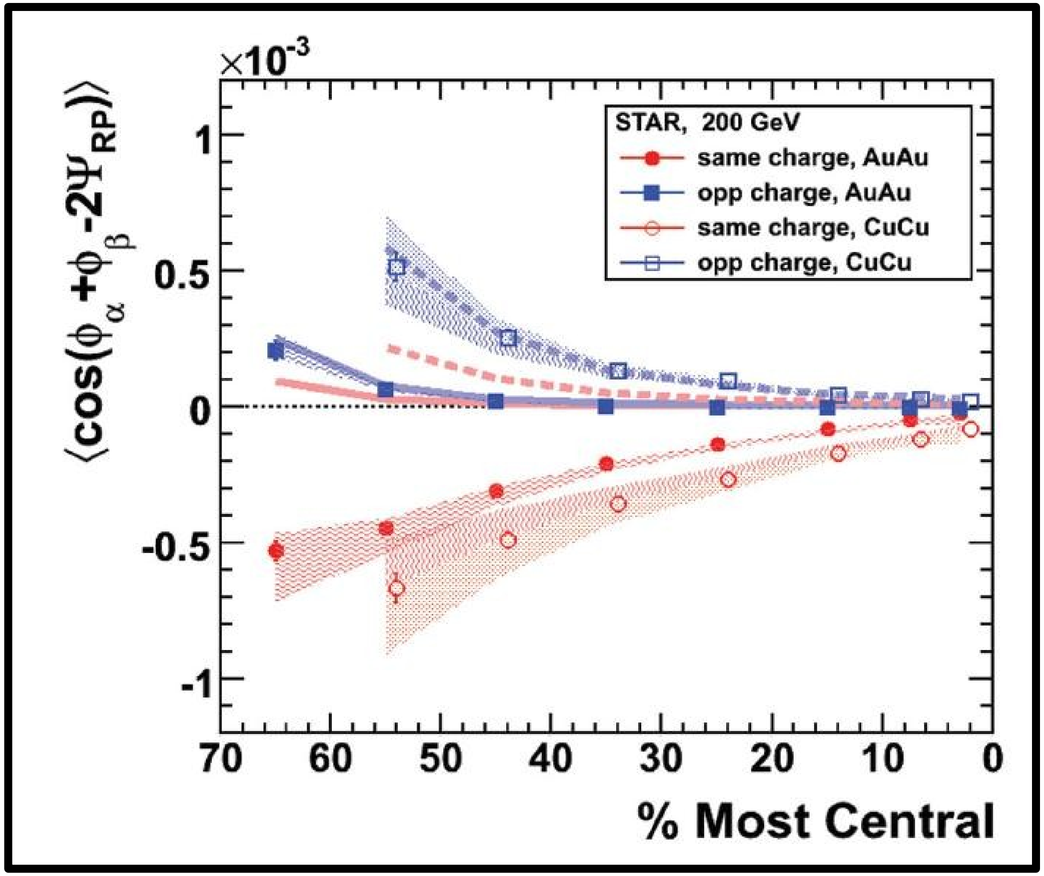
PLB633 (2006) 260–264 ; Nulcear Physics A 803 , (2008) 227-253 ; PRD 78, (2008) 074033

- The azimuthal distribution of produced particles with parity odd observables may have the following form

$$\frac{dN}{d\phi} \sim 1 + \sum_{n=1}^{\infty} (2v_n \cos[n(\phi - \Psi_R)] + 2a_n \sin[n(\phi - \Psi_R)])$$

- Sine term represents the charge separation and the parameter a_n describes the parity violation effect.
- A charge dependent three particle correlator is used to measure experimentally chiral magnetic effects. It is defined as

$$\gamma =< \cos(\phi_1 + \phi_2 - 2\psi_{RP}) >$$



- Three particle correlator in Au+Au and in Cu+Cu collisions at $\sqrt{s_{NN}}$ = 200 GeV.
- Same charge (++, --) correlation has negative value and opposite charge correlation (+-) has positive value.
- The signal inCu+Cu collisions is larger than the signal in Au+Au collisions at the same centrality.

Simulating chiral magnetic effect using balance function and elliptic flow observables

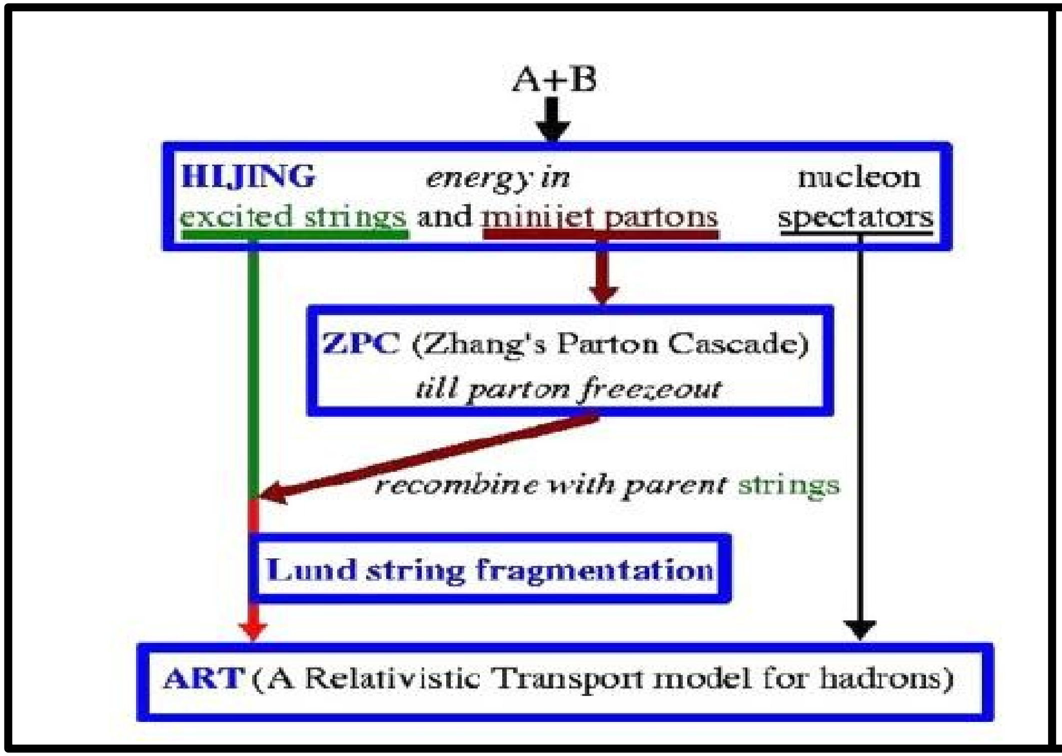
Procedure of generating charge separation in AMPT:

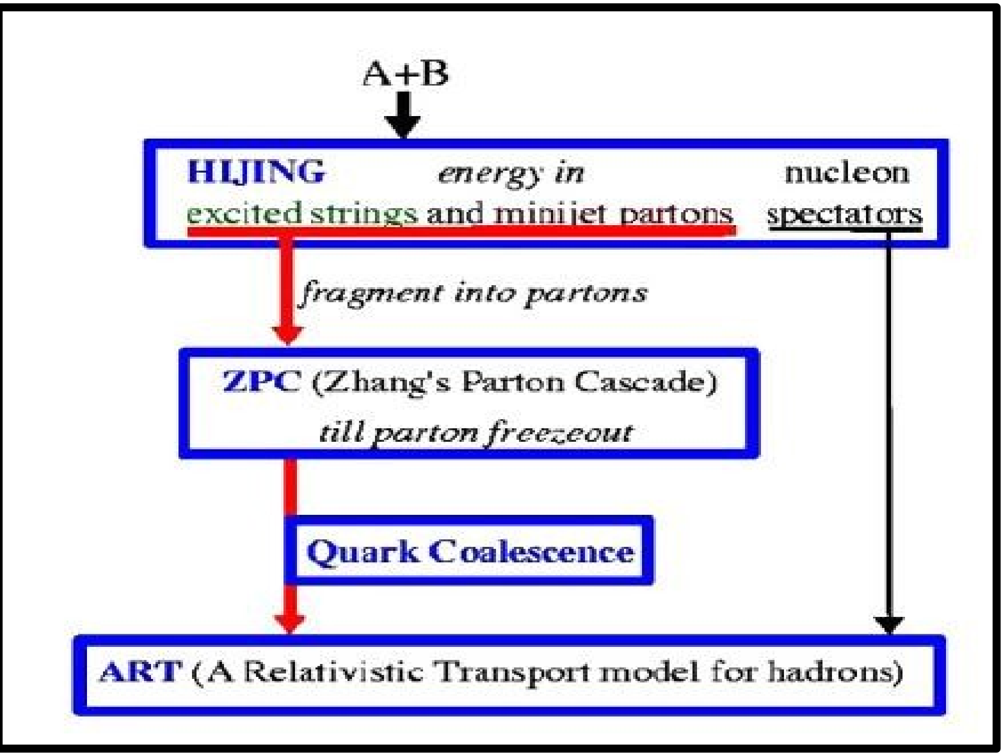
➔ A Multi Phase Transport (AMPT) model is used for simulation work.

➔ The AMPT model consists of different components.

- HIJING to implement the initial conditions
- Zhang's parton cascade (ZPC) for modeling the partonic scatterings.
- The Lund string fragmentation model or a quark coalescence model for hadronization.
- A relativistic trans-port (ART) model for hadronic rescattering.

➔ AMPT model has two version. In this work, string melting version is used.





- We have implemented charge separation at partonic level in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV using AMPT model via creating electric dipole moment.

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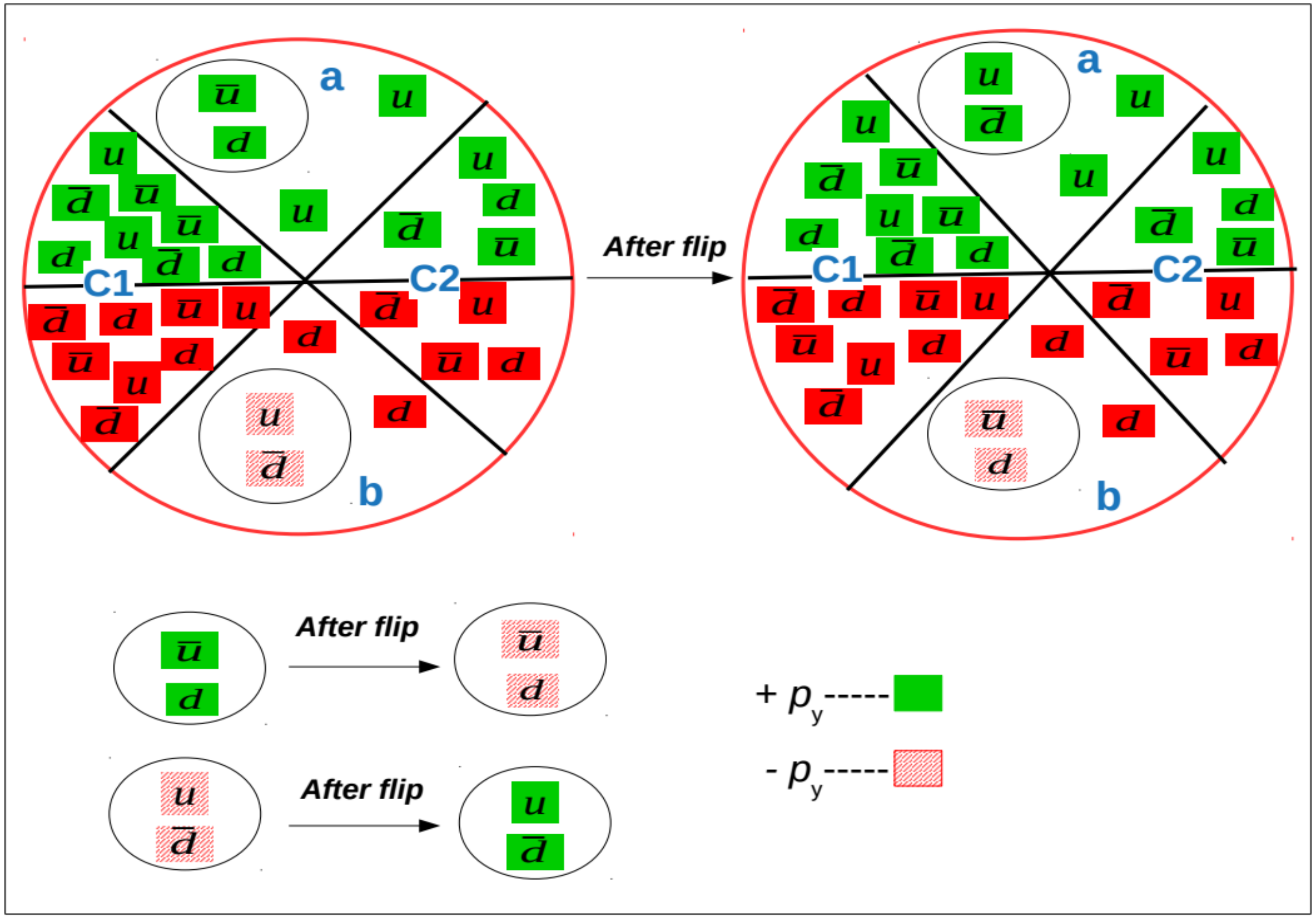
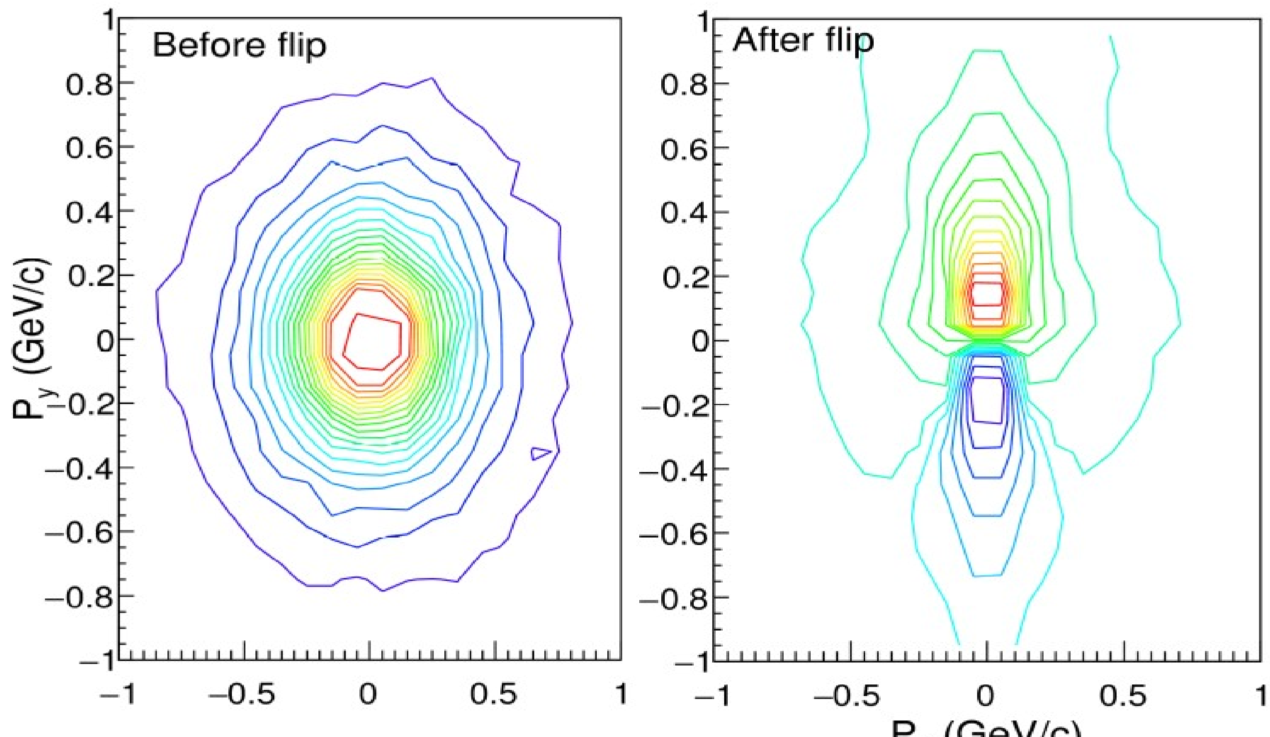


- u, ū, d and đ which have azimuthal angle between | 1.0472 c | to | 2.0944 c | .
- Before flipping, each of the regions marked with a and b lying perpendicular to the reaction plane is with net-charges of 1/3 e. Now after flipping the corresponding regions are with charges of 7/3 e and − 5/3 e respectively.
- The fraction of the total number of quarks that have been flipped is taken as an input parameter.
- In this work, f = 0, 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6 have been used.

Dipole moment



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- Net electric charge distributions on the transverse plane before and after flipping with a 20% flipping fraction.

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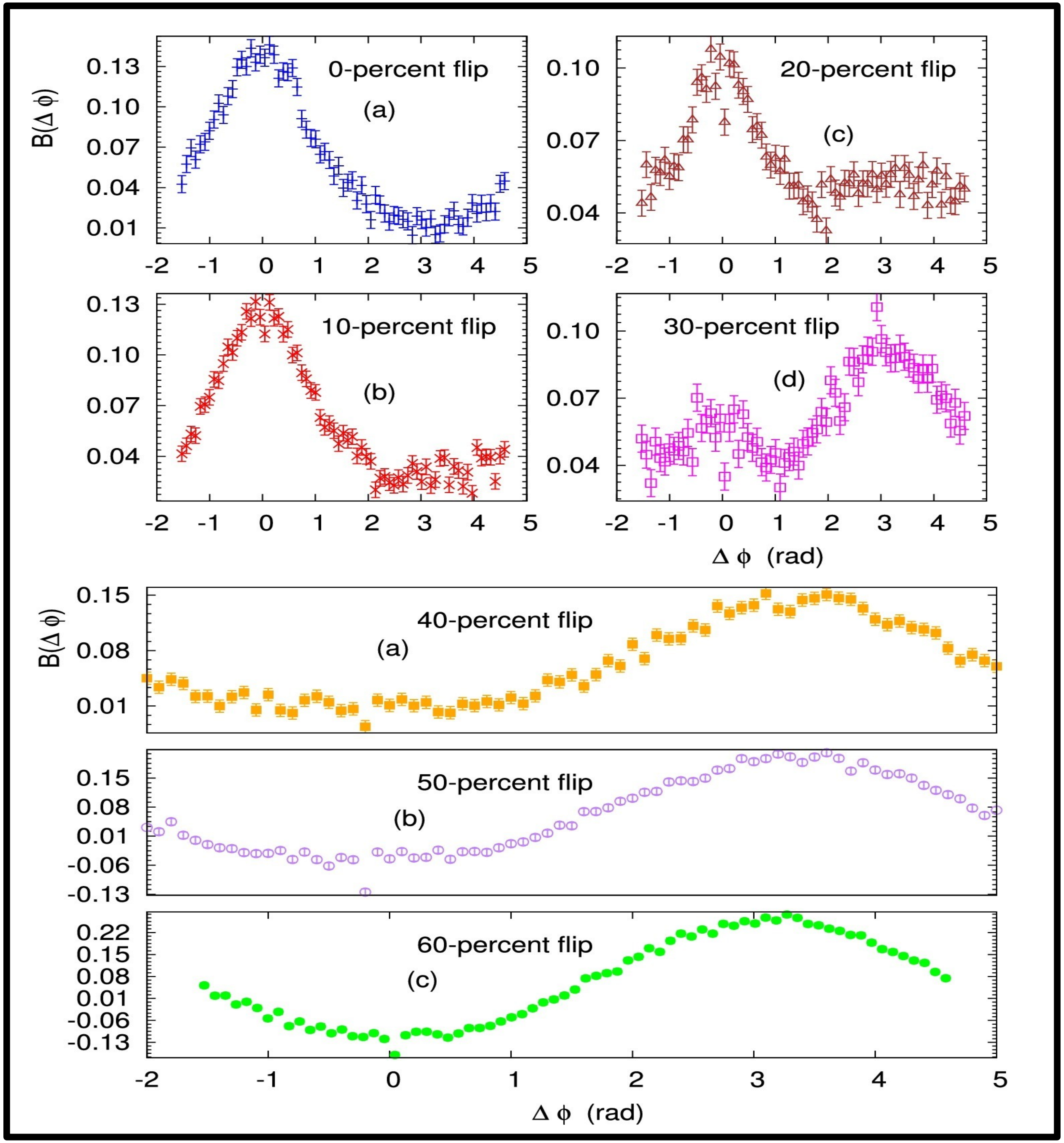


- Charged particle balance function at different flipping fractions.
- Shape of the balance function evolves with the flipping fraction.
- More balancing pairs are emitted in the direction perpendicular to the reaction plane for large flipping fraction.
- The peak shifts towards π^c when flipping for charge separation is 30% or greater.
- For parity violation, balance function should have a peak at $\Delta\varphi \sim \pi$.

- We have calculated parity violation terms in the form of balance function moments.

$$\gamma_P = \cos(\varphi_i + \varphi_j) = \cos(2\varphi_i)\cos(\Delta\varphi) - \sin(2\varphi_i)\sin(\Delta\varphi)$$

$\Delta\varphi = \varphi_j - \varphi_i$

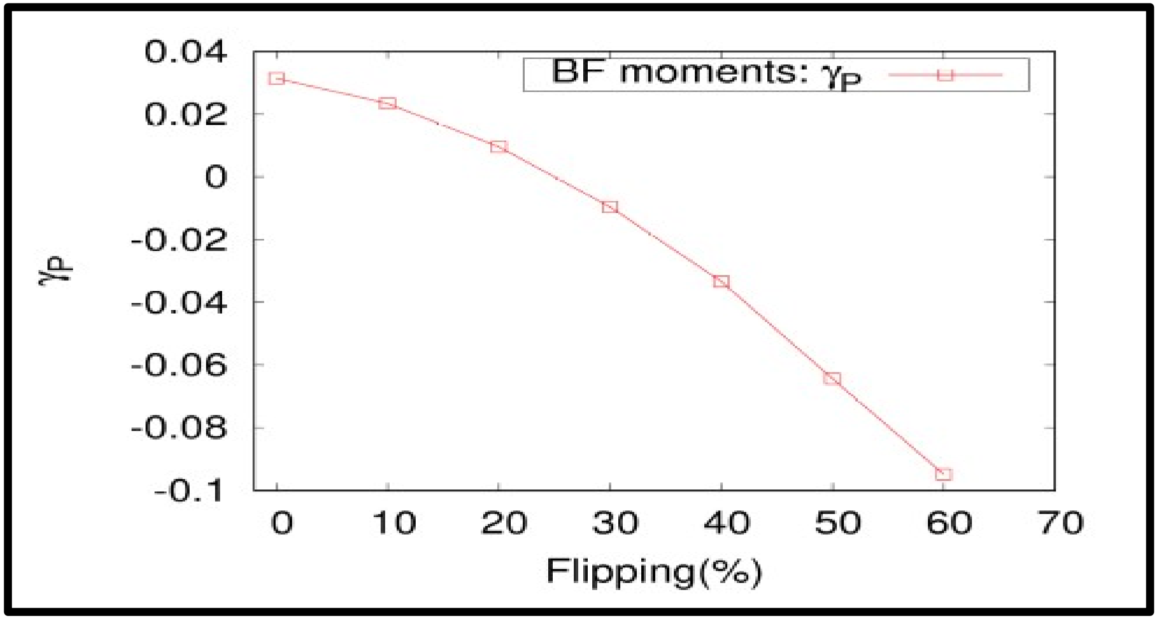
- γ_P can be expressed when weighted with azimuthal distribution of particles as

$$\gamma_P = \langle C_b \cos(2\phi)\rangle - \langle S_b \sin(2\phi)\rangle$$

$$C_b = \frac{1}{Z_b}\int d\Delta\phi B(\Delta\phi)\cos(\Delta\phi),$$

$$S_b = \frac{1}{Z_b}\int d\Delta\phi B(\Delta\phi)\sin(\Delta\phi),$$

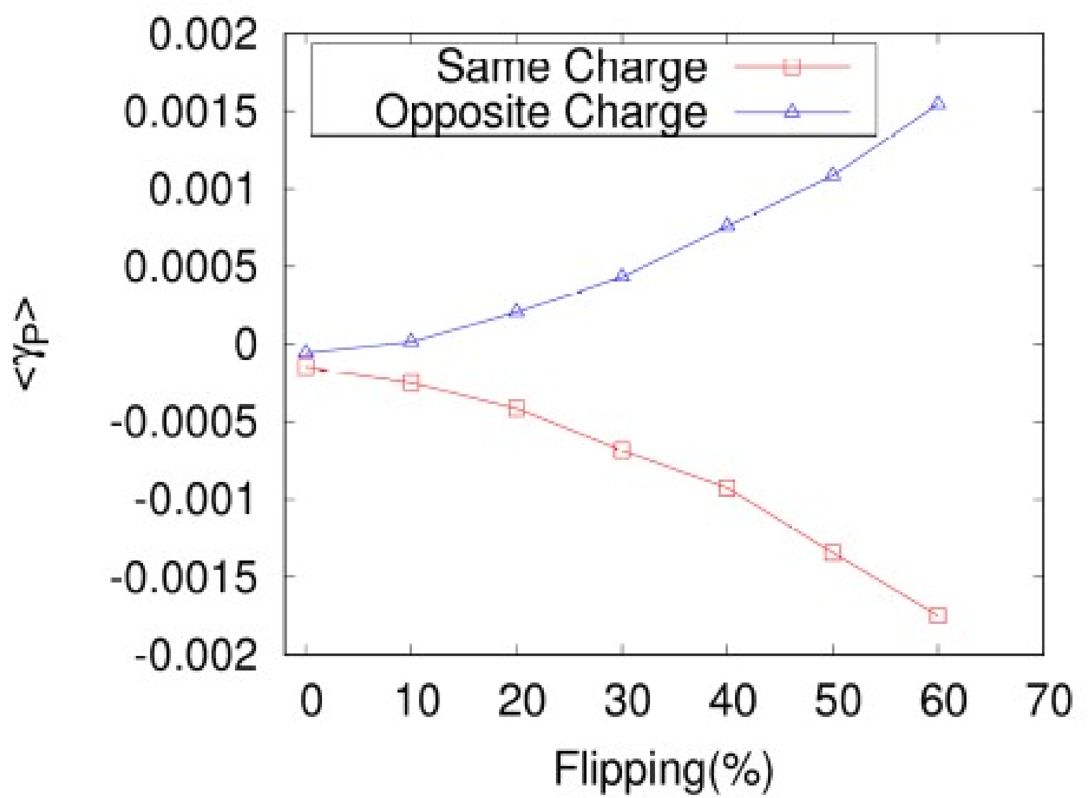
$$Z_b = \int d\Delta\phi B(\Delta\phi)$$



- The parity odd observable in form of BF moments becomes negative when flipping fraction is ~ 30% or higher.
- Presence of more balancing pairs in out-of-plane relative to that of in-plane direction.

- γ_P averaged with N_{part} (number of participants) distribution defined as

$$\langle\gamma_P(N_{part})\rangle = \frac{\int d(N_{part})\gamma_P(N_{part})N_{part}}{\int d(N_{part})N_{part}}$$



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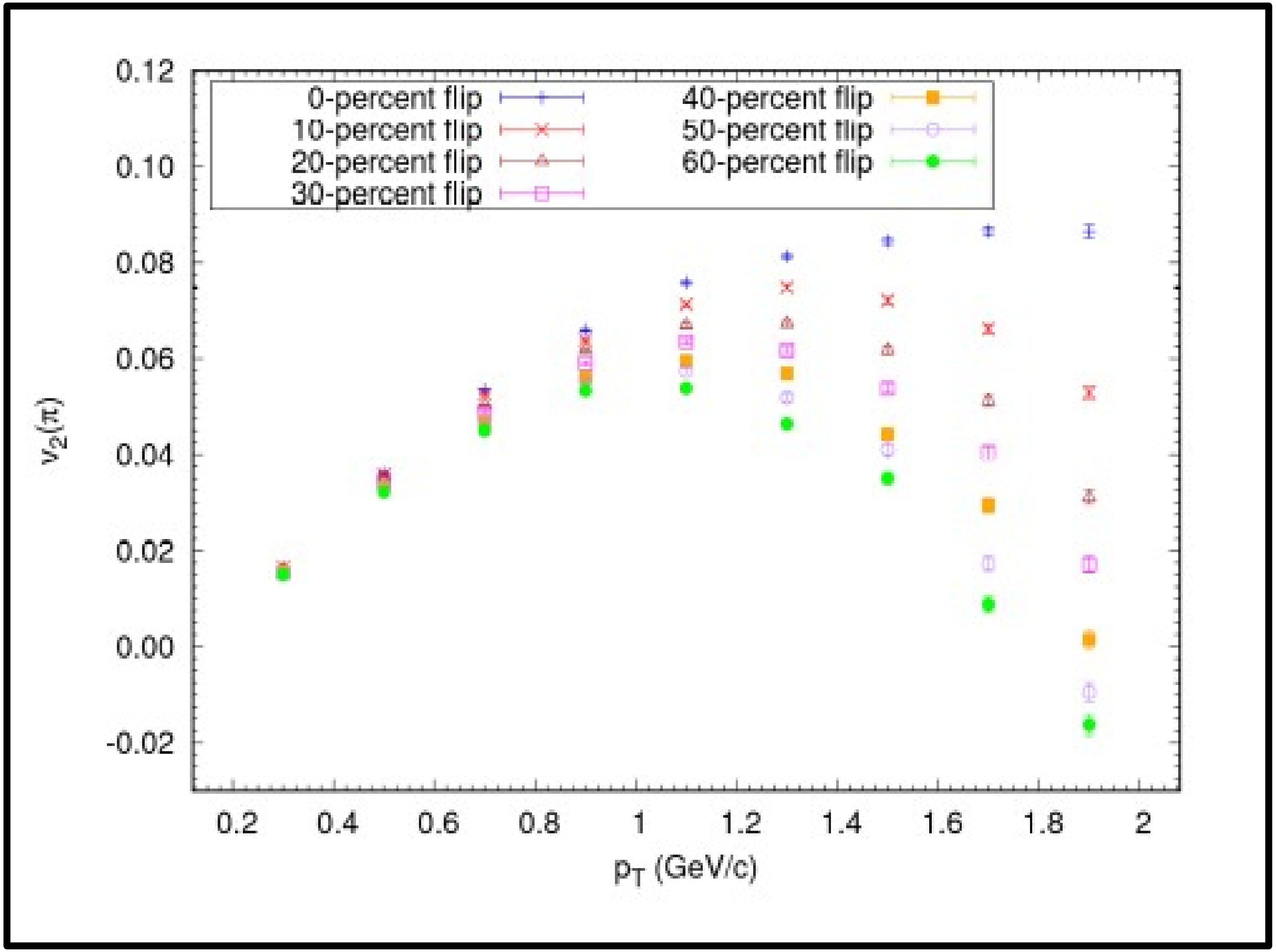
- $<\gamma_P>$ with same charges and opposite charges have negative and positive values respectively.
- Gamma correlator has larger magnitudes with higher flipping fraction for both same and opposite charge correlation.

Elliptic flow of pions with different flipping fraction



- Elliptic flow (v_2) of pions as a function of p_T for different flipping fractions.
- It is observed that the elliptic flow of pion increases upto $p_T \sim 1.1$ GeV/c and then decreases at higher p_T.
- v_2 shows a decreasing trend for higher flipping fractions.

Summary

1. Measurement of the balance functions for Pb+Pb collisions at $\sqrt{s}_{NN}$ = 2.76 TeV with ALICE experiment in Δy and Δφ have been calculated.

2. According to theory , width of the balance function should be significantly reduced by late hadronization.

3. We observe a narrowing of the balance function for more central collisions for charged pion pair.

4. A depletion in the correlation pattern is observed around (Δy, Δφ) = (0, 0). This depletion has significant centrality dependence.

5. it is caused by charge dependent short range correlations i.e. coulomb attraction and repulsion , or quantum statistics correlations instead of detector effects.

6. Momenta of initial partons of AMPT generator have been flipped to generate an out-of-plane charge separation in Au + Au collisions at $\sqrt{s}_{NN}$= 200 GeV. This charge separation represents the effect of parity-odd observable in heavy ion collisions.

7. Varying fraction of flipping, both the BF and v2show significant sensitivity with the peak of the BF shifting from Δφ = 0 towards Δφ = π with increasing flipping fraction and v_2 of pions decreases at higher p_T .

8. $<\gamma_P>$ for same charge correlation and opposite charge correlation have opposite values and varies with charge separation.

Future Plan

1. I would like to probe chiral magnetic effects in terms of balance function basis using ALICE Pb+Pb 2.76 TeV and 5.02 TeV data .

2. I have a plan to start work on γ-hadron correlation. Here γ will be taken as a trigger particles with high p_T . γ-hadron correlation can trace flow of energy lost from hard partons.

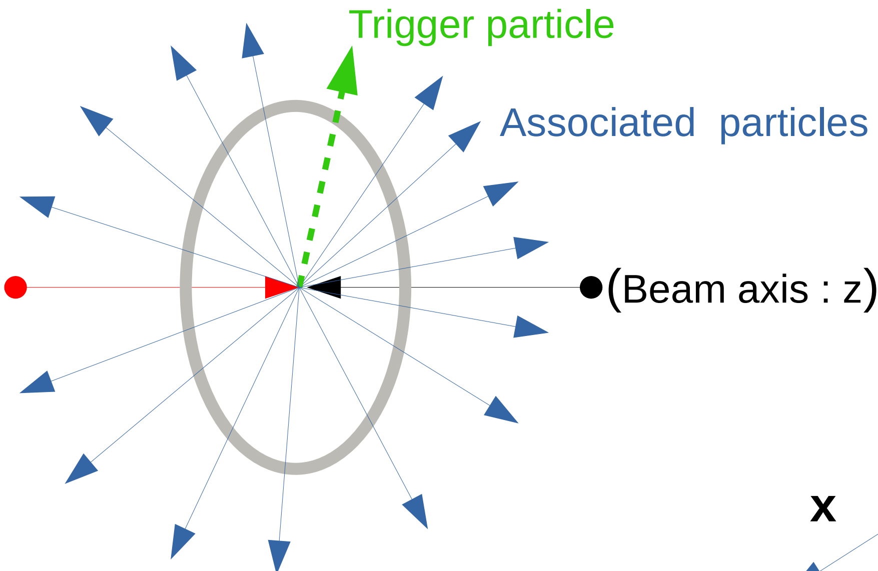
3. ***https://arxiv.org/pdf/1903.04622.pdf*** : Signed balance function

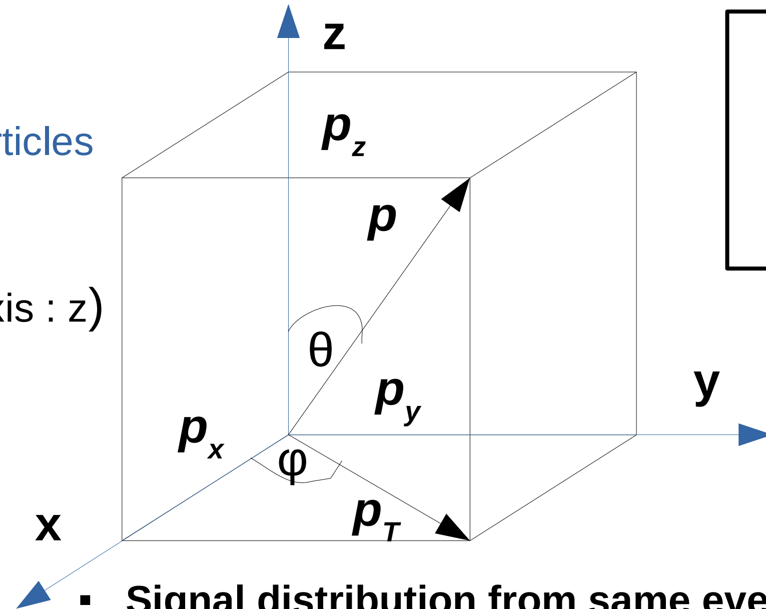
4. Want to do some data analysis and phenomenological works on momentum kick model to reveal ridge structure in small system .

Thank you

Backup slides

Definition of two particles correlation and balance function





$$\varphi = \arctan(\frac{p_y}{p_x})$$

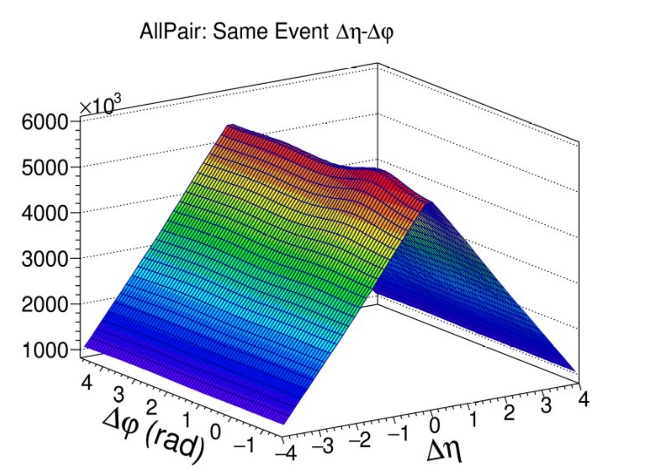
$$\eta = -ln(tan\frac{\theta}{2})$$

$$\Delta\eta = \eta_{trigg} - \eta_{asso}$$

$$\Delta\varphi = \varphi_{trigg} - \varphi_{asso}$$

- **Signal distribution from same event's particles pairs**

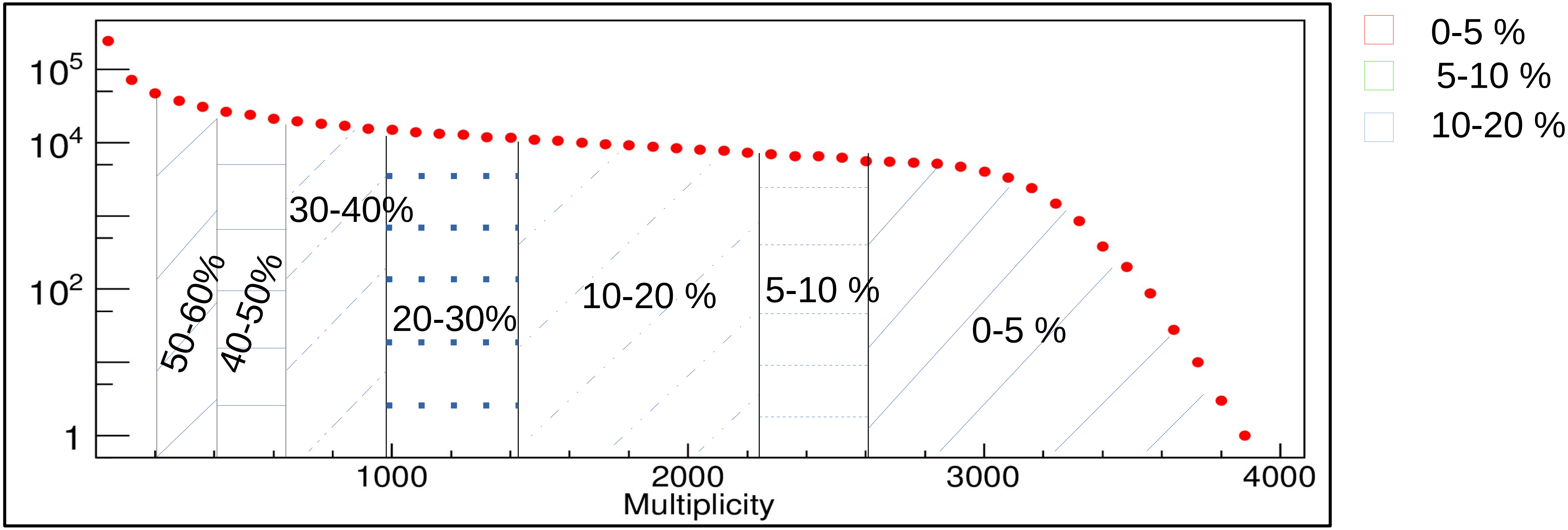
$$S(\Delta\eta, \Delta\varphi) = \frac{1}{N^{Signal}_{pairs}} \frac{d^2 N^{Signal}_{pairs}}{d\Delta\eta\Delta\varphi}$$



- Signal distribution needs correction in detector and tracking inefficiencies as well as in acceptance effects.
- The tracking efficiency is extracted from a Monte Carlo simulation of the ALICE detector based on GEANT3.
- The acceptance correction factors is extracted from mixed events. Mixed event method is described in next slide.

Definition of two particles correlation and balance function

Mixed Event technique:



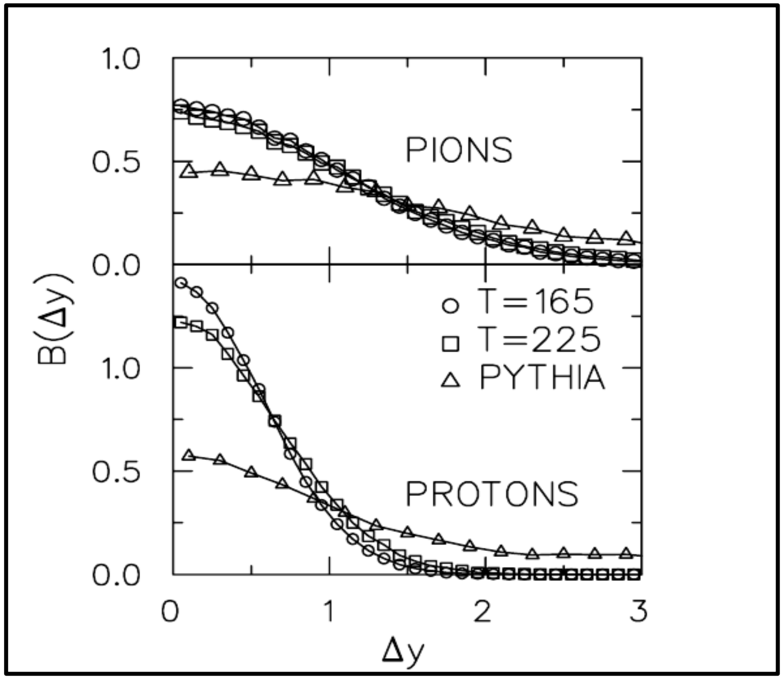
- Create pools i.e some places for storing events of same centrality bins and vertex-z bins.

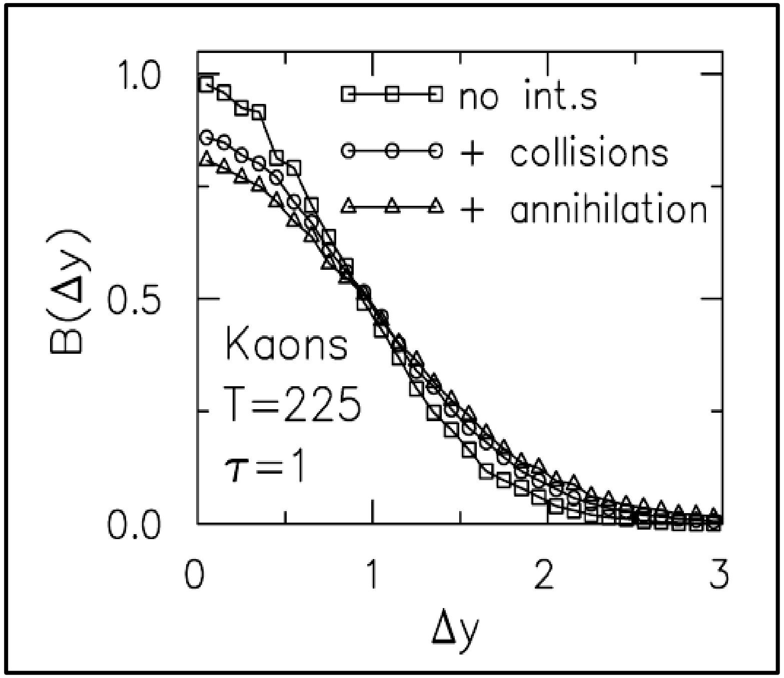
1 3 5 7 9 10 18 25 26	2 4 8 16 20 22 27 29 31	11 15 17 35 37 12 40 23 45	deque →	5 3 1 10 9 7 26 25 18	8 4 2 22 20 16 31 29 27	17 15 11 12 37 35 45 23 40

- The mixed events correlation are generated by taking all two-particles using non-same event combinations.

$$B(\Delta\eta, \Delta\varphi) = \frac{1}{N_{pairs}^{Mixed}} \frac{d^2 N_{pairs}^{Mixed}}{d\Delta\eta\Delta\varphi}$$

Previous results (Theory and Experimental results)



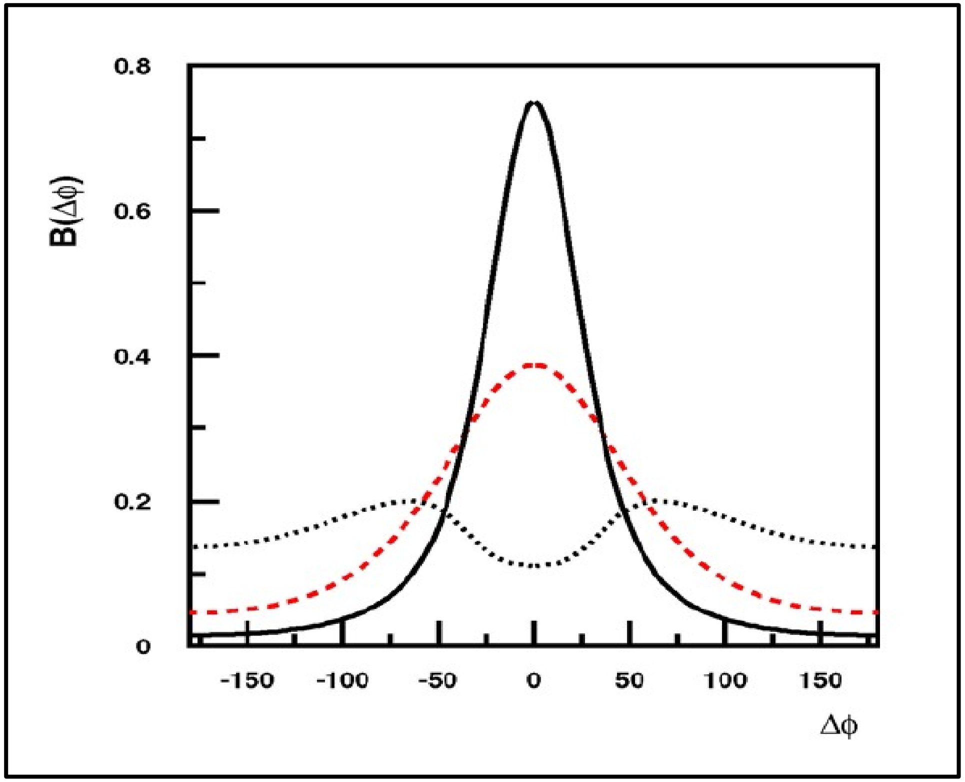


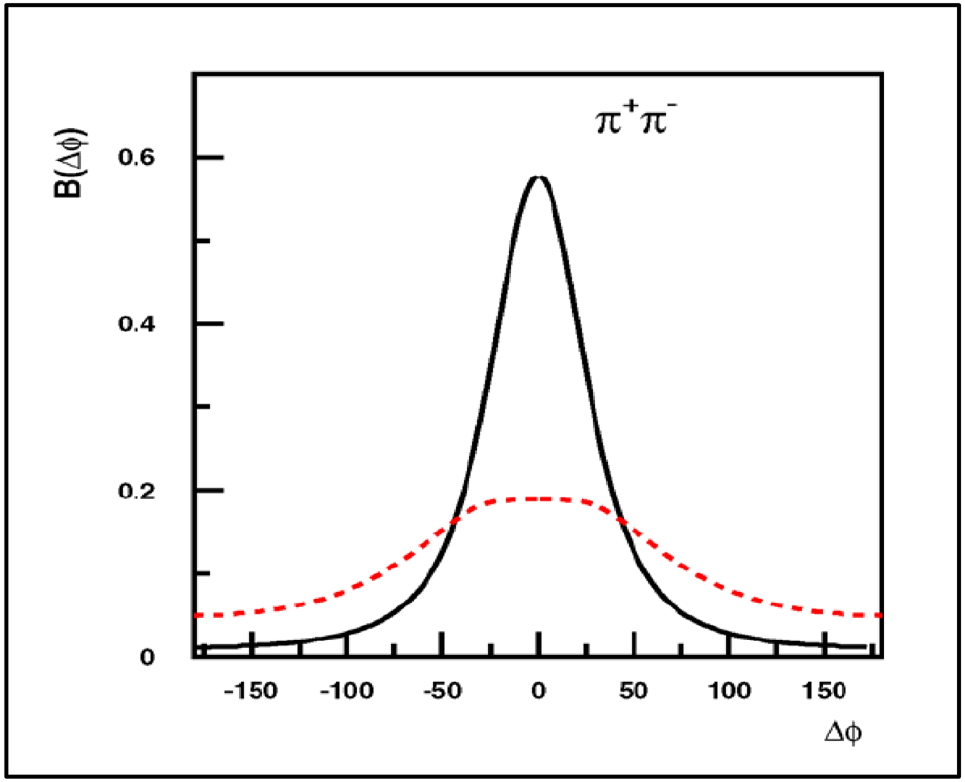
- Pions and Protons and their anti-charges are generated using a local thermal distribution i.e. Maxwell-Boltzmann distribution at same space time point.

$$\boxed{p(v) = 4\pi v^2 \left(\frac{m}{2\pi kT}\right)^{3/2} e^{-\frac{1}{2}\frac{mv^2}{kT}}}$$

- Temperature 165 and 225 MeV are used for producing particles.
- Width of BF distribution : $\boxed{\sqrt{\frac{2T}{m}}}$
- The balance functions of the more massive particles are sensitive to the temperature.
- Pythia BF is broader than thermally generated BF.
- Lower temperature ---> later times in the evolution of heavy-ion reaction.
- K_+K_- balance function with N_{coll} = 0 and N_{coll} = 10.
- Kaons are created at τ = 1 fm/c (T = 225 MeV) and cease to collide at τ_f = 15 fm/c (T=120 MeV).

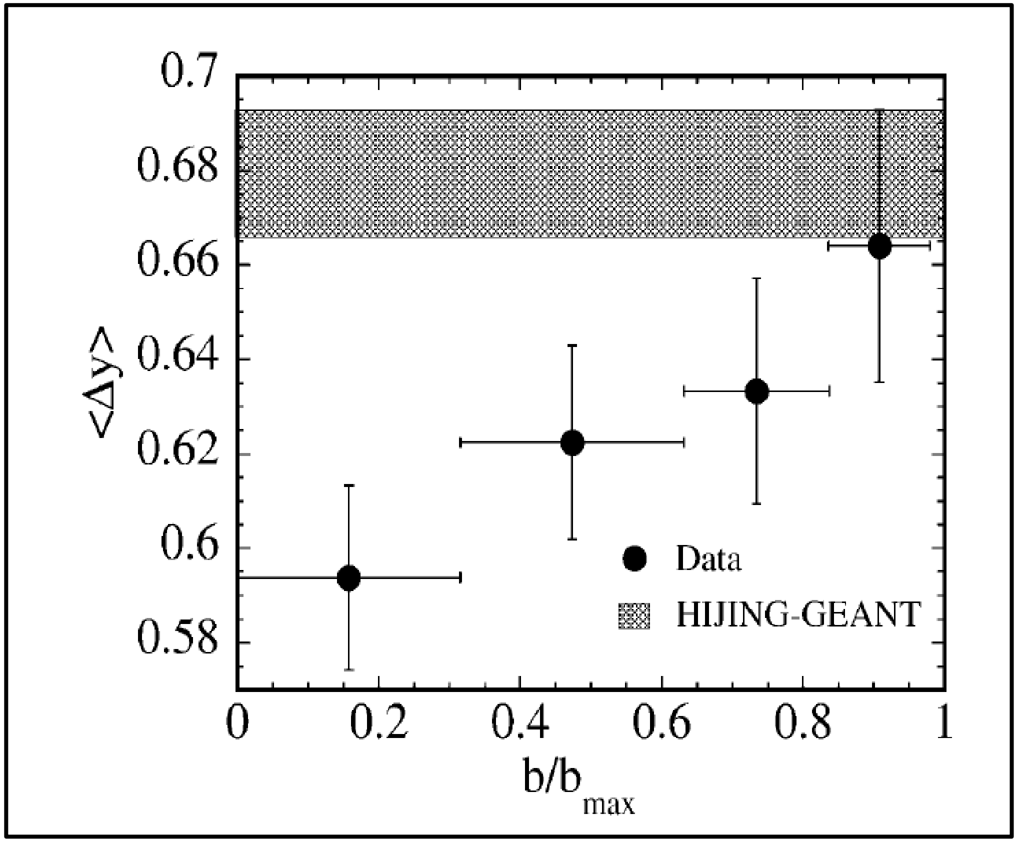
Phys. Rev. Lett. 85, (2000) 2689.

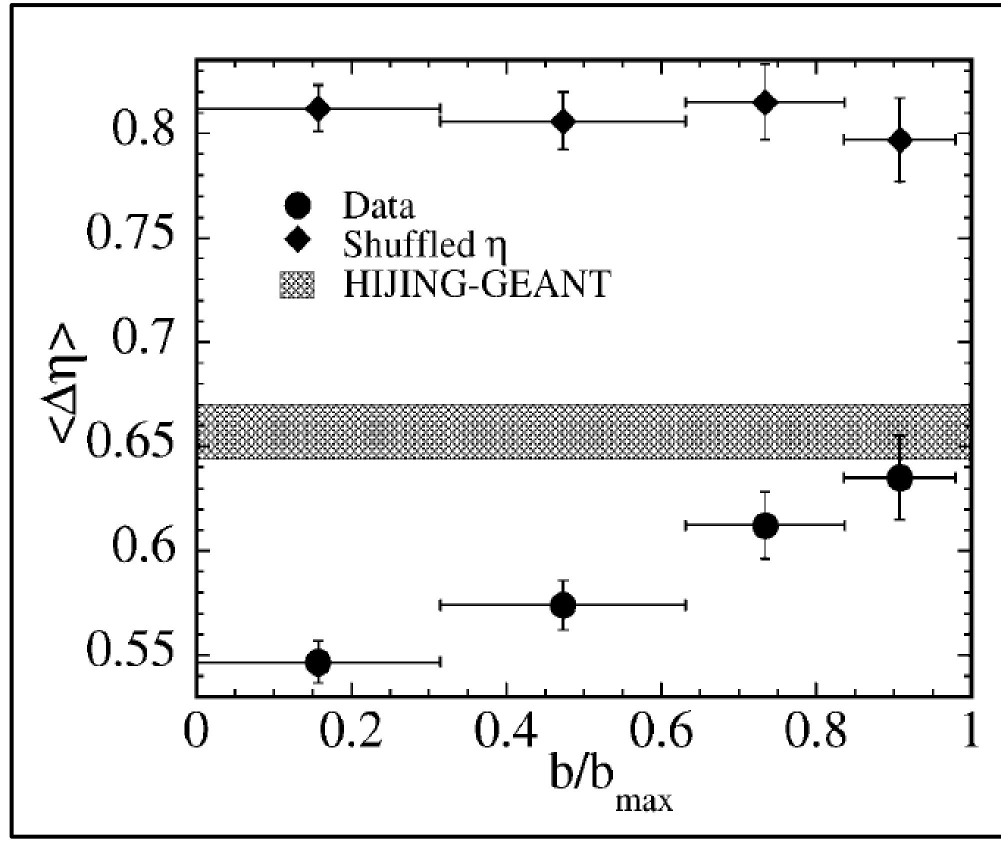




- Balance functions are computed using thermal models with two different set of parameters, corresponding to a large freeze-out temperature and a moderate transverse flow or a small temperature and a large transverse flow.
- BF of pions from resonance decay (dotted line) and non-resonant decay (dashed line) with T= 165 MeV and $\langle\beta\rangle$ =0.5 .
- BF of non-resonant pions (solid line) with T=90 MeV and $\langle\beta\rangle$ = 0.6 .
- Small temperature --- > smaller relative momentum
- Boost from rapidly moving source pointing momentum of pion’s pair approximately in the same direction.
- Large temperature and small transverse flow (β) makes BF wider.

PLB 609 , (2005), 247



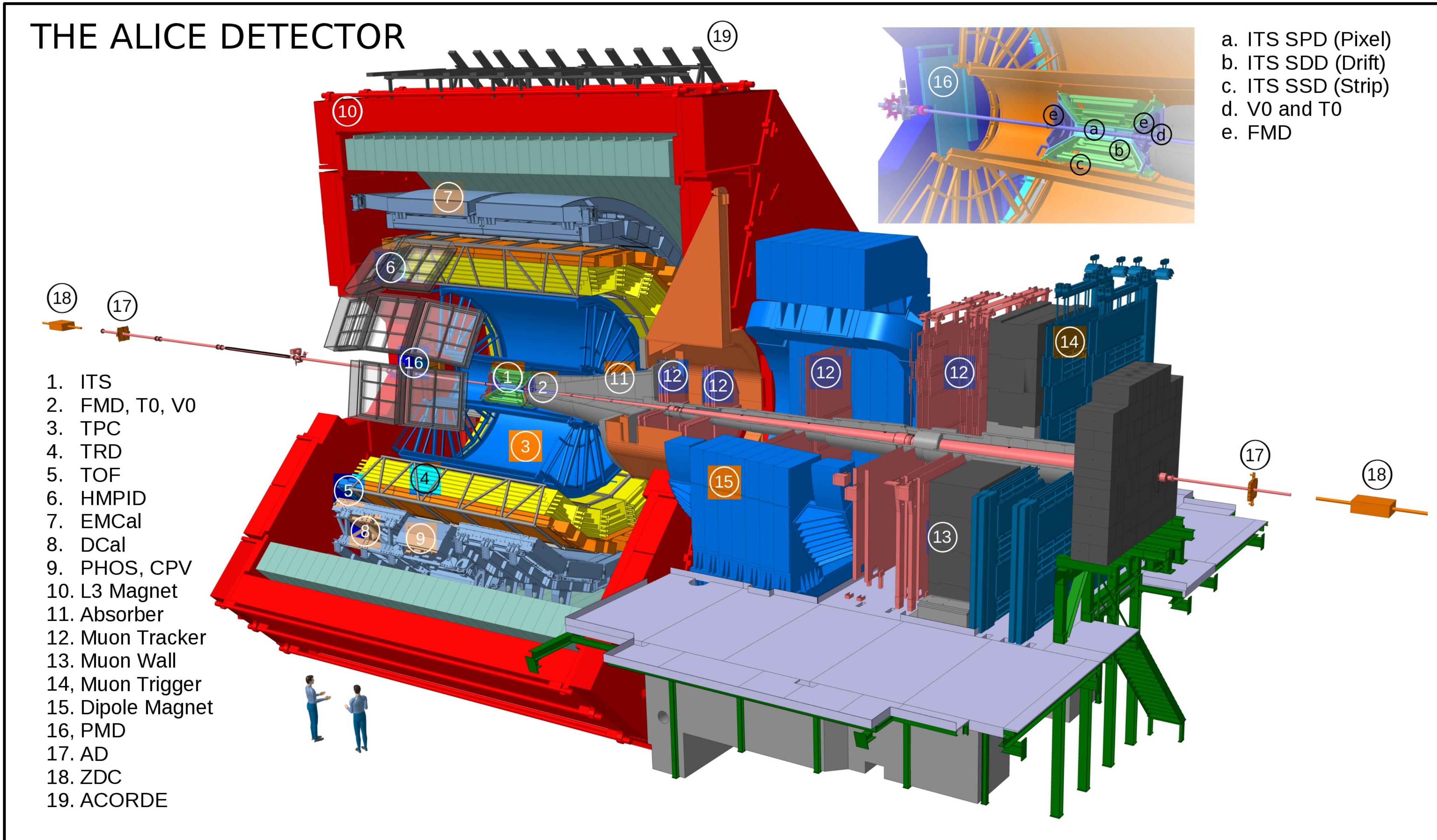


- Collisions system Au+Au with $\sqrt{s_{NN}}$ = 130 GeV.
- A narrowing of the balance function for more central collisions for all charged particle pairs and for charged pion pairs.
- There is no centrality dependence of balance function from HIJING data.

PRL 90 , (2003), 172301 (STAR)

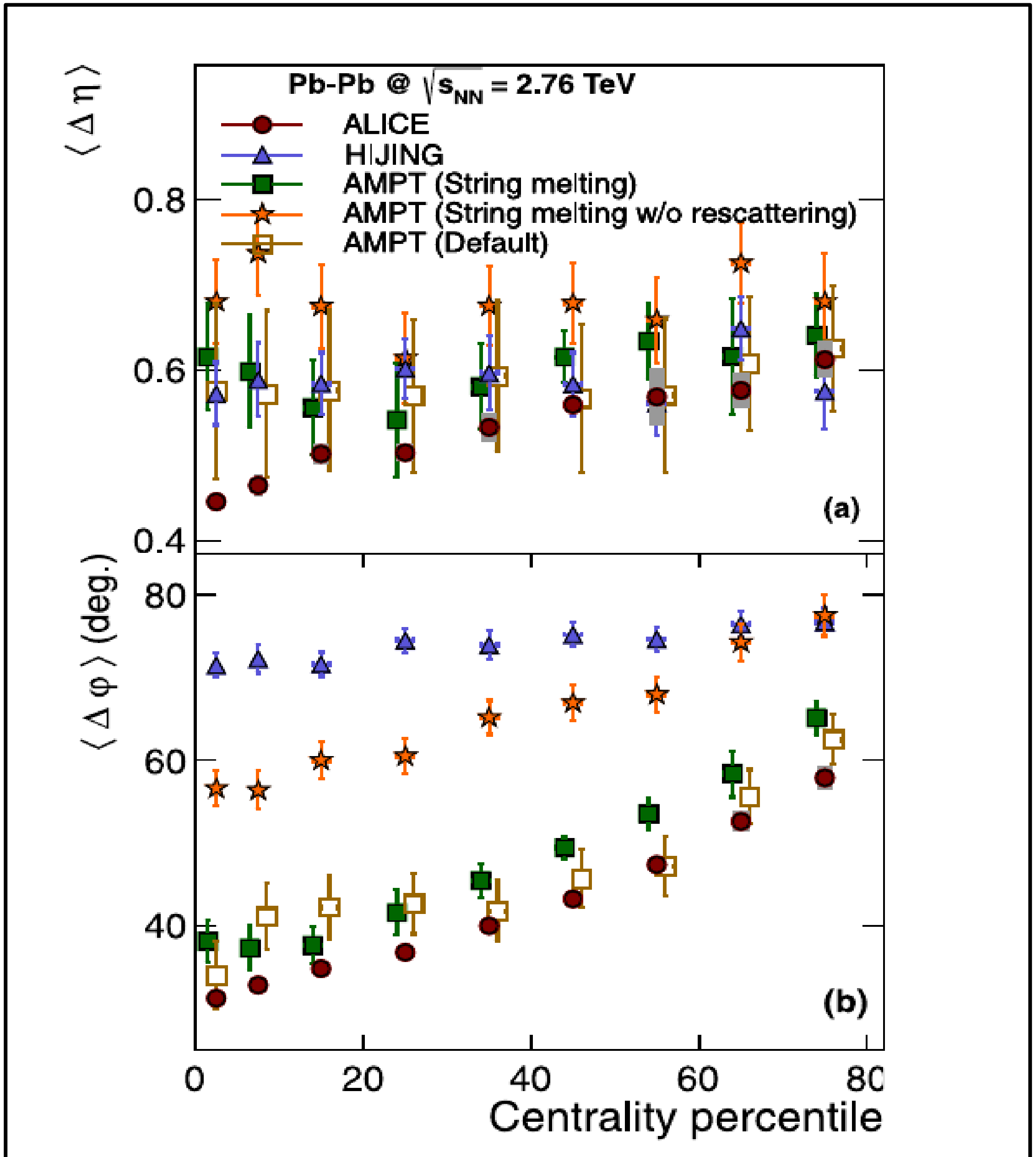
Data analysis and results

ALICE experimental setup



Physics Letters B 723 (2013) 267–279 (Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV)

- $|\eta| < 0.8$; $0.3 < p_T < 1.5$ GeV/c



- $0.0 < \Delta\eta < 1.6$; $0^o < \Delta\varphi < 180^o$.
- Central (peripheral) collisions correspond to small (large) centrality percentile.
- The experimental data points, represented by the full red circles, exhibit a strong centrality dependence: **more central collisions correspond to narrower distributions.**
- Data results are compared to different model predictions, such as HIJING and different versions of a multi-phase transport model (AMPT).
- The centrality dependence is not reproduced by HIJING, while AMPT, a model which incorporates strings and parton rescattering, exhibits qualitative agreement with the measured correlations in Δφ but fails to describe the correlations in Δη.
- This is consistent with the expectation that the balance function when studied as a function of Δφ can be used as a measure of radial flow of the system.
- The balance function widths generated by HIJING are much larger than those measured in the data, consistent with the fact that the model lacks collective flow.

Analysis details

- The analysis was done using ALICE Pb+Pb collision data recorded at energy $\sqrt{s_{NN}}$ = 2.76 TeV in 2010 LHC Run I.
- Approximately 11.98 million minimum-bias events had been analysed (A minimum bias trigger was used, requiring two pixel chips hit in the SPD in coincidence with a signal in the VZERO-A and VZERO-C detectors).
- An offline event selection was also applied in order to reduce the contamination from background events, such as electromagnetic and beam-gas interactions.
- The centrality of the collision was estimated using the charged particle multiplicity distribution and the distribution of signals from the VZERO scintillator detectors.
- At least 70 reconstructed space points out of the maximum of 159 possible in the TPC were used to select charged particles with high efficiency and to minimize the contribution from background tracks.
- A cut on the distance of closest approach between the tracks and the primary vertex (dca) was applied with d_{xy} = 2.4 cm and d_z = 3.2 cm .
- Electrons originating from ɣ-conversion and π_0-Dalitz decays were removed based on the energy loss (dE/dx) measured by the TPC. Tracks for which the measured dE/dx lied within $3\sigma_{dE/dx}$ of the Bethe-Bloch parametrization of dE/dx for electrons and at least $3\sigma_{dE/dx}$ away from the relevant parametrizations for pions, kaons, and protons, were removed.
- The contribution from track splitting and track merging in the active volume of the TPC were taken care by applying cut with a minimum pseudorapidity difference of $|\Delta\eta| < 0.02$ and angular distance $|\Delta\varphi^*| < 0.02$ rad.

$$\boxed{\Delta\varphi^* = \varphi_1 - \varphi_2 - \arcsin\left(0.0075\frac{B_z.r}{p_{T1}}\right) + \arcsin\left(0.0075\frac{B_z.r}{p_{T2}}\right)}$$

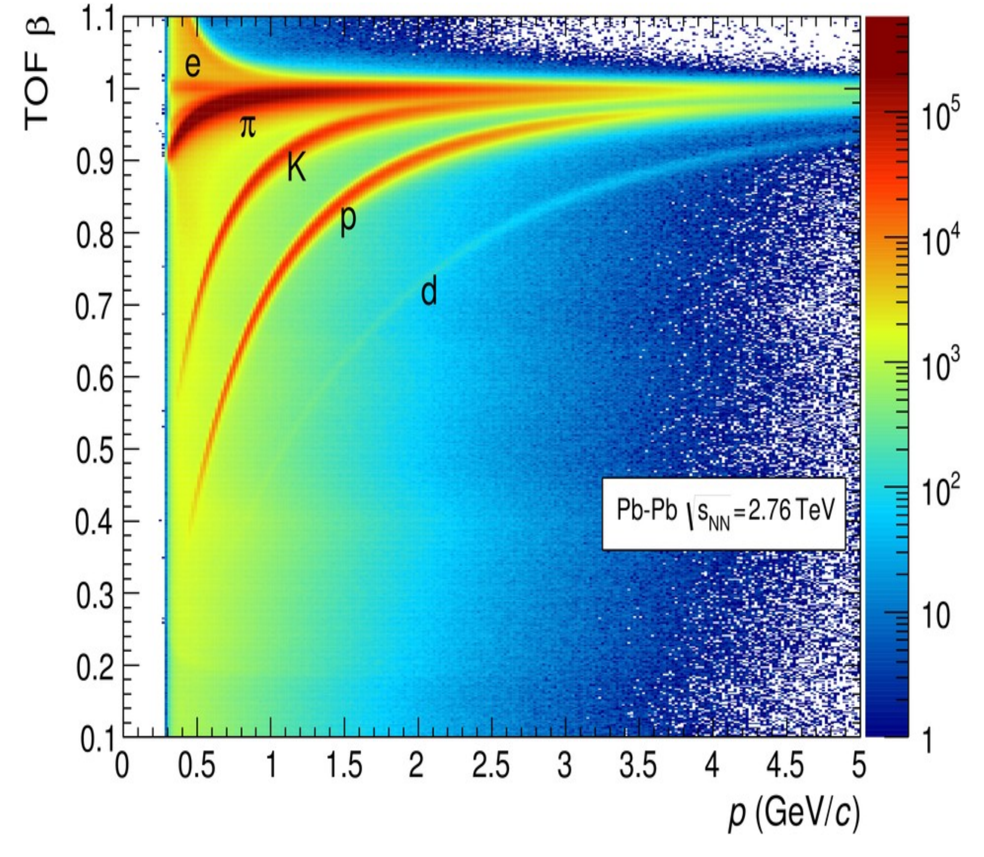
- $|\eta| < 0.8$ and $0.2 < p_T < 1.4$ GeV / c were used for this analysis.

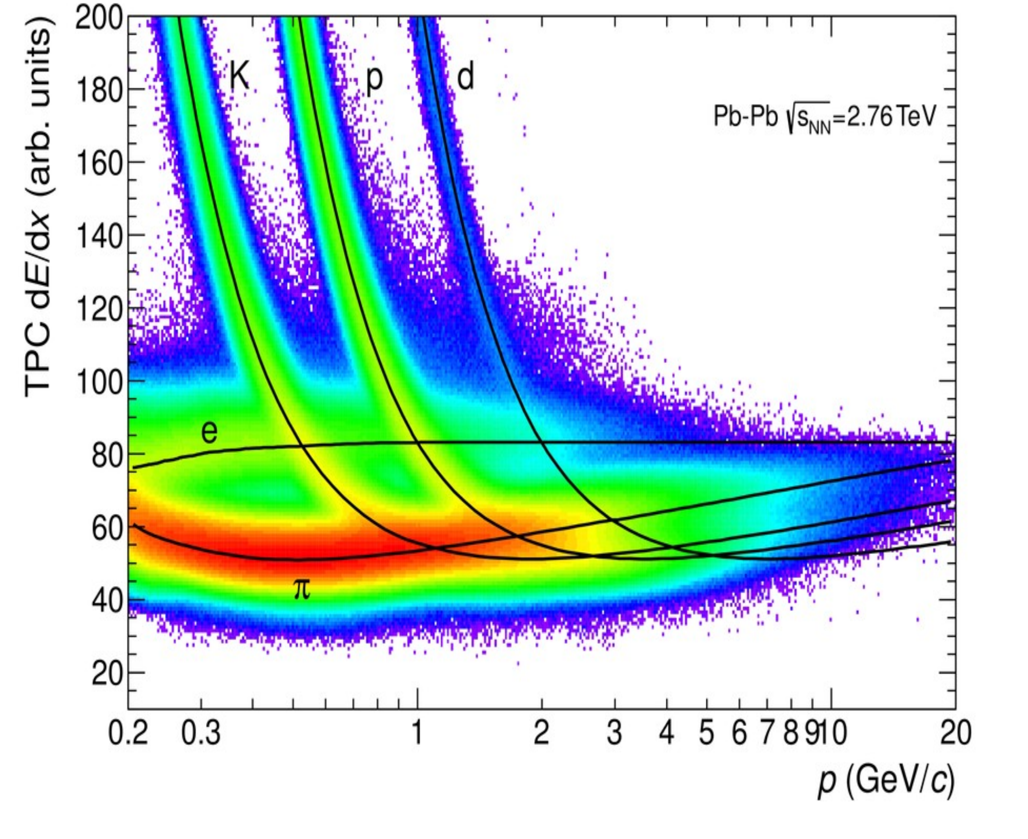
Particle identification

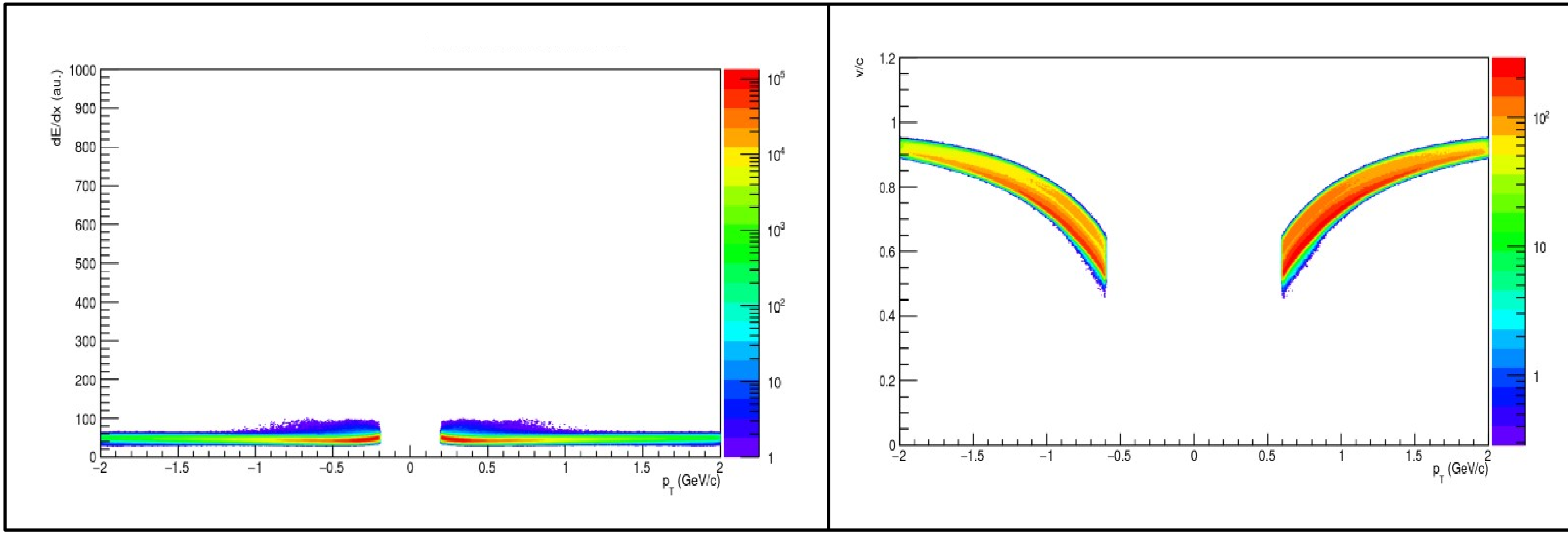
- $n\sigma$ method is used to identify particles.
- $n\sigma$ is defined as

$$n\sigma = \frac{Signal_{PID} - Signal_{Expected}}{\sigma}$$

- Signal means β=v/c and relative energy loss w.r.t distance for TOF and TPC respectively.







- After sigma cut , pions are identified using TPC (left plot) and TOF (right plot).
- Pions are selected for transverse momentum range 0.2 to 2.0 GeV/c .

Correction

- Particles used for balance function analysis are also corrected for misidentification of particles.

- The correction for tracking efficiency and contamination is done in the following way. Contamination is defined as

$$\boxed{\lambda = \frac{N_{Conta}}{N_{Conta} + N_{Reco}}}$$

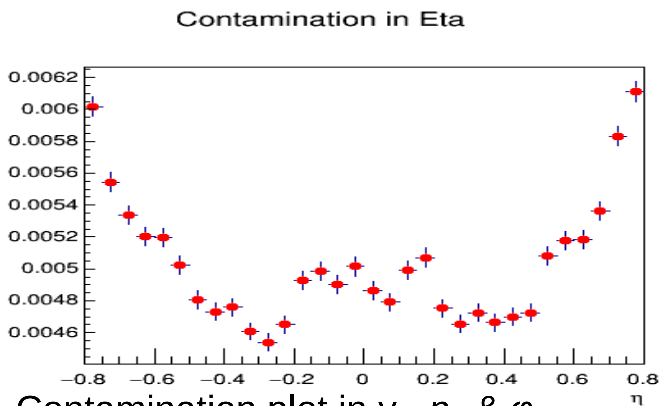
- N_{Conta} : Number of mis-identified particles
- N_{Reco} : Number of reconstructed primary particles
- N_{Truth} : Number of generated primary particles

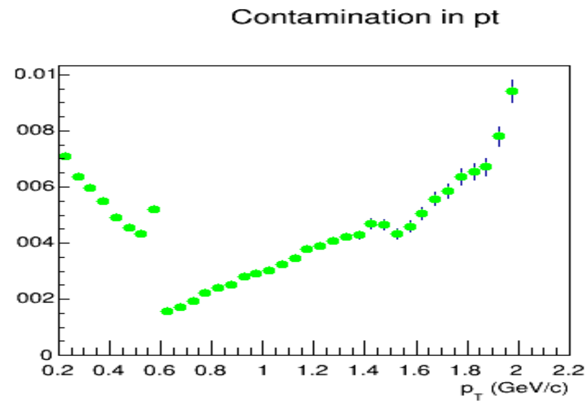
- Efficiency is define as

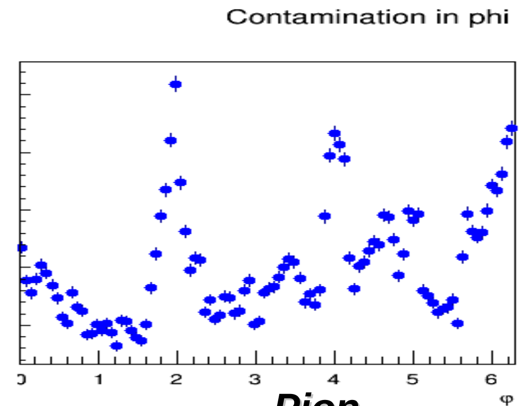
$$\boxed{\zeta = \frac{N_{Reco}}{N_{Truth}}}$$

- Correction factor defined as $\boxed{C = \frac{1-\lambda}{\zeta}}$. It is applied to each track for each event as a weighting factor.

λ



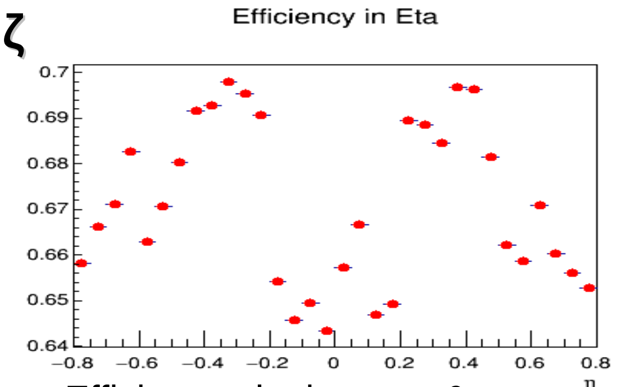


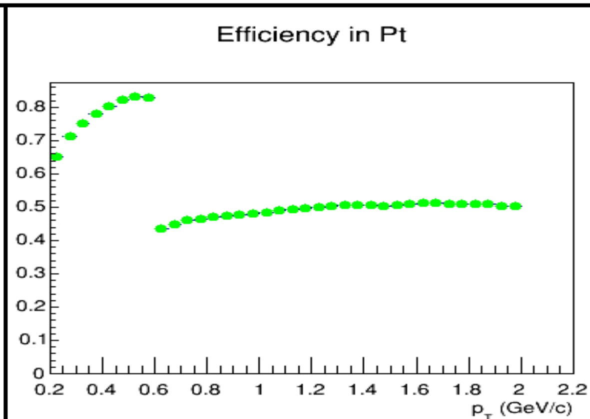


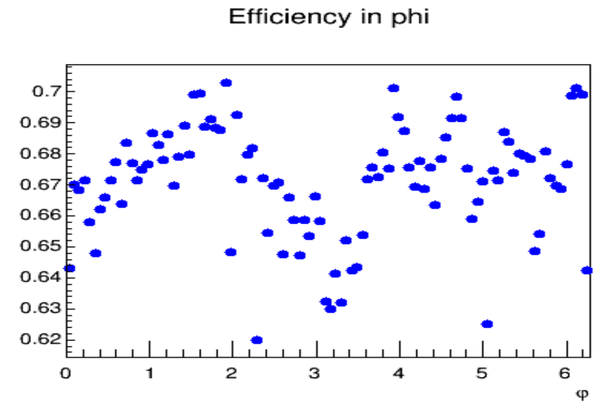
➔ Contamination plot in y , p_T & φ

Pion

ζ

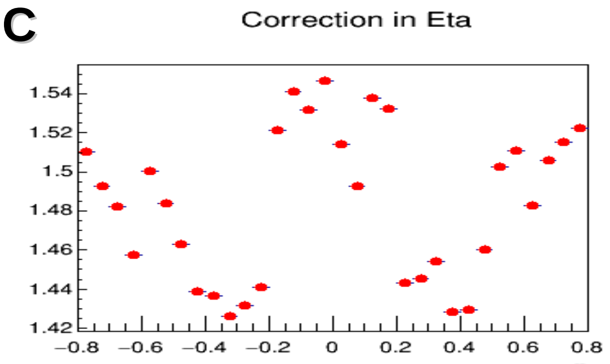


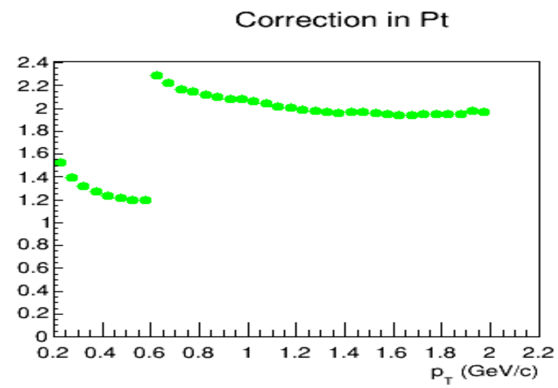


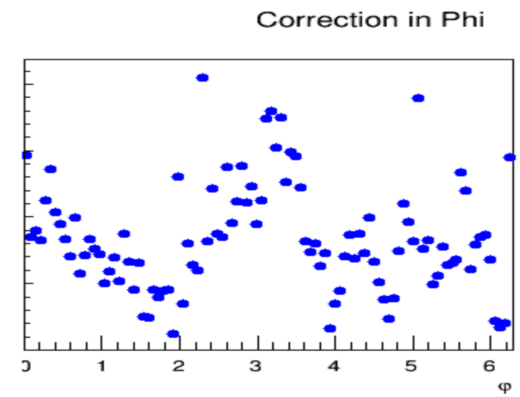


- Efficiency plot in y , p_T & φ

C







- Correction plot in y , p_T & φ