Recent developments in particle yield fluctuation measurements

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What do we mean by “fluctuation measurements”

Many “event-averaged” observables can be studied:
particle yields, spectra, flow harmonics, two-particle correlations…

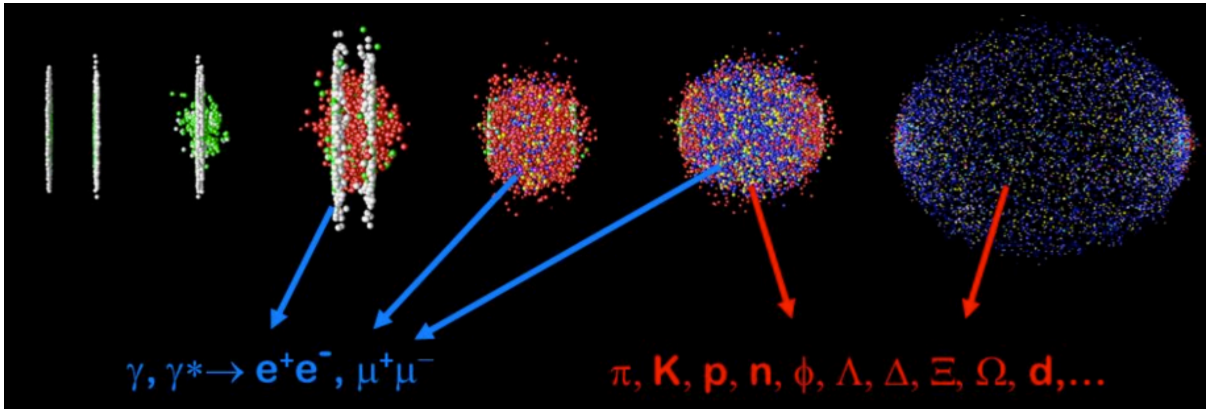
Fluctuation measurements:
when a given observable is measured on *an event-by-event basis,*
and the fluctuations are studied over the ensemble of the events.

- fluctuating net-charge, number of protons, mean-p_T, forward-backward yields, etc.

Why e-by-e fluctuations:

- they help to characterize the **properties of the “bulk” of the system**
- fluctuations also are closely related to **dynamics of the phase transitions**

→ A non-monotonic behaviour with experimentally varied parameter such as the collision energy, centrality, system size, rapidity



What do we want from observables?

Usually we want to have an observable which is (1) sensitive to some particular physics phenomena and (2) insensitive to other.

***E-by-e* analyses are much more sensitive to different biases**
(than "event-averaged" observables). **"A long list" of troubles:**

- non-flat efficiency, its dependence on multiplicity
- contamination by secondary particles
- detector acceptance
- conservation laws
- resonance decays
- trivial fluctuations of collision geometry ("volume fluctuations")

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Our experience teaches: it's not enough just to define an arbitrary observable:

- need to know how robust it is in a real experiment
- provide a correction procedure if needed

In this talk:

- some observables will be discussed (properties, experimental results)
- new fluctuation observables are introduced

1 Measures for multiplicity fluctuations: the ν_{dyn} observable

Particle number fluctuations can be quantified by:

- Variance – an *extensive* observable, "bad"
- Scaled variance – *intensive*, but affected by "volume fluctuations"
- **Observables which are robust to "volume fluctuations"**

$$\omega = \frac{\langle n^2\rangle - \langle n\rangle^2}{\langle n\rangle}$$

Take particle number ratio:

$$R = n_A/n_B \Rightarrow \nu \equiv \frac{\langle \Delta R^2\rangle}{\langle R\rangle^2} = \left\langle \left(\frac{n_A}{\langle n_A\rangle} - \frac{n_B}{\langle n_B\rangle} \right)^2 \right\rangle$$

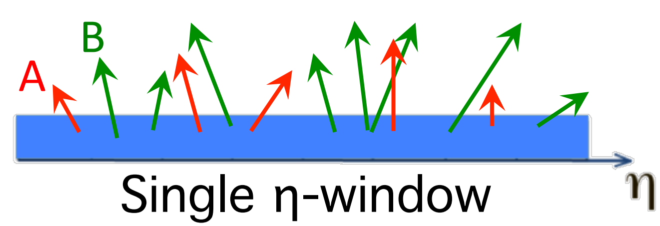
In case of Poissonian particle production:

$$\nu_{stat} = \frac{1}{\langle n_A\rangle} + \frac{1}{\langle n_B\rangle}, \quad \nu_{dyn} = \nu - \nu_{stat}$$

$$\nu_{dyn} = \frac{\langle n_A(n_A-1)\rangle}{\langle n_A\rangle^2} + \frac{\langle n_B(n_B-1)\rangle}{\langle n_A\rangle^2} - 2\frac{\langle n_A n_B\rangle}{\langle n_A\rangle\langle n_B\rangle}$$

Pruneau, Voloshin, Gavin
Phys.Rev. C66 (2002) 044904

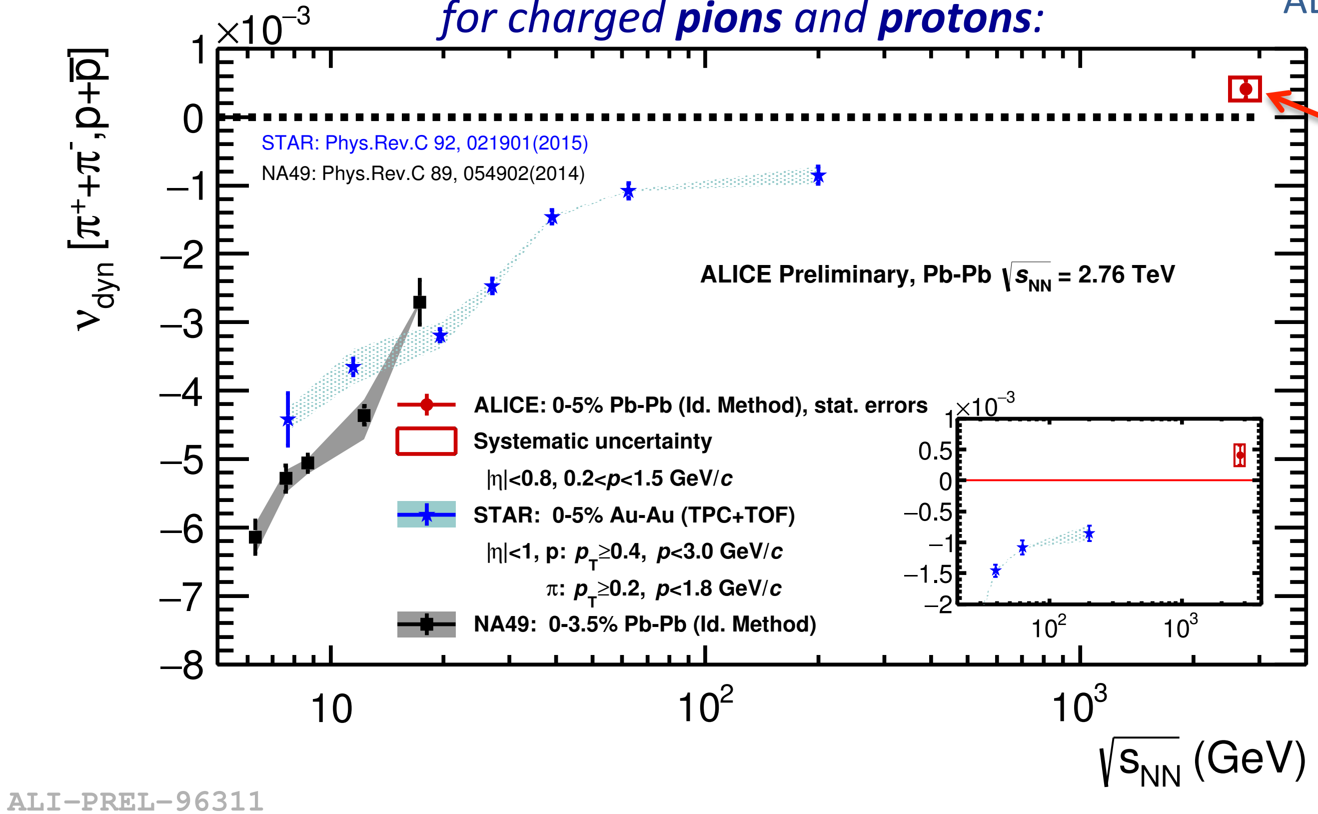
- Measures deviations from Poissonian behaviour
- Correlations between particles A, B
- Robust against efficiency losses
- Is a single-window observable



1 Multiplicity fluctuations with v_{dyn} at different energies

ALICE, arXiv:1712.07929 (2017)

*for charged **pions** and **protons**:*



Sign change at LHC energies!

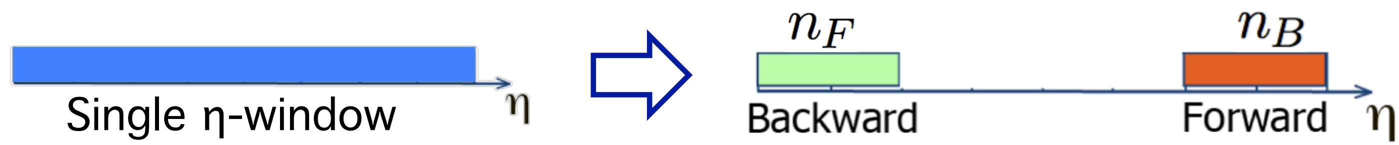
- Sign change! But it is seen also in the **URQMD** and **HSD** where there are no quark-gluon degrees of freedom

  → String and resonance dynamics used in the models?

→ No sign of critical behavior so far…

- Acceptance coverage is crucial, also resonance contributions should be better understood

Forward-backward multiplicity fluctuations with Σ



A strongly-intensive observable:

M. I. Gorenstein, M. Gazdzicki
PRC 84, 014904 (2011)

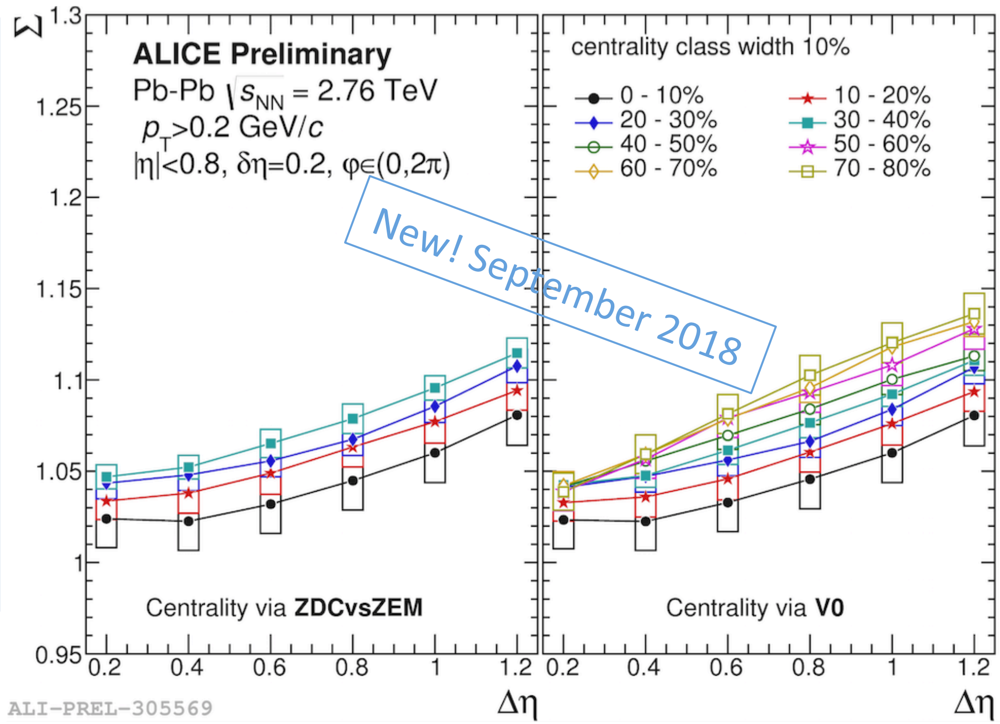
$$\Sigma(n_F, n_B) \equiv \frac{\langle n_F \rangle \omega_{n_B} + \langle n_B \rangle \omega_{n_F} - 2\,\mathrm{cov}(n_F\, n_B)}{\langle n_F \rangle + \langle n_B \rangle}$$

- *In independent sources model:*
measures the properties of a single source.

E.Andronov, V.Vechernin
arXiv:1808.09770 (2018)

- *For Poissonian particle production: Σ=1*

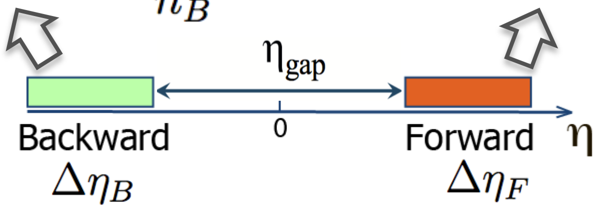
- Σ is robust to volume fluctuations:
  - no dependence on centrality bin width and estimator
- easy correction (needed just for <n_{ch}>)



- *ALICE data:* peculiar change of Σ with centrality
- Not reproduced in models so far

3 Not only FB *multiplicity* correlations – can take *mean* p_T!

$$B \equiv \overline{p_T}_B = \frac{\sum_{i=1}^{n_B} p_T^{(i)}}{n_B} \qquad F \equiv \overline{p_T}_F = \frac{\sum_{j=1}^{n_F} p_T^{(j)}}{n_F}$$

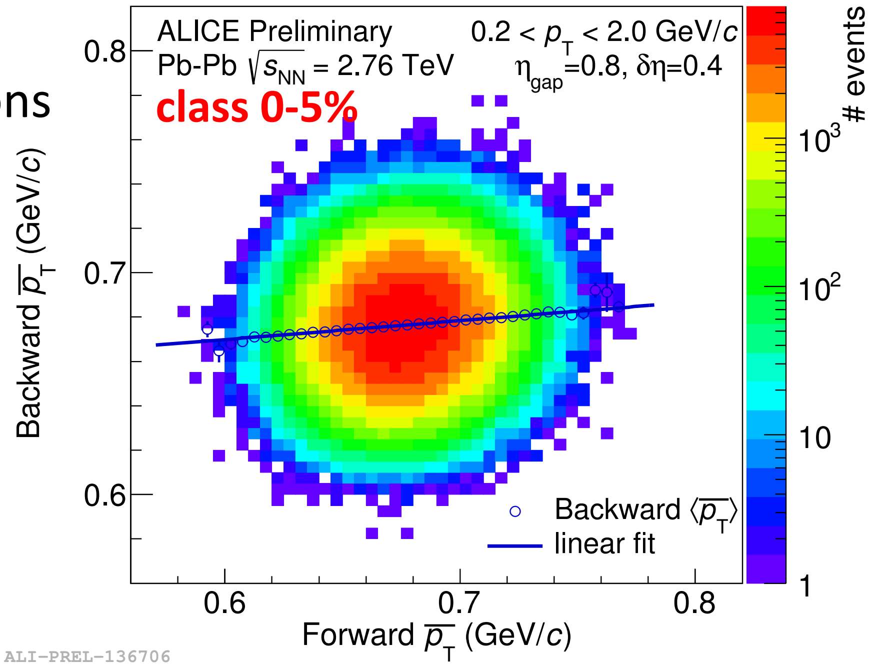


Quantify correlations using the correlation coefficient:

$$b_{corr}^{p_T - p_T} = \frac{\langle \overline{p_F}\,\overline{p_B} \rangle - \langle \overline{p_F} \rangle \langle \overline{p_B} \rangle}{\langle \overline{p_F}^2 \rangle - \langle \overline{p_F} \rangle^2}$$

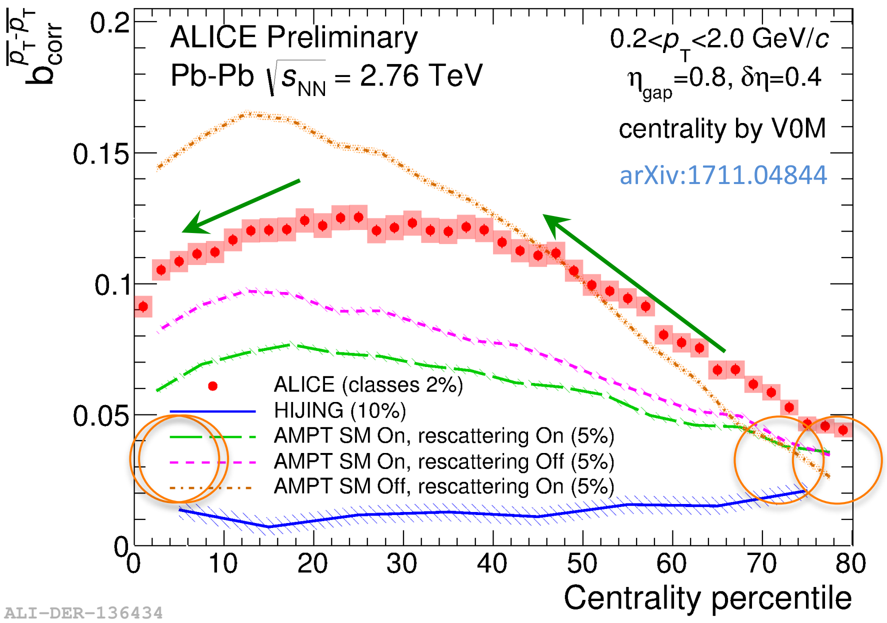
ALICE, J. Phys. G: Nucl. Part. Phys. 32 1295 (2006)

Example:
correlation in central collisions



→ Correlation coefficient b_{corr} is the slope of the linear fit.

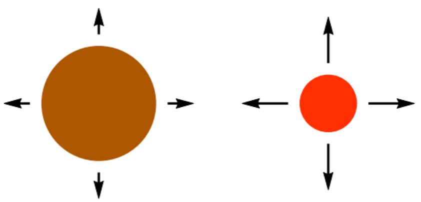
3 FB *mean-p_T* correlations: data and the interpretation



What can cause mean-p_T FB correlations?

Size fluctuations ↔ p_T fluctuations

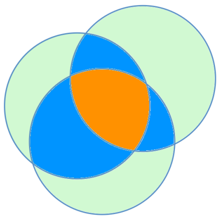
Phys. Rev. C 96, 014904 (2017)



– pressure gradients in the fireball reflect the fluctuations of the density in the fireball.

String fusion model

Nucl. Phys. B 390 542–558 (1993)



strings overlap
→ modification of string tension
→ increased p_T of particles from the fused strings

Monte Carlo realization: arXiv:1308.6618

Correlation strength:
- robust to volume fluctuations!
- rises from peripheral to mid-central
- **drops towards central collisions**

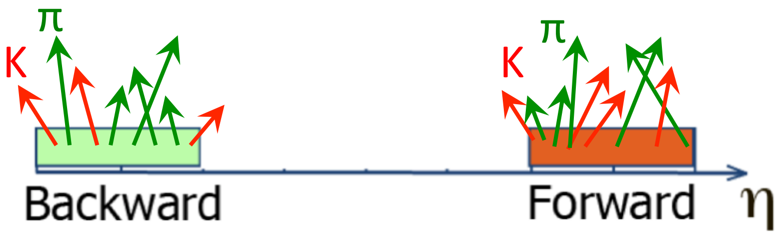
- **Mean-p_T correlations** are sensitive to the properties of the initial state.
  - Non-trivial to explain **the centrality trend of mean-p_T correlations.**

4 FB correlations between ratios of particle yields

Definition:

take ratios r^F and r^B of particle yields in F and B windows event-by-event and define *a correlation strength* as:

$$b_{\mathrm{corr}} = \frac{\langle r^F \cdot r^B \rangle}{\langle r^F \rangle \langle r^B \rangle} - 1$$



Example: kaon-to-pion ratio $\boldsymbol{r = n_K / n_\pi}$.

Some properties:

- if independent particle production → $b_{\mathrm{corr}} = 0$
- if only short-range effects (decays, jets) suppressed at large η_{gap} → $b_{\mathrm{corr}} = 0$
  – not the case for the "classical" ν_{dyn}!

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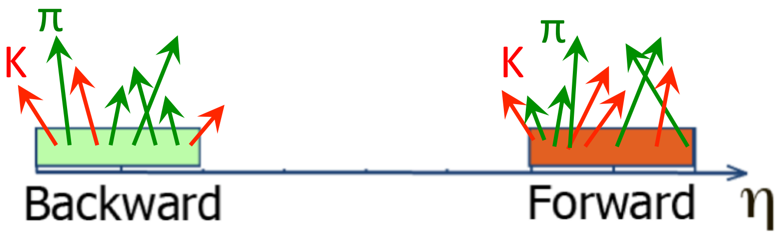

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Physics case of interest:

correlations between strangeness production at large η gaps (string interactions, thermal models, ...)

4 Approximation for the correlation strength

<u>If number of produced particles is large</u> (i.e. non-peripheral A-A):

$$\alpha_F = \frac{\Delta n_K^F}{\langle n_K^F \rangle},\ \beta_F = \frac{\Delta n_\pi^F}{\langle n_\pi^F \rangle},\ \alpha_B = \frac{\Delta n_K^B}{\langle n_K^B \rangle},\ \beta_B = \frac{\Delta n_\pi^B}{\langle n_\pi^B \rangle},$$

$$\Rightarrow \quad b_{\mathrm{corr}} = \frac{\langle r^F \cdot r^B \rangle}{\langle r^F \rangle \langle r^B \rangle} - 1 \quad \approx ?$$

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$$= \frac{\langle \alpha_F \alpha_B \rangle + \langle \beta_F \beta_B \rangle - \langle \alpha_F \beta_B \rangle - \langle \alpha_B \beta_F \rangle - \langle \alpha_F \beta_F \rangle - \langle \alpha_B \beta_B \rangle + \langle \beta_F^2 \rangle + \langle \beta_B^2 \rangle - \langle \beta_F^2 \rangle - \langle \beta_B^2 \rangle + \langle \alpha_F \beta_F \rangle + \langle \alpha_B \beta_B \rangle}{1 + \langle \beta_F^2 \rangle + \langle \beta_B^2 \rangle - \langle \alpha_F \beta_F \rangle - \langle \alpha_B \beta_B \rangle}$$

$$\approx \langle \alpha_F \alpha_B \rangle + \langle \beta_F \beta_B \rangle - \langle \alpha_F \beta_B \rangle - \langle \alpha_B \beta_F \rangle \ .$$

$$b_{corr} \approx \frac{\langle n_K^F n_K^B \rangle}{\langle n_K^F \rangle \langle n_K^B \rangle} + \frac{\langle n_\pi^F n_\pi^B \rangle}{\langle n_\pi^F \rangle \langle n_\pi^B \rangle} - \frac{\langle n_K^F n_\pi^B \rangle}{\langle n_K^F \rangle \langle n_\pi^B \rangle} - \frac{\langle n_\pi^F n_K^B \rangle}{\langle n_\pi^F \rangle \langle n_K^B \rangle}$$

"same-species" terms — "cross-species" terms

$$\equiv R_{KK} + R_{\pi\pi} - R_{K\pi} - R_{\pi K}$$

- ✓ robust to efficiency (as ν_{dyn})
- ✓ it's possible **to apply the Identity Method** for this class of observables!

(discussed later)

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<u>If number of produced particles is large</u> (i.e. non-peripheral A-A):

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$$\Rightarrow\ b_{\mathrm{corr}} = \frac{\langle r^F \cdot r^B\rangle}{\langle r^F\rangle\langle r^B\rangle} - 1 \approx \frac{\left\langle \frac{(1+\alpha_F)(1+\alpha_B)}{(1+\beta_F)(1+\beta_B)}\right\rangle}{\left\langle \frac{1+\alpha_F}{1+\beta_F}\right\rangle\left\langle \frac{1+\alpha_B}{1+\beta_B}\right\rangle} - 1 =$$

$$= \frac{\langle\alpha_F\alpha_B\rangle + \langle\beta_F\beta_B\rangle - \langle\alpha_F\beta_B\rangle - \langle\alpha_B\beta_F\rangle - \langle\alpha_F\beta_F\rangle - \langle\alpha_B\beta_B\rangle + \langle\beta_F^2\rangle + \langle\beta_B^2\rangle - \langle\beta_F^2\rangle - \langle\beta_B^2\rangle + \langle\alpha_F\beta_F\rangle + \langle\alpha_B\beta_B\rangle}{1 + \langle\beta_F^2\rangle + \langle\beta_B^2\rangle - \langle\alpha_F\beta_F\rangle - \langle\alpha_B\beta_B\rangle}$$

$$\approx \langle\alpha_F\alpha_B\rangle + \langle\beta_F\beta_B\rangle - \langle\alpha_F\beta_B\rangle - \langle\alpha_B\beta_F\rangle\ .$$

$$b_{\mathrm{corr}} \approx \frac{\langle n^F_{\mathrm{K}} n^B_{\mathrm{K}}\rangle}{\langle n^F_{\mathrm{K}}\rangle\langle n^B_{\mathrm{K}}\rangle} + \frac{\langle n^F_{\pi} n^B_{\pi}\rangle}{\langle n^F_{\pi}\rangle\langle n^B_{\pi}\rangle} - \frac{\langle n^F_{\mathrm{K}} n^B_{\pi}\rangle}{\langle n^F_{\mathrm{K}}\rangle\langle n^B_{\pi}\rangle} - \frac{\langle n^F_{\pi} n^B_{\mathrm{K}}\rangle}{\langle n^F_{\pi}\rangle\langle n^B_{\mathrm{K}}\rangle}$$

"same-species" terms — "cross-species" terms

$$\equiv R_{KK} + R_{\pi\pi} - R_{K\pi} - R_{\pi K}$$

- ✓ robust to efficiency (as ν_{dyn})
- ✓ it's possible **to apply the Identity Method** for this class of observables!

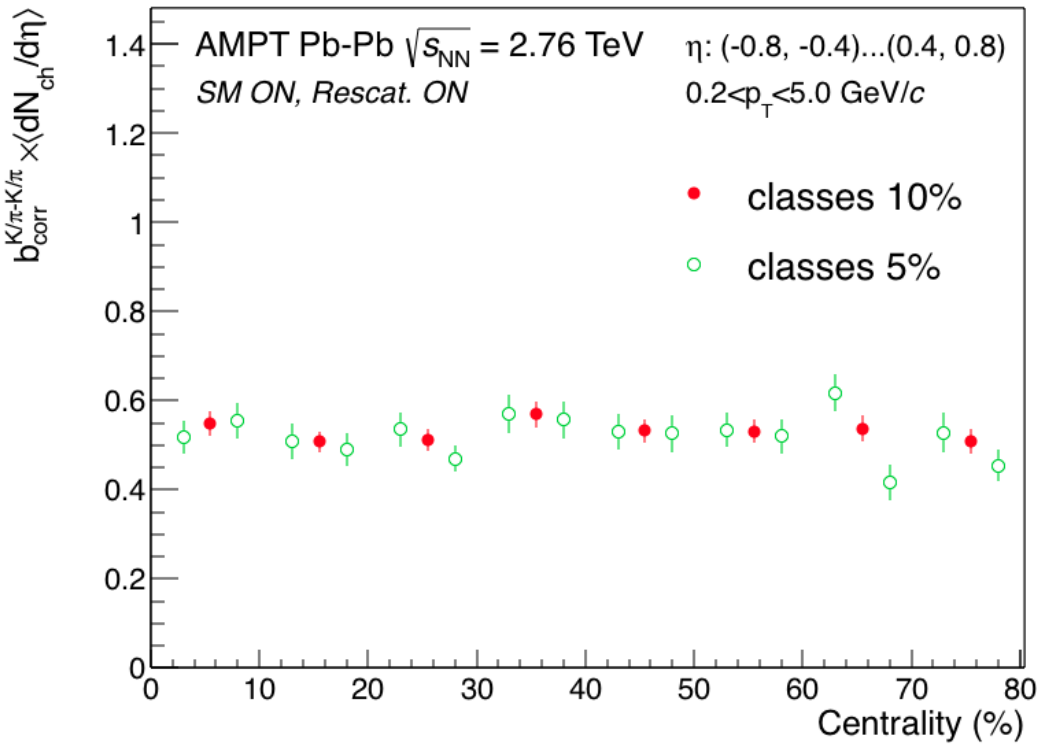
(discussed later)

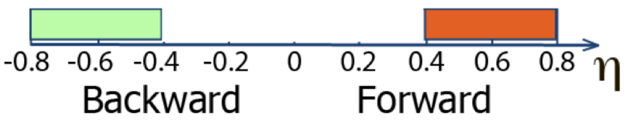
Note: we can recognize a similar "structure" of the observable as in the balance function:

$$\mathrm{BF} \sim R_{++} + R_{--} - R_{+-} - R_{-+}$$

⇨ BF can be considered as the approximation to forward-backward b_{corr} between $r = n+/n-$!

4 FB correlations between K/π ratios in models





$$b_{corr} \approx \frac{\langle n_K^F n_K^B \rangle}{\langle n_K^F \rangle \langle n_K^B \rangle} + \frac{\langle n_\pi^F n_\pi^B \rangle}{\langle n_\pi^F \rangle \langle n_\pi^B \rangle} - \frac{\langle n_K^F n_\pi^B \rangle}{\langle n_K^F \rangle \langle n_\pi^B \rangle} - \frac{\langle n_\pi^F n_K^B \rangle}{\langle n_\pi^F \rangle \langle n_K^B \rangle}$$

In an independent sources model:

$$b_{corr} = \frac{1}{\langle N_{sources} \rangle} b_{corr}^{source}$$

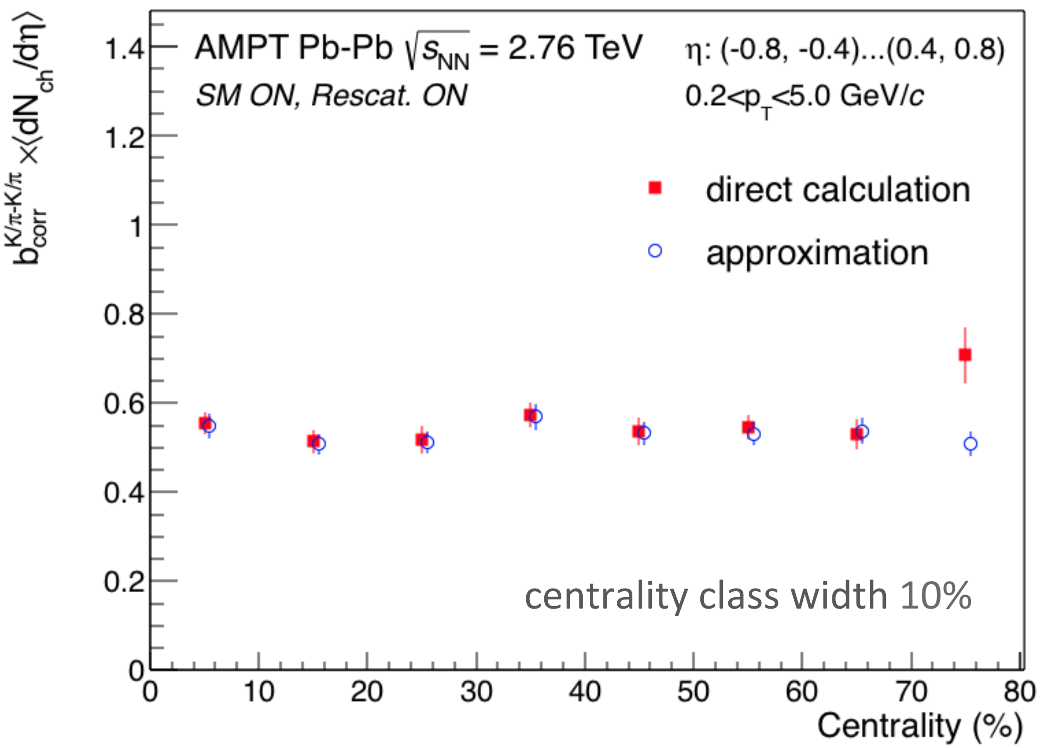
A convenient experimental quantity:

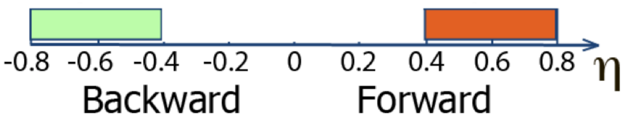
$$b_{corr} \cdot \langle N_{sources} \rangle \sim b_{corr} \cdot \langle dN/d\eta \rangle$$

(as for ν_{dyn})

Observables of this type are robust to volume fluctuations (as ν_{dyn}).

4 FB correlations between K/π ratios in models



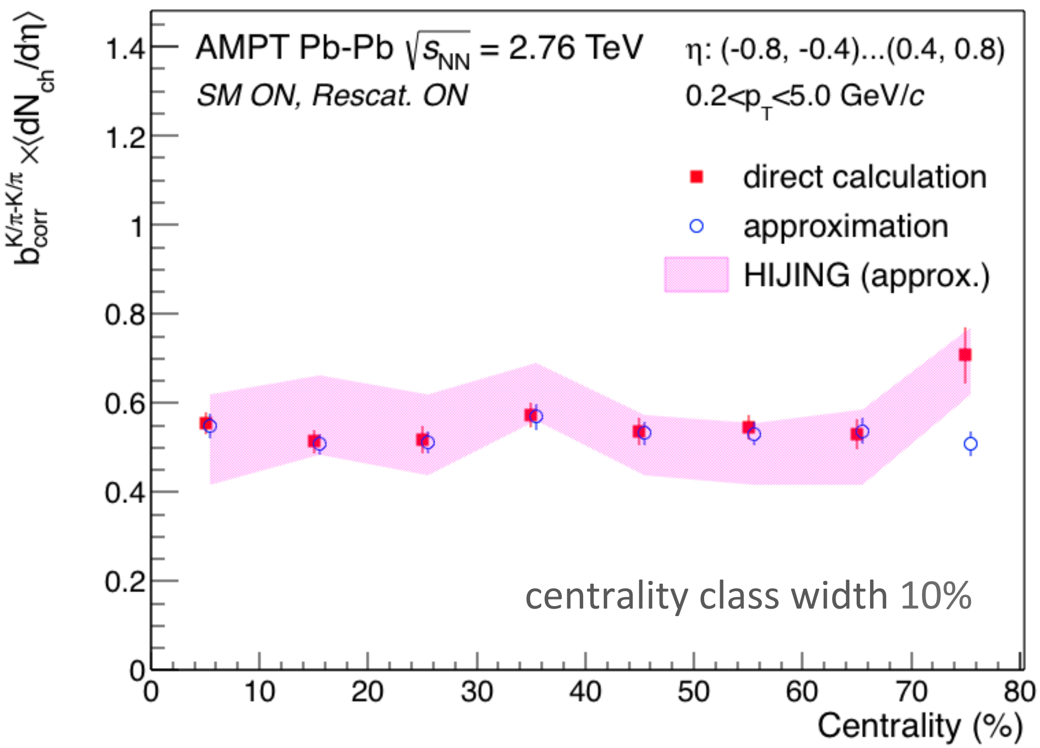


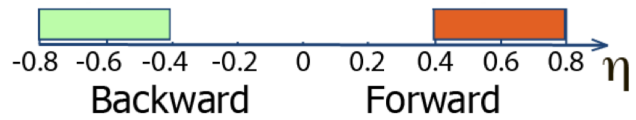
$$b_{\rm corr} = \frac{\langle r^F \cdot r^B \rangle}{\langle r^F \rangle \langle r^B \rangle} - 1$$

$$b_{\rm corr} \approx \frac{\langle n_{\rm K}^F n_{\rm K}^B \rangle}{\langle n_{\rm K}^F \rangle \langle n_{\rm K}^B \rangle} + \frac{\langle n_\pi^F n_\pi^B \rangle}{\langle n_\pi^F \rangle \langle n_\pi^B \rangle} - \frac{\langle n_{\rm K}^F n_\pi^B \rangle}{\langle n_{\rm K}^F \rangle \langle n_\pi^B \rangle} - \frac{\langle n_\pi^F n_{\rm K}^B \rangle}{\langle n_\pi^F \rangle \langle n_{\rm K}^B \rangle}$$

- good agreement between direct calculations and the approximation
- **a flat trend in AMPT with centrality**
- impact from resonance decays (ρ^0, ϕ)?

FB correlations between K/π ratios in models





$$b_{\text{corr}} = \frac{\langle r^F \cdot r^B \rangle}{\langle r^F \rangle \langle r^B \rangle} - 1$$

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- good agreement between direct calculations and the approximation
- **a flat trend in AMPT with centrality**
- impact from resonance decays (ρ^0, ϕ)?

AMPT and **HIJING** give consistent results – quite an unusual case!

→ Looking forward for real data results…

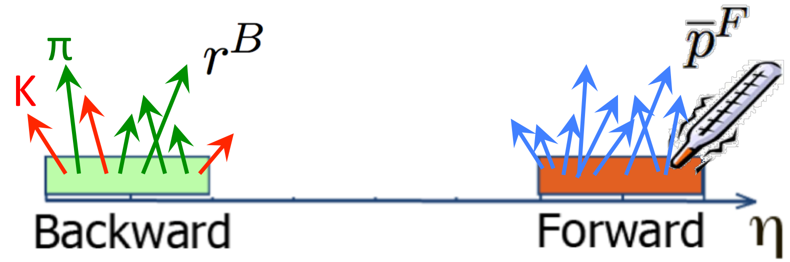
5 FB correlations between yield ratio and average p_T

Definition:

determine event-by-event mean transverse momentum in F window and r^B in B, and define *a correlation strength* as:

$$b_{\mathrm{corr}}^{r,\bar{p}} = \frac{\langle \bar{p}^F \cdot r^B \rangle}{\langle \bar{p}^F \rangle \langle r^B \rangle} - 1$$

$$r^B = n_{\mathrm{K}}^B / n_{\pi}^B,\ \ \bar{p}^F = \sum_{i=1}^{n_{tracks}} p_{\mathrm{T},i}^F$$



Approximation:

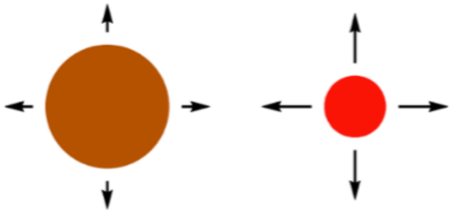
$$b_{\mathrm{corr}}^{r,\bar{p}} \approx \frac{\langle \bar{p}^F \cdot n_{\mathrm{K}}^B \rangle}{\langle \bar{p}^F \rangle \langle n_{\mathrm{K}}^B \rangle} - \frac{\langle \bar{p}^F \cdot n_{\pi}^B \rangle}{\langle \bar{p}^F \rangle \langle n_{\pi}^B \rangle}$$

Properties:

- Properties are the same as of the b_{corr} between ratios

Physics case of interest:

correlations between strangeness production and density of the fireball ↔ average p_T



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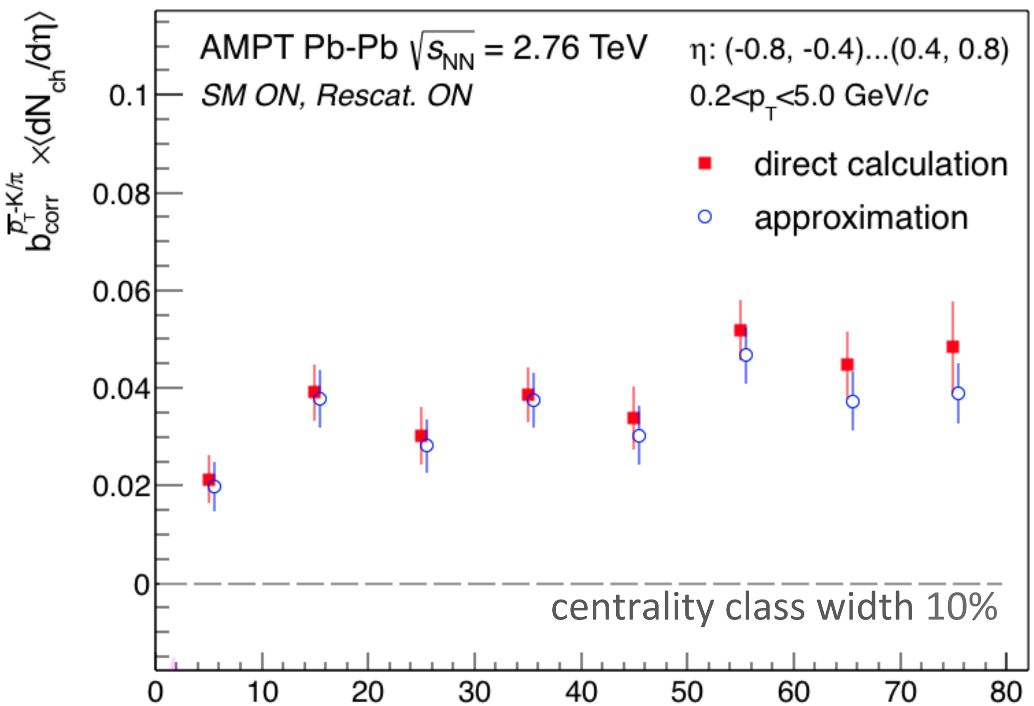

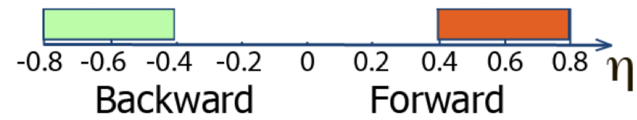

$$b_{\mathrm{corr}}^{r,\overline{p}} = \frac{\langle \overline{p}^F \cdot r^B \rangle}{\langle \overline{p}^F \rangle \langle r^B \rangle} - 1$$

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- impact from resonance decays (ρ^0, ϕ)?
- some evolution with centrality in AMPT (?)

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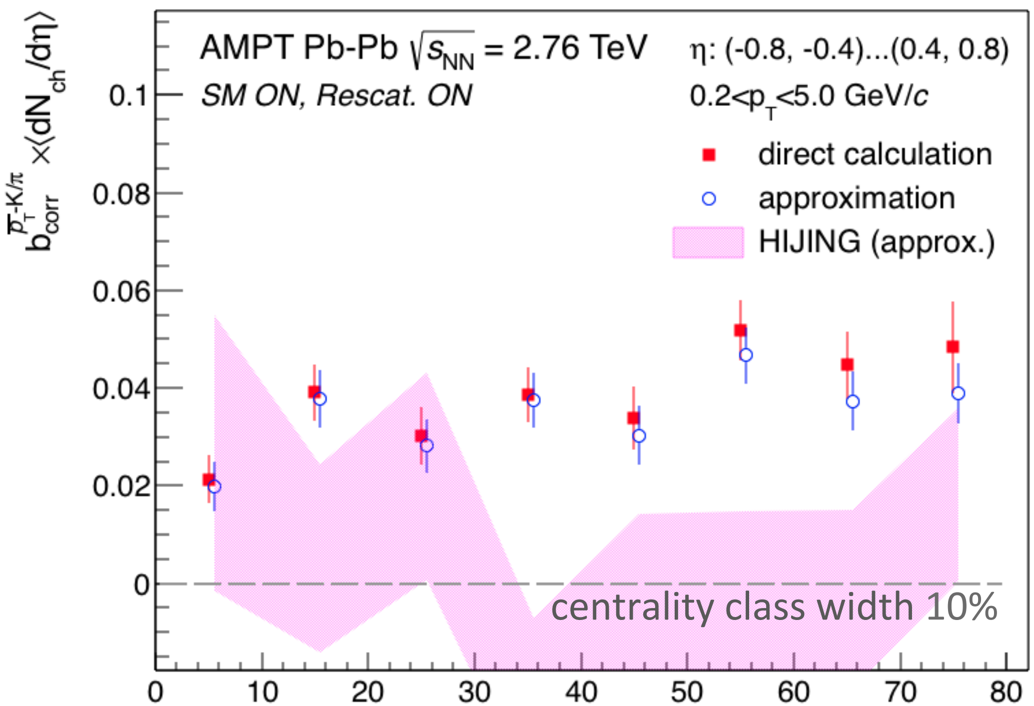
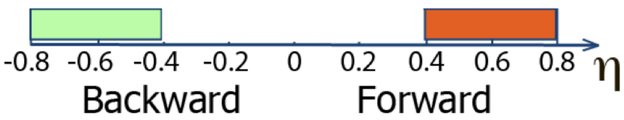


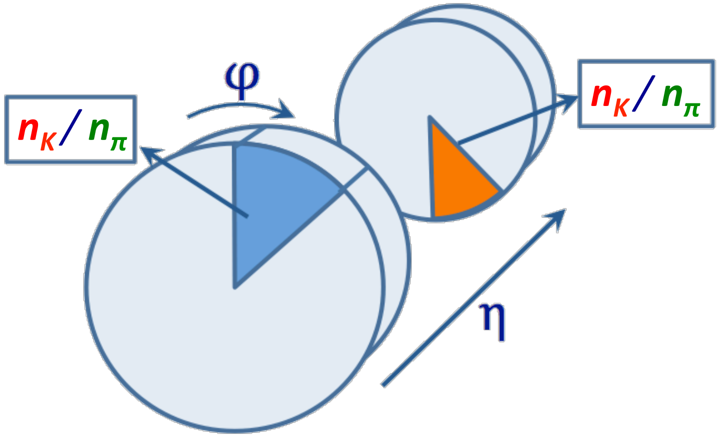


$$b^{r,\bar{p}}_{\mathrm{corr}} = \frac{\langle \bar{p}^F \cdot r^B \rangle}{\langle \bar{p}^F \rangle \langle r^B \rangle} - 1$$

$$b^{r,\bar{p}}_{\mathrm{corr}} \approx \frac{\langle \bar{p}^F \cdot n^B_{\mathrm{K}} \rangle}{\langle \bar{p}^F \rangle \langle n^B_{\mathrm{K}} \rangle} - \frac{\langle \bar{p}^F \cdot n^B_{\pi} \rangle}{\langle \bar{p}^F \rangle \langle n^B_{\pi} \rangle}$$

- good agreement between direct calculations and the approximation
- impact from resonance decays (ρ^0, ϕ)?
- some evolution with centrality in AMPT (?)
- absence of correlations in HIJING?

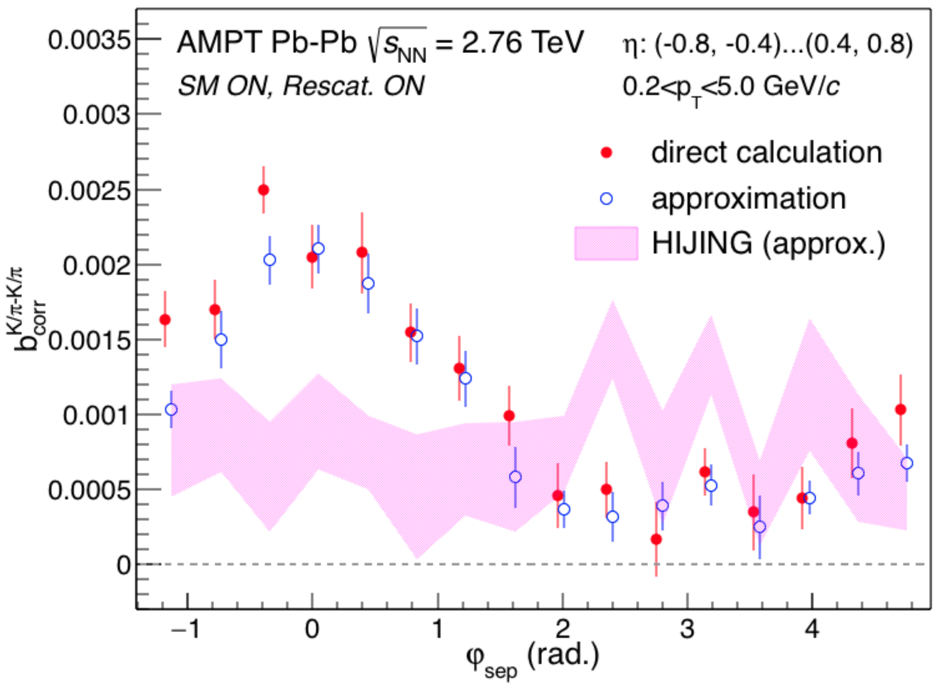
6 What if sub-divide also into φ sectors?



FB correlations between K/π ratios:

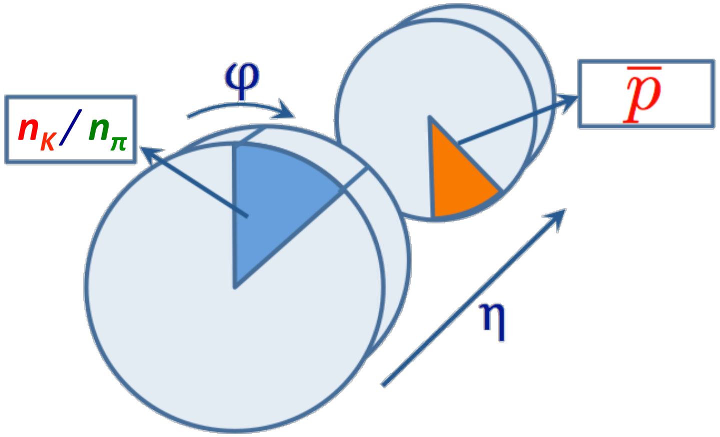
$$b_{\rm corr} = \frac{\langle r^F \cdot r^B \rangle}{\langle r^F \rangle \langle r^B \rangle} - 1$$

$$b_{\rm corr} \approx \frac{\langle n_K^F n_K^B \rangle}{\langle n_K^F \rangle \langle n_K^B \rangle} + \frac{\langle n_\pi^F n_\pi^B \rangle}{\langle n_\pi^F \rangle \langle n_\pi^B \rangle} - \frac{\langle n_K^F n_\pi^B \rangle}{\langle n_K^F \rangle \langle n_\pi^B \rangle} - \frac{\langle n_\pi^F n_K^B \rangle}{\langle n_\pi^F \rangle \langle n_K^B \rangle}$$



- The approximation works well (even when numbers of kaons in windows are small)
- **AMPT**: a visible azimuthal structure, while **HIJING** seems to give a constant

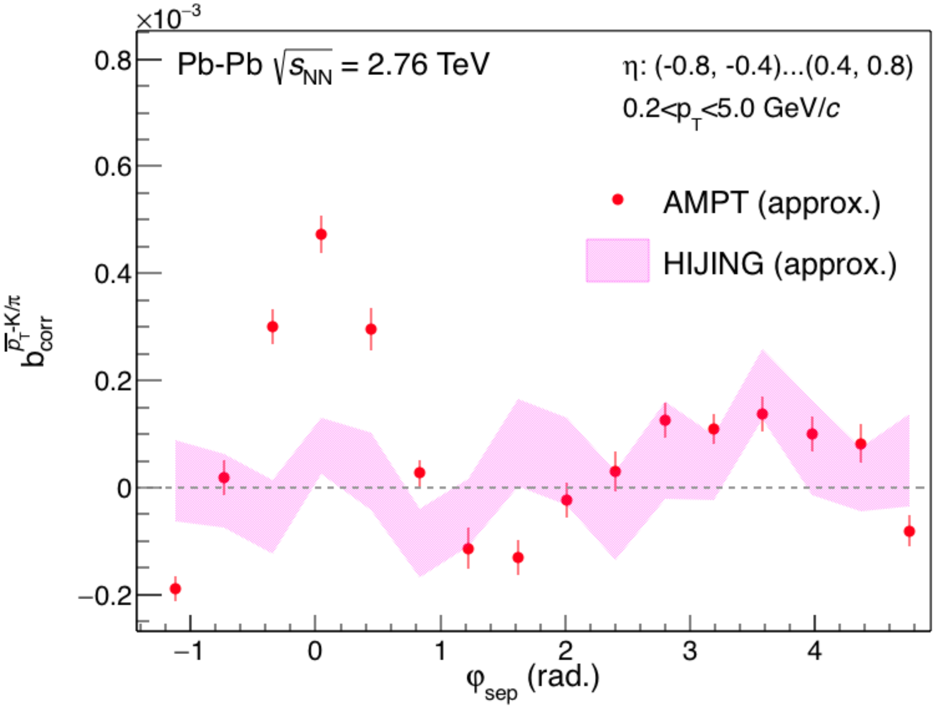
6 What if sub-divide also into φ sectors?



FB correlations between K/π and average p_T:

$$b_{\rm corr}^{r,\bar{p}} = \frac{\langle \bar{p}^F \cdot r^B \rangle}{\langle \bar{p}^F \rangle \langle r^B \rangle} - 1$$

$$b_{\rm corr}^{r,\bar{p}} \approx \frac{\langle \bar{p}^F \cdot n_{\rm K}^B \rangle}{\langle \bar{p}^F \rangle \langle n_{\rm K}^B \rangle} - \frac{\langle \bar{p}^F \cdot n_{\pi}^B \rangle}{\langle \bar{p}^F \rangle \langle n_{\pi}^B \rangle}$$

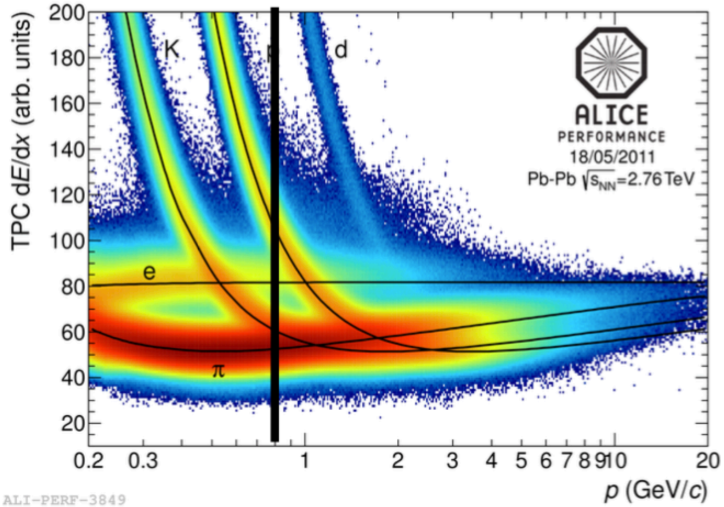


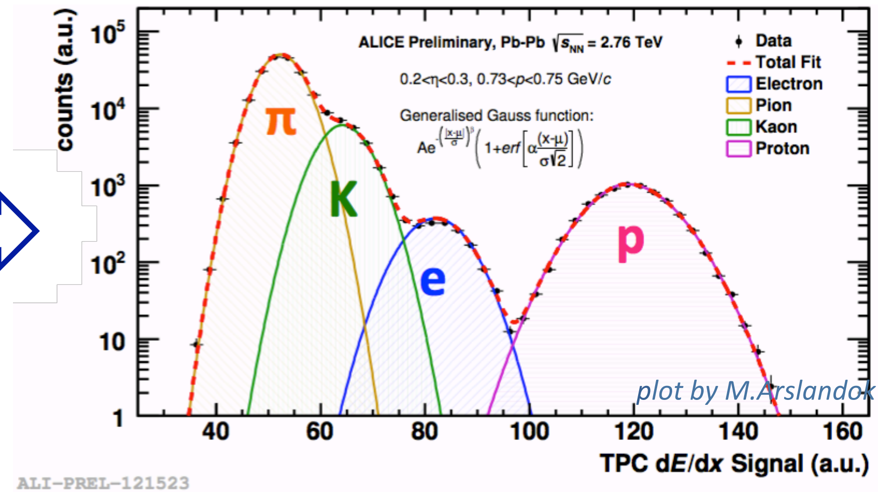
- **AMPT** shows clear azimuthal structure, while **HIJING** is consistent with zero

Finally: prospects with the Identity Method

PRC 86, 044906 (2012), PRC 89, 054902 (2014)

Allows to solve the problem with particle mis-identification!





$$\omega_j(x_i) \in [0,1] \Rightarrow W_j \equiv \sum_{i=1}^{N(n)} \omega_j(x_i) \Rightarrow \langle N_j^n \rangle = \mathrm{A}^{-1} \langle W_j^n \rangle$$

– correction for the moments!

- Used in ALICE for corrections of $\nu_{dyn}[\pi,K]$, $[\pi,p]$, $[p,K]$ (arXiv:1712.07929)
- **Can be directly used for FB correlations with the introduced observables!**
- Implementation is available:
  M. Arslandok, A. Rustamov, arXiv:1807.06370

$$b_{\mathrm{corr}} \approx \frac{\langle n_{\mathrm{K}}^F n_{\mathrm{K}}^B \rangle}{\langle n_{\mathrm{K}}^F \rangle \langle n_{\mathrm{K}}^B \rangle} + \frac{\langle n_{\pi}^F n_{\pi}^B \rangle}{\langle n_{\pi}^F \rangle \langle n_{\pi}^B \rangle} - \frac{\langle n_{\mathrm{K}}^F n_{\pi}^B \rangle}{\langle n_{\mathrm{K}}^F \rangle \langle n_{\pi}^B \rangle} - \frac{\langle n_{\pi}^F n_{\mathrm{K}}^B \rangle}{\langle n_{\pi}^F \rangle \langle n_{\mathrm{K}}^B \rangle}$$

Summary

- **Event-by-event measurements** help to characterize the properties of the “bulk” of the system, they also are closely related to dynamics of the phase transitions.

- **Challenges from the experimental point of view:**
  - fluctuations of the volume of the created system
  - corrections on efficiency and contamination, limited acceptance
  - difficult to interpret the data due to resonance decays, conservation laws

- **Over the past years:**
  - a set of robust variables has been proposed and measured in experiments
  - powerful correction methods, such as Identity method, have been developed

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  - sensitive to correlation between strangeness production ↔ fireball density
  - possible to measure in experiments with strong PID capabilities (ALICE, STAR, MPD?)
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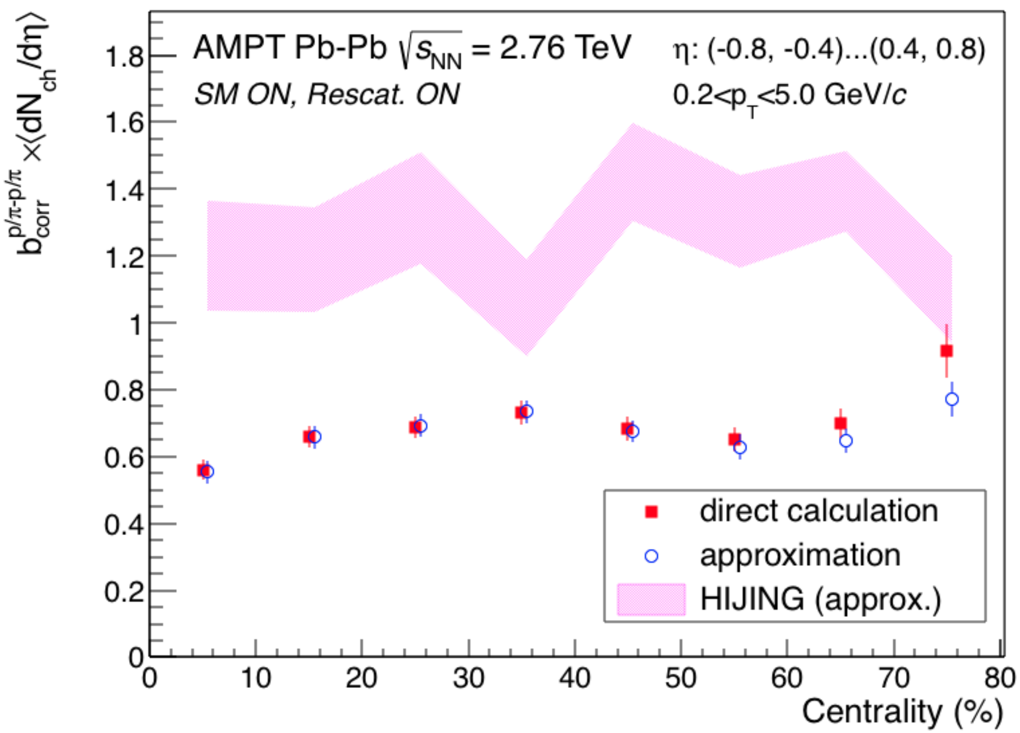
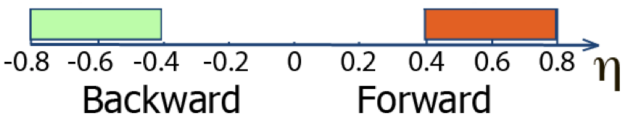
Thank you for your attention!

This work is supported by the Russian Science Foundation, grant 17-72-20045.

Backup

FB correlation strength between p/π ratios



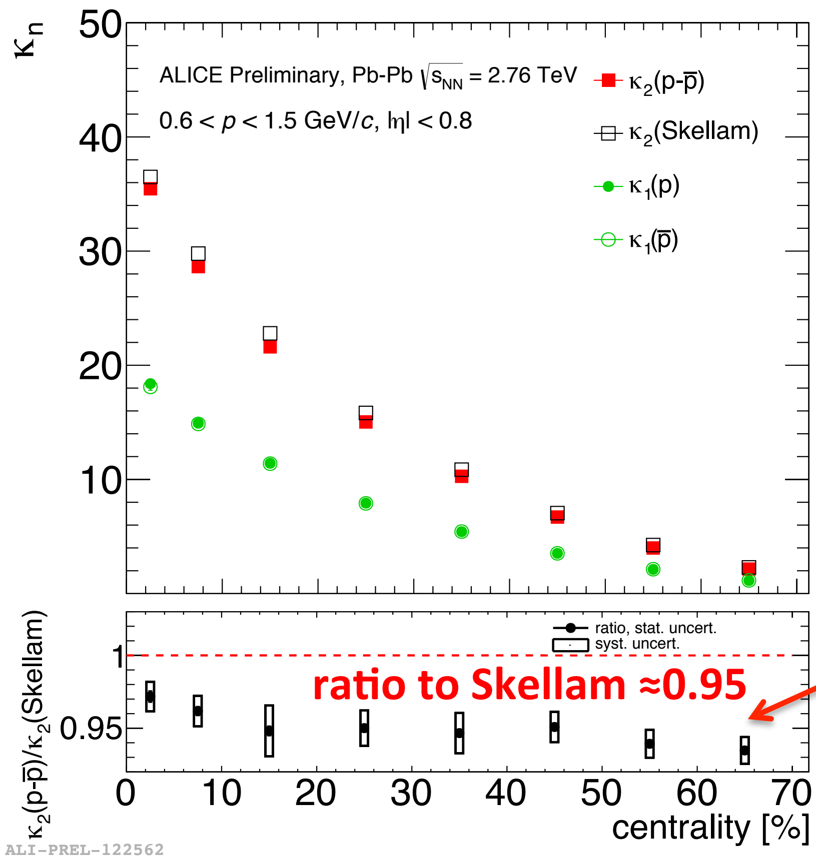


- good agreement between direct calculations and approximation
- robust to centrality class width
- HIJING vs AMPT: need deeper investigations to understand the difference

Net-proton fluctuations in Pb-Pb: *the 2nd moment*

Protons and antiprotons with **0.6<*p*<1.5 GeV/*c*** and **|η|<0.8**

1st and 2nd cumulants:
$$\kappa_1(\Delta n_B) = \langle \Delta n_B \rangle$$
$$\kappa_2(\Delta n_B) = \left\langle \Delta n_B^2 \right\rangle - \langle \Delta n_B \rangle^2 = \underbrace{\kappa_2(n_B) + \kappa_2(n_{\bar{B}})}_{\text{if Skellam}} - \underbrace{2\left(\langle n_B n_{\bar{B}} \rangle - \langle n_B \rangle \langle n_{\bar{B}} \rangle\right)}_{\text{correlation term}}$$



Skellam distribution:
prob. distribution of *difference of two random variables*, each generated from *statistically independent* Poisson distributions.

$$\kappa_n(Skellam) = \langle X_1 \rangle + (-1)^n \langle X_2 \rangle$$

Deviation from Skellam:
genuine physics or non-dynamical contributions?

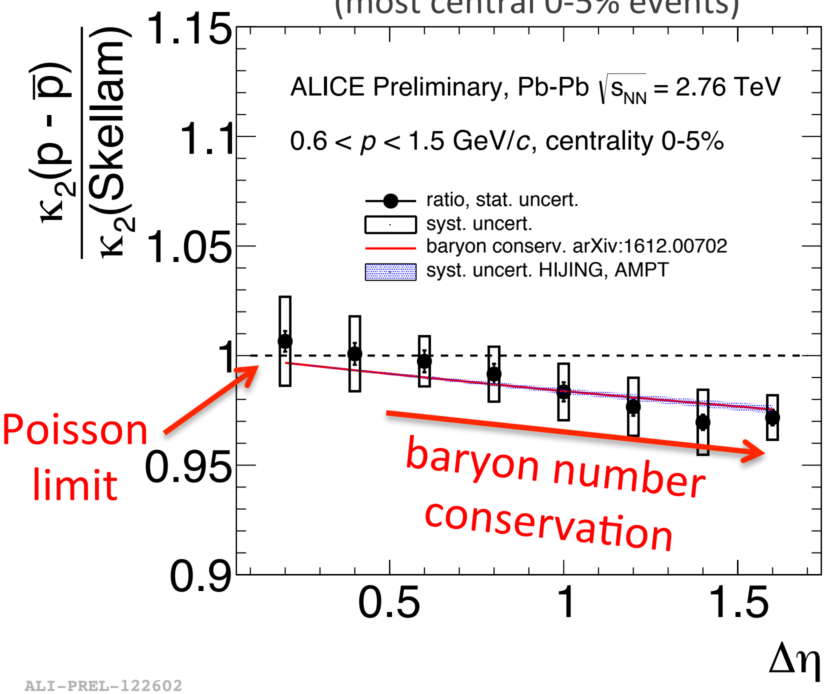
Net-proton fluctuations in Pb-Pb: *the 2nd moment*

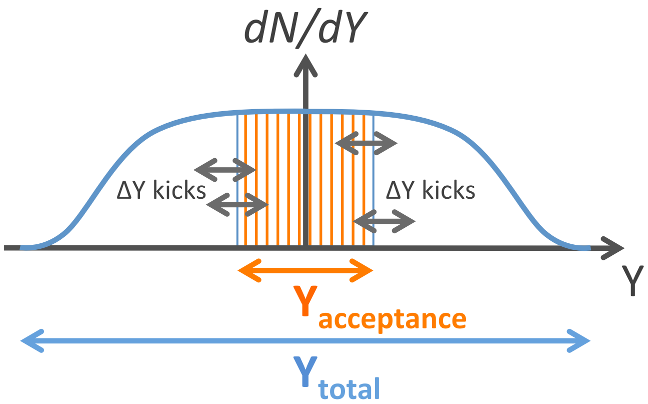
ALICE

In addition to critical fluctuations, the correlation term may emerge from the **global conservation laws**.

→ Study acceptance dependence:

(most central 0-5% events)





→ Deviation from Skellam can be well explained by global baryon number conservation.

No evidence for dynamical fluctuations

$$\frac{\kappa_2(p-\bar{p})}{\kappa_2(Skellam)} = 1-\alpha \quad \alpha = \frac{\langle p \rangle^{measured}}{\langle B \rangle^{4\pi}}$$

Model by A.Rustamov et al., Nucl.Phys.A 960 (2017) 114, arXiv:1612.00702

Net-Λ fluctuations in Pb-Pb: *the 2nd moment*

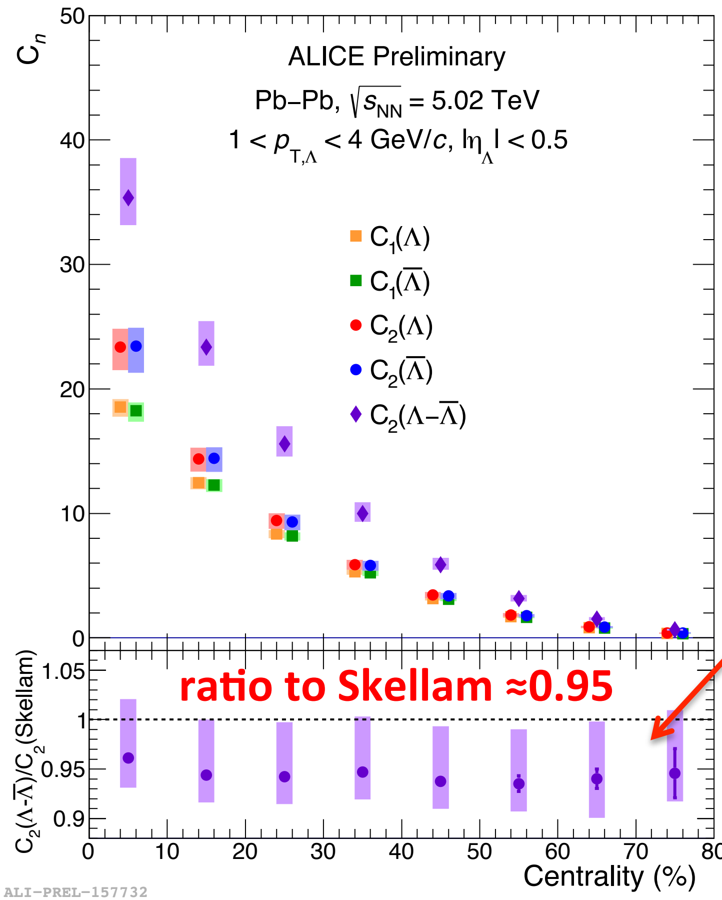
QM2018 talk by A.Ohlson

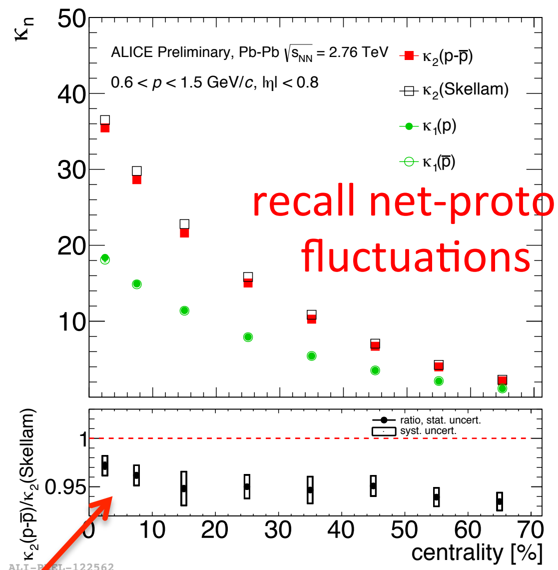
Why measure net-Λ fluctuations?

→ to explore correlated fluctuations of baryon number and strangeness

- different contributions from resonances, etc., than in net-proton measurement

$$\kappa_2(\Delta n_B) = \left\langle \Delta n_B^2 \right\rangle - \langle \Delta n_B \rangle^2 = \kappa_2(n_B) + \kappa_2(n_{\bar{B}}) - 2\left(\langle n_B n_{\bar{B}} \rangle - \langle n_B \rangle \langle n_{\bar{B}} \rangle\right)$$





Note changed notations:
κ_n → C_n

- different kinematic range
- different contributions from resonance decays

Qualitatively similar conclusion as for net-protons.

Net-proton fluctuations in Pb-Pb: *the 2nd moment*

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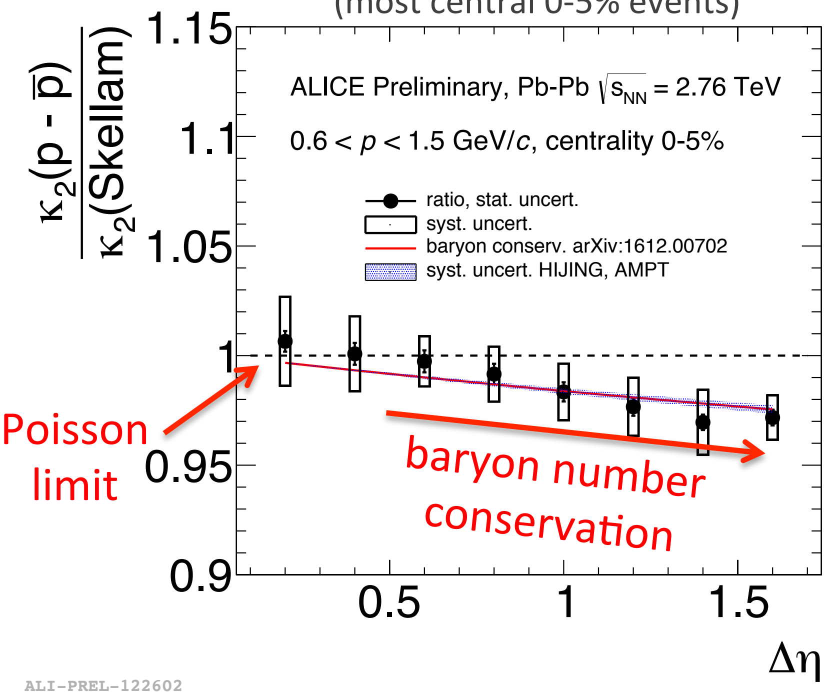
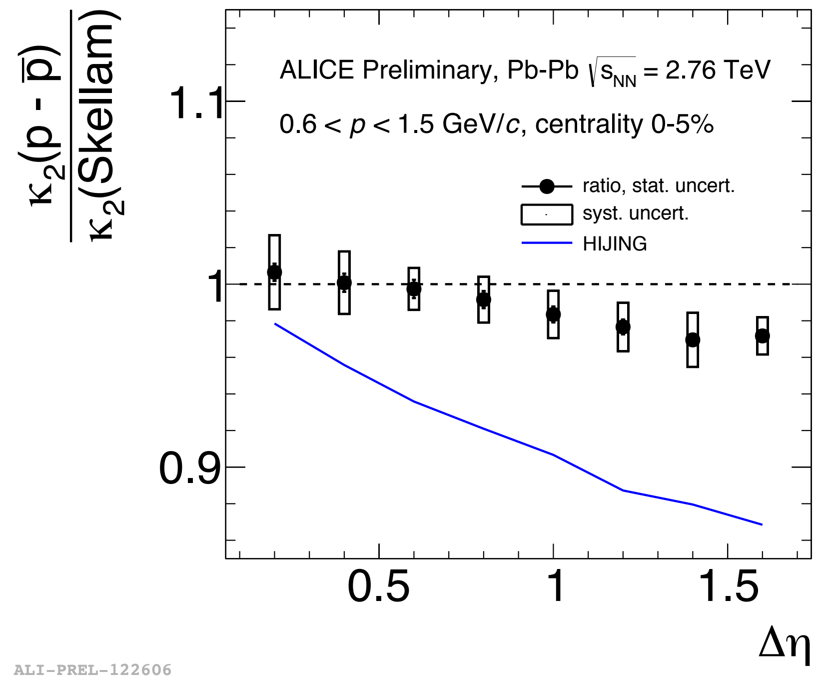


Comparison with HIJING:



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