# Long-range two particle correlations in small system

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# Outline

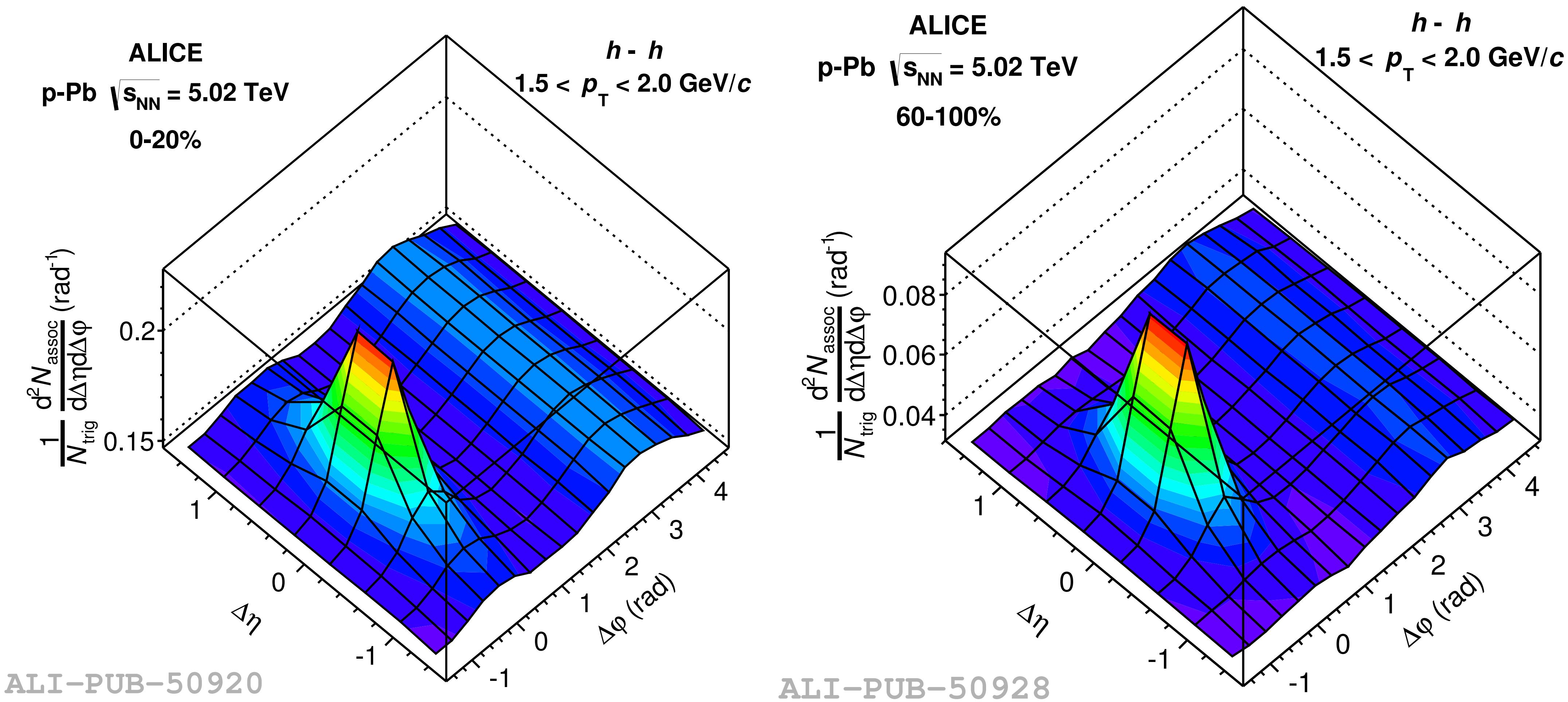
- Two particle correlation analysis in ALICE
- PID $v_2$
- Forward/backward $v_2$ in pPb
- Heavy flavor and J/Psi $v_2$ in pPb
- Model comparison for PID $v_2$
- Event plane decorrelation in PbPb and pPb.
- Outlook
- Summary

# 2 particle correlation analysis in ALICE

$$\frac{1}{N_{trig}}\frac{d^2N_{assoc}}{d\Delta\eta d\Delta\varphi} = \frac{S(\Delta\eta,\Delta\varphi)}{B(\Delta\eta,\Delta\varphi)} \qquad S(\Delta\eta,\Delta\varphi) = 1/N_{trig}\ d^2N_{same}/d\Delta\eta d\Delta\varphi$$

$$B(\Delta\eta,\Delta\varphi) = \alpha\, d^2N_{mixed}/d\Delta\eta\, d\Delta\varphi$$

Phys. Lett. B 726 (2013) 164-177

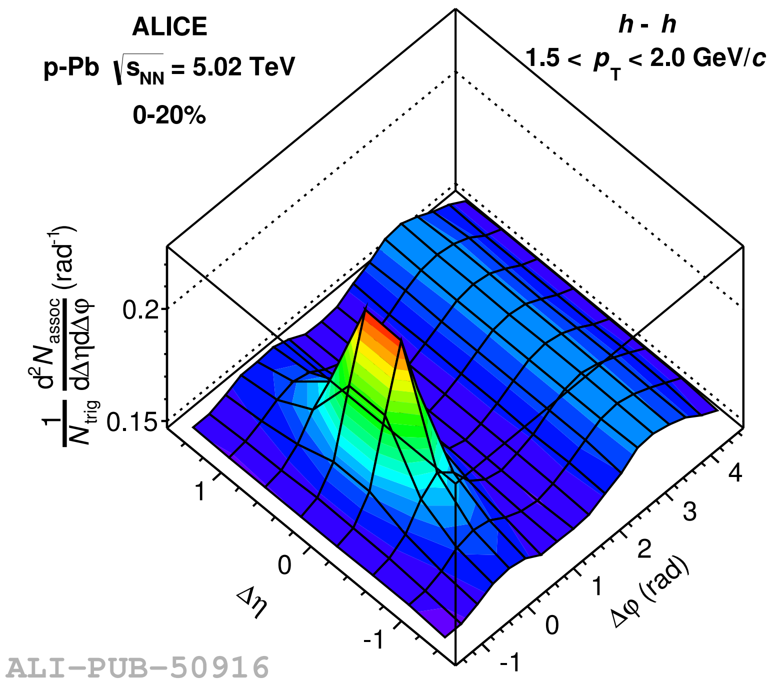



- Associate yields per trigger in same events are divided by the mixed events to cancel acceptance effects.
- Jet peak at (Δη,Δϕ)~(0,0) and recoil jet at Δϕ~π.
- Near-side ridge is visible in 0-20%.

# Non flow subtraction in ALICE

- Subtract 60-100% from 0-20%

Phys. Lett. B 726 (2013) 164-177

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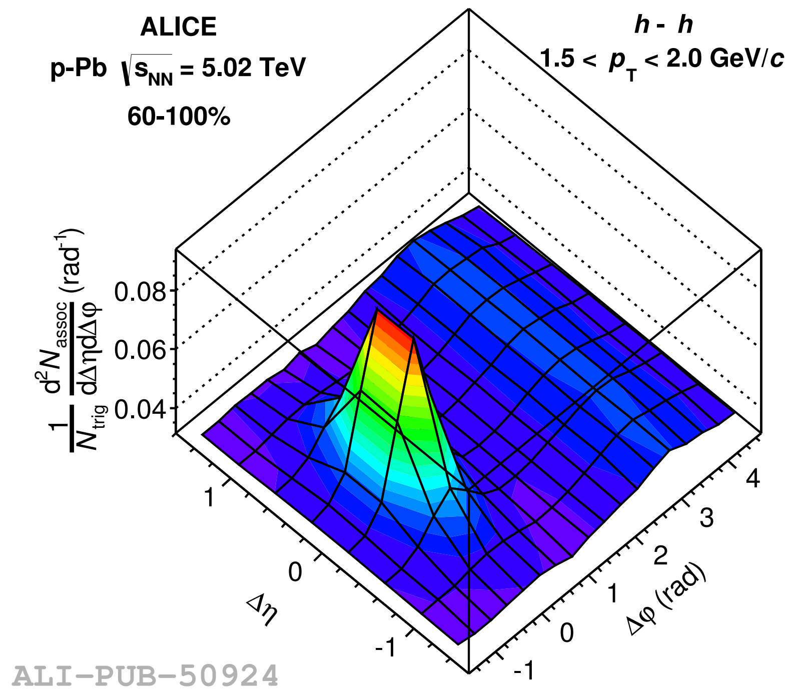


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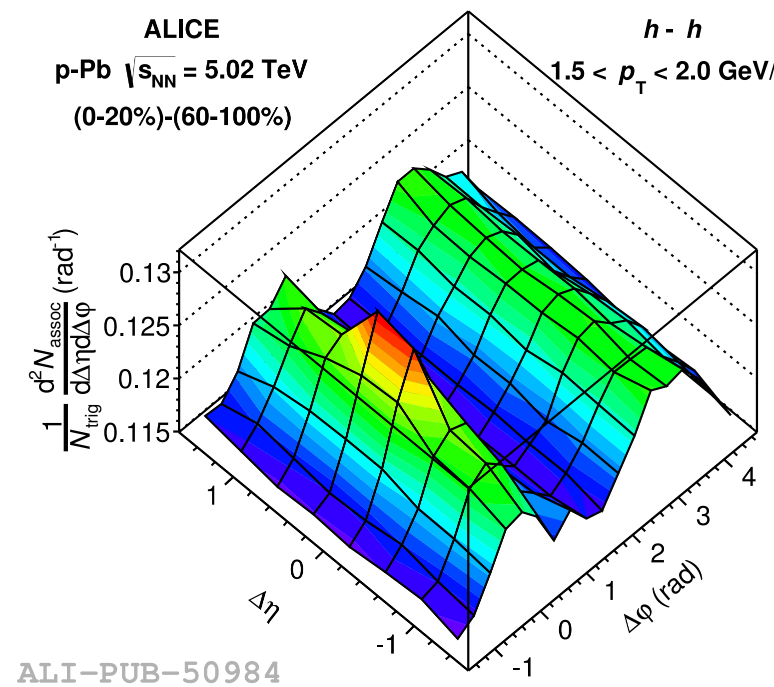
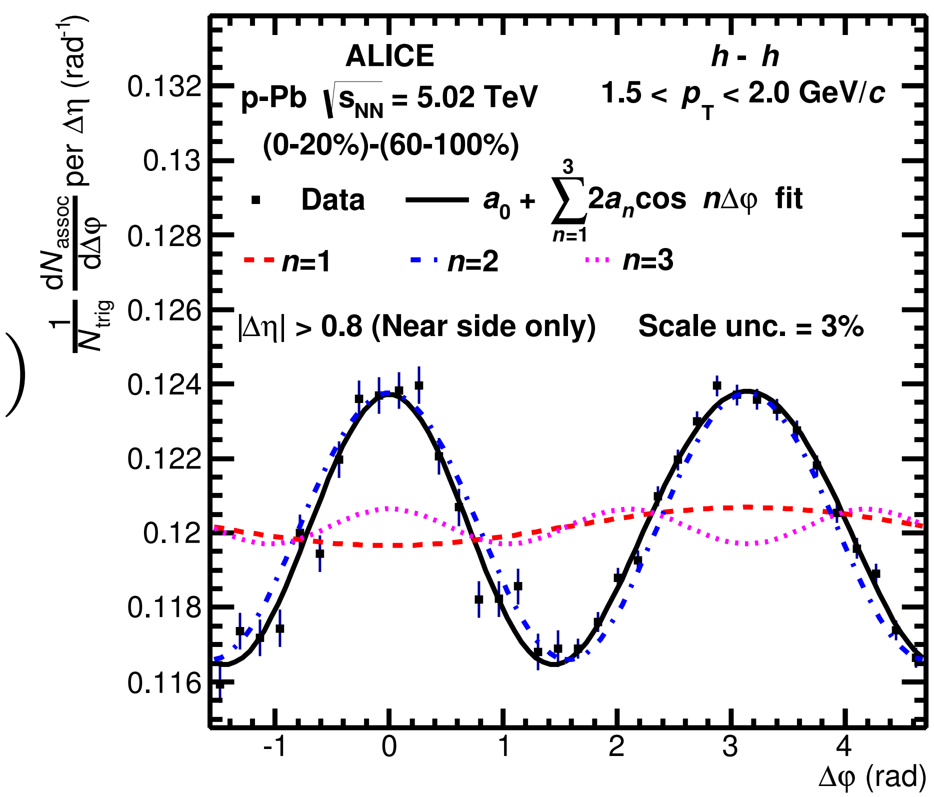


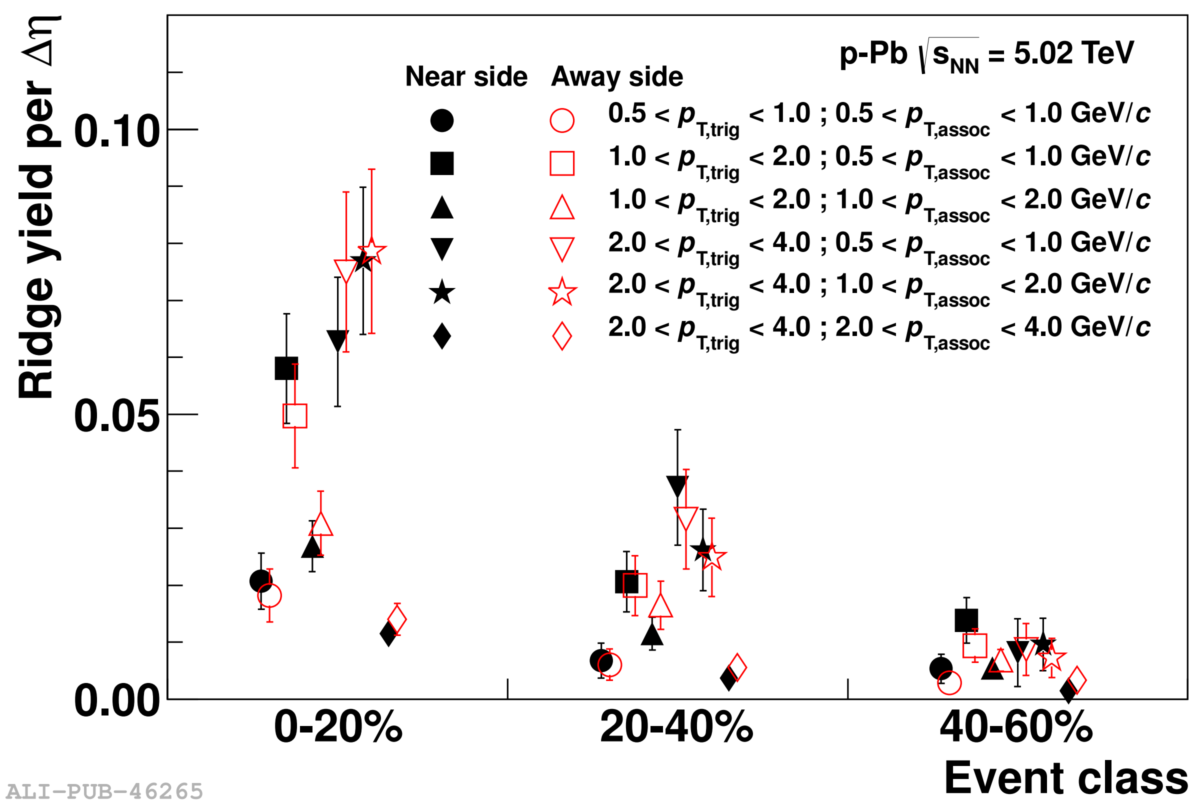

- Exclude |Δη|<0.8 in near-side

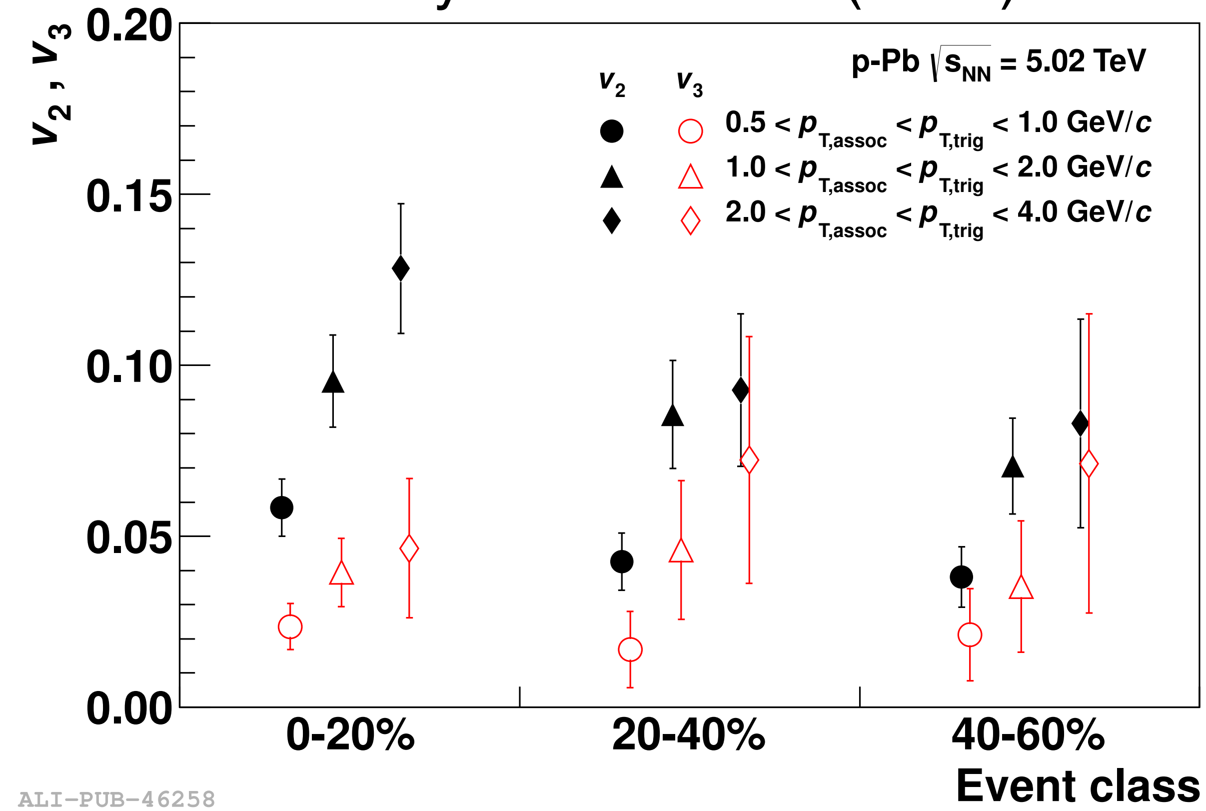
$$\frac{1}{N_{trig}}\frac{dN_{asso}}{d\Delta\phi} = a_0 + \sum_{n=1}^{3} 2a_n cos(n\Delta\phi)$$



# Ridge yield and flow coefficient

Phys. Lett. B 719 (2013) 29-41




- Near-side yield is comparable to away-side yield.
  - Double ridge is reproduced by CGC.

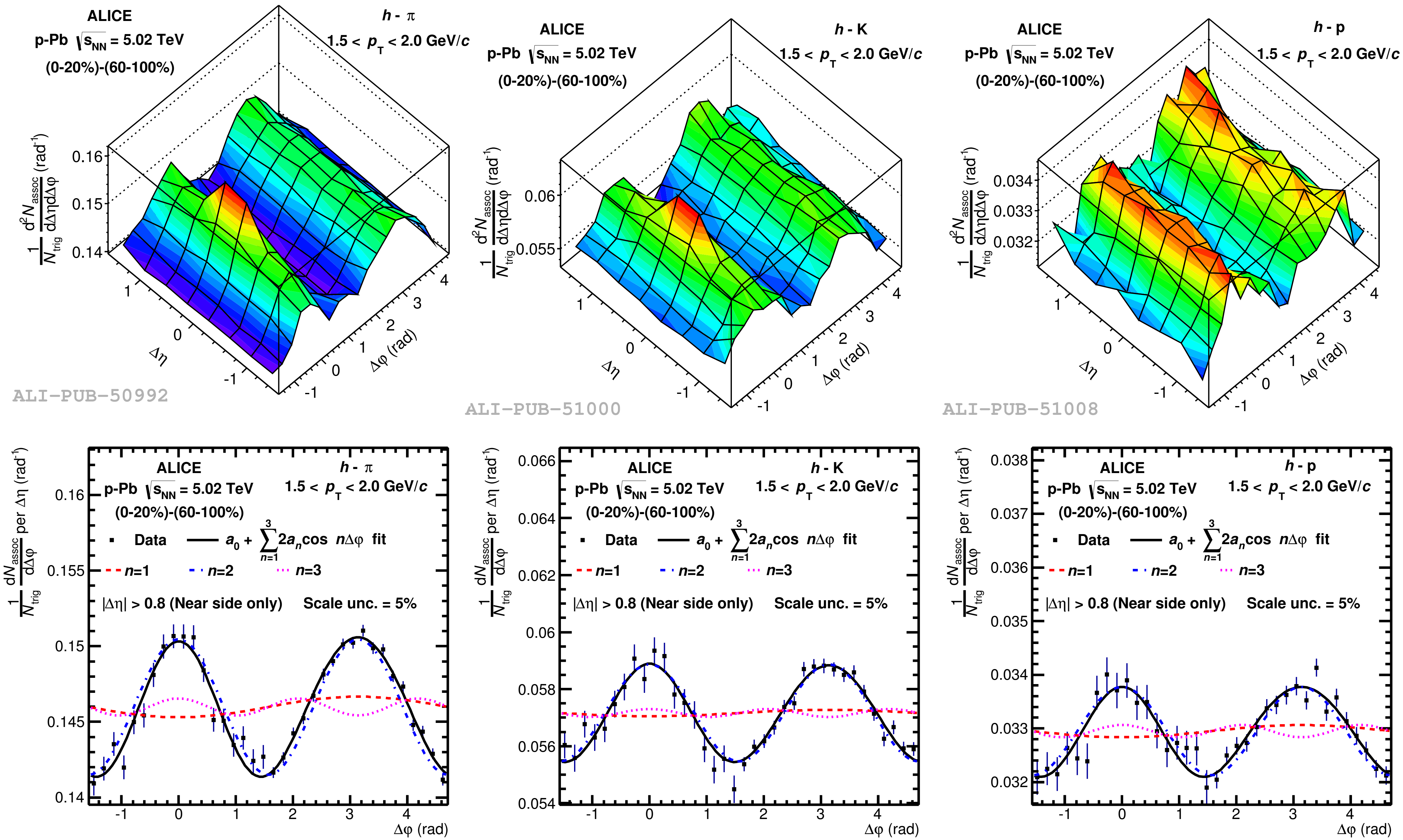
    K. Dusling and R. Venugopalan, Phys.Rev. D87 (2013), 054014
- Extracted $v_2$, $v_3$ depend on $p_T$ and centrality.

$$V_{n\Delta}^{h-i}\{2PC\} = a_n^{h-i}/a_0^{h-i} \qquad v_n^h\{2PC\} = \sqrt{V_{n\Delta}^{h-h}}$$

- $v_2$ and $v_3$ are qualitative agreement with hydro calculation.

P. Bozek and W.Broniowski, Phys.Lett. B718 (2013) 1557-1561

# Double ridge with PID

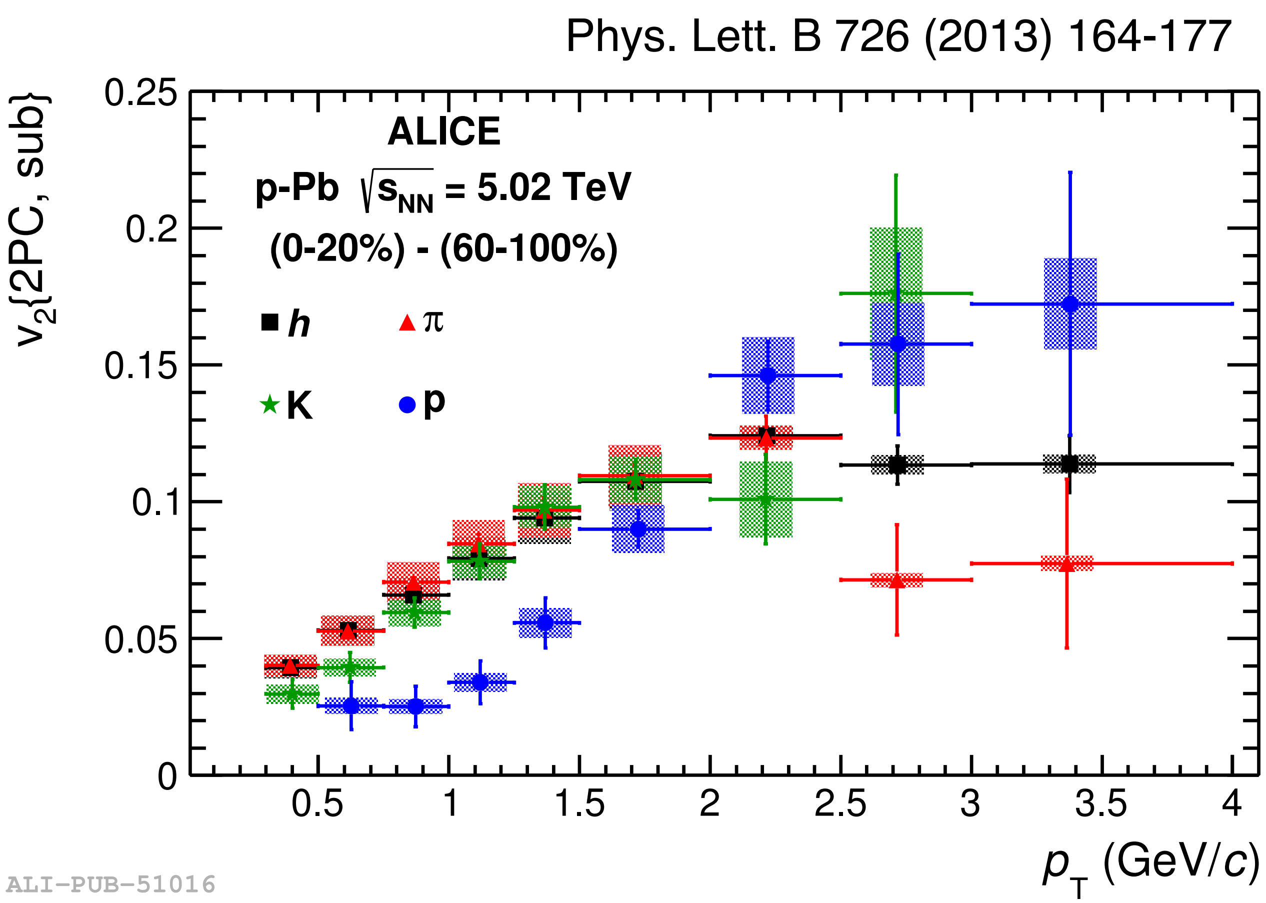



- Double ridge structure for π, K, and p.

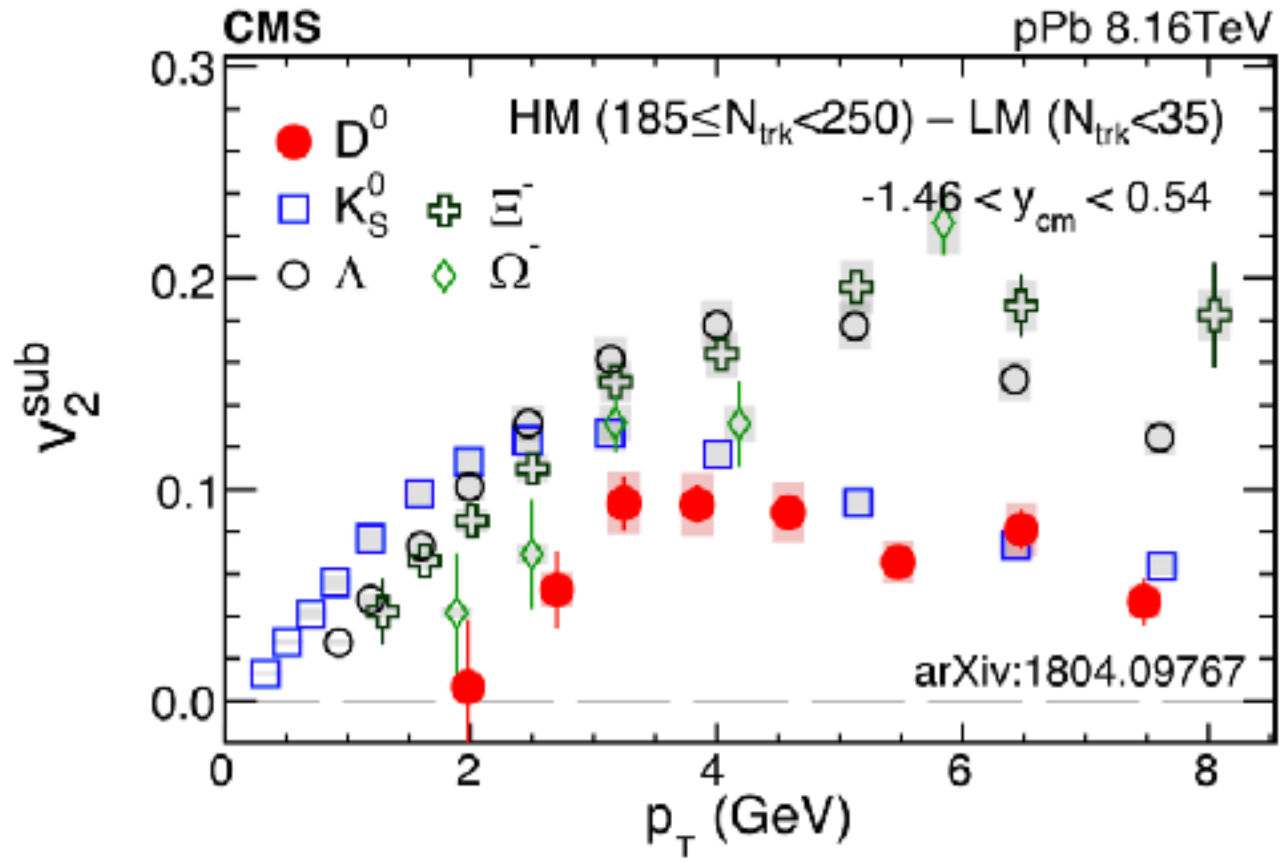
Phys. Lett. B 726 (2013) 164-177

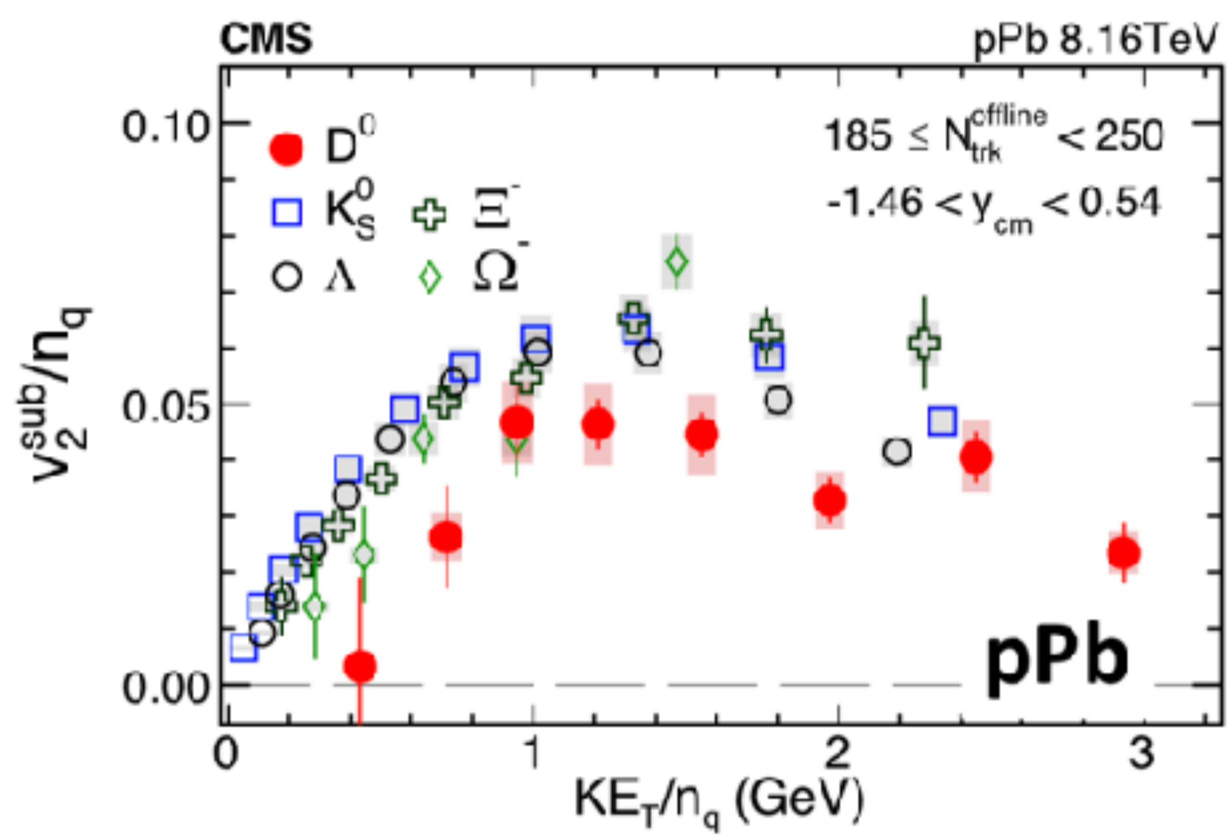
$$V_{n\Delta}^{h-i}\{2PC\} = a_n^{h-i}/a_0^{h-i} \qquad v_n^i\{2PC\} = \frac{V_{n\Delta}^{h-i}}{\sqrt{V_{n\Delta}^{h-h}}}$$

# $v_2$ of identified hadrons in pPb




$$V_2^{sub} = V_2^{HM} - V_2^{LM} \frac{N_{assoc}^{LM}}{N_{assoc}^{HM}} \frac{Y_{jet}^{HM}}{Y_{jet}^{LM}}$$

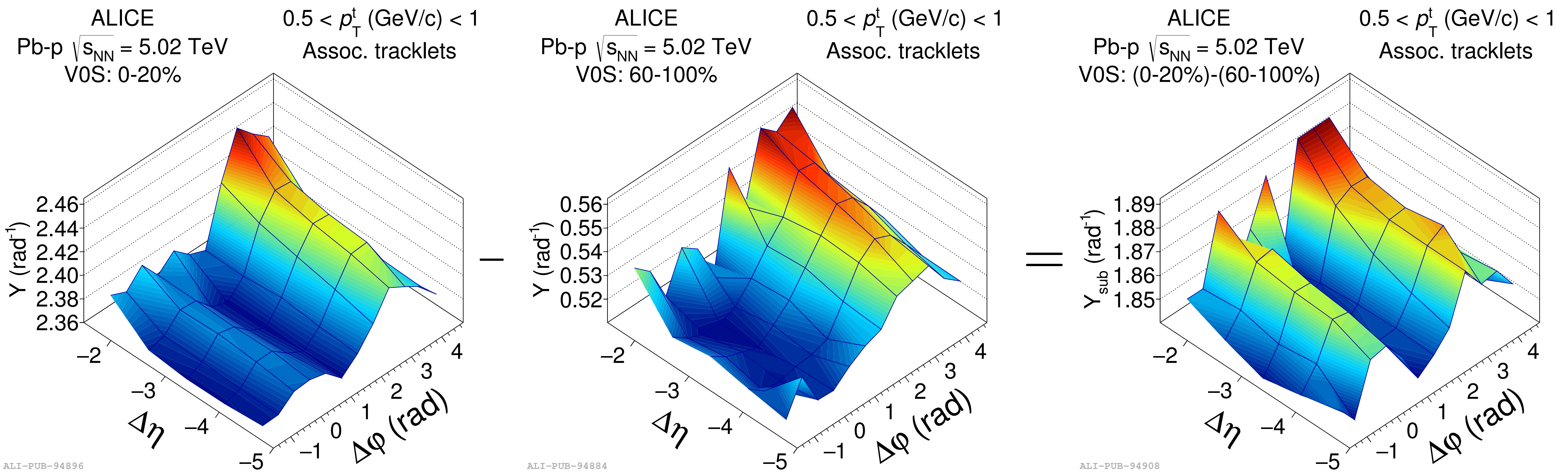


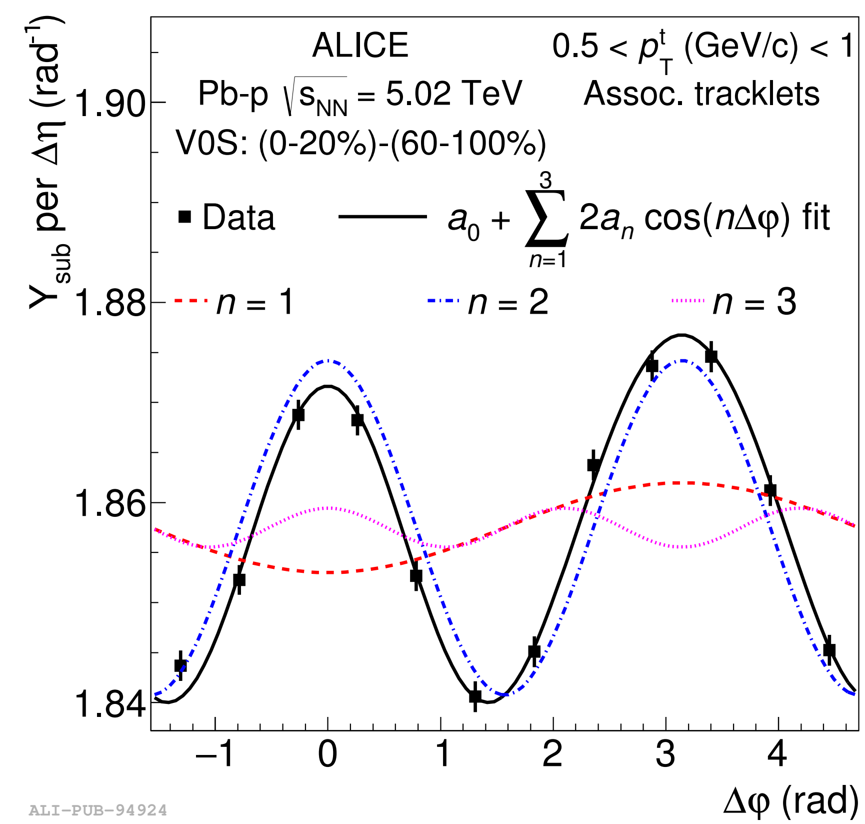

- Mass ordering at $p_T$<2 GeV/c.
- Quark number scaling succeeded except $D^0$.
  - Different trend from PbPb.

# Forward/Backward-Central correlations

Phys. Lett. B 753 (2016) 126-139

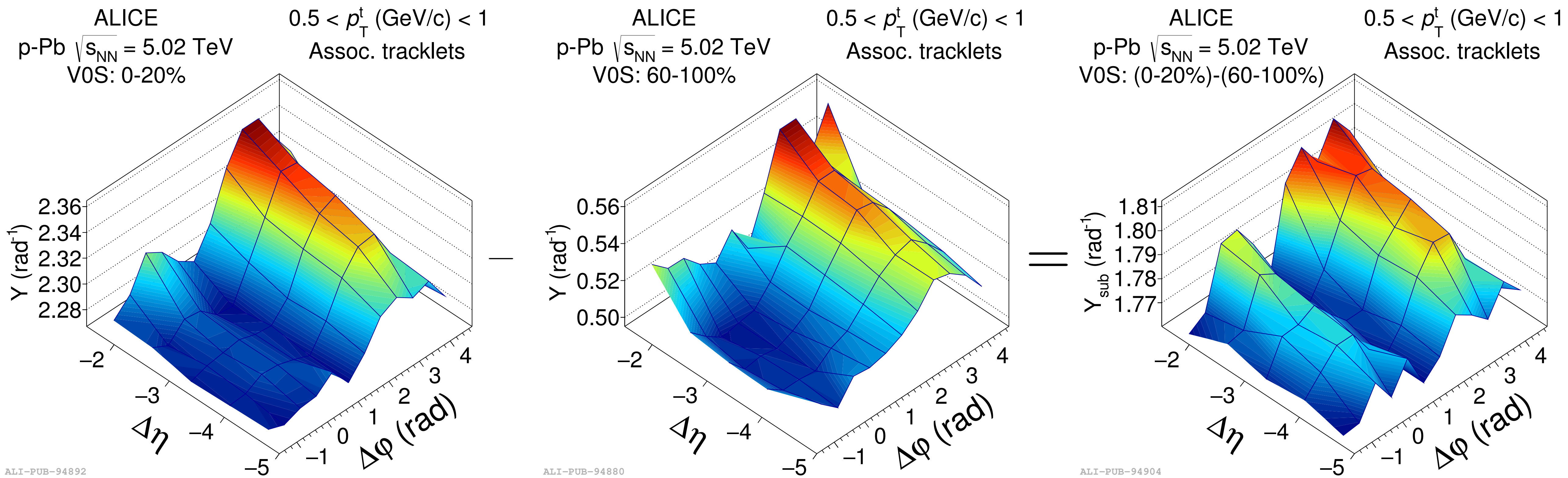



- Correlations between muons at forward rapidity at - 4 < η < -2.5 in Pb-going and charged particle at mid rapidity.



# Forward/Backward-Central correlations

Phys. Lett. B 753 (2016) 126-139

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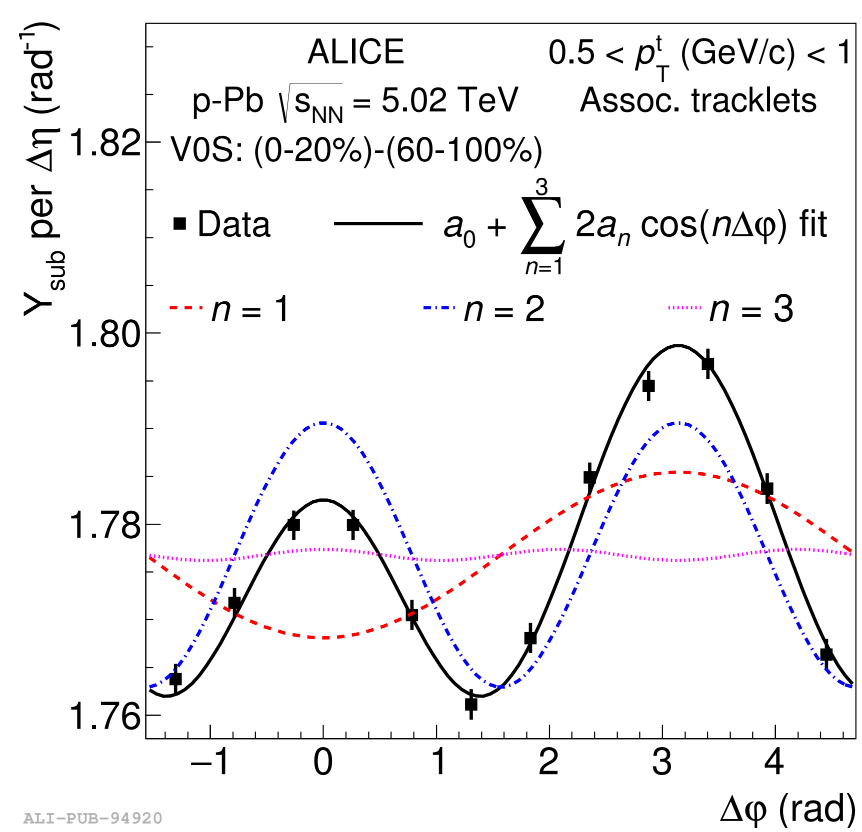
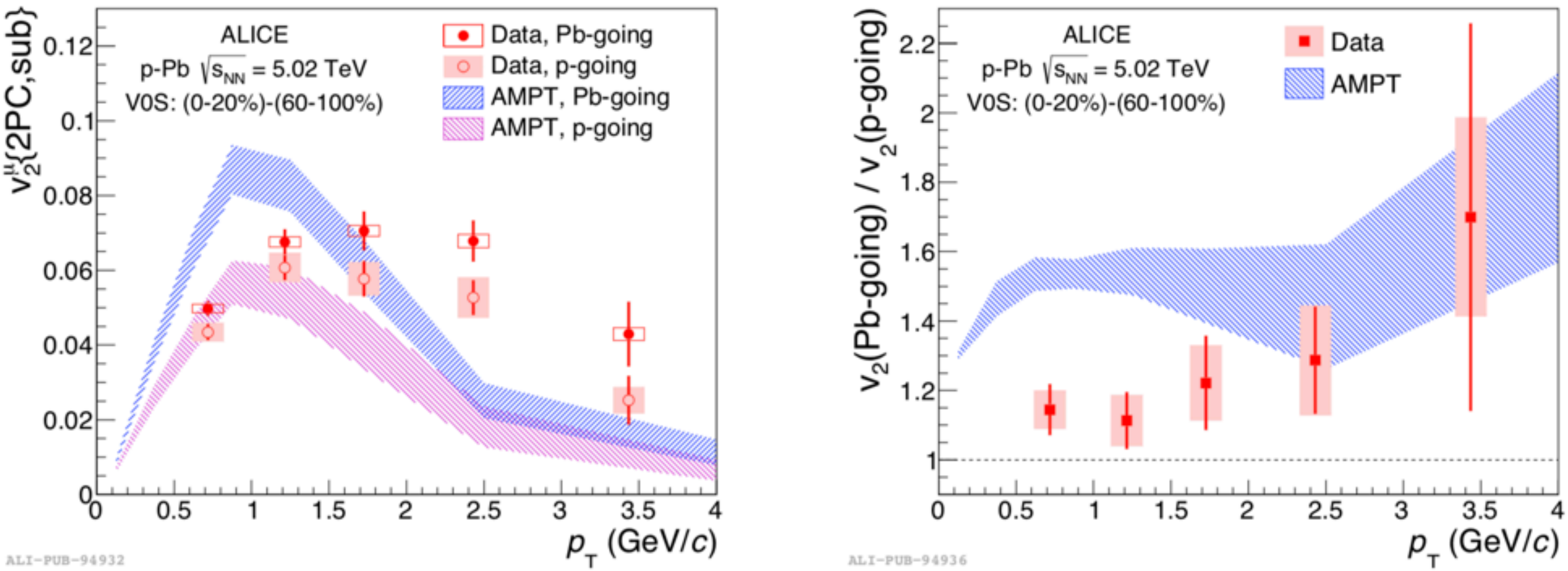


# $v_2$ at forward and backward rapidity in pPb collisions

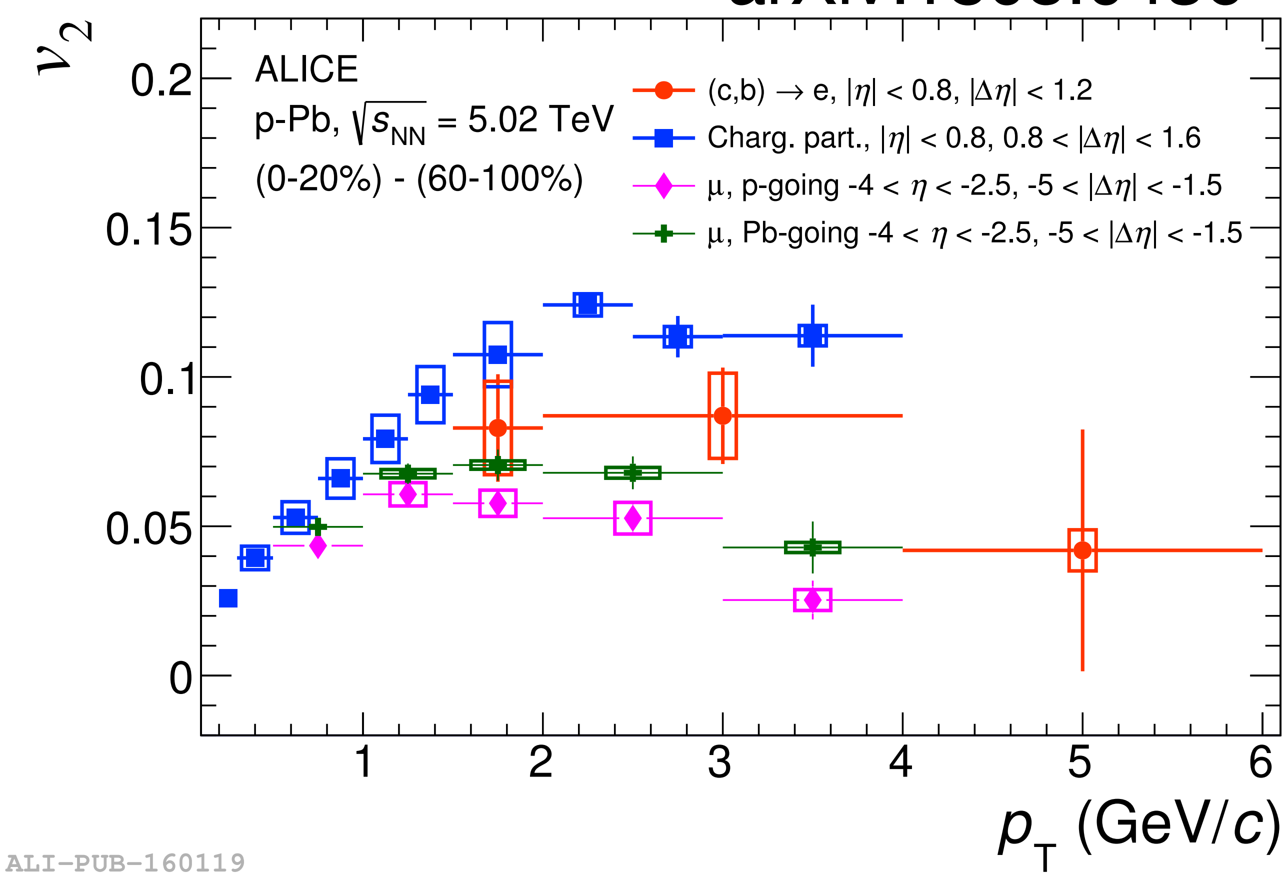
Phys. Lett. B 753 (2016) 126-139



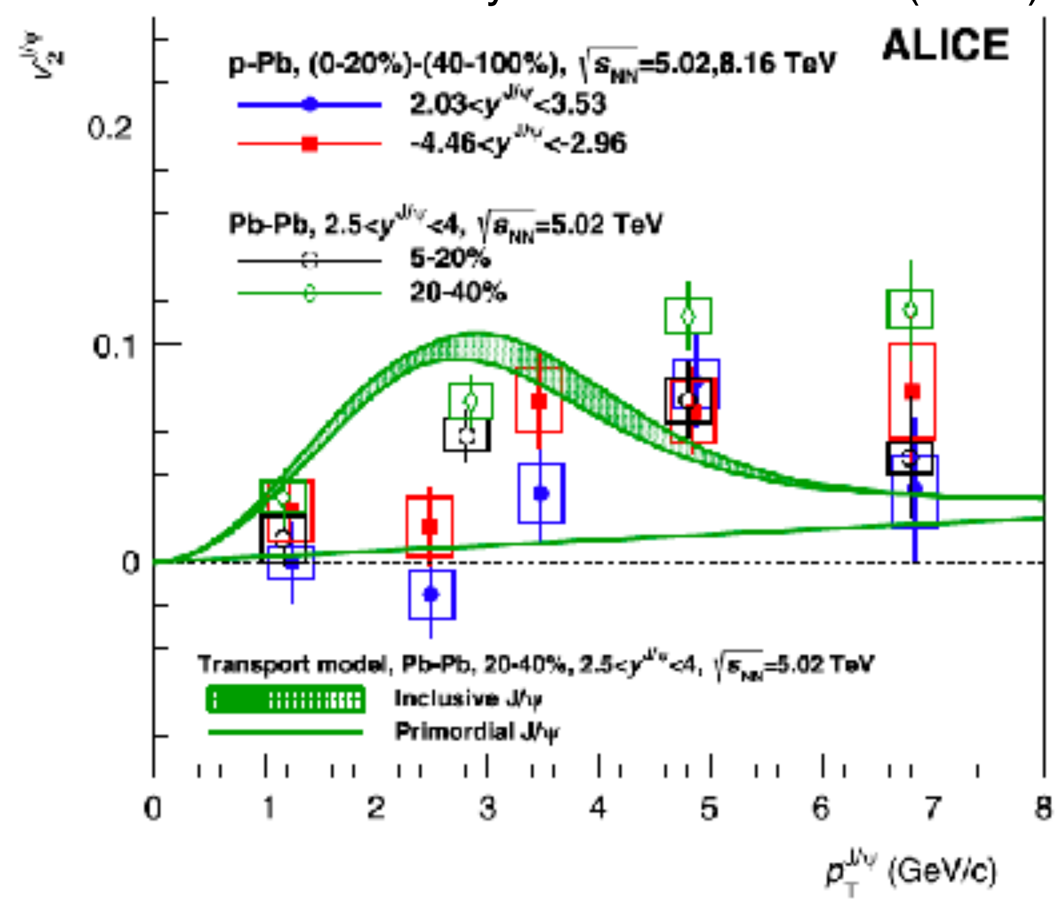

- $v_2$ in Pb going is larger by 16%±6% than in p going.
- p going side probe small-x in Pb while large x in Pb going.
- Multiplicity in Pb going is larger than in p going.
- AMPT trend is similar to the data.

# $v_2$ of Heavy flavor decay electron and J/Ψ

arXiv:1805.0436

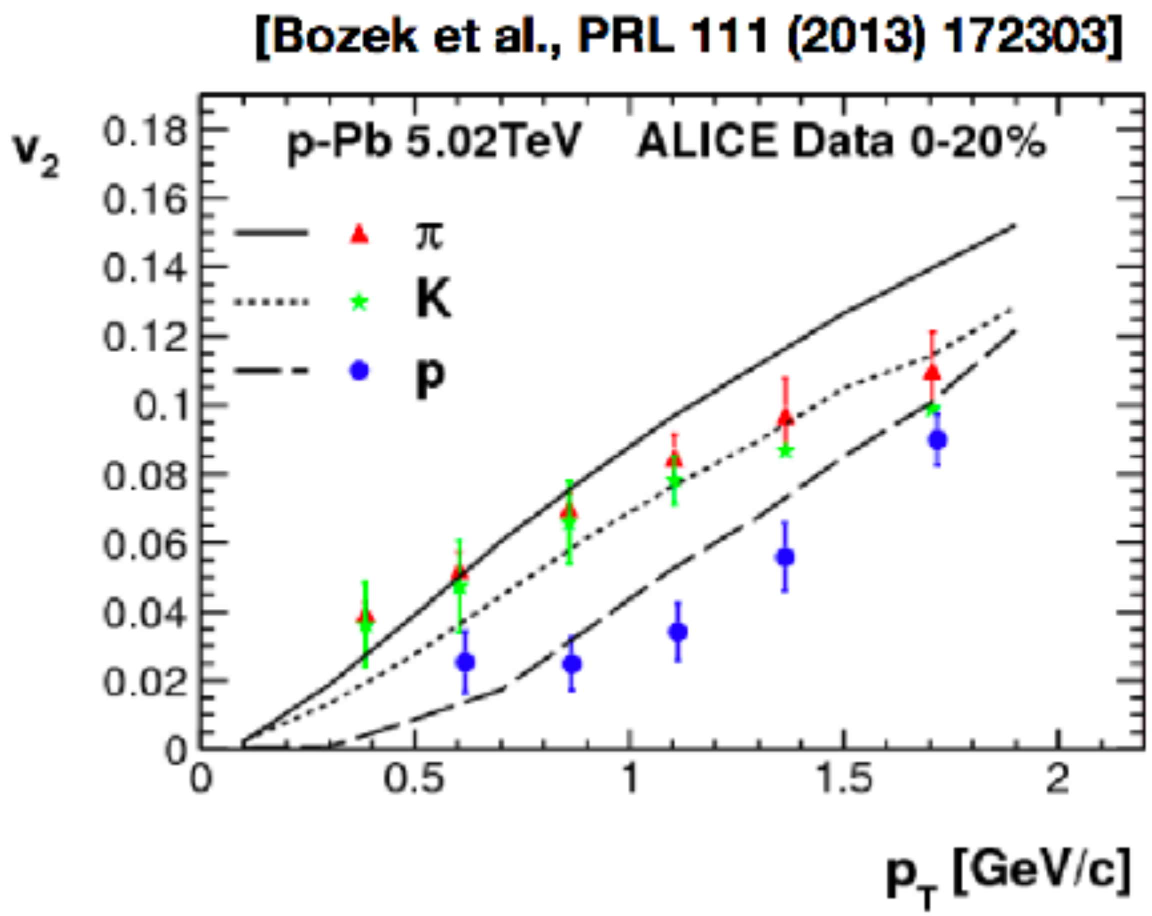


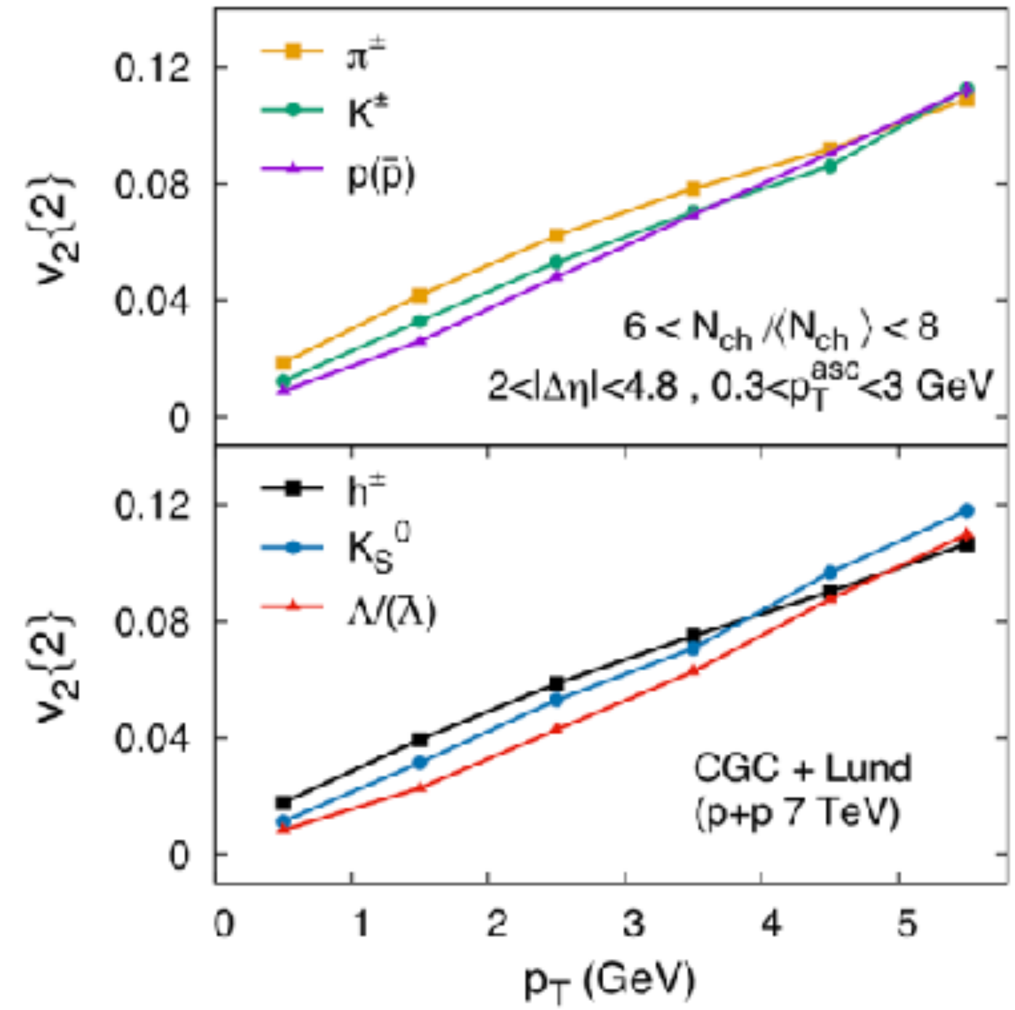

Physics Letters B 780 (2018)




- HFe $v_2$ is significant with more than 5σ at $1.5<p_T<4$.
- Significant J/ψ $v_2$. Evidence of charm flow.
- Large $v_2$ even at high $p_T$.

# Model comparison




- Hydro describes data in pPb.
- Initial effects only reproduce mass ordering in pp.
  - qualitatively similar to CMS results in pp for h, $k^0_s$, and Lamda.

▶ Need to disentangle initial and final state dynamics.
- ▶ $v_2(\eta)$, correlation of different harmonics, event plane decorrelation.
  - ▶ $v_2(\eta)$ is sensitive to longitudinal dynamics.
  - ▶ Correlation of different EP are sensitive to transverse + longitudinal fluctuation.

# Event plane decorrelations in PbPb

Phys. Rev. C 92 (2015)

- $r_2(\eta^a,\eta^b)$ is defined as

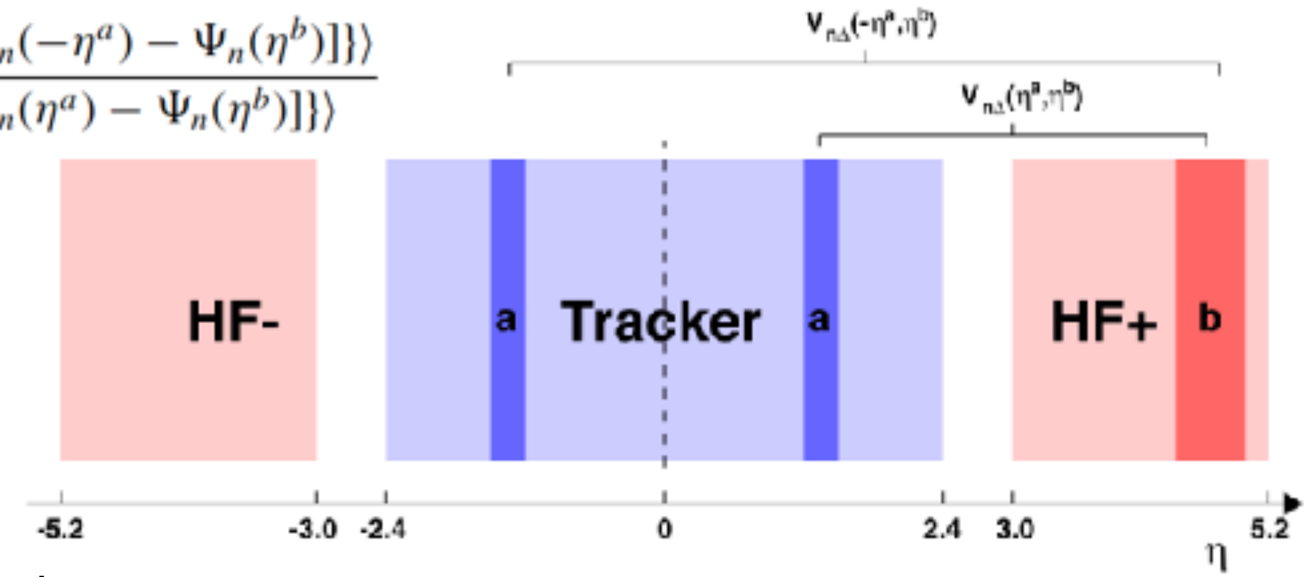
$$r_n(\eta^a,\eta^b) \equiv \frac{V_{n\Delta}(-\eta^a,\eta^b)}{V_{n\Delta}(\eta^a,\eta^b)} = \frac{\langle v_n(-\eta^a)v_n(\eta^b)\cos\{n[\Psi_n(-\eta^a)-\Psi_n(\eta^b)]\}\rangle}{\langle v_n(\eta^a)v_n(\eta^b)\cos\{n[\Psi_n(\eta^a)-\Psi_n(\eta^b)]\}\rangle}$$

- Simple empirical parametrization is introduced

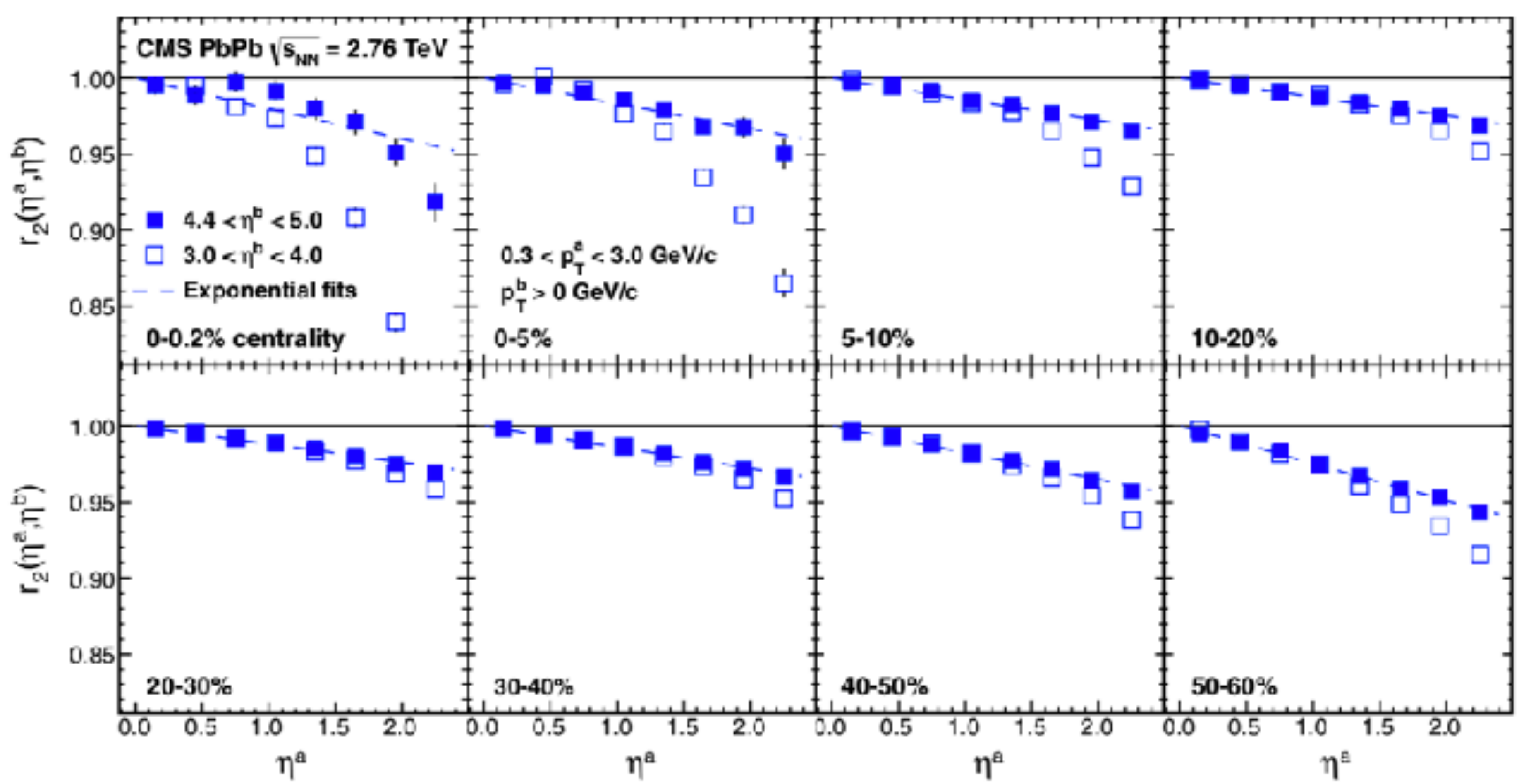
$$\cos\{n[\Psi_n(\eta^a)-\Psi_n(\eta^b)]\} = e^{-F_n^\eta|\eta^a-\eta^b|},$$

- $r_2(\eta^a,\eta^b)$ can be expressed as bellow.

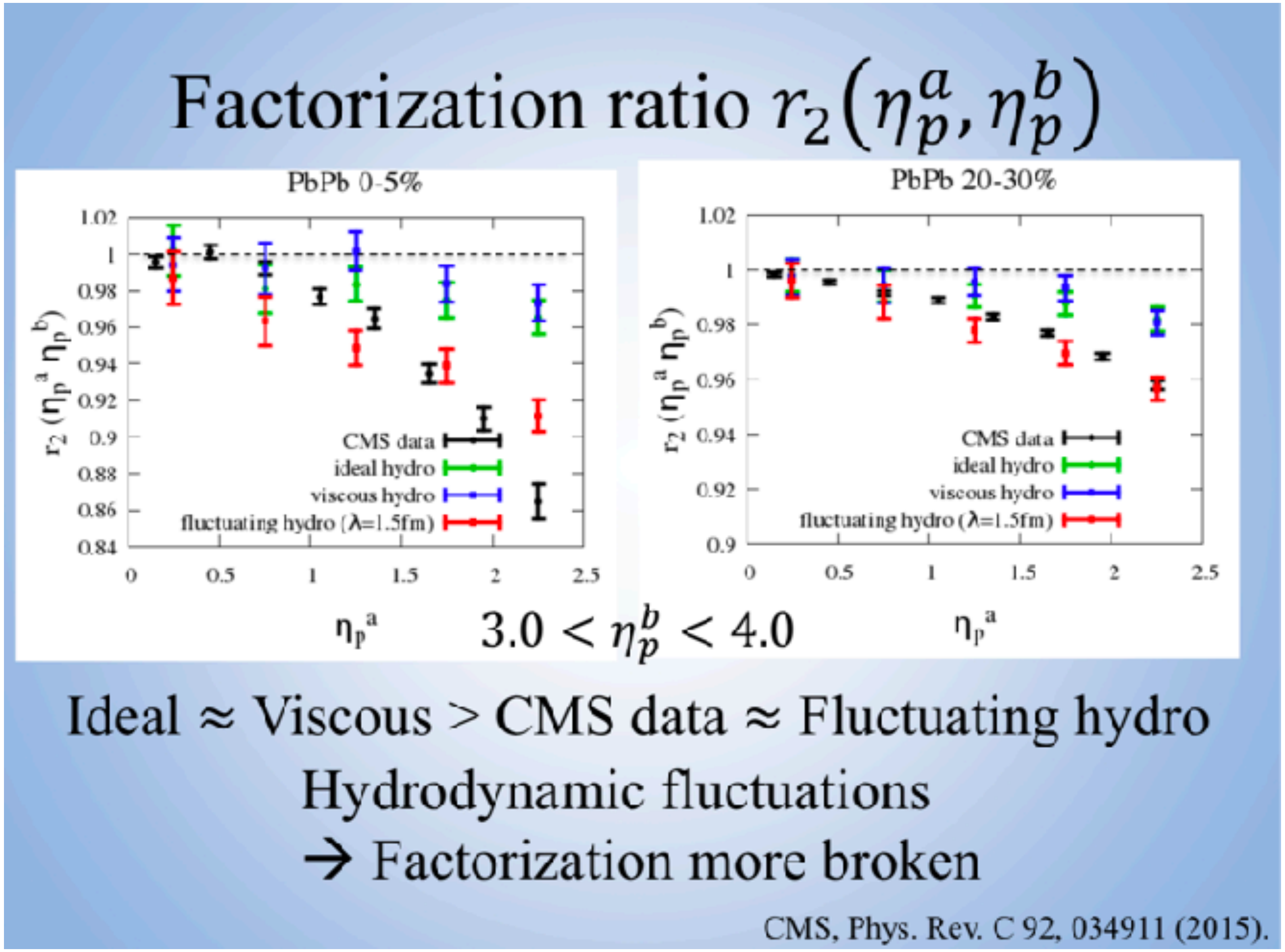
$$r_n(\eta^a,\eta^b) \approx e^{-2F_n^\eta \eta^a}$$




- $r_2(\eta^a,\eta^b)$ decrease significant decrease linearly as $\eta^a$ increase.



# Decorrelation from final effect

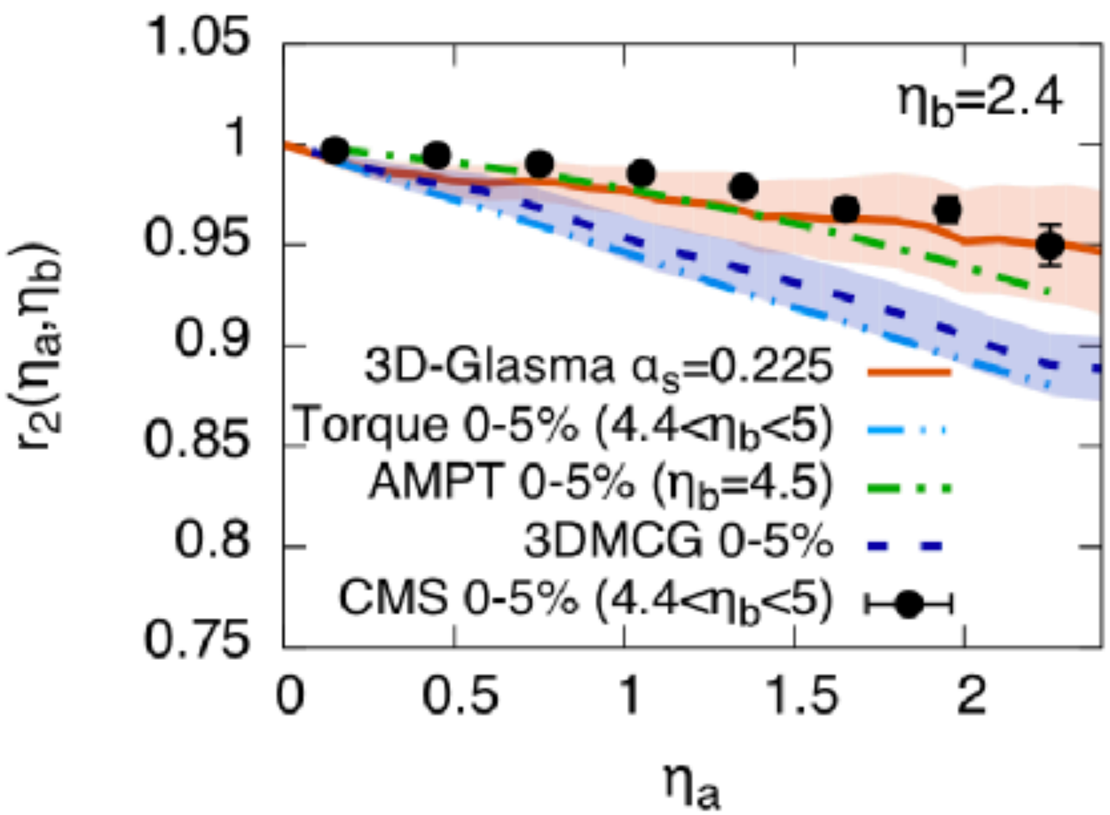


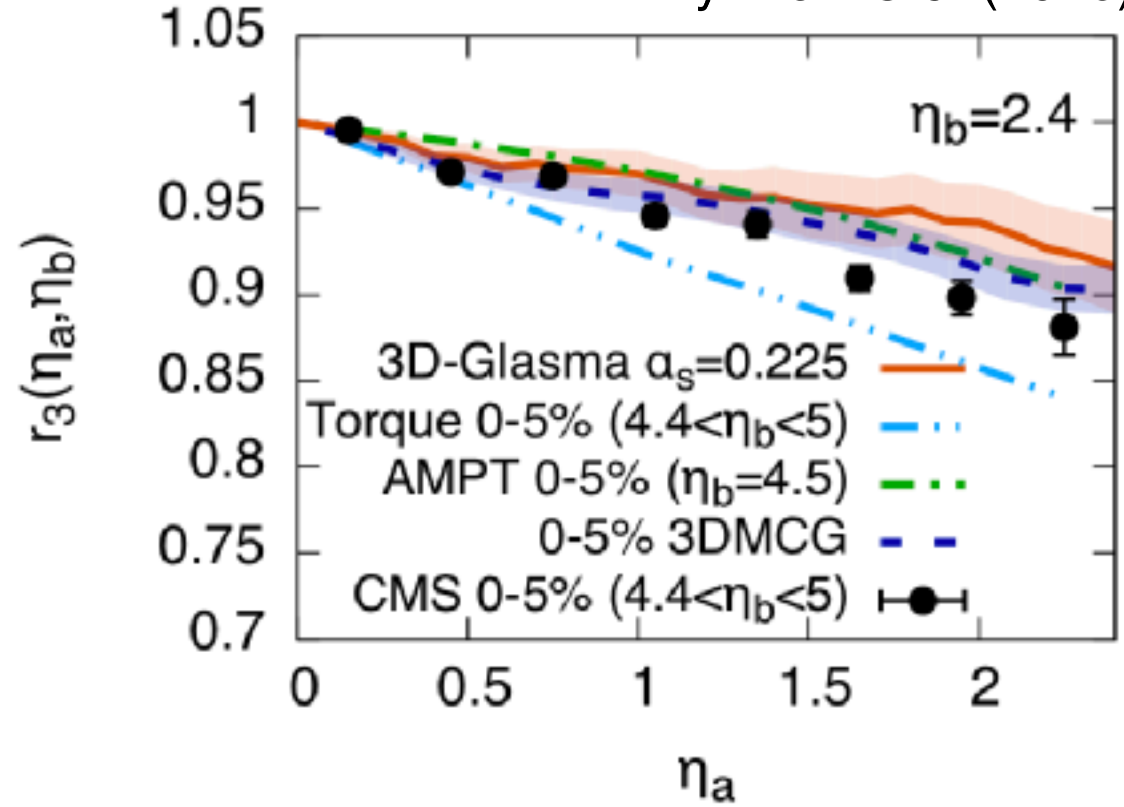

**QM2018**
**A. Sakai**

- Hydrodynamic fluctuation reproduce the CMS data.
- Importance to understand the final state fluctuation(much less in pPb collisions?)

# Decorrelation from initial fluctuation

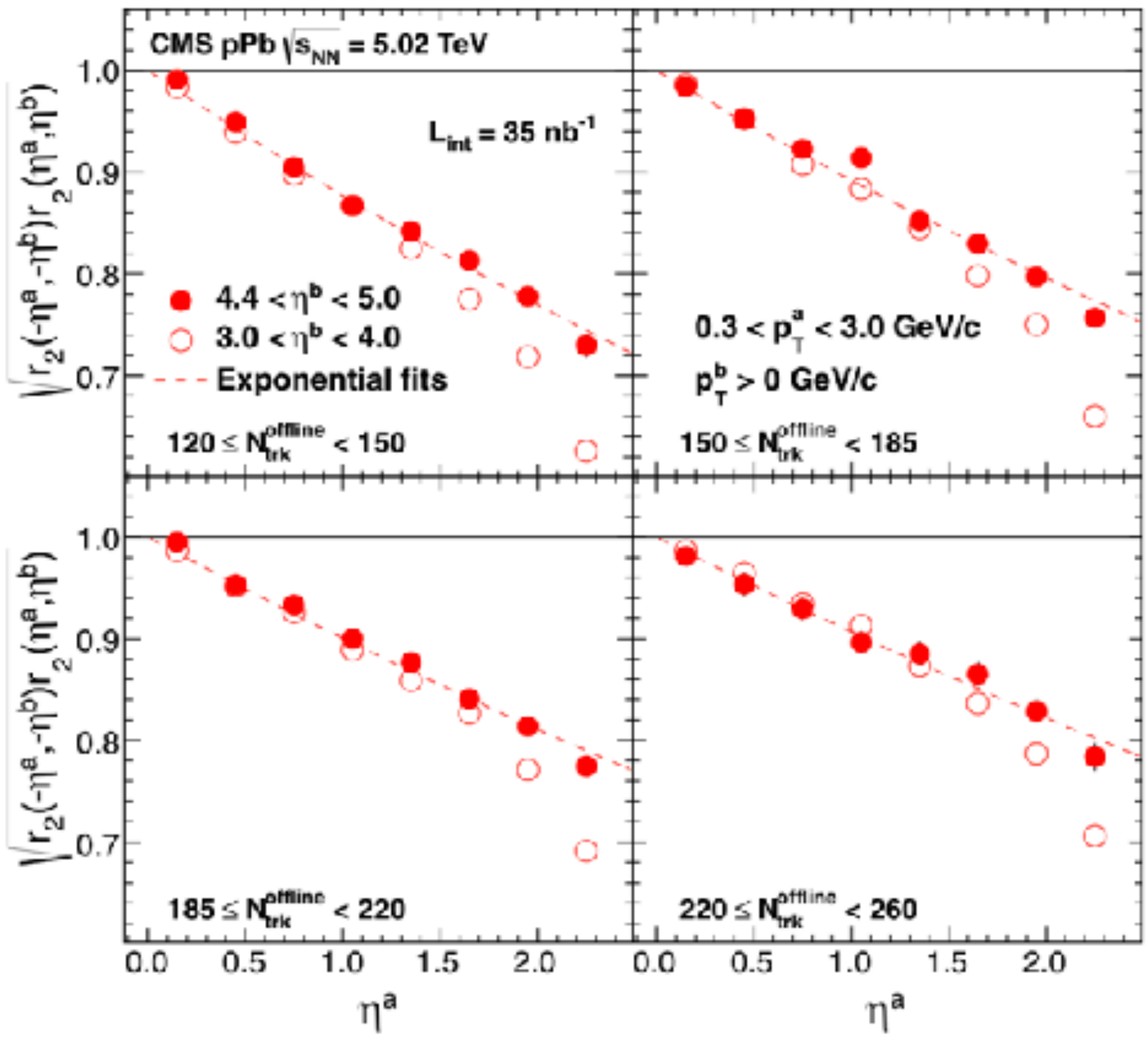
Phy. Rev. C 94(2016)



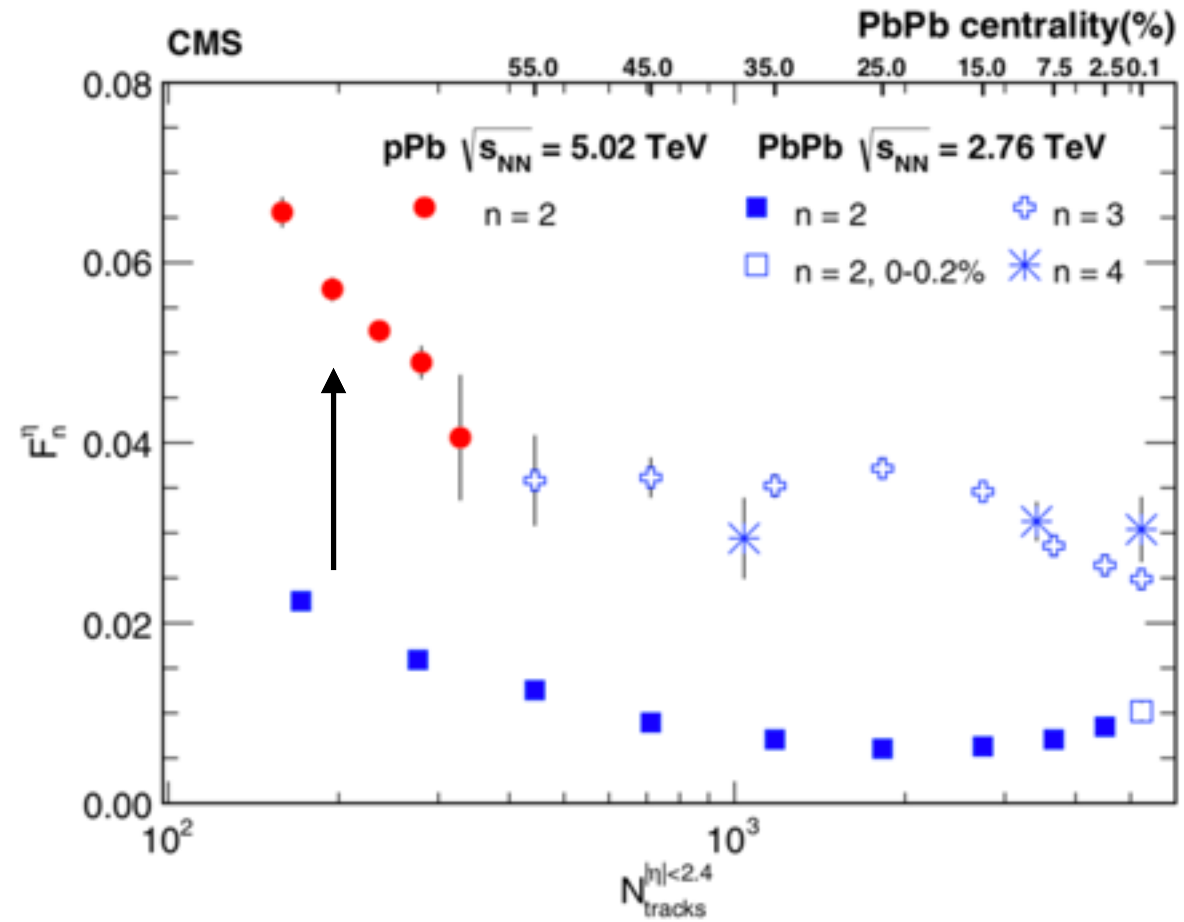




- $r_2(\eta^a,\eta^b)$ is reproduced with the model only with initial fluctuation.
- Both final fluctuation and initial fluctuation can describe data for PbPb.
- Initial fluctuation is much important for pPb.

# Event plane decorrelation in pPb




Phys. Rev. C 92 (2015)



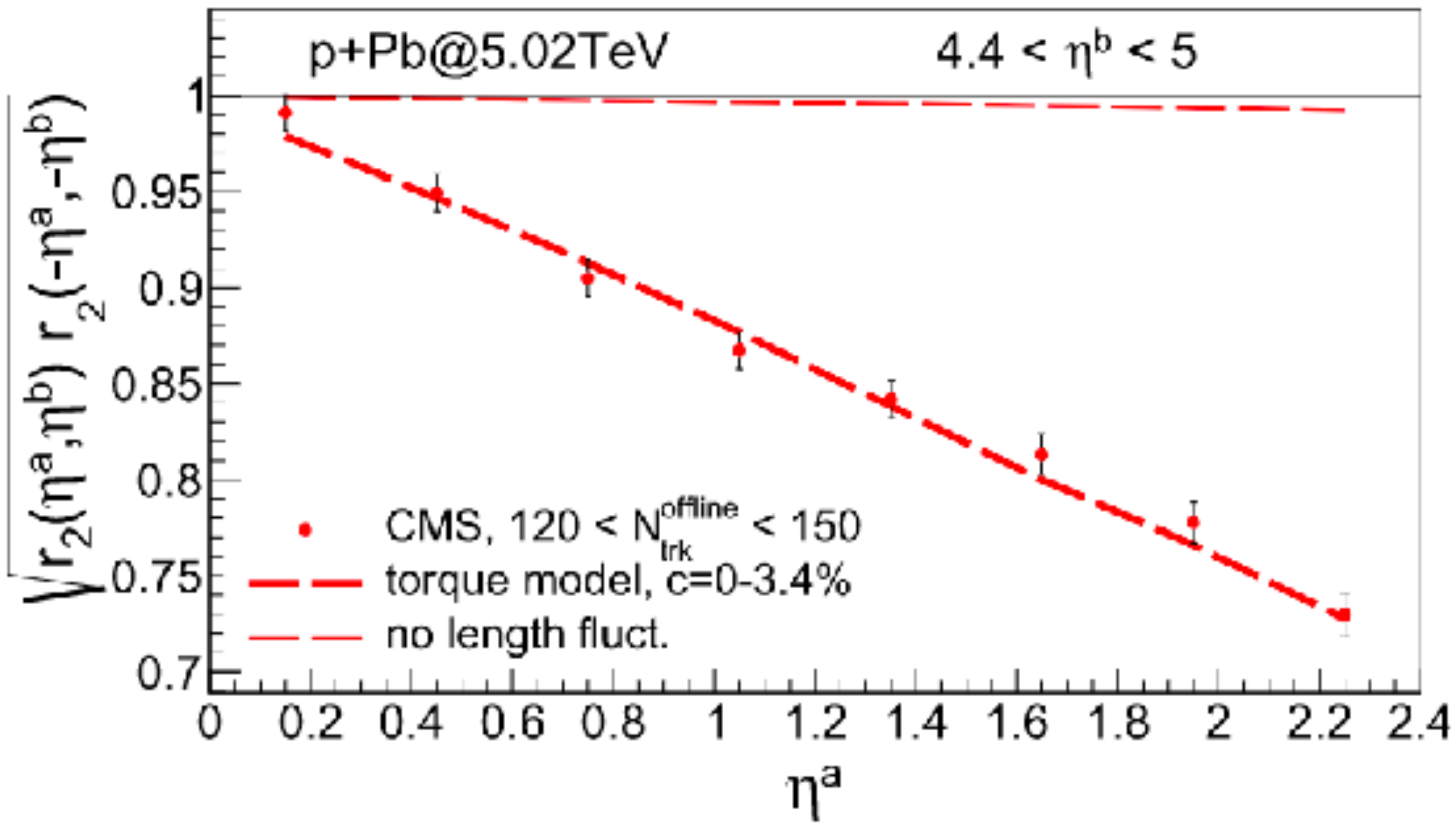

- Use following equation to remove magnitude $v_2$.

$$\sqrt{r_n(\eta^a,\eta^b)r_n(-\eta^a,-\eta^b)} \approx \sqrt{\frac{\langle\cos\{n[\Psi_n(-\eta^a)-\Psi_n(\eta^b)]\}\rangle}{\langle\cos\{n[\Psi_n(\eta^a)-\Psi_n(\eta^b)]\}\rangle}\frac{\langle\cos\{n[\Psi_n(\eta^a)-\Psi_n(-\eta^b)]\}\rangle}{\langle\cos\{n[\Psi_n(-\eta^a)-\Psi_n(-\eta^b)]\}\rangle}}. \quad \approx e^{-2F_n^\eta\eta^a}$$

- $F^\eta_n$ in pPb is larger than in PbPb.

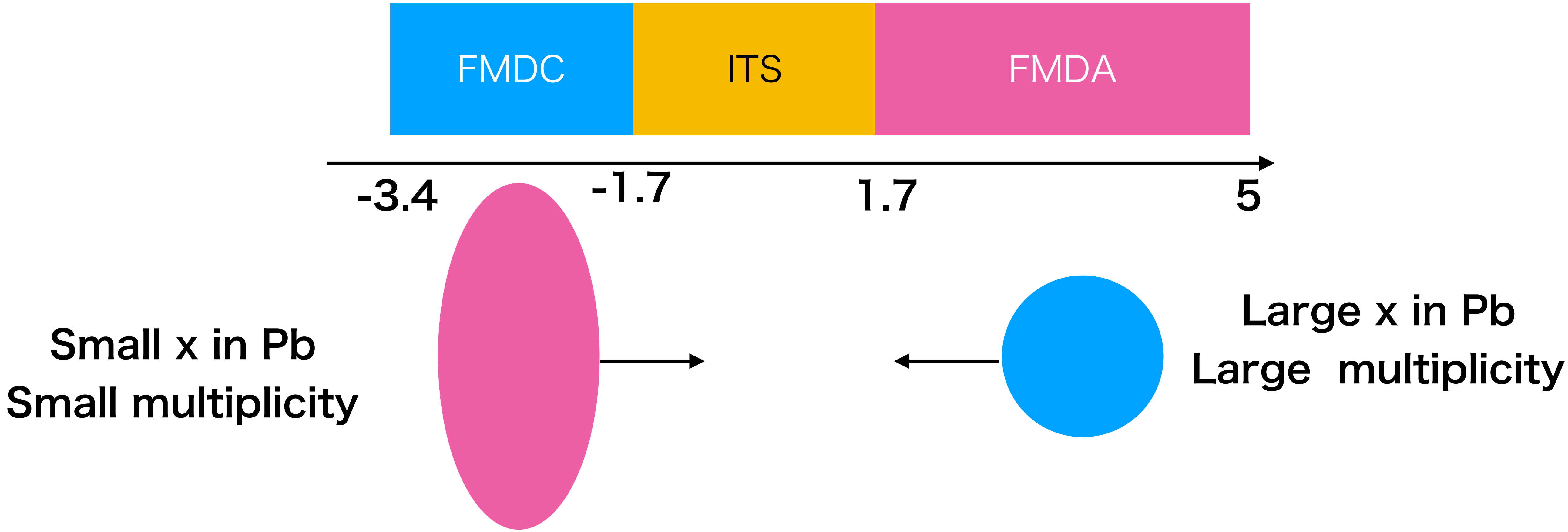
# Event plane decorrelation in pPb

Physics Letters B 752 (2016)

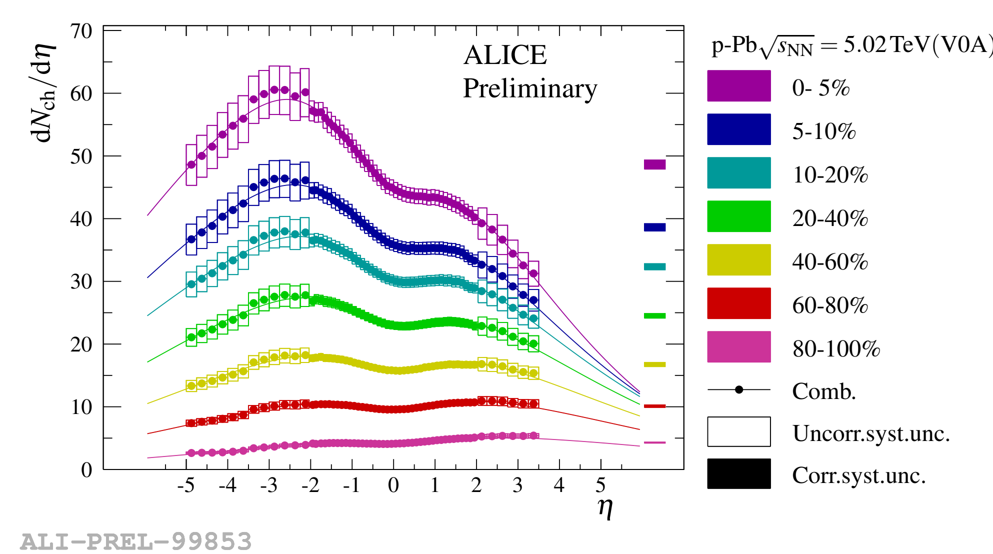



- Initial fluctuation, Toque model, describe data well.
- The model describe also $r_2$ and $r_3$ of PbPb for semi-central and peripheral collisions.
- Further accurate simulation with 3+1D hydro and nonflow.

# Outlook: Central-Forward-Backward correlations in pPb collisions with ALICE




- $v_2(\eta)$ with Central-forward, Central-backward, and Forward-Backward.
  - Suppress non-flow by large eta gap.
- Correlation of Event plane
- Correlation of $v_2$ and $v_3$ at forward rapidity.



# Summary

- Long range correlation is observed in p-Pb collisions.
  - Mass ordering in mid rapidity.
  - Similar to Pb-Pb collisions.
  - Hydro and CGC described data.
  - Significant $v_2$ of heavy flavor decay electrons.
  - Significant $v_2$ of J/ψ.
- Correlation between forward muon and charged hadrons
  - $v_2$ in Pb going is larger by 16%±6% than in p going.
  - AMPT trend similar to data at low $p_T$.
- Event plane decorrelation
  - Empirical parameter $F^{\eta}_{n}$ quantifies a Δη-dependent event-plane decorrelation
  - Hydrodynamic fluctuation and initial fluctuation describe the data.

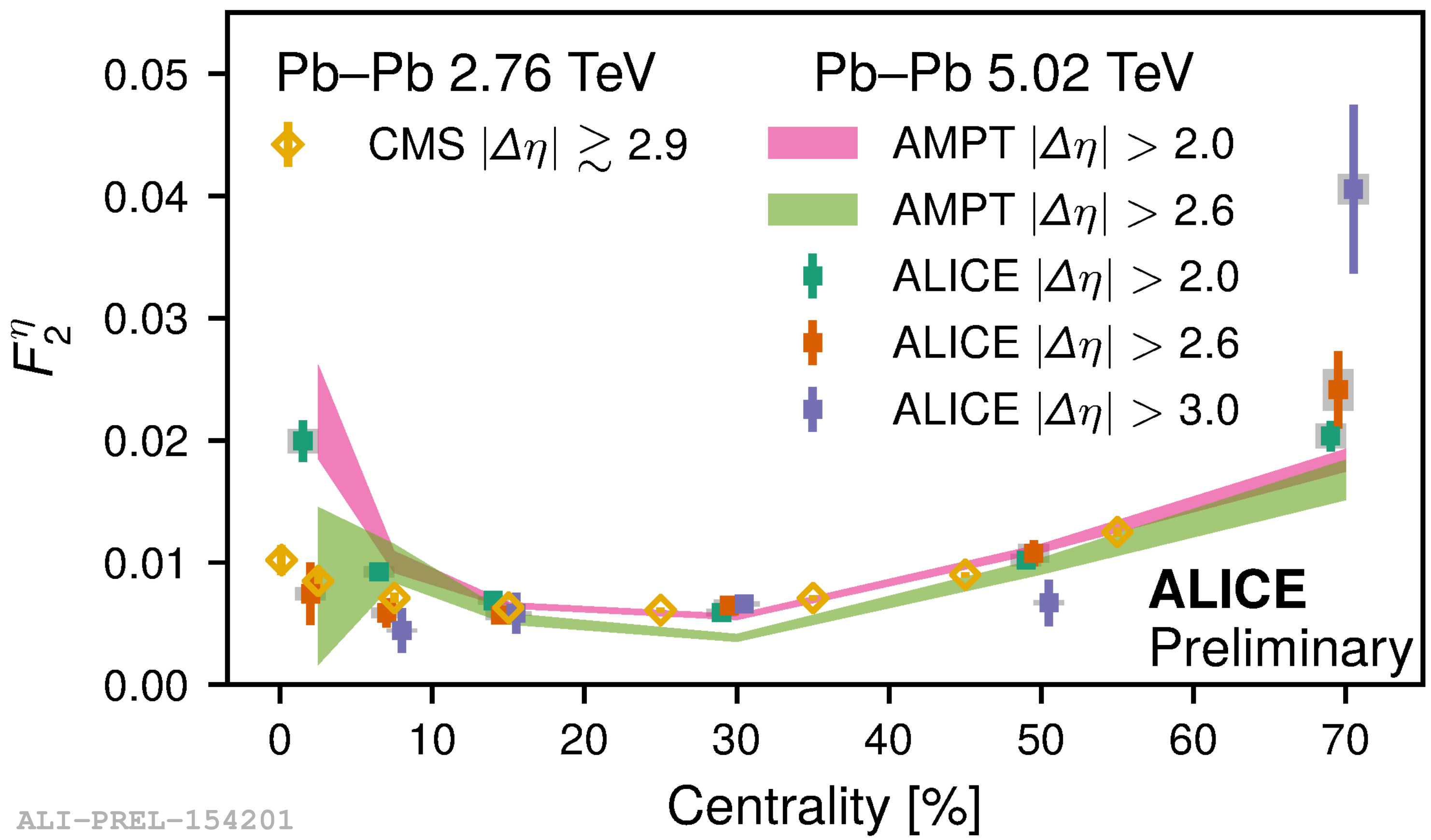
▶Further measurements are needed to understand origin of ridge.

# backup

# Event plane decorrelation

- $v_n(\eta^a, \eta^b)$ is assumed to be factorized into flow coefficients and a simple event plane decorrelation factor.

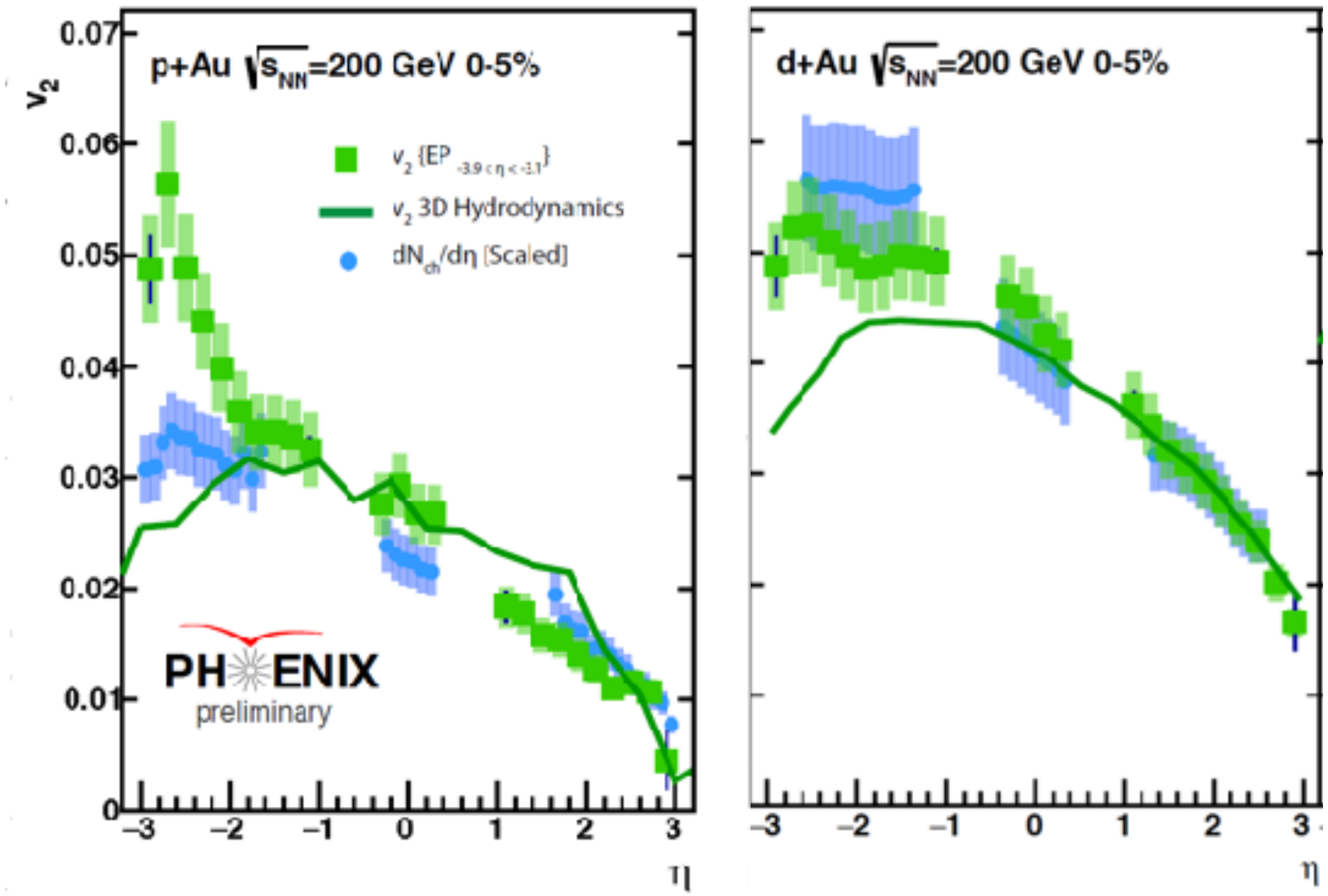
$$\hat{v}_n(\eta^a, \eta^b) = v_n(\eta^a) v_n(\eta^b) e^{-F_n^\eta |\eta^a - \eta^b|}$$

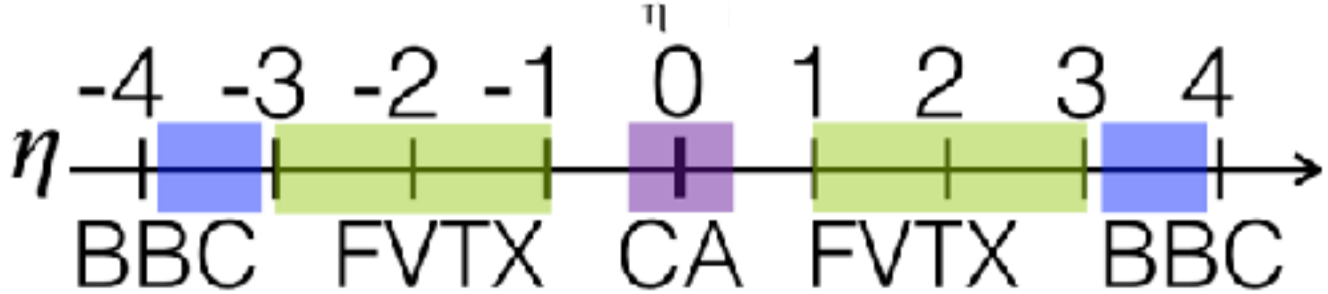


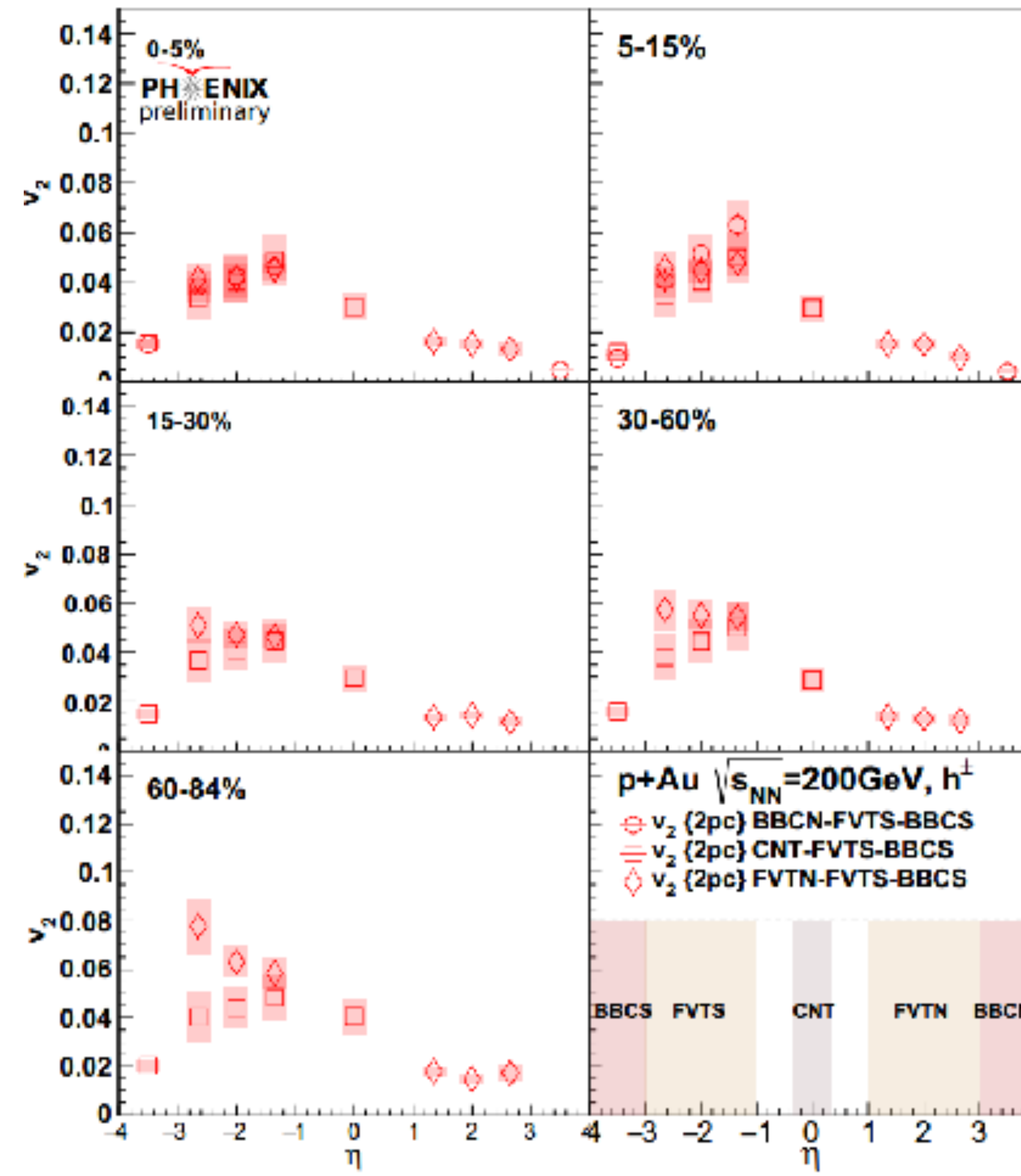

**QM2018**
**C. Boujau**

- Empirical parameter $F^\eta_n$ quantifies a Δη-dependent event-plane decorrelation.
- $F^\eta_n$ depends on centrality.
- Consistent with CMS results.
- AMPT also describe the data.
  - Initial fluctuation is propagated to decorrelation.

# $v_2$ as a function of pseudo-rapidity in small system in RHIC



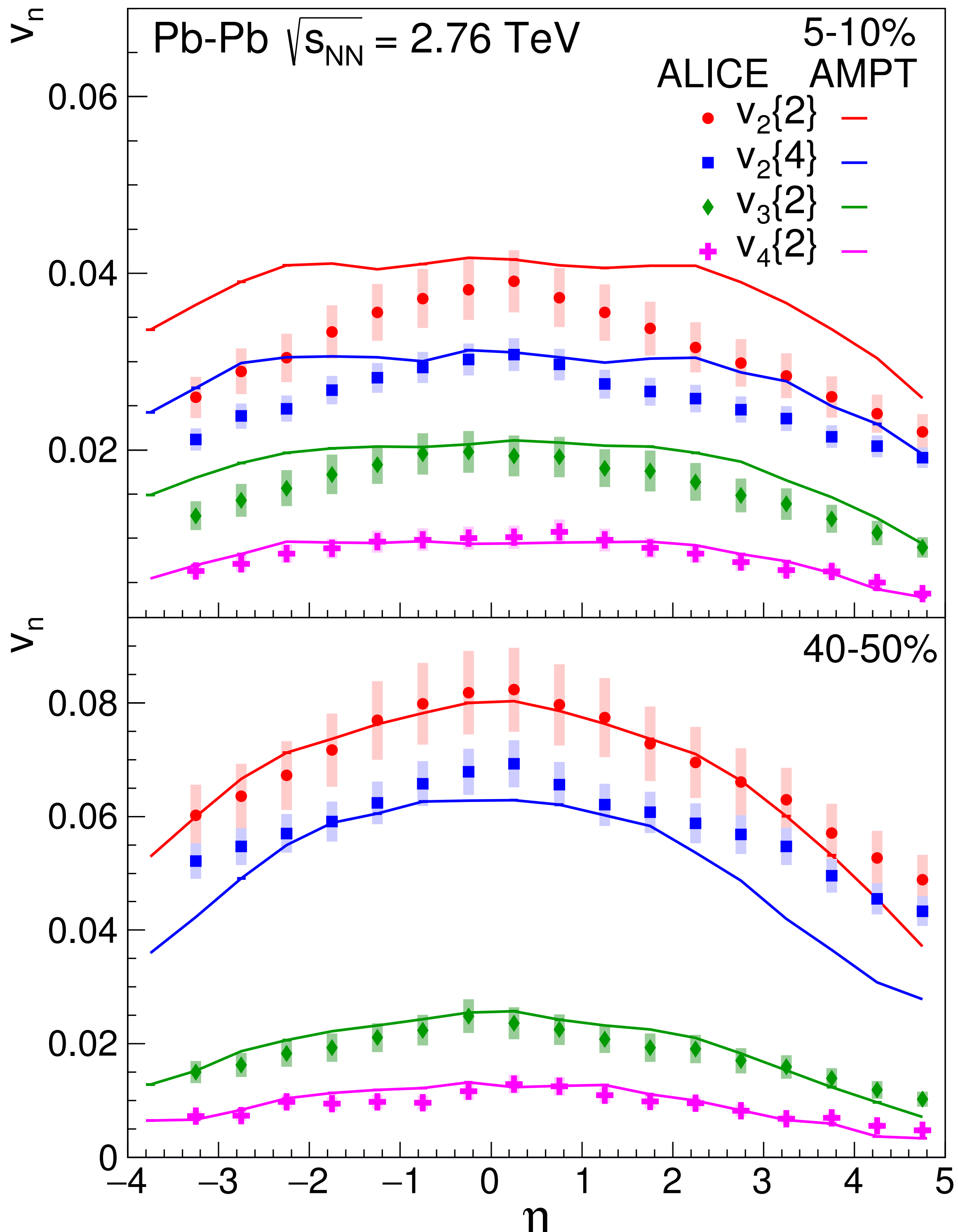




- Au going is larger than p/d going.
- 3D hydro describes d-Au well and p-Au except $\eta<-2$ in Au-going.
- 2 particle correlations with large $\eta$ gap can suppress non-flow effects.

# Investigate initial condition in PbPb

- The understanding of the initial condition is crucial for the subsequent hydrodynamic expansion.



# Perfect factorization model

- The two-particle Fourier coefficients $v_{n,n}(\eta^a, \eta^b)$ are computed from the reduced two-particle distribution $r_2$.

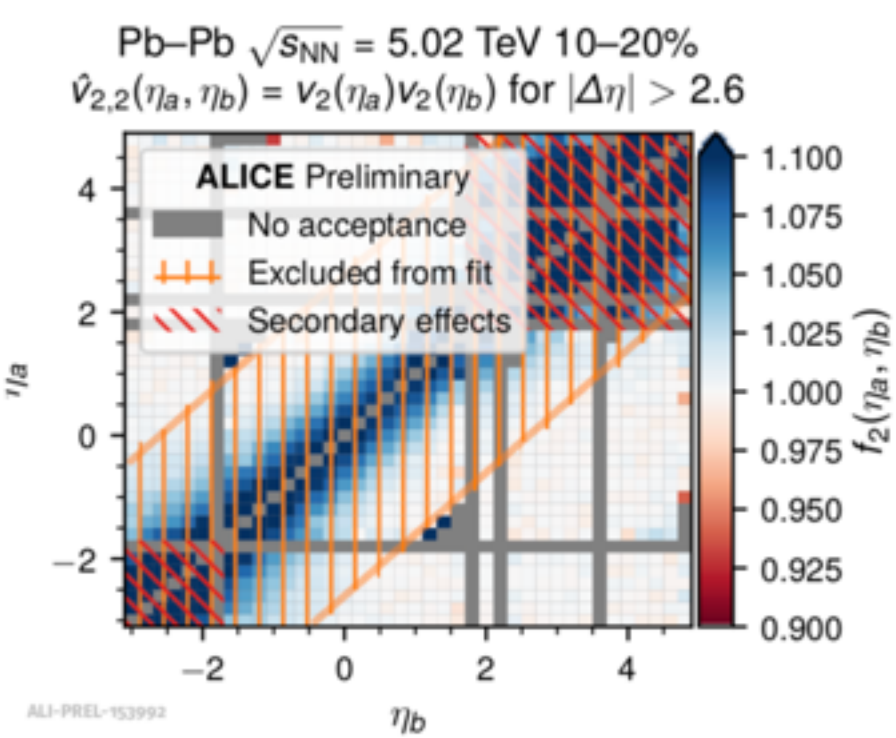
$$r_2(\eta^a, \eta^b, \phi^a, \phi^b) = \frac{< n_a n_b >}{< n_a >< n_b >} \xrightarrow[transform]{Fourier} \hat{v}_{n,n}(\eta^a, \eta^b)$$

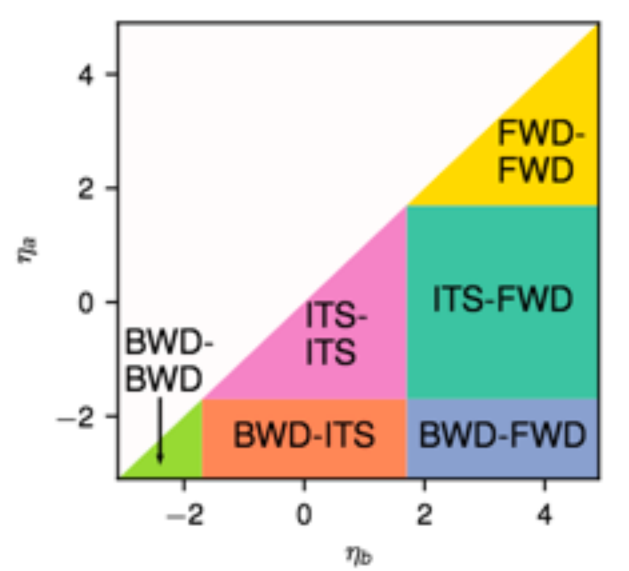
$$\hat{v}_{n,n}(\eta^a, \eta^b) = v_n(\eta^a) v_n(\eta^b) f_n(\eta^a, \eta^b)$$

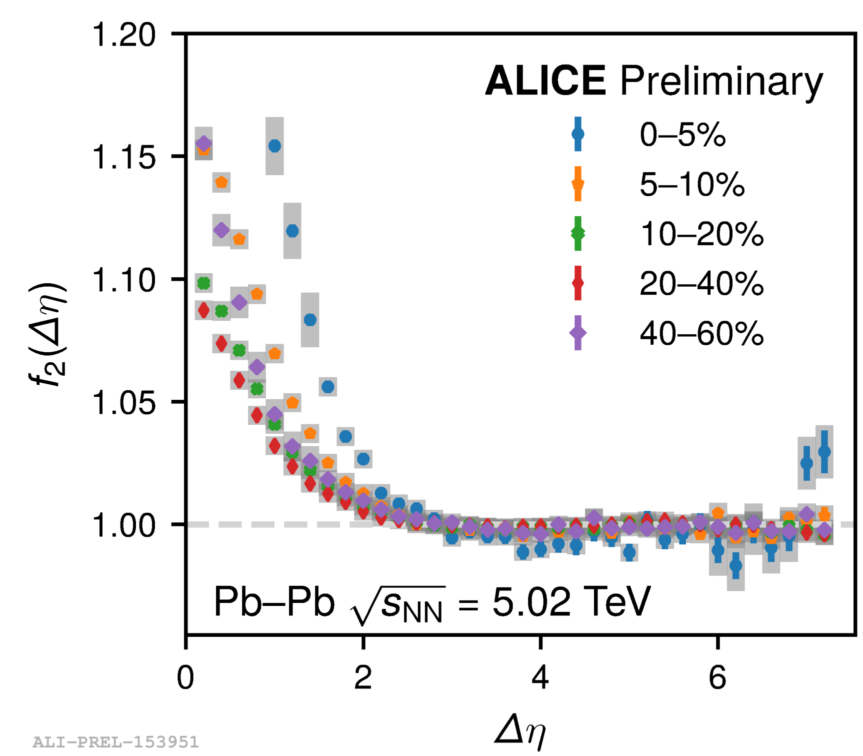
$$f_n(\eta^a, \eta^b) = \frac{\hat{v}_{n,n}(\eta^a, \eta^b)}{v_2(\eta^a) v_2(\eta^b)}$$

**Factorization hold** $\longrightarrow f_n(\eta^a, \eta^b) = 1$

**Factorization break** $\longrightarrow f_n(\eta^a, \eta^b) \neq 1$




- Factorization assumption holds well for $|\Delta\eta| > 2.6$