Correlations among net-charge, net-proton and net-kaon in Pb-Pb collisions at LHC energies

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Motivation: Correlations of net-conserved quantities

- Correlations between net-conserved quantities such as net-baryon (*B*), net-charge (*C*), and net-strangeness (*S*) number can provide valuabe insights ito the QCD phase structure.

- They are sensitive probes for the equation of state and can be directly related to the thermodynamic susceptibilities, calculable within the lattice QCD (LQCD) framework.

$$\chi^{lmn}_{\mathrm{B,S,Q}} = \left[\frac{\partial^{(l+m+n)}(P(\hat{\mu}_{\mathrm{B}}, \hat{\mu}_{\mathrm{S}}, \hat{\mu}_{\mathrm{Q}})/T^4)}{\partial \hat{\mu}^l_{\mathrm{B}} \partial \hat{\mu}^m_{\mathrm{S}} \partial \hat{\mu}^n_{\mathrm{Q}}} \right]_{\vec{\mu}=0}$$

- They can be studied in thermal model and measurements can constrain the thermal properties of the QCD medium formed at LHC.

Can be compared to RHIC lower energy (STAR experiment)

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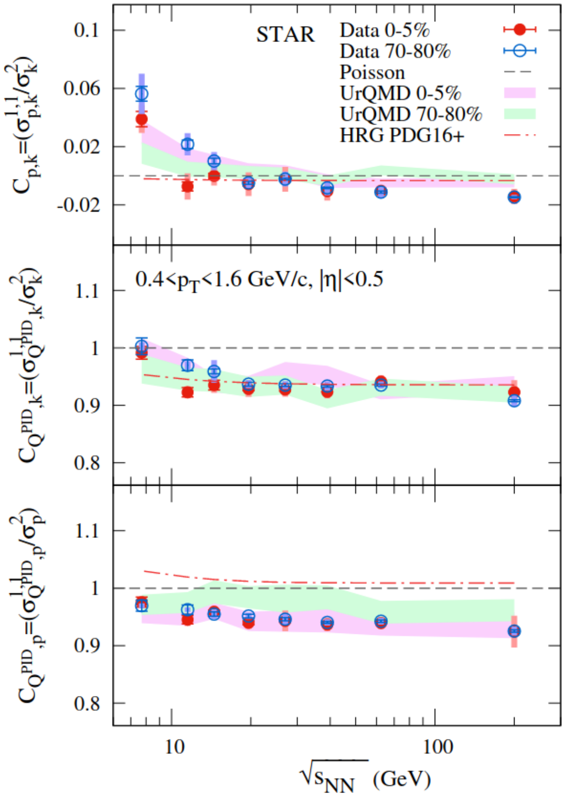
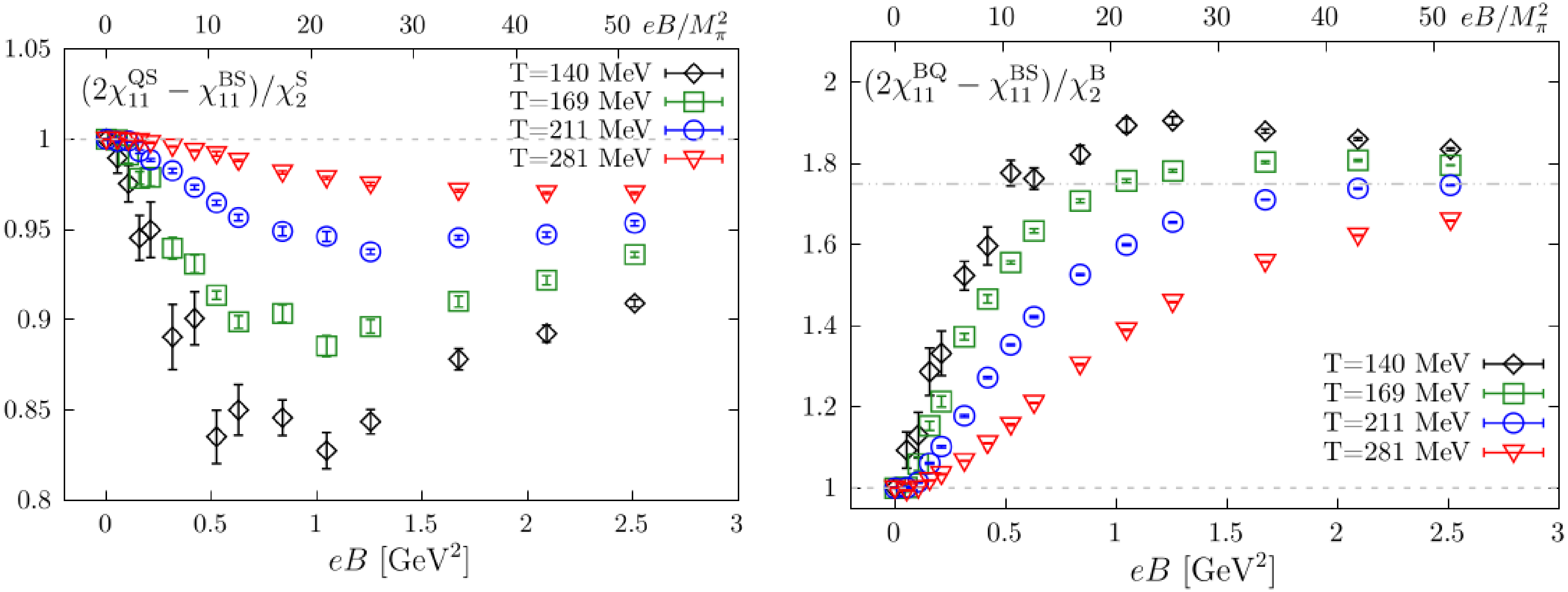


Motivation: Correlations of net-conserved quantities

LQCD computation in the presence of external magnetic fields showed certain combinations of susceptibilities of *B*, *Q,* and *S* can be useful probe for isospin symmetry breaking.

at B = 0

$$2\chi_{11}^{QS} - \chi_{11}^{BS} = \chi_2^{S}$$
$$2\chi_{11}^{BQ} - \chi_{11}^{BS} = \chi_2^{B}$$



Eur. Phys. J. A (2021) 57:202

Centrality dependence study of the observables can probe the possible existence of a magnetic field in the early stage of heavy-ion collisions.

Observables

- The susceptibilities are related to the cumulants (σ) of the event-by-event distribution of the associated conserved charges.

$$\chi^{lmn}_{\mathrm{B,S,Q}} = \frac{1}{VT^3}\sigma^{lmn}_{\mathrm{B,S,Q}}$$

- Due to the limitation in detecting all baryons and strange hadrons experimentally, net-proton (p) and net-kaon (K) are considered as proxies for the net-baryon and net-strangeness.

$$\sigma^{11}_{BS} = \langle BS\rangle - \langle B\rangle\langle S\rangle$$
$$\sigma^{11}_{QS} = \langle QS\rangle - \langle Q\rangle\langle S\rangle$$
$$\sigma^{11}_{QB} = \langle QB\rangle - \langle Q\rangle\langle B\rangle$$

$$\sigma^{2}_{S} = \langle S^2\rangle - \langle S\rangle^2$$
$$\sigma^{2}_{B} = \langle B^2\rangle - \langle B\rangle^2$$
$$\sigma^{2}_{Q} = \langle Q^2\rangle - \langle Q\rangle^2$$

$$\mathrm{C}_{BS} = \sigma^{11}_{BS}/\sigma^{2}_{S}$$
$$\mathrm{C}_{QS} = \sigma^{11}_{QS}/\sigma^{2}_{S}$$
$$\mathrm{C}_{QB} = \sigma^{11}_{QB}/\sigma^{2}_{B}$$

Proxies:
- Charge (Q): K, π, p
- Baryon (B): p
- Strangeness (S): K

B = no of baryons – no of anti-baryons
S = no of strange particles – no of anti-strange particle
Q = no of pos. charged particle – no of neg. charged paritcle

Analysis details

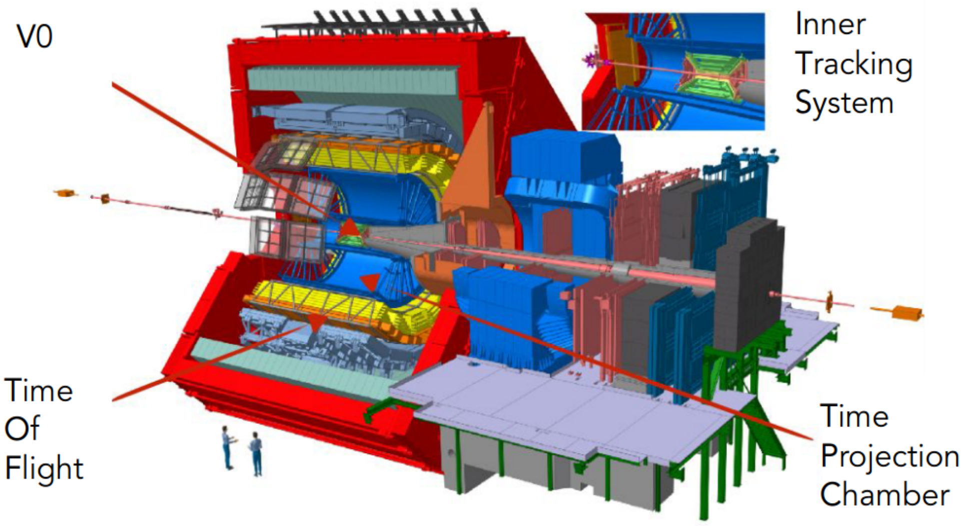
Detectors (used in this analysis): ITS, TPC, TOF and V0

- Dataset: Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
  Periods: LHC15o (pass2) (80 million)
- MC production: HIJING
  Period: LHC20j6a (2 million)

- Event selection:
  - Trigger: kINT7
  - $|V_Z| < 10$ cm
  - AliEventCut (with strict Pileupcut)
  - Centrality estimator: V0M

- Track selection: FilterBit 96

- Kinematic cuts:
  - $0.2 < p_T$ [GeV/c] < 2.0 ($0.4 < p_T$ [GeV/c] < 1.6)
  - $|\eta| < 0.8$
  - Centrality/Multiplicity: V0



- V0 (V0A +V0C): trigger and centrality estimation.

- ITS: tracking and vertexing.
- Pions, kaons, and protons are selected using information from TPC and TOF.

V0A ($2.8 < \eta < 5.1$) and V0C ($-3.7 < \eta < -1.7$)

Particle identification

Pion selection: $p_T < 0.5$ GeV/c, $N_\sigma = |N_{\sigma TPC}| < 2.0$

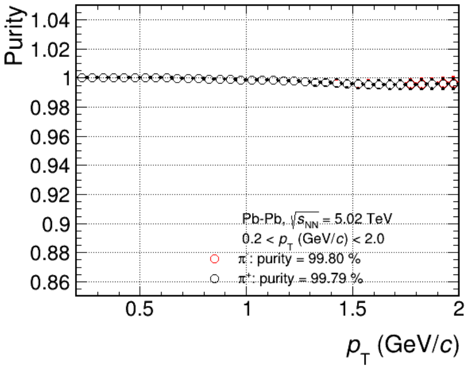
$p_T > 0.5$ GeV/c, N_σ (TPC+TOF) < 2.0

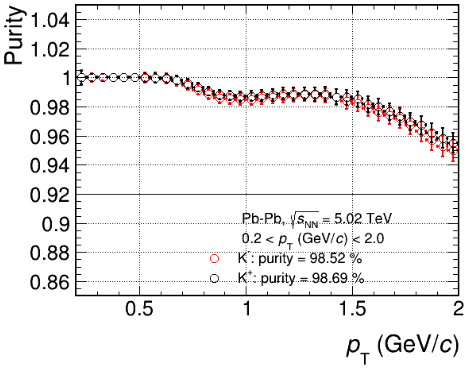
Kaon selection: $p_T < 0.5$ GeV/c, $N_\sigma = |N_{\sigma TPC}| < 2.0$

$p_T > 0.5$ GeV/c, N_σ (TPC+TOF) < 2.0

Proton selection: $p_T < 0.6$ GeV/c, $N_\sigma = |N_{\sigma TPC}| < 2.0$

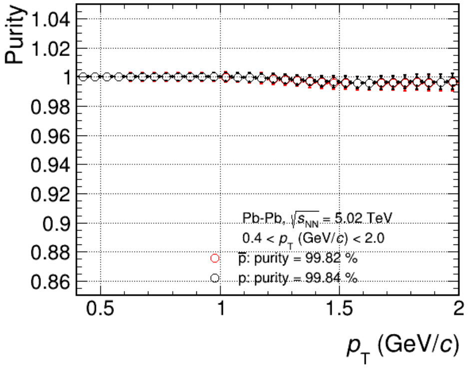
$p_T > 0.6$ GeV/c, N_σ (TPC+TOF) < 2.0





To reduce contamination from background, additional cuts are applied for each of the analysed particles:

- Pion: $p_T > 0.2$ GeV/c;
- Kaon: $p_T > 0.2$ GeV/c;
- Proton: $p_T > 0.4$ GeV/c



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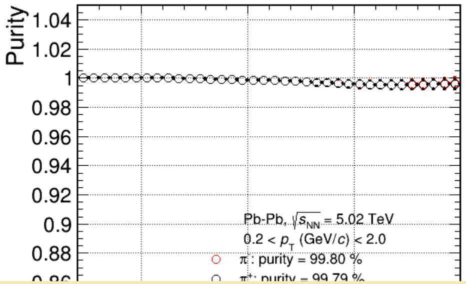
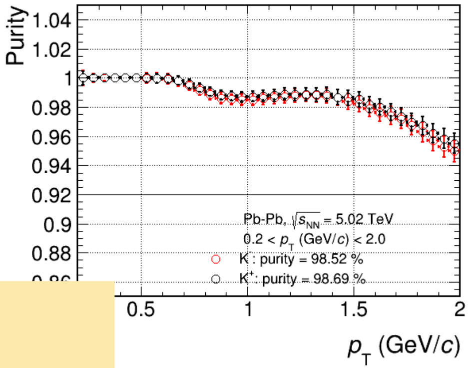
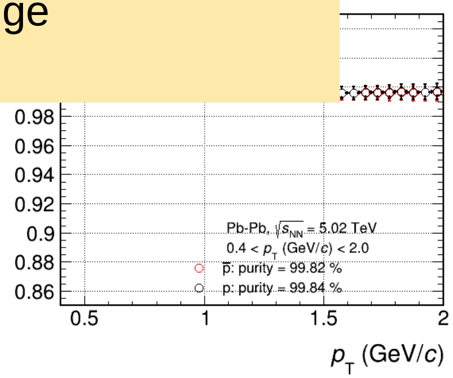
Proton selection:





High purity sample: Obtained purity is greater than 96 %
for all the particles in the selected p_T range



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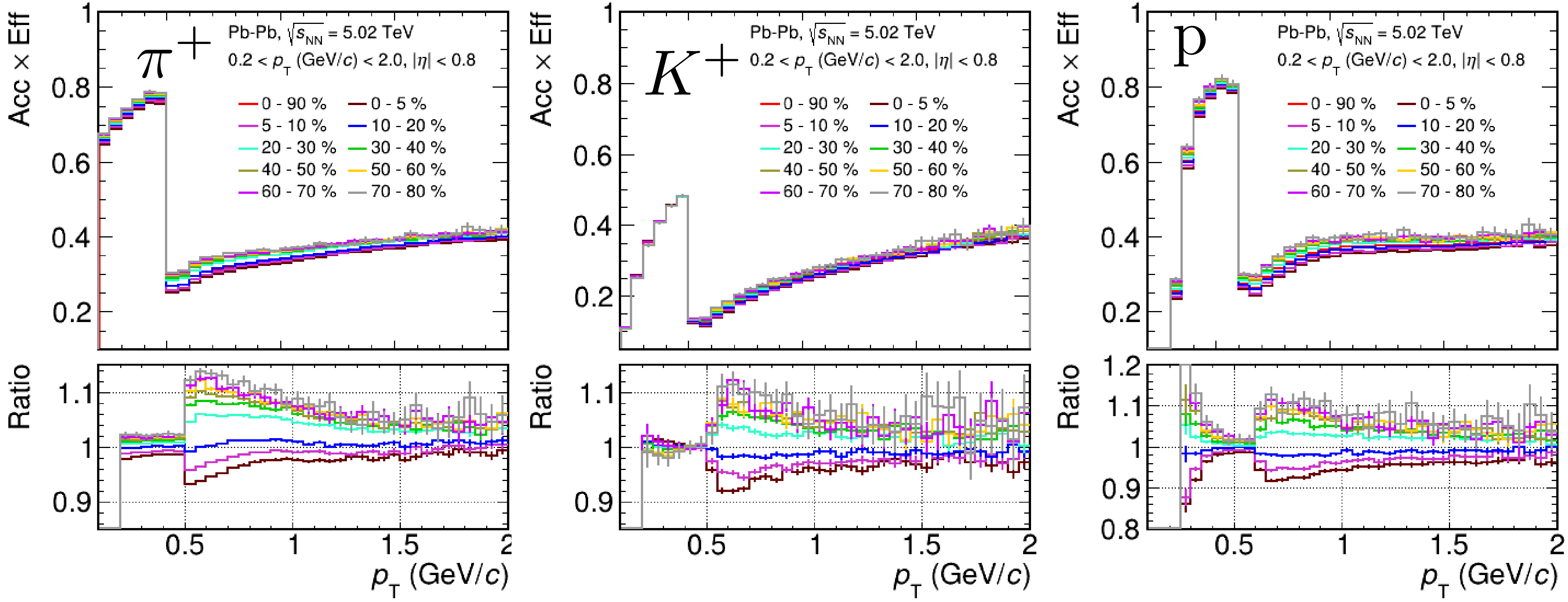
Efficiency correction: Distributions of efficiency vs. p_T



Ratios are w.r.t 0-90 % centrality class. Variation is around ~10%. Using this efficiencies, corrected number of net-proton, net-kaon and net charge are calculated.

Similar distribution of efficiencies are obtained for the anti-particles.

Efficiency correction: Method

Considering detector response to be binomial, efficiency correction of the second-order cumulants and correlation of net-proton, net-kaon, and net-pion are calculated

$$C_2(Q) = \langle q^2_{(1,1)} \rangle - \langle q_{(1,1)} \rangle^2 + \langle q_{(2,1)} \rangle - \langle q_{(2,2)} \rangle$$

If mixed charges x, y have no particles in common,

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$$C_{11}(Q_x Q_y) = \langle q^{(x)}_{(1,1)} q^{(y)}_{(1,1)} \rangle - \langle q^{(x)}_{(1,1)} \rangle \langle q^{(y)}_{(1,1)} \rangle$$

If mixed charges x, y have particles in common,

$$C_{11}(Q_x Q_y) = \langle q_{(1,0,1)} q_{(0,1,1)} \rangle + \langle q_{(1,1,1)} \rangle - \langle q_{(1,1,2)} \rangle - \langle q_{(1,0,1)} \rangle \langle q_{(0,1,1)} \rangle$$

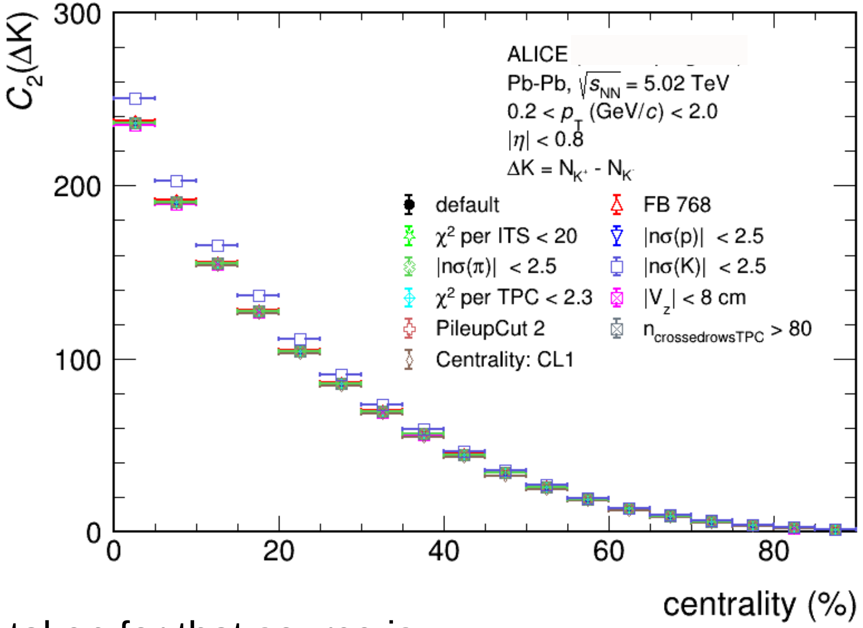
where, $q_{(m,n)} = \sum_{i=1}^{M} \frac{a_i^m}{\epsilon_i^n} N_i$ and $q_{(r,s,t)} = \sum_{i=1}^{M} \frac{x_i^r y_i^s}{\epsilon_i^t} N_i$

- a_i is the charge or baryon or strangeness number that takes into account both the particle and anti particle
- M is the no of p_T bins
- ϵ_i is the efficiency in the i^{th} p_T bin calculated as a function of p_T
- N_i is the number of particles for the i^{th} p_T bin
- x, y will refer to charge, kaon, proton

Uncertainties (statistical and systematic)

- Statistical error is estimated by Bootstrap sampling method, sample no = 100

Sources of systematic uncertainty	Default	Variation
V_z (in cm)	10	8
$\chi^2 TPC/n_{TPCclusters}$	2.5	2.3
$\chi^2 ITS/n_{ITSclusters}$	25	20
Pileup Cut	1	2
Centrality estimator	V0M	CL1
nσ PID cut	2.0	2.5 (p,K,π)
$n_{TPCcrossedRows}$	70	80
Filterbit	96	768

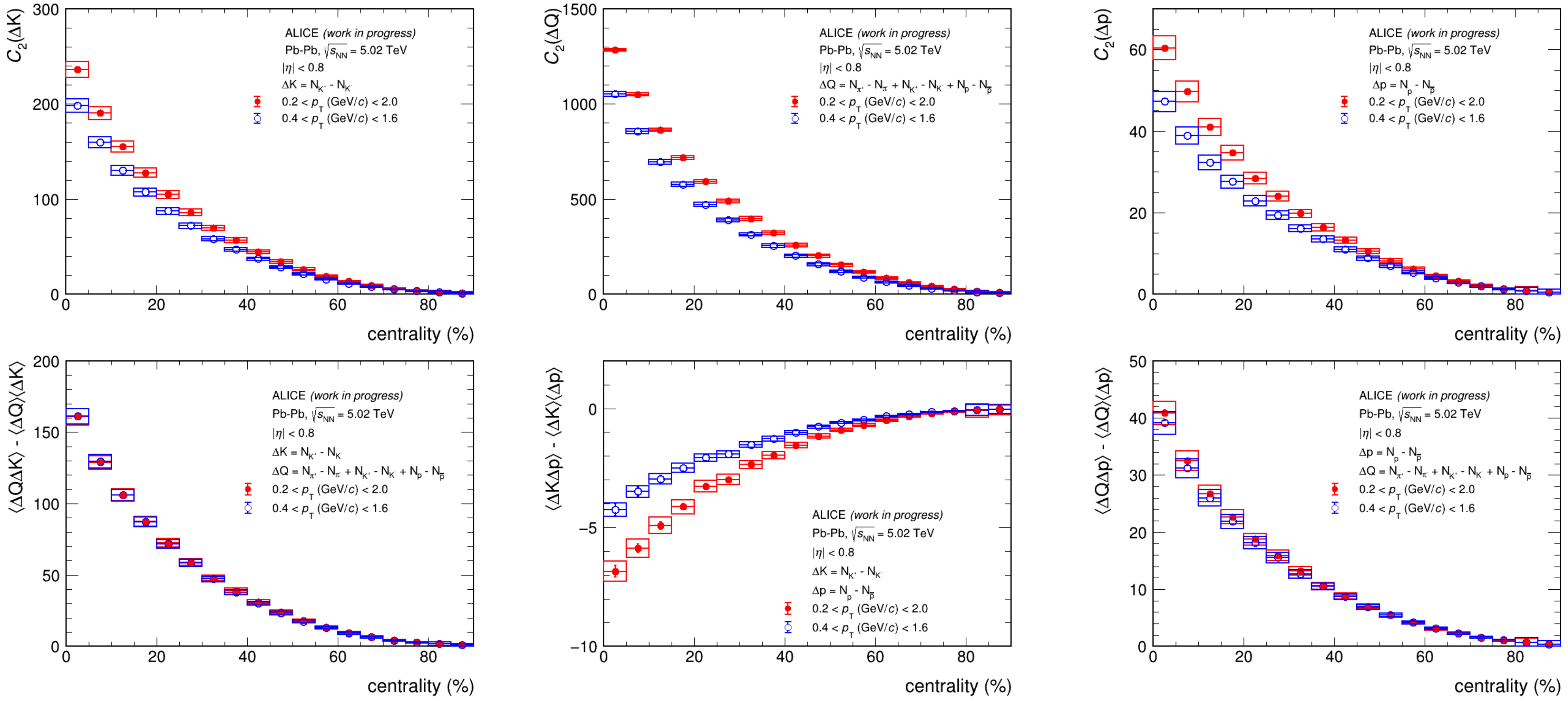


- Relative error for a given source where N is the no. of variation taken for that source is

$$\left(\frac{\Delta y}{y}\right)_{\text{source1}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{y_{\text{default}} - y_i}{y_{\text{default}}}\right)^2}$$

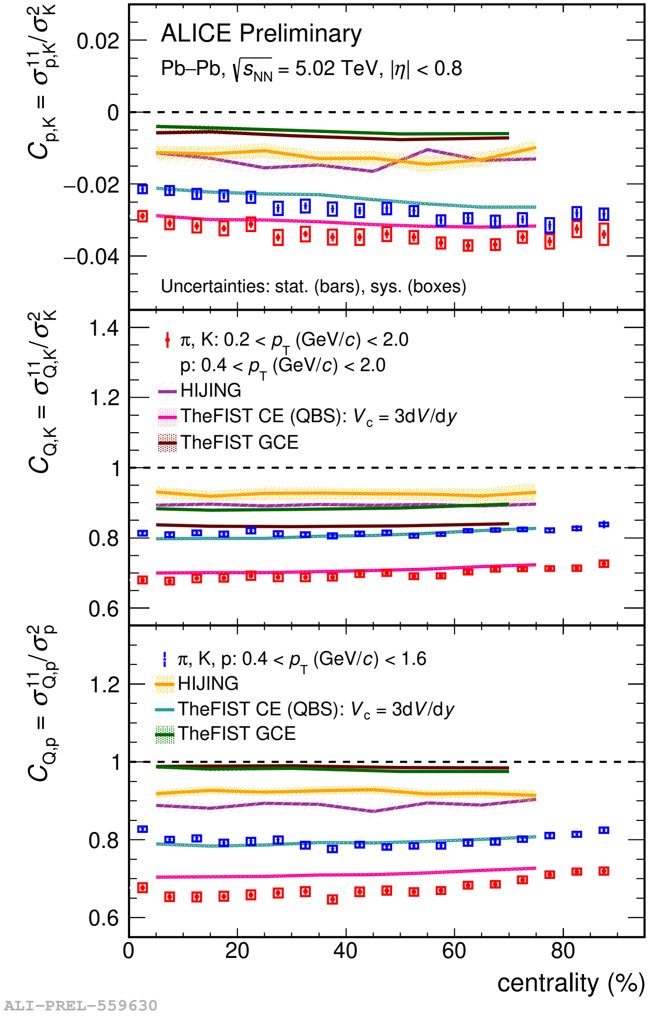
- All the sources are considered uncorrelated and added in quadrature to obtain total systematic uncertainity

Diagonal and off-diagonal cumulants of Q, K and p



Efficiency corrected diagonal and off-diagonal cumulants of net-pion, net-kaon and net-proton calculated as a function of centrality with systematic uncertainties.

Correlations between Q, K and p



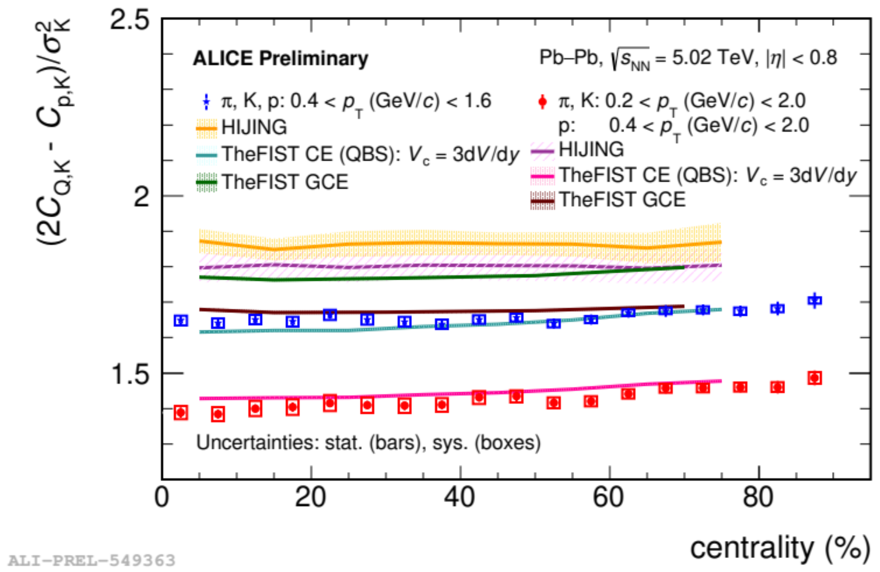
** Q: net-charge, K: net-kaon and p: net-proton

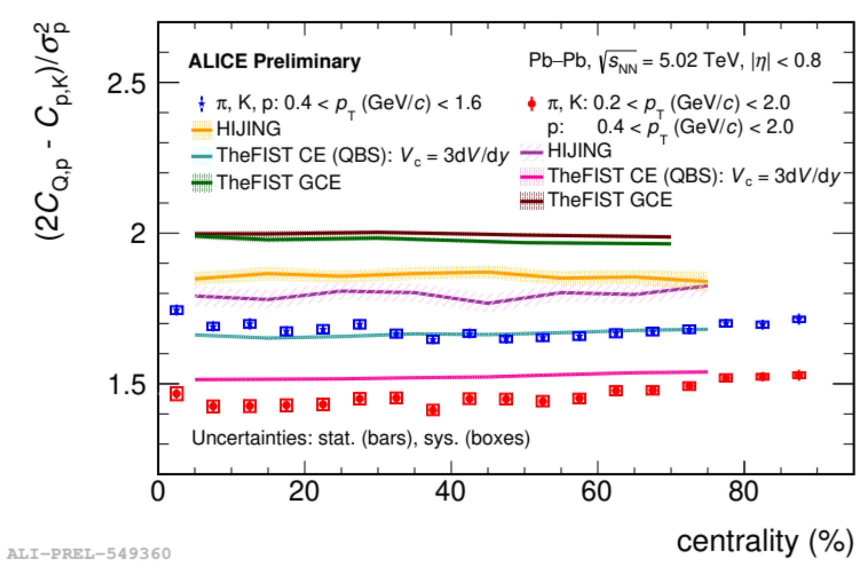
#Parametrization of CE-SHM from centrality (or multiplicity) dependent functions Phys. Rev. C 100, 054906

#for GCE-SHM, parameters are fixed from the fit for each centrality

- $C_{p,K}$, $C_{Q,K}$ and $C_{Q,p}$ vs. centrality changes with p_T acceptance.
- Suppressed correlations observed compared to the Poissonian baseline.
- HIJING model predictions overestimate the data.
- Canonical ensemble (CE) treatment of conserved charges in the thermal model is required to explain data.

Quantities to probe magnetic field





- HIJING, which is based on the Lund string model with a much smaller correlation length, fails to describe the data.
- CE predictions from the thermal model with V_c = 3dV/dy and Q, B, S conservation are in good agreement with the data.
- Slight indication of an increase as a function of centrality.

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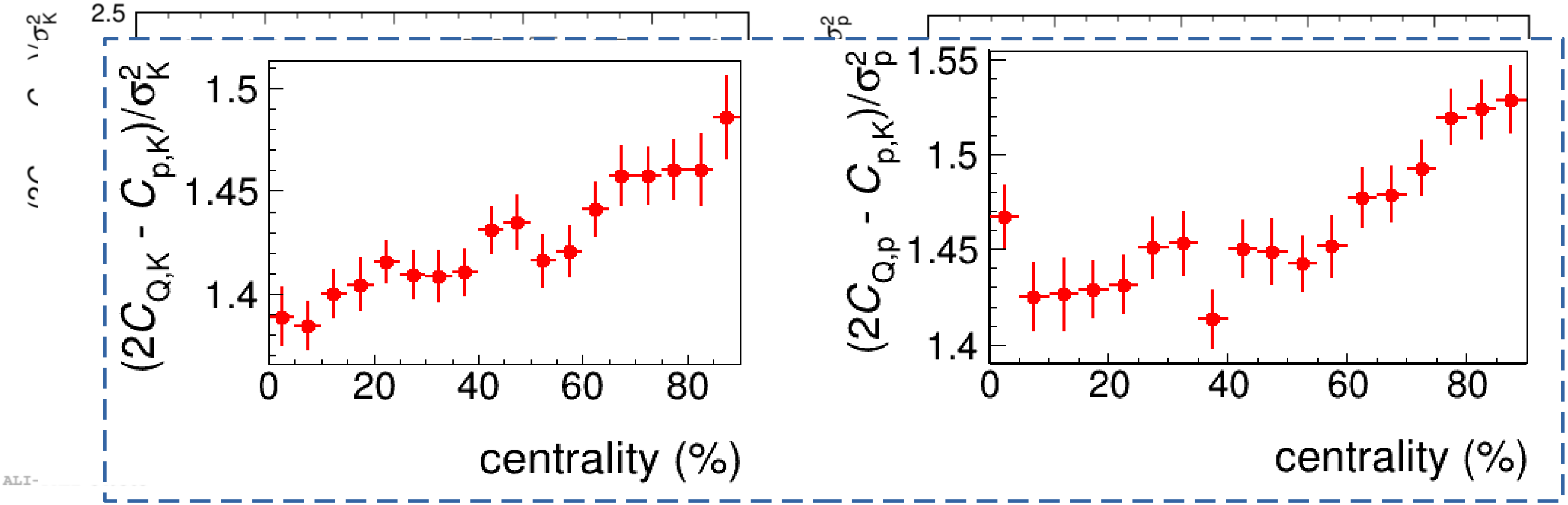

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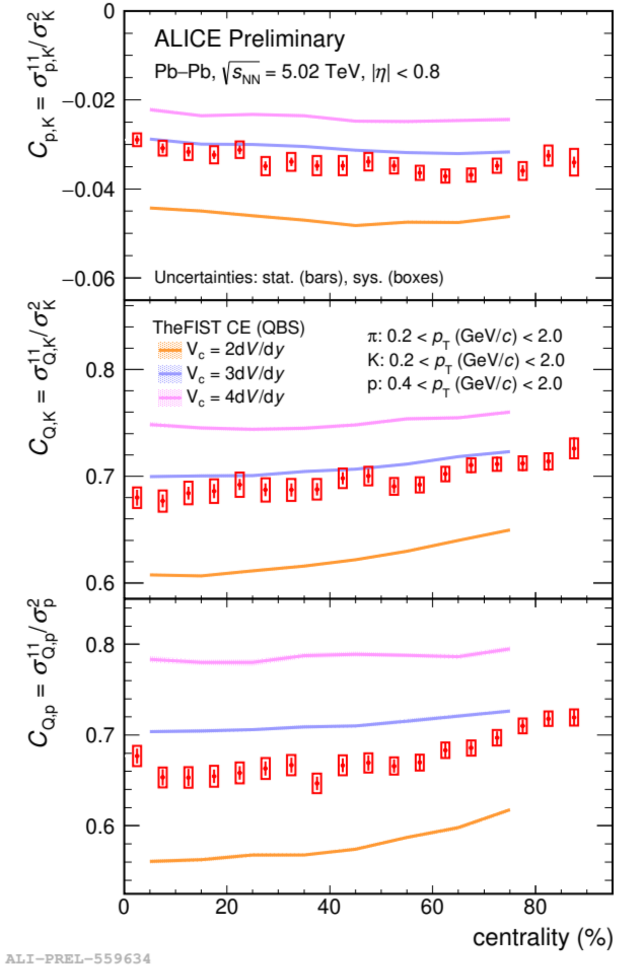
Effect of correlation volume

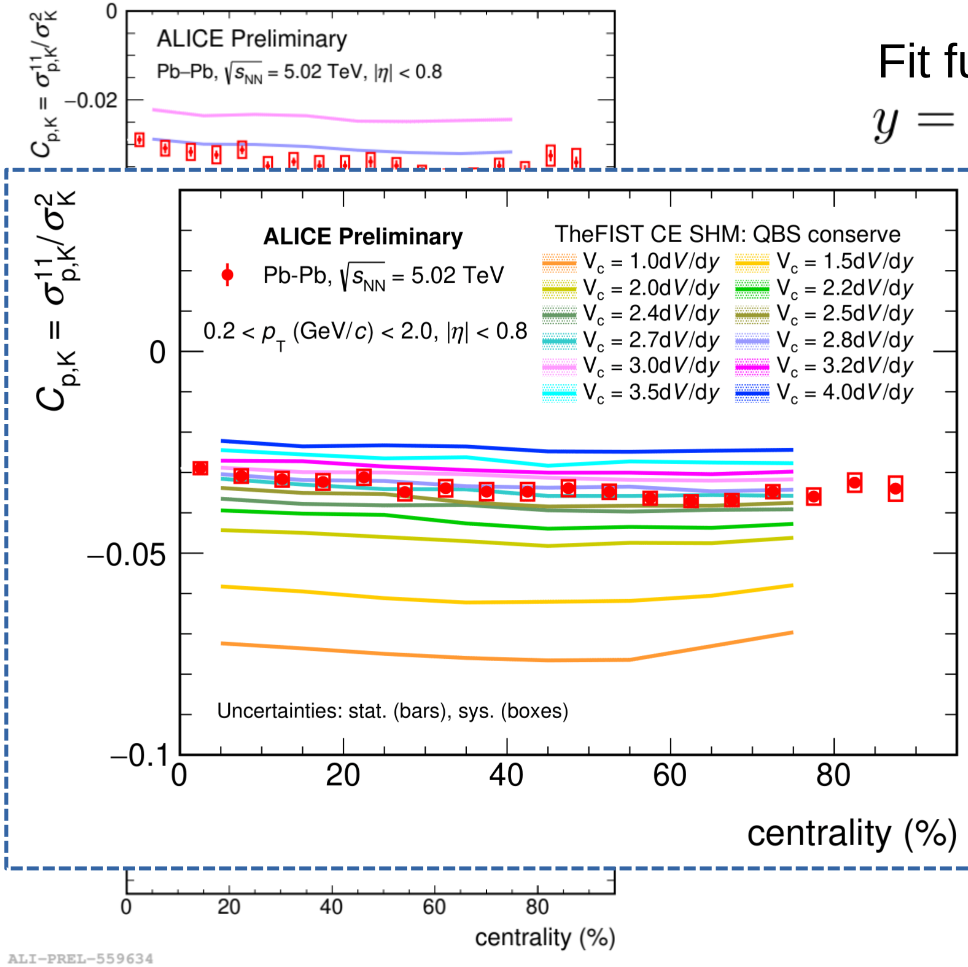


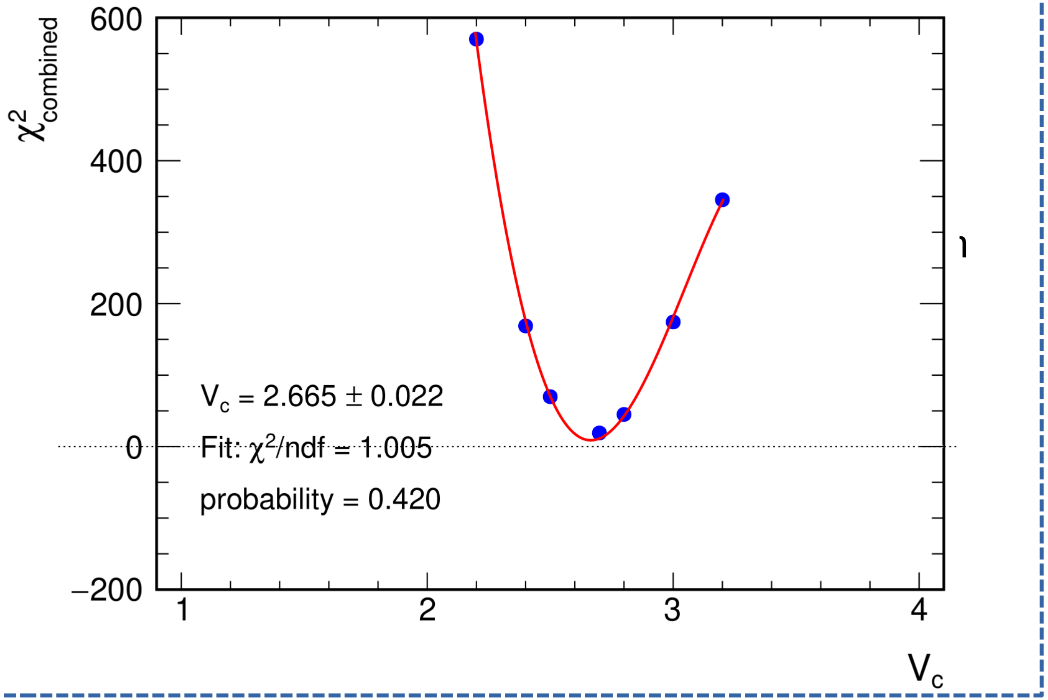
- Correlations of p, K, Q, ($C_{p,K}$, $C_{Q,K}$ and $C_{Q,p}$) are sensitive to the correlation volume (V_c) in thermal model.
- Reduction of V_c suppresses the correlations.
- V_c = 3dV/dy is in good agreement with data for Q+B+S conservation in γ_s- CSM (TheFIST) model.

Effect of correlation volume

Fit function:

$$y = a + b(x-c)^2 + d(x-c)^4 + e(x-c)^6$$





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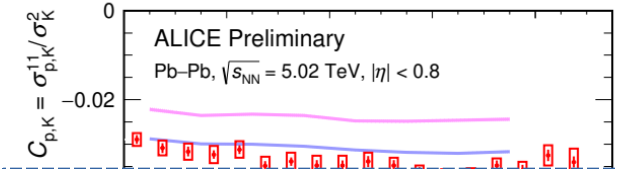
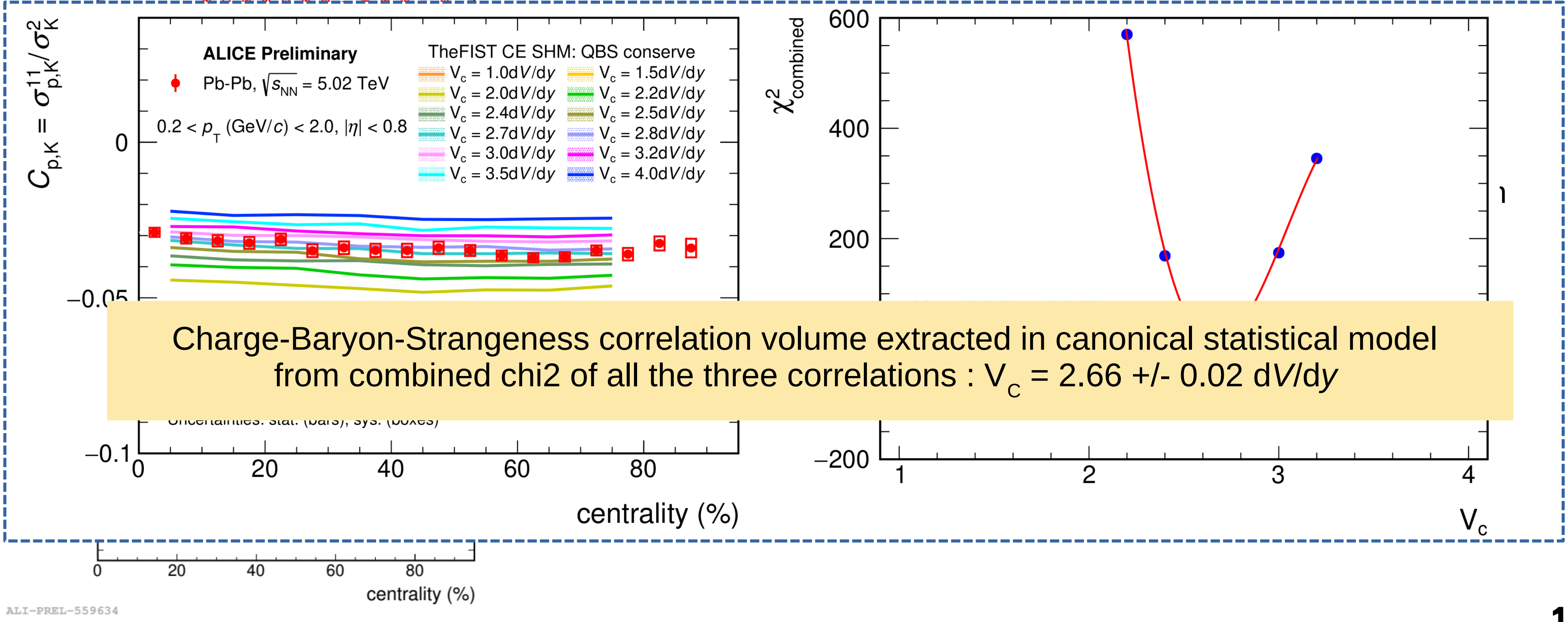
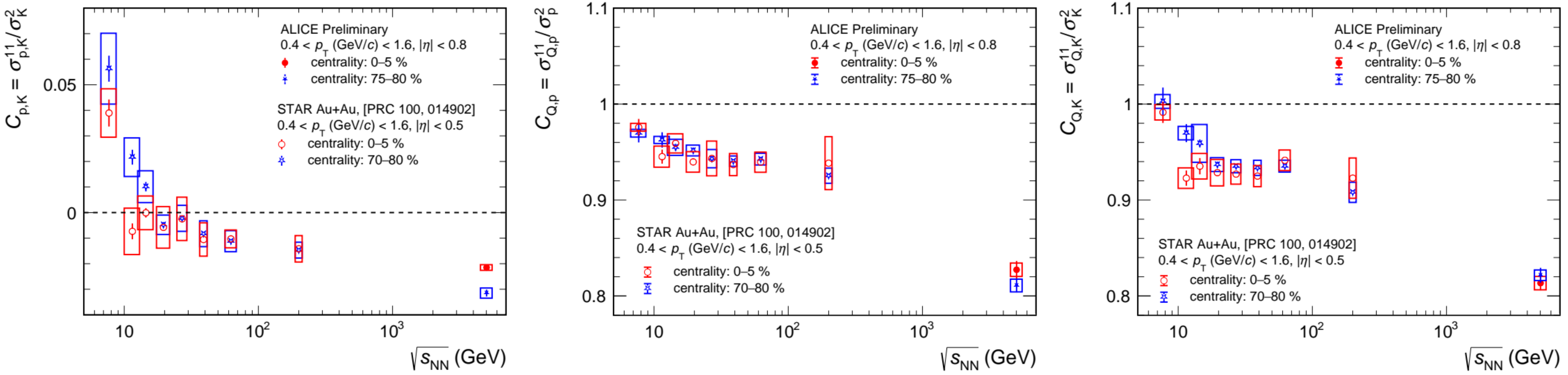




Charge-Baryon-Strangeness correlation volume extracted in canonical statistical model from combined chi2 of all the three correlations : V_C = 2.66 +/- 0.02 d*V*/dy

Energy dependence



- Monotonic decrease of the correlations, $C_{p,K}$, $C_{Q,K}$, and $C_{Q,p}$ with increase in collsion energy.
- More suppressed correlation from poissonian baseline at LHC energy.

Summary

- First measurement of cross-correlations betweeen net-charge, net-kaon, and net-proton ($C_{p,K}$, $C_{Q,K}$, and $C_{Q,p}$) at LHC energies (Results are approved as preliminary in ALICE collaboration).

- The correlations, $C_{p,K}$, $C_{Q,K}$, and $C_{Q,p}$ are suppressed compared to the Poissonian baseline and expectations from grand-canonical ensemble calculation in the thermal model.

- HIJING model calculations overestimate the data.

- Thermal model (γ_s- CSM in TheFIST) calculations for the charge, baryon, and strangeness number conservation with V_c = 3dV/dy seems to describe data.

Outlook:

- Aiming paper proposal in the collaboration on December.

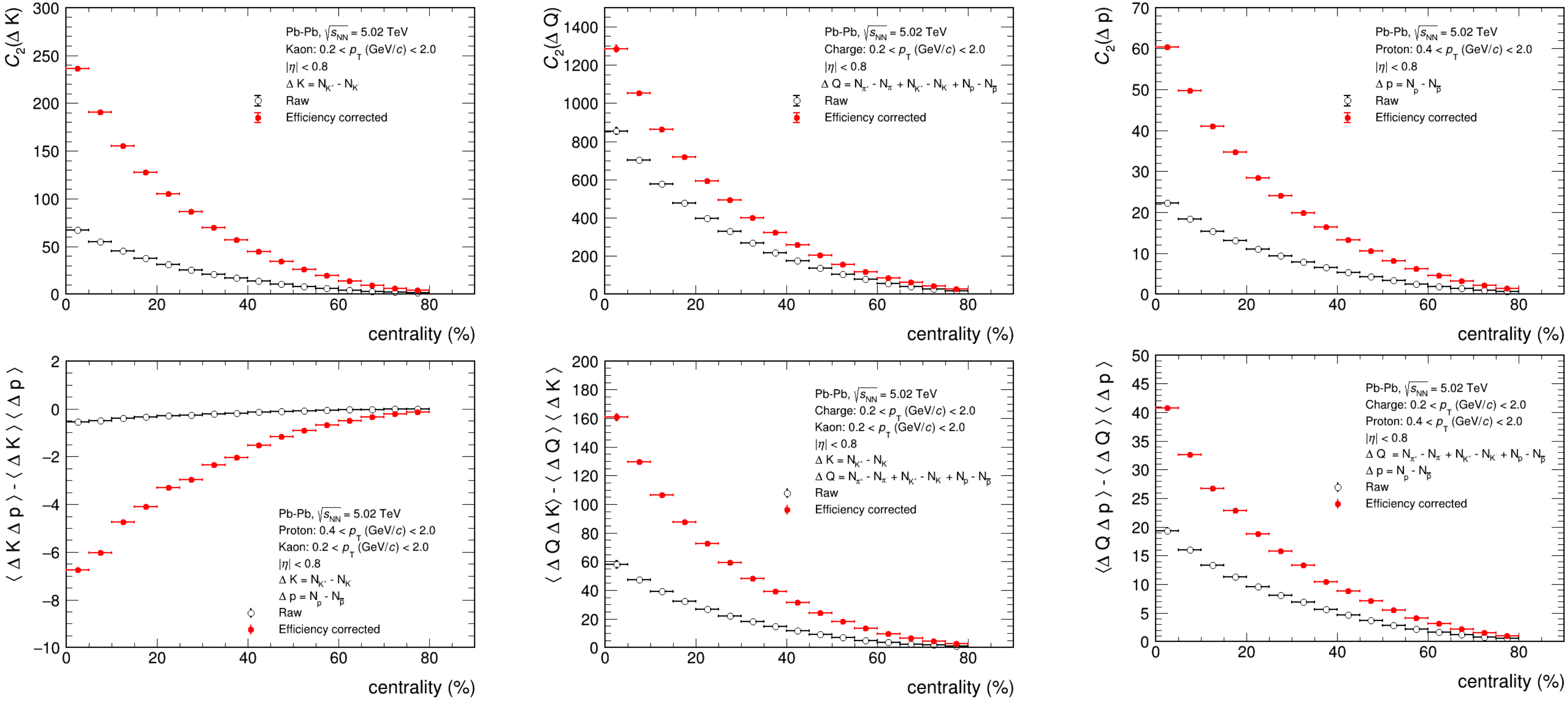
Analysis note: https://alice-notes.web.cern.ch/node/1425

Poster presentation:
- XXXth International Conference on Ultra-relativistic Nucleus-Nucleus Collisions (QM2023) [3/09/2023 – 9/09/2023] at Houston, Texas, USA.
  Title:Correlations of net-charge, net-kaon and net-proton in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ALICE

THANK YOU

Heartfelt thanks to my supervisor, Prof. Bedangadas Mohanty, Dr. Ranbir Singh, Dr. Varchaswi Kashyap, ALICE collaborators and lab-mates for their support and guidance.

Efficiency correction: Impact on results

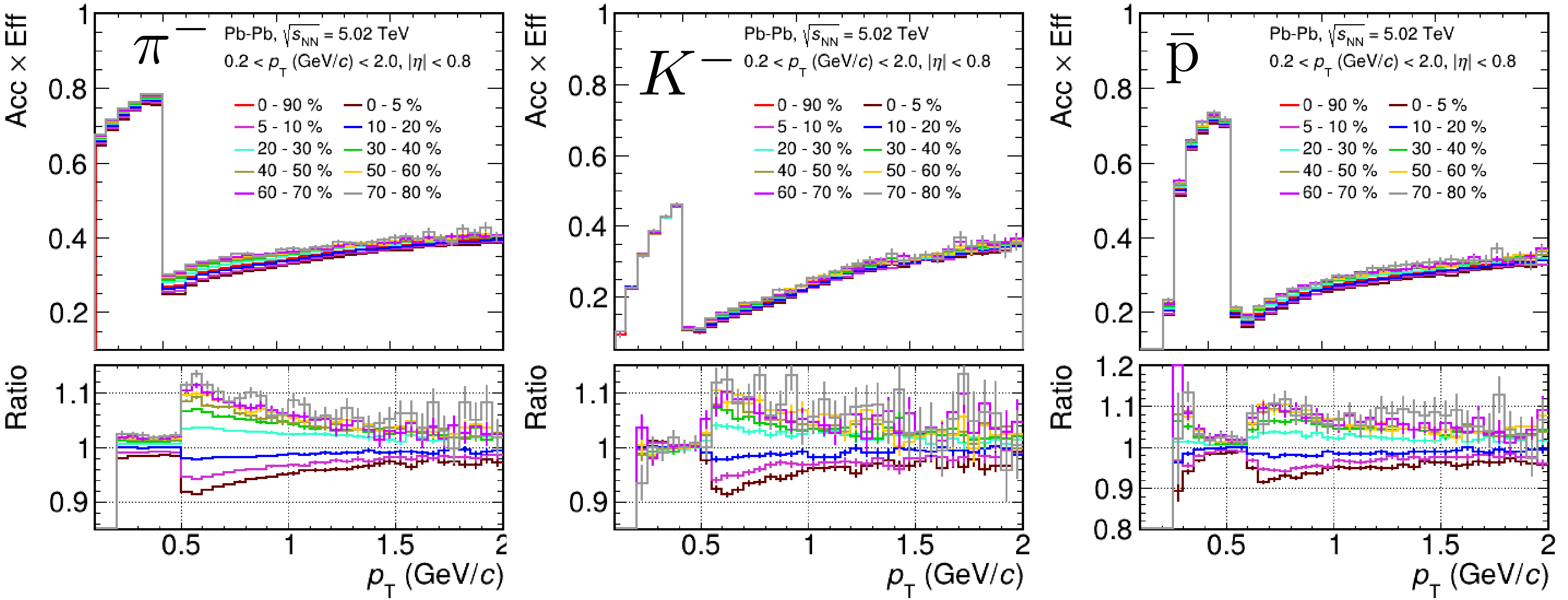


Cumulants using the efficiency corrected numbers of net-pion, net-kaon and net-proton are compared with the results obtained using uncorrected numbers.

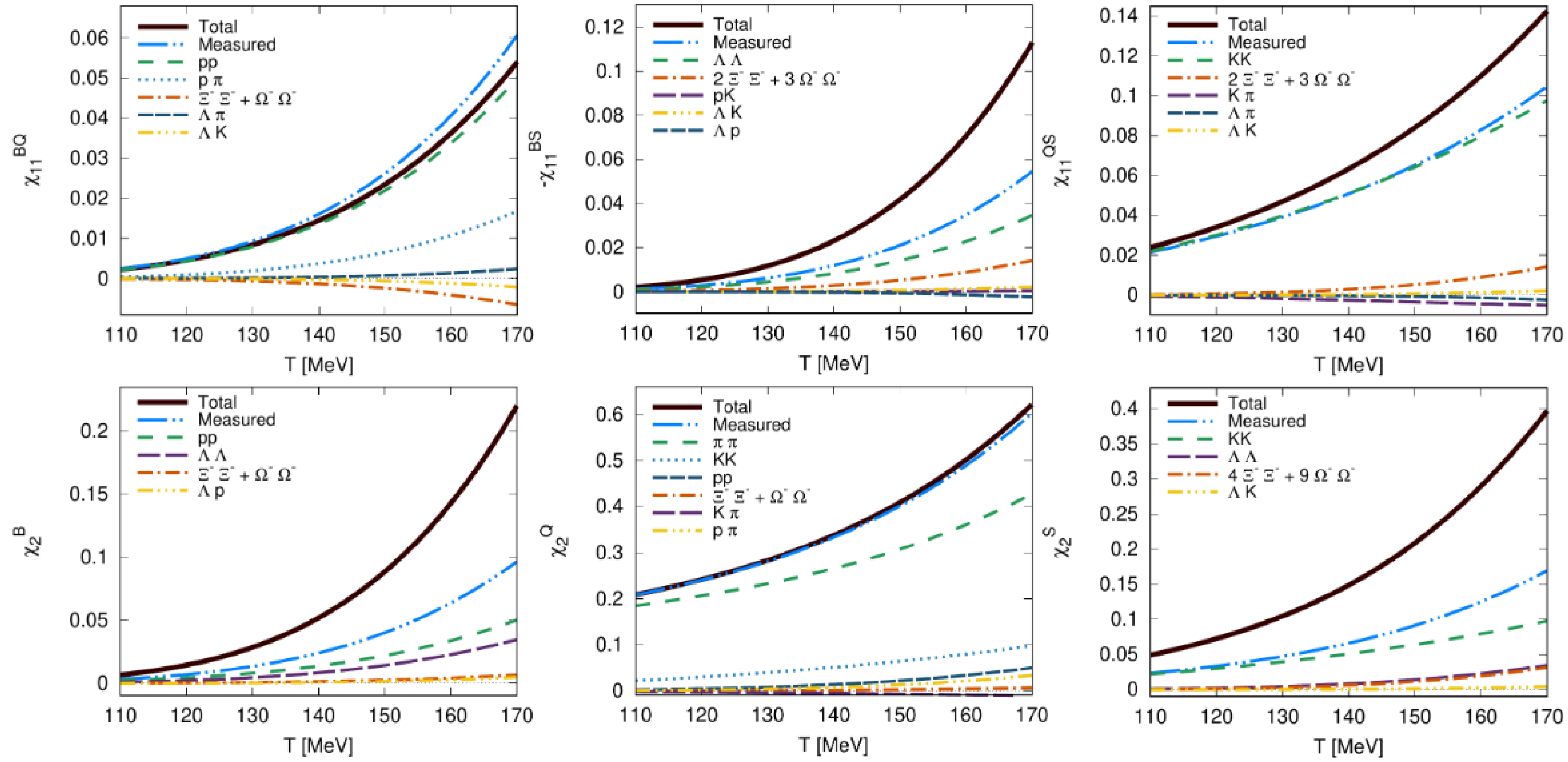
Track selection: Filterbit 96 cut

Standard tracks with tight DCA cut (bit 96 = 32 + 64)
SetMinNCrossedRowsTPC(70)
SetMinRatioCrossedRowsOverFindableClustersTPC(0.8)
SetMaxChi2PerClusterTPC(4)
SetAcceptKinkDaughters(kFALSE)
SetRequireTPCRefit(kTRUE)
SetRequireITSRefit(kTRUE)
SetClusterRequirementITS(kSPD, kAny)
SetRequireSigmaToVertex(kFALSE)
SetMaxChi2PerClusterITS(36)
SetMaxChi2TPCConstrainedGlobal(36)
SetMaxDCAToVertexXYPtDep("0.0105+0.035/pt^1.1")
SetMaxDCAToVertexZ(2)
SetDCAToVertex2D(kFALSE)
for 64: SetClusterRequirementITS(kSPD, kNone)
for 64: SetClusterRequirementITS(kSDD, kFirst)

Distributions of efficiency vs. p_T (anti-particles)



Breakdown of hadronic contribution



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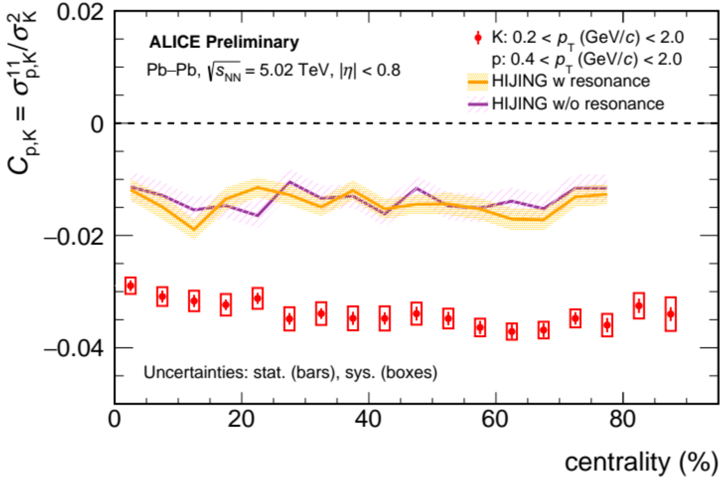
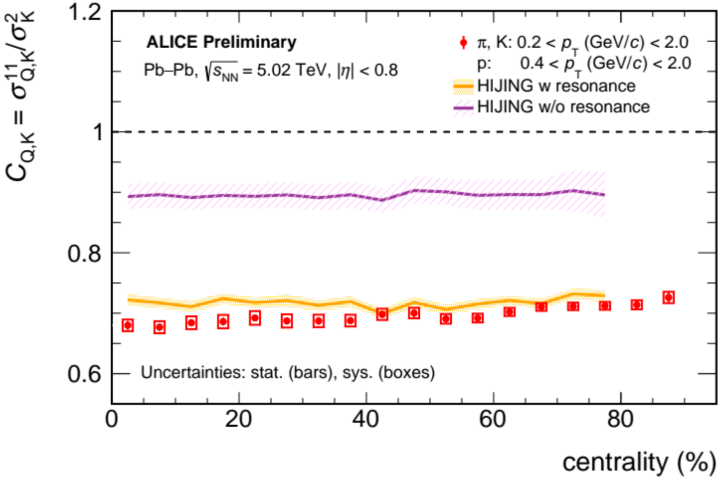
Effect of resonances





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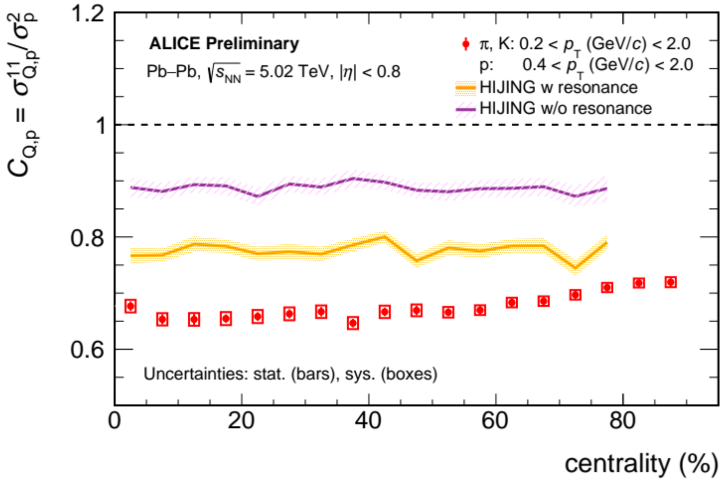
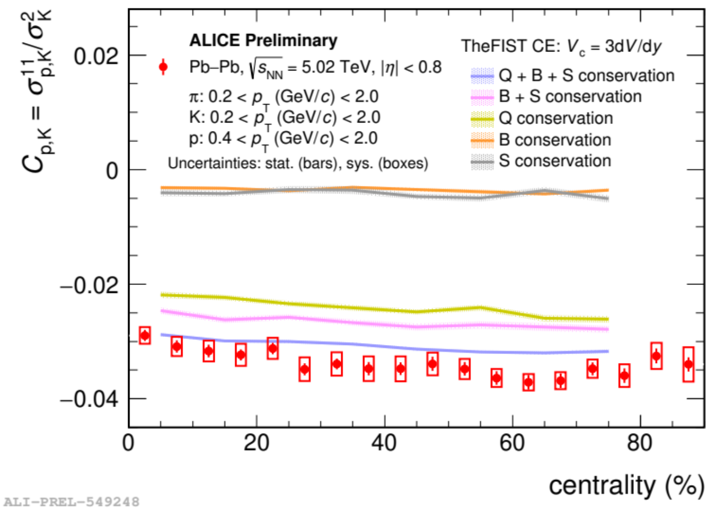
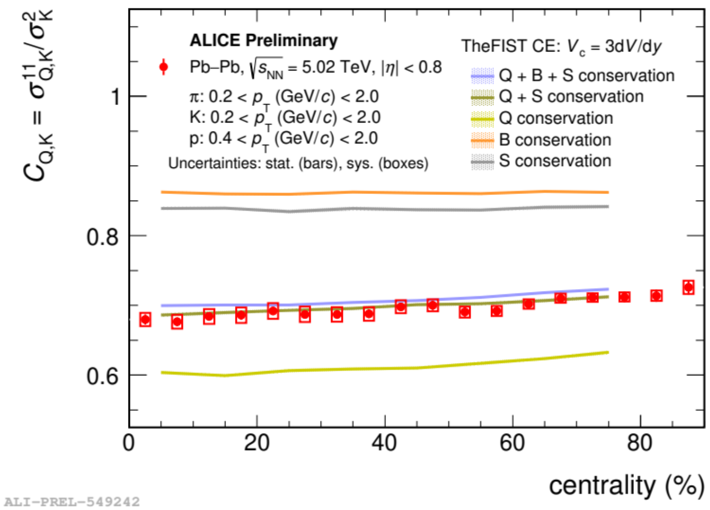


- Impact of resonance decays is studied in the HIJING model for $C_{p,K}$, $C_{Q,K}$ and $C_{Q,p}$.
- Negligible effect of resonance decays on $C_{p,K}$.
- Resonance decay suppresses the correlation. Measurement of $C_{Q,K}$ and $C_{Q,p}$ are influenced by resonance decays.

Effect of conservation of charges in canonical ensemble





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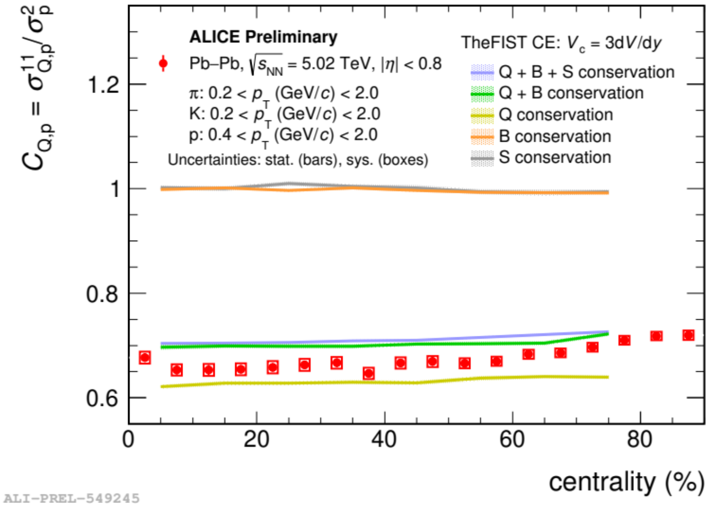

- Q conservation results in more suppression of the correlations compared to B and S conservation.
- Observed $C_{p,K}$, $C_{Q,K}$ and $C_{Q,p}$ in data is mostly captured by B+S, Q+S and Q+B conservation respectively in thermal model.
- Q+B+S conservation seems to explain best all the three correlation simultaneously.

Extracting Vc from combined Chi2

$$\chi^2_{\mathrm{combined}} = \chi^2_{C_{\mathrm{p,K}}} + \chi^2_{C_{\mathrm{Q,K}}} + \chi^2_{C_{\mathrm{Q,p}}}$$