Measurements of fluctuations of identified particles in ALICE at the LHC

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for the ALICE Collaboration

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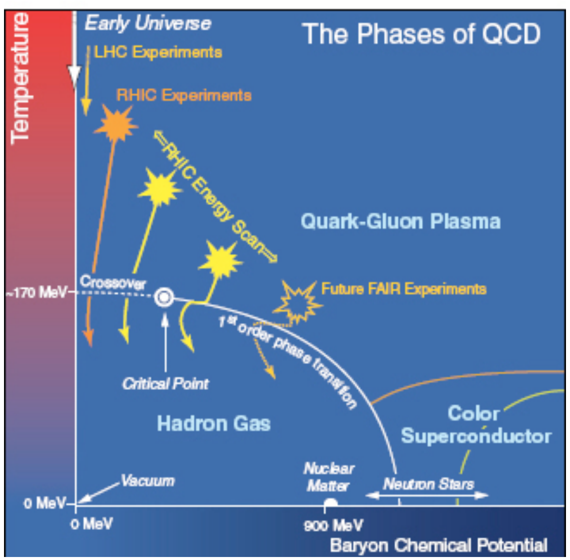
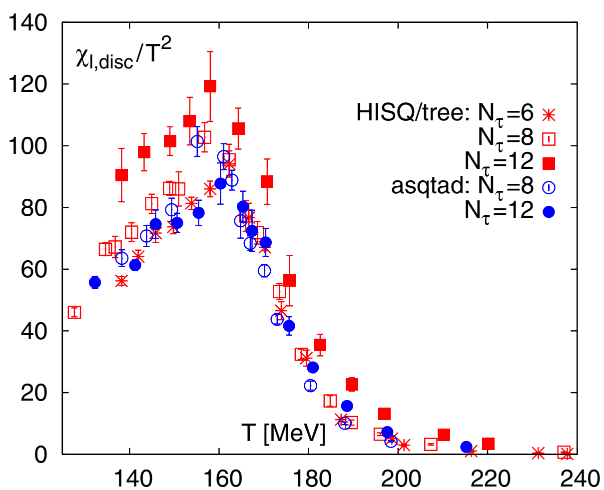
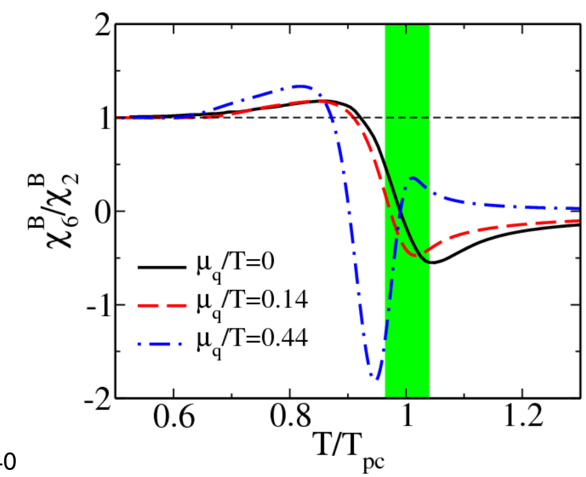
Fluctuations in heavy ion collisions

- Event-by-event fluctuations of particle multiplicities are used to study properties and phase structure of strongly-interacting matter
- In heavy-ion collisions at the LHC:
  - test lattice QCD predictions at $\mu_B = 0$
  - look for signs of criticality (may persist far from the phase transition!)





A. Bazavov et al. PRD 85 (2012) 054503, arXiv:1111.1710 [hep-lat]



K. Redlich, Central Eur. J. Phys. 10 (2012) 1254, arXiv:1207.2610 [hep-ph]

Connecting theory to experiment

- Thermodynamic susceptibilities χ
  - describe the response of a thermalized system to changes in external conditions, fundamental properties of the medium
  - can be calculated within lattice QCD
  - within the Grand Canonical Ensemble, are related to event-by-event fluctuations of the number of conserved charges

Theory:
susceptibilities

$$\chi_n^B = \frac{\partial^n \left(P/T^4\right)}{\partial\left(\mu_B/T^4\right)^n}$$

Experiment:
particle multiplicity distributions

$$\Delta N_B = N_B - N_{\bar{B}}$$

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Theory: susceptibilities

$$\chi_n^B = \frac{\partial^n \left(P/T^4\right)}{\partial\left(\mu_B/T^4\right)^n}$$

$$\langle \Delta N_B \rangle = VT^3 \chi_1^B$$

$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle\right)^2 \right\rangle = VT^3 \chi_2^B = \sigma^2$$

$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle\right)^3 \right\rangle \Big/ \sigma^3 = \frac{VT^3 \chi_3^B}{\left(VT^3 \chi_2^B\right)^{3/2}} = S$$

$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle\right)^4 \right\rangle \Big/ \sigma^4 - 3 = \frac{VT^3 \chi_4^B}{\left(VT^3 \chi_2^B\right)^2} = k$$

Experiment: particle multiplicity distributions

$$\Delta N_B = N_B - N_{\bar{B}}$$

Connecting theory to experiment

- Thermodynamic susceptibilities χ
  - describe the response of a thermalized system to changes in external conditions, fundamental properties of the medium
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Theory:
fixed volume,
particle bath in
GCE

$$\langle \Delta N_B \rangle \neq VT^3 \chi_1^B$$

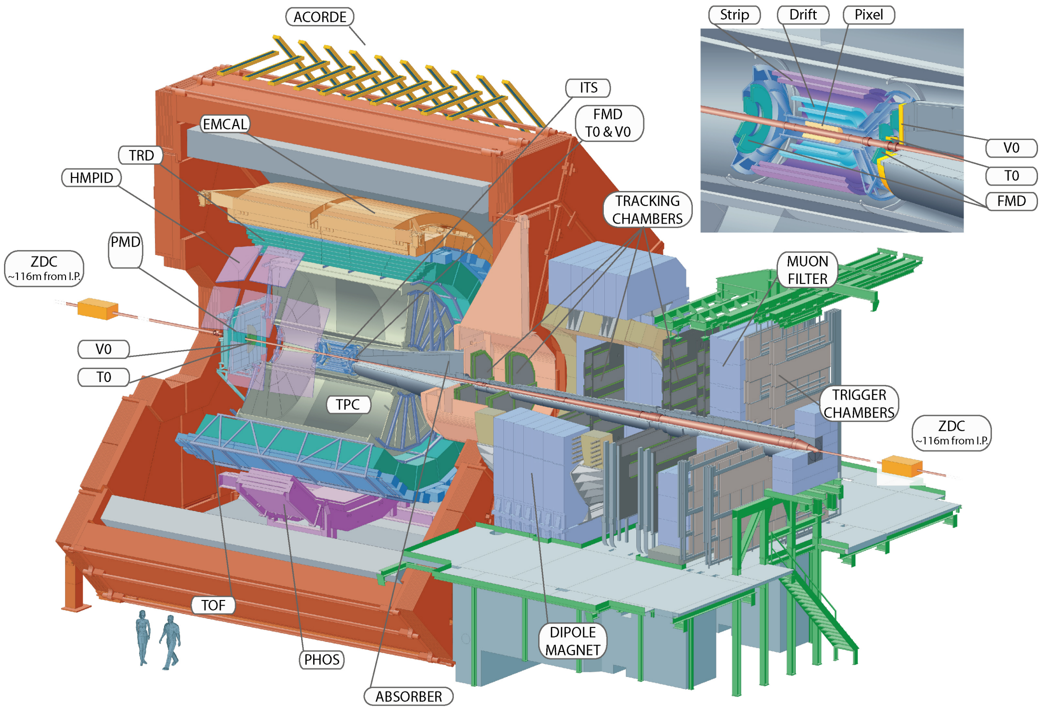
$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle \right)^2 \right\rangle \neq VT^3 \chi_2^B = \sigma^2$$

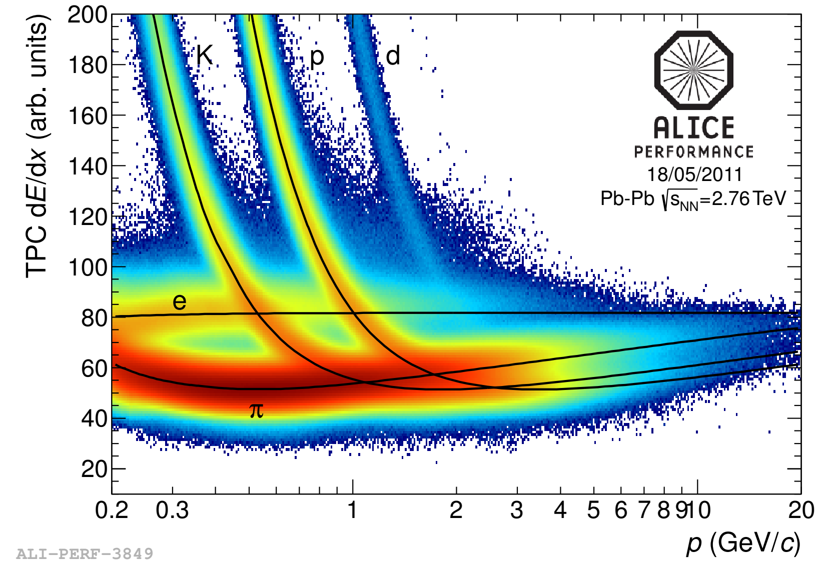
$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle \right)^3 \right\rangle / \sigma^3 \neq \frac{VT^3 \chi_3^B}{\left(VT^3 \chi_2^B \right)^{3/2}} = S$$

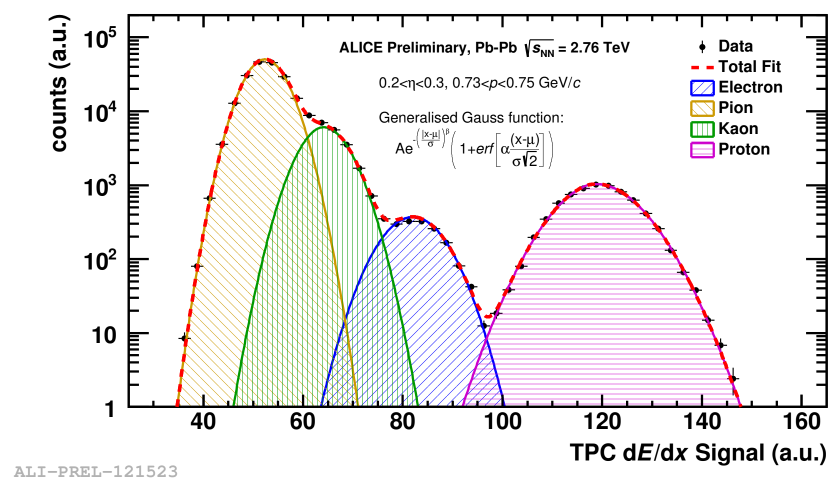
$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle \right)^4 \right\rangle / \sigma^4 - 3 \neq \frac{VT^3 \chi_4^B}{\left(VT^3 \chi_2^B \right)^2} = k$$

Experiment:
event-by-event
volume
fluctuations,
global
conservation
laws

Experimental Details







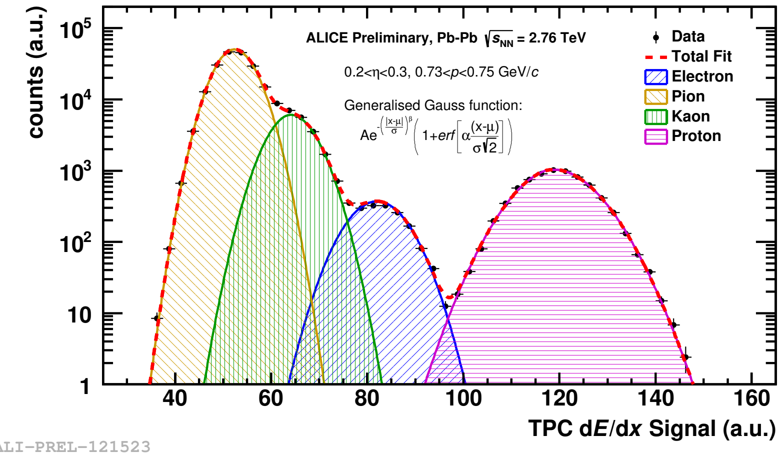
- Charged particle tracking using ITS+TPC
- Particle identification with dE/dx in the TPC
- Centrality determination in V0
  (-3.7 < η < -1.7 and 2.8 < η < 5.1)

Identity Method

- Particles are identified statistically, weights ($\omega_{\pi,K,p}$) are assigned according to probability that particle is of a given species
- Incorporate weights when calculating particle multiplicity in a given event

$$W_{\pi,K,p} = \sum_{tracks} \omega_{\pi,K,p}$$

- Find moments of W distribution, then transform into true moments
- Identity Method allows us to account for misidentification without lowering efficiency with strict d*E*/dx or TOF cuts



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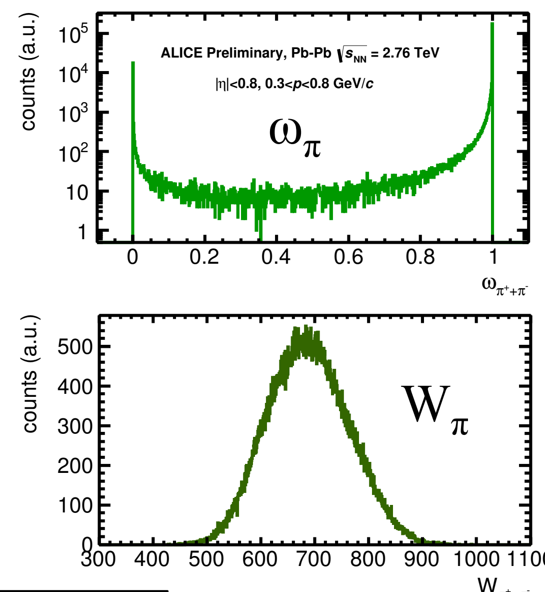

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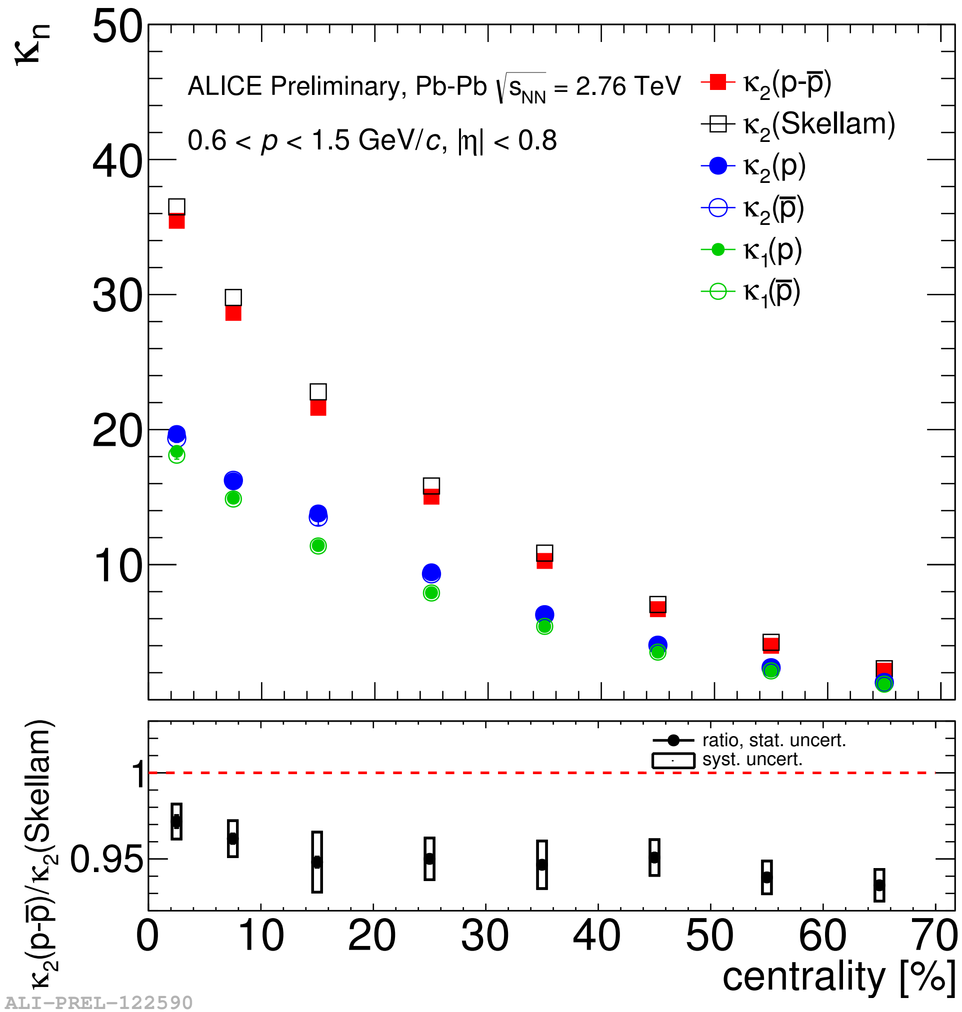
M. Gazdzicki et al., PRC 83 (2011) 054907, arXiv:1103.2887 [nucl-th]	M. I. Gorenstein, PRC 84, (2011) 024902, arXiv:1106.4473 [nucl-th]	A. Rustamov et al., PRC 86 (2012) 044906, arXiv:1204.6632 [nucl-th]

Net-proton fluctuations



$$\kappa_1(p) = \langle N_p \rangle \qquad \kappa_2(p) = \left\langle \left(N_p - \langle N_p \rangle \right)^2 \right\rangle$$

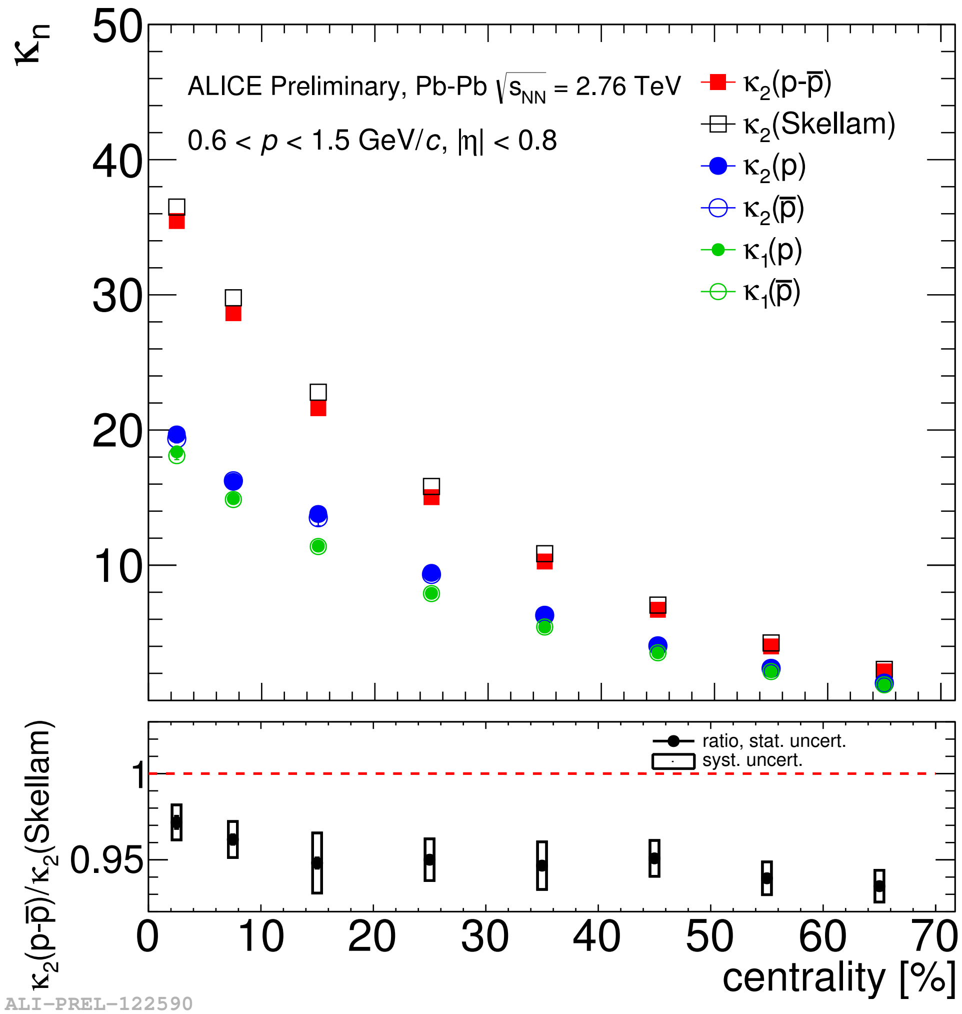
$$\kappa_2(p-\bar{p}) = \left\langle \left(N_p - N_{\bar{p}} - \langle N_p - N_{\bar{p}} \rangle \right)^2 \right\rangle$$

$$= \kappa_2(p) + \kappa_2(\bar{p}) - 2\underbrace{\left(\langle N_p N_{\bar{p}} \rangle - \langle N_p \rangle \langle N_{\bar{p}} \rangle \right)}_{\text{correlation term}}$$

- If multiplicity distributions of protons and anti-protons are Poissonian and uncorrelated
  → Skellam distribution for net-protons

$$\kappa_2(Skellam) = \kappa_1(p) + \kappa_1(\bar{p})$$

Net-proton fluctuations



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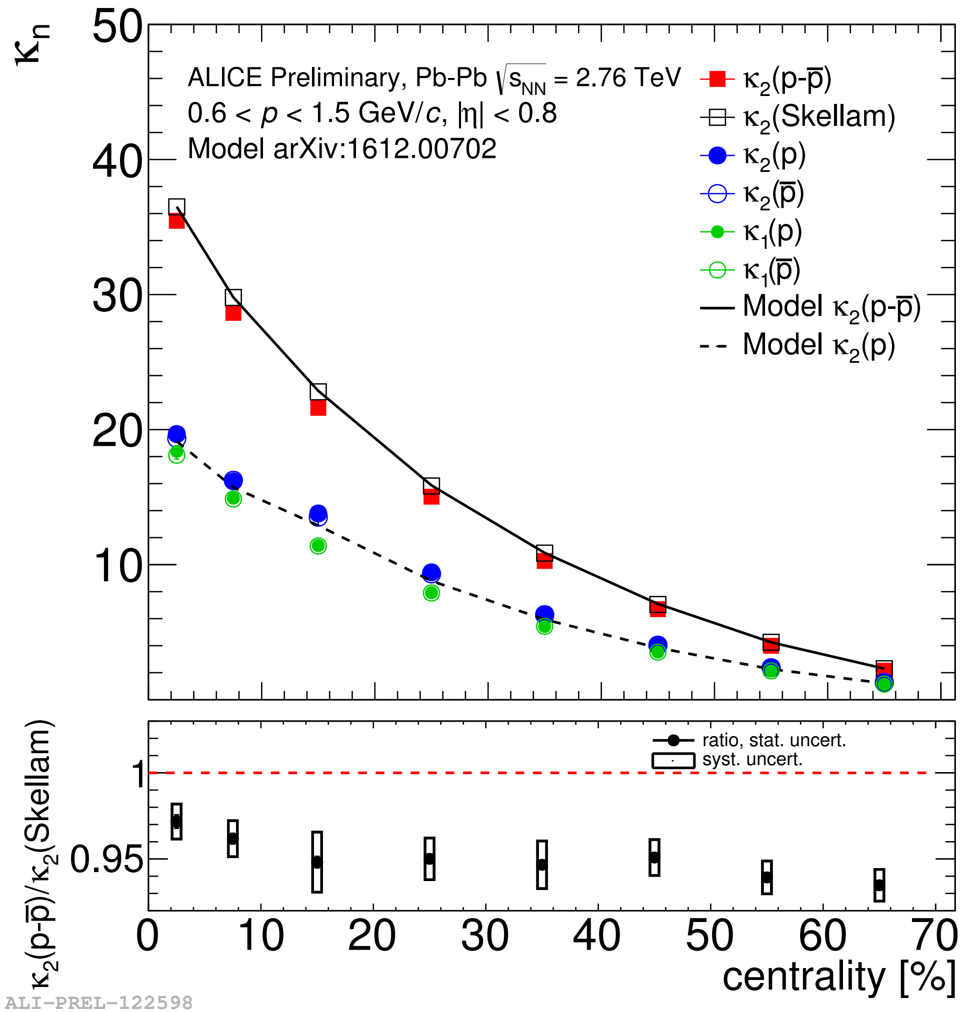
- $\kappa_2(p-\bar{p})$ shows deviation from Skellam prediction
  - due to correlation term?
  - are protons and anti-protons Poissonian?

$$\kappa_2(Skellam) = \kappa_1(p) + \kappa_1(\bar{p})$$

Net-proton fluctuations



- Modeling the effects of participant fluctuations

P. Braun-Munzinger et al., NPA 960 (2017) 114, arXiv:1612.00702 [nucl-th]

- Inputs to the model: $\kappa_1(p)$, $\kappa_1(\bar{p})$, centrality determination procedure

- Model gives a consistent picture of $\kappa_2(p)$, $\kappa_2(\bar{p})$ and $\kappa_2(p-\bar{p})$ without need of correlations or critical fluctuations

Global conservation laws

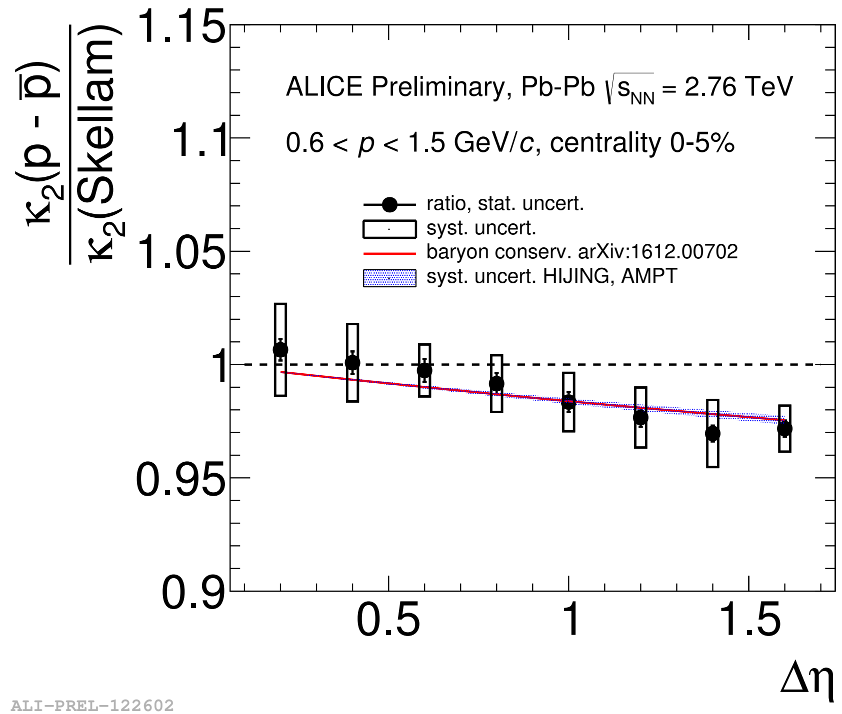
- Contribution from global baryon number conservation calculated as

$$\frac{\kappa_2(p-\bar{p})}{\kappa_2(Skellam)} = 1 - \frac{\langle N_p^{meas} \rangle}{\langle N_B^{4\pi} \rangle}$$

- Inputs for $<N_B^{acc}>$ from

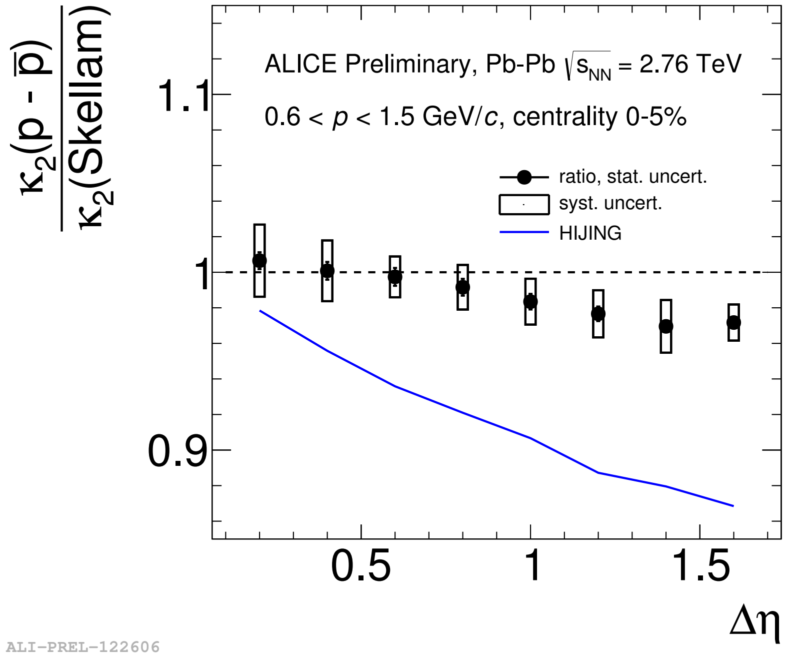
P. Braun-Munzinger et al., PLB 747 (2015) 292, arXiv:1412.8614 [hep-ph]

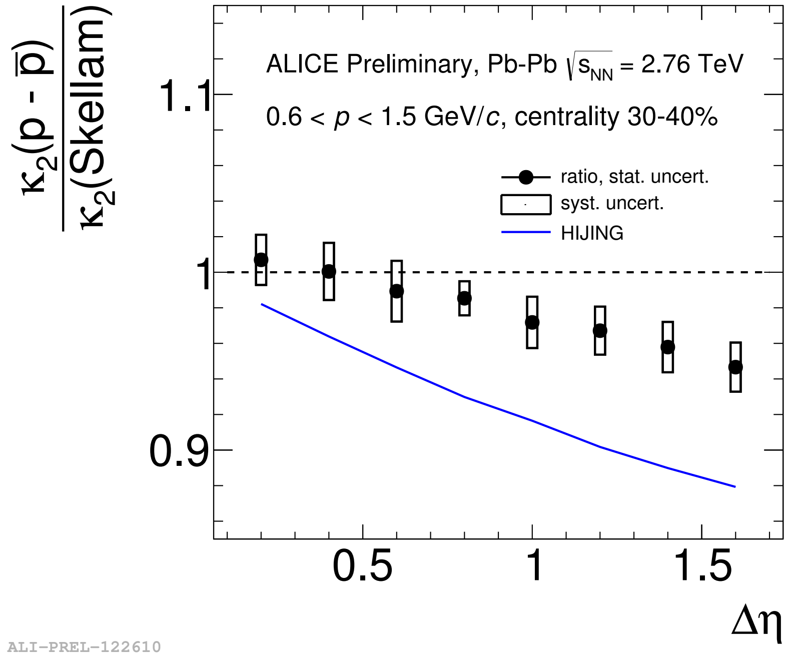
Extrapolation from $<N_B^{acc}>$ to $<N_B^{4\pi}>$ using AMPT and HIJING



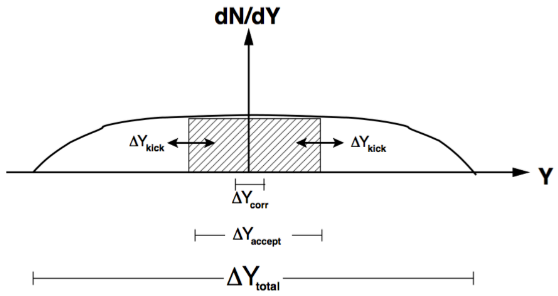
- Deviation from Skellam baseline accounted for by global baryon number conservation

Pseudorapidity dependence

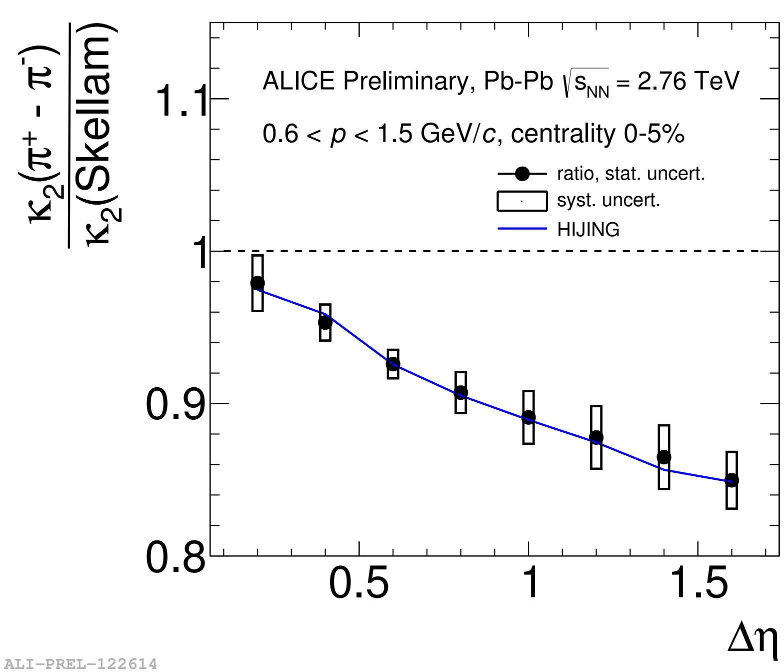


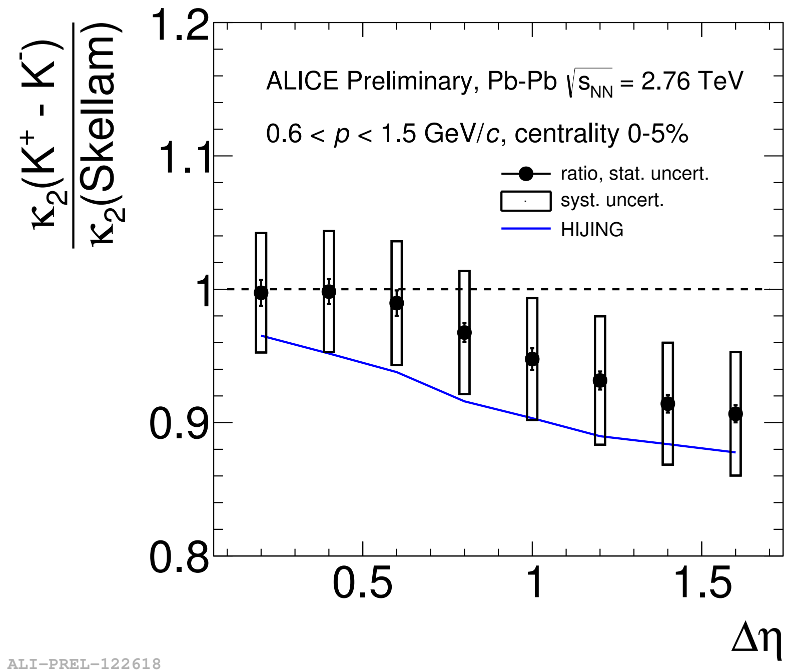


- Deviations from Skellam can be attributed global baryon number conservation, more significant in more peripheral collisions
- Disagreement with HIJING



Net-pion and net-kaon fluctuations





- Pions show good agreement with HIJING
- Production of pions and kaons from resonance decays contributes significantly to the measurement
- Skellam distribution is not a proper baseline for net-pions and net-kaons

Identified particle fluctuations -- ν_{dyn}

- Second moment of event-by-event correlated fluctuations of identified particle yields
  - N_A, N_B = number of pions, kaons, or protons in an event

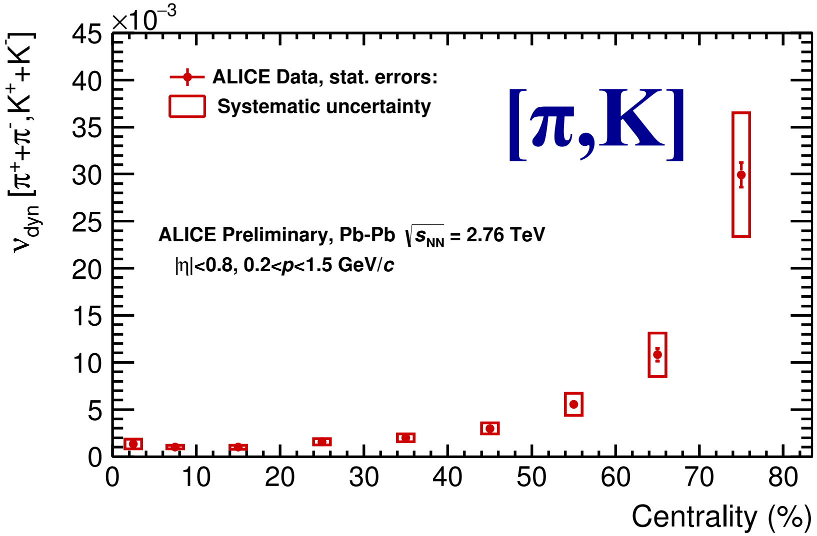
$$\nu = \left\langle \left(\frac{N_A}{\langle N_A \rangle} - \frac{N_B}{\langle N_B \rangle} \right)^2 \right\rangle$$

$$\boxed{\nu_{dyn}} = \underbrace{\frac{\langle N_A^2 \rangle}{\langle N_A \rangle^2} + \frac{\langle N_B^2 \rangle}{\langle N_B \rangle^2} - 2\frac{\langle N_A N_B \rangle}{\langle N_A \rangle \langle N_B \rangle}}_{\nu} - \underbrace{\left(\frac{1}{\langle N_A \rangle} + \frac{1}{\langle N_B \rangle} \right)}_{\nu_{stat}}$$

- $\nu_{dyn} = 0$ if N_A and N_B have Poissonian distributions and are uncorrelated

C. Pruneau et al., PRC 66 (2002) 044904, arXiv:nucl-ex/0204011

Dynamical fluctuations of π, K, p



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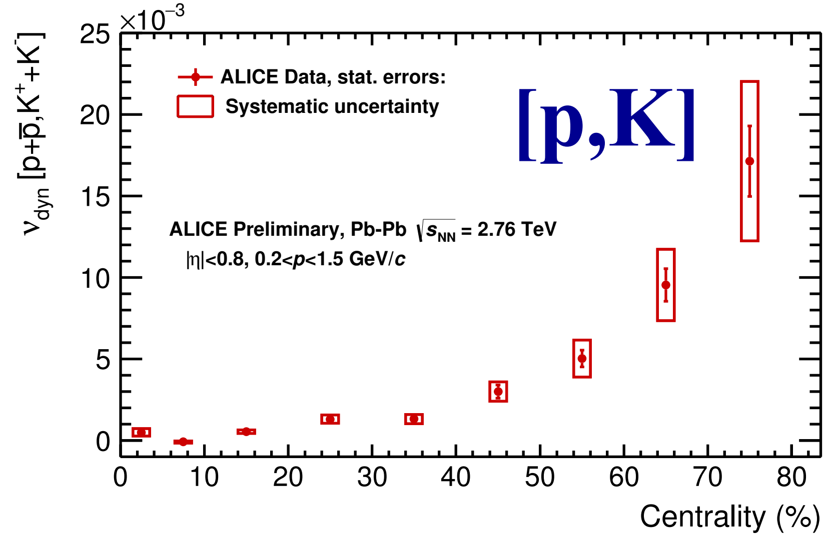

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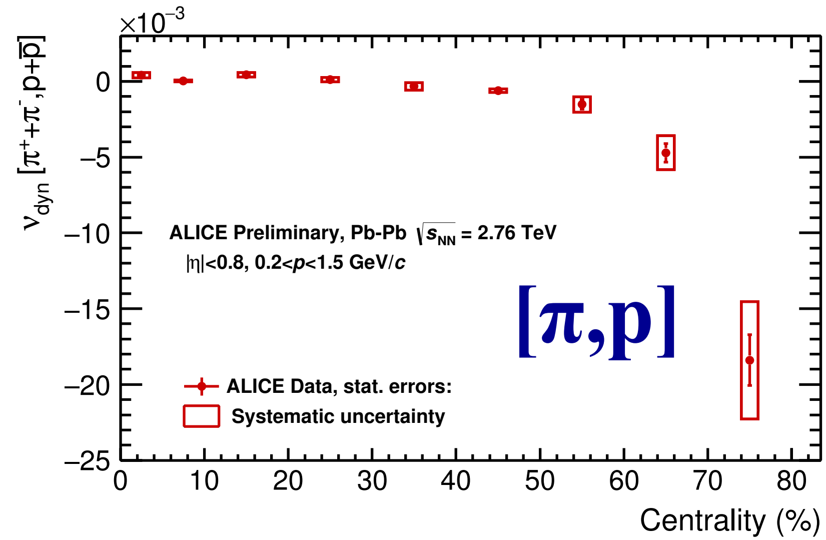
- Small ν_{dyn} in central events
- Deviations from Poisson expectation observed particularly in peripheral events
  - correlations due to jets, resonance decays, etc
  - multiplicity scaling



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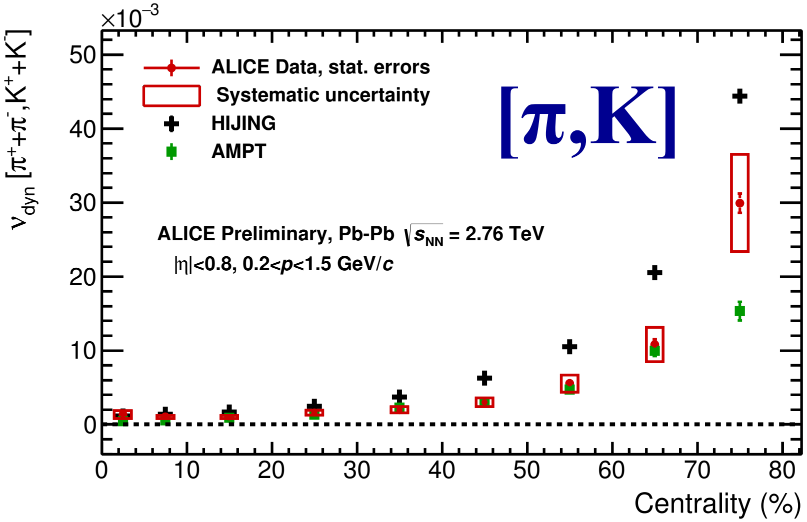
Model comparisons



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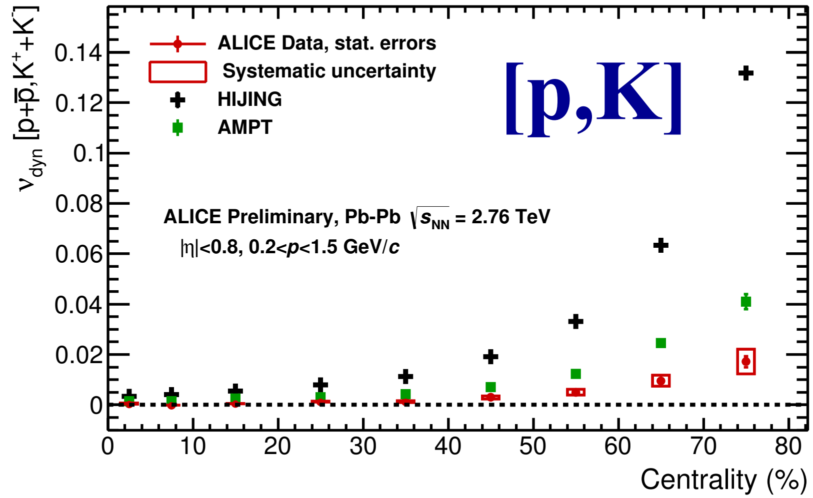

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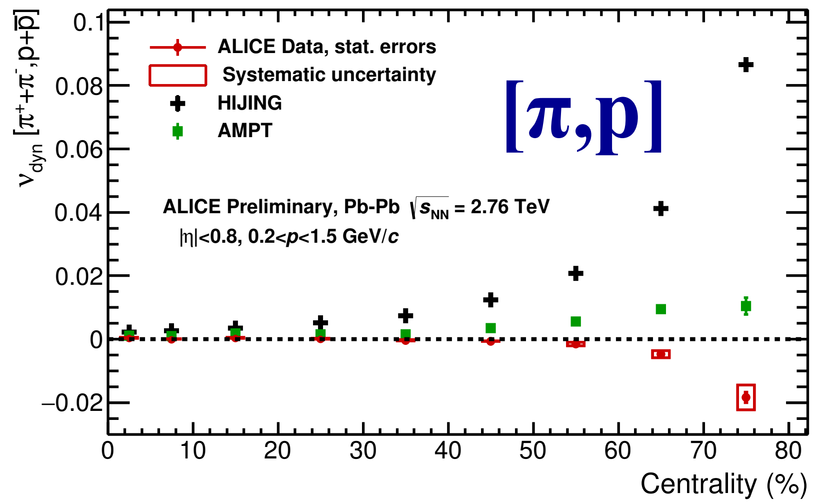
- Qualitative agreement with AMPT and HIJING for ν_{dyn}[π,K] and ν_{dyn}[p,K]
- Trend in peripheral collisions not reproduced for ν_{dyn}[π,p]



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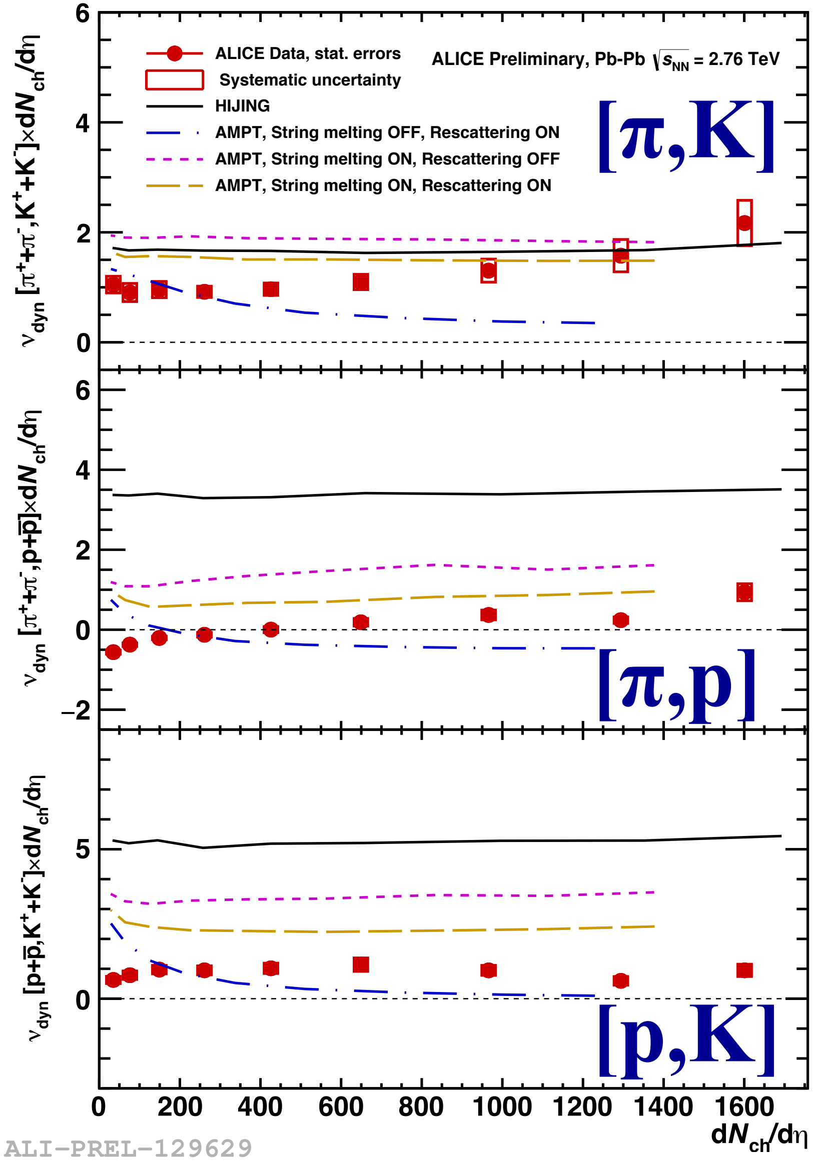
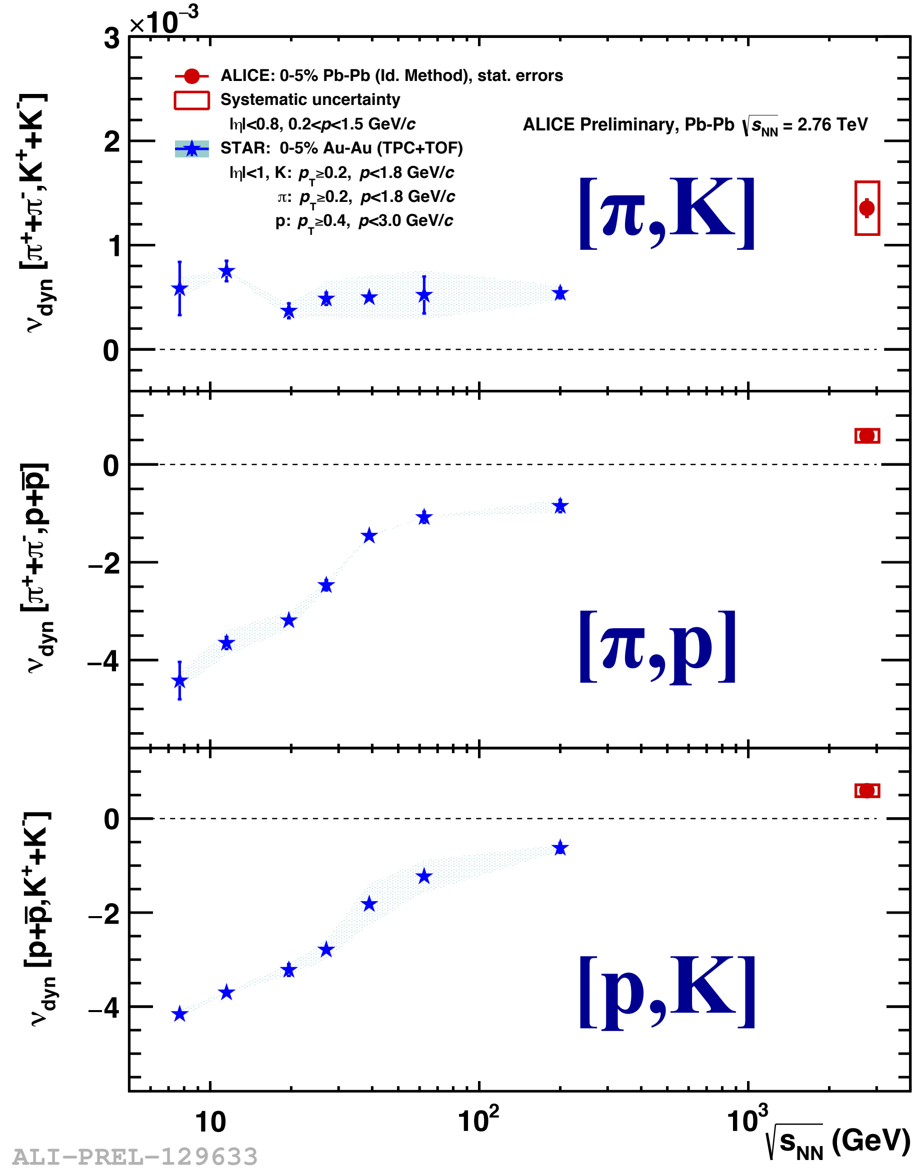
Multiplicity scaling

- ν_{dyn} contains multiplicity scaling, remove by multiplying by $dN_{ch}/d\eta$
- HIJING shows flat trend, but deviations from constant trend observed in data
- Changing settings in AMPT produces quantitatively different trends, but none show quantitative agreement with data



Energy dependence

- Roughly smooth evolution from RHIC BES energies to LHC
- Sign change in ν_{dyn} in most central events observed for $\nu_{dyn}[\pi,p]$ and $\nu_{dyn}[p,K]$



Conclusions

- Event-by-event fluctuations of identified particles
  - yield information on properties of the QGP medium
  - allow us to test LQCD predictions at $\mu_B = 0$
  - allow us to look for effects of criticality
- Studies of the second moments of multiplicity distributions have been performed with novel Identity Method
- Effects of volume fluctuations and global baryon number conservation are assessed
- Net-proton fluctuations: no deviations from Skellam baseline observed after accounting for baryon number conservation, agreement with LQCD predictions, disagreement with HIJING,
- $\nu_{dyn}[\pi,K]$, $\nu_{dyn}[p,K]$, $\nu_{dyn}[\pi,p]$ show qualitative agreement with models, sign change but smooth evolution with beam energy
- Investigations of higher moments (and more) are ongoing with Run 2 data... stay tuned!

backup

Energy dependence including NA49